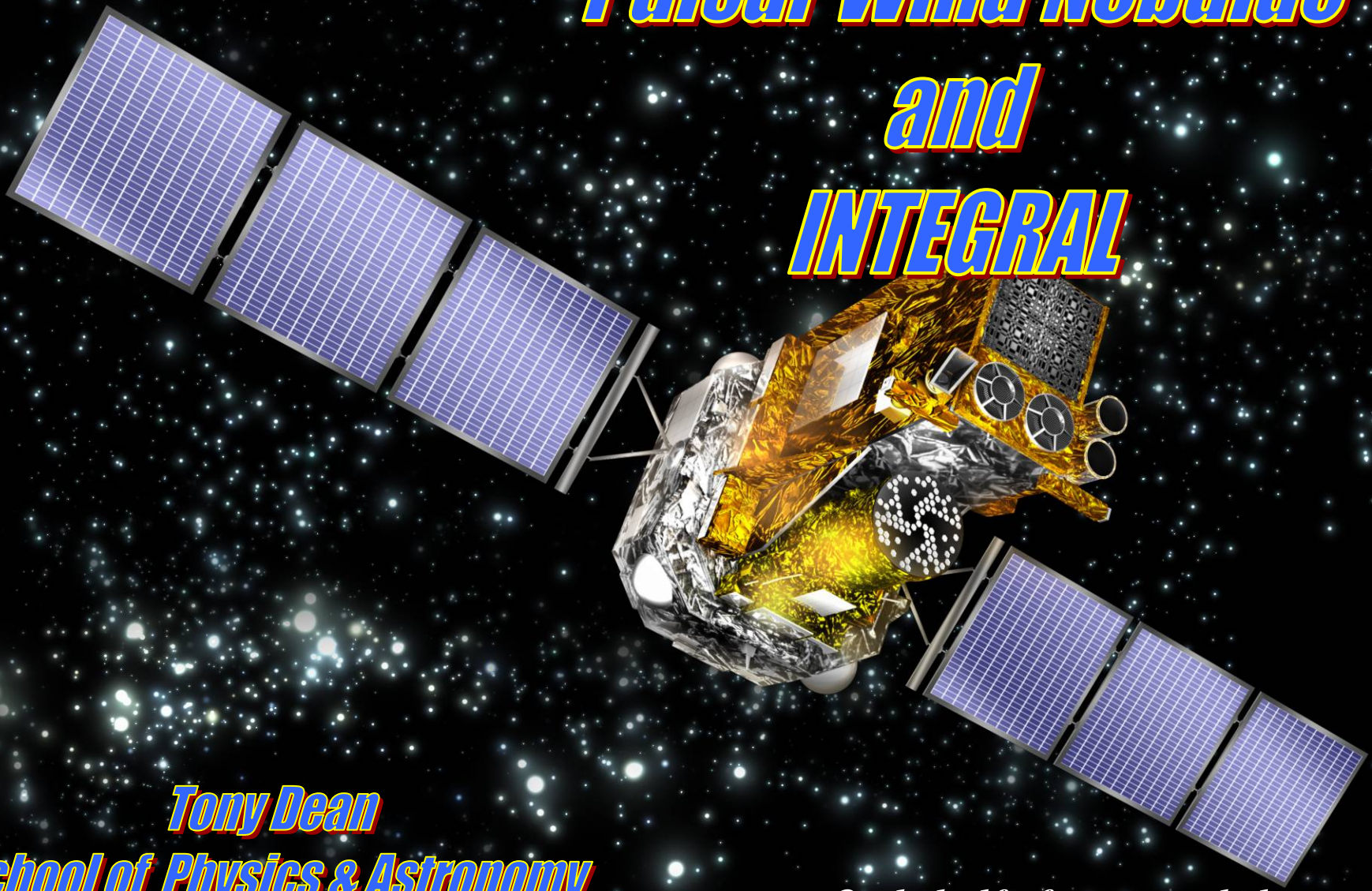
Pulsar Wind Nebulae and INTEGRAL



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On behalf of an extended Bologna, Rome & Southampton Team

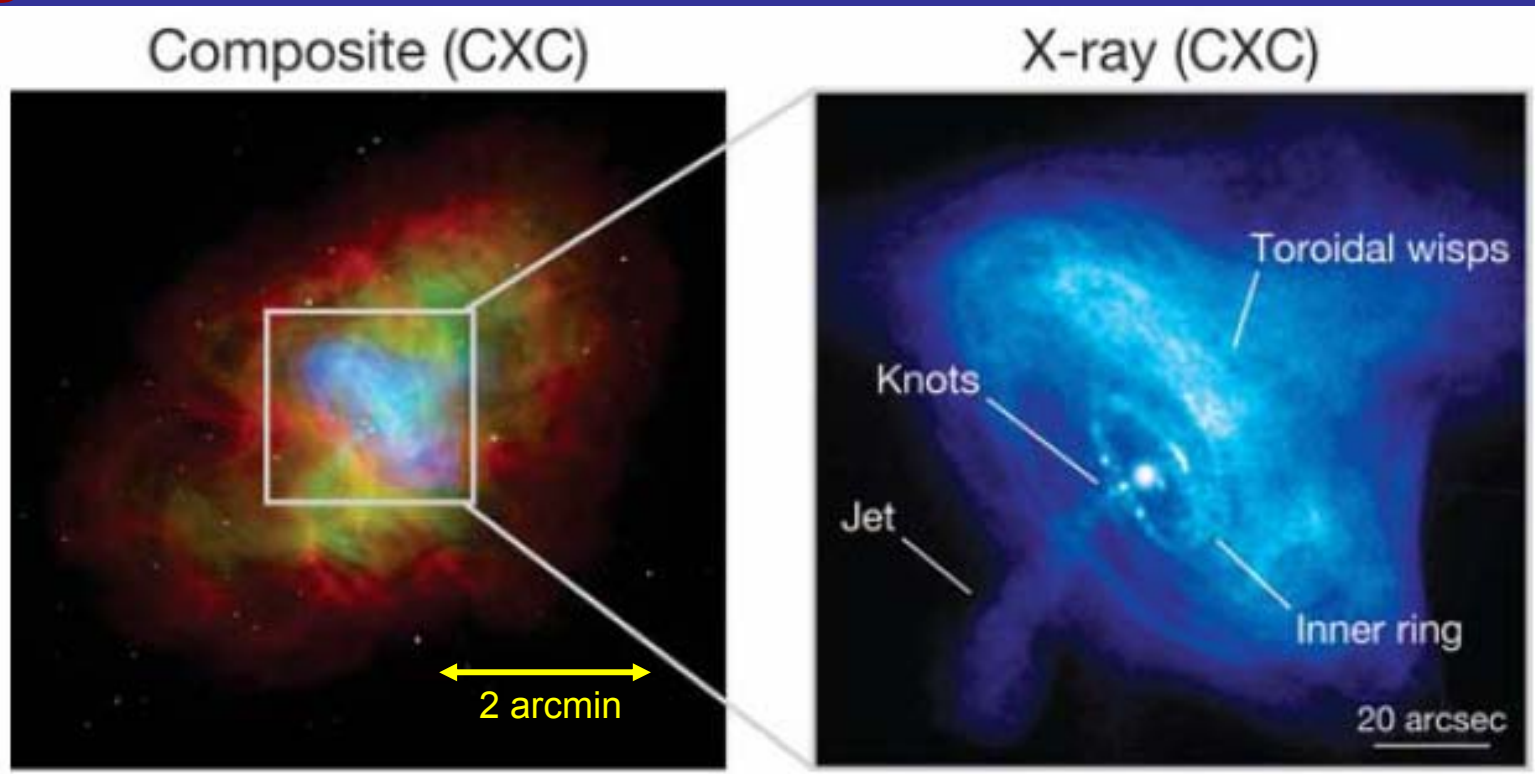
INTEGRAL Studies of PWN Systems

- **The Source list of PWN:**
  - *Selection based on the Mallory Roberts* ***The Pulsar Wind Nebula Catalogue***
  - *http://www.physics.mcgill.ca/~pulsar/pwncat.html*
  - *Interest heightened by the association with a number of HESS Sources*
- **Three types of PWN for IBIS/ISGRI:**
  - *Seen by IBIS - discussed here ~ 10 (16%)*
  - *Pulsar seen in radio but not seen by IBIS ~ 25 (42%)*
  - *No radio pulsar ~ 25 (42%) – Possibly one seen by IBIS*

PWN Systems seen by INTEGRAL

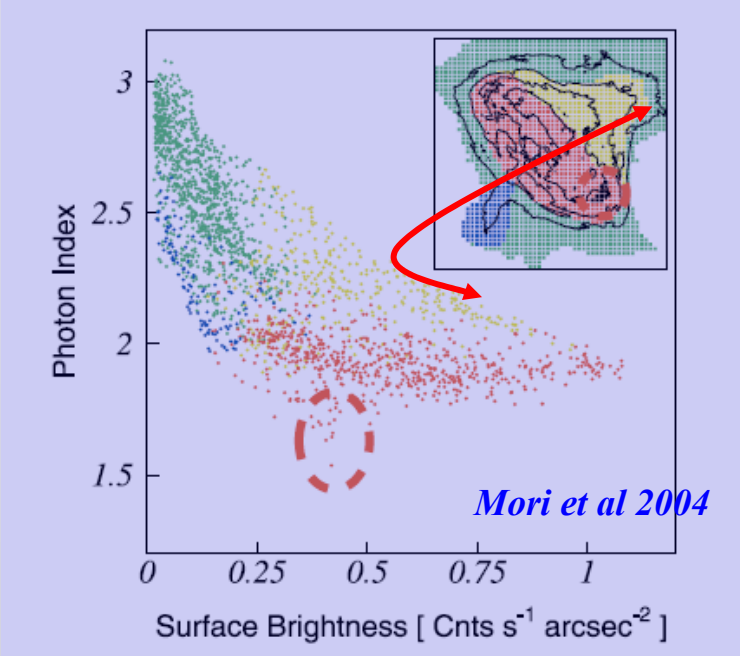
- *Crab*
- *J0540-6919 (LMC)*
- *J0835-4519 (Vela)*
- *J1302-6350 (Be accretor)*
- *J1513-5906 (MSH 15-52)*
- *J1617-5055*
- *J1717-2958 (Mouse) ?*
- *J1811-1925 (Turtle)*
- *J1833-1034*
- *J1846-0258 (Kes 75)*
- *IGR J18135-1751 – HESS J1813-178 (Pulsar?)*

Images of the Crab Nebula



- *LHS - Composite Radio/Optical/Chandra of Crab*
- *RHS - Chandra image showing toroidal and jet structure*
- *NOTE elliptical morphology along jet axis*
- *Synch cooling makes size inverse function of photon frequency*

Where do the soft gamma-rays come from ?



INTEGRAL spectrum has

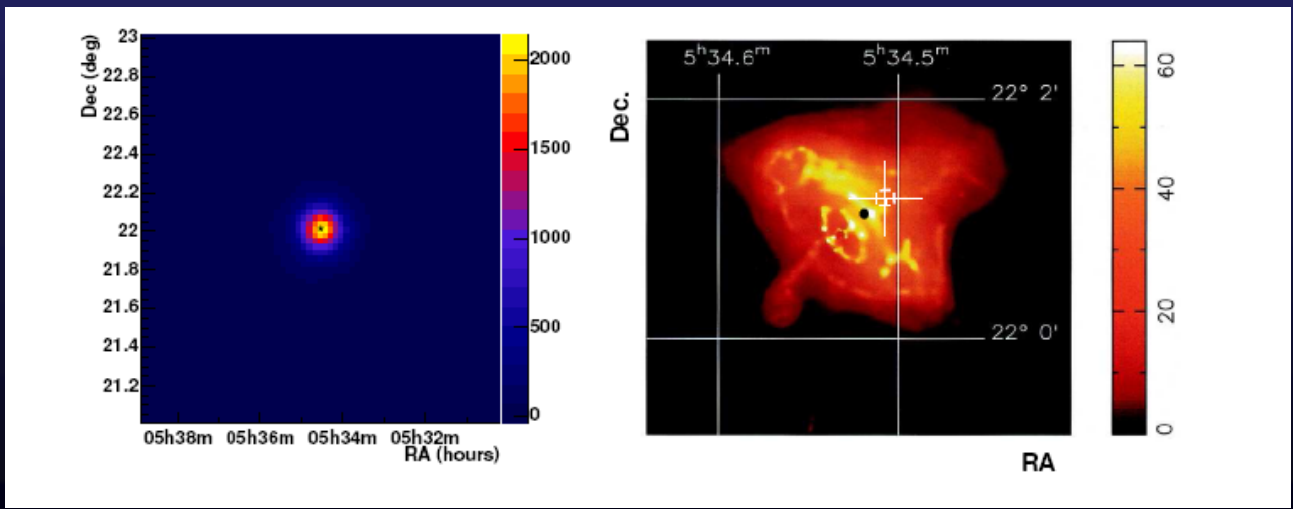
photon index of $\Gamma \sim 2.23$

i.e similar to Jet/Counterjet

$\dot{E} = 4.6 \times 10^{38}$ erg s^{-1}

$L_{(20\text{-}100)} \sim 7 \times 10^{36}$ erg s^{-1} ~1.5% $\dot{E}$

$L_{1\text{-}10TeV} \sim 3.4 \times 10^{33}$ erg s^{-1} ~10^{-3} % $\dot{E}$



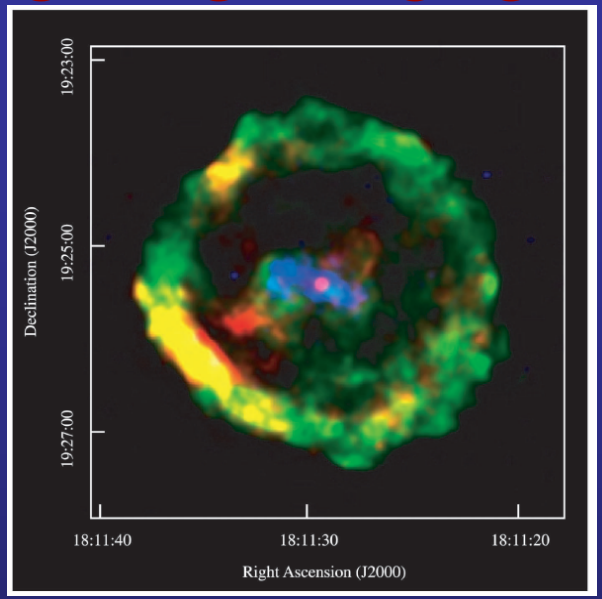
HESS spectrum has

$\Gamma \sim 2.57$

Centroid shown

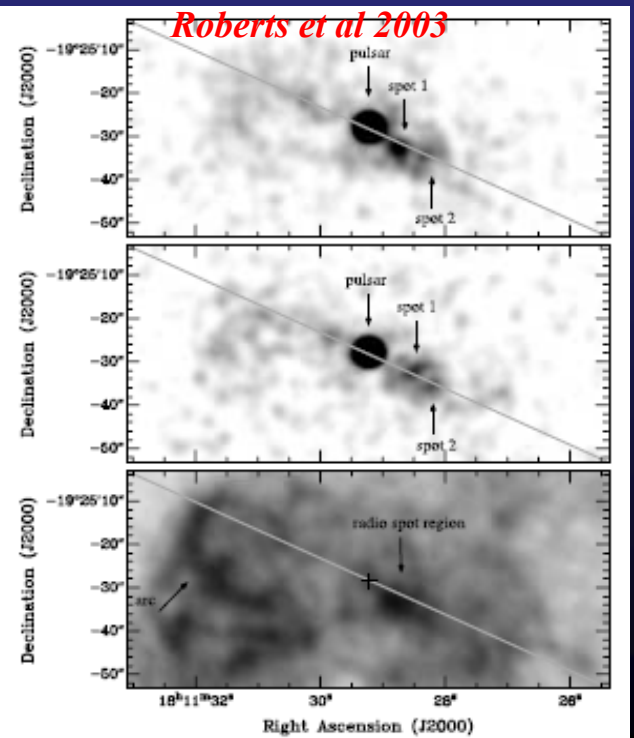
PSF ~0.14°

PSR J1811-1925 : The Turtle

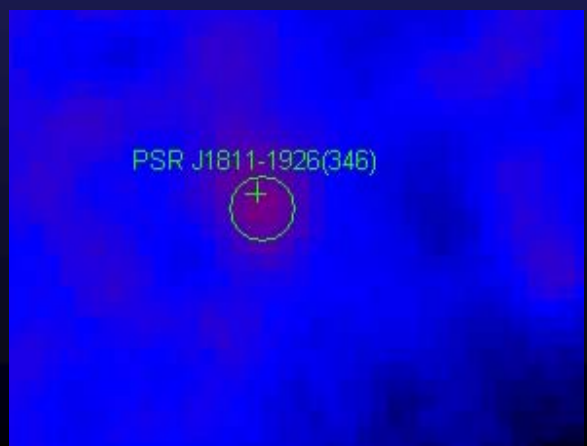


Chandra Spectral Images

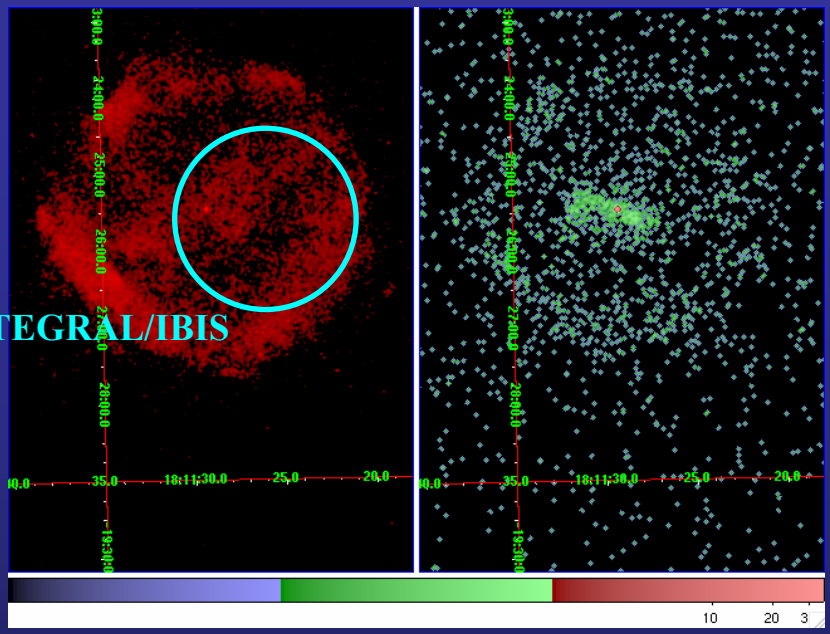
- *"Classic" SNR/PWN/Pulsar configuration*
- *4'5 diameter SNR has thermal kT ~ 0.6 keV*
- *65ms Pulsar has Γ ~ 0.97*
- *Bilateral elongated PWN has Γ ~ 1.8*



- *Blobs move along jet with ~ 1.4c and 0.8c*
- *IBIS/ISGRI : Γ = 1.8 like Chandra PWN*
- *$L_{(20\text{-}100)}$ ~ 0.66% Ė @ 5 kpc*



PSR J1811-1925 :



Where do the gamma-rays come from?

- *INTEGRAL error circle lies within SNR*

- *SNR spectrum is thermal, kT~ 0.6 keV*
- *Good fit between INTEGRAL and Chandra PSR + "jet"*

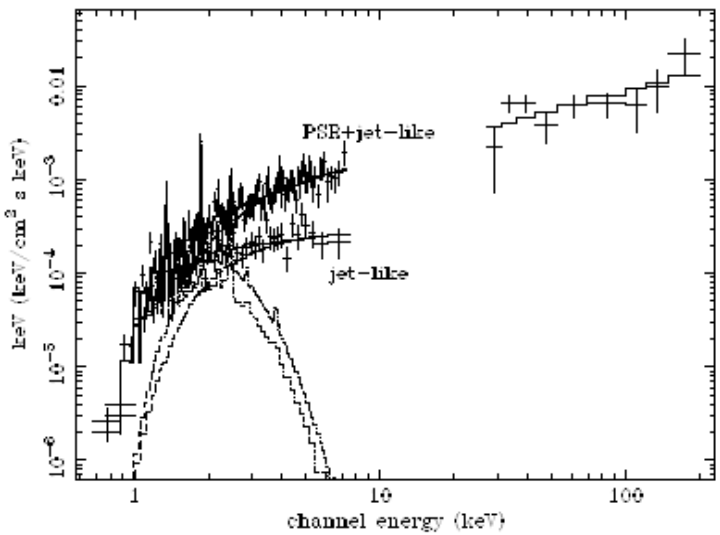
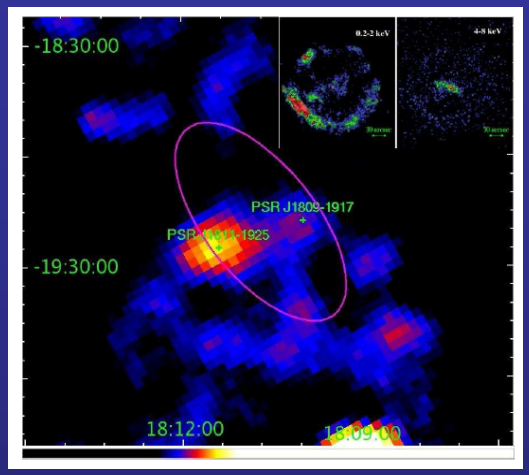


Fig. 2. Composite spectrum *Chandra* and *INTEGRAL* . The two data set in the *Chandra* energy range are the spectra extracted from the jet-like feature (region A in the text) and PSR+jet-like feature (region B in the text).

PSR J1811-1925 & HESS J1809-193



Is there enough power?

Pulsar	$\dot{E}$ (erg/s)	Distance (kpc)	L_{HESS} (% $\dot{E}$)
PSR J1811–1925	6.4×10^{36}	5	0.6
PSR J1809–1917	1.8×10^{36}	3.5	1.2

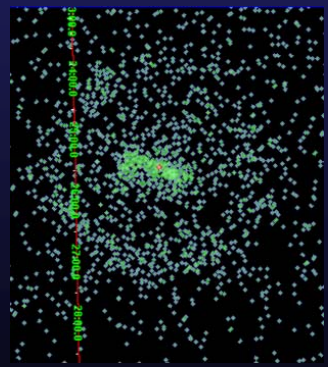
Table 1. Characteristics of the pulsars located near to the HESS J1809-193 source. L_{HESS} covers the 1–10 TeV energy range.

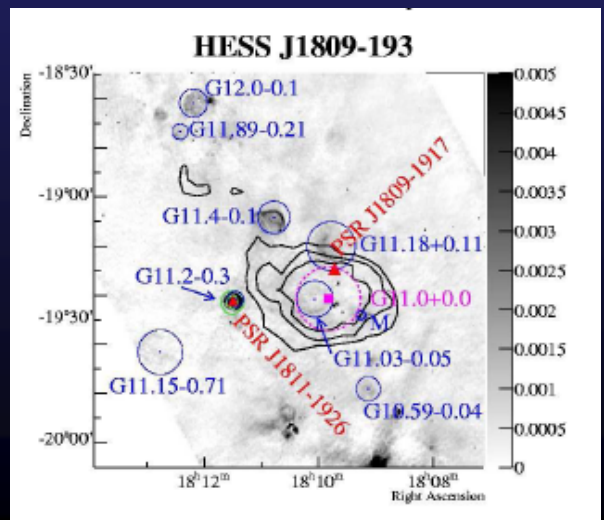
Can PSR J1811 feed HESS 1809?

- *@ 5 kpc centroid of HESS ~29 pc from pulsar*
- *Lifetime of 30+ TeV electrons enough to get there*
- *IC process for TeV gammas*

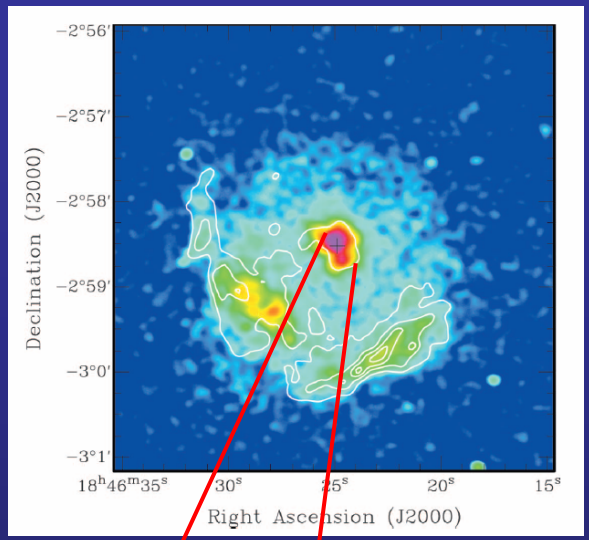
Aharonian et al 2007

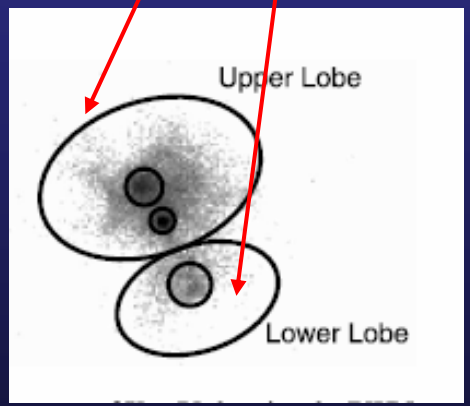
Down the "jet"?





PSR J1846-0258 : Kes75





Helfand et al 2003

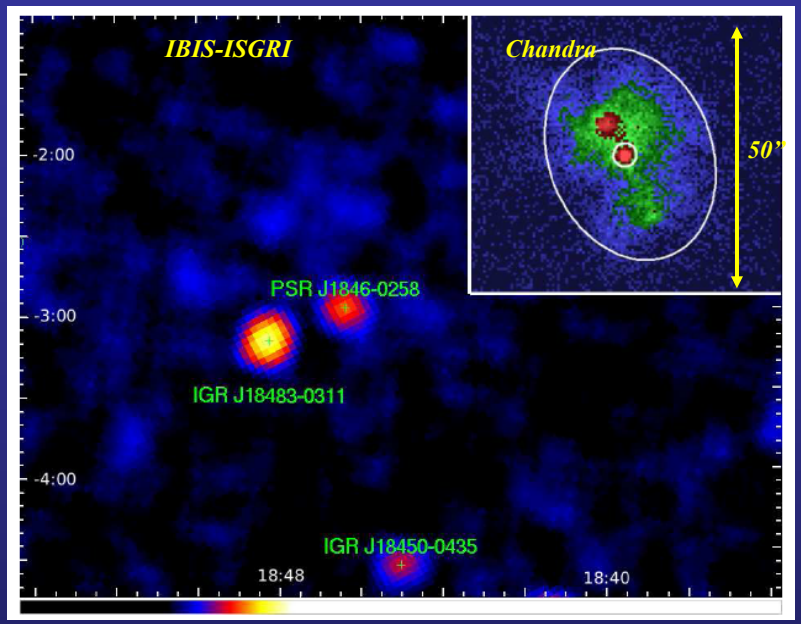
Chandra Spectral Images

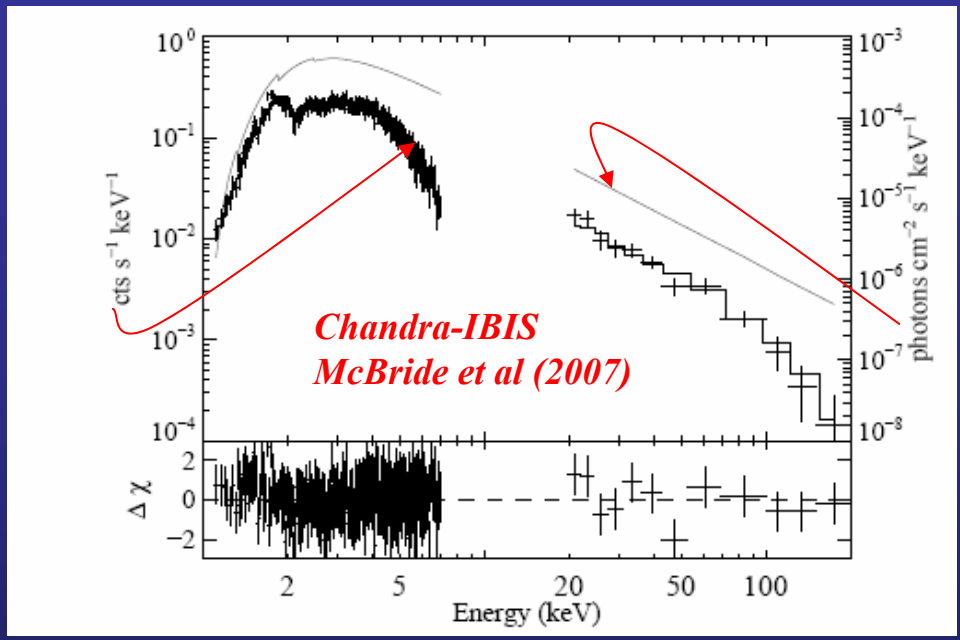
- Very young (~700y) system @ 19kpc
- *P = 324 ms*
- *dP/dt = 7.1 × 10 $^{-12}$ ss $^{-1}$*
- *PWN/PSR close to centre of composite SNR*
- *SNR, thermal, kT ~ 2.9 keV*
- *Pulsar has Γ ~ 1.39*
- *Axisymmetric elongated PWN has Γ ~ 1.92*

- *Hot spots along axis on either side of pulsar*
- *Exceptional timing properties : P & dP/dt > 10 Crab*
- *Result of extreme B value of 4.8 10^{13} G ?*

Youngest with longest period

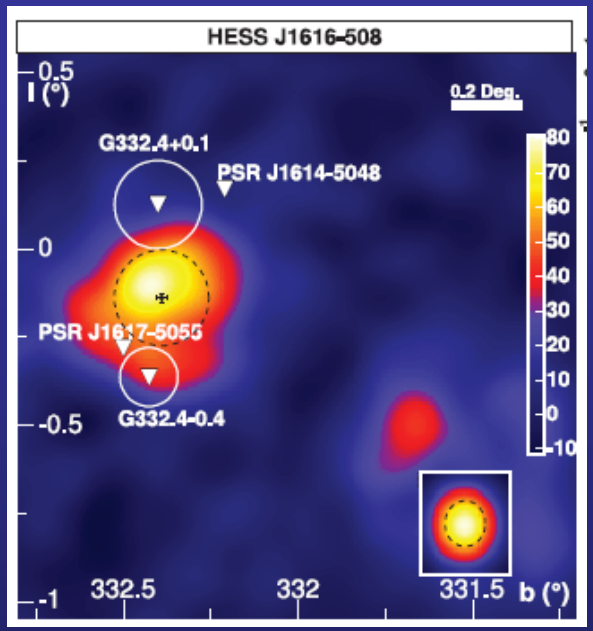
PSR J1846-0258 : Kes75



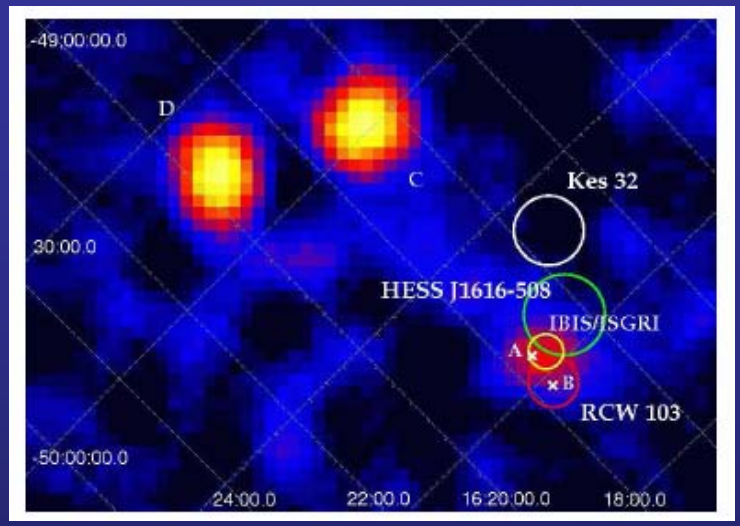


- *IBIS "coincident" with Pulsar/PWN complex*
- *IBIS/ISGRI : Γ = 2.0 ⇨ includes PWN + Pulsar*
- *$\dot{E}$ = 8.4 × 10^{36} erg s^{-1}*
- *$L_{(20\text{-}100)}$ = 1.3 × 10^{36} erg s^{-1} @ 19kpc*
- *Extraordinary $L_{(20\text{-}100)}$ ~ 15% $\dot{E}$!!! – But some concerns over 19 kpc*

PSR J1617 -5055 - HESS J1616-508



HESS image

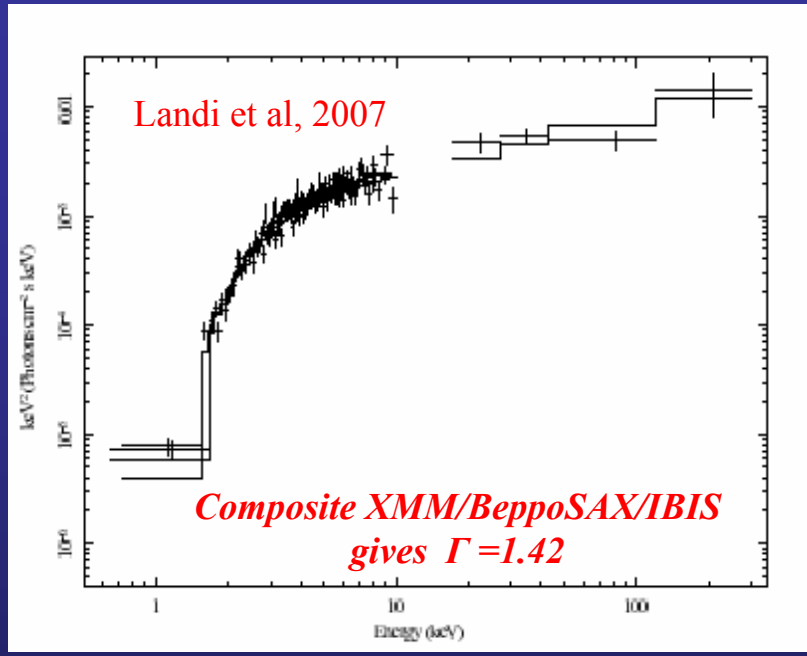


INTEGRAL image

- HESS extended and one sided, source size decreases with Eγ
- INTEGRAL, point like, coincident with 69ms PSR
- Soft γ-ray emission $\Gamma = 1.91$
- X-rays, small extension, coincident with pulsar

PSR J1617 -5055 - HESS J1616-508

Composite XMM-Newton/MOS, BeppoSAX/MECS and INTEGRAL/ISGRI spectrum



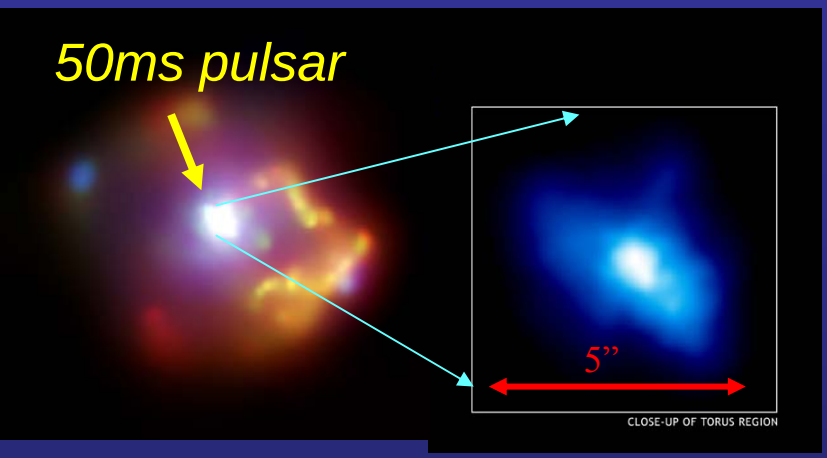
Is there enough power?

- $\dot{E} = 1.6 \times 10^{37}$ erg s^{-1}
- Characteristic age ~ 8ky
- $L_{(20\text{-}100)} = 7.4 \times 10^{34}$ erg s^{-1} ~0.5% $\dot{E}$
- L_{TeV} ~ 1.2% $\dot{E}$
- **d ~ 6.5 kpc**

Mechanisms:

- X/soft γ-rays: synchrotron, $E_e \sim 10^{13}$ -10^{14} eV, $\tau \sim$ 500y
- TeV: IC on (partly) CMB, $E_e \sim 10^{12}$ -10^{13} eV, $\tau \sim$ 3-5000y
- 10 μGauss field

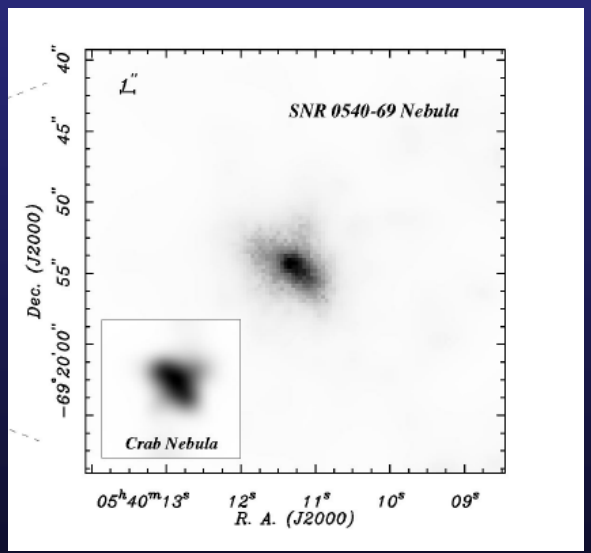
PSR J0540-6919 in LMC - Crab Twin?

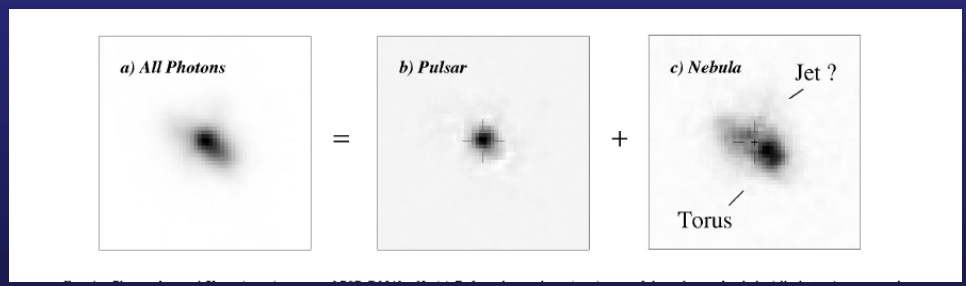


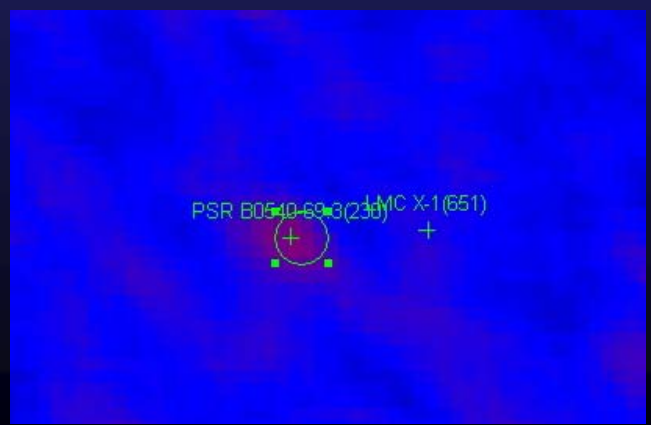
Chandra spectrum has Γ~1.92 pulsar, ~2 – 2.1 nebula

INTEGRAL spectrum has Γ~2.2
Nebular emission?

$\dot{E} = 1.5 \times 10^{38}$ erg s^{-1}
$L_{(20-100)}$ ~5.95 10^{36} erg/s ~ 4 % $\dot{E}$

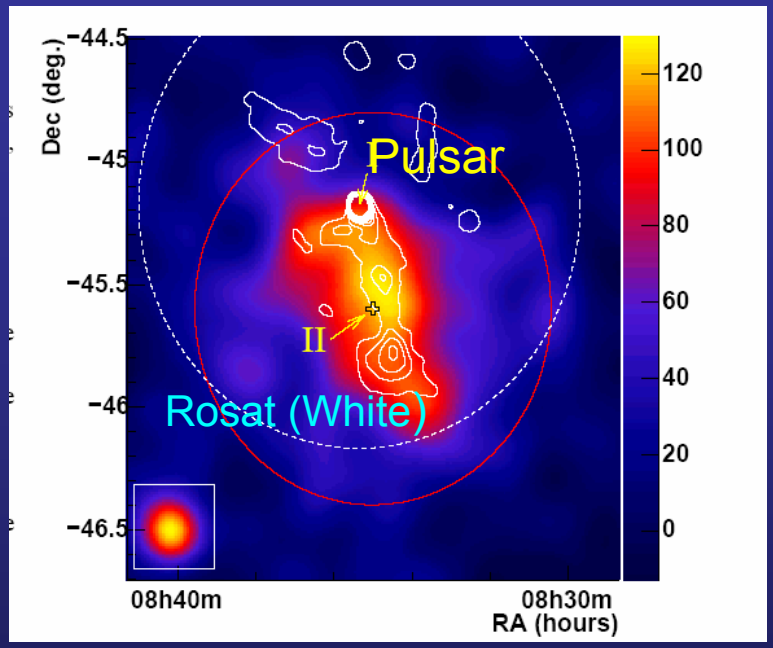


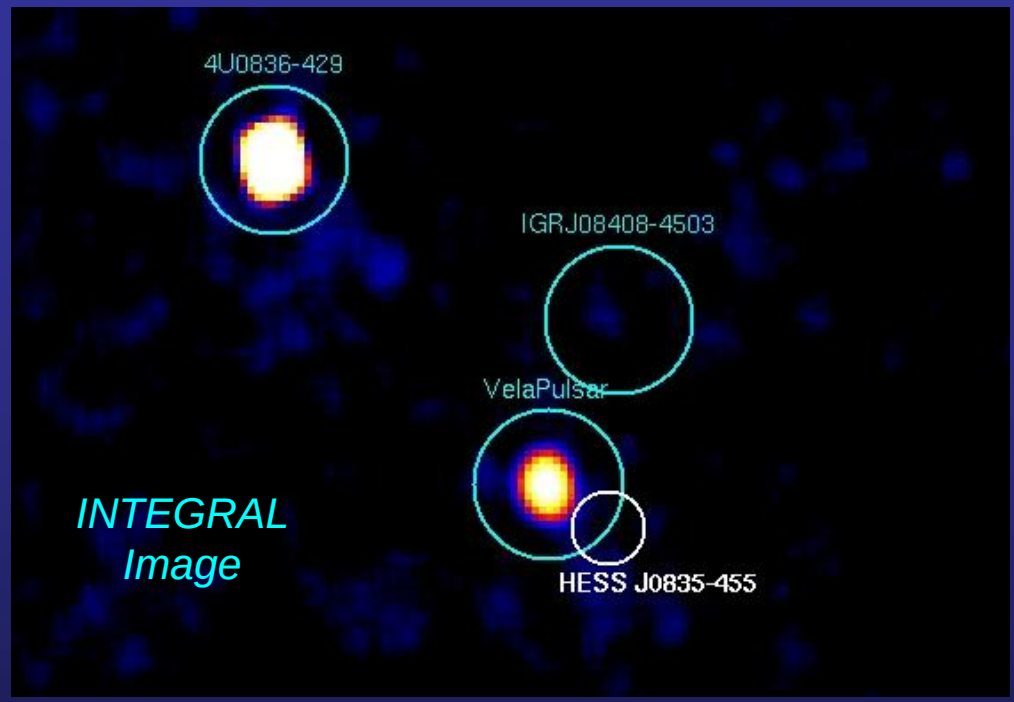




PSR J0835-4510 - Vela

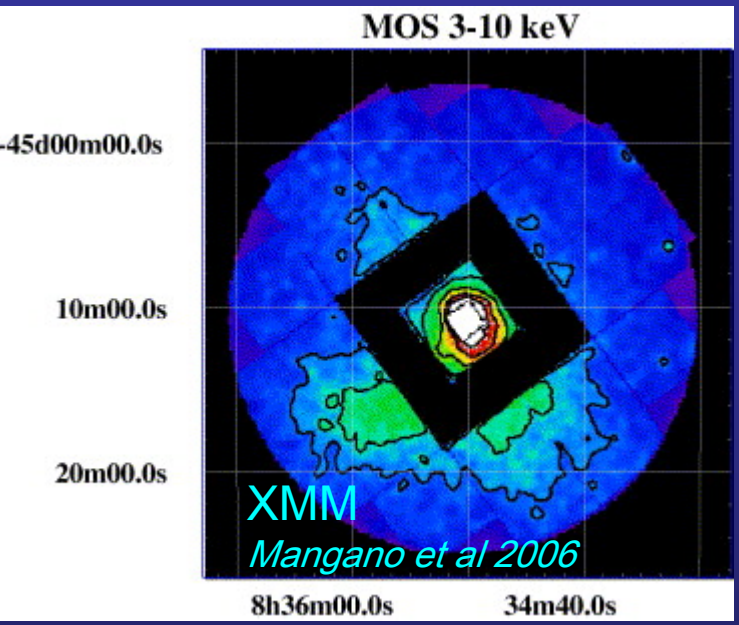
Aharonian et al 2006



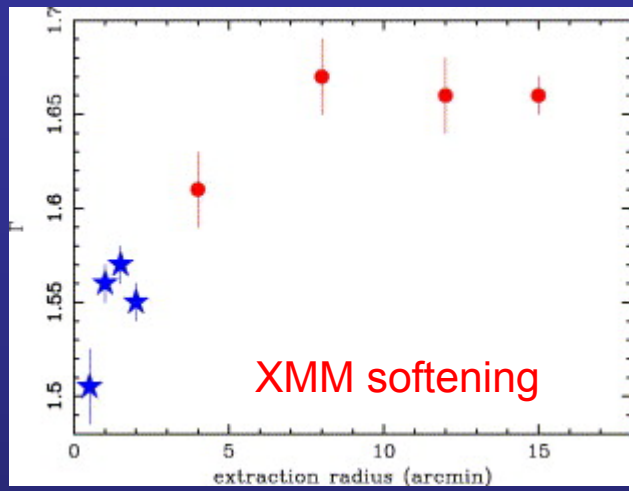


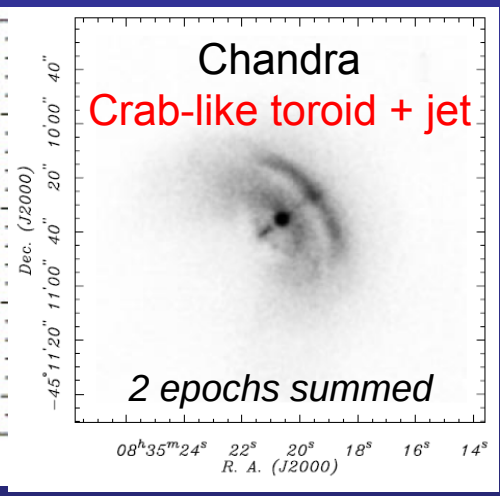
- *Youngish Vela Pulsar (89 ms, 290pc, $\dot{E}$ = 7x10^{36}ergs^{-1}, τ ~ 11ky)*
- *HESS extended source south of pulsar (B0833-45)*
- *Rosat/ASCA Vela X jet like feature corresponds to a one-sided PWN*
- *No IBIS excess from extended PWN,*
- *No HESS excess from pulsar*

PSR J0835-4510 - Vela



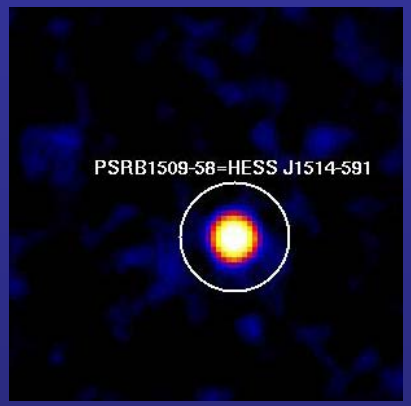
Helfand et al. 2001

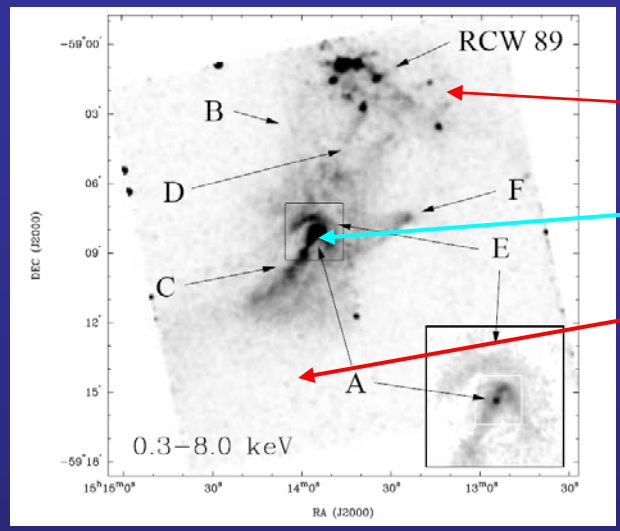


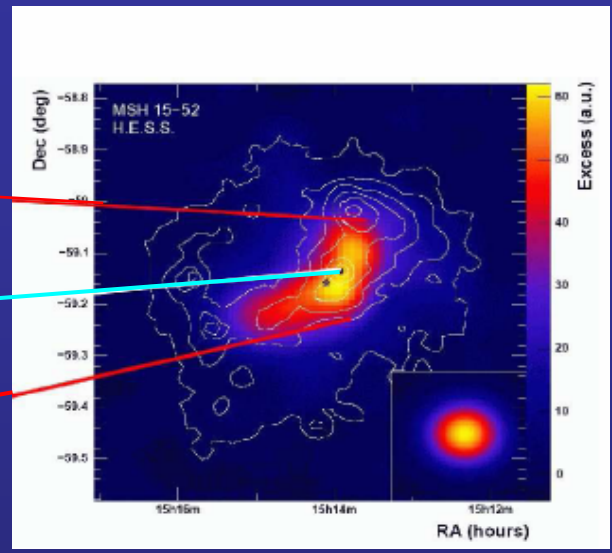


- *XMM softens with distance from pulsar*
- *Synch cooling in X-ray domain ?*
- *Chandra has jets $\Gamma \sim 1.1 - 1.2$, rapidly moving blobs $\Gamma \sim 1.1 - 1.4$*
- *INTEGRAL has $\Gamma = 2.07$*
- *$L_{(20\text{-}100)} = 1.2 \times 10^{33}$ erg $s^{-1} \sim 1.6 \times 10^{-2}$ $\dot{E}$*
- *Vela is about 16 times smaller than the Crab*

PSR J1513-5906 MSH 15-52







- *PSR J1509-58, (5kpc, ~1500y, 150ms, Ė = 1.8x10^{37}ergs^{-1}, B=1.5 10^{13}G)*
- *Chandra shows torus and & jet with pulsar +*
- *HESS Elliptically around pulsar (1st* **extended** *PWN jet seen in VHE)*

Chandra Spectral Images

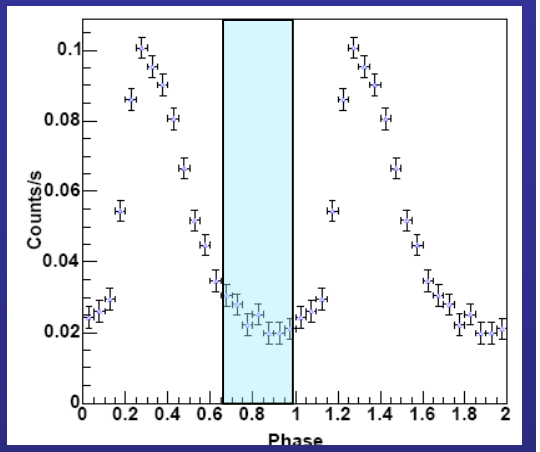
- *Pulsar, (A)* $\Gamma = 1.4$
- *Jet ,(C)* $\Gamma = 1.6$
- *Arc, (E)* $\Gamma = 1.6$
- *PWN* $\Gamma = 2.05$

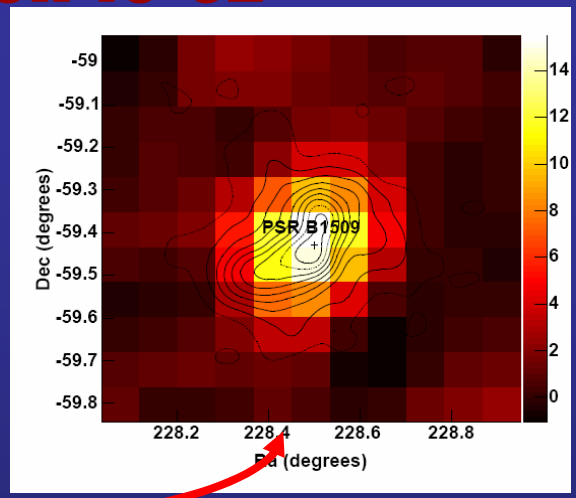
INTEGRAL Spectrum

- *IBIS/ISGRI :* $\Gamma = 1.89$
- $L_{(20\text{-}100)} \sim 2.44\%$ Ė

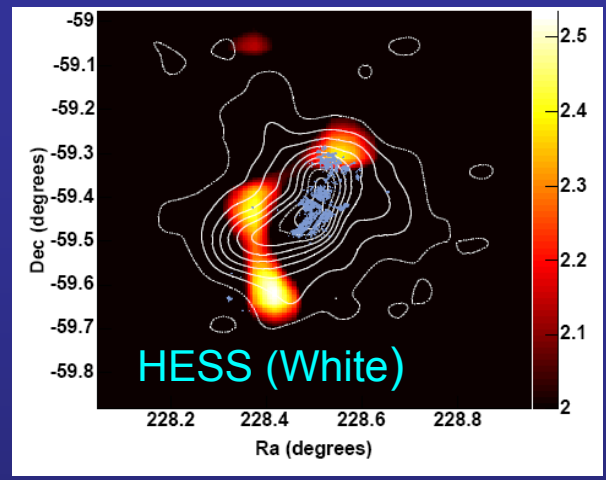
PSR J1513-5906 MSH 15-52

Forot et al, ApJL (2006)



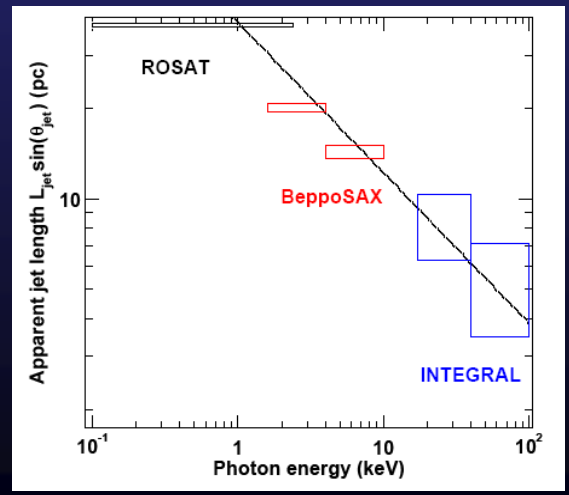


Off pulse ISGRI image

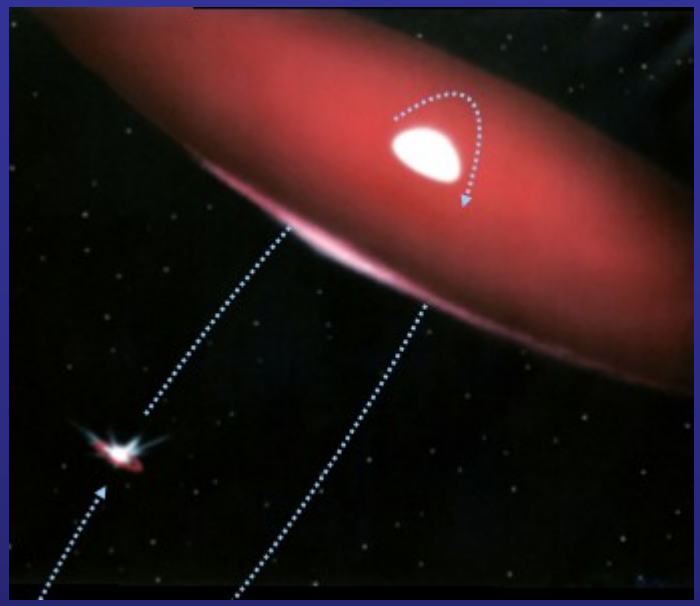


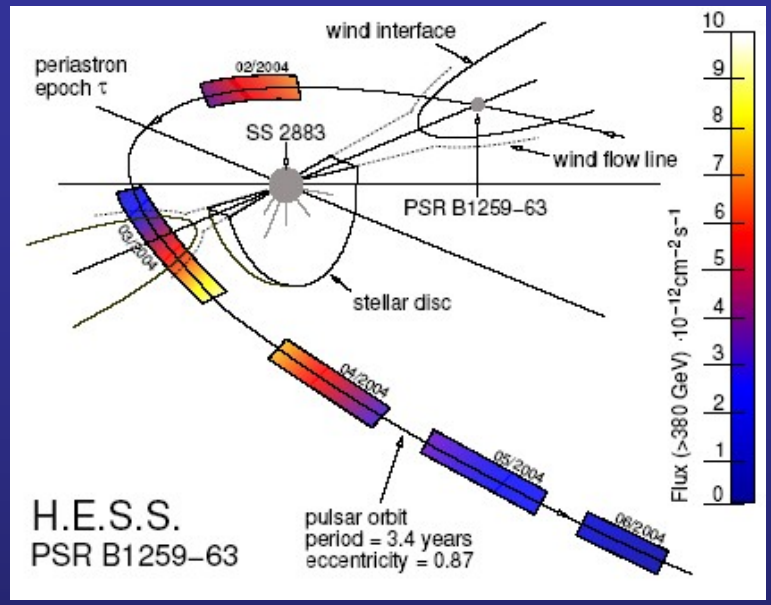
PSF removal

- *Pulsar contamination removed by phase analysis to study pulsar wind*
- *Off pulse image slightly extended*
- *Significance map after PSF removal shows excess compatible with HESS*
- *The length of the 'jet' decreases with E_X*
- *Synchrotron ageing jet model works*
- *Hard X-rays dominated by jet emission?*

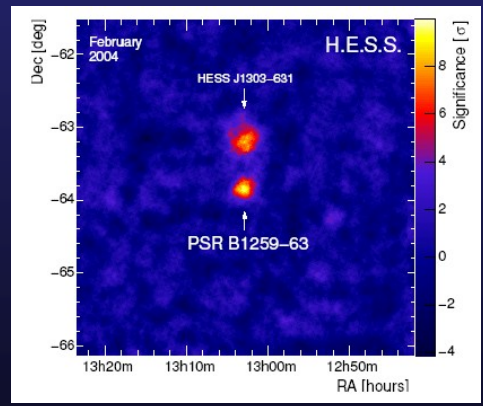


PSR J1302-6350 - a unique PWN in a Be Binary





- *47ms Pulsar in 3.5 yr binary – 2 passages through disk*
- *Also a HESS source average Γ ~2.7*
- *X-ray and soft γ-ray spectra vary in intensity and index through orbit*
- *Γ_X varies from 1.8 before entry to disk to 1.2 after (XMM)*
- *$\Gamma_{S\gamma}$ found to be ~1.3 near periastron & ~2.7 averaged*



- *L(20-100) ~ 2.8% Ė BUT this is an*
- *Accretion dominated system*

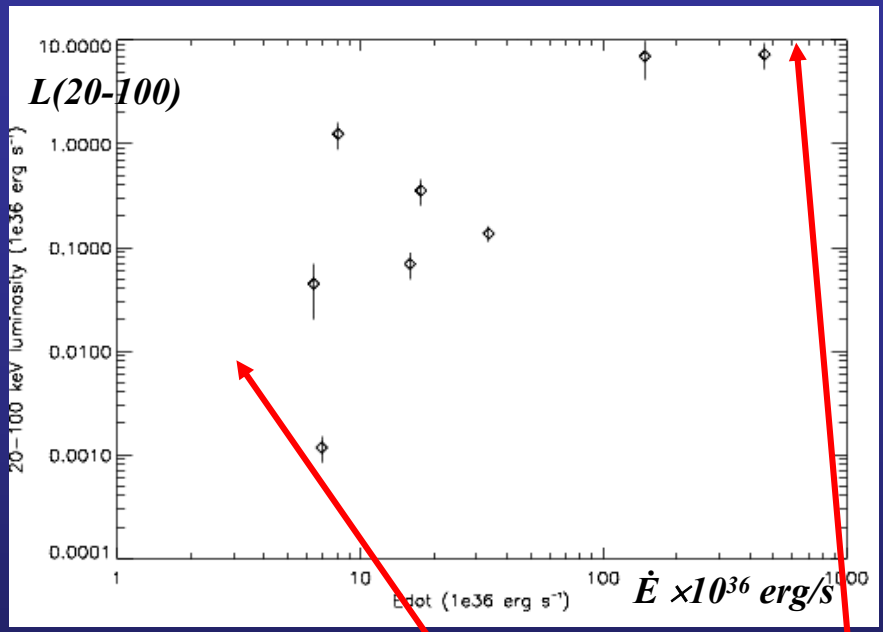
Where do the soft gamma-rays come from ?

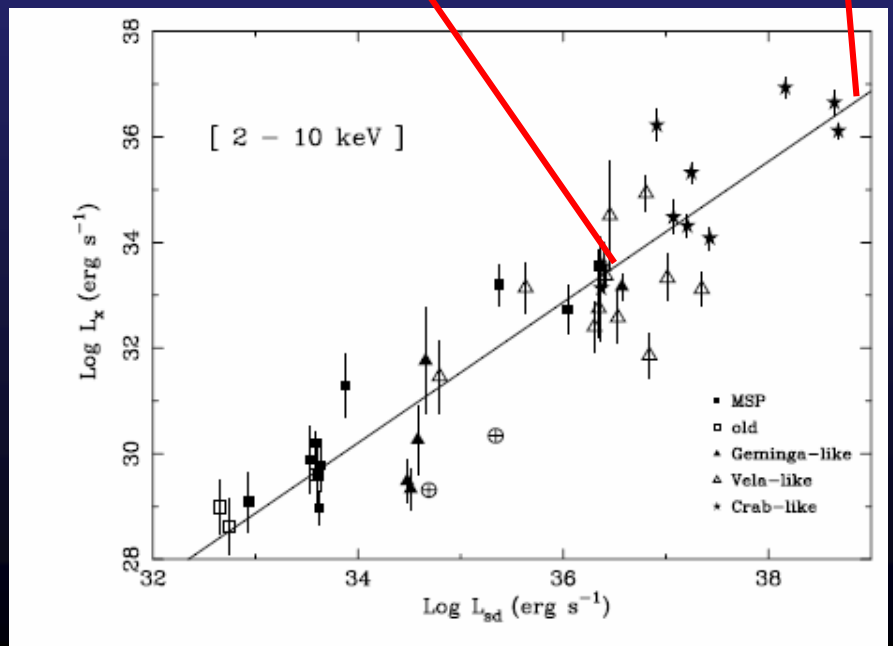
- ***Positional location*** *: Tantalisingly close to pulsar, within PWN?*

Crab	Inner Jet
J0540-6919 (LMC)	PWN/"jet"
J0835-4519 (Vela)	PWN/"jet"
J1302-6350 (Be)	? Be accretor
J1513-5906 (MSH 15-52)	PWN/"jet"
J1617-5055	near pulsar (X-PWN? – No jet)
J1811-1925 (Turtle)	PWN/"jet"
J1833-1034	Somewhere in outer PWN – No jet
J1846-0258 (Kes 75)	PWN/"jet"

- ***IBIS Site must be close to electron accelerator***
  - *Synchrotron lifetime of soft γ-ray producing electrons in PWN fields is $\tau \sim 10 - 100y$*
  - *NOTE that $\geq 67\%$ of the soft γ-emitting systems have "jets"*

Correlations with the pulsar characteristics - 20-100 keV Luminosity





INTEGRAL

NOTE: They are all young, short period (~ 100ms), energetic pulsars, spin down ages in range

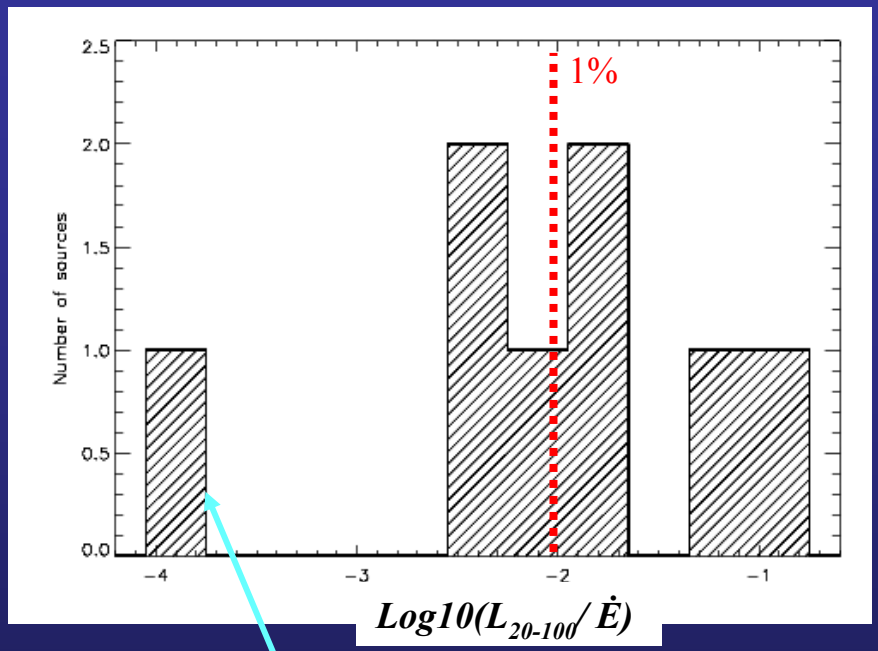
$700 \leq \tau \geq 20{,}000$ y

X-rays

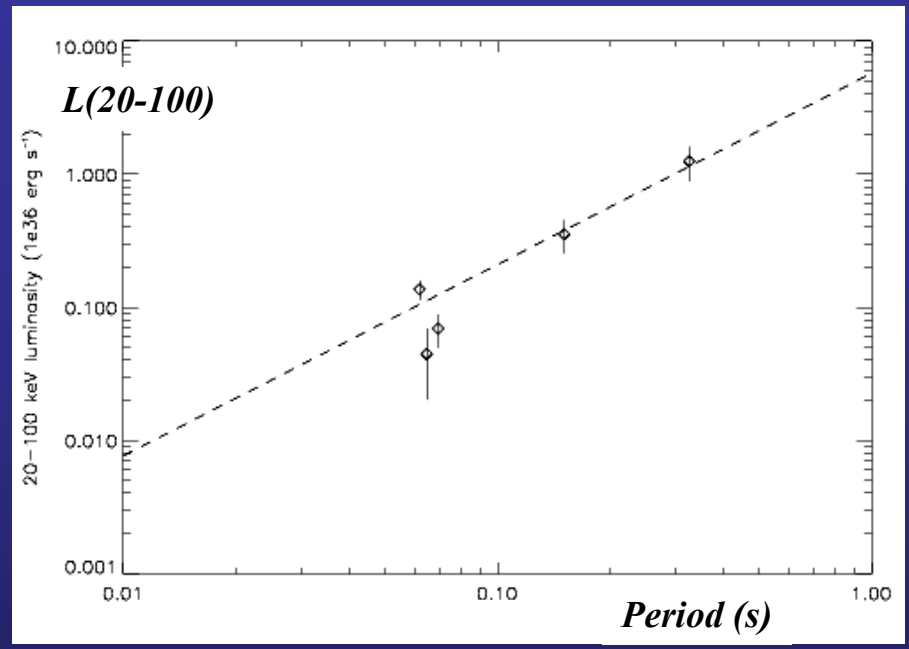
$\text{Log } L_{X(2\text{-}10)} = 1.34 \text{Log} L_{SD} - 15.34$

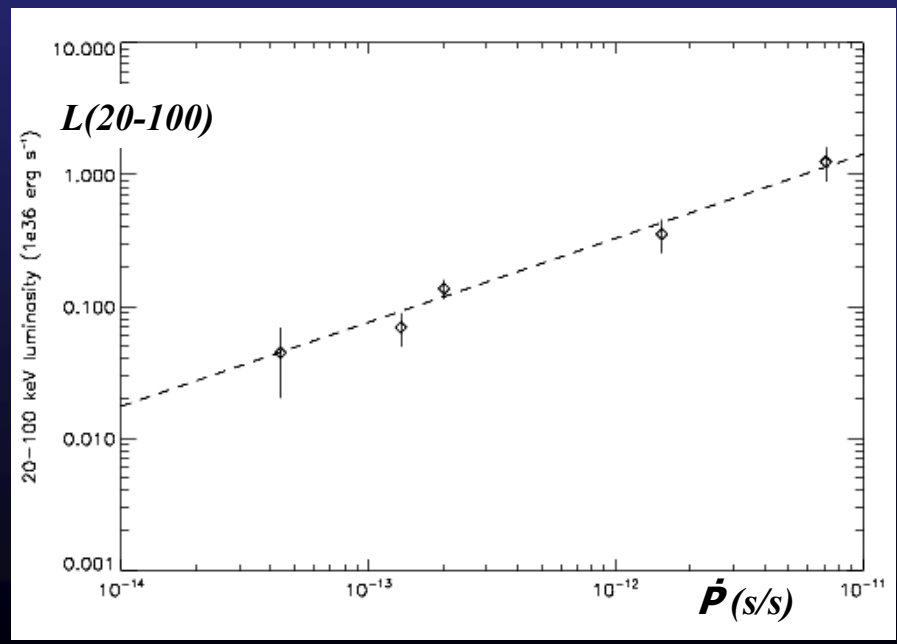
(Possenti et al 2002)

Correlations with the pulsar characteristics

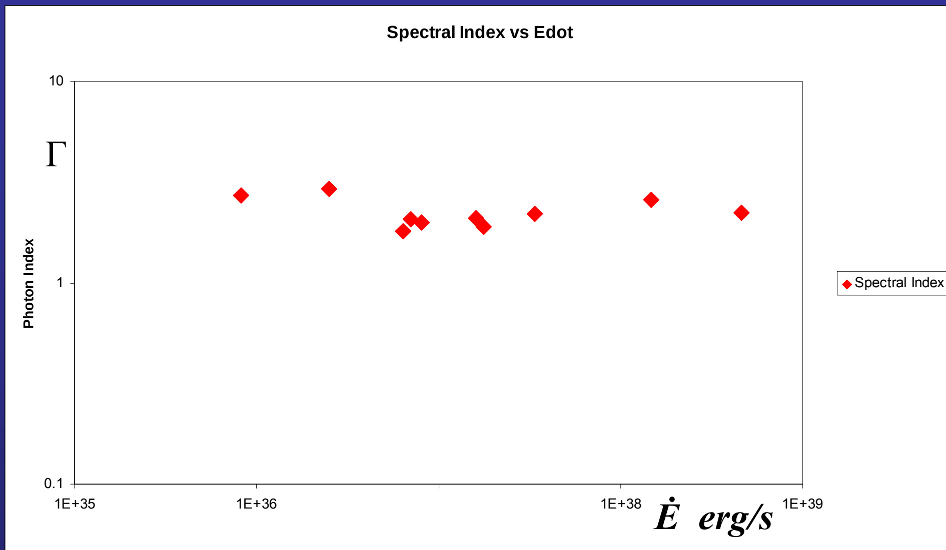


J0835-4519 (Vela)

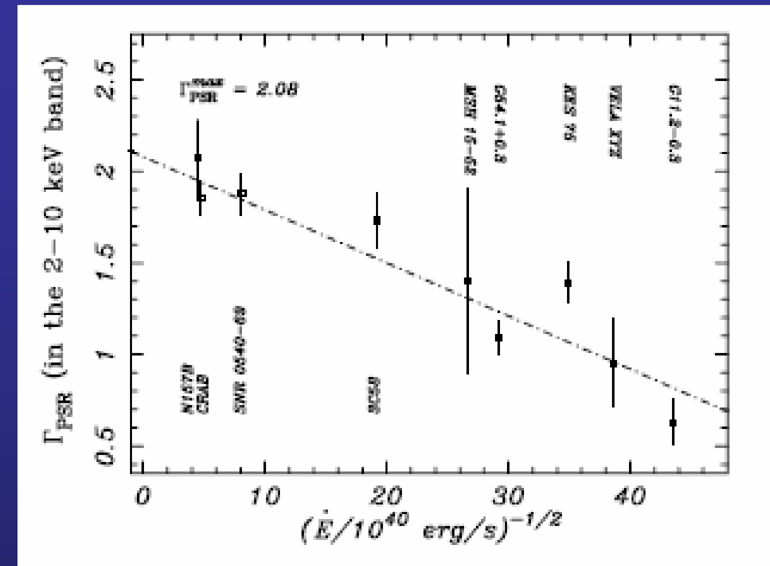




Correlations with the pulsar characteristics



INTEGRAL



X-rays

Weighted mean 20-100 keV photon spectral index:

Γ = 2.13 $\pm$ 0.15

$$\Gamma_{\rm PSR} = 2.08(0.07) - 0.029(0.003)\dot{E}_{40}^{-1/2} \ ,$$

$$\Gamma_{\rm PWN} = 2.36(0.33) - 0.021(0.005)\dot{E}_{40}^{-1/2} \ .$$

Some general characteristics of INTEGRAL PWN

- *A young energetic pulsar is needed*
- $L_{(20\text{-}100)} \sim 1\%\ \dot{E}$, & $L_{(20\text{-}100keV)} \approx L_{(1\text{-}10TeV)}$
- *A jet-like feature is generally present*
- *The soft gamma-ray photon index is* $\Gamma \sim 2$
- *INTEGRAL source is "coincident" with the pulsar/PWN &* $\Gamma_{INTEGRAL} \approx \Gamma_{X\text{-}rayPWN}$
- *When accompanied by a TeV source, Synchrotron for soft gammas and Inverse Compton for TeV works well.*
- *NOTE the energies of the soft gamma producing electrons is ~ 10× TeV producing electrons*