Progenitor & Explosion Properties of Core-collapse Supernova Remnants

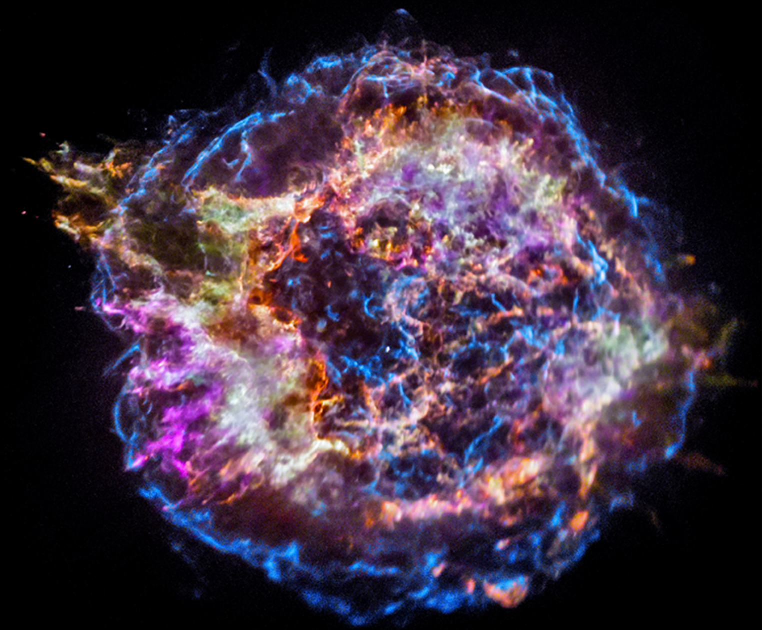
Tea Temim

Space Telescope Science Institute

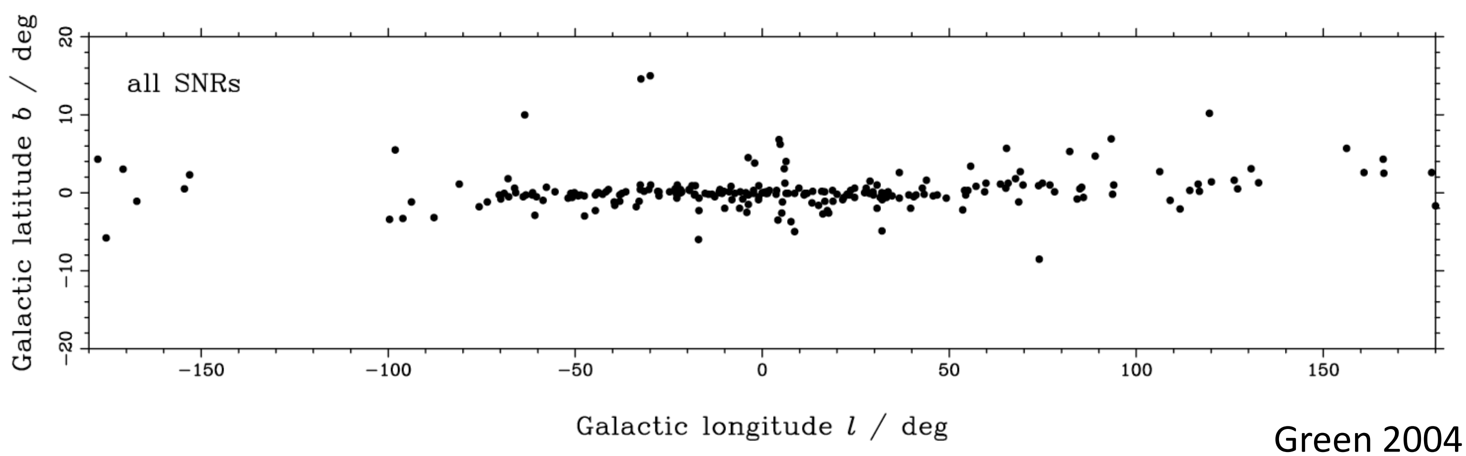
Fifty-One Erg, May 24, 2019

Supernova Remnants

- SNRs bear the imprint of the SN explosion, nucleosynthesis of the progenitor star, and the surrounding circumstellar environment
- > 500 known SNRs, visible for tens of thousands of years
- Studies of individual SNRs and SNR populations provide information about the progenitor and explosion properties



NASA/CXC/SAO



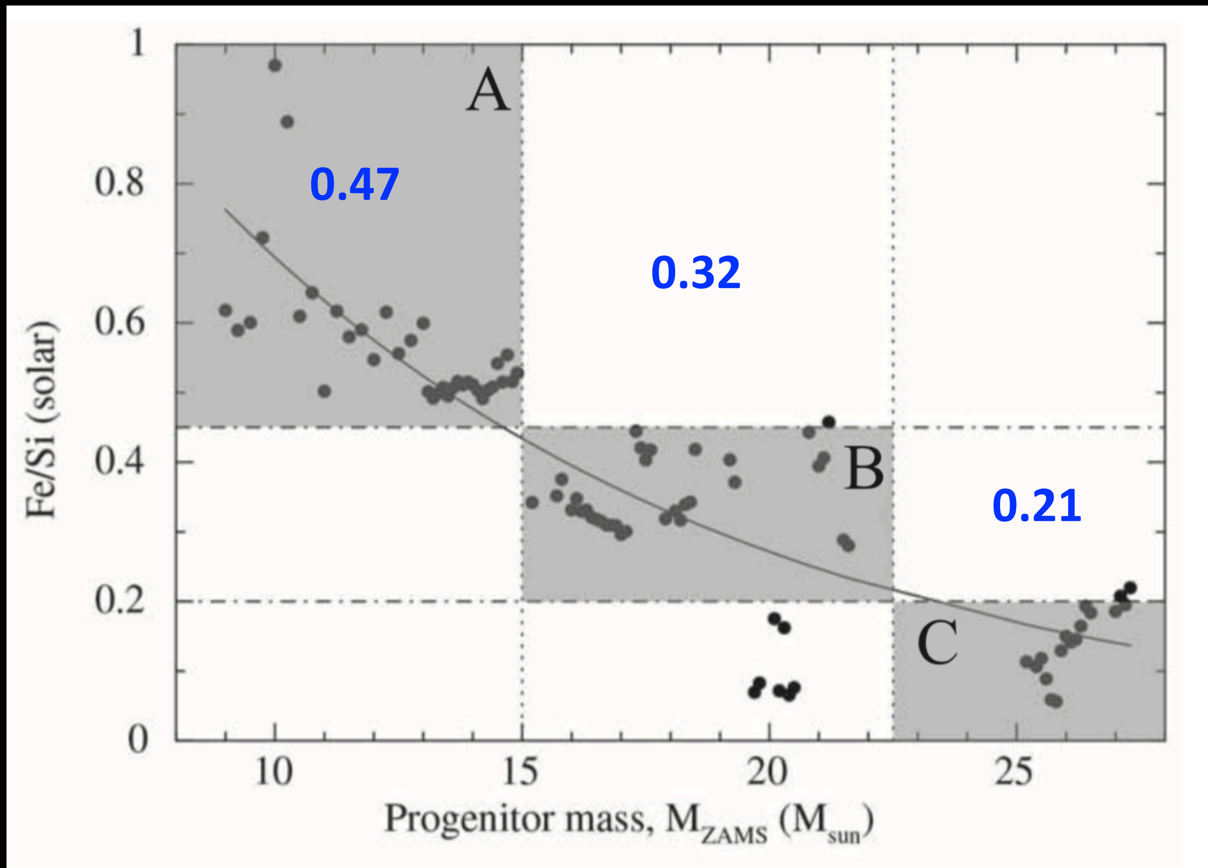
Green 2004

Explosion/Progenitor Properties of CC SNRs

- Light echoes (e.g. Rest et al. 2005, Krause et al. 2008)
- Fe-K line centroids (Yamaguchi et al. 2014, Patnaude et al. 2015)
- Surrounding stellar population (e.g. Badenes et al. 2009, Jennings et al. 2014, Díaz-Rodríguez et al. 2018, Auchettl et al. 2018, Williams et al. 2019)
- Elemental abundance fractions
- Distribution of ejecta
- Dynamical modeling (e.g. SNR expansion, PWN evolution)
- Dust properties

Elemental Abundances

Galactic and MC SNRs (Katsuda et al. 2018)



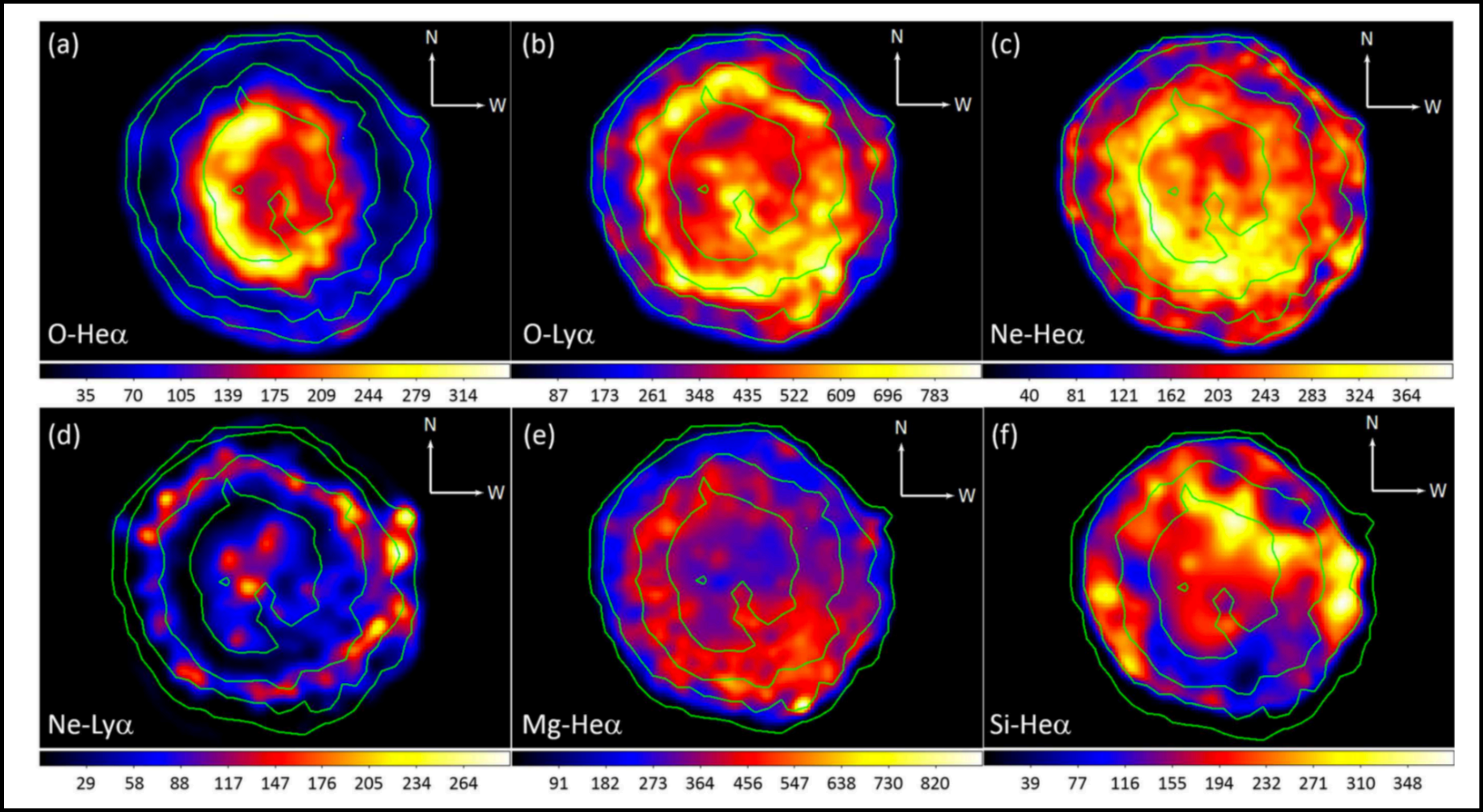
Previous:
fA : fB : fC =
0.27:0.27:0.46

Fe/Si ratio sensitive to the CO core mass (based on models of Sukhbold et al. 2016)
In agreement with Salpeter IMF

Elemental Abundances in 1E 0102.2-7219

Alan et al. 2018

Spatially resolved spectral analysis on archival Chandra data (265 ks)



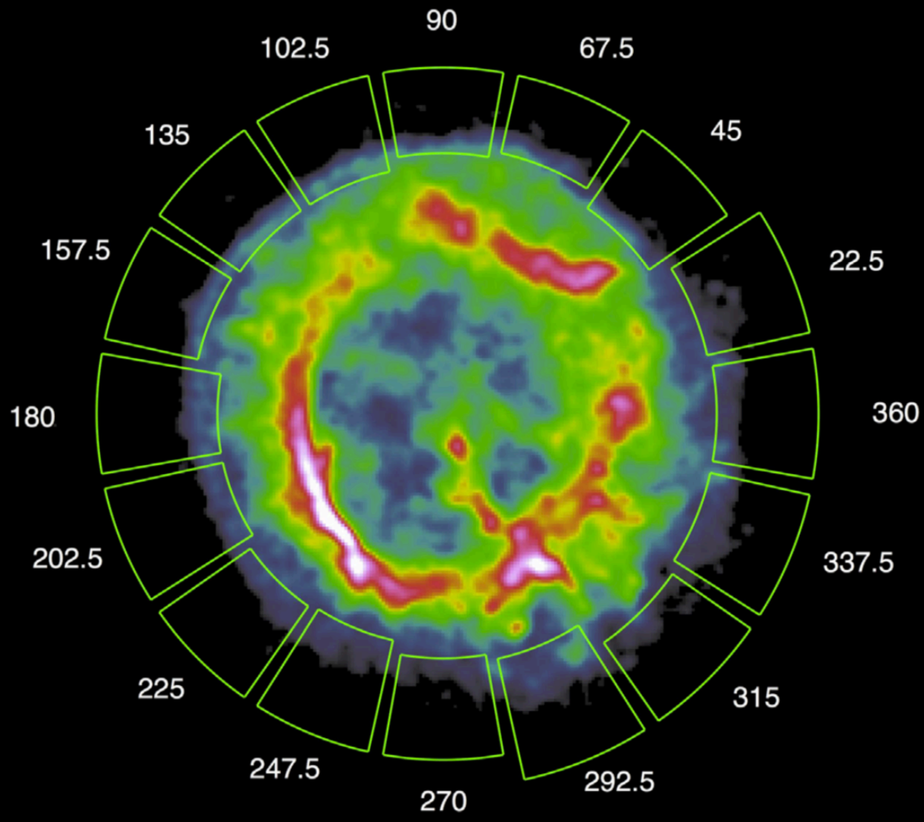
O/Ne, O/Mg, and Ne/Mg ratios are consistent with a 40 $M_\odot$ progenitor

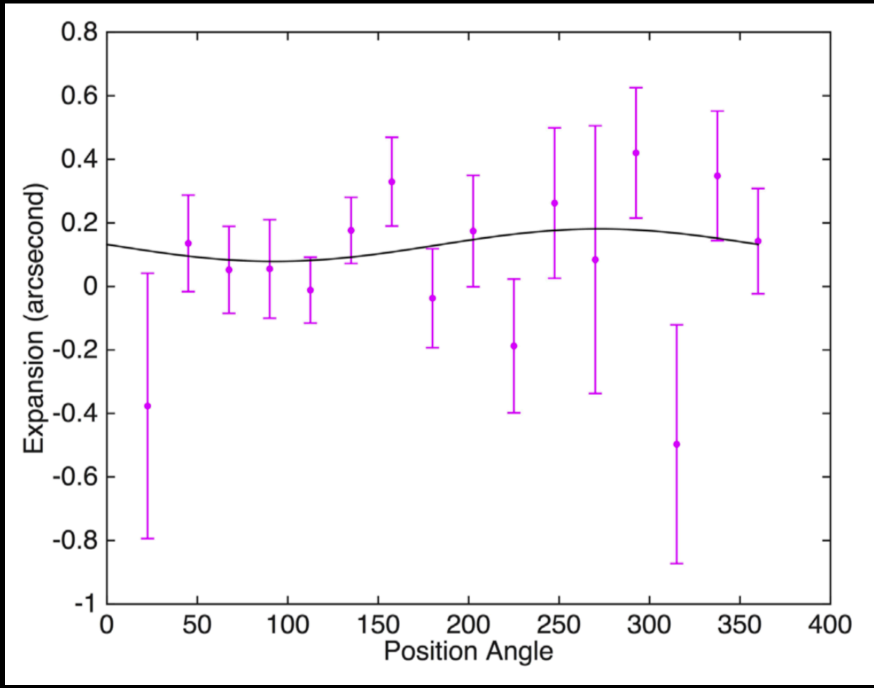
Abundances in the shell imply a low metallicity environment

Dynamics of 1E 0102.2-7219

Xi et al. 2019

Direct measurement of the forward shock expansion (17 yrs of Chandra data)





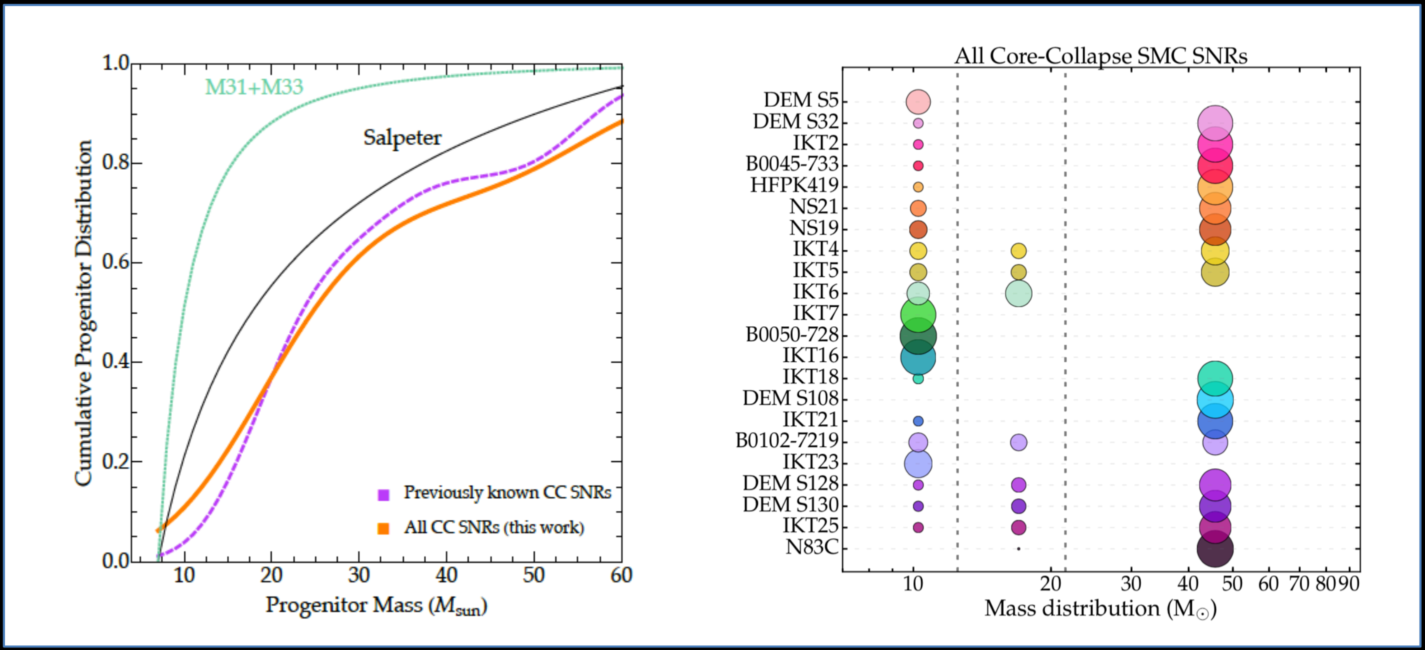
Expansion rate of 0.025% +/- 0.006% per year → FS velocity of 1600 km/s

If E_{SN} = 0.5-1.5 FOE, simple dynamical model implies a 30-60 $M_{\odot}$ progenitor

Stellar population in the vicinity of SNRs

- **M31 & M33** (Jennings et al. 2014, Díaz-Rodríguez et al. 2018) **M83** (Williams et al. 2019)**:** Progenitor distribution steeper than a Salpeter IMF → SNR catalogs biased against youngest SF regions or highest mass stars do not produce SNe

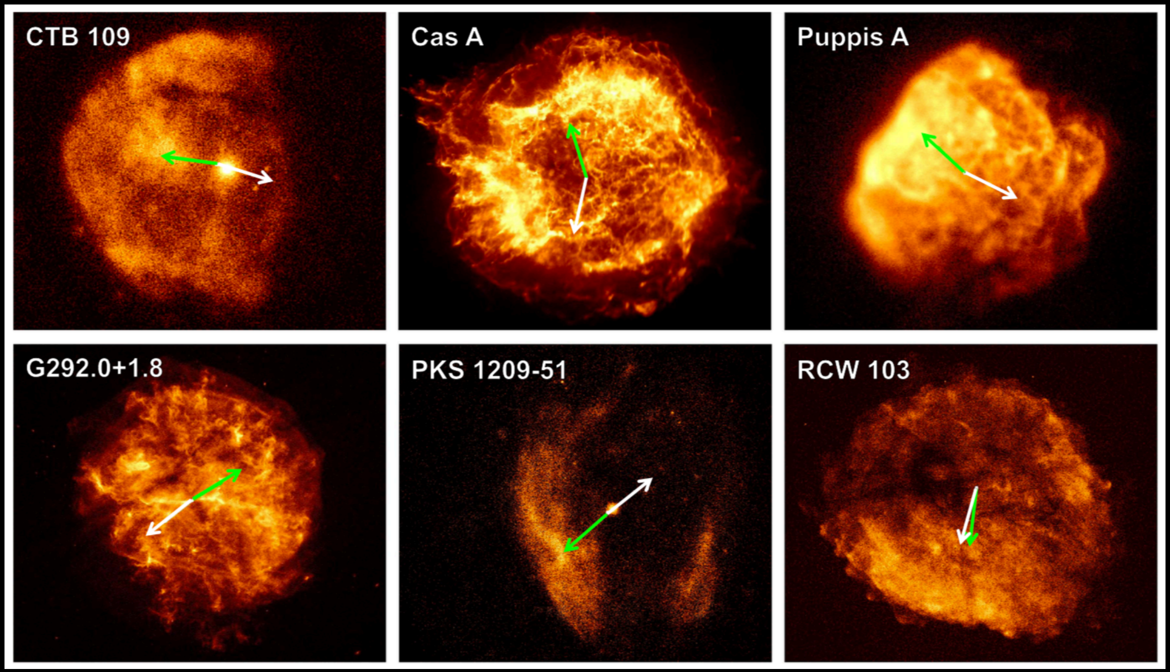
- **SMC:** Progenitor distribution similar to Salpeter IMF, evidence of high mass progenitors. A number of CC SNRs associated with burst of star formation 50–200 Myr ago → delayed CC due to binary interaction, rapid rotation, or low metallicity (Auchettl et al. 2018)



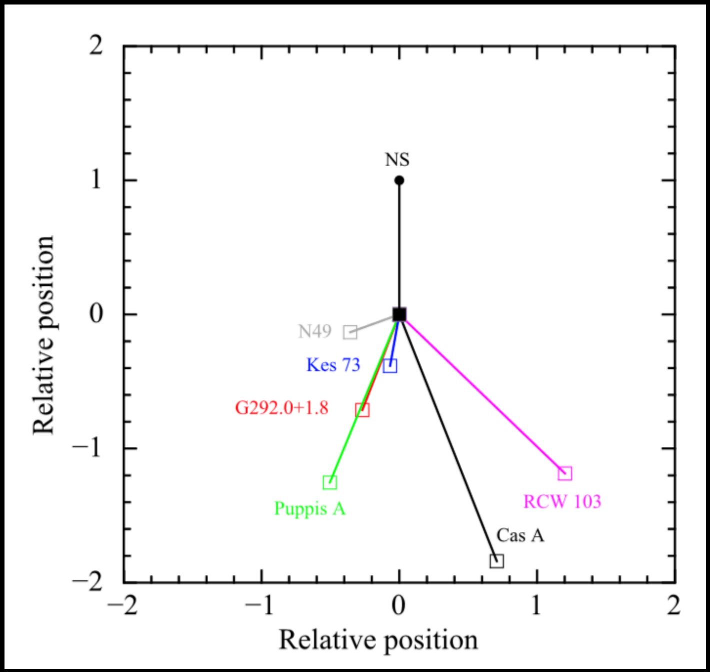
Auchettl et al. 2018

Distribution of Ejecta & Neutron Star Kicks

Holland-Ashford et al. 2017



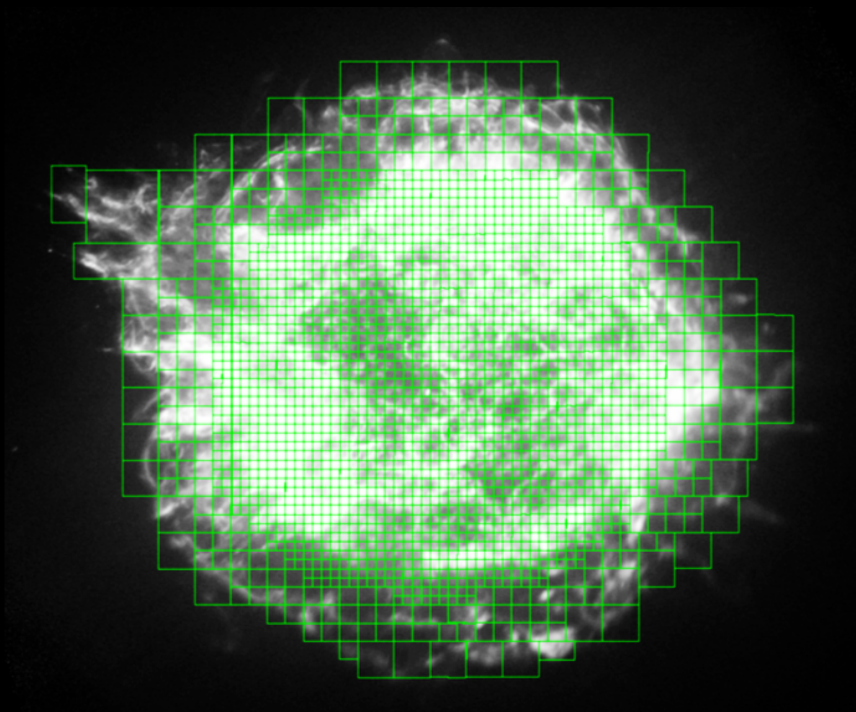
Katsuda et al. 2018



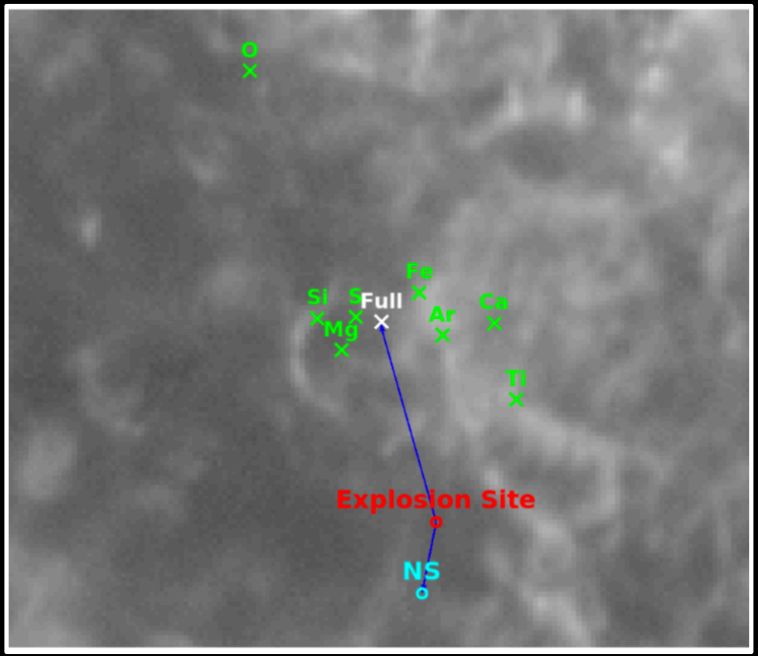
NS moving opposite of the bulk of the X-ray emission (i.e. SN ejecta), consistent with 3D simulations that predict ejecta asymmetries dominate over non-spherical neutrino emission in accelerating neutron stars (Wongwathanarat et al. 2013, Janka 2017)

Distribution of Elements in Cas A

Holland-Ashford et al. 2019



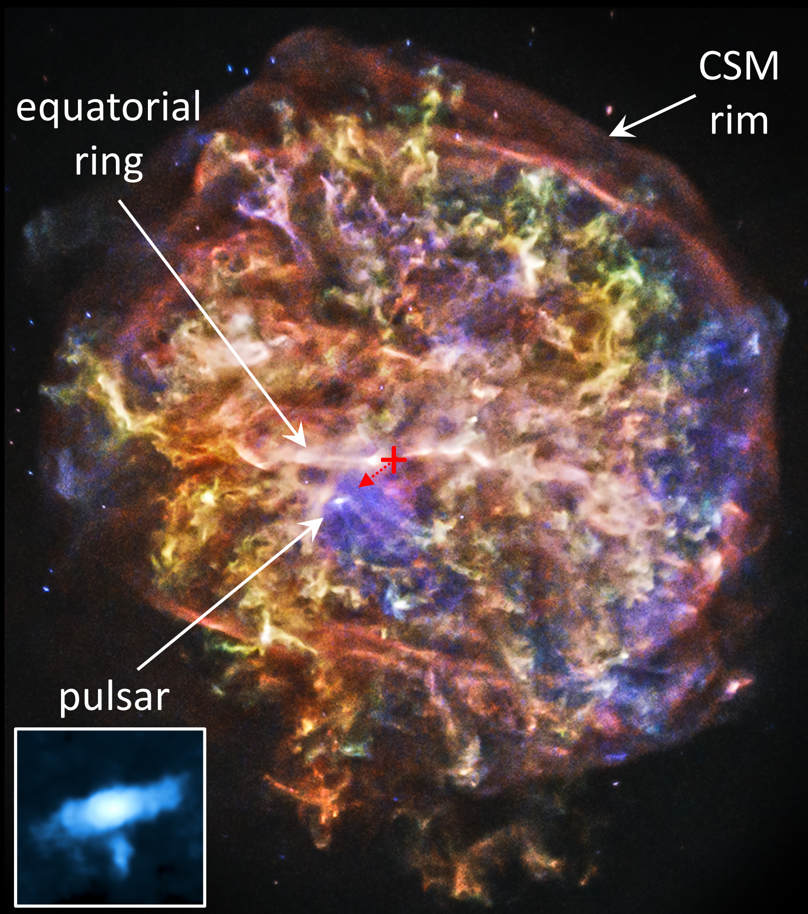
Spatially-resolved spectral analysis

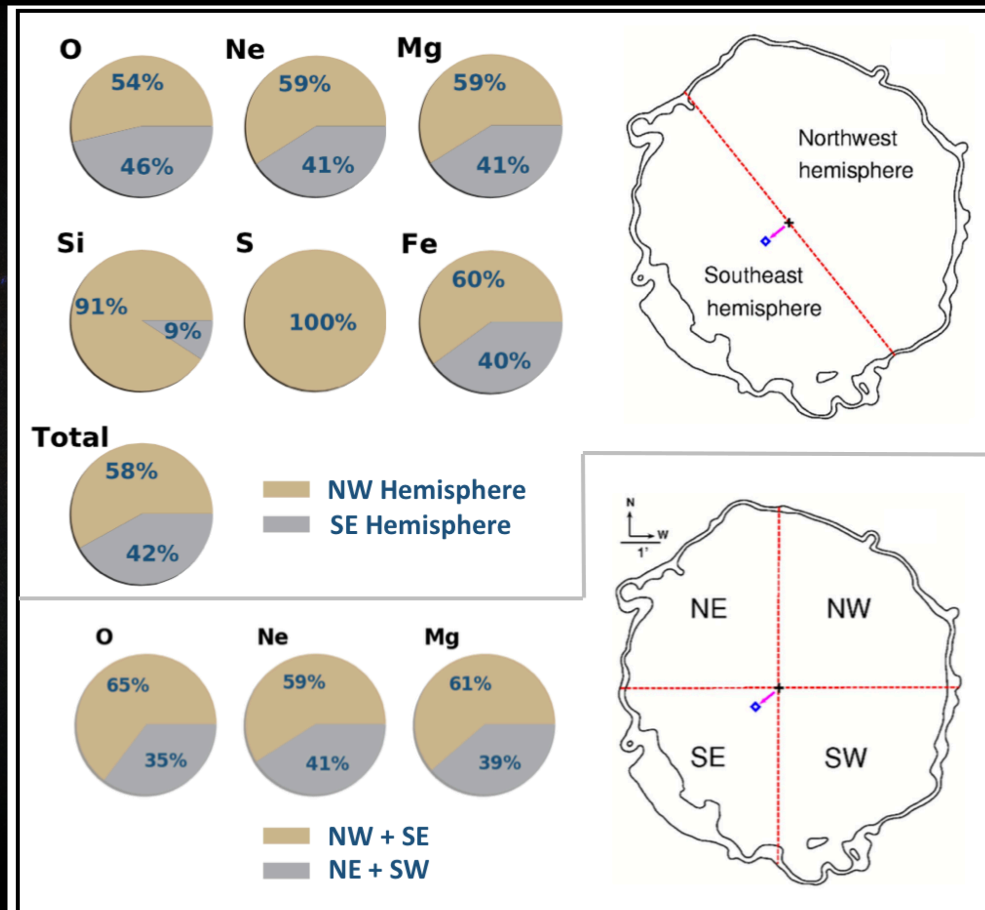


Heavier elements more directly opposed to NS direction of motion than lighter elements, consistent with gravitational tug-boat mechanism (Wongwathanarat et al. 2013, Janka 2017)

Distribution of Elements in G292.0+1.8

Bhalerao et al. 2019

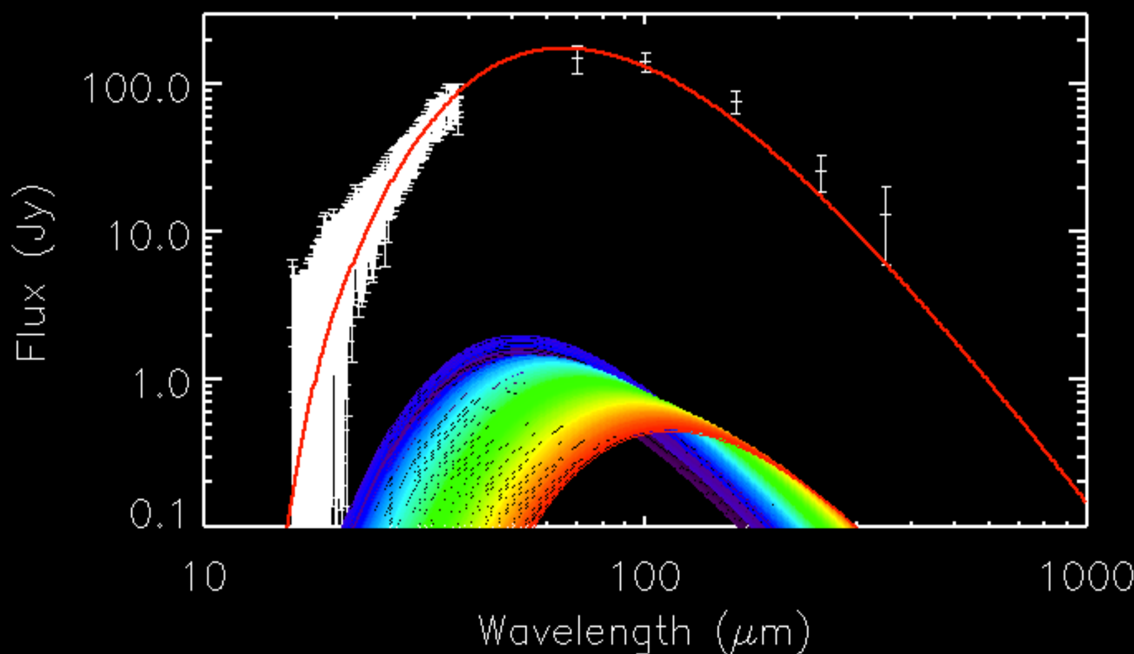




Larger amounts of ejecta opposite the inferred direction of the NS kick, particularly products from the explosive nucleosynthesis (Si, S, Fe)

Dust Properties in the Crab Nebula

PWN-heated dust



$M_d = 0.13 \pm 0.01\ M_\odot$ silicates

$0.02^{+0.01}_{-0.003}\ M_\odot$ carbon

Most of the dust mass is in the larger grains > 0.1 μm
(Temim & Dwek 2015, Owen & Barlow 2015)

Consistent with a low mass/energy SN → higher density and slower ejecta allow larger grains to form (e.g., Kozasa et al. 2009)

Progenitor in SNR 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, 2017)

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

Progenitor in SNR G54.1+0.3

Stellar population of host cluster

Table 4
Spectral Types and Extinctions Derived in the SED Fits Using Photometric Observations with Fixed Distance of 6 kpc

Object	Temperature[a,b] (K)	Spectral Type	A_V (mag)	χ^2_{red}
1	32000	O9.5	7.4 ± 0.1	2.7
2	...	...	...	...
3	20000	B2.5	8.0 ± 0.2	2.3
4	23000	B1.5	7.6 ± 0.2	3.0
5	27000	B0.5	7.4 ± 0.1	13.0
6	33000	O9	11.0 ± 0.2	11.0
7	25000	B1	8.0 ± 0.1	6.8
8	26000	B1	7.0 ± 0.2	4.0
9	21000	B2	8.1 ± 0.2	6.6
10	24000	B1.5	7.3 ± 0.1	12.2
11	22000	B2	7.1 ± 0.1	6.0

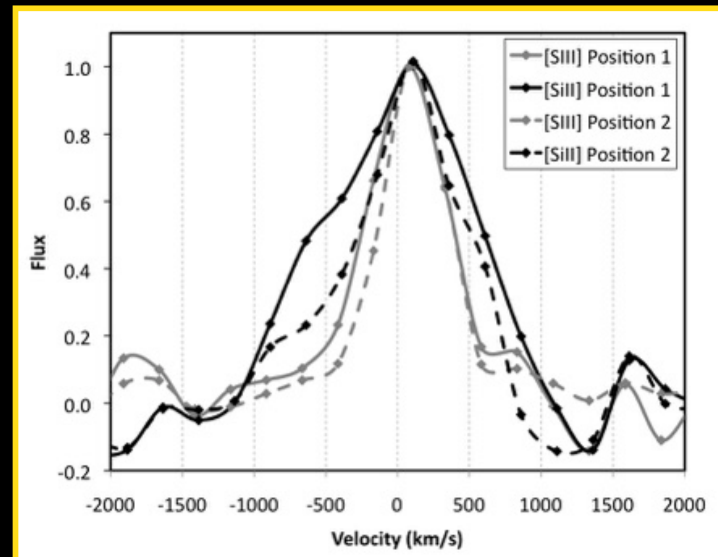
NIR spectroscopy of cluster stars revealed their spectral types

Earliest spectral type star (O9) sets a lower mass limit on the progenitor of 17 $M_\odot$

Kim et al. 2013

Progenitor in SNR G54.1+0.3

Shock diagnostics of ejecta lines



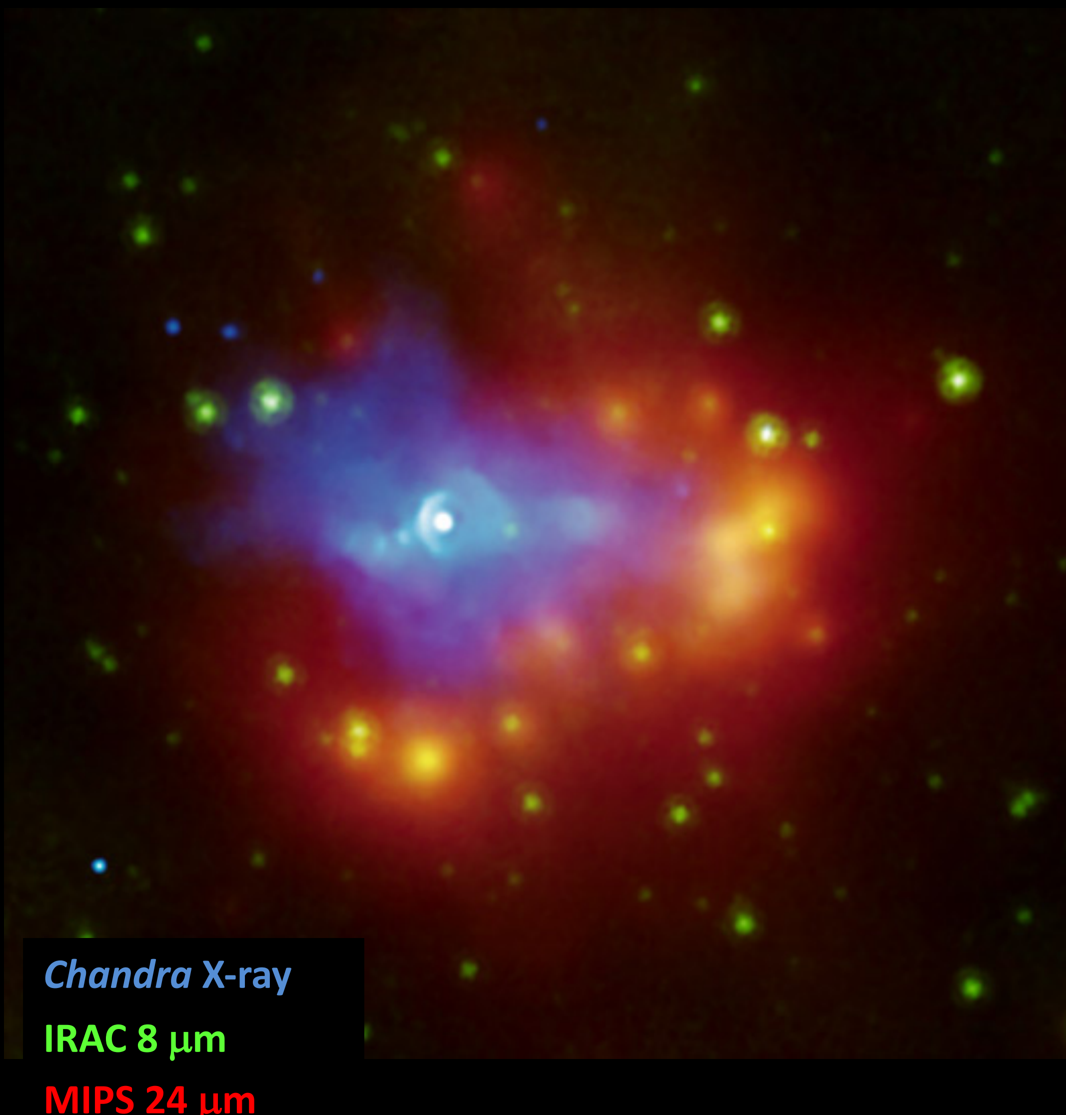
500 km/s expansion velocity

PWN drives a 25 km/s shock

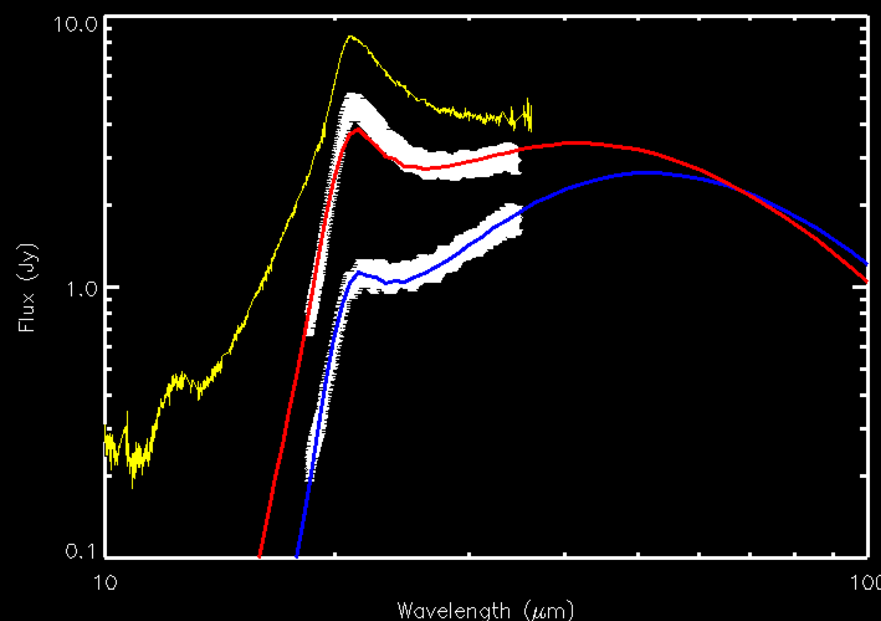
Ne, Si, S, Ar, Cl, and Fe line abundances imply a massive progenitor

Temim et al. 2010

Progenitor in SNR G54.1+0.3



Properties of the SN-formed dust



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

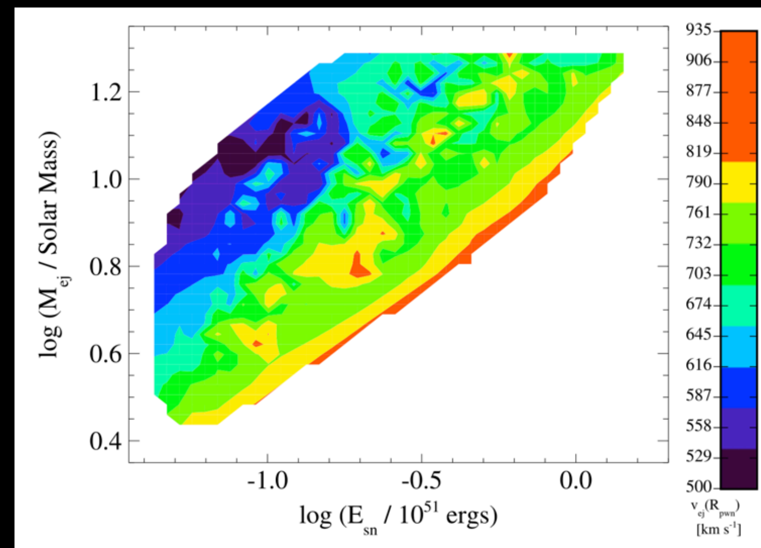
Species of dust same as in Cas A
Dust composition and mass of > 0.3 $M_{\odot}$ suggest a progenitor mass range of 16-27 $M_{\odot}$

Temim et al. 2017

Progenitor in SNR G54.1+0.3

Chandra X-ray
IRAC 8 μm
MIPS 24 μm

Dynamical modeling of the PWN



500 km/s ejecta velocity at the PWN radius is consistent with a 15-20 $M_{\odot}$ progenitor (and a low explosion energy)
Gelfand, Slane, & Temim 2015

See Samayra Straal's talk for more details

The innermost ejecta in Kes 75

Chandra X-ray (Gavriil et al. 2008)

PWN radius = 15” (0.4 pc @ 5.8 kpc)

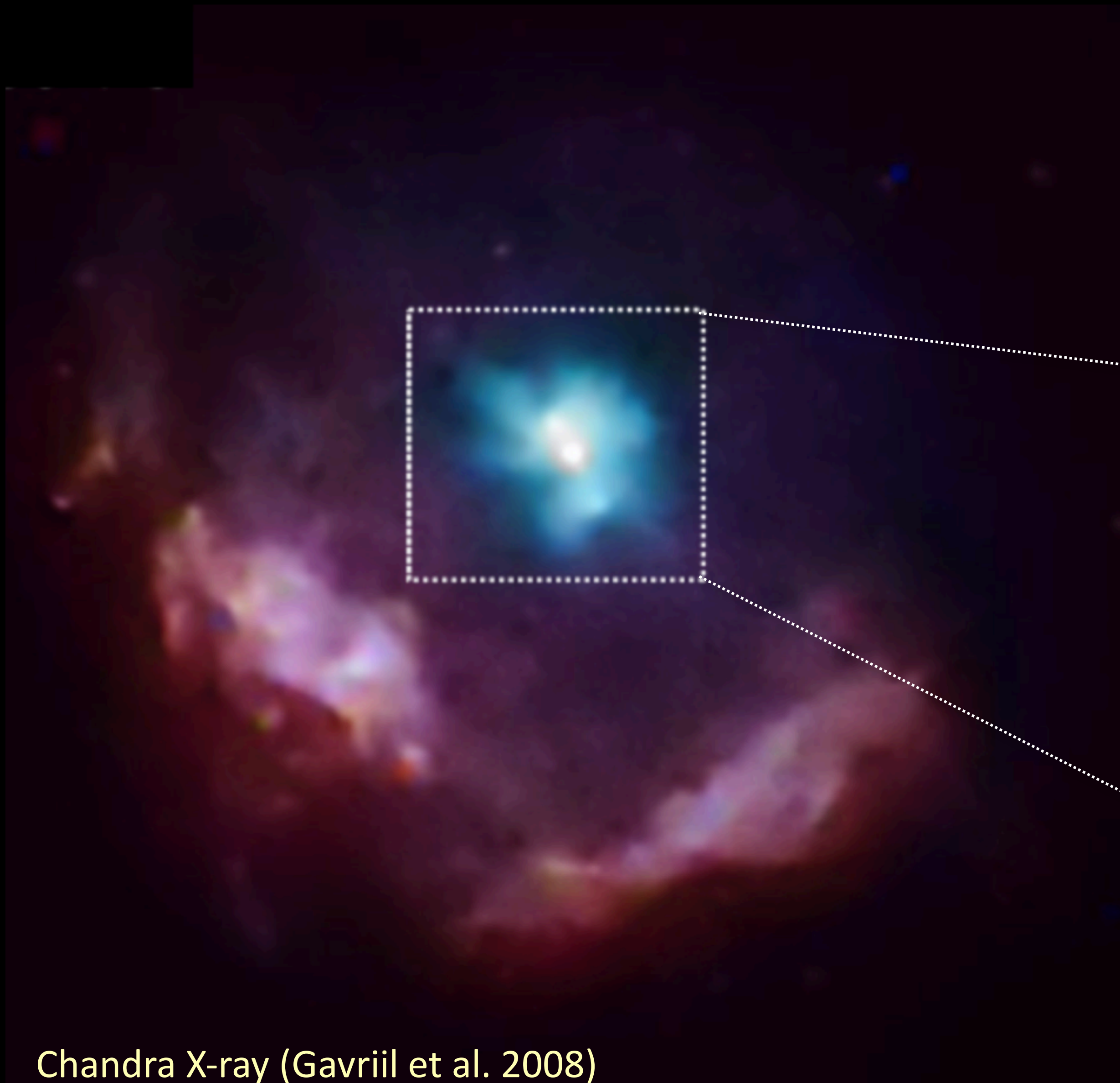
True age of the pulsar ≈ 500 yr
V_{PWN} = 1000 km/s
(Reynolds et al. 2018)

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)

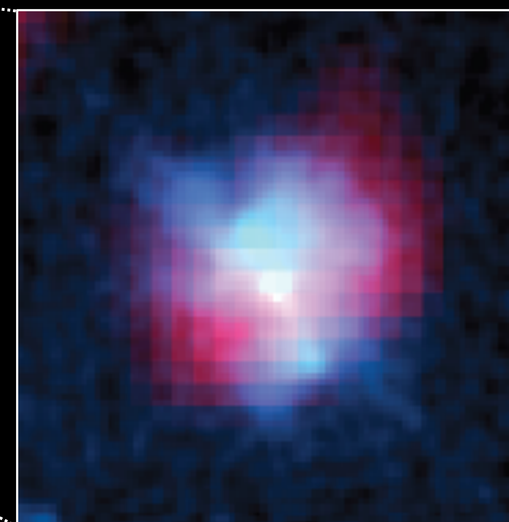
Reynolds et al. 2018 propose a more typical Type IIP explosion

The innermost ejecta in Kes 75



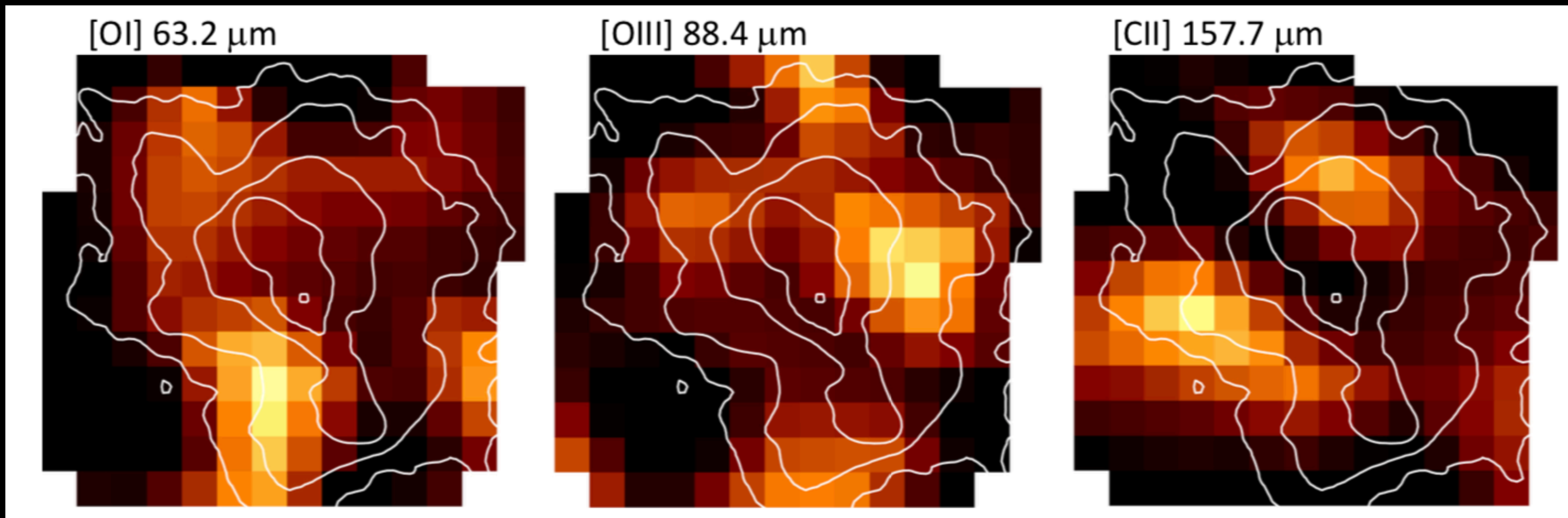
PWN radius = 15” (0.4 pc @ 5.8 kpc)

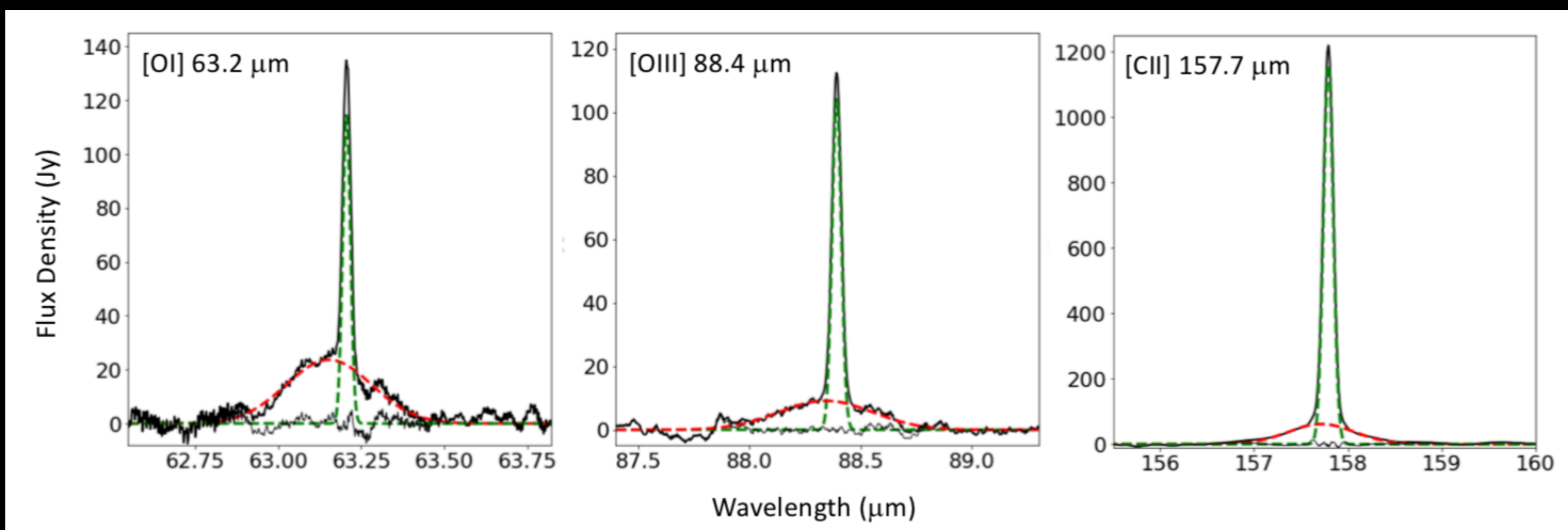
Far-infrared emission detected around the pulsar wind nebula (Temim et al. 2017)



Herschel 70 μm
Chandra X-ray

The innermost ejecta in Kes 75

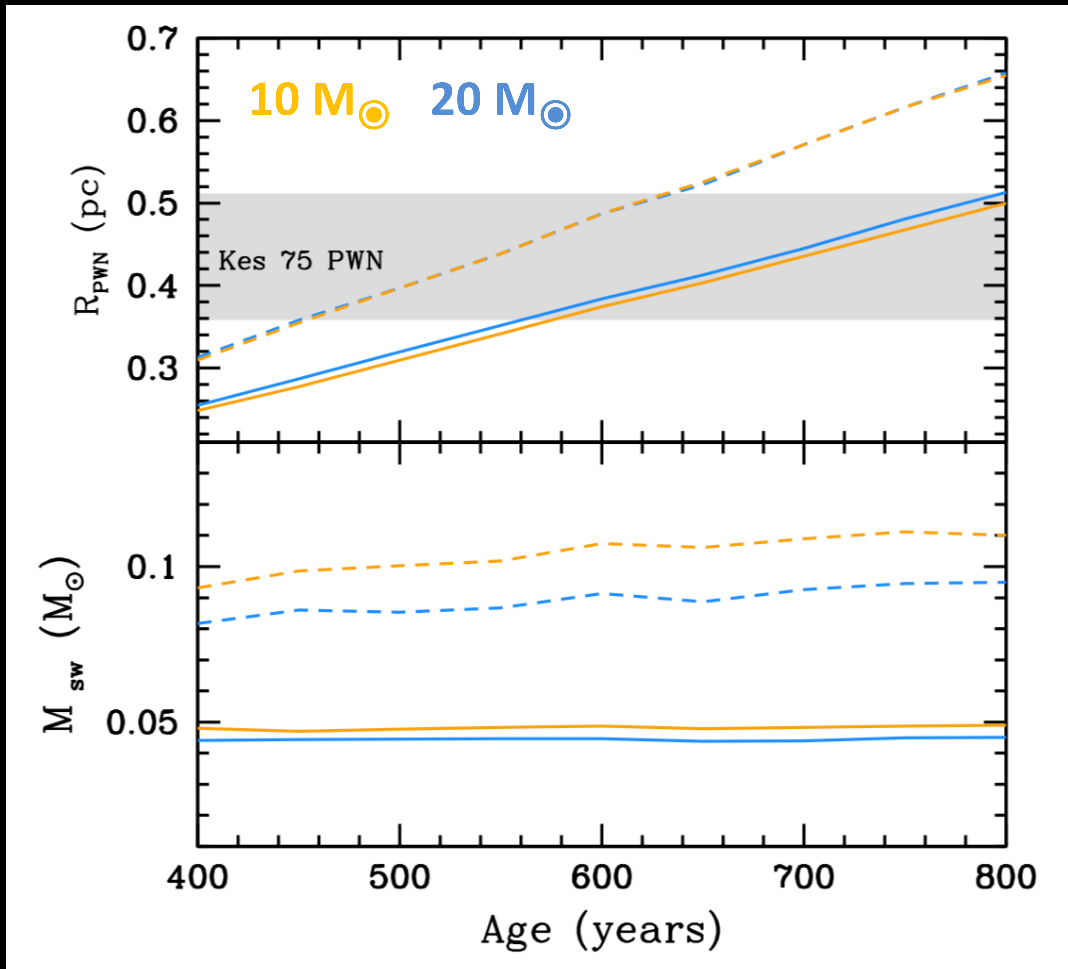




$V_{ej} \approx 750$ km/s

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

How much material has been swept-up?



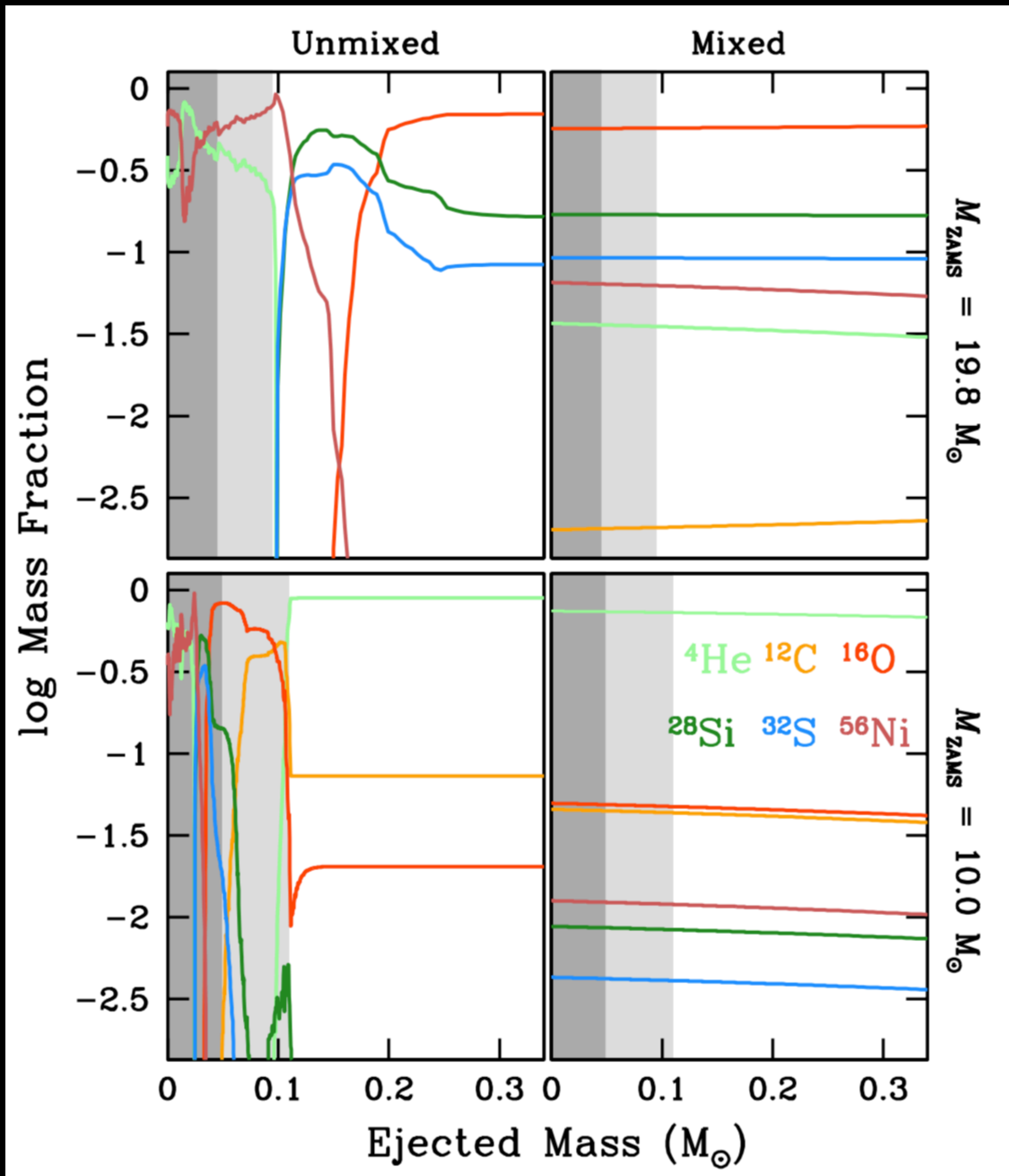
HD MODEL INPUT PARAMETERS

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?



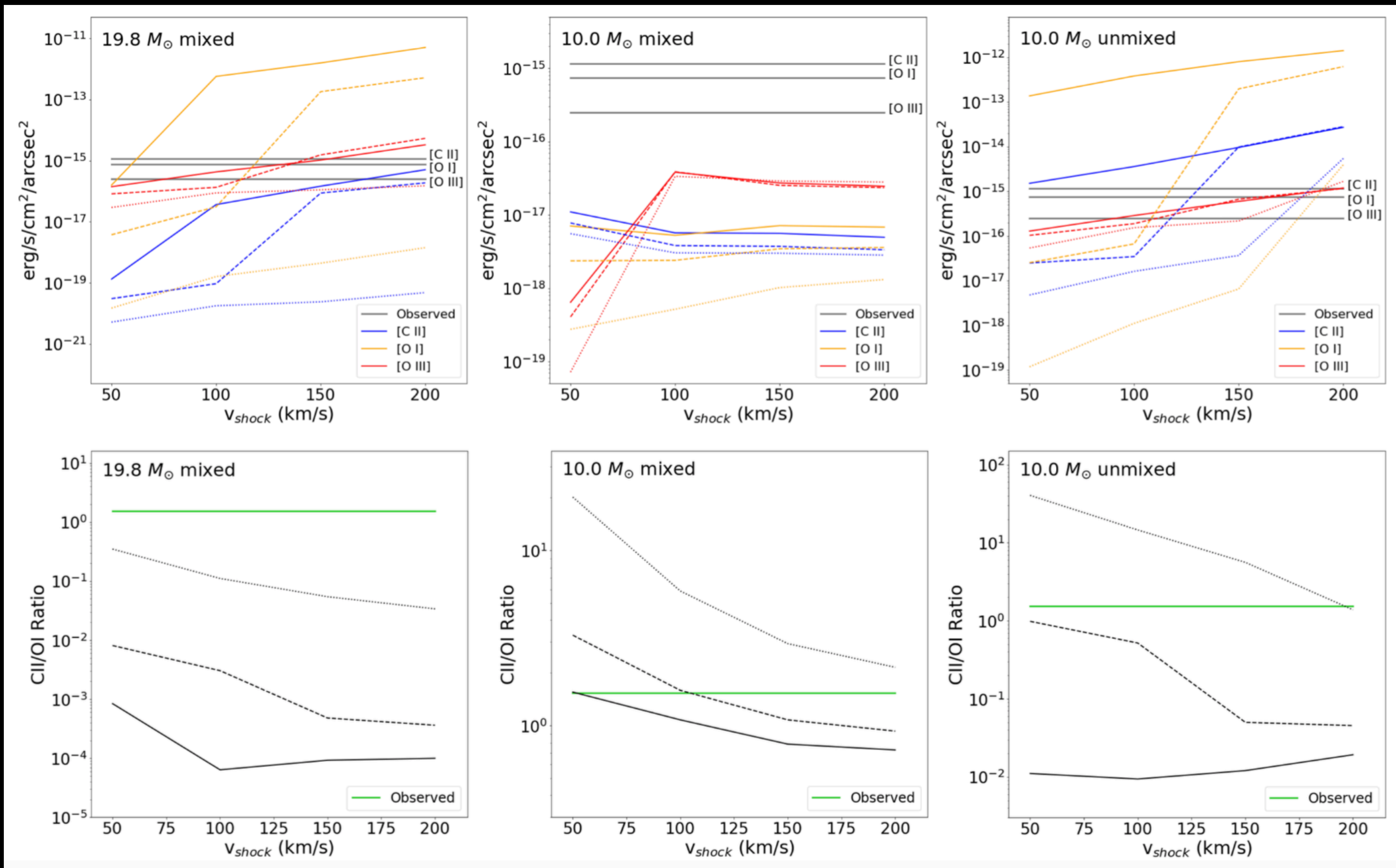
Ejecta composition vs. mass coordinate for two progenitor masses (based on models of Sukhbold et al. 2006)

Left panels: Ejecta distribution assuming no mixing

Right panels: Ejecta distribution after applying artificial mixing profile

Temim et al. 2019

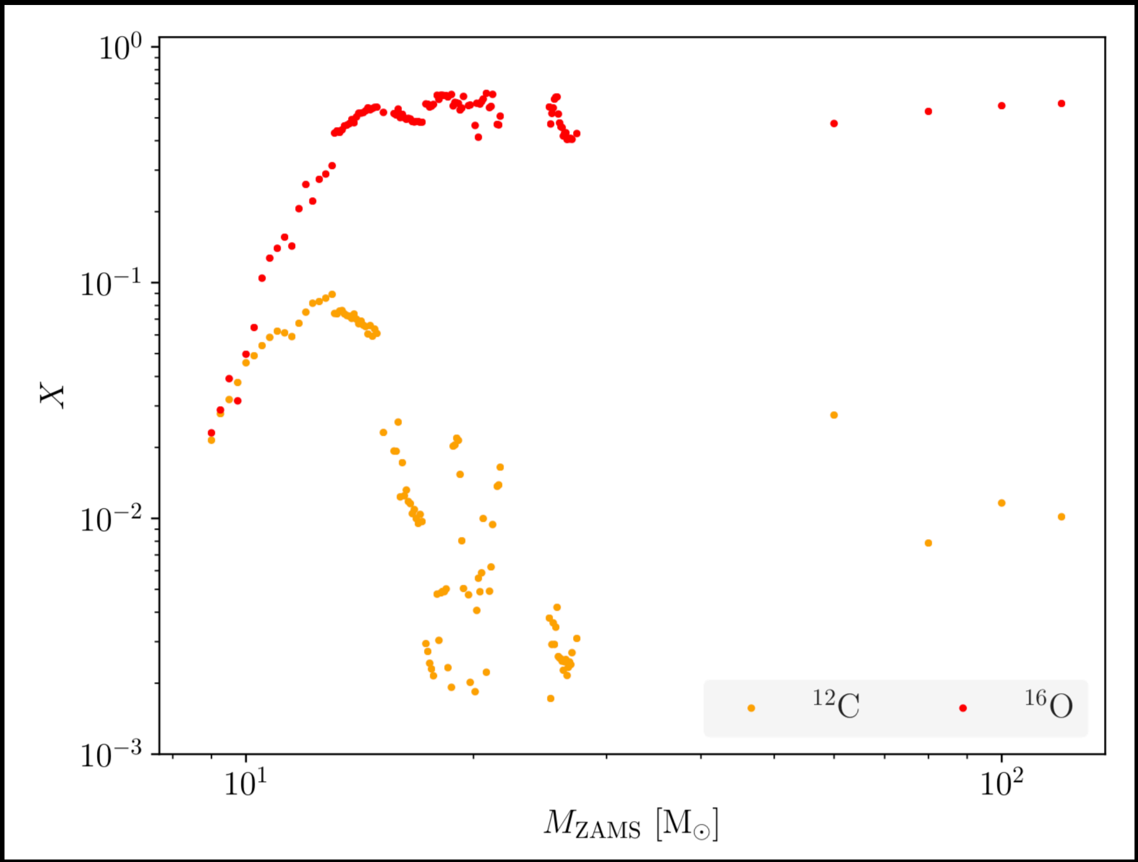
What do shock models predict?



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

Temim et al. 2019

What can we say about the progenitor?



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

Summary

Various method exist for probing progenitor & explosion properties of SNRs – recent results from studies of core-collapse SNRs:

- Elemental abundances and nearby stellar populations used to constrain the progenitor mass distribution
- SN ejecta in young SNRs distributed opposite of the neutron star direction of motion, consistent with kicks due to ejecta asymmetries
- Ejecta masses constrained by SNR and PWN expansion measured from multi-epoch observations
- Dust properties in SNRs consistent with independent estimates of progenitor mass
- Young pulsar wind nebulae powerful probes of the innermost ejecta layers → constraints on the progenitor properties and degree of mixing