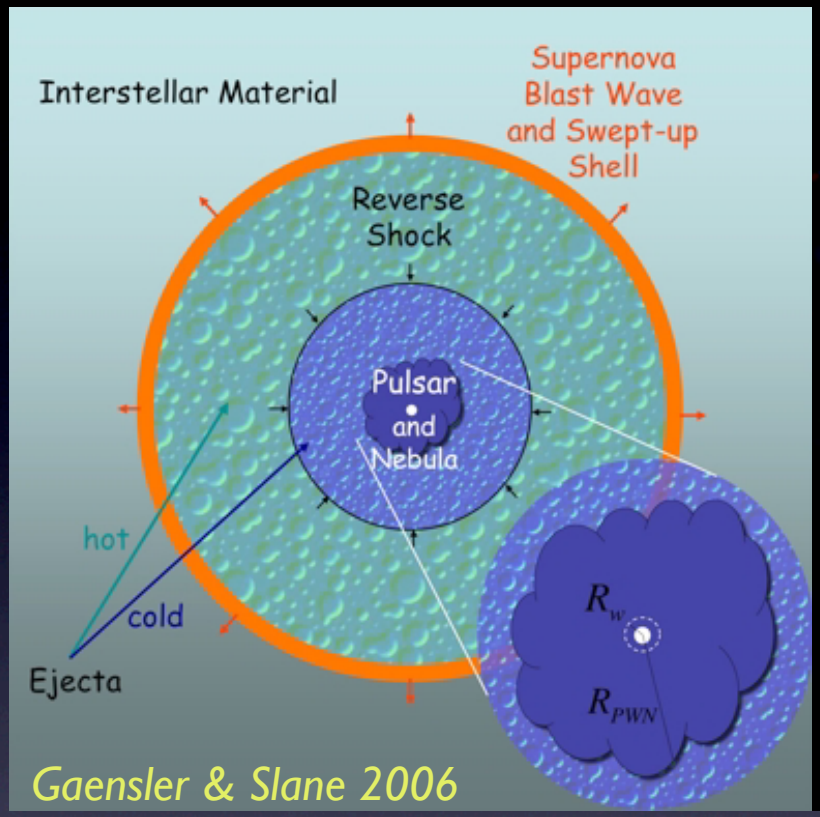
Plerionic Supernova Remnants

On their diversity

Samar Safi-Harb
University of Manitoba, Canada

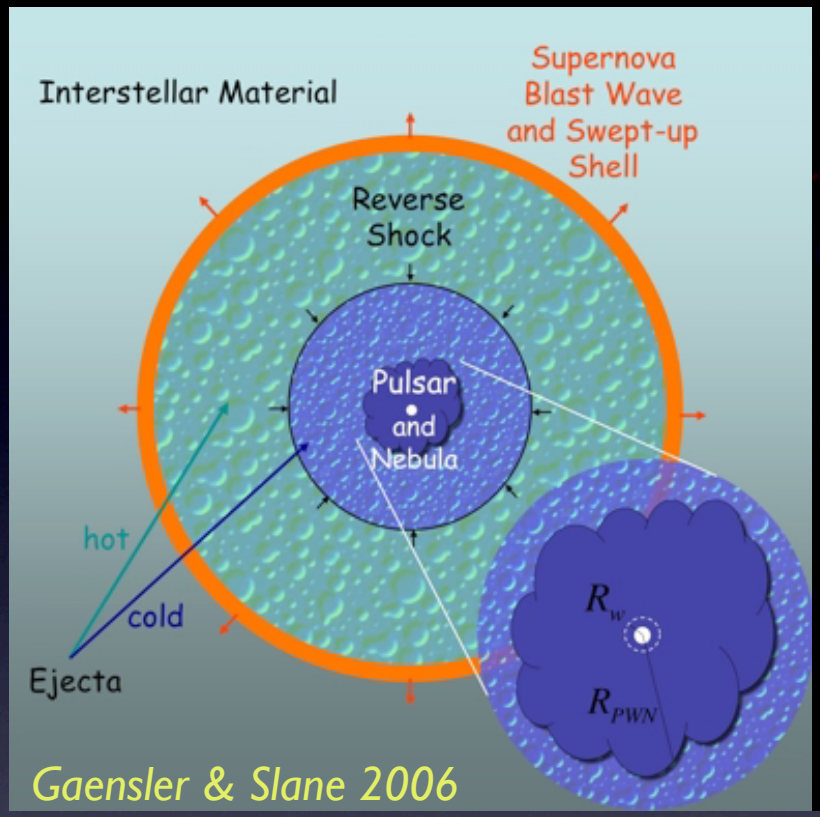
5th Symposium on HE gamma-ray astronomy
Heidelberg, July 9-13 (2012)

Plerionic SNRs



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

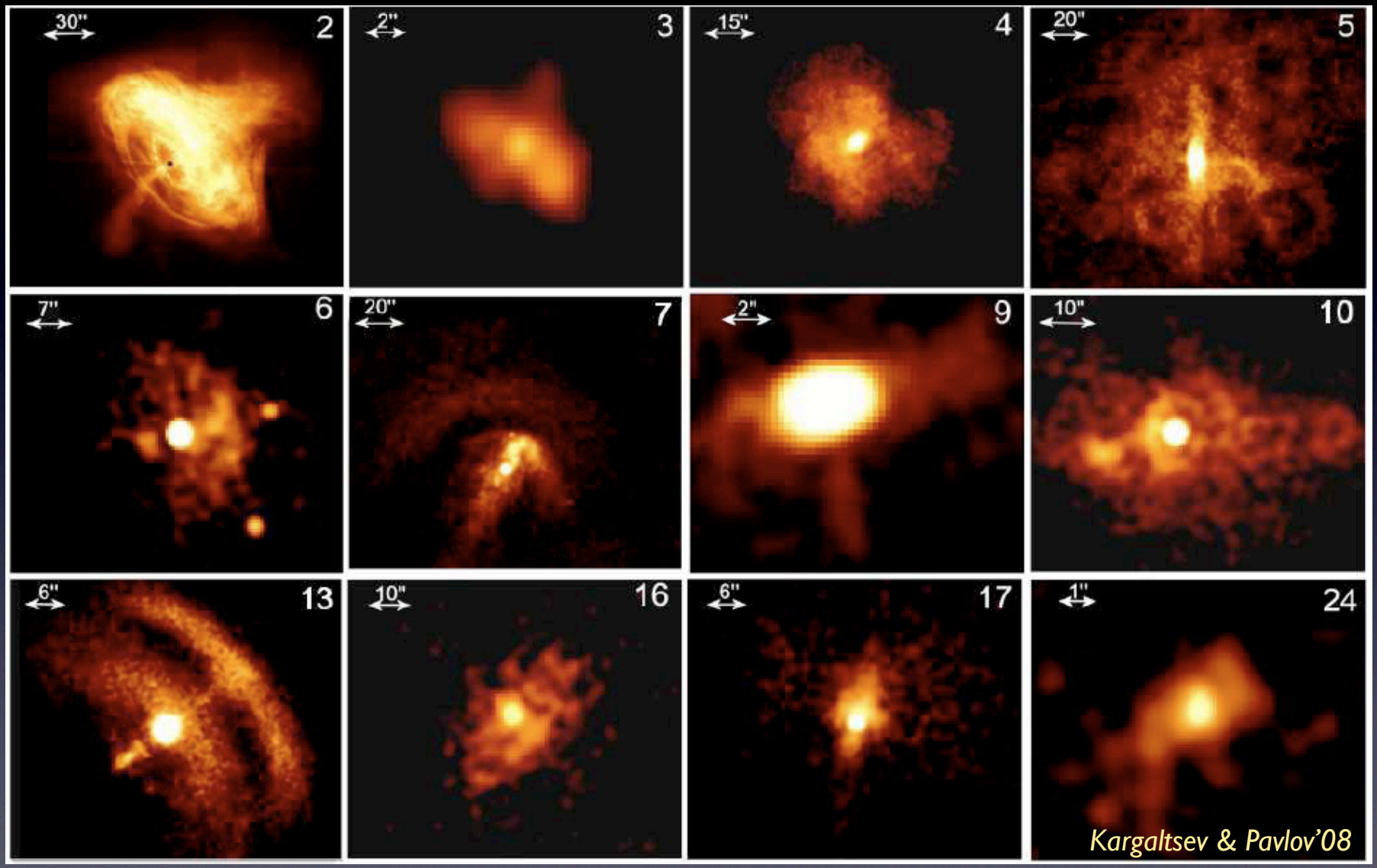
Plerionic SNRs



Observationally:

- Centrally-filled morphology: pure plerions (Crab), plerionic Composites
- Flat radio spectral index, $\alpha < 0.5$
- Observed from radio to high-energy (TeV) energies
  - ✓ R-X: Synchrotron emission
  - ✓ gamma-ray: IC scattering (synchrotron, CMB, IR, starlight), pion decay (hadronic)

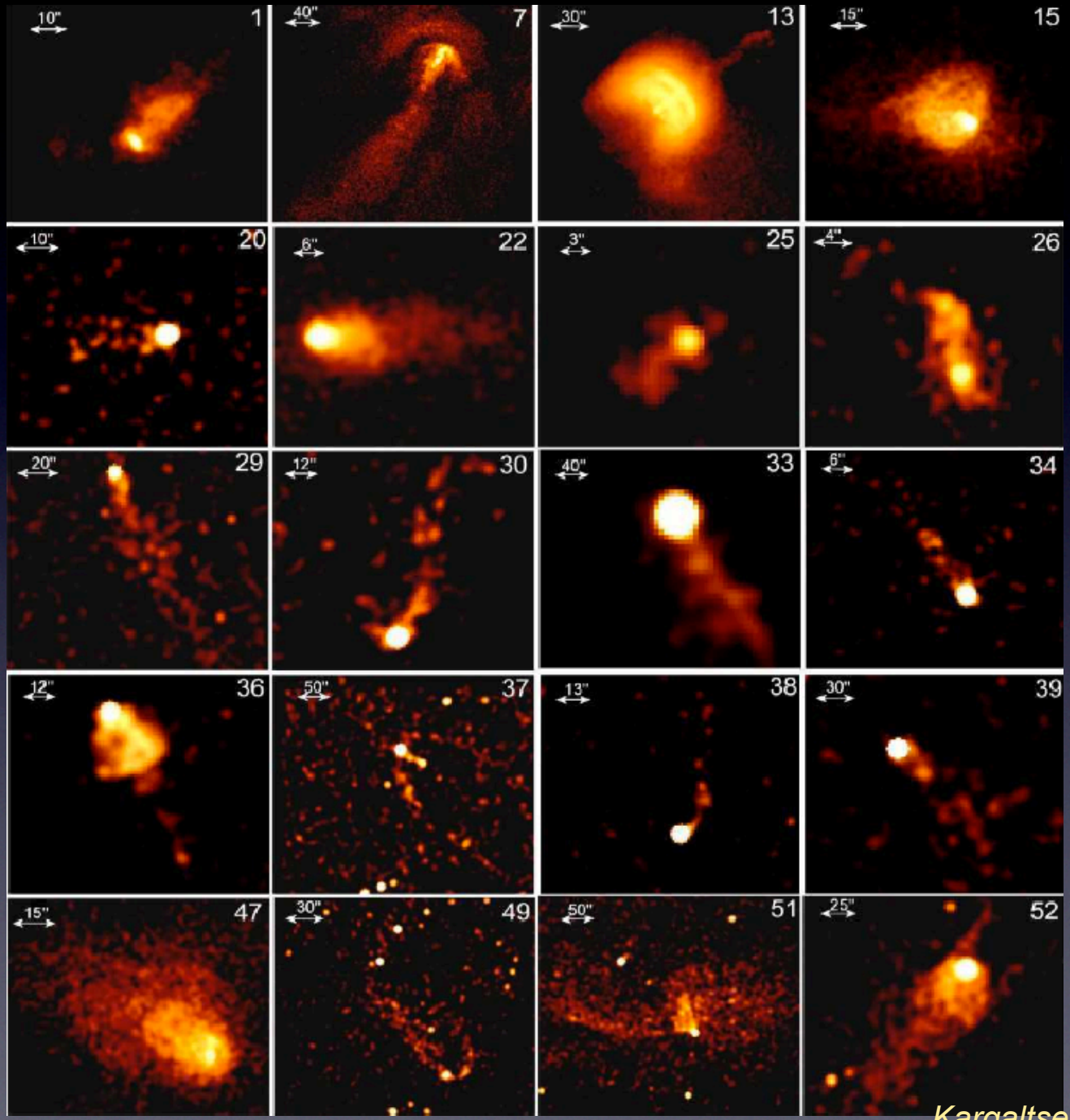
Chandra: New/Sharp Eyes on Plerions



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

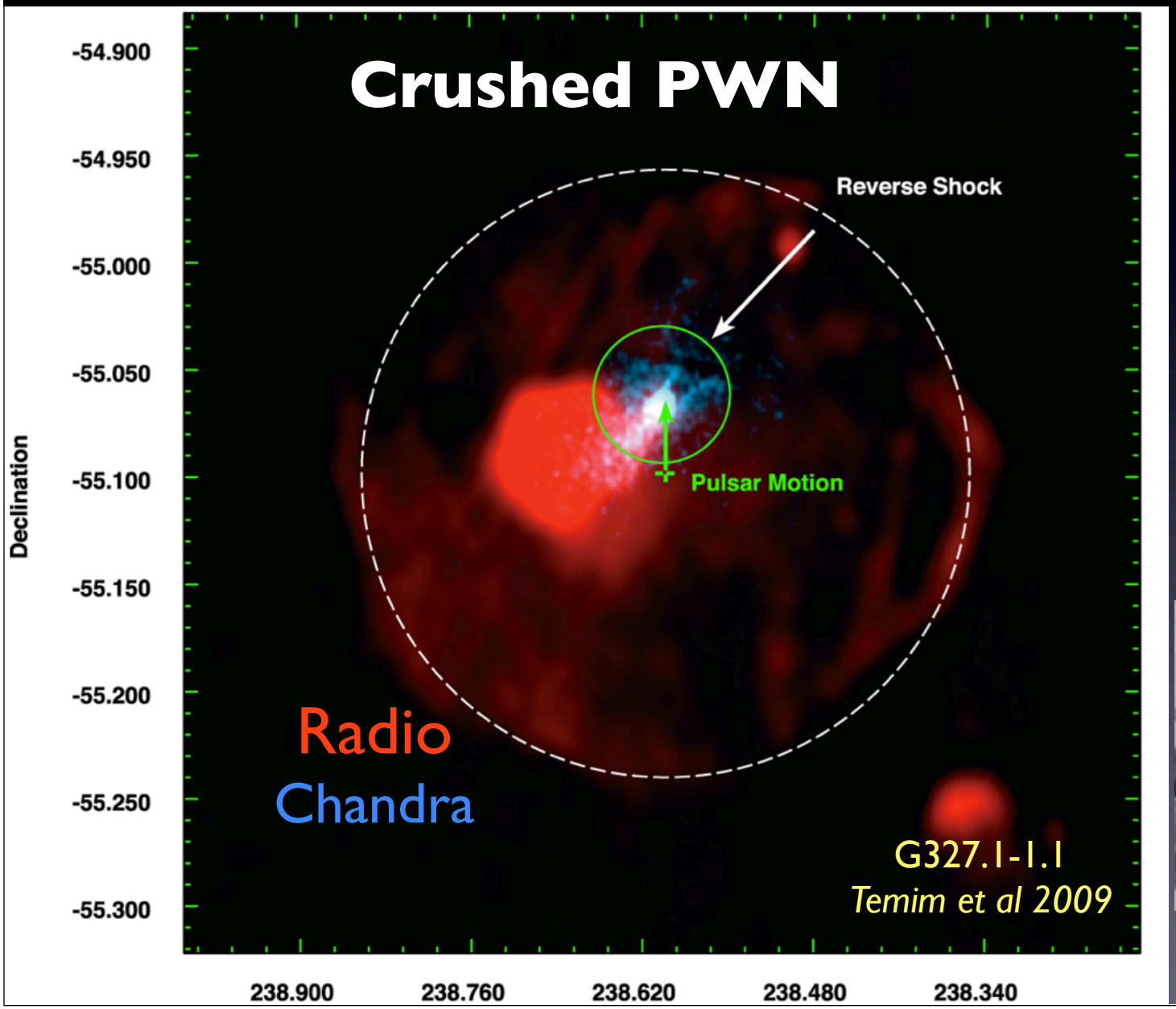
(e.g. Del Zanna et al.'06, Buccianitni et al.'04; van der Swaluw et al.'04; Blondin, Chevalier,Frieson'01)

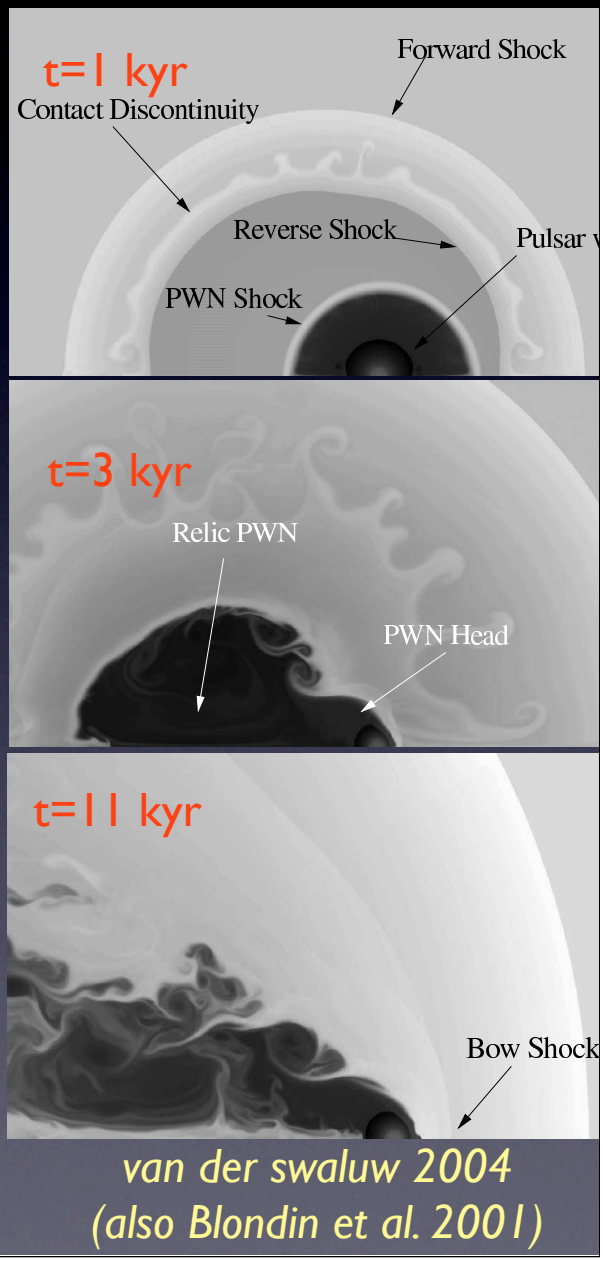
Bow-Shock PWNe



Kargaltsev & Pavlov 2008

Evolved "Relic" Plerions





Some Statistics

- Currently we know of 303 Galactic SNRs (*new and up-to-date HE SNRcat, which complements Dave Green's catalogue in radio*)
- Out of these, <~100 contain plerions or candidates, about 30 of which **lack shells** (including Crab): "naked PWNe"
- Out of these, 57 are powered by known pulsars
- Out of the 70 Galactic TeV known sources, ~half are identified as PWNe or PWN candidates

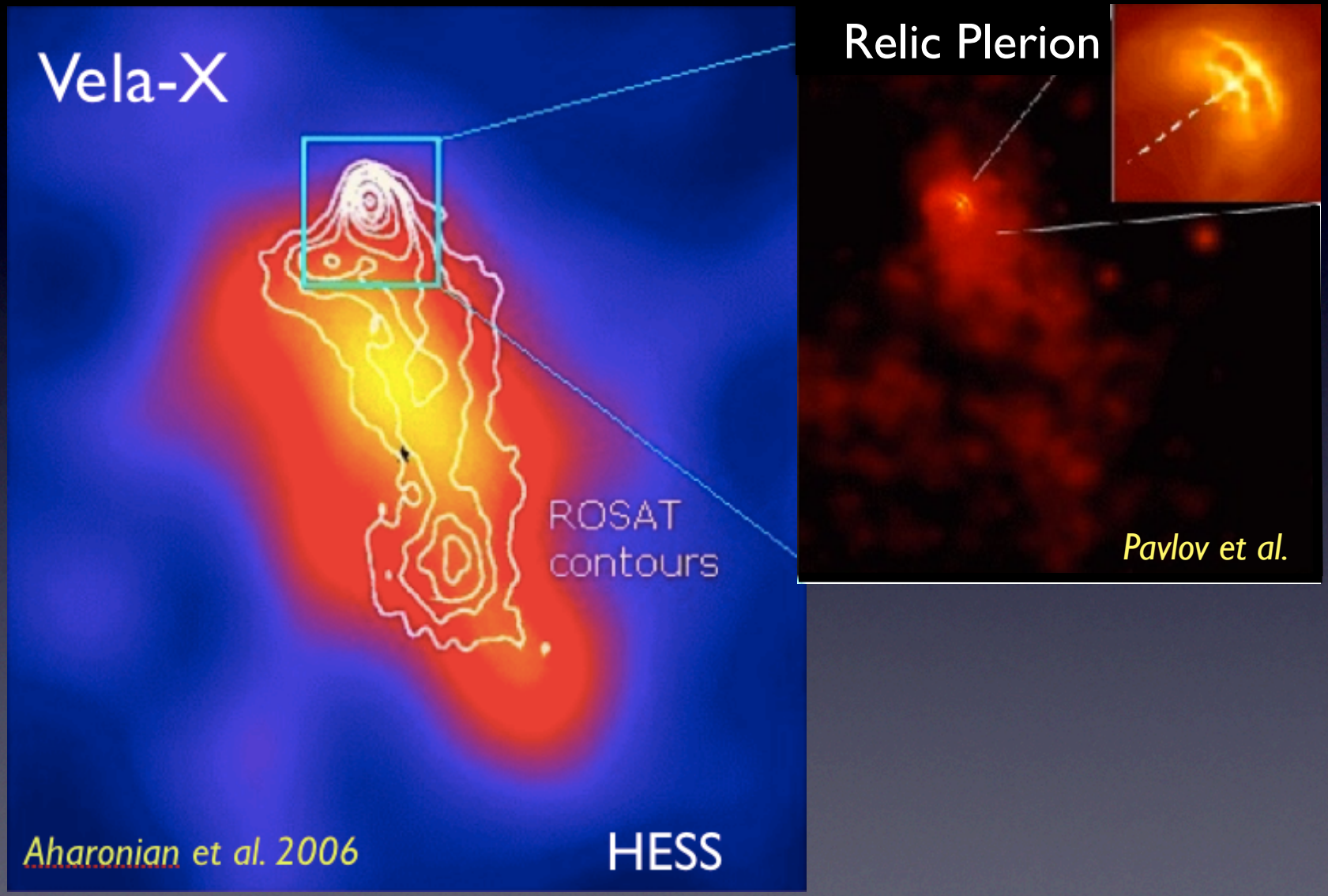
✓ TeV emission: "Offset" from R or X

✓ evolved ('relic') PWNe, e.g. Vela-X

✓ low-B field

NEW!

A New High-Energy (X+g) SNRs catalogue:
http://www.physics.umanitoba.ca/snr/SNRcat
Ferrand & Safi-Harb 2012, AdvSpRes
currently being updated with PWN data
(a dedicated, up-to-date, PWN catalogue)

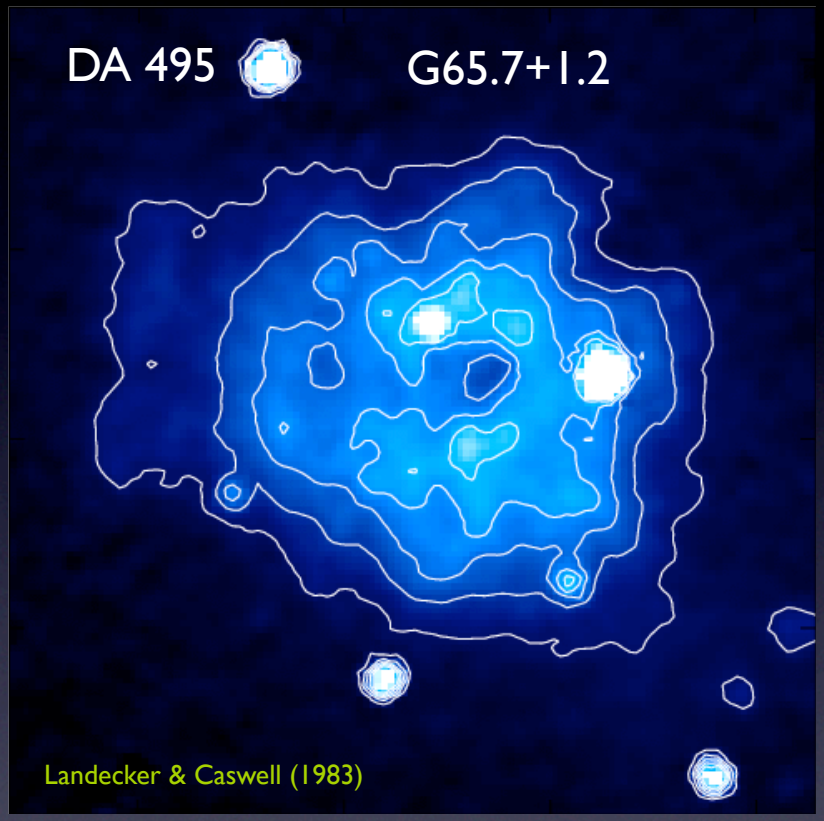

Vela-X
ROSAT
contours
Aharonian et al. 2006
HESS
Relic Plerion
Pavlov et al.

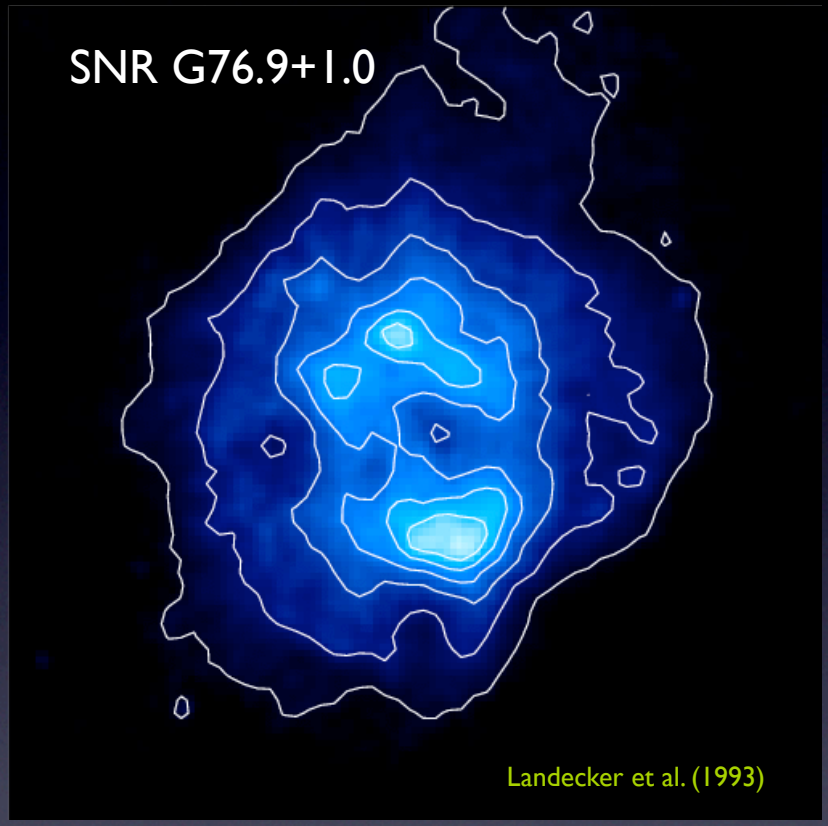
"Atypical" Plerions

- DA495 & G76.9+1.0
- CTB87 (& G63.7+1.1)
- PWNe associated with high-B pulsars/ magnetars? "Magnetar Wind Nebulae"

Studies focused on new X-ray observations (driven by radio studies)

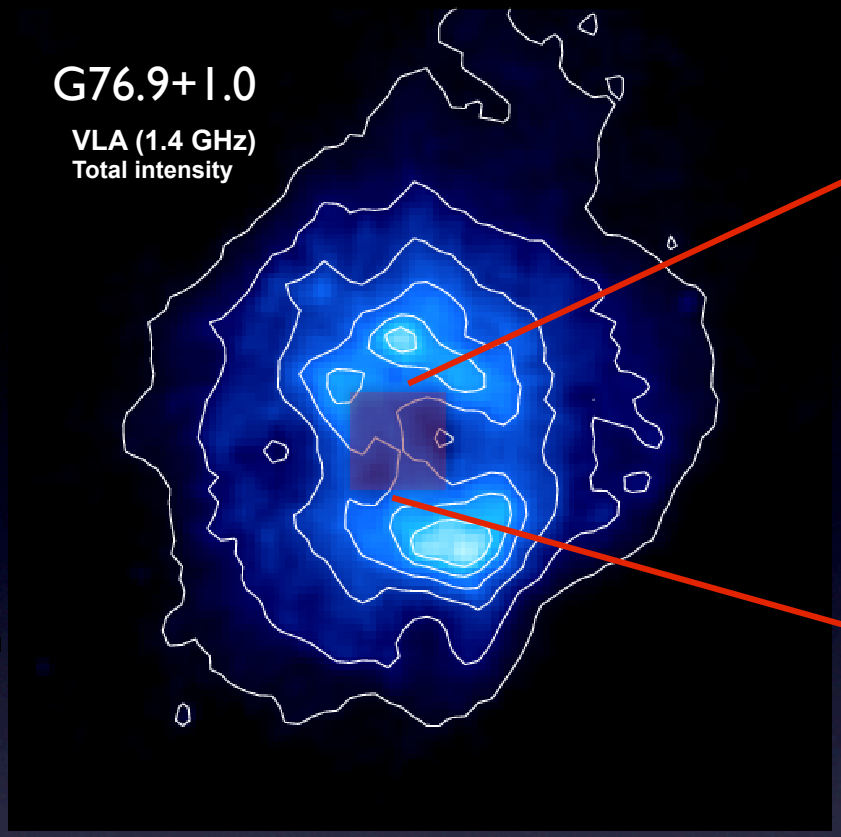
Two unusual Radio Nebulae

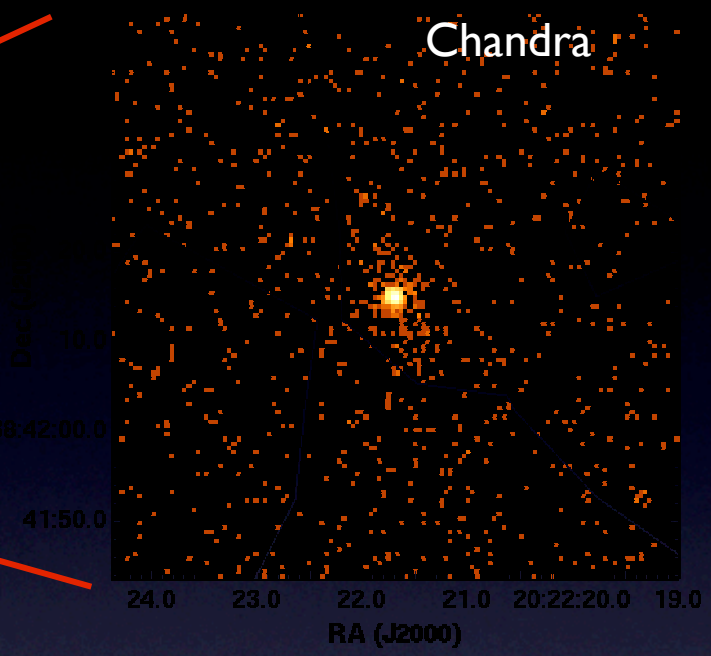




- Roughly annular morphologies with inner/outer radii of ~ 1'/10'
- Unlike shell-type SNRs, not limb-brightened
  ✓ their non-thermal flux falls off away from centre, implying a central engine (pulsar)
- Radio spectrum too steep for a plerion, $\alpha \approx 0.6$, more typical of shells
- Low-frequency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

G76.9+1.0

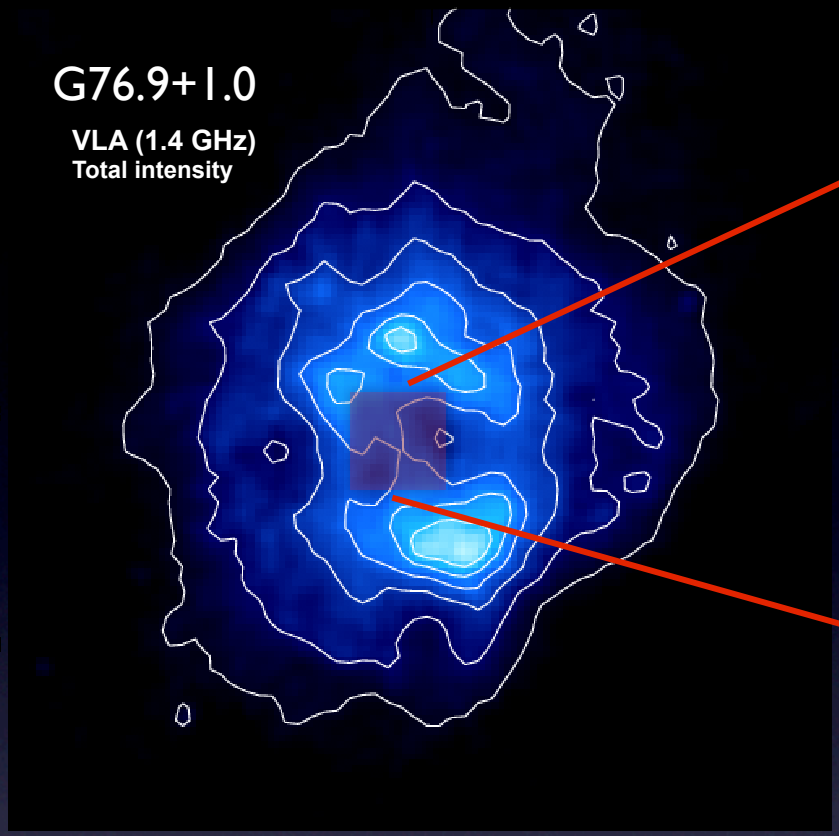


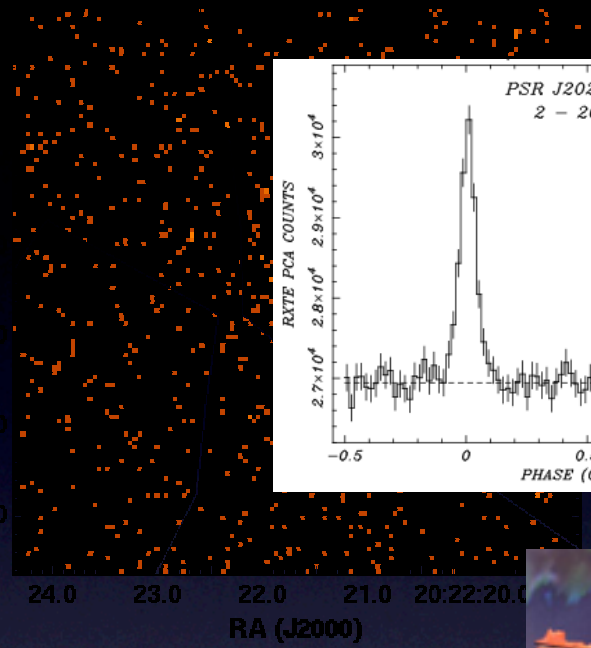


Chandra
pinpoints a "pulsar" candidate

Arzoumanian, Gotthelf, Ransom, SSH, Landecker & Kothes 2011, ApJ

G76.9+1.0



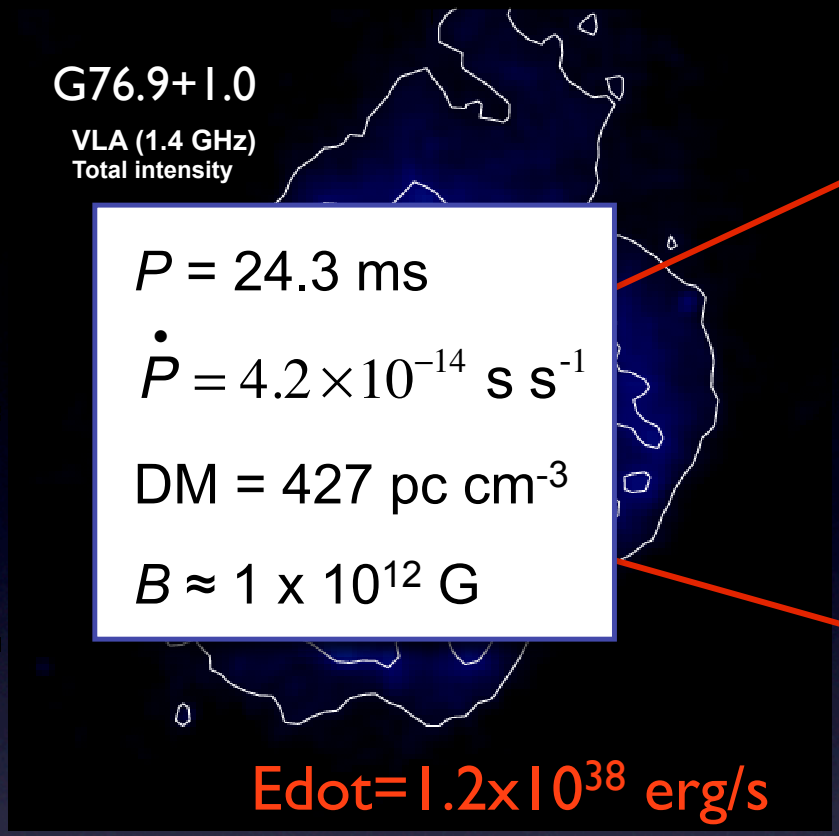


Radio and X-ray pulsar searches lead to the discovery of a very energetic pulsar!

The 2nd most energetic after the Crab pulsar and the fastest known pulsar in our Galaxy!!

Arzoumanian, Gotthelf, Ransom, SSH, Landecker & Kothes 2011, ApJ

G76.9+1.0



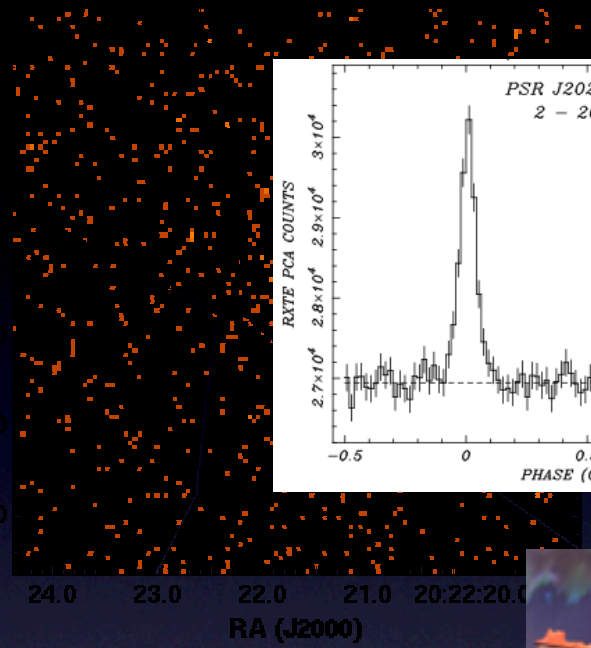
P = 24.3 ms

$\dot{P} = 4.2 \times 10^{-14}$ s s^{-1}

DM = 427 pc cm^{-3}

$B \approx 1 \times 10^{12}$ G

Edot=1.2x10^{38} erg/s

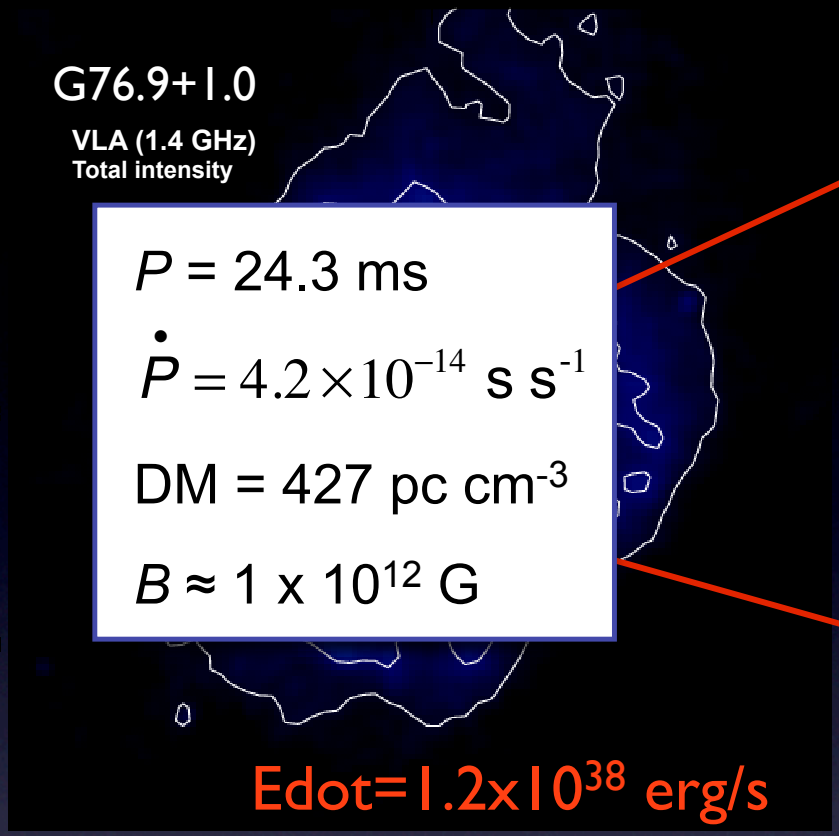


Radio and X-ray pulsar searches lead to the discovery of a very energetic pulsar!

The 2nd most energetic after the Crab pulsar and the fastest known pulsar in our Galaxy!!

Arzoumanian, Gotthelf, Ransom, SSH, Landecker & Kothes 2011, ApJ

G76.9+1.0



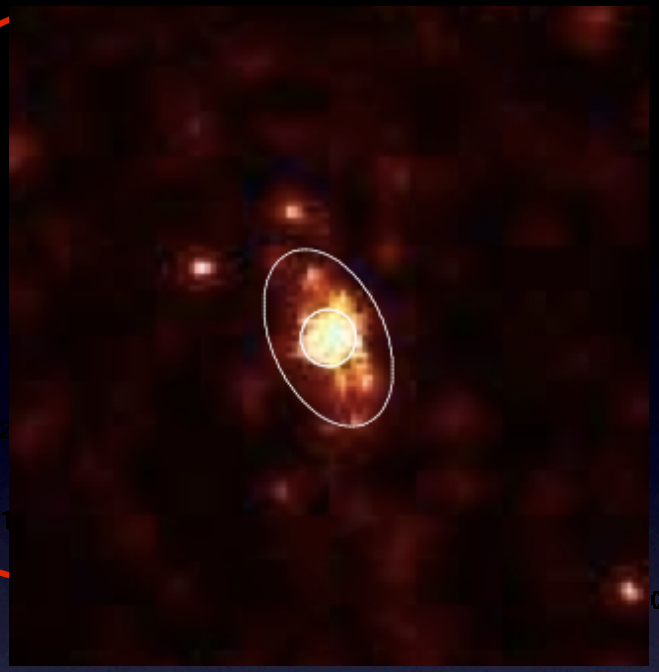
P = 24.3 ms

$\dot{P} = 4.2 \times 10^{-14}$ s s^{-1}

DM = 427 pc cm^{-3}

$B \approx 1 \times 10^{12}$ G

Edot=1.2x10^{38} erg/s



Chandra
pinpoints a "pulsar" candidate

Spectral fits (Chandra)		
Component	Nebula	PSRJ2022
Model	Power Law	Power Law
Γ	1.4	**1.0 ± 0.2**
n_H (10^{22} cm^{-2})	$(1.6 \pm 0.3) \times 10^{22}$ cm^{-2}	
Flux (abs 2–10 keV; ergs cm^{-2} s^{-1})	4×10^{-14}	5.3×10^{-13}
Lx (2-10 keV)	5.6x10^{32}	7x10^{33}

- Unusually hard X-ray spectrum
- Unusually low Lx/Edot
- PWN appears "old"
  but PSR appears "young"

Arzoumanian, Gotthelf, Ransom, SSH, Landecker & Kothes 2011, ApJ

G76.9+1.0: Vela-like

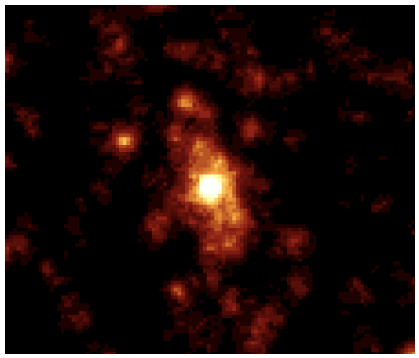
G76.9+1.0

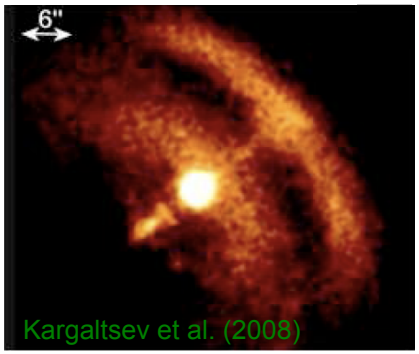
Age = 9 kyr

$\dot{E} = 1.1 \times 10^{38}$ ergs/s

$d \approx 7$ kpc

$R_{PWN} \sim 8 \times 10^{17}$ cm





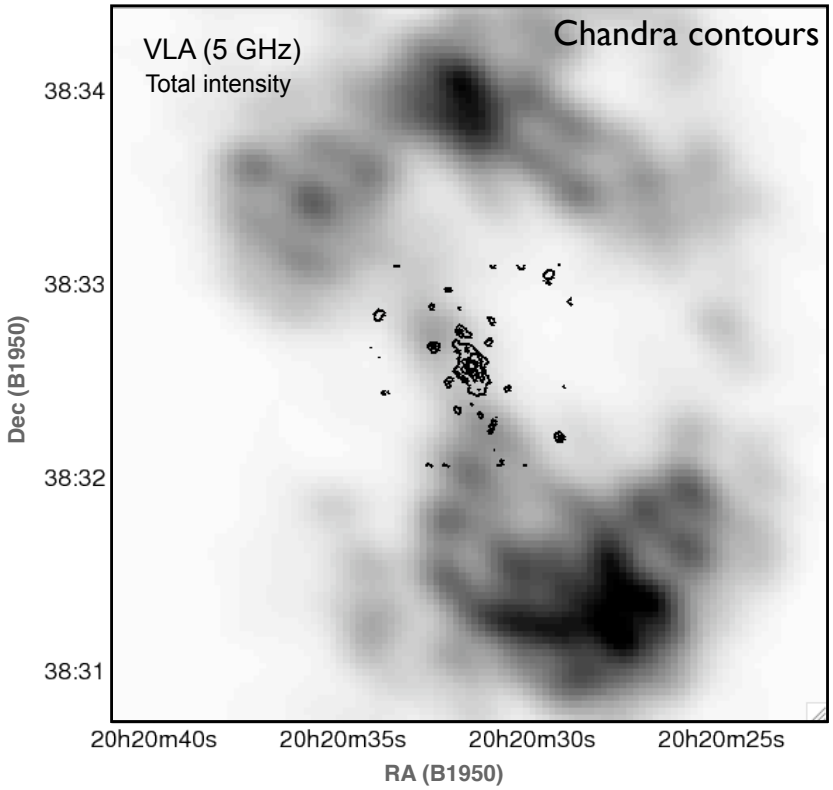
Vela

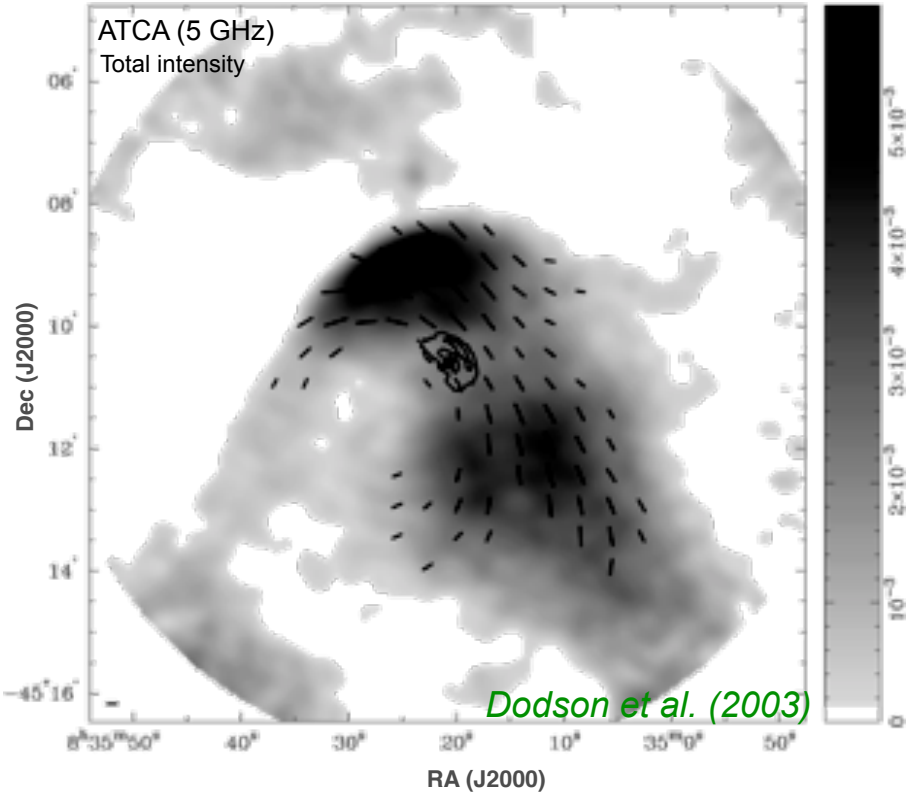
Age = 11 kyr

$\dot{E} = 6.9 \times 10^{36}$ ergs/s

d = 290 pc

$R_{PWN} \sim 1.6 \times 10^{17}$ cm

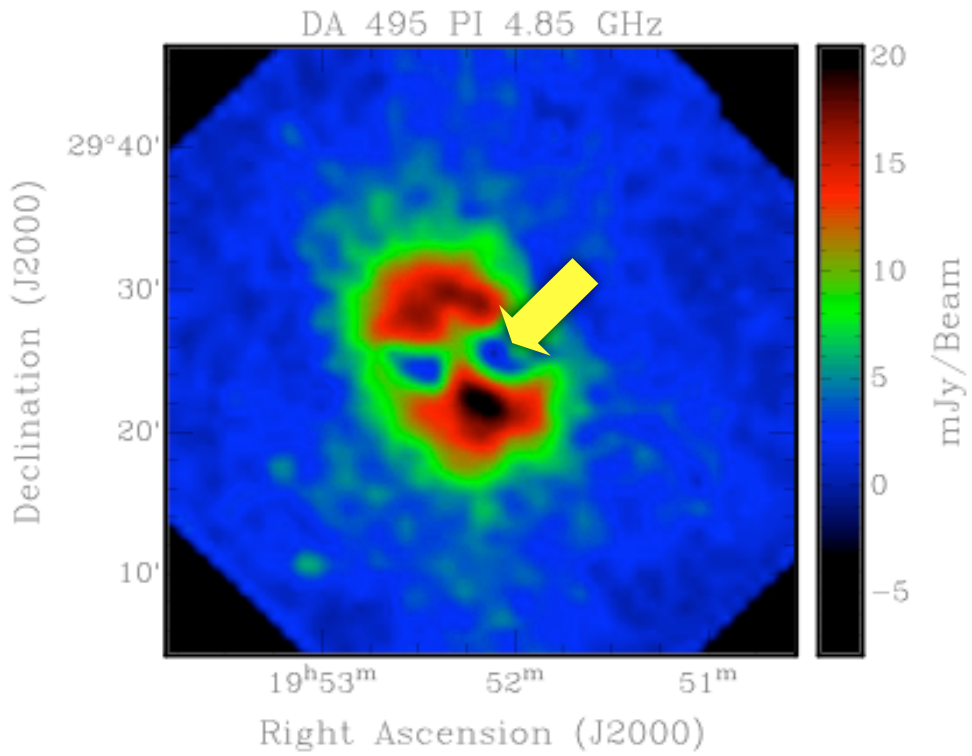




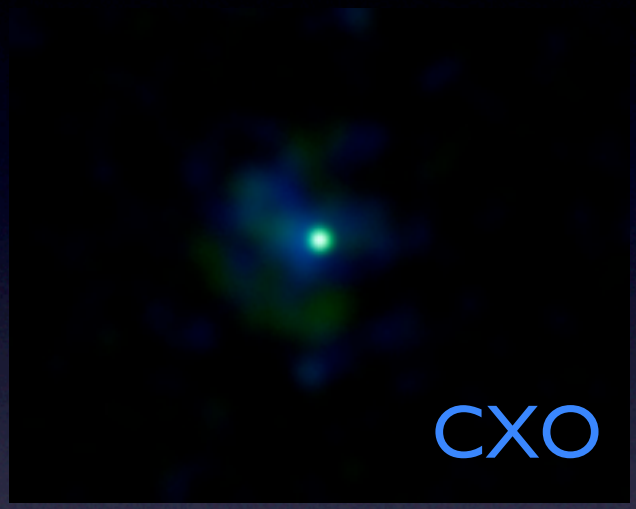
(see also *Chevalier and Reynolds arXiv:1109.1752v1*)

Arzoumanian et al.

DA495: G65.7+1.2



Highly polarized radio "lobes"



Red: 0.5-1.5 keV
Green: 1.5-2.5 keV
Blue: 2.5-7 keV

A point source and a PWN inside the radio "hole"

Arzoumanian, SSH, et al. 2004 & 2008

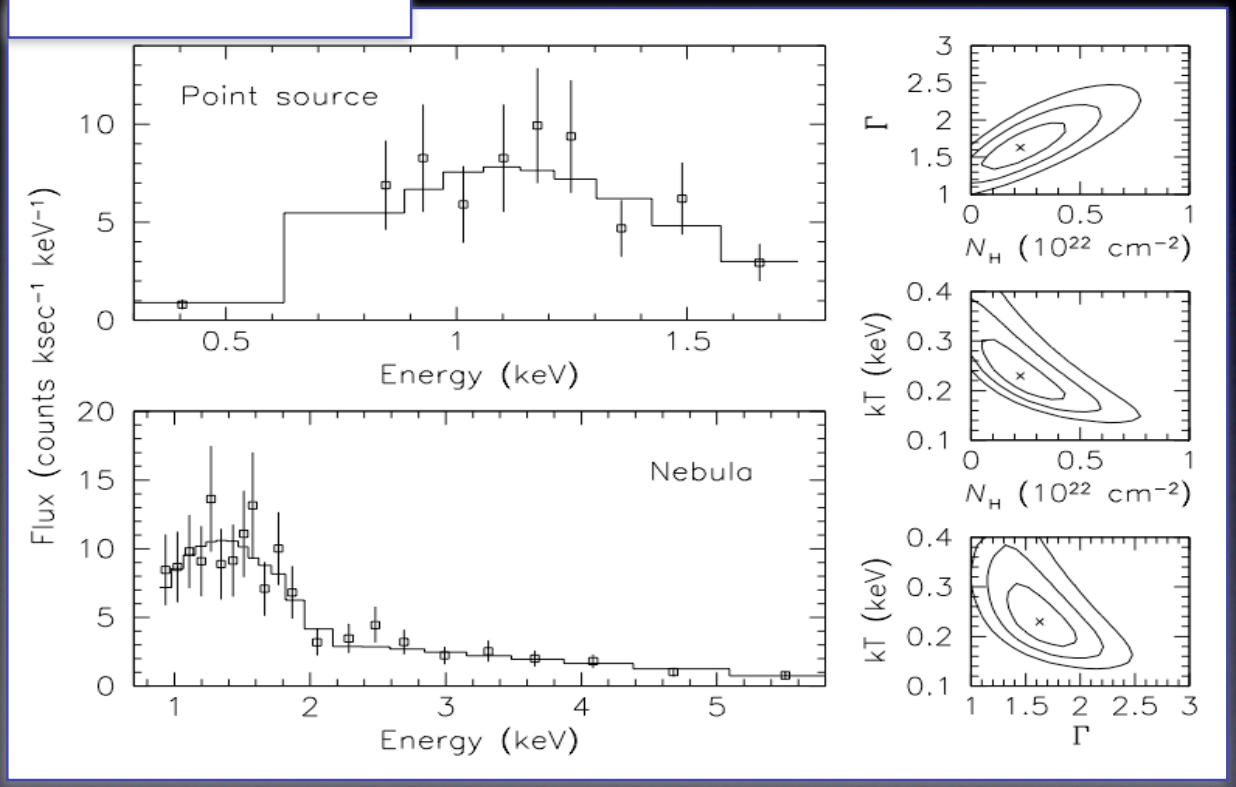
DA 495's plerion

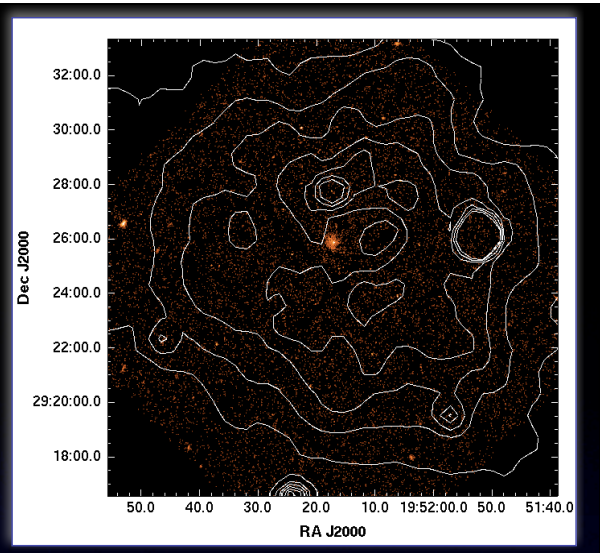
$D \approx 1$ kpc

Age ≈ 20 kyr

R_{PWN} ≈ 6.4×10^{18} cm
radio

R_{PWN} ≈ 2.4×10^{17} cm
X-ray





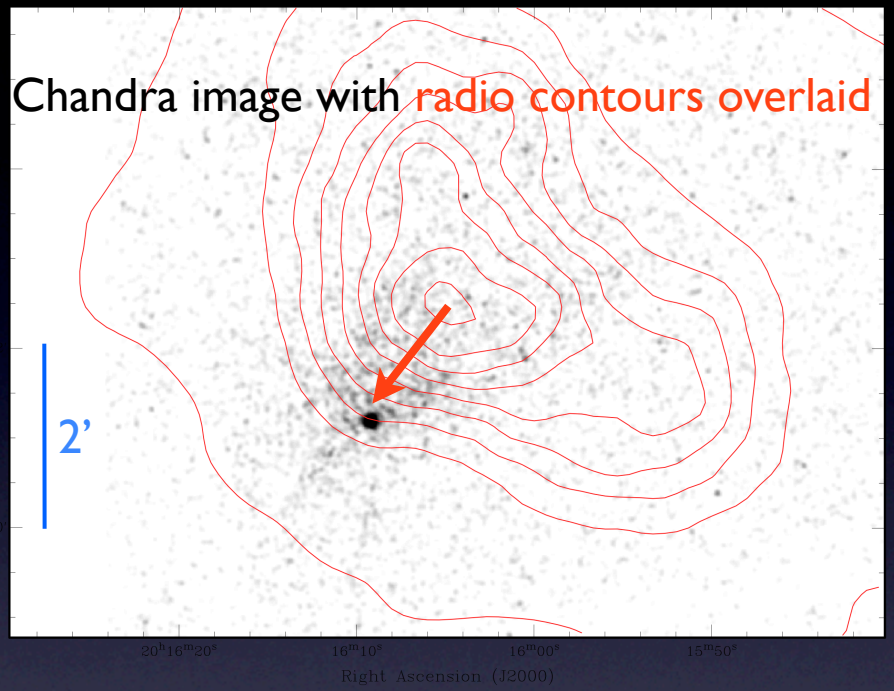
Spectral fits (Chandra)		
Component	**Nebula**	**Pt srce**
Model	Power Law	Blackbody
Γ / kT_{eff} (MK)	1.6	2.5
n_H (10^{22} cm^{-2})	< 0.4	
Flux (unabs 0.5–10 keV; ergs cm^{-2} s^{-1})	1.7×10^{-13}	8×10^{-14}
Lx (0.5-10 keV)	**3.3×10^{31}**	**~10^{31}**

- Spectral and energetic modelling suggest **20 kyr** age and strong, ~1 mG, PWN field.
- Candidate for Pulsar Search. Implied spin-down luminosity: ~10^{35} ergs/s
- No pulsations in Arecibo and XMM-Newton searches.

Arzoumanian, SSH, et al. 2004 & 2008
Kothes, Landecker, Reich, SSH, Arzoumanian 2008

CTB 87 (G74.9+1.2)

Chandra reveals an "offset" PWN

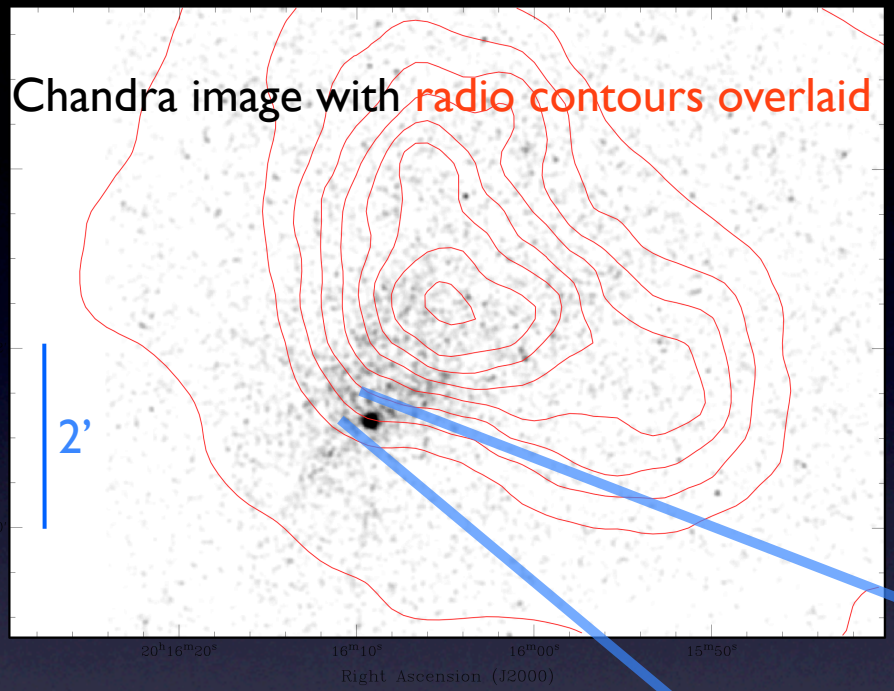


- Plerion (radio)
- 8'x6' size in the radio (red contours)
- Low-frequency spectral break, no pulsar
- New sensitive radio studies:
  - ✓ a larger size of ~16': a linear size of ~28 pc (at 6.1 kpc) and indicating a highly evolved SNR
  - ✓ Unusually steep spectral index, $\alpha \approx 0.48$ (for the central cpt)

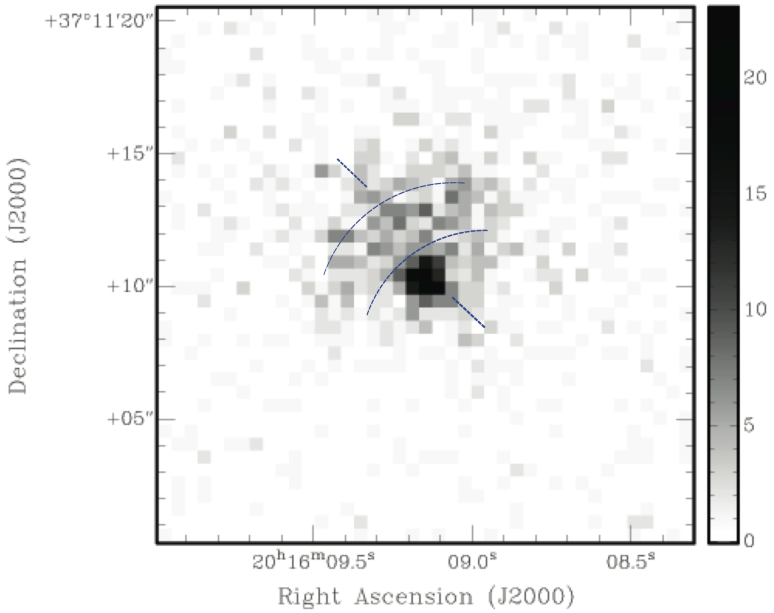
SSH et al. 2011; Matheson, SSH & Kothes 2012 (in prep); Kothes, SSH et al. (in prep)

CTB 87 (G74.9+1.2)

Chandra reveals an "offset" PWN



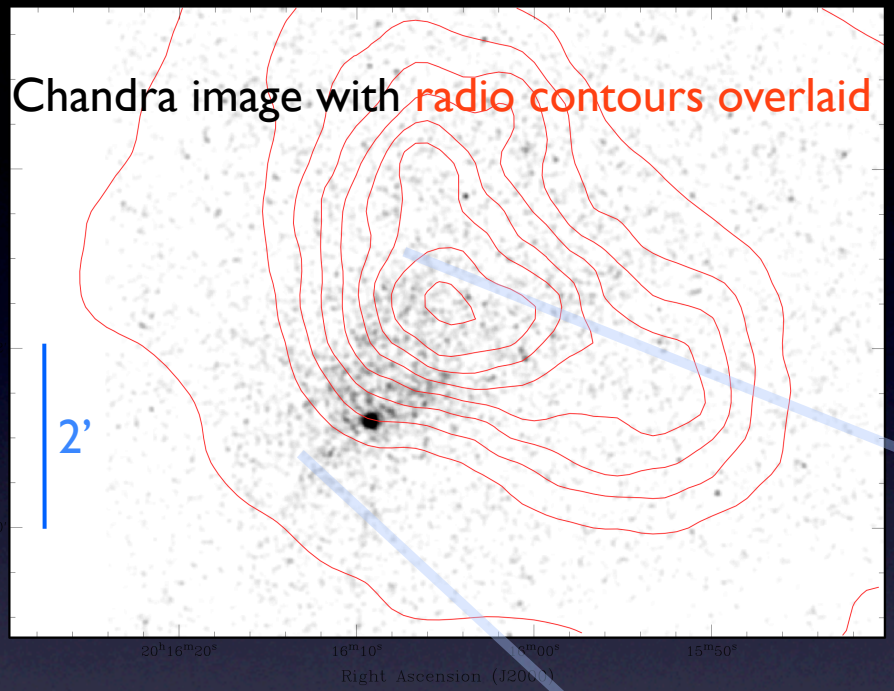
Compact Nebula resolved

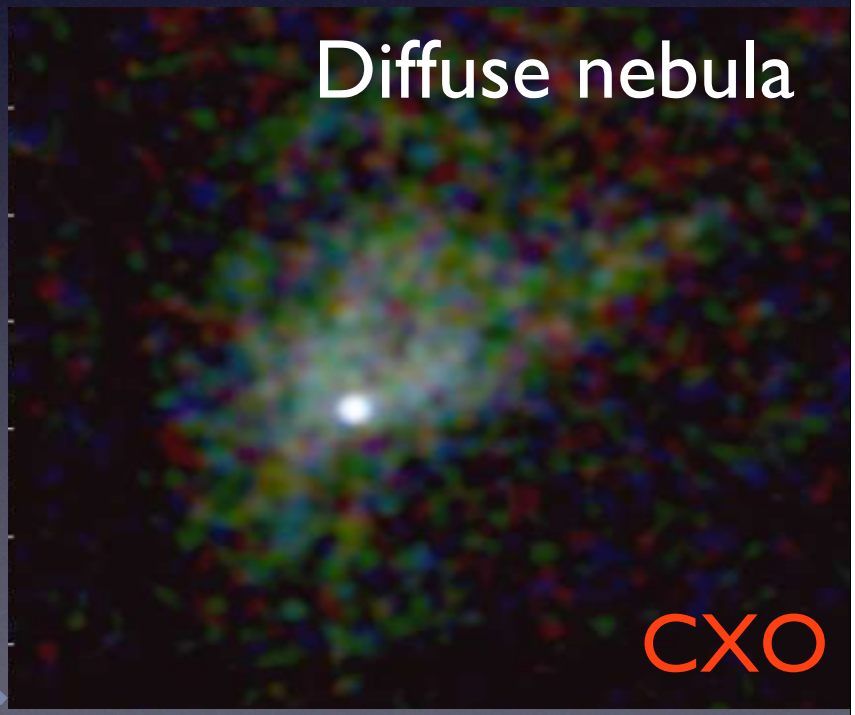


SSH et al. 2011, Matheson, SSH & Kothes 2012 (in prep)

CTB 87 (G74.9+1.2)

Chandra reveals an "offset" PWN



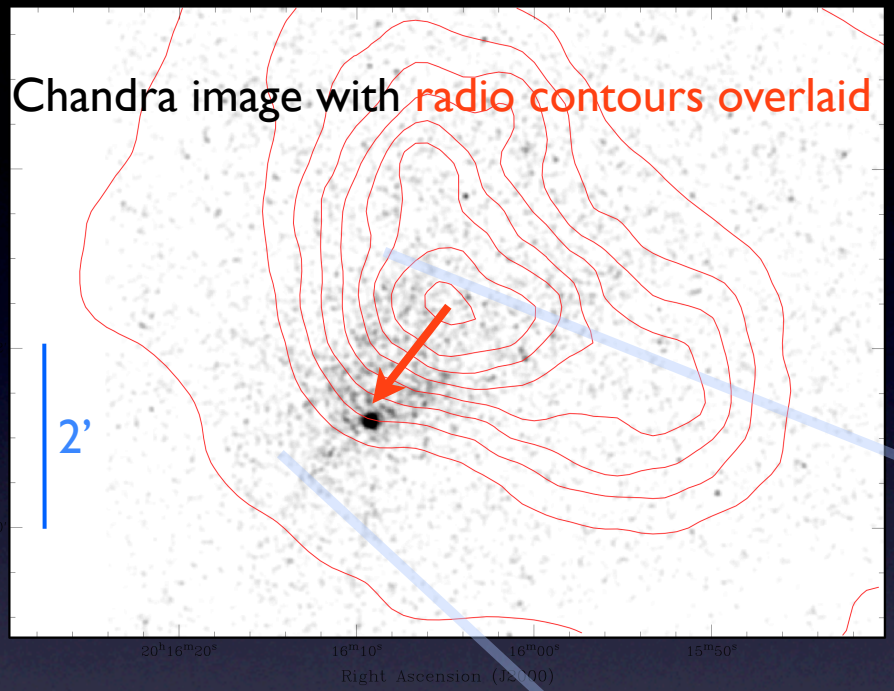


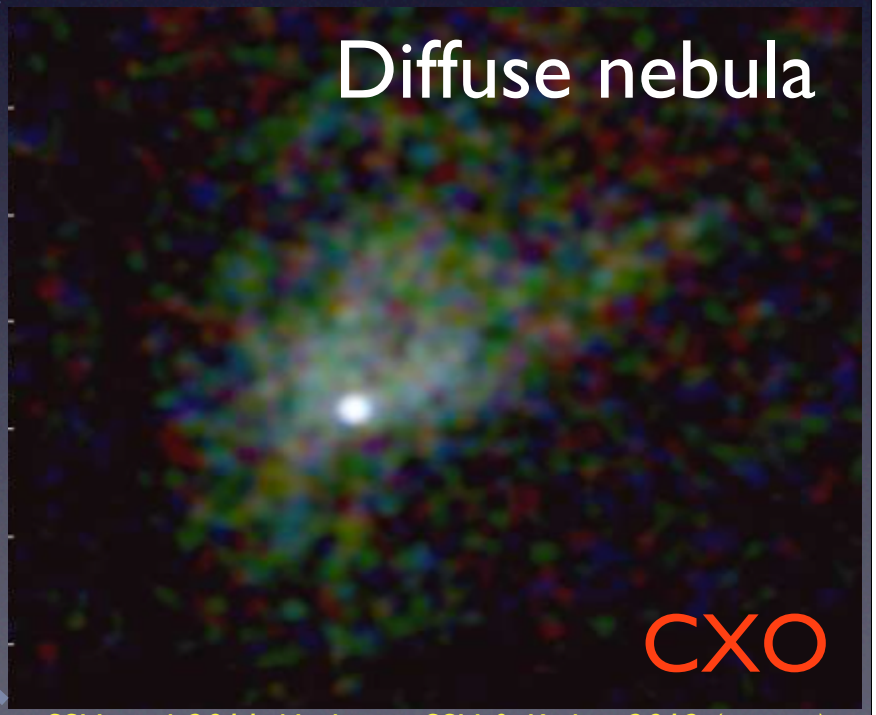
- X-ray spectrum is non-thermal (PWN):
  - ✓ N_H=1.38 (1.21-1.57)x10^{22} cm^{-2}
  - ✓ Photon index = 1.7 (1.5-1.8)
  - ✓ steepens away from point source
- L_x~3x10^{32} erg/s, (pt source)
- L_x~1.5x10^{34} erg/s (nebula)

SSH et al. 2011, Matheson, SSH & Kothes 2012 (in prep)

CTB 87 (G74.9+1.2)

Chandra reveals an "offset" PWN





•Nebula: cometary morphology

✓ Bow shock: neutron star (candidate) moving to the south-east?

Offset of ~2' requires a speed of ~175 (km/s)/τ_{20}

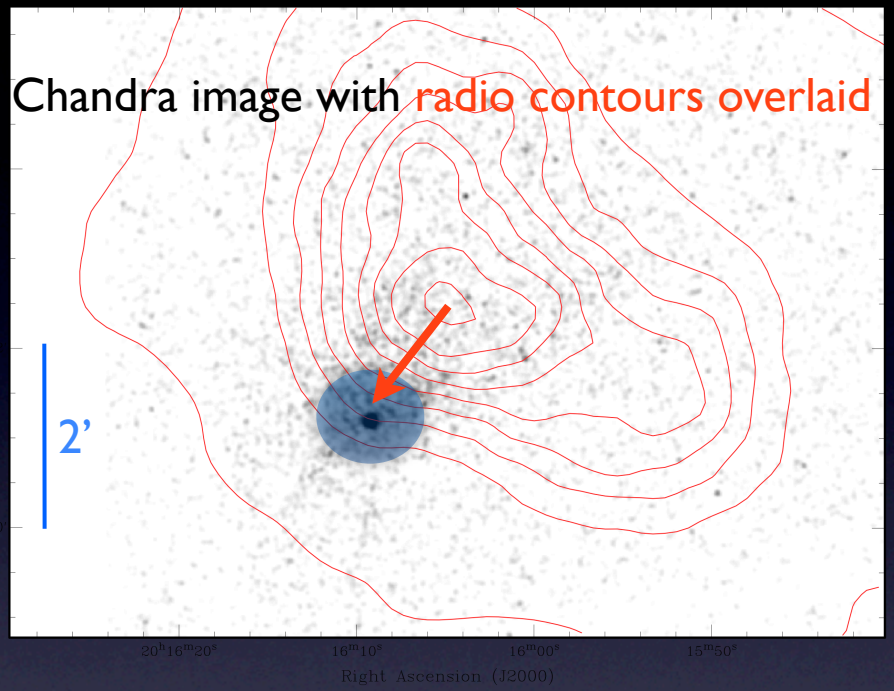
✓Crushed and evolved plerion?

as in Vela-X, G327.1-1.1..

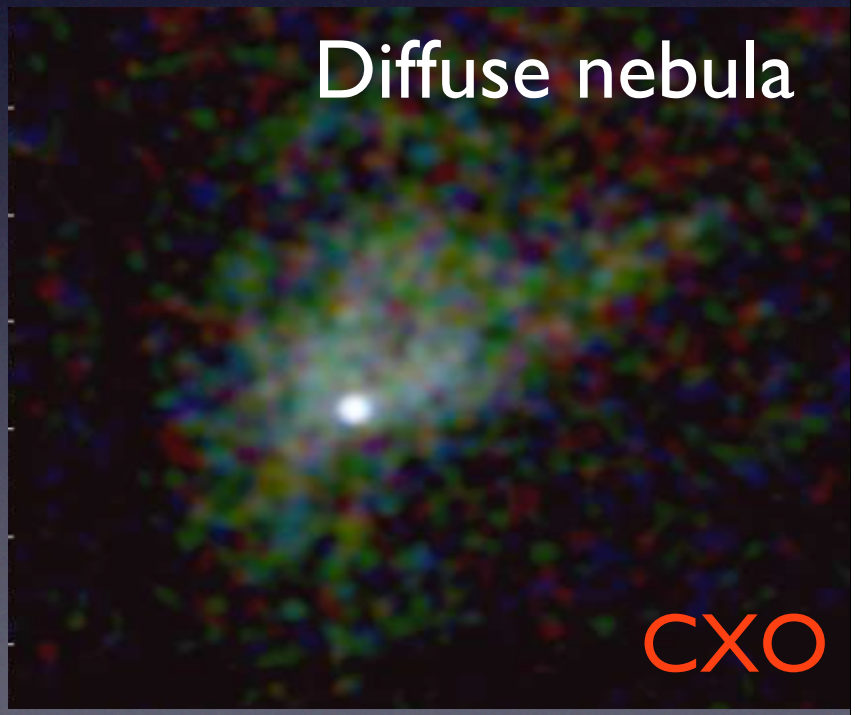
SSH et al. 2011; Matheson, SSH & Kothes 2012 (in prep)

CTB 87 (G74.9+1.2)

Chandra reveals an "offset" PWN



Pt source candidate for pulsar search



SSH et al. 2011, Matheson, SSH & Kothes 2012 (in prep)

- So far no evidence for thermal X-ray emission
- Gamma-ray and deep X-ray observations needed to confirm the evolved PWN scenario

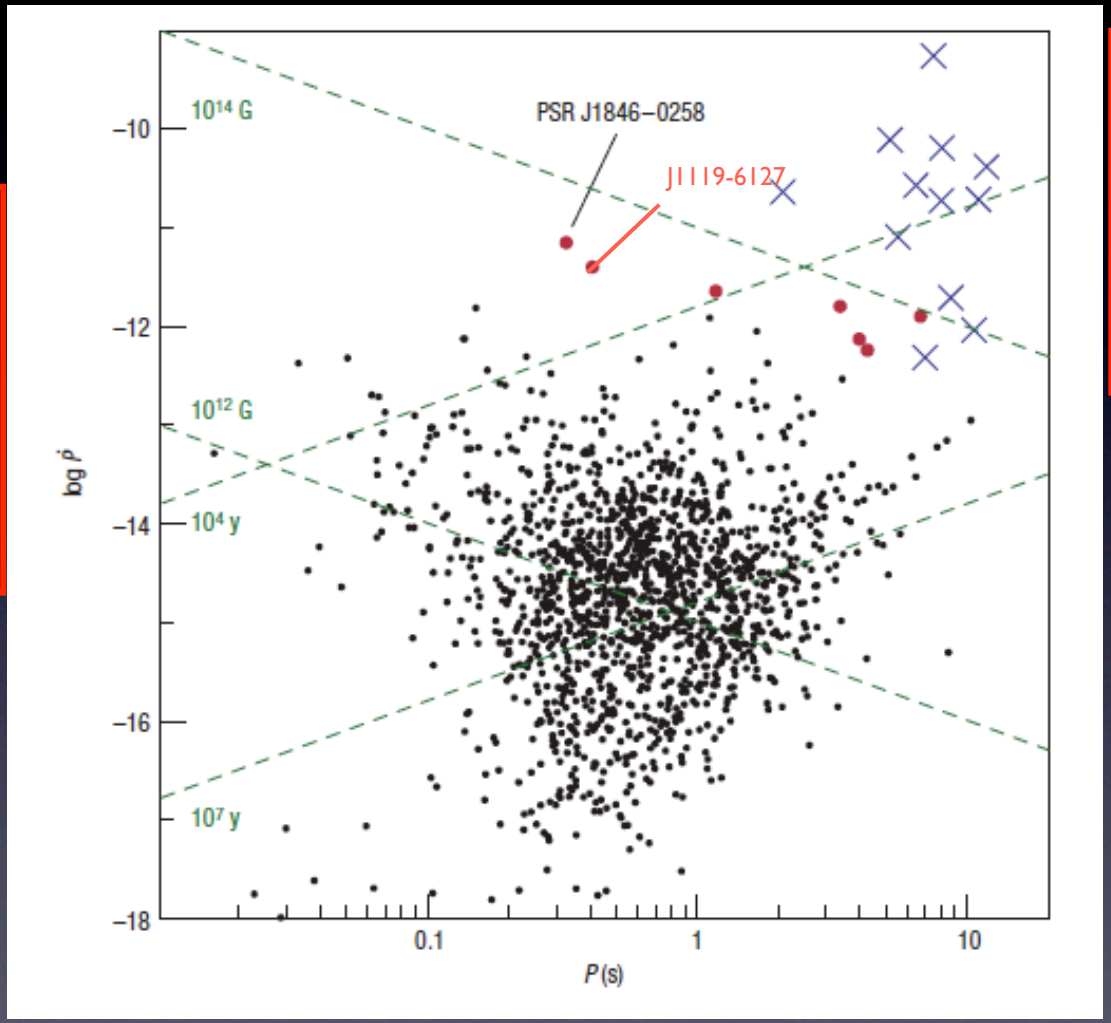
Note: *CTB87 has been suggested to be associated with an EGRET source, detected with Fermi but probably unrelated (Fermi second source catalogue), MILAGRO (unresolved) and more recently with VERITAS (Aliu et al. 2011)*

High-B Pulsars (HBPs) in SNRs

$\sim 10^{13} < B\ (\text{Gauss}) < \sim 10^{14}$

PSR J1846-0258
Crab-like pulsar
P = 0.3 s
$B = 5 \times 10^{13}$ G
($>B_{QED}$)

Edot=8.3e36 erg/s
Age~725 years



PSR J1119-6127

P=408 ms

B=4.1e13 Gauss~B_{QED}

Edot=2.3e36 erg/s

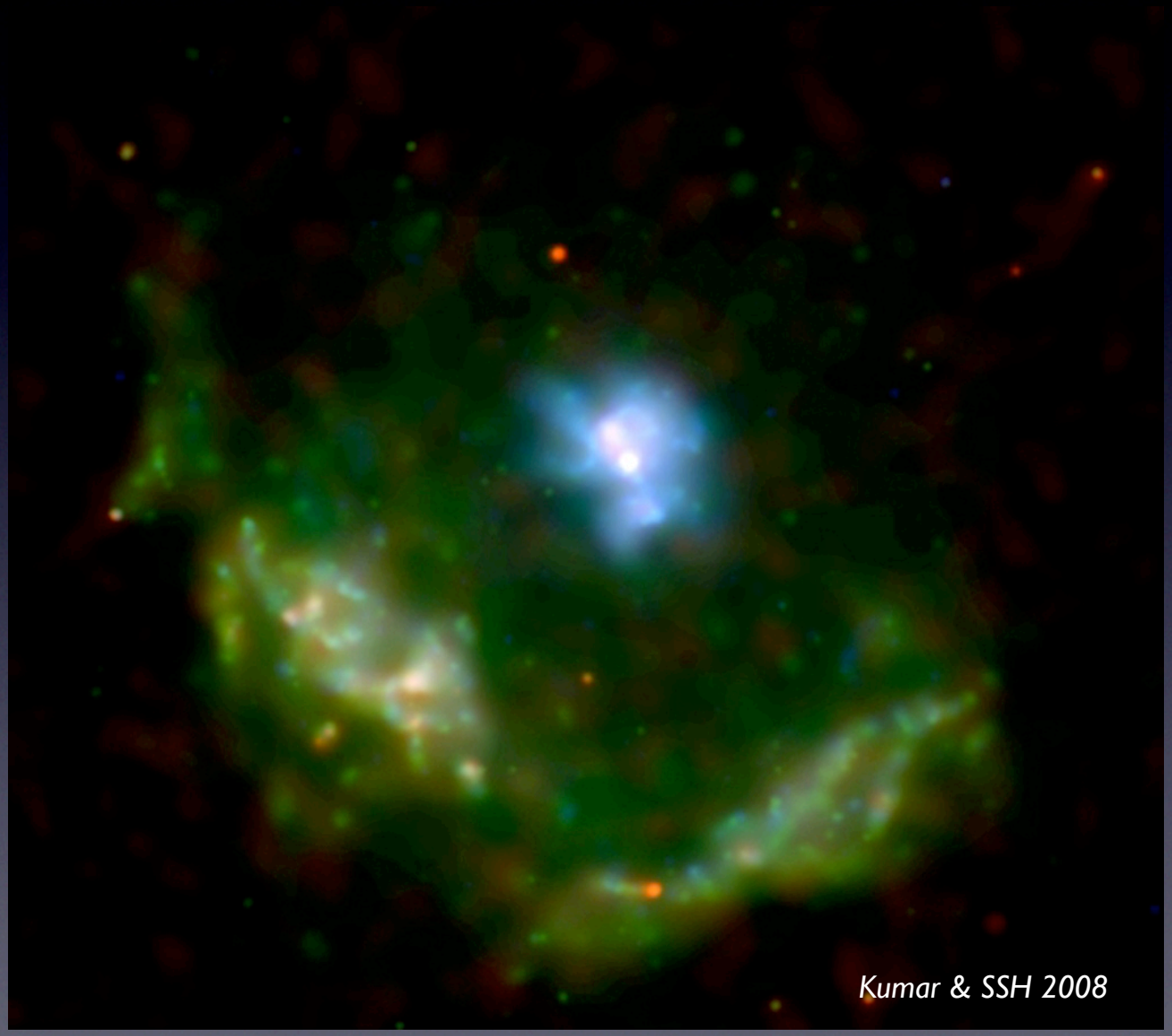
Age ~ 1,600 yrs

Are HBPs connected to magnetars? ($B \sim 10^{14\text{-}15}$ G)?

Do HBPs power nebulae?

J1846-0258 in SNR Kes75

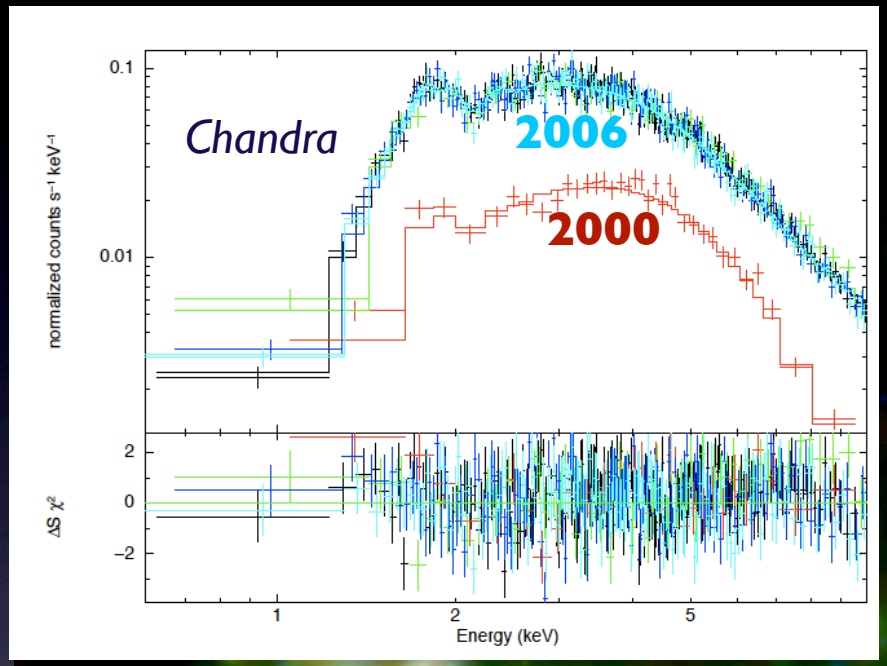
powered by both rotation and magnetism



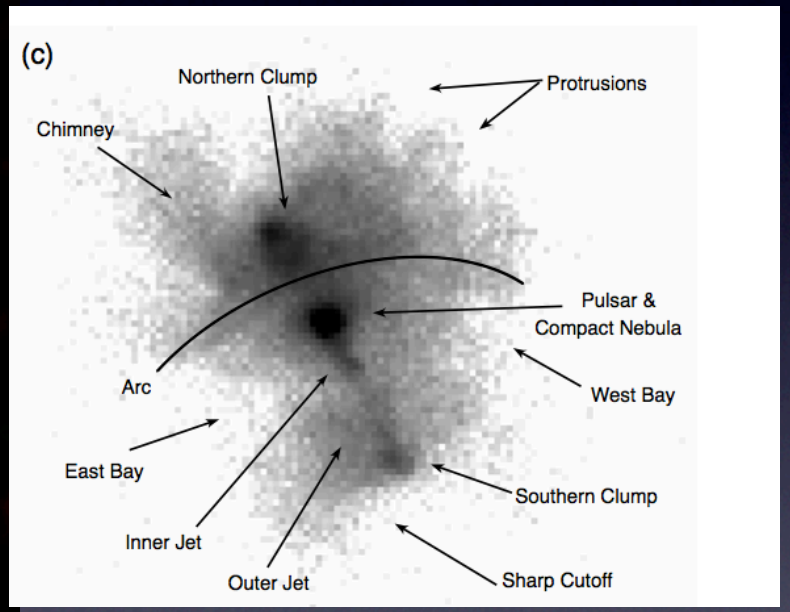
see F. Camilo, Nature Physics, 2008

J1846-0258 in SNR Kes75

powered by both rotation and magnetism



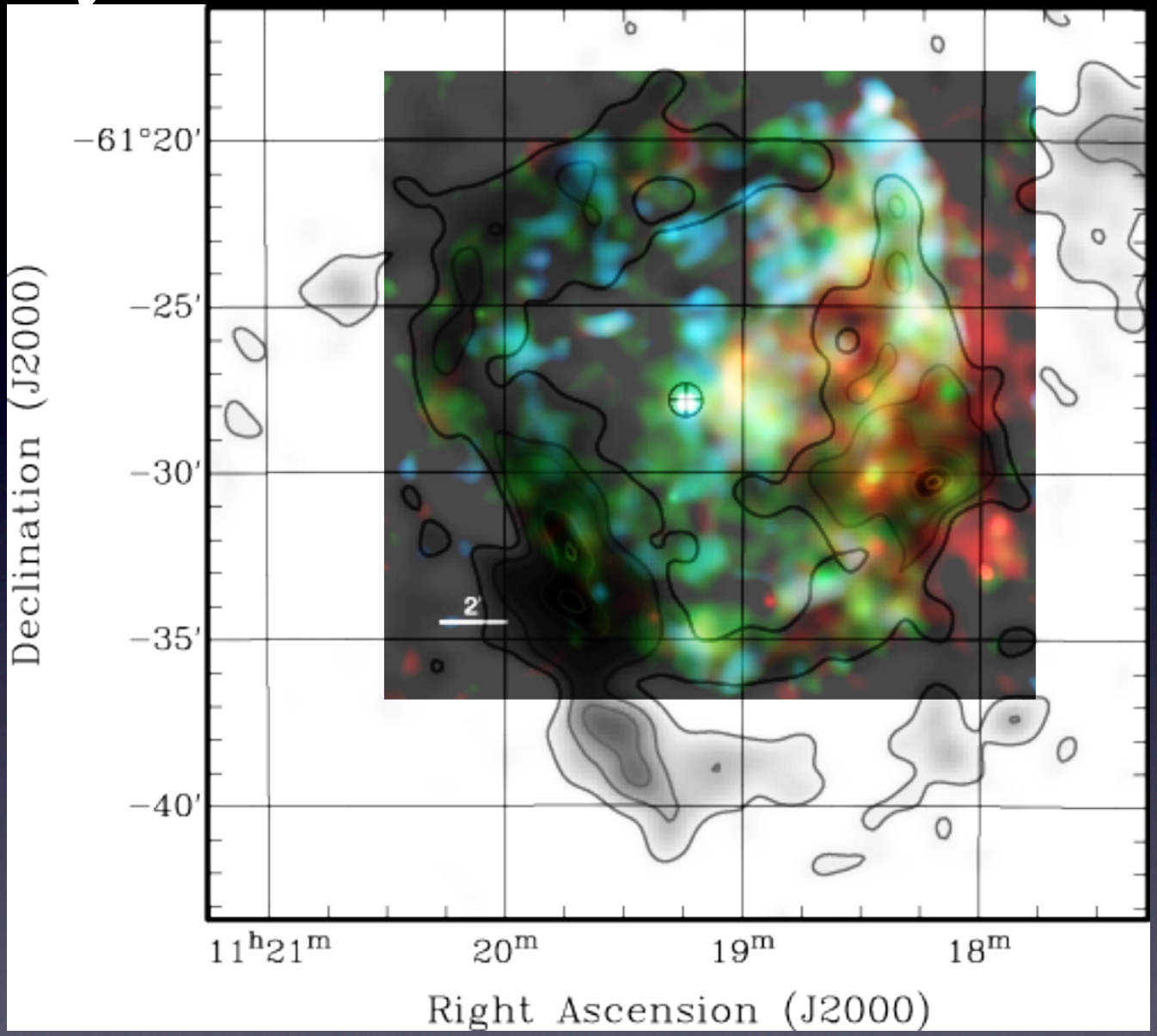
Kumar & SSH 2008



Crab-like pulsar showing a magnetar-like behaviour!

Variability in the PWN following magnetar-like bursting activity *(Kumar & SSH 2008; Gavriil et al. 2008; Ng et al. 2008)*

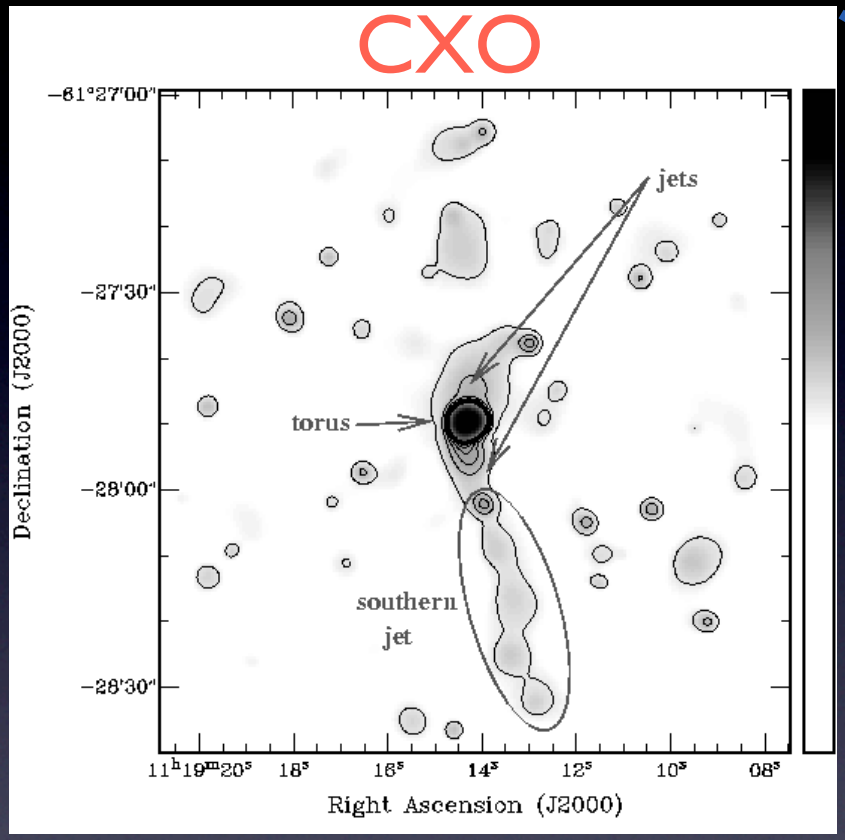
J1119-6127 in SNR G292.2-0.5

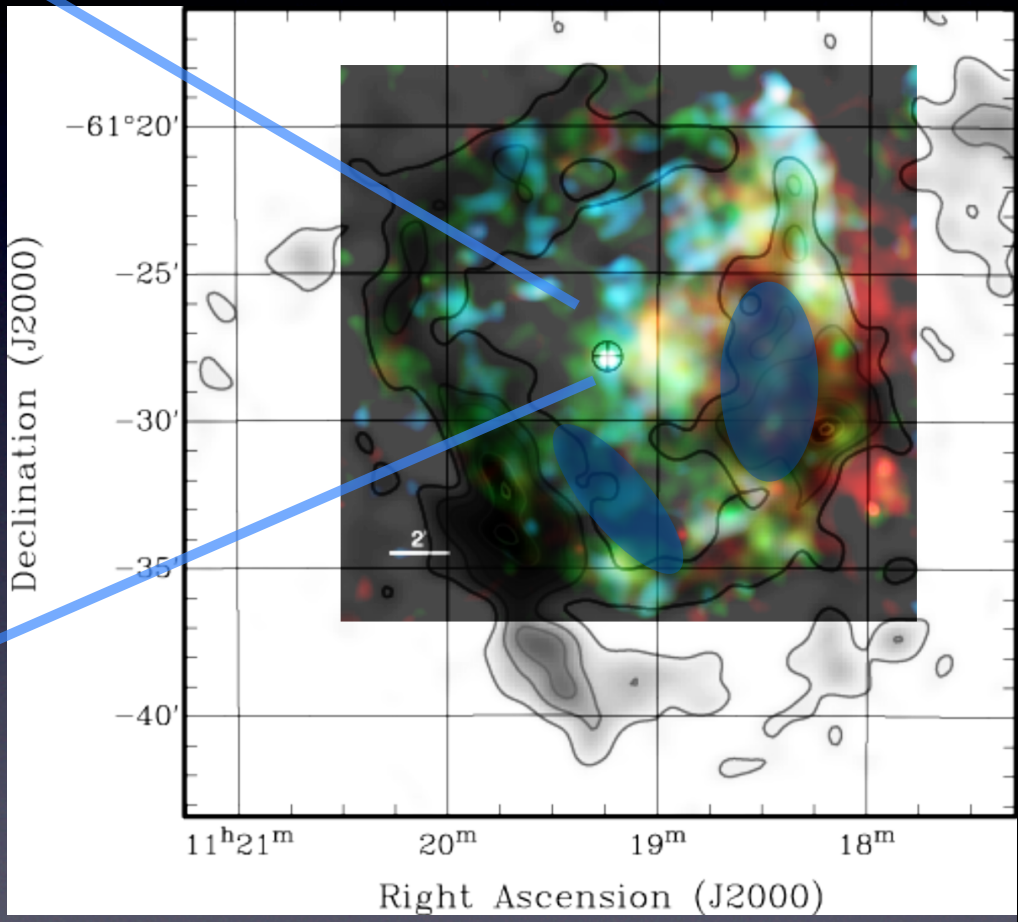


XMM-Newton Energy Image of SNR
radio contours overlaid

Kumar, SSH & Gonzalez 2012, ApJ (arXiv:1205.5766)

J1119-6127 in SNR G292.2-0.5





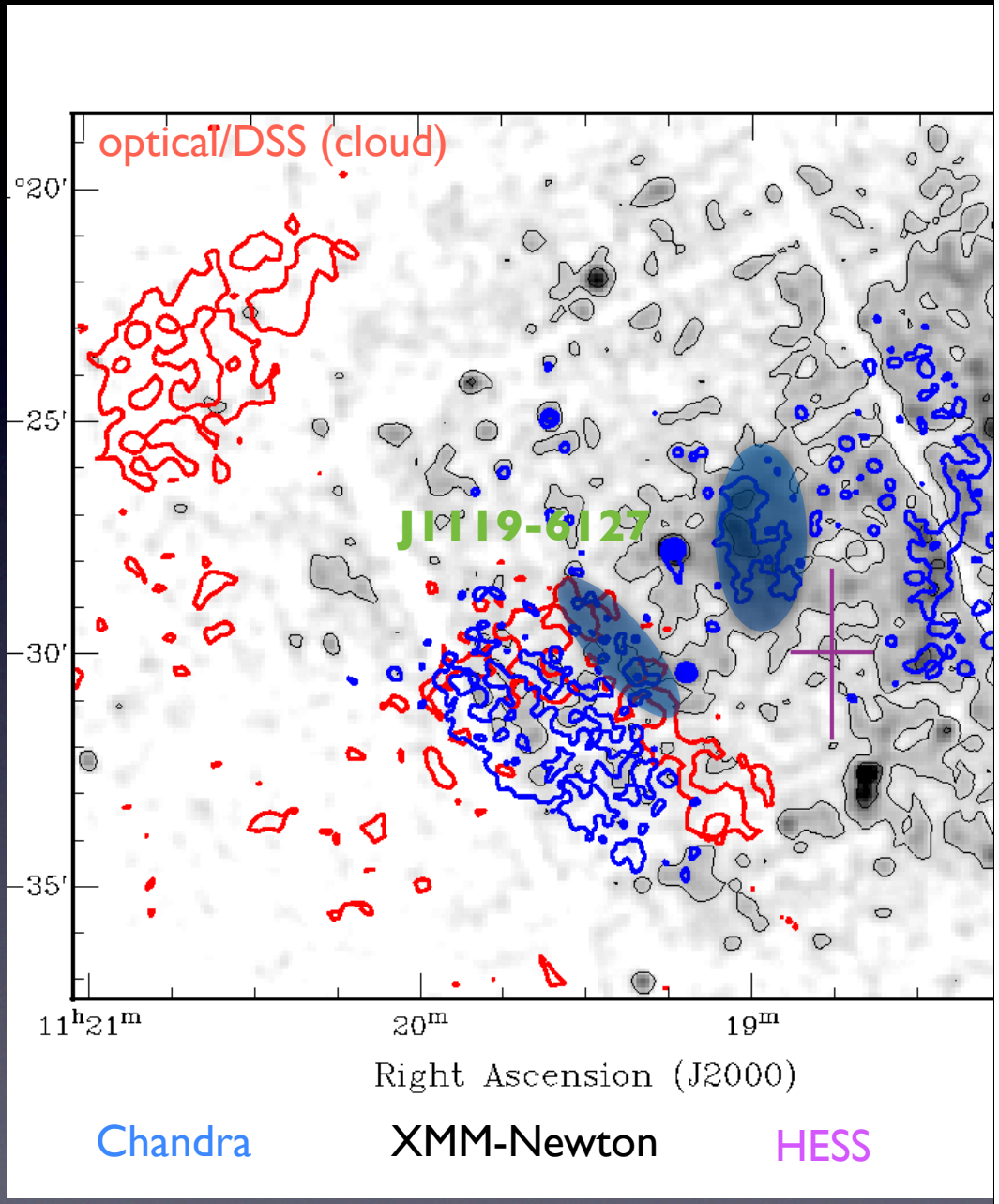
- X-ray counterpart to PSR J1119-6127 (*Gonzalez & SSH 2003*)
- Compact PWN
- Southern Jet
- Power law with a hard photon index
- Energetics can be explained by pulsar's Edot
- So far no evidence of magnetar-like activity

SSH & Kumar 2008

XMM-Newton Energy Image
radio contours overlaid
Kumar, SSH & Gonzalez 2012, ApJ

J1119-6127 in SNR G292.2-0.5

X-ray spectroscopy with Chandra and XMM-Newton:
First evidence for reverse-shock heated ejecta from the SNR

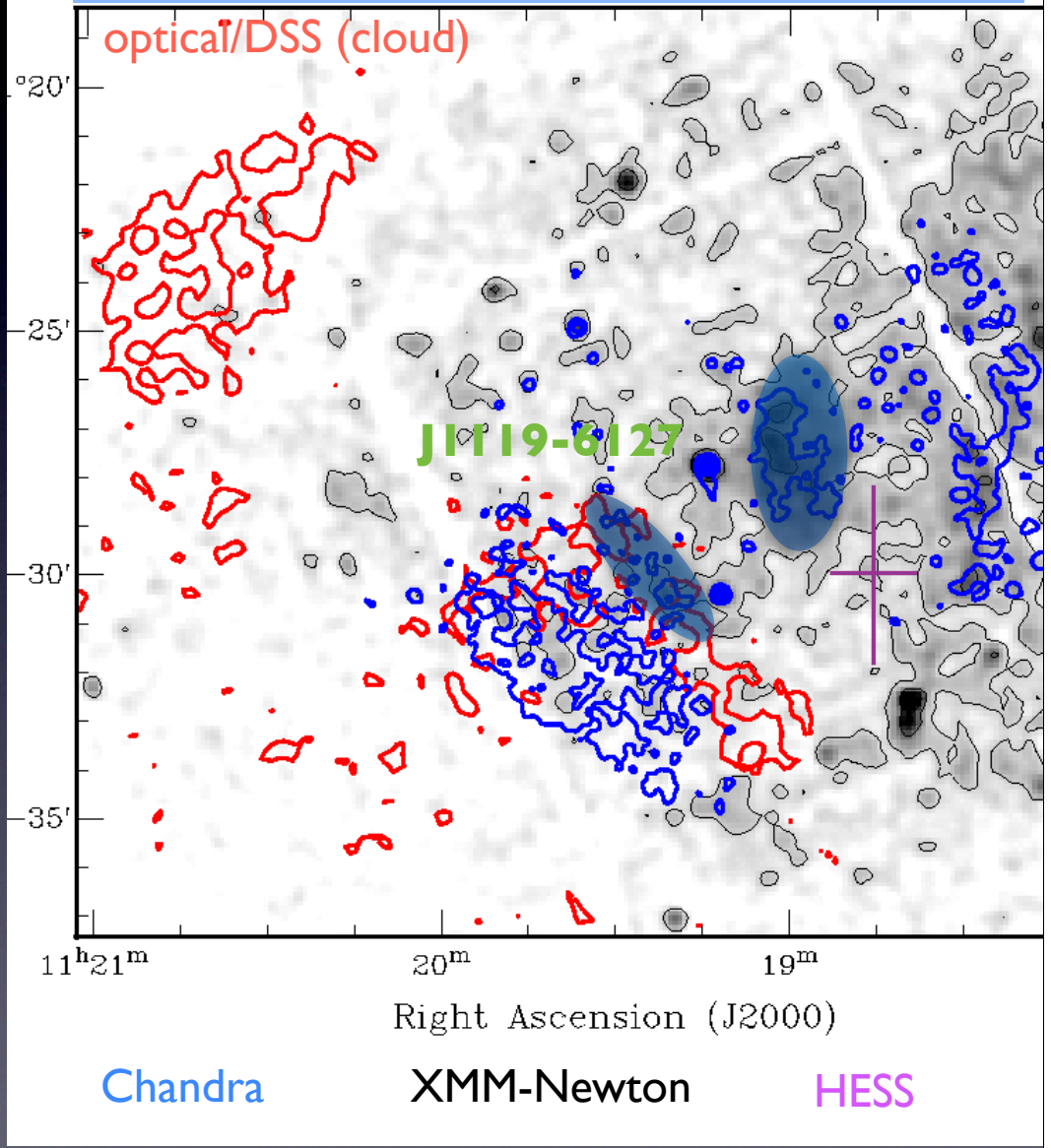


Kumar, SSH & Gonzalez 2012, ApJ

J1119-6127 in SNR G292.2-0.5

- SNR west:
  - hard X-ray emission dominates
  - soft X-rays absorbed by a cloud in the foreground or interacting with the SNR
- very hard X-ray emission east and west of pulsar (within the SNR, see ellipses)
- HESS Detection in the west (*Djannati-Atai et al. 2009*):
  - ✓SNR/ISM interaction (unlikely)
  - ✓PWN/reverse shock?
    supported by our X-ray study

X-ray spectroscopy with CXO and XMM:
First evidence for reverse-shocked ejecta from the SNR



Kumar, SSH & Gonzalez 2012, ApJ

Some Conclusions and questions

On the diversity of plerions (or non-Crab like):

✓ Evolved but with no direct evidence of interaction with Reverse shock or ISM (DA495 and G76.9), no shell

highly magnetized winds? high-B nebulae?
low-density environment? Progenitor?

✓ Evolved candidates with interaction with the RS (or ISM)? "offset" PWNe (e.g. CTB 87)

If so, why no thermal X-ray emission?

✓ Nebulae around High-B Pulsars/Magnetars (G292.2-0.5, Kes75), and magnetars, e.g. Swift J1834.9–0846 (*Younes et al'12*)

Do all high-B pulsars power PWNe?
Are they powered by rotation/magnetism/both?

Some Conclusions and questions

On the diversity of plerions (or non-Crab like):

✓ Evolved but with no direct evidence of interaction with Reverse shock or ISM (DA495 and G76.9), no shell

highly magnetized winds? high-B nebulae? low-density environment? Progenitor?

✓ Evolved candidates with interaction with the RS or ISM? "offset" PWNe (e.g. CTB 87)

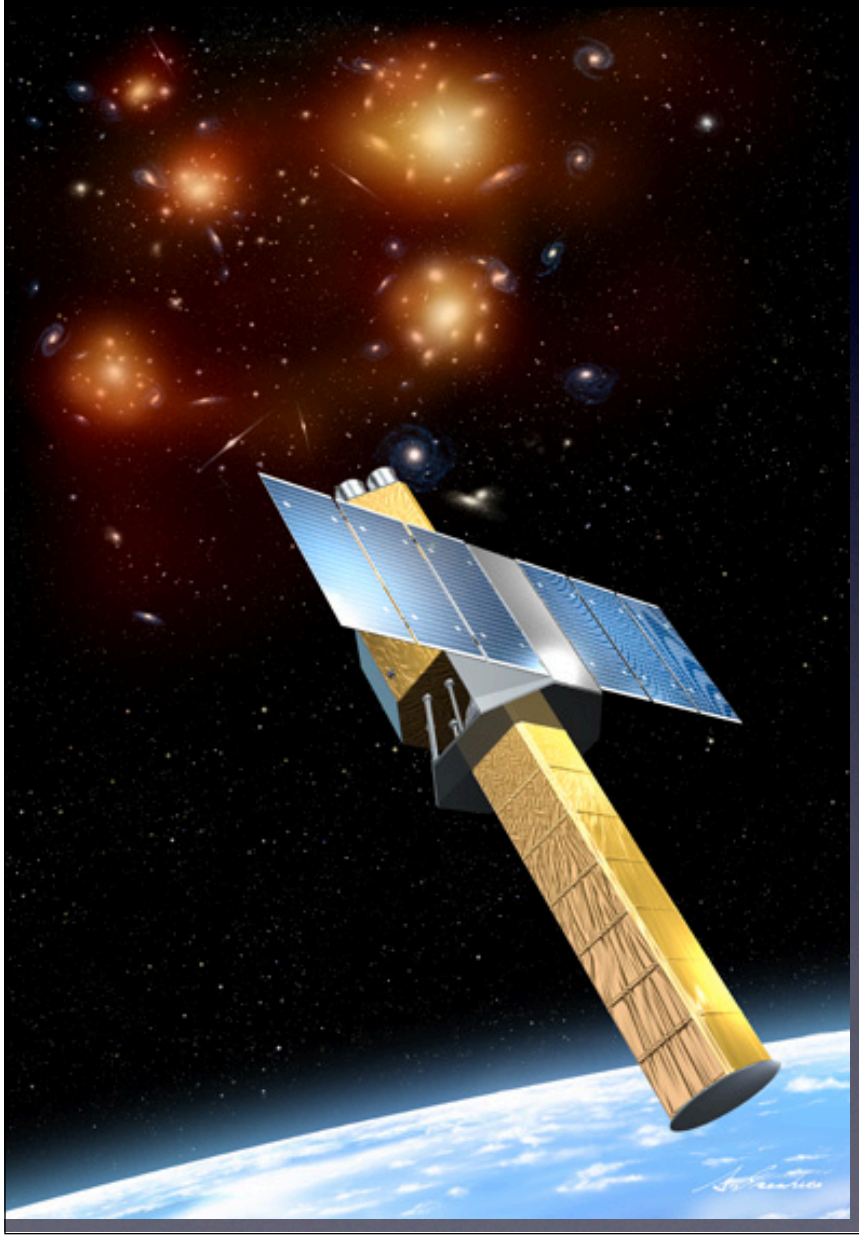
If so, why no thermal X-ray emission?

✓ Nebulae around High-B Pulsars/Magnetars (G292.2-0.5, Kes75), and magnetars, e.g. Swift J1834.9–0846 (*Younes et al'12*)

Gamma-ray searches/Dedicated multi-wavelength studies can shed light on these questions

Astro-H

(2014)



- **Soft X-ray Spectroscopic** system
  (SXS, 0.3-12 keV, 3' FOV, ~5eV resolution)
- **Soft X-ray Imaging system**
  (0.3-12 keV. 38' FOV)
- **Hard X-ray Imager**
  (5-80 keV, 9' FOV, 1.7')
  (comparable to NuSTAR)
- Soft Gamma-Ray Detector
  (50-600 keV)

0.3-600 keV!

✓ simultaneous modelling of both the thermal and non-thermal plasma in SNR,

✓ searching for thermal emission from synchrotron dominated SNRs/PWNe

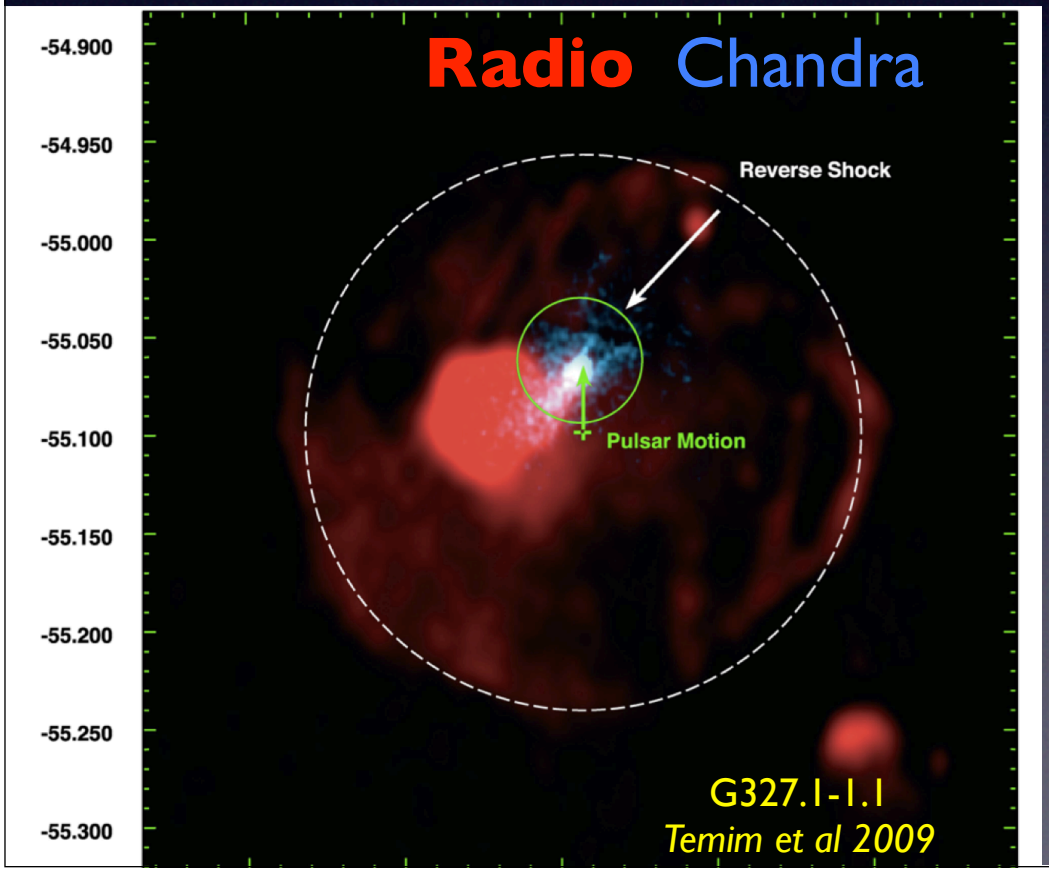
Astro-H and Plerions

G21.5-0.9

Matheson & Safi-Harb
(0.5 Msec with Chandra)

Naked PWNe (Crab-like):

With the SXS, search for the long-sought **missed thermal emission** associated with the blast wave/ shocked ejecta (as hinted e.g. in G21.5-0.9).



Evolved PWNe:

With the SXS (+HXD), one can study the interaction between the reverse shock and the (crushed) PWN. Mixed (soft) thermal and (hard) non-thermal X-ray emission detected, e.g. in G327.1-1.1.

Comments, Updates, Corrections to the SNR catalogue
X+g entries, please use the Feedback Form on:
www.physics.umanitoba.ca/snr/SNRcat
or email samar@physics.umanitoba.ca

Funding Acknowledgments:

Some (radio) collaborators: Z. Arzoumanian, Roland Kothes, Tom Landecker..

Thank you gamma2012!