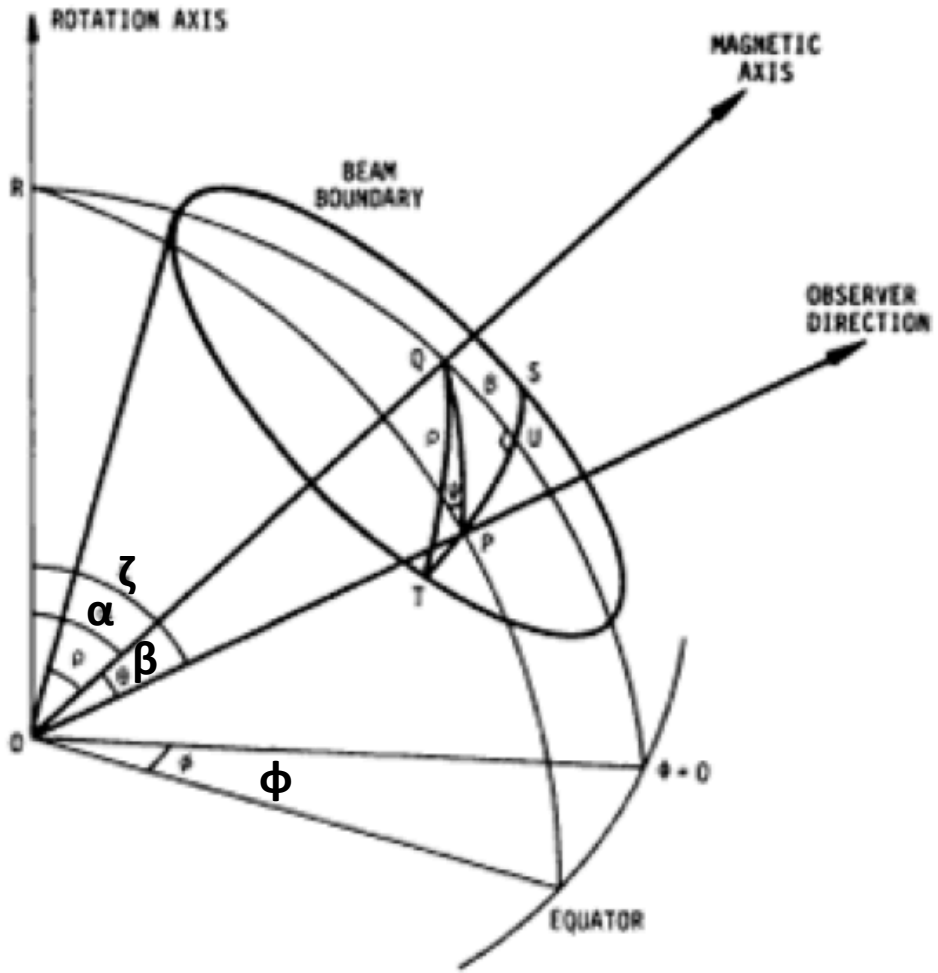
Is there a useful connection between the pulsar magnetosphere geometry and PWN morphology?

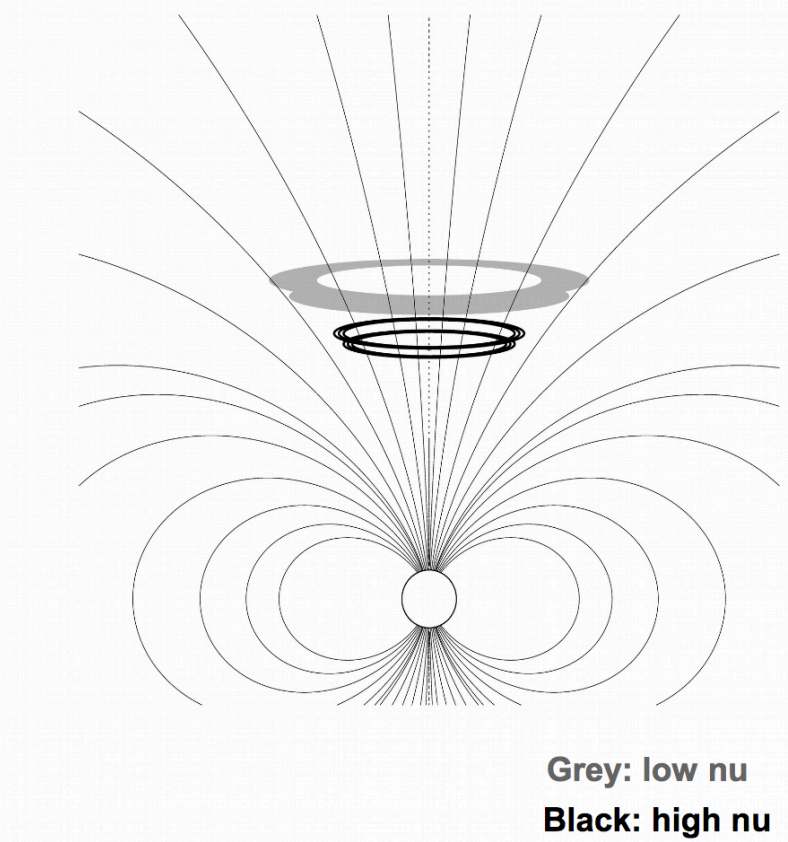
O. Kargaltsev (GWU)

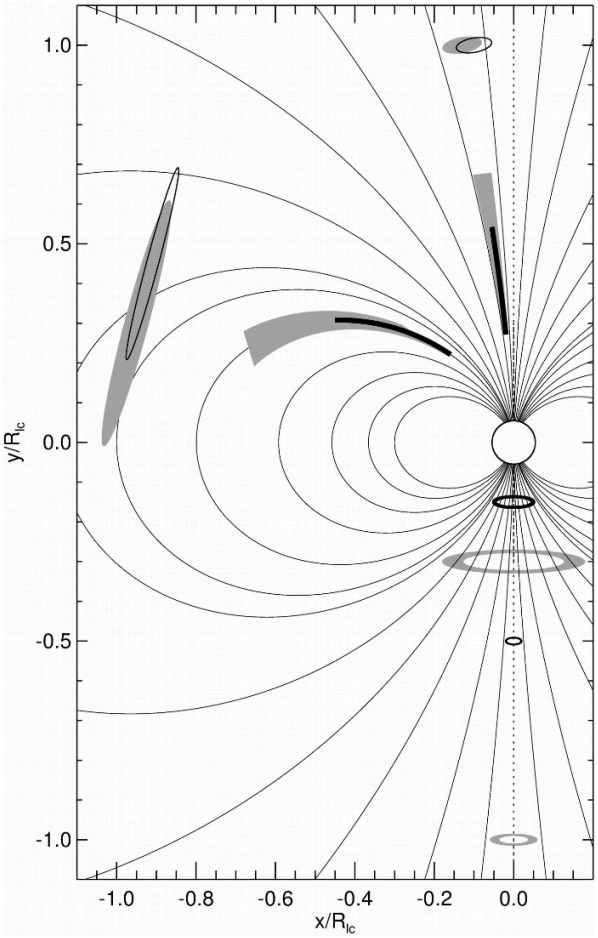
Introduction: Rotating Vector Model RVM



Radio emission

Geometry of radio emission is not simple (not pensil beams), possibly more something like on the left. Radio profiles of older pulsars shown in this review tend to be simple, more like a single pulse or two pulses separated by 0.5 in phase. For younger pulsar there likely to be region in the outer magnetosphere that radiate in the radio.





from Dykes et al. 2015

Dynamic illustration:

- Relativistic effects -> ETA surface would be more complex then dipolar field surface (Romani…)
- Plasma currents distort magnetosphere geometry (Spitkovskii …)
- GR effects also can matter (Petri …)
- We do not know where the high-energy emission is coming from (outer gap, slog gap, two pole outside the light cylinder…) - REFS

Assumptions about lightcurves

- Radio comes from the plasma filled region just above the polar cap (magnetic pole). This seems to be too simplistic to accommodate the data. One must resort to nested hollow cones or fan beam configurations
- Thermal X-rays come from polar cap. Still Ok but in some cases pulse fractions are very high.
- Gamma-rays come crom further away in the magnetosphere

Implications:

- Single (or absent) radio pulse, weak or no gamma-rays -> line of sight is relatively close to magnetic dipole axis which are close to rotation axis
- Strong gamma-rays, no radio, orthogonal rotator viewed close to edge on

Intro:

- Nonthermal emission lightcurves are thought to be the most direct probe of the PWN magnetosphere geometry

Recent lightcurve modeling results:

Atlases are being created by modeling groups:

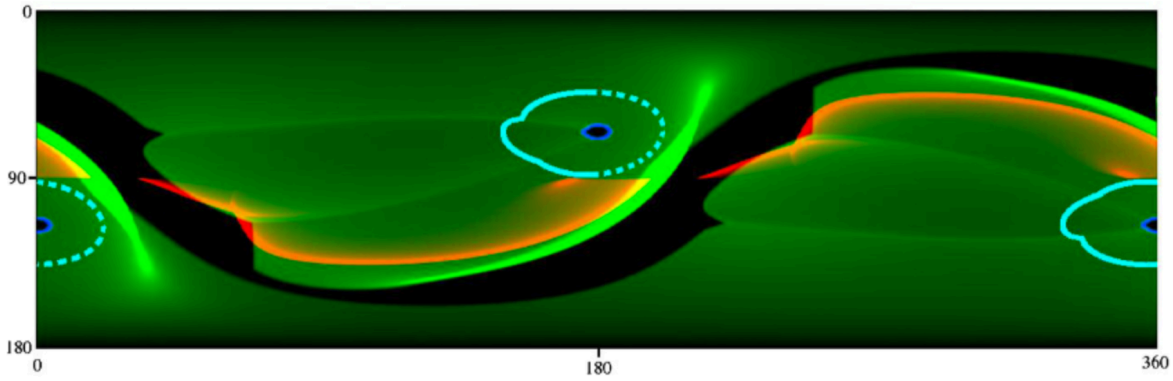
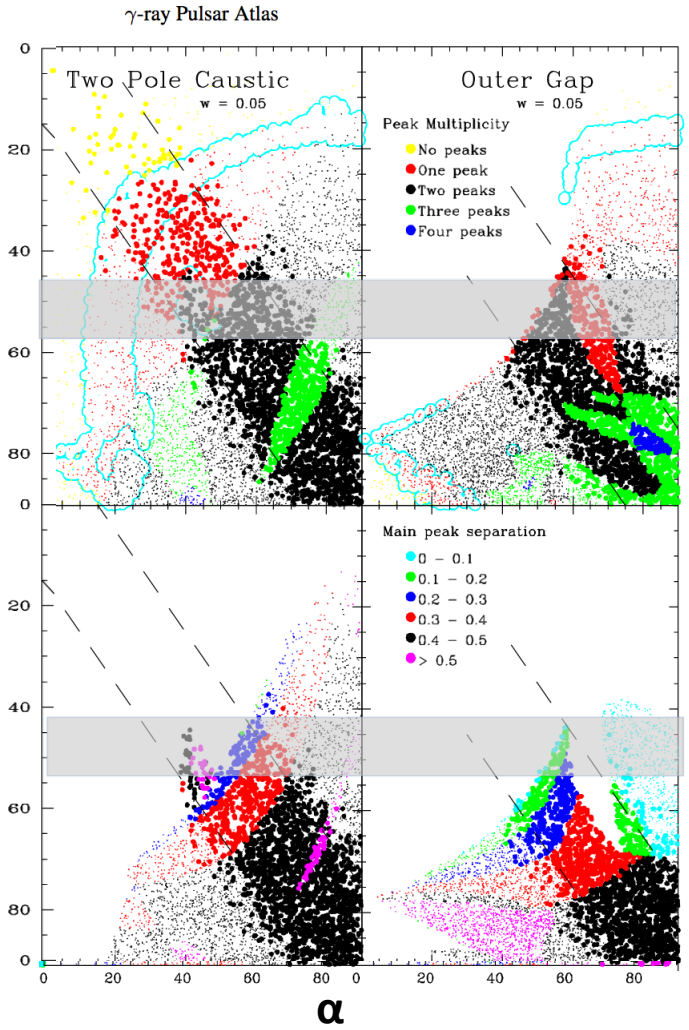


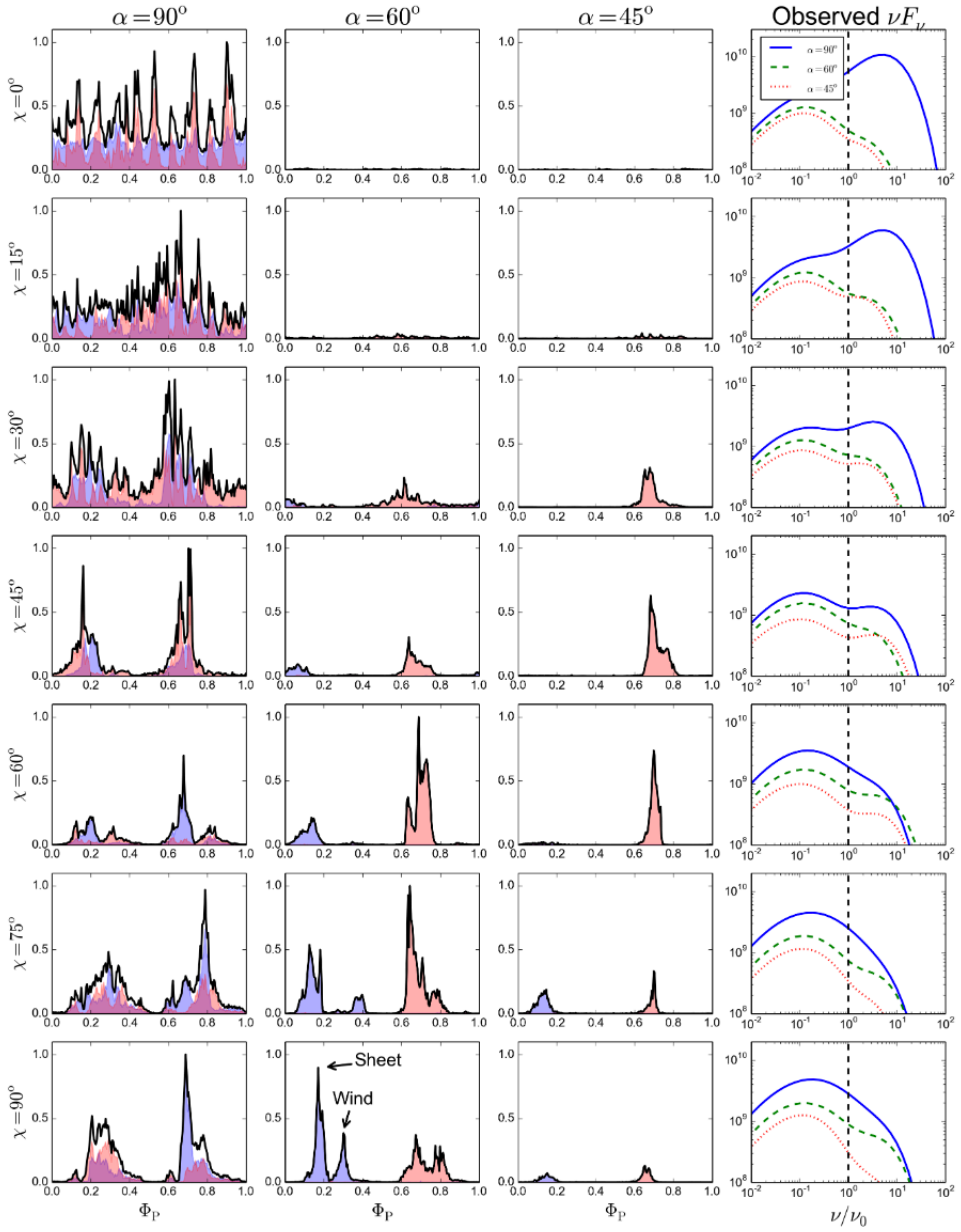
Figure 1. Sample antenna intensity patterns for $\alpha = 65°$ with the horizontal axis of pulsar phase (ϕ) and vertical axis of viewing angle (ζ). The TPC model $w = 0.05$ is shown in green, the OG model for $w = 0.1$ is shown in red, and the PC emission site is shown in blue. The cyan lines show the locus of the possi high-altitude ($r = 500$ km, here for $P = 0.2$ s) radio emission, with the radiating front half shown solid and the back half dashed (see Section 3.3).

Watters et al. 2009

Even knowing only ζ helps a lot!



Lightcurves from first principles



Cerutti et al. 2016

Smaller

Intro:

- Nonthermal emission lightcurves are thought to be the most direct probe of the PWN magnetosphere geometry
- PWNe morphologies can be indicative of magnetosphere geometry and orientation with respect to the observer's line of sight

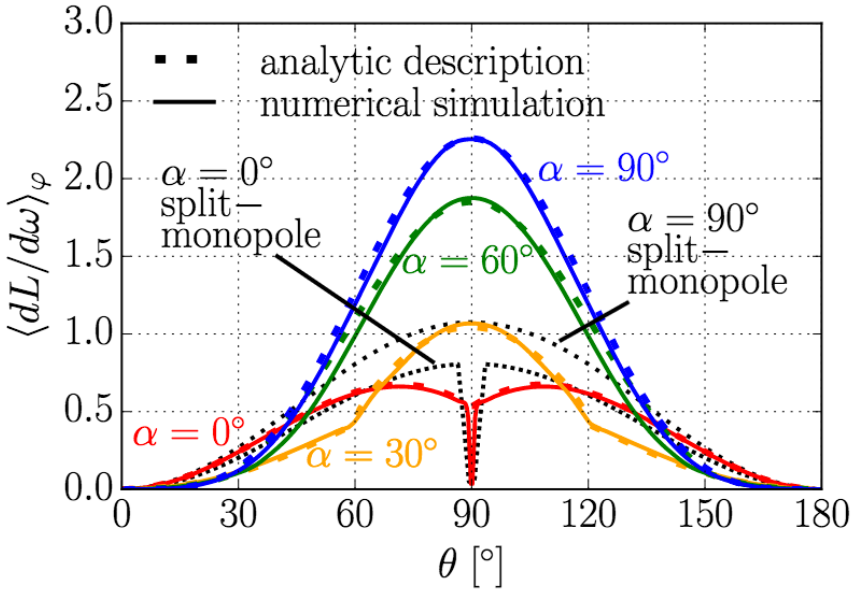
PWN morphlogy:

- Assymetry (e.g. one jet brighter than the other) or the expected ring appears as an ellipese tells about ζ
- PWNe often show equatorial and polar components. Their relative strength is likey to be indicative of the angle α
- One can expect PWN luminosity to be correlated with the size of the reconnection layer in the equatorial plane (absent for aligned rotator)
- Varying PWN X-ray spectra (from uncooled SED) may also be telling something

Simulations:

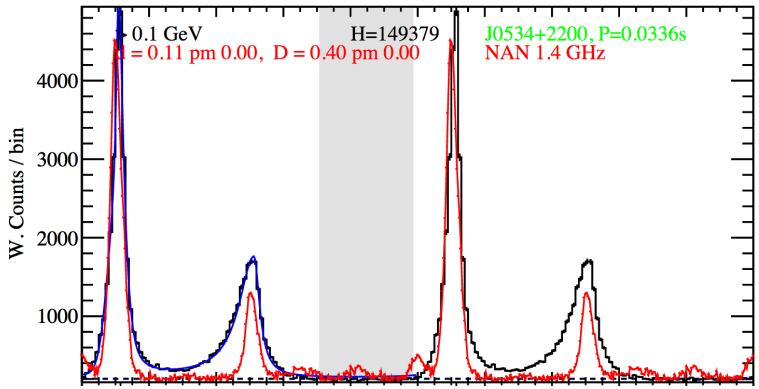
“”…for a field line to contribute to spindown most efficiently, it [magnetic field line] needs to be close to the equatorial plane (θ=π/2). As we tilt the pulsar, its magnetic pole, which is the region of enhanced magnetic field, approaches the rotational equator. This leads to an enhancement in the spindown.”

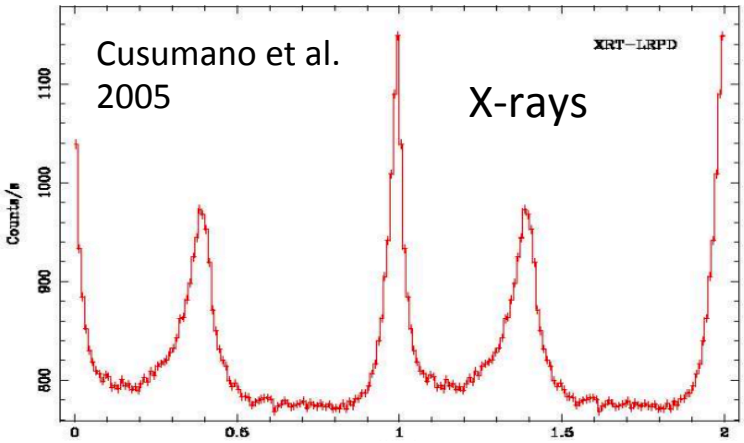
$$\langle S_r \rangle_\varphi \equiv \left\langle \frac{\partial L}{\partial \omega} \right\rangle_\varphi = \frac{\Omega^2}{4\pi c} \langle B_r^2 \rangle_\varphi r^2 \sin^2 \theta,$$

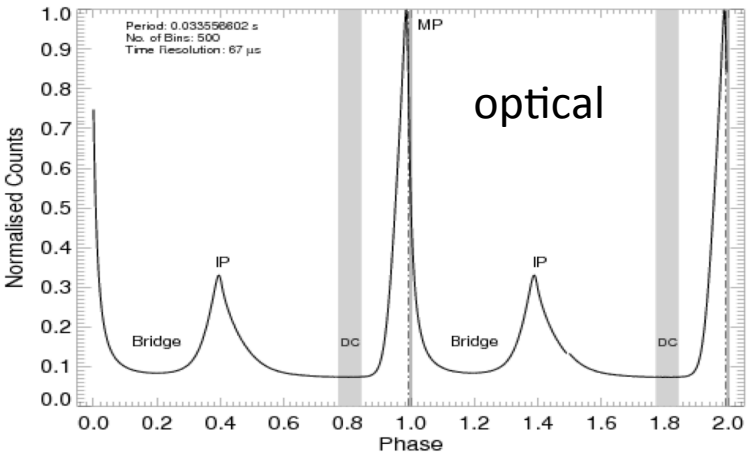


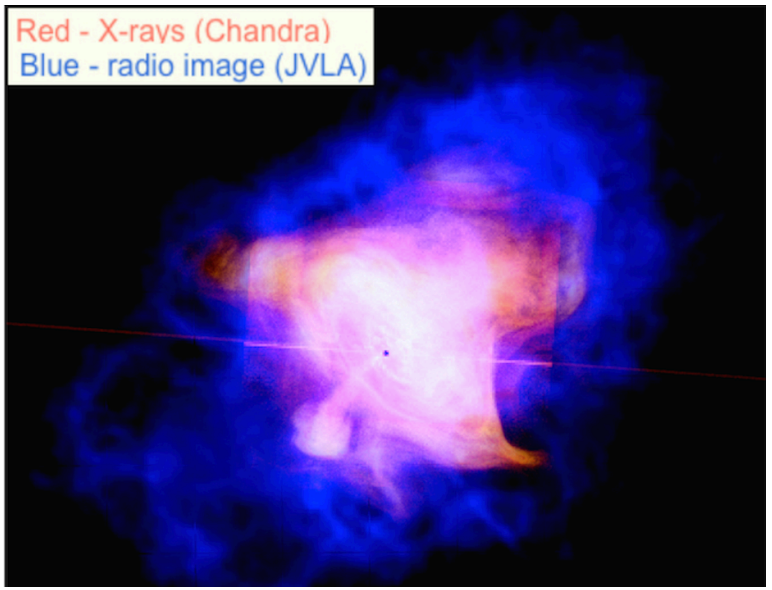
Tchekhovskoy et al. 2016

Confident Examples: Crab





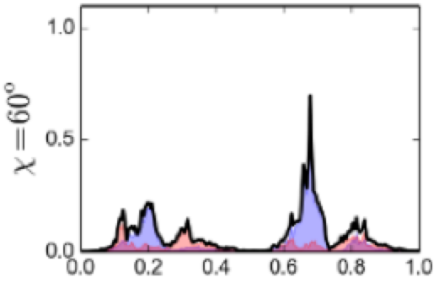




Γ_{PWN}=2.1

PWN suggests: α = 90
ζ= 62 (Ng & Romani 2008)

Likley gamma-rays, X-rays, gamma-rays and radio are produced in nearly the same location in the magnetosphere



Confident Examples: B0540-69

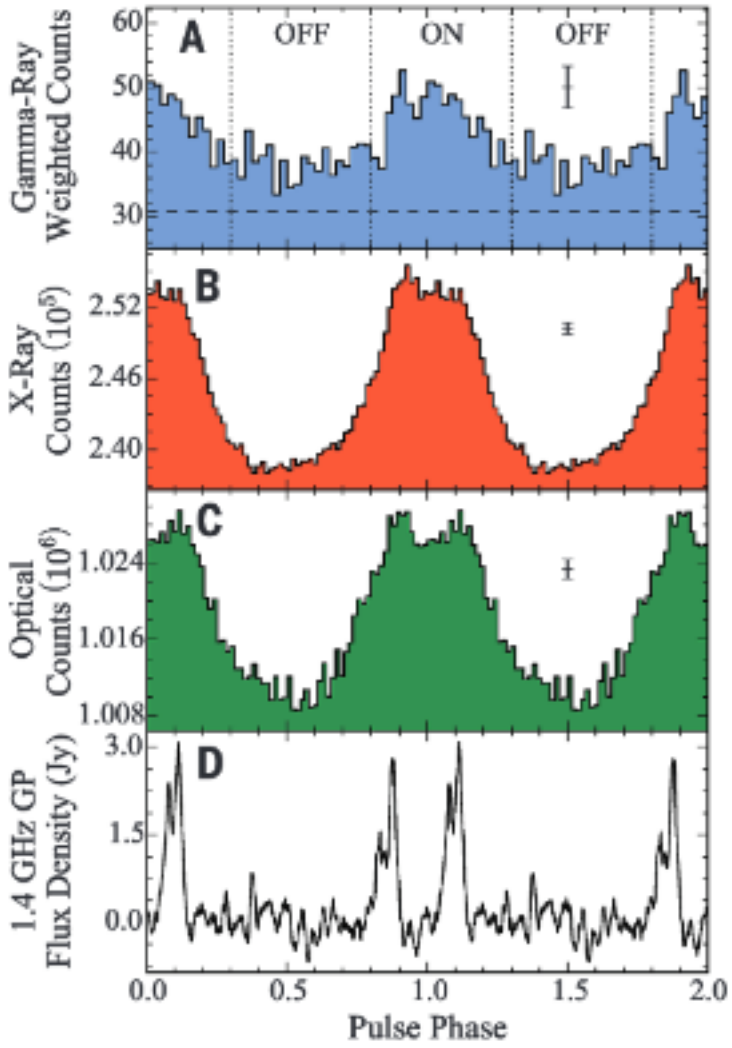
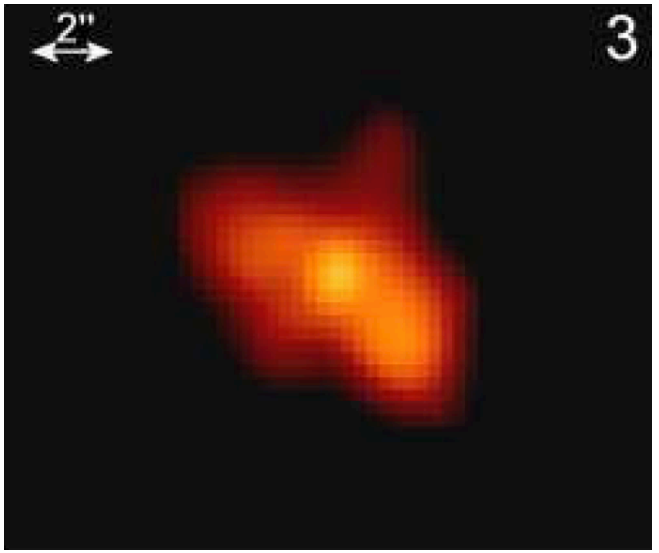


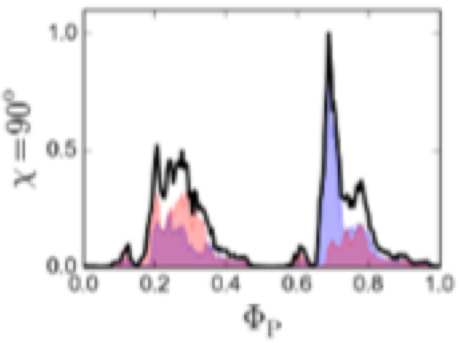
Fig. 2. Pulse profiles for PSR J0540–6919.

Fermi LAT collaboration, 2015

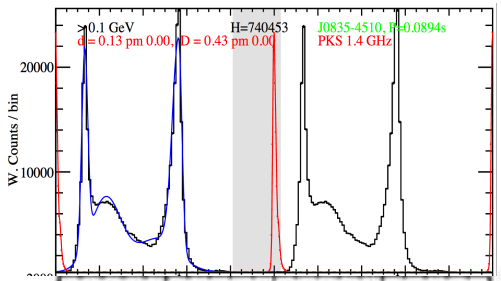


Little Crab? Γ_{PWN}=1.85

PWN suggests: α= Crab, ζ=93



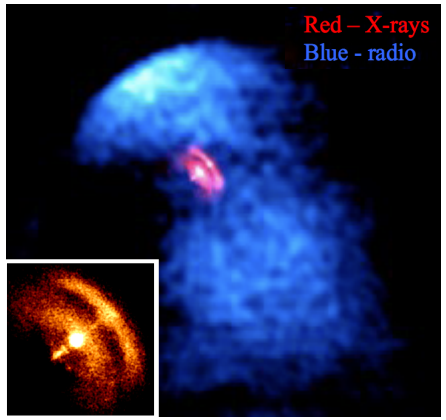
Confident Examples: Vela

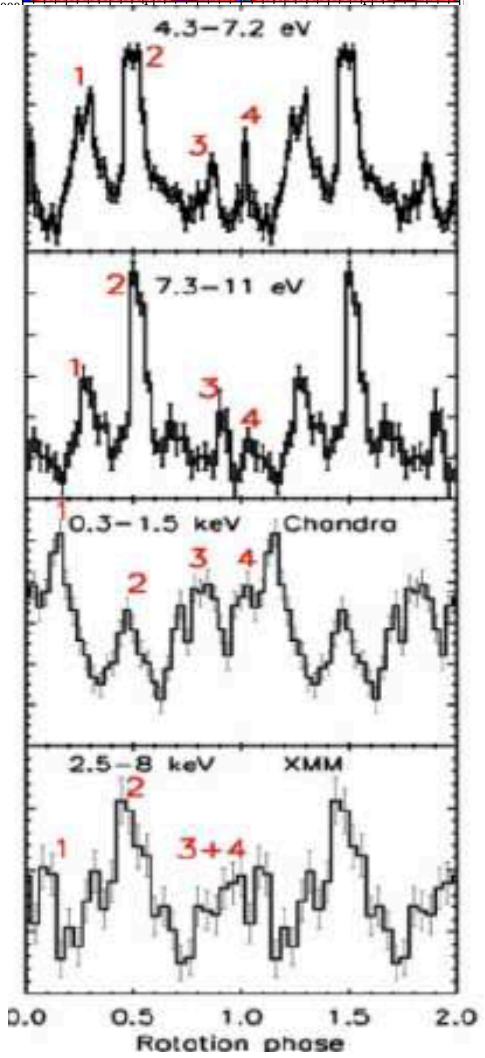


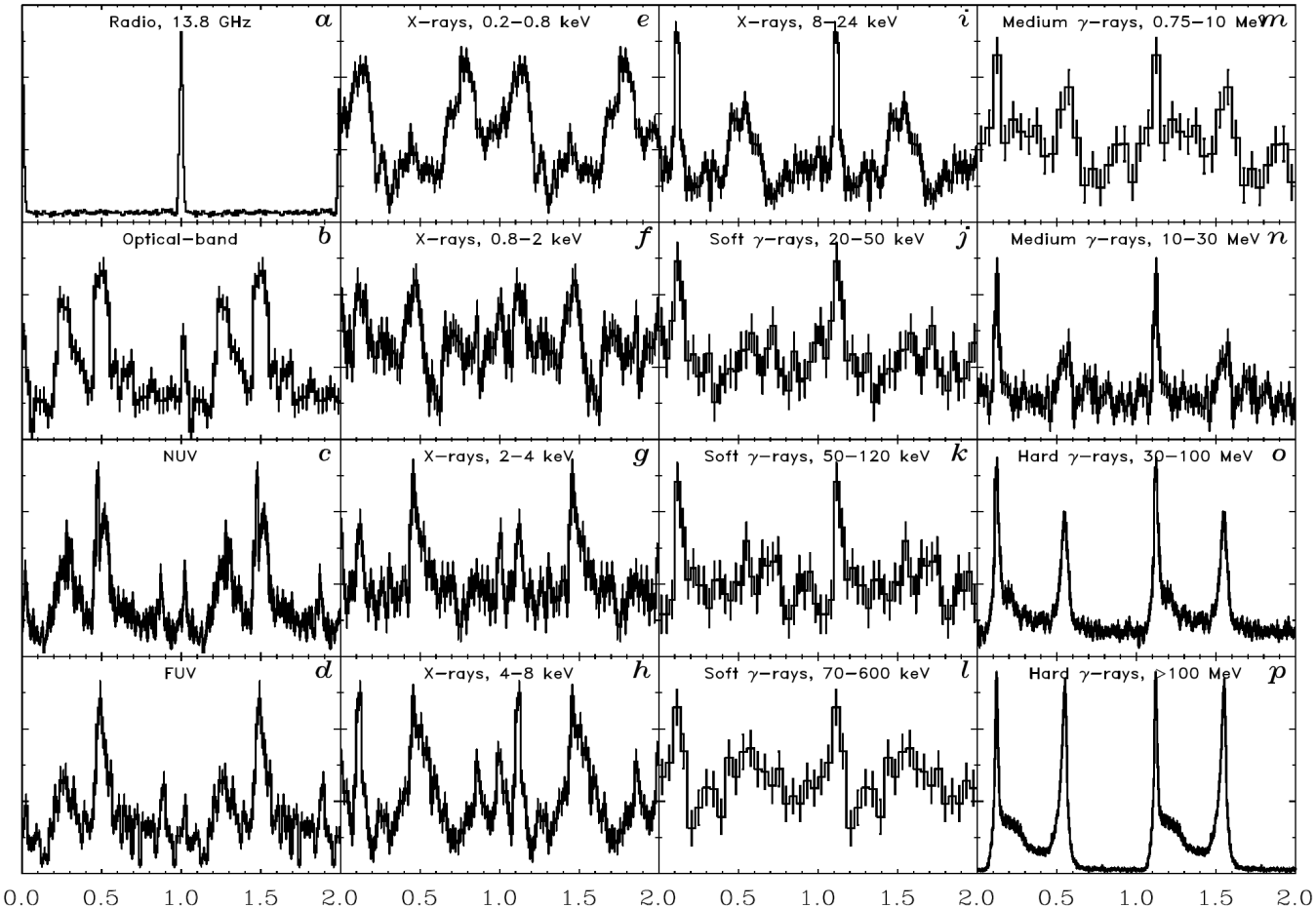
PWN suggests: α=60-70 , ζ=50-60

Helfand et al. 2001

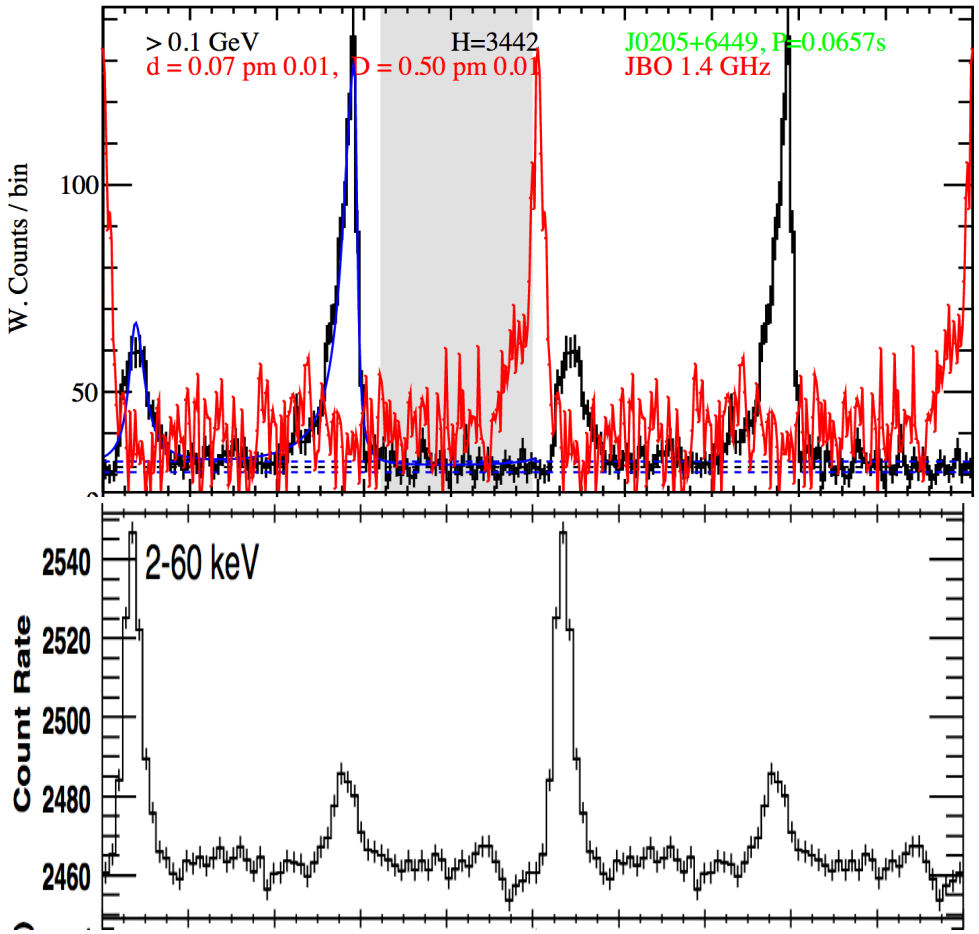
Γ_{PWN}=1.4

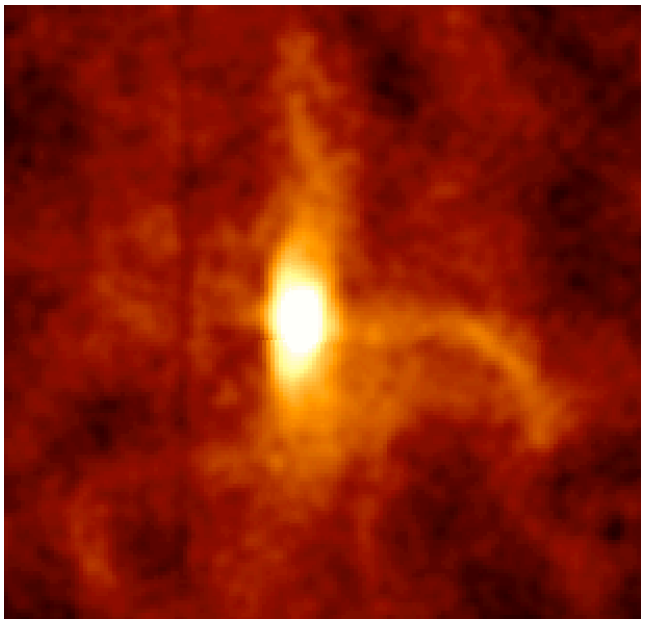






J0205+6449





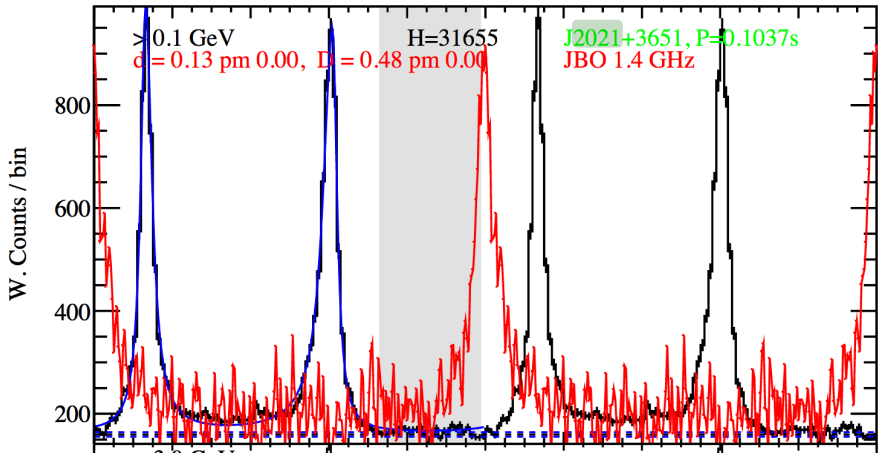
Γ_{PWN}=2.0

Vela-like configuration, strong equatorial component suggests α≈90, and ζ close to 90 but not exactly.

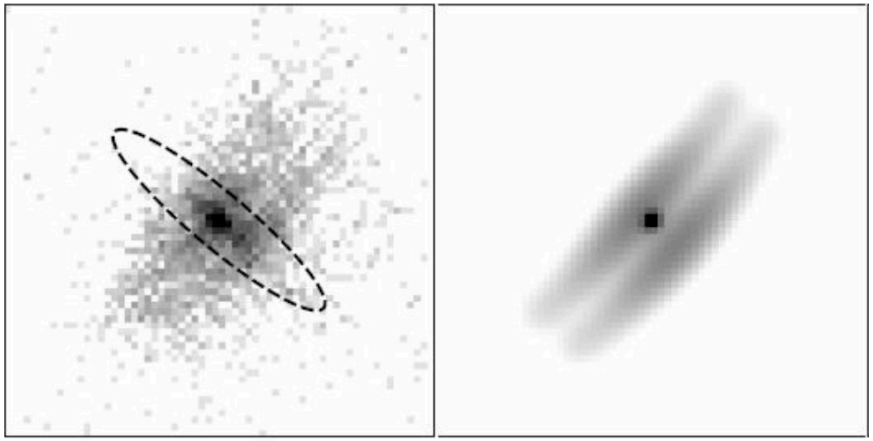
Why only single radio pulse unlike Crab?

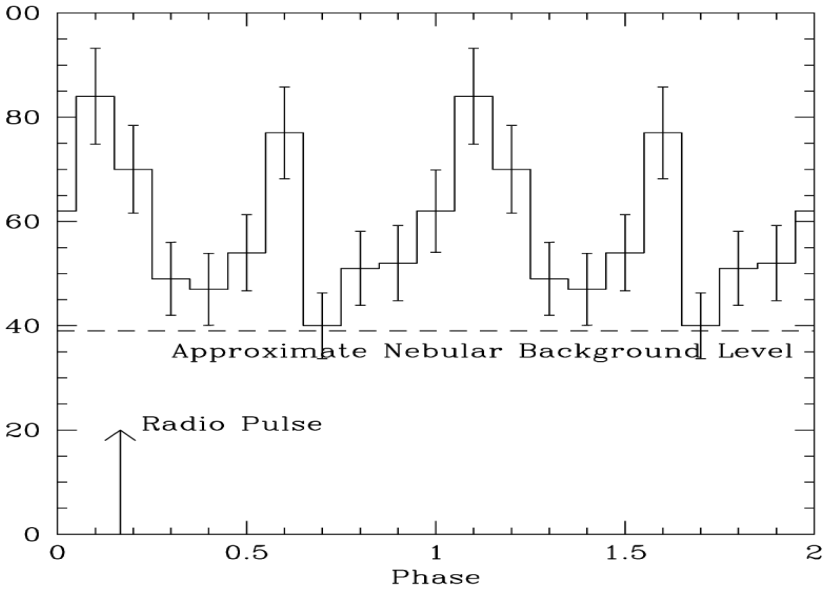
No difference in spectral shape is found for the two pulses in the X-ray/soft gamma-ray band. The gamma-ray lightcurve (> 100MeV) also shows two pulses, aligned with the X-ray pulses, but now the strongest gamma-ray pulse coincides with the weakest X-ray pulse, indicating different spectral behaviours of the two pulses when considering the full 0.5 keV to 10 GeV band.

J2021+3651



Van Etten et al. 2008



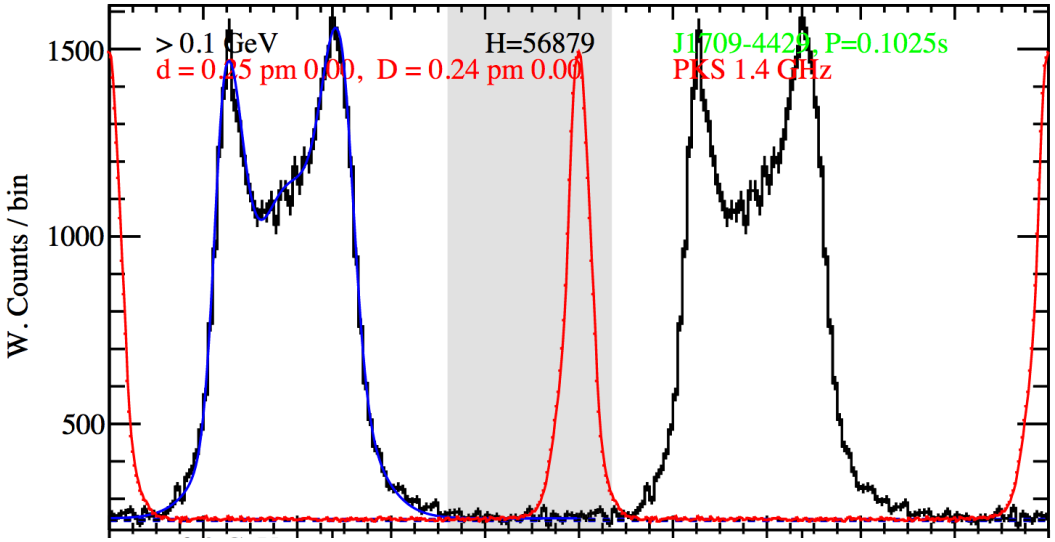


Hessels et al. 2004

Weak jets, strong equatorial component.
Double ring structure reminicent of Vela
but seen nearly edge-on;
α= Vela, ζ closer to 90 than in Vela

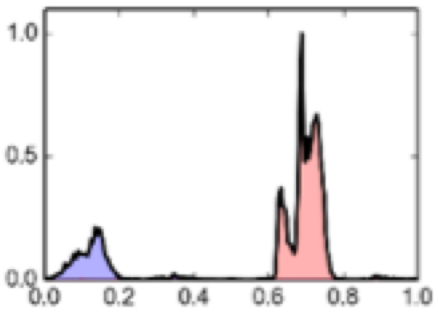
Unclear why only one radio pulse is seen!

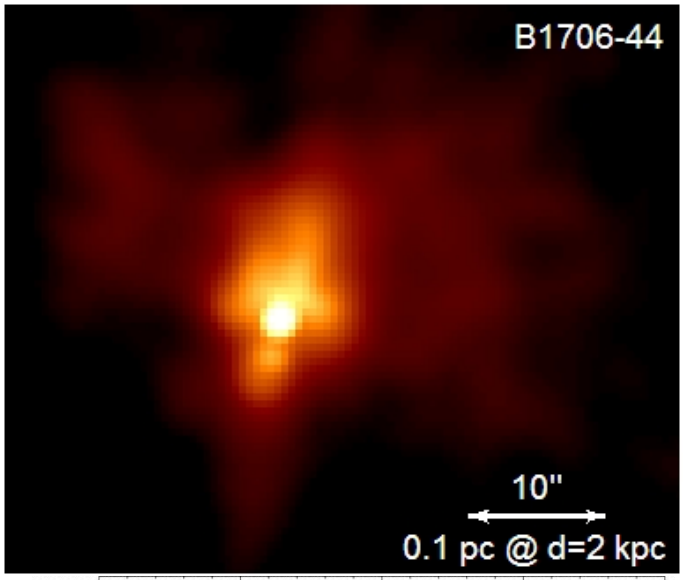
B1706-44

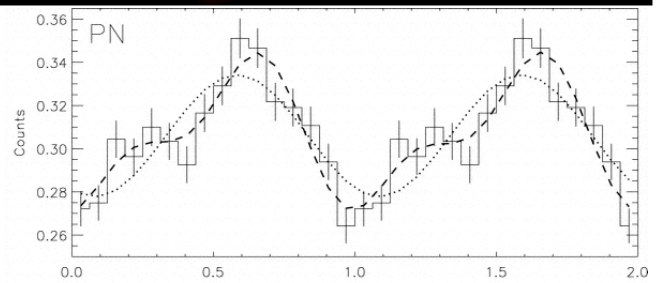


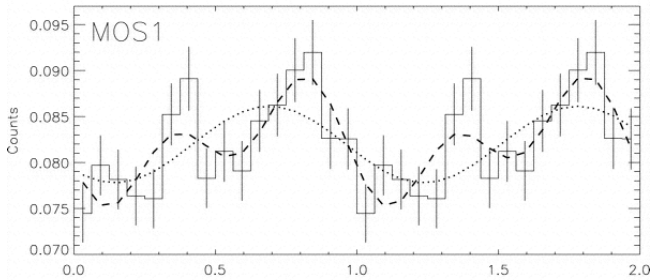
Little Crab but equatorial component is weaker compared to jets, likely more of an aligned rotator

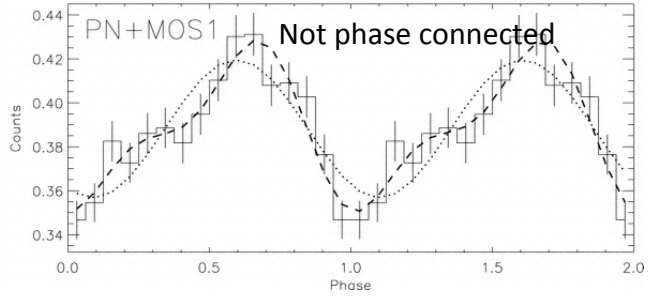
α< 50, ζ=50-60



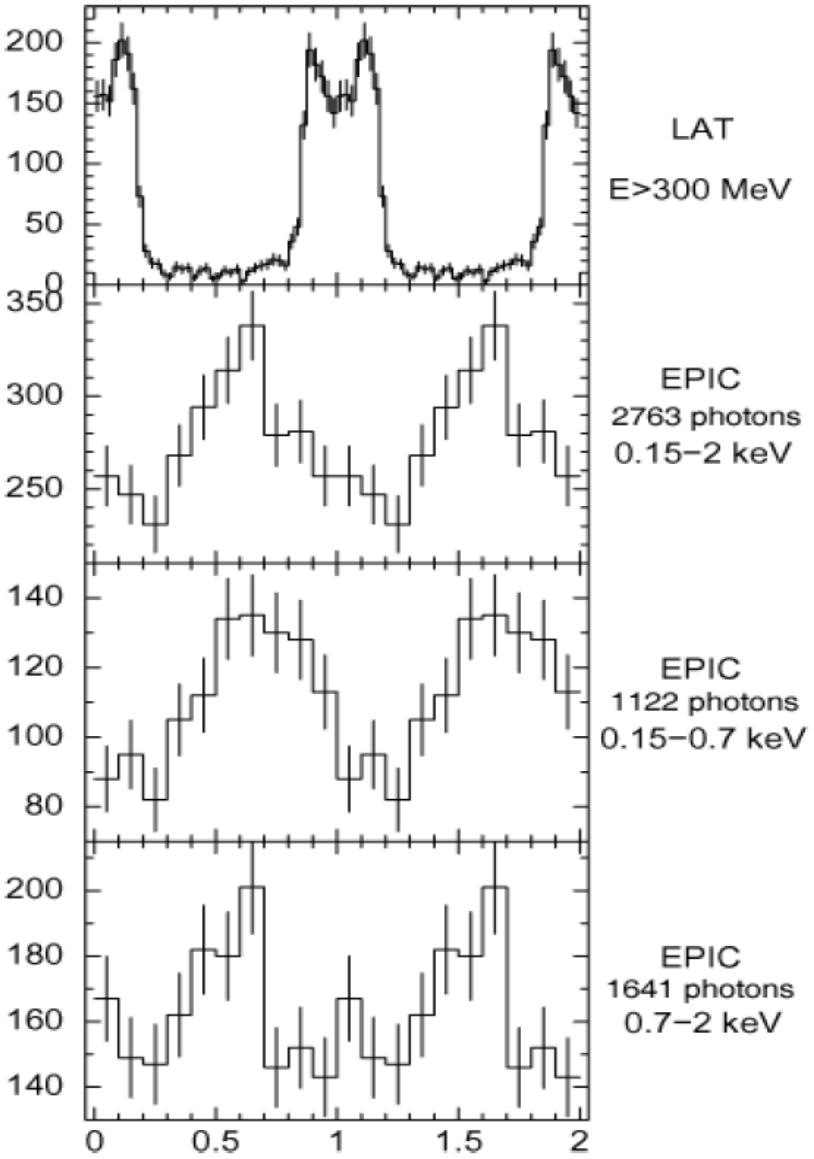


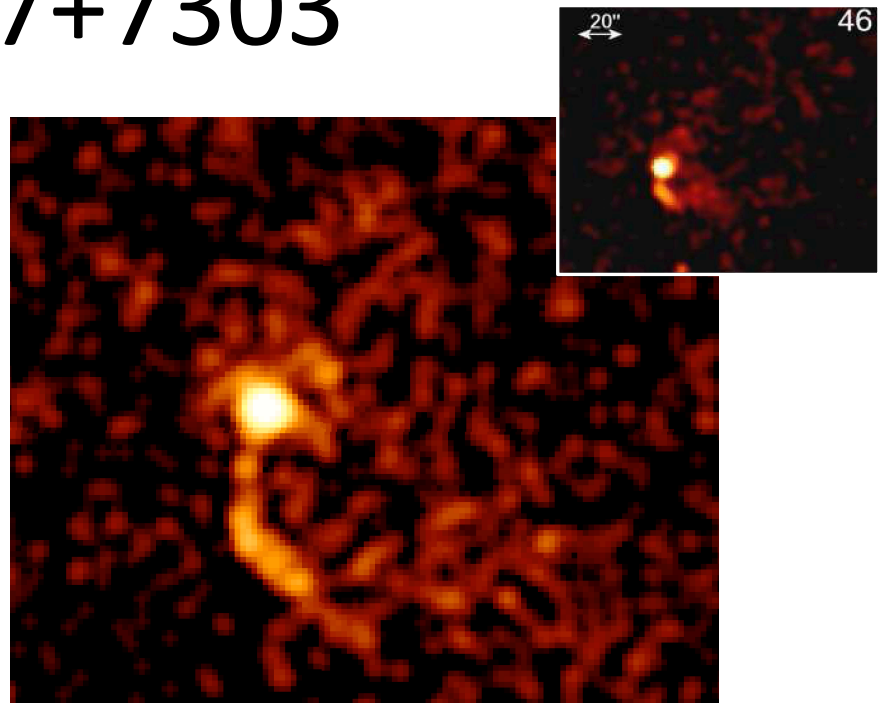




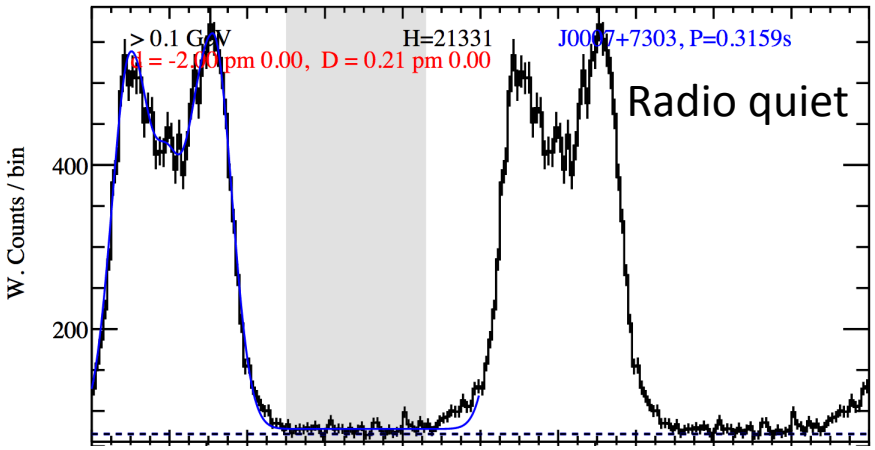


PSR J0007+7303

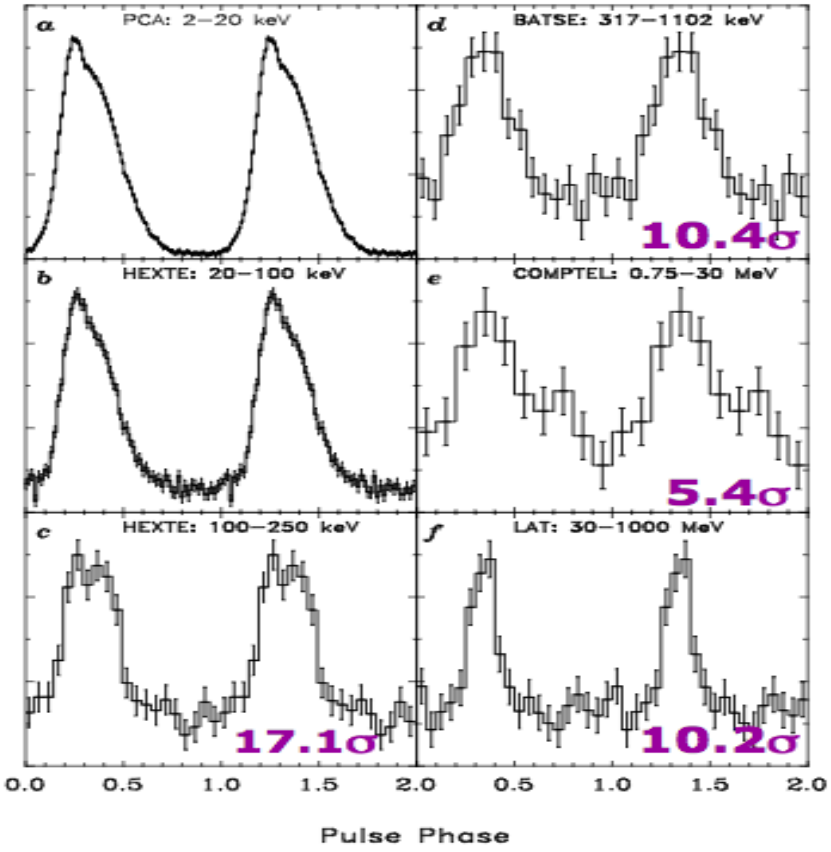


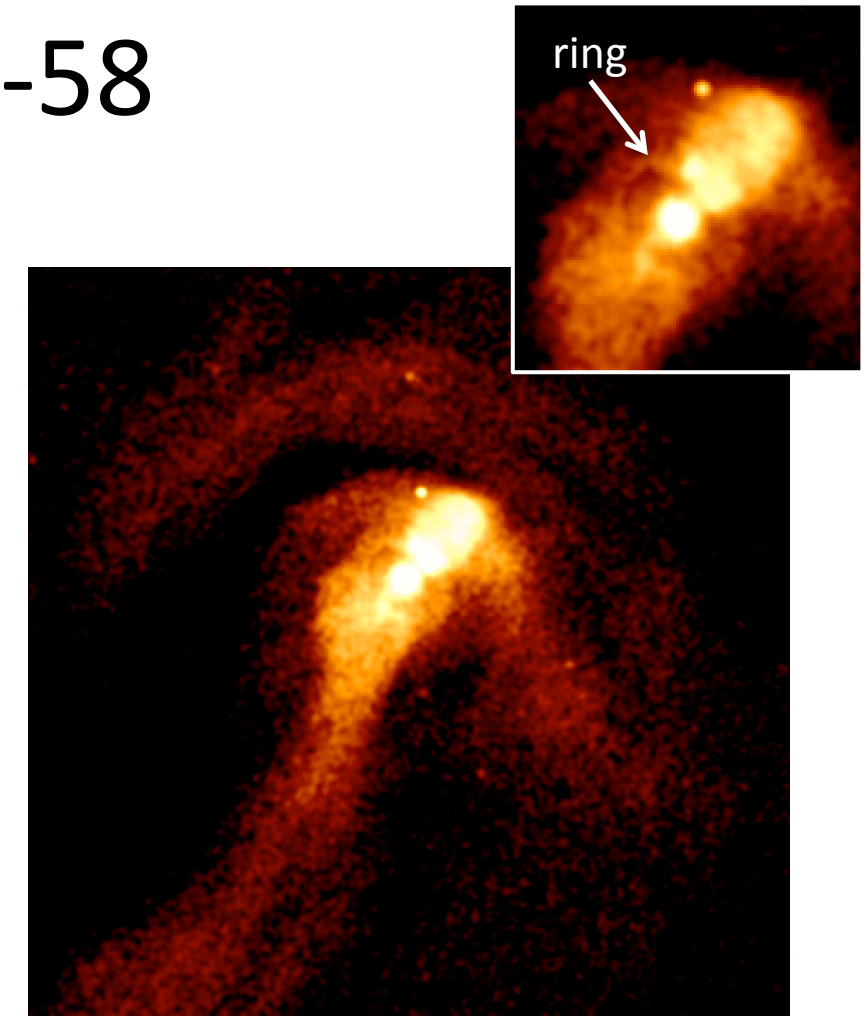


Relatively weak equatorial component;
α is small, ζ is not small
Explains radioquietness



B1509-58

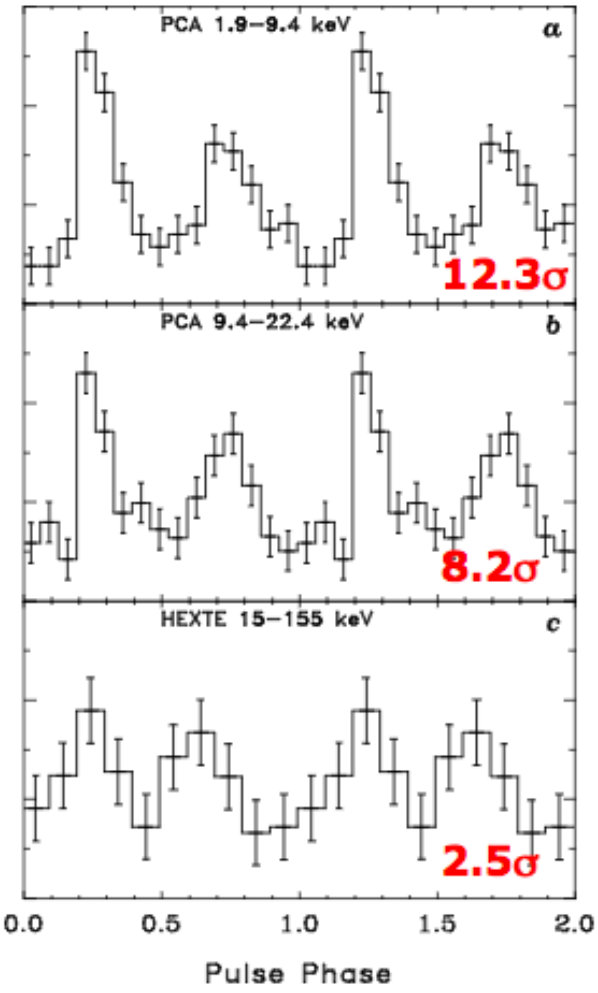




Γ_{PWN}=1.5

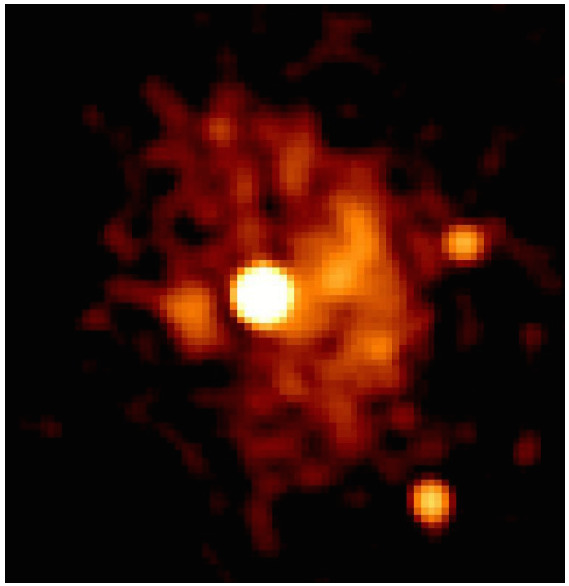
Ring suggests ζ~60,
Strong polar outflows and faint ring indicate that α may be small
This explains the radio quietness.

J2229+6114

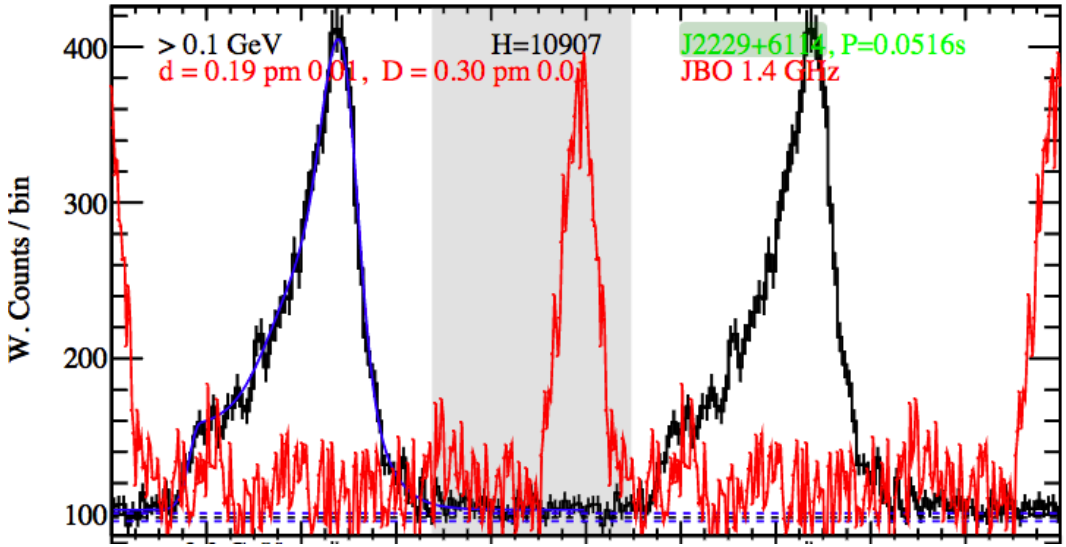


If the enhancements are the jets along the rotation axis then , ζ~30-40, but this is unclear…

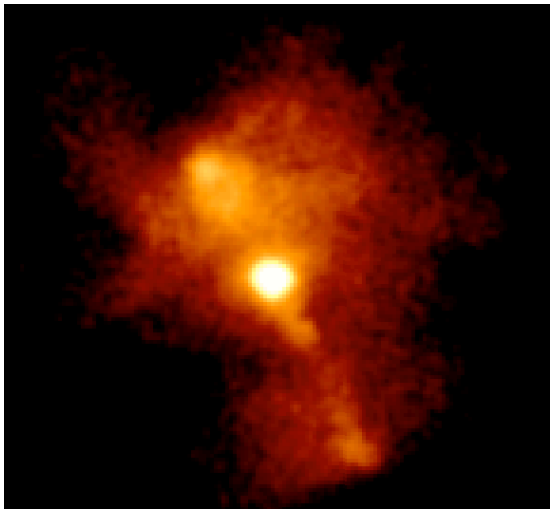
Ng & Romani 2008 suggest , ζ= 46, less than in Vela, α may be close to 90



Γ_{PWN}=2.0

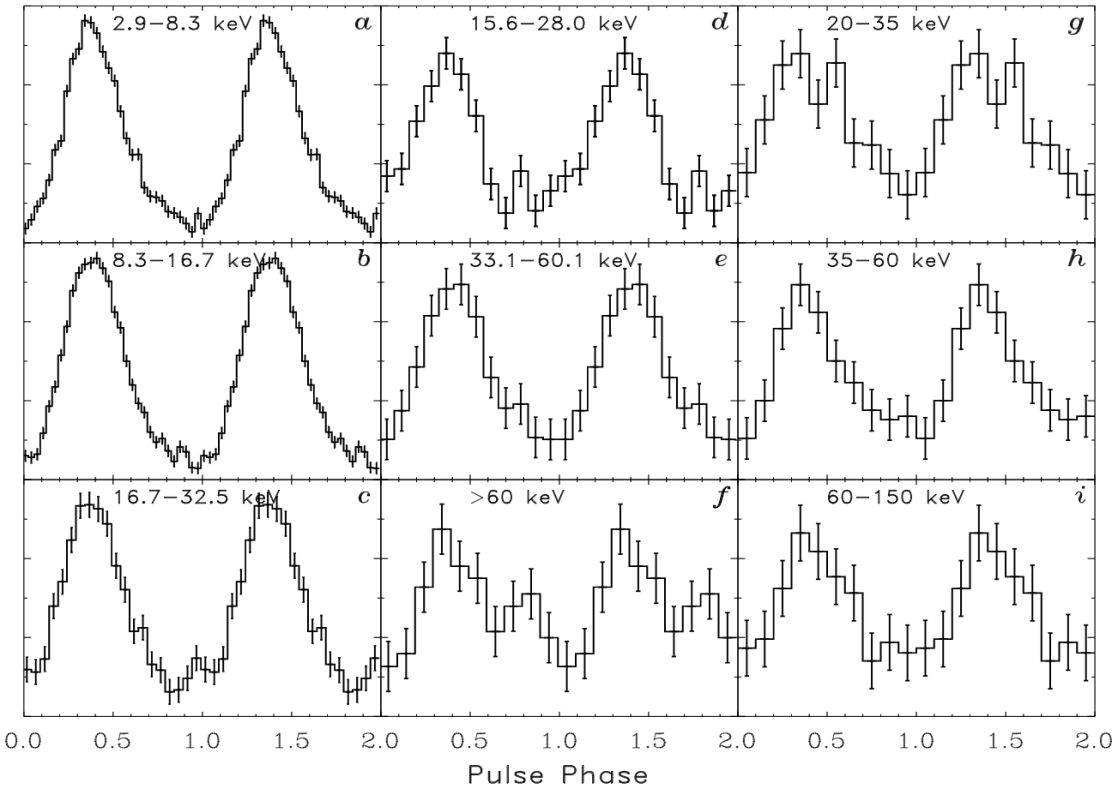


PSR J1846-0258



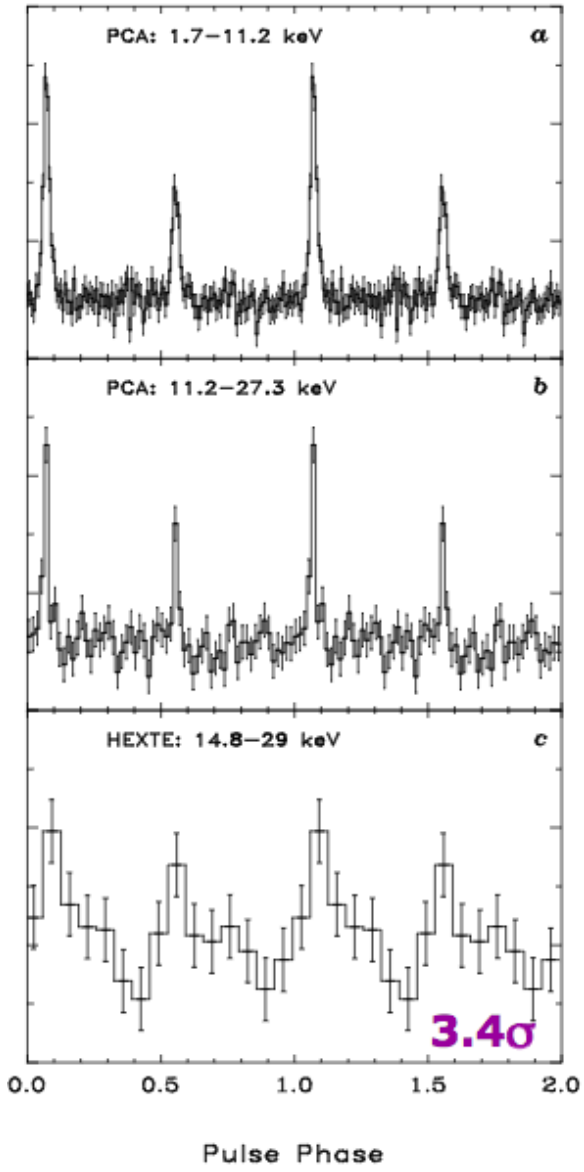
No gamma-ray emission
No radio emission despite deep GBT observation

Likely aligned rotator, ζ is probably moderately large



Kuiper & Hermsen 2009

PSR J2022+3842 in G76.9+1.0



Arumugasamy et al. 2014

Arzoumanian et al. 2011:
Underluminous PWN, hard spectrum:

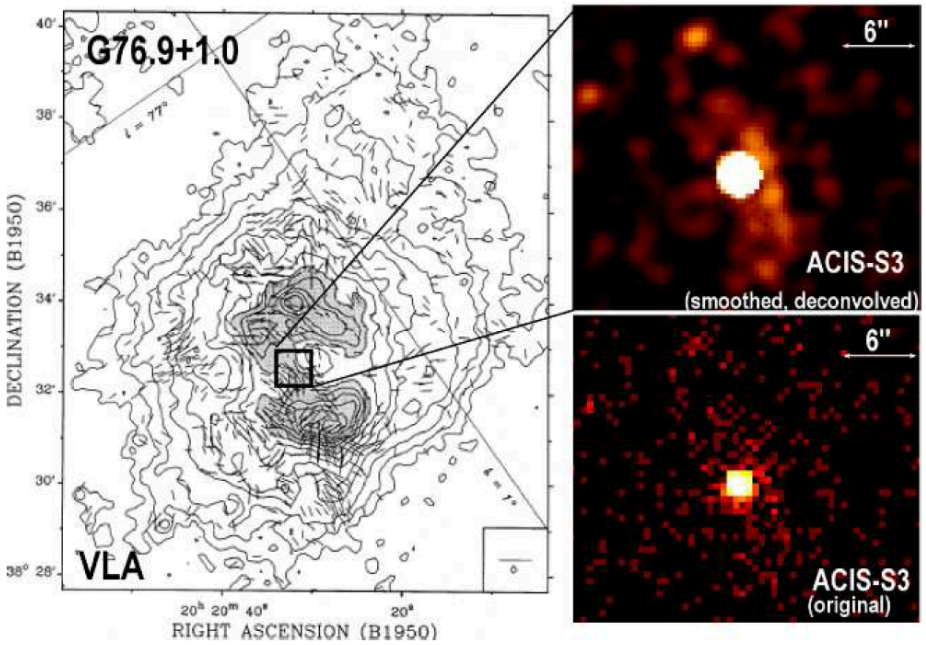
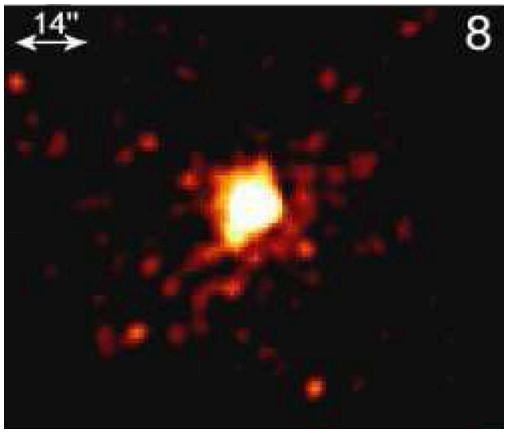


Figure 2: *Left:* Radio 1.5 GHz VLA image of G76.0+1.0 from Landecker et al. (1993). *Right: Chandra* ACIS images of the G76.0+1.0 central region revealing the bright point source surrounded by faint extended emission.

Very narrow pulse in X-rays;
Radio pulsar (number of peaks??);
PWN is very underluminous (the distace is wrong?)
but likely the equatorial component dominates;
Likely, ζ close to 90 and α is not small.

PSR J1617-5055



Underluminous PWN, hard spectrum
Single peak in radio and X-rays (are they aligned?)

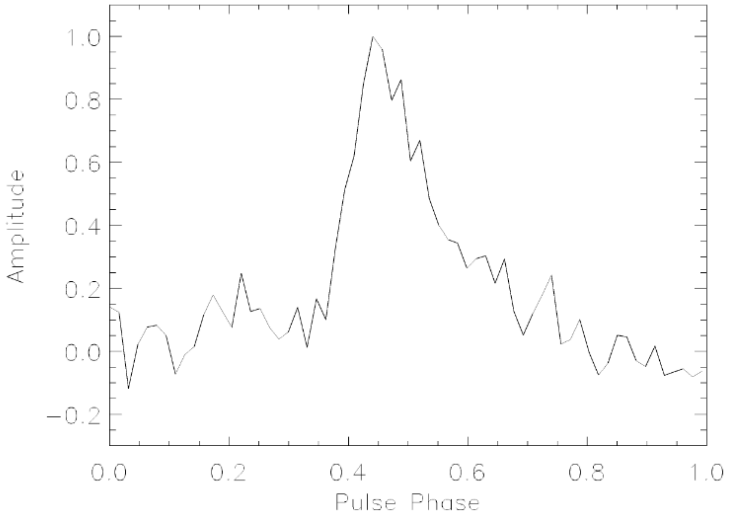
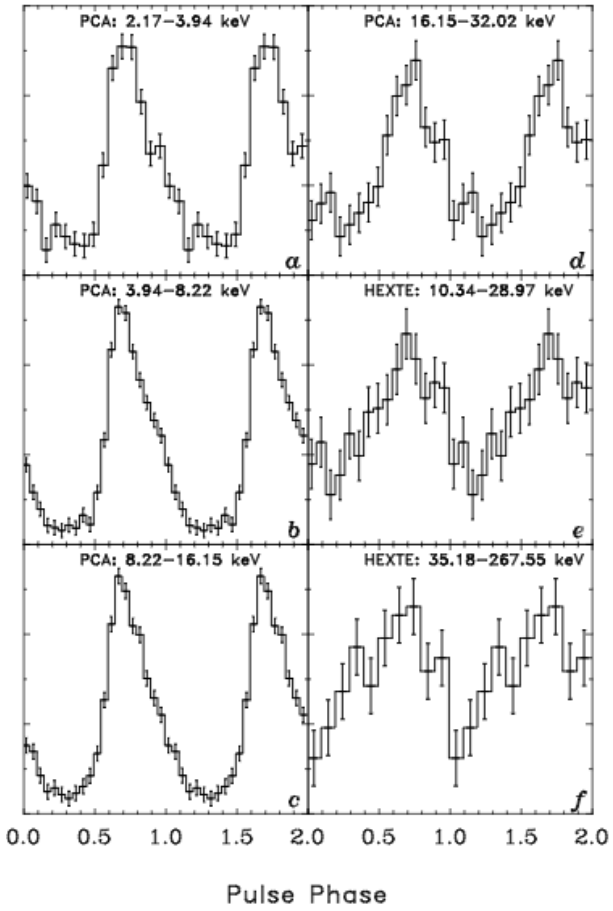
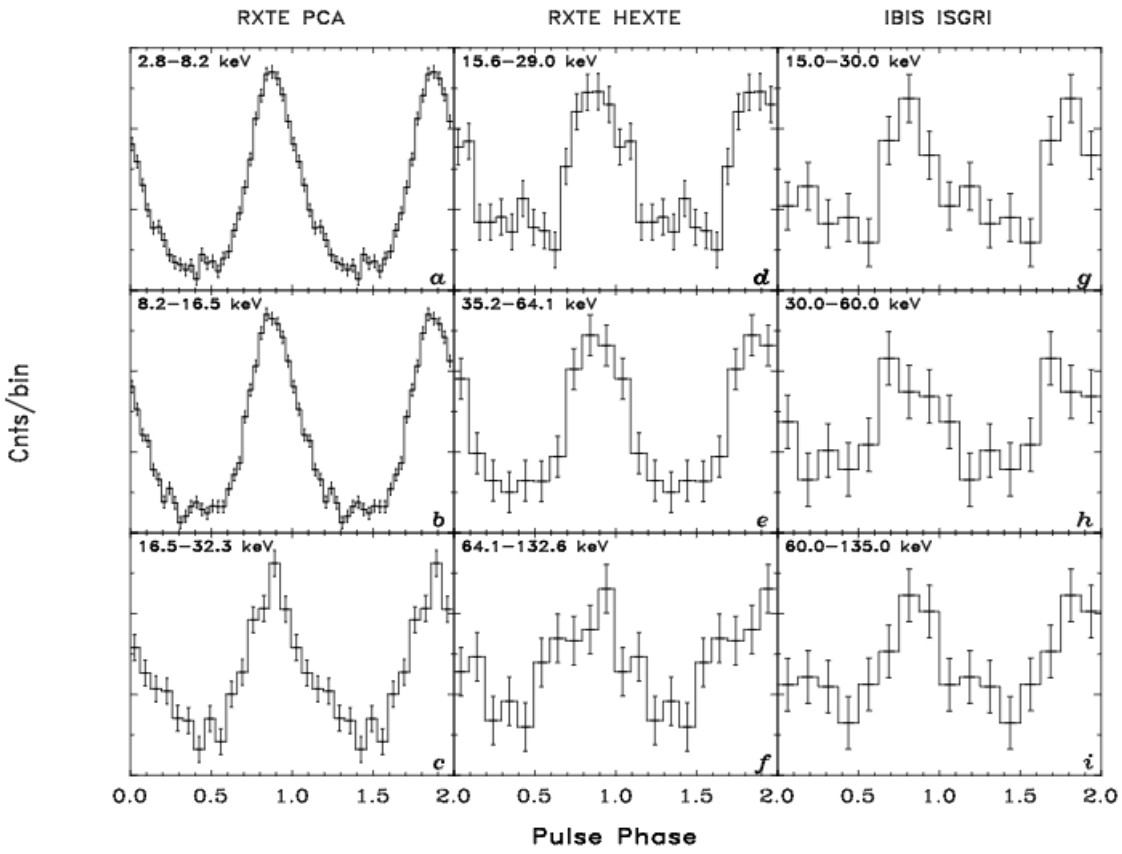


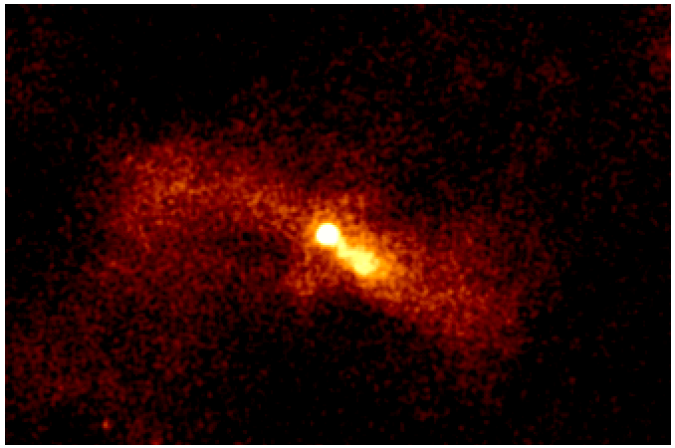
FIG. 1.—Pulse profile of PSR J1617−5055 at 1.4 GHz



J1811–1925

Radio quiet
Gamma-ray quiet

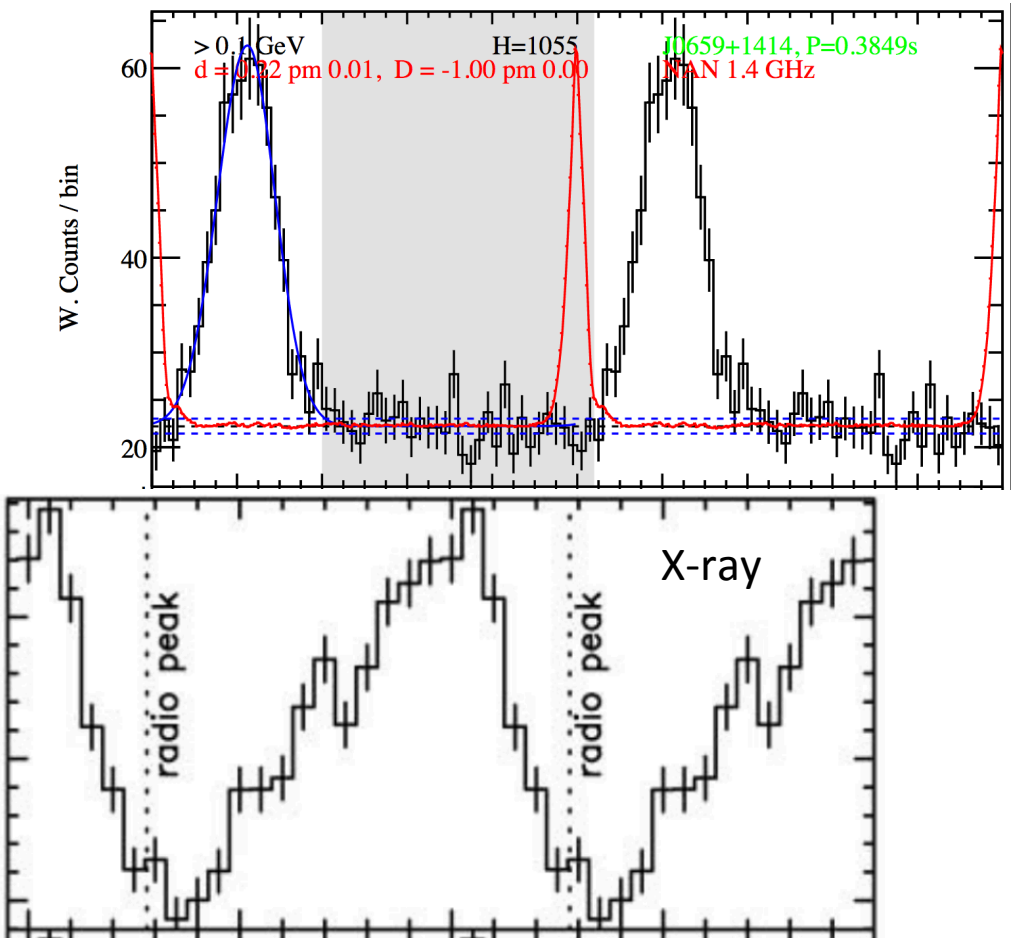




Only very weak equatorial component but the jets are prominent;

Likely, ζ close to 45 and α is small.

J0659+14145 (B0656+14)

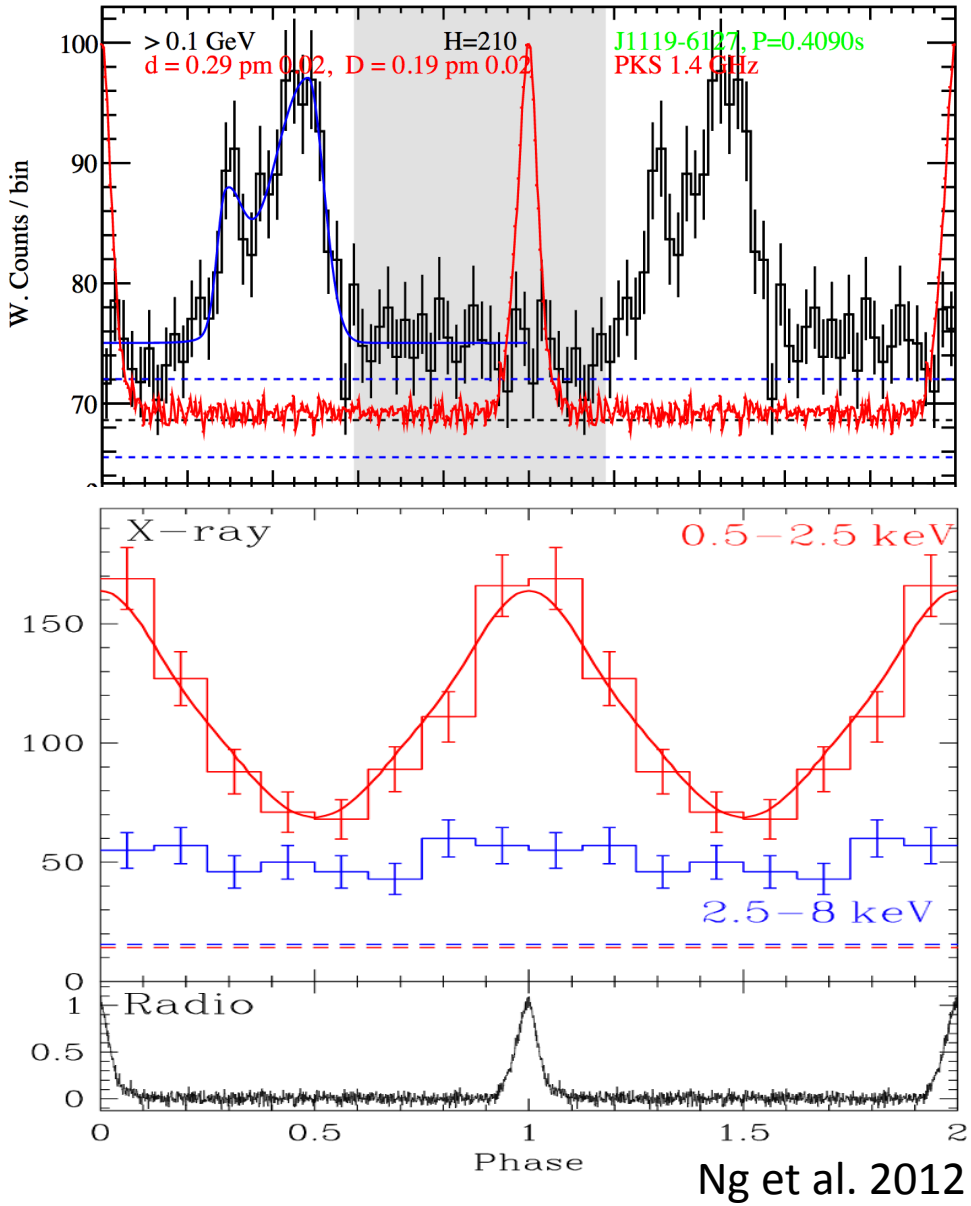


De Luca et al. 2005

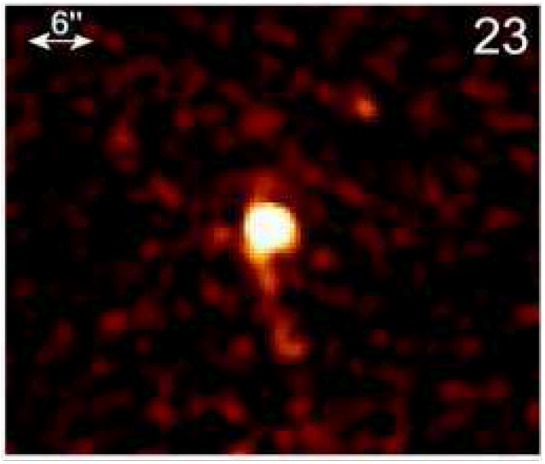
Faint (or non-existent) X-ray PWN

Thermal (?) X-rays peak at 0.5 off (in phase) from the radio peak.

J1119-6127



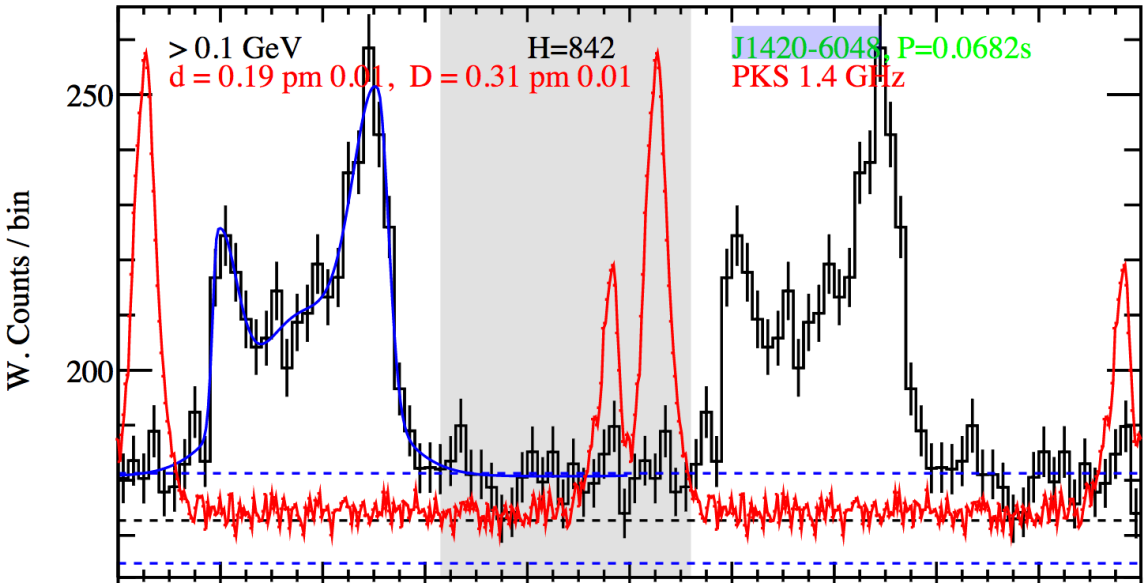
Ng et al. 2012



No nothermal X-ray emission (Kuiper et al. 2016).
Faint X-ray PWN with uncertain morphology.

Thermal (?) X-rays peaks in phase with radio.

J1420-6048



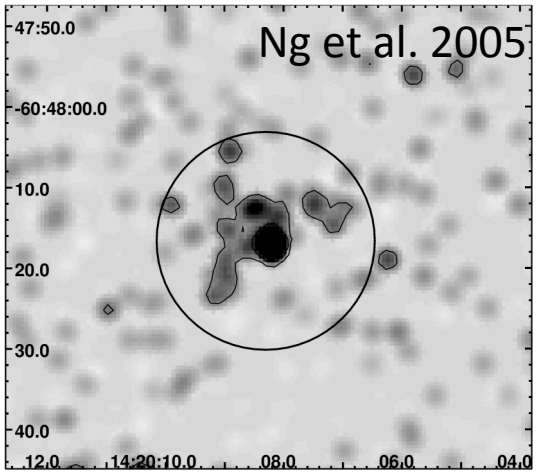


FIG. 2.—Inner K3 nebula, which is embedded in faint diffuse emission (Fig. 1). An arc of X-ray photons partly surrounds the point source, PSR J1420−6048. The 13″.5 circle shows the extraction region for spectra of the inner nebula.

Very underluminous PWN

J1357-6429

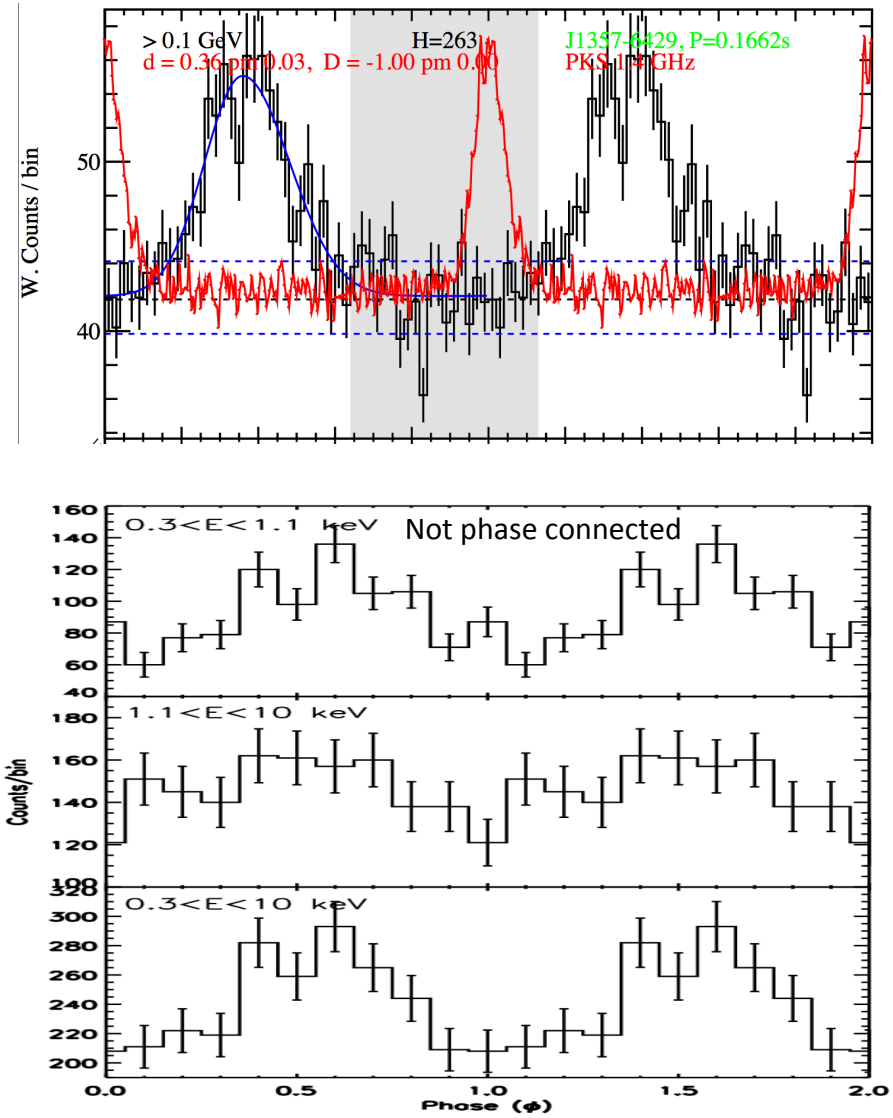
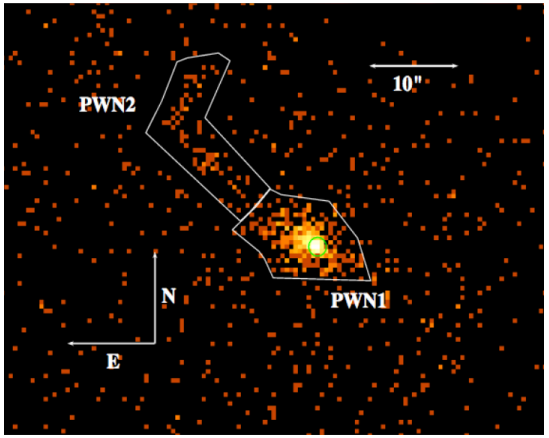


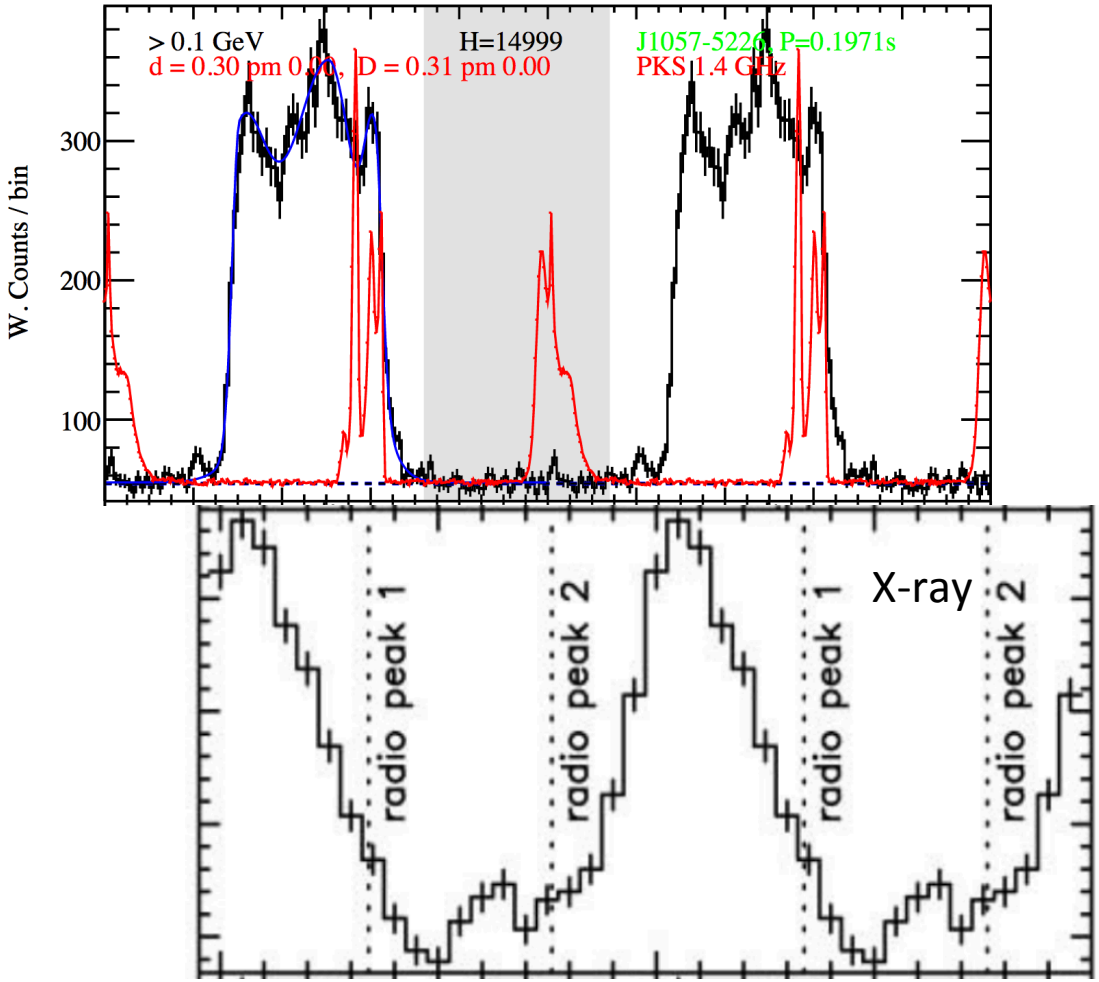
Fig. 12.— Pulse profiles of J1357 extracted from the EPIC PN data in three energy bands.



No nothermal X-ray emission
(Kuiper et al. 2016)
Faint X-ray PWN

Chang et al. 2012

J1057-5226 (B1055-52)



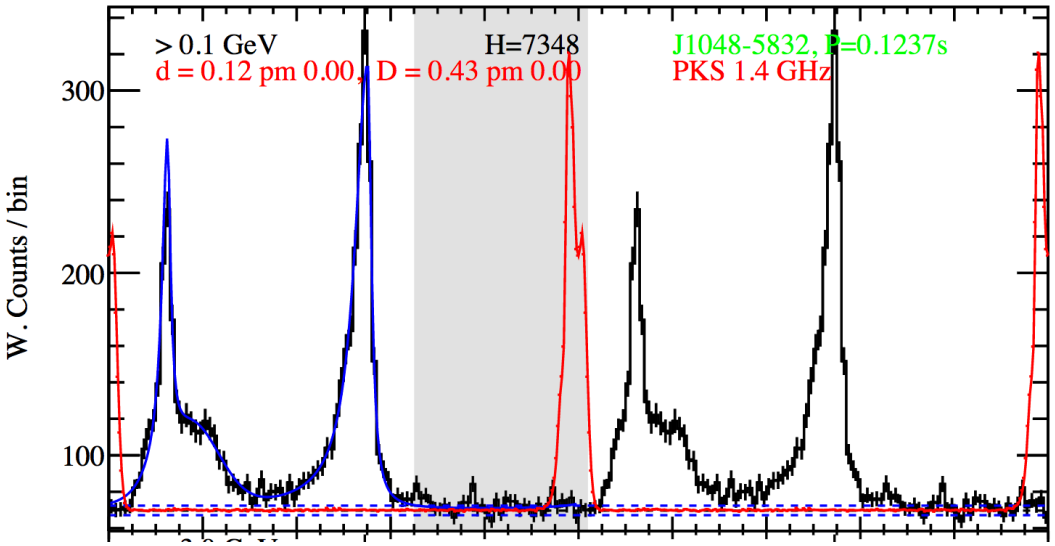
Thermal (?) X-rays peak at 0.5 off (in phase) from the radio peak.

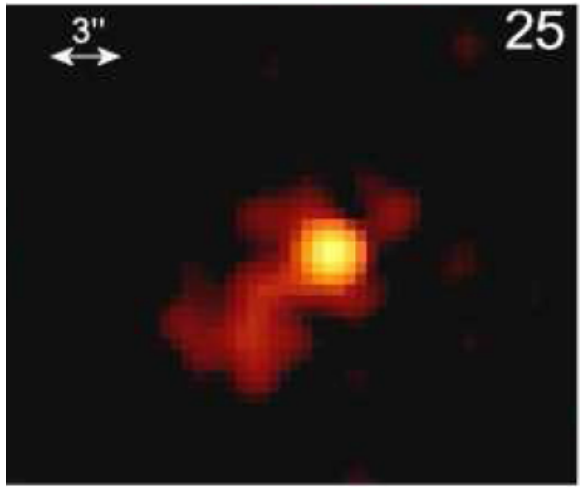
De Luca et al. 2005

Bowshock PWNe

- Focus on morphology of compact heads
- Interpretation of the feature is not as obvious asin other cases

B1046-58

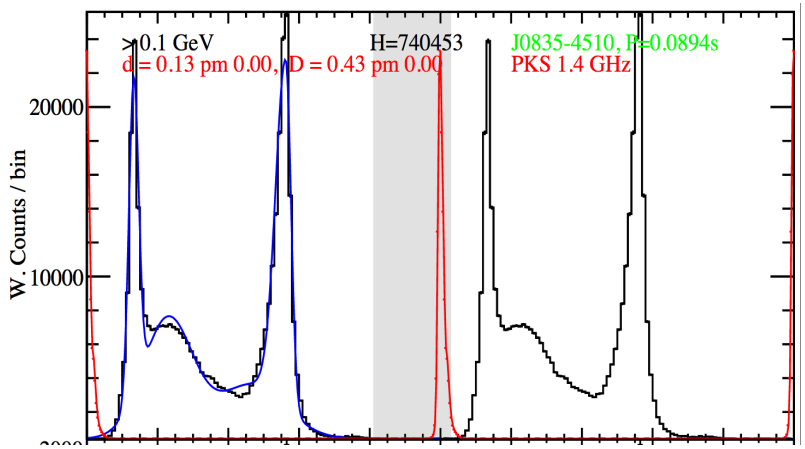




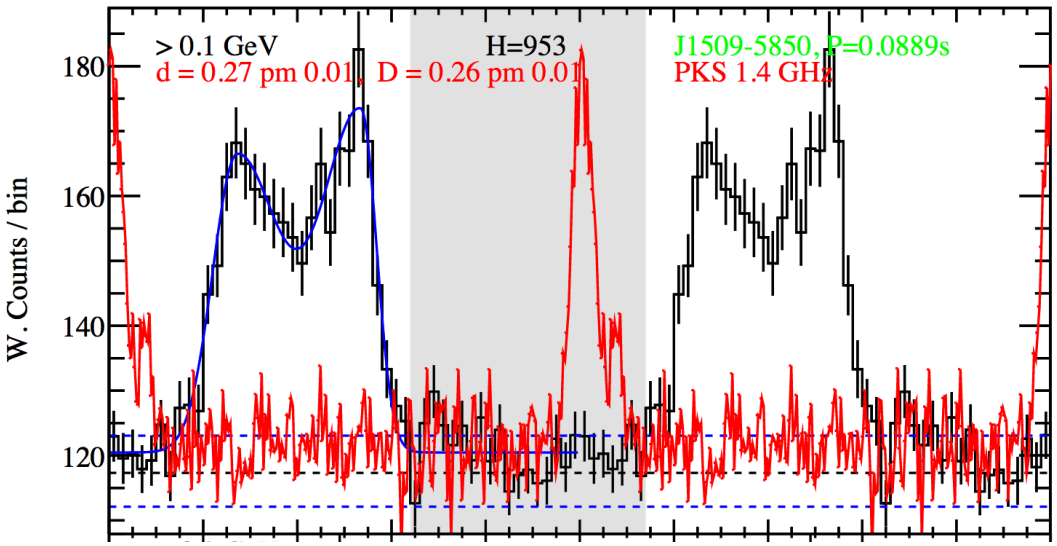
X-ray pulsations not detected

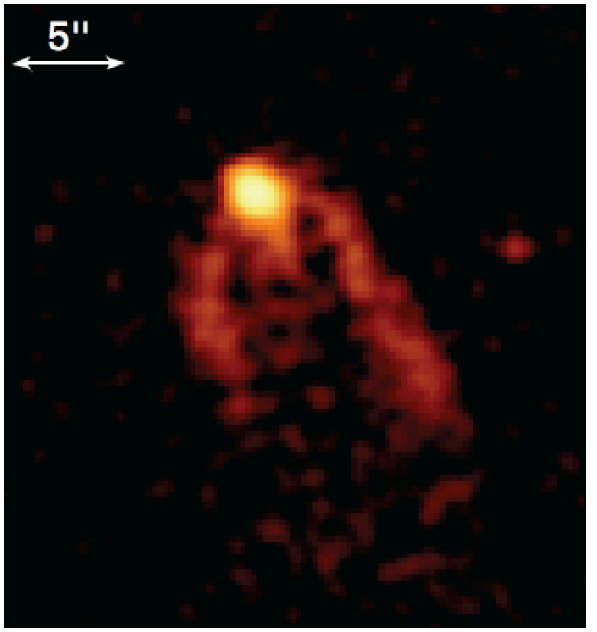
Likely, ζ is close to 90 and α is not small.

Pulse profile reminisent of Vela:

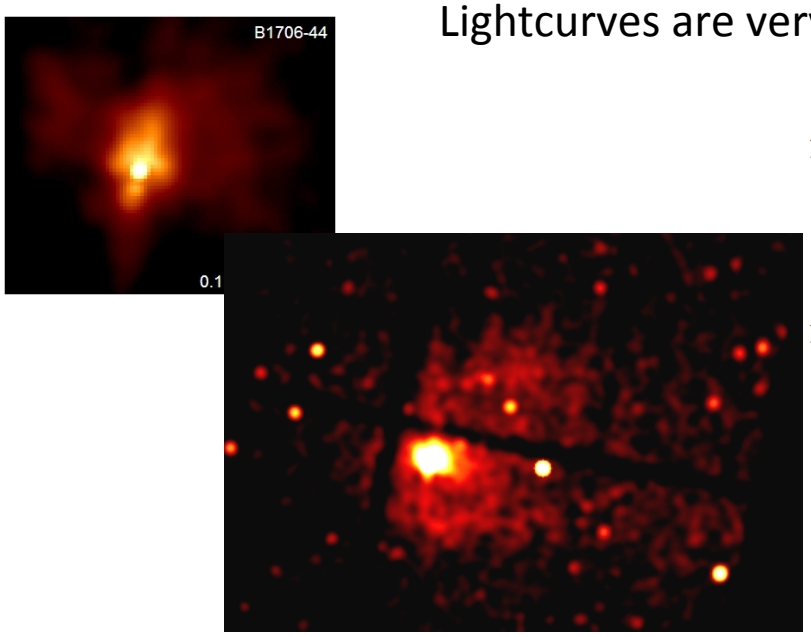


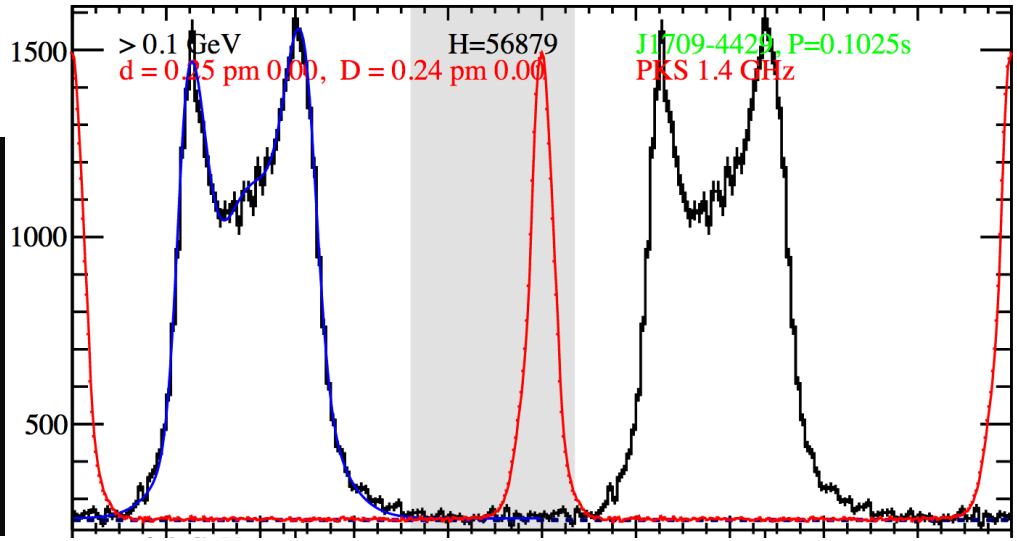
J1509-5850



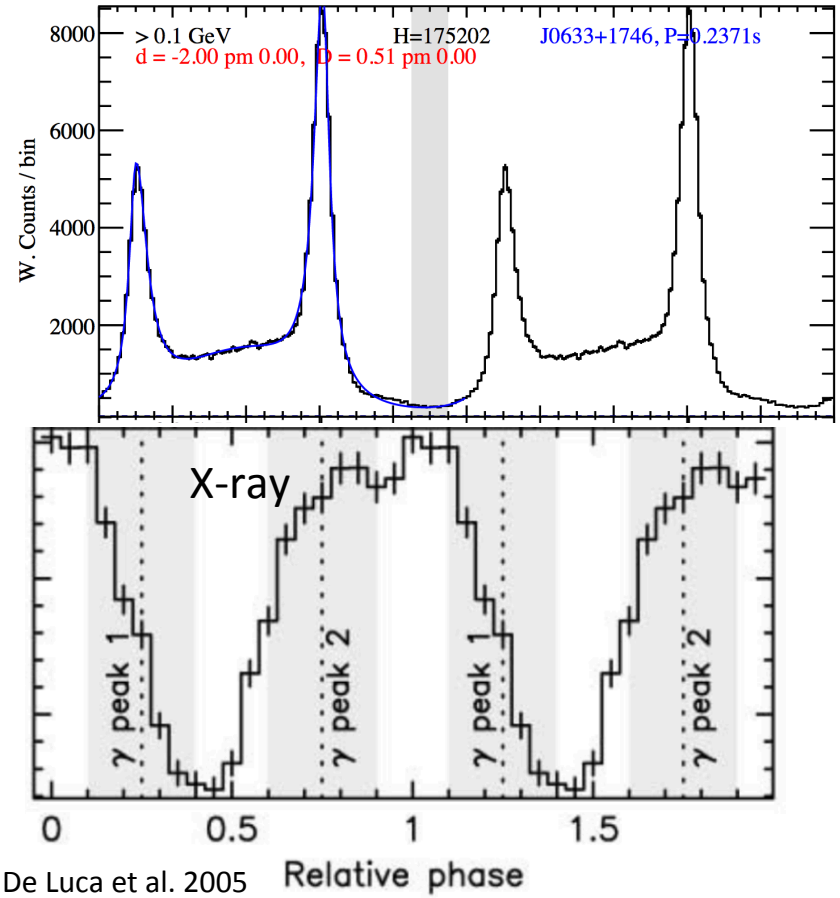


Lightcurves are very similar to to B1706-44 (α< 50, ζ=50-60):

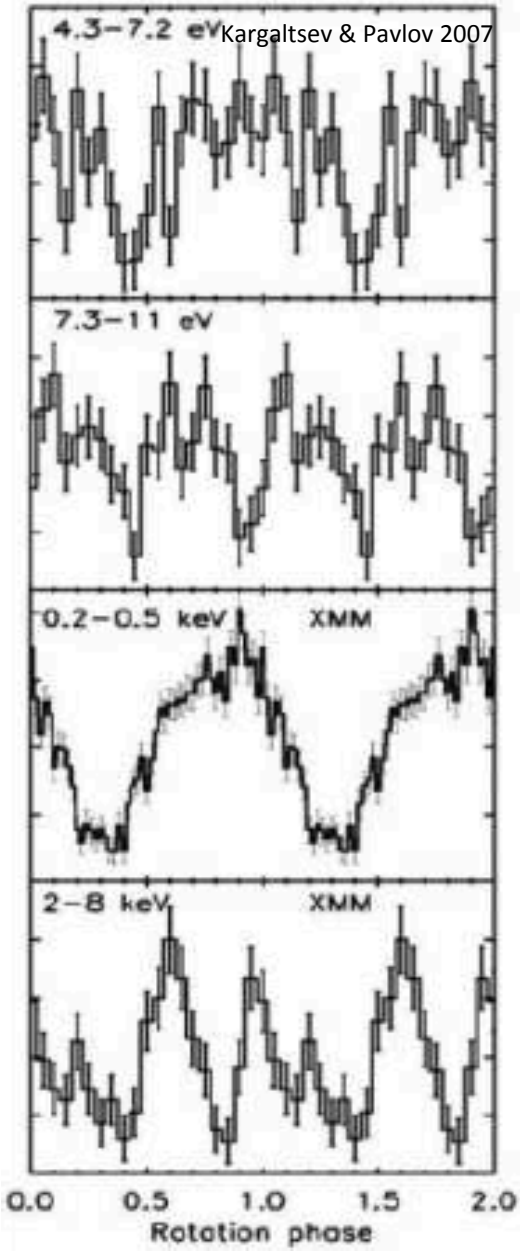


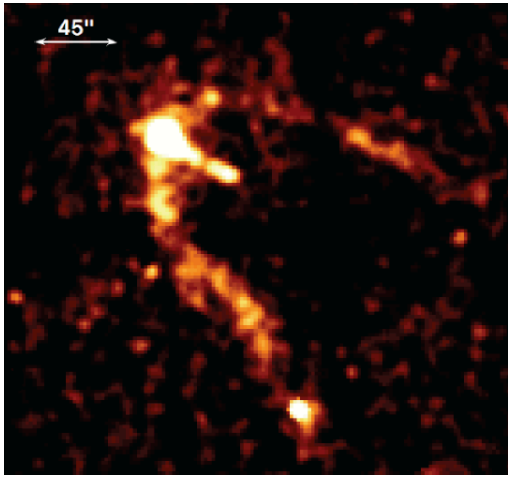


Geminga (J0633+1746)



De Luca et al. 2005





Radio quiet. Why?

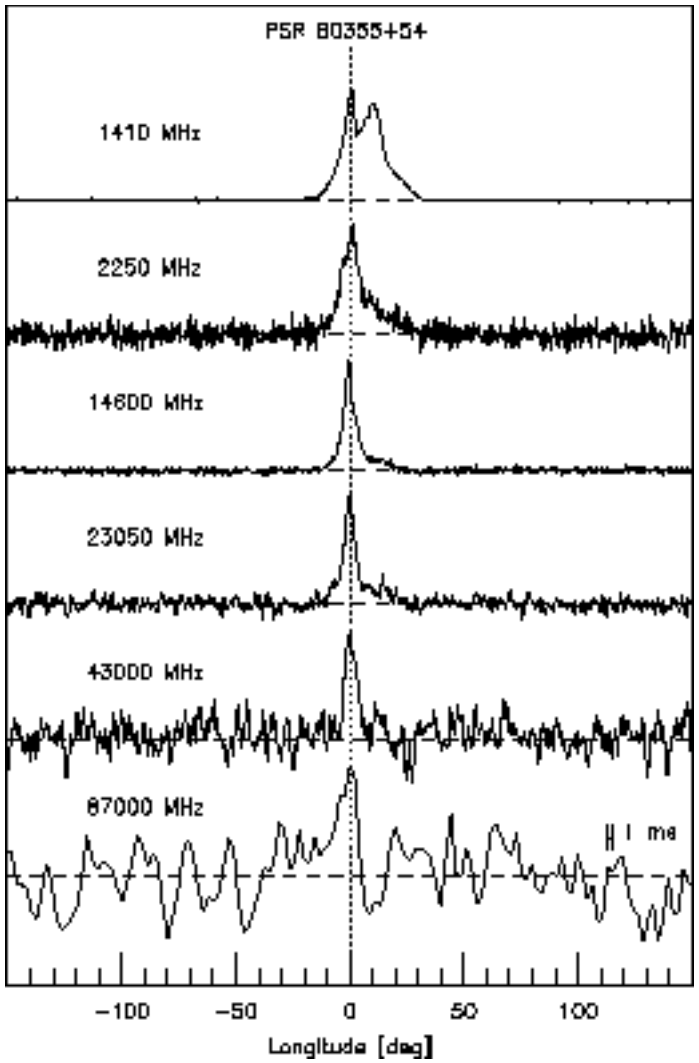
Gamma-ray lightcurve of Geminga is similar to that of Vela, J2021+3651, B1046-58 all of which are radio loud.

However, Geminga is a factor of >10 older.

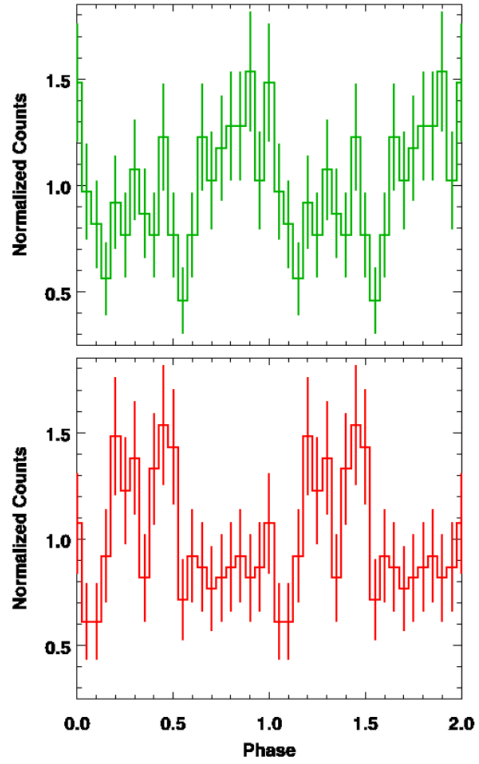
Is it a more aligned rotator then the above mentioned ones?

α small, ζ>50?

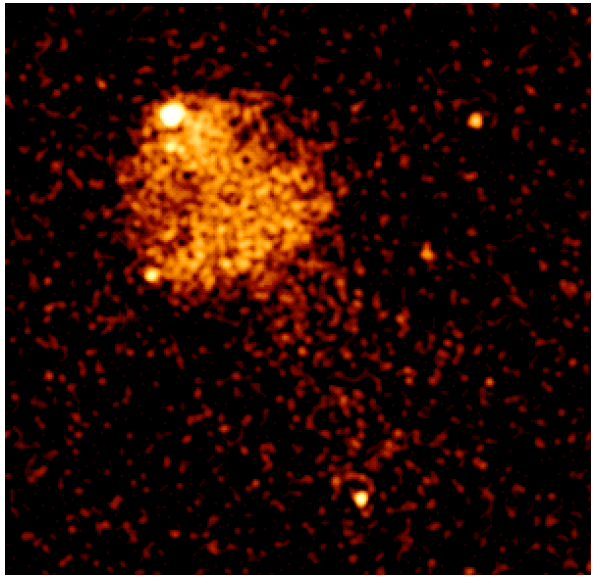
B0355+54



Morris et al. 1997

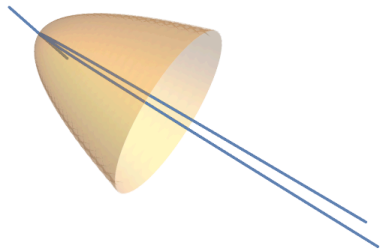


McGowan et al. 2008

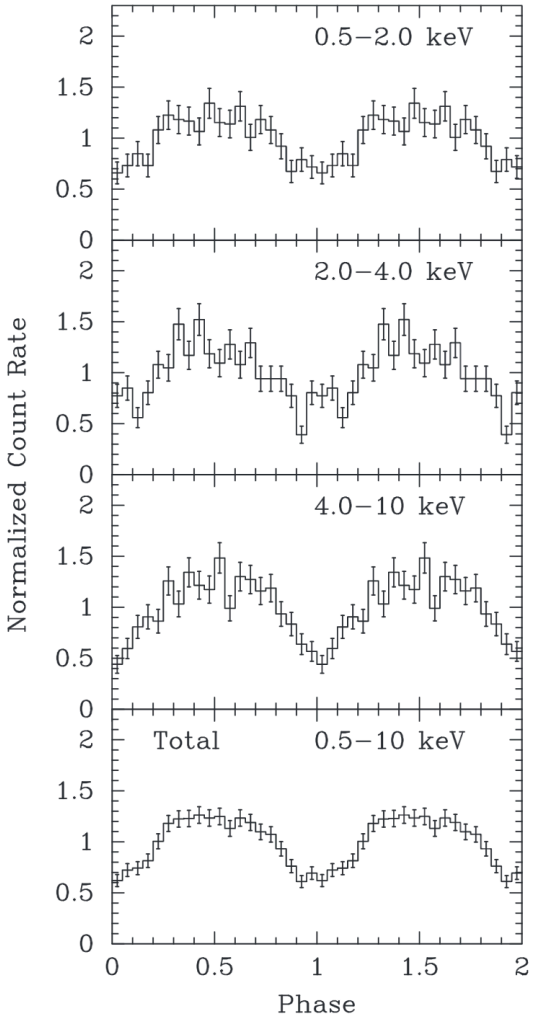


No gamma-ray detection
No firm X-ray pulsations
Strong equatorial component, weak jets (Klingler et al. 2016)

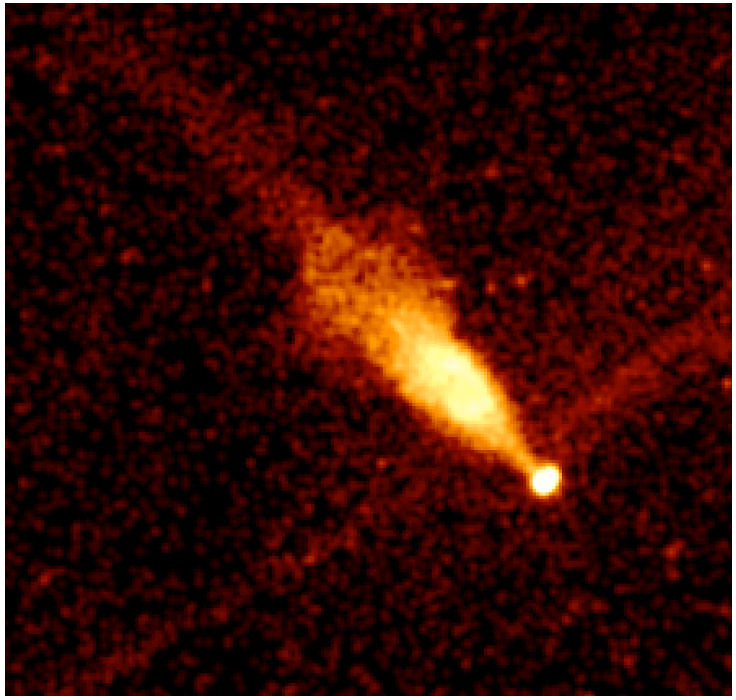
Orthogonal rotator with
ζ close to 0?



PSR J1101-6101



Halpern et al. 2014



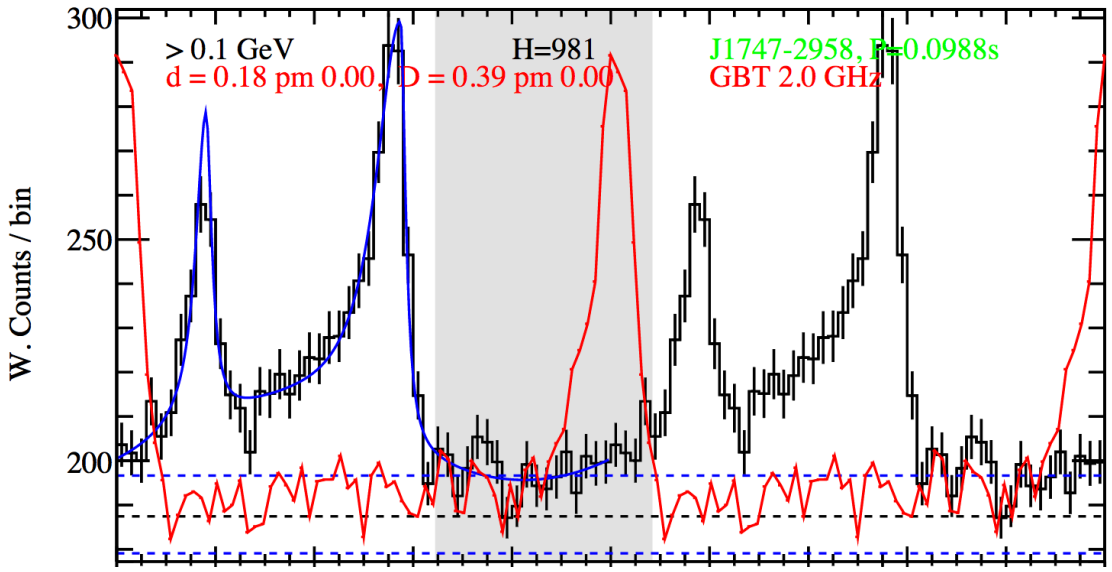
IGR J11014-6103 – likely soft gamma-ray pulsar but
no detection of pulsations in this band yet (Kuiper et al. 2016);

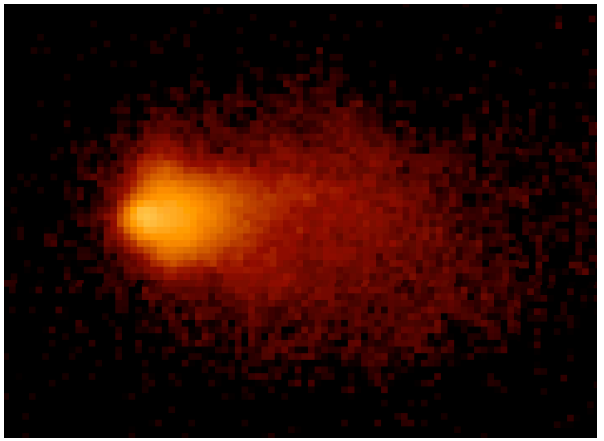
PWN only appears to brighten at some distance from the pulsar

Special magnetospheric geometry?

No gamma-ray or radio pulsations.

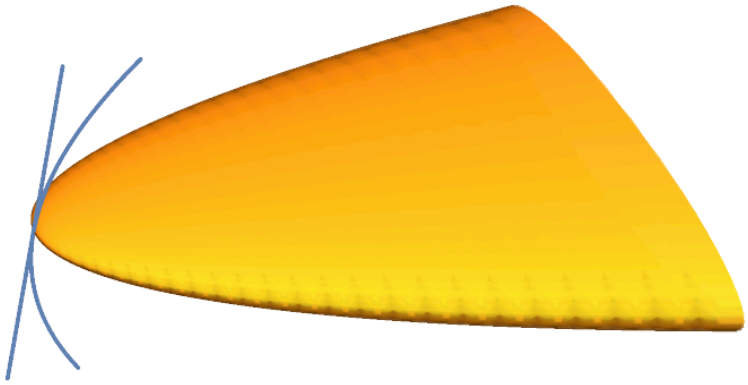
J1747-2958

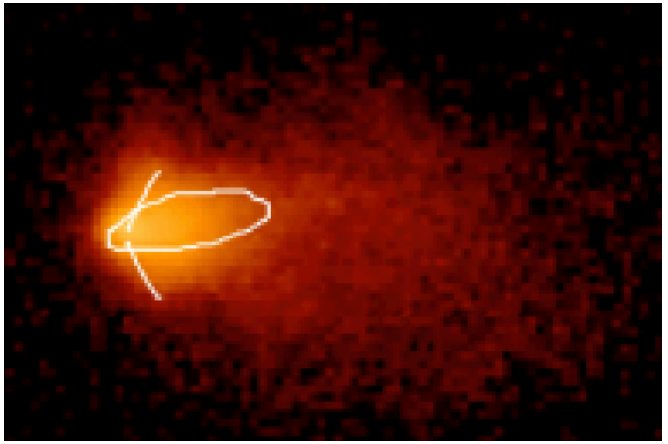




No hard X-ray or soft X-ray pulsations detacted (perhaps due to bright unresolved PWN)

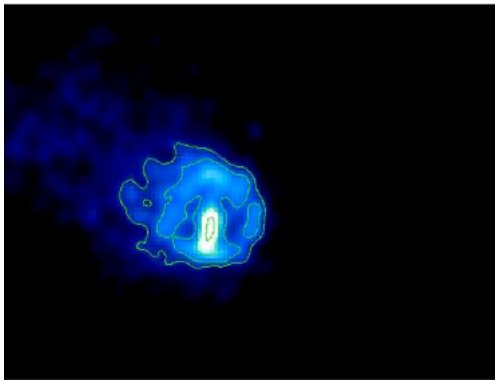
Likely, strong equatorial component, weak jets





Undetected pulsar in IC 443

Likely ζ is small (equatorial shock seen as a ring),,
and α is moderately large. The image suggest that
the impact parameter angle β would then be large
which would explain the lack of radio pulsations
even in radio is emitted in the nested cone or fan beam.

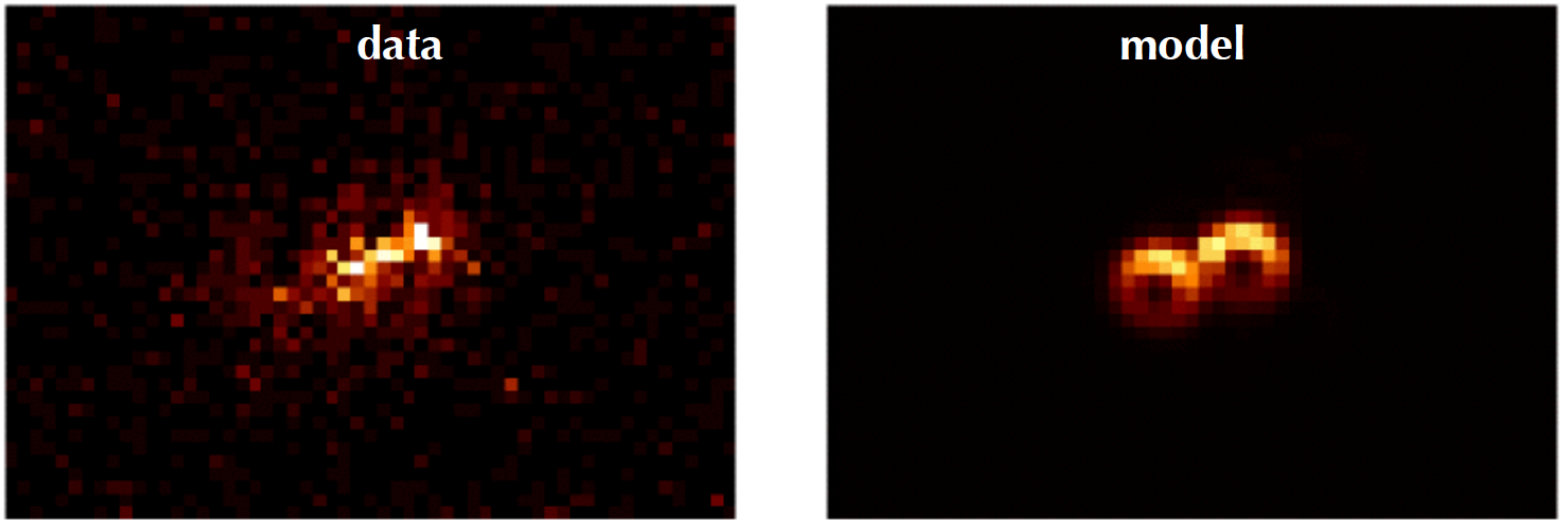


Swartz et al. 2015

J0855-4644

Maitra et al. 2015

- Spin inclination angle $\zeta = 34.6 \pm 1.4^\circ \pm 4.5^\circ$

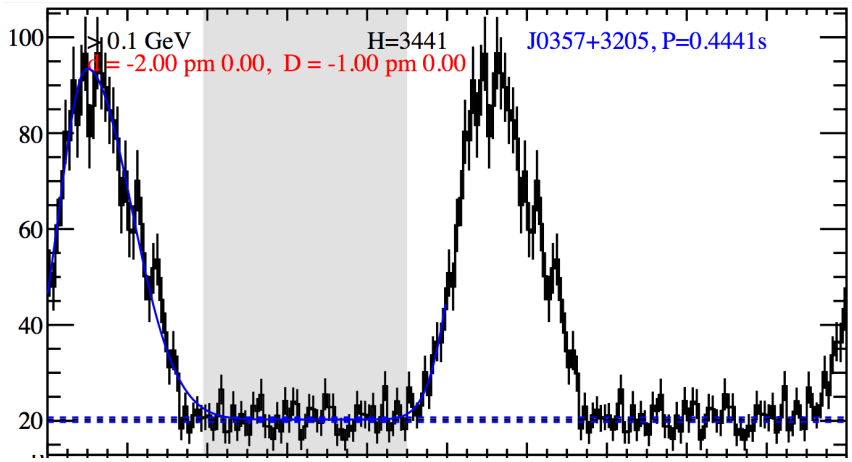


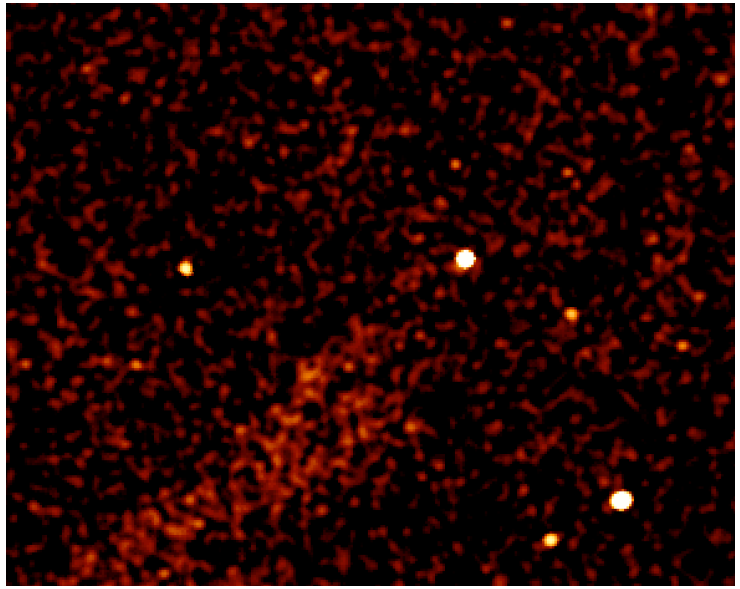
Small can explain th elack of gamma-ray emission

Lightcurve modeling based on Venter et al. (2009, 2012)

- $\zeta < |40|^\circ$
- $\beta = |\alpha - \zeta| < 20^\circ$

J0357+3205





No radio or X-ray pulsations;
No compact X-ray PWN