Progenitor Properties of Composite Supernova Remnants

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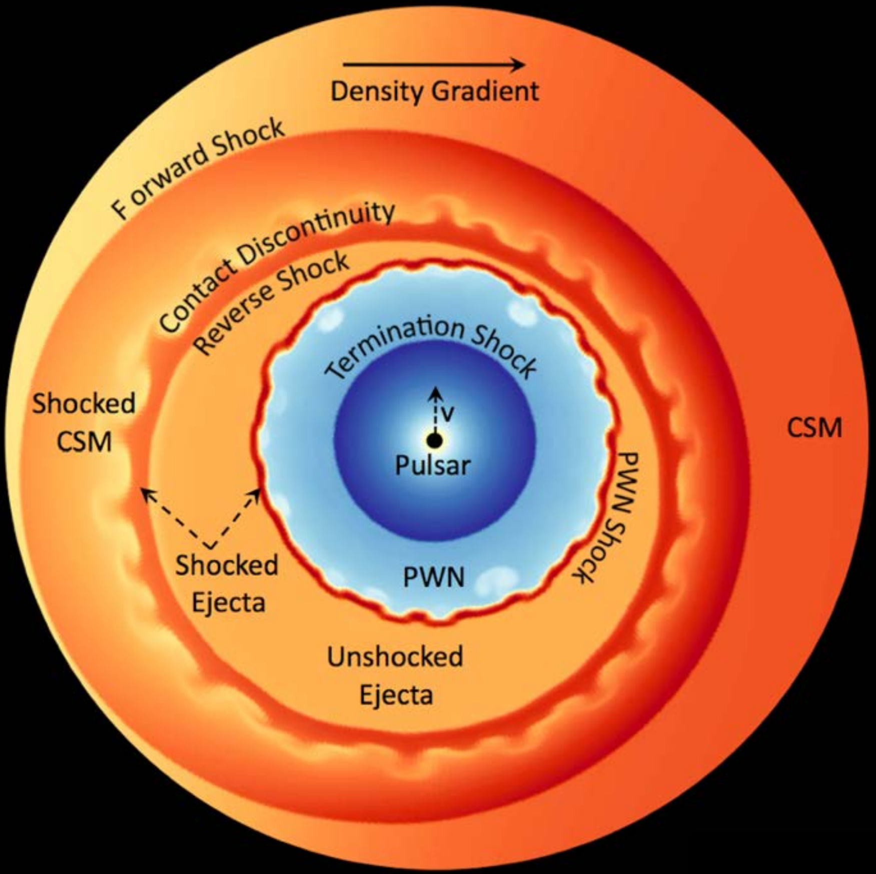
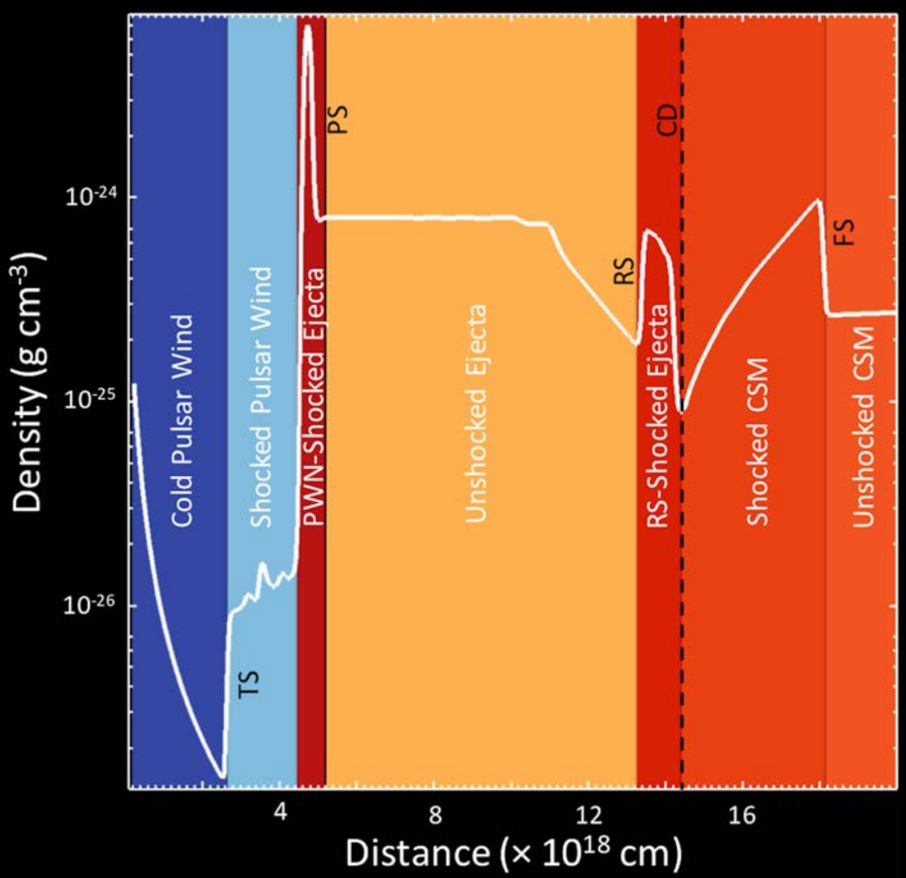
SNR2019, Chania – June 5, 2019

Image credit: NASA/CXC/H.Matheson & S.Safi-Harb

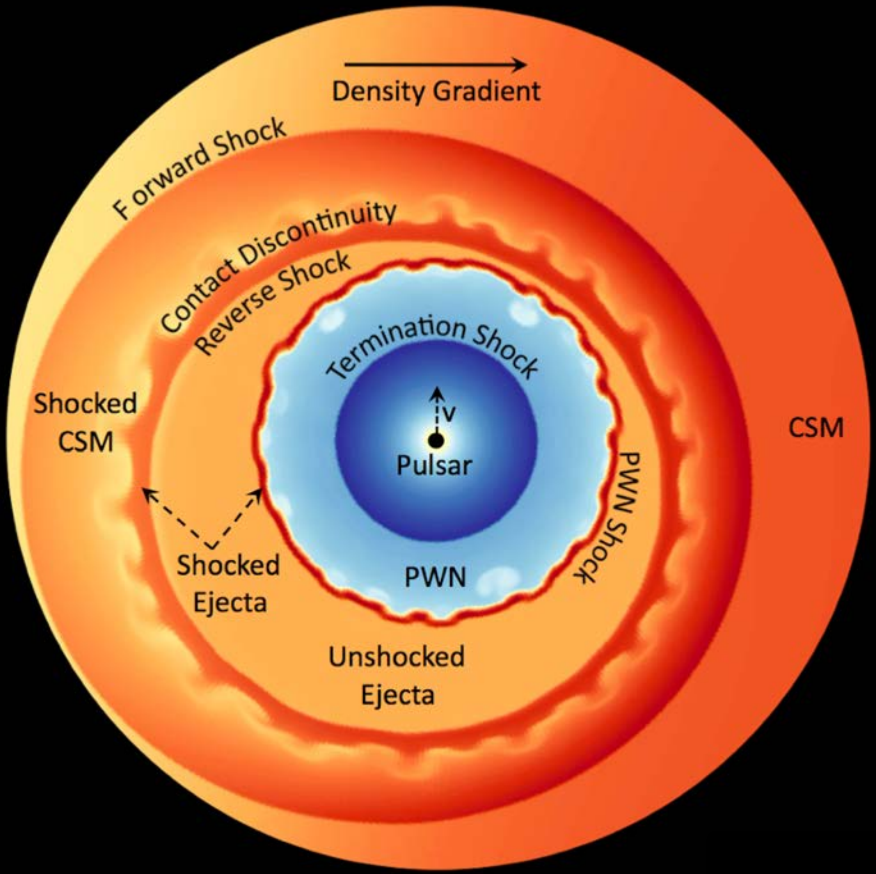
Structure of a Composite SNR





Slane 2016

Evolutionary Stages



Early evolution:

PWN drives a shock into the inner SN ejecta

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

(e.g., Chevalier 1977, Reynolds & 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)

Slane 2016

Progenitor & Explosion Properties

- Young systems
  - Dynamical modeling of the PWN expansion
  - Probe innermost SN ejecta abundances
  - Constrain SN dust properties
- Older systems
  - Probe SN ejecta (reverse-shocked or mixed-in with PWN)
  - Model the SNR evolution & PWN's interaction with the SNR reverse shock to constrain properties (ejecta mass, ISM/CSM environment, pulsar kick)

The PWN in Kes 75

Chandra X-ray (Gavriil et al. 2008)

PWN radius = 15” (0.4 pc @ 5.8 kpc)

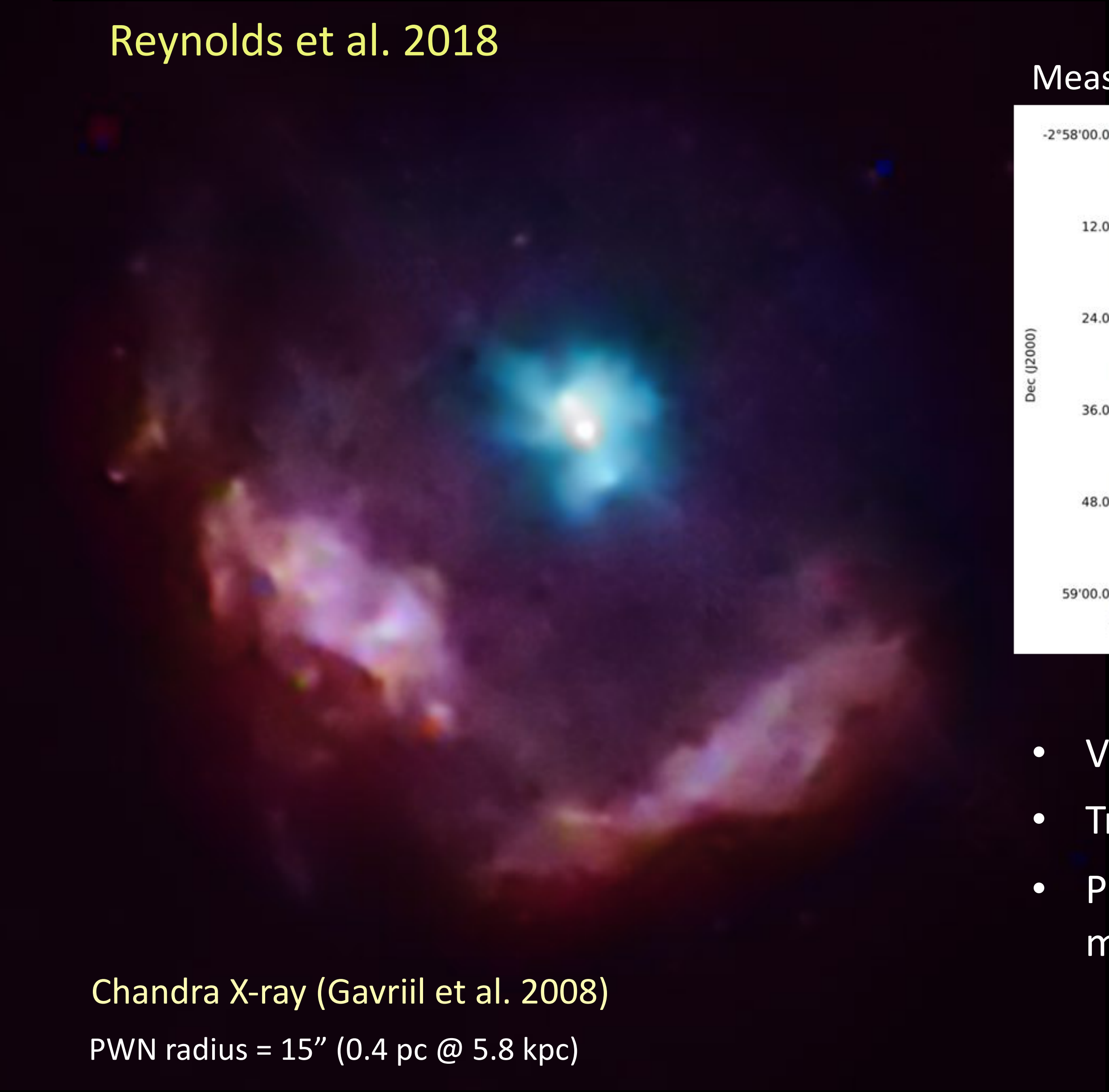
Youngest known pulsar
(Reynolds et al. 2018)

Magnetar-like activity
(e.g. Gavriil et al. 2008)

Previously hypothesized to have resulted from a Type Ib/c explosion (large size and clumpy CSM, but based on d=19 kpc)
(e.g. Helfand et al. 2003, Chevalier 2005)

The PWN in Kes 75

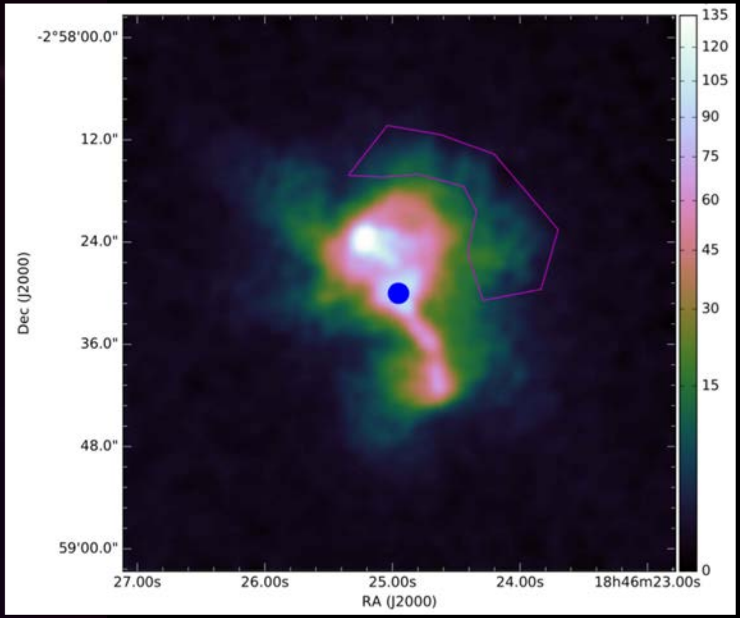
Reynolds et al. 2018



Chandra X-ray (Gavriil et al. 2008)

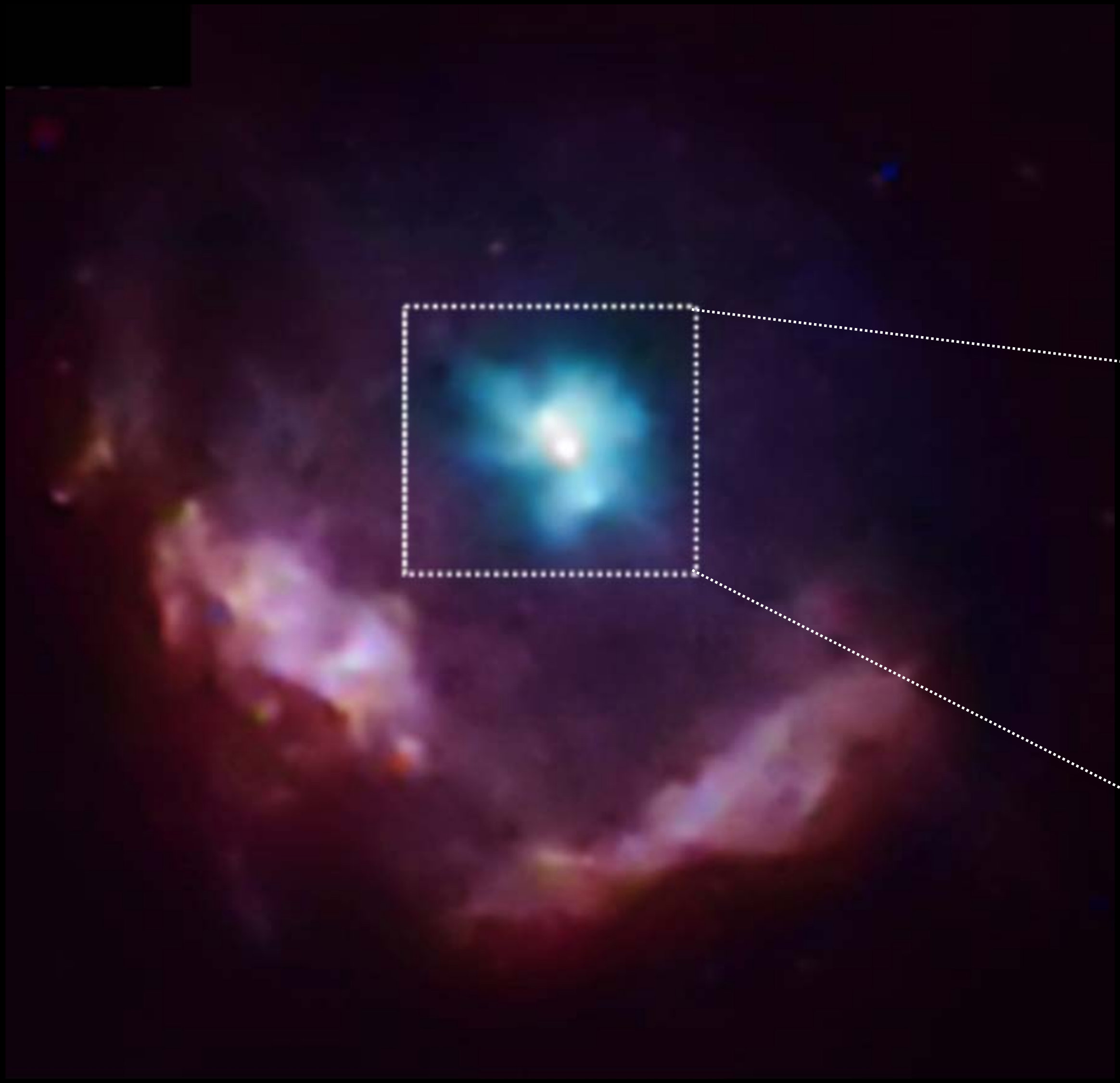
PWN radius = 15” (0.4 pc @ 5.8 kpc)

Measured expansion from 2006 to 2016

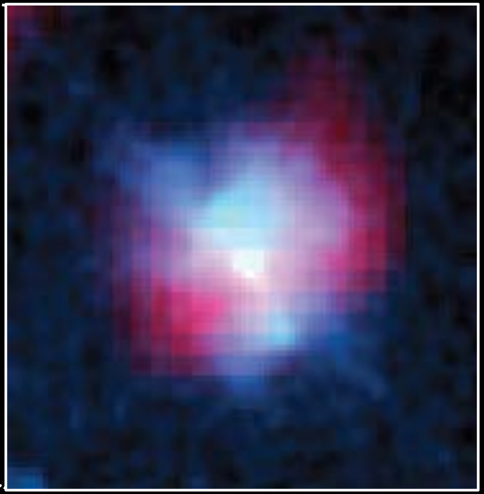


- V_{PWN} = 1000 km/s
- True age of the pulsar ≈ 500 yr
- Proposed to have results from a more typical Type IIP explosion

The innermost ejecta in Kes 75



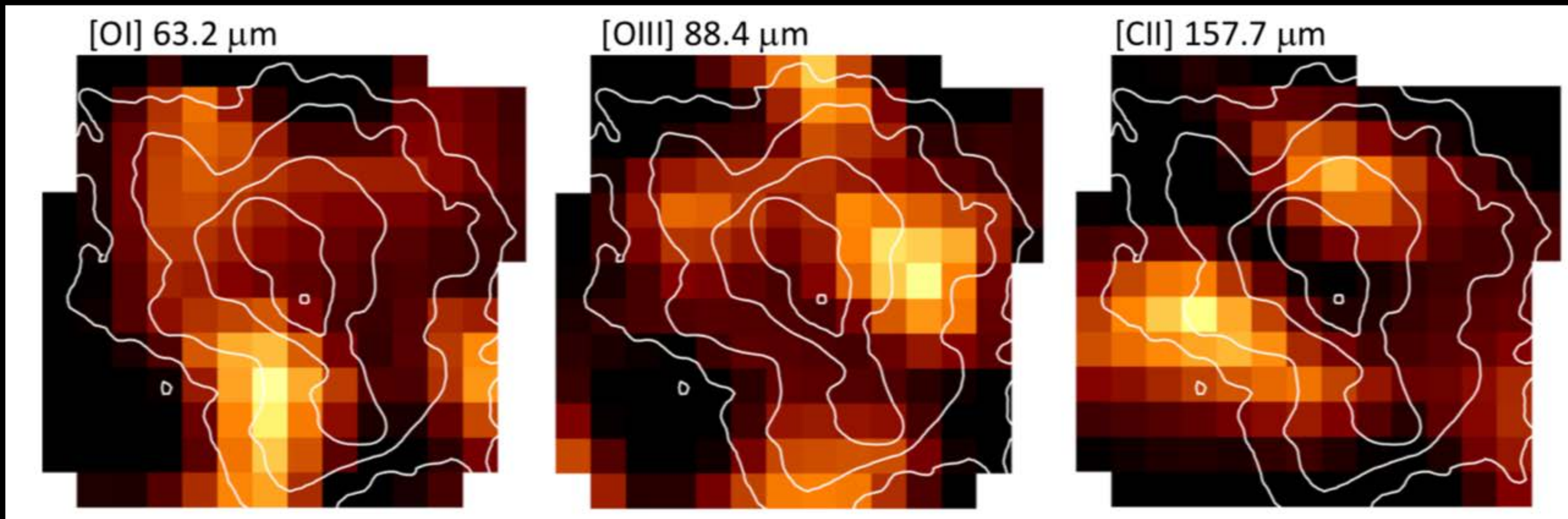
Far-infrared emission detected around the pulsar wind nebula

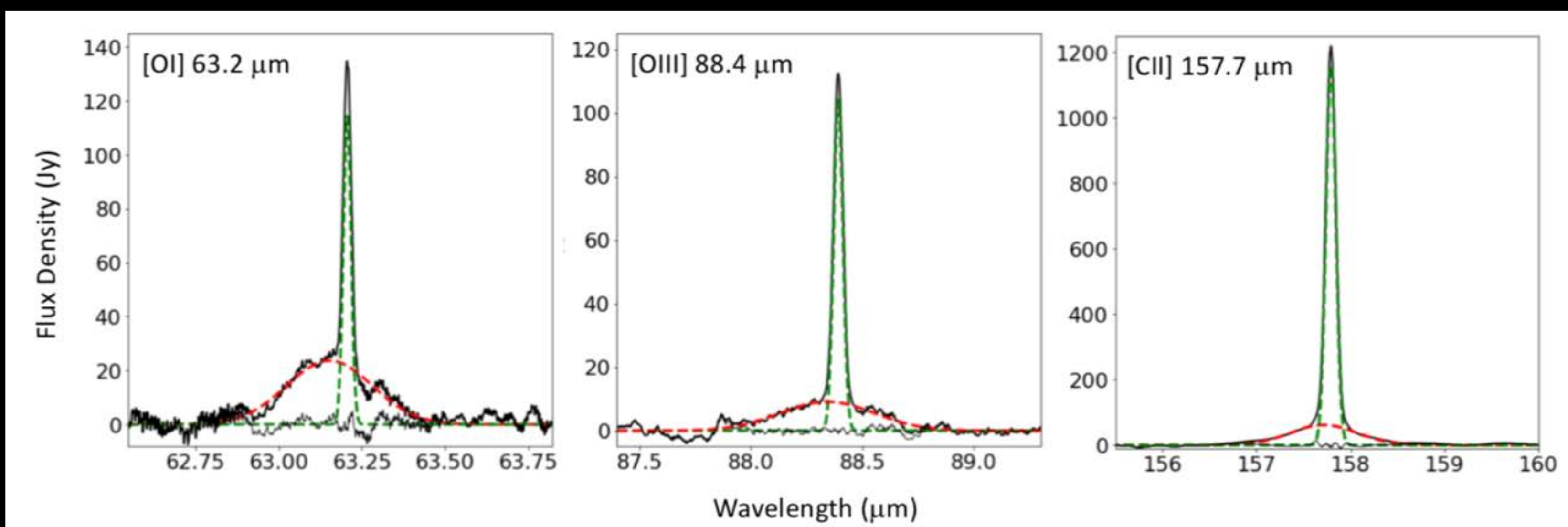


Herschel 70 μm
Chandra X-ray

T. Temim, P. Slane, T. Sukhbold, B. Koo, J.C. Raymond, J.D. Gelfand, ApJL, 2019

The innermost ejecta in Kes 75

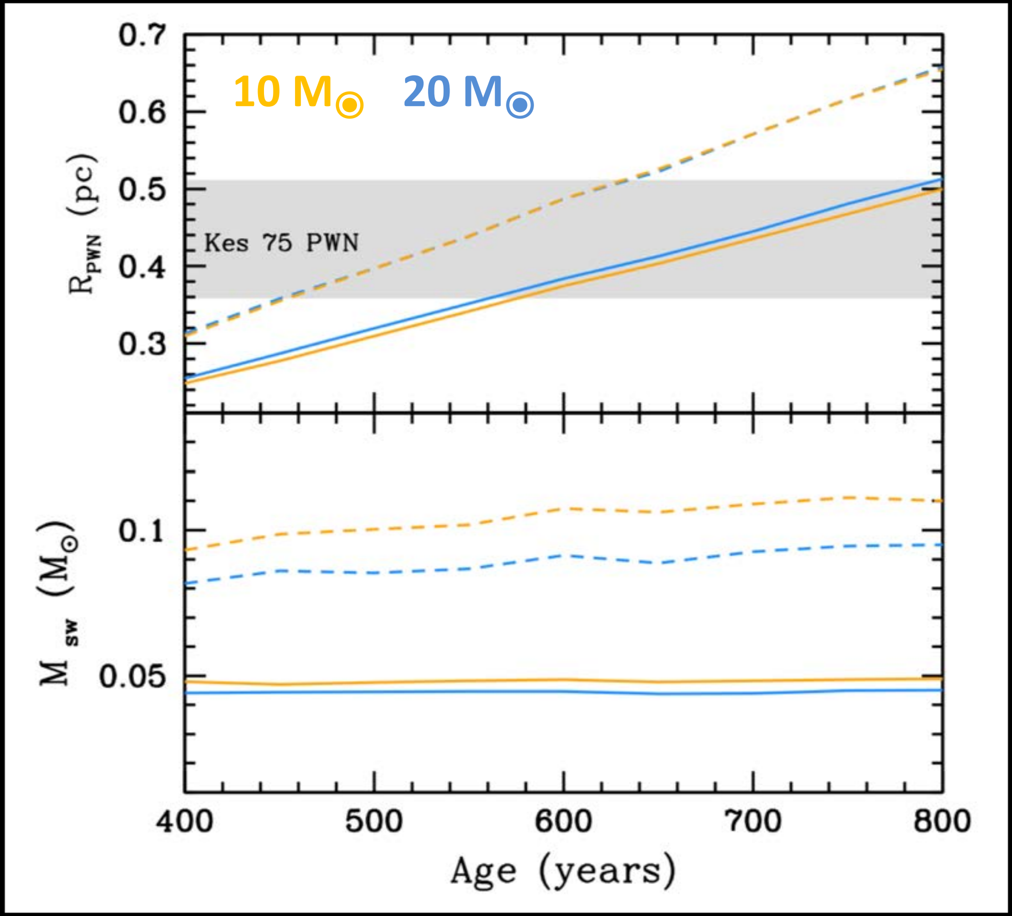




$V_{ej} \approx 750$ km/s

T. Temim, P. Slane, T. Sukhbold, B. Koo, J.C. Raymond, J.D. Gelfand, ApJL, 2019

How much material has been swept-up?



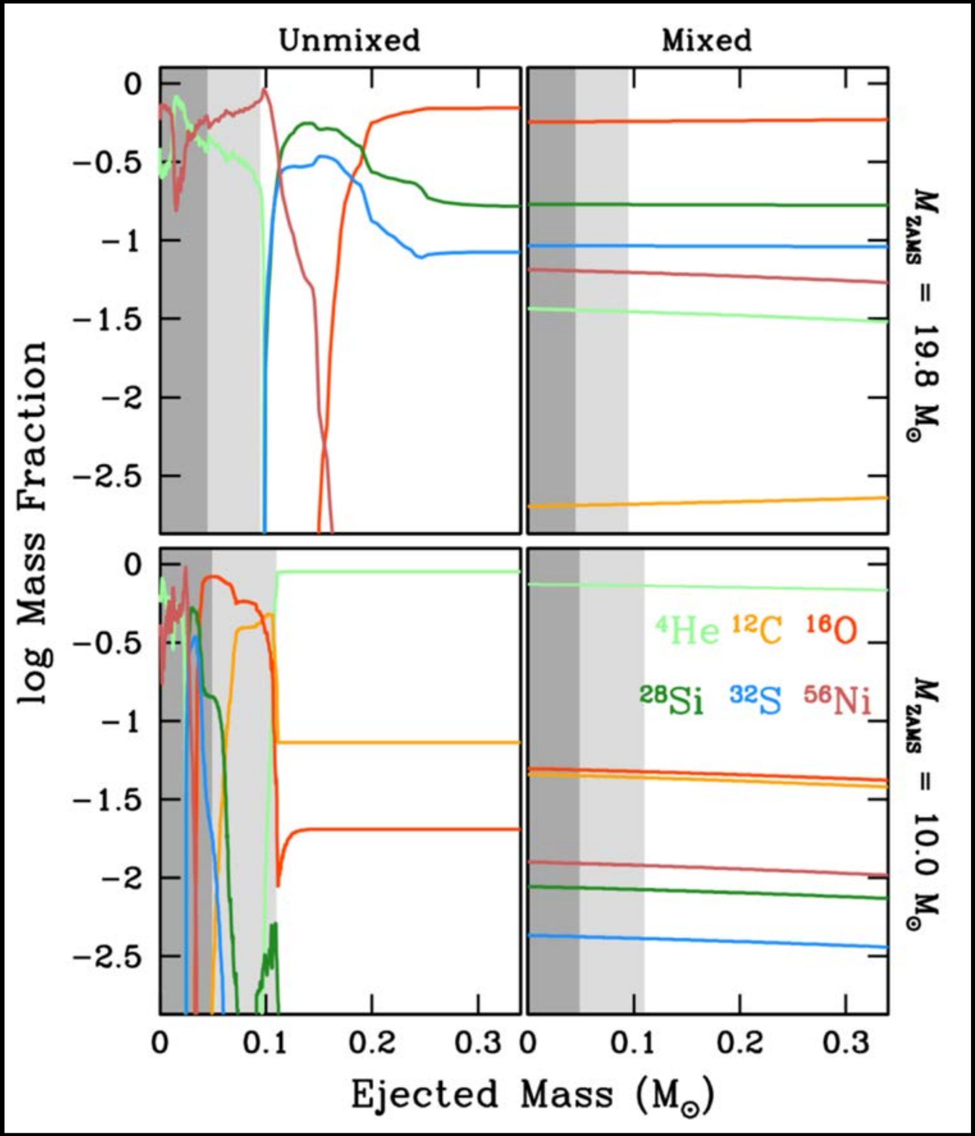
HD MODEL INPUT PARAMETERS

Run	E_{51} (10^{51} erg)	M_{ej} ($M_\odot$)	n_0 (cm^{-3})	$\dot{E}_{0,38}$ (erg s^{-1})	n_{psr}	τ_0 (yr)
1	2.1	16.3	2.00	1.66×10^{38}	2.12	226
2	0.6	8.2	0.25	1.66×10^{38}	2.12	226

HD simulation results: Only 0.05-0.1 $M_\odot$ of ejecta so far swept up by the PWN

Temim et al. 2019

What are the abundance fractions at the shock?



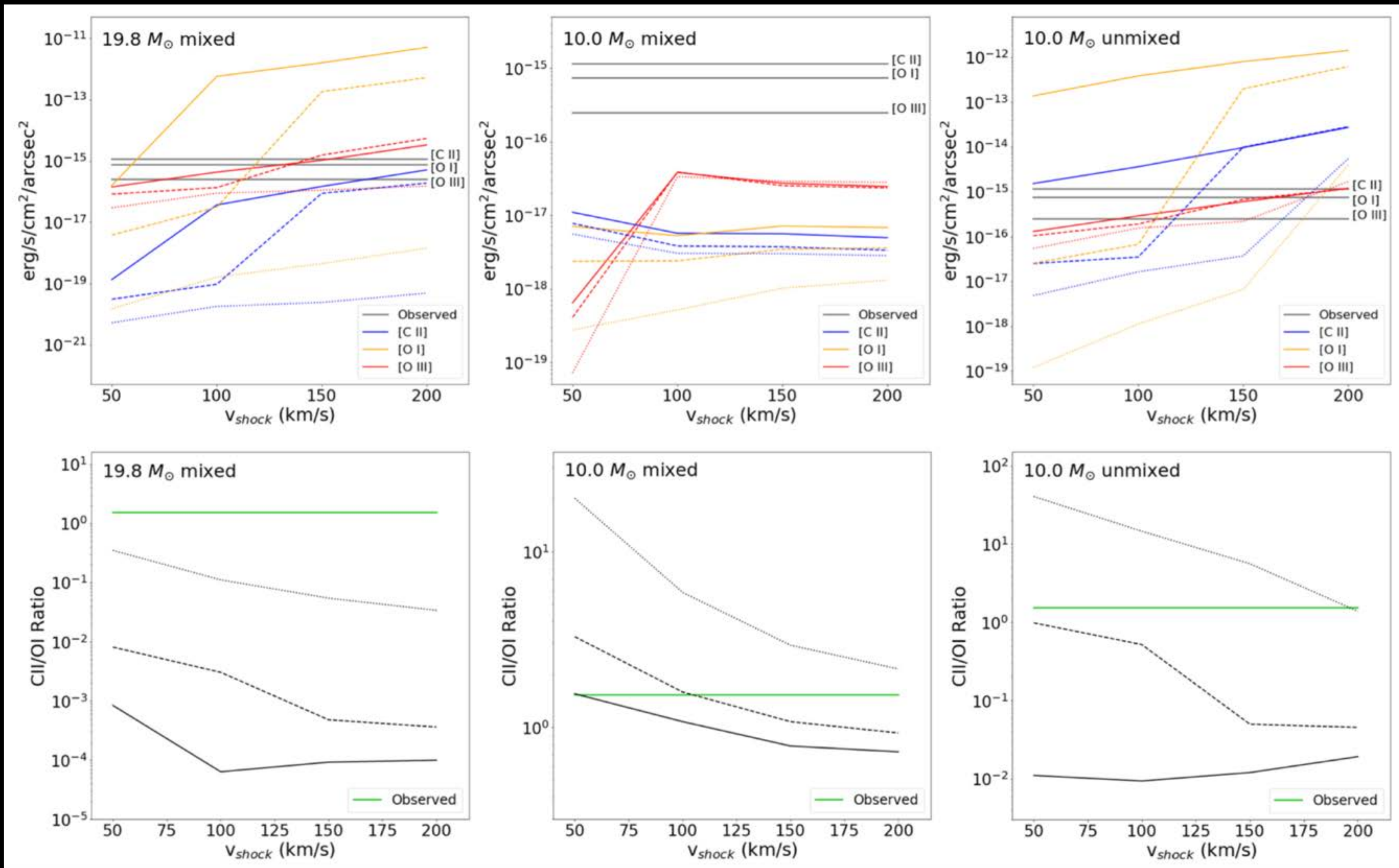
Ejecta composition vs. mass coordinate for two progenitor masses (based on models of Sukhbold et al. 2006)

Left panels: Ejecta distribution assuming no mixing

Right panels: Ejecta distribution after applying artificial mixing profile

Temim et al. 2019

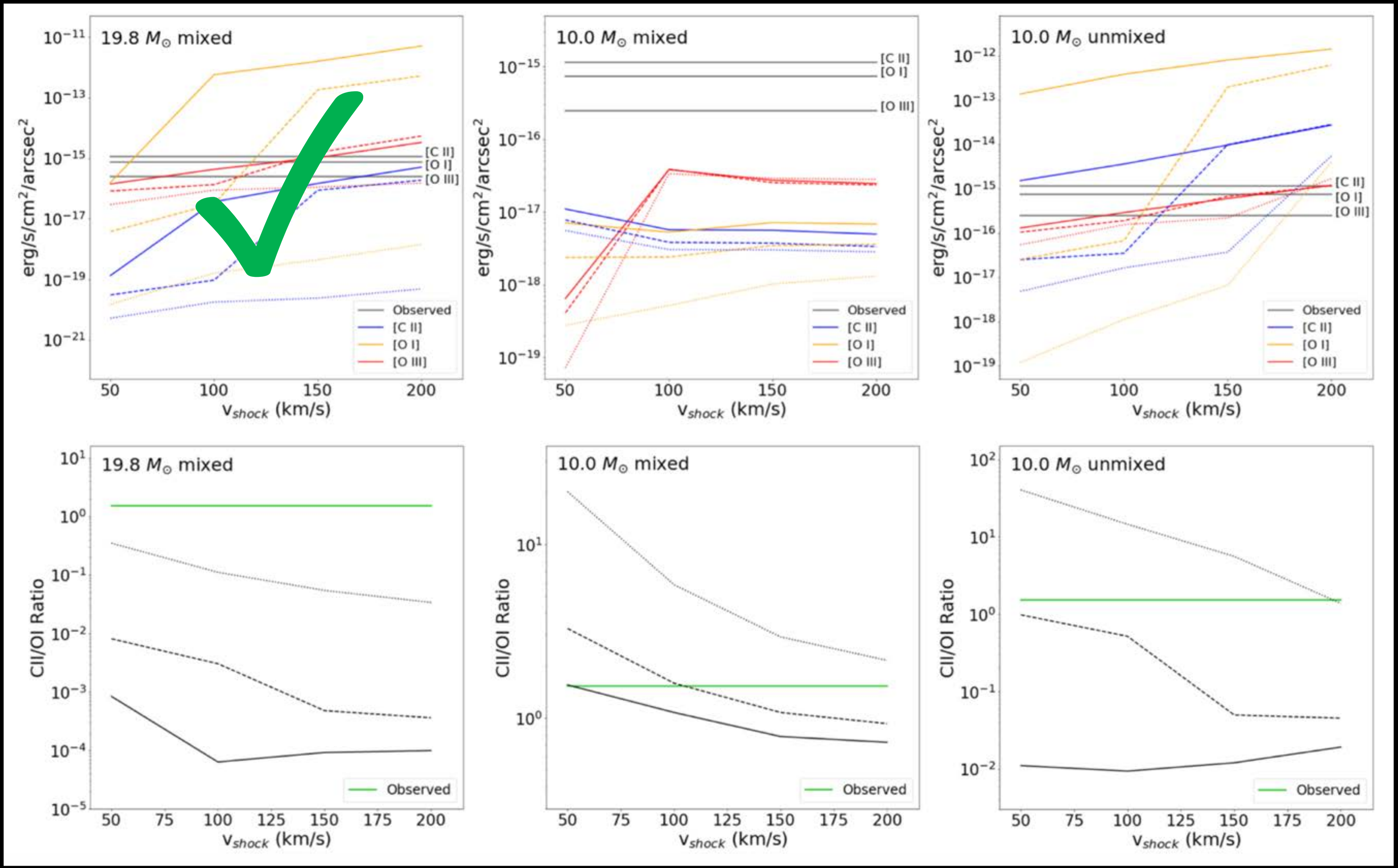
What do shock models predict?



1D HD code for planar shocks (Raymond 1979, Cox & Raymond 1985)

Temim et al. 2019

What do shock models predict?



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Temim et al. 2019

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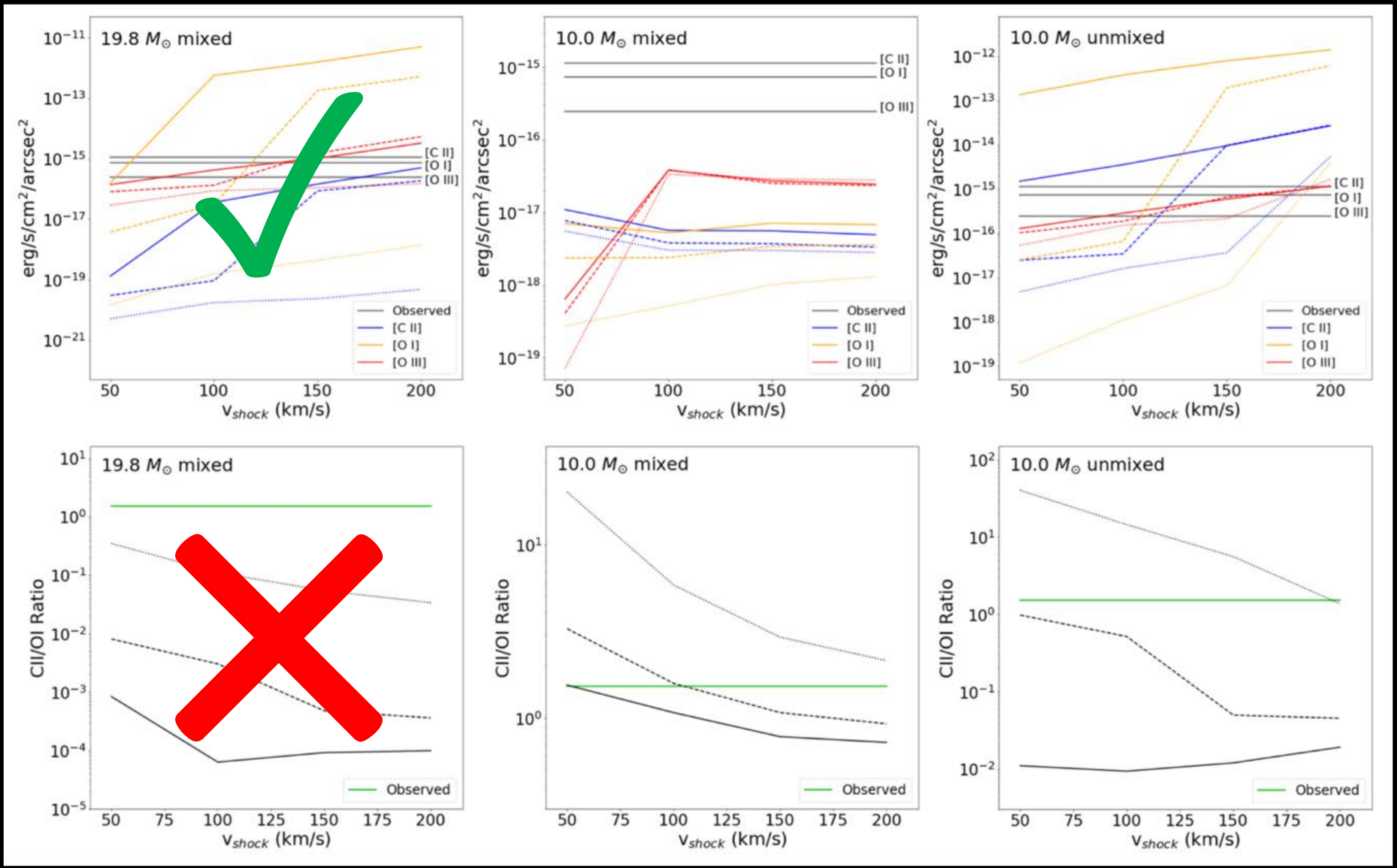

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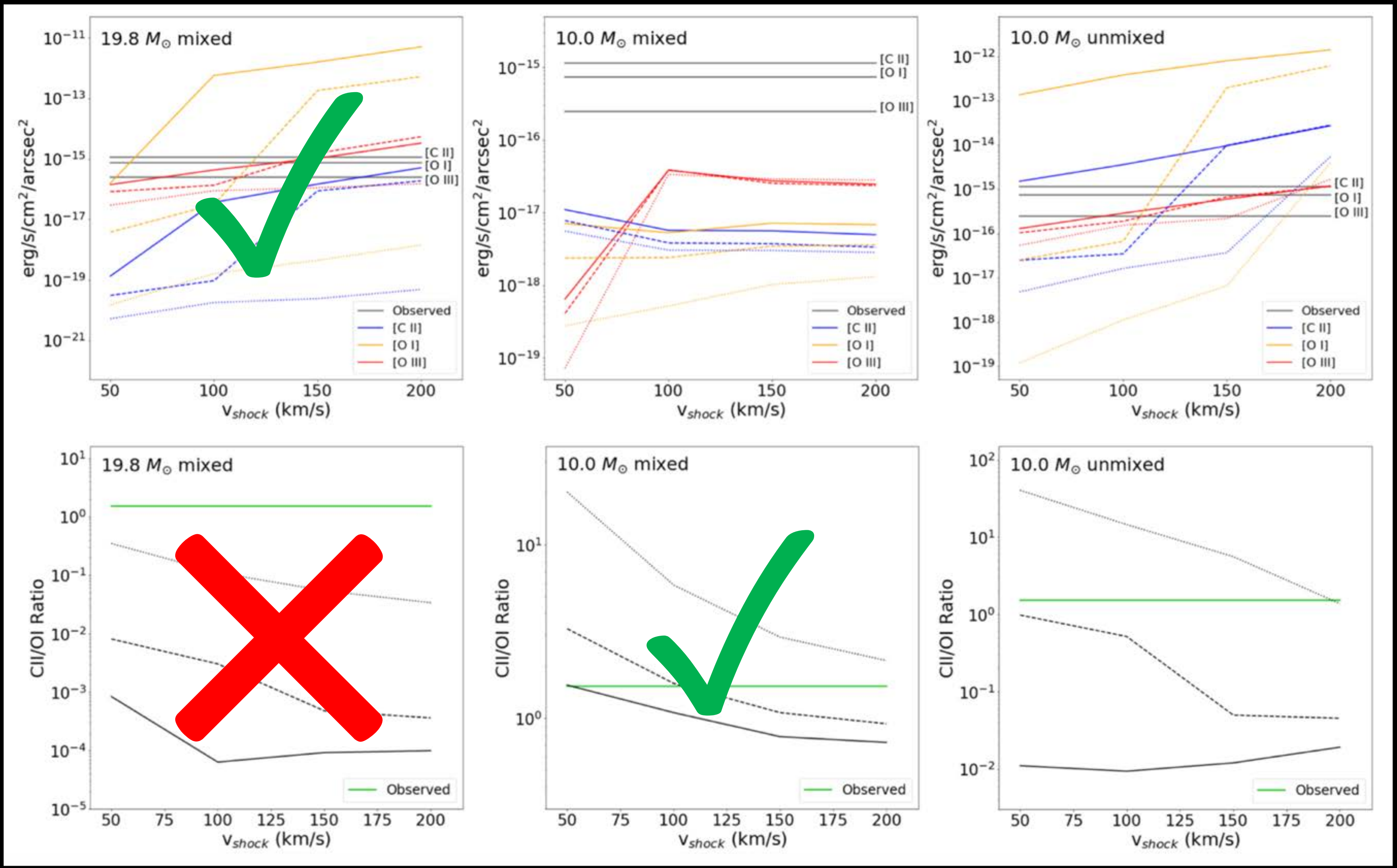

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Temim et al. 2019

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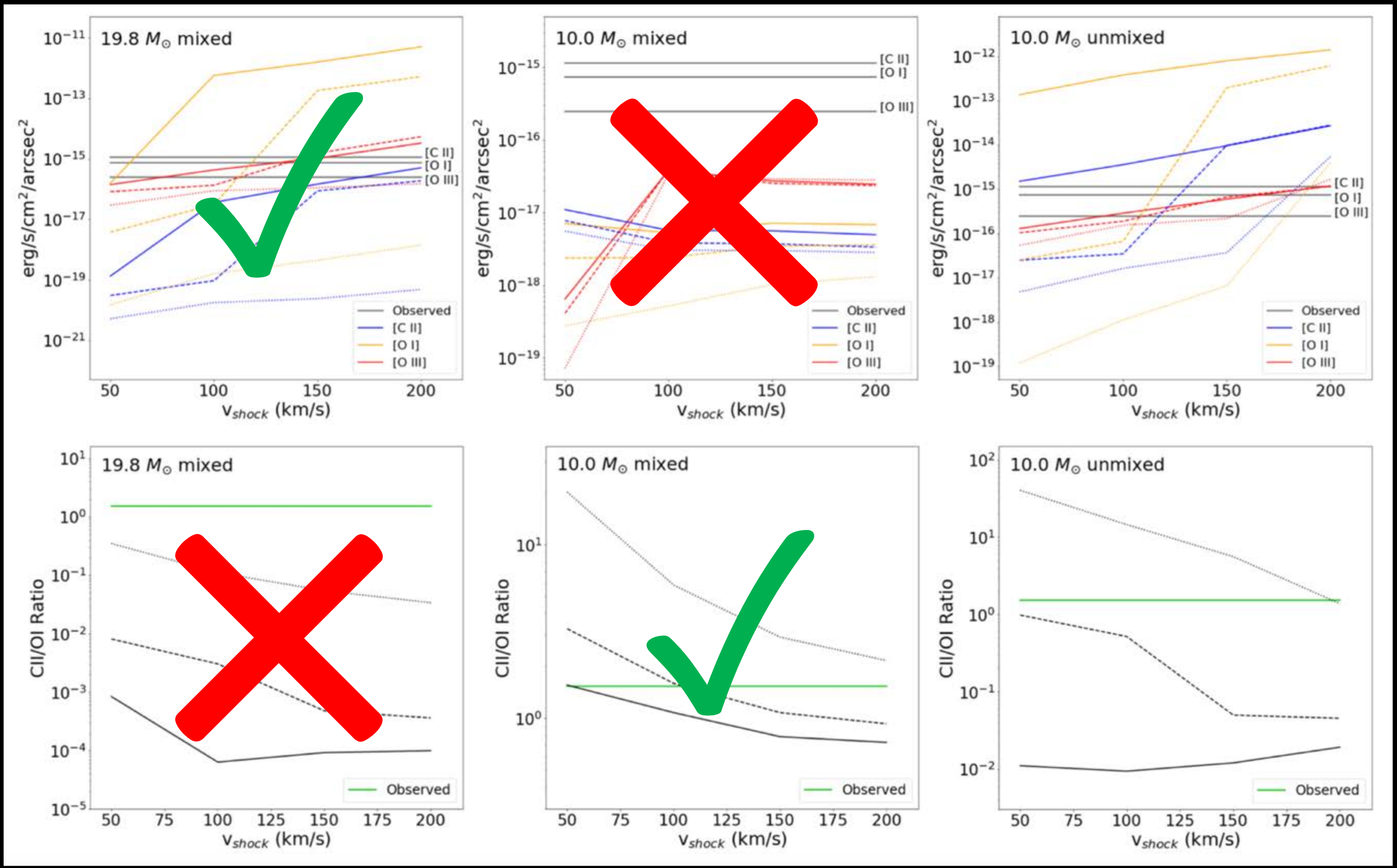

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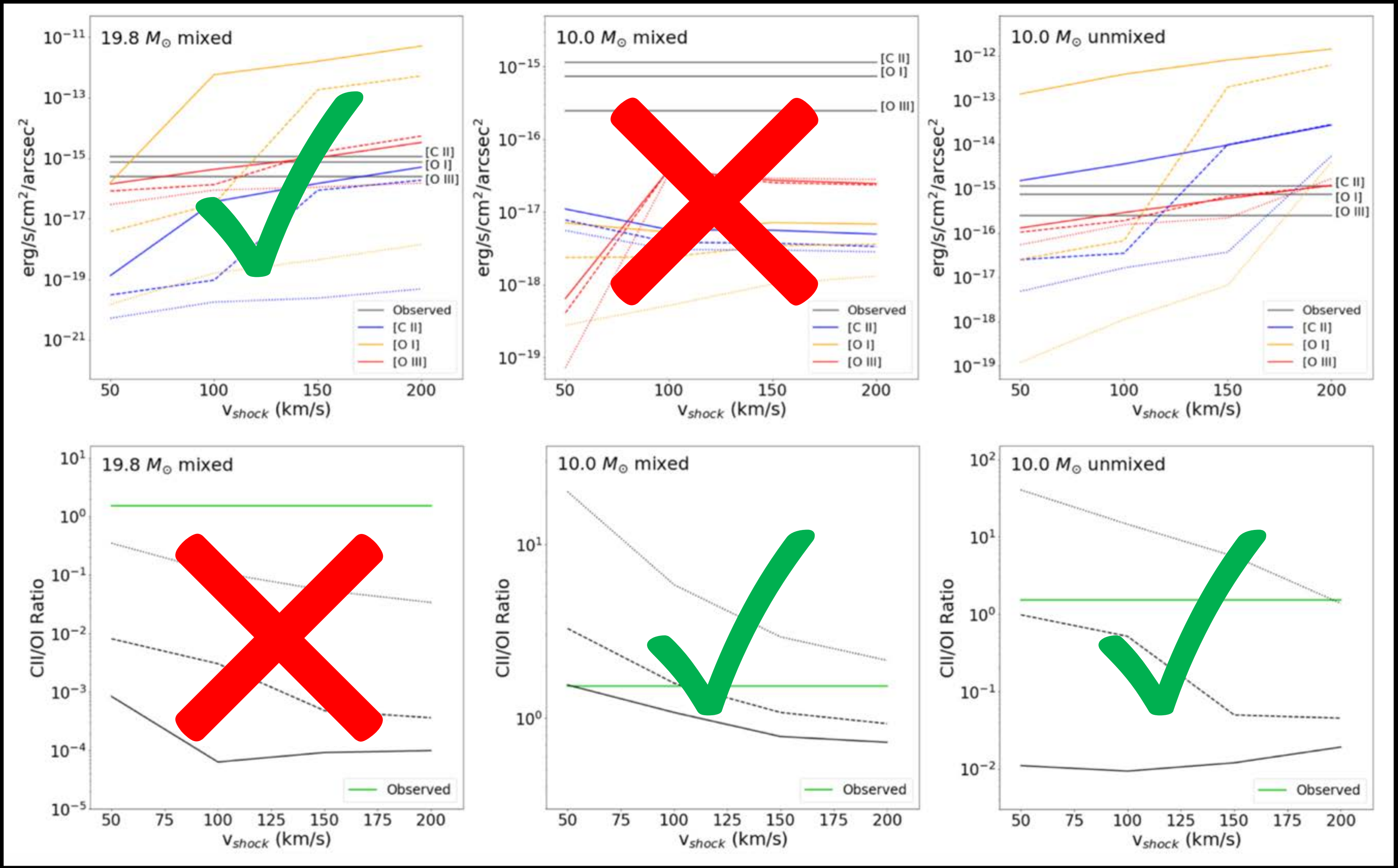

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Temim et al. 2019

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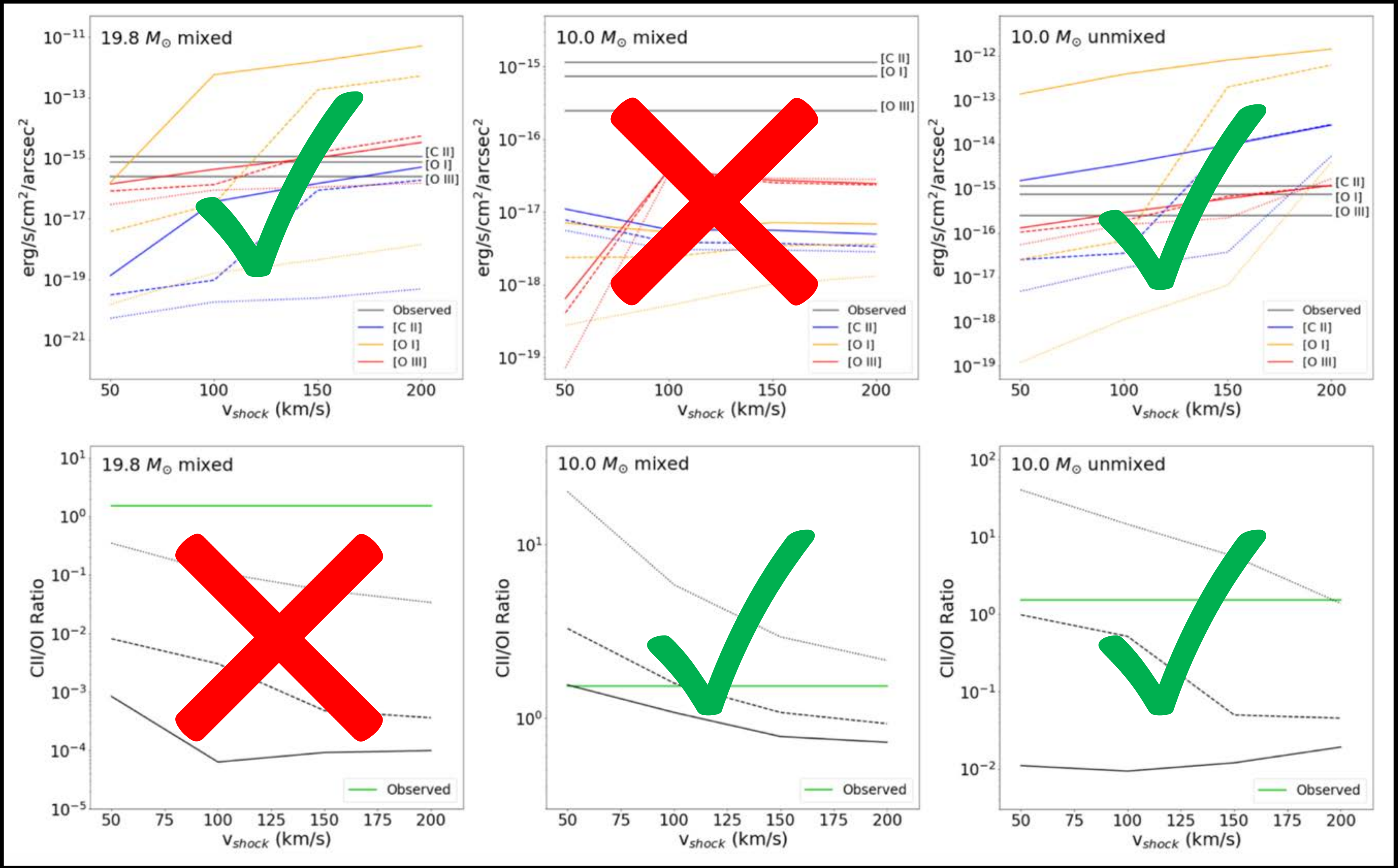

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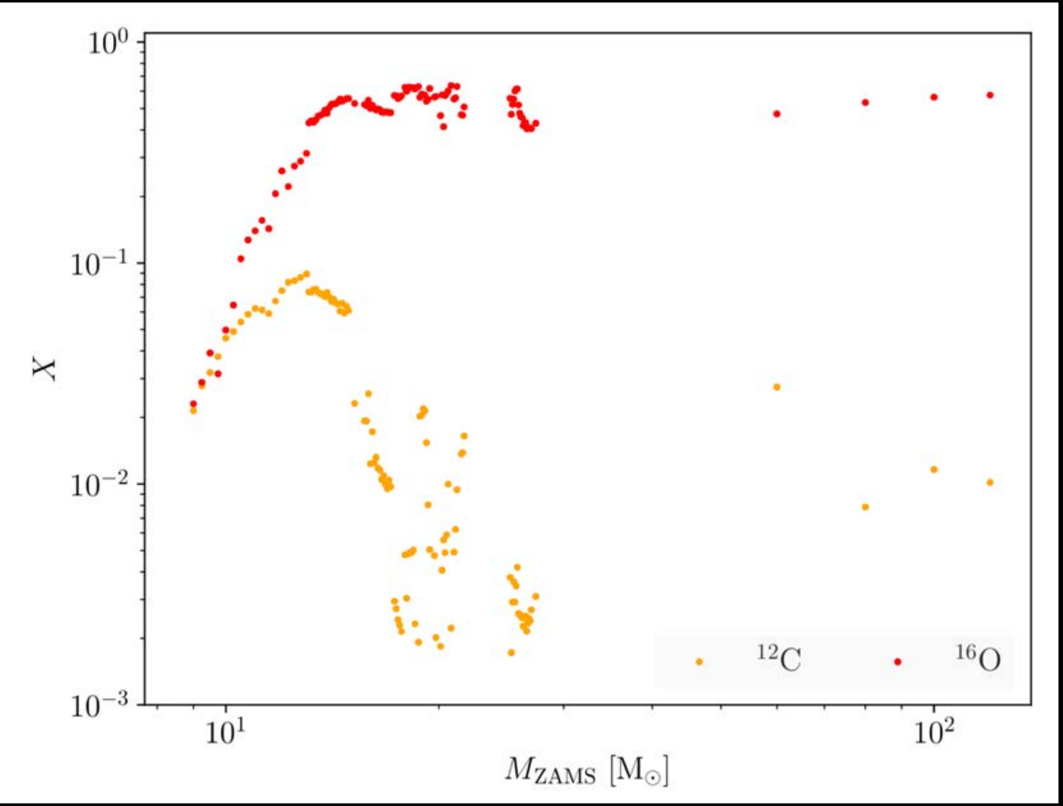
Temim et al. 2019

The innermost ejecta in Kes 75



Carbon and oxygen mass fractions
(based on Sukhbold et al. 2016)

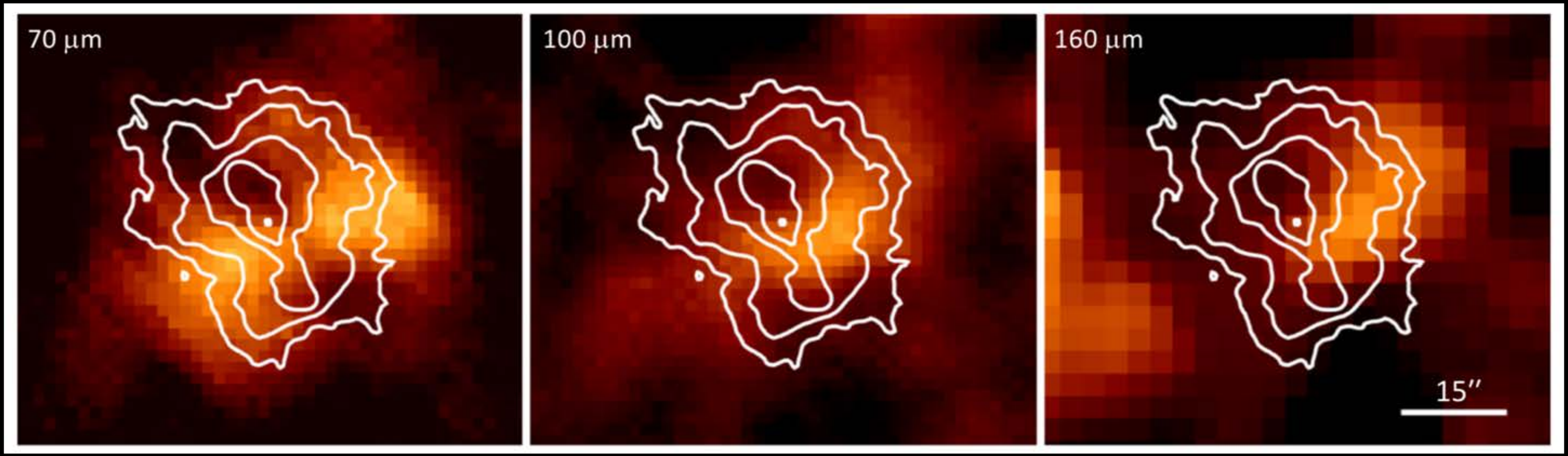
Lower mass and explosion energy SN progenitors with mildly mixed ejecta profiles are favored

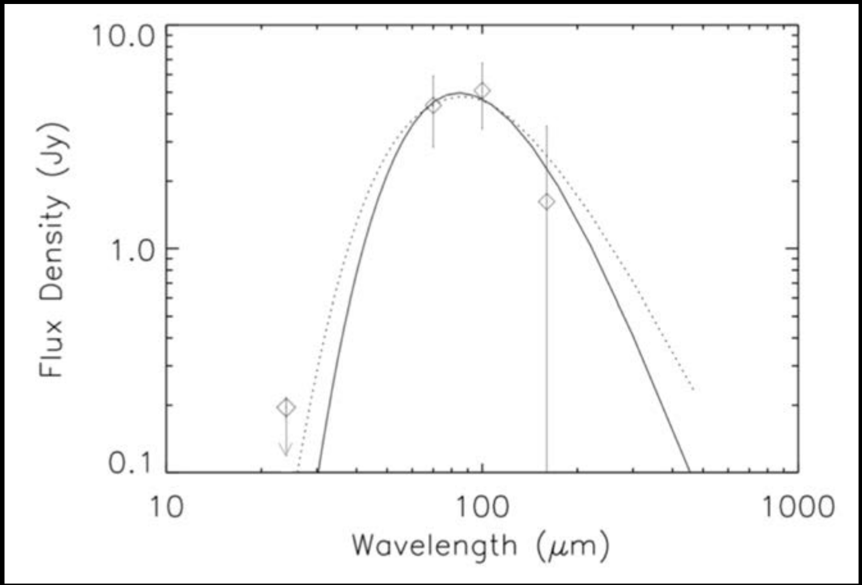
Based on the comparison with models, Kes 75 likely resulted from a progenitor with mass $\lesssim 12\ M_\odot$

JWST will provide more constraints

Temim et al. 2019

Dust in the innermost ejecta of Kes 75



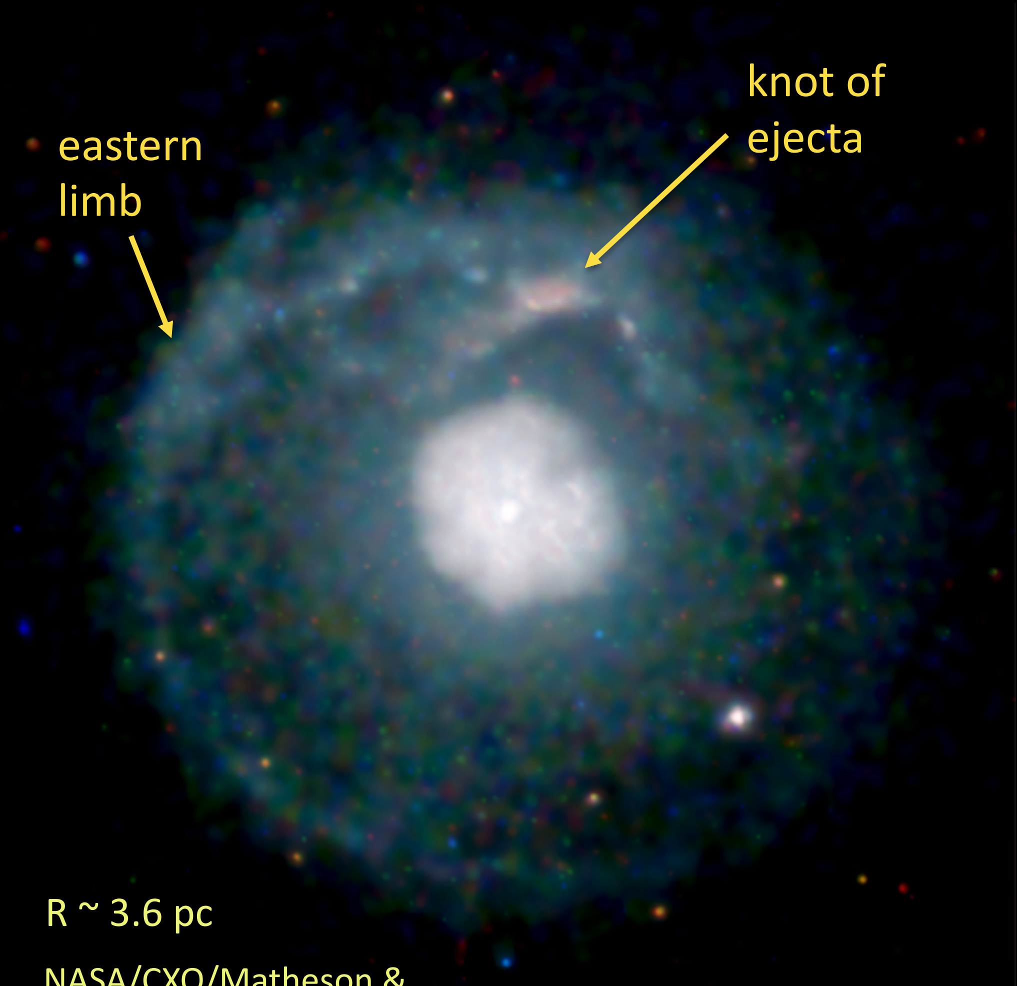


~ 0.003 $M_\odot$ of shock-heated dust
(still a high dust-to-gas mass ratio)

Temim et al. 2019

Progenitor of G21.5-0.9

Deepest imaging and spectroscopic study
Guest et al. 2019



NASA/CXO/Matheson & Safi-Harb 2010

Based on spectrum of the eastern limb:

$T = 0.37$ keV
$v_{shock} = 560$ km/s
Age = 1200 yr (at D = 5 kpc)
$n_e = 0.19\ \mathrm{cm}^{-3}$,

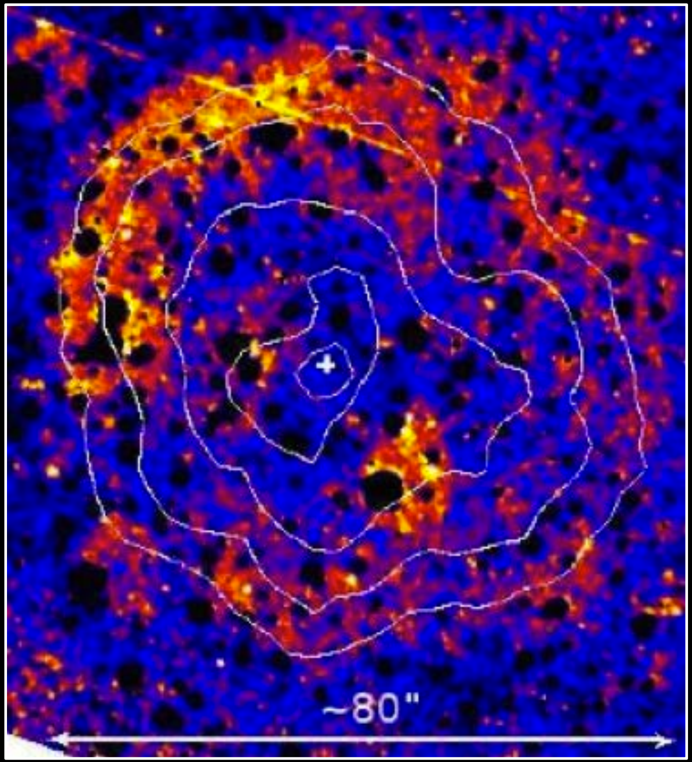
Extending limb to full sphere leads to $E_{SN} = 3 \times 10^{49}$ erg

SNR expanding into wind-blown bubble produced by progenitor?

Progenitor of G21.5-0.9

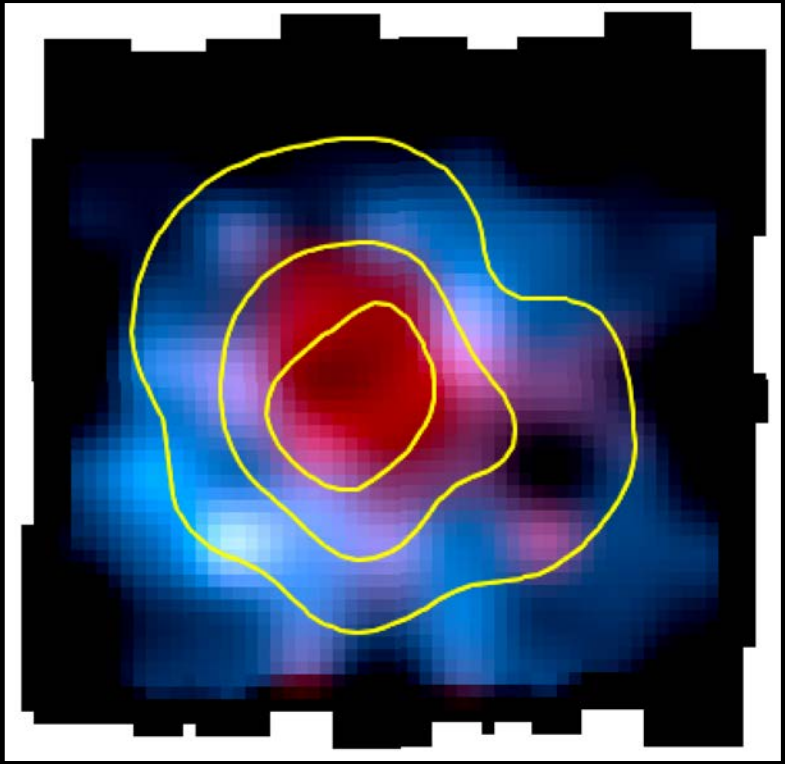
Detection of innermost SN ejecta

Zajczyk et al. 2012



[Fe II] 1.64 μm (VLT/ISAAC)

Herschel detection



[C II] 157 μm V_{ej} = 400 km/s

Progenitor of G54.1+0.3

PWN surrounded by ejecta and dust produced in the explosion

Material heated by the stars in the host cluster

(Temim et al. 2010)

Progenitor of G54.1+0.3

Evidence for massive progenitor

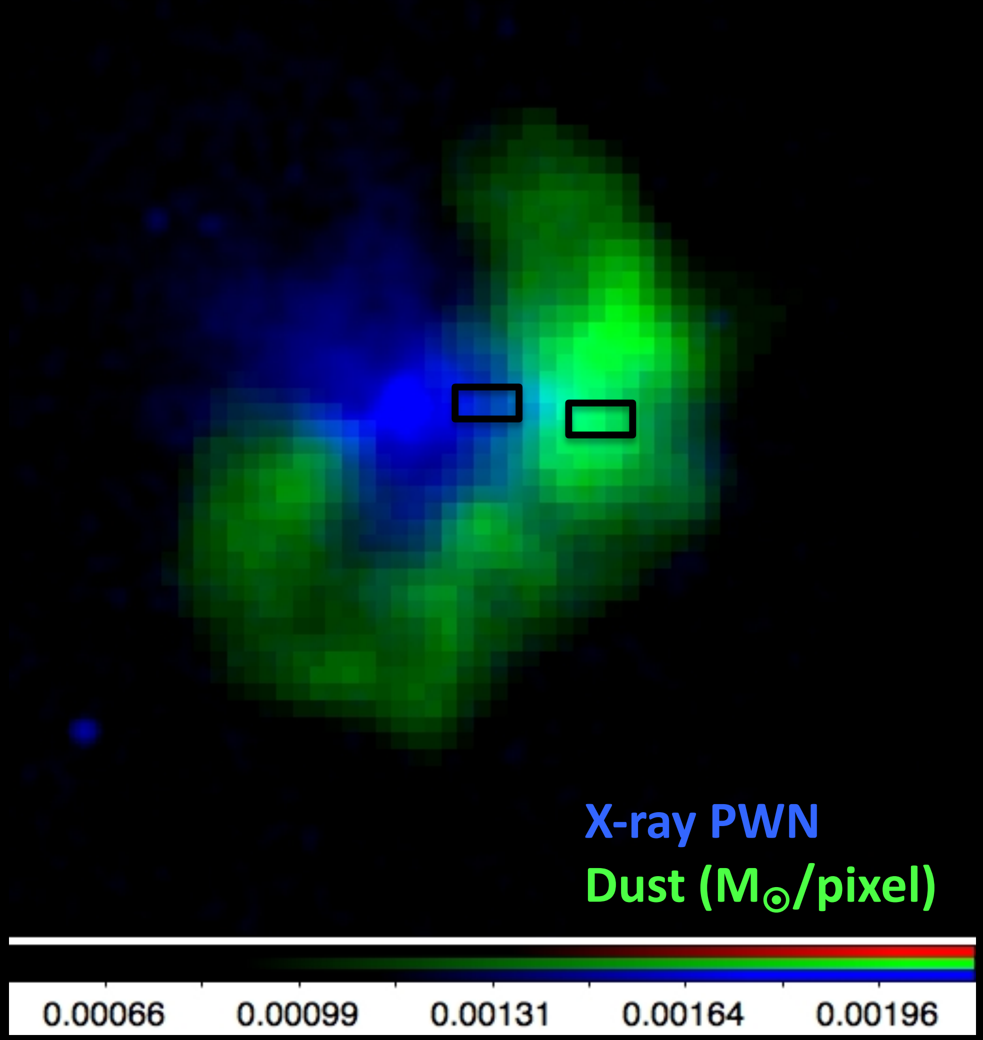
Shock diagnostics – emission from Ne, Si, S, Ar, and Cl, FWHM of 1000 km/s
(Temim et al. 2010)

Stellar spectral types, earliest spectral type is O9 star: > 17 $M_{\odot}$
(Kim et al. 2013)

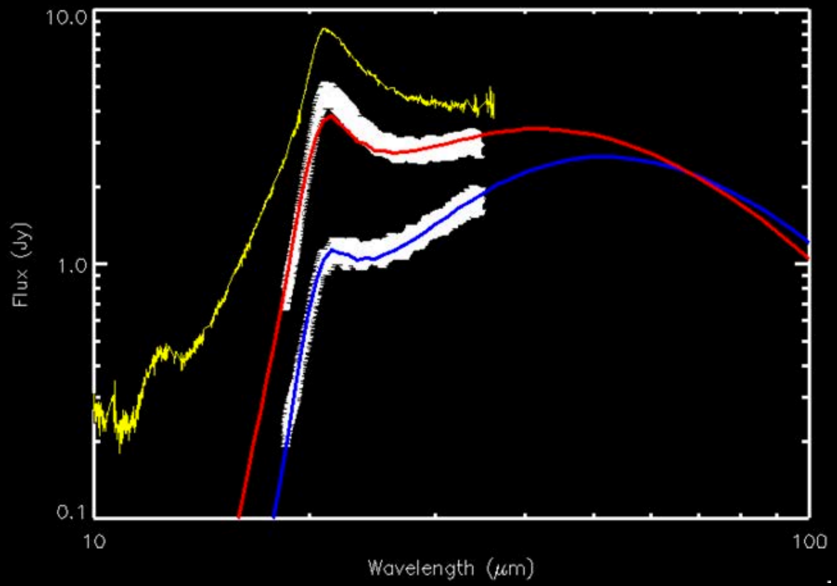
Dynamical modeling of PWN: 15-20 $M_{\odot}$
(Gelfand, Slane, & Temim 2015)

Progenitor of G54.1+0.3

Temim et al. 2017



Properties of the SN-formed dust

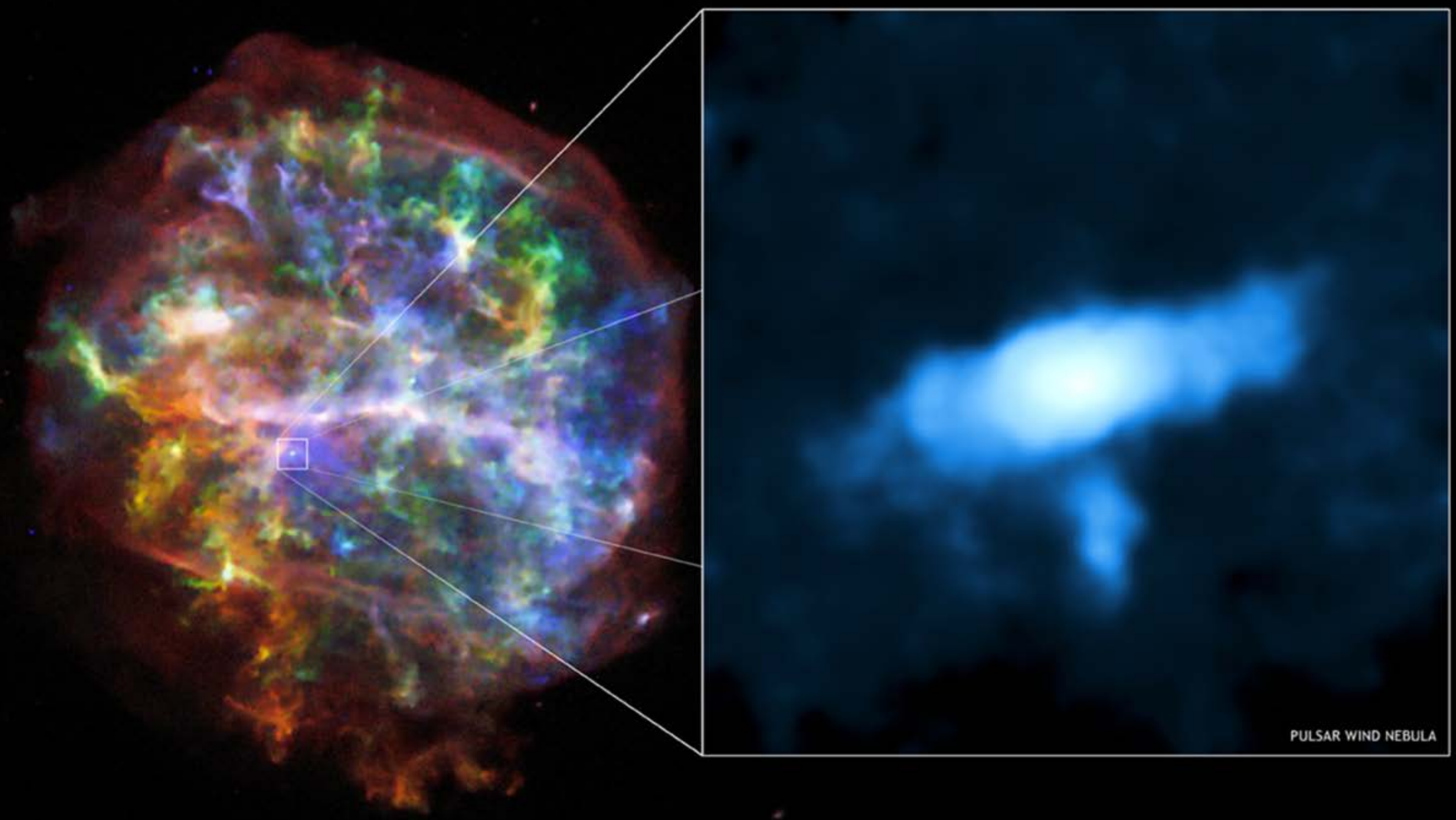


Dust composition: $Mg_{0.7}SiO_{2.7}$
($MgO/SiO_2 = 0.7$)

Species of dust same as in Cas A
Dust composition and mass of $> 0.3\ M_\odot$ suggest a progenitor mass range of 16-27 $M_\odot$

T. Temim, E. Dwek, R.G. Arendt, K.J. Borkowski, S.P. Reynolds, P. Slane, J. Gelfand, J.C. Raymond, ApJ, 2017

Ejecta Properties in G292.0+1.8

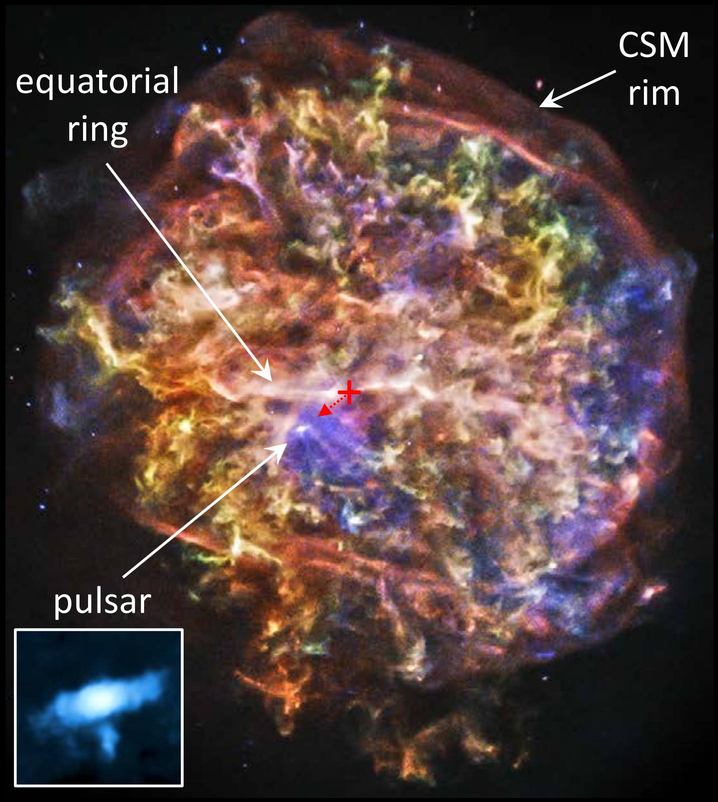


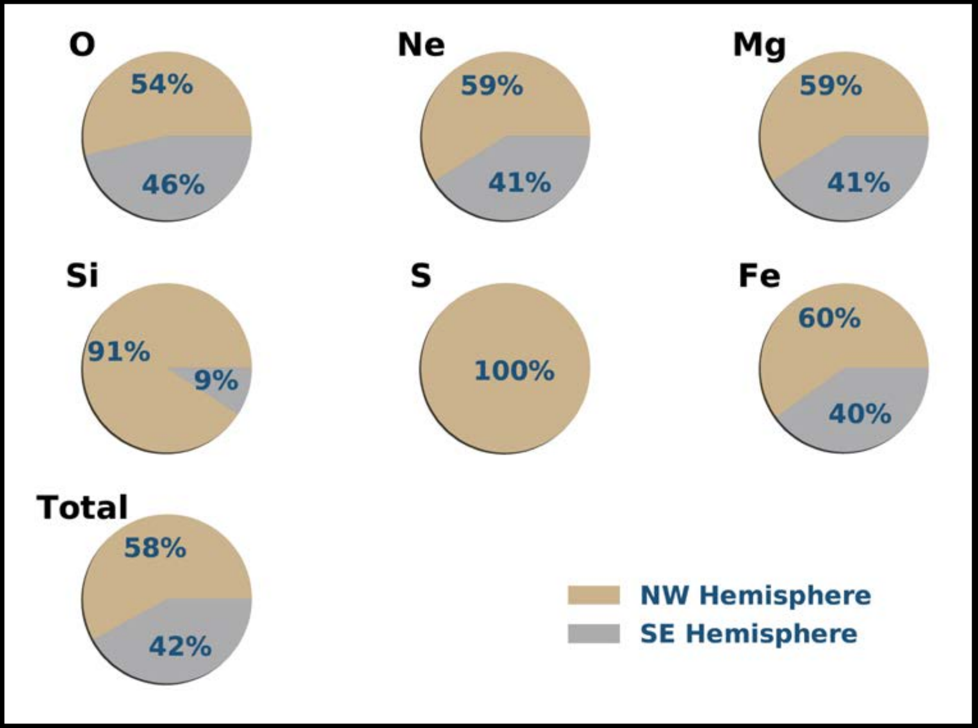
G292.0+1.8

NASA/CXC/S.Park et al.

Ejecta Properties in G292.0+1.8

Bhalerao et al. 2019 (deep *Chandra* study)





Larger amounts of ejecta opposite the inferred direction of the NS kick, particularly Si, S, Fe (recently found for other SNRs Holland-Ashford et al. 2017, 2019, Katsuda et al. 2018 – see Friday talk by T. Holland-Ashford)

Consistent with 3D simulations that predict ejecta asymmetries dominate over non-spherical neutrino emission in accelerating neutron stars (Wongwathanarat et al. 2013, Janka 2017)

Ejecta Properties in G292.0+1.8

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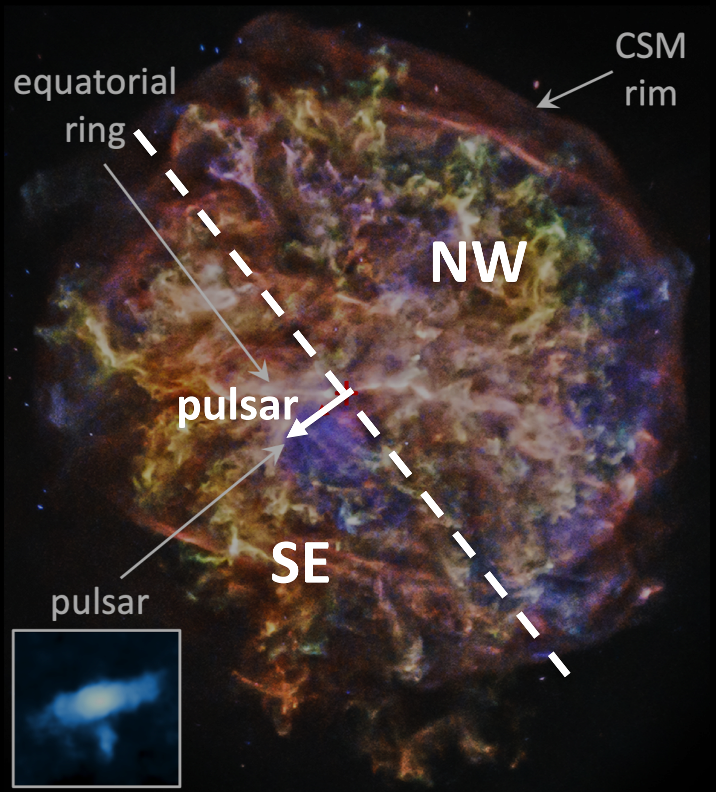

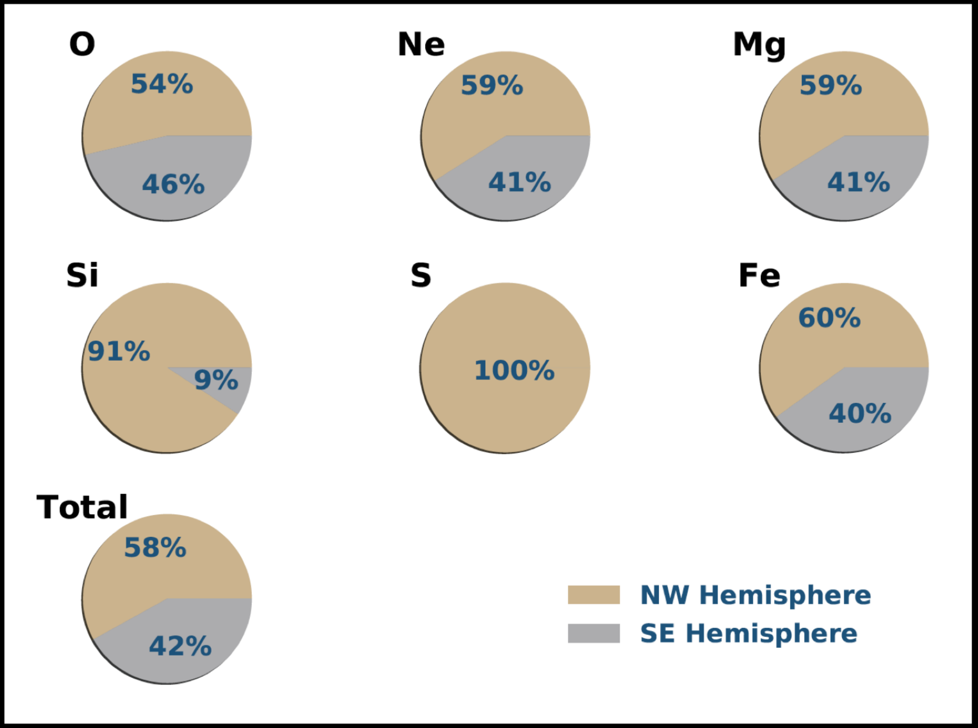

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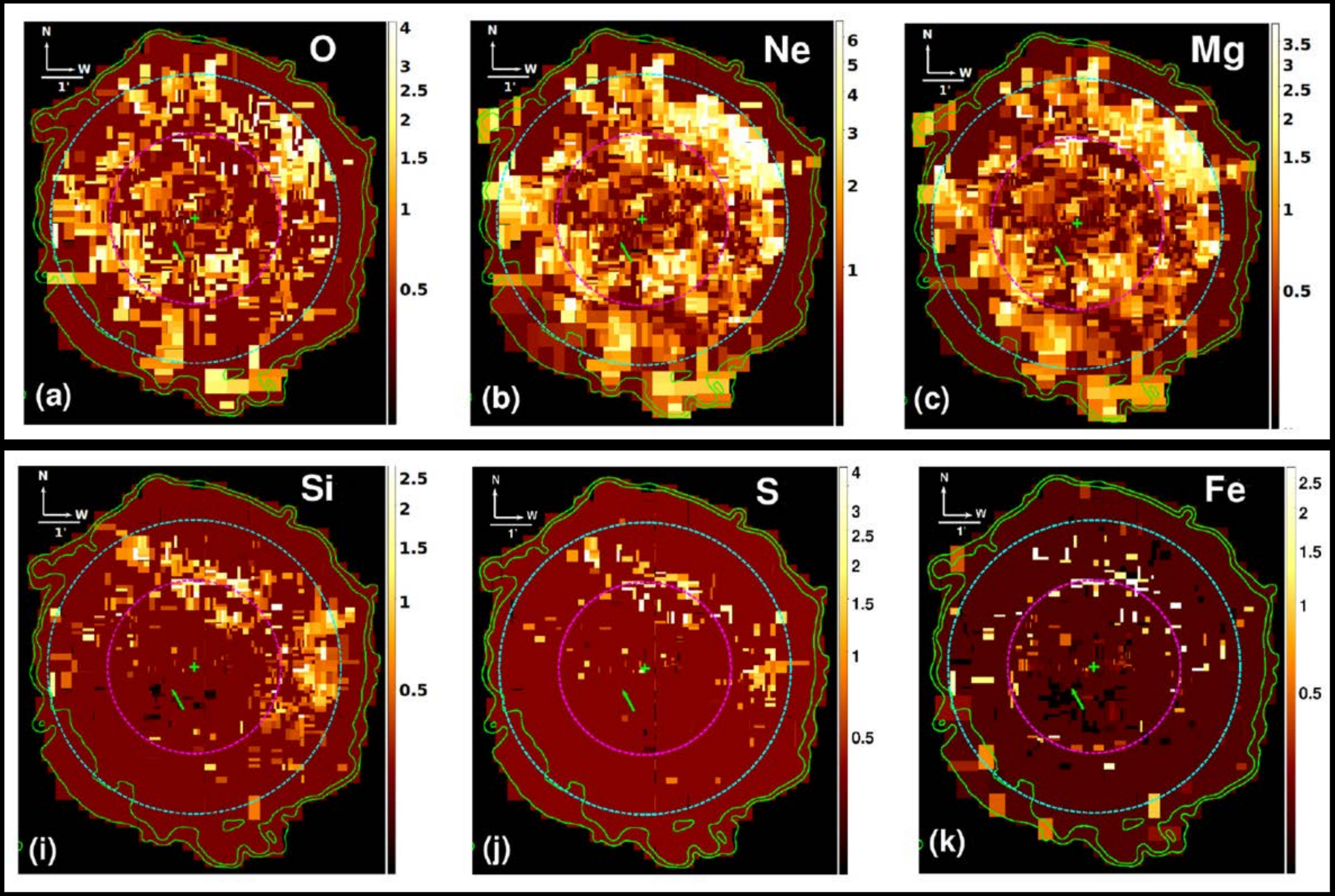
Ejecta Properties in G292.0+1.8

Bhalerao et al. 2019 (deep *Chandra* study)

Abundances relative to solar



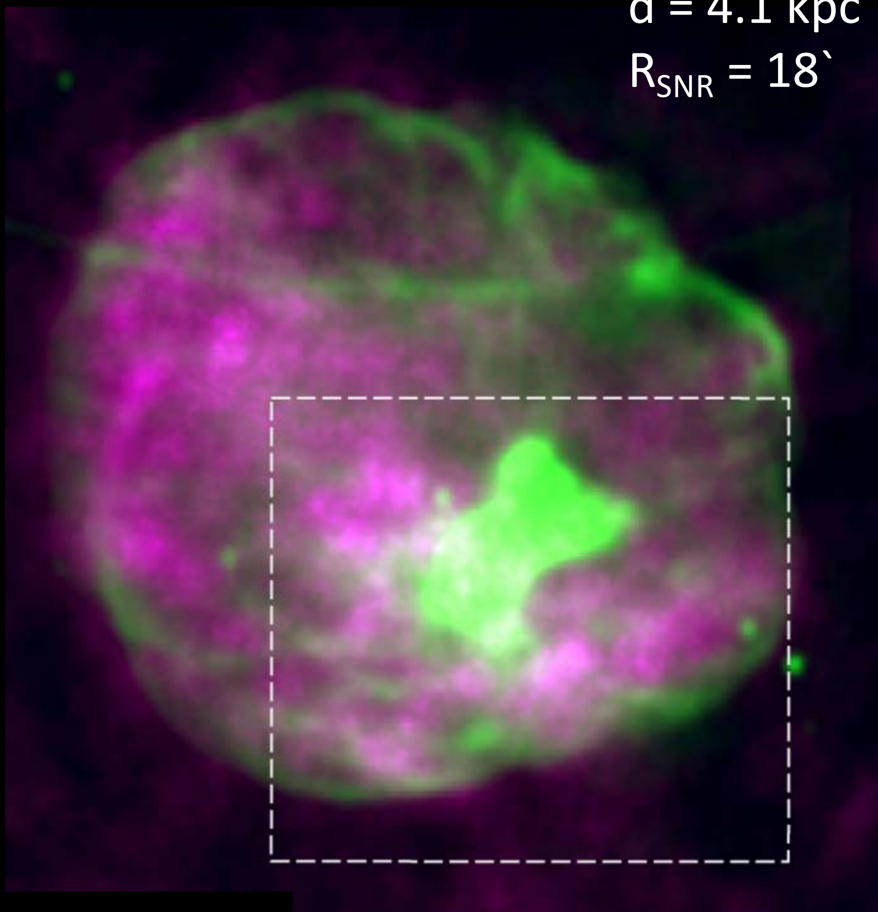
Elemental abundance ratios and estimates of ejecta and CSM masses are consistent with a 13-30 $M_\odot$ progenitor mass

PWN/RS Interaction in MSH 15-56

Temim et al. 2017

d = 4.1 kpc

R_{SNR} = 18`

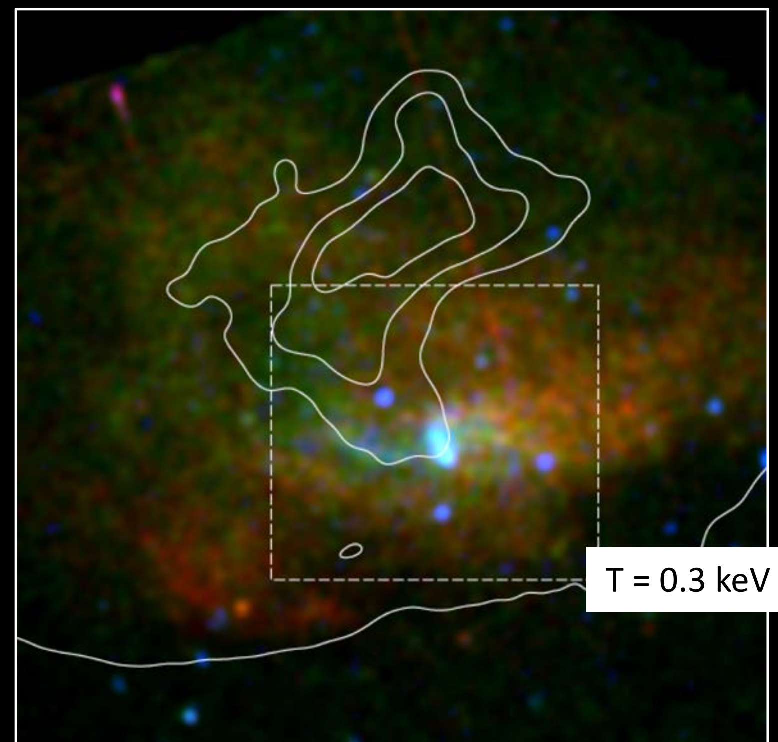


X-ray (*ROSAT)*

Radio

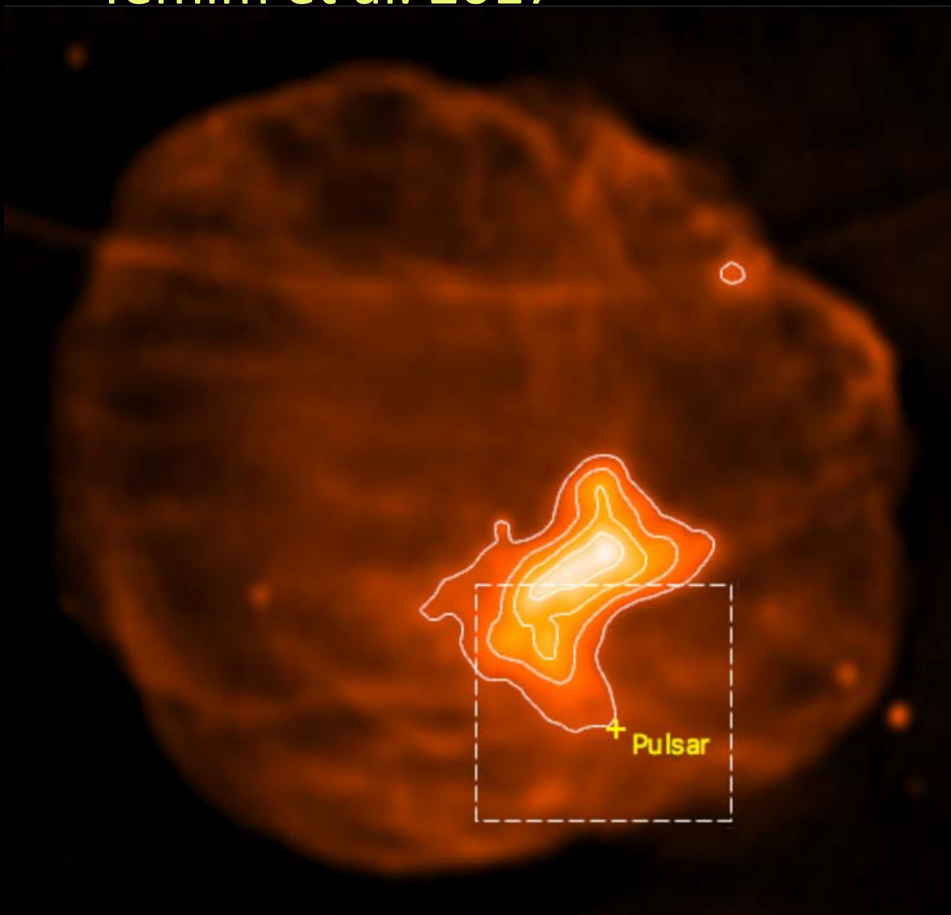
XMM

Temim et al. 2013

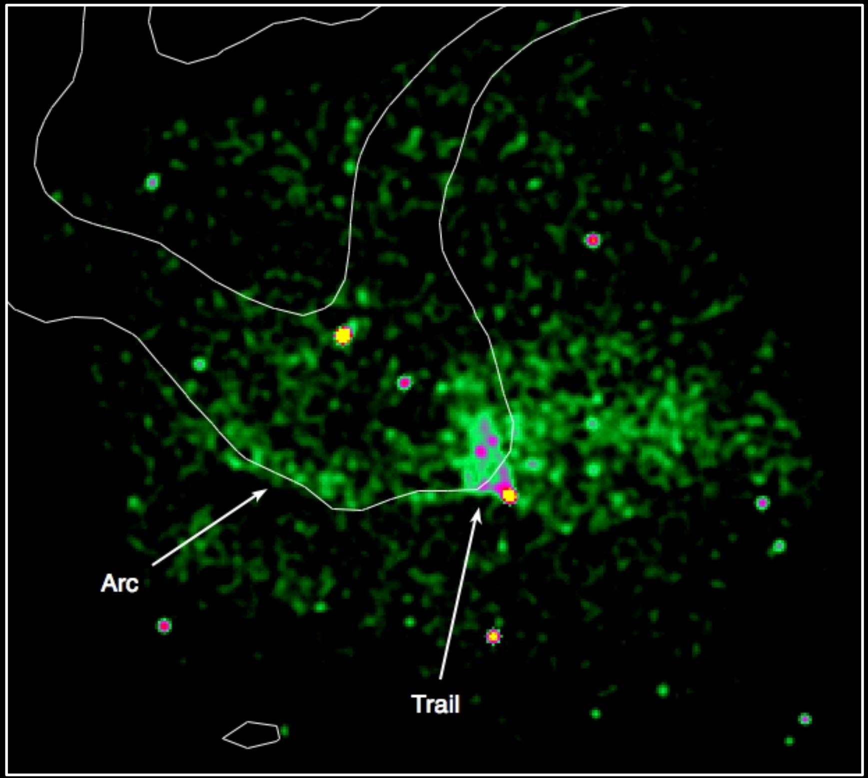


PWN/RS Interaction in MSH 15-56

Temim et al. 2017

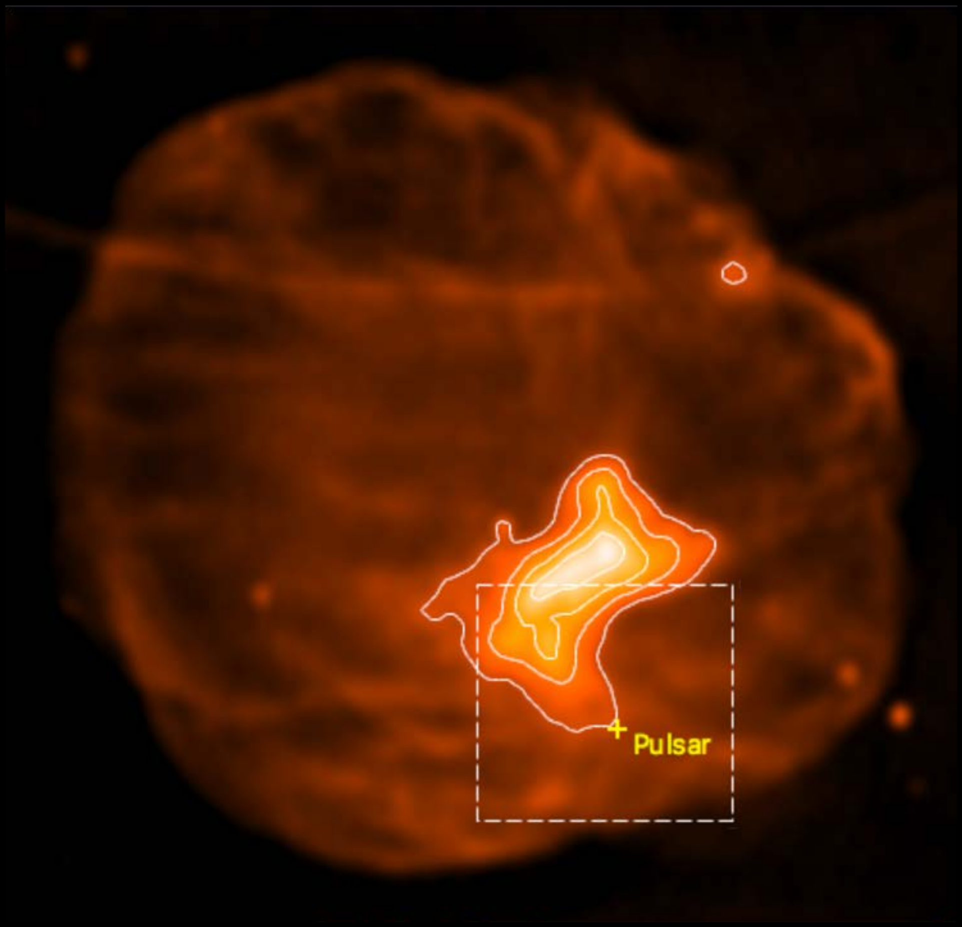


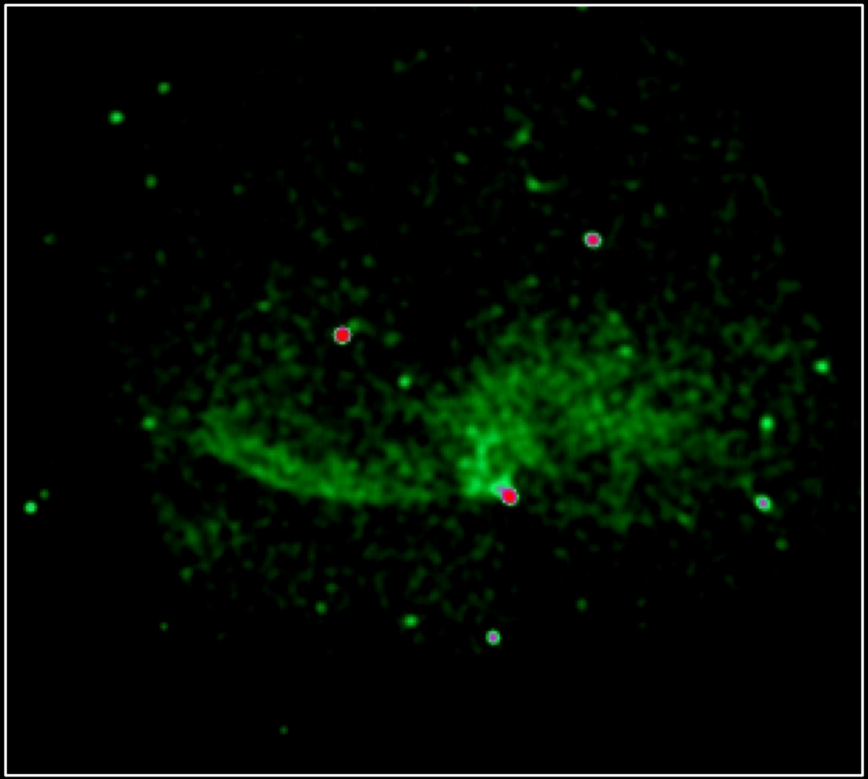
Radio emission from the SNR shell and the crushed PWN



Chandra 56 ks

PWN/RS Interaction in MSH 15-56



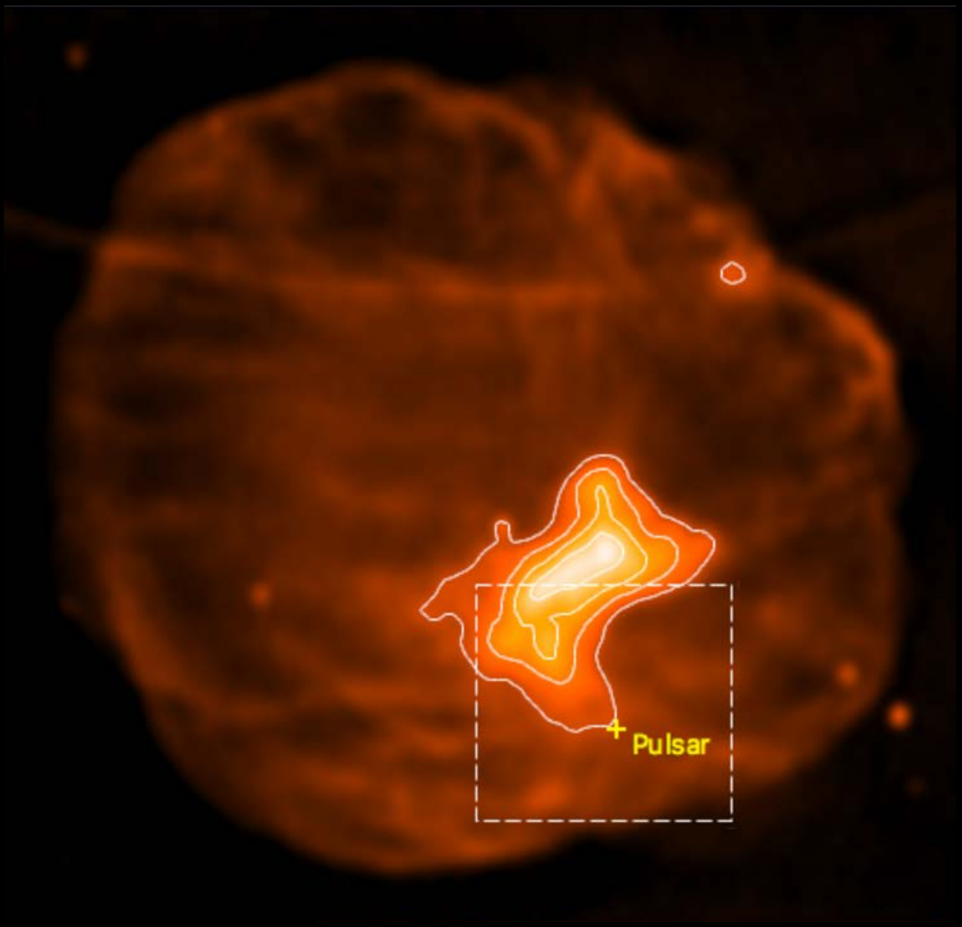


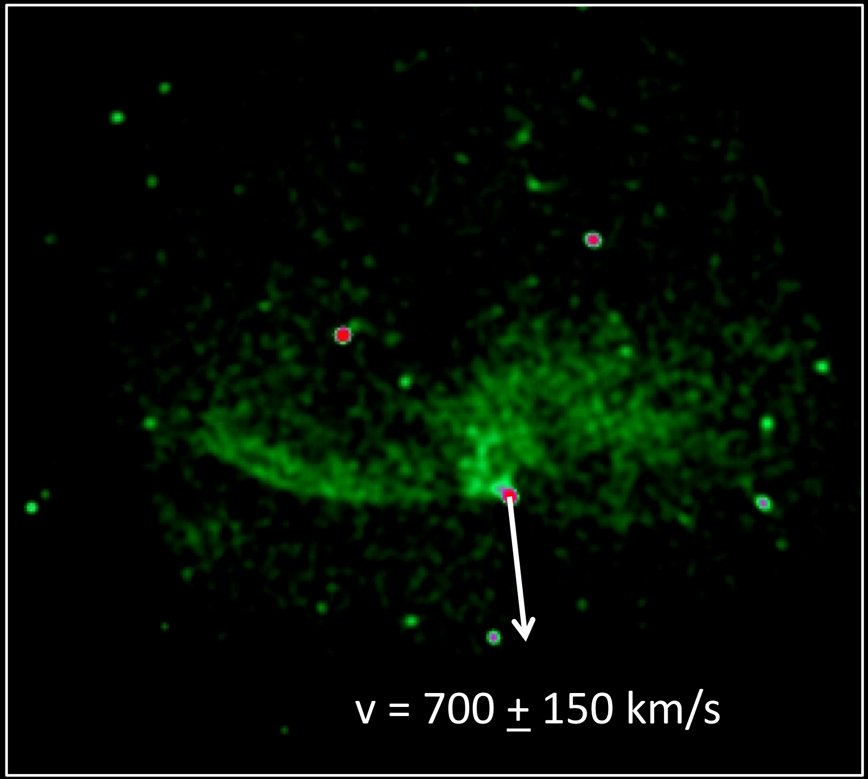
Chandra 175 ks

Deeper *Chandra* observation of the PWN region

Temim et al. 2017

PWN/RS Interaction in MSH 15-56



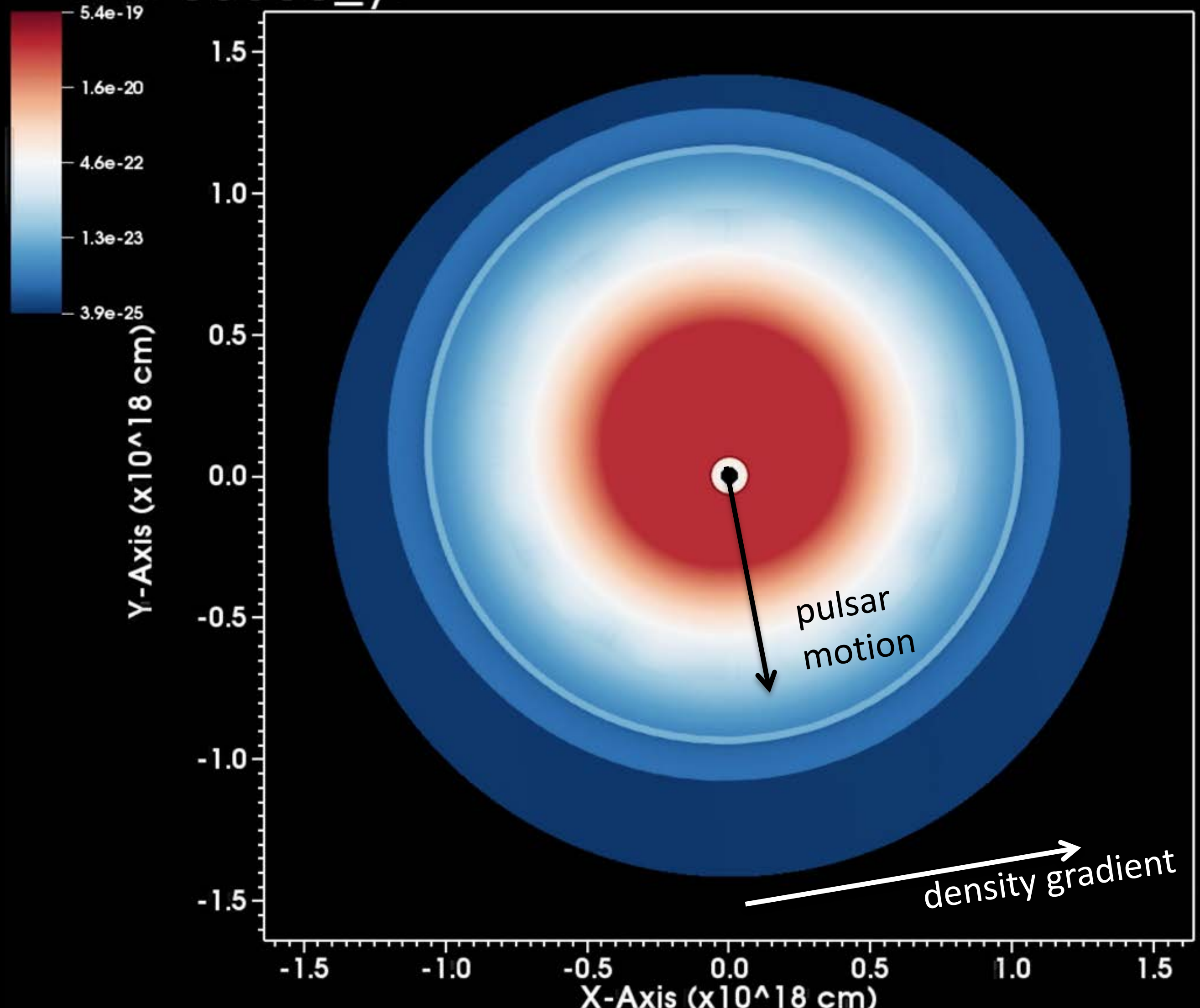


Chandra 175 ks

Two *Chandra* observations of the PWN region provided a 15 yr baseline, allowing us to measure the pulsar's velocity and direction of motion

Temim et al. 2017

SNR age: 00000_yr



$E_{SN} = 10^{51}$ erg

$M_{ej} = 20\ M_{\odot}$

$n_0 = 0.4\ cm^{-3}$

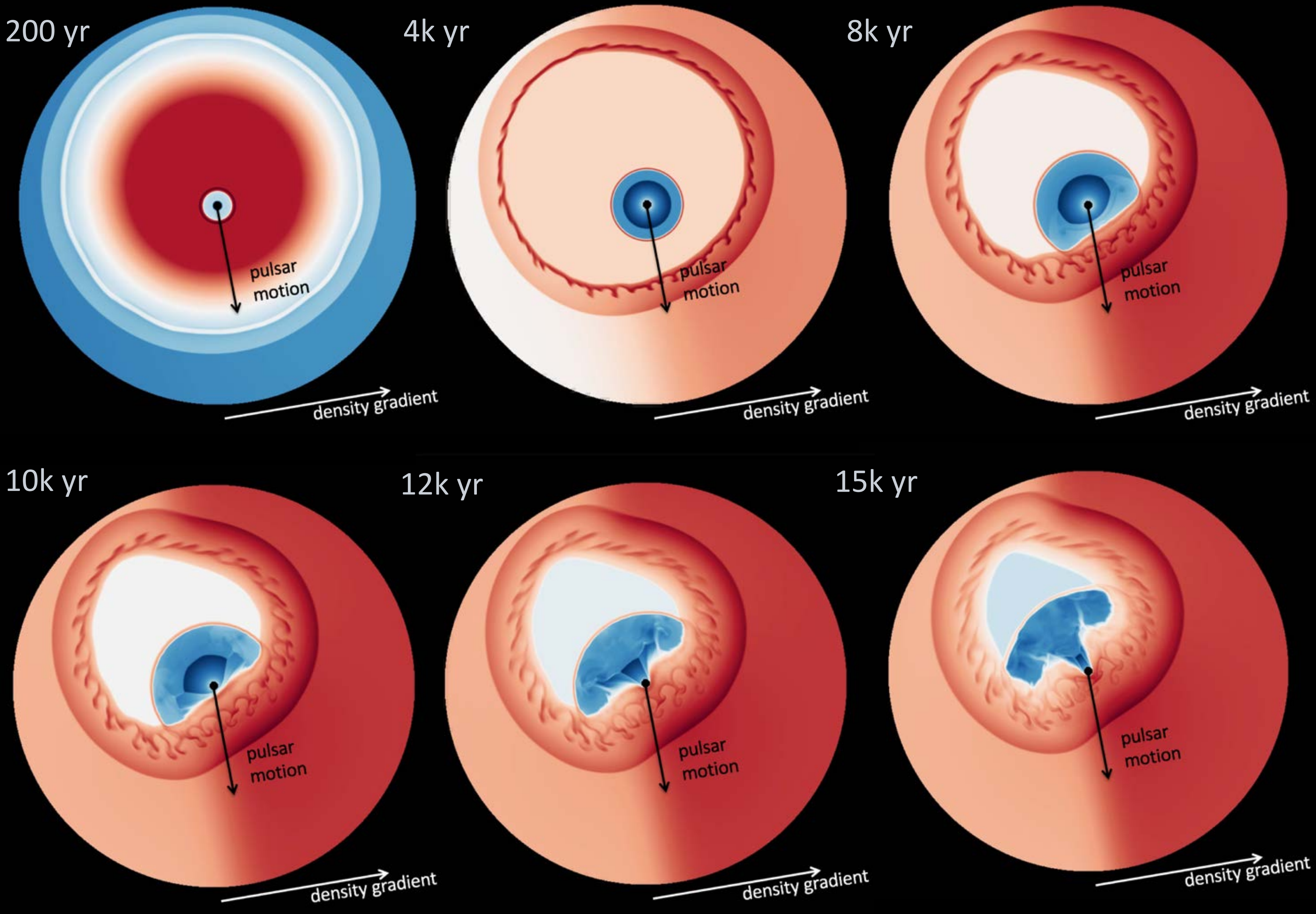
$t_{SNR} = 15$ kyr

$v_{pulsar} = 700$ km/s

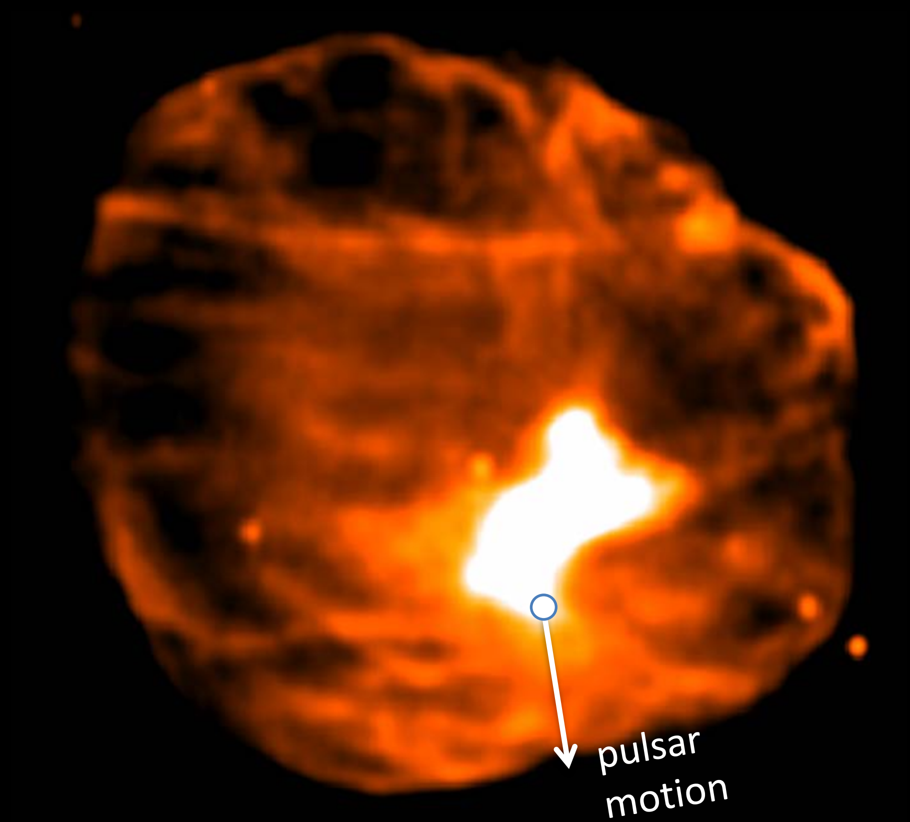
$\tau_0 = 2000$ yr

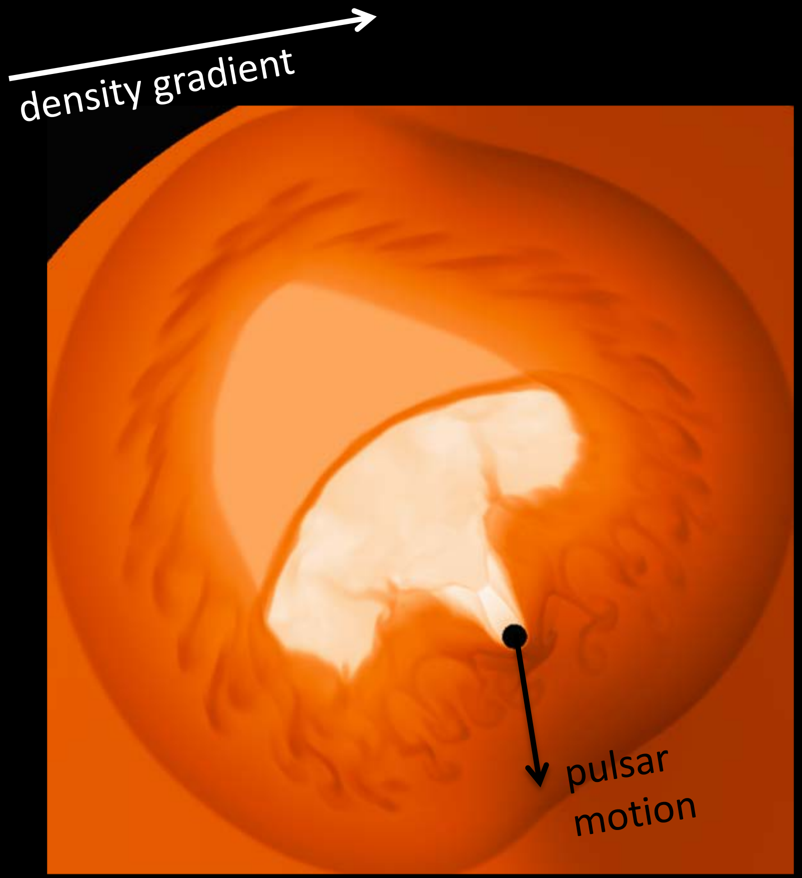
$dE_0/dt = 7e38$ erg/s

Temim et al. 2017


200 yr
pulsar motion
density gradient
4k yr
pulsar motion
density gradient
8k yr
pulsar motion
density gradient
10k yr
pulsar motion
density gradient
12k yr
pulsar motion
density gradient
15k yr
pulsar motion
density gradient

PWN/RS Interaction in MSH 15-56

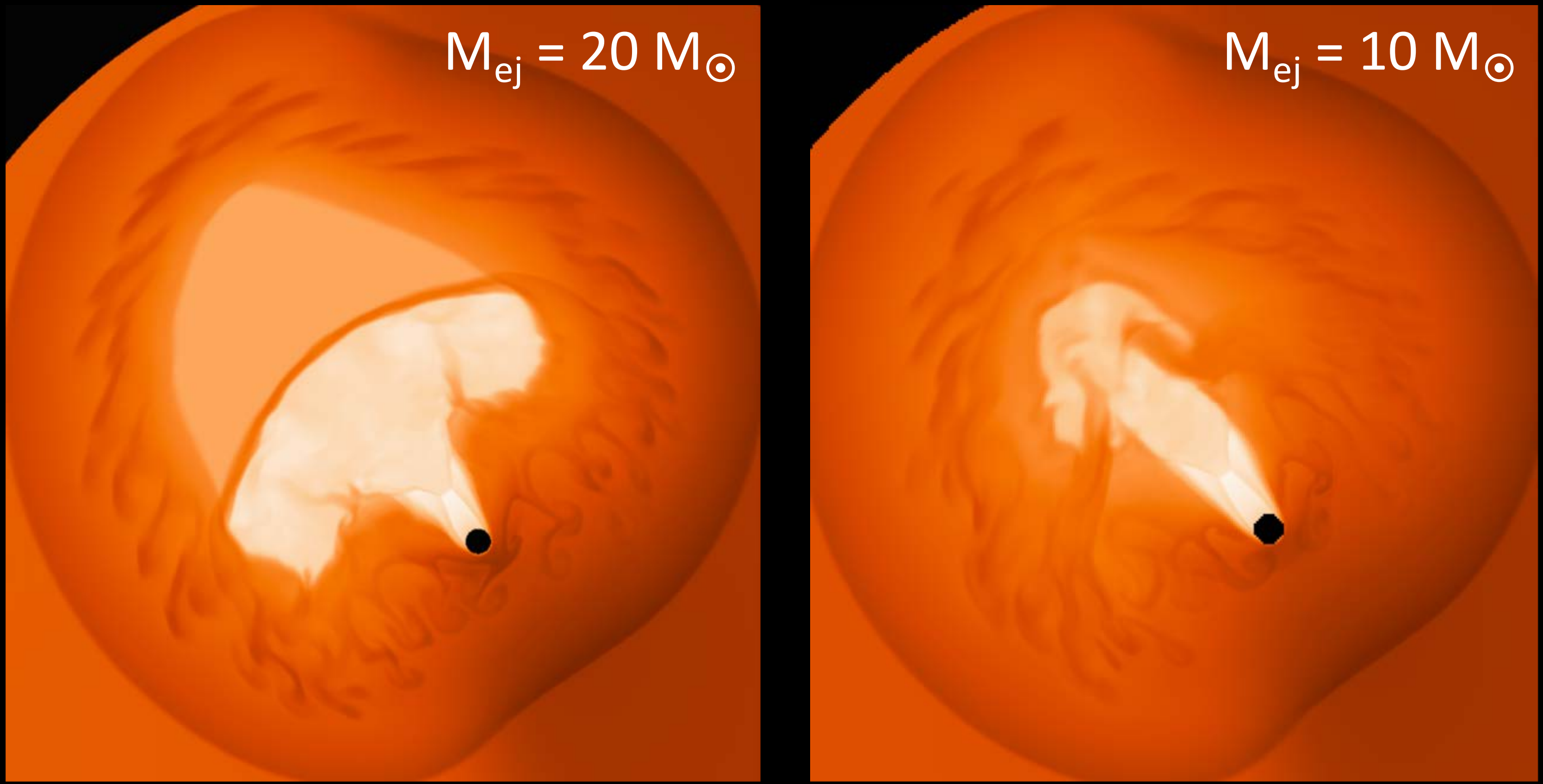




Comparison with radio observations

Temim et al. 2017

PWN/RS Interaction in MSH 15-56



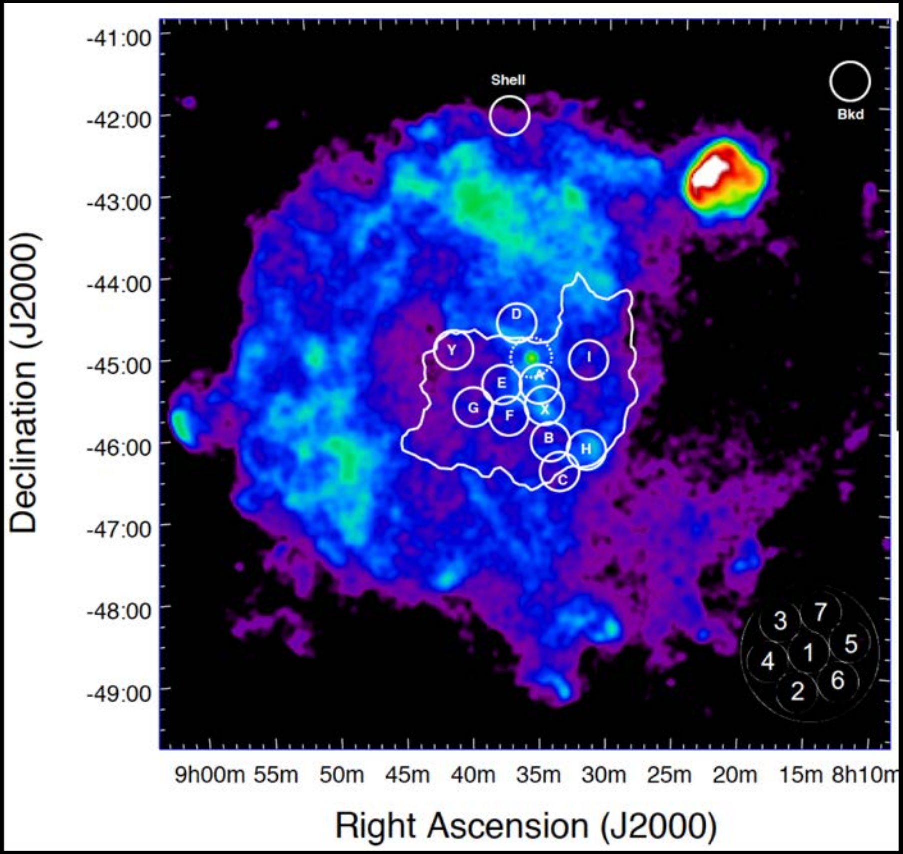
Simulations favor a higher SN ejecta mass

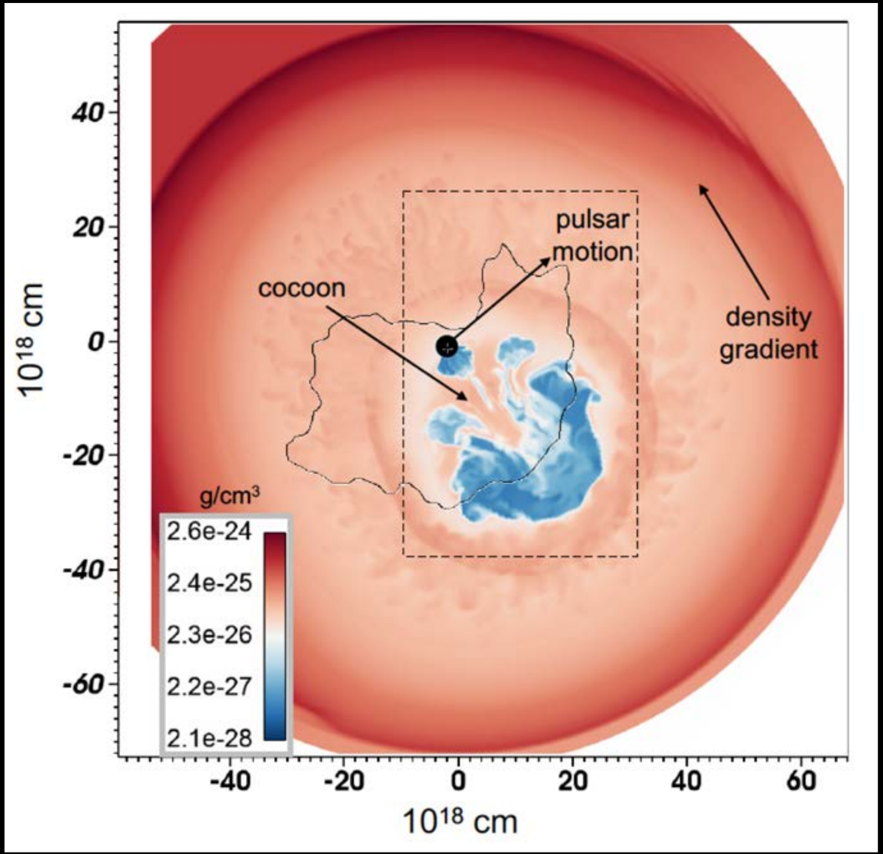
(unless SNR is much younger or ISM density lower)

Temim et al. 2017

Structure of Vela X and the Ambient ISM

Large *XMM* + *Chandra* study
Slane et al. 2018





- Study confirms presence of ejecta within Vela X
- The cocoon appears to result from the RS displacing the PWN from the NE

Summary

Progenitor & explosion properties of composite SNRs can be constrained from observations and modeling of pulsar wind nebulae themselves and their interaction with the host SNR

- Young pulsar wind nebulae powerful probes of the innermost ejecta layers → constraints on the progenitor properties and degree of mixing
  (e.g. Kes 75, G21.5-0.9)

- Young pulsar wind nebulae also allow us to probe SN dust properties
  (e.g. G54.1+0.3)

- Progenitor/explosion properties constrained by PWN expansion and pulsar motion measured from multi-epoch observations (e.g. Kes 75, MSH 15-56)

- Modeling of RS/PWN interaction in evolved systems provides information about SN ejecta and the ambient medium (e.g. Vela X, MSH 15-56)