Pulsar Wind Nebulae

High-Energy emission and Diversity

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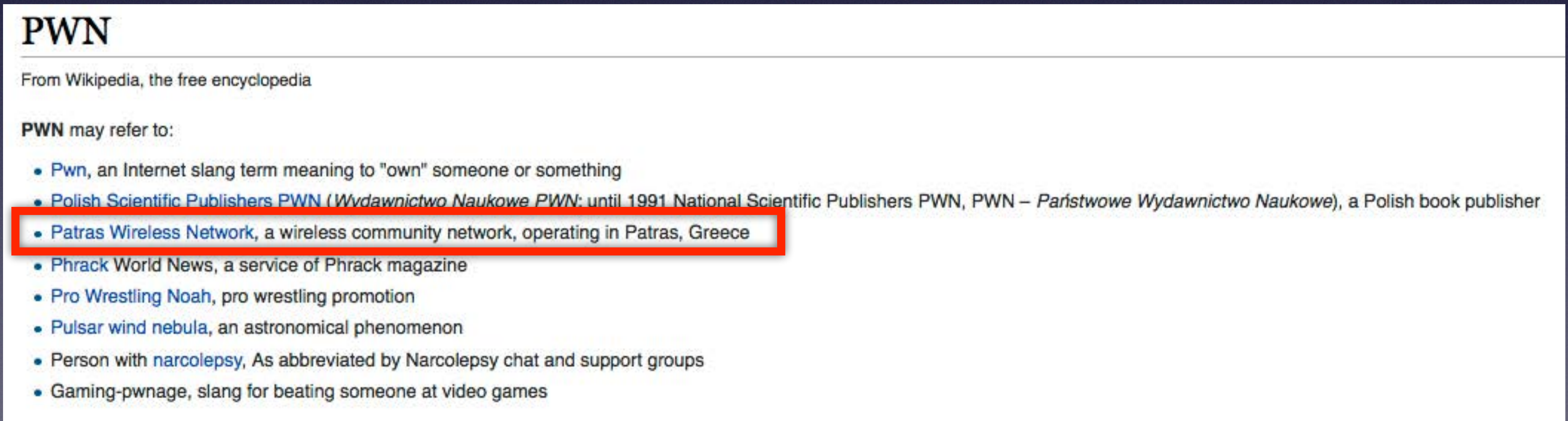
Pulsar Wind Nebulae (Plerions)
The Connection to Greece

K.W. Weiler: 03/1943-04/2016

PWN=Pulsar Wind Nebula, also known as "**plerion**": from the Greek word "πλήρης" ("pleres") meaning "full"—a term coined by Weiler & Panagia (1978)

N. Panagia



PWN

From Wikipedia, the free encyclopedia

PWN may refer to:

- Pwn, an Internet slang term meaning to "own" someone or something
- Polish Scientific Publishers PWN (*Wydawnictwo Naukowe PWN*; until 1991 National Scientific Publishers PWN, PWN – *Państwowe Wydawnictwo Naukowe*), a Polish book publisher
- Patras Wireless Network, a wireless community network, operating in Patras, Greece
- Phrack World News, a service of Phrack magazine
- Pro Wrestling Noah, pro wrestling promotion
- Pulsar wind nebula, an astronomical phenomenon
- Person with narcolepsy, As abbreviated by Narcolepsy chat and support groups
- Gaming-pwnage, slang for beating someone at video games

Galactic PWNe

- As of 2016/06, we know of 379 Galactic SNRs***
- Out of these, 110 (~30%) contain PWNe or candidates
  - 90/110 (81%) are Chandra detected
  - 53/110 (48%) **lack shells** (including Crab): "naked PWNe"

    including ~12 bow shock nebulae
- 70/110 (64%) are powered by detected pulsars
- Out of the 78 Galactic TeV known sources, 38 are identified as PWNe or PWN candidate sources (e.g. *H.E.S.S. Collaboration; Carrigan+13*)

✓ Fermi-LAT: 5 confirmed PWNe + 11 candidates

(Acero et al. 2013)

***

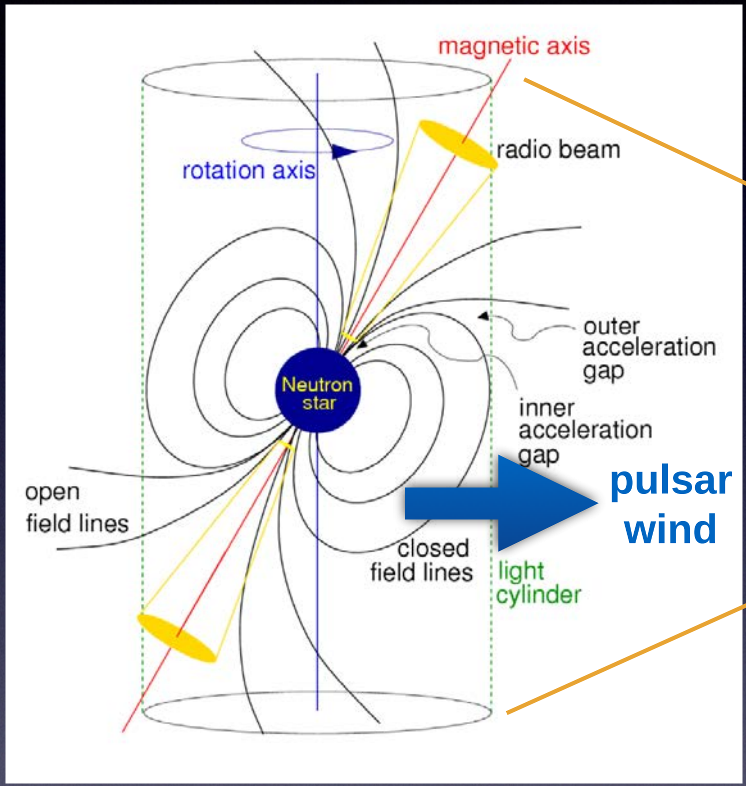
SNRcat: **High-Energy** SNRs catalogue:
http://www.physics.umanitoba.ca/snr/SNRcat

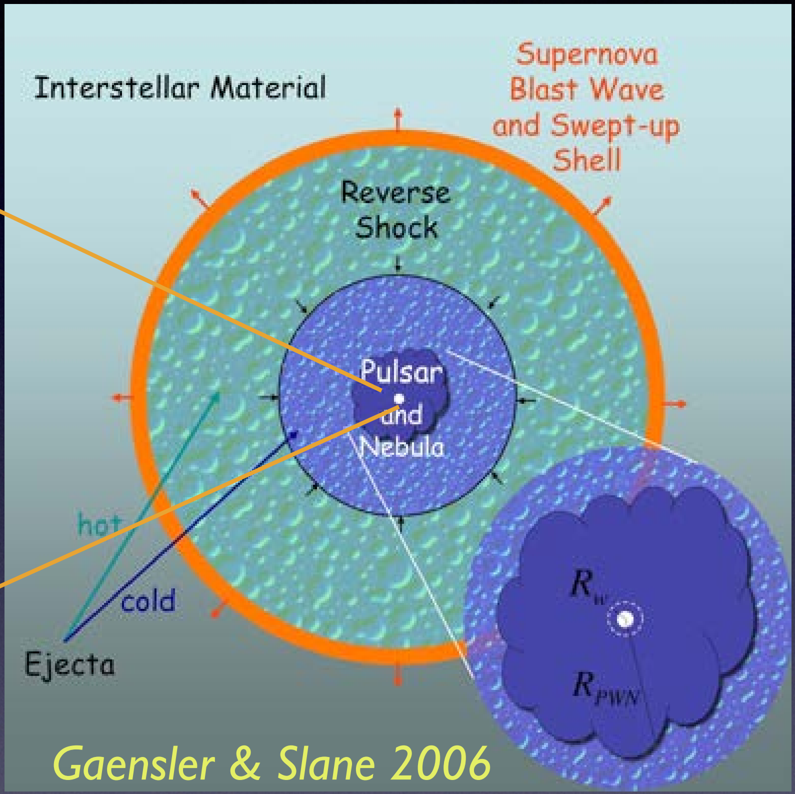
Ferrand & Safi-Harb 2012
updated in 2015 with PWN data

See Ryan Chaves talk (HGPS) and Grondin/M.Lemoine-Goumard (Fermi-LAT), A. Weinstein (VERITAS)

Pulsar Wind Nebulae
Why Bother? Relativistic Outflows

$$\dot{E} \equiv 4\pi^2 I \frac{\dot{P}}{P^3}$$





- **PWN: Bubbles of relativistic particles inflated by pulsar's wind**

Edot=rotational energy loss of Pulsar
PC=Confining/Nebular pressure

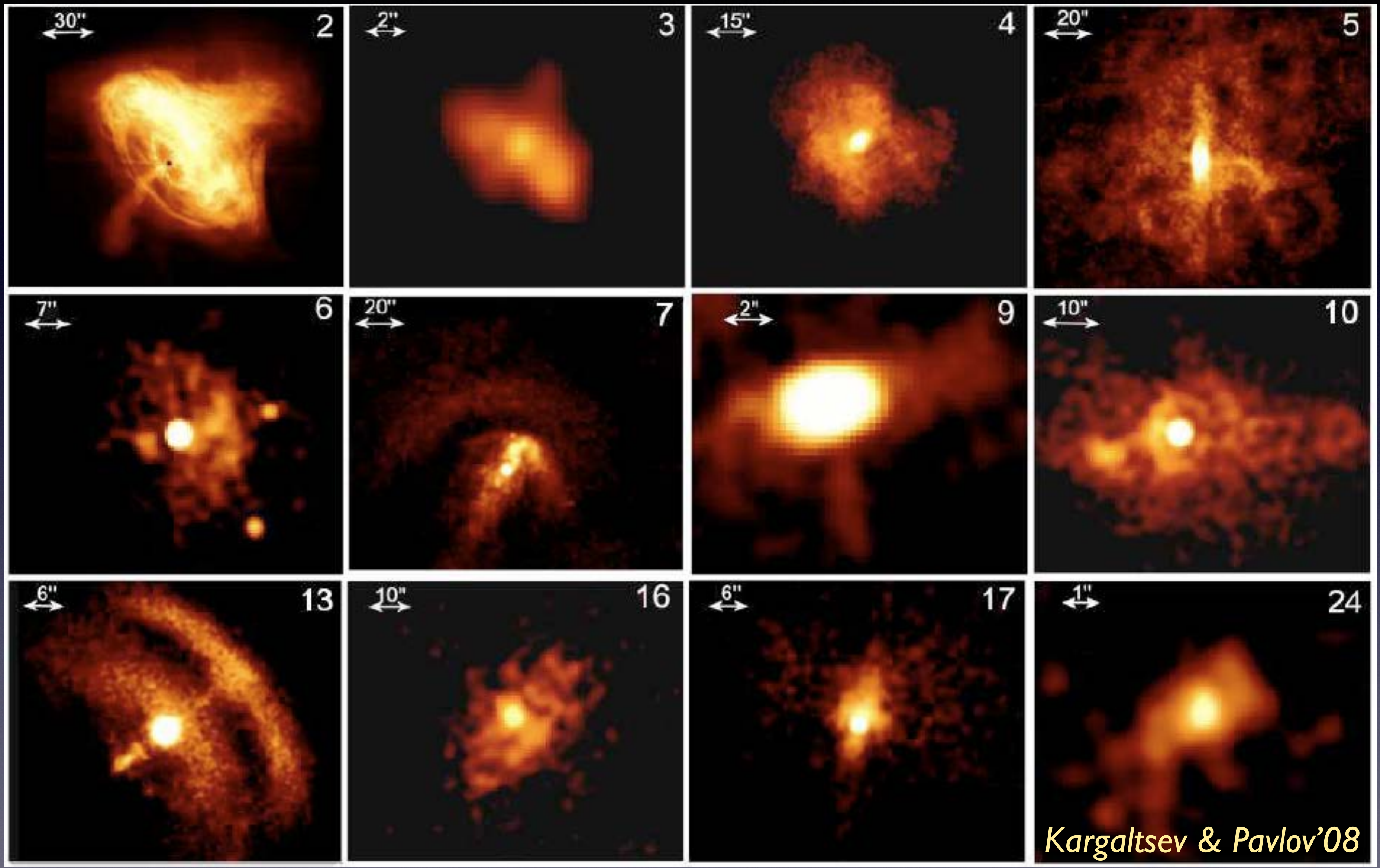
$$R_w \sim \left(\frac{\dot{E}}{4\pi c P_c}\right)^{1/2}$$

Sub-arcsecond imaging: A legacy for Chandra! (….NuSTAR)

Chandra: New/Sharp Eyes on PWNe

Jets and torii

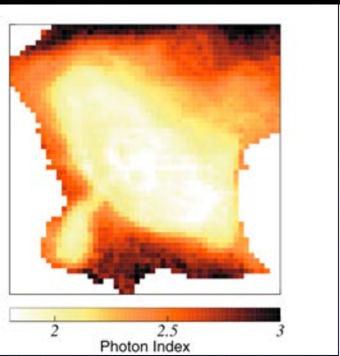
See B. Olmi's Talk



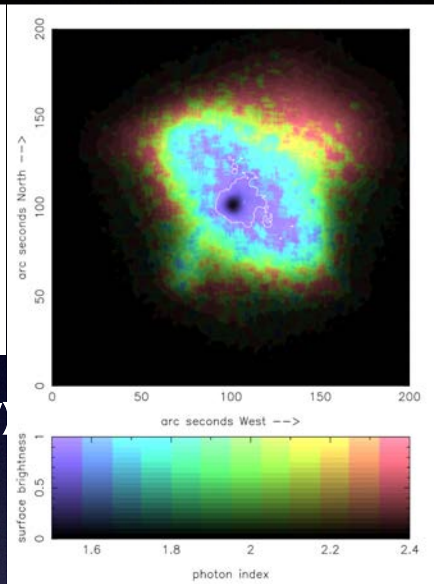
Jets/Torus: Numerical Simulations following the time-dependent evolution

(e.g. Del Zanna et al.'06, Buccianitni et al.'04; van der Swaluw et al.'04; Blondin, Chevalier, Frieson'01)

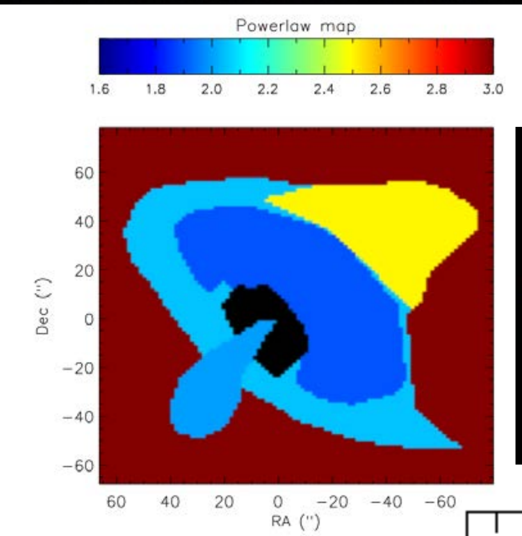
Spectral Index Maps=> Wind Models



Chandra (0.5-10 keV)
Mori et al. 2004

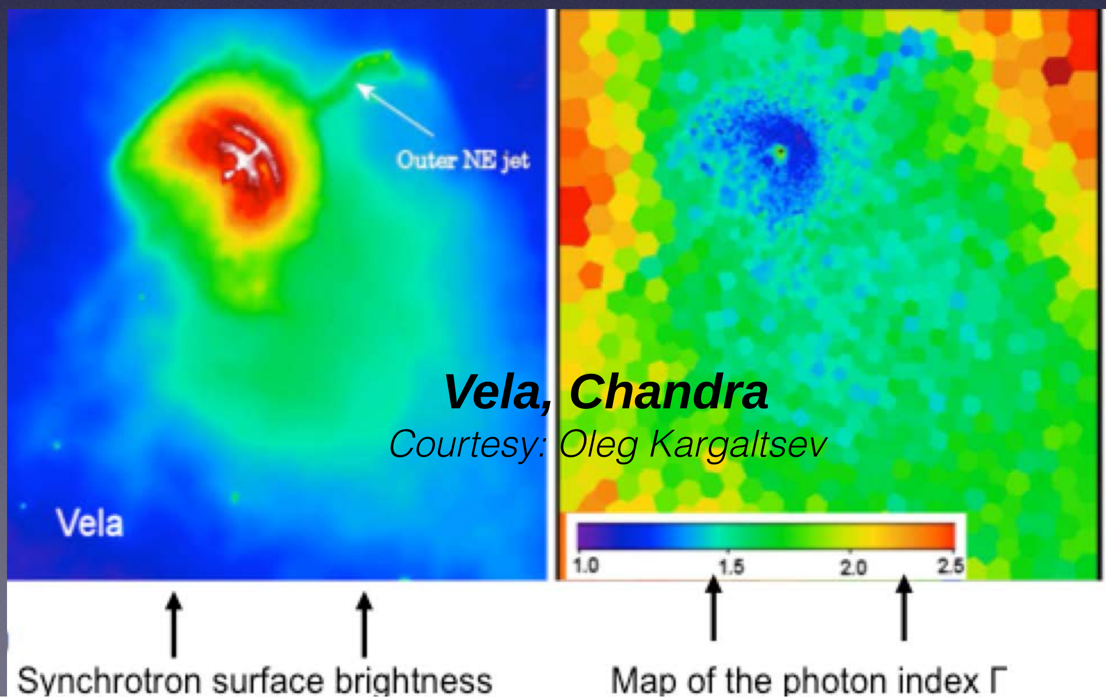


XMM (0.5-10 keV)
Willingale et al. 2001

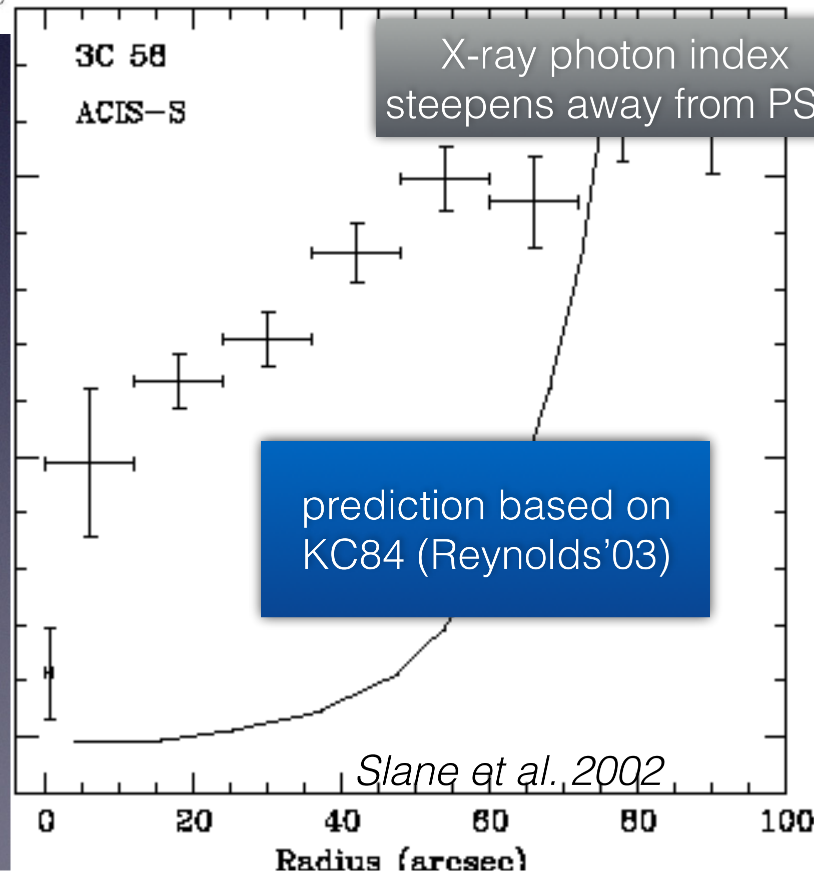


NuSTAR (3-78 keV)
Madsen et al. 2015

3C58 (Chandra, radio)



Vela, Chandra
Courtesy: Oleg Kargaltsev

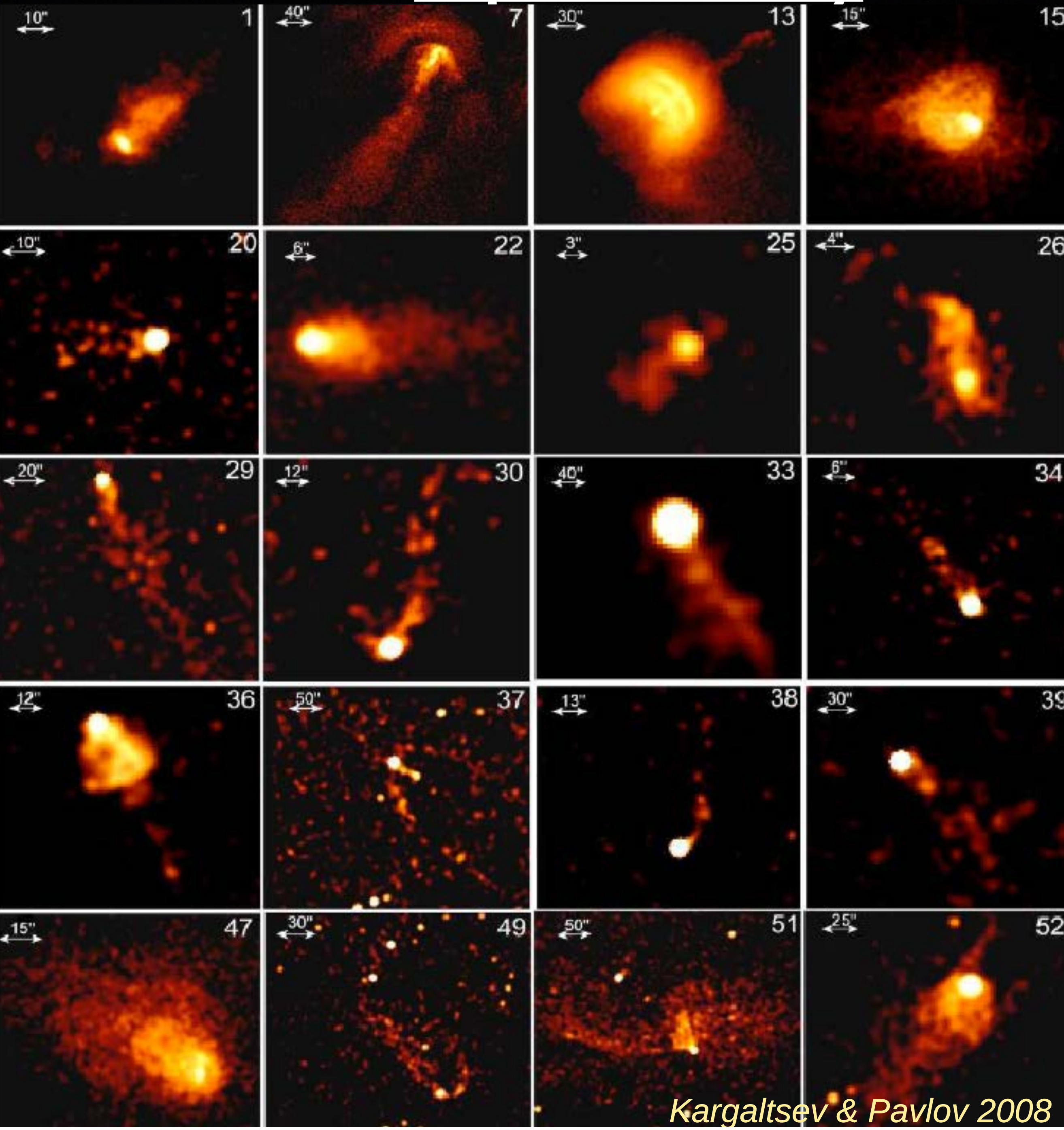


X-ray photon index steepens away from PSR

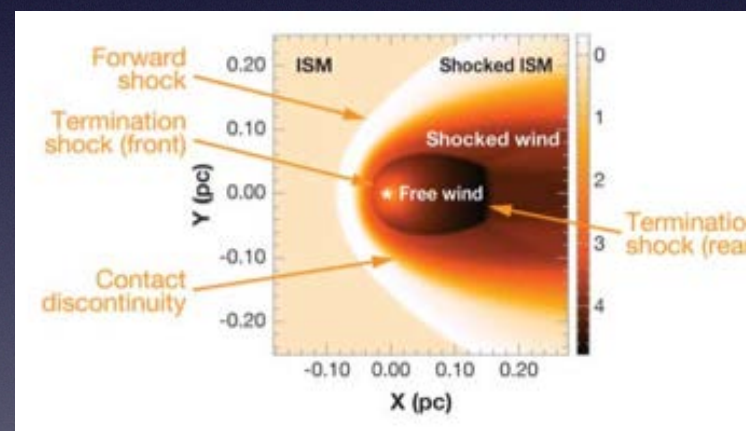
prediction based on KC84 (Reynolds'03)

Slane et al. 2002

Bow-Shock PWNe (tails and trails): supersonically moving PSRs



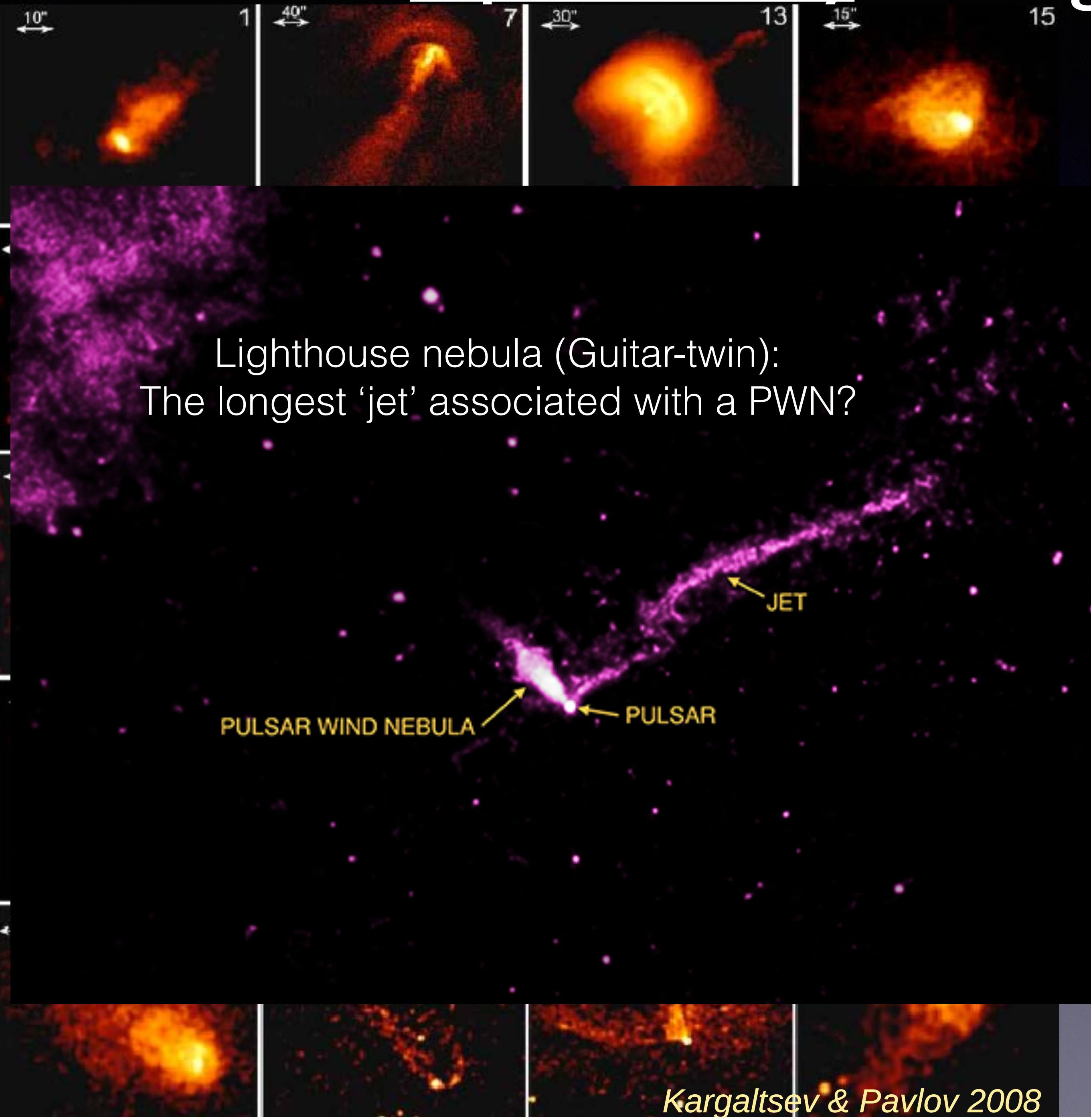
Kargaltsev & Pavlov 2008



Gaensler & Slane 2006

$$\frac{\dot{E}}{4\pi\omega R_{w0}^2 c} = \rho_0 V_{\mathrm{PSR}}^2$$

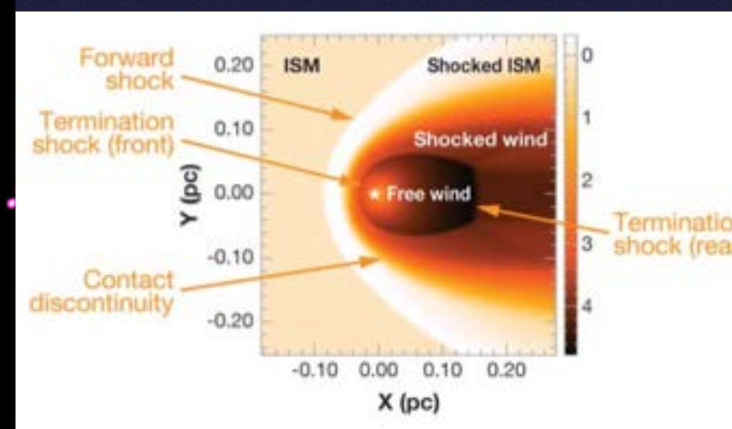
Bow-Shock PWNe (tails and trails): <u>supersonically</u> moving PSRs



Lighthouse nebula (Guitar-twin):
The longest 'jet' associated with a PWN?

Kargaltsev & Pavlov 2008

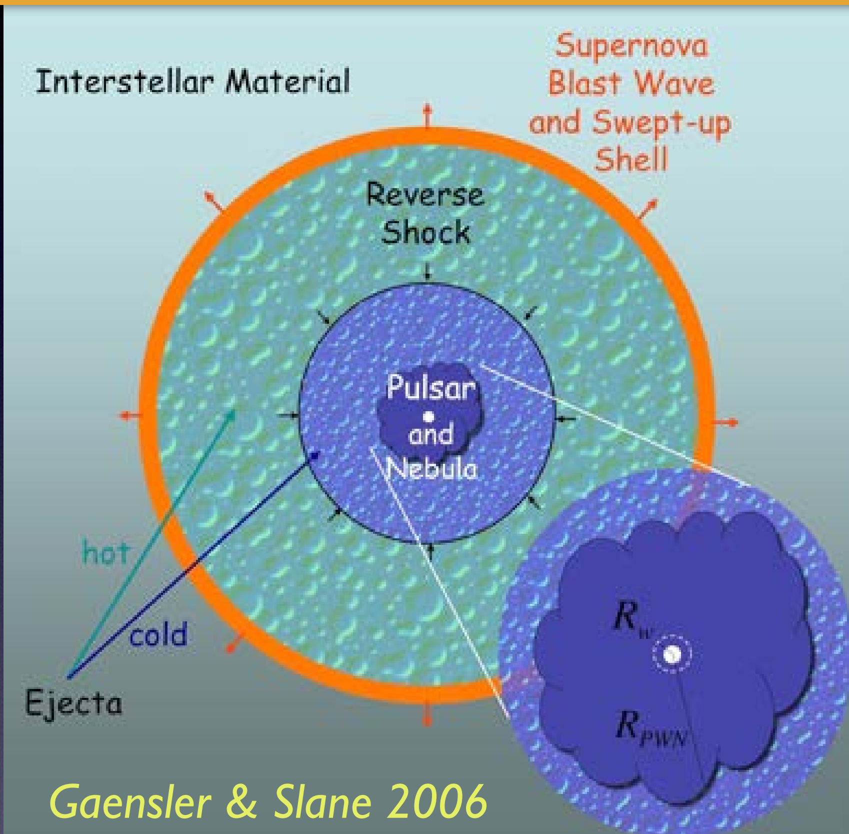
see **Puhlhofer's** and **Green**'s talks



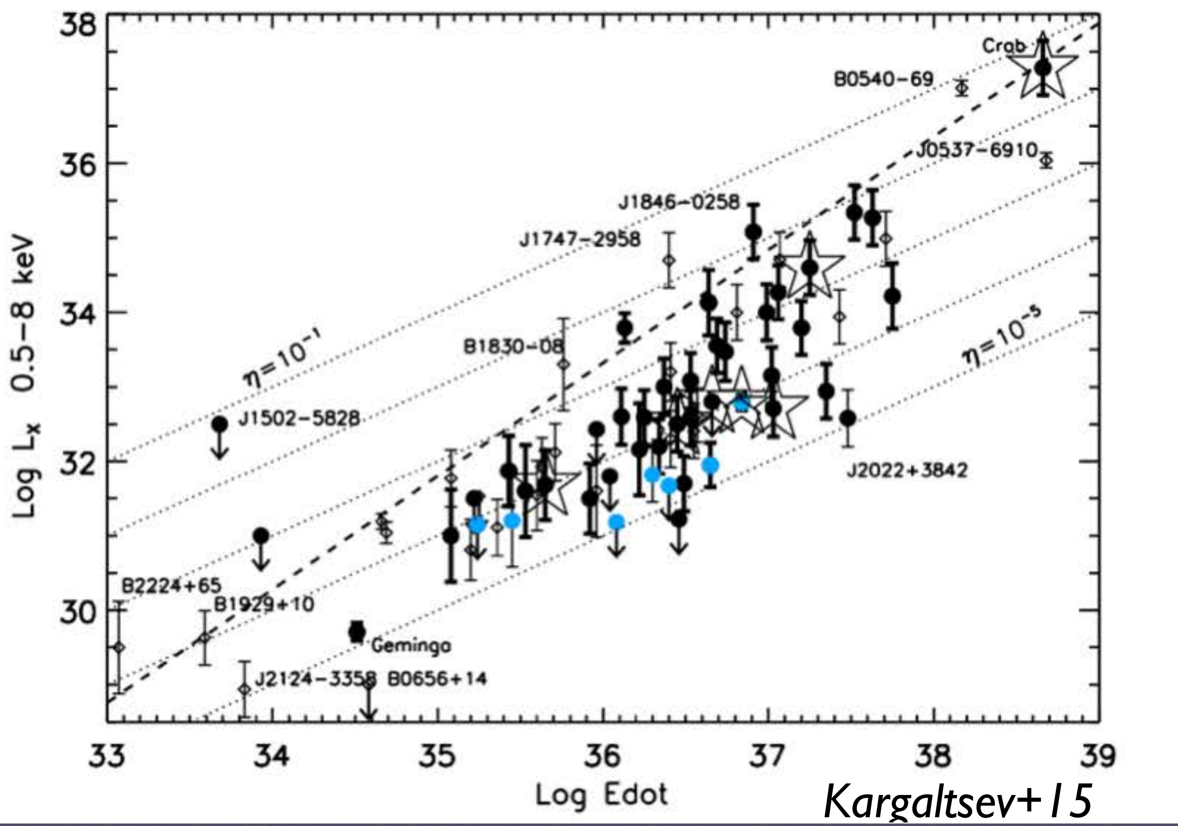
Gaensler & Slane 2006

$$\frac{\dot{E}}{4\pi\omega R_{w0}^2 c} = \rho_0 V_{PSR}^2$$

Pulsar Wind Nebulae
Why Bother? Pulsar Pathfinders

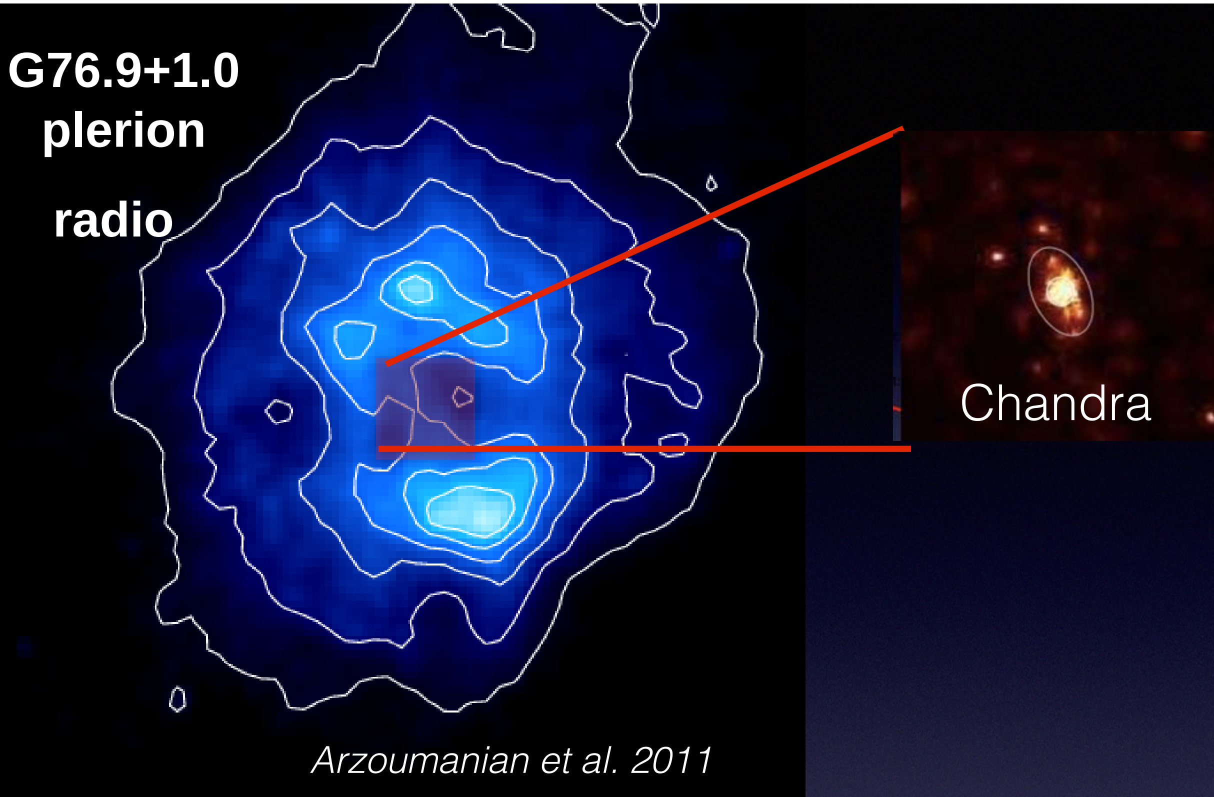


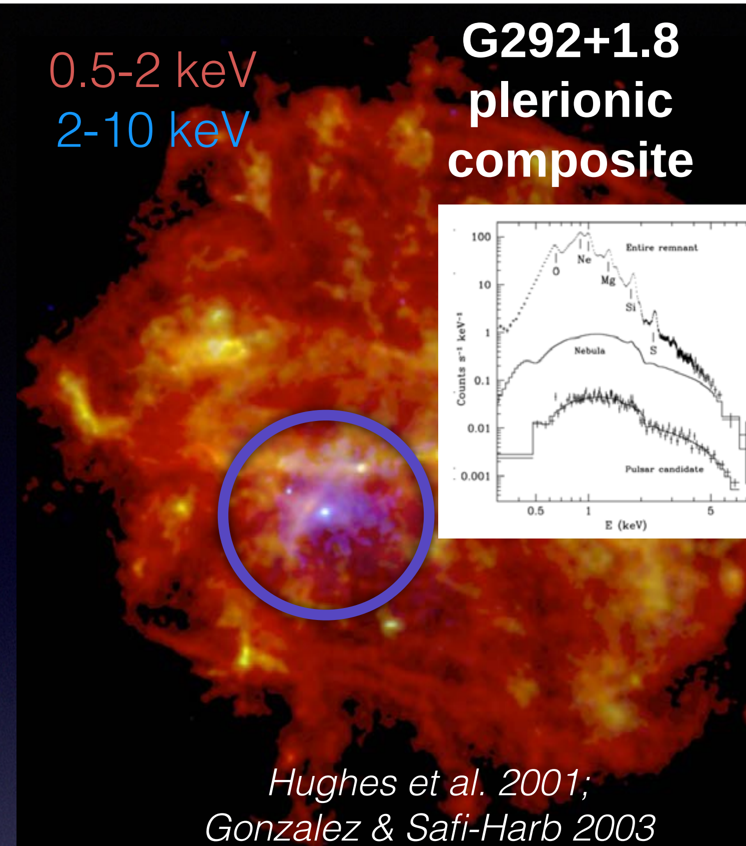
Gaensler & Slane 2006

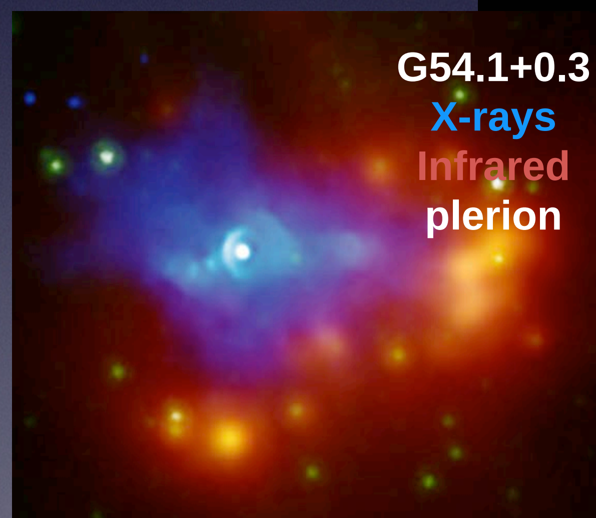


Kargaltsev+15

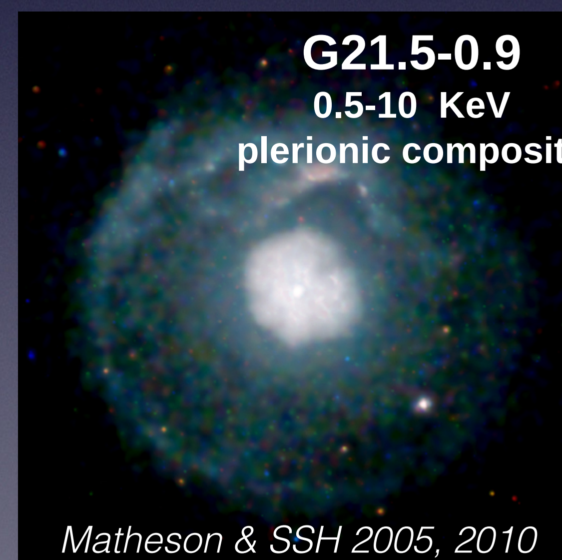
- PWN: Bubbles of relativistic particles inflated by pulsar's relativistic wind
- **"Calorimeters"/Pathfinders for Pulsar Discovery!**
- Seed the Galaxy with energetic particles and magnetic fields
- Efficient Engines for Cosmic Ray Acceleration up to TeV energies
- Probes for the Interaction of their relativistic winds with the surrounding: SN ejecta (earlier) or ISM (later)







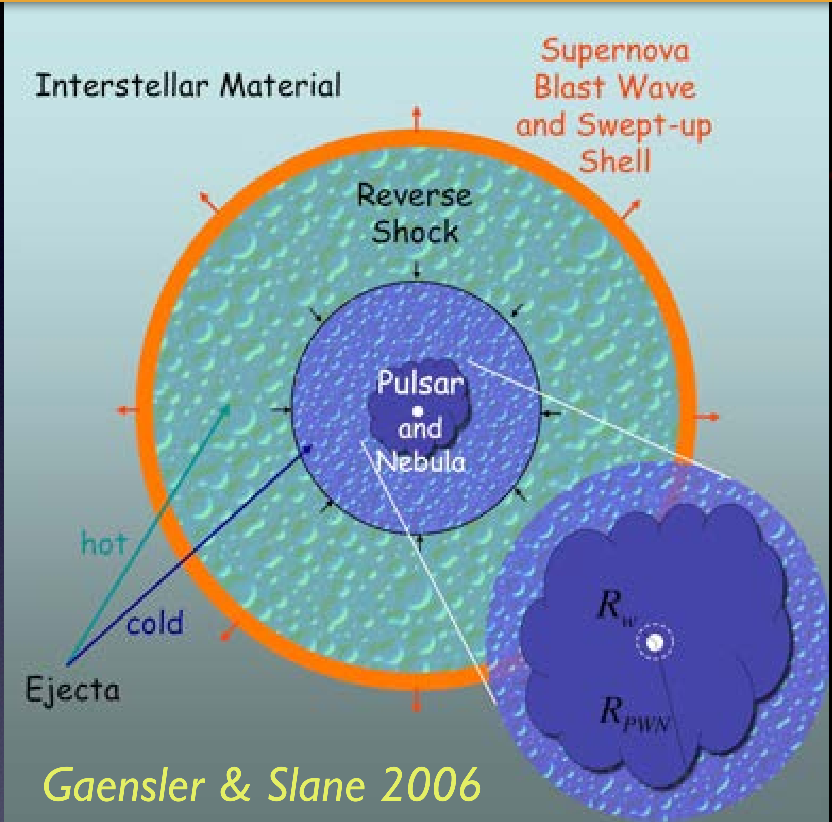
CXO/Temim, Lu et al.

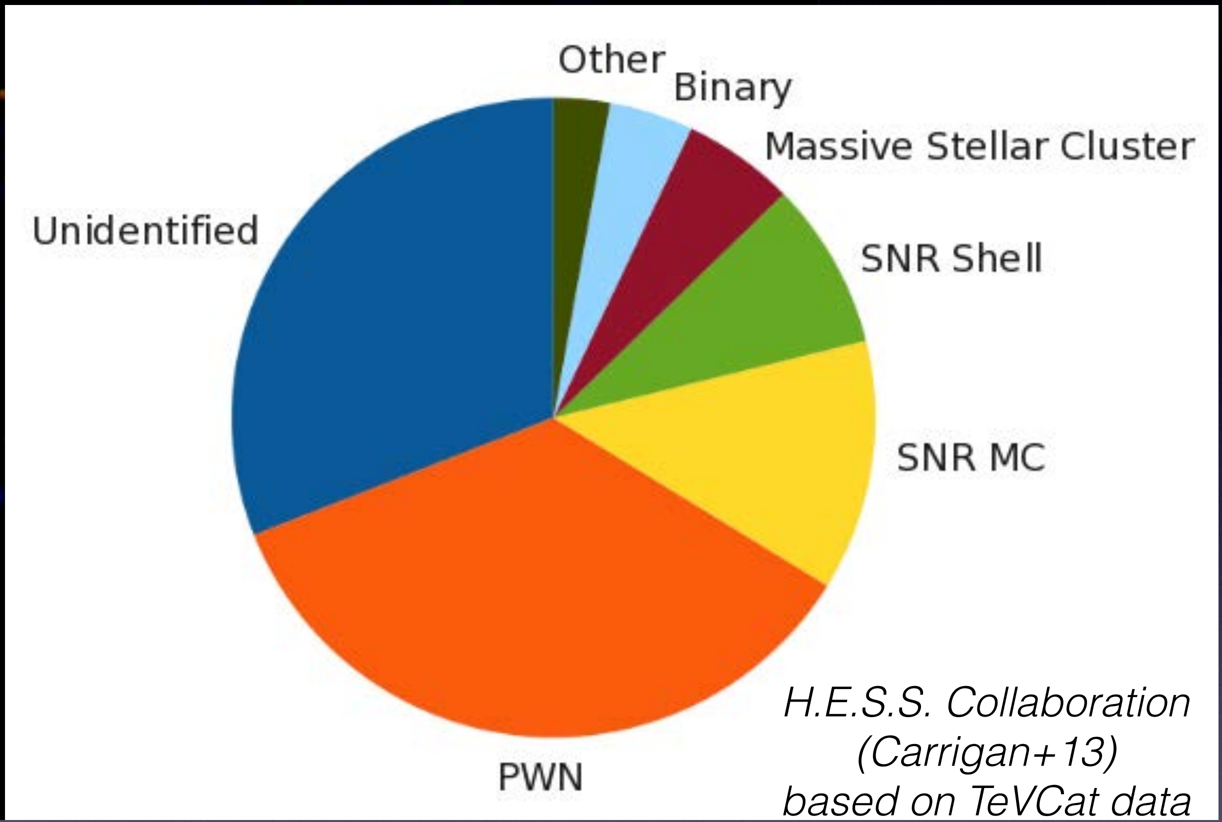


Pulsars detected following Chandra imaging and radio timing
Pulsar properties ~ those predicted from PWN energetics!

Pulsar Wind Nebulae

Why Bother? Particle Accelerators and Cosmic Pevatrons!





- PWN: Bubbles of relativistic particles inflated by pulsar's wind
- "Calorimeters"/Pathfinders for Pulsar Discovery!
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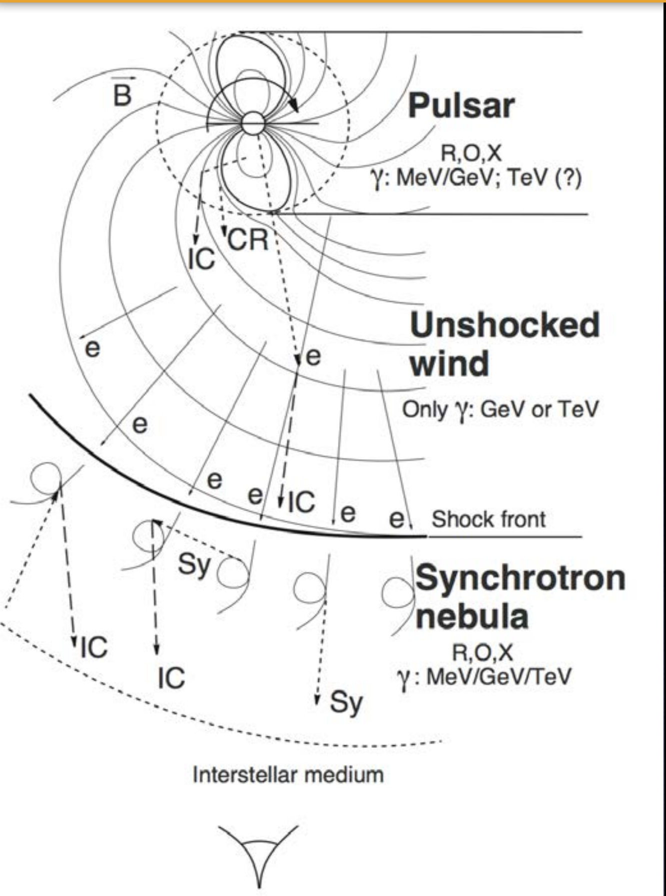
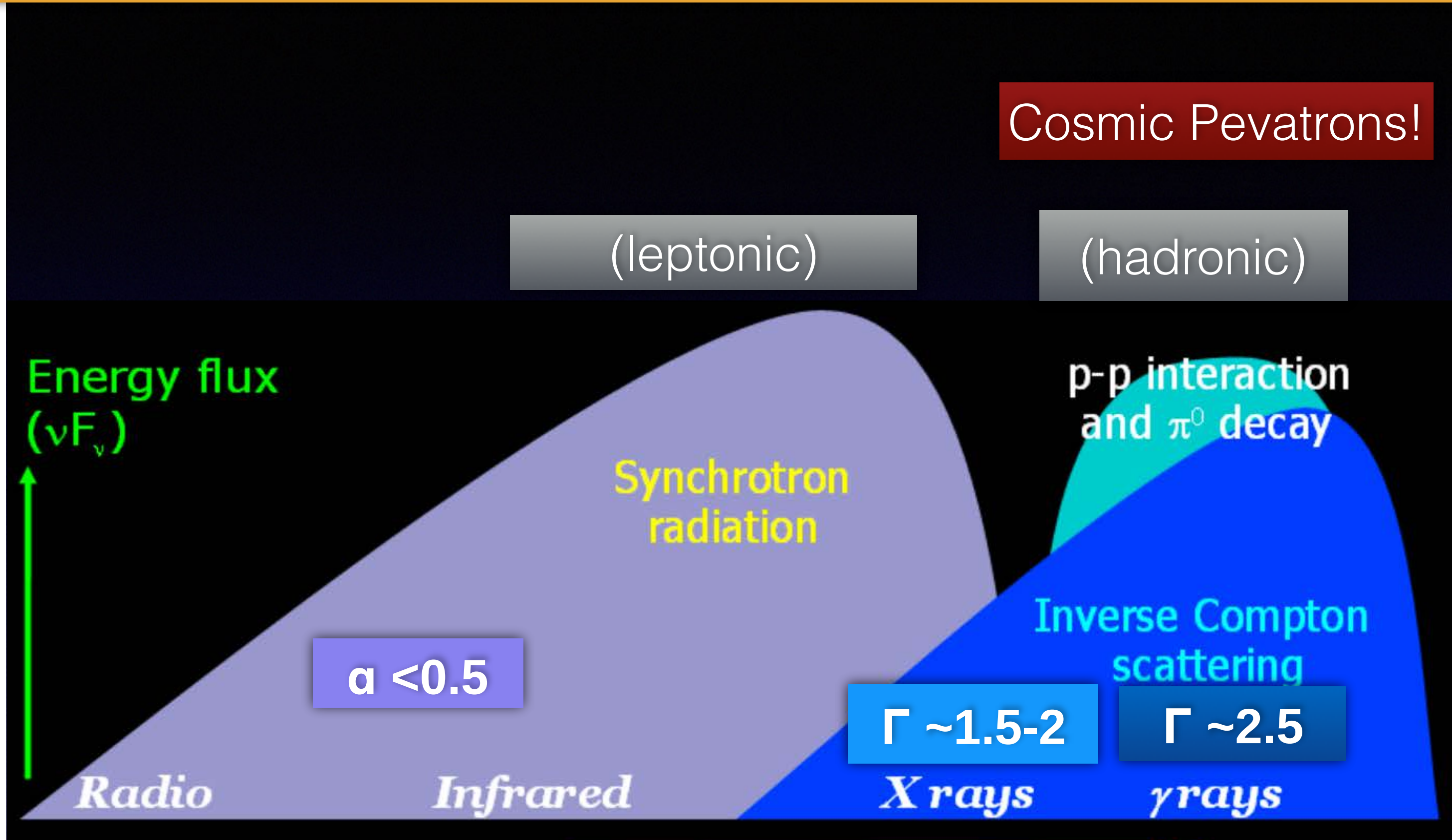
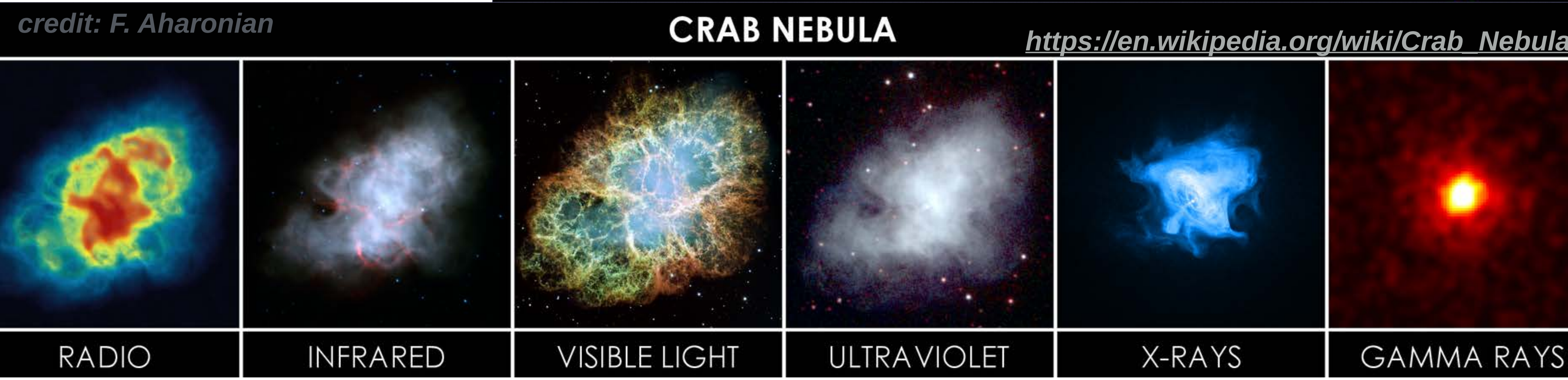
PWN: Multi-wavelength emission



credit: F. Aharonian

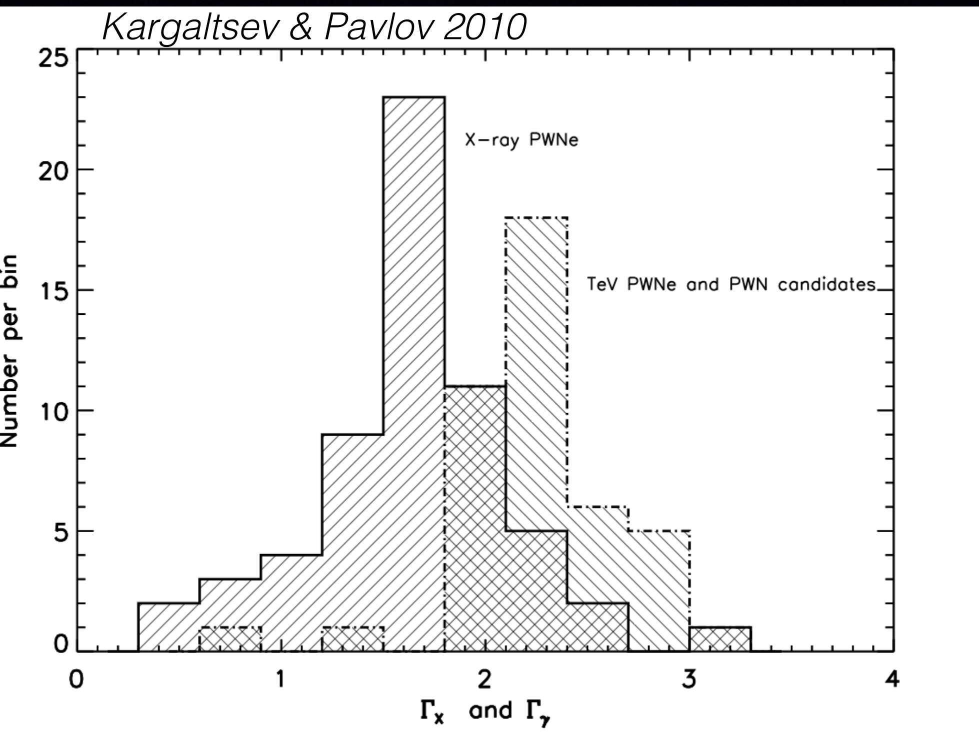


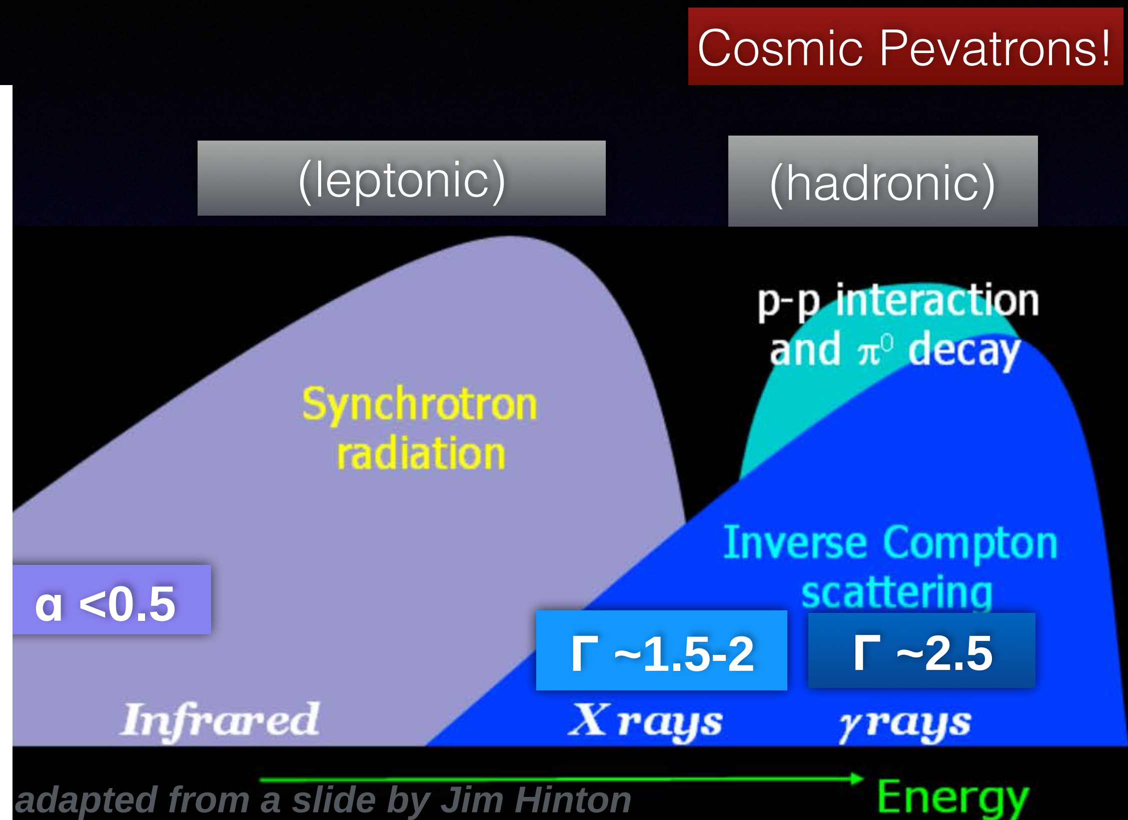
Credit: adapted from a slide by Jim Hinton

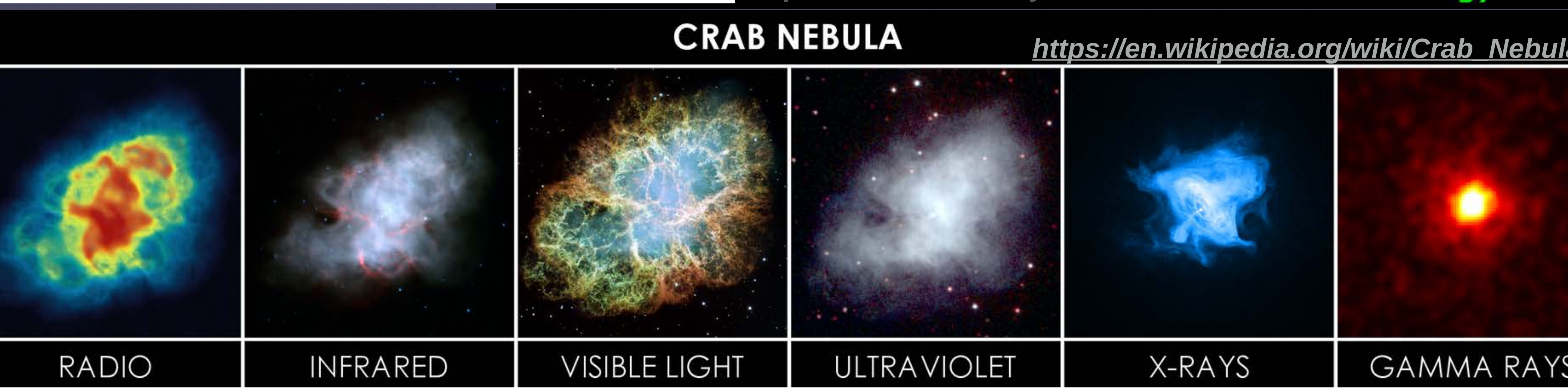


https://en.wikipedia.org/wiki/Crab_Nebula

PWN: Multi-wavelength emission



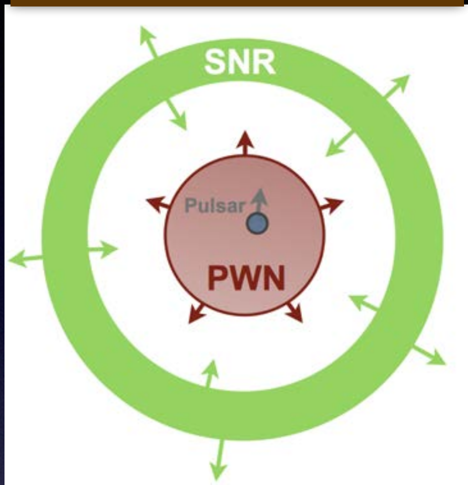




Pulsar Wind Nebulae

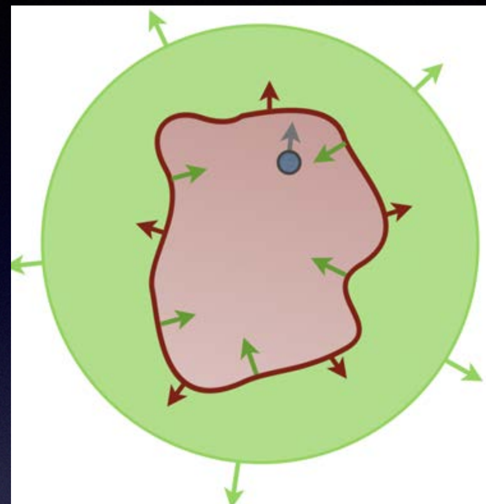
Why Bother? Evolution and Interaction with ISM/CSM

free expansion



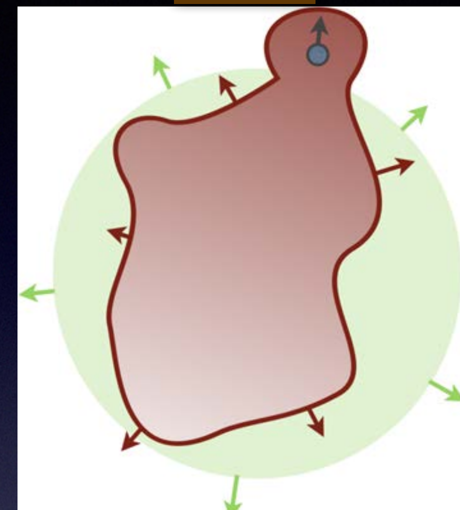
Young

reverse shock interaction

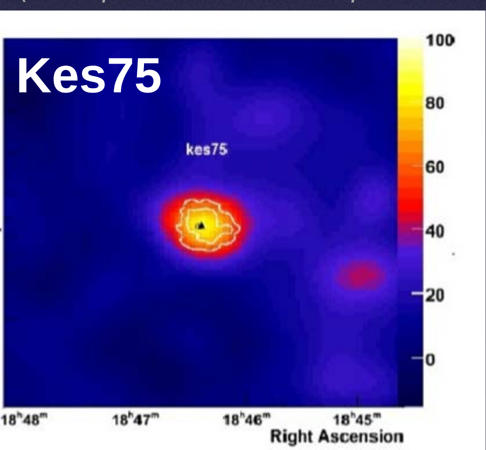


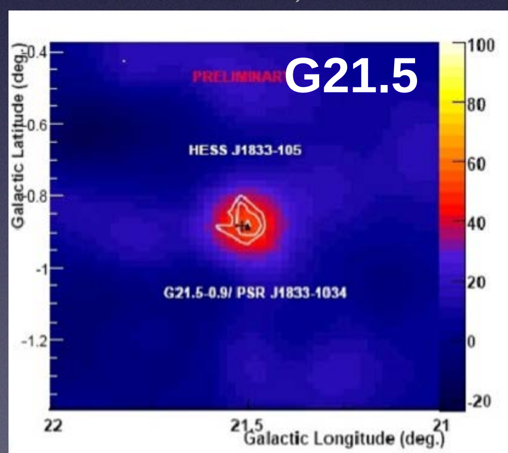
Evolved

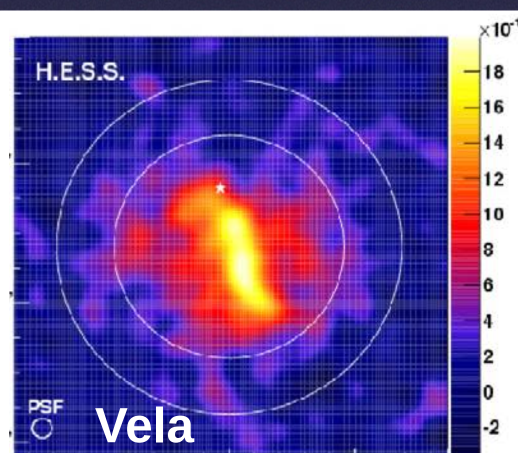
relic

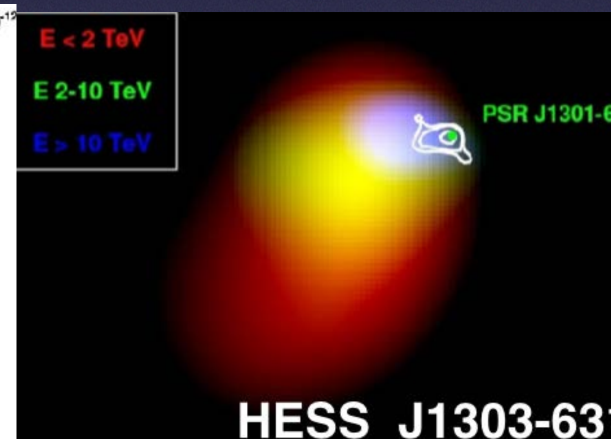


(adapted from Klepser+HESS team, 2015)









Hewitt & Lemoine-Goumard 2016

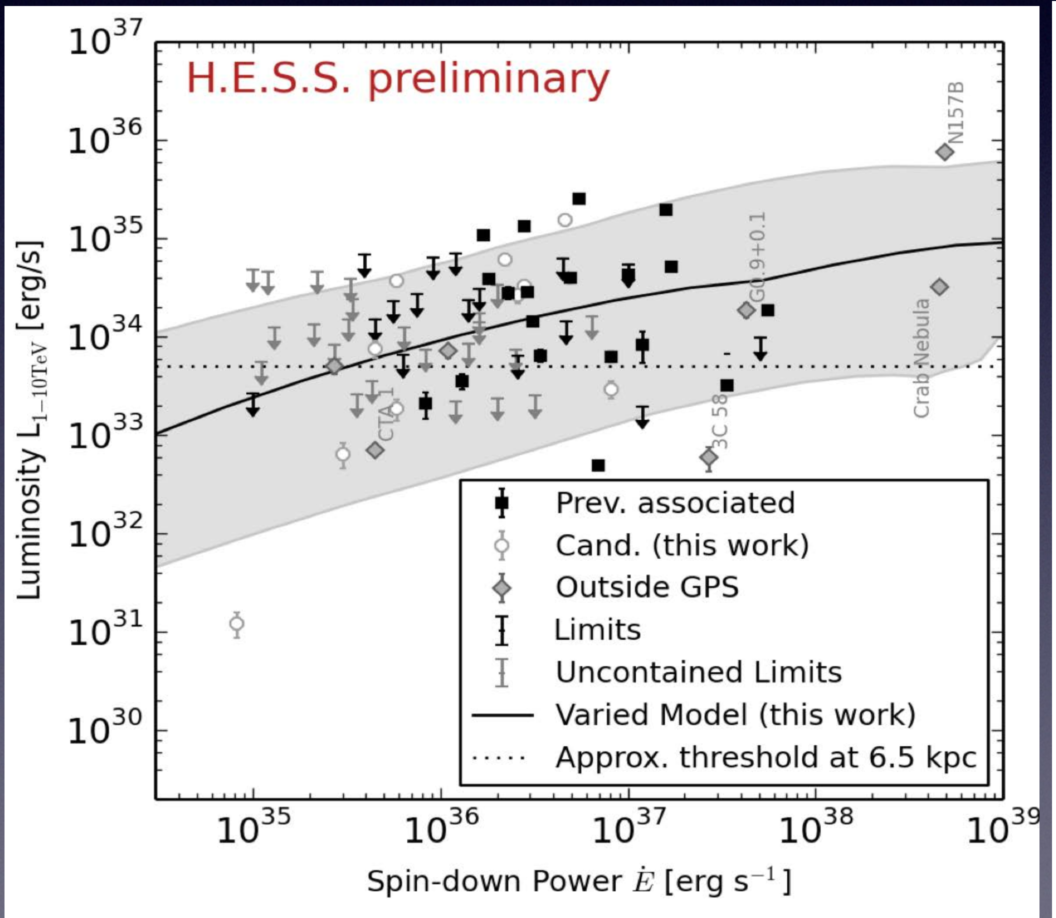
- **Probes for studying their evolution and their Interaction of their relativistic winds with the surrounding: SN ejecta, CSM/ISM, etc.**

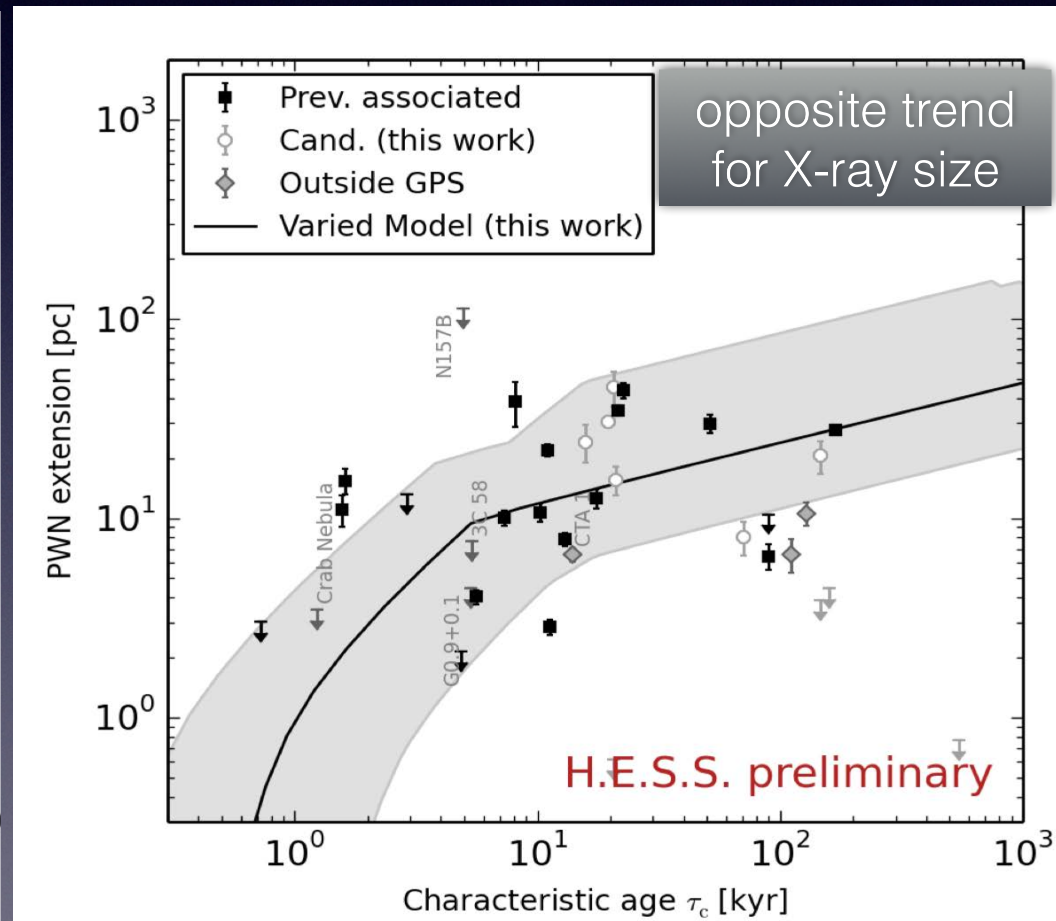
(Evolution to be covered by Tea Temim)

TeV population Study of PWNe

- PWNe: The most abundant class of TeV sources!
- Fading with Time (?)

Expanding with time



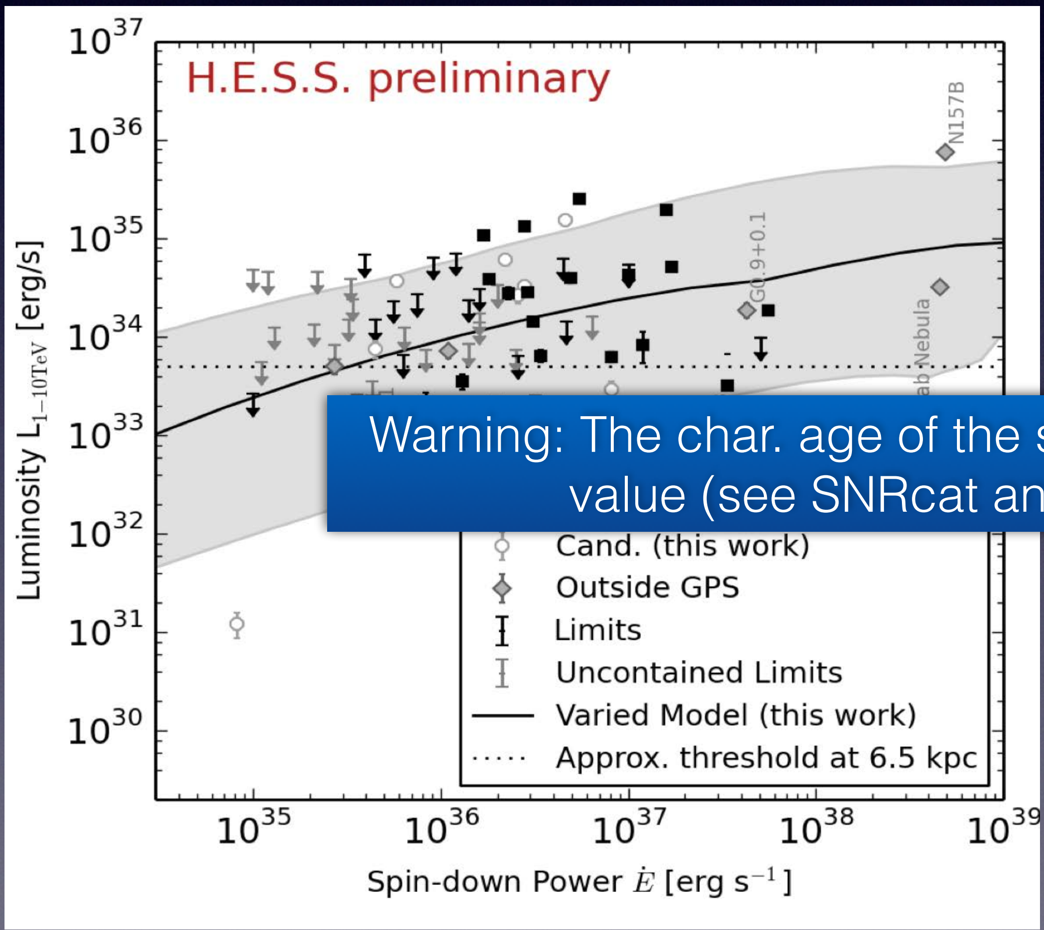


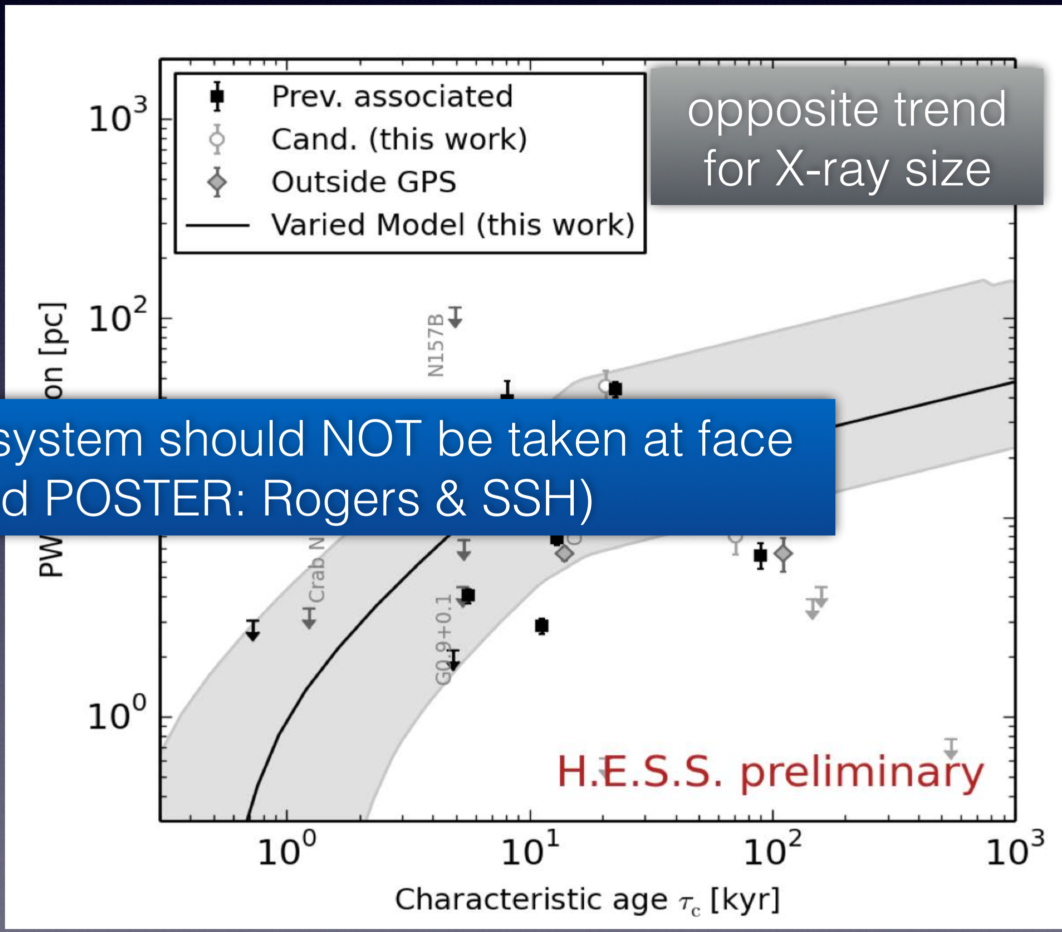
Klepser, HESS team, 2015 ICRC

TeV population Study of PWNe

- PWNe: The most abundant class of TeV sources!
- **Fading with Time (?)**

Expanding with time

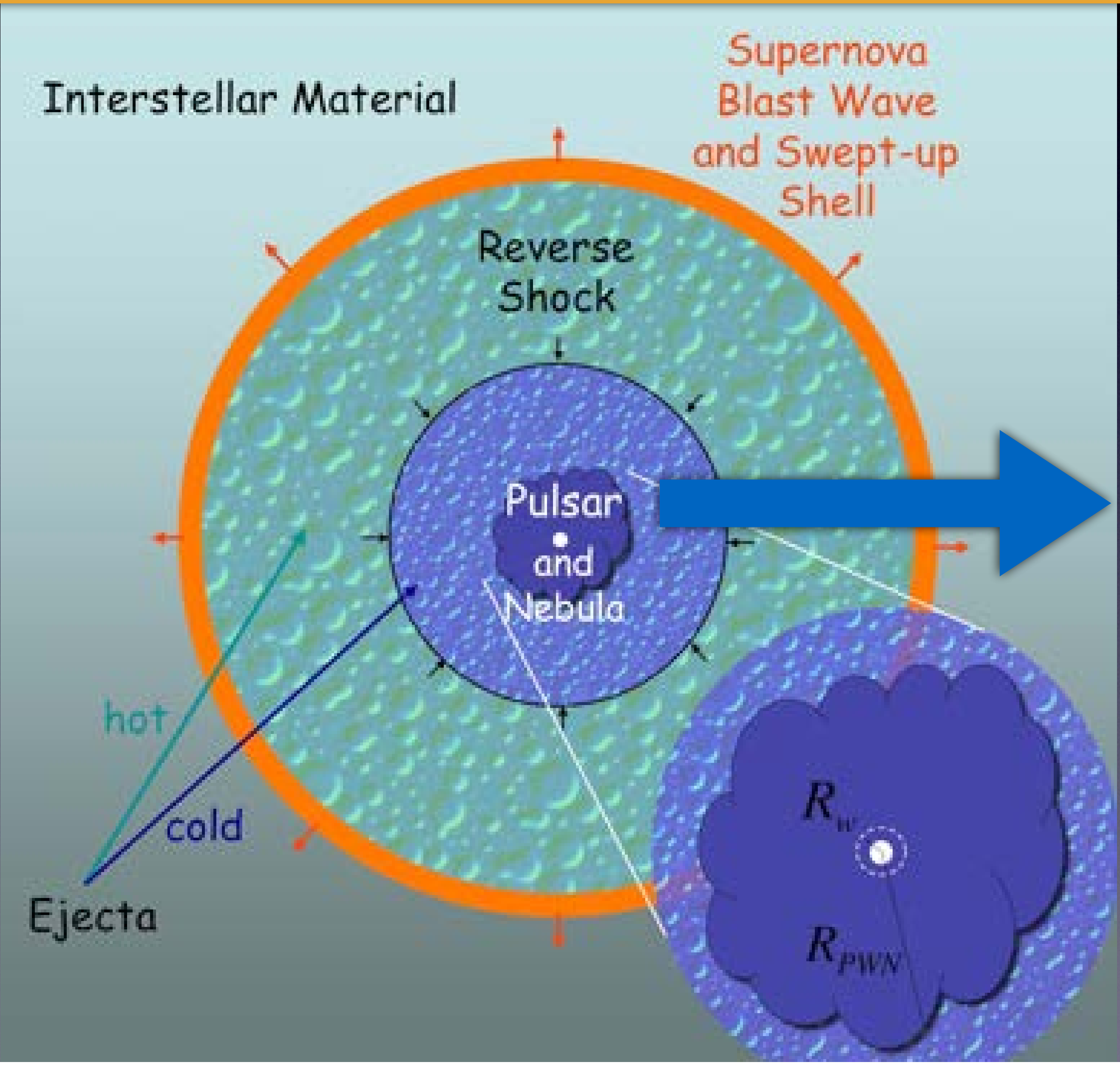




Warning: The char. age of the system should NOT be taken at face value (see SNRcat and POSTER: Rogers & SSH)

Klepser, HESS team, 2015 ICRC

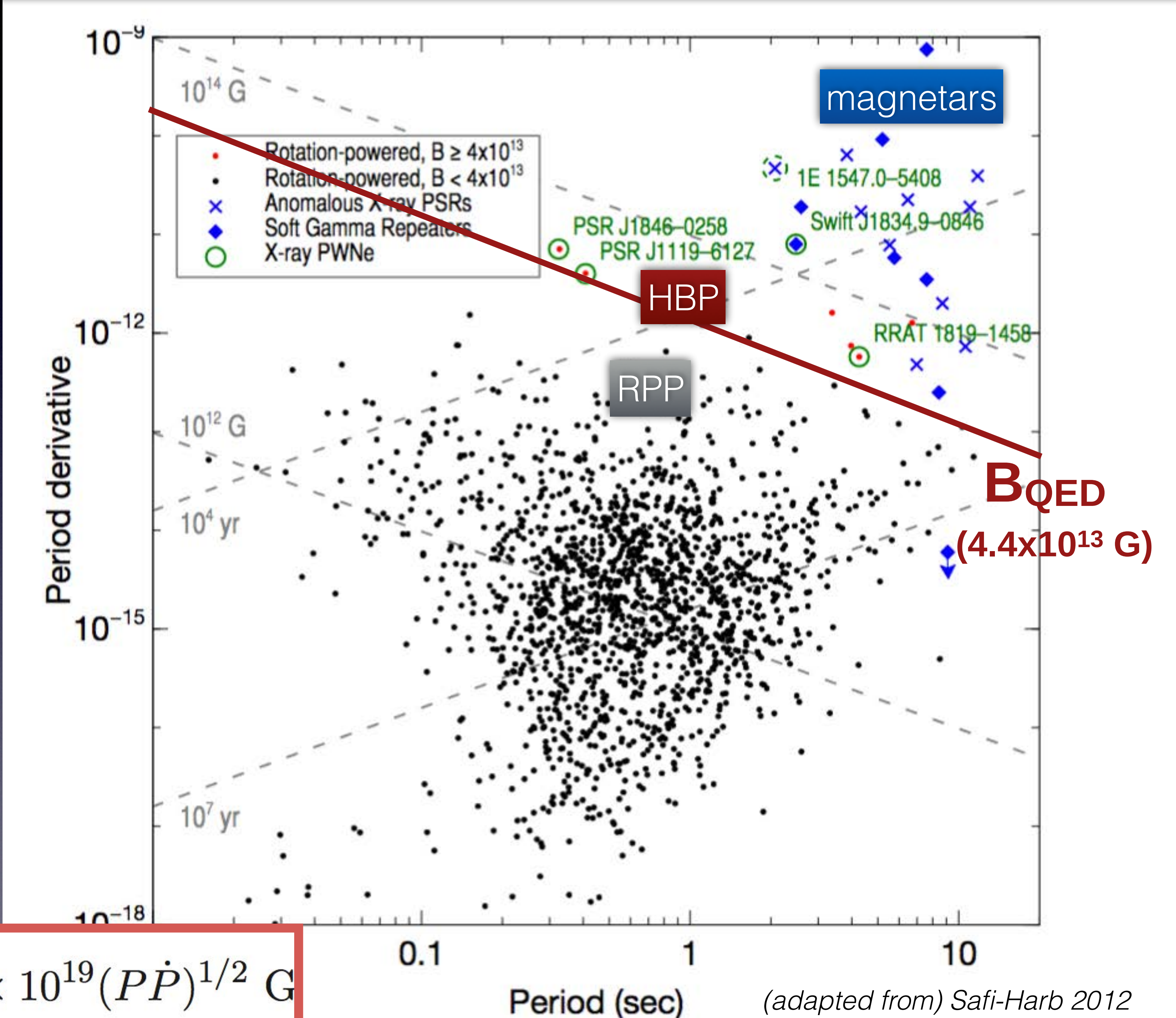
PWN Diversity:
I. The Engine



- Rotation-powered (classical)
- Supersonic (bow-shock nebulae)
- Magnetically Powered(magnetar wind nebula, MWN)?

best resolved with Chandra!

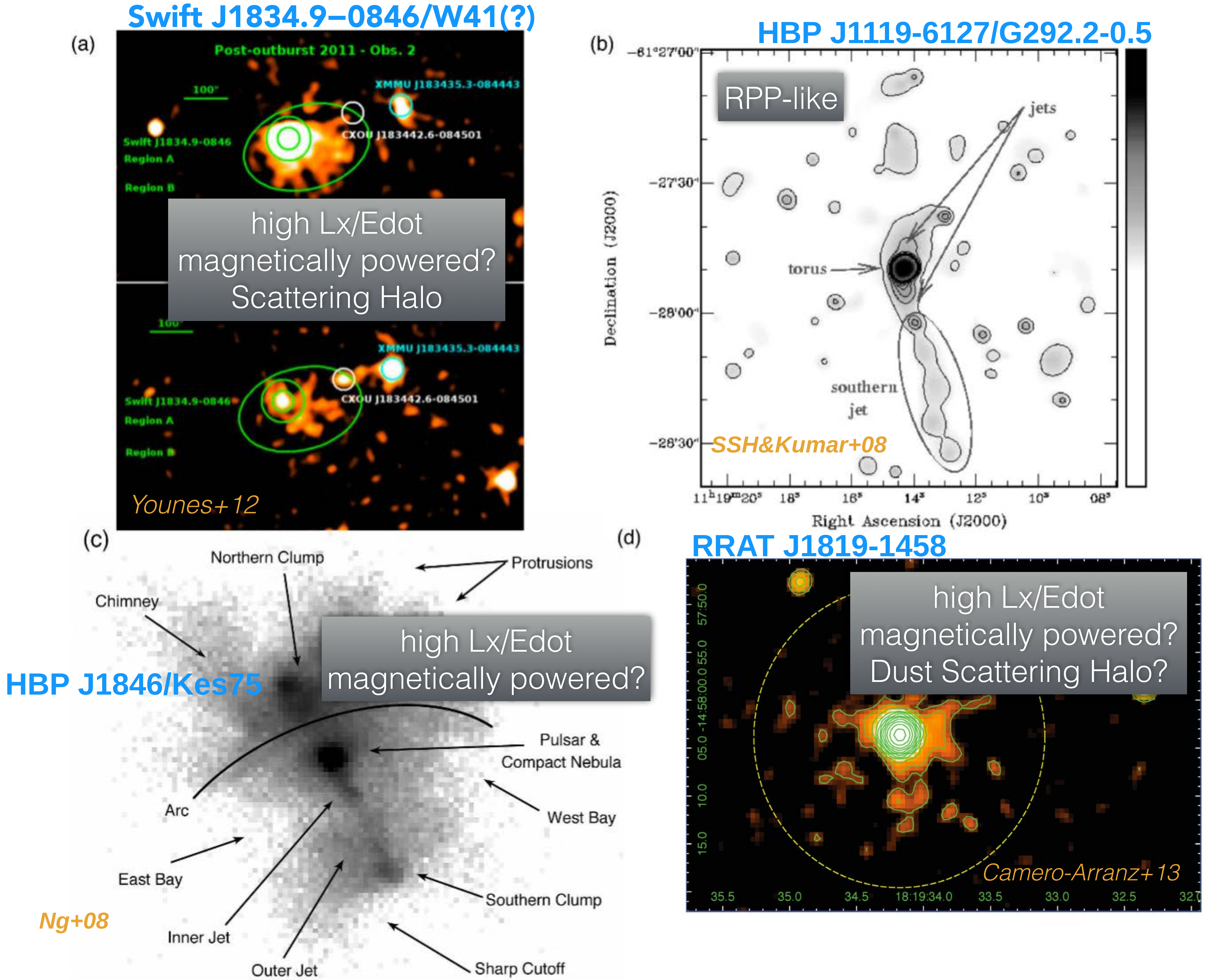
The engines' diversity



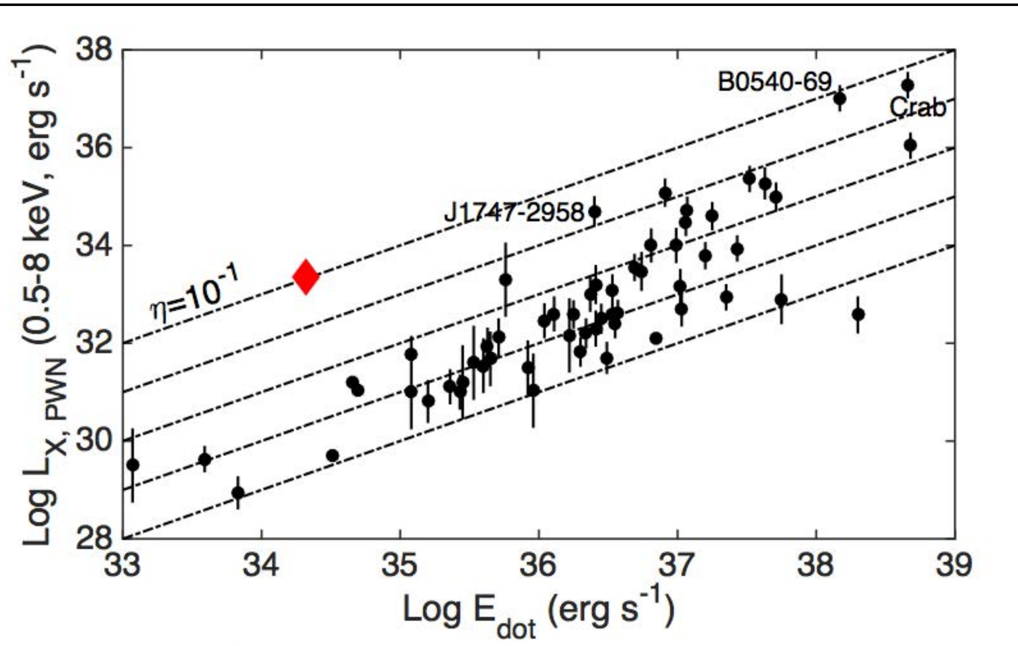
(adapted from) Safi-Harb 2012

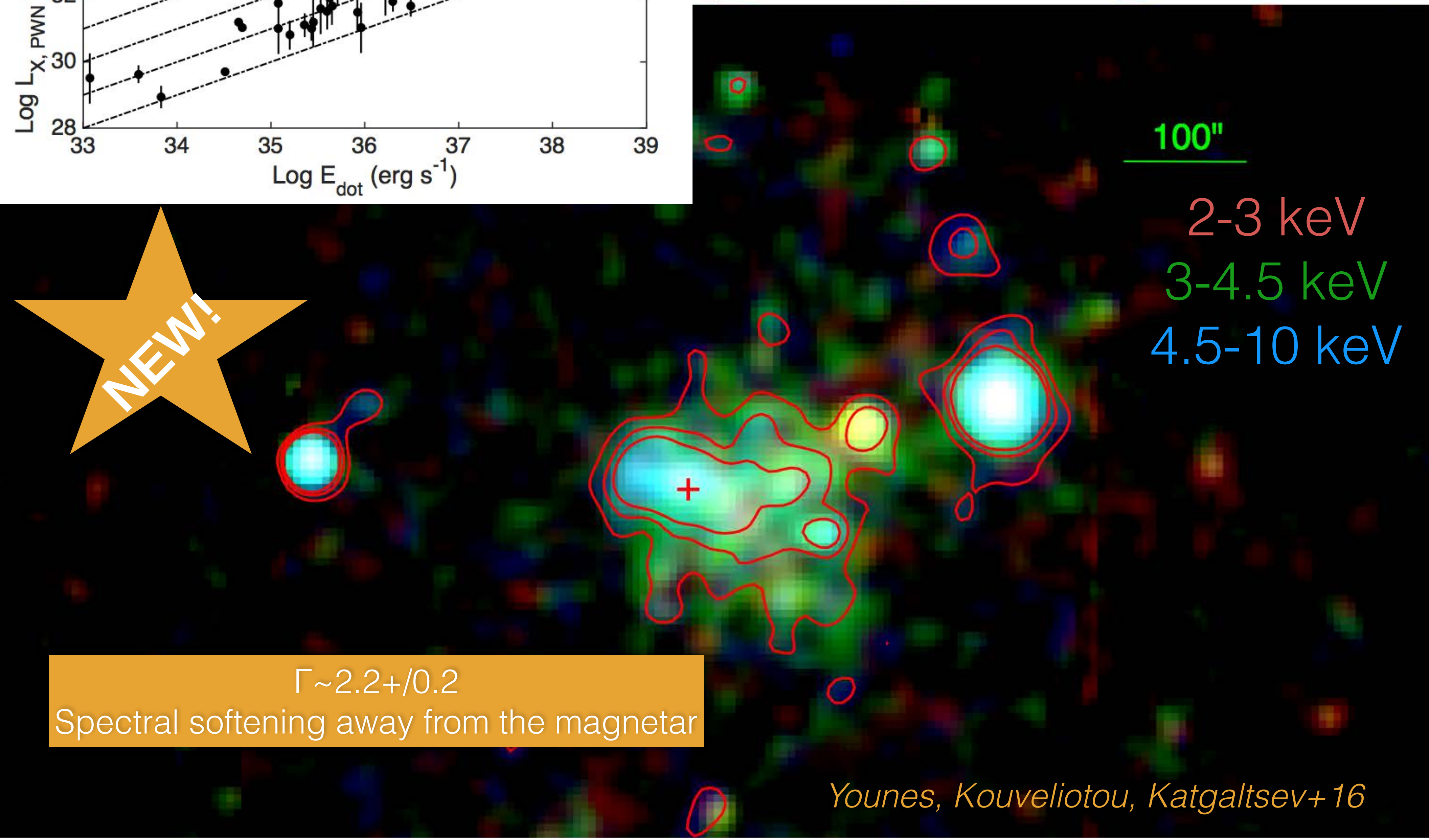
$$\tau_c \equiv \frac{P}{2\dot{P}}$$

$$B_p \equiv 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ G}$$


Swift J1834.9–0846/W41(?)
(a)
Post-outburst 2011 - Obs. 2
100"
XMMU J183435.3-084443
CXOU J183442.6-084501
Swift J1834.9-0846
Region A
Region B
high Lx/Edot
magnetically powered?
Scattering Halo
Younes+12
HBP J1119-6127/G292.2-0.5
(b)
RPP-like
jets
torus
southern
jet
SSH&Kumar+08
Declination (J2000)
Right Ascension (J2000)
(c)
Northern Clump
Protrusions
Chimney
high Lx/Edot
magnetically powered?
HBP J1846/Kes75
Pulsar &
Compact Nebula
Arc
West Bay
East Bay
Southern Clump
Inner Jet
Outer Jet
Sharp Cutoff
Ng+08
(d)
RRAT J1819-1458
high Lx/Edot
magnetically powered?
Dust Scattering Halo?
Camero-Arranz+13

SwiftJ1834.9-0846
W41/HESSJ1834-087
A New Magnetar Wind Nebula





Γ~2.2+/0.2
Spectral softening away from the magnetar

Younes, Kouveliotou, Katgaltsev+16

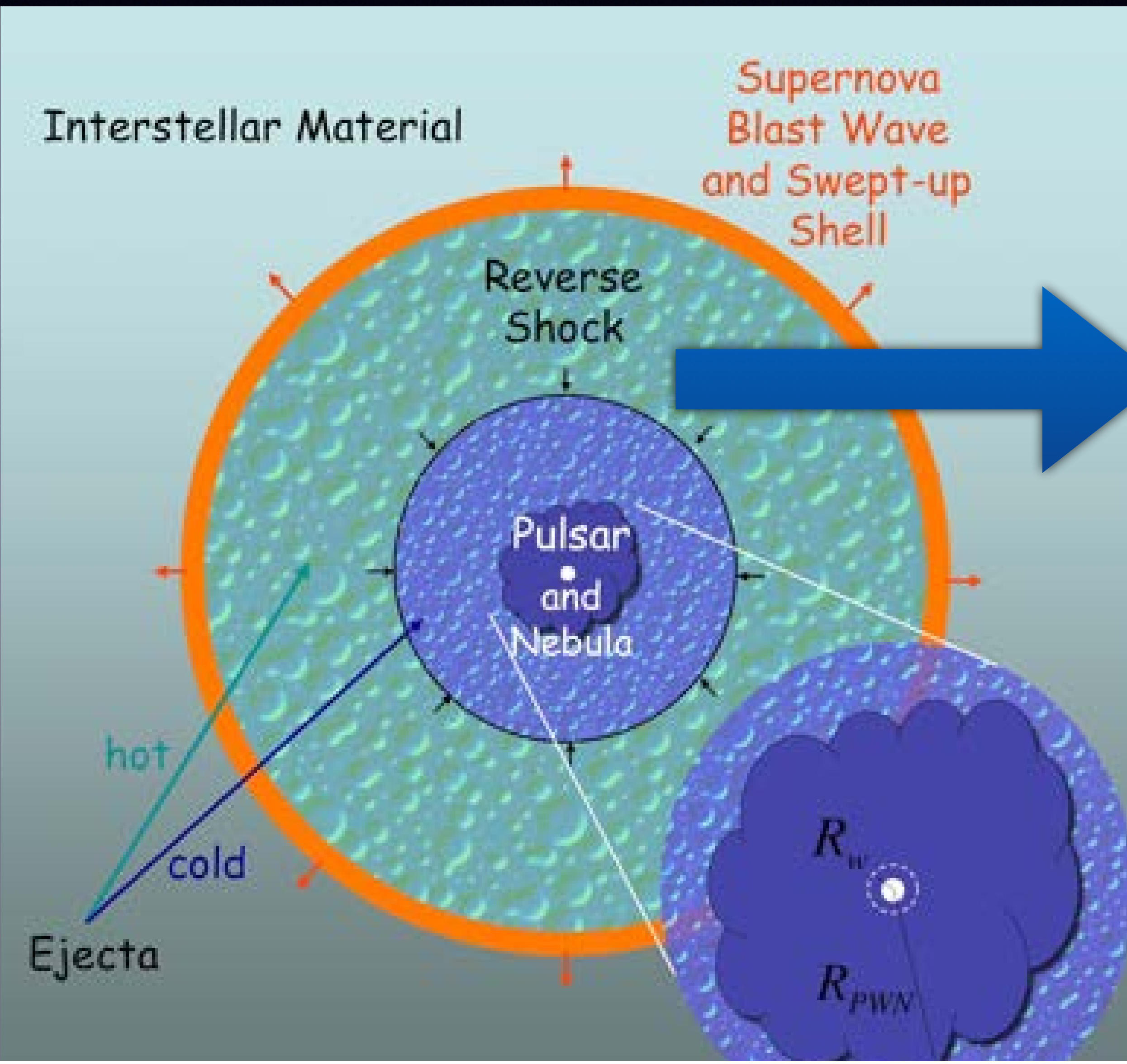
X-ray (Magnetar Wind?) Nebulae around highly magnetized PSRs

(6 HBPs + 1 RRAT, ~26 magnetars)

PSR	B (	Edot	PWN extent	Photon index	L Edot	Comment	Ref.
J1119-6127	4.1	2.3E+36	6”x15” 20” jet	1.1 1.4+	5E-04	properties similar to RPP’s PWNe (Lx/Edot~1e-6-1e-2, gamma~1-2.5)	Gonzalez & SSH 2003 SSH & Kumar 2008
J1846-0258 Crab+magnetar-like	5	8.3E+36	~40”	~1.9 (1.7-2.2)	~0.2-0.3	variable	Kumar & SSH 2008 Ng et al. 2008
RRAT1819-1458	5	3E+32	13”	3.0+/-1.5	~0.2		Rea et al. 2009 Camero+13
Swift J1834.9-0846 MWN?	14	2.1E+34	80”-130”	2.2+/-0.2	~0.1	properties similar to RPP PWN	Younes et al. 2012, 2016
~~1E 1547.0–5408~~	~~22~~	~~1E+35~~	~~45” (2.9’)~~	~~~3.5~~	~~0.01~~	~~most likely dust scattering halo~~	~~Bamba & Vink 09 Olausen et al. 2011~~
NEW! SGR1935+2154/ G25.7+0.8	22	1.7E+34	1”-1’	3.8	0.35	dust scattering halo, MWN??	Isarel et al. 2016

Whether nebulae (if detected) around highly magnetized pulsars are powered by rotation and/or magnetism is still an open question..

PWN Diversity: II. The Evolutionary Stage

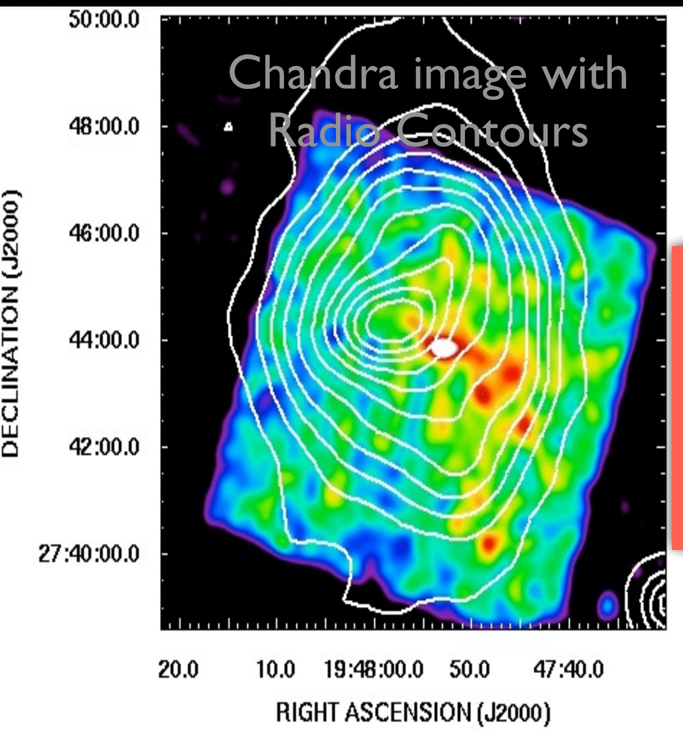


- Has the reverse shock crushed the PWN?
- Is the PWN expanding into an inhomogenous medium?

enlightened by combined gamma+radio observations

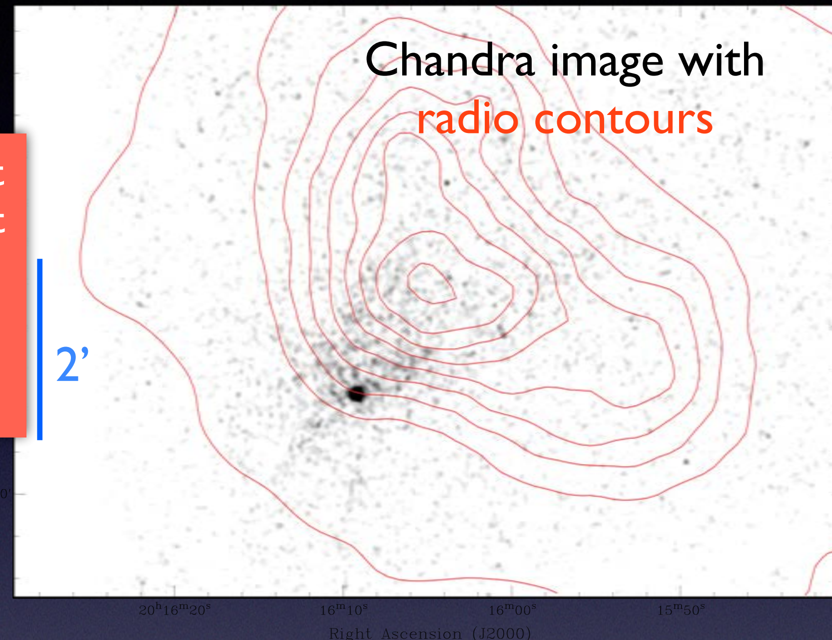
(see Tea Temim's talk)

Curious shell-less PWNe (G63.7+1.1 and G74.9+1.2)



- Radio: steep central component (alpha~0.4-0.5) with a harder cpt
- Low-freq. spectral break
- X-ray peak offset from radio peak
- Large, implying evolved

Matheson, SSH, Kothes+16 (in press)
Kothes, SSH et al. (in prep)
Matheson, SSH & Kothes 2013



G63.7+1.1: A PWN interacting with a molecular cloud??

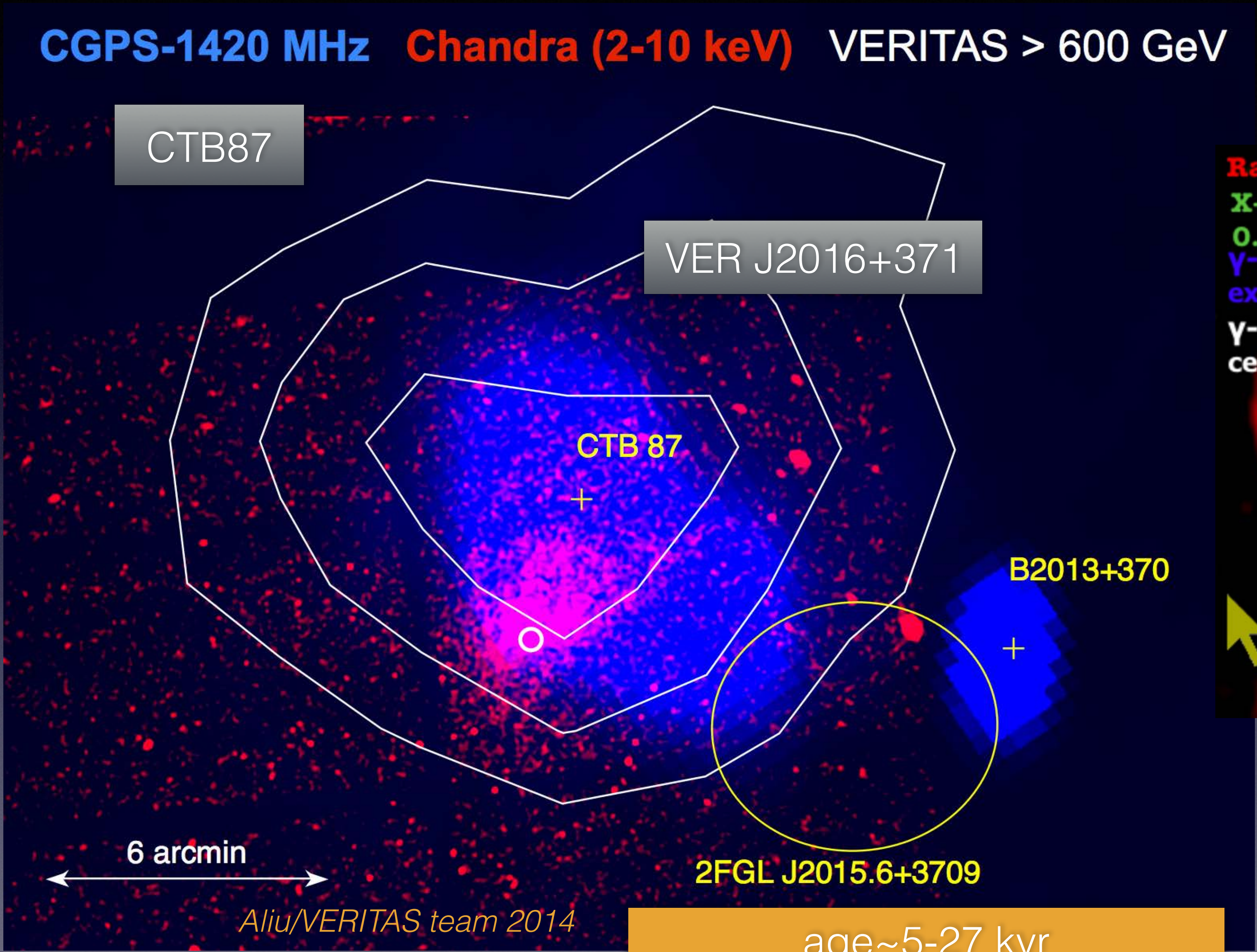
G74.9+1.2: A Relic/Evolved PWN?

N_H = 1.6 (1.1 - 2.1) × 10^{22} cm^{-2}
Γ = 1.8 (1.4-2.2)
✓ steepens away from peak of X-rays
L_x (6 kpc, 0.5-10 keV) ~ 2 × 10^{33} erg s^{-1}

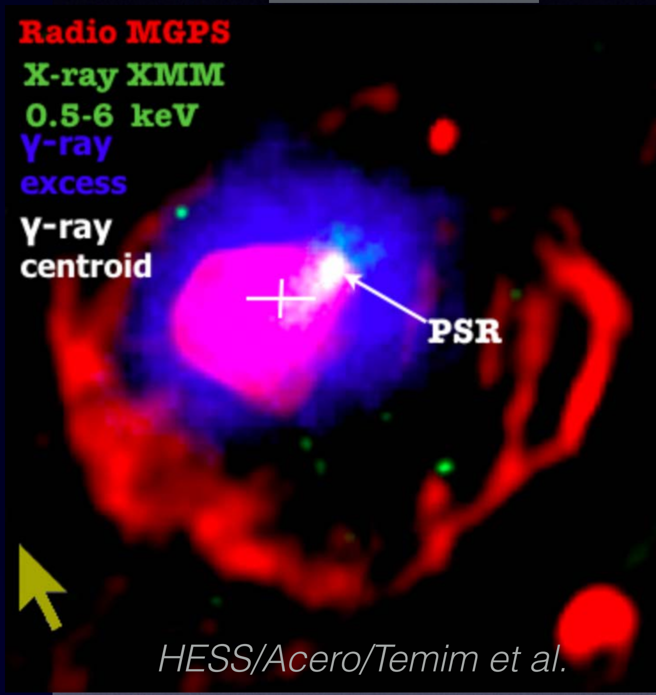
N_H=1.38 (1.21-1.57)x10^{22} cm^{-2}
Γ = 1.7 (1.5-1.8)
✓ steepens away from point source
- L_x (6.1 kpc, 0.5-10 keV)~1.5x10^{34} erg/s

Chandra (and XMM) led to the discovery of very low-luminosity, "offset", evolved (10's kyr-old) X-ray nebulae

Radio-X-gamma Synergy
Relic PWNe



G327.1-1.1

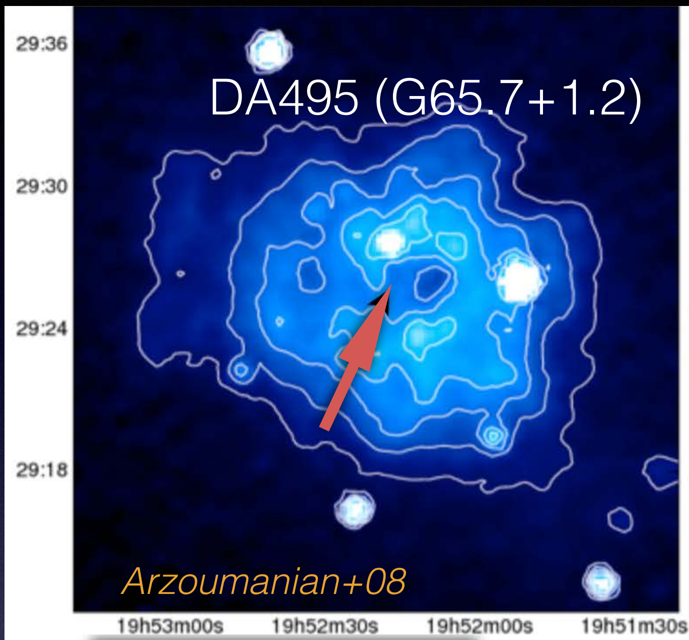


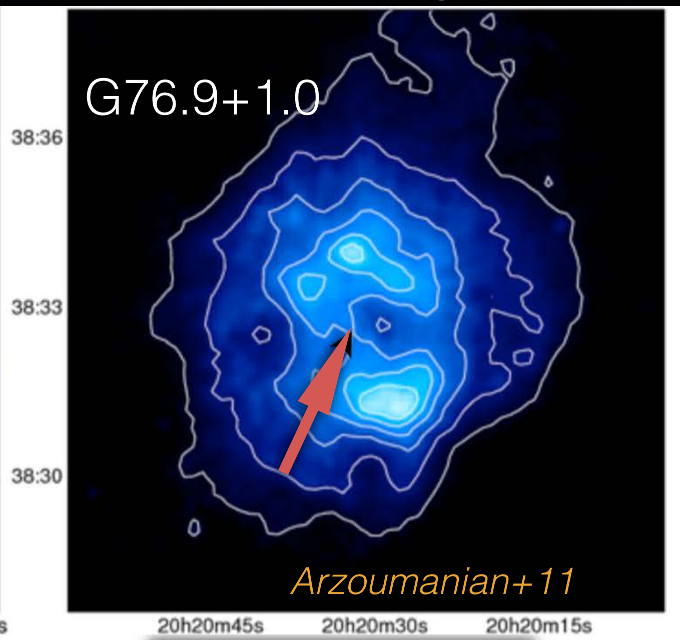
(similar..but with an SNR shell!)

age~5-27 kyr
n0<0.2 cm^{-3} (from X-rays)
B~5-50 muG
(Aliu+14, Matheson SSH & Kothes+13)

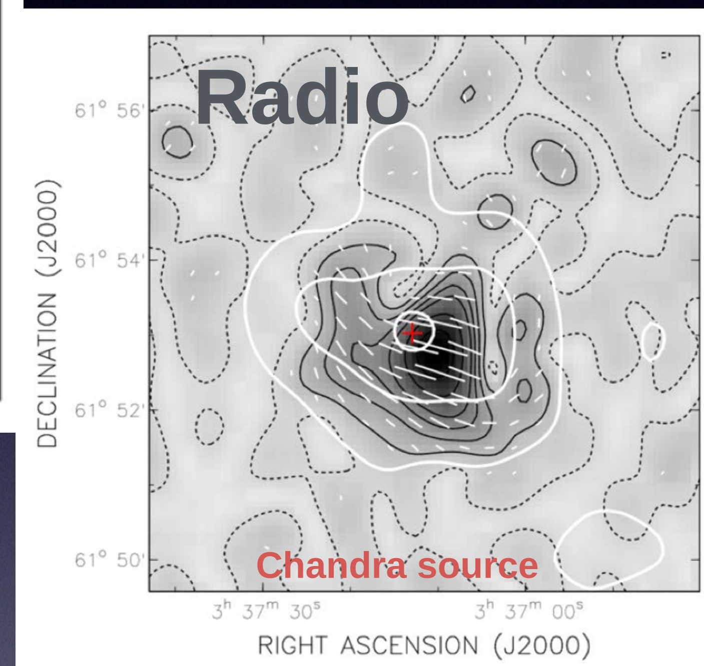
Radio PWNe that defy classification?!

Radio Images





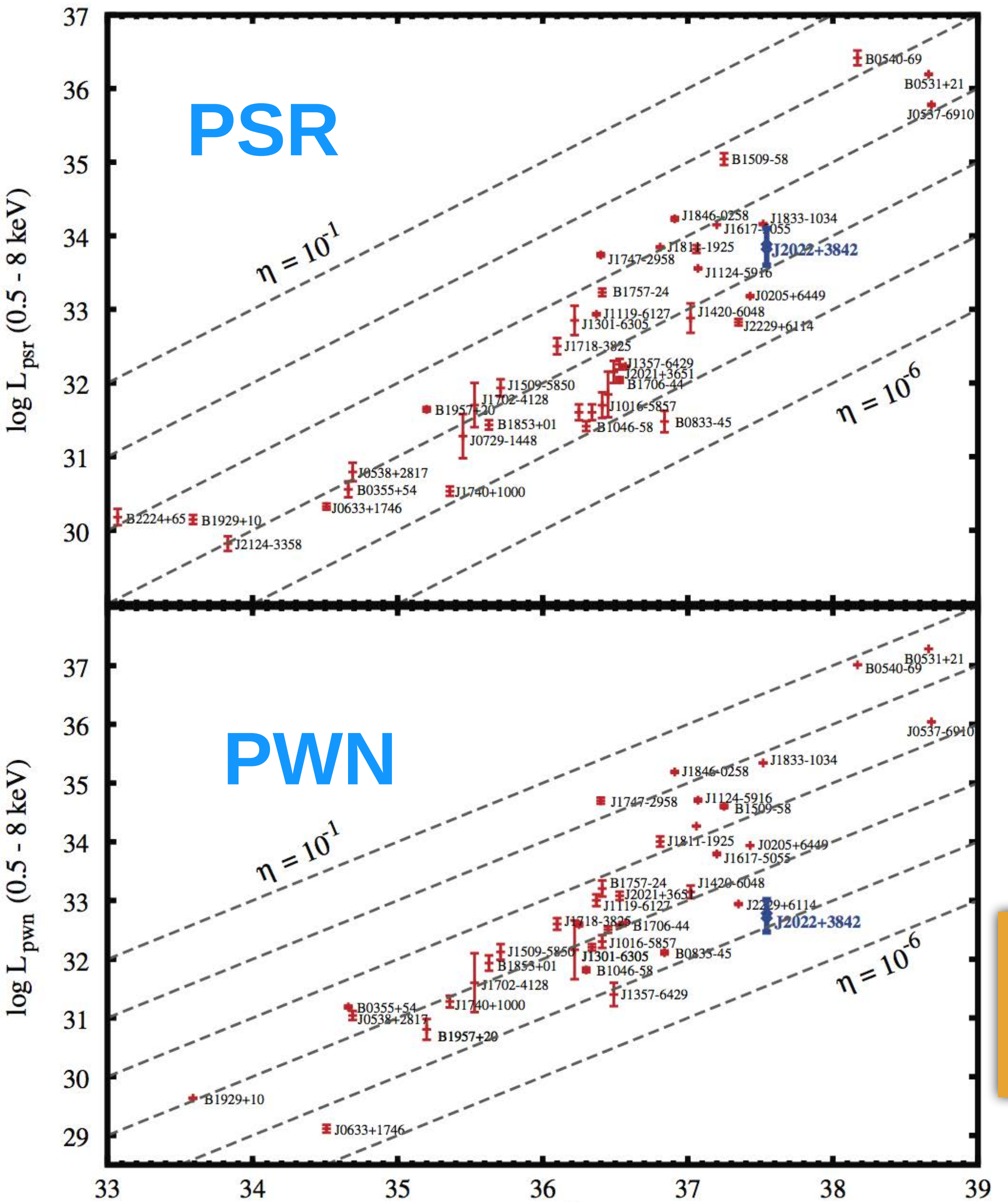
G141.2+5.0 (new PWN)



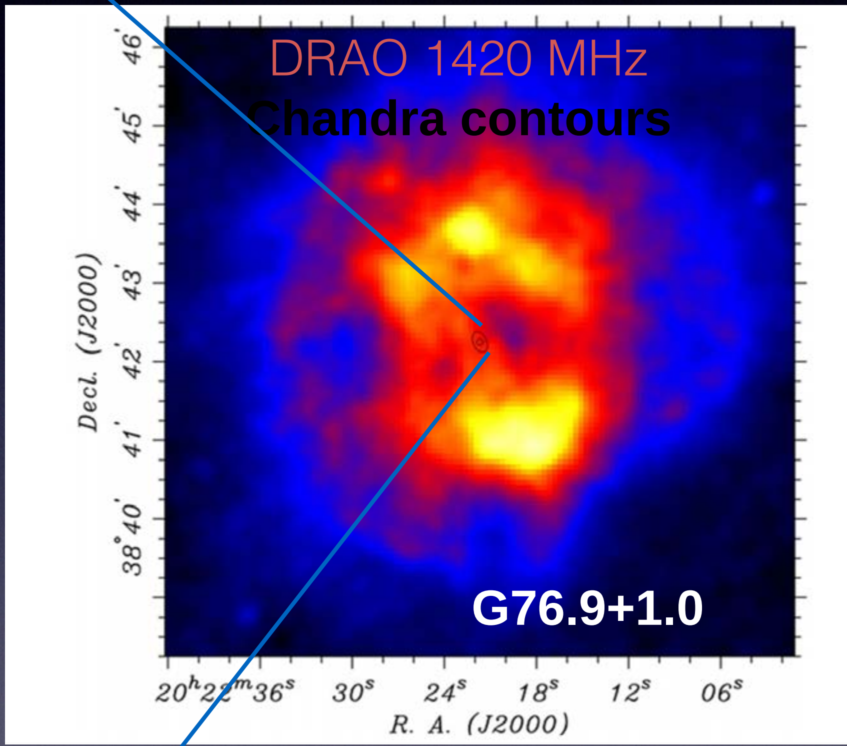
Reynolds & Borkowski+16
Kothes+14

- Roughly annular morphologies (highly polarized) with inner/outer radii of ~ 1'/10'
- Their non-thermal flux falls off away from centre, implying a central engine (**not limb-brightened**)
- Radio spectrum too steep for a plerion, $\alpha \approx$ **0.6**, more typical of shells
- Low-frequency (radio) spectral break
- In polarized emission, **strong axisymmetry** and double-lobed morphology

Very low Lx (PWN)/Edot….

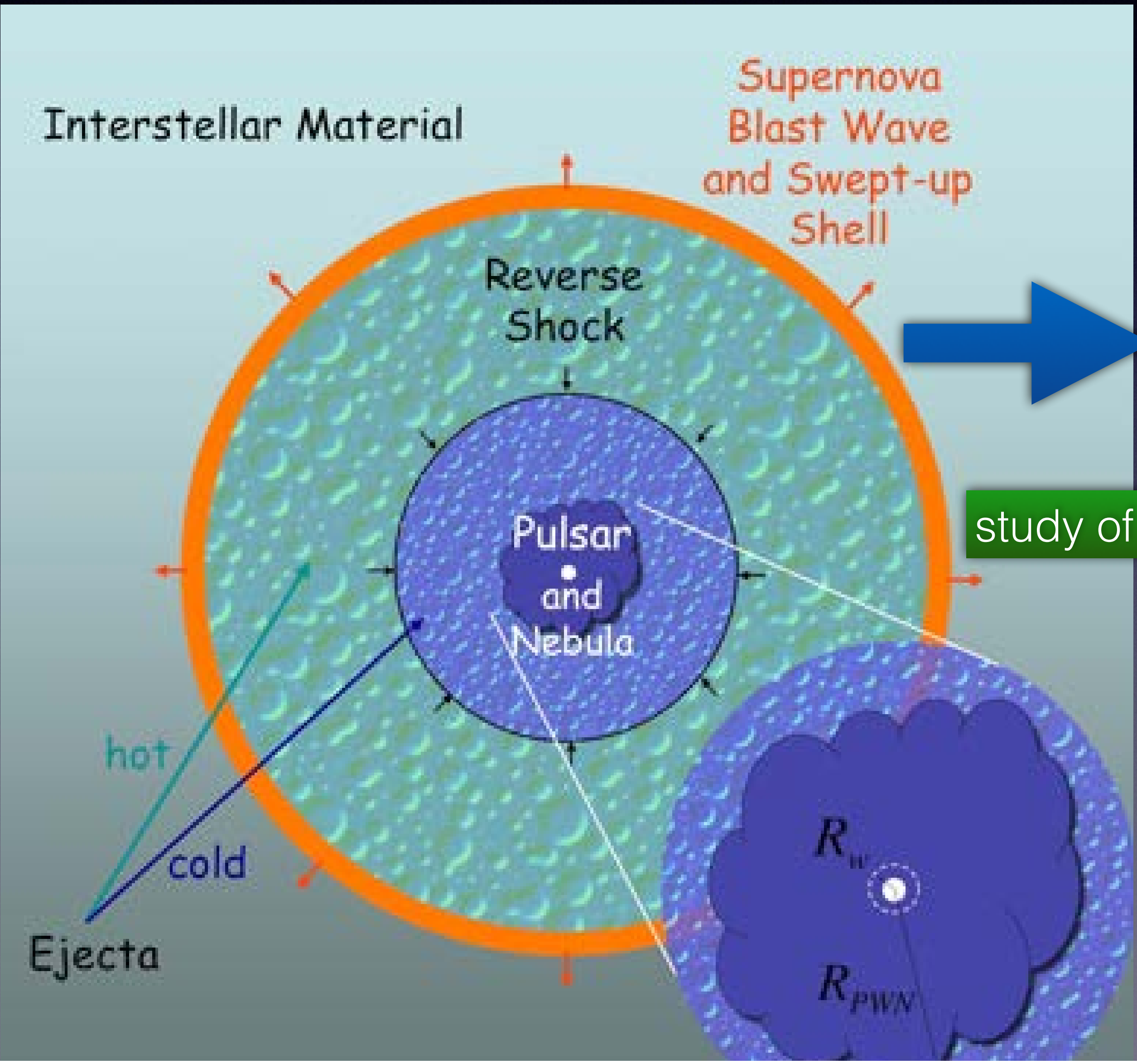


Arumugasamy et al. 2014



Among the most powerful pulsars (3e37 erg/s), but among the least efficient at converting Edot into Lx

PWN Diversity:
III. The SN progenitor/energetics

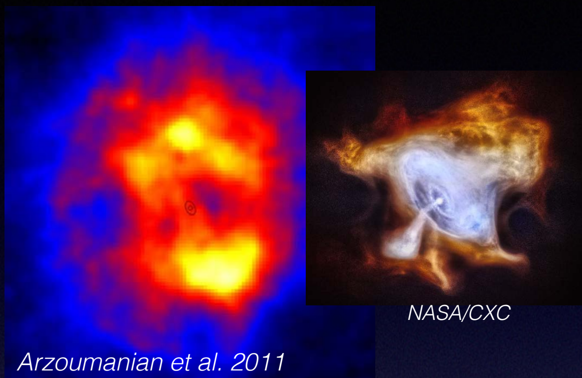


- SN progenitor/ explosion energy

study of SN ejecta, and shell **when** detected

NO SHELL

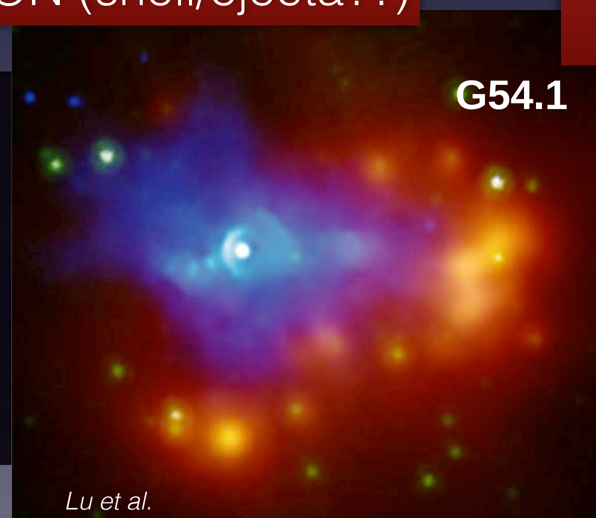
G76.9



BRIGHT THERMAL X-RAY EMISSION FROM SNR SHELL

PSR1509-58/RCW89

WEAK THERMAL X-RAY EMISSION (shell/ejecta??)

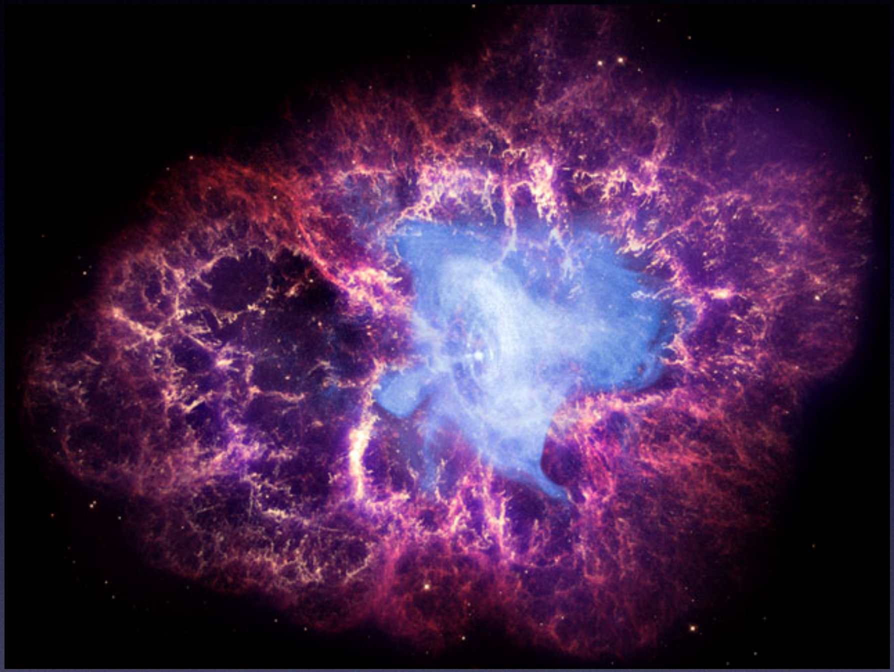


WEAK, but NON-THERMAL X-RAY EMISSION (shell??)

All are powered by RPPs with pseudo-similar properties (P, B, Edot), but clearly the SNR emission can be present or absent (Naked PWNe or Pure Plerions)…

Why many PWNe are shell-less?

53/110(48%) lack shells (ref: SNRcat)



Mar. 1943-Apr. 2016

The SNR shell in the Crab and other PWNe is still missing, despite deep searches!

"The reason for presence (in PS—plerion shell or composite SNRs) or lack (in PP—pure plerionic SNRs) of a shell has not been resolved. Weiler (1985a) suggests that it is due to a ***more tenuous ISM*** *surrounding the pure plerions, leading to lack of formation or formation of an undetectably faint shell"*

Weiler 1988

or are they low-energy/different type of core-collapse explosions??

The Crab Progenitor

The SNR shell is still missing despite deep searches!

letters to nature

Nature 299, 803 - 805 (28 October 1982); doi:10.1038/299803a0

1982

The Crab Nebula's progenitor

KEN'ICHI NOMOTO*, WARREN M. SPARKS†, ROBERT A. FESEN‡, THEODORE R. GULL‡, S. MIYAJI‡ & D. SUGIMOTO*

*Department of Earth Science and Astronomy, University of Tokyo, College of General Education, 3-8-1 Komaba, Meguro, Tokyo 153, Japan
†Group X-5, Mail Stop F669, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
‡Laboratory for Astronomy and Solar Physics, Goddard Space Flight Center, Greenbelt, Maryland 20771, USA

The study of supernovae is hampered by an insufficient knowledge of the initial stellar mass for individual supernova. Because of large uncertainties in estimating both the total mass of a remnant (including the pulsar or black hole) and any mass loss during the pre-supernova stages, the main sequence mass of the progenitor cannot be accurately determined from observations alone. To calculate an initial mass, one must rely on a combination of both theory and observation. Limits on the progenitor's mass range can be estimated by the presence of a compact remnant and comparison of the observed nebular chemical abundances with detailed evolutionary calculations[1]. The Crab Nebula is an excellent choice for investigation because it contains a unique combination of characteristics: a central neutron star (pulsar) and a bright, well studied nebula having little or no swept-up interstellar material. In fact, several studies[1–4] have suggested an initial mass of ~10$M_\odot$ for the Crab progenitor. Recently, Davidson *et al.*[5], quoting two of us (K.N. and W.M.S.), state that the Crab's progenitor had a mass slightly larger than 8 $M_\odot$. Here we present in detail the reasoning behind this statement and suggest the explosion mechanism.

Chevalier 2005: Type IIP

Mon. Not. R. Astron. Soc. **000**, 1–?? (2002) Printed 5 June 2013 (MN LaTeX style file v2.2)

2013

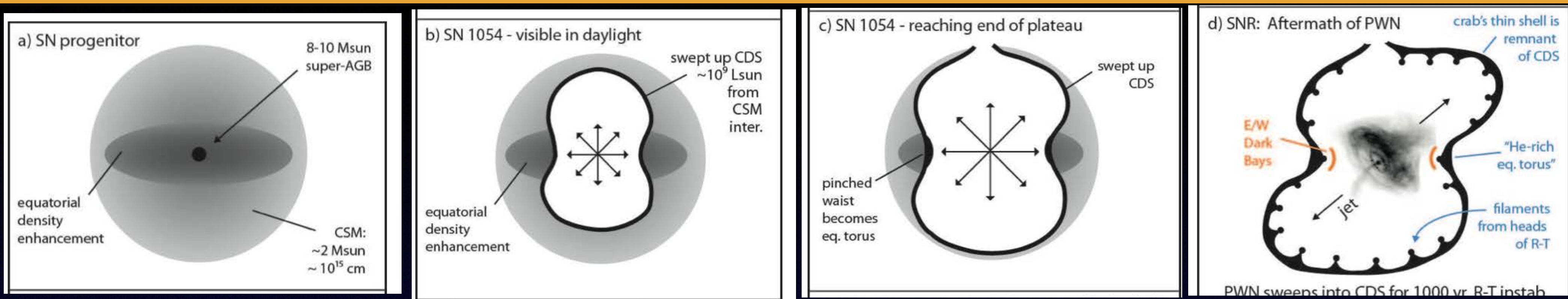
The Crab Nebula and the class of Type IIn-P supernovae caused by sub-energetic electron capture explosions

Nathan Smith*
Steward Observatory, 933 N. Cherry Ave., Tucson, AZ 85721, USA

see also Yang & Chevalier 2015
low E SN ~1e50 ergs!

2013

The Crab Progenitor

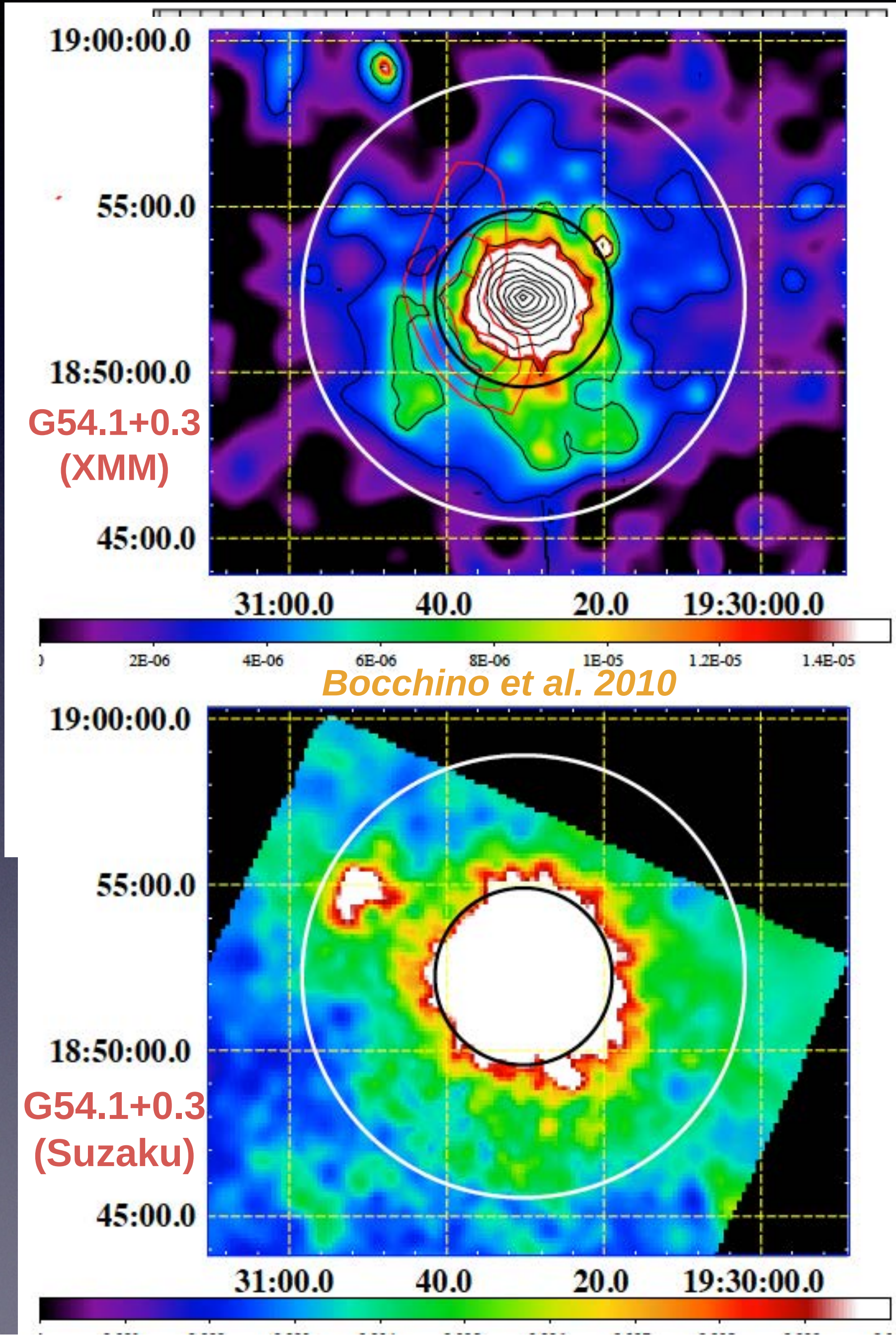


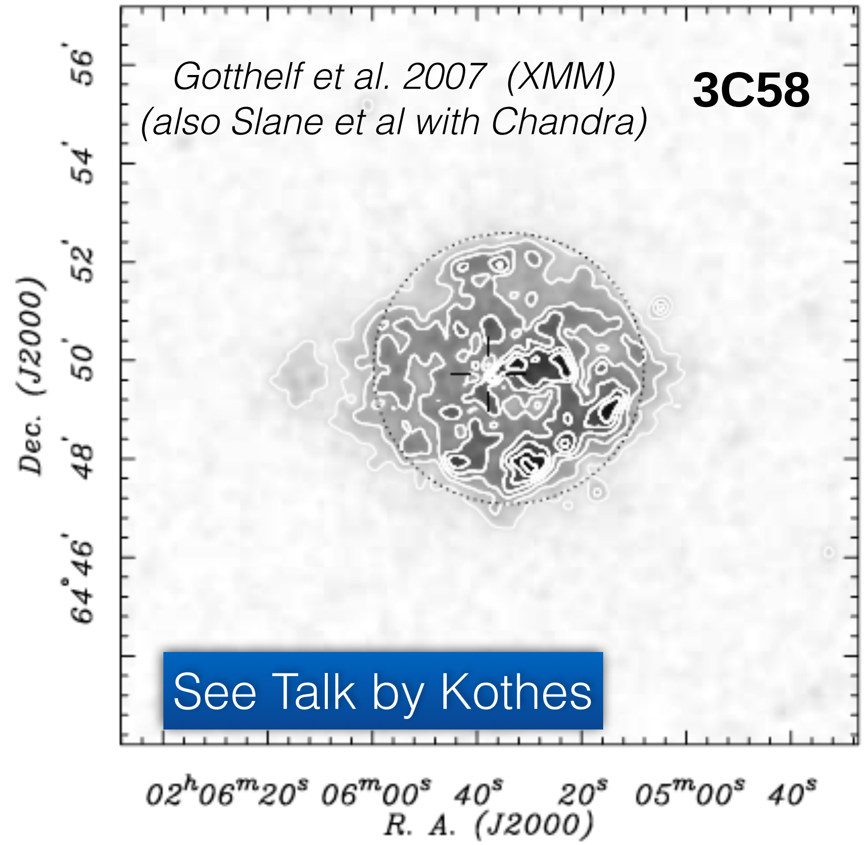
Smith 2013

- Initial mass: **8-10 solar masses**
- ~5 M⊙ expanding at ~1200 km s^{-1}, K.E. **only 7×10^{49} ergs**.
- Yet SN1054 was **very bright** (compared to normal SNe II-P and IIb, with a peak absolute visual magnitude of ~ −18); but see *Yang and Chevalier (2015)*
- SNe IIn: dominated by **intense CSM interaction**, which sweeps up most of the mass into a **cold dense shell (CDS)** that collapses as a result of radiative cooling.

see Talk by Bientenholz

Very Weak Thermal X-ray Emission from the "Naked" PWNe

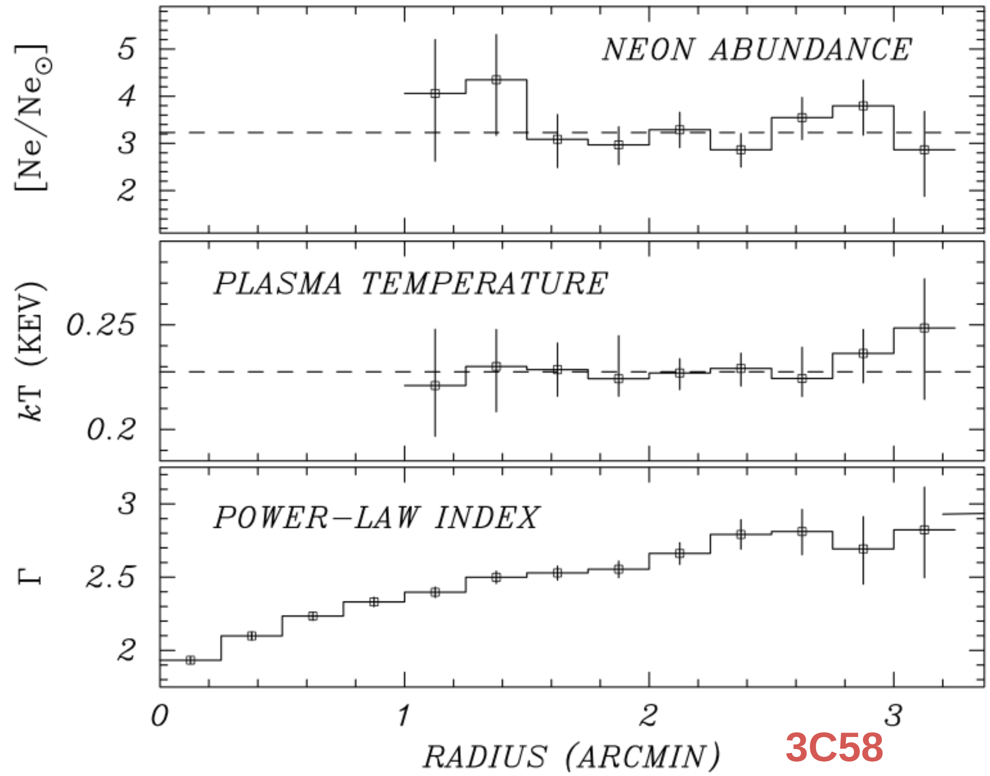




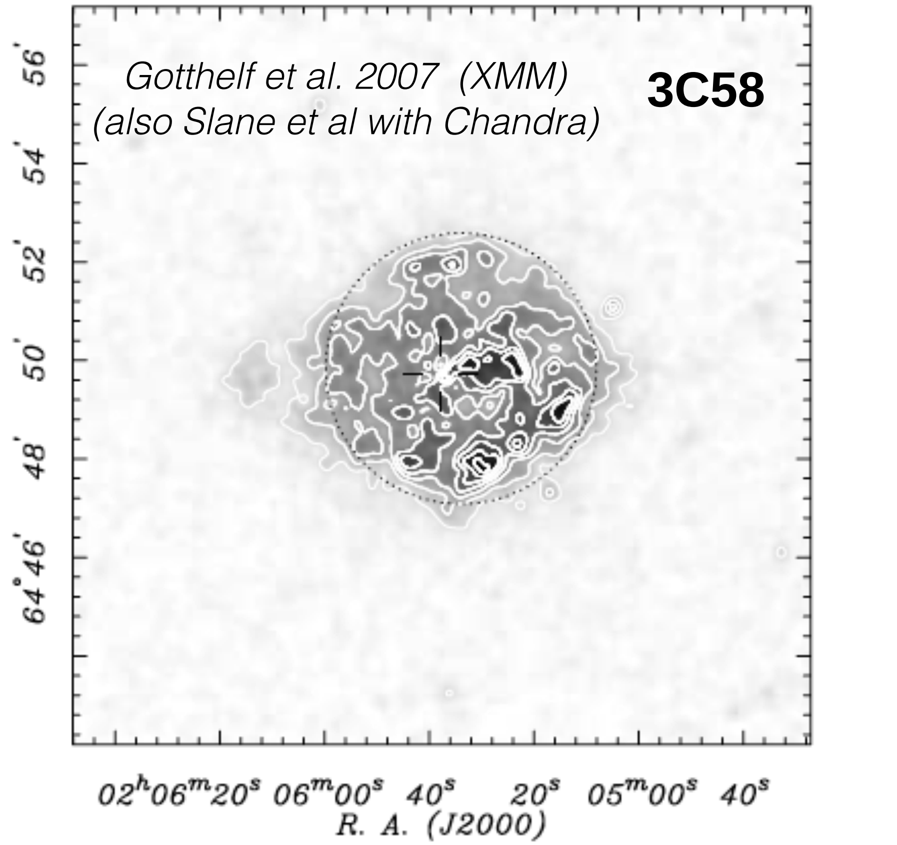
ejecta or shocked ISM/CSM?

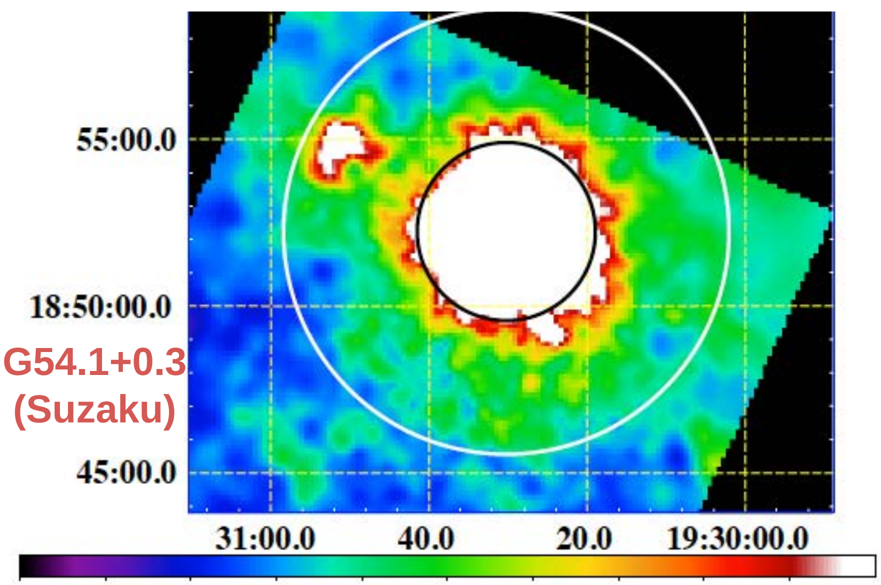
H-rich spectra
Weak C/ISM interaction:
Type IIP? (Chevalier+05)
15-20 solar masses
(see also Gelfand +15)

Very Weak Thermal X-ray Emission from the “Naked” PWNe



3C58





G54.1+0.3
(Suzaku)

ejecta or shocked ISM/CSM?

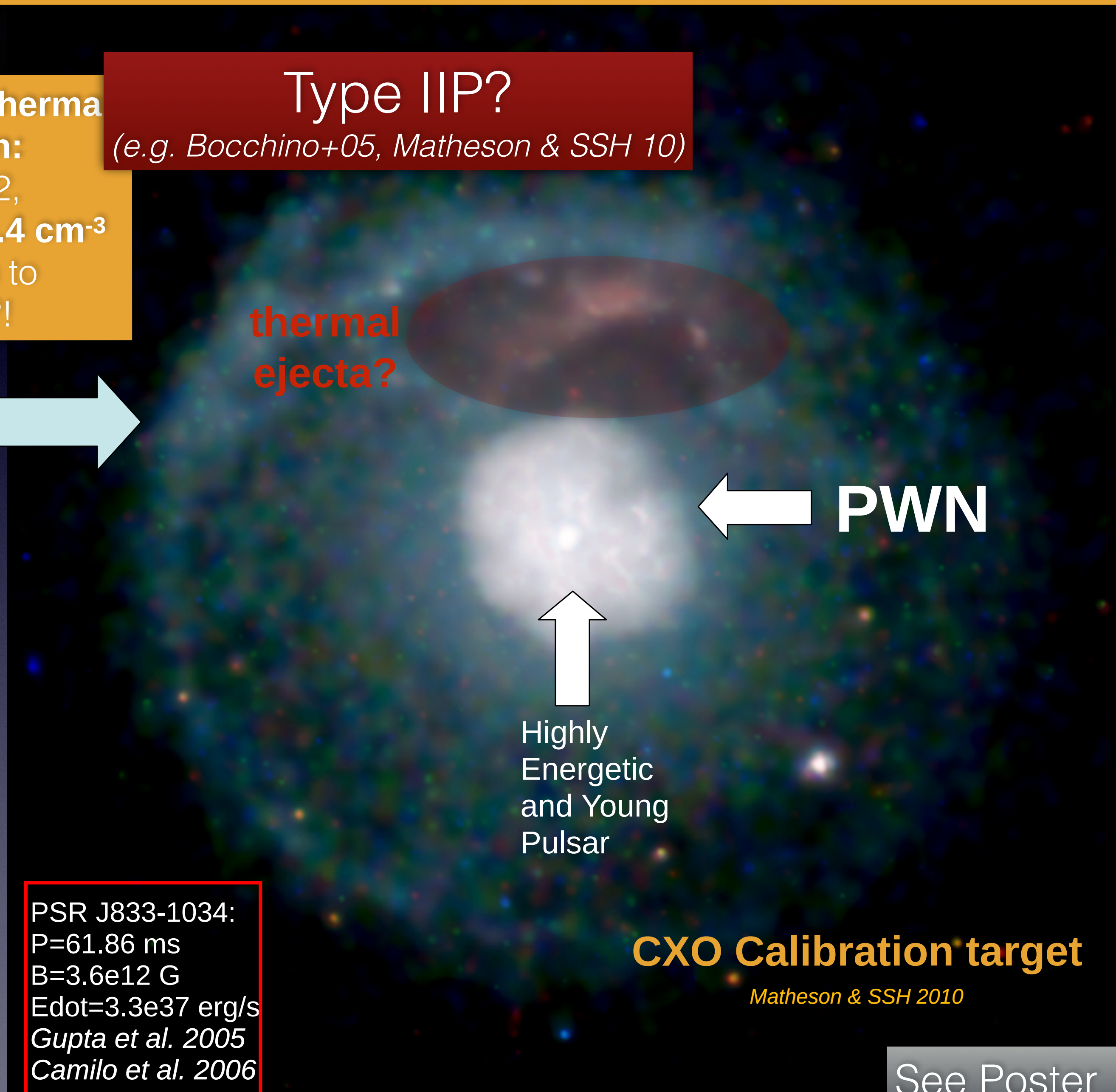
H-rich spectra
Weak C/ISM interaction:
Type IIP? (Chevalier+05)
15-20 solar masses
(see also Gelfand +15)

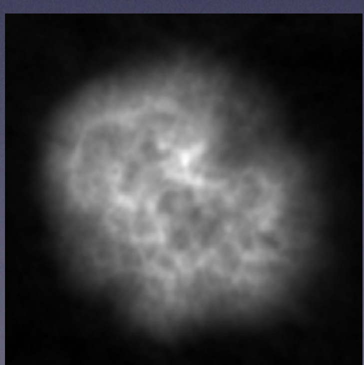
It's there in G21.5-0.9!
but still..primarily non-thermal/very hard

dominated by **non- therma[l]**
X-ray emission:
photon index~2,
ambient density <0.4 cm^{-3}
CR acceleration to
TeV energies?!

Blast wave?

no radio detection
(*Bietelnholz et al. 2012*)





PWN (radio)
Bietenholz et al.

See Poster (Guest & SSH)

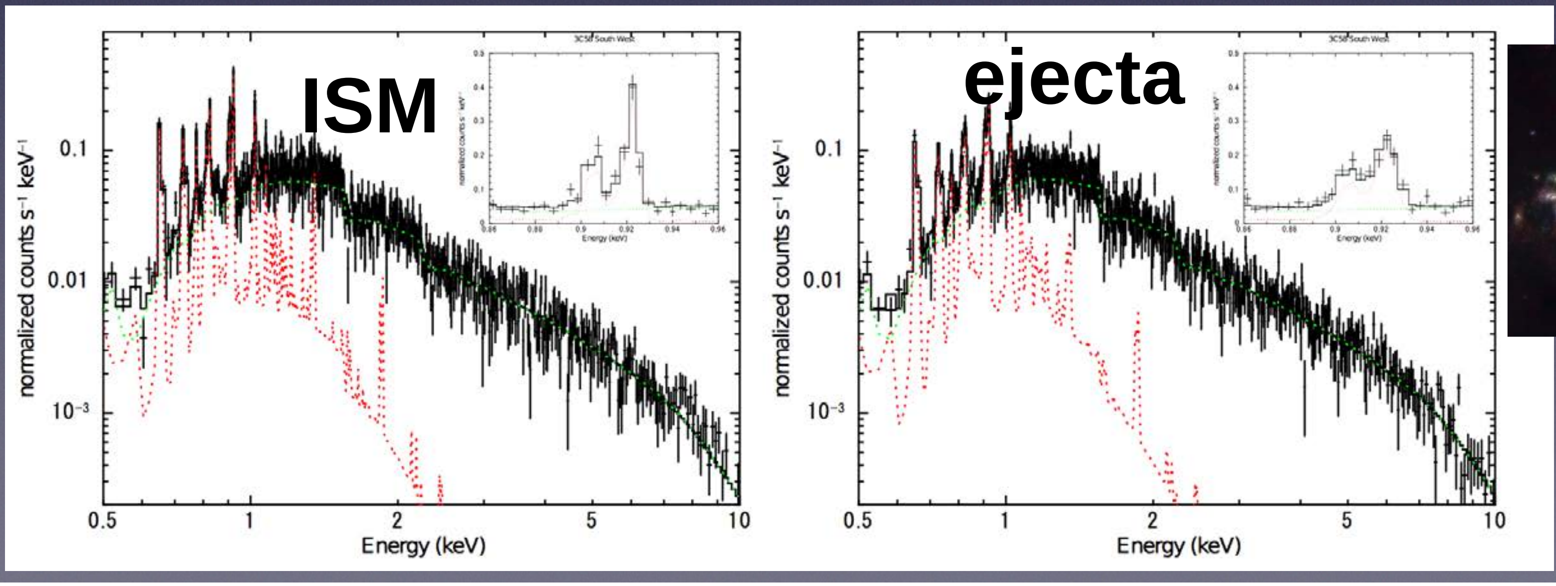
Outlook

- May Chandra, XMM-Newton, NUSTAR live long!
  - Chandra (2030?!)

Outlook

- May Chandra and XMM-Newton live long!
  - Chandra (2030?!)
- Progenitor Studies: Thermal X-ray emission
  - Sensitive and High-resolution X-ray spectroscopy
  - 😥 **ASTRO-H** (Hitomi) as a pathfinder for **ATHENA**
  - 😀Power of X-ray Spectroscopy however proven with **first light SXS** data (*Takahashi+16, Nature*)

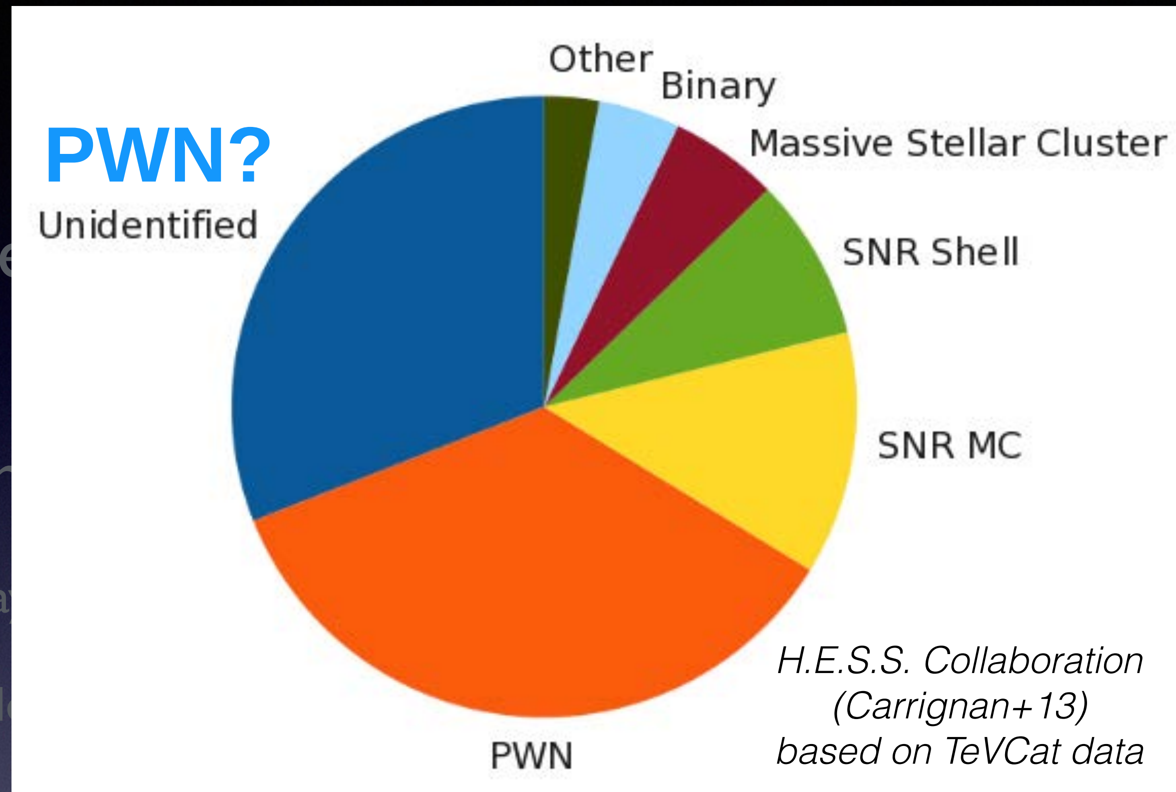
100 ks **simulation** with ASTRO-H to study the thermal plasma=>progenitor



Astro-H white paper:
Long et al. 2014

Outlook

- May Chandra and XMM-Ne
  - Progenitor Studies: Therr
    - Sensitive and High-resolution X-ra
    - **ASTRO-H** (Hitomi) as a pathfind



H.E.S.S. Collaboration (Carrignan+13) based on TeVCat data

- Unveiling the nature of many **unID gamma-ray** sources and completing the census (particle acceleration and evolution): Non-thermal X-ray emission:
  - High throughput with (sub-)arcsecond resolution (e.g. ATHENA and the **X-ray Surveyer**)
  - synergy with the **Cherenkov Telescope Array** and **Square Kilometer Array** Pathfinders

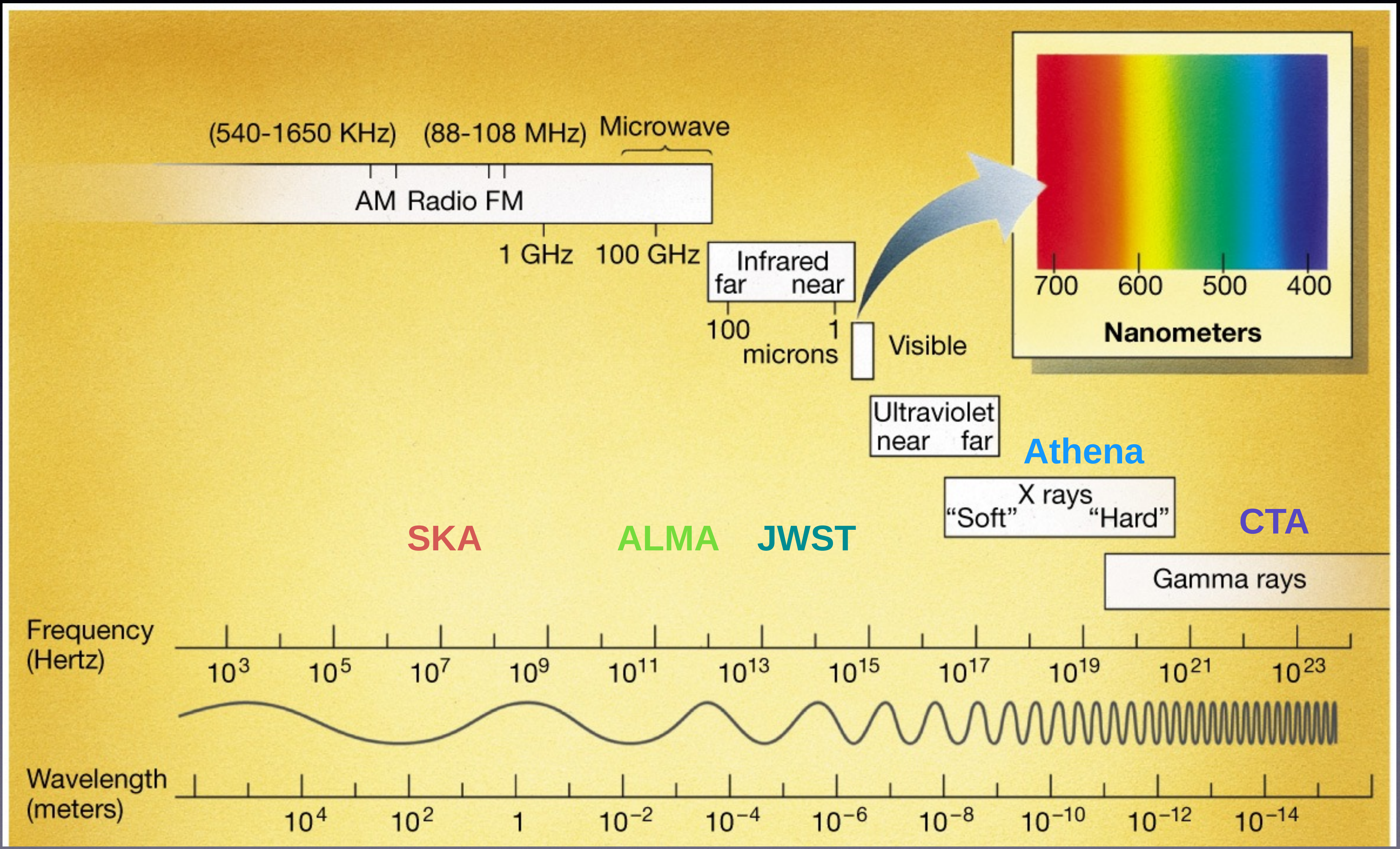
ID	names	context	SN	age	distance	type	CHANDRA	XMM	SUZAKU	ROSAT	ASCA	FERMI	AGILE	HESS	VERITAS	MAGIC
							all	all	all	all	all	all	all	all	all	all
G000.0+00.0	Sgr A East, *CXOGC J174545.5-285829, 1FGL J1745.6-2900c, 2FGL J1745.6-2858, 1FHL J1745.6-2900, 3FGL J1745.6-2859c, HESS J1745-290*	contains CXOGC J174545.5-285829 = the Cannonball = NS candidate and possibly PWN, close to BH Sgr A*, interacts with molecular cloud		1200 - 10000 yr	8 kpc	thermal composite	CHANDRA	XMM	SUZAKU		ASCA	FERMI		HESS	VERITAS	
G000.1-00.1	G0.13-0.12, *1FGL J1746.4-2849c, 2FGL J1746.6-2851c, 1FHL J1746.3-2851, 3FGL J1746.3-2851c*	contains PWN G0.13-0.11, interacts with molecular cloud??				thermal & plerionic composite?	CHANDRA	XMM				FERMI				
G000.9+00.1	*HESS J1747-281*	contains PSR J1747-2809 + PWN G0.87+0.08		1900 yr PSR: 5000 yr	8.5 - 10 kpc PSR: 13 kpc	plerionic composite	CHANDRA	XMM			ASCA	FERMI		HESS		
G005.4-01.2 ?	Milne 56, ~~G5.3-1.0~~, ~~G5.27-0.9~~, *2FGL J1802.3-2445c*	offset PSR J1801-2451 = B1757-24 = the Duck + PWN G5.27-0.9, interacts with molecular cloud		PSR: 15488 yr	4.3 - 5.2 kpc PSR: 5 kpc	plerionic composite?	CHANDRA					FERMI				
G006.4+04.9	*0FGL J1742.1-2054, 1FGL J1741.8-2101, 2FGL J1741.9-2054, 3FGL J1741.9-2054*	bow shock PWN and PSR J1741-2054		PSR: 386000 yr	PSR: 0.3 kpc	filled-centre	CHANDRA	XMM				FERMI				
G007.5-01.7 ?	*CXOU J180950.2-233223, 0FGL J1809.5-2331, 1FGL J1809.8-2332, 2FGL J1809.8-2332, 1FHL J1809.8-2329, 3FGL J1809.8-2332*	contains PWN G7.4-2.0 = Taz, close to PSR J1809-2332		50000 yr PSR: 22908 yr	1.7 - 2 kpc PSR: 2 kpc	thermal & plerionic composite	CHANDRA	XMM		ROSAT	ASCA	FERMI				
G008.7-00.1	(W30), ~~G8.6-0.1~~, *CXOU J180351.4-213707, CXOU J180432.4-214009, CXOU J180441.9-214224, Suzaku J1804-2142 and J1804-2140, 0FGL J1805.3-2138, 1FGL J1805.2-2137c and J1806.8-2109c, 2FGL J1805.6-2136e, 1FHL J1805.6-2136e, 3FGL J1805.6-2136e, 1AGL J1805-2143, HESS J1804-216*	inside W30 complex, PSR J1803-2137 = B1800-21 and PWN G8.40+0.15 at the edge, close to new SNR G8.3-0.0, interacts with molecular cloud		15000 - 28000 yr PSR: 15800 yr	3.2 - 6 kpc PSR: 4 kpc	thermal & plerionic composite?	CHANDRA		SUZAKU	ROSAT		FERMI	AGILE	HESS		
G010.9-45.4	~~G10.93-45.44~~, *1FGL J2124.7-3358, 2FGL J2124.6-3357, 3FGL J2124.7-3358*	PWN G10.92-45.43 and PSR J2124-3358		PSR: 3801894000 yr	PSR: 0.25 kpc	filled-centre	CHANDRA	XMM			ASCA	FERMI				
G011.1+00.1	~~G11.18+0.11~~, *3FGL J1810.1-1910, HESS J1809-193*	PWN G11.09+0.08, close to SNR G11.2-0.3 with PSR J1811-1925 = the Turtle + PWN G11.18-0.35 and PSR J1809-1917, close to PSR J1809-1943										FERMI		HESS		
G011.2-00.3	*3FGL J1811.3-1927c, HESS J1809-193*	contains PSR J1811-1925 = the Turtle + PWN G11.18-0.35, close to SNR G11.1-1.0 with PSR J1809-1917 + PWN G11.09+0.08, close to PSR J1809-1943, ~~interacts with molecular cloud~~	386 ??	1400 - 2400 yr PSR: 23500 yr SN: 1630 yr ??	5 - 10 kpc PSR: 5 kpc	plerionic composite	CHANDRA	XMM		ROSAT	ASCA	FERMI		HESS		
G012.8-00.0	W33, ~~G12.82-0.02~~, ~~G12.83-0.02~~, *AX J1813-178, 0FGL J1814.3-1739, 1AGL J1815-1732, HESS J1813-178*	close to W33 complex, contains PSR J1813-1749 + PWN G12.82-0.02, ~~interacts with molecular cloud~~		1200 yr PSR: 5000 yr	≥ 4 kpc PSR: 4.7 kpc	plerionic composite	CHANDRA	XMM			ASCA	FERMI	AGILE	HESS		MAGIC
G016.7+00.1	~~G16.73+0.08~~	contains PWN G16.73+0.08, interacts with molecular cloud		2100 yr	10 - 14 kpc	plerionic composite	CHANDRA	XMM			ASCA	FERMI		HESS		
G018.0-00.7	Turkey, *1FGL J1821.1-1425c and J1825.7-1410c, 2FGL J1826.1-1256 and J1824.5-1351e, 1FHL J1824.5-1351e, 3FGL J1824.5-1351e, 1AGL J1827-1227, HESS J1825-137*	(bow shock?) PWN G18.00-0.69 = Turkey and PSR J1826-1334 = B1823-13		PSR: 21400 yr	PSR: 4 kpc	filled-centre?	CHANDRA	XMM	SUZAKU	ROSAT		FERMI	AGILE	HESS		
G018.5-00.4	Eel, *AX J1826.1-1257, 0FGL J1825.9-1256, 1FGL J1826.1-1256, 2FGL J1826.1-1256, 3FGL J1826.1-1256*	PWN G18.5-0.4 = the Eel and PSR J1826-1256		PSR: 14400 yr	PSR: 7 kpc	filled-centre	CHANDRA				ASCA	FERMI				
G018.9-01.1	~~G18.95-1.1~~, ~~G18.94-1.04~~, *3FGL J1829.7-1304*	contains PWN and PSR candidate CXOU J182913.1-125113, interacts with molecular cloud??			2 kpc	plerionic composite	CHANDRA			ROSAT	ASCA	FERMI				
G020.0-00.2	~~G20.07-0.14~~, *1FGL J1827.9-1128c, 2FGL J1828.3-1124c, 3FGL J1828.4-1121*	contains PWN?			4.5 kpc	filled-centre	CHANDRA					FERMI				
G021.5-00.9	*1FGL J1833.5-1034, 2FGL J1833.6-1032, 3FGL J1833.5-1033, HESS J1833-105*	contains PSR J1833-1034 + PWN G21.50-0.89		720 - 1070 yr PSR: 4900 yr	4.3 - 5.1 kpc PSR: 4.7 kpc	plerionic composite	CHANDRA	XMM	SUZAKU	ROSAT	ASCA	FERMI		HESS		
G029.4+00.1 ?	G29.3667+0.1000, *AX J1844.7-0305, HESS J1843-033*	PWN G29.37+0.1?, close to radio galaxy PMN J18440306			5.2 - 15.8 kpc	plerionic composite?	CHANDRA				ASCA			HESS		
G029.7-00.3	Kes 75, *HESS J1846-029*	contains high-B PSR J1846-0258 (magnetar?) + PWN, interacts with molecular cloud		400 - 1000 yr PSR: 700 yr	5.1 - 7.5 kpc PSR: 6 kpc	plerionic composite	CHANDRA				ASCA	FERMI		HESS		
G032.6+00.5 ?	*HESS J1849-000*	PWN candidate G32.64+0.53 and PSR J1849-0001		PSR: 42900 yr	PSR: 7 kpc	filled-centre?	CHANDRA	XMM				FERMI		HESS		
G034.0+20.3		PWN G34.01+20.27 and PSR J1740+1000		PSR: 114800 yr	PSR: 1.4 kpc	filled-centre	CHANDRA	XMM								

A lot of black boxes still to colour :-)

SNRcat

Athena (~2028)

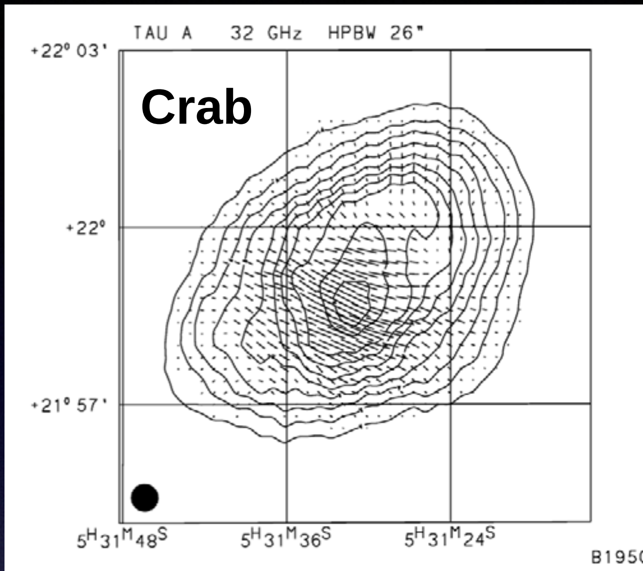
The Advanced (X-ray) Telescope for High-Energy Astrophysics



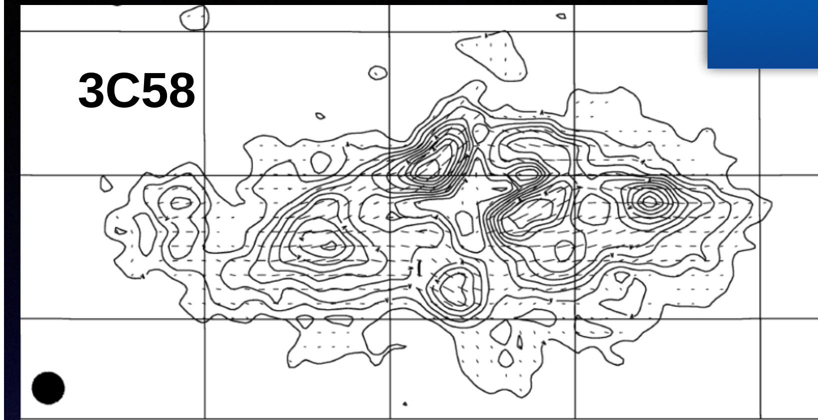
Synergy with future multi-wavelength (big) facilities

Magnetic Fields in PWNe

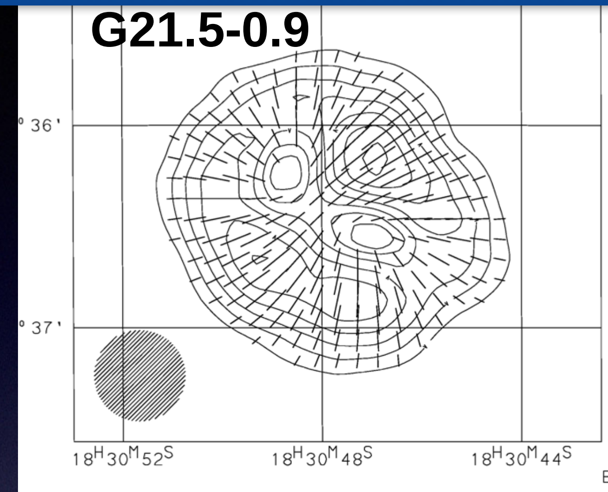
See Talks by *Reynolds and Reich*
Poster by *Stephen Ng*



Reich+02

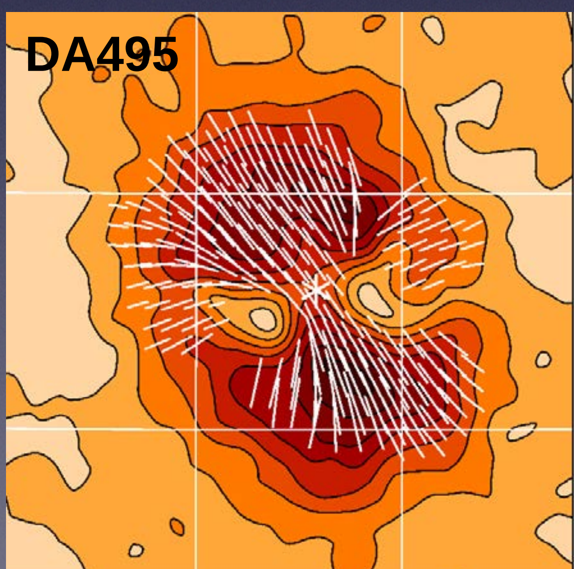


Reich+98

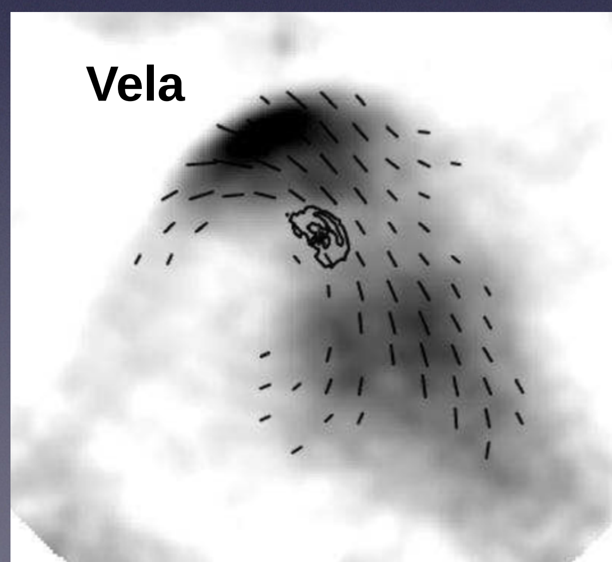


Fürst+88, Reich+02

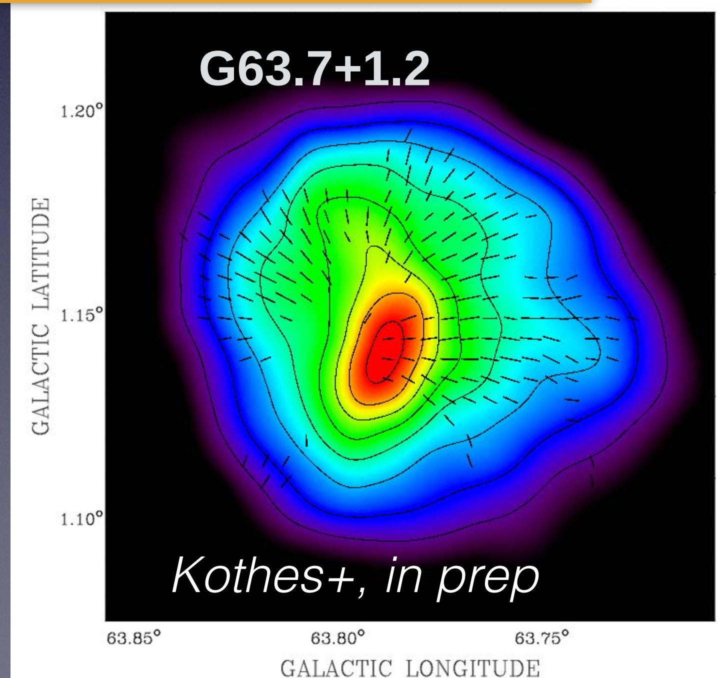
X-ray Polarimetry will open a new window! (IXPE, XIPE, PRAXyS,…)



Kothes+08



Dodson+03



Kothes+, in prep

Acknowledgments and thanks..

- Collaborators: Roland Kothes, Zaven Arzoumanian, Tom Landecker
- U. of Manitoba's SNR/PWN group
- HESS + ASTRO-H teams, PWN researchers

….with many thanks to the organizers and funding agencies…

NSERC CRSNG

Canada Research Chairs

CSA ASC