Evolution of Pulsar Wind Nebulae Inside Supernova Remnants

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John Raymond (CfA)
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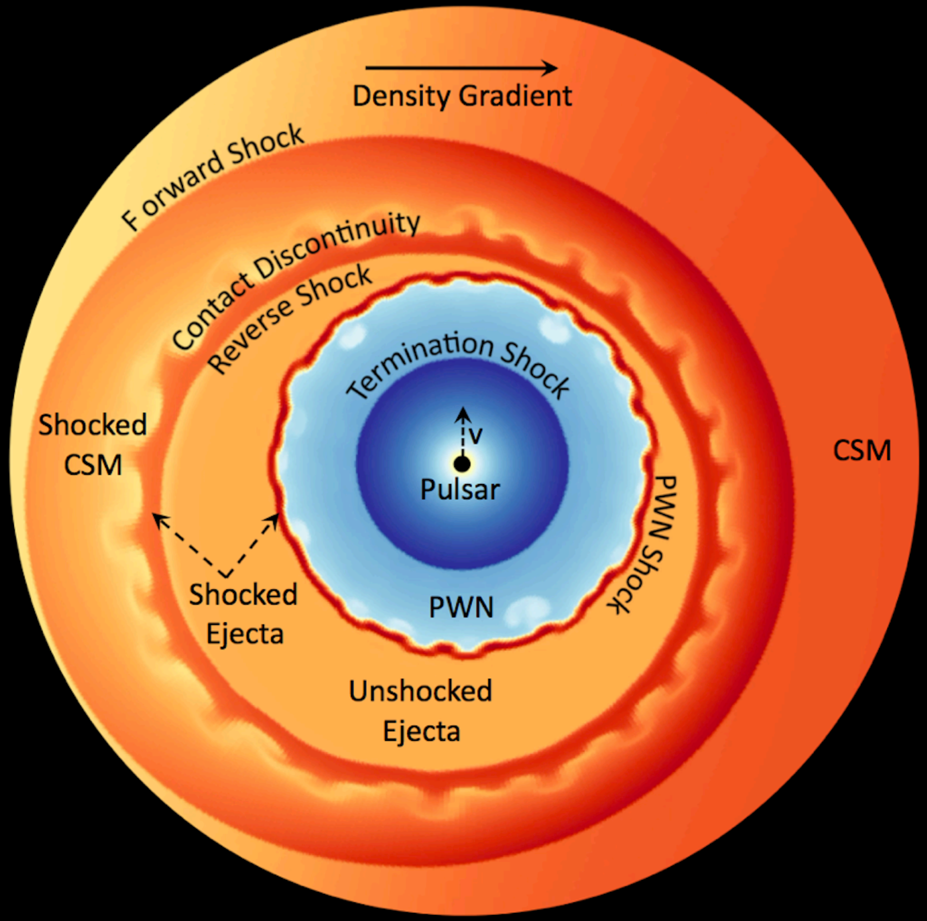
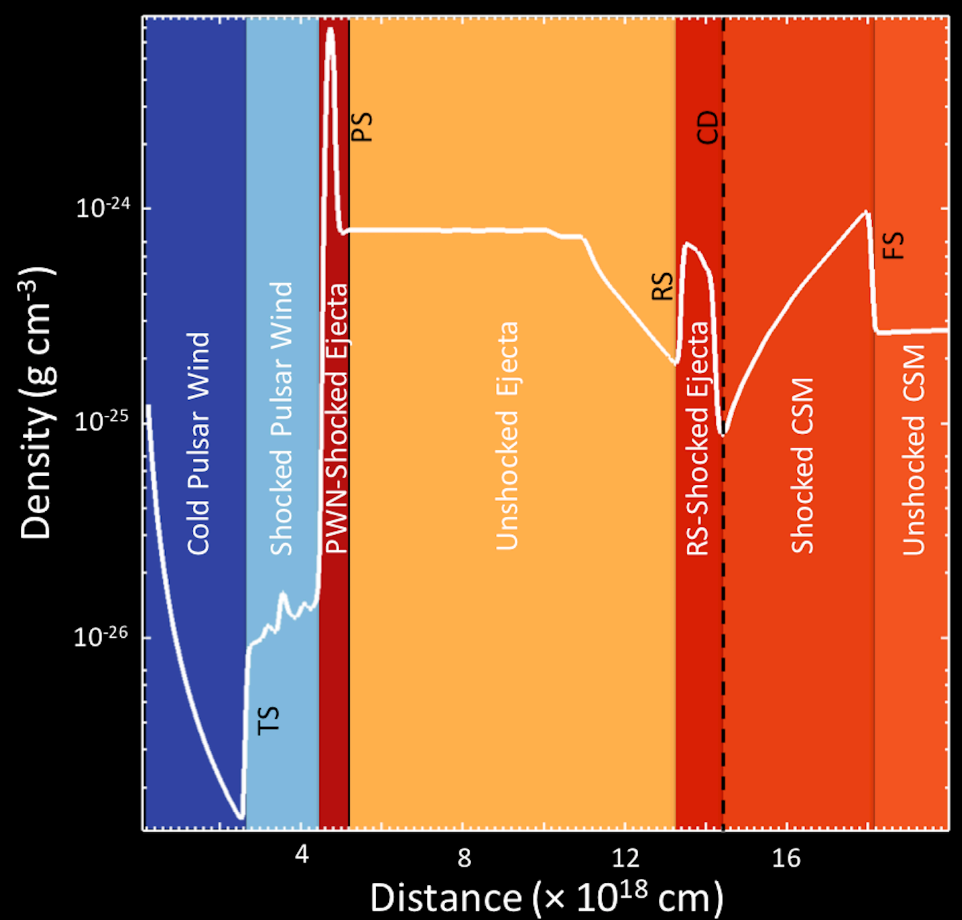
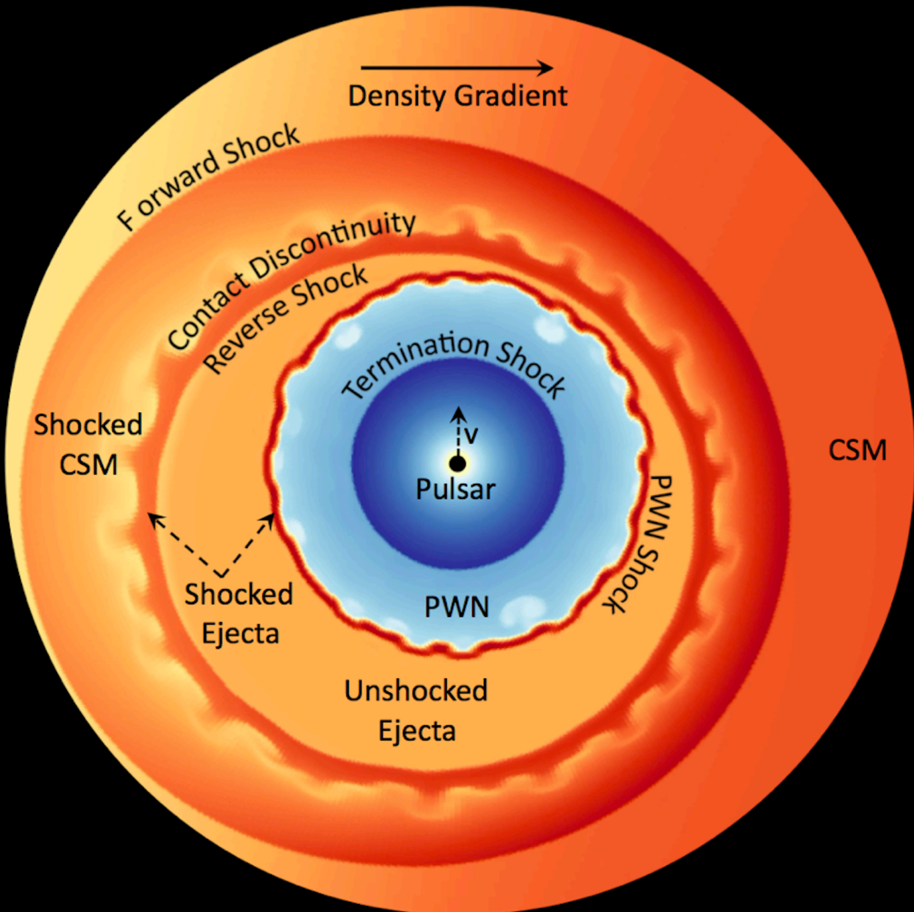
Structure of a Composite SNR





Slane 2016

Evolutionary Stages



Early evolution: PWN drives a shock into the inner SN ejecta

$$R_{PWN} \approx 1.5\dot{E}_0^{1/5} E_{SN}^{3/10} M_{ej}^{-1/2} t^{6/5}$$

([illegible] Chevalier 1984)

Late evolution:
PWN interacts with the SN reverse shock, usually asymmetrically *(e.g., Blondin et al. 2001, van der Swaluw et al. 2004)*

- Pulsar motion
- Non-uniform ISM

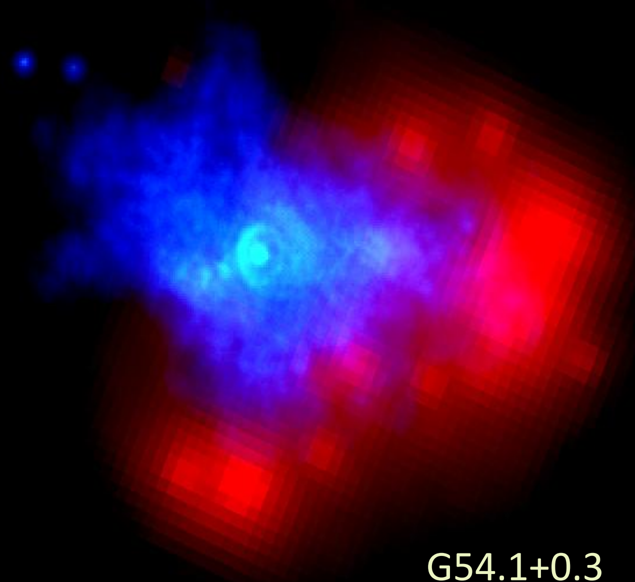
Slane 2016

What We Can Learn

- Young systems: PWNe sweeping-up SN ejecta
  - Probe SN ejecta (progenitor type and explosion mechanisms)
  - SN dust (origin of dust in galaxies, high z)
- Older systems: PWNe interacting with the SNR reverse shock
  - SN ejecta, ISM/CSM environment, explosion asymmetry
  - Injected particle population, fate of energetic particles, Galactic cosmic ray population

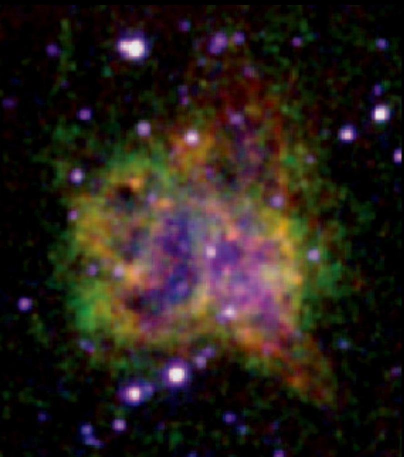
Young Systems

Crab



G54.1+0.3

G21.5-0.9



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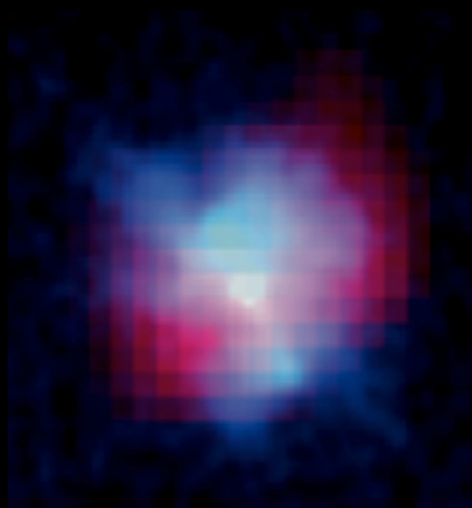
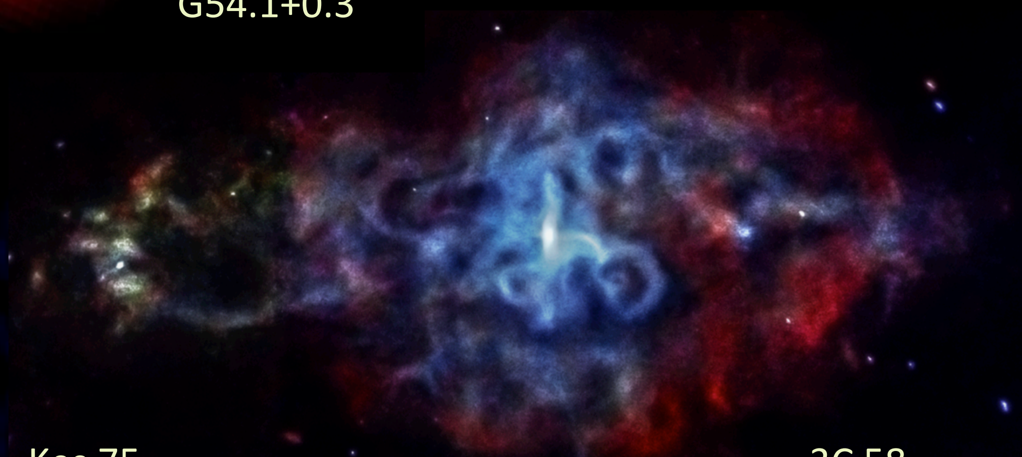
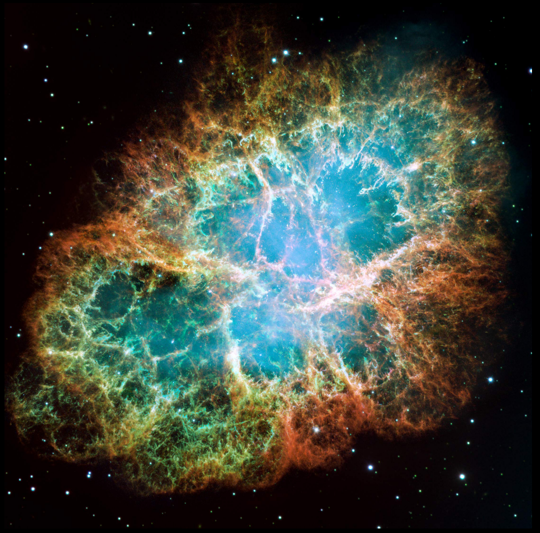


Kes 75



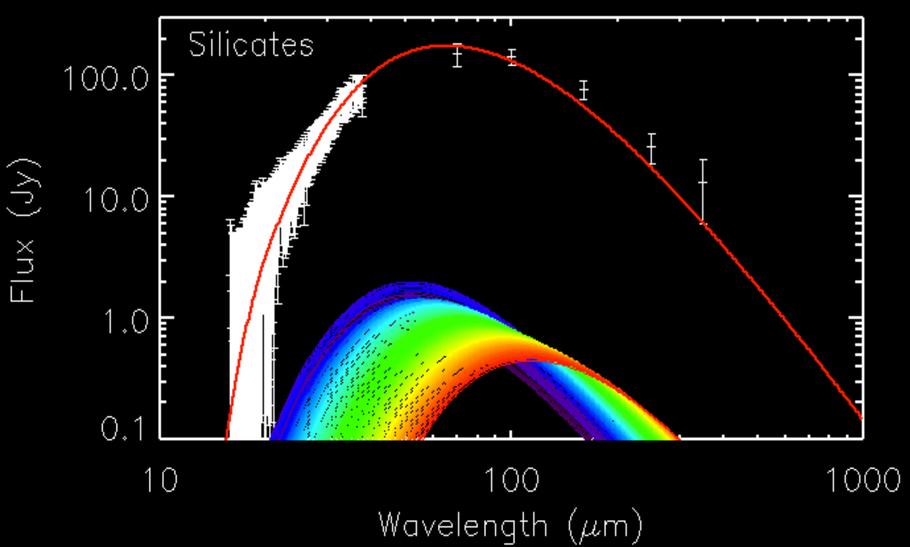
3C 58

Crab Nebula: Ejecta & Dust



Based on M_{ej} = 4.6 $M_\odot$ and v_{ej} = 1700 – 1800 km/s (1200 km/s for the filaments) →
low energy electron-capture SN with E_{51} ~ 0.1
Yang & Chevalier 2015

PWN-heated dust



M_d ~ 0.1 $M_\odot$

- Most of the dust mass is in the larger grains > 0.1 μm
- Consistent with Type IIP SN - higher density and slower ejecta allow larger grains to form (e.g., Kozasa et al. 2009)

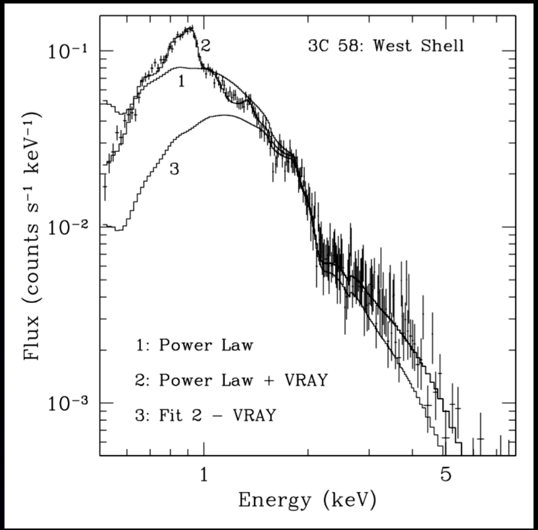
Gomez et al. 2012, Temim & Dwek 2015, Owen & Barlow 2015

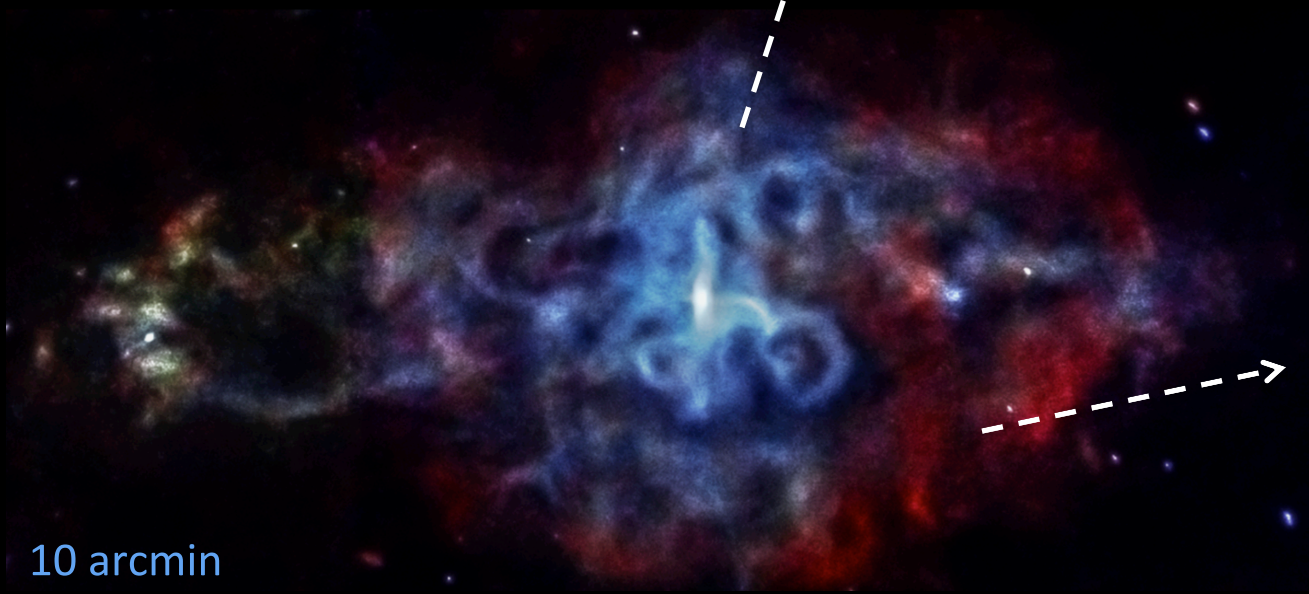
3C 58

Chandra (350 ks)

Slane et al. 2004

nonthermal emission
magnetic loops





shell of swept-up ejecta
enhanced Ne & Mg

T = 0.23 keV

M_{ej} = 0.5-1.0 $M_{\odot}$

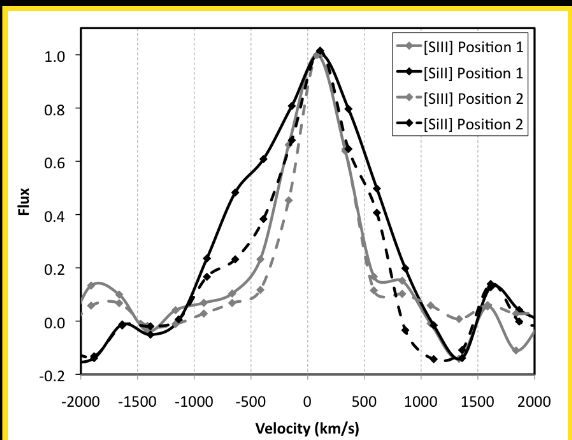
10 arcmin
d = 3.2 kpc

Mass and temperature of swept-up ejecta (*Bocchino et al. 2001, Slane et al. 2004*) and the presence of slow H-rich material (*Fesen et al. 1988*) suggest an age of ~ 2400 yr and a Type IIP progenitor, similar to the Crab (*Chevalier 2005*)

G54.1+0.3

Temim et al. 2010, 2016
Koo et al. 2008

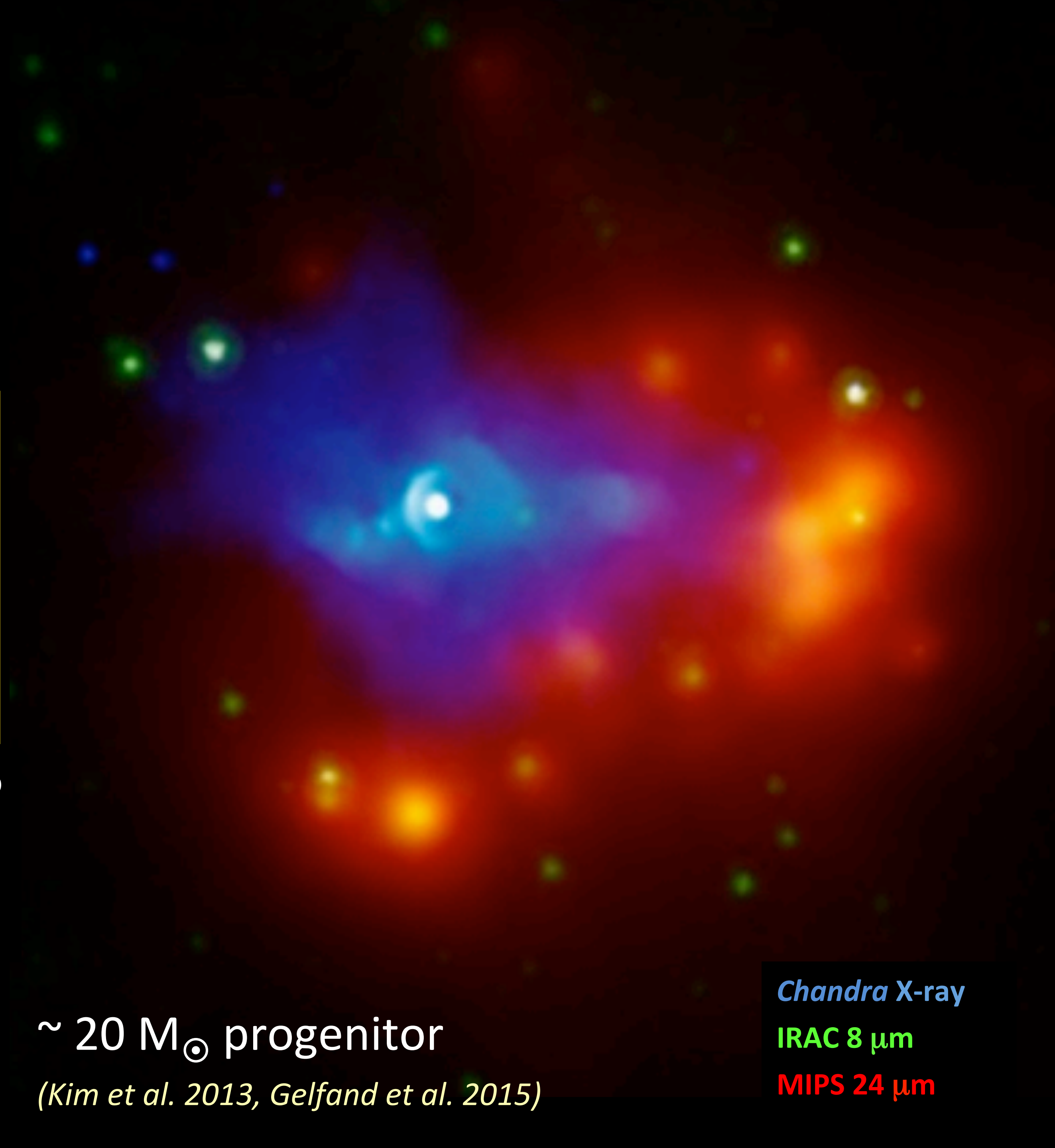
Spitzer line emission



Emission lines broadened to 1000 km/s

PWN overtakes ejecta with v_s ~ 25 km/s

NASA/CXC/SAO/
Temim et al. 2010



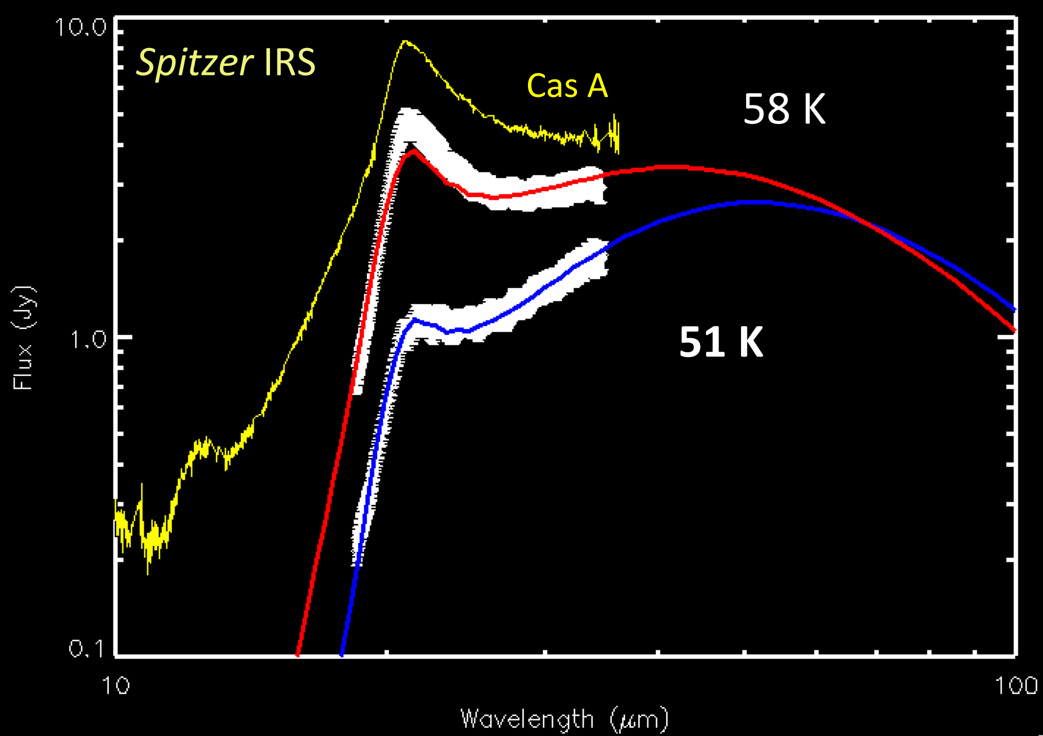
~ 20 $M_\odot$ progenitor

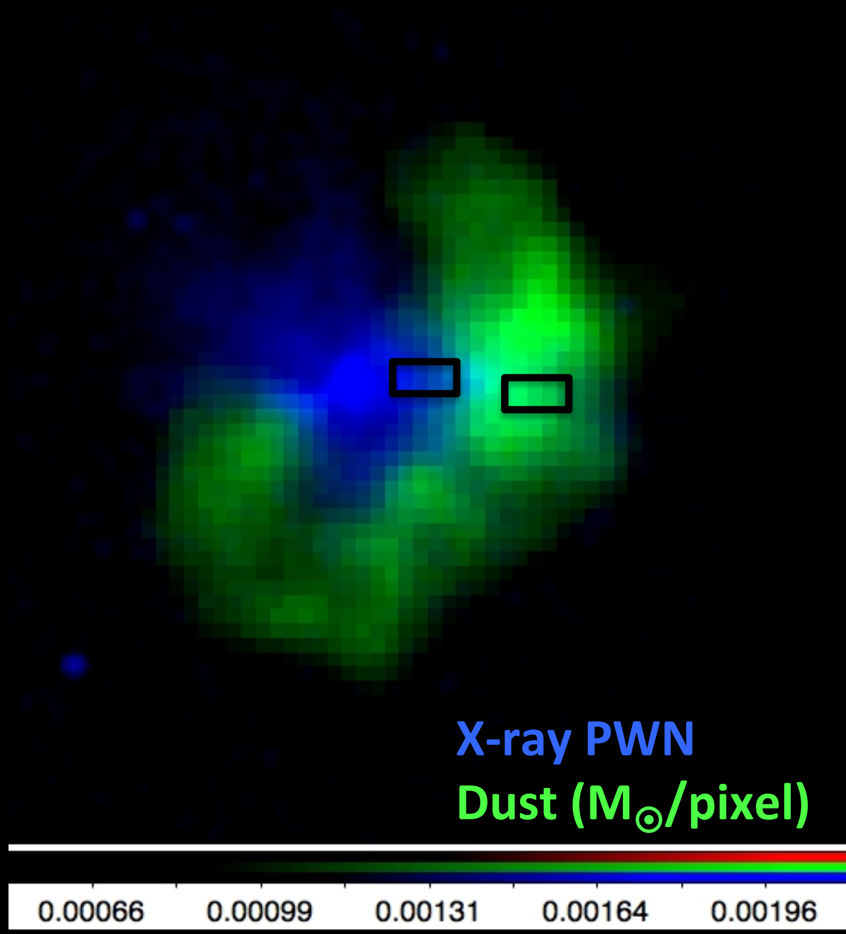
(Kim et al. 2013, Gelfand et al. 2015)

G54.1+0.3

Dust composition: $Mg_{0.7}SiO_{2.7}$ (MgO/SiO_2 = 0.7)

Same as in Cas A
(Arendt et al. 2014)





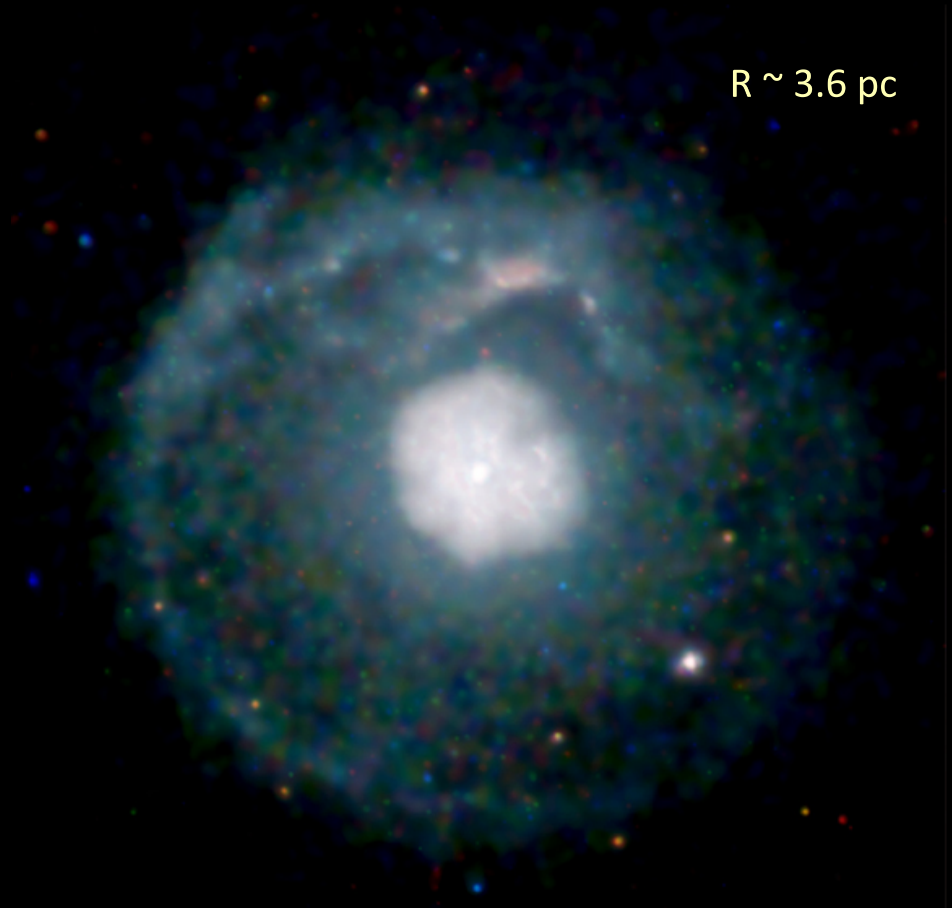
$M_d \leq 0.3\ M_\odot$

→ 20 – 30 $M_\odot$ progenitor

Temim et al. 2016, in prep

G21.5-0.9: PWN-Shocked Ejecta

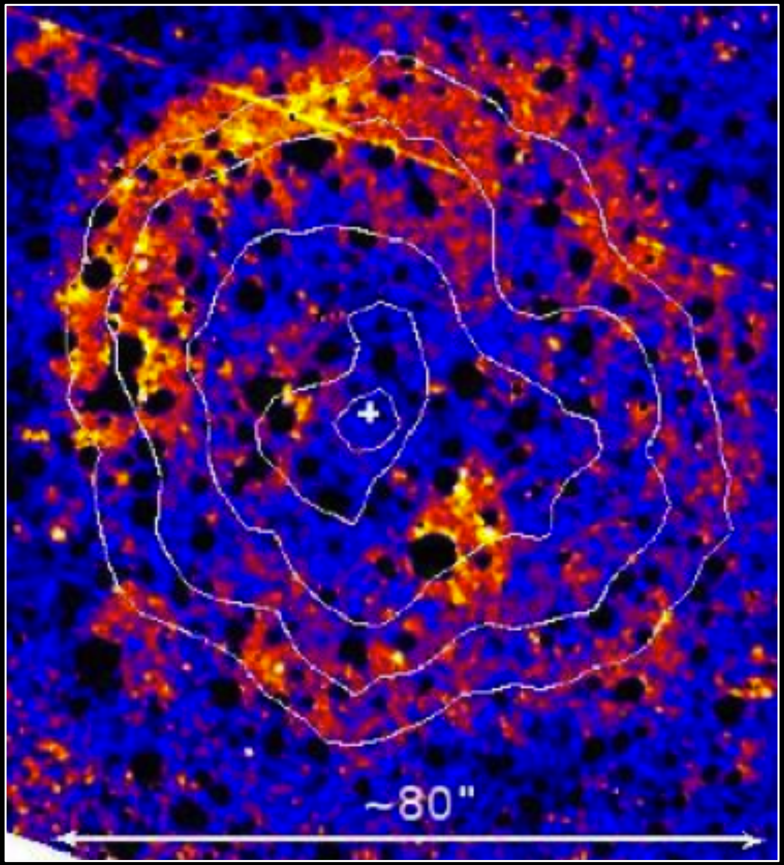
- SNR age < 1000 yr
- X-ray shell: dust scattering halo and synchrotron emission from particles accelerated by the forward shock.
- See new results from deep *Chandra* observations: Poster S3.2 (B. Guest)



NASA/CXO/Matheson & Safi-Harb 2010

e.g., Slane et al. 2000, Bocchino et al. 2005, Matheson & Safi-Harb 2010

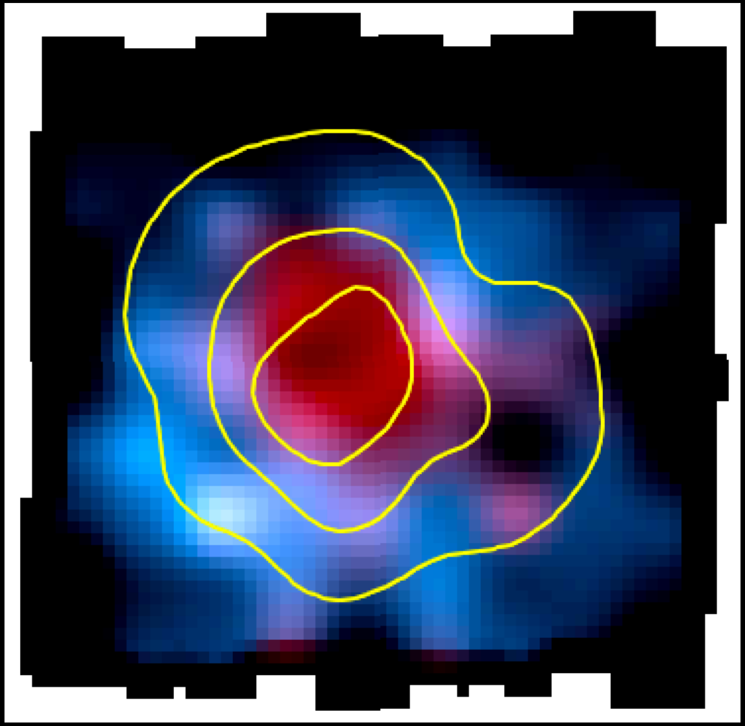
G21.5-0.9: PWN-Shocked Ejecta



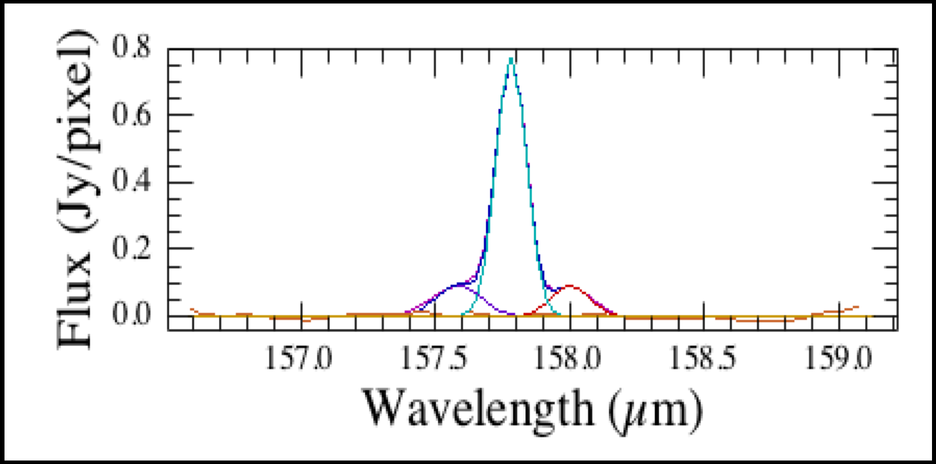
[Fe II] 1.64 μm (VLT/ISAAC)

Zajczyk et al. 2012

G21.5-0.9: *Herschel* Spectroscopy



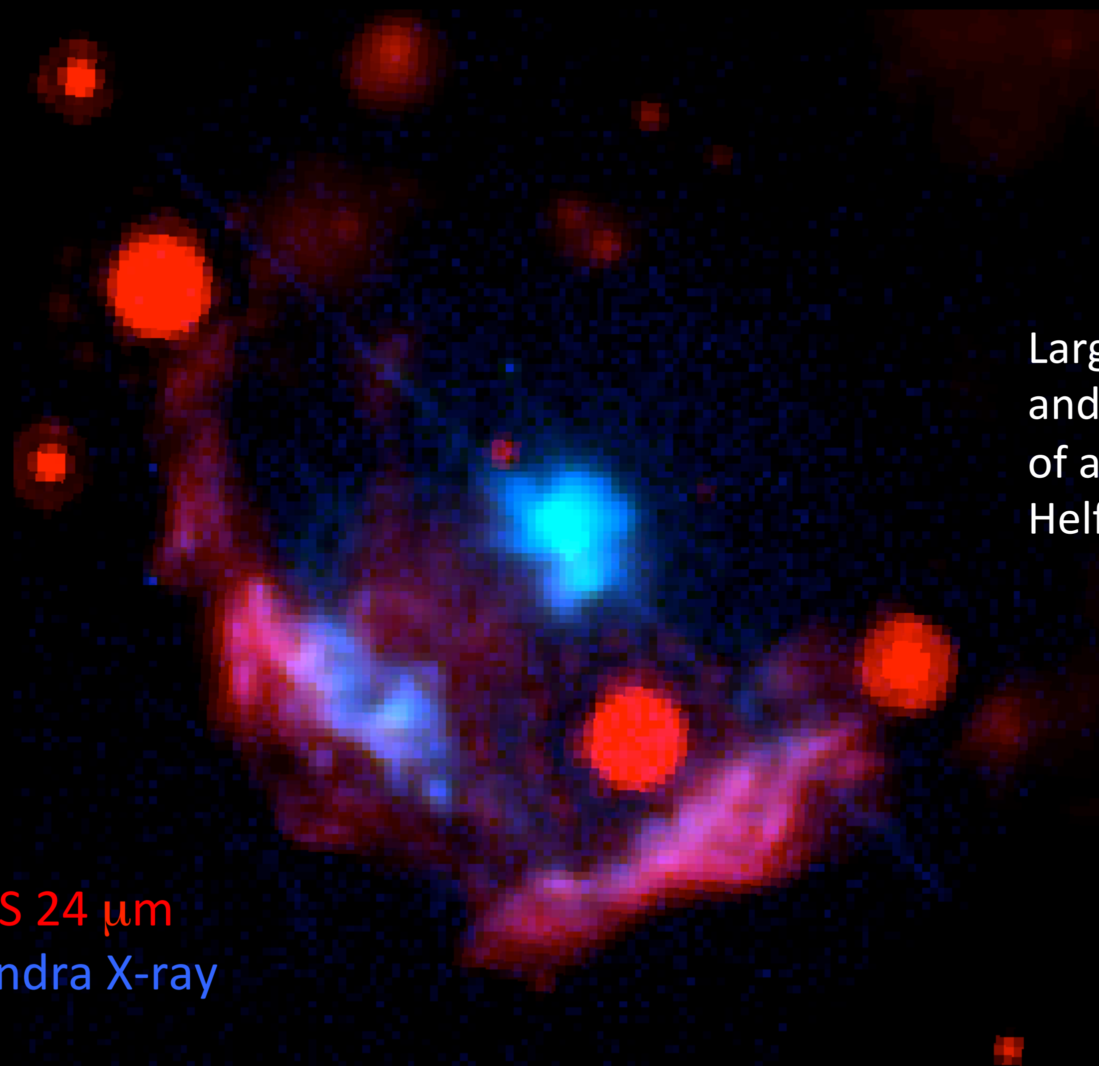
[C II] 157 μm



Ejecta velocity = 400 km/s

- Line at rest shown in blue → limb brightened emission from shocked ejecta
- Red and blue shifted line emission in red → line of sight shocked ejecta

Kes 75: First detection of SN ejecta

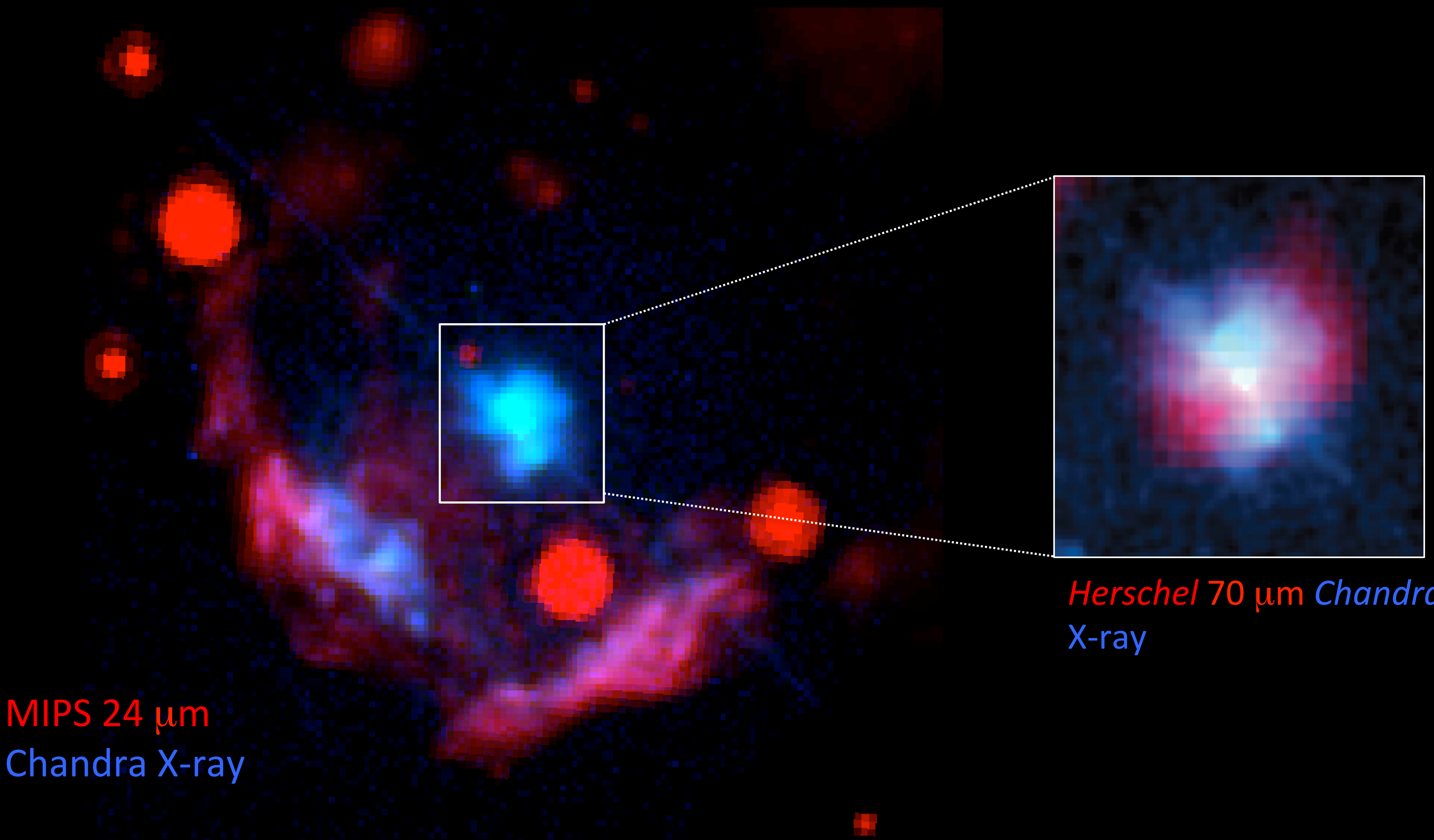


Pulsar age ~ 800 yr, among youngest in the Galaxy *(Gotthelf et al. 2000)*

Large SNR size/expansion velocity, and clumpy CSM are characteristic of a WR progenitor (e.g Helfand et al. 2003)

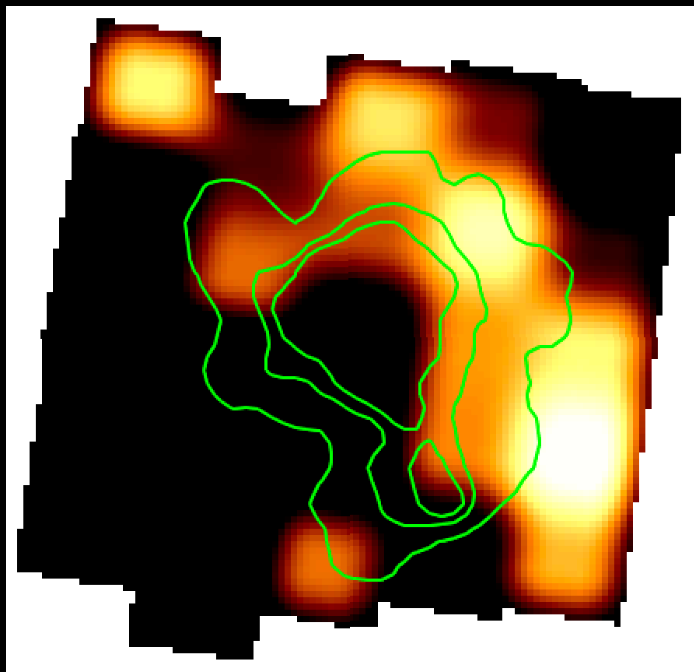
Temim et al. 2013

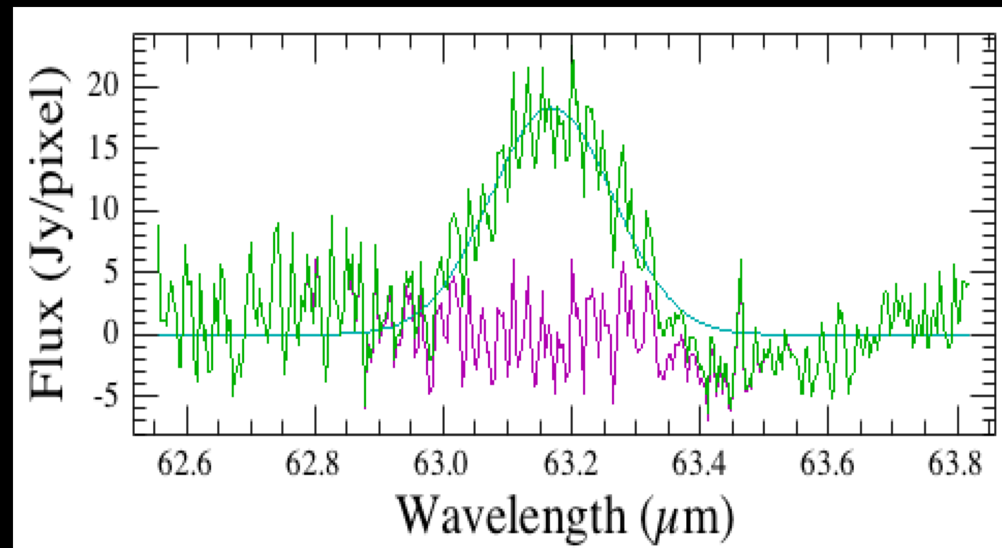
Kes 75: A dusty shell?



Temim et al. 2016, in prep

Kes 75: *Herschel* Spectroscopy





[O I] 63.18 μm line, FWHM = 1000 km/s

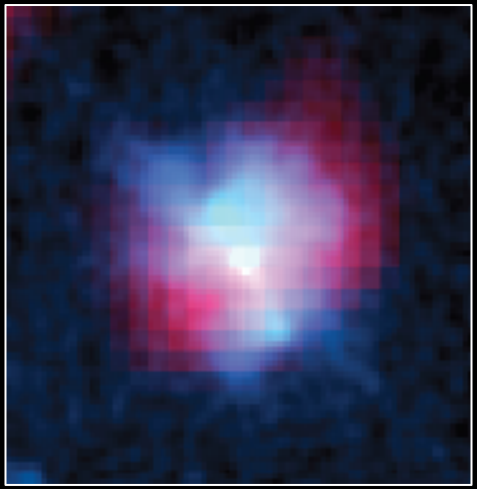
Ejecta expansion velocity of ~ 500 km/s

Temim et al. 2016, in prep

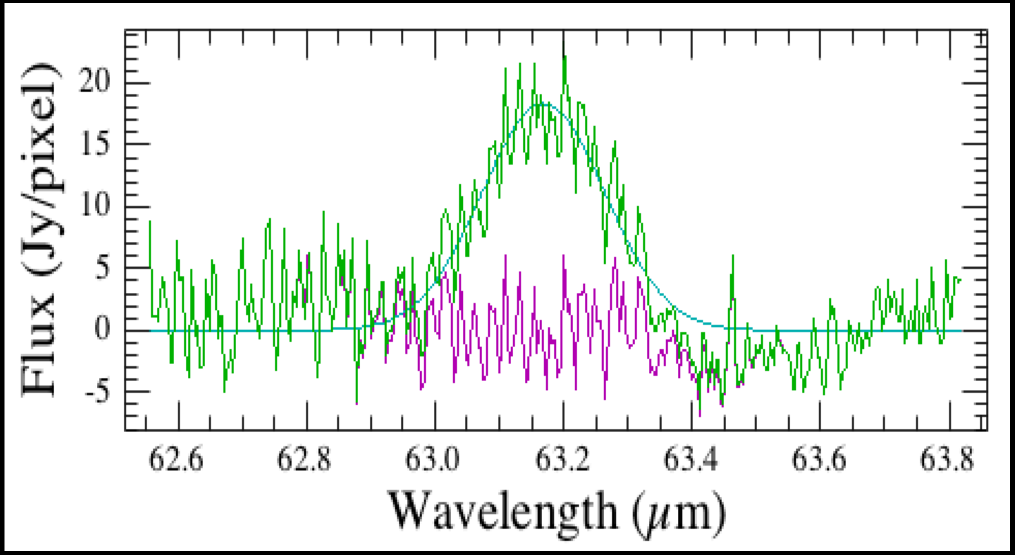
Kes 75: *Herschel* Spectroscopy

Temim et al. 2016, in prep

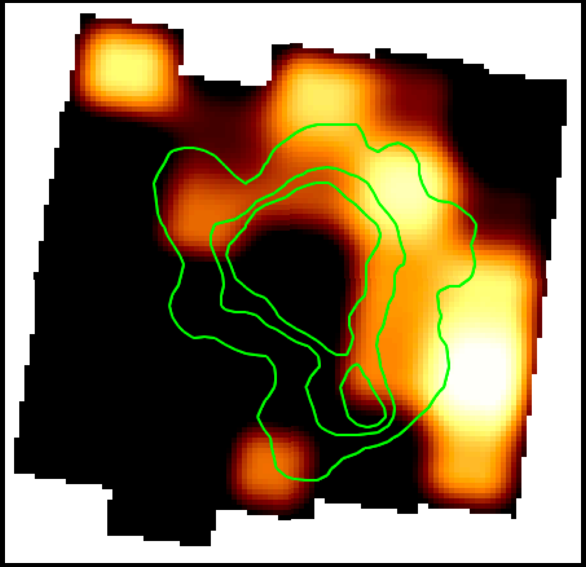
Ejecta velocity of ~ 500 km/s



Chandra, *Herschel* 70 μm

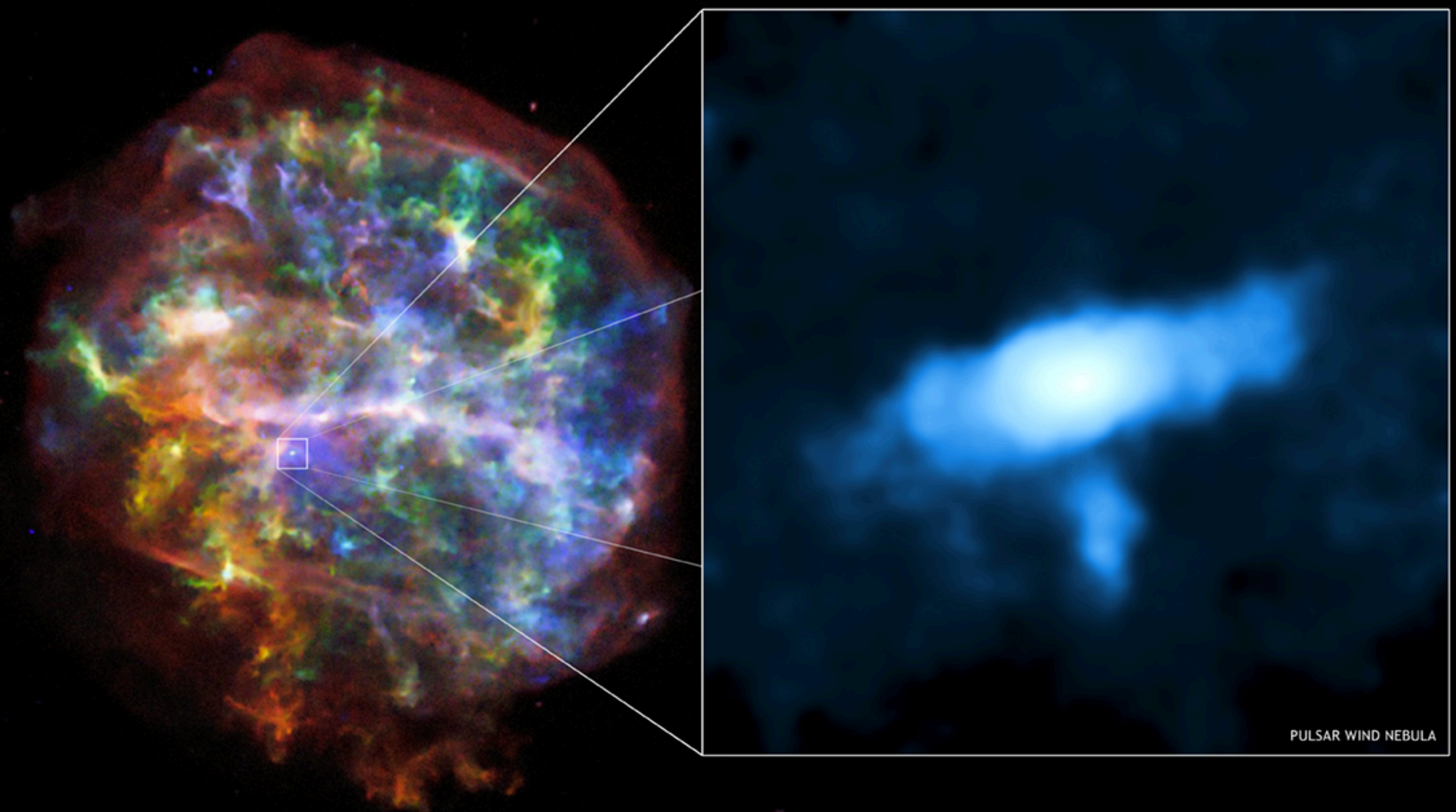


[O I] 63.18 μm line, FWHM = 1000 km/s



[O I] 63.18 μm line image

Transitional Stage:
Reverse Shock Reaching the PWN

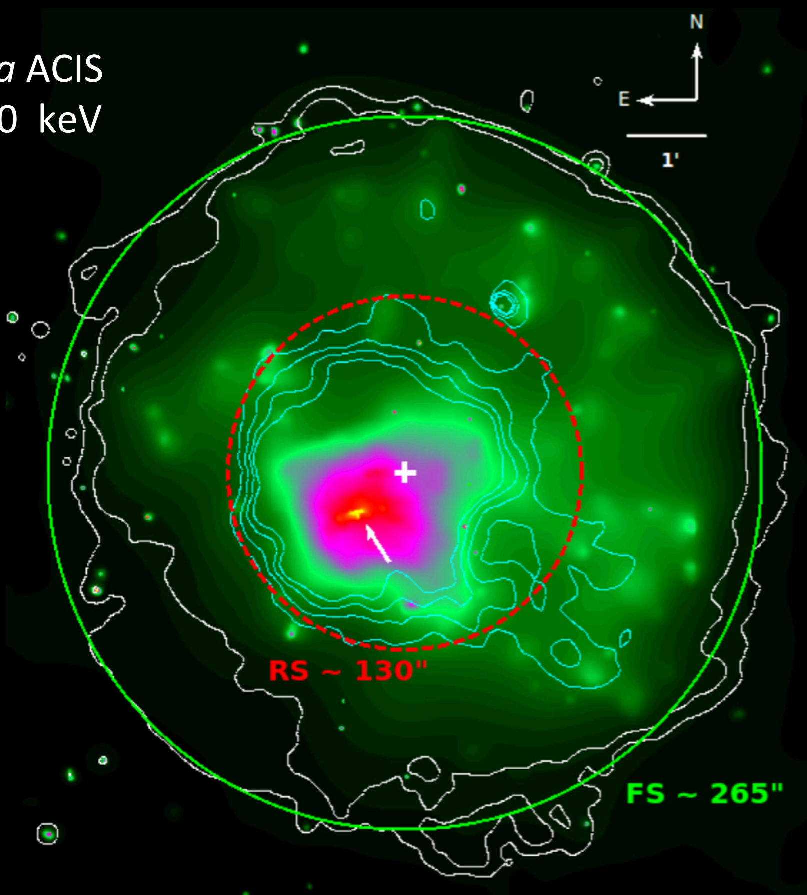


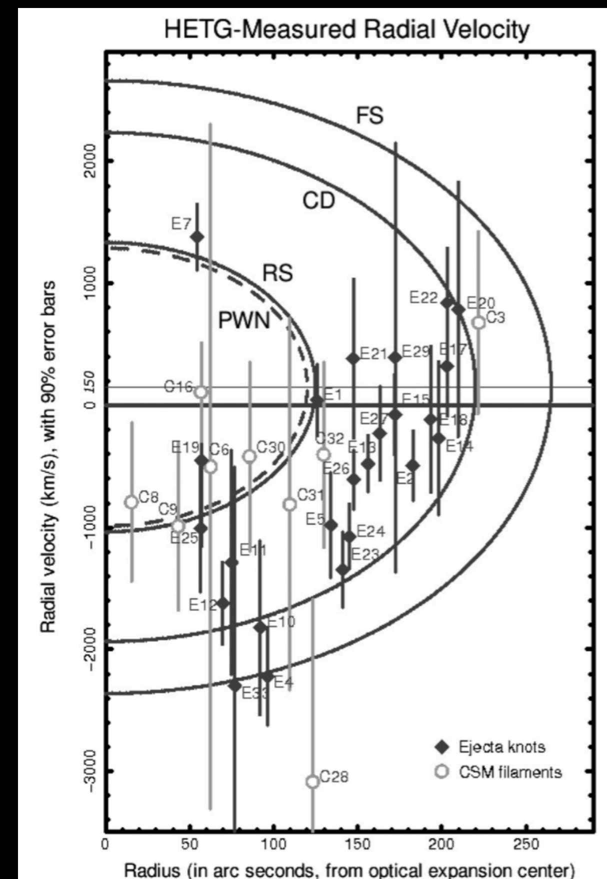
G292.0+1.8
NASA/CXC/S.Park et al.

G292.0+1.8

Bhalerao et al. 2015

Chandra ACIS
4.0 – 8.0 keV



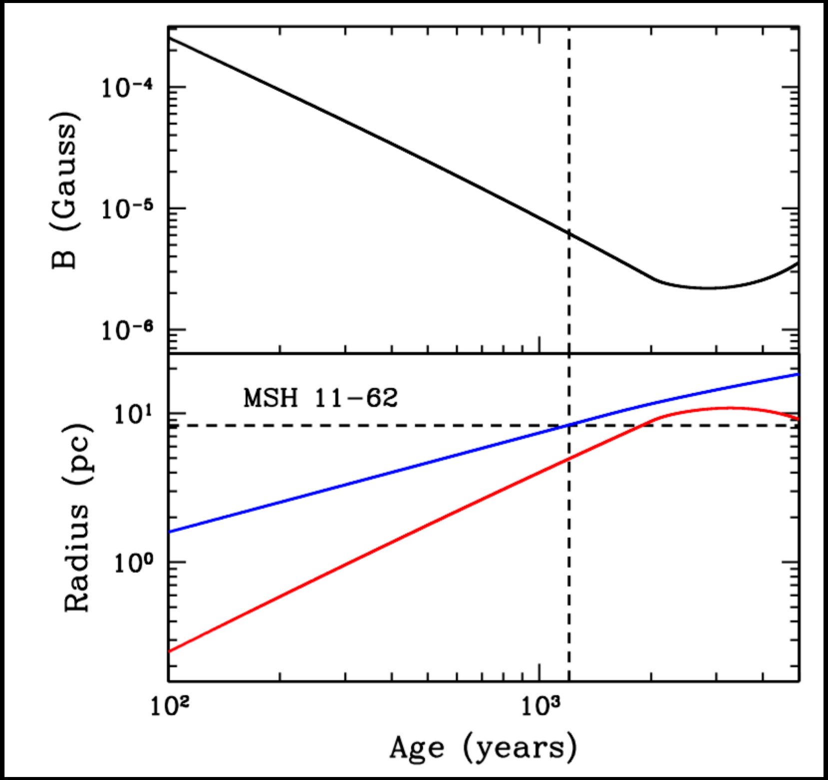


Distribution of ejecta knots puts RS at the boundary of the radio PWN

MSH 11-62

Slane et al. 2012

Age ~ 1200 yrs

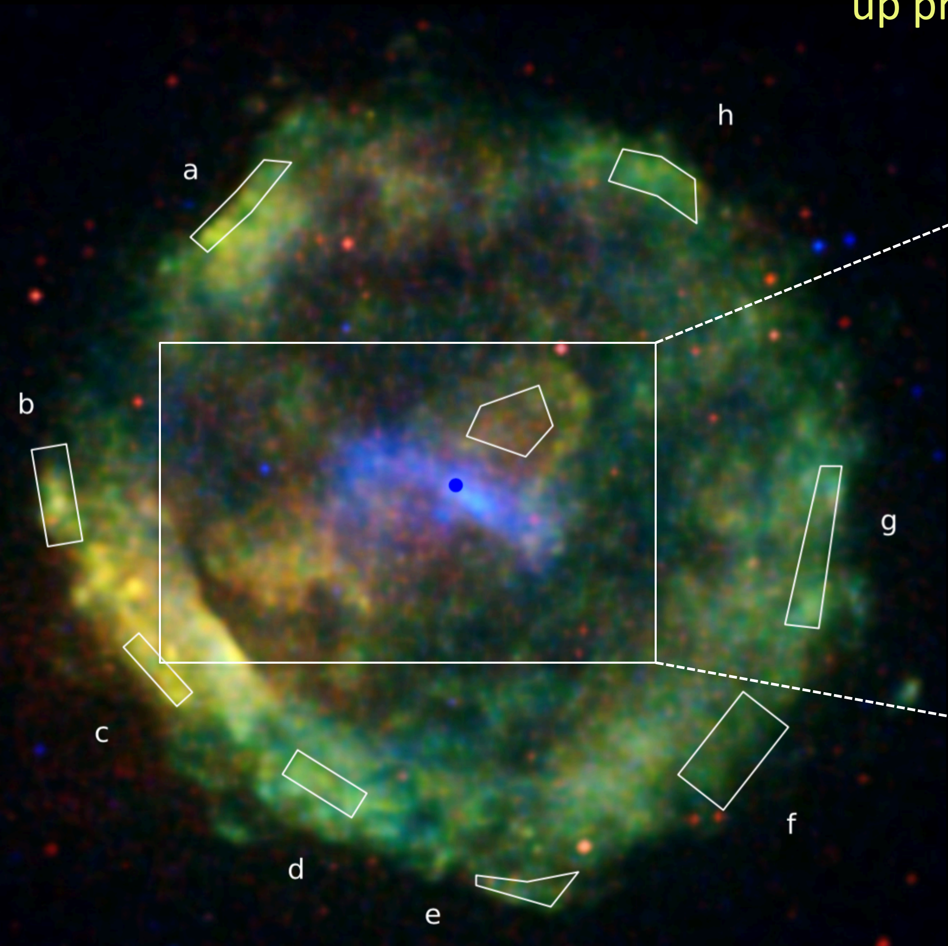


PWN morphology and modeling of the system suggest that the reverse shock has begun compressing the PWN

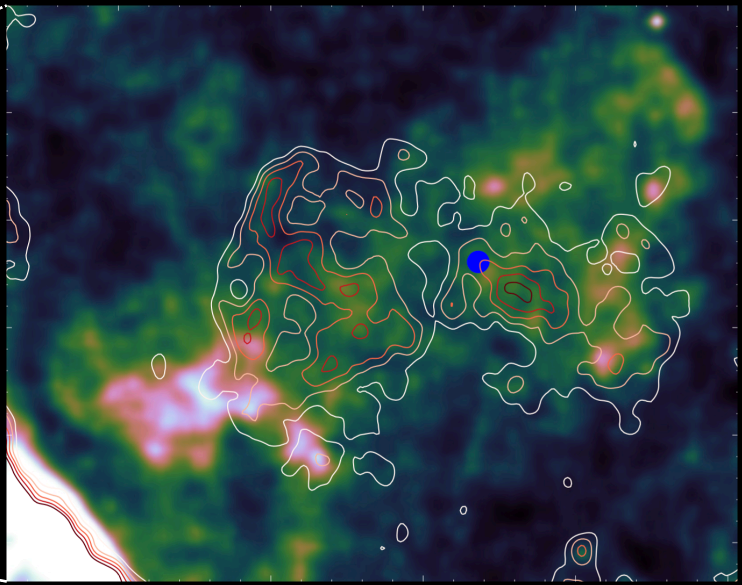
G11.2-0.3

Borkowski et al. 2016

- Expansion rate → age = 1400 – 2400 yrs
- Possibly a stripped-envelope SN that swept up previously lost mass into dense shell

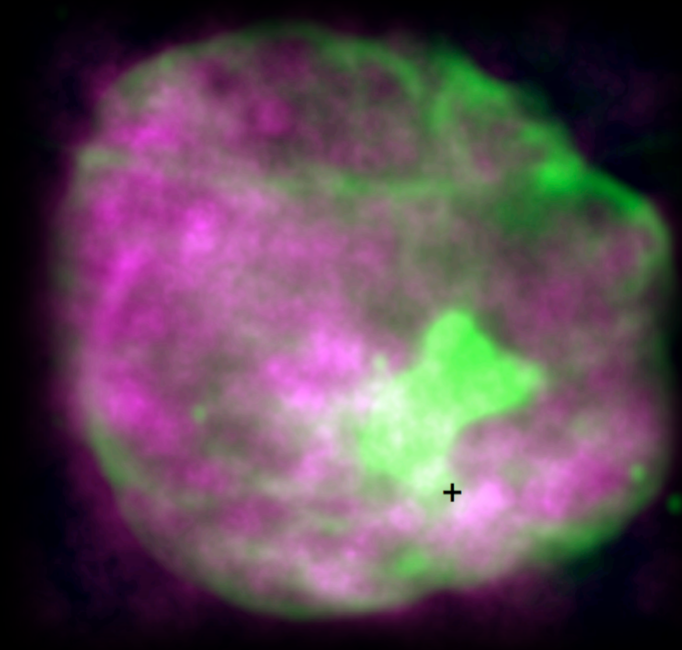


400 ks *Chandra* image

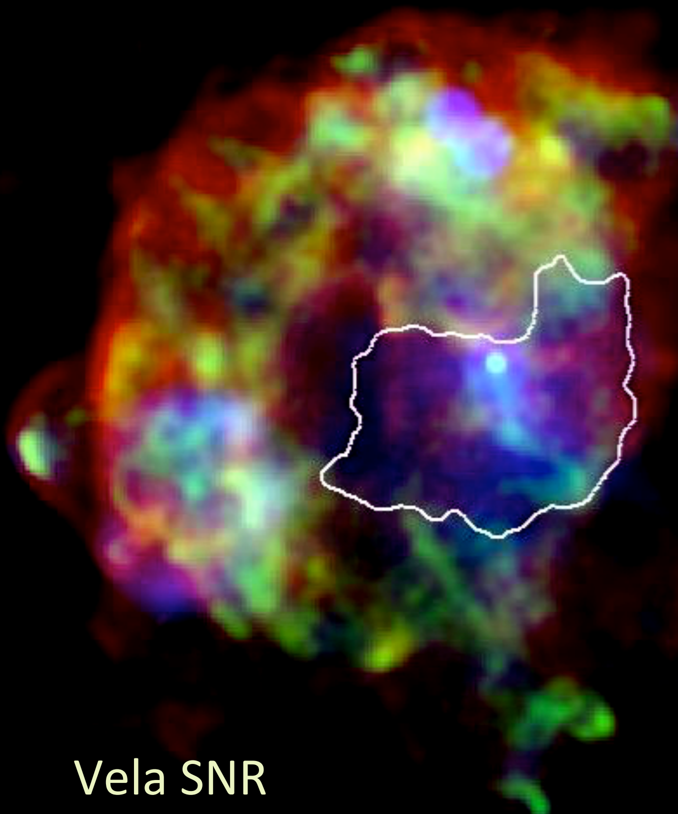


Radio PWN & thermal X-rays anticorrelated → RS has reheated all ejecta and compressed the PWN

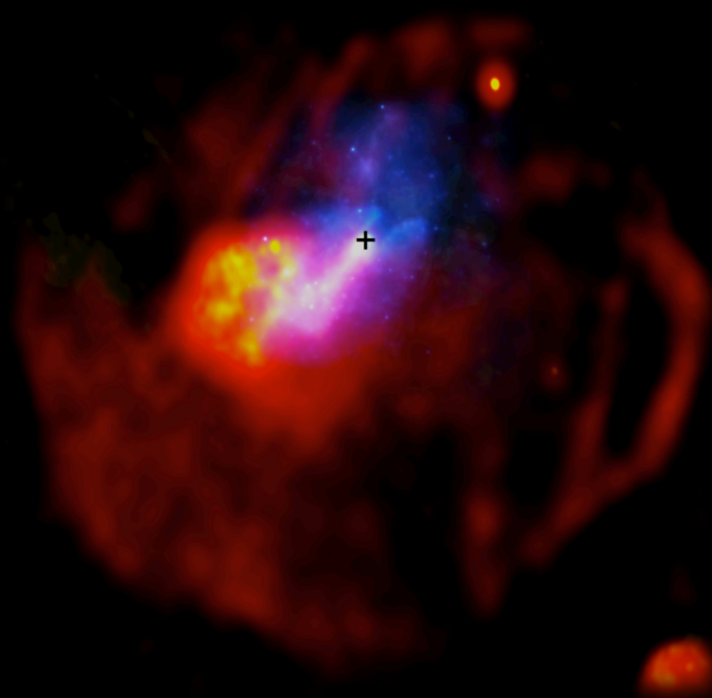
Evolved Systems



MSH 15-56

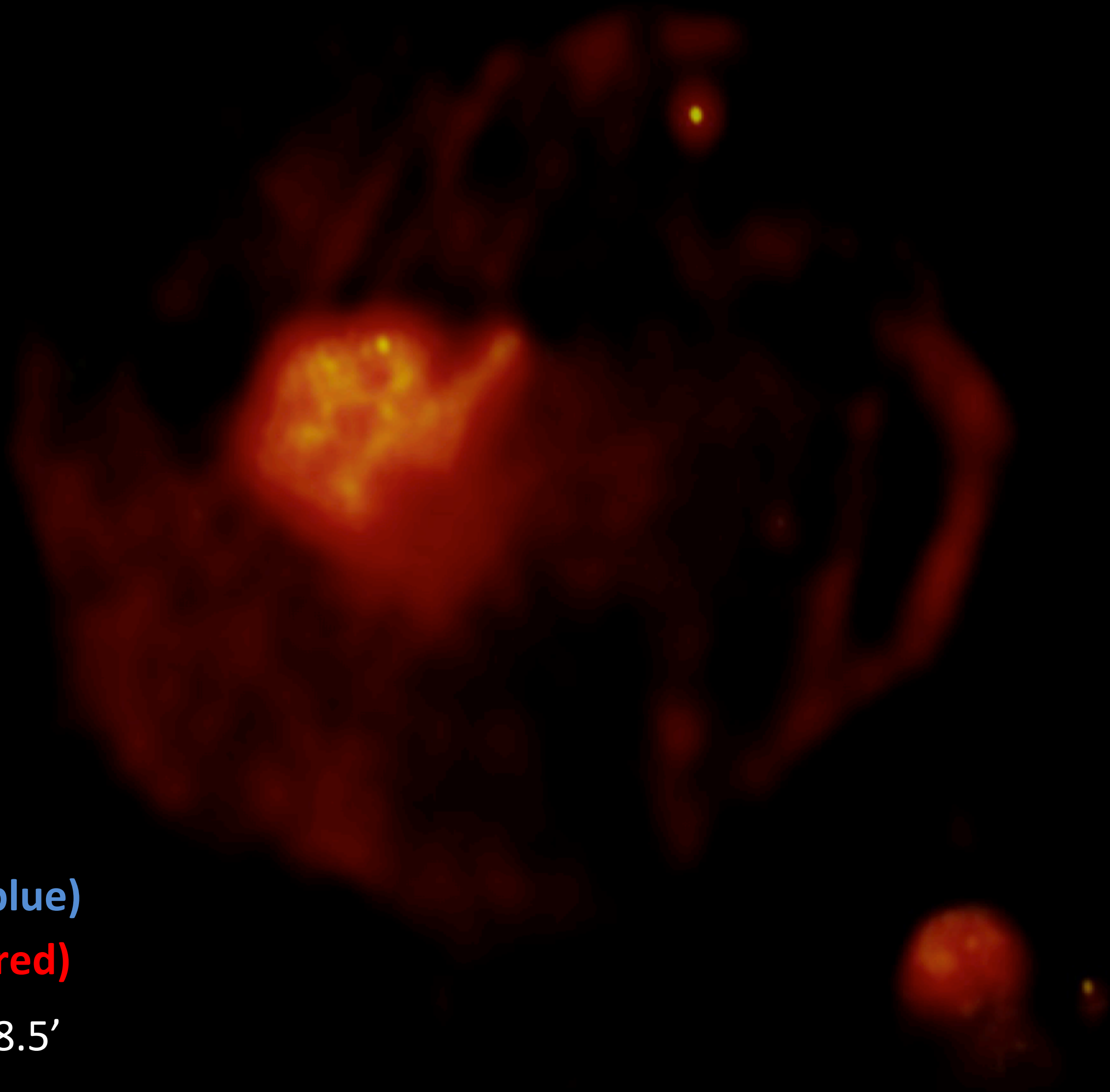


Vela SNR



G327.1-1.1

SNR G327.1-1.1: Crushed PWN in an evolved SNR



Sedov

(d = 9 kpc)

R = 22 pc

$n_0 = 0.12\ cm^{-3}$

Age = 17k yr

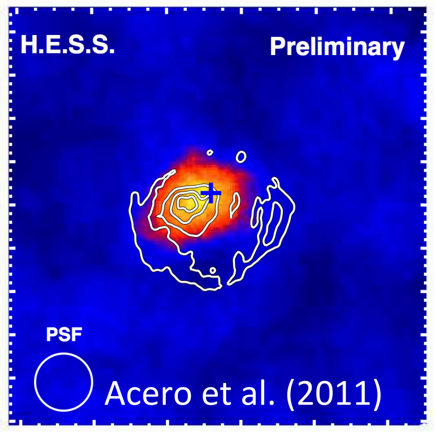
T = 0.3 keV

$v_s = 500$ km/s

$N_H = 2 \times 10^{22}\ cm^{-2}$

v_{PSR} = 400 km/s

Also a γ-ray source



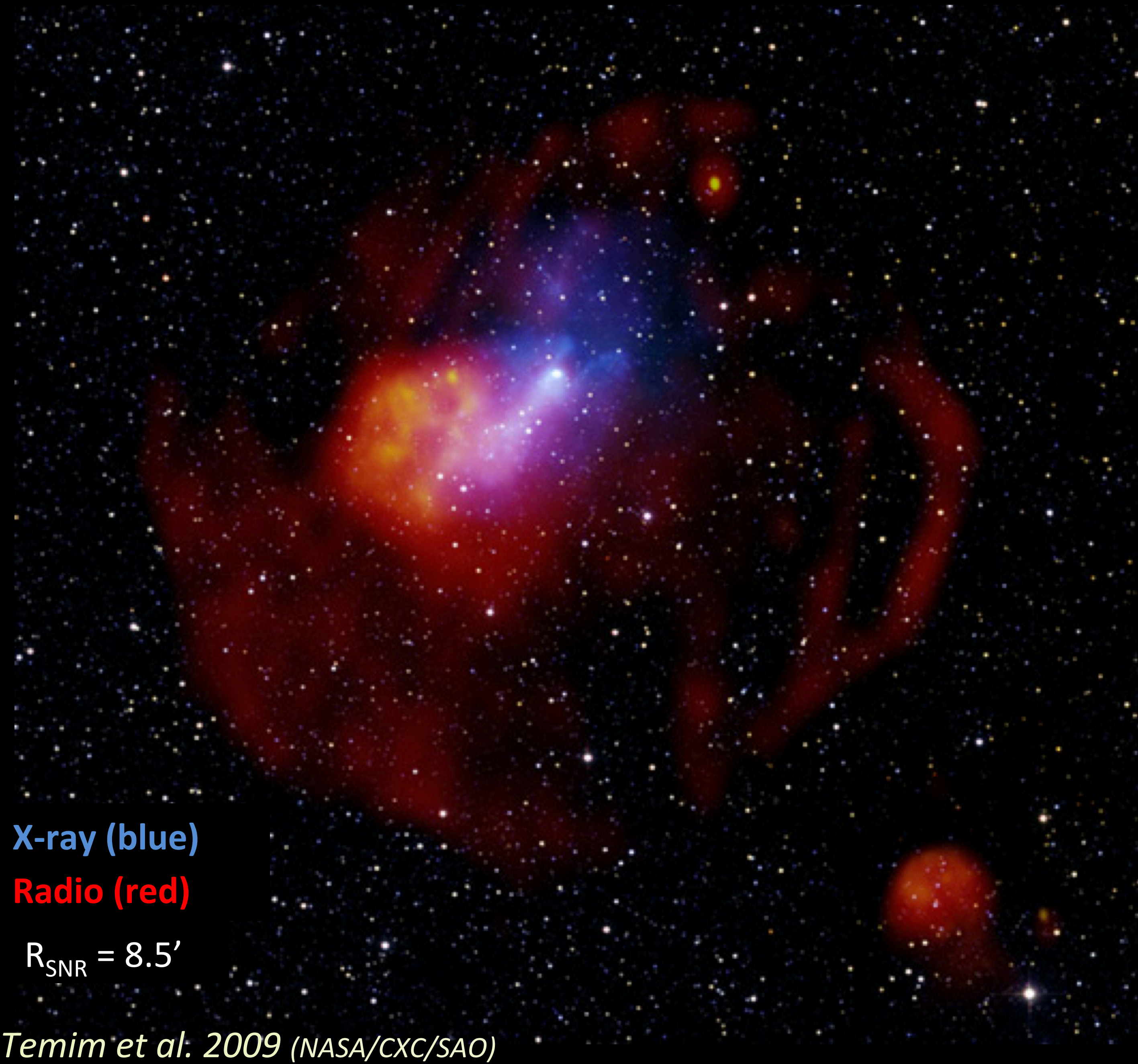
X-ray (blue)

Radio (red)

R_{SNR} = 8.5'

Temim et al. 2009

SNR G327.1-1.1: Crushed PWN in an evolved SNR



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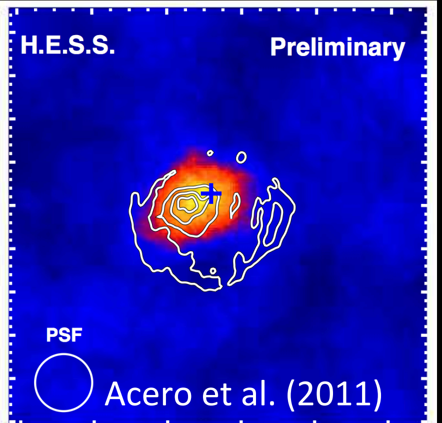
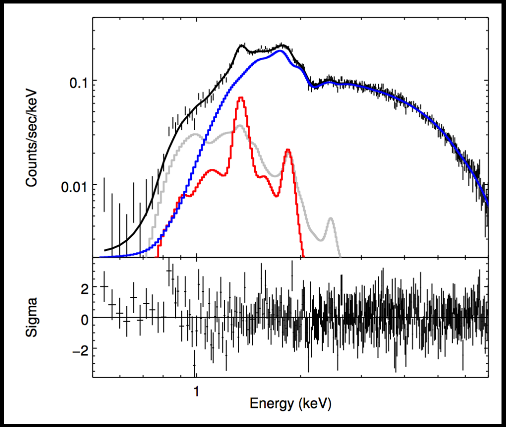
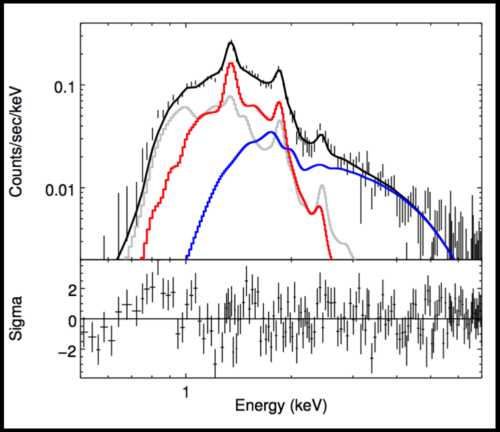


Chandra 350 ks observation

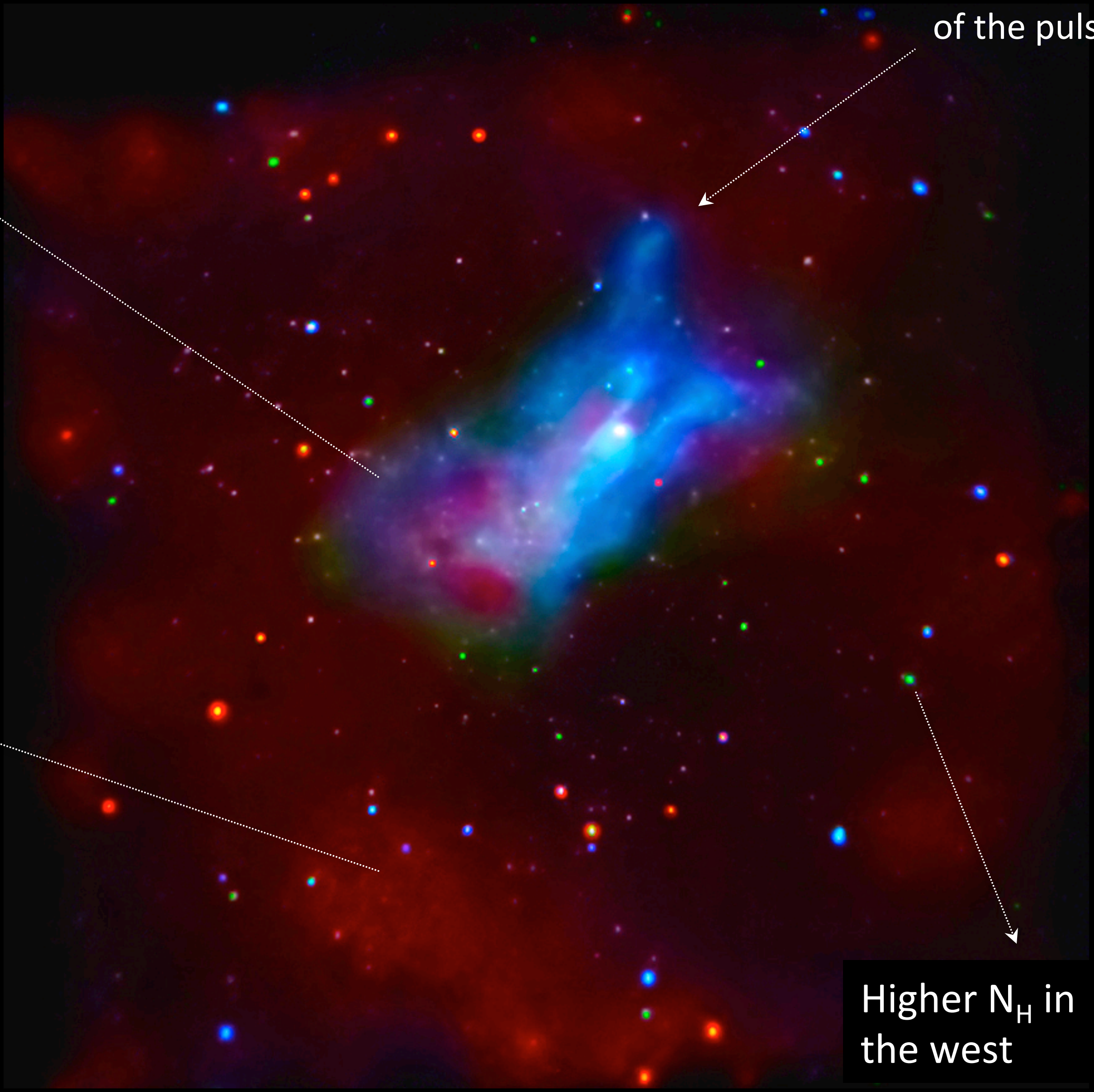
X-ray emission from relic PWN, mixed-in ejecta



Thermal X-ray emission from SNR shell, T= 0.3 keV



Outflow ahead of the pulsar?



T. Temim, P. Slane, C. Kolb, J. Blondin, J. Hughes, N. Bucciantini, 2015

Chandra 350 ks observation

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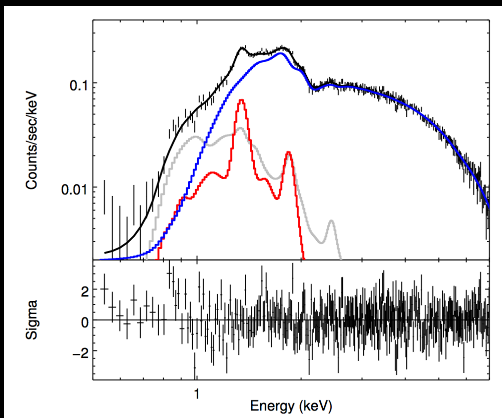
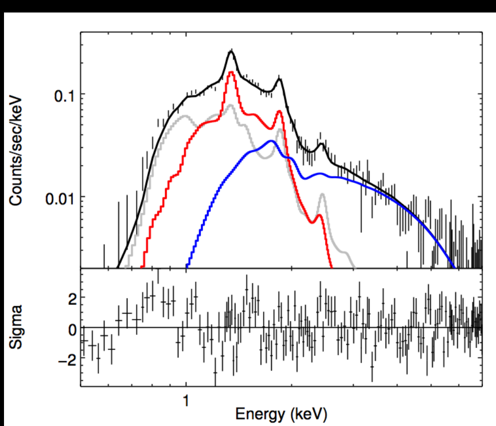
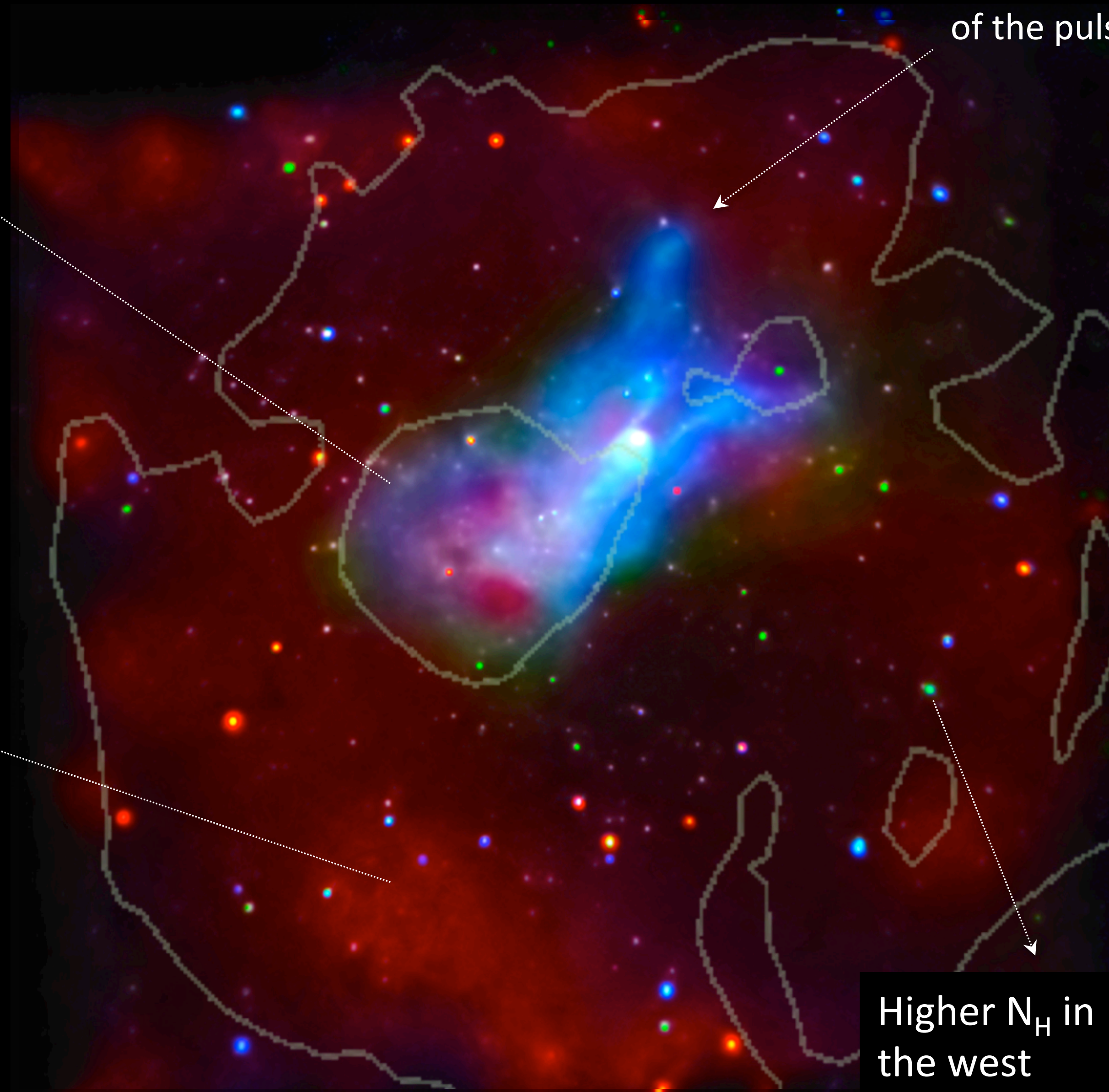


Thermal X-ray emission from SNR shell, T= 0.3 keV



Outflow ahead of the pulsar?



Higher N_H in the west

T. Temim, P. Slane, C. Kolb, J. Blondin, J. Hughes, N. Bucciantini, 2015

HD Model of a PWN Expanding Inside a Supernova Remnant

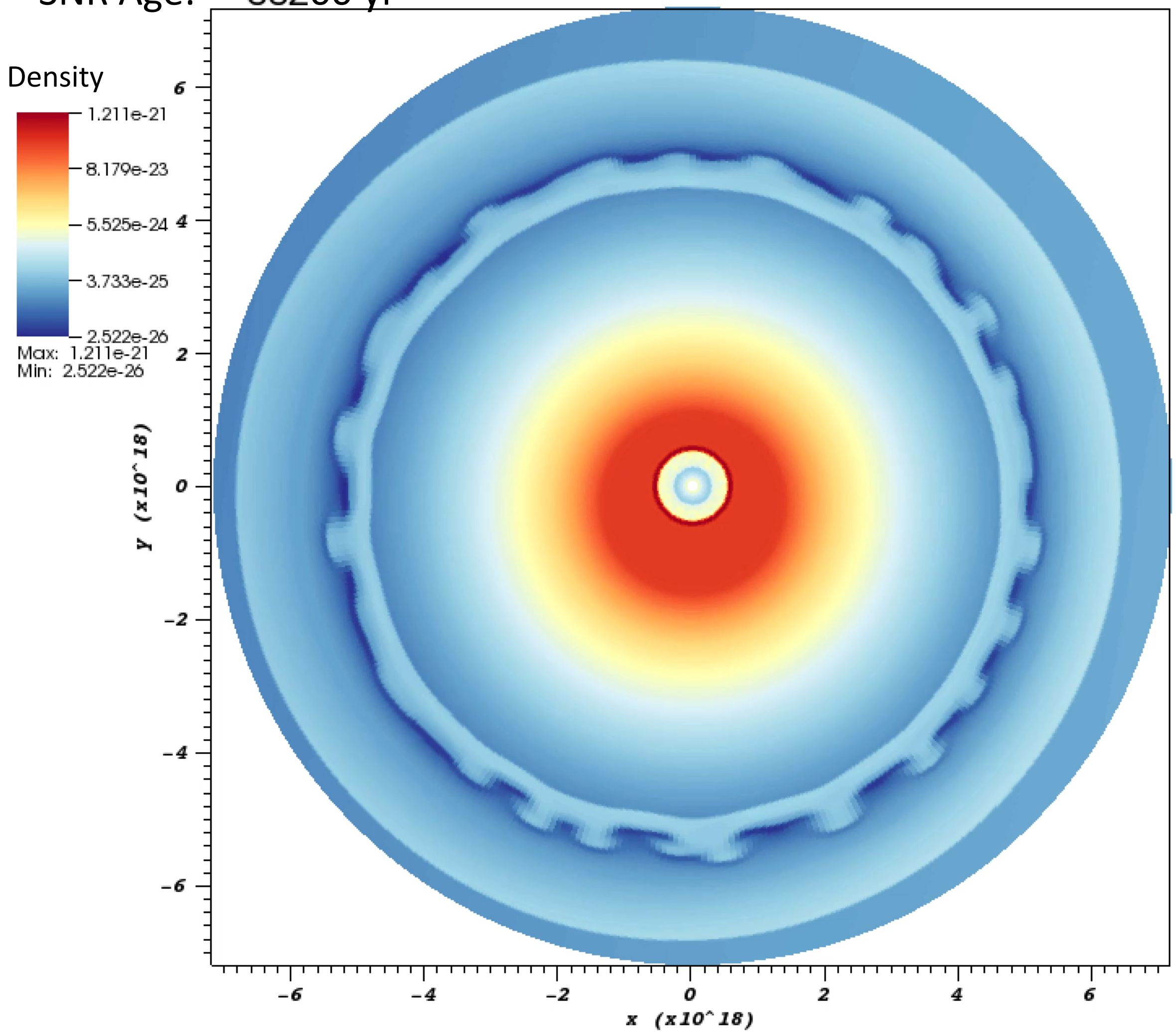
Parameter	Description	Value
SNR Properties:		
D (kpc)*	SNR distance	9.0
R_{SNR} (pc)*	SNR radius	22
v_s (km/s)*	Shock velocity	500
t (yr)*	SNR age	17400
n_0 (cm^{-3})	Average ambient density	0.12
E_{51} (10^{51} erg)	Explosion energy	0.5
M_{ej} ($M_{\odot}$)	SN ejecta mass	4.5
PWN Properties:		
R_{PWN} (pc)*	PWN radius	5.0
v_p (km/s)	Pulsar velocity	400 (north)
$L_{X(2-10)}$ (erg/s)	PWN X-ray luminosity	7.2×10^{34}
$\dot{E}_0$ (erg/s)	Initial spin-down luminosity	2.8×10^{38}
n	Pulsar braking index	3.0
τ_0 (yr)	Spin-down timescale	2000
B (μG)	PWN magnetic field	11
Density Gradient:		
x	Density contrast of 12.5	1.08
H (pc)	Characteristic length scale	5.2
Orientation		East/West

Time dependent pulsar spin-down power driving the PWN:

$$\dot{E} = \dot{E}_0\left(1+\frac{t}{\tau}\right)^{-\frac{n+1}{n-1}}$$

Parameters in blue adjusted to produce the desired PWN morphology and SNR/PWN dimensions at the estimated SNR age of ~ 17,000 yr.

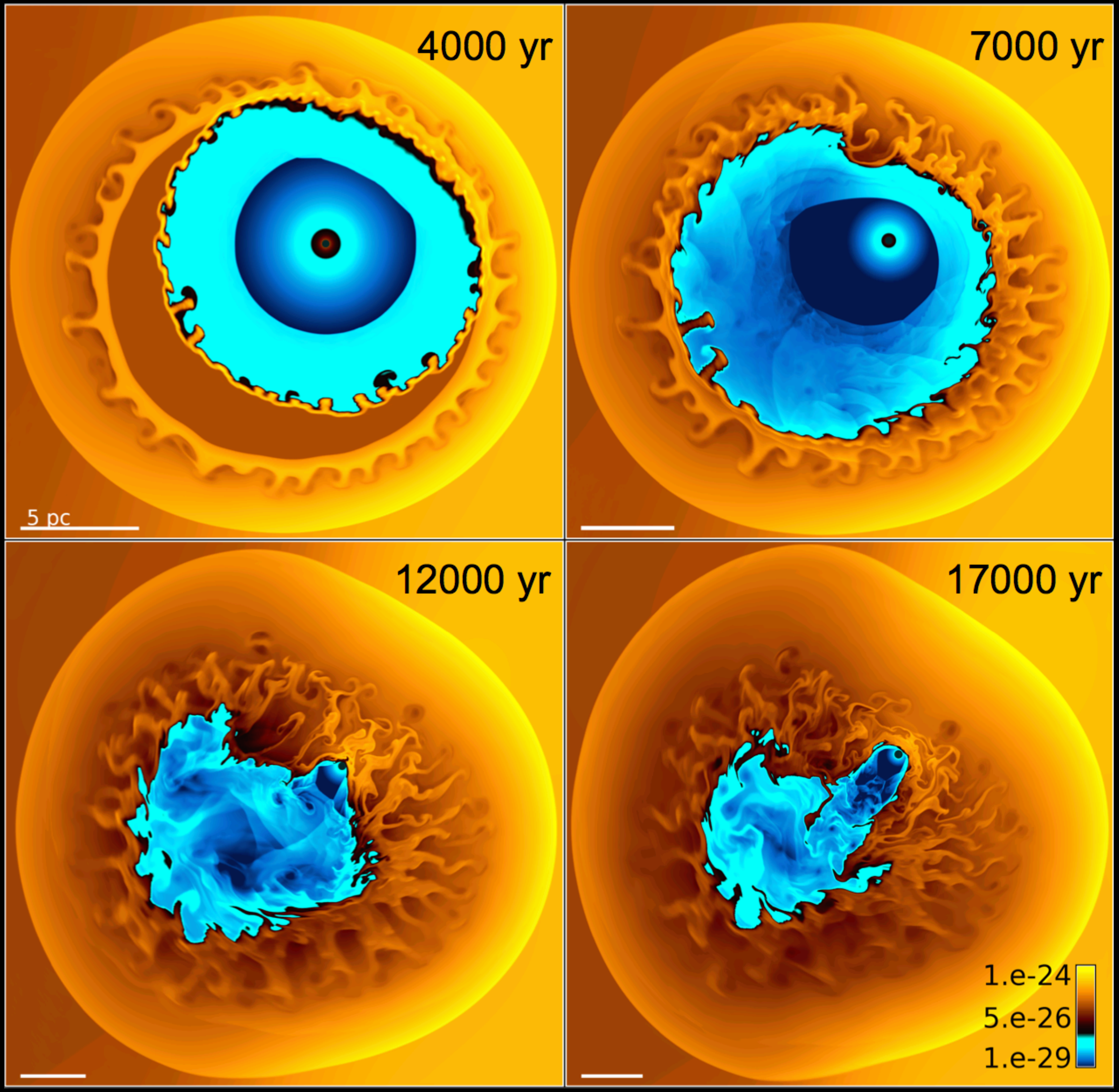
SNR Age: 00200 yr



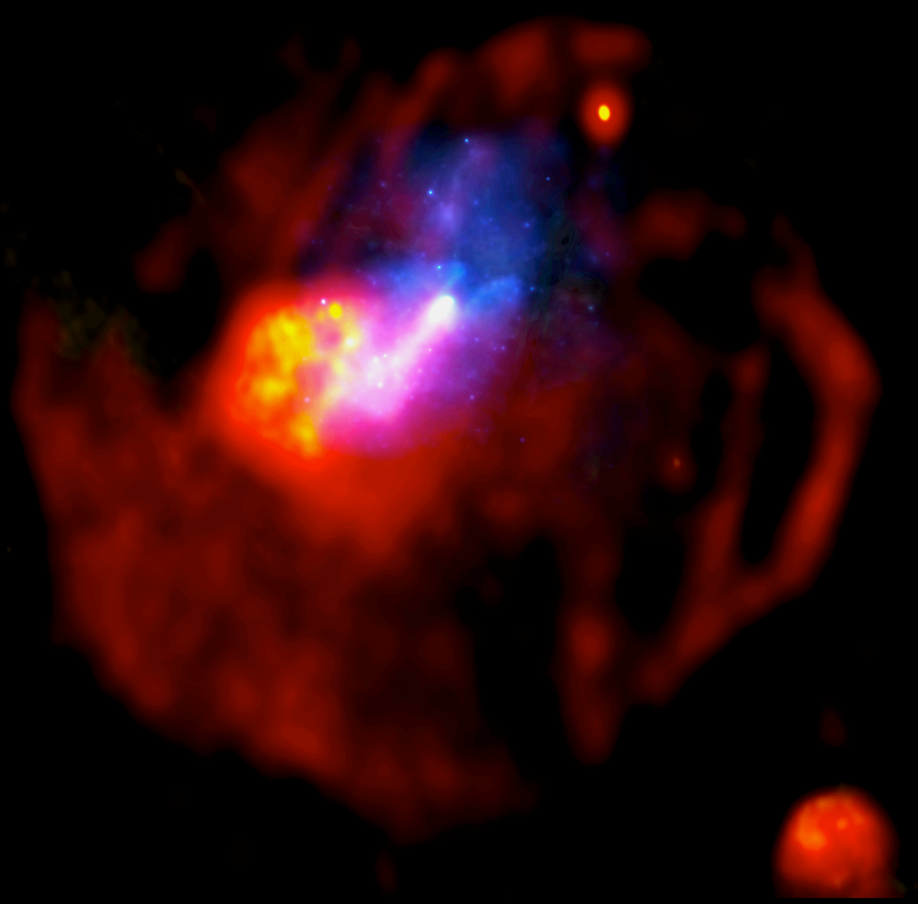
Pulsar velocity 400 km/s

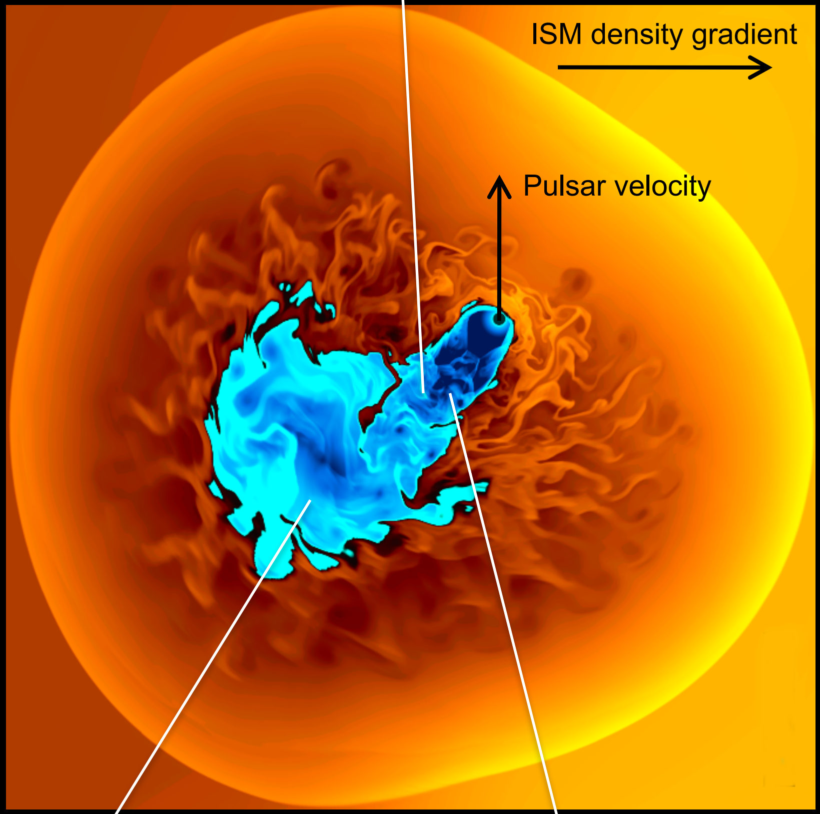
ISM density gradient

Modified VH-1 (Blondin et al. 2001)


4000 yr
5 pc
7000 yr
12000 yr
17000 yr
1.e-24
5.e-26
1.e-29

Morphology Comparison





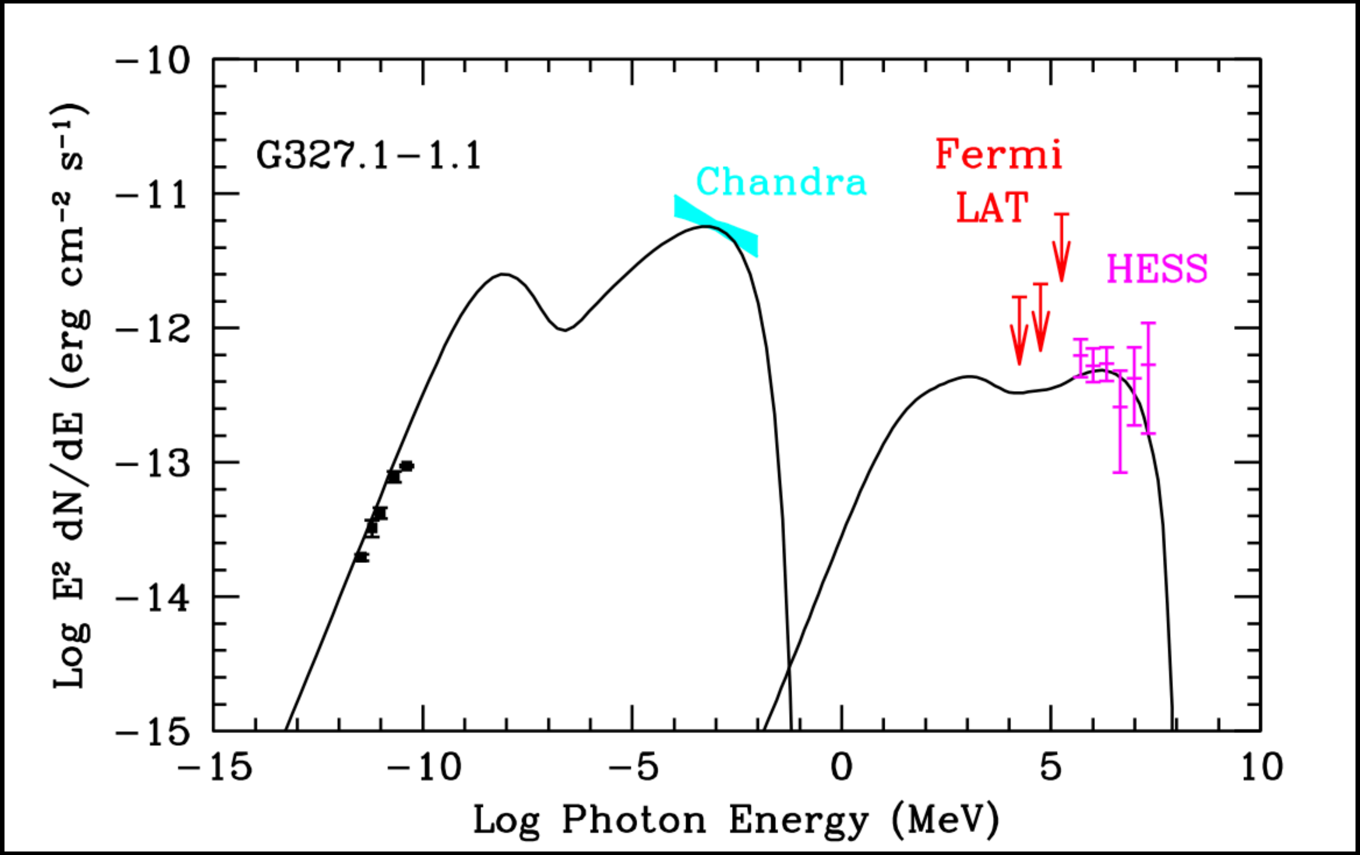
Trail thickness → pulsar's spin down luminosity

Displacement of "relic" PWN → orientation of density gradient

Orientation of trail → combination of gradient and pulsar motion direction

Temim et al. 2015

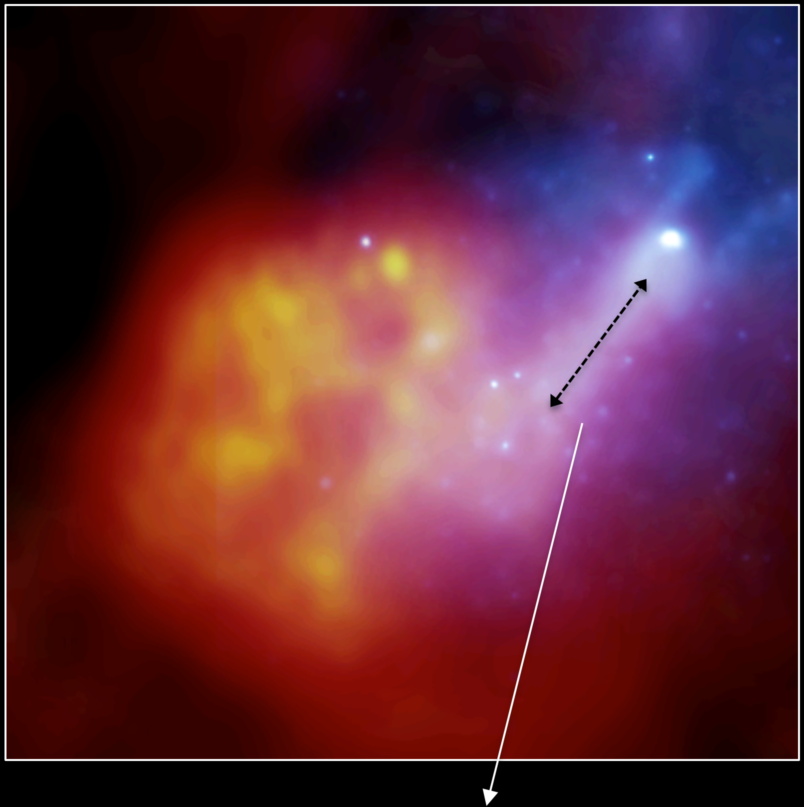
Broadband Spectrum of the PWN at 17,000 yrs

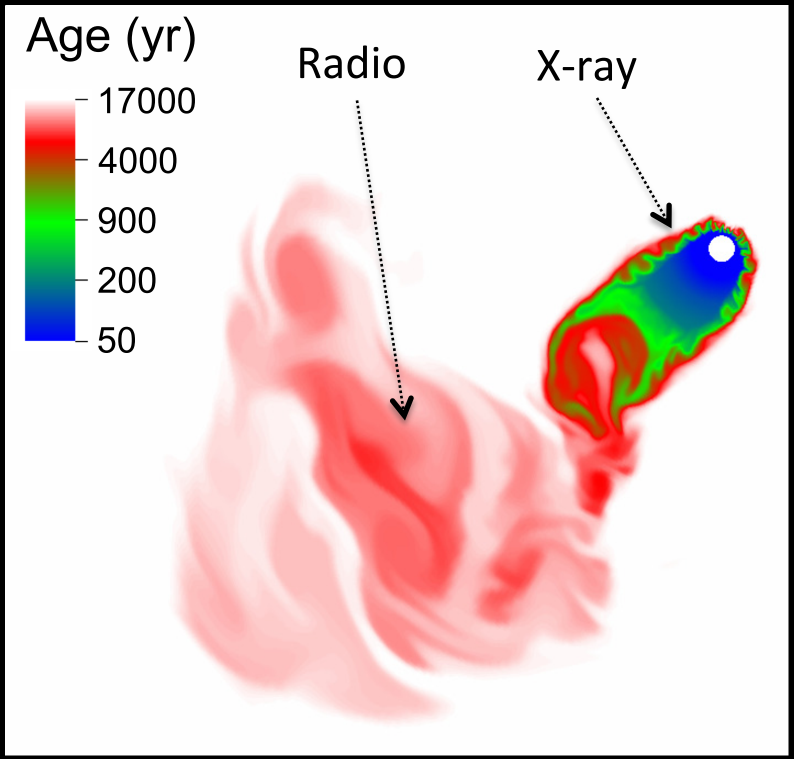


- Model for radiative evolution of the PWN - Gelfand et al. (2009)
- Input parameters from observational constraints and HD model

→ B = 11 μG and an electron energy break at 300 GeV

Age of particles injected by the pulsar at SNR age of 17,000 yr





Photon index in the trail steepens from 1.76 to 2.28:

$\Delta\Gamma = 0.52 \pm 0.17$

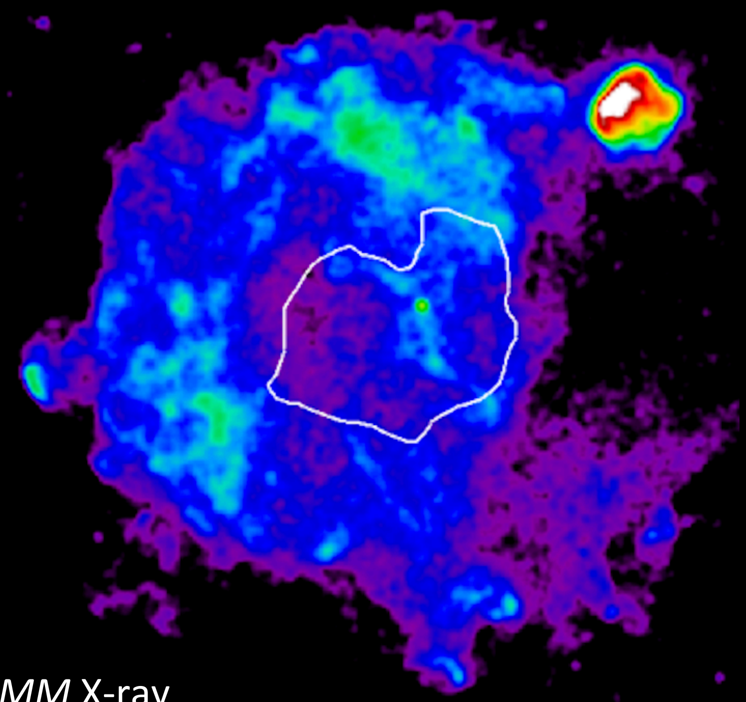
Synchrotron lifetime ~ 1700 yr

→ Expect spectral steepening of 0.5 over a synchrotron lifetime

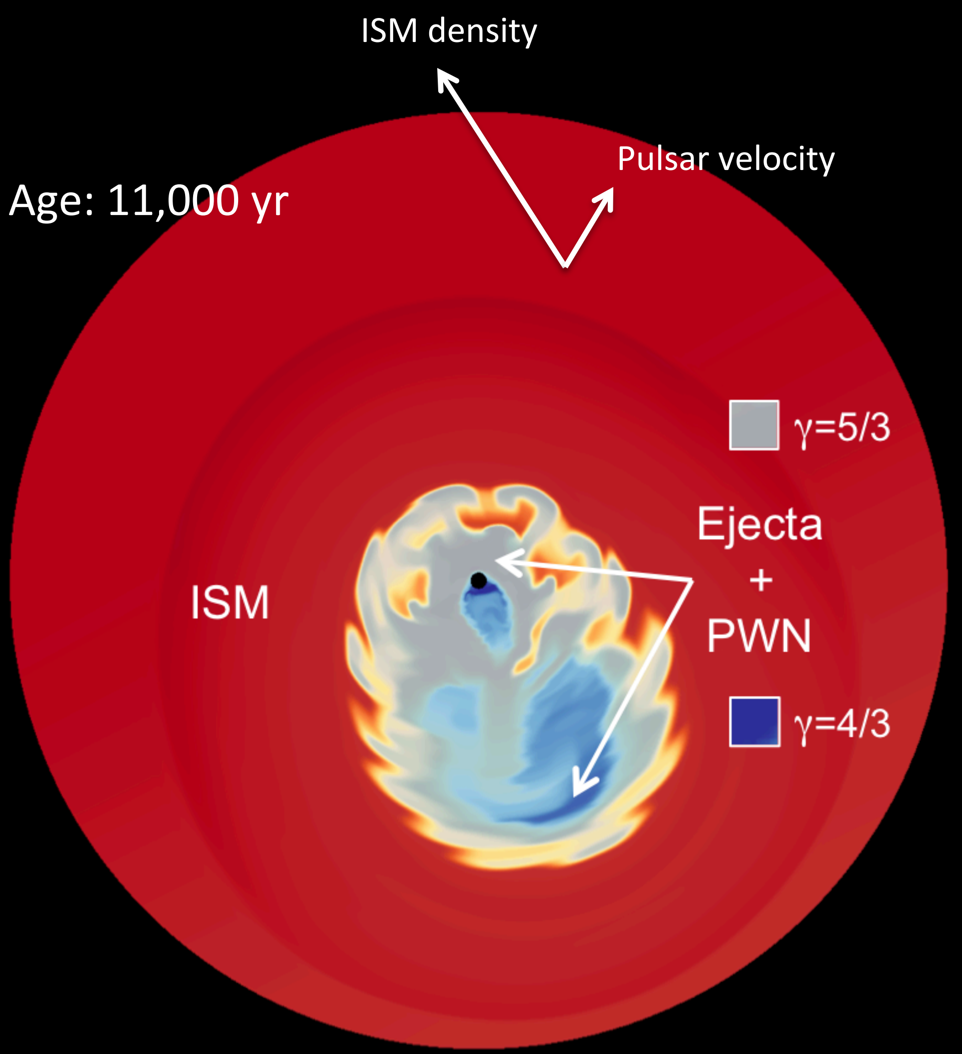
Temim et al. 2015

Vela SNR

Slane et al. 2016

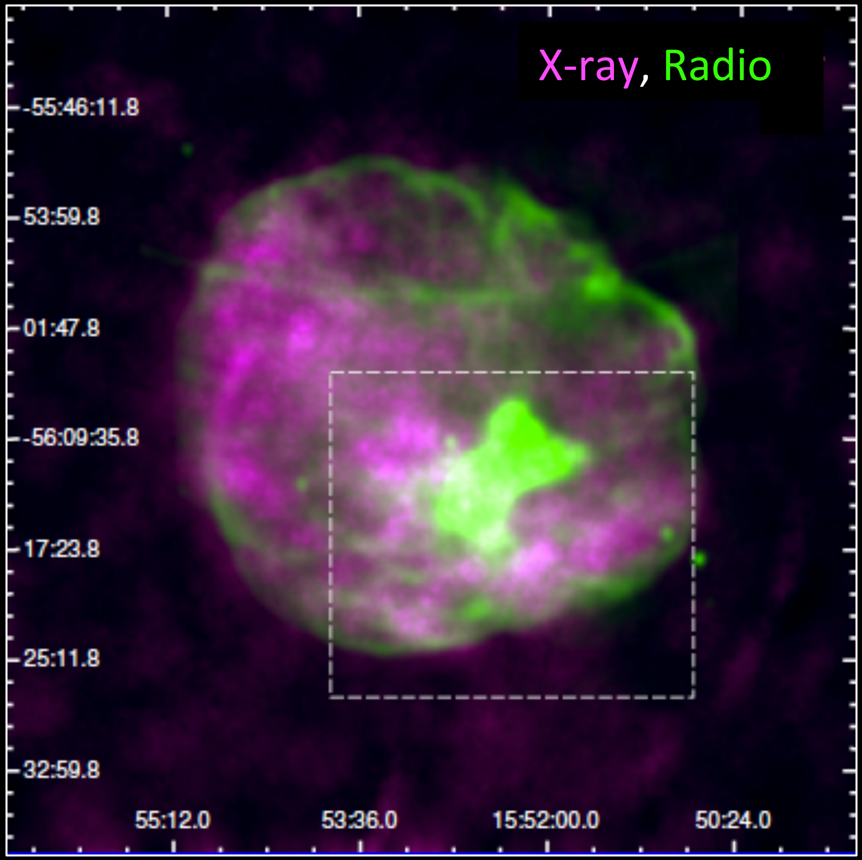


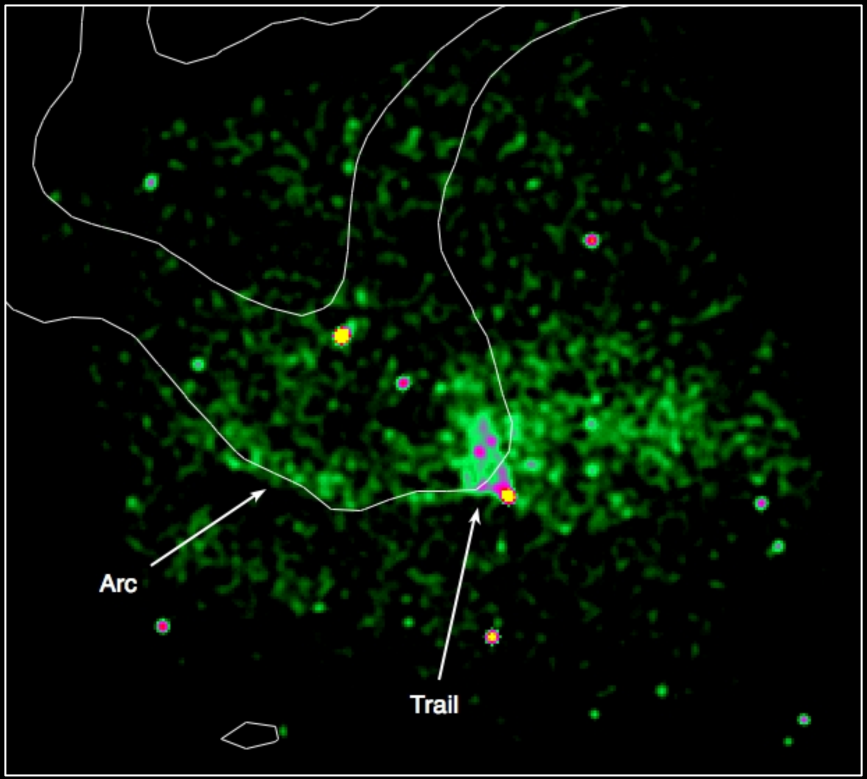
XMM X-ray



Simulation shows mixing of ejecta and PWN gas throughout the disrupted nebula, consistent with observations *(LaMassa et al. 2008)*

RS Interaction in SNR MSH 15-56





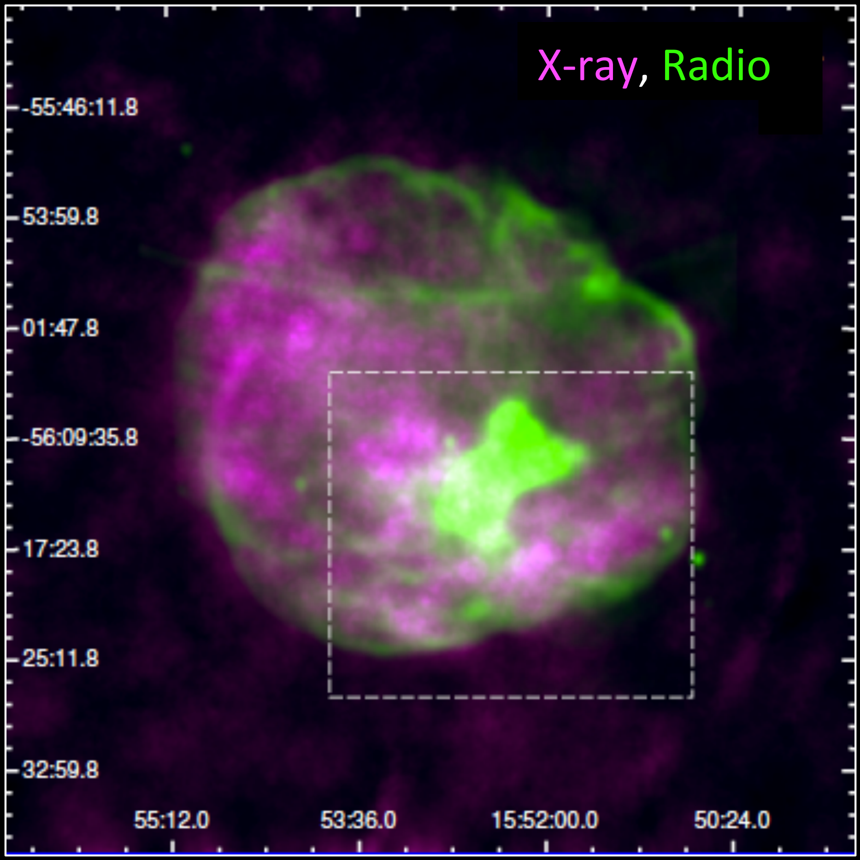
Chandra 56 ks

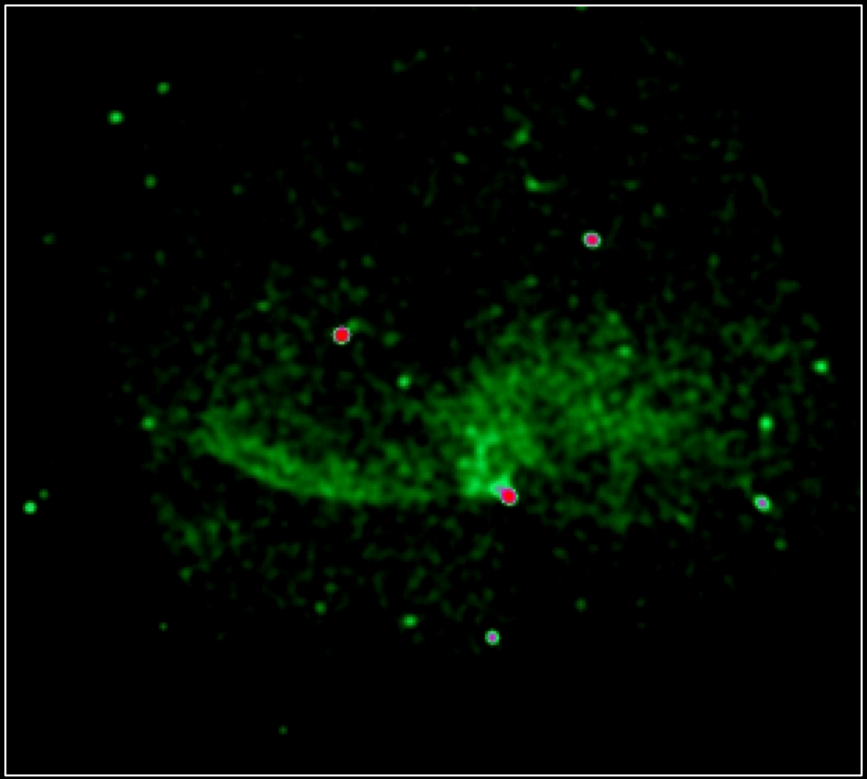
Temim et al. 2013

New *Chandra* observation of the PWN region provides 15 yr baseline to measure the pulsar's velocity

See Poster S1.4 (J. Devin) on γ-ray emission from MSH 15-56

RS Interaction in SNR MSH 15-56



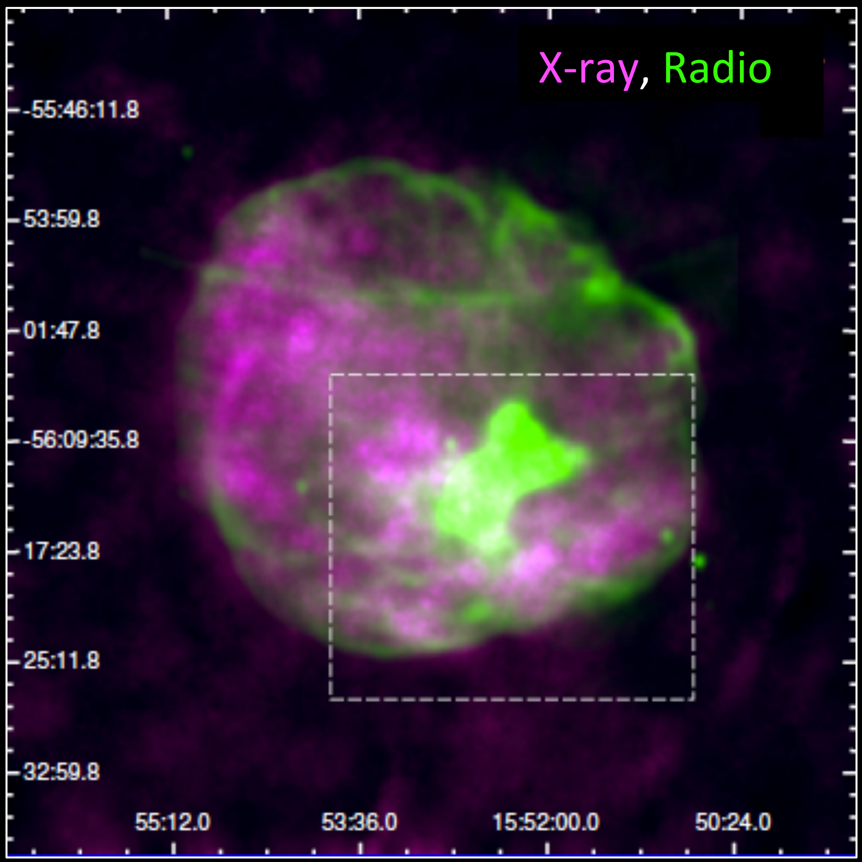


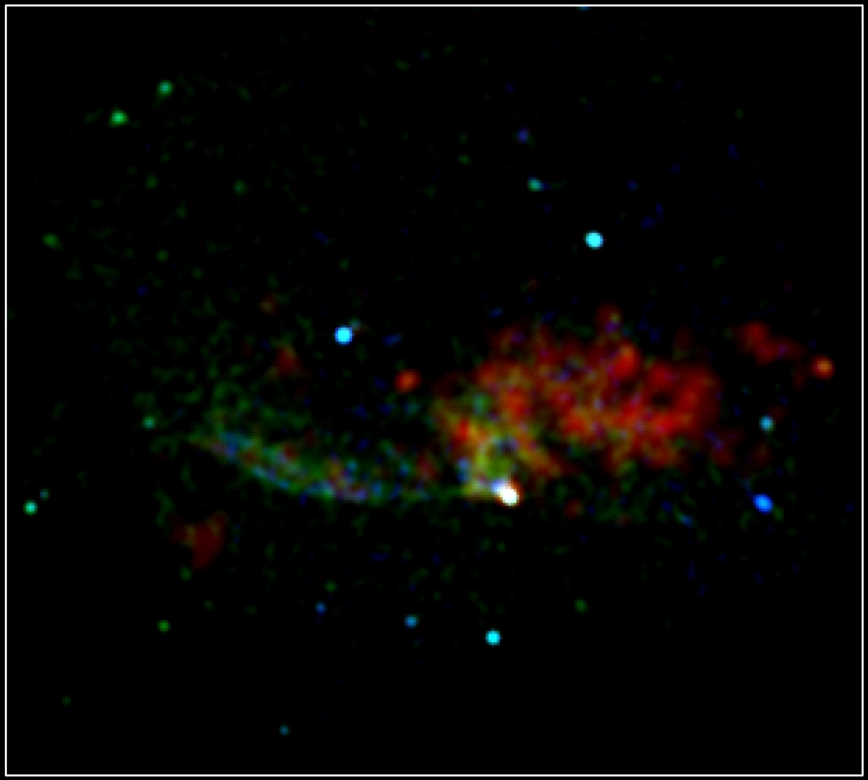
Chandra 175 ks

New *Chandra* observation of the PWN region provides 15 yr baseline to measure the pulsar's velocity

See Poster S1.4 (J. Devin) on γ-ray emission from MSH 15-56

RS Interaction in SNR MSH 15-56





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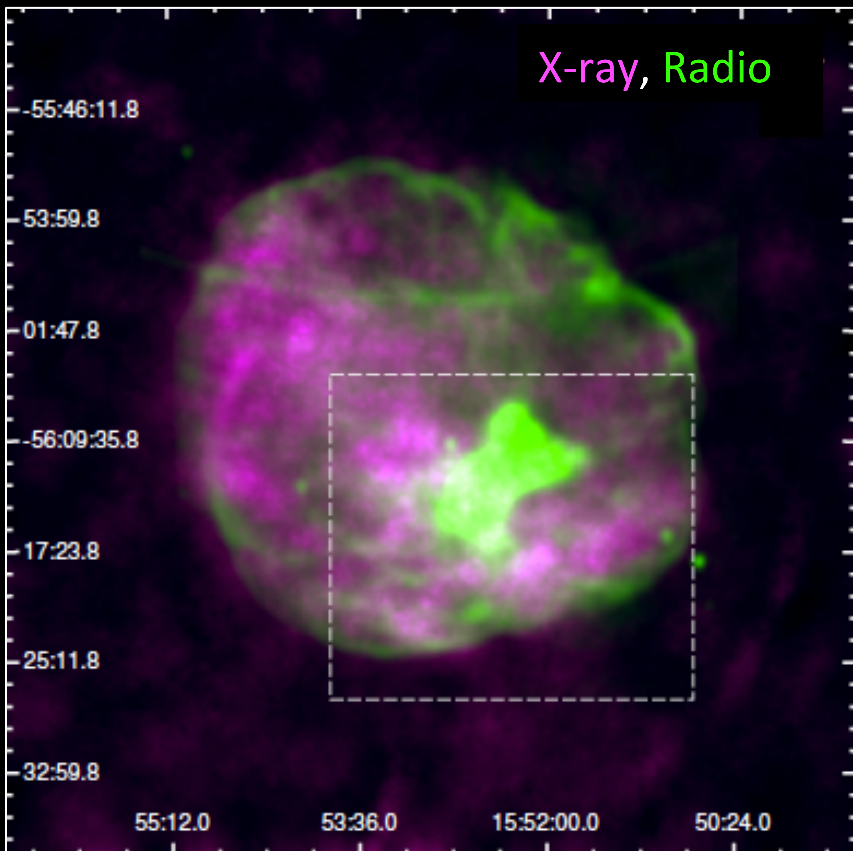
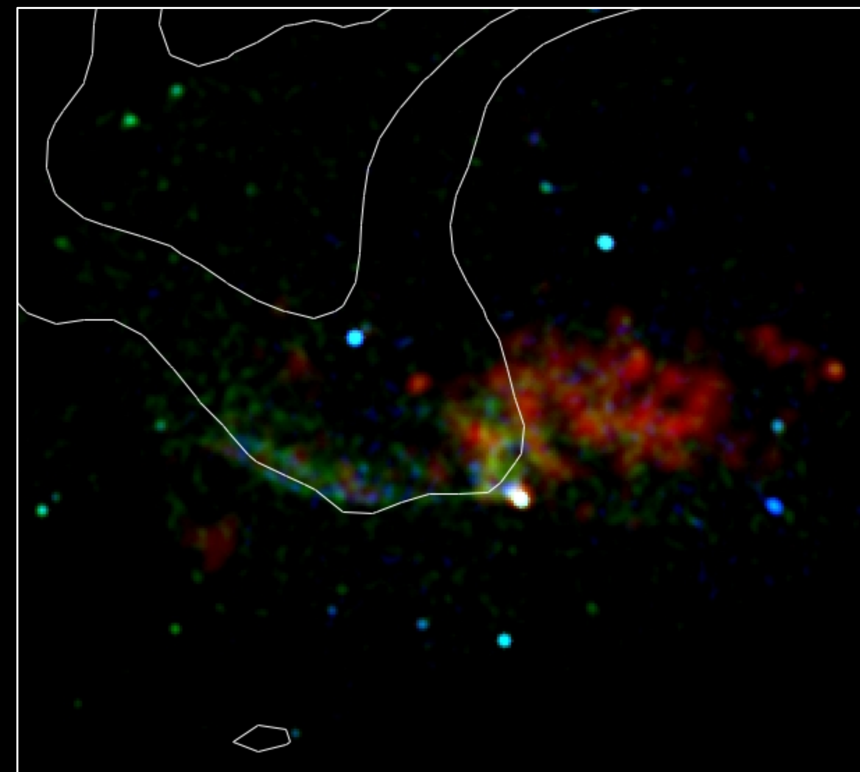




Chandra 175 ks

New *Chandra* observation of the PWN region provides 15 yr baseline to measure the pulsar's velocity

See Poster S1.4 (J. Devin) on γ-ray emission from MSH 15-56

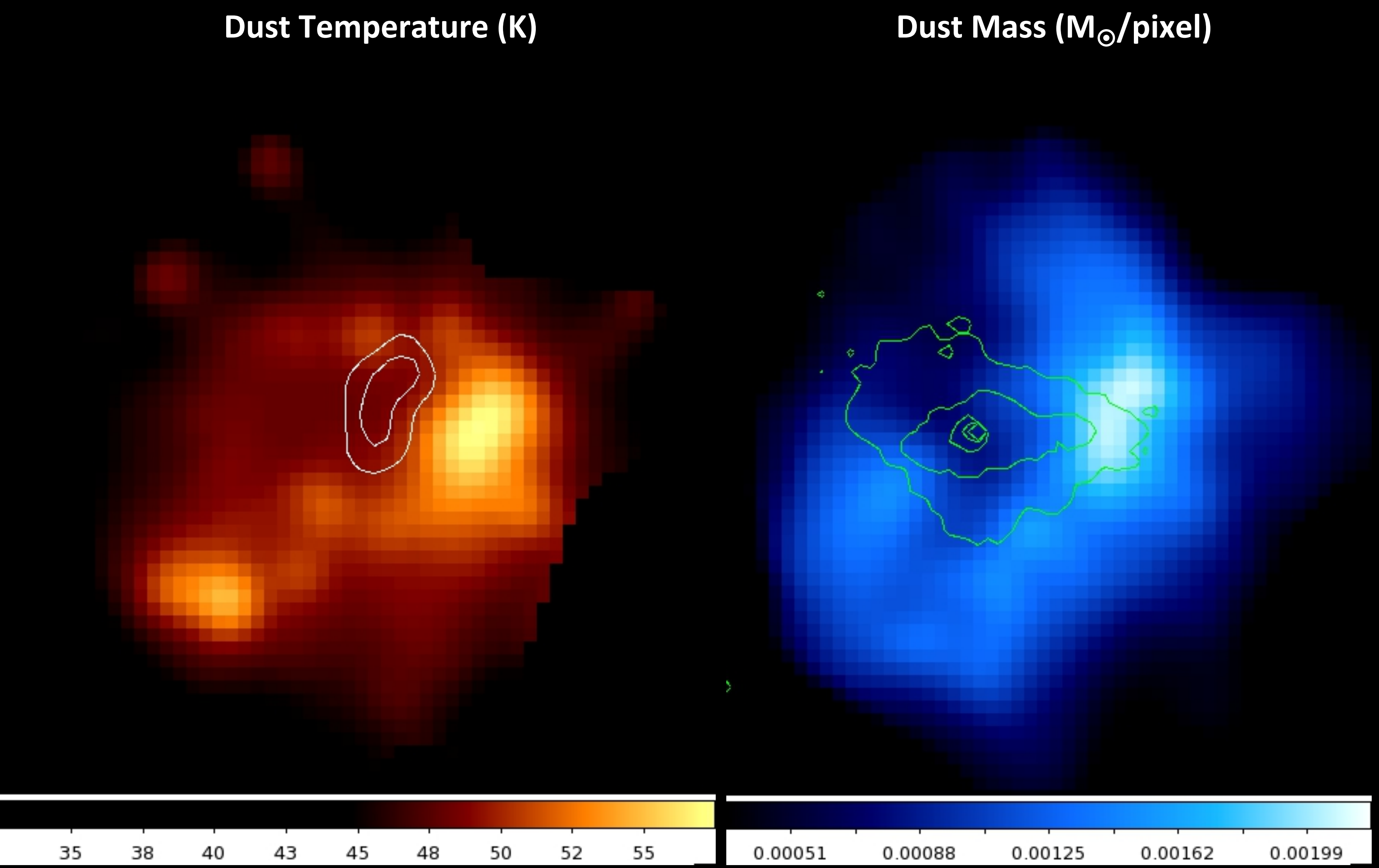
Conclusions

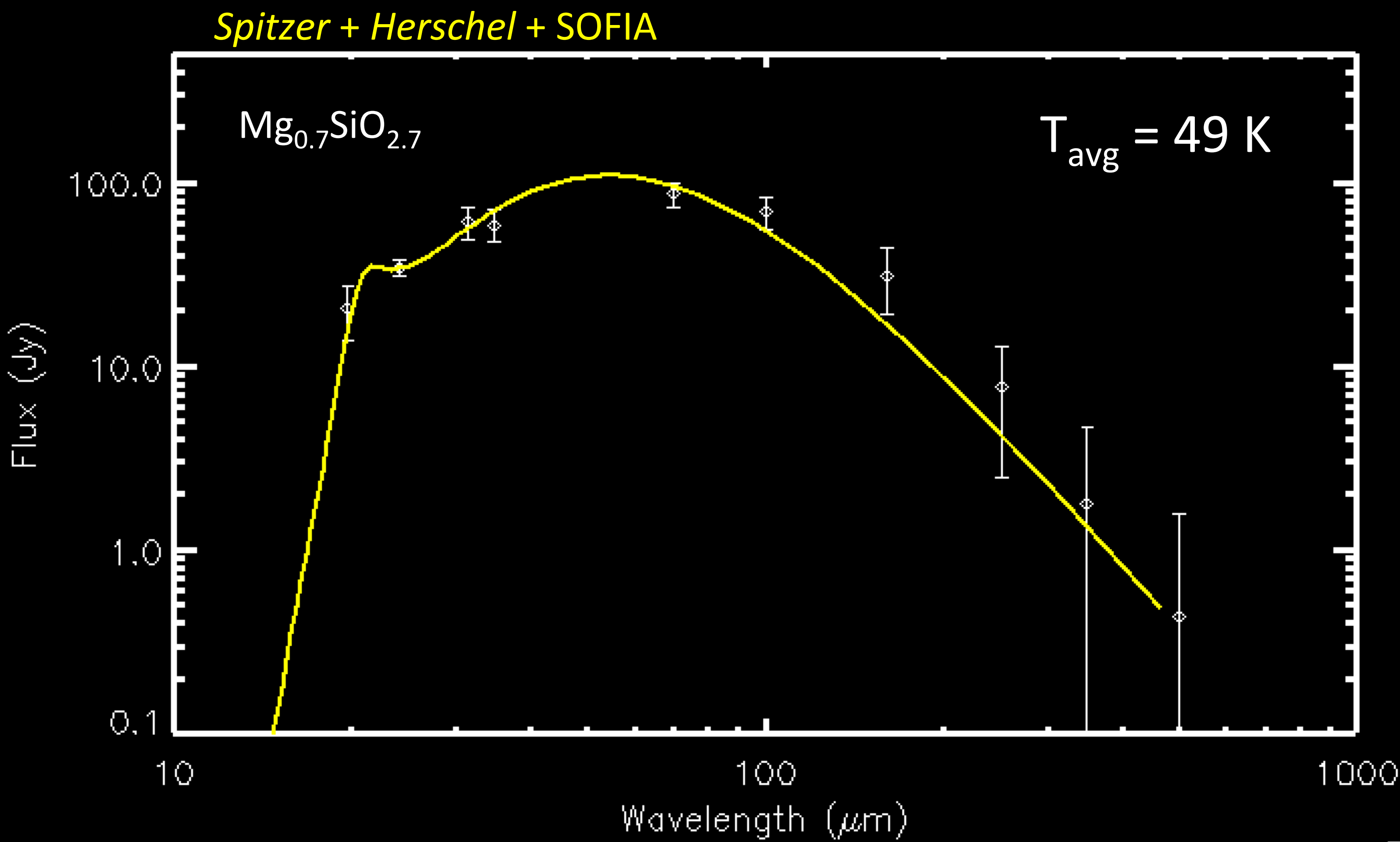
- Multi-wavelength observations of PWNe inside SNRs at various stages of evolution have significantly improved our understanding of composite SNRs

- Young PWN expanding into SN ejecta give insight into PWN/SNR dynamics, properties of the SN ejecta and dust, and nature of the SN progenitor

- New HD simulations of evolved systems give insight into the structure and evolution of composite SNRs and clues on what physical parameters determine the morphology of the systems → information about ambient ISM, SN ejecta, pulsar properties, energetic particle population

- Future studies combining HD and radiative evolution models with detailed observational constraints will improve our understanding of the PWN/SNR interaction


Dust Temperature (K)
Dust Mass (M$_\odot$/pixel)
35
38
40
43
45
48
50
52
55
0.00051
0.00088
0.00125
0.00162
0.00199



$M_d \geq 0.3\ M_\odot$ Largest after SN 1987A

$20 - 30\ M_\odot$ progenitor

Temim et al. 2016, in prep