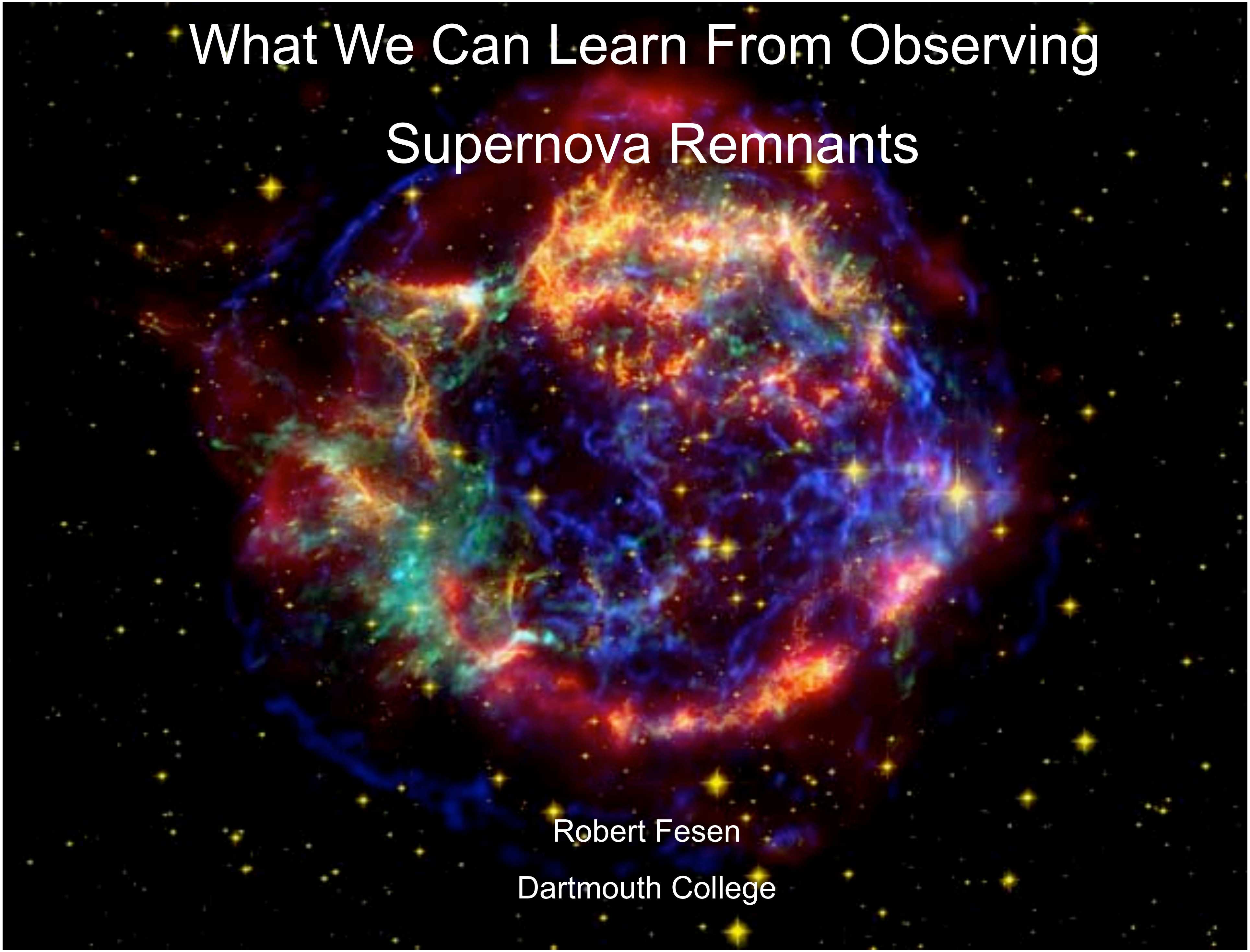
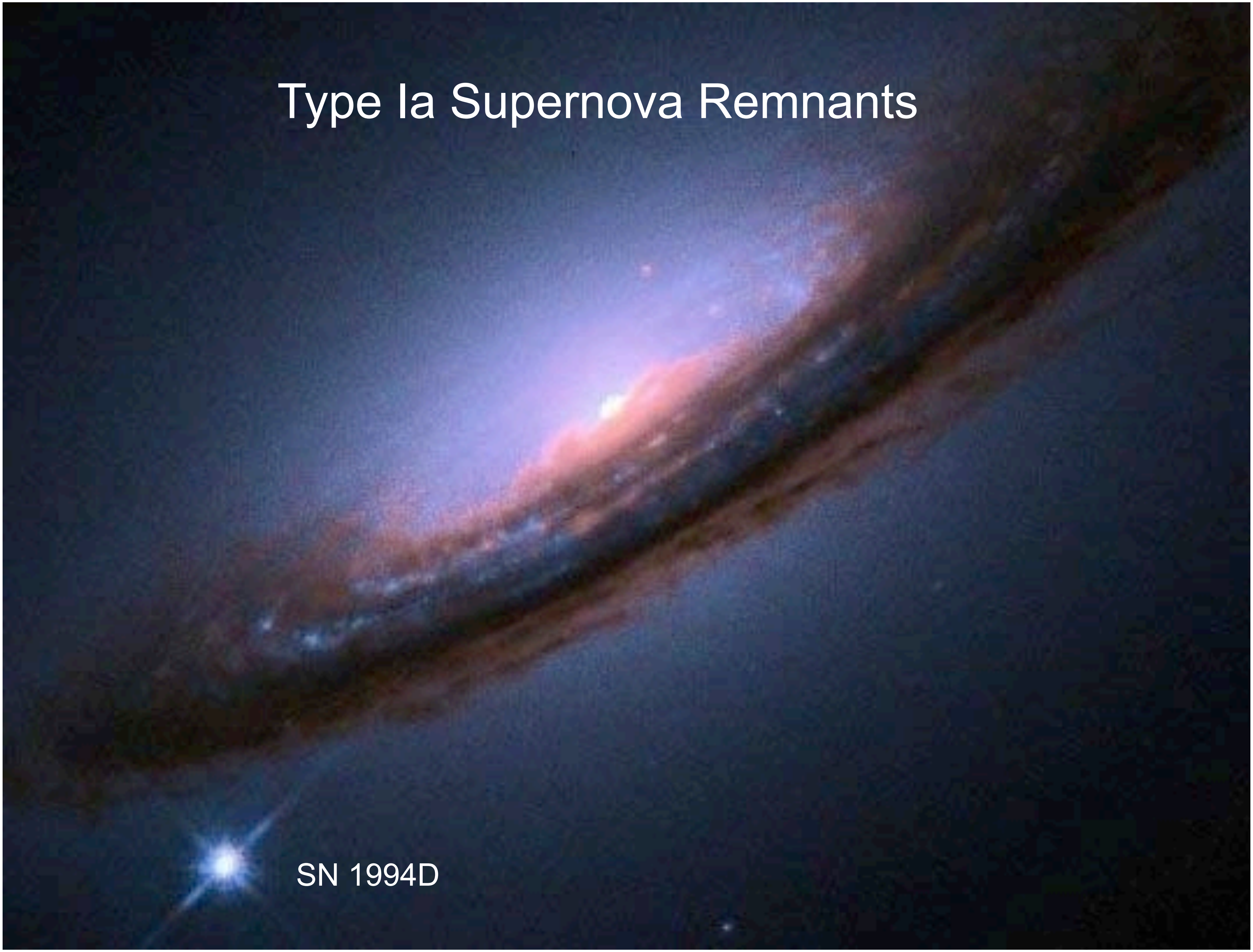
What We Can Learn From Observing Supernova Remnants



Robert Fesen

Dartmouth College

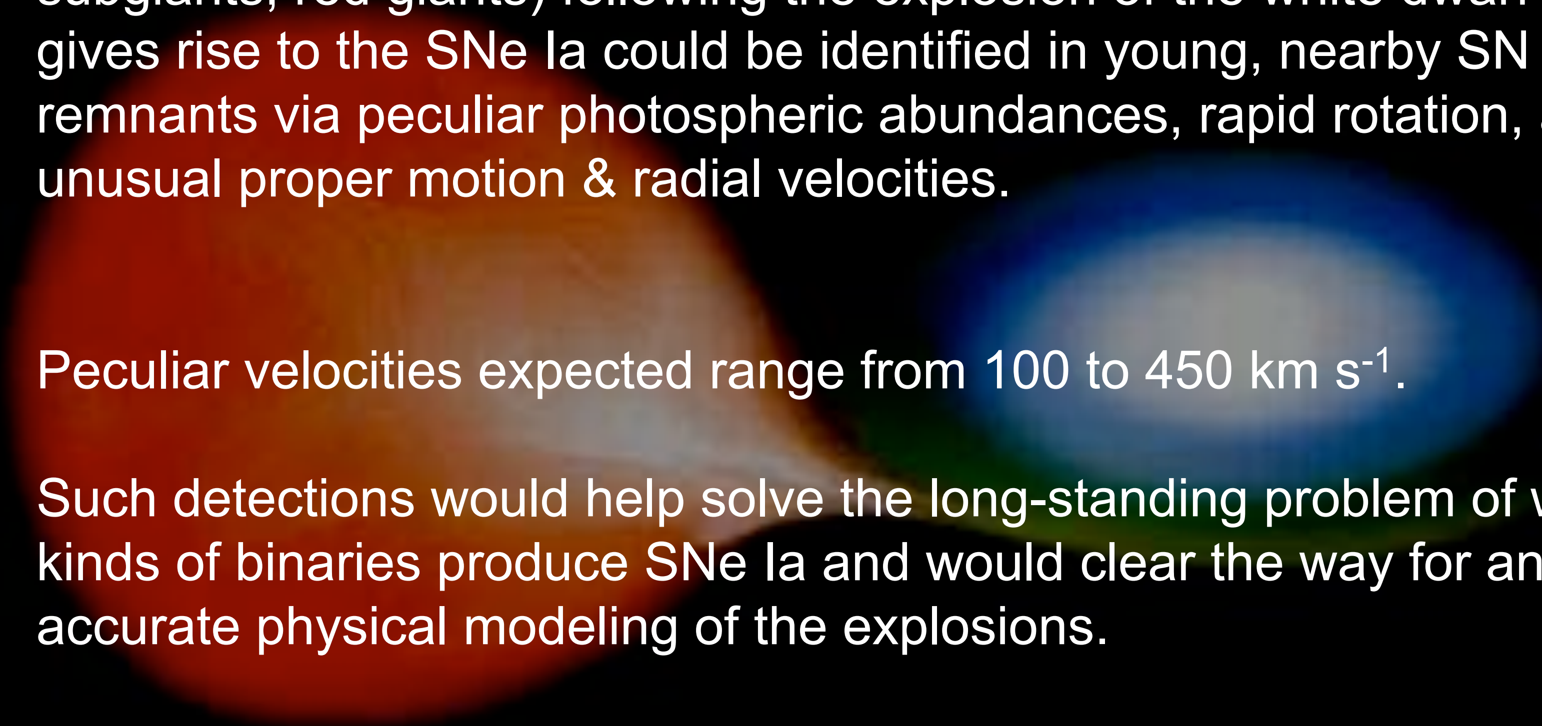

Type Ia Supernova Remnants
SN 1994D

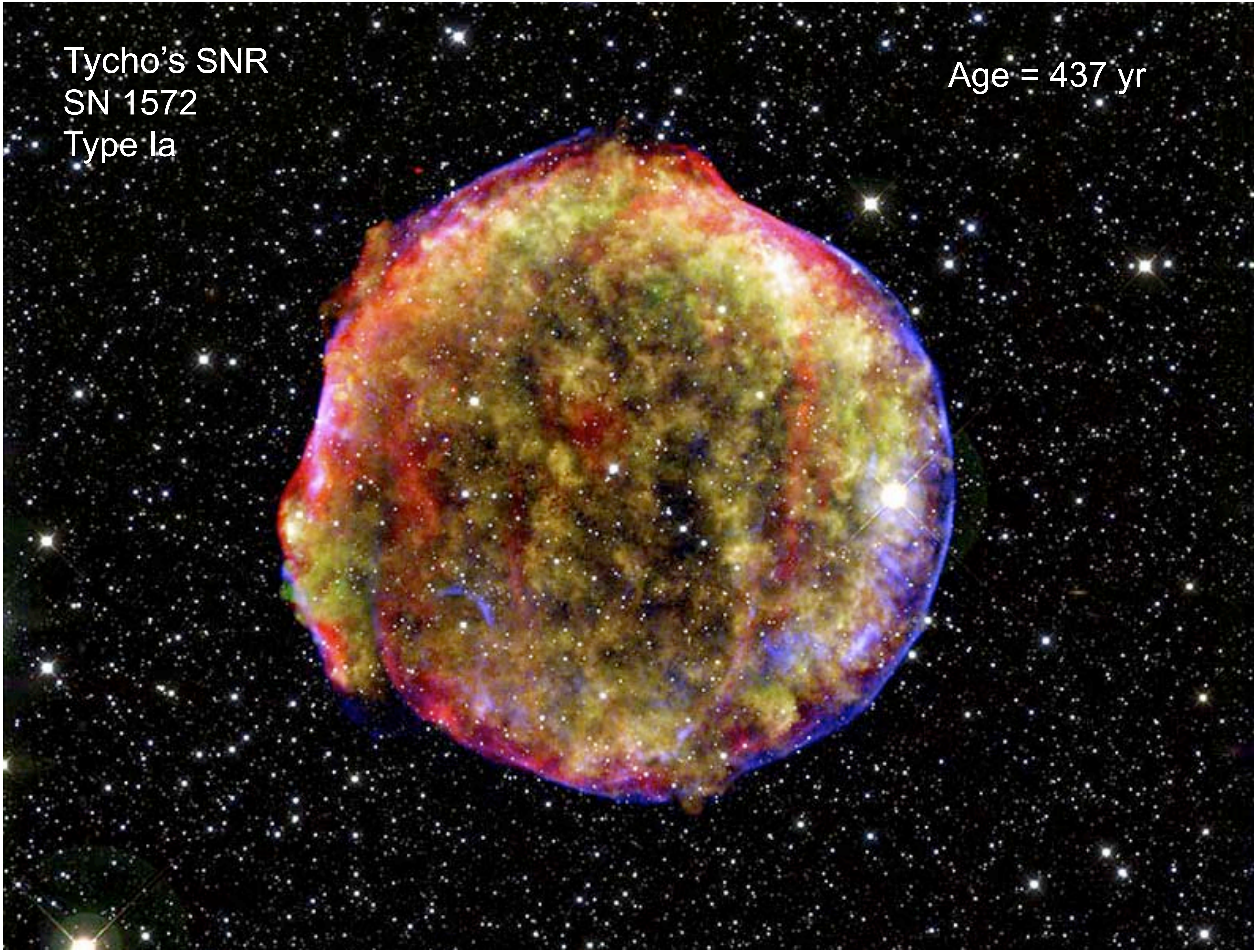
The nature of the binary systems giving rise to Type Ia supernovae (SNe Ia) remains a major unsolved problem.

Possible non-degenerate binary companions (main-sequence stars, subgiants, red giants) following the explosion of the white dwarf that gives rise to the SNe Ia could be identified in young, nearby SN Ia remnants via peculiar photospheric abundances, rapid rotation, and/or unusual proper motion & radial velocities.

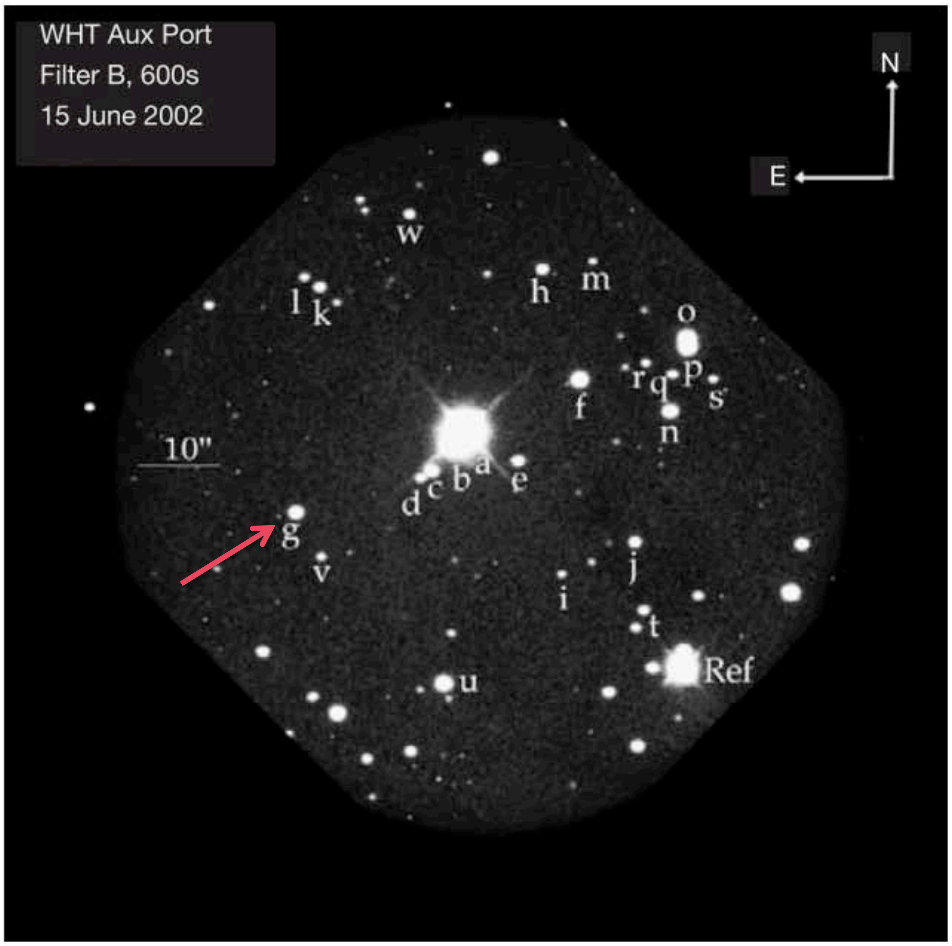
Peculiar velocities expected range from 100 to 450 km s^{-1}.

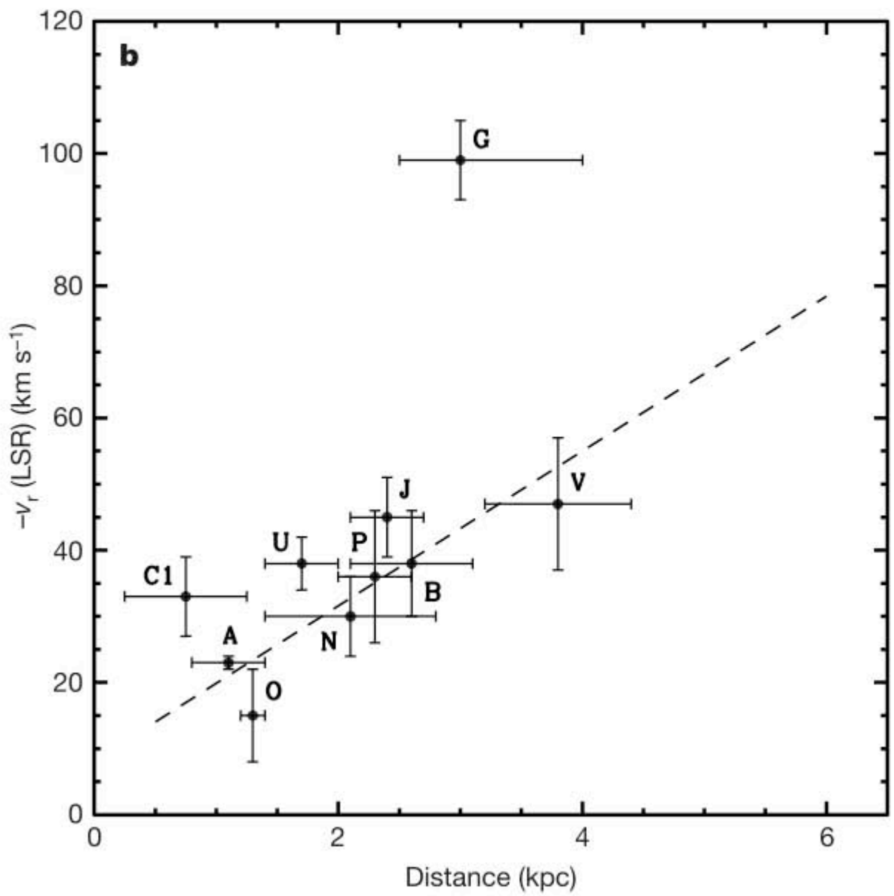
Such detections would help solve the long-standing problem of which kinds of binaries produce SNe Ia and would clear the way for an accurate physical modeling of the explosions.




Tycho's SNR
SN 1572
Type Ia
Age = 437 yr

In 2004, Ruiz-Lapuente et al. announced that they found a type G2 subgiant moving at more than three times the mean velocity of the stars at that distance and thus was the likely surviving companion of the supernova.





Ruiz-Lapuente et al. 2004

Gonzales Hernandez et al. 2009 also report that Star G appears to have some enhanced abundances.

A [Ni/Fe] = 0.16, compared to the average Galactic value of -0.05
With Co possibly enhanced too.

It also exhibits a surprisingly high Li abundance for a post-MS star.

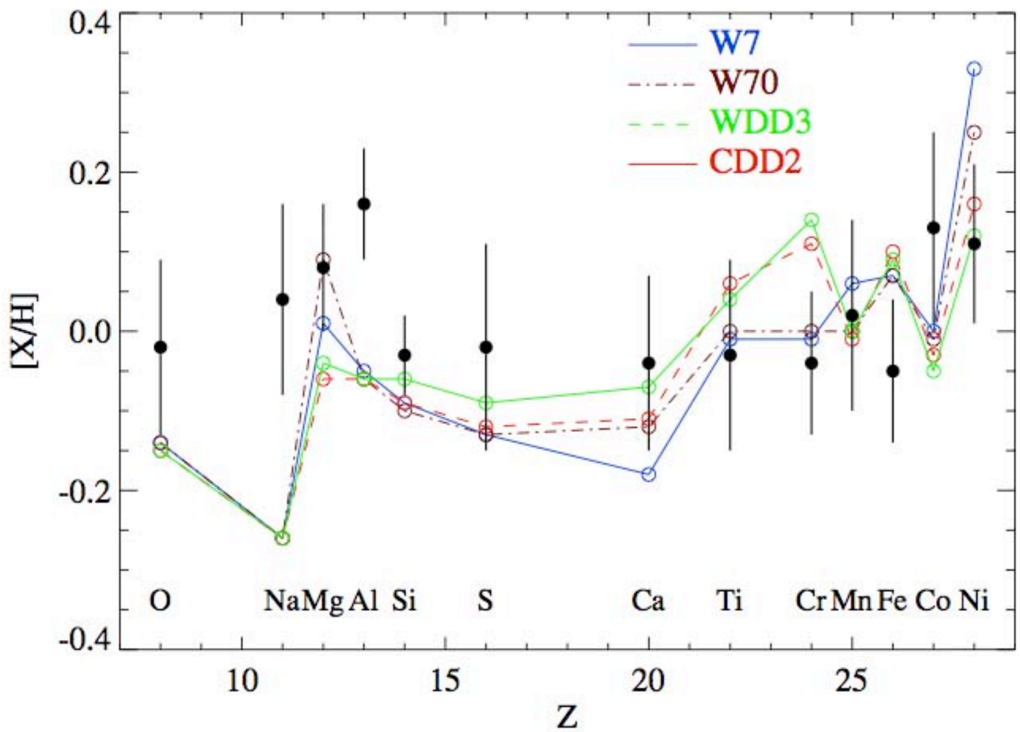
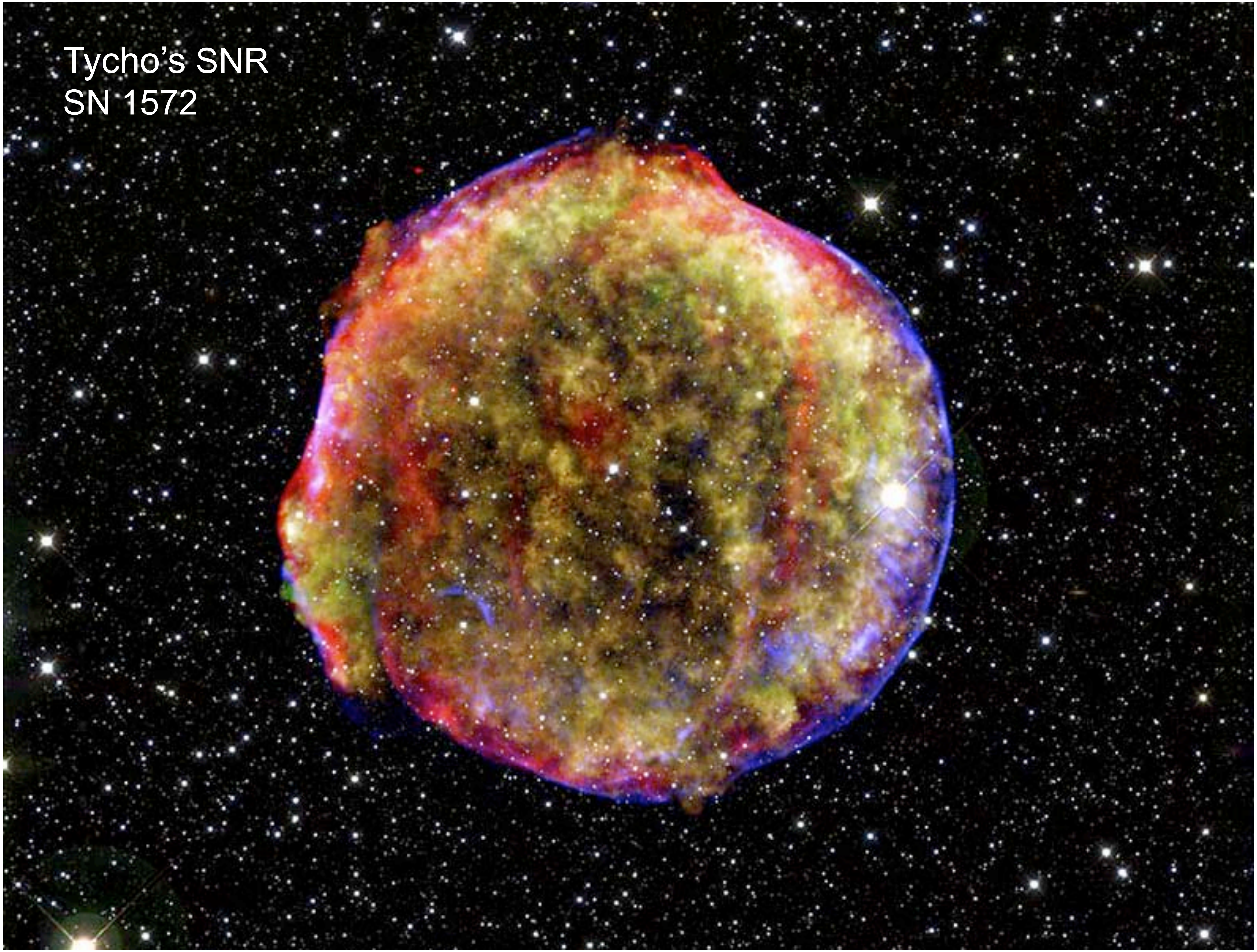


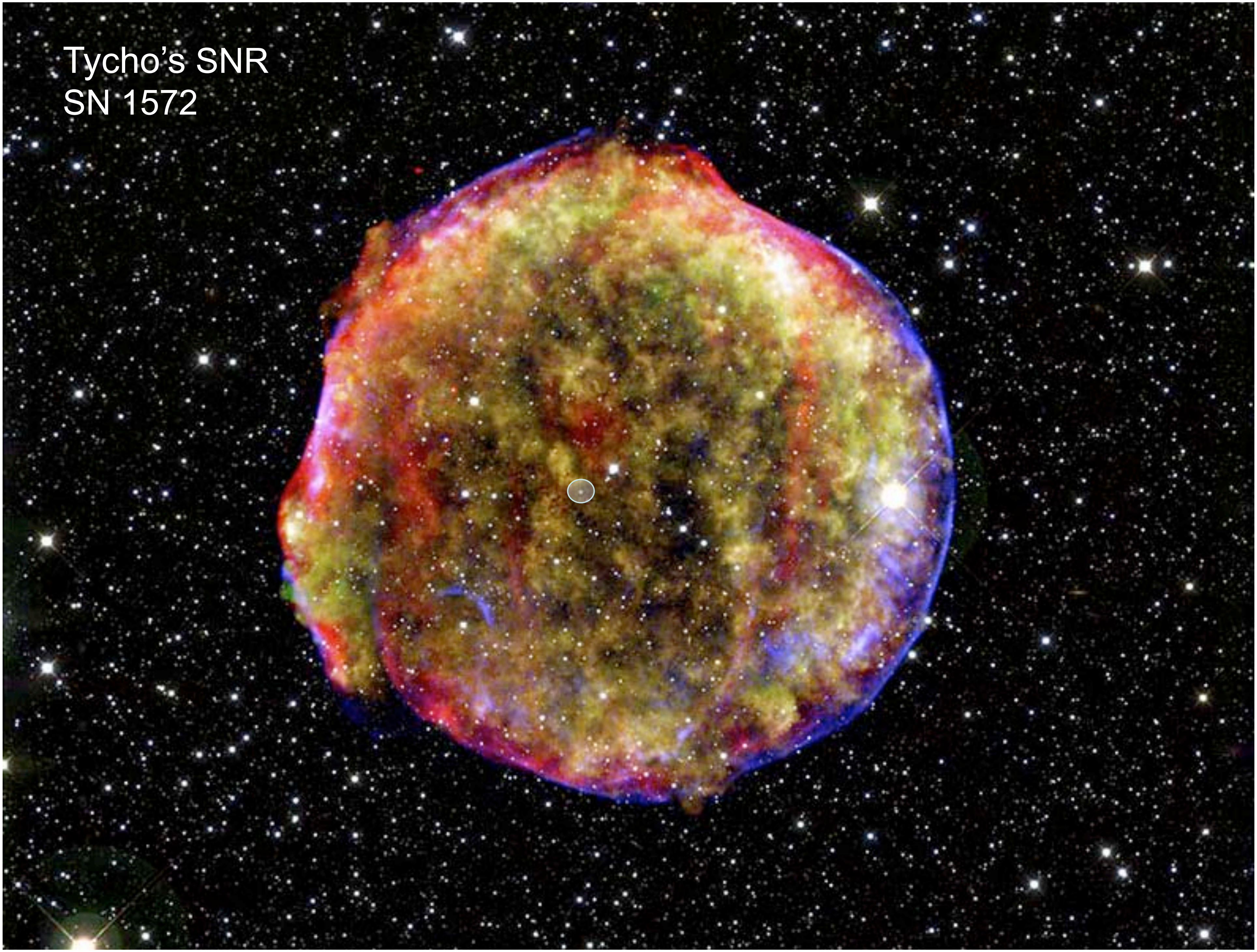
Figure 11. Expected abundances in Tycho G after contamination from the nucleosynthetic products in SN Ia models (Iwamoto et al. 1999), in comparison with the observed abundances.

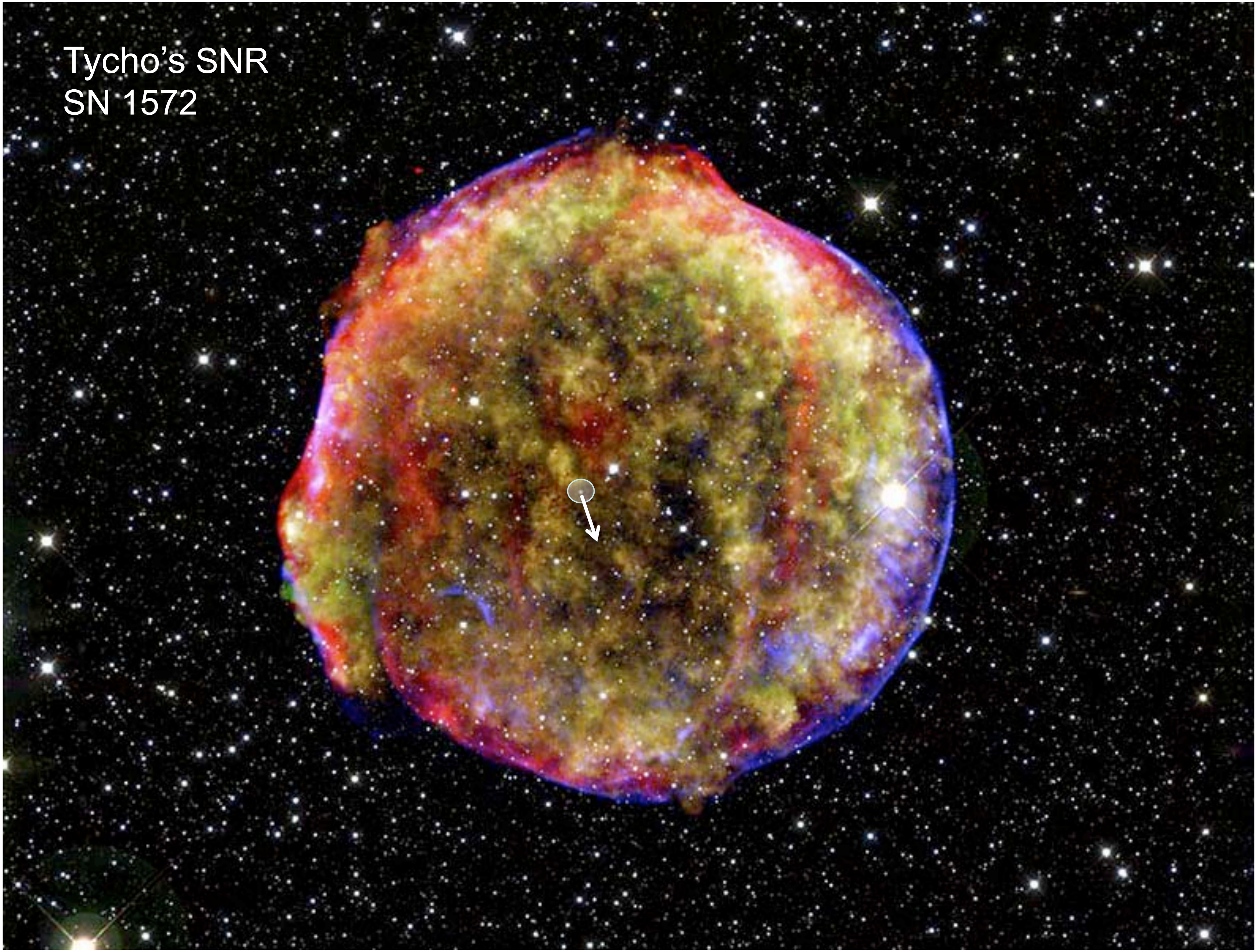
They used SN Ia yields to model the possible contamination of the star from the SN ejecta,

And report reasonable agreement with the observed abundances in Star G.

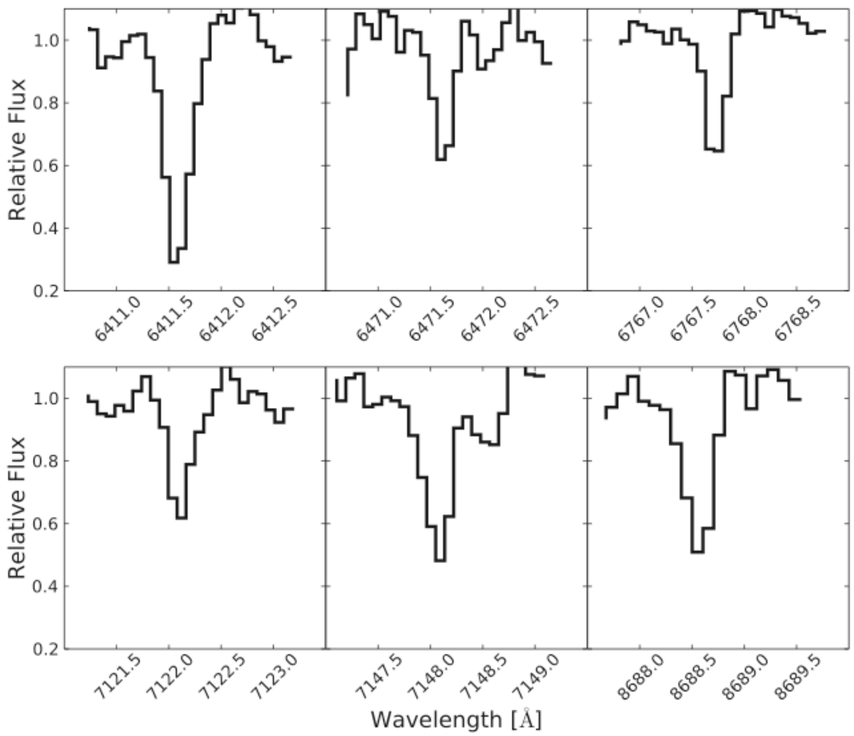
Gonzalez Hernandez et al. 2009

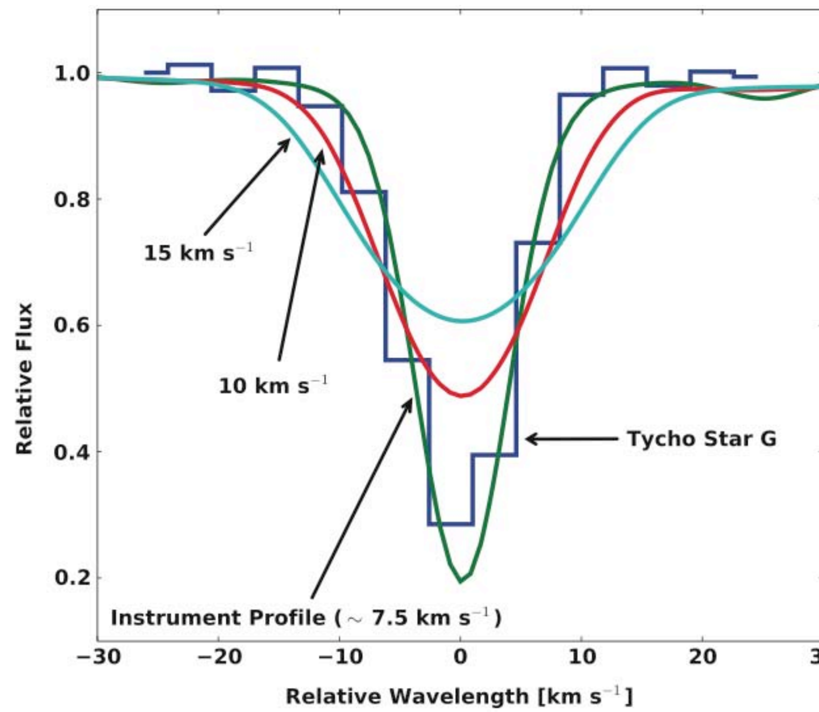

Tycho's SNR
SN 1572


Tycho's SNR
SN 1572


Tycho's SNR
SN 1572

Both Kerzendorf et al. and Gonzales Hernandez et al. report star G to be a slow rotator, in contrast to an expected rapid rotation due to expectations of strong tidal coupling of a Roche-lobe filling donor/companion star.





Fuhrmann (2005) suggested that star G could simply be a thick-disk star passing close to the Tycho remnant (d = 3 kpc).

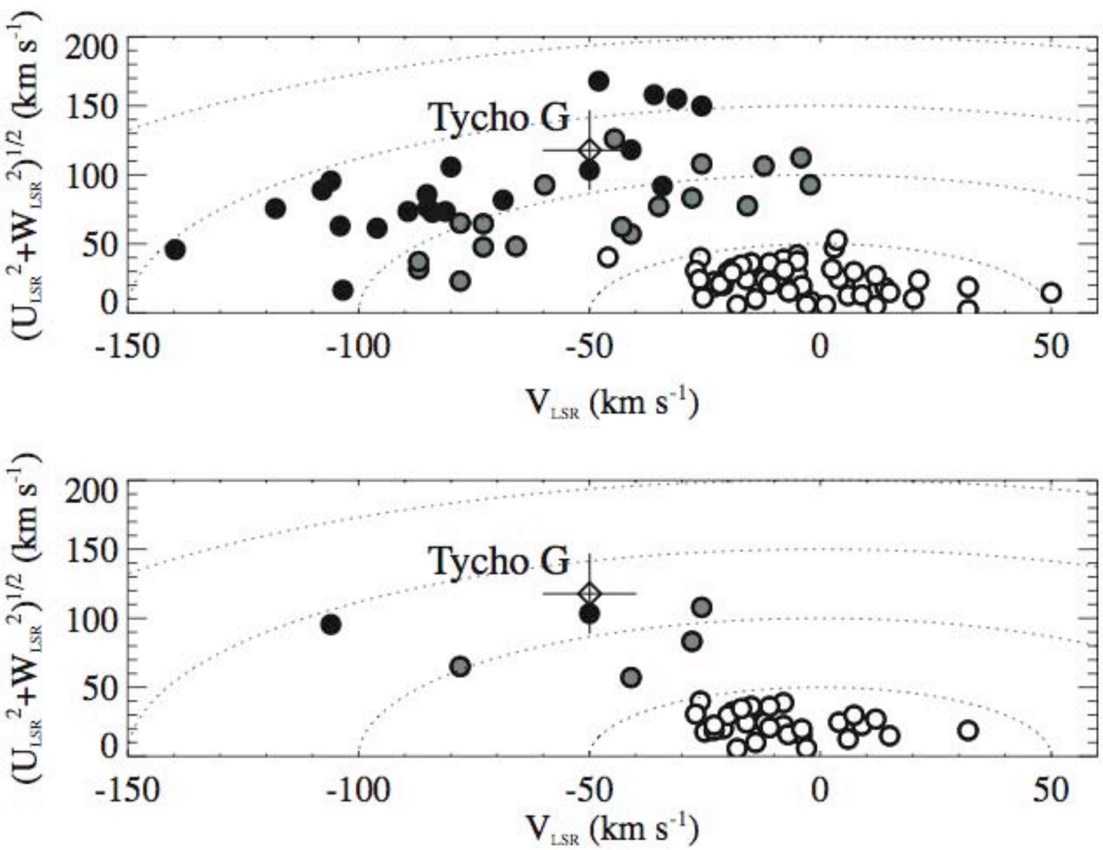
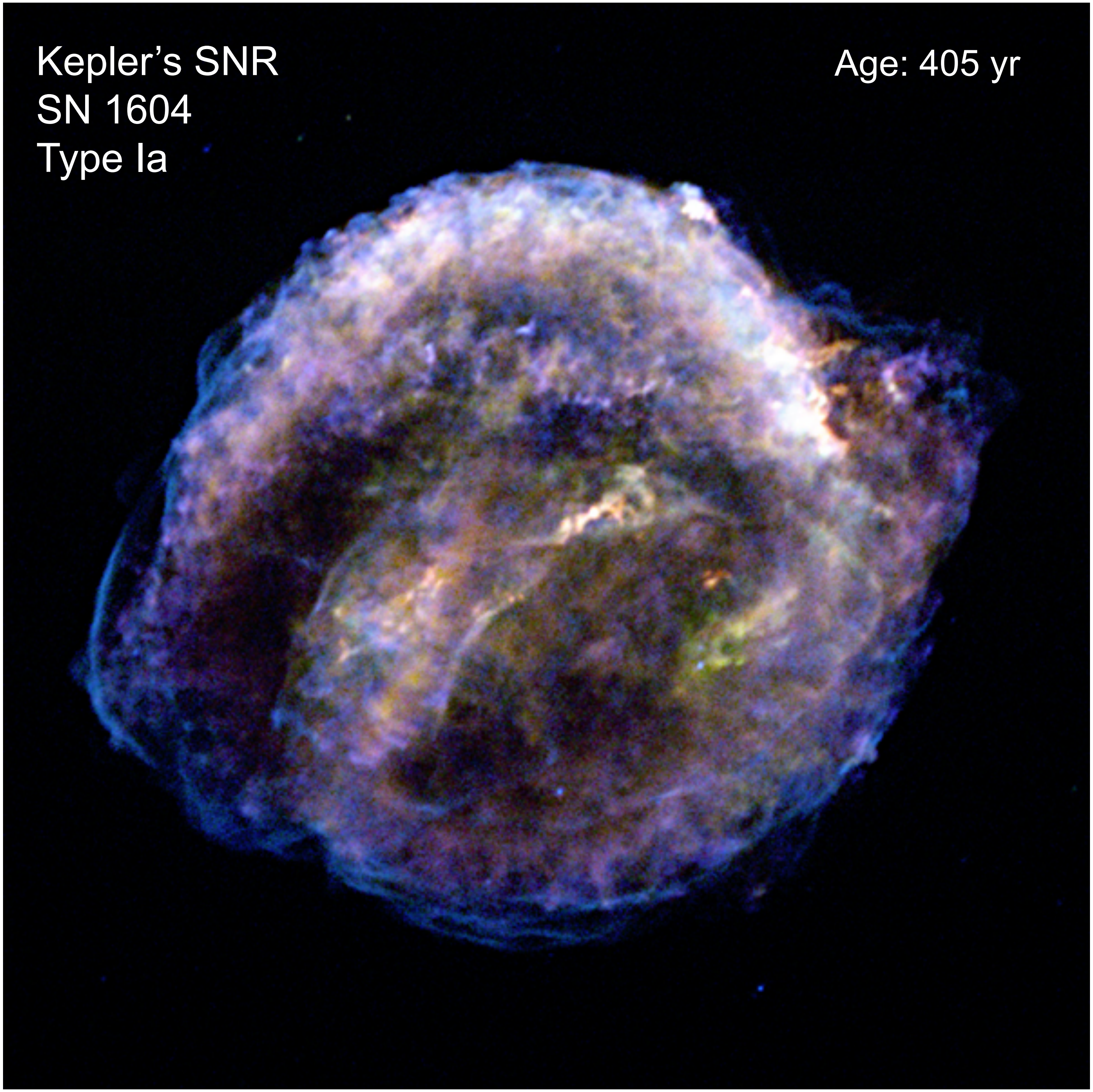
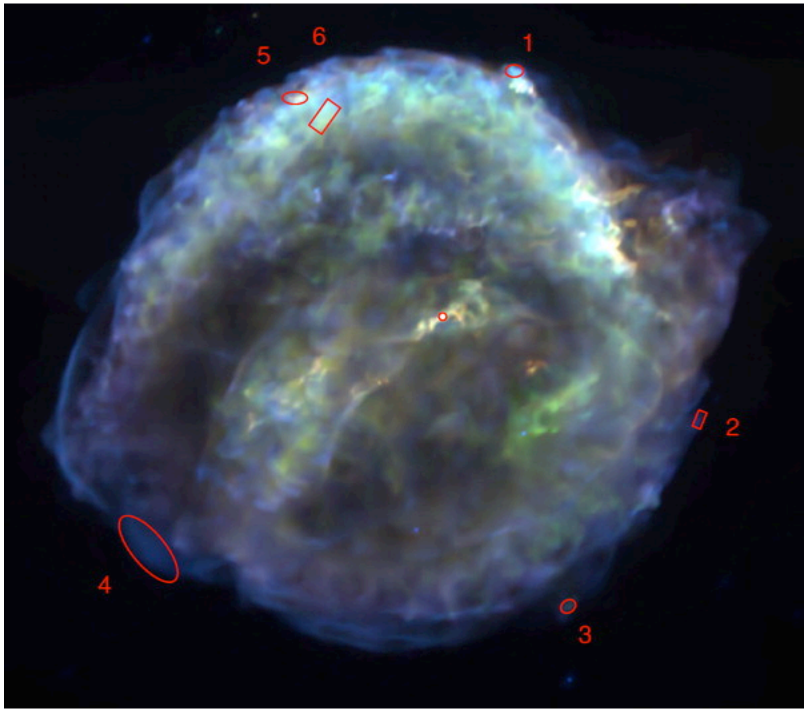
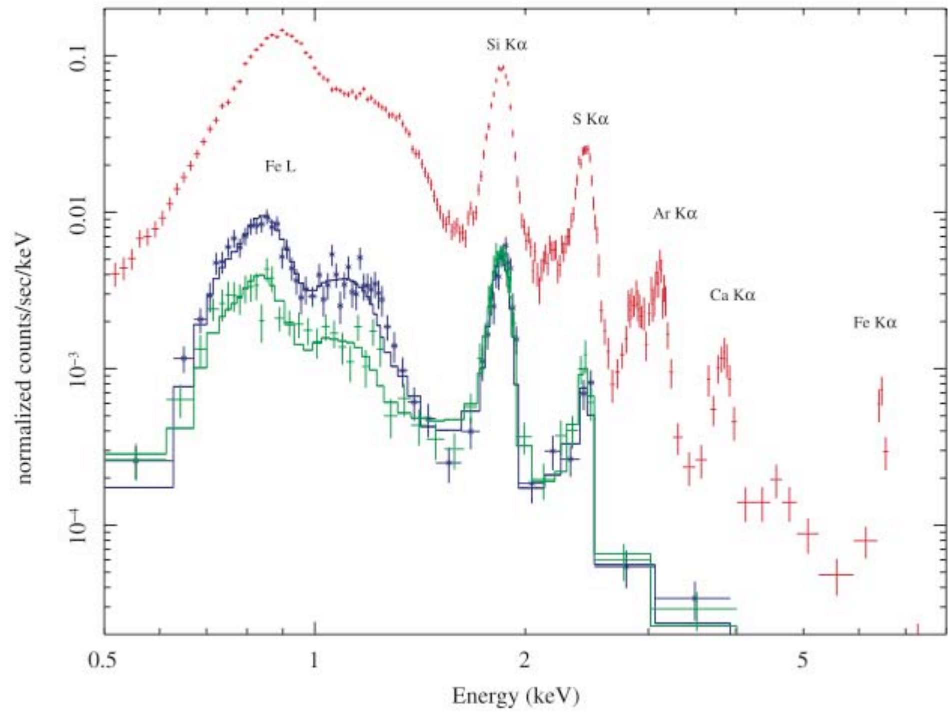


Figure 10. Upper panel: Toomre diagram of the thick-disk stars (black filled circles), thin-disk stars (open circles), and transition stars (grey filled circles) from Bensby et al. (2003, 2005). The star Tycho G is displayed as a rhombus. Lower panel: the same as upper panel, but for stars with metallicity greater than or equal to the metallicity of Tycho G.

Gonzalez Hernandez et al. 2009


Kepler's SNR
SN 1604
Type Ia
Age: 405 yr





Reynolds et al. 2007

Chandra spectra of three outer knots show little in the way of O-rich ejecta
-- such outer knots might show the lightest nucleosynthetic products
e.g. O-rich ejecta indicating a core-collapse SN –

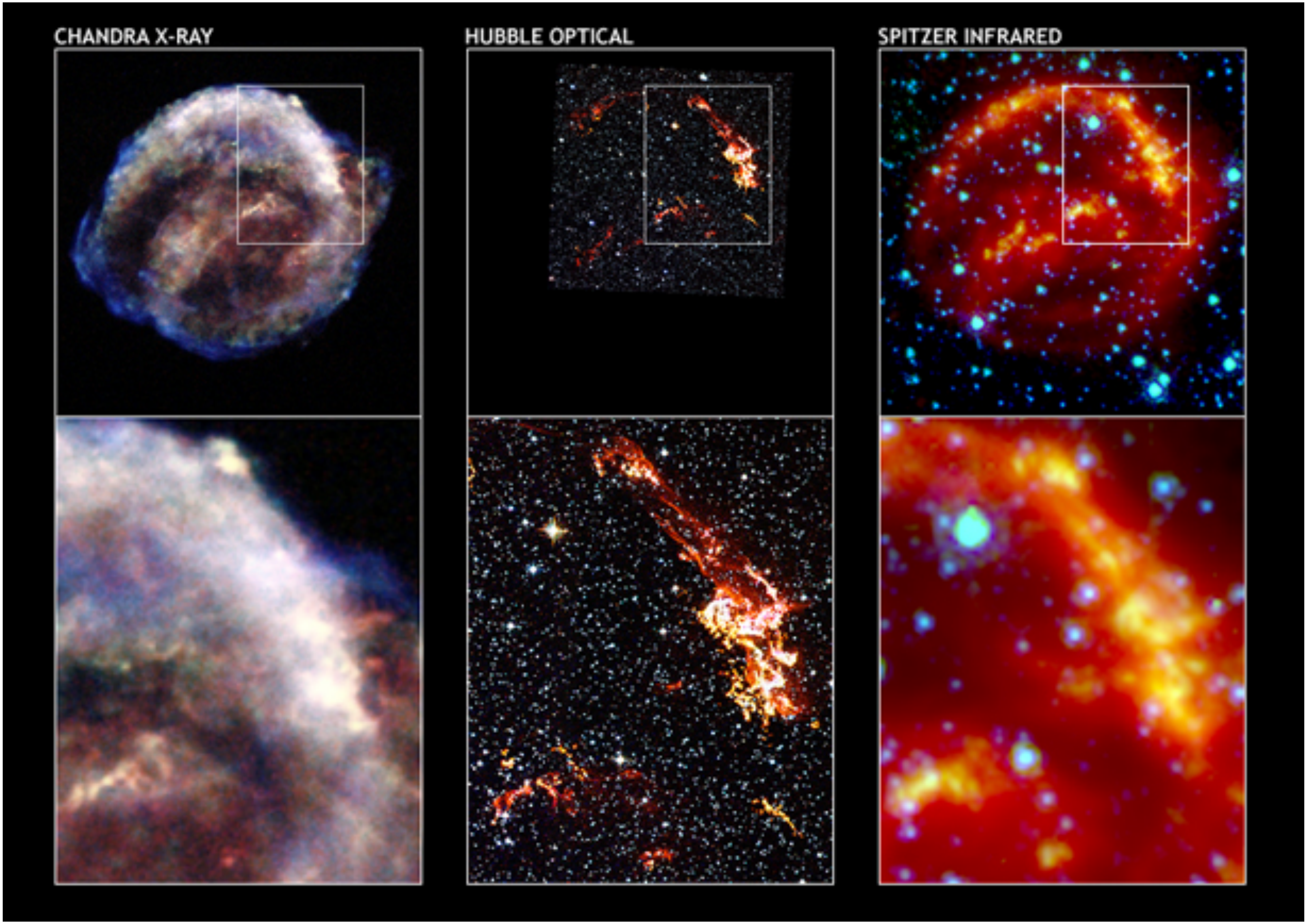
Instead, all show strong Si, S, and Fe L emission, consistent with a Type Ia SNR.

So…Kepler's SN of 1604 was likely a Type Ia SN remnant.

But…the Chandra observations also confirm what has been long known from optical observations (van den Bergh 1970).

Namely, that Kepler's blast wave is encountering ISM material with at least solar metallicity, coincident with optically emitting N-enhanced material.

This material is most likely N-rich CSM lost by a fairly massive star.

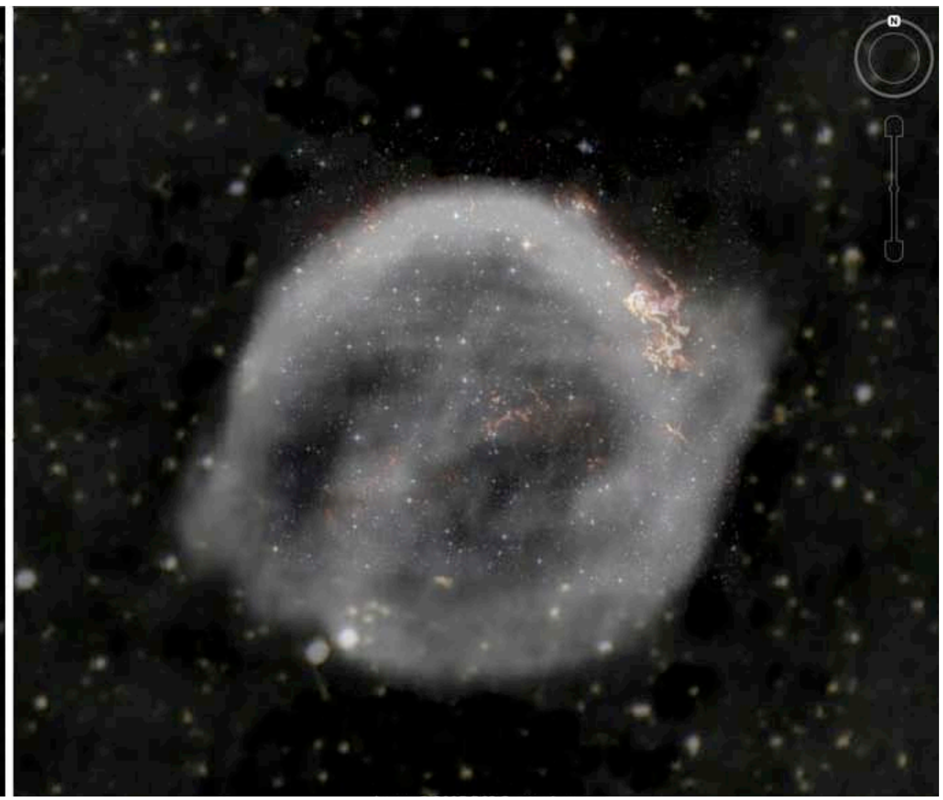


CHANDRA X-RAY
HUBBLE OPTICAL
SPITZER INFRARED

Interactions with CSM, especially dense clumps rich in nitrogen is unexpected for Type Ia events. Especially far off the galactic plane.

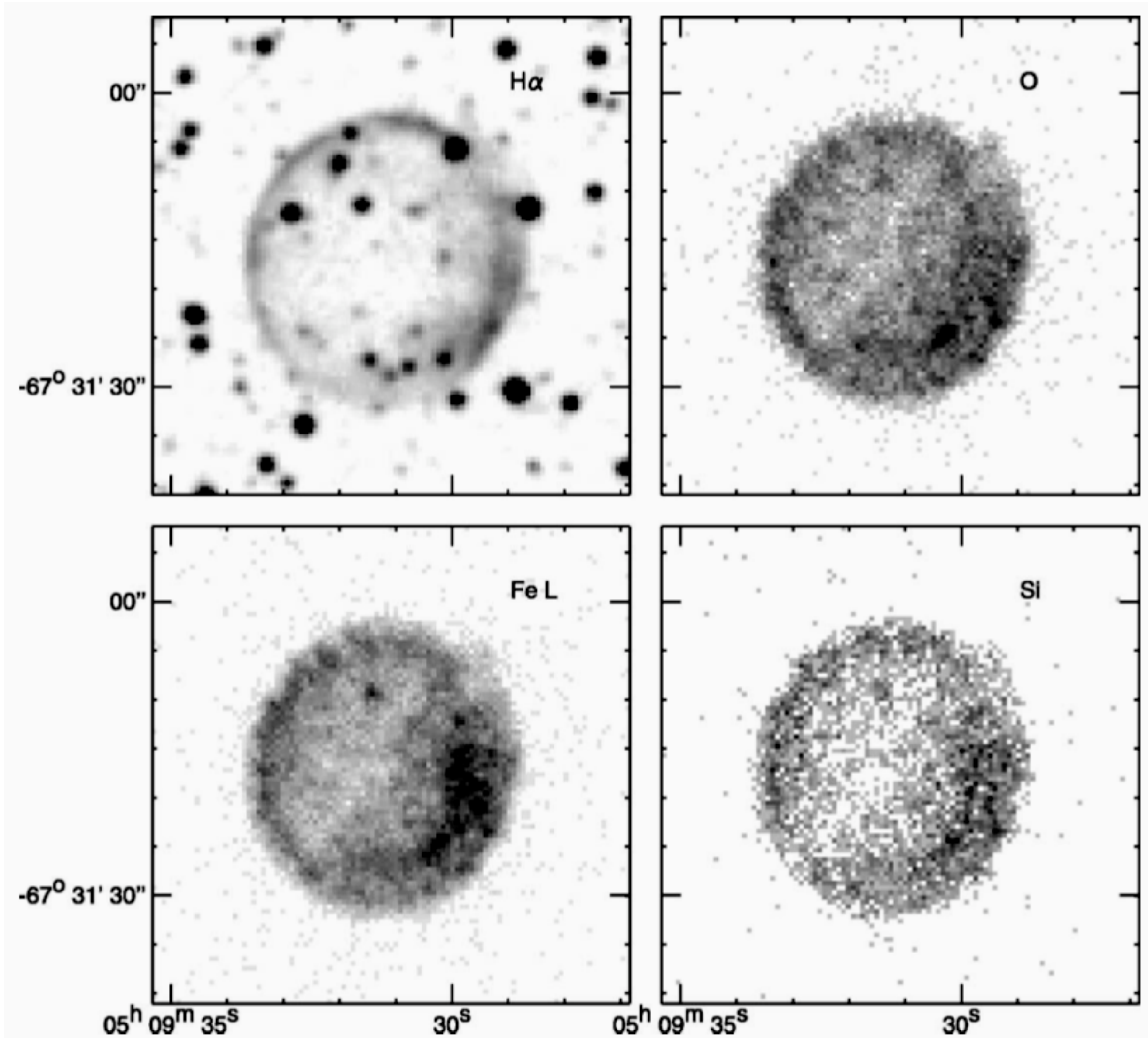
This CSM might indicate an origin in a young, massive binary system.

Thus Kepler's SNR supports suggestions of a younger, more `prompt' Type Ia progenitor channel (age < 1 Gyr) in addition to the "old" population (delay ~ many Gyr) seen in later type galaxies.



Clues to Type Ia Supernova Physics from the LMC Remnant 0509-67.5

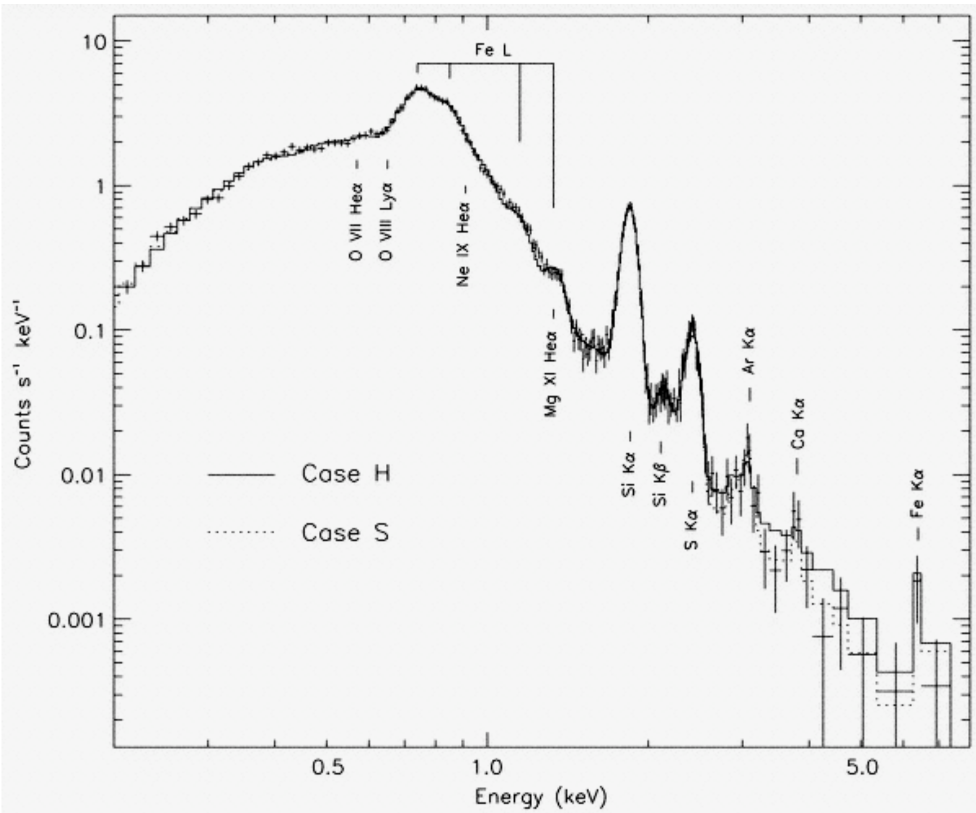
LMC SNR 0509-67.5
SN ~ 1610 +/-120
Type Ia



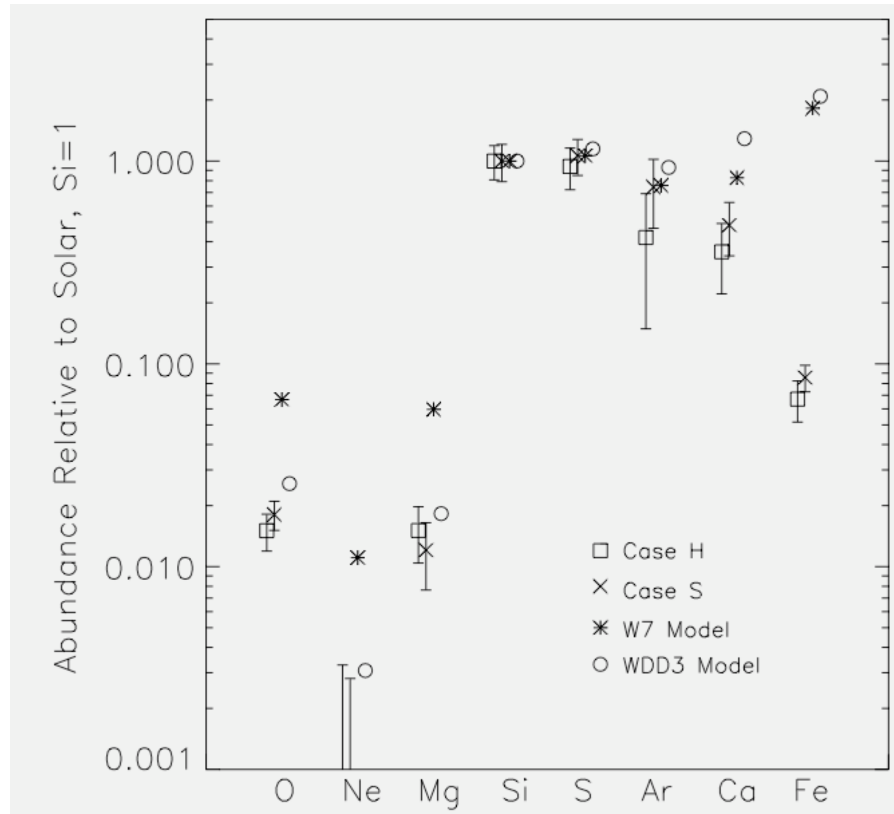
Warren and Hughes 2004

Spectral fits confirm that 0509-67.5 is a SN Ia remnant

Global X-ray spectrum
of SNR 0509-67.5



Abundances of the elements, relative
to solar & normalized to Si = 1.

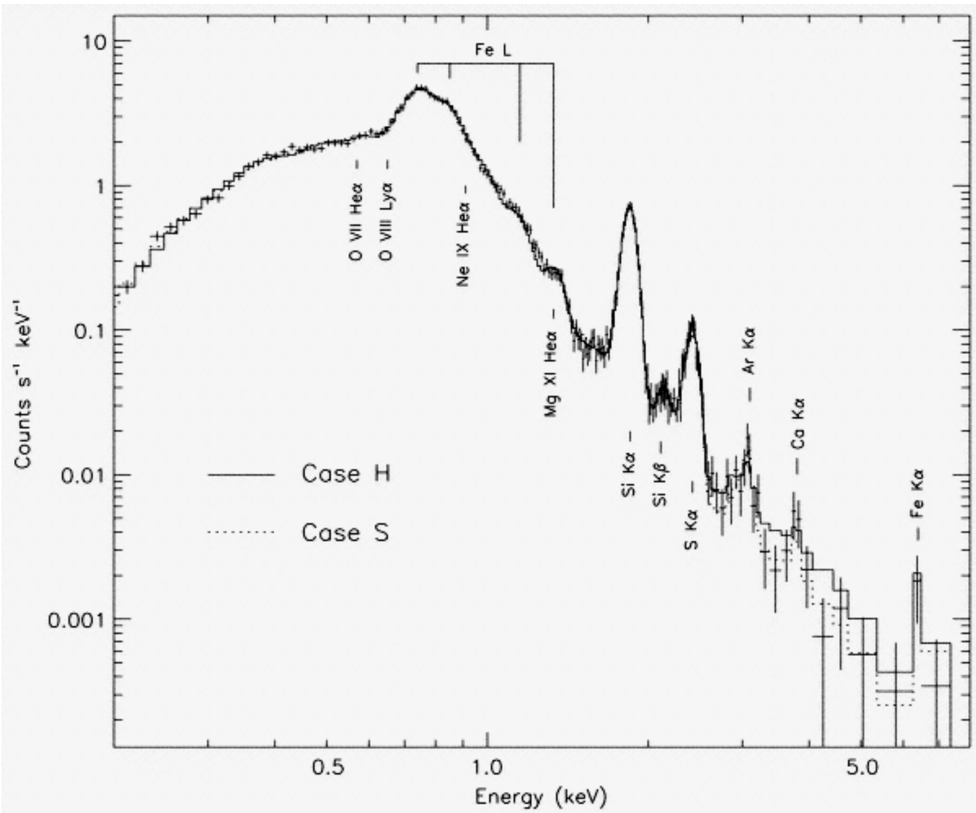


Continuum emission was modeled:
Model H: thermal bremsstrahlung from e^- on H
Model S: non-thermal synchrotron

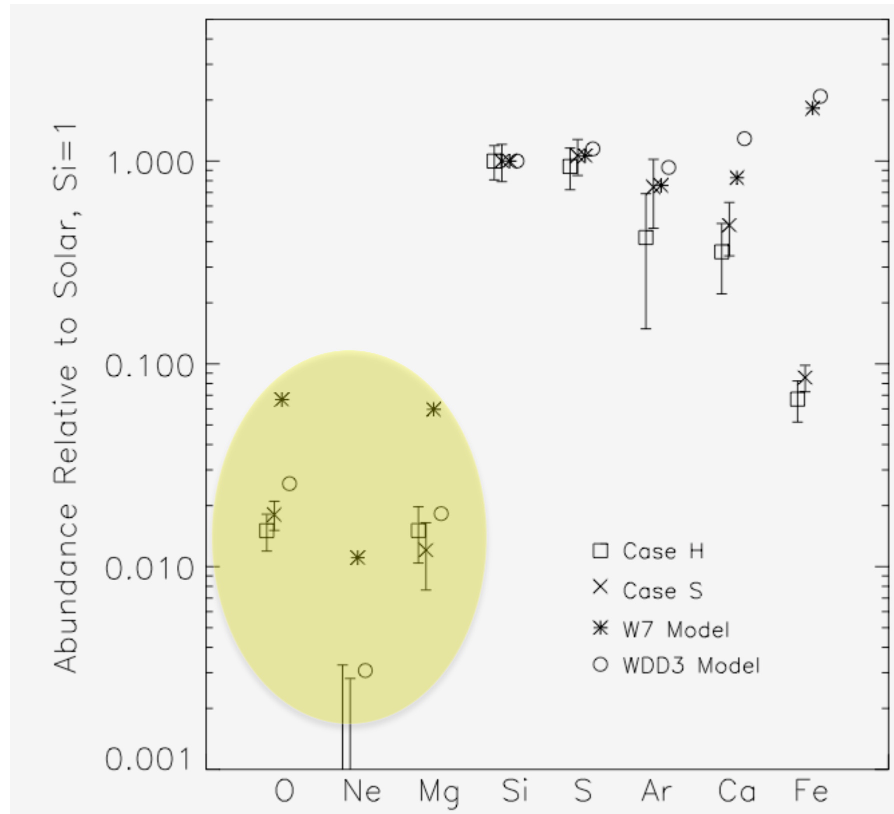
Warren and Hughes 2004

Spectral fits confirm that 0509-67.5 is a SN Ia remnant

Global X-ray spectrum of SNR 0509-67.5



Abundances of the elements, relative to solar & normalized to Si = 1.



Continuum emission was modeled:
Model H: thermal bremsstrahlung from e^- on H
Model S: non-thermal synchrotron

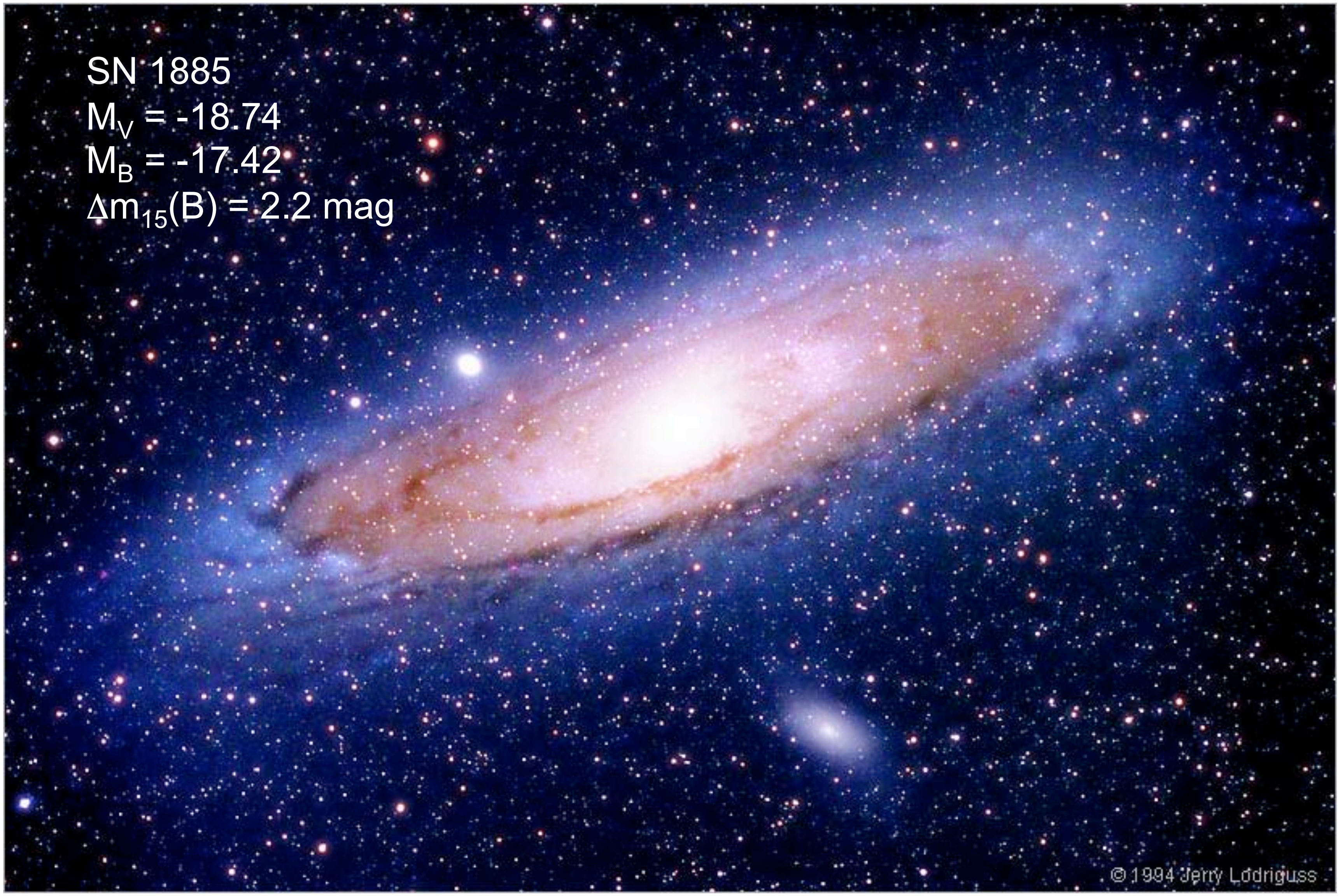
Warren and Hughes 2004

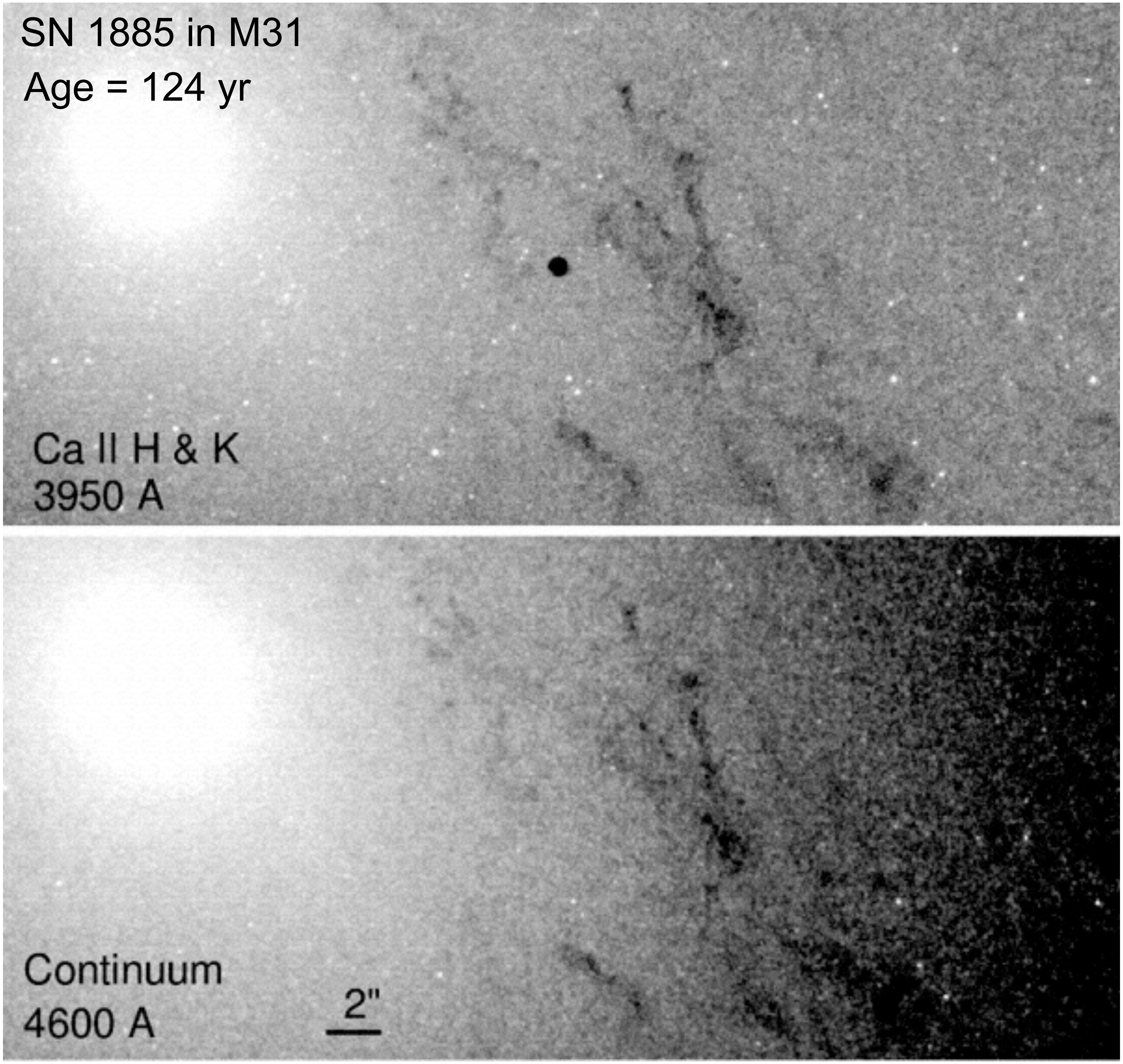
- Abundances of O, Ne, & Mg show a clear preference for delayed- detonation explosion models for this SN Ia (WDD3; Iwamoto et al. 1999).

- The spectrum of the brightest isolated knot in the remnant shows enhanced iron by a factor of roughly 2 relative to the global remnant abundances suggesting the presence of modest small-scale composition inhomogeneities in SNe Ia.

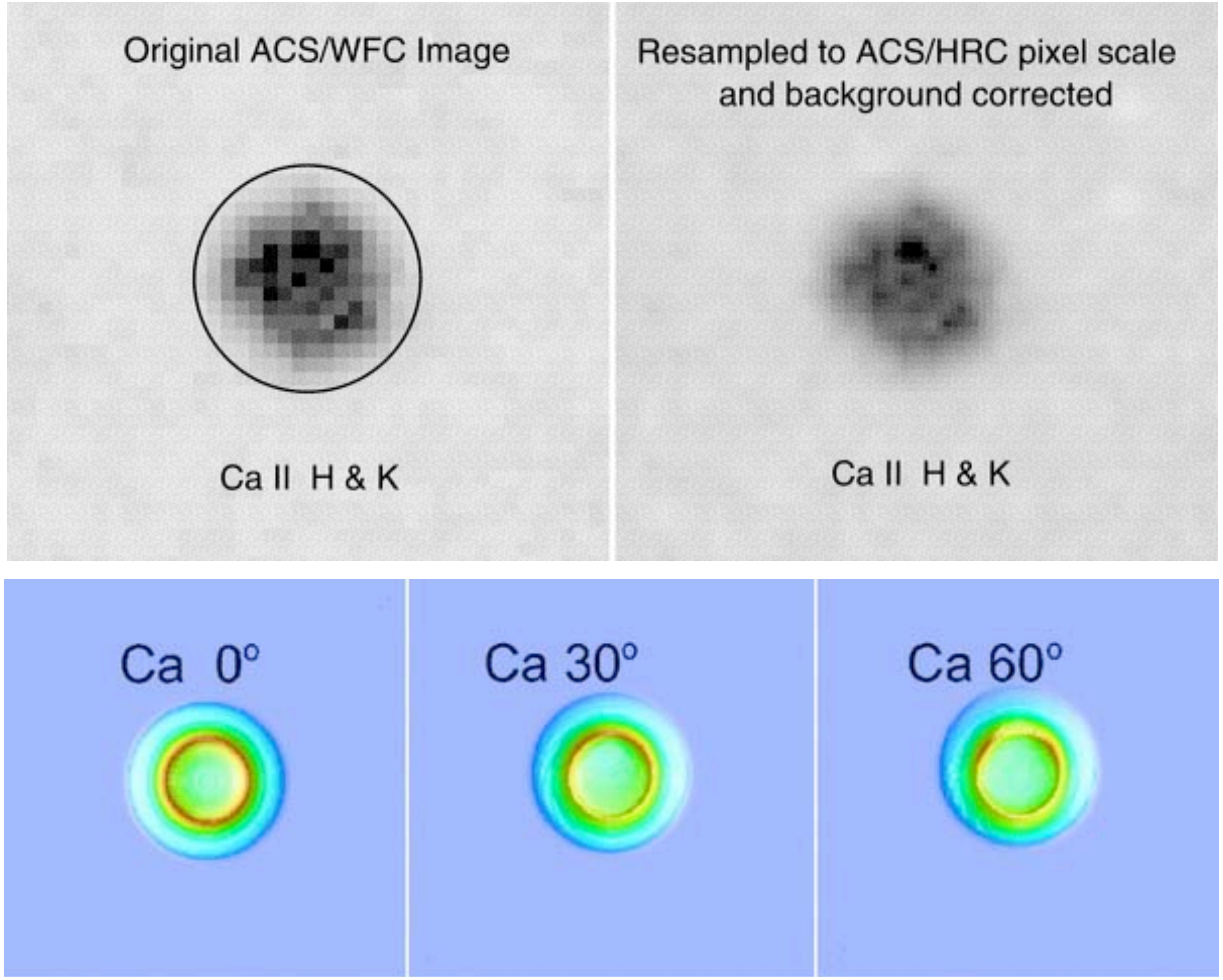
- Knot to knot Si/Fe abundance variations suggest that these knots arise from the transition region between the Si- and Fe-rich zones.

The first recorded extragalactic SN was seen in 1885 in the bulge of M31.
It is believed to have been a subluminous Ia (de Vaucouleurs & Corwin 1985).



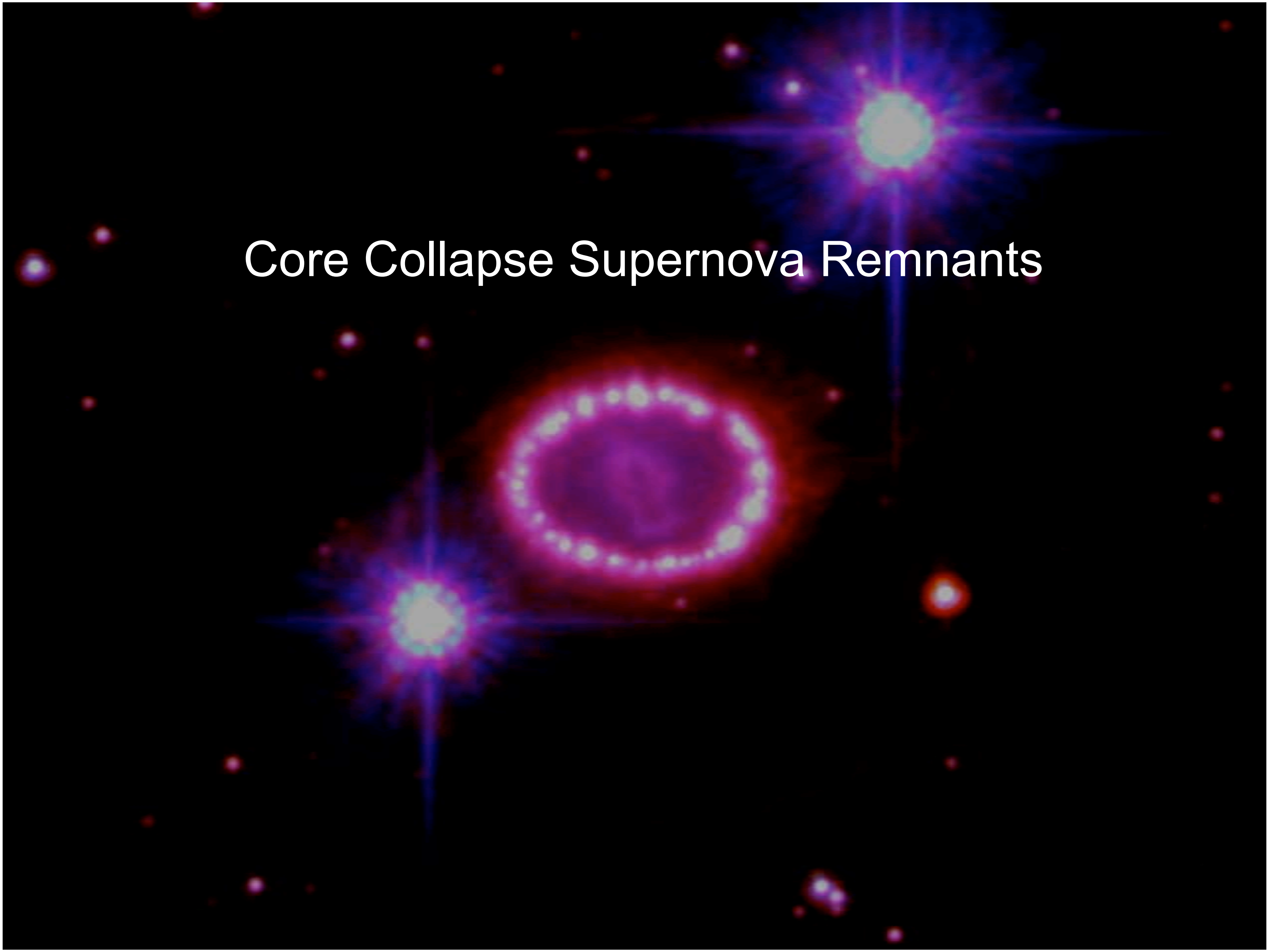


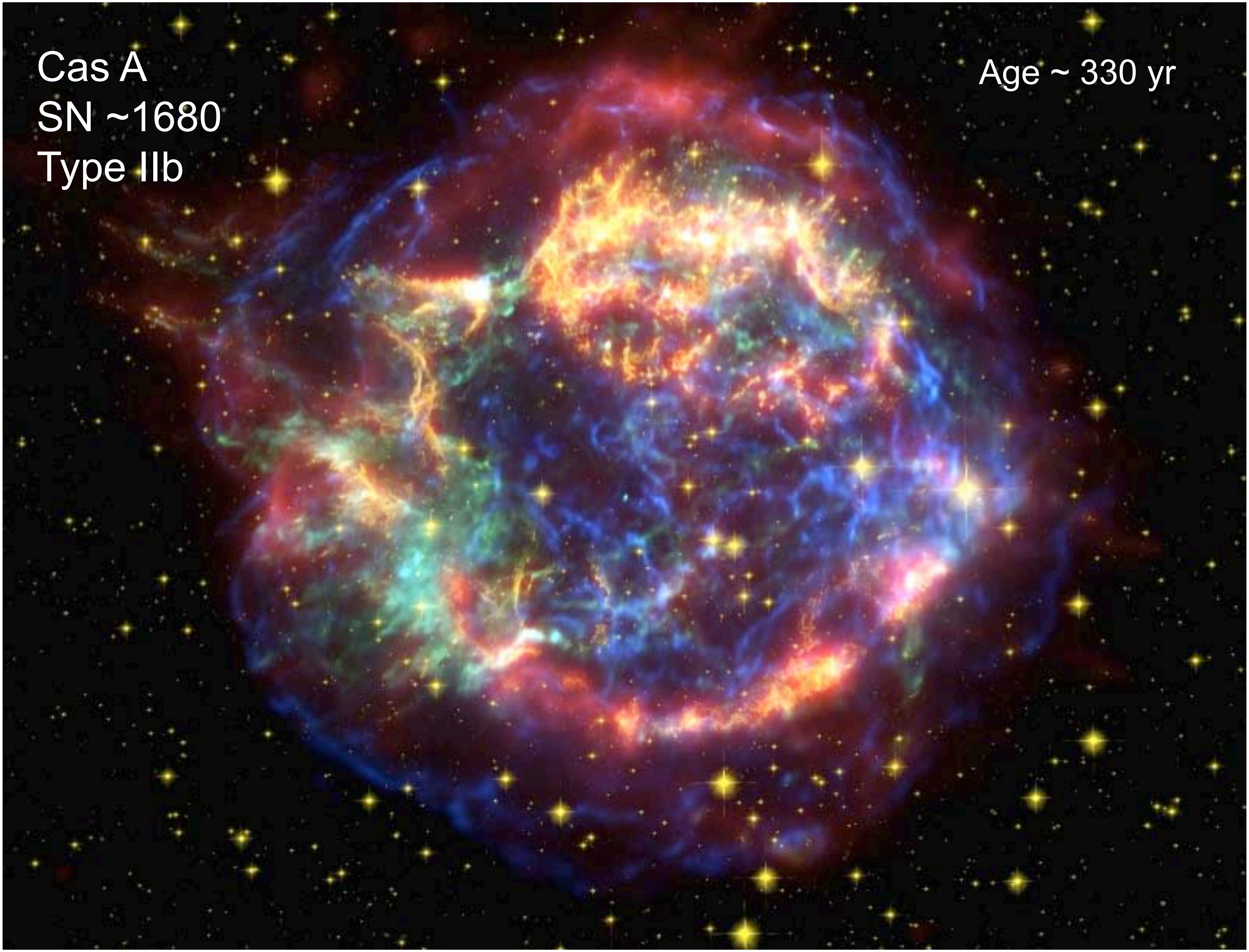
SN 1885 in M31
Age = 124 yr
Ca II H & K
3950 A
Continuum
4600 A
2"



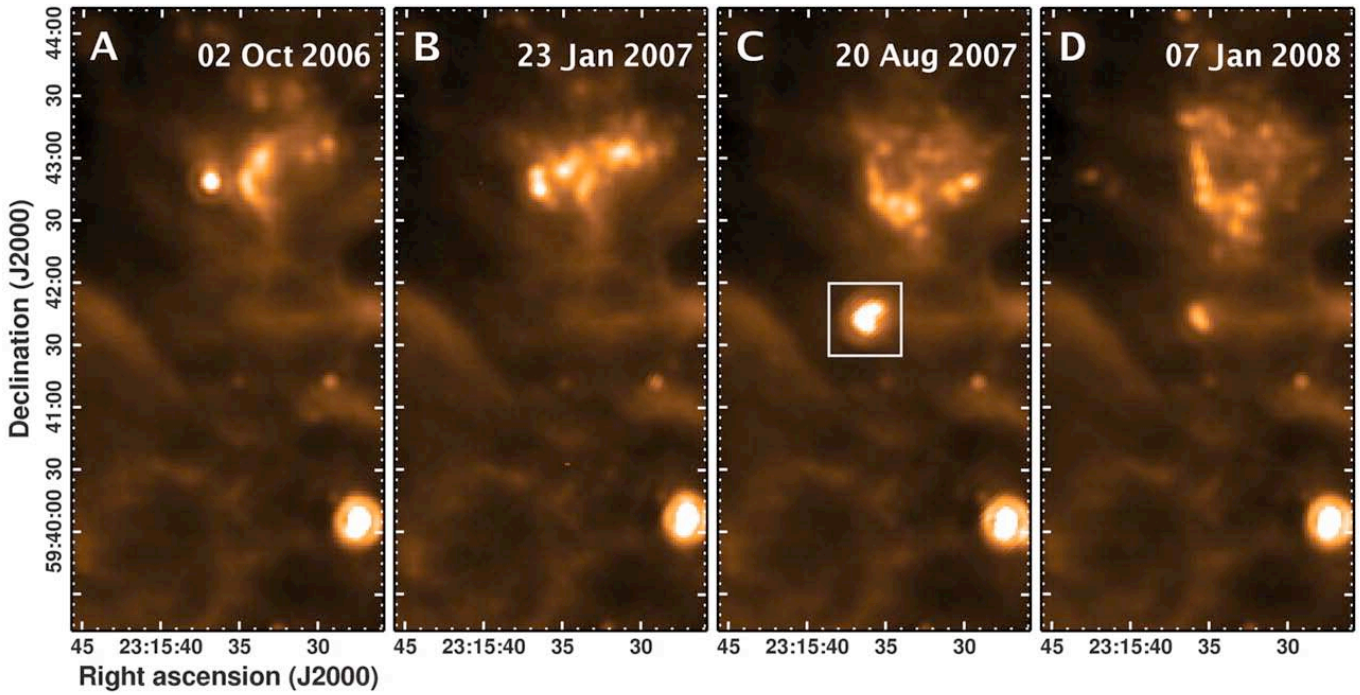
Column depths for the convolution of the density and chemical profiles for Ca as seen from various inclinations for an off-center DDT model with 0.3 solar masses of ^{56}Ni. If viewed pole-on (90°), the chemical structure for Ca is a continuous ring that starts to break up at lower latitudes.

Fesen et al. 2007

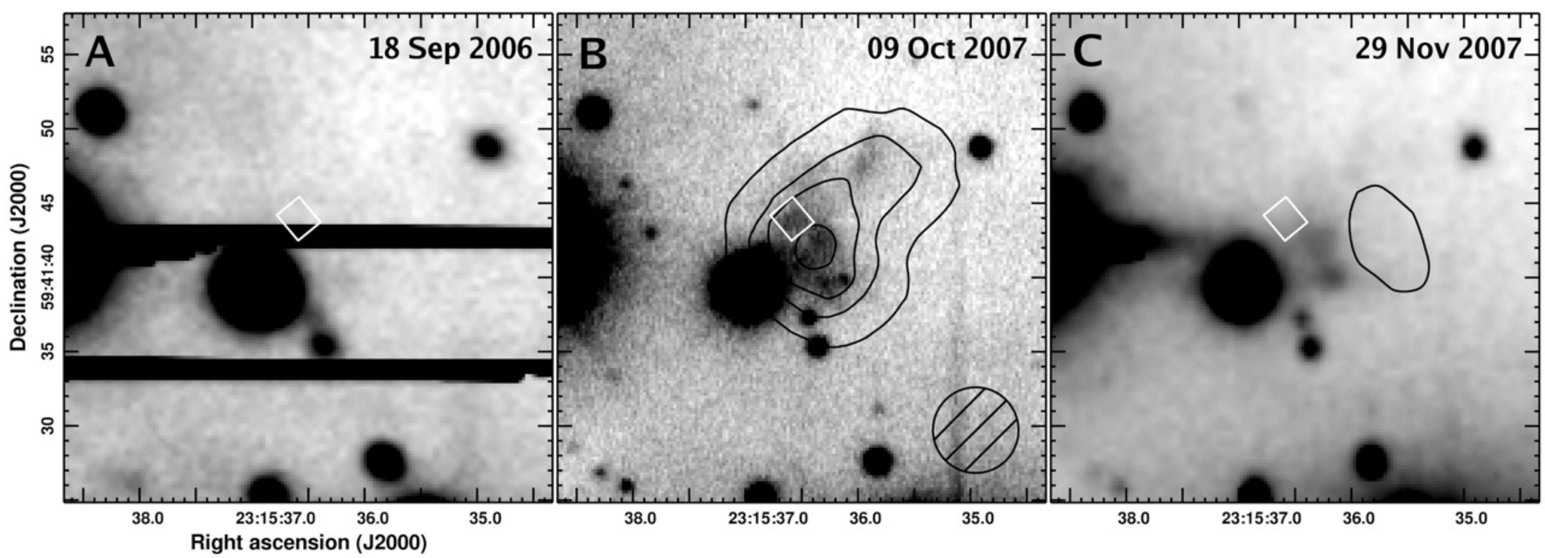

Core Collapse Supernova Remnants


Cas A
SN ~1680
Type IIb
Age ~ 330 yr

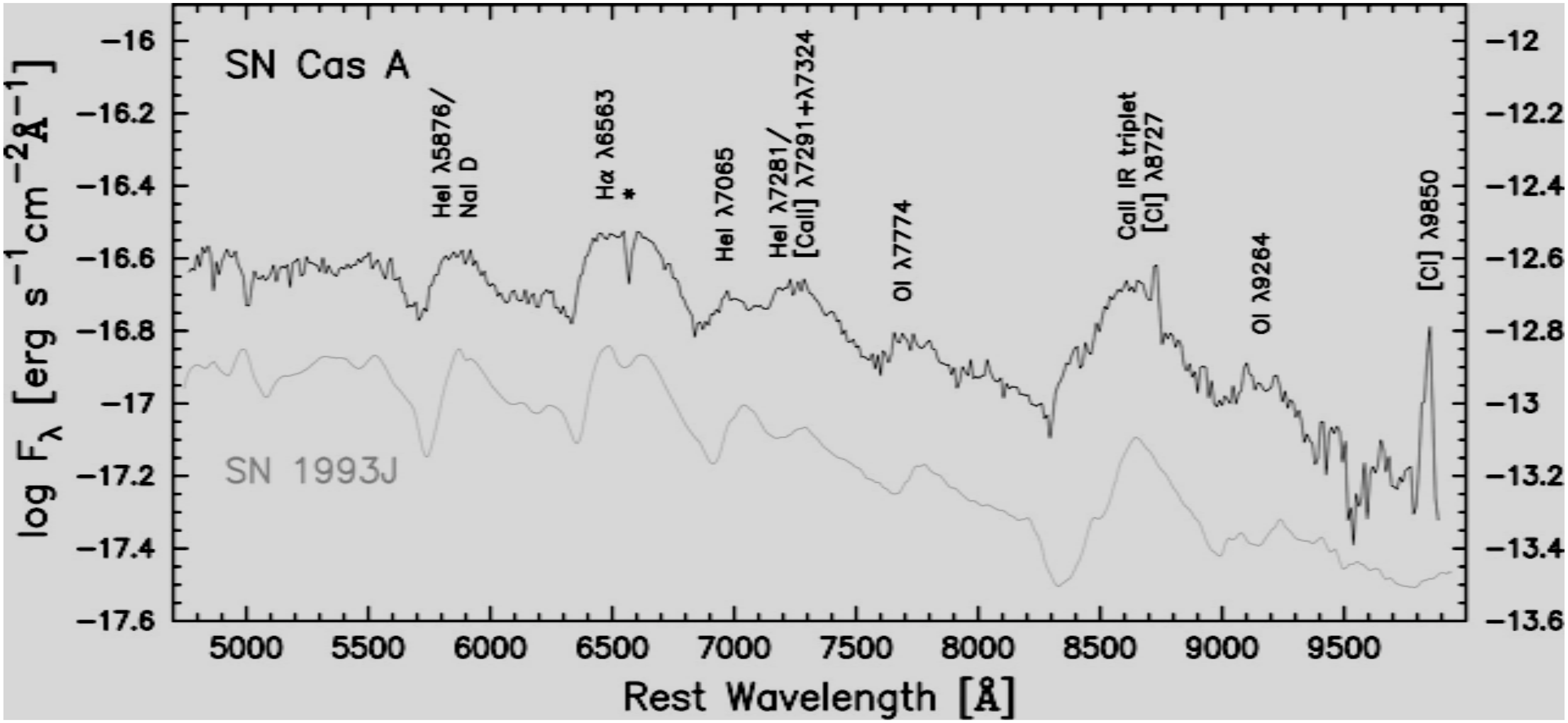
Infrared echoes



Optical echoes

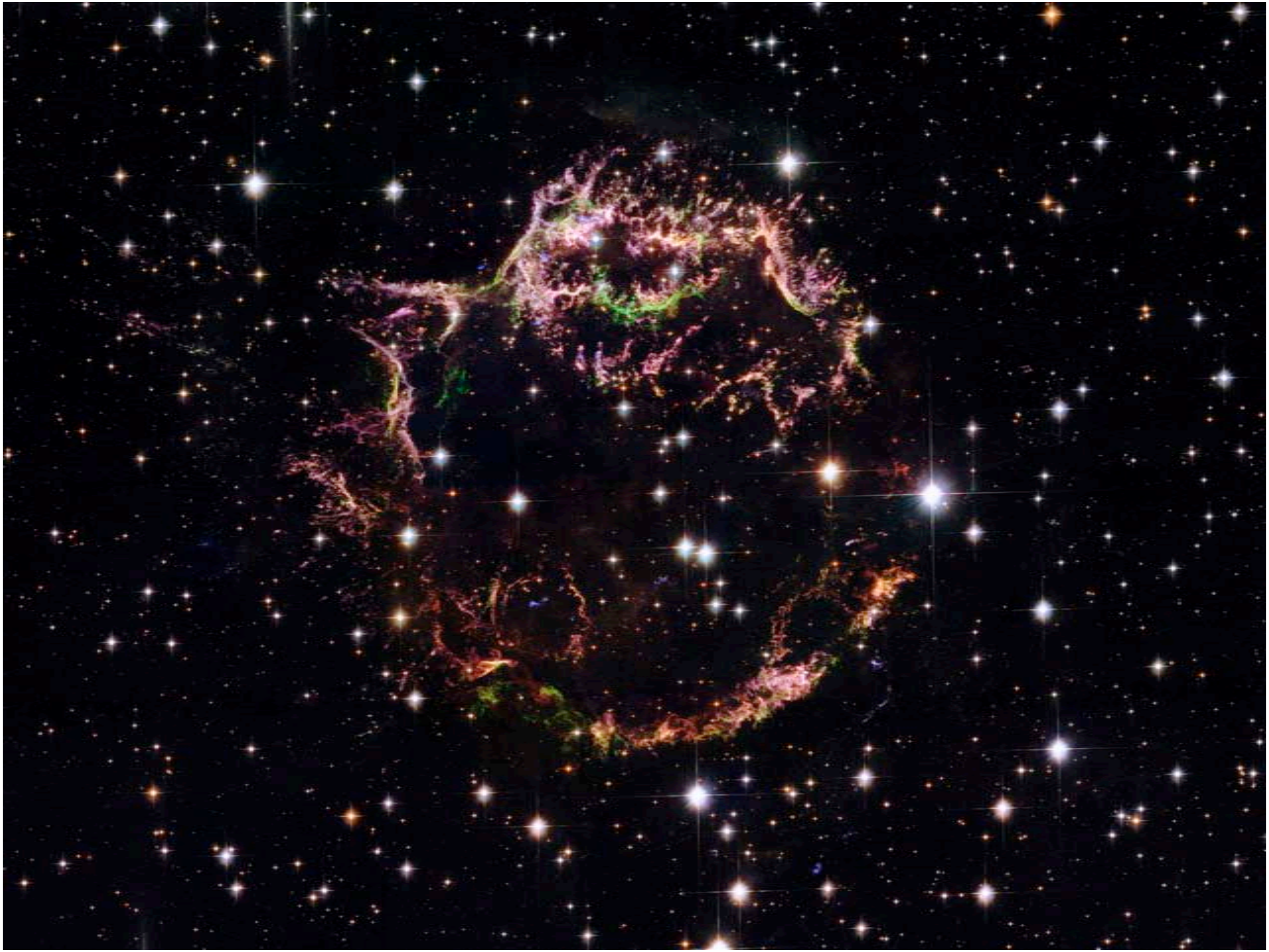


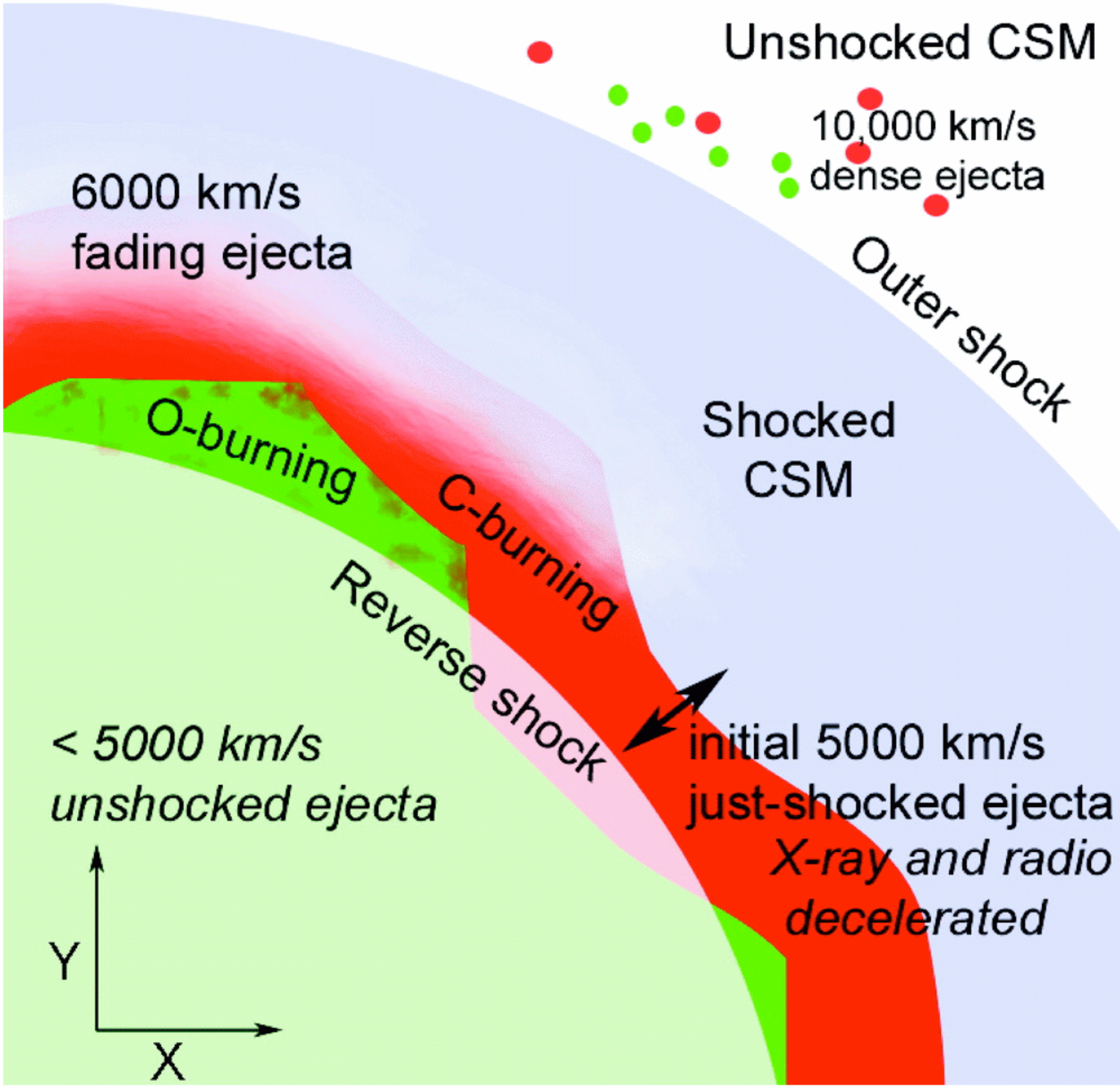
Krause et al. 2008, Science



Spectrum of the Cas A supernova vs. SN 1993J.

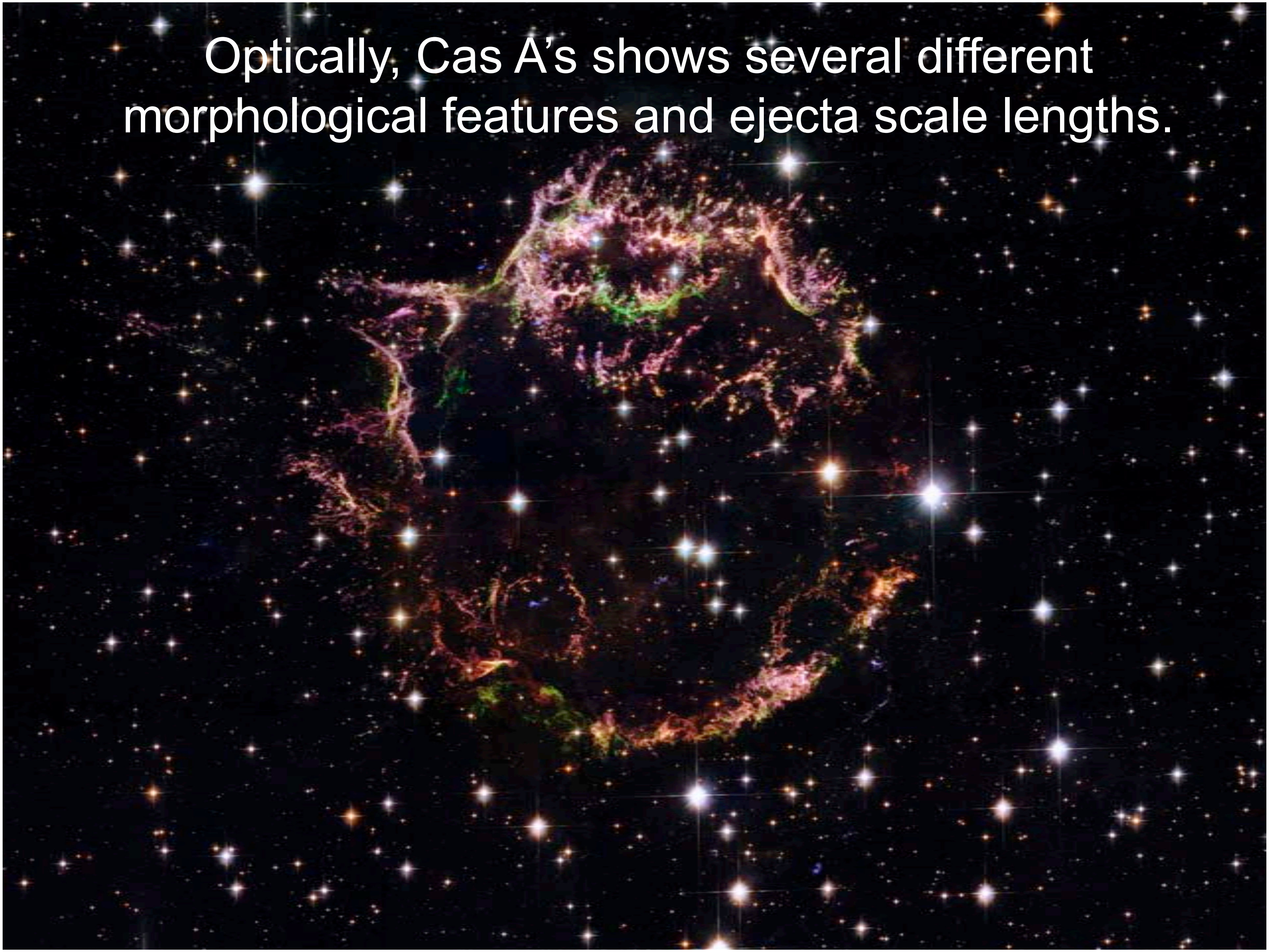
Krause et al. 2008, Science

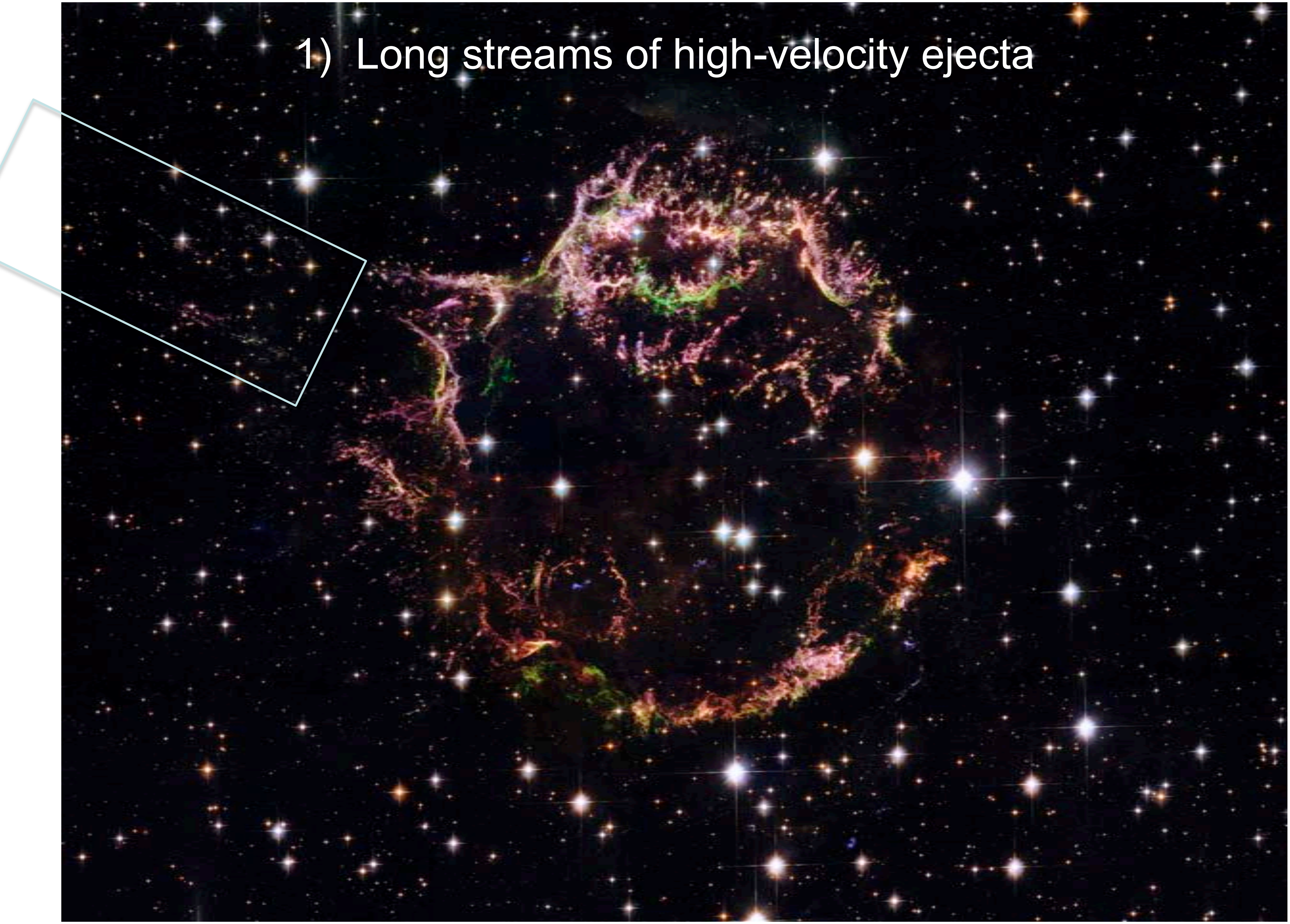




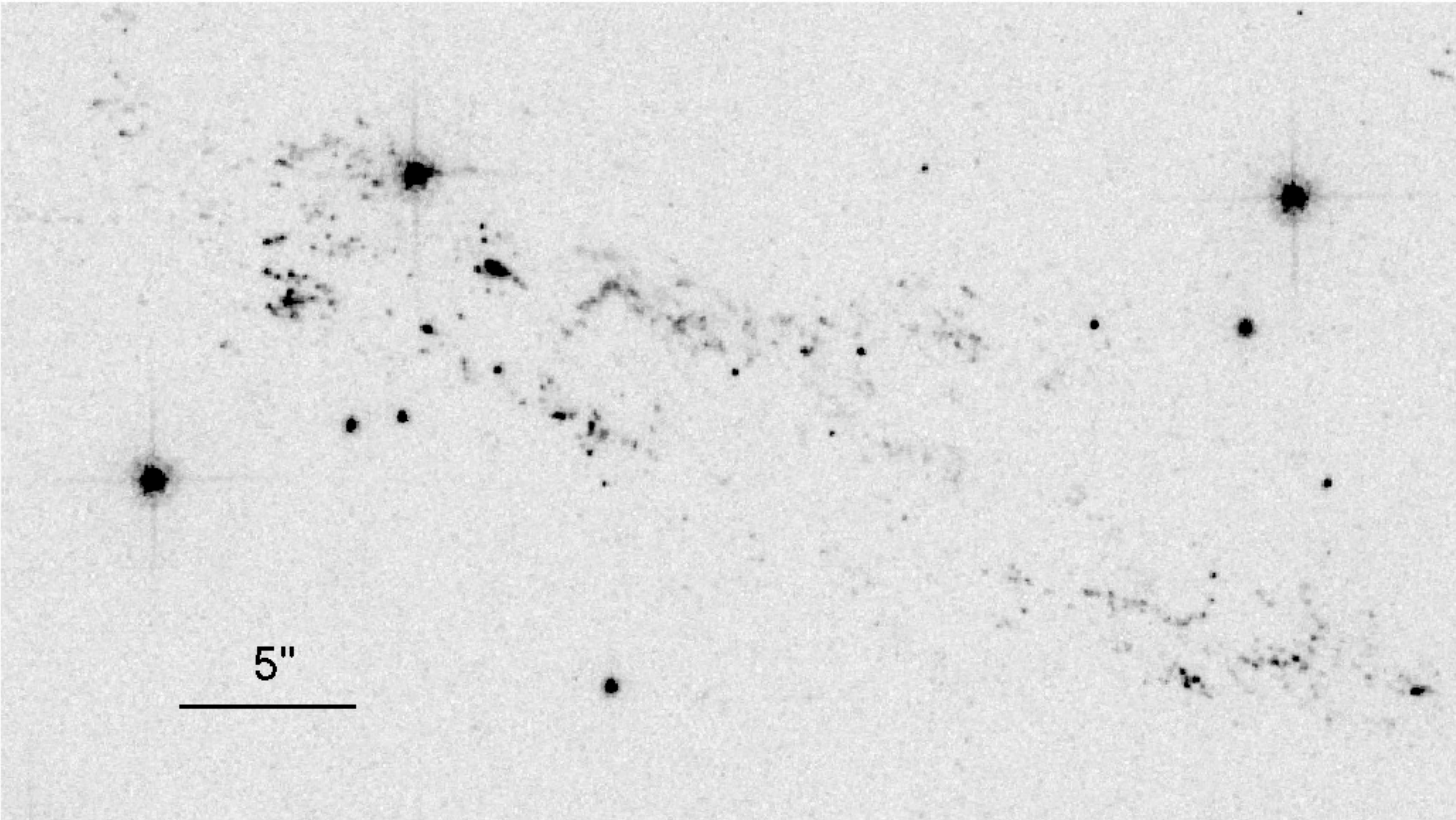
Ennis et al. 2006

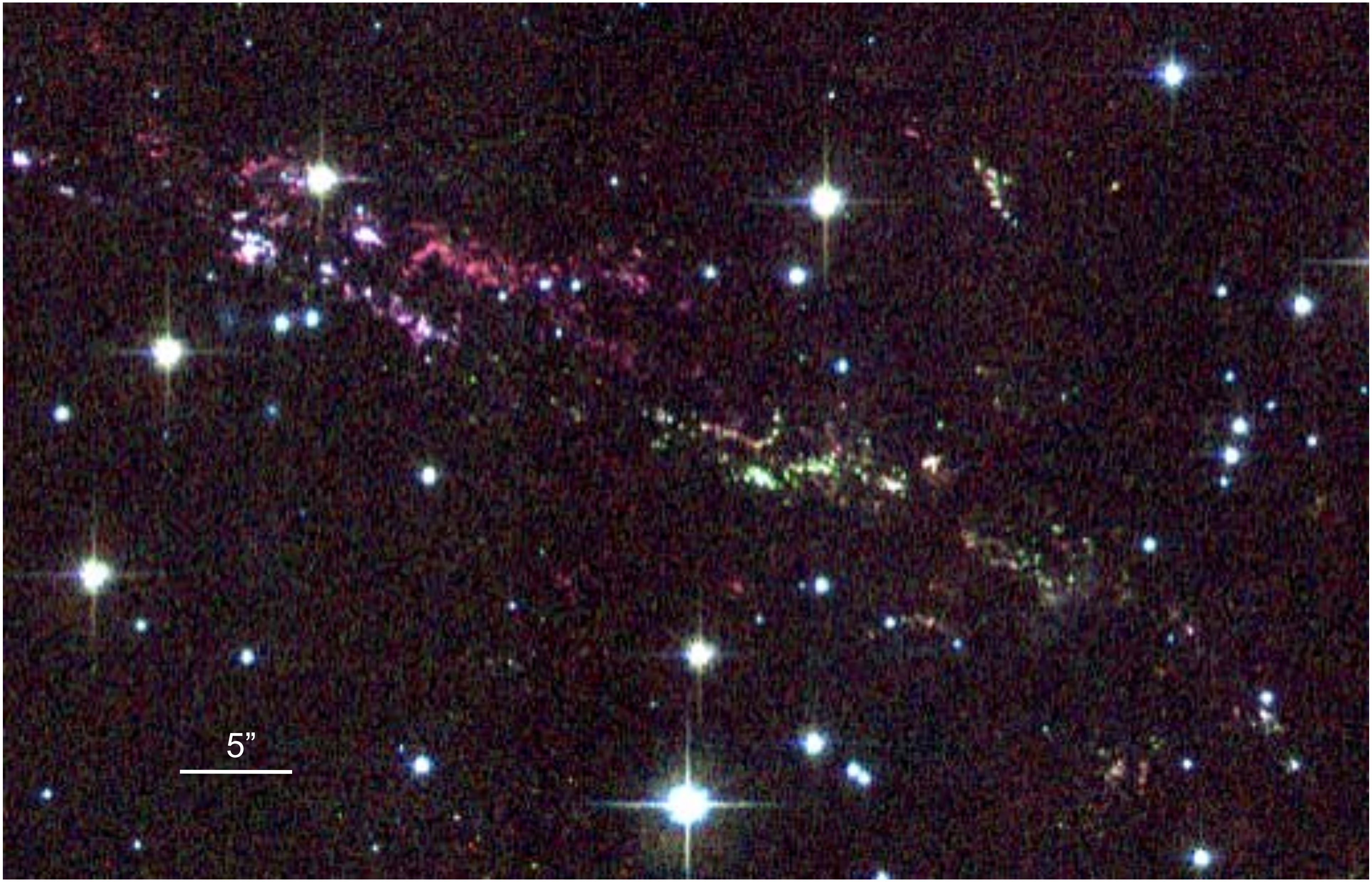
Optically, Cas A’s shows several different morphological features and ejecta scale lengths.



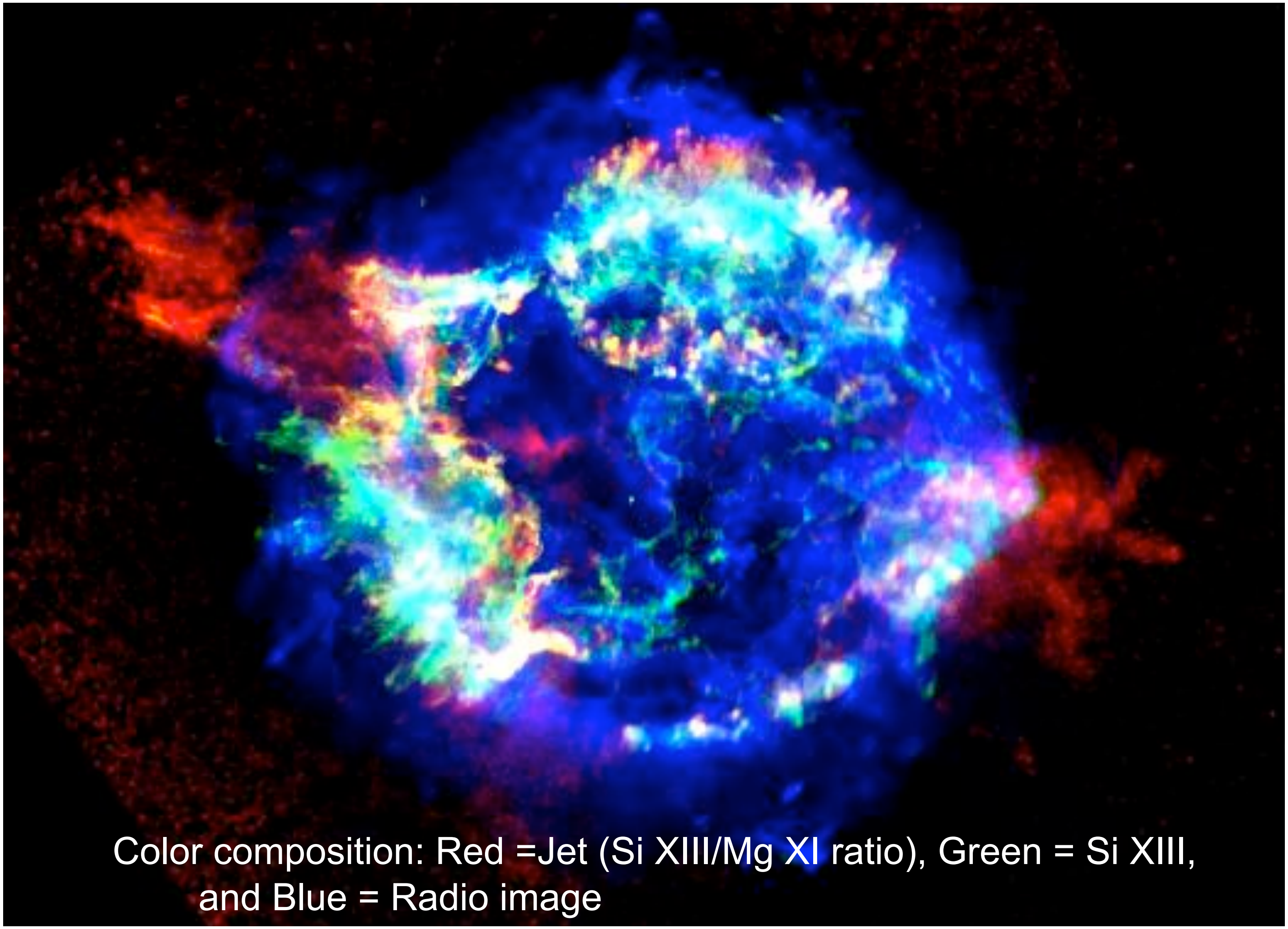

1) Long streams of high-velocity ejecta

The northeast “jet”



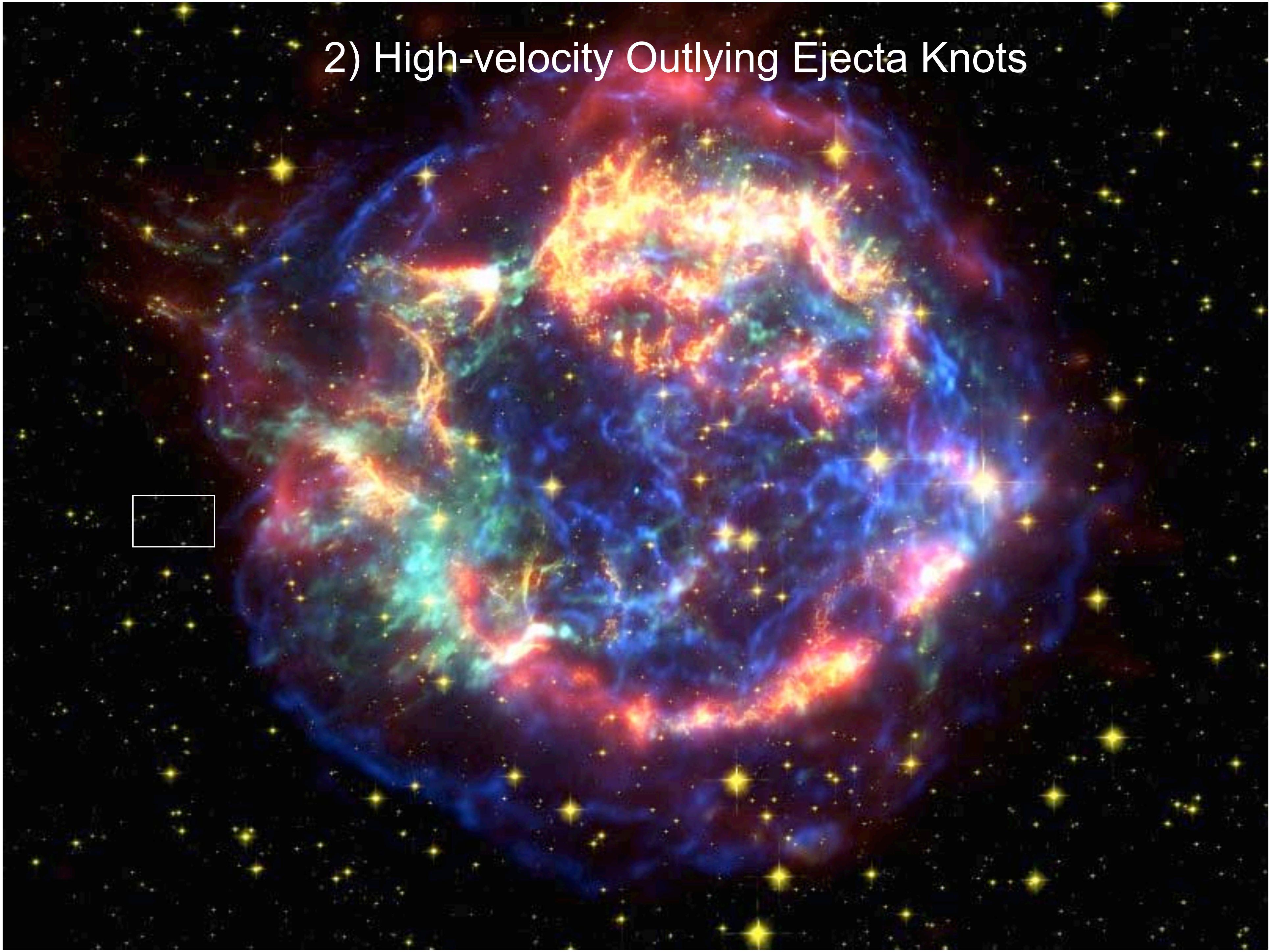

5”

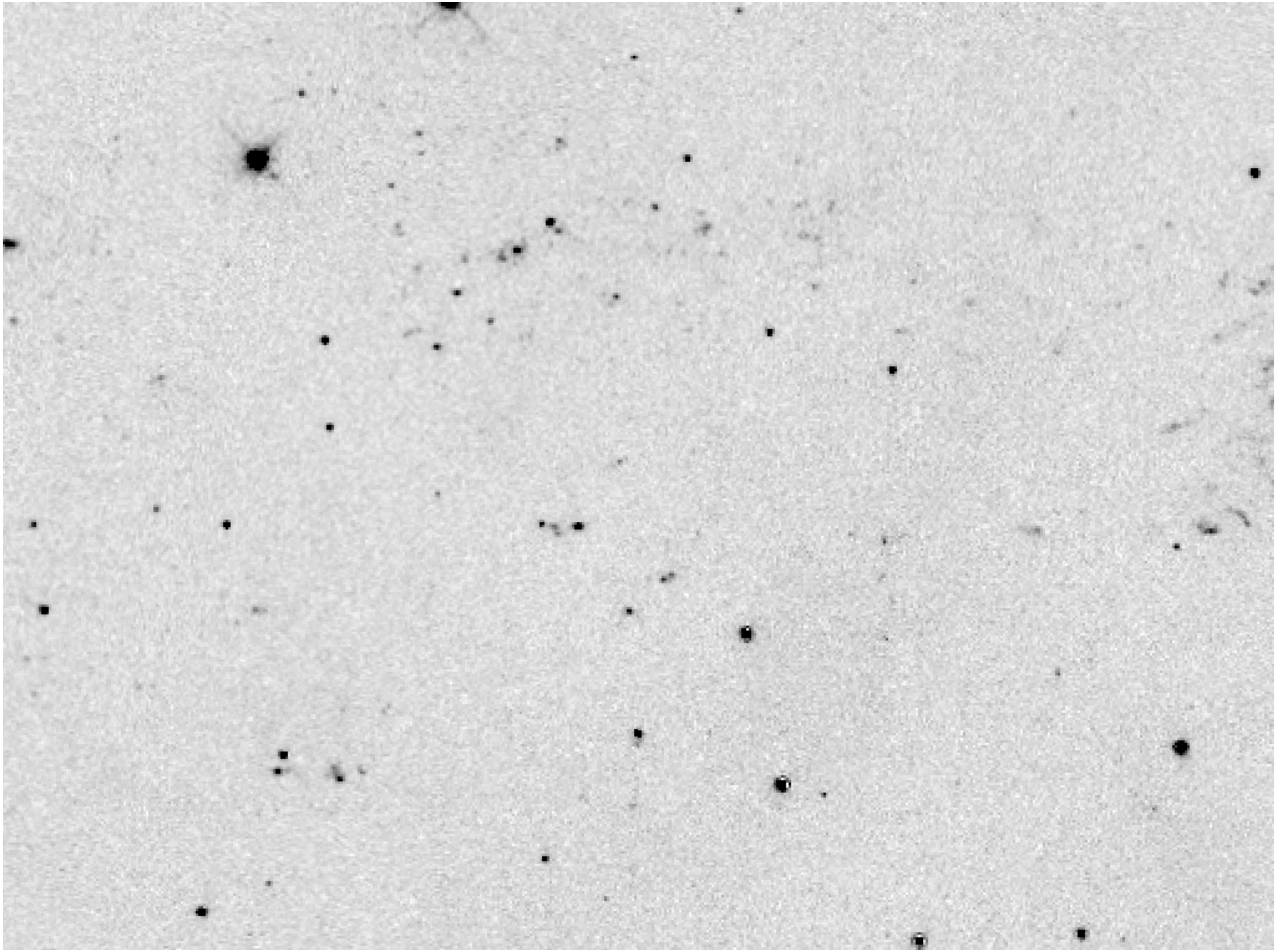
The X-ray properties of the jets show them to be chemically different from the rest of the remnant’s outlying ejecta.



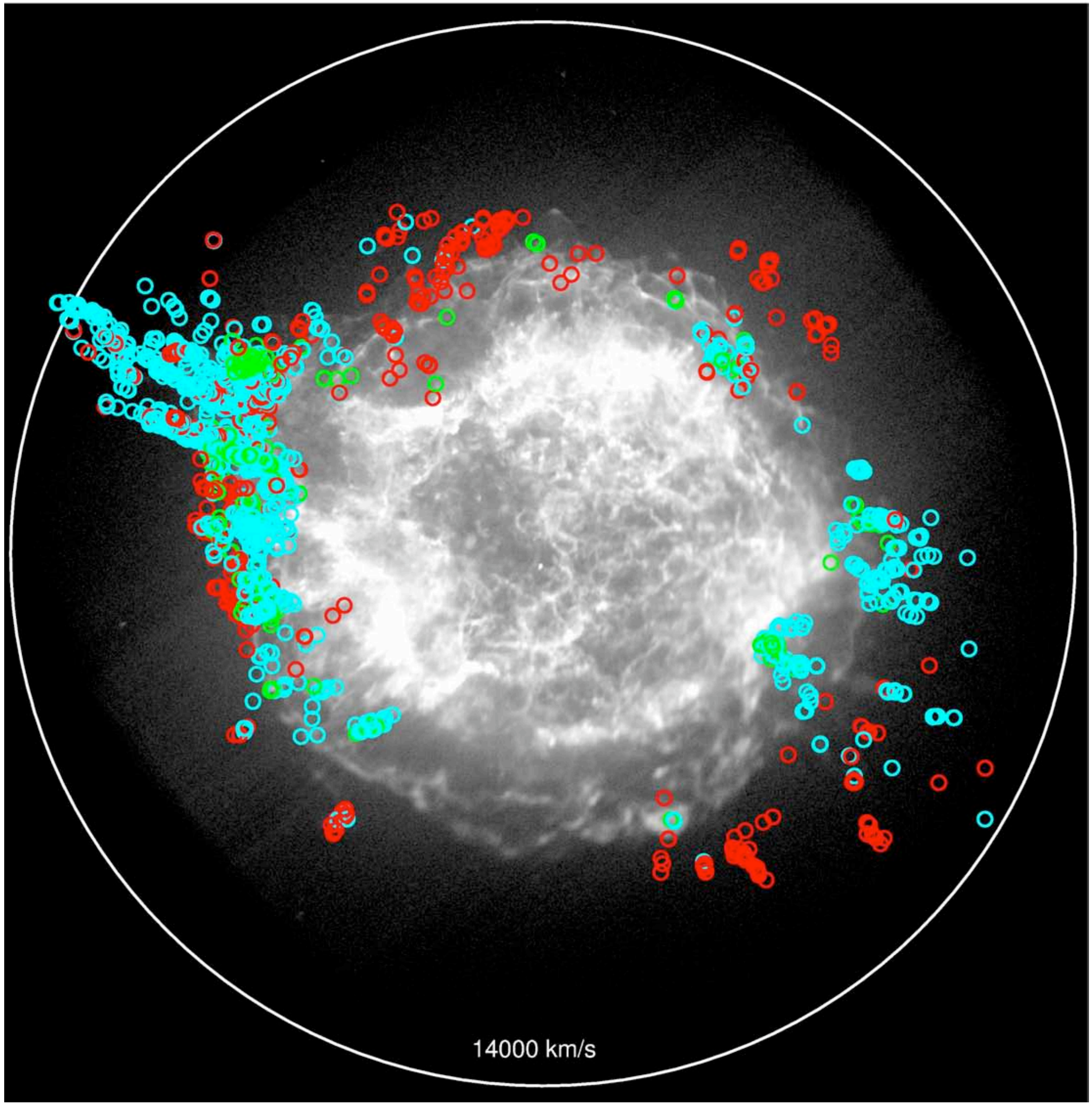
Color composition: Red =Jet (Si XIII/Mg XI ratio), Green = Si XIII, and Blue = Radio image

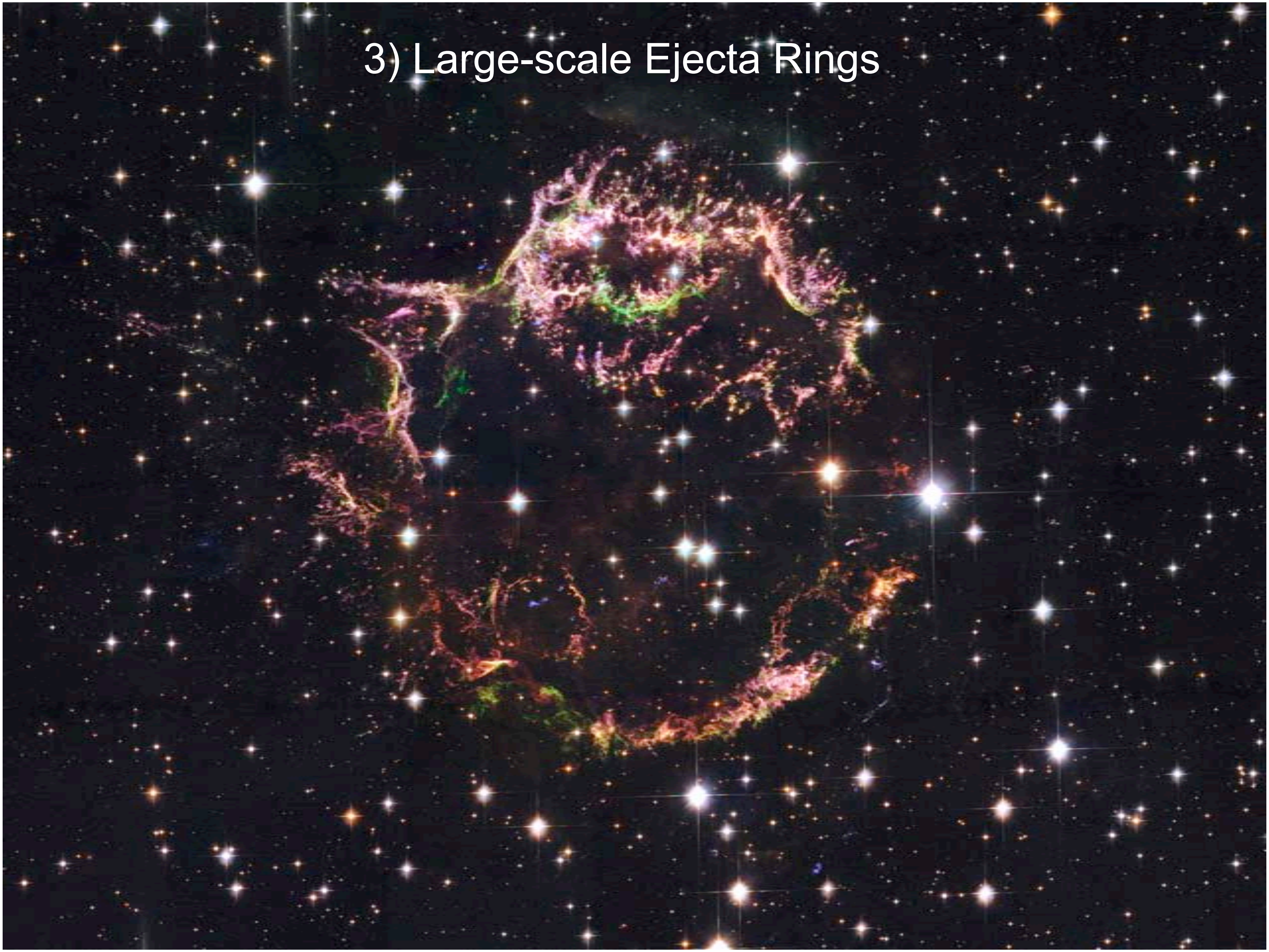
Vink 2004

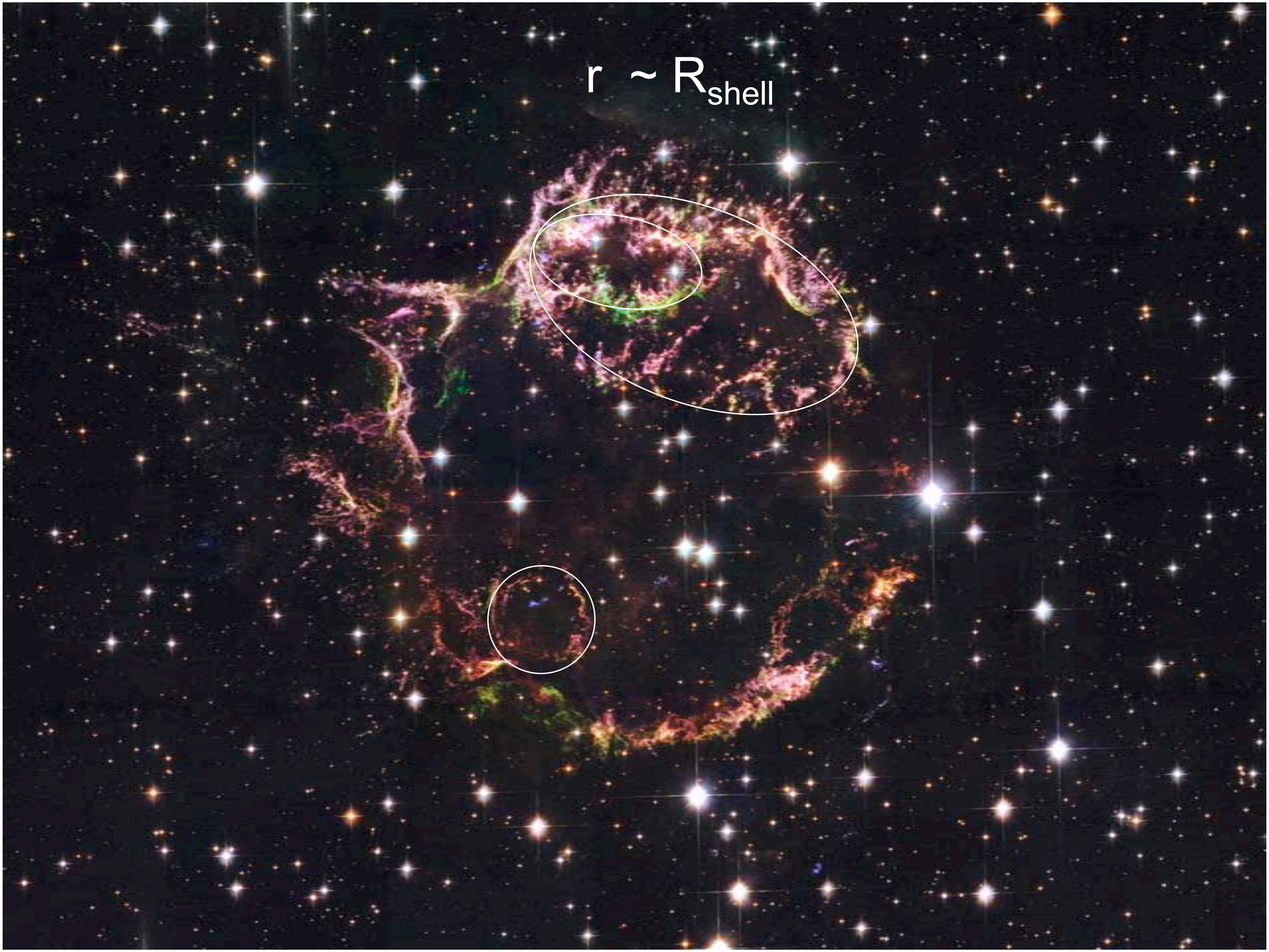

2) High-velocity Outlying Ejecta Knots



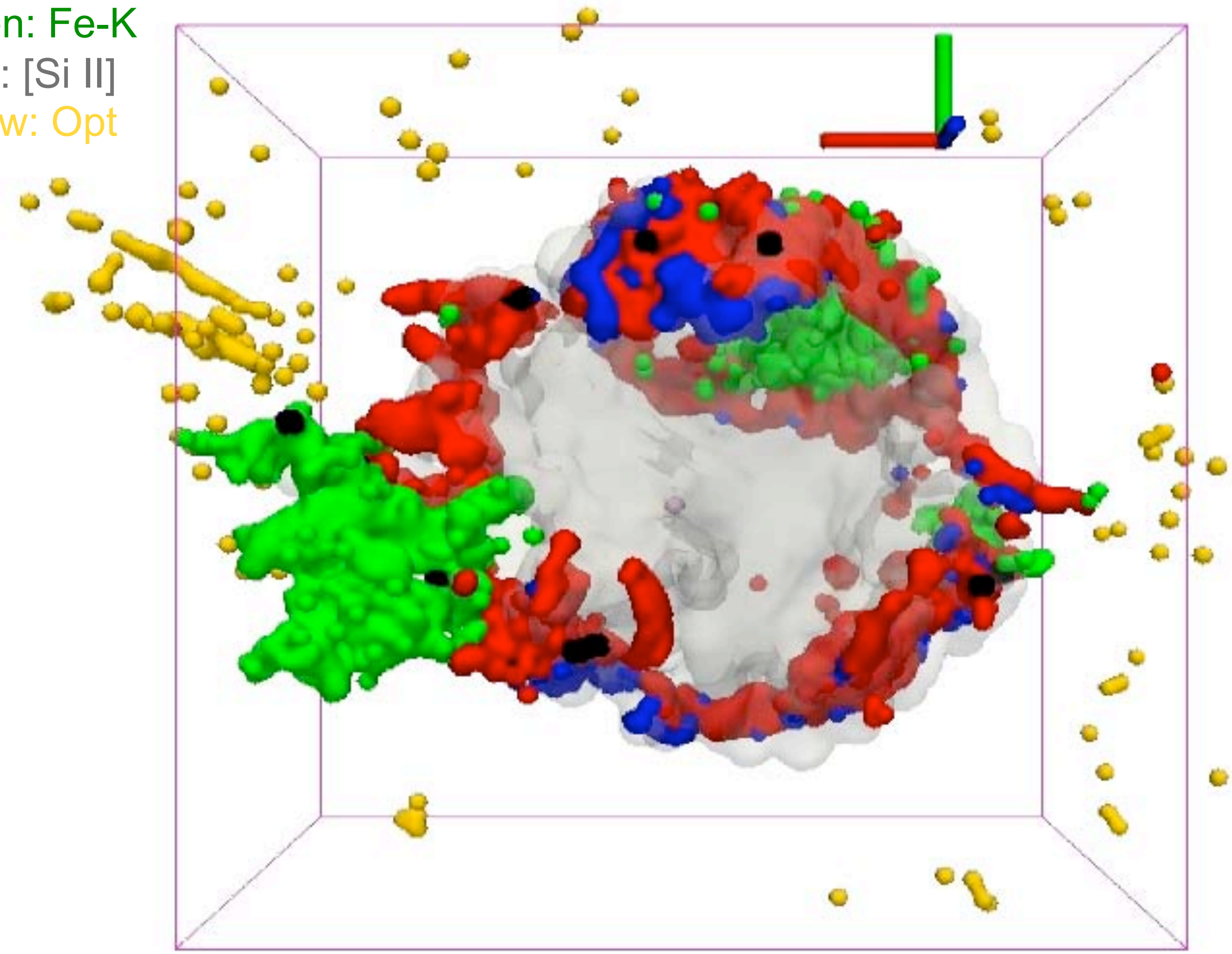
Blue: S-rich
Red: N-rich
Green: O-rich




3) Large-scale Ejecta Rings

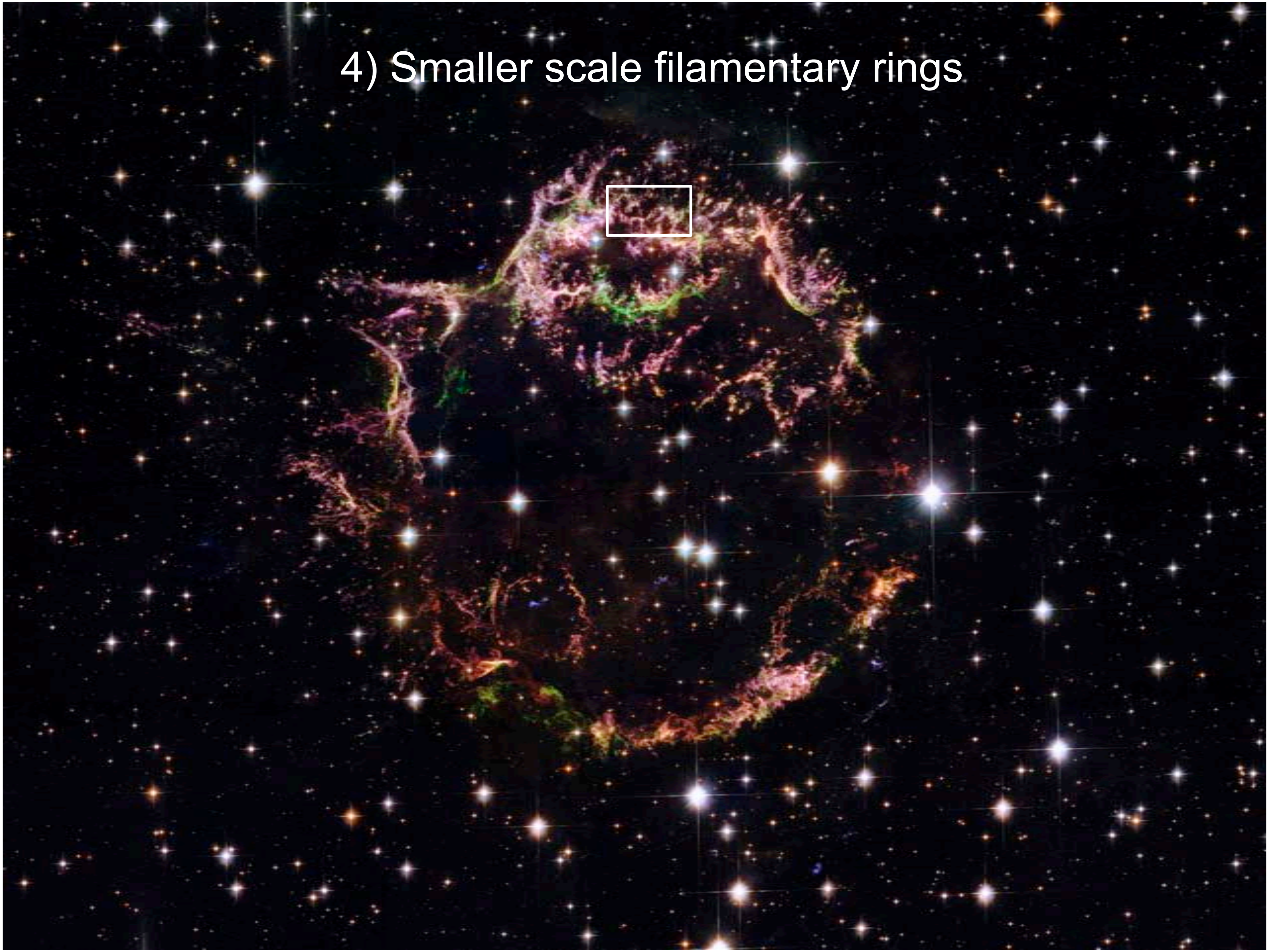

$r \sim R_{shell}$

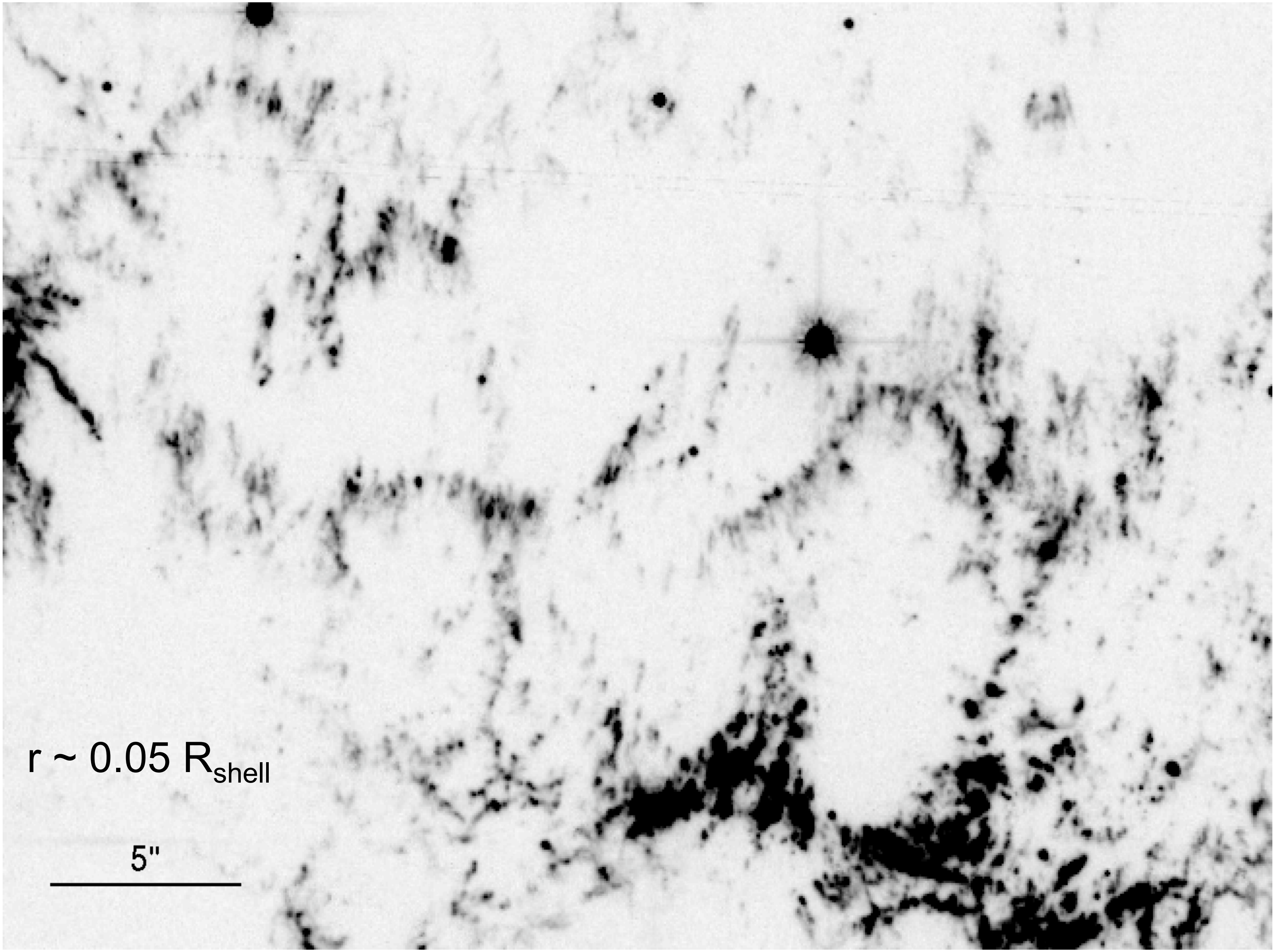
RED: [Ar II]
Blue: [Ne II]
Green: Fe-K
Grey: [Si II]
Yellow: Opt

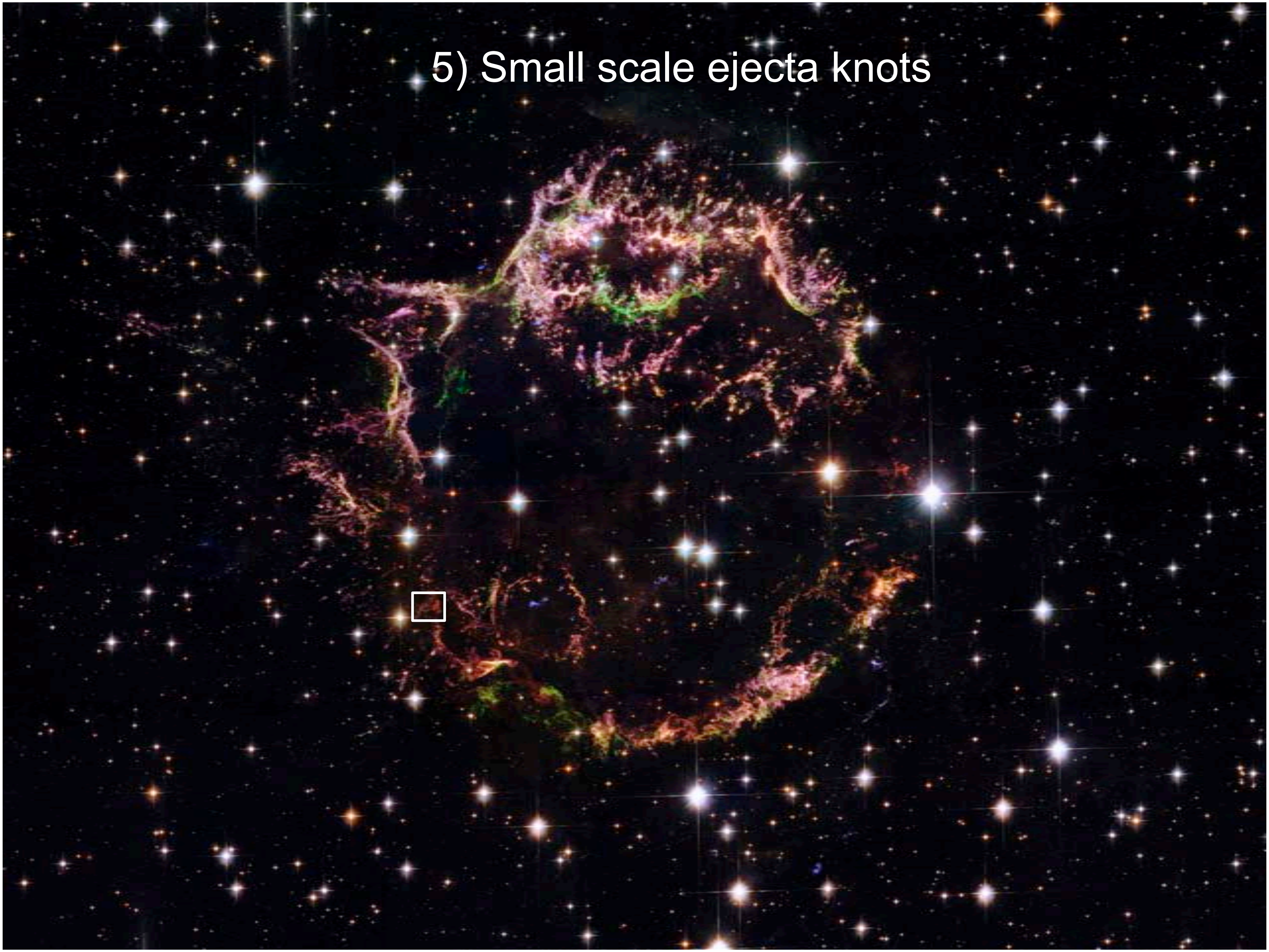


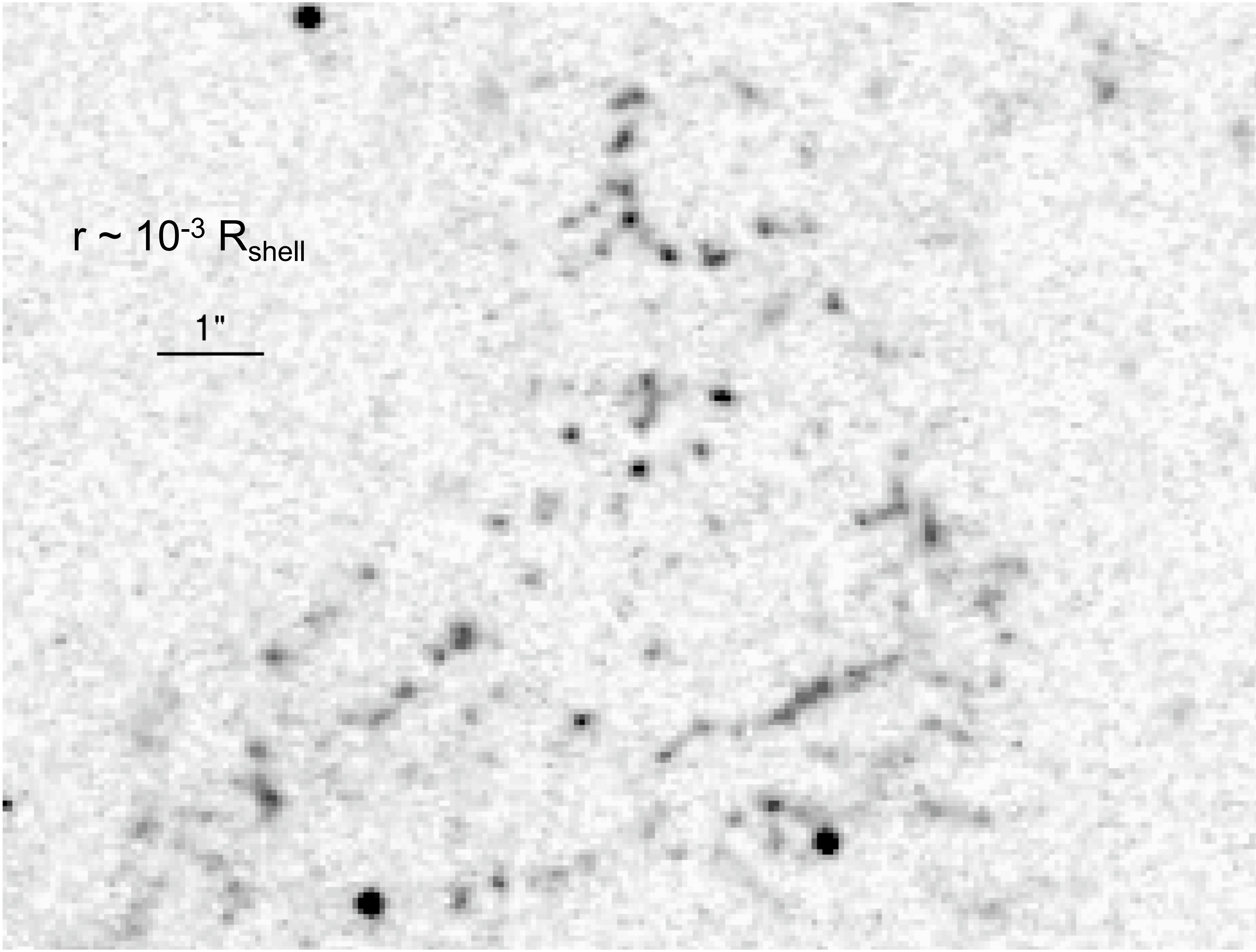
DeLaney et al. 2009

4) Smaller scale filamentary rings

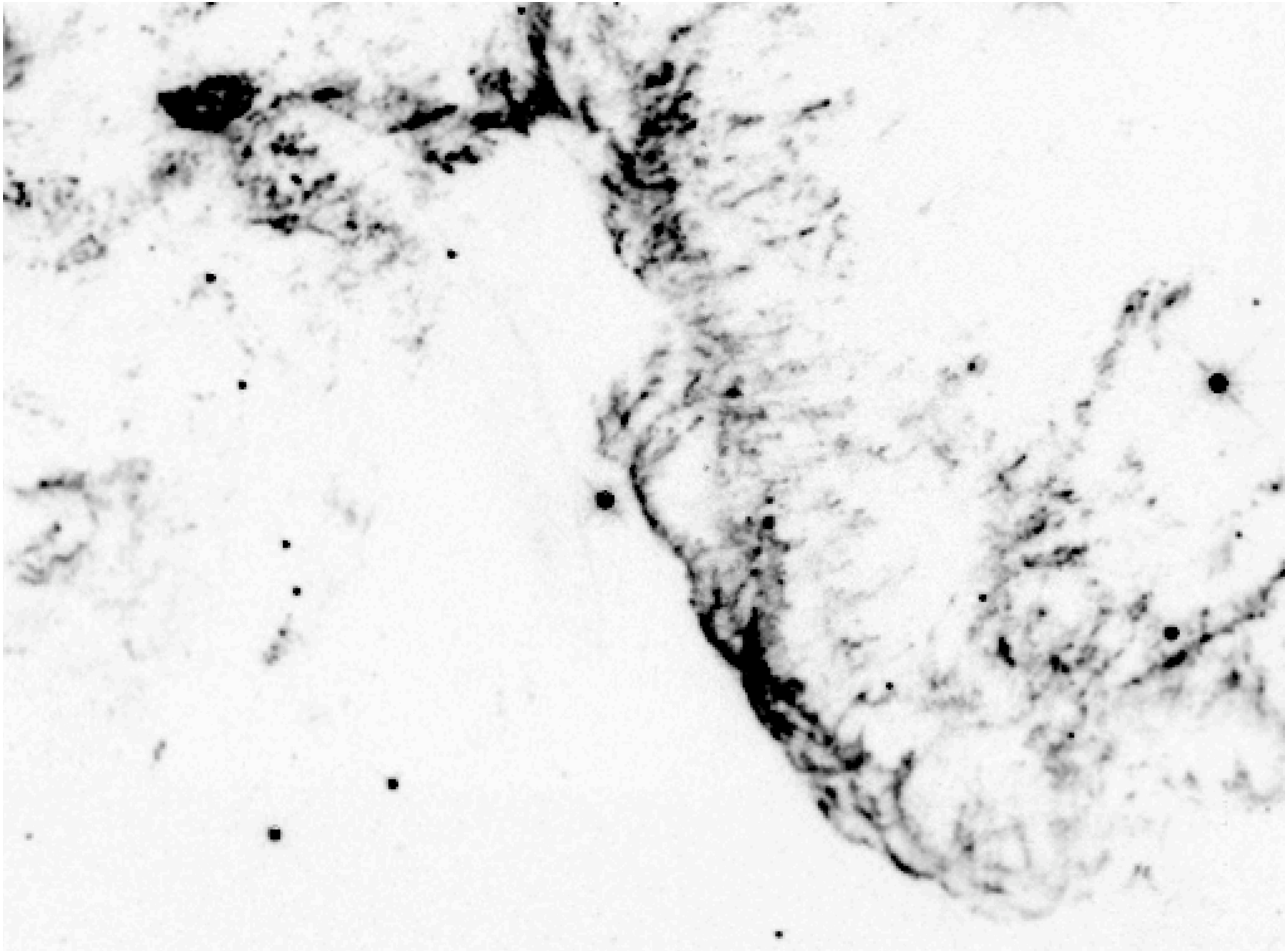


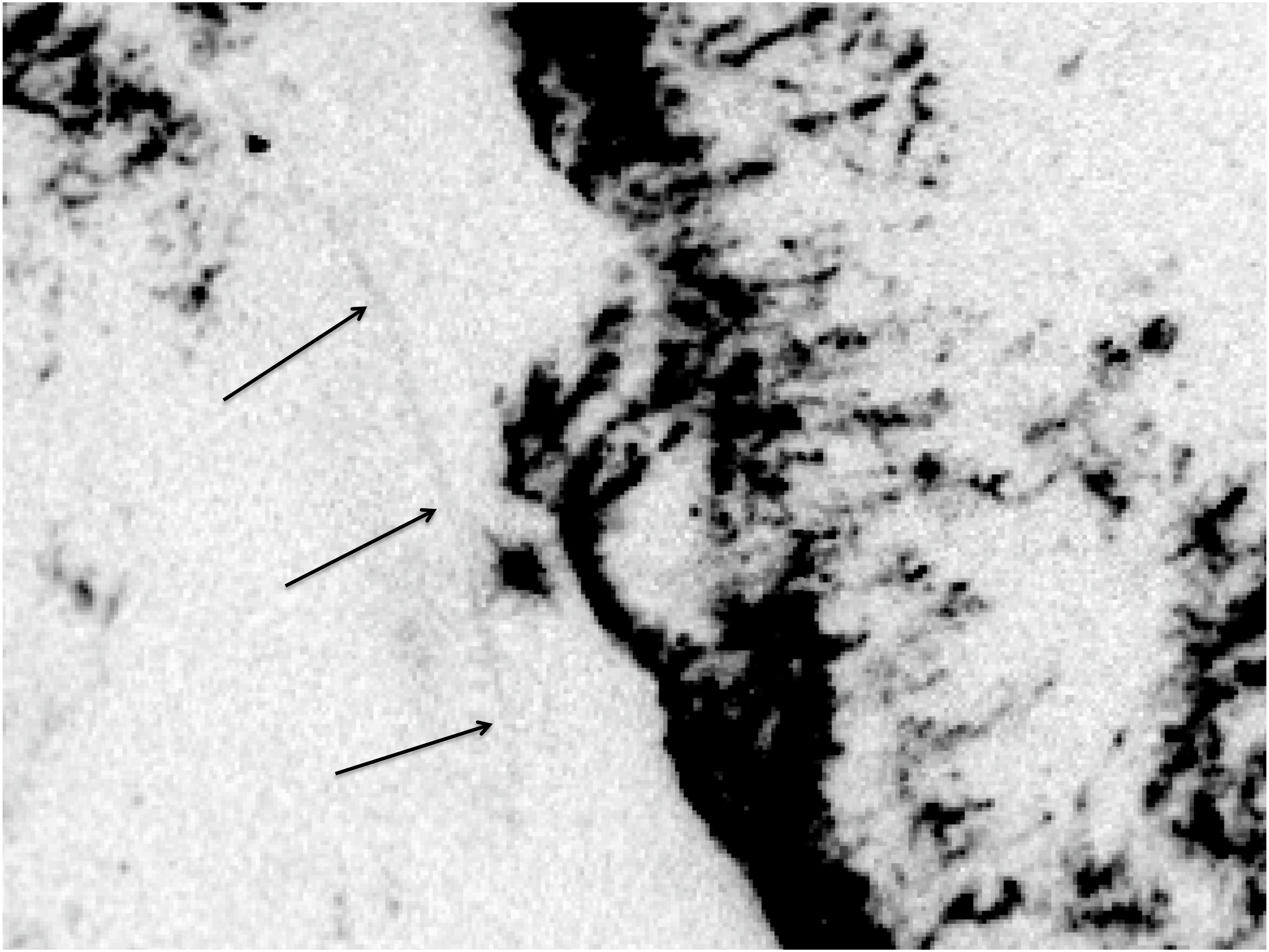

r ~ 0.05 R_shell
5"

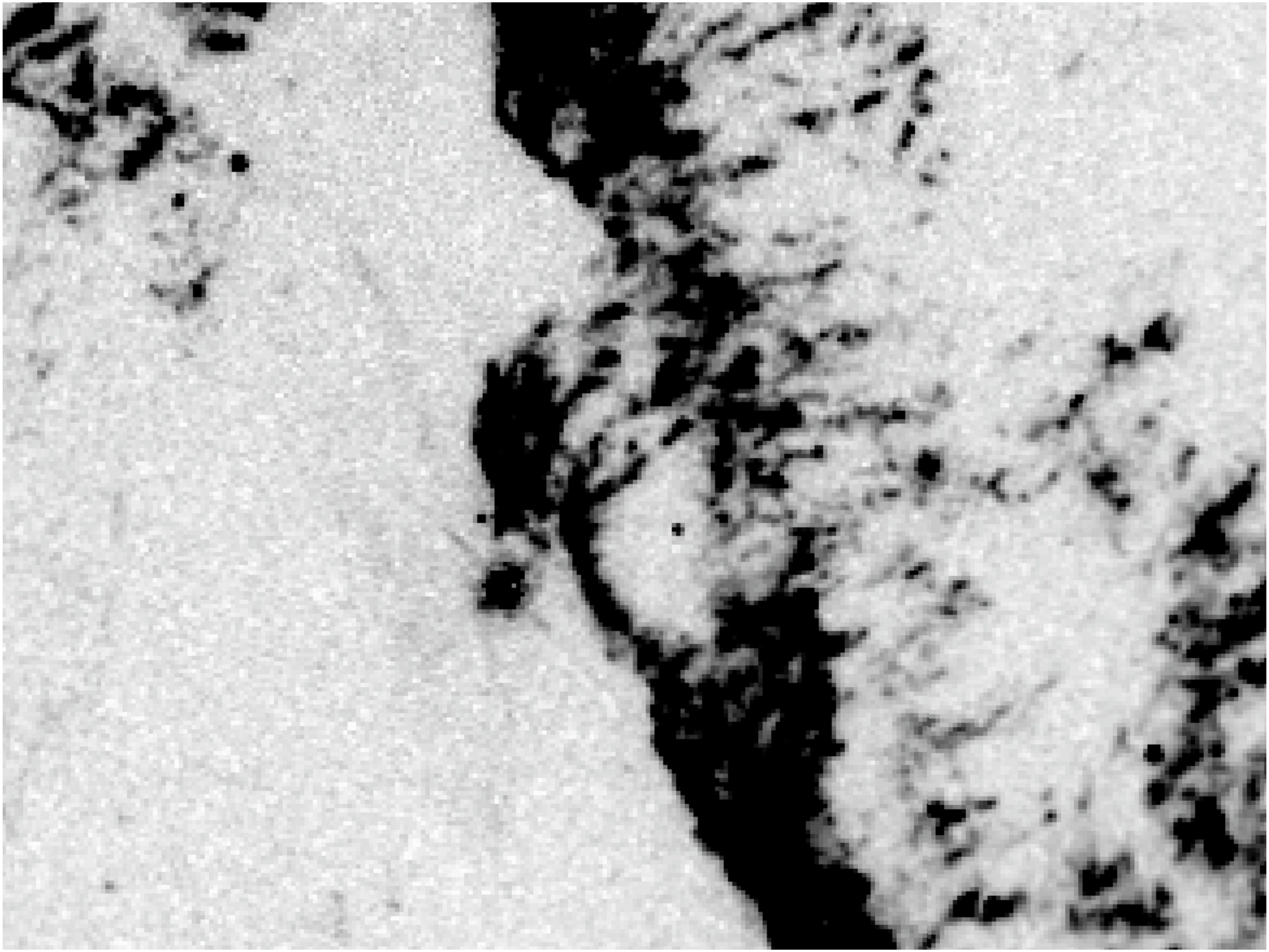

5) Small scale ejecta knots

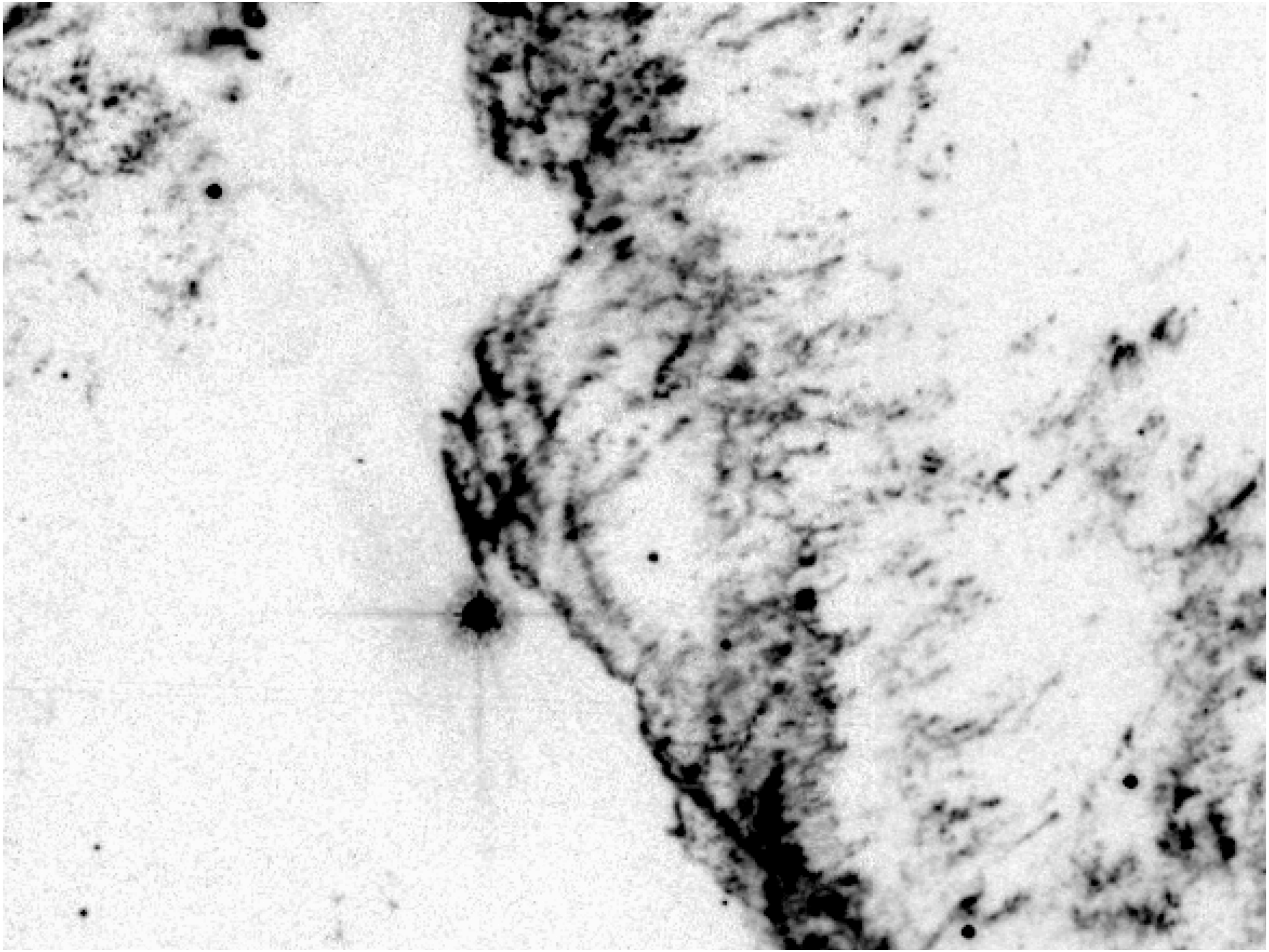


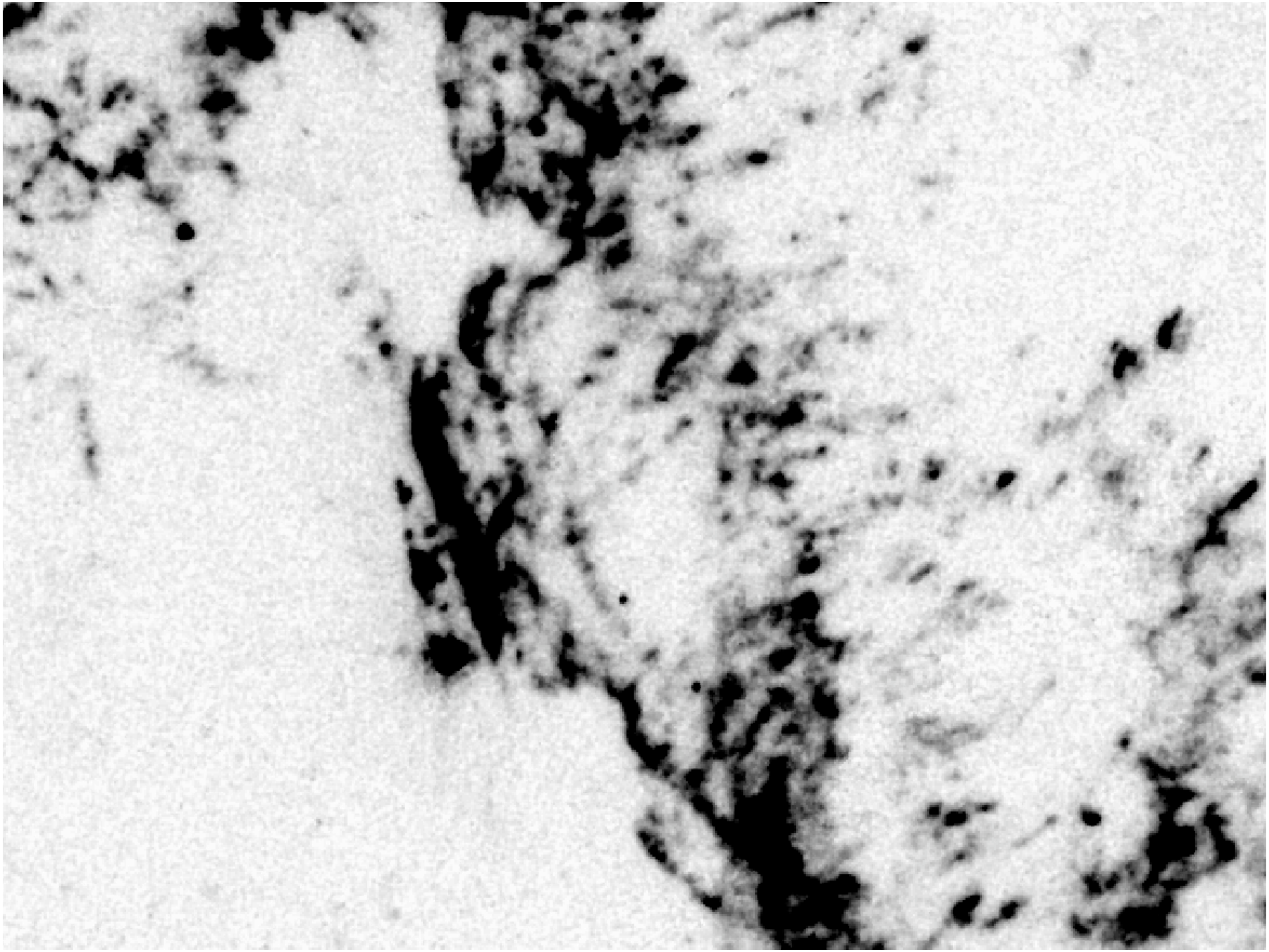
r ~ 10-3 Rshell
1"

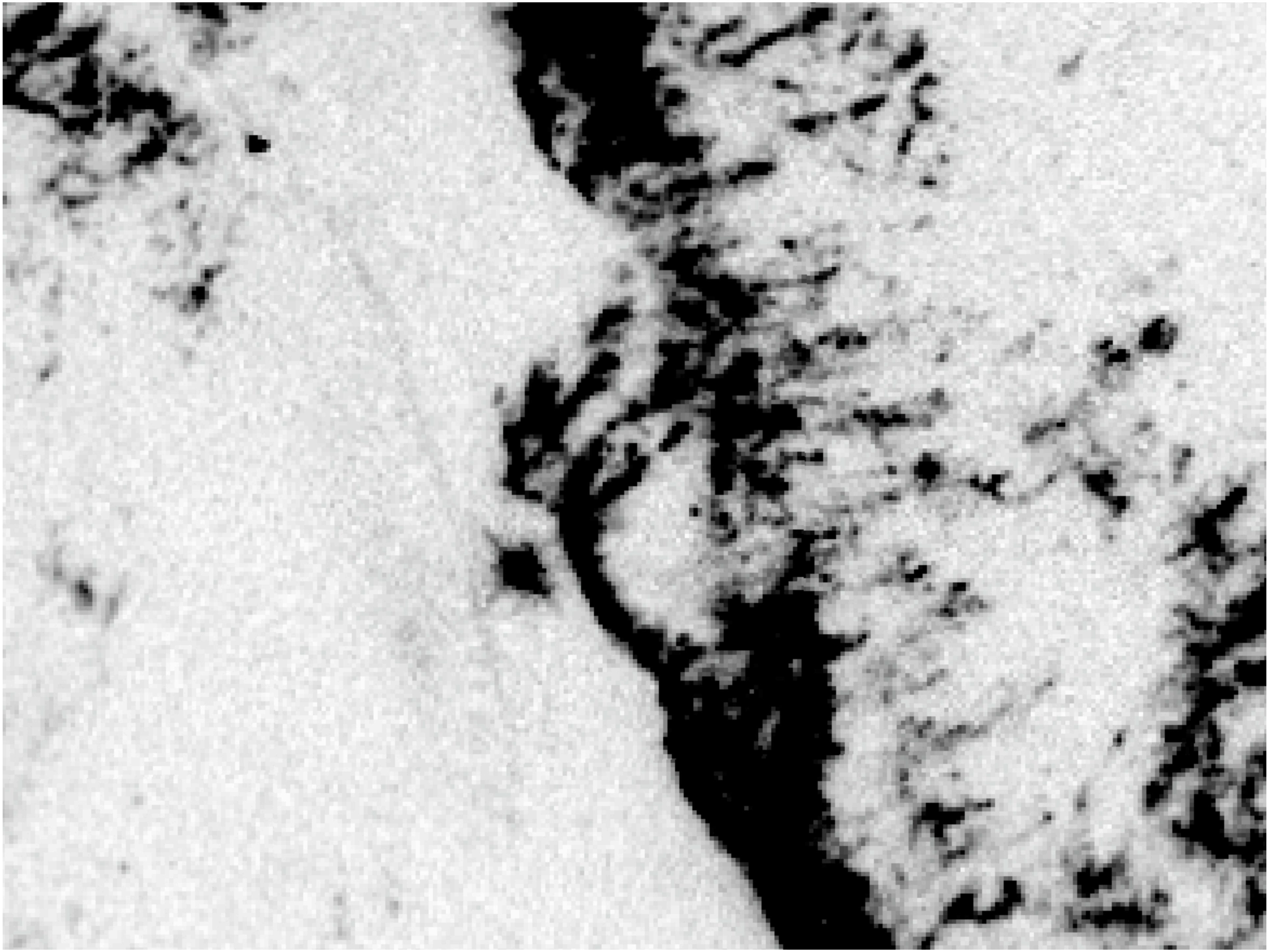


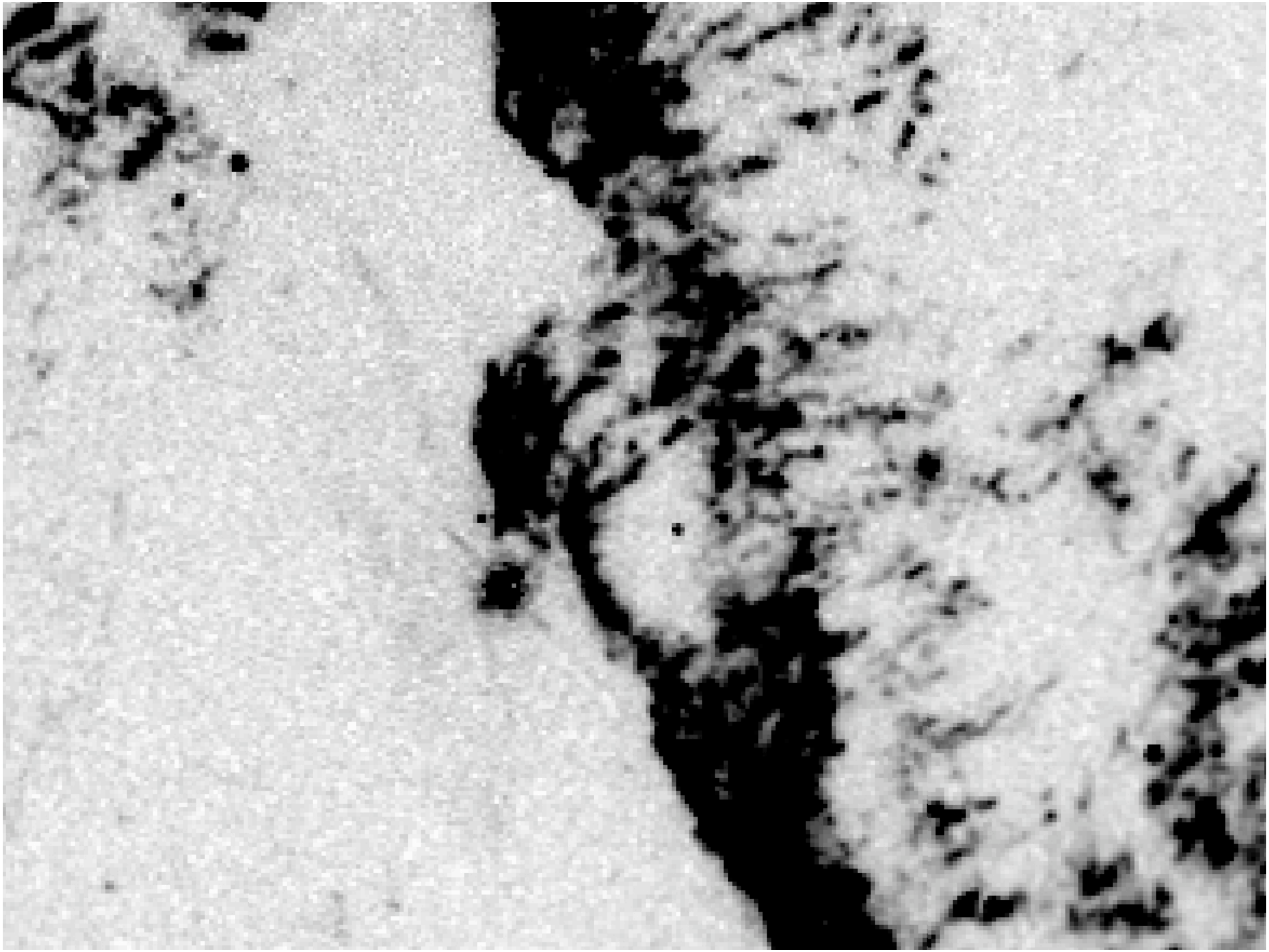


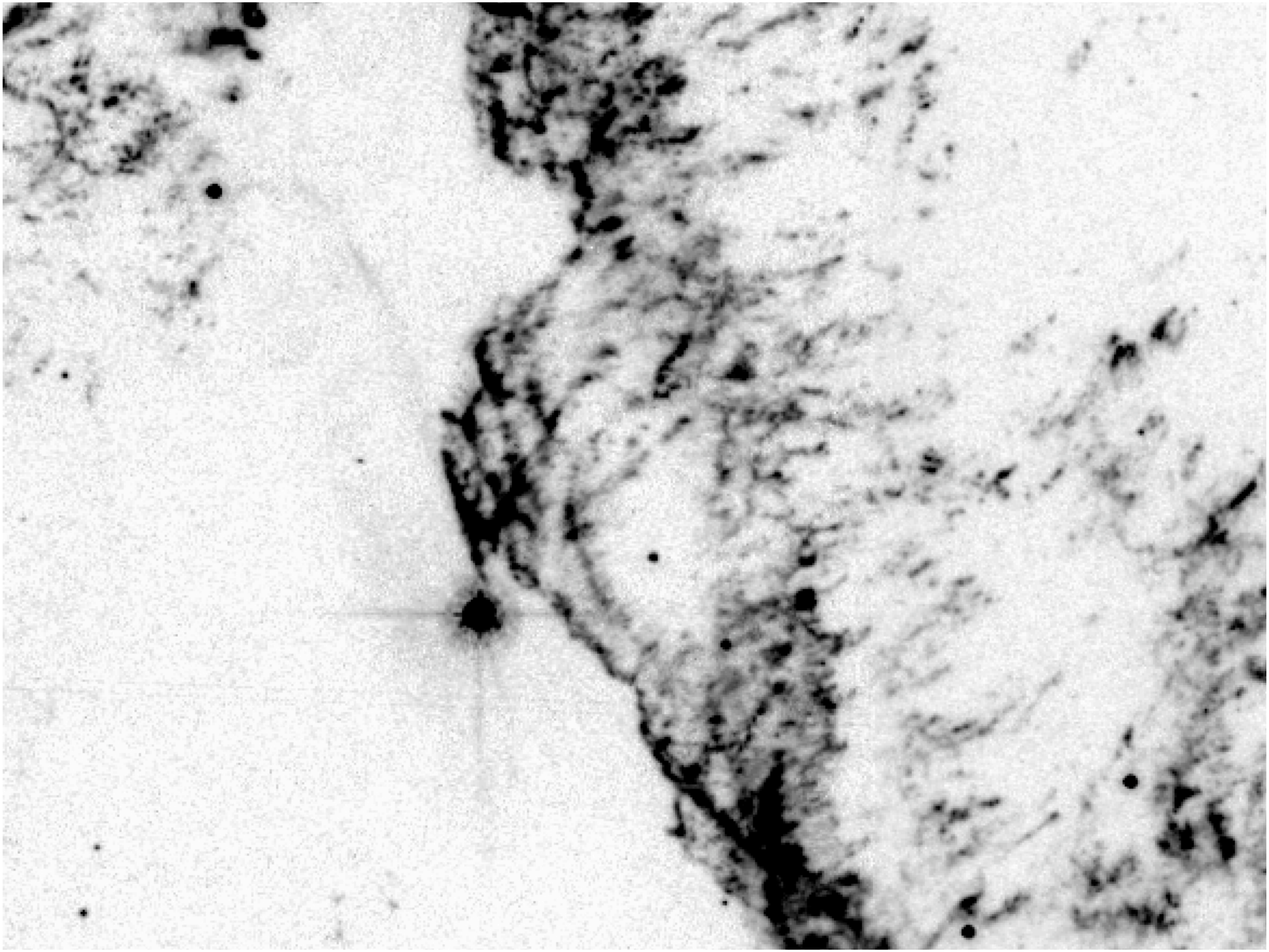


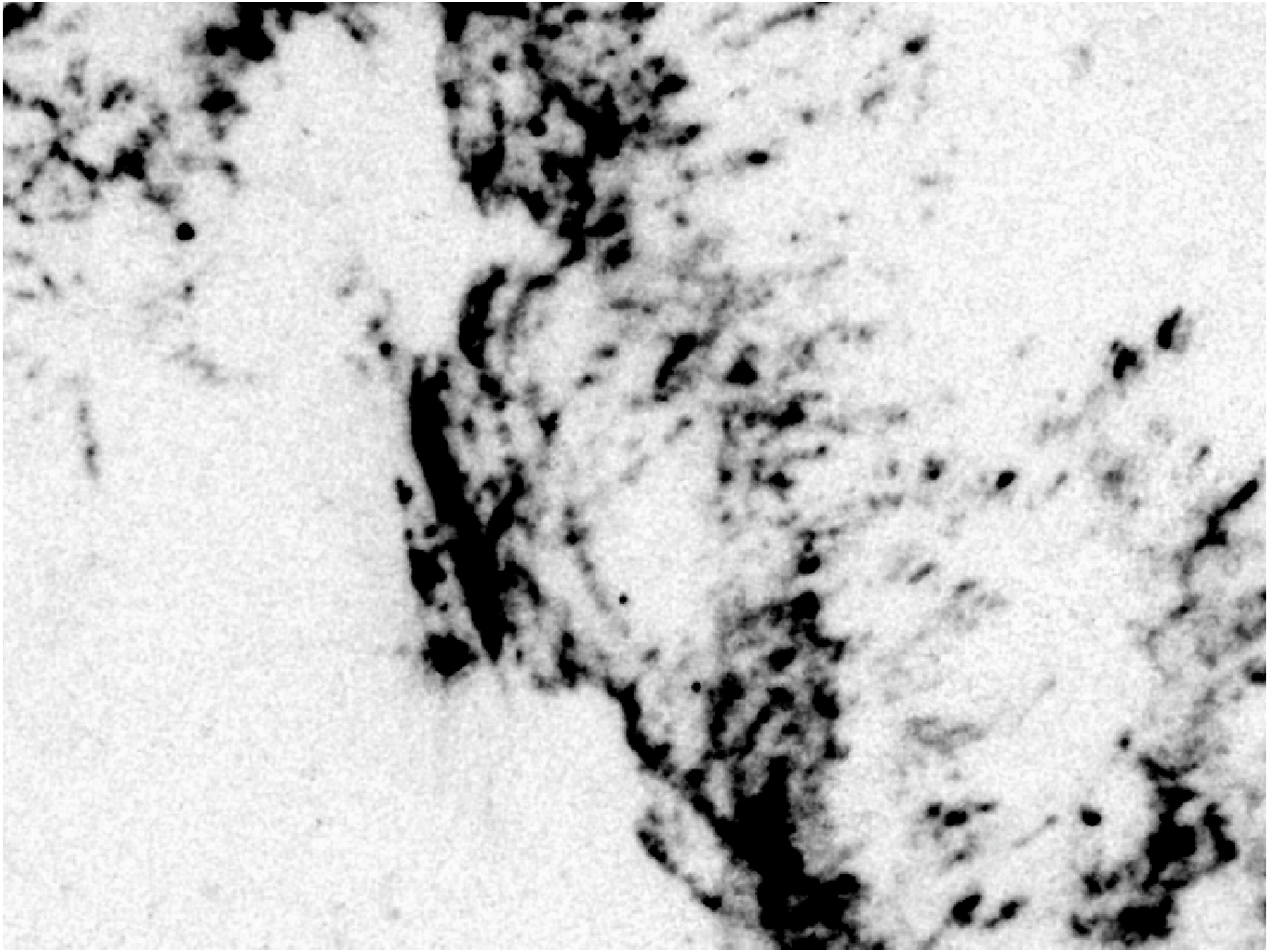




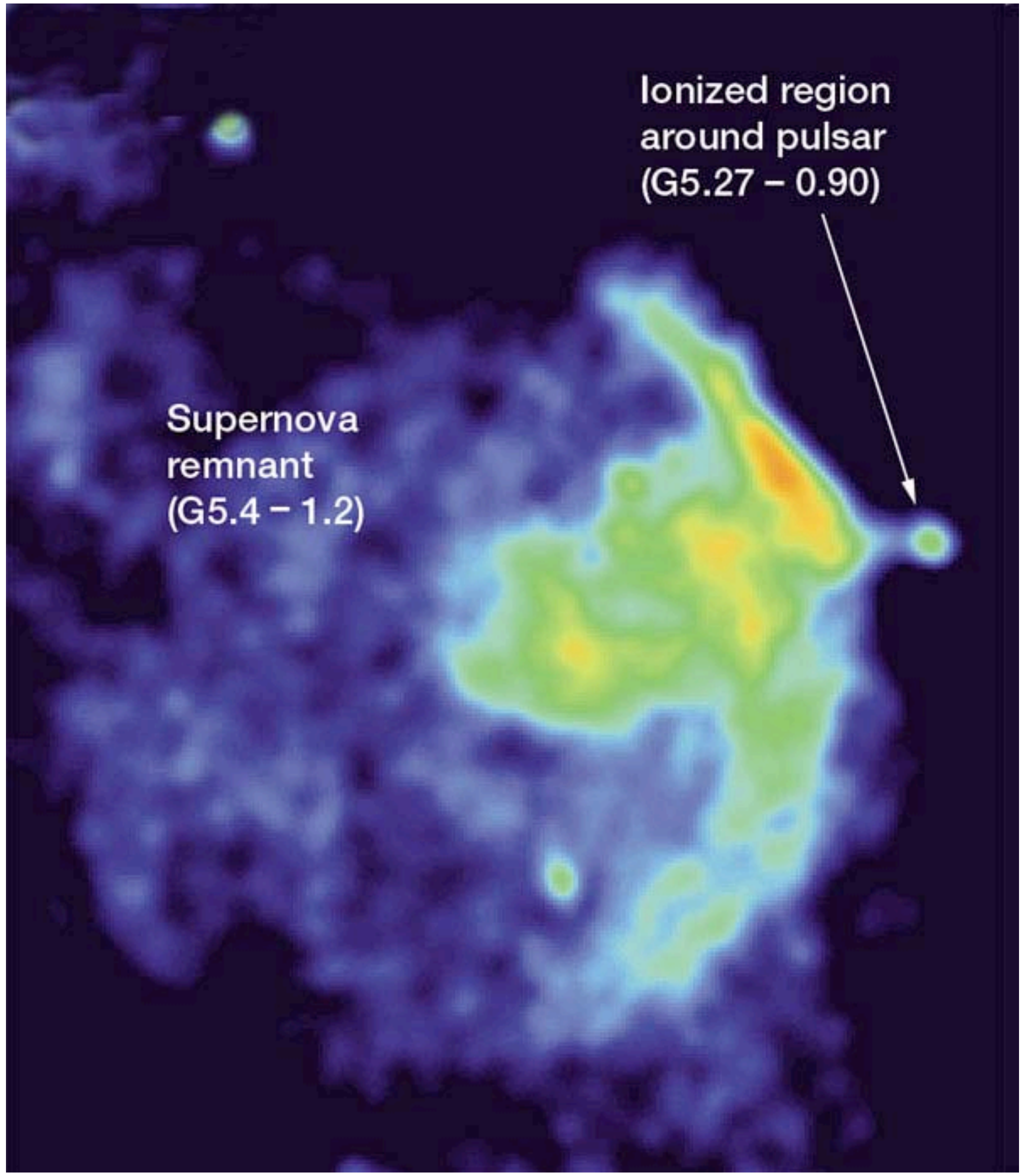




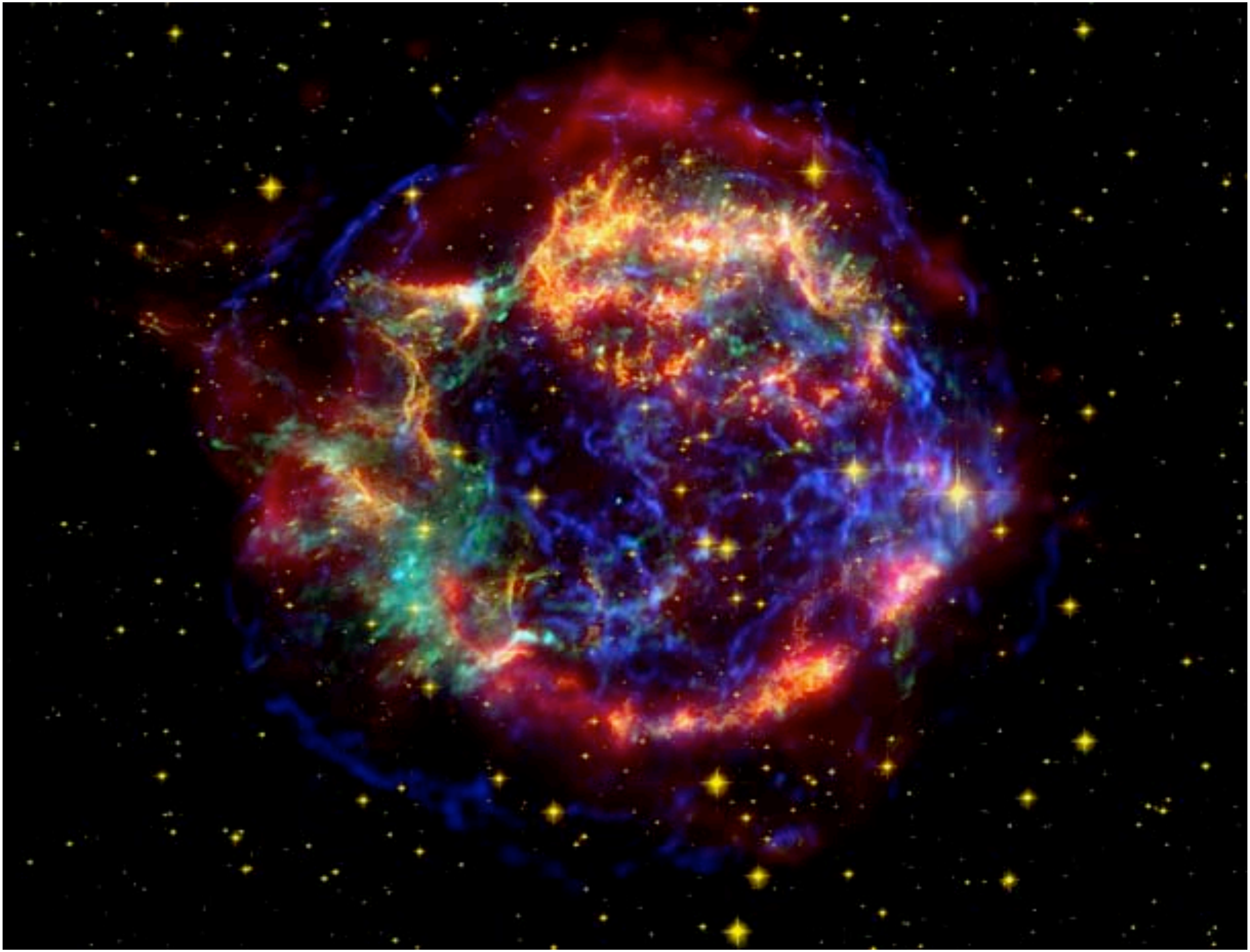


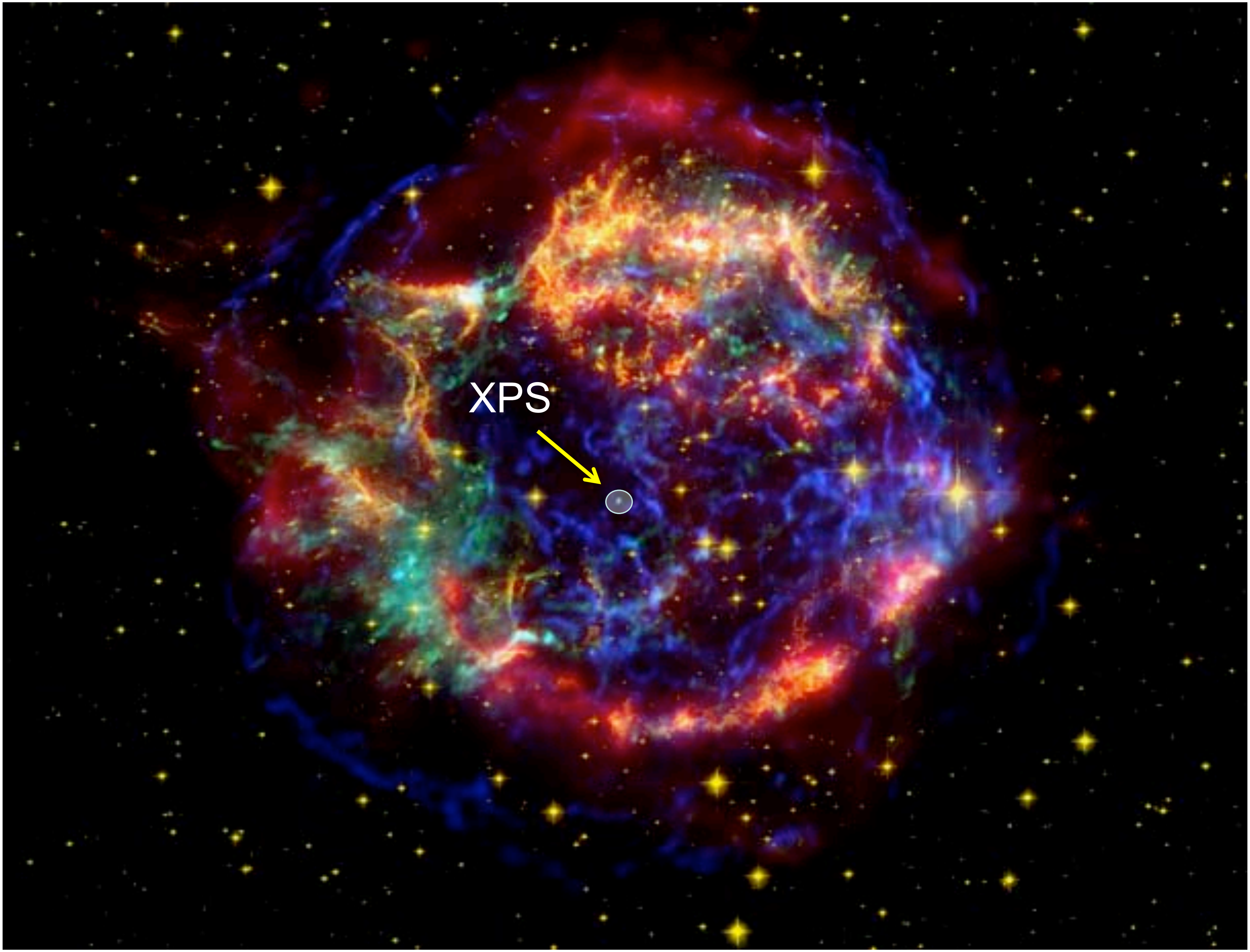


Kicks to Central Compact Objects

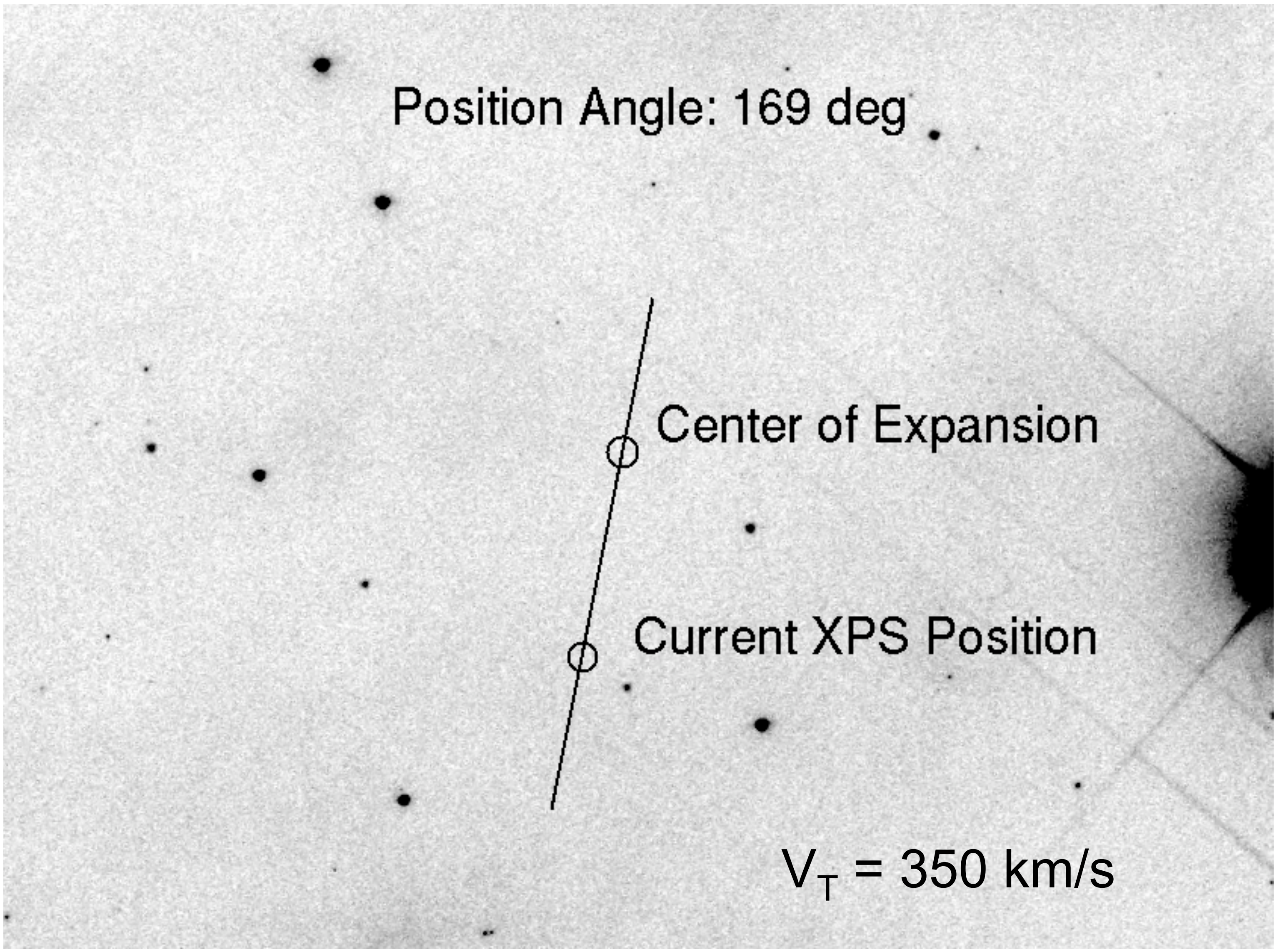


But in what direction?

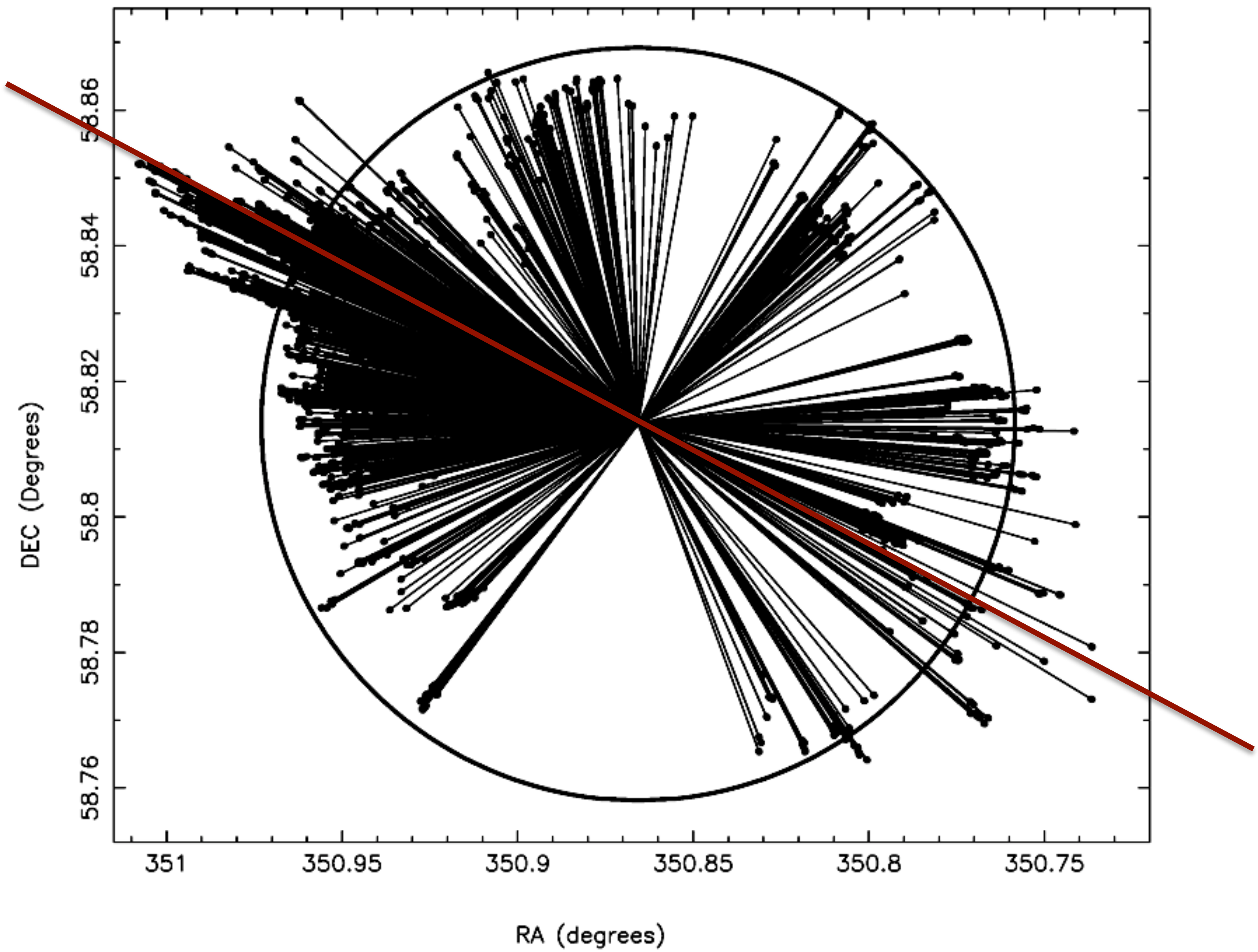



XPS

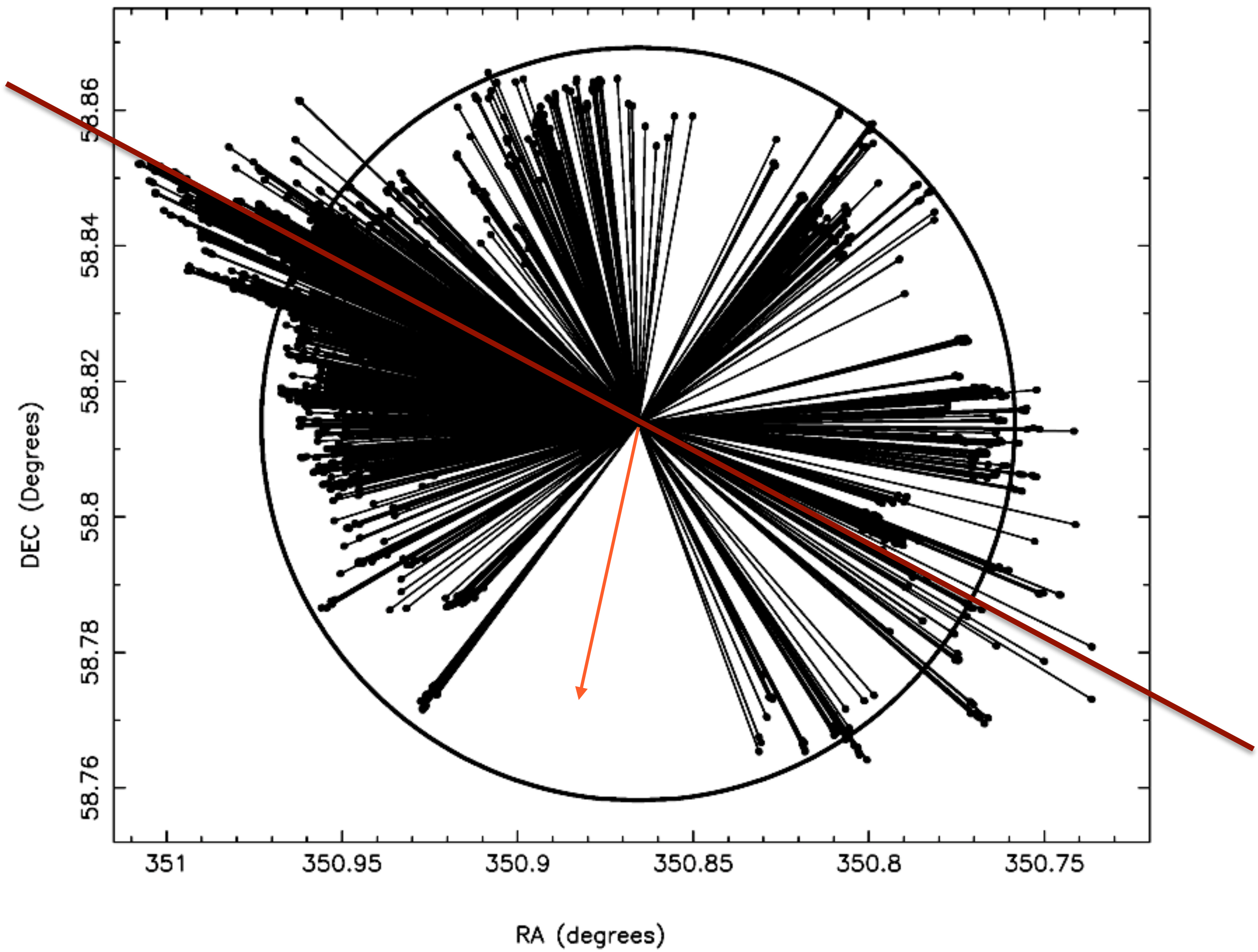
We know both the expansion center and the current XPS position to +/- 0.5 arcsec.

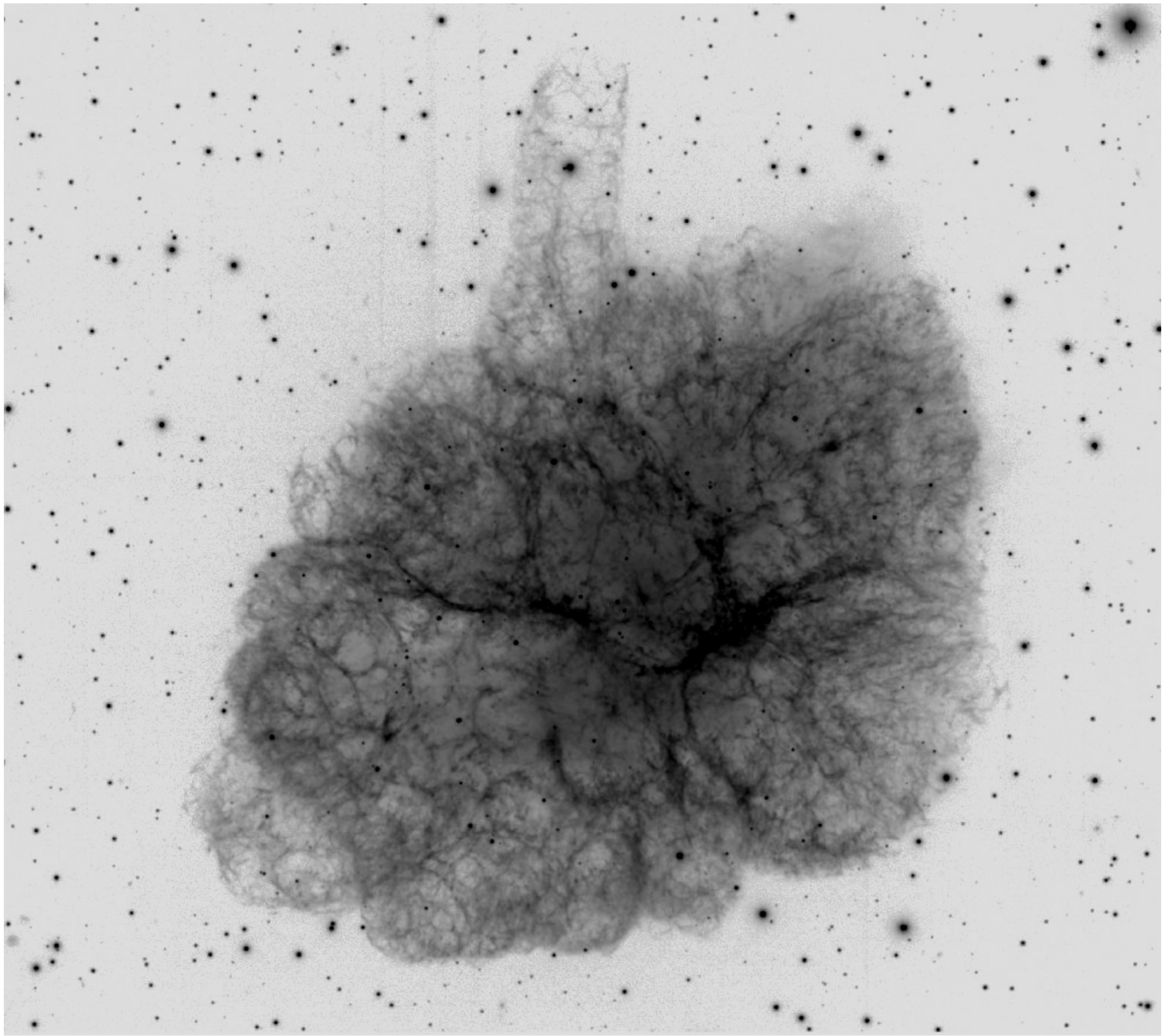


Cas A's central compact object (CCO) is moving ~ 350 km/s nearly orthogonal to the jets .



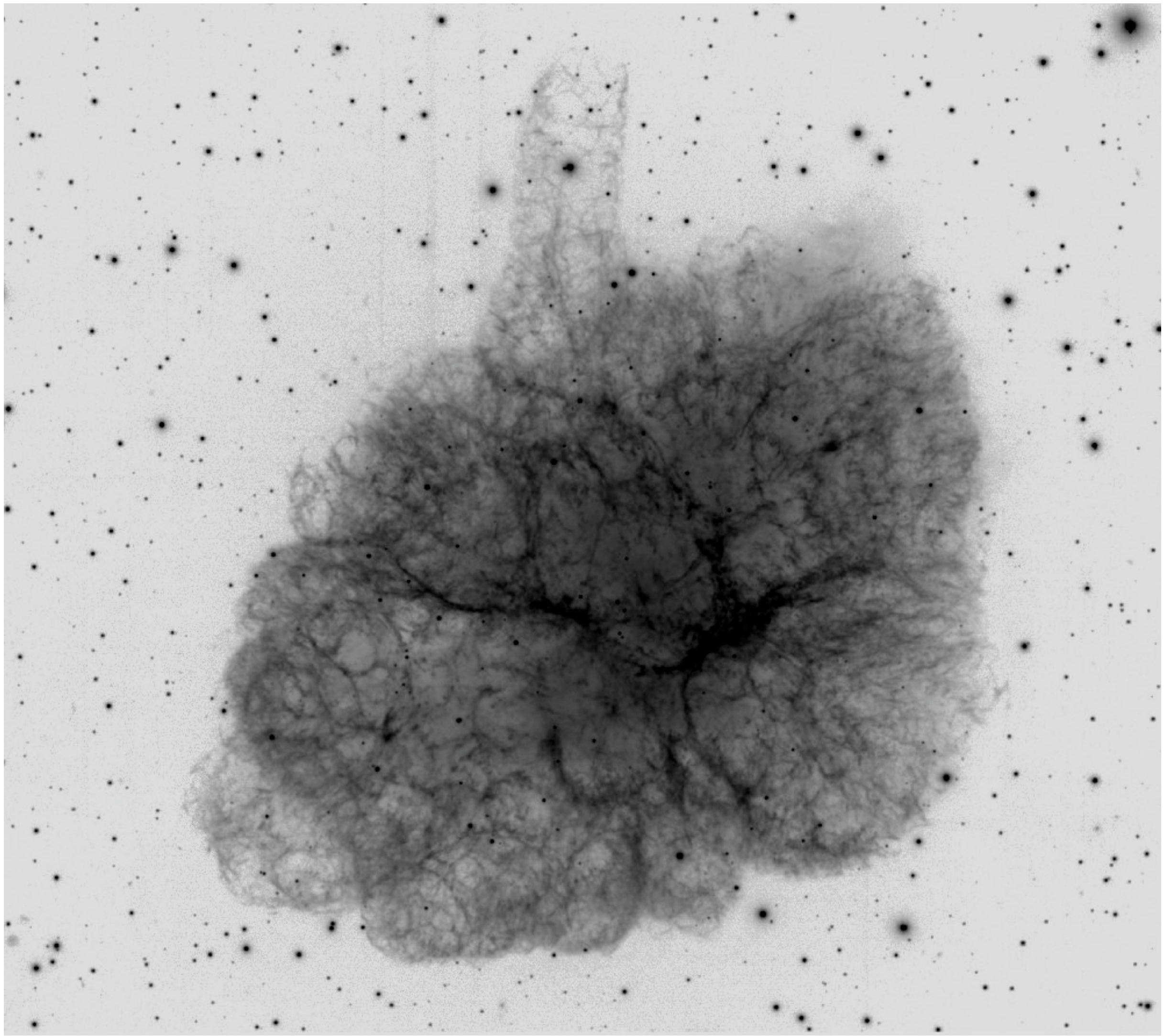
Cas A's central compact object (CCO) is moving ~ 350 km/s nearly orthogonal to the jets .

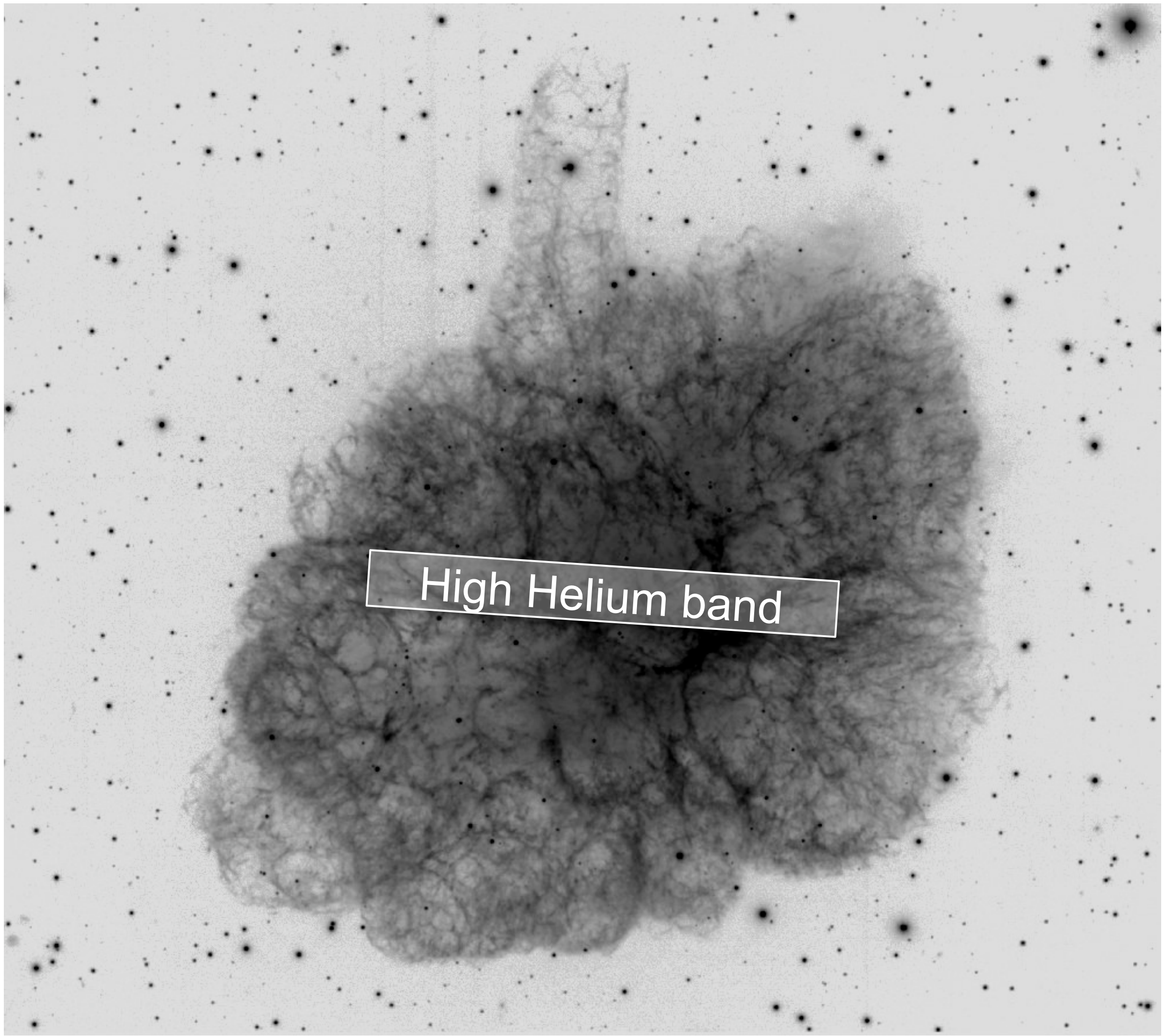


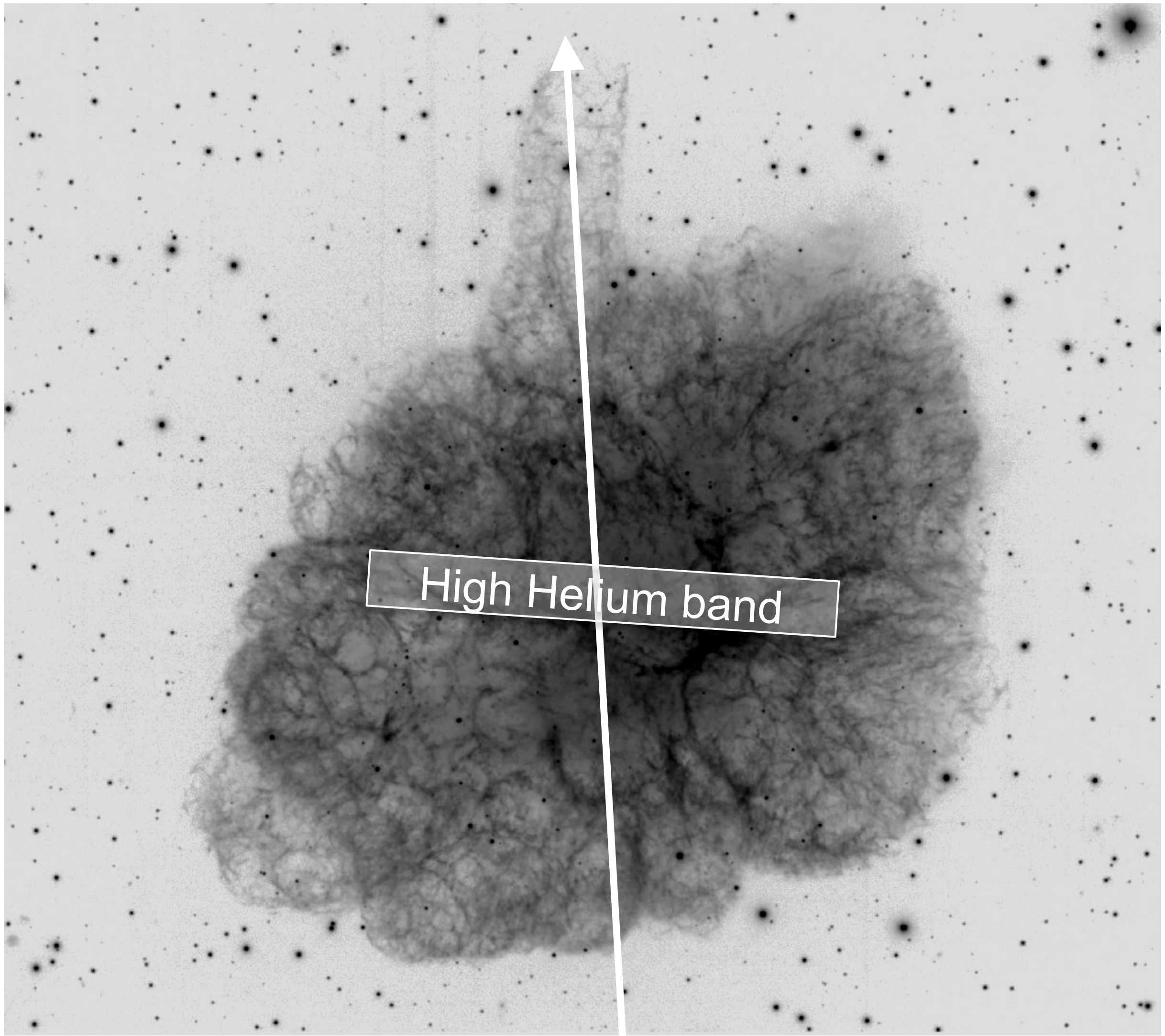


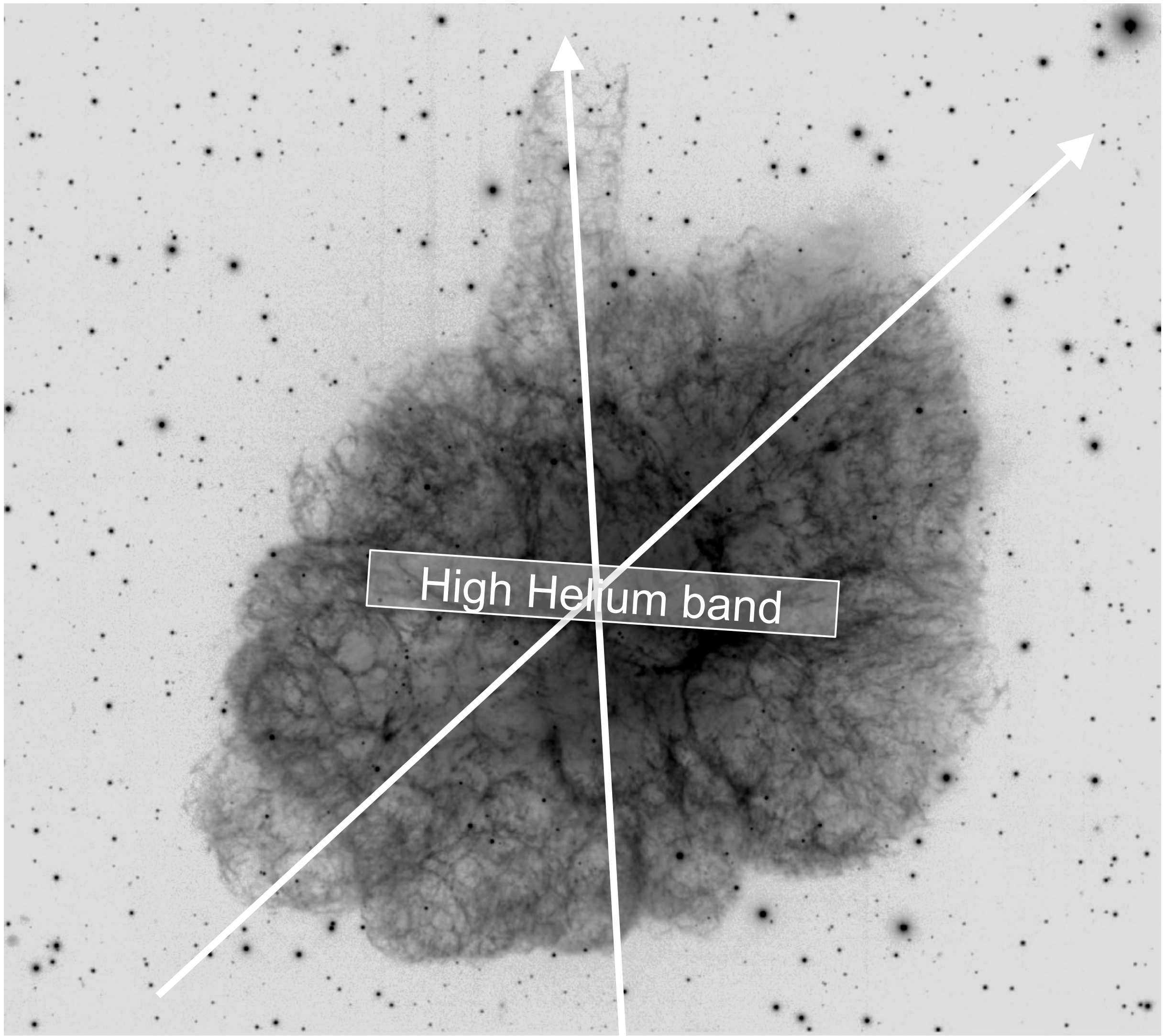
The Crab Nebula also has a jet… but just one.

Why precisely there?

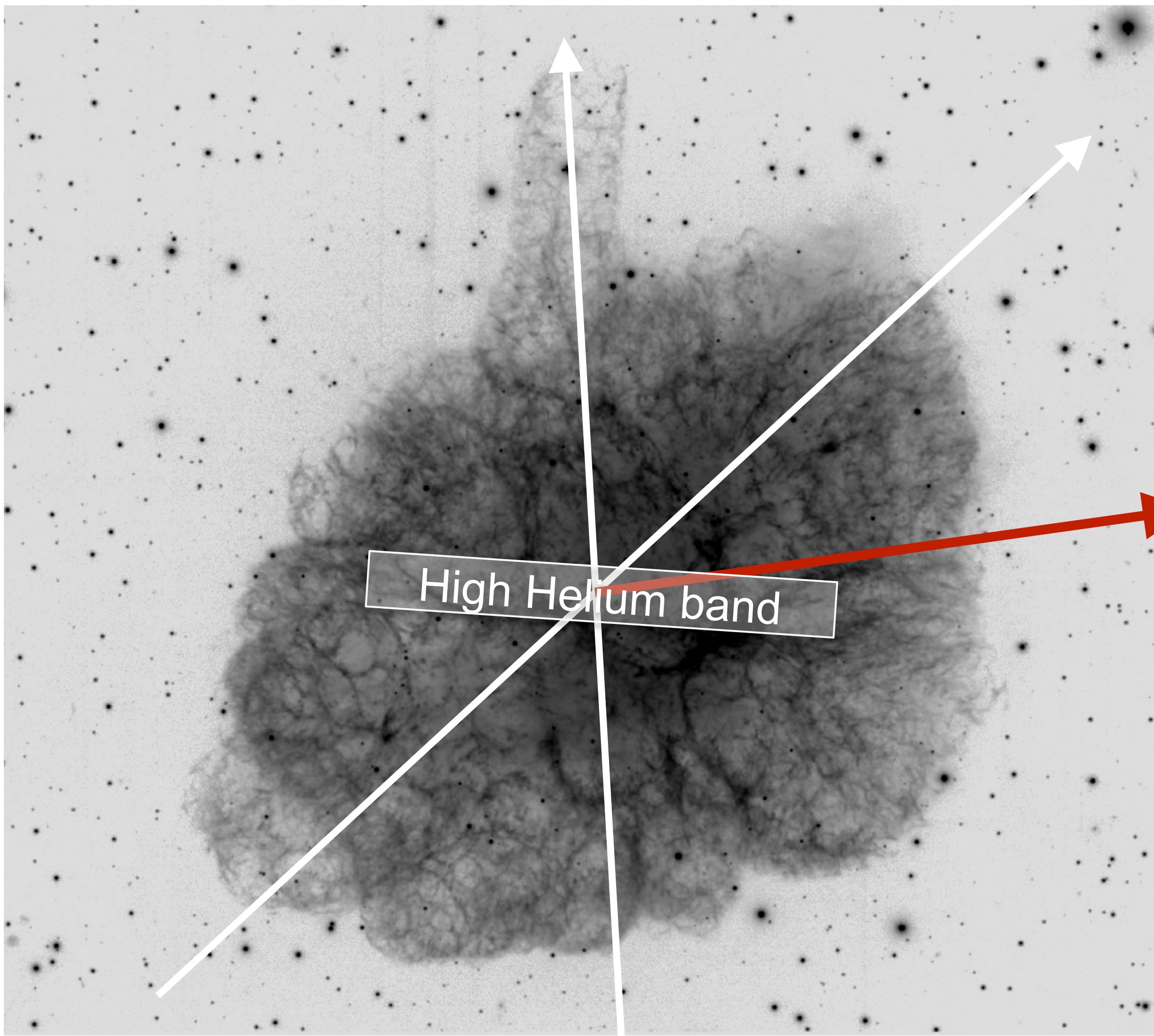



High Helium band


High Helium band

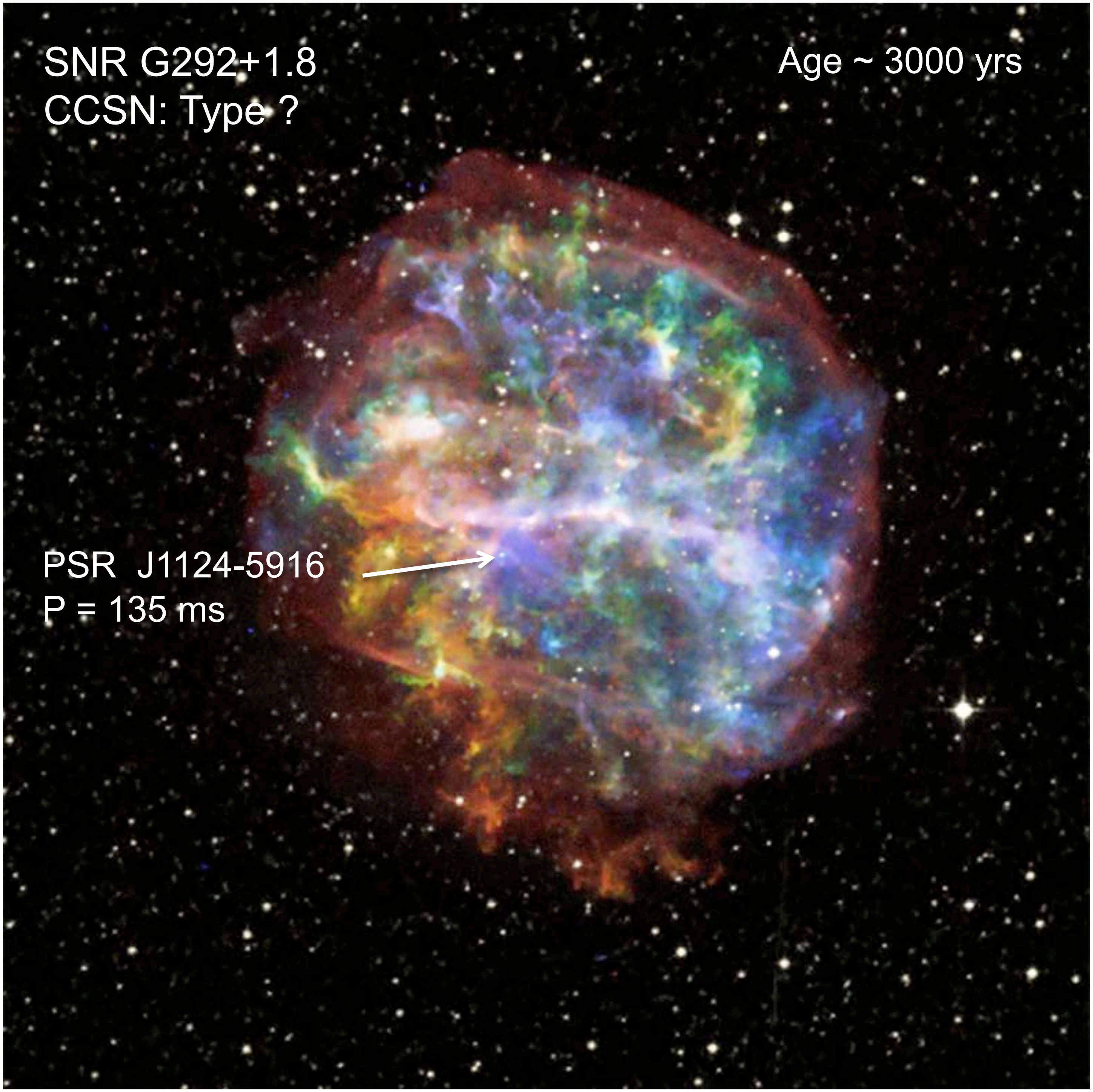


Pulsar spin axis:
PA = 304º
(Ng & Romani 2004)

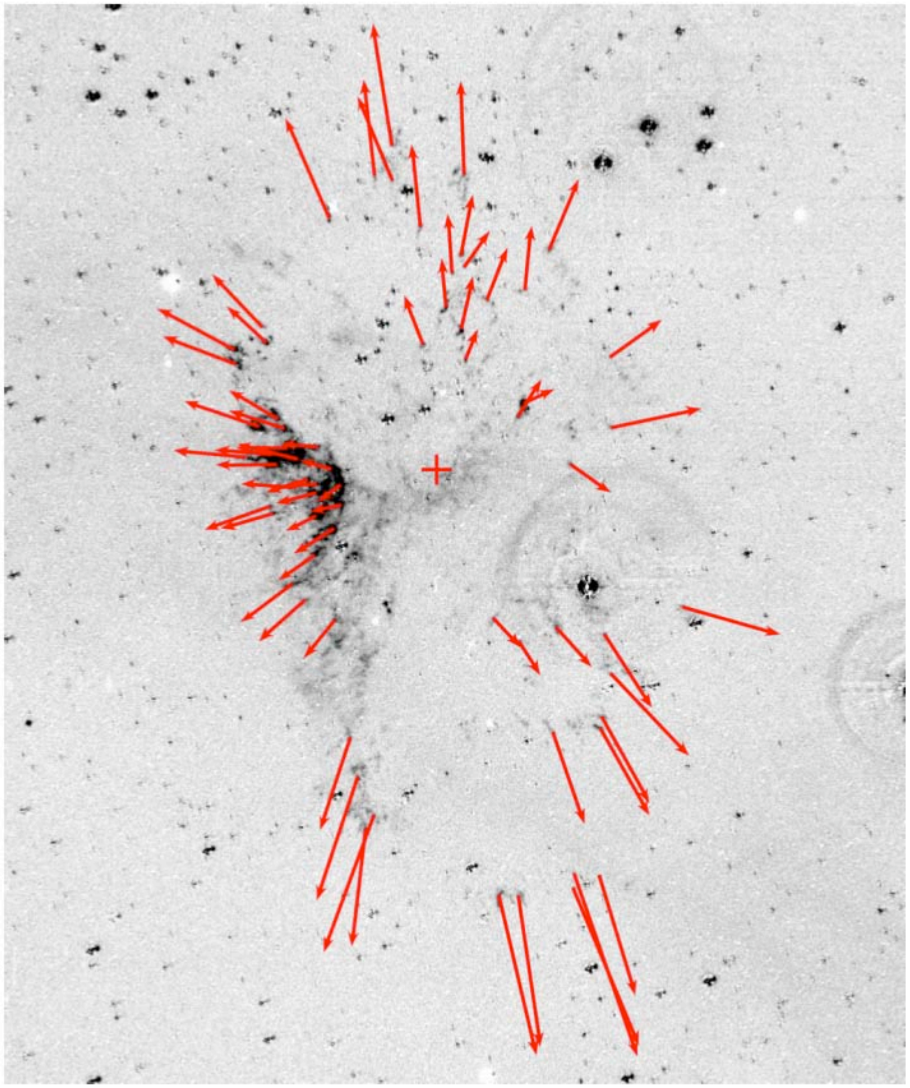


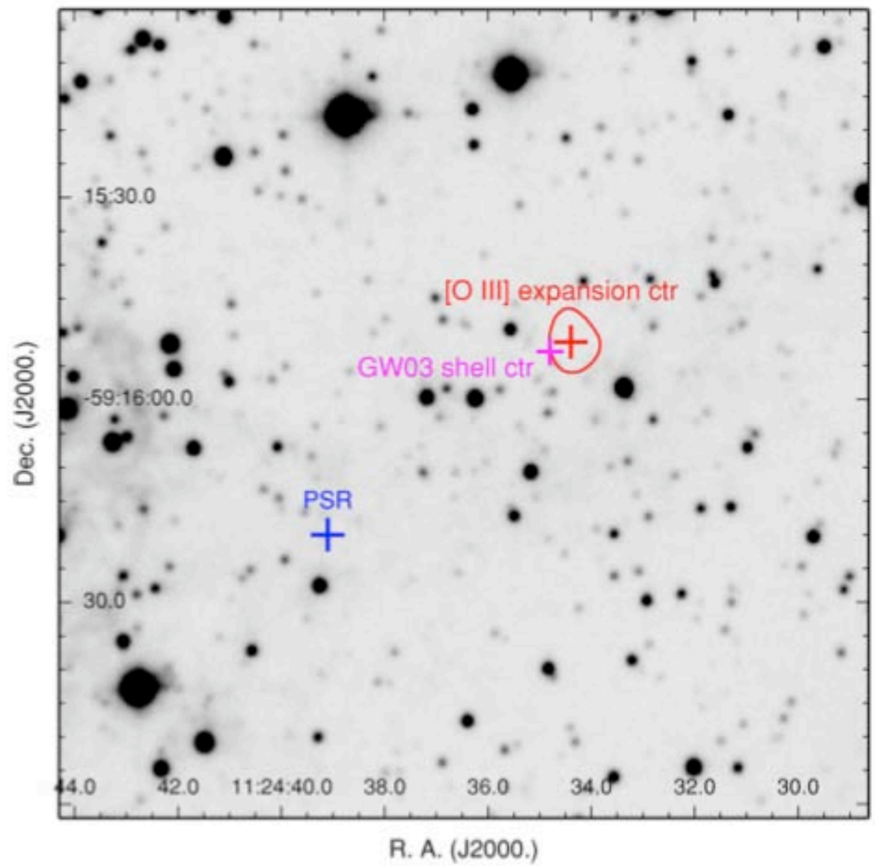
Pulsar spin axis:
PA = 304º
(Ng & Romani 2004)

Pulsar motion:
PA = 278 +/-3º
(Ng & Romani 2006)


SNR G292+1.8
CCSN: Type ?
Age ~ 3000 yrs
PSR J1124-5916
P = 135 ms

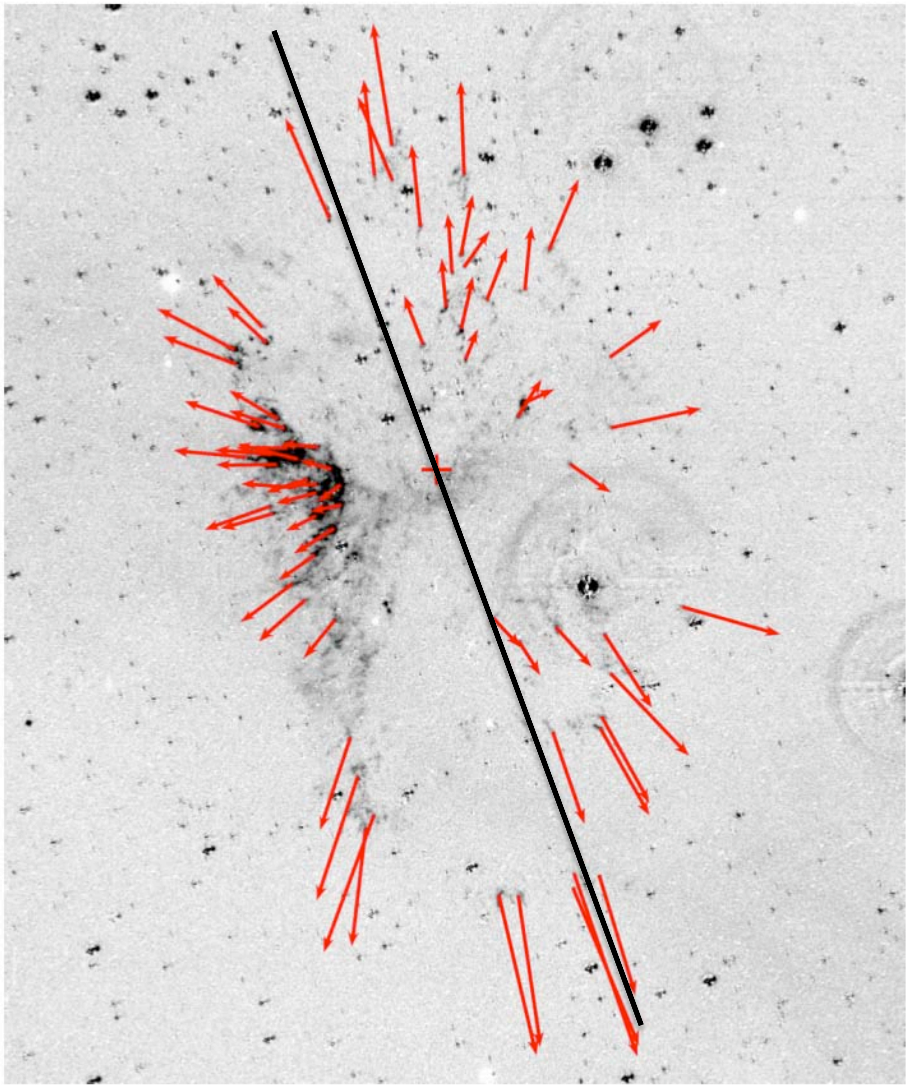
G292.0+1.8 SNR



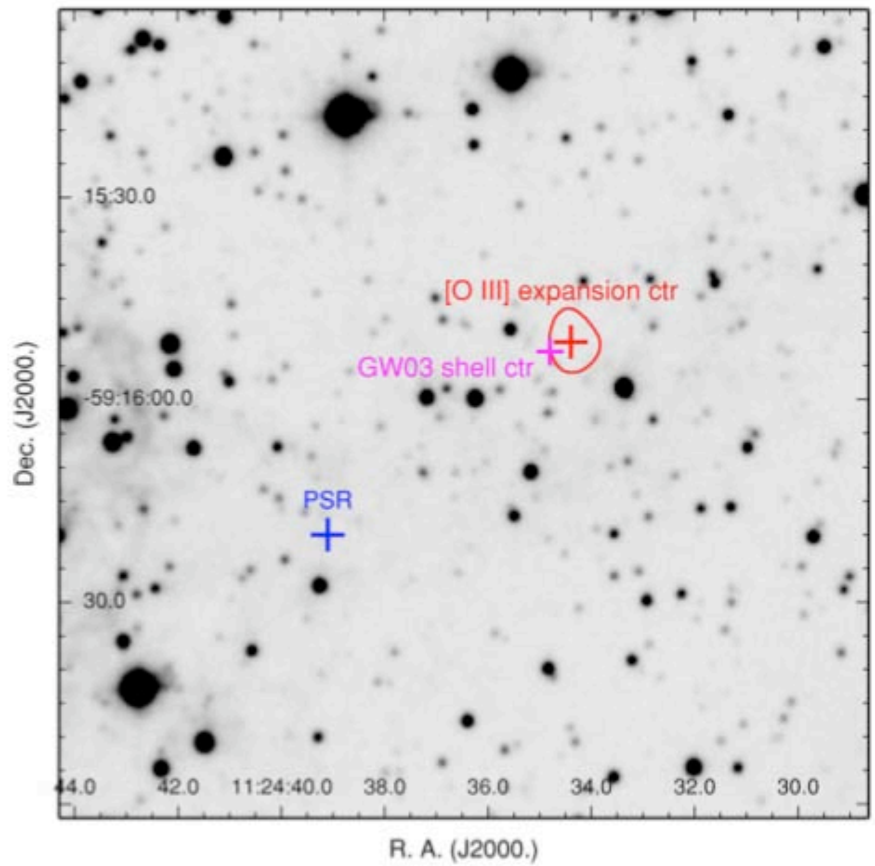


Winkler et al. 2009

G292.0+1.8 SNR

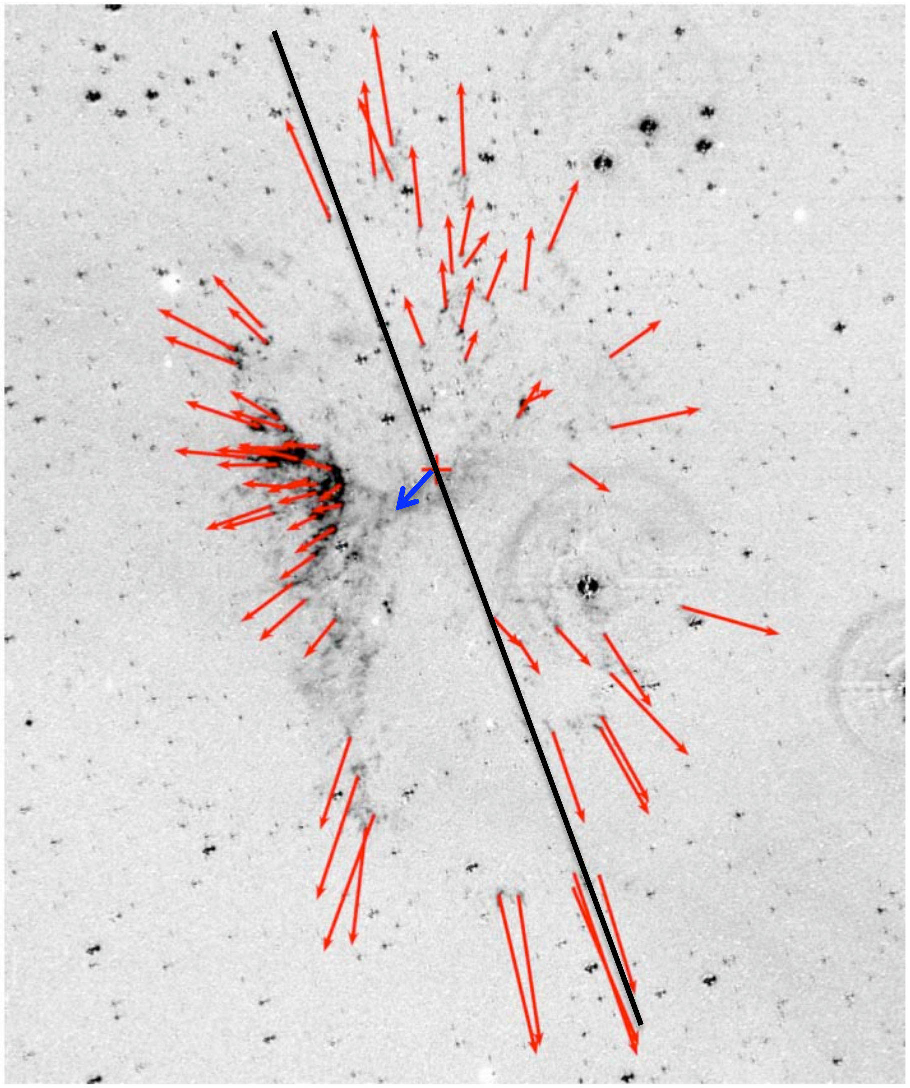


SNR kinematic age ~ 3000 yrs



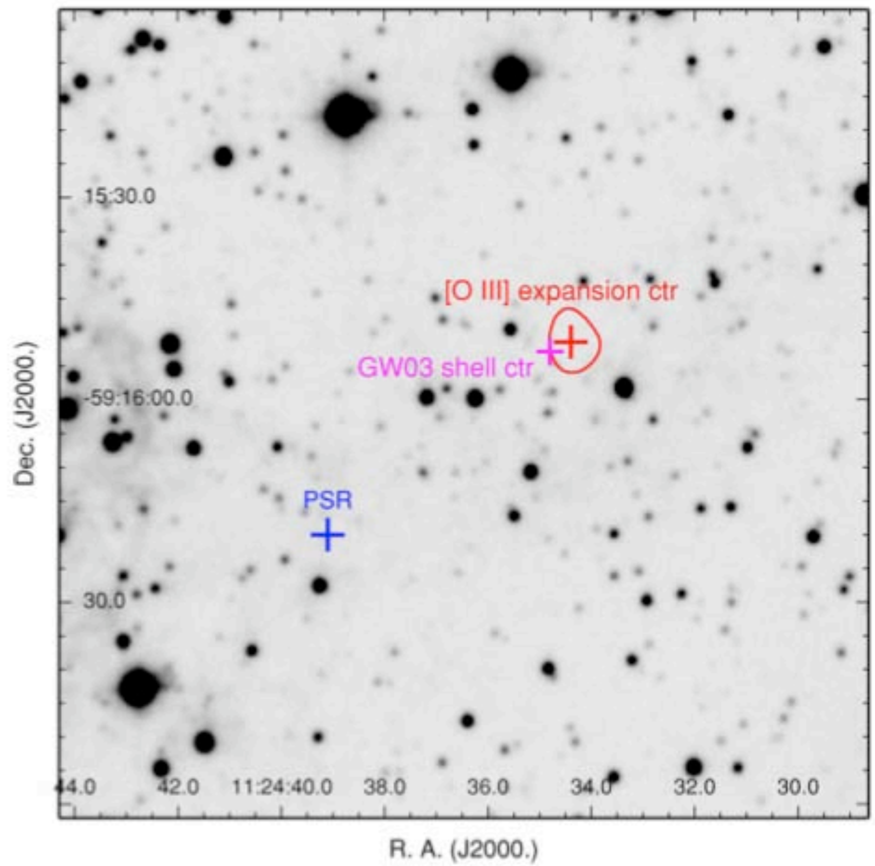
Winkler et al. 2009

G292.0+1.8 SNR



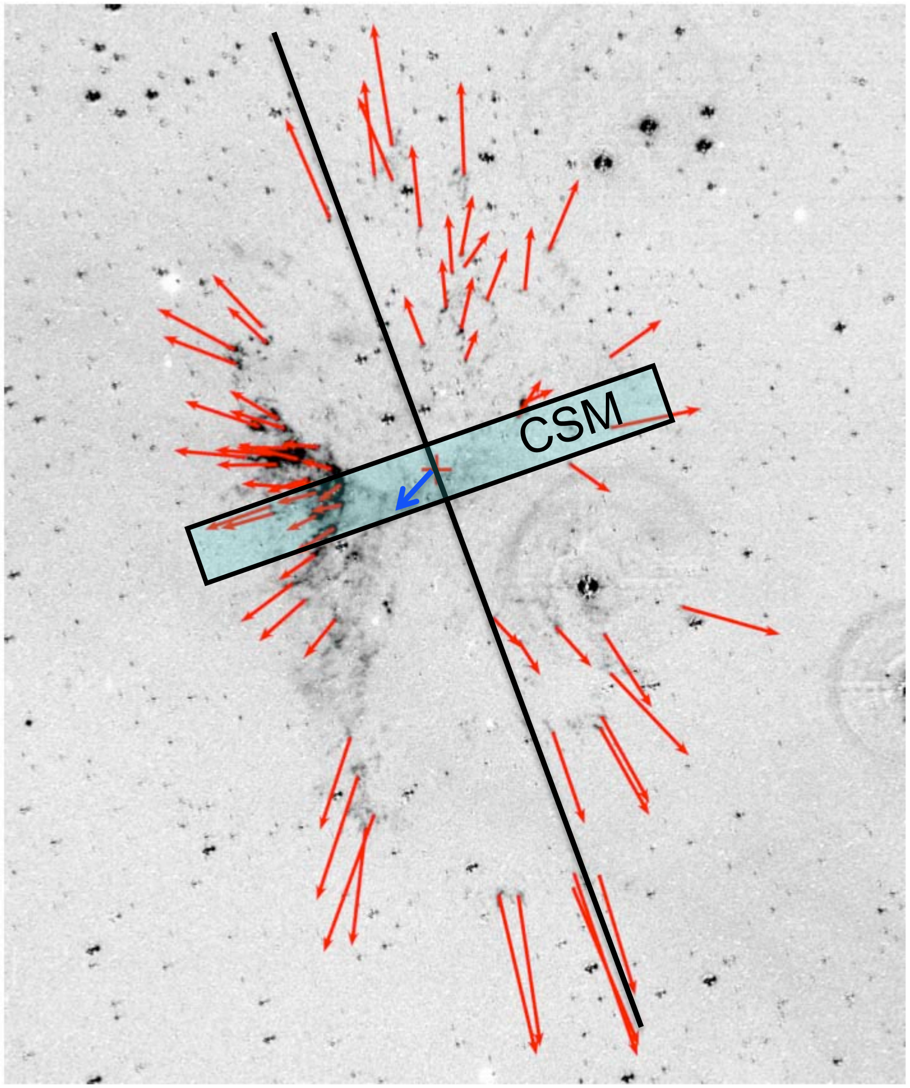
SNR kinematic age ~ 3000 yrs

$V_{T\ (Pulsar)}$ = 440 km s^{-1}



Winkler et al. 2009

G292.0+1.8 SNR



SNR kinematic age ~ 3000 yrs

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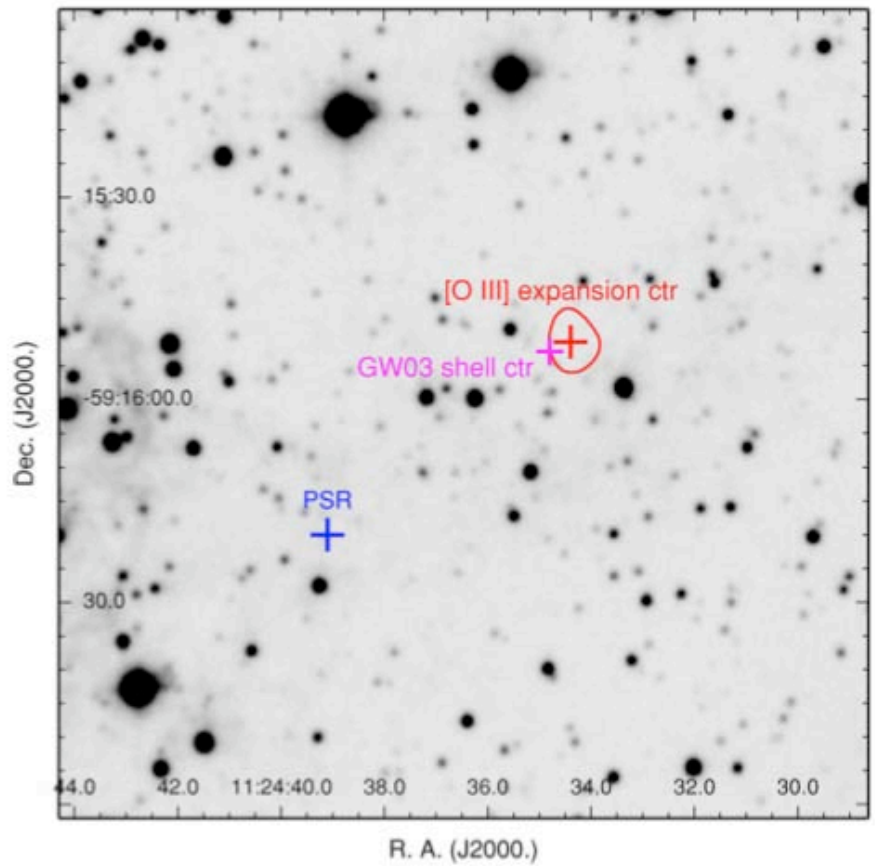
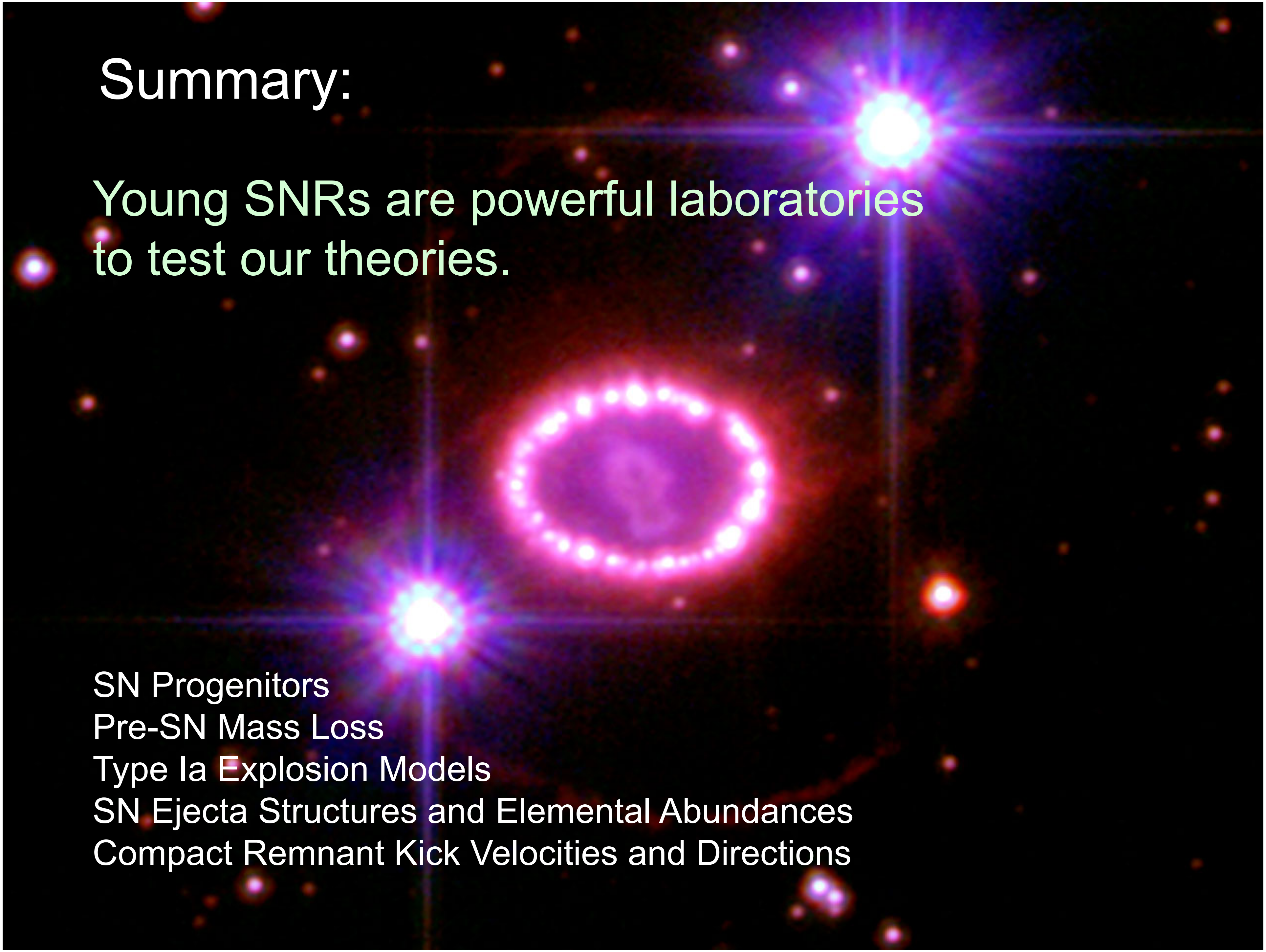


Winkler et al. 2009


Summary:
Young SNRs are powerful laboratories
to test our theories.
SN Progenitors
Pre-SN Mass Loss
Type Ia Explosion Models
SN Ejecta Structures and Elemental Abundances
Compact Remnant Kick Velocities and Directions