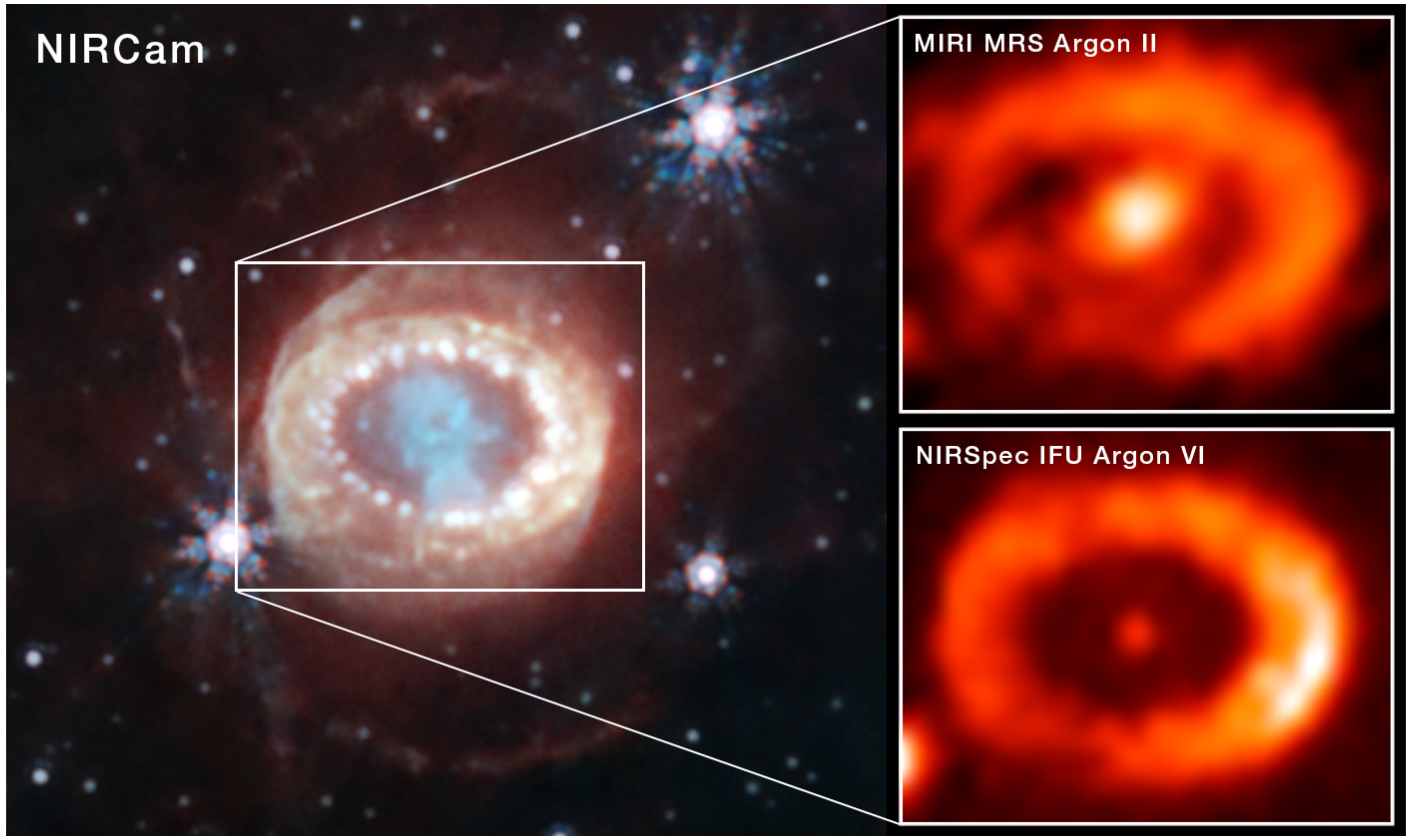
SN 1987A in the JWST era



Josefin Larsson

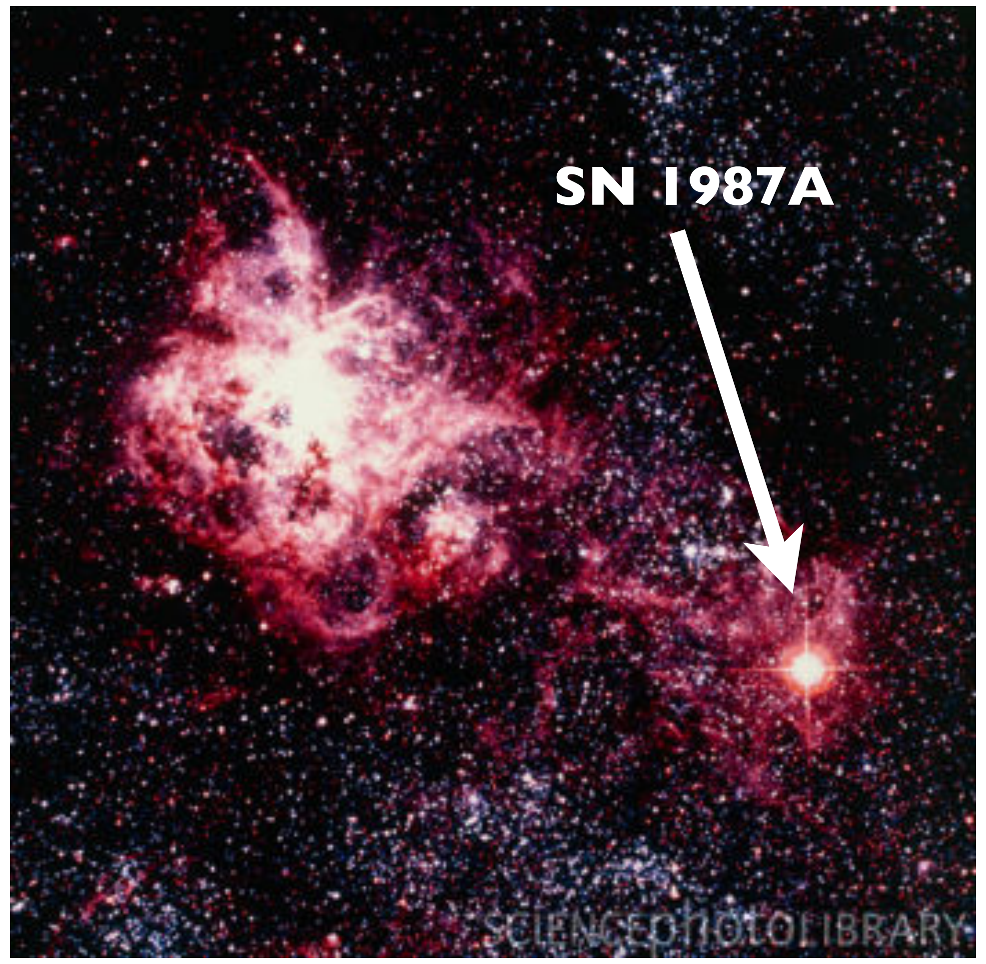
KTH & OKC

& the SN1987A JWST GTO Cycle 1 team: Claes Fransson, Mike Barlow, Olivia Jones, Patrick Kavanagh, Beth Sargent, Tea Temim, Patrice Bouchet, Margaret Meixner, Gillian Wright, et al.

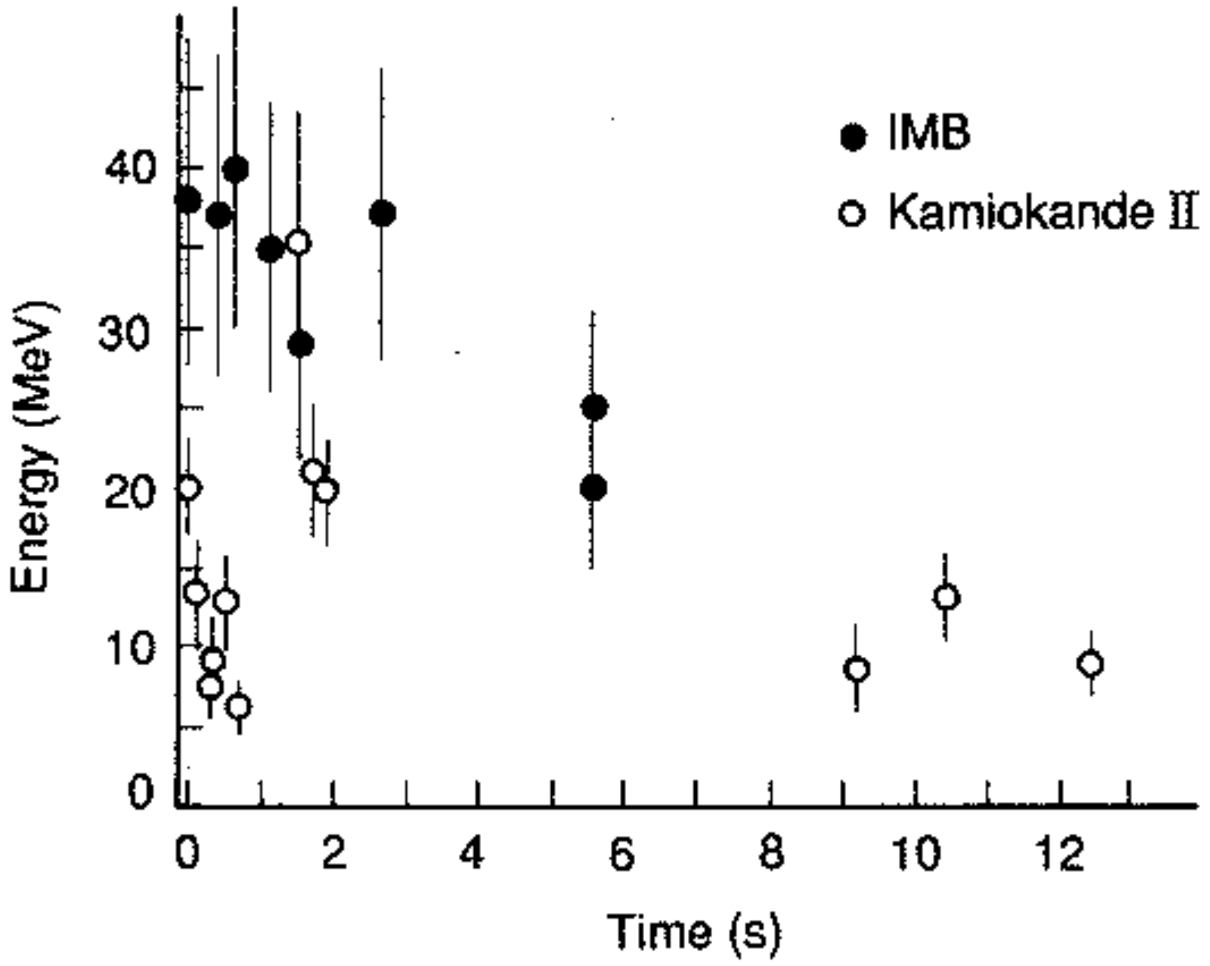
& other 87A collaborators: Christos Tegkelidis, Sophie Rosu, Mikako Matsuura, Jason Spyromilio, Bruno Leibundgut,…

The Supernova of a lifetime

23rd Feb 1987 in the LMC



Neutrinos detected



Progenitor identified in pre-explosion images

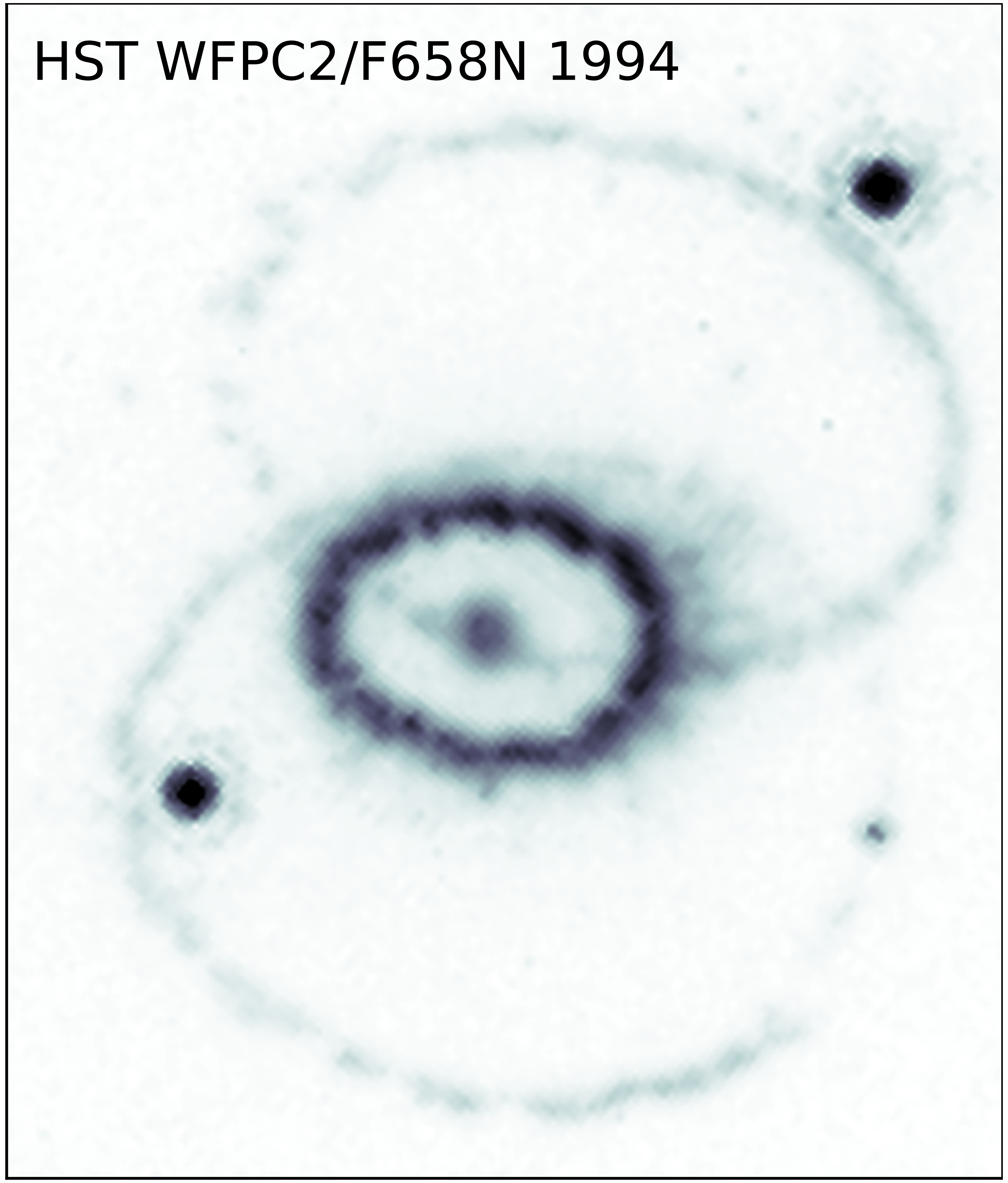
Sanduleak -69 202

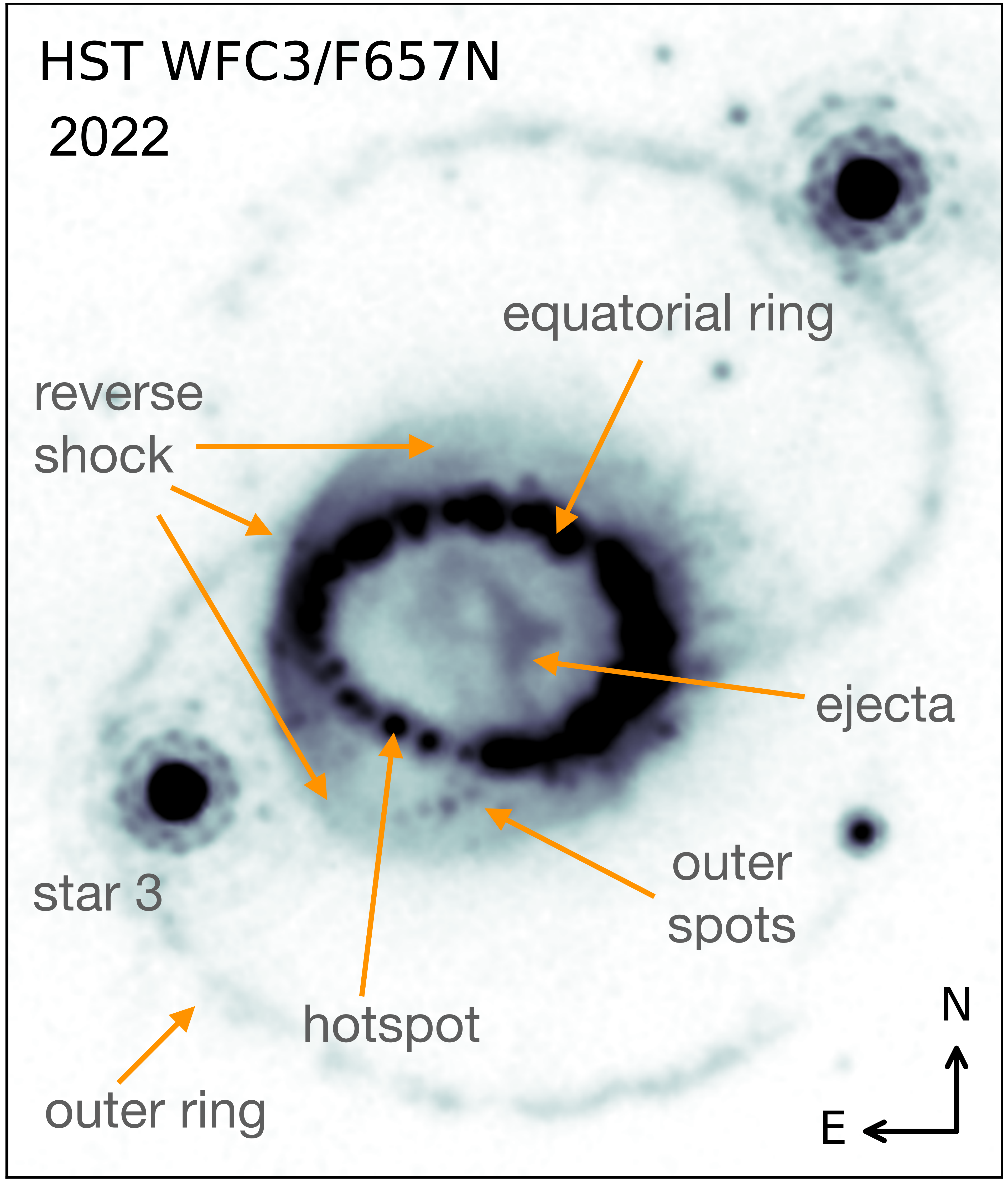
HST revealed triple-ring nebula, ejected 20,000 years before explosion. Binary merger?

Inclination 45 degrees
Radius of inner ring ~ 0.6 ly (0.8")

The evolution from SN to SNR has been monitored regularly at all wavelengths…

Time evolution



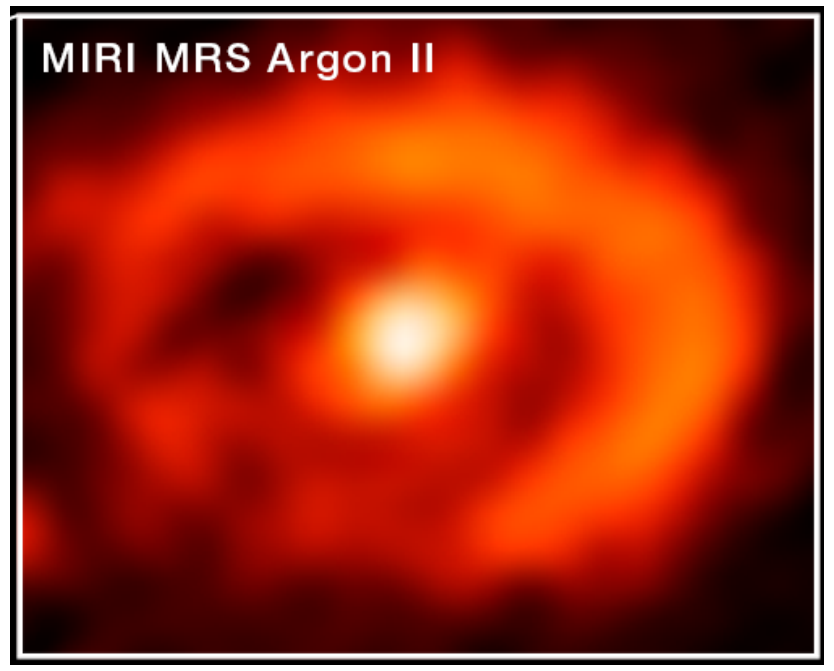


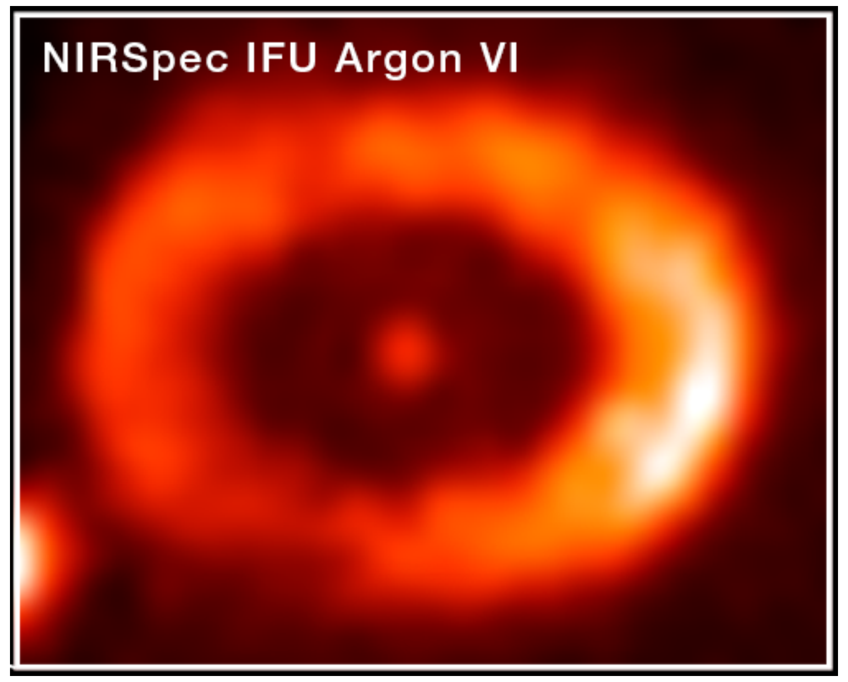
(*Rosu et al. 2024*)

A new window on SN 1987A with JWST

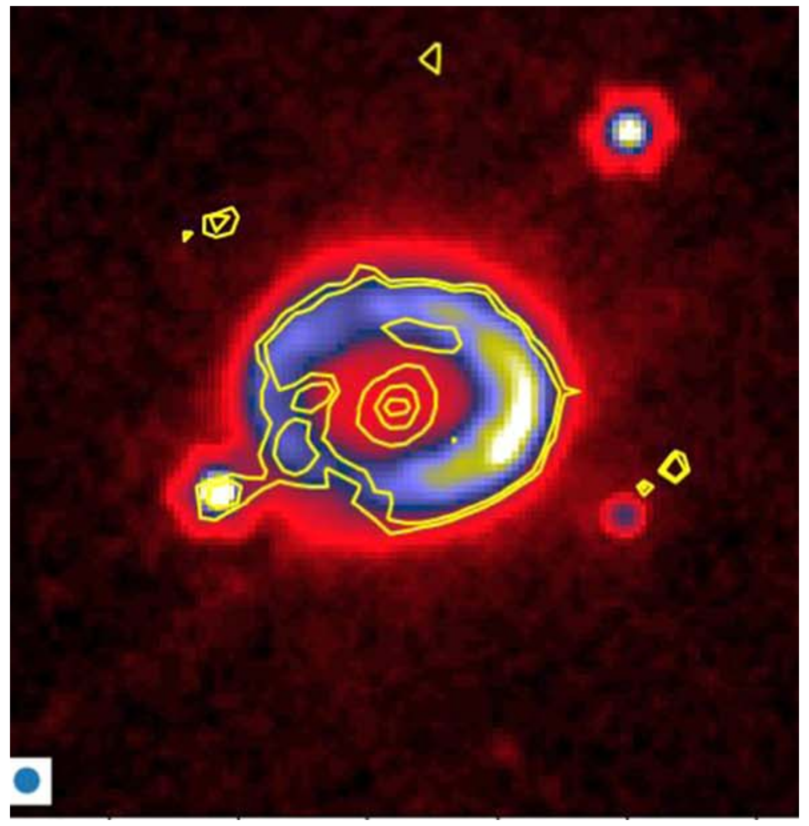
Cycle 1 GTO observations

✧ Compact object
(Fransson *et al.* 2024)

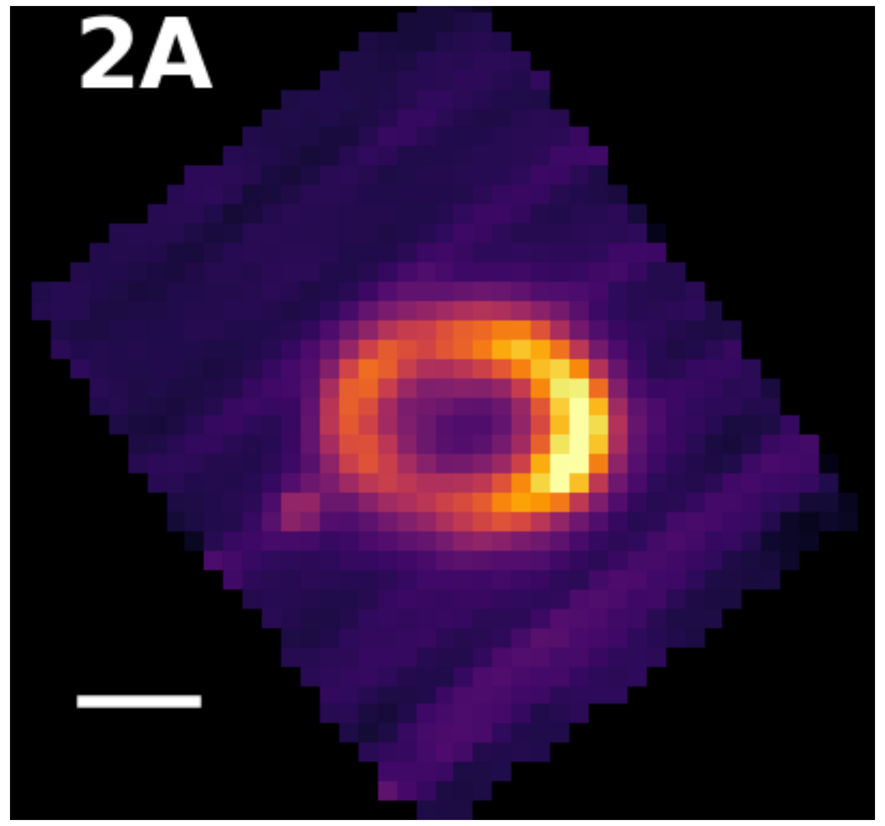




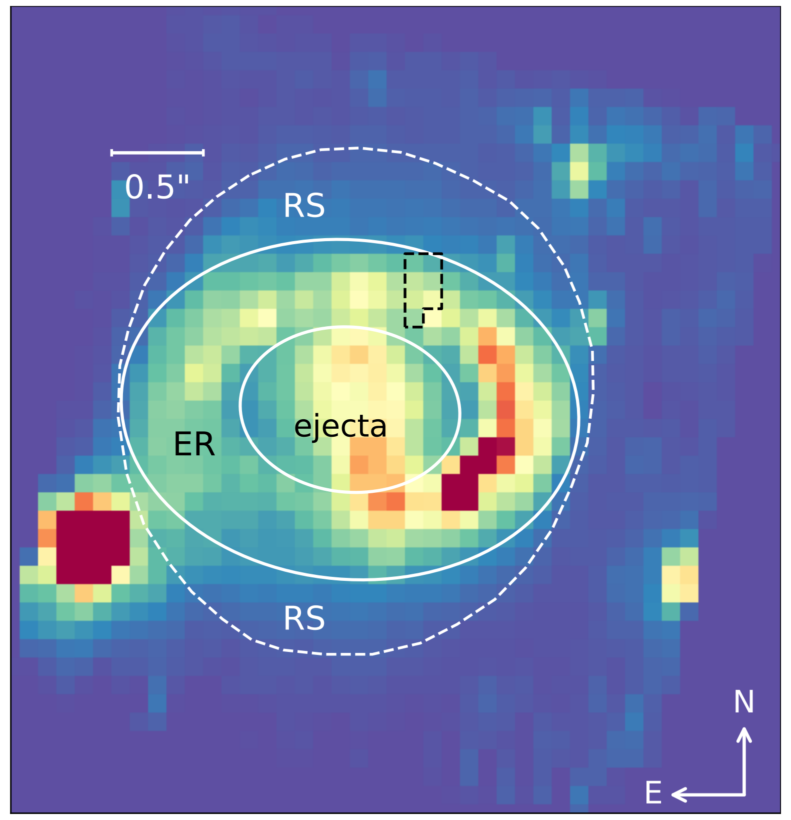
✧ MIRI Imager
(*Bouchet et al., 2024*)



✧ MIRI MRS
(*Jones et al., 2023*)



✧ NIRSpec IFU
(*Larsson et al. 2023*)



Cycle 1 GO observations

✧ NIRCam (*Arendt et al., 2023, Matsuura et al. 2024*)

See talk by Mikako!

Cycle 2 GTO observations with MRS and GO observations with NIRSpec

Work in progress…

OUTER EJECTA & CSM INTERACTION

THE ASYMMETRIC INNER EJECTA

THE INNERMOST EJECTA &
COMPACT OBJECT

OUTER EJECTA & CSM INTERACTION

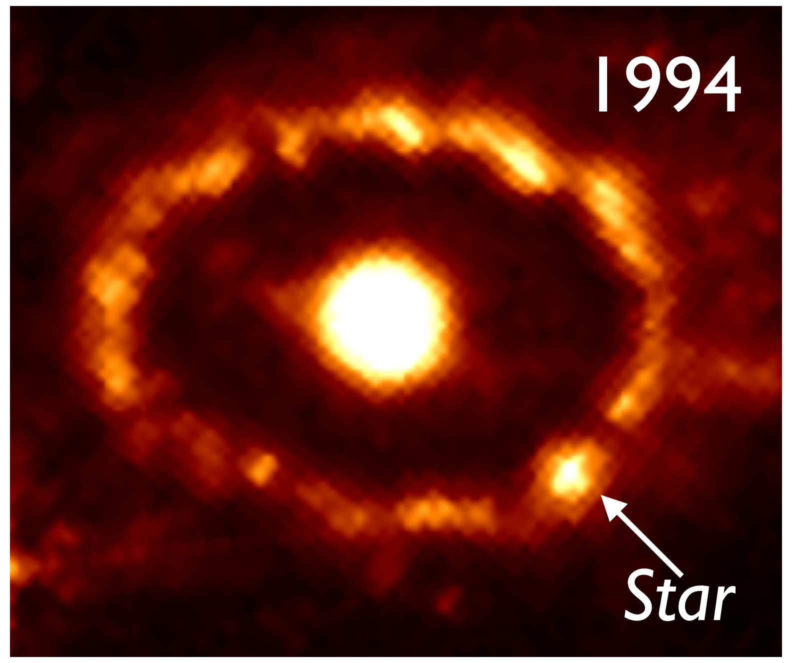
The rise and fall of the ring

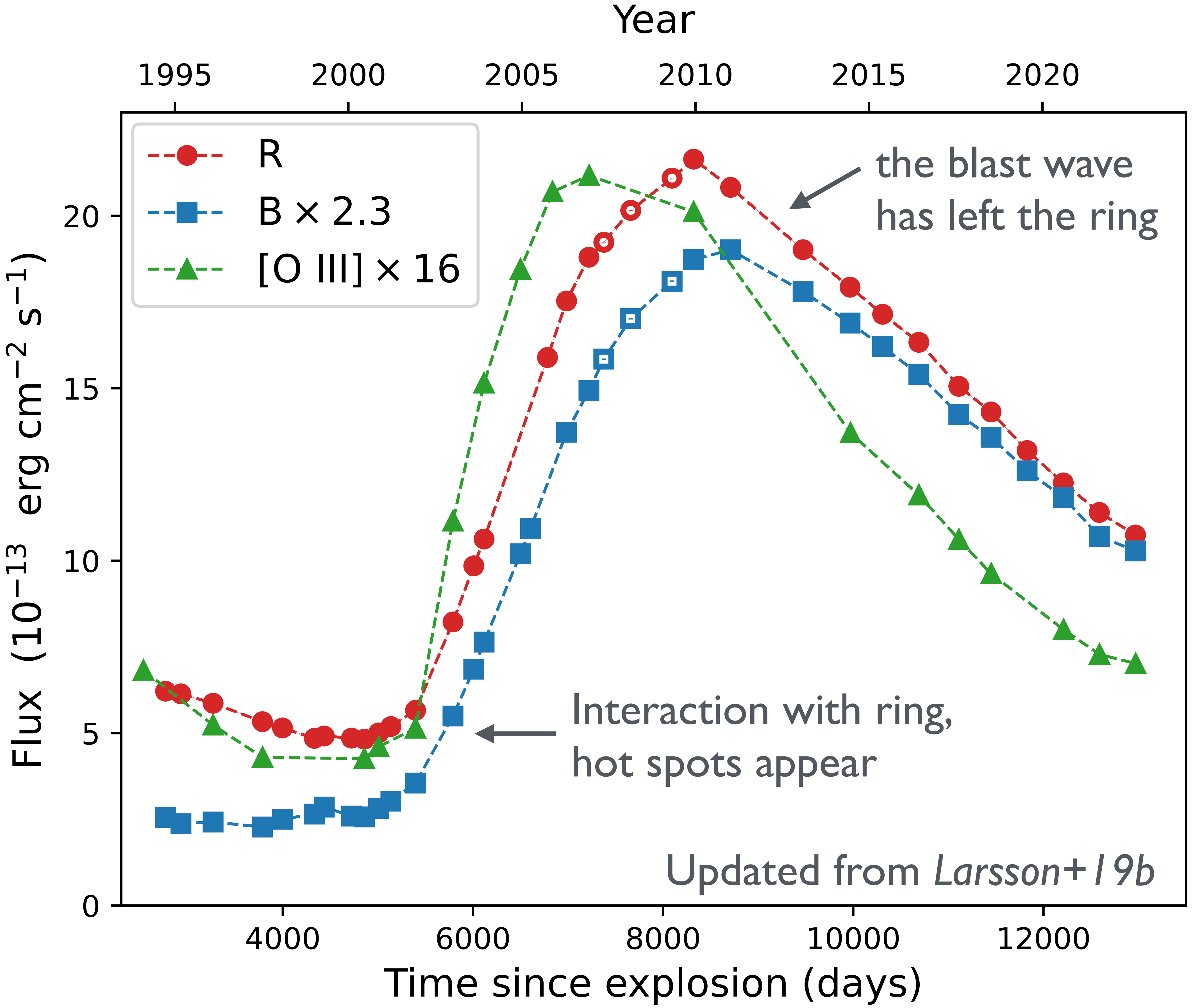
1987

flash-ionisation of the rings

1990

Interaction with H II region inside ring (radio and X-rays)

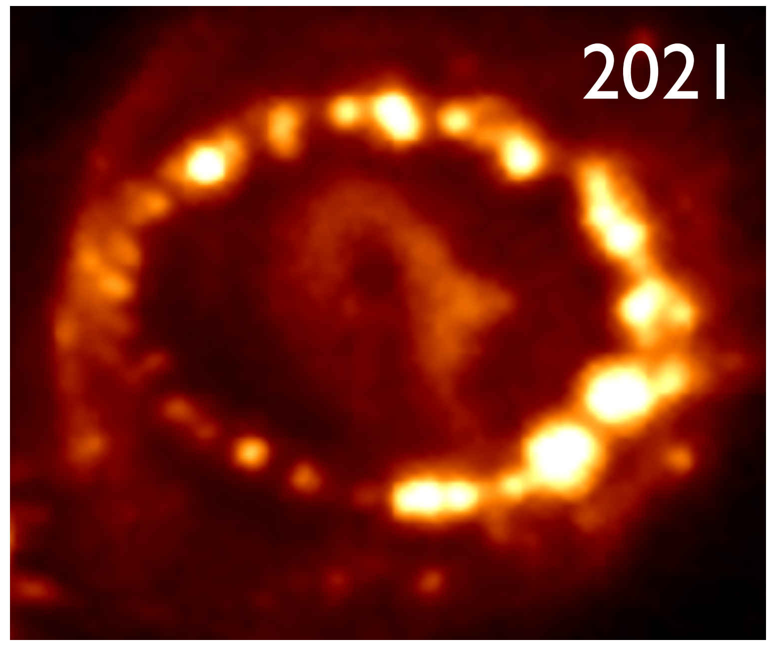


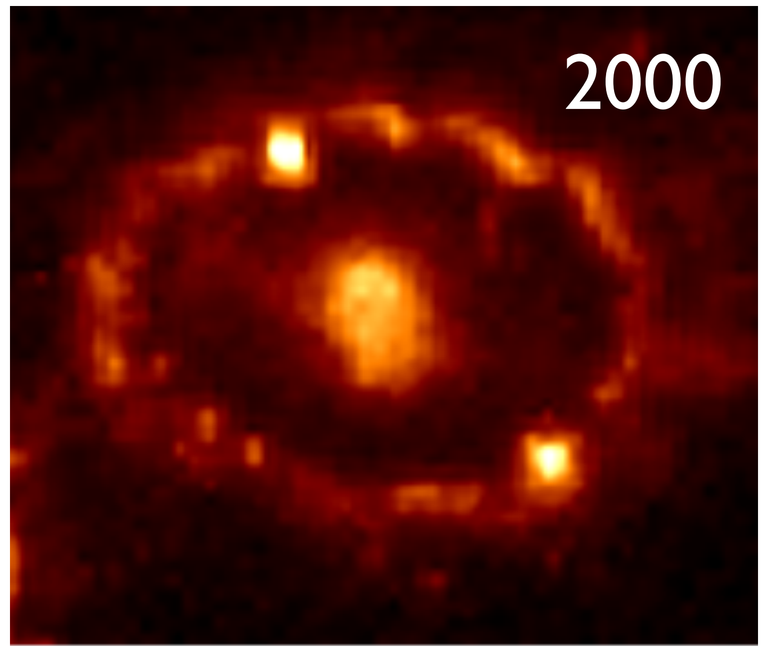


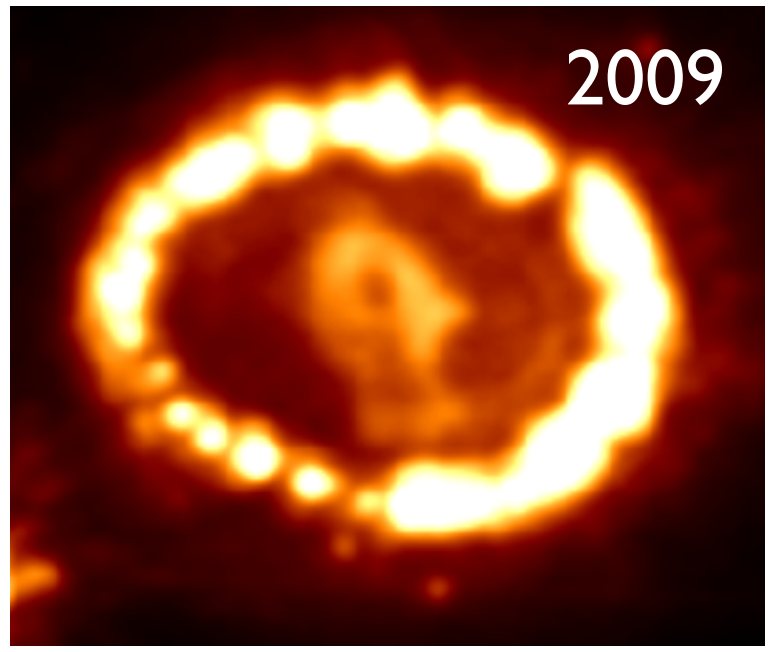
the blast wave has left the ring

Interaction with ring, hot spots appear

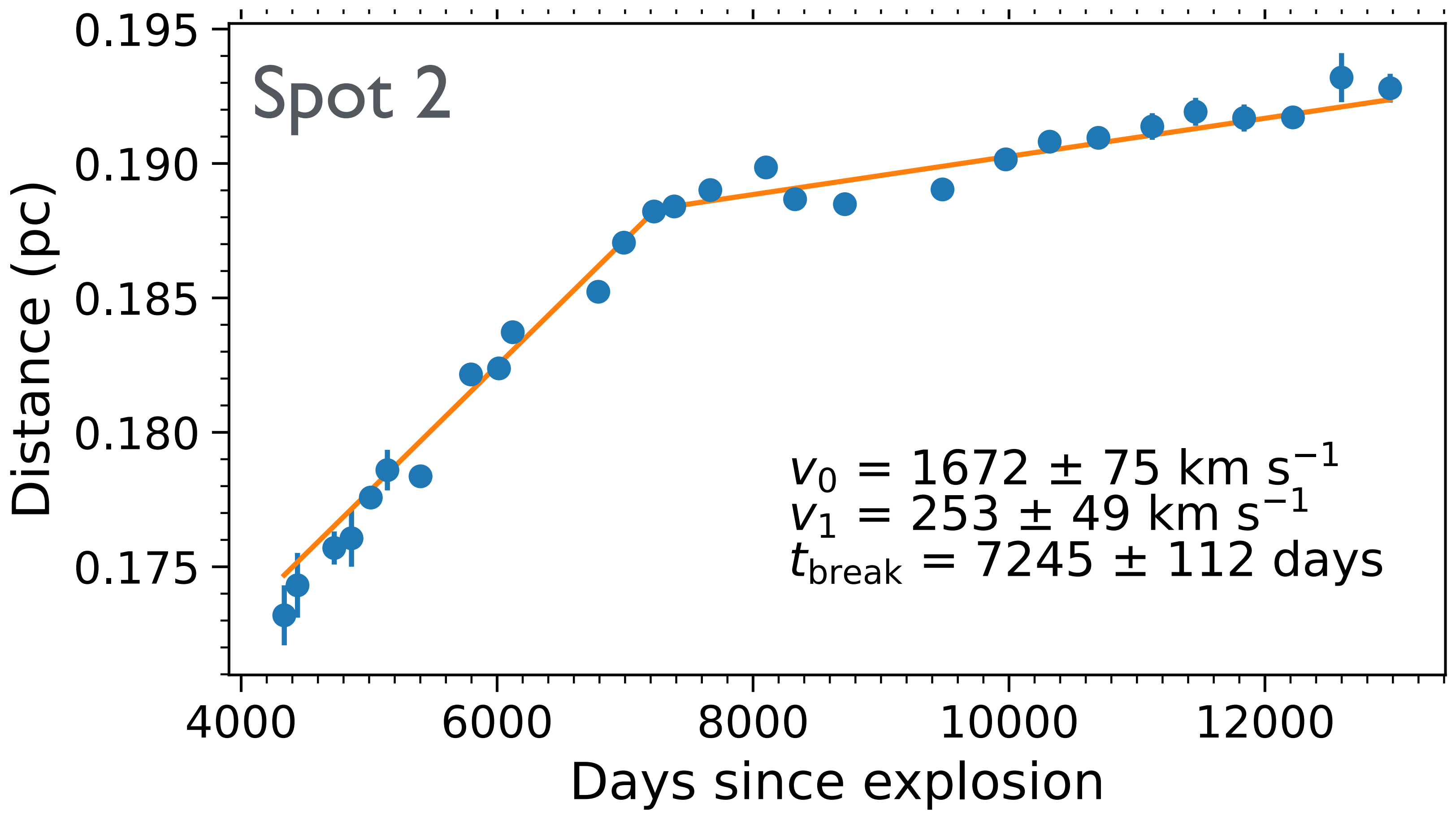
Updated from *Larsson+19b*

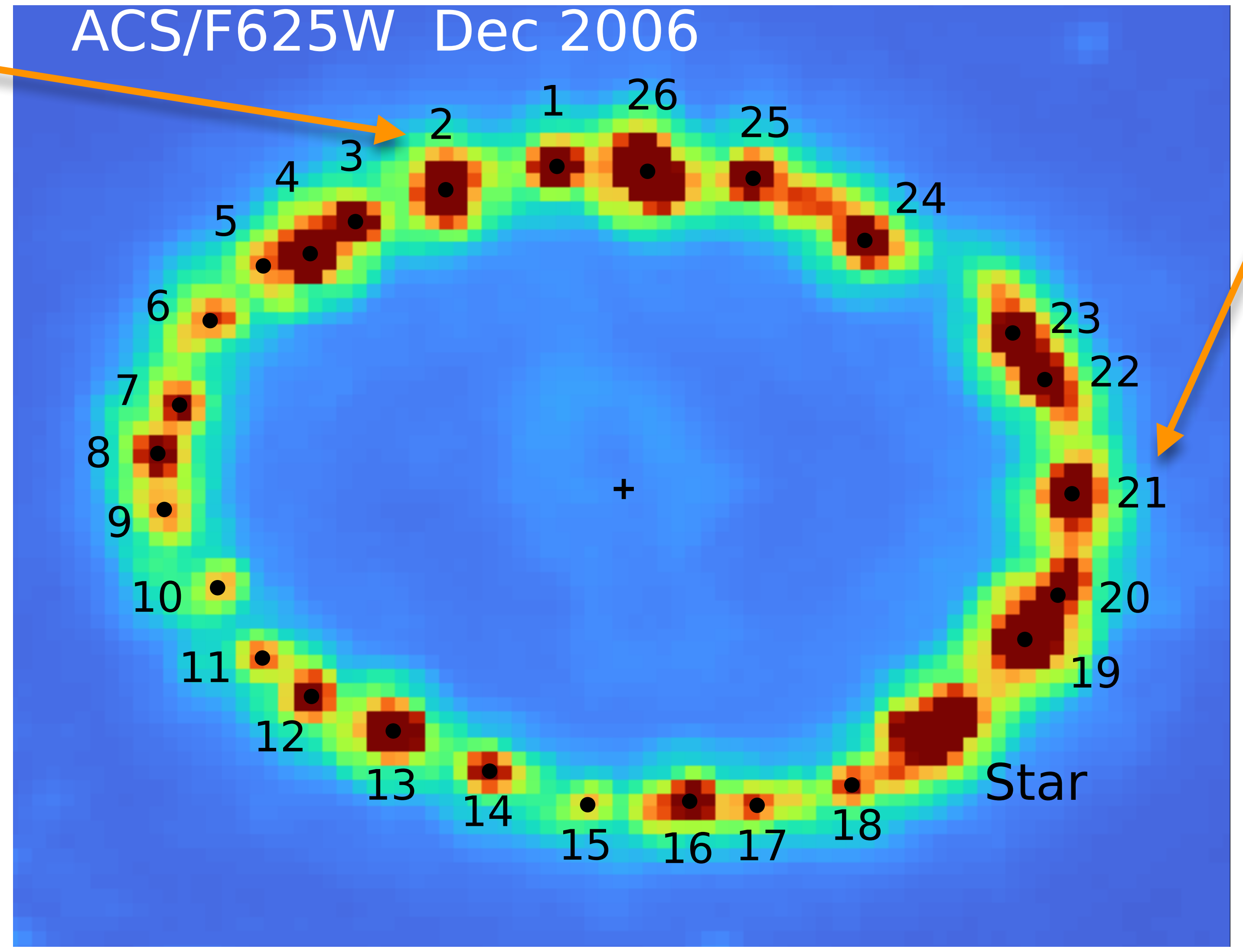


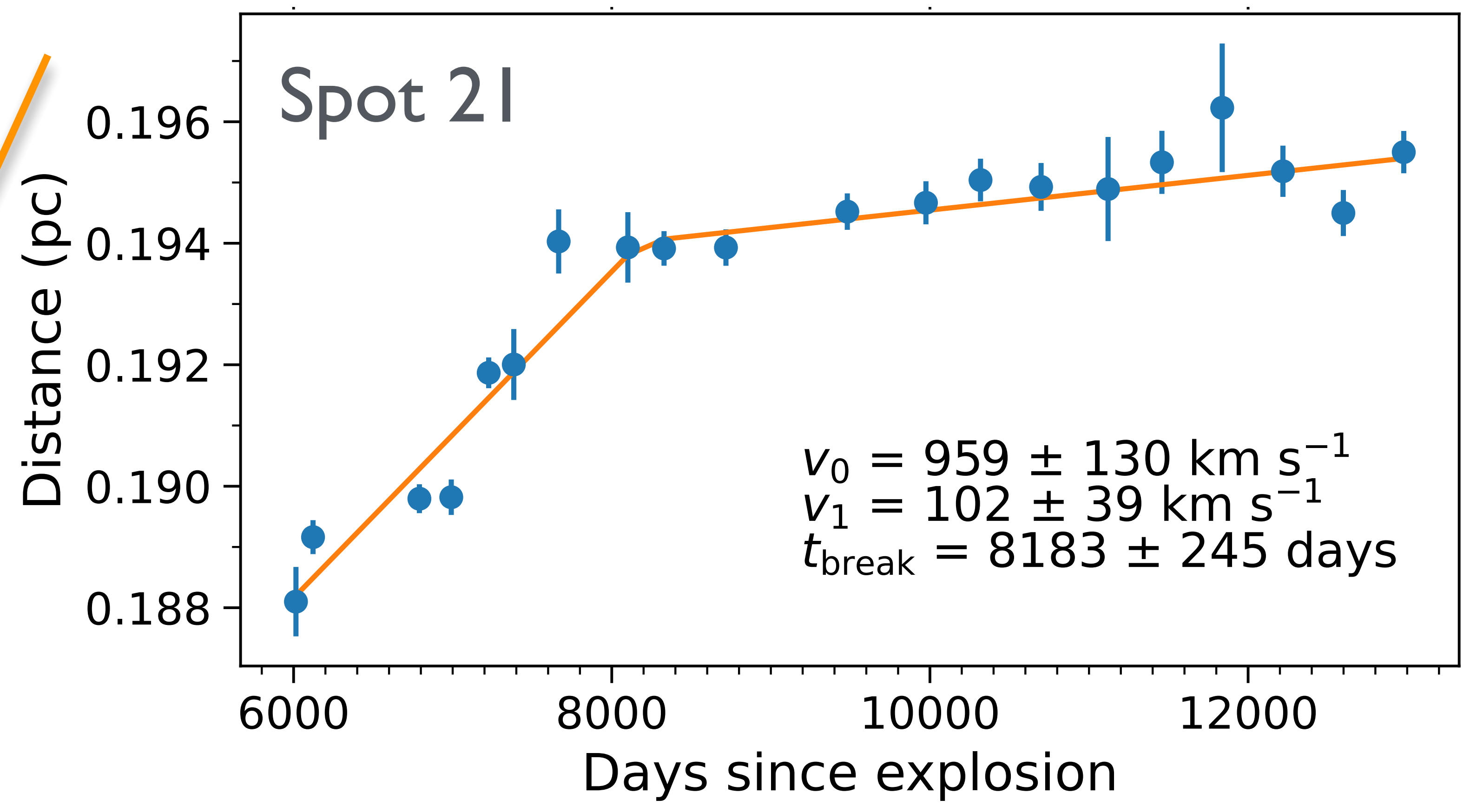




Tracking the hotspots over decades







Likely explanation: each hotspot comprises dense substructures embedded in less dense gas.

Most hotspots show:

-high initial velocities (median 960 km s^{-1}) ← phase velocities

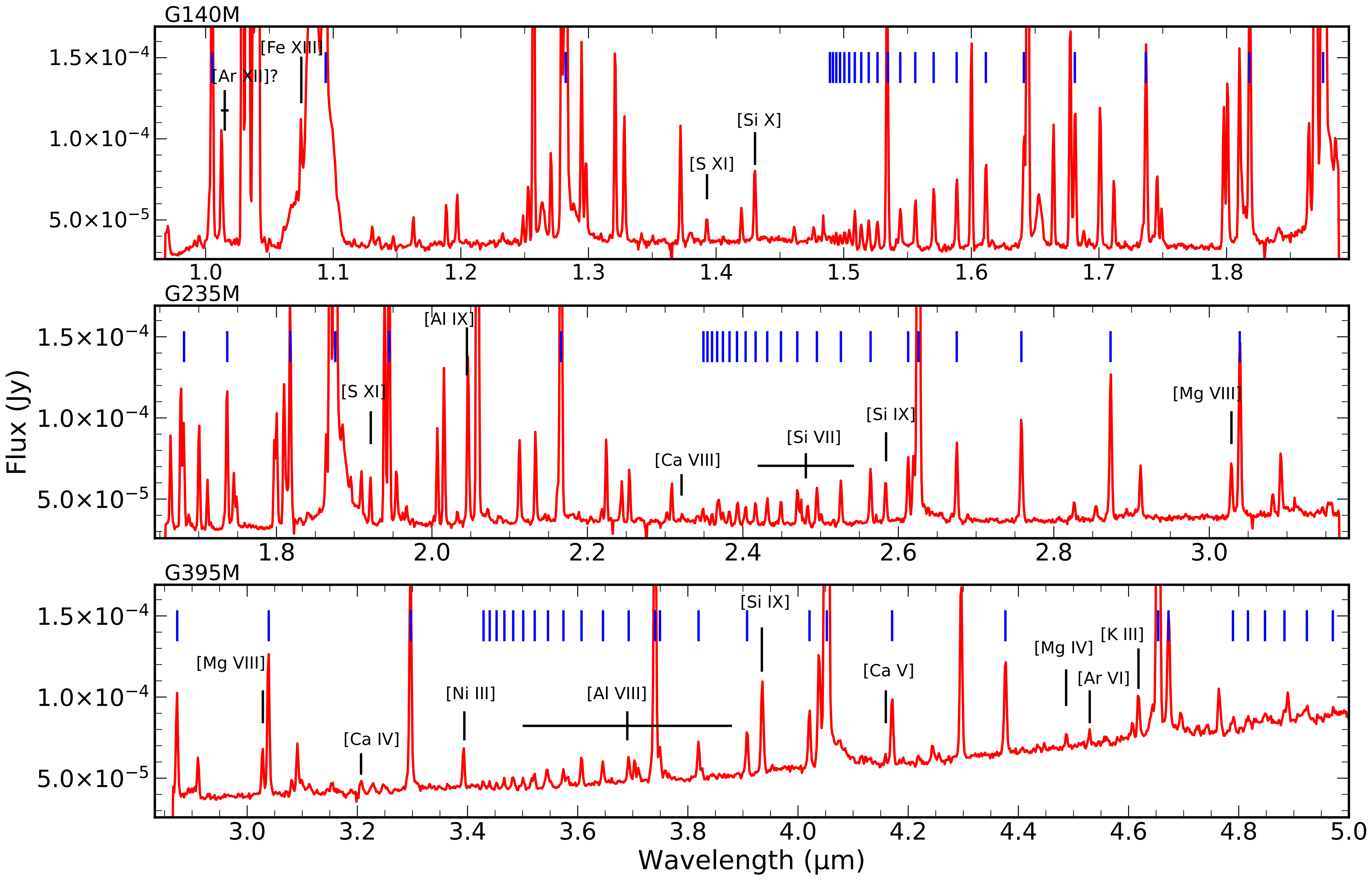
-breaks around 8000 days (similar to the light curve peak) ← blast wave leaves the ring

-lower final velocities, median 260 km s^{-1} ← velocities of the dense, optically emitting clumps.

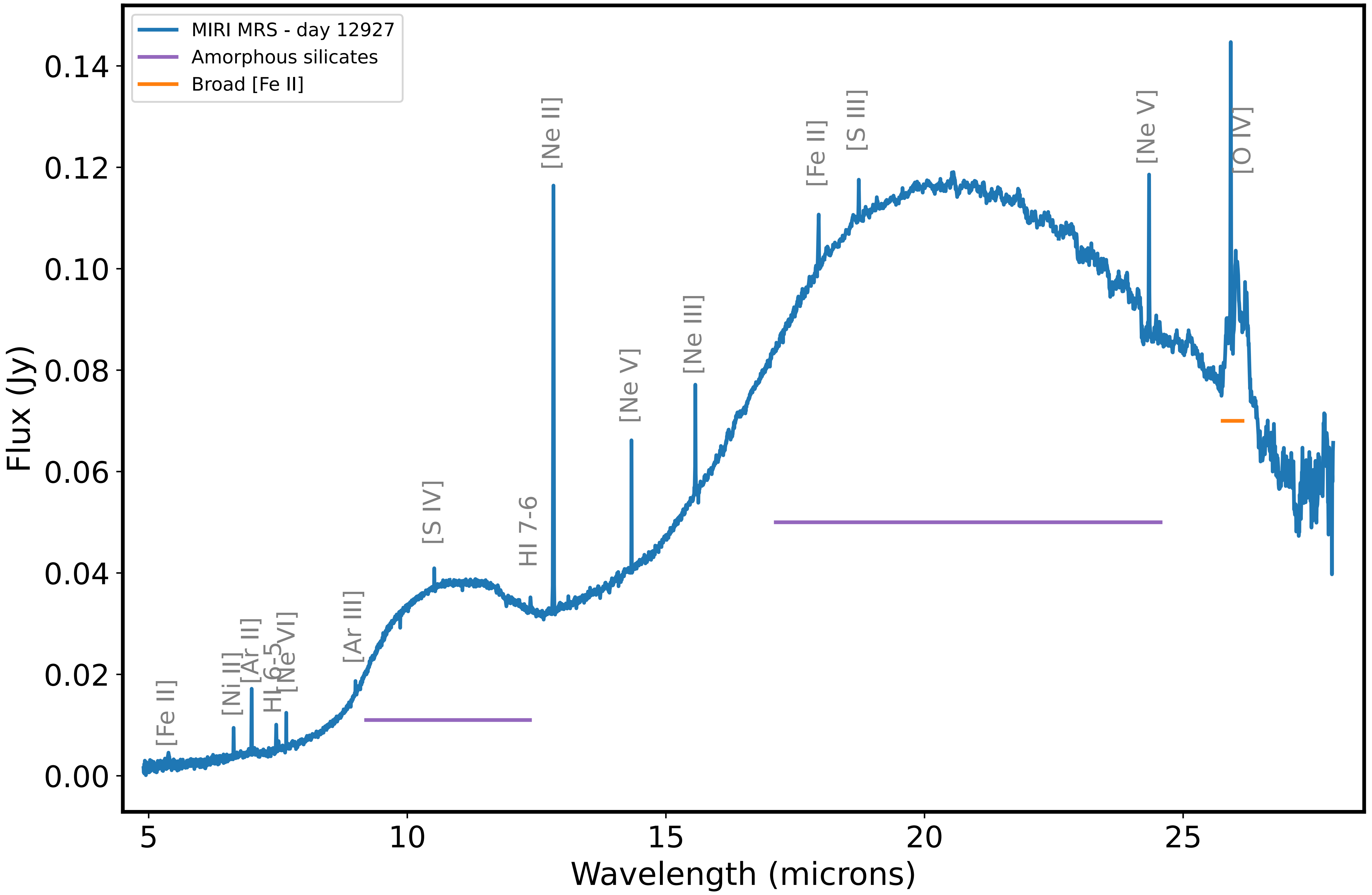
Tegkelidis et al, submitted

The ring with JWST NIRSpec + MIRI MRS

Shocked gas + dust in the ring



(*Larsson+23*)



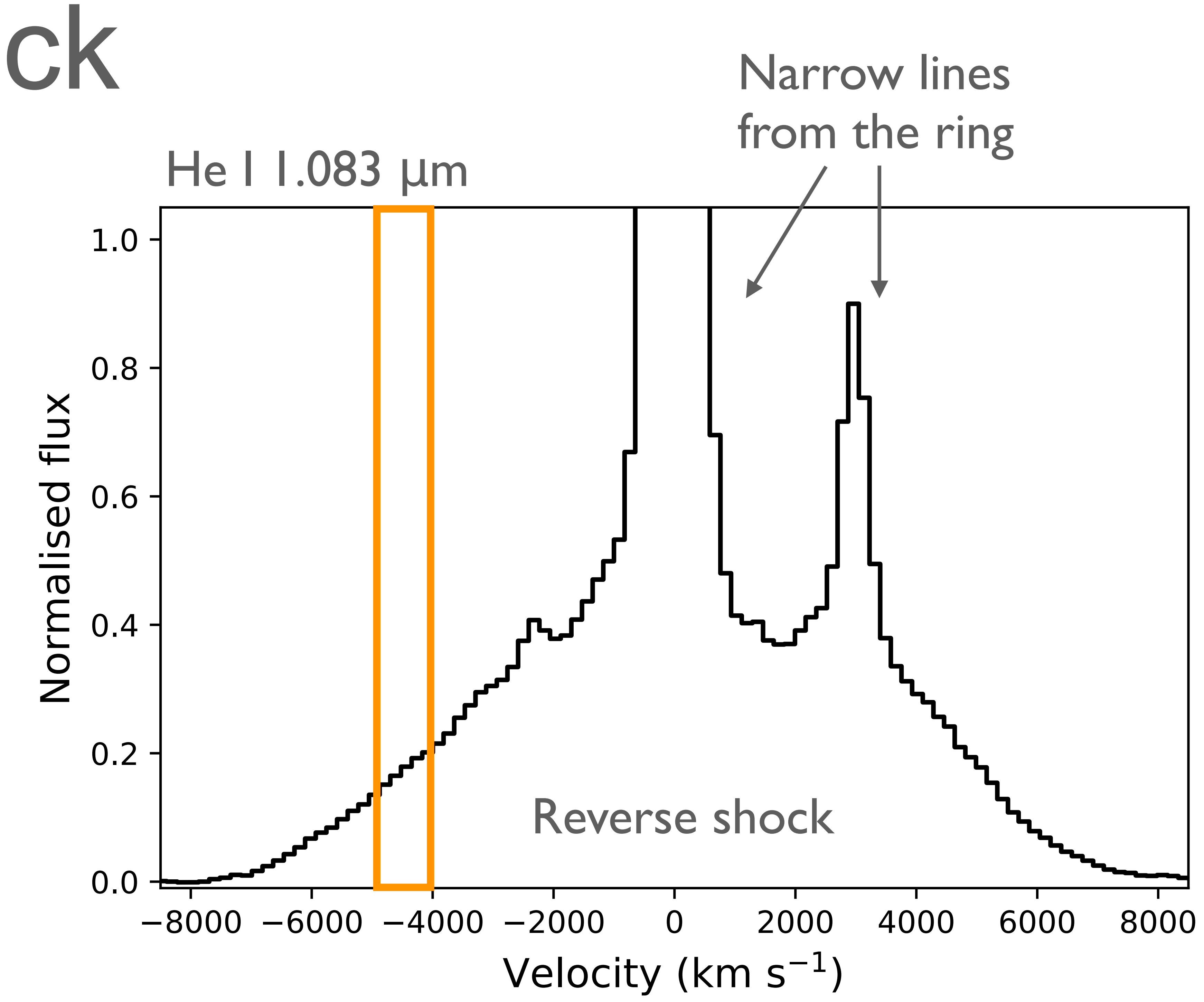
(*Jones+23*)

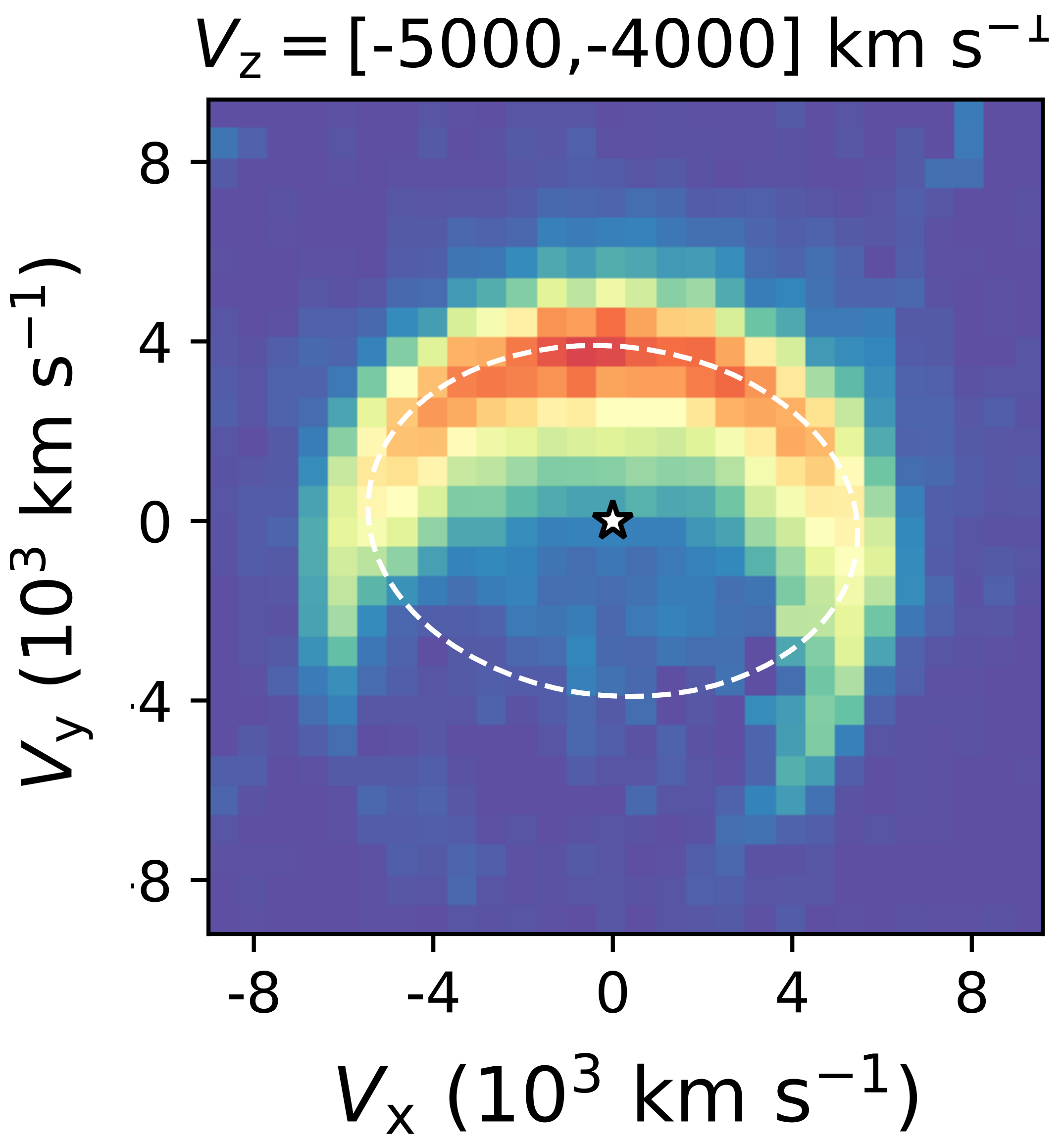
The reverse shock

Emission from fast ejecta excited by the reverse shock — strong H and He lines with very broad profiles

Reconstruct 3D emissivity using NIRSpec IFU data, assuming freely expanding ejecta

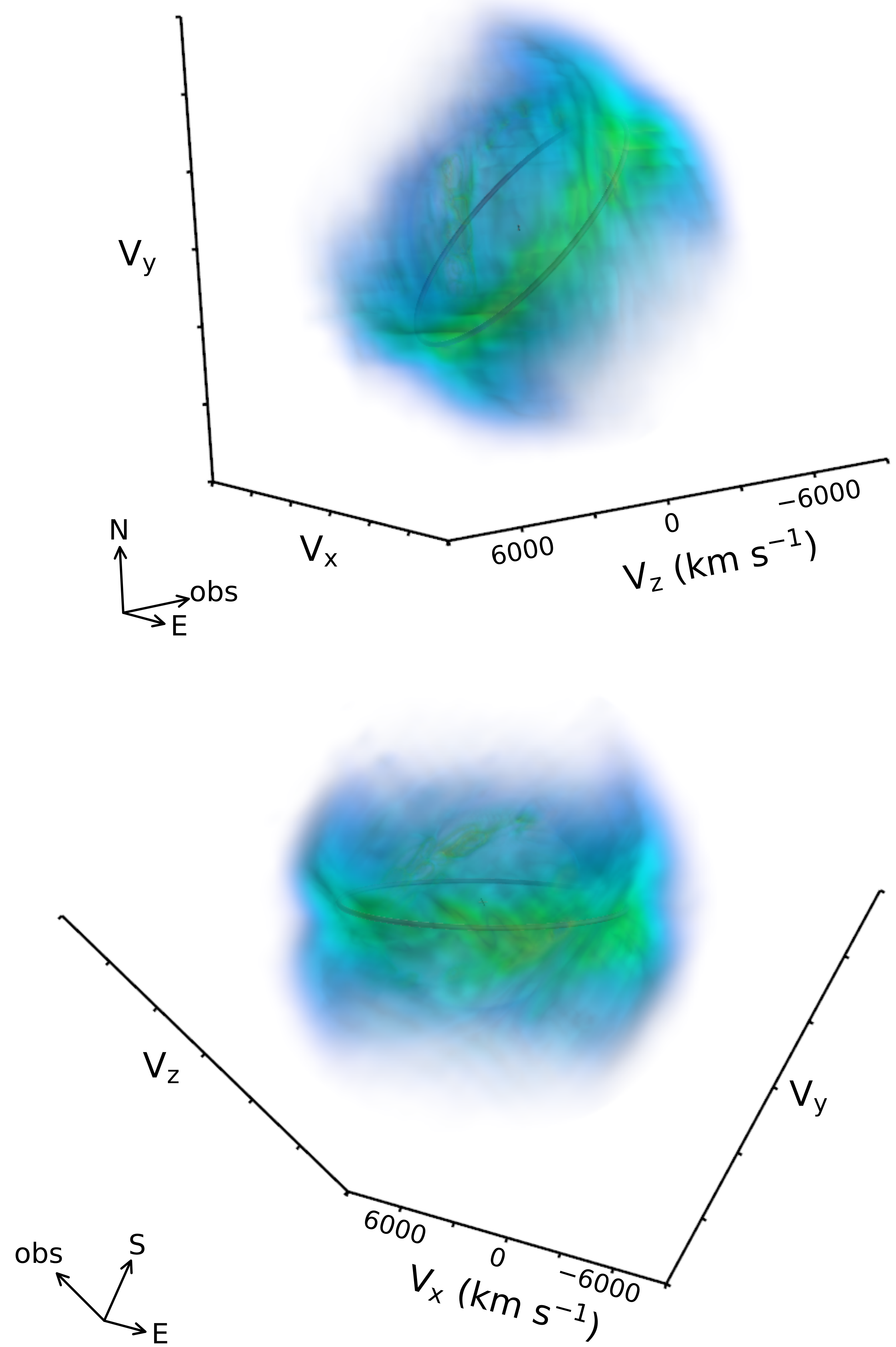
- Distance from centre = velocity × time since explosion
- Images give 2D, Doppler shifts give third dimension
- For reference, velocity of ejecta reaching the ring in July 2022 is ~5400 km s^{-1}

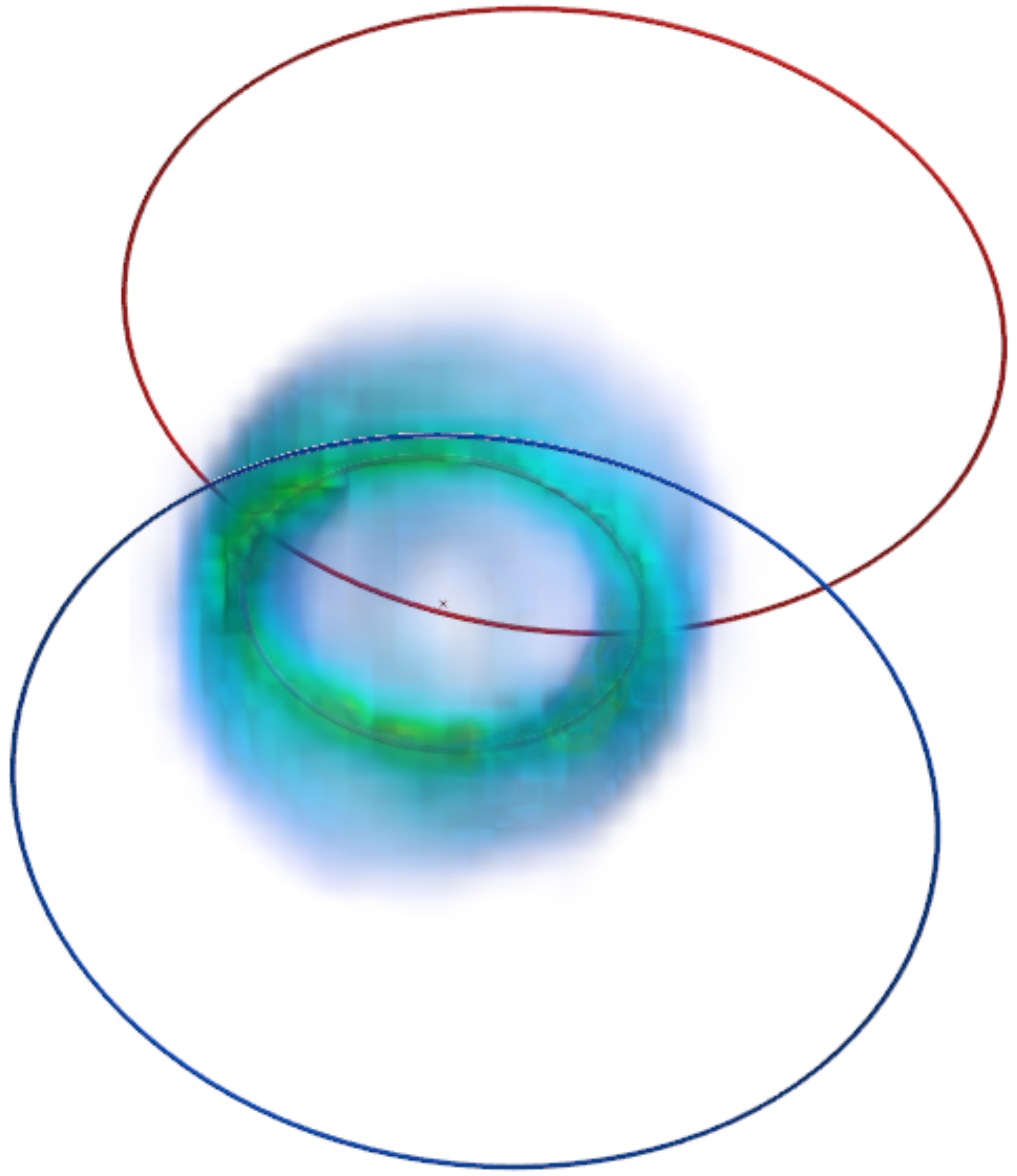




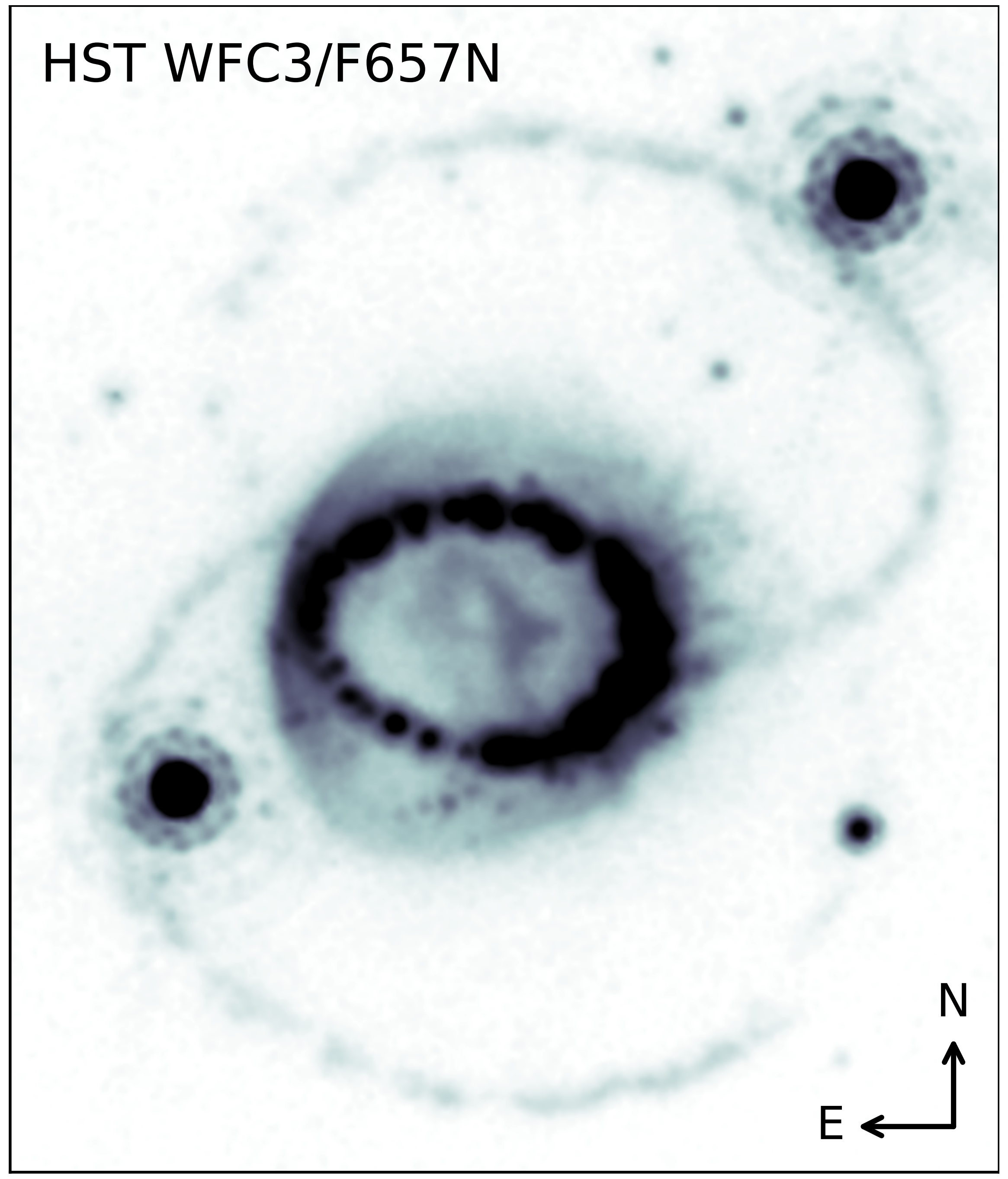
The reverse shock in 3D

NIRSpec He I 1.083 μm





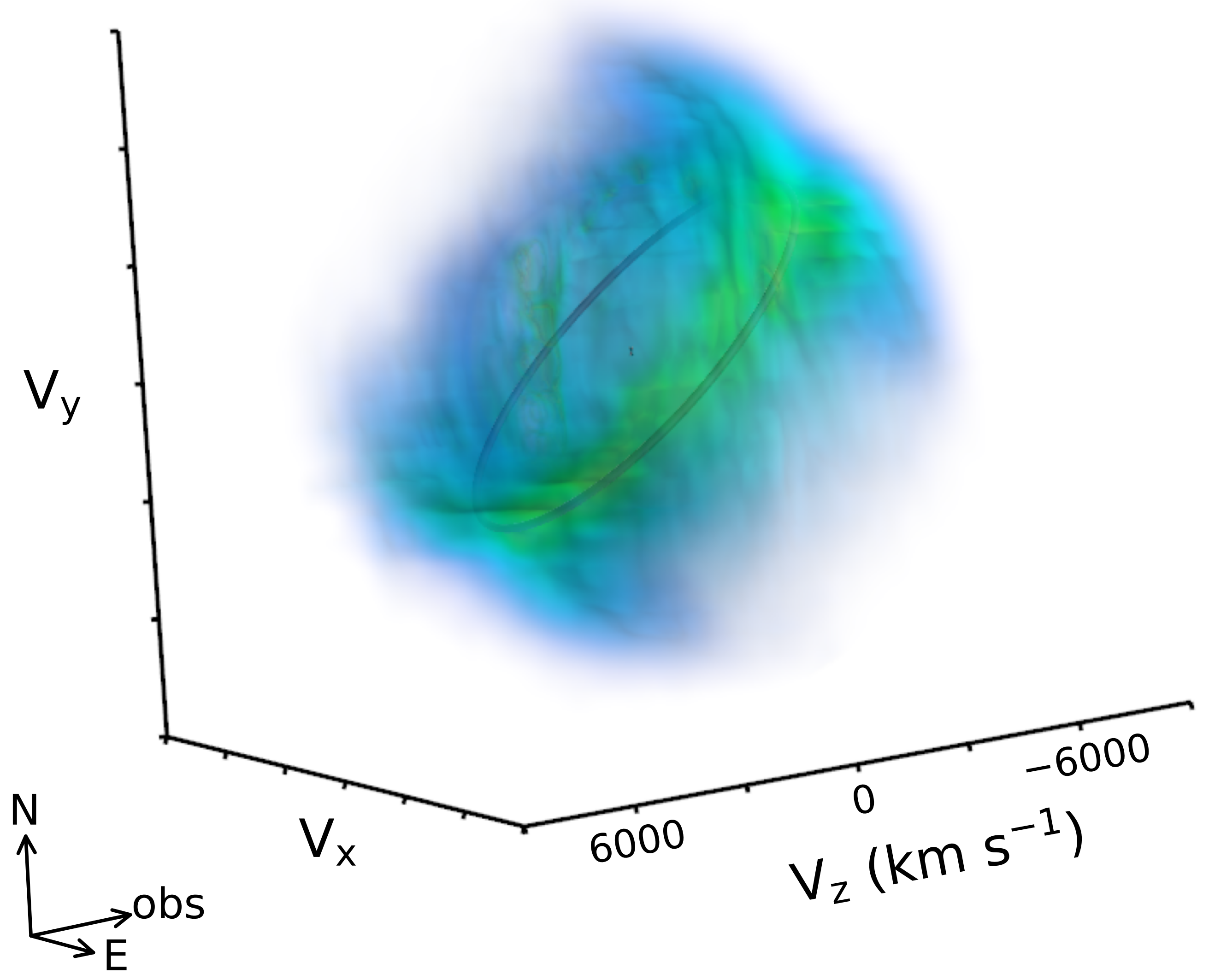
Sky projection of He I



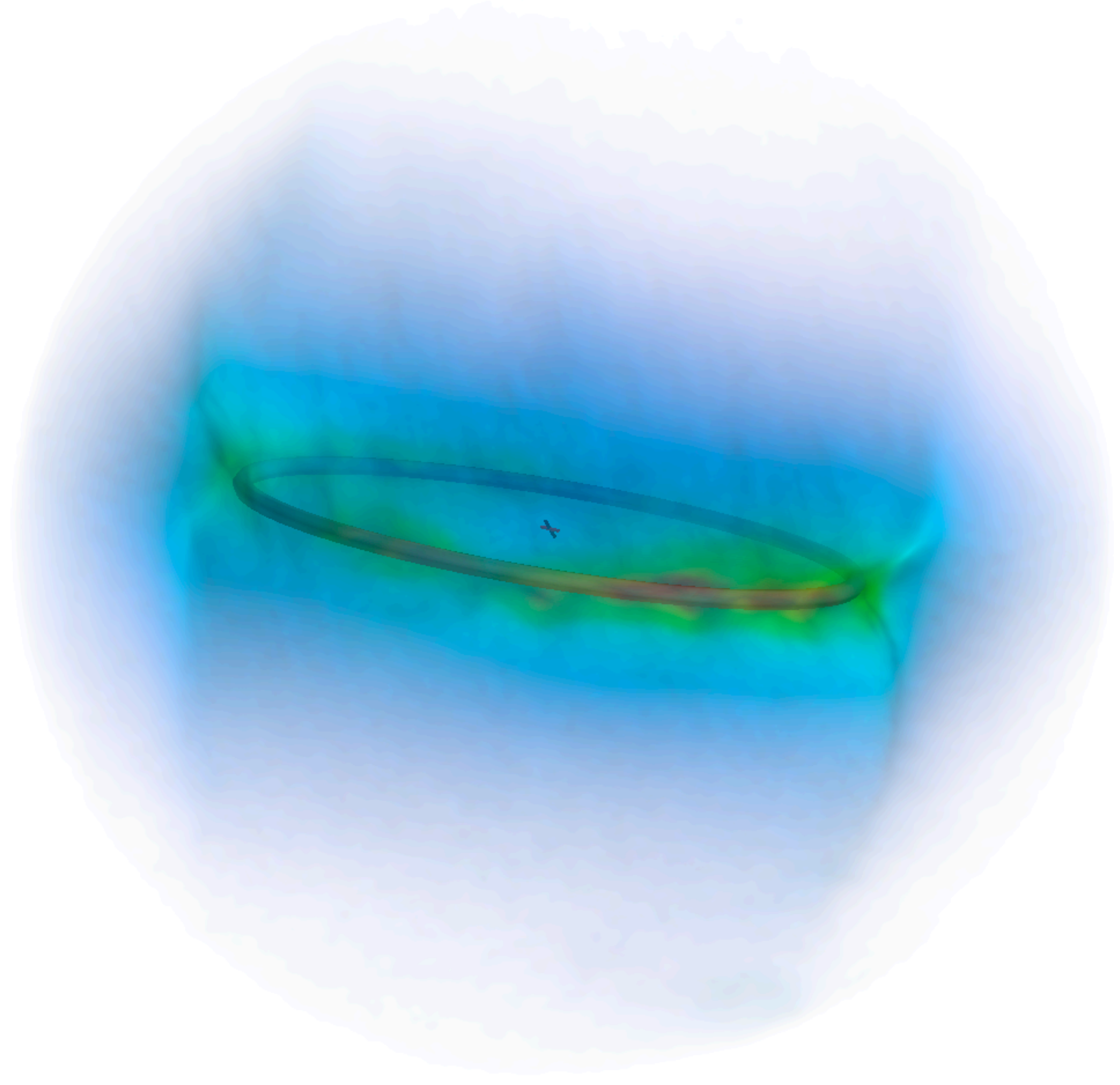
Note similarity with the diffuse emission in Hα!

The reverse shock in 3D

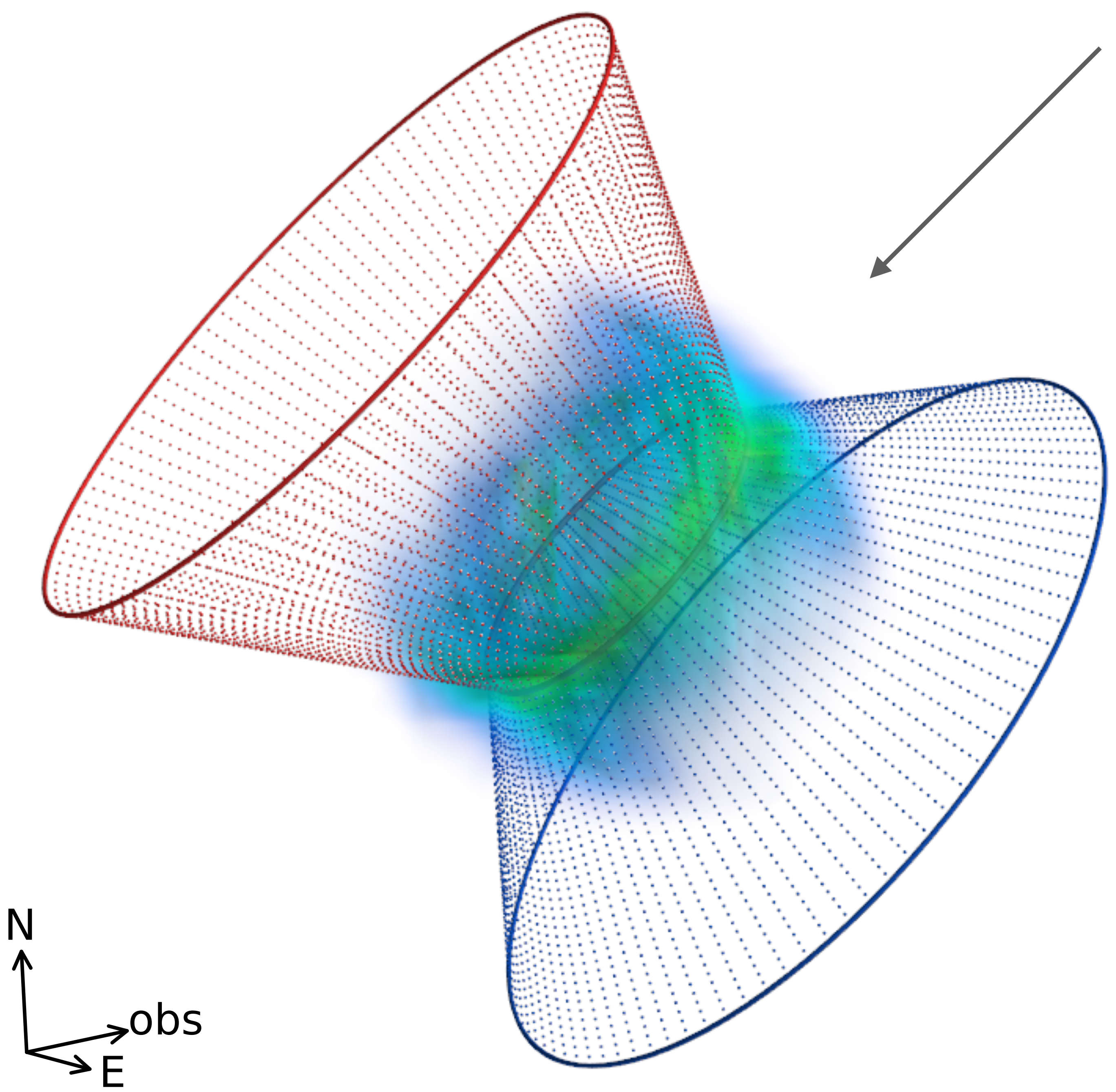
NIRSpec He I 1.083 μm



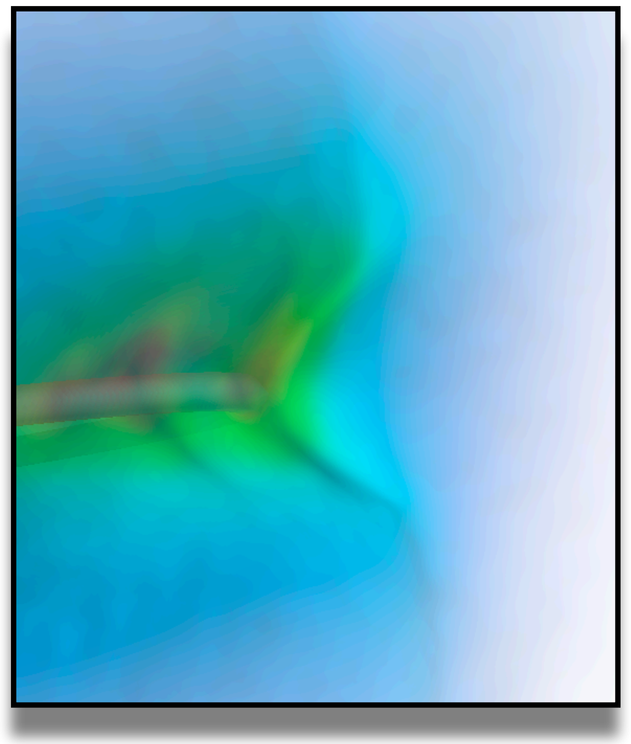
MUSE H? (preliminary)



MUSE observations reveal the same overall structure in H?.



The bubble is inside the outer rings.



Overall structure is a bubble pinched at the "waist" by the dense ring.

Traces CSM between the rings at high latitudes.

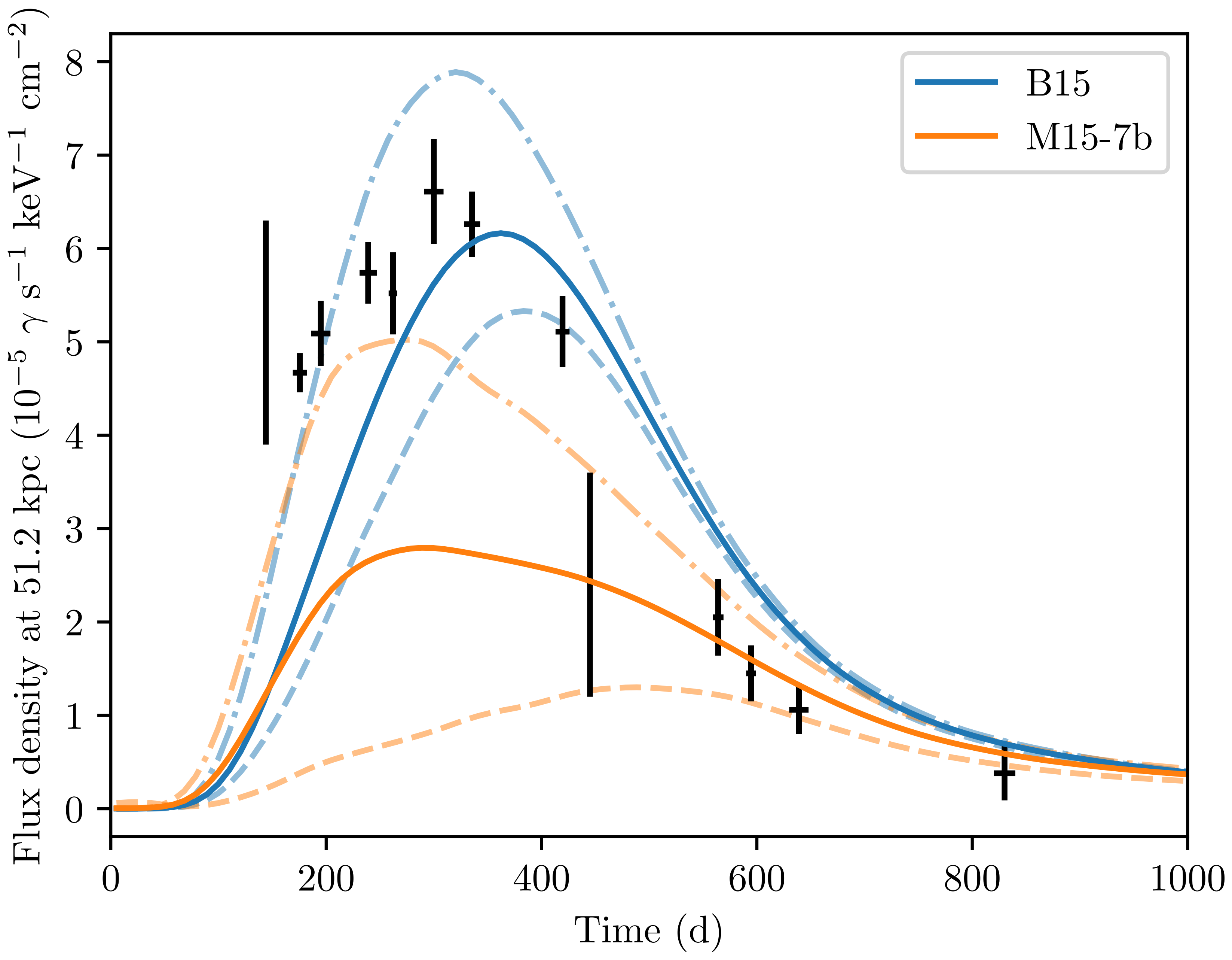
THE ASYMMETRIC INNER EJECTA

The asymmetric inner ejecta

Early evidence of asymmetries from wide range of observations

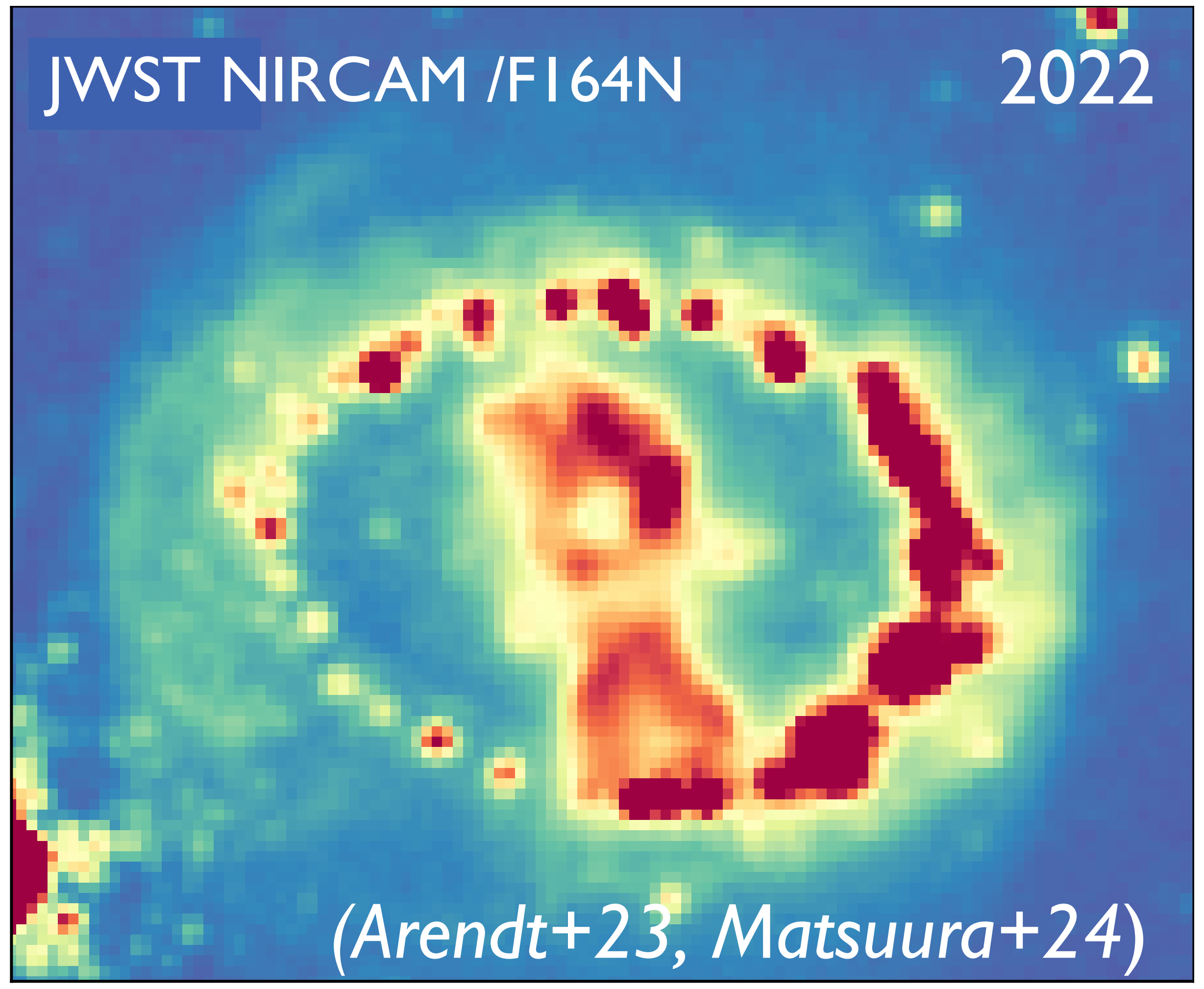
polarimetry, line profiles, "Bochum event", light echoes, early emergence of hard X-rays/gamma rays etc *(e.g., Schwarz+87, Hanuschik+90, Sinnott+13, Alp+19, Jerkstrand+20)*.

➜ large-scale asymmetry & mixing of ejecta, including radioactive Ni mixed to high velocities

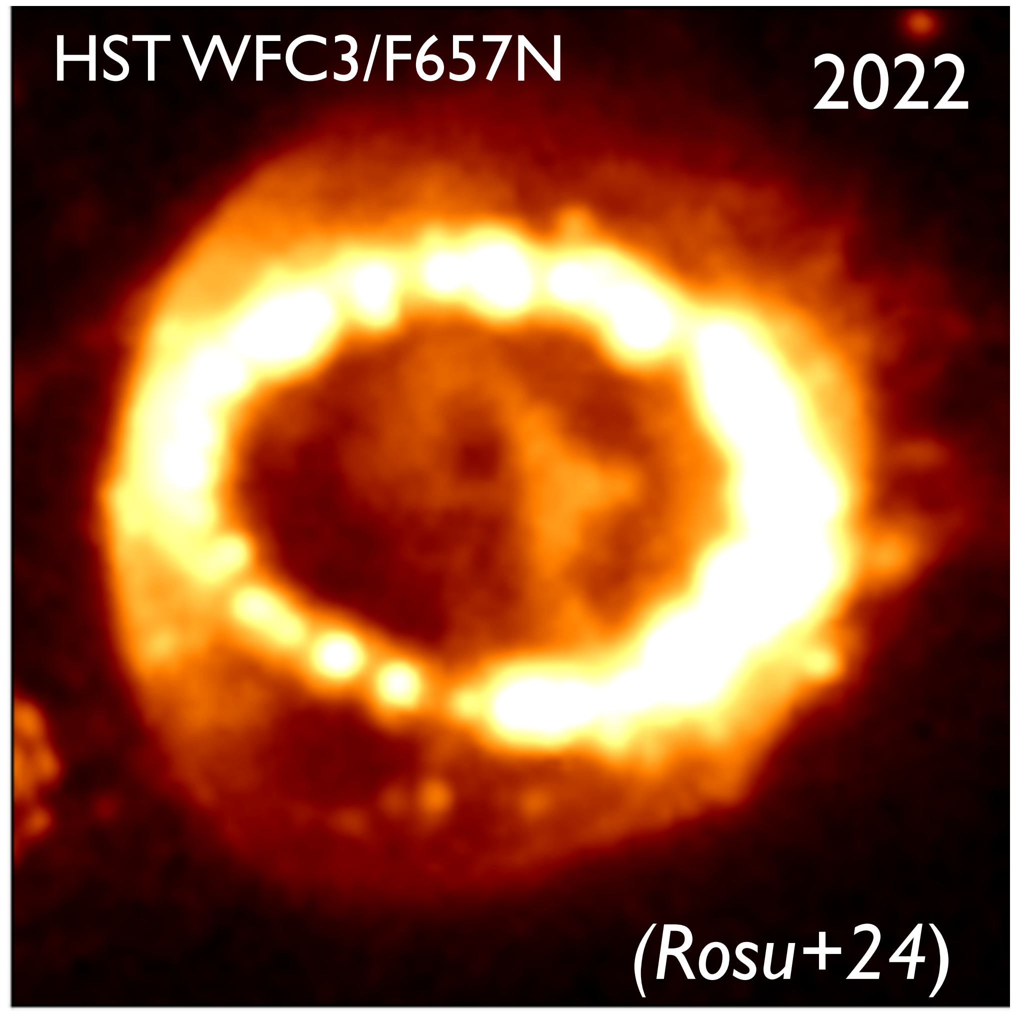


Light curve of hard X-ray continuum compared to 3D simulations of neutrino-driven explosions (Alp+19).

A spatially resolved view of the ejecta



(Arendt+23, Matsuura+24)



(Rosu+24)

All images of atomic lines show a similar elongated ejecta morphology, position angle ~15° east of north.

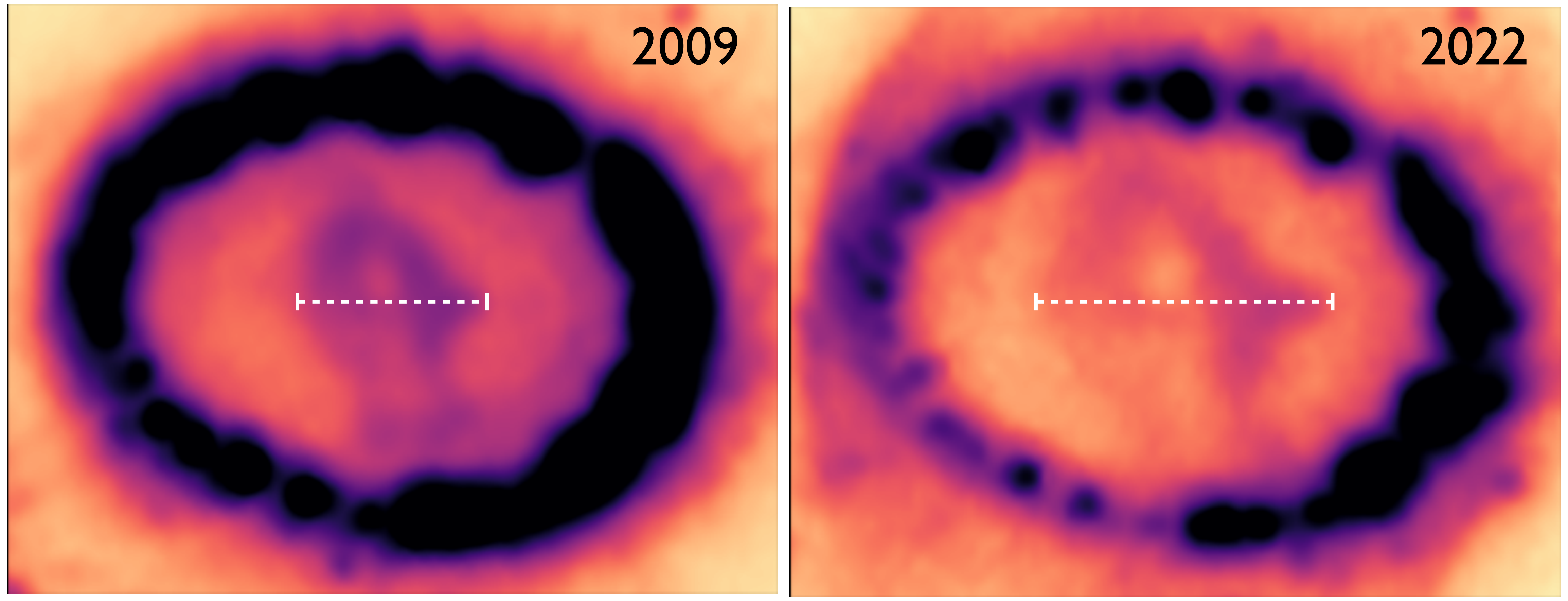
Energy sources and dust in the ejecta

1. Radioactive decay of ^{44}Ti

- Slow decay, dominates for Fe and Si lines

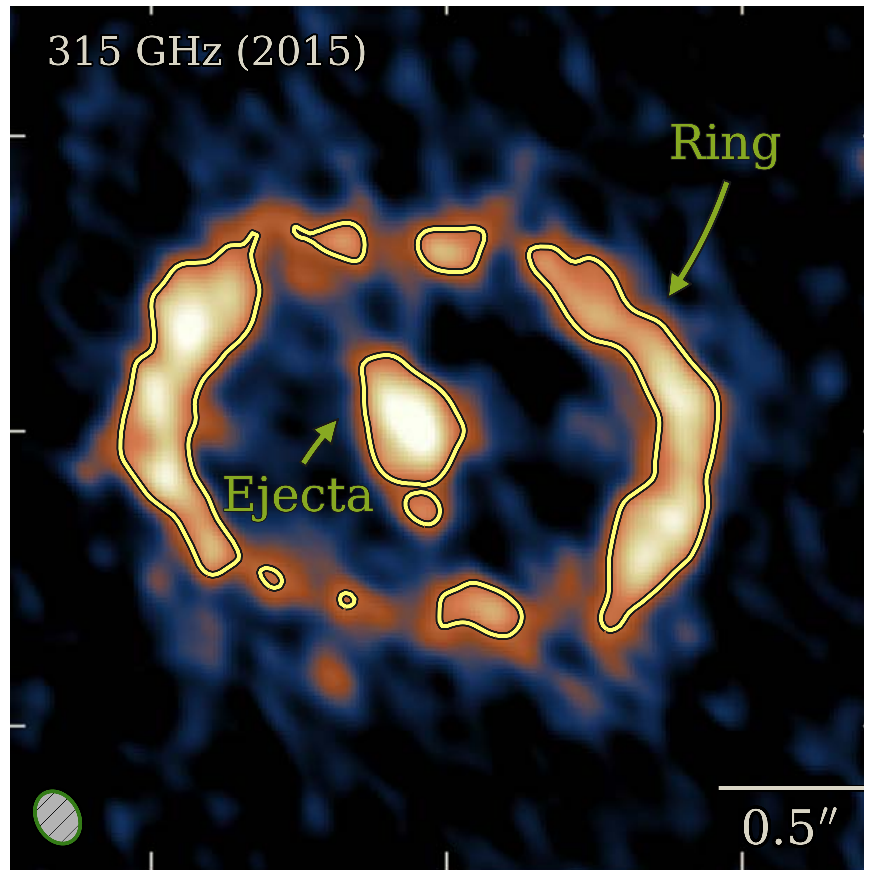
2. X-rays from the interaction with the ring

- Causes brightening of ejecta (*Larsson+11*)
- especially important for H lines
- leads to limb-brightened morphology (*Fransson+13*)



3. The compact object

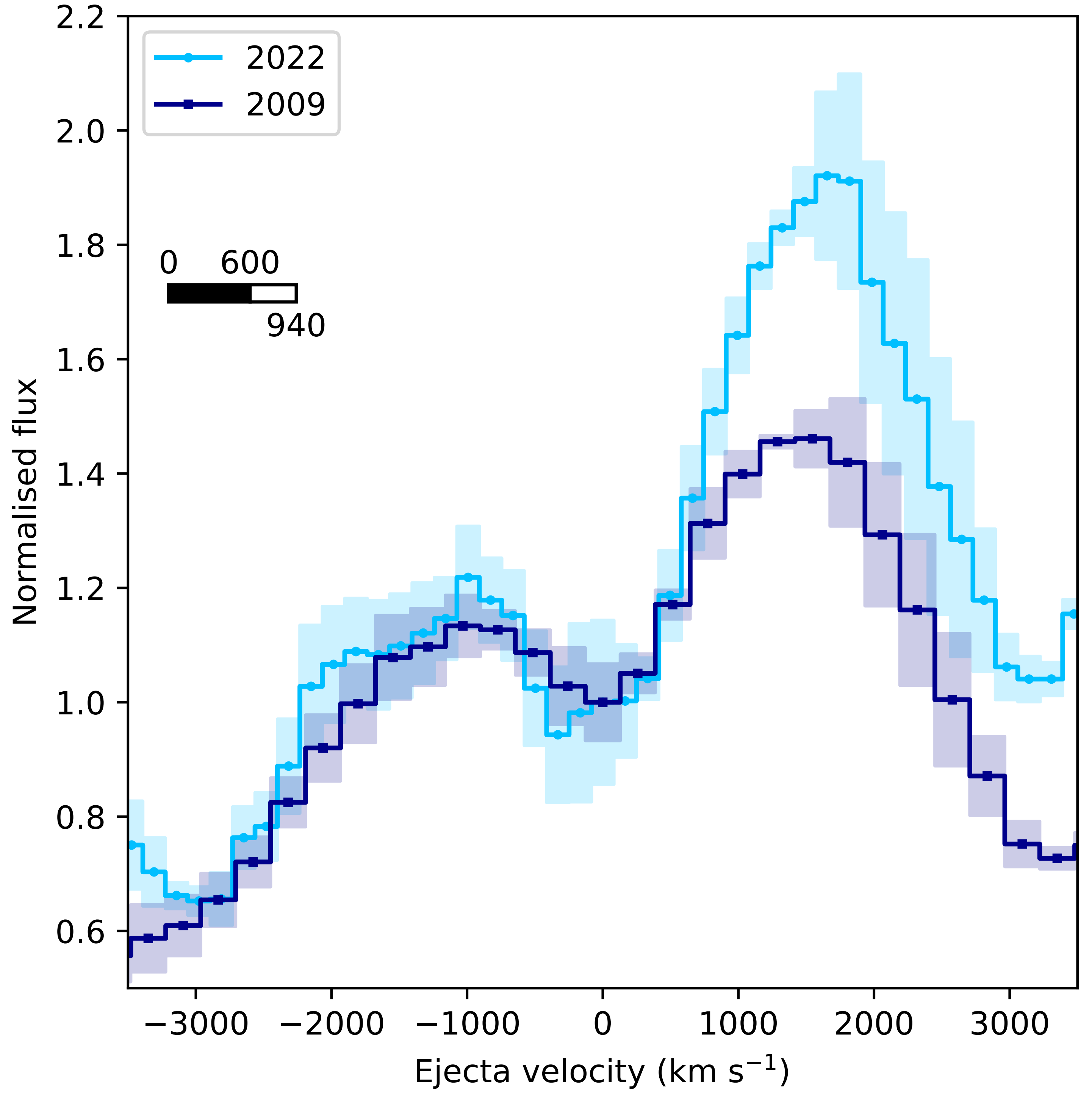
- More later…



+ Dust

- About 0.5 $M_\odot$ of cold dust in the ejecta observed by Herschel and ALMA (*Matsuura+11,15, Cigan+19*).

Homologous expansion, but brightening on west side due to X-rays (Rosu+24).

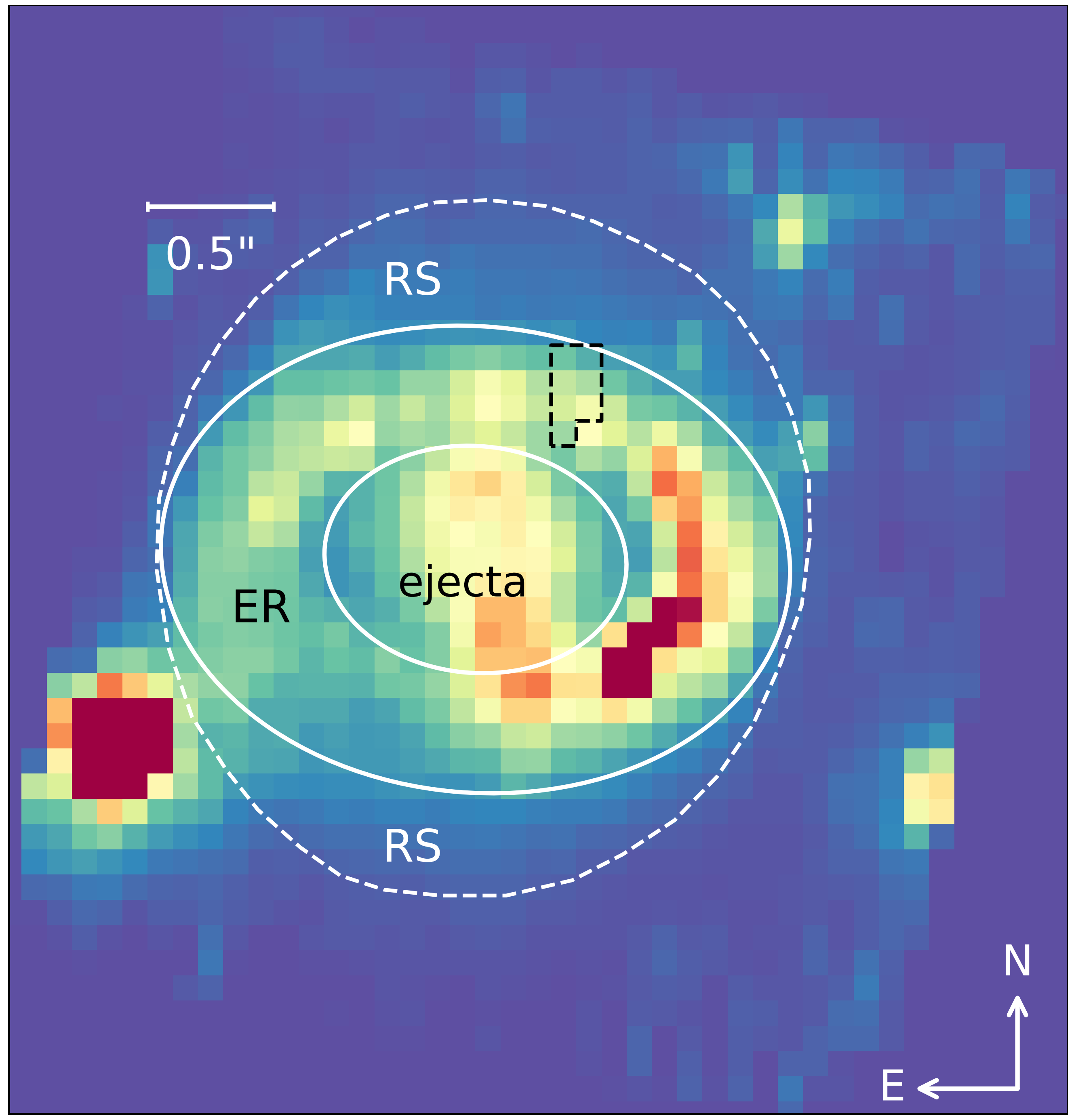


JWST NIRSpec ejecta spectrum

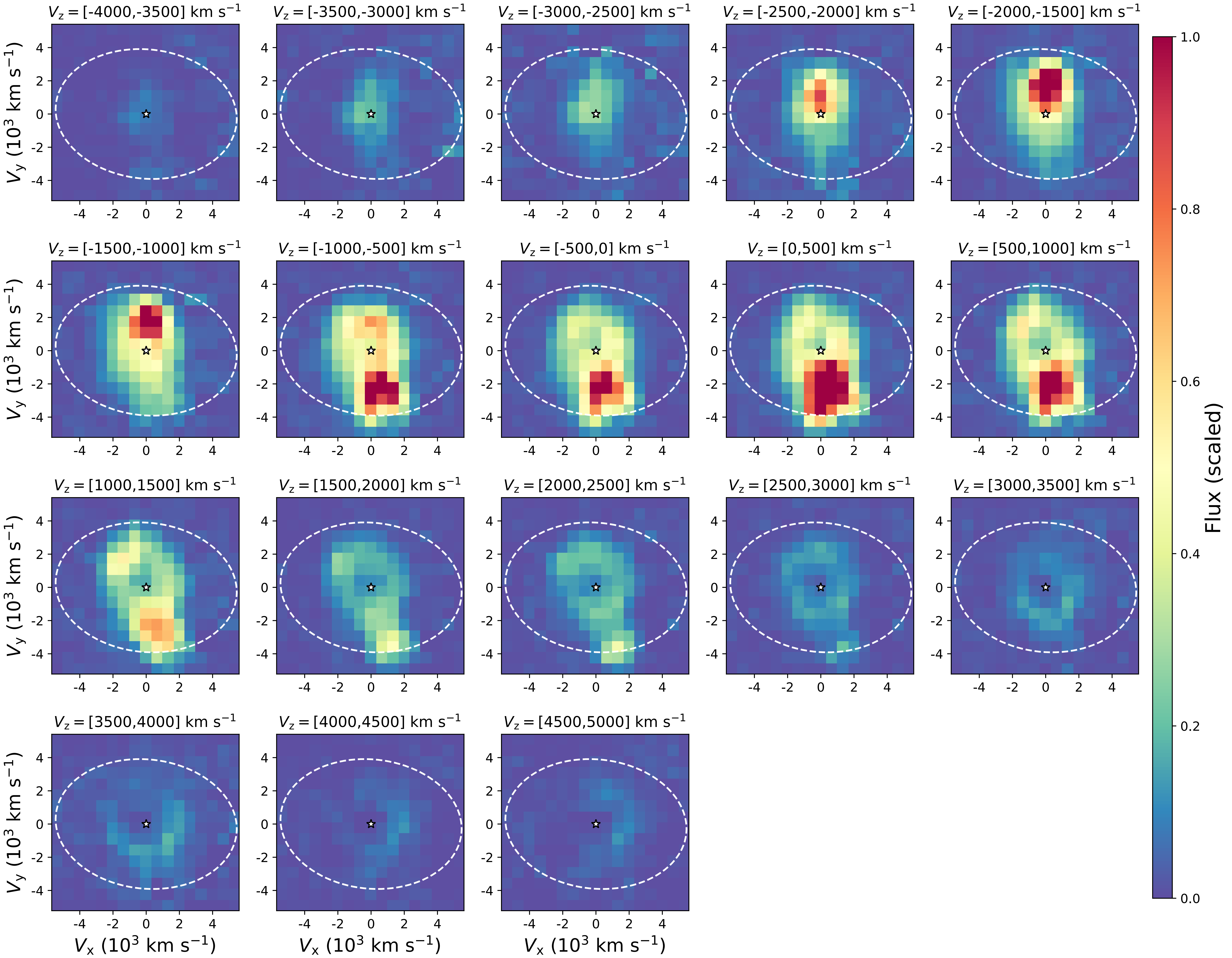
(*Larsson+23*)

[Fe I] 1.443 μm line good probe of Fe distribution. Minimal blending with other lines. Not observed since 1995!

“Doppler slices” of the [Fe I] emission

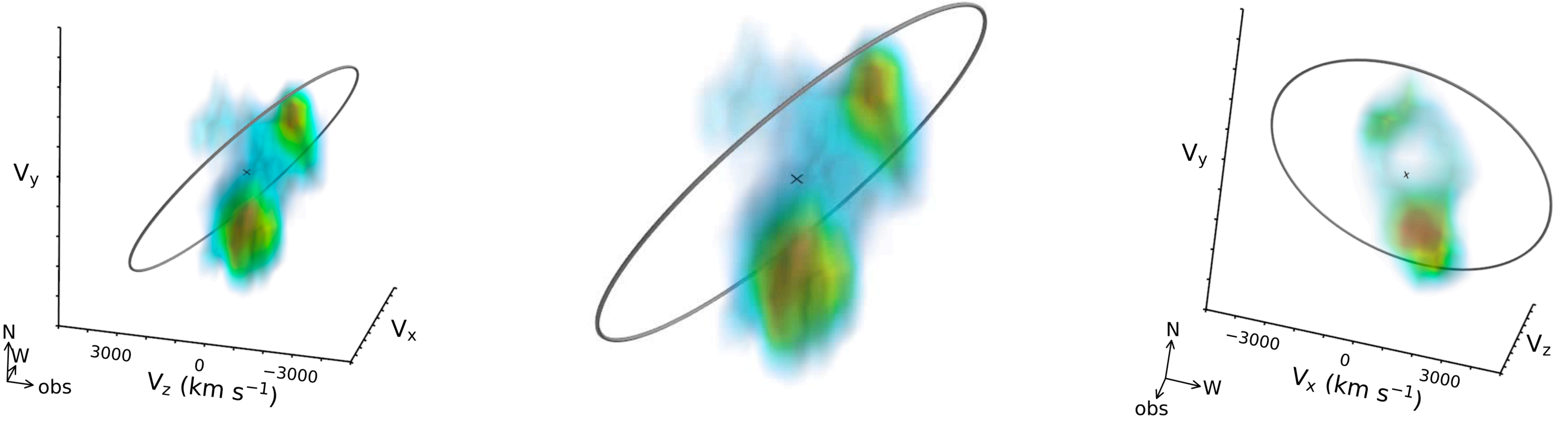


Integrated image before removal of other emission components



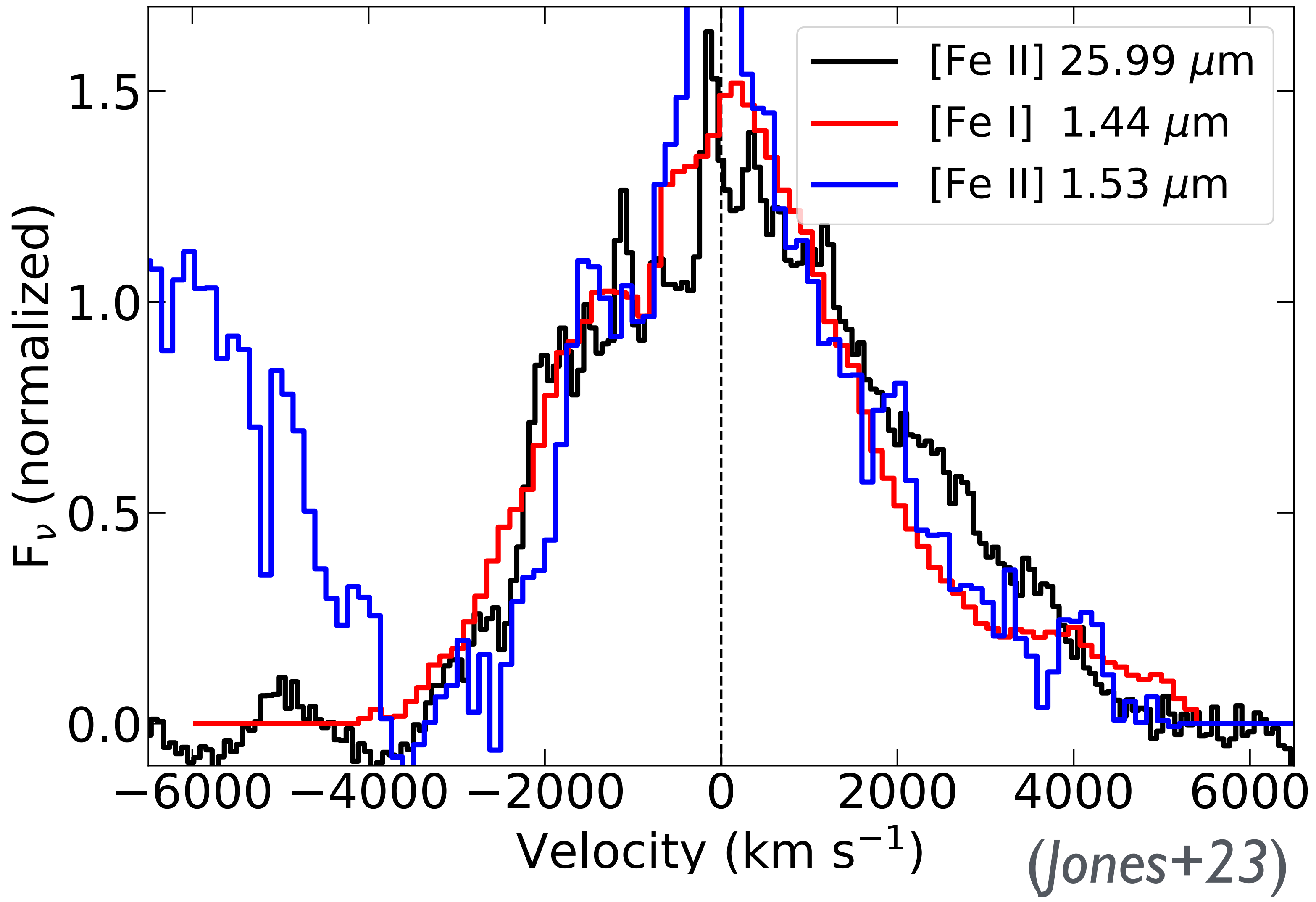
(Larsson+23)

Only Doppler shifts > 1000 km s^{-1}



(*Larsson+23*)

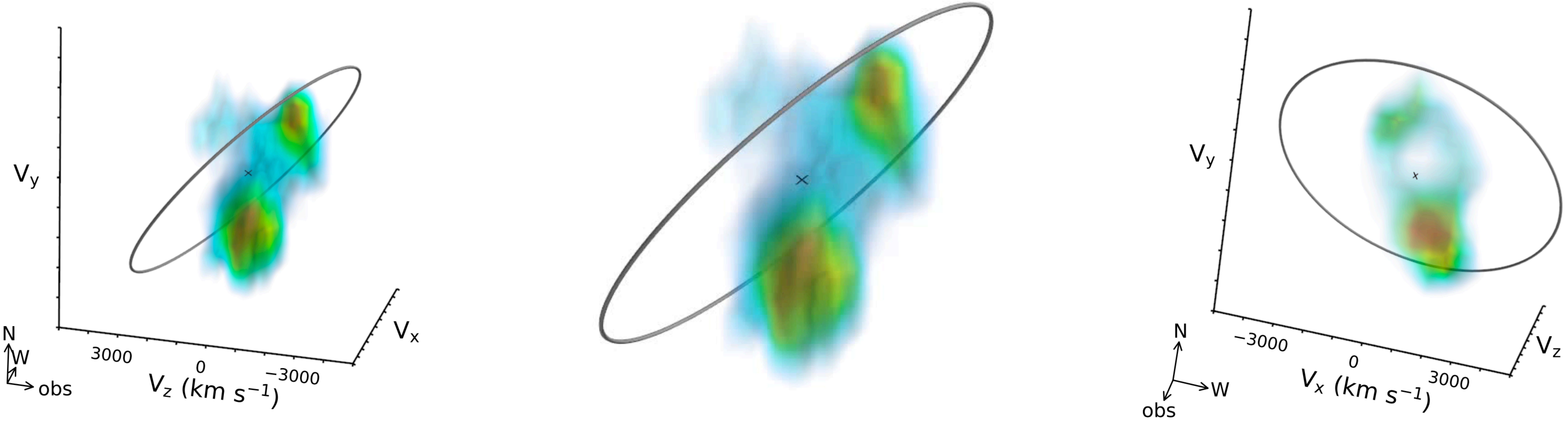
Integrated Fe line profiles



(*Jones+23*)

- Distribution dominated by two clumps centred at velocities of ~2300 km s^{-1}, but not along the same axis (offset by ~45°)
- Ring/torus structure with radius ~1700 km s^{-1}.
- Similar overall geometry as previously observed in other lines.

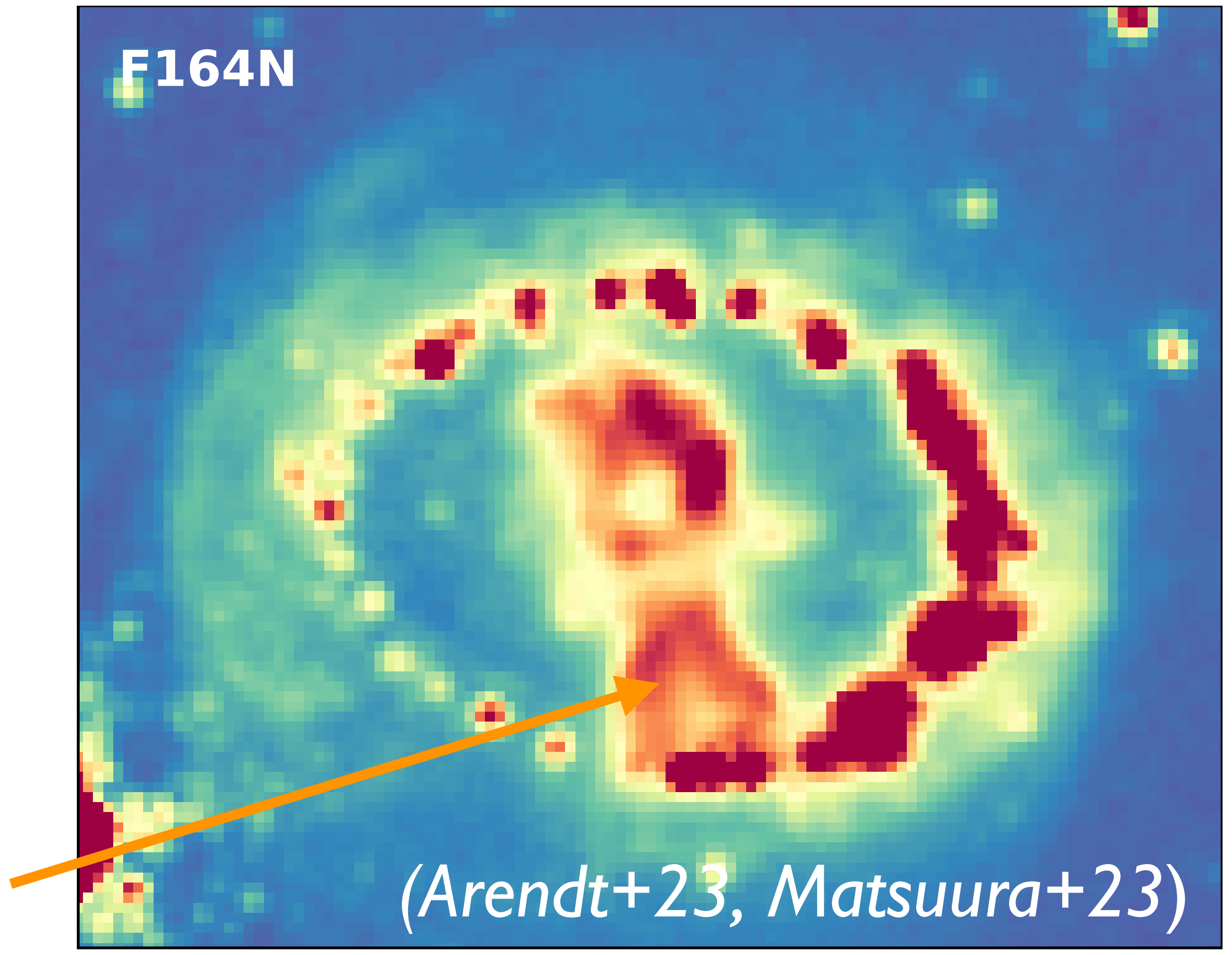
Only Doppler shifts > 1000 km s^{-1}



(*Larsson+23*)

- Distribution dominated by two clumps centred at velocities of ~2300 km s^{-1} , but not along the same axis (offset by ~45°)
- Ring/torus structure with radius ~1700 km s^{-1}.
- Similar overall geometry as previously observed in other lines.

Comparison with NIRCam/ F164N
[Fe II] + [Si I] 1.64 μm blend (-2000—1300 kms^{-1})
Better spatial resolution

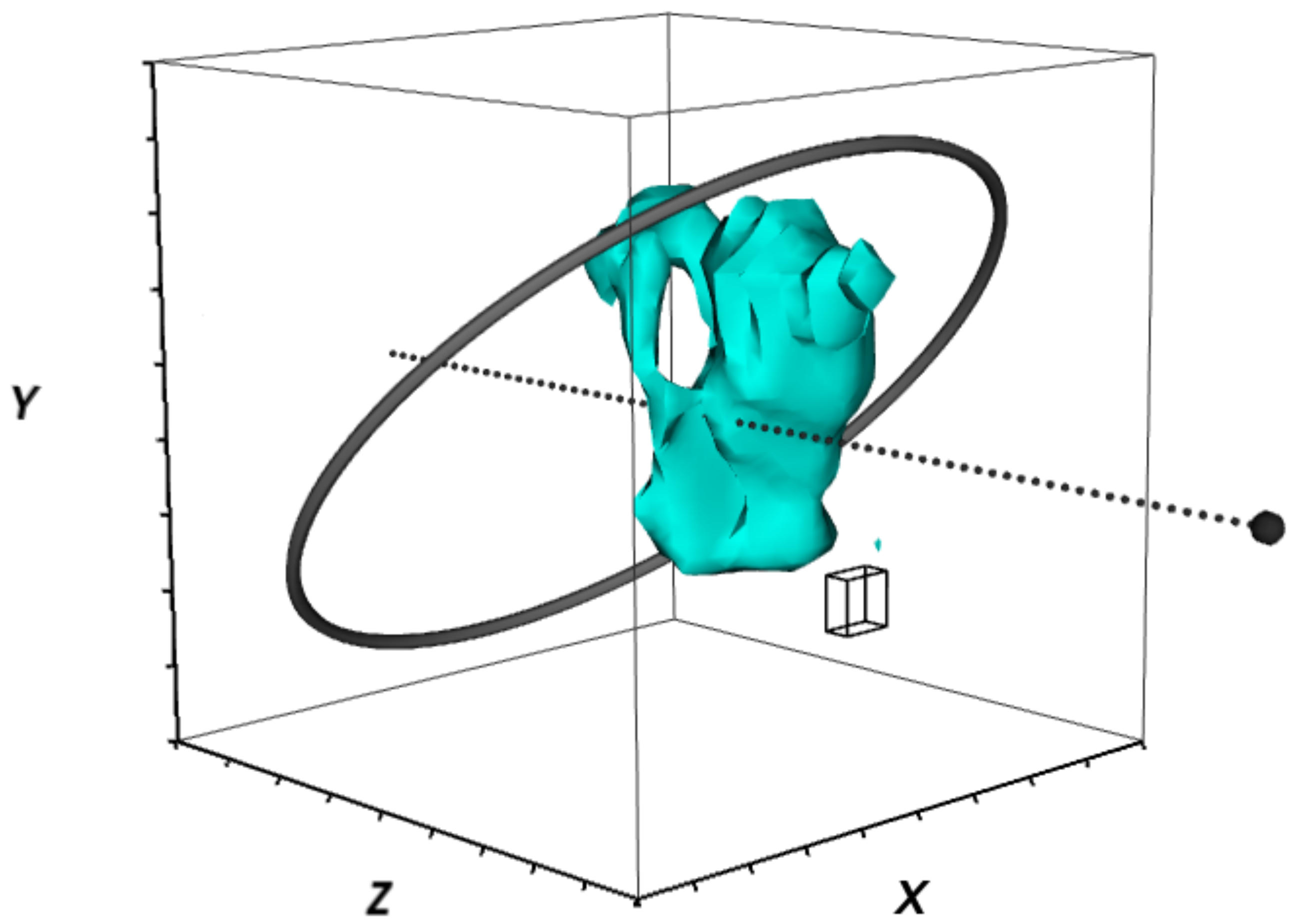


One more ring

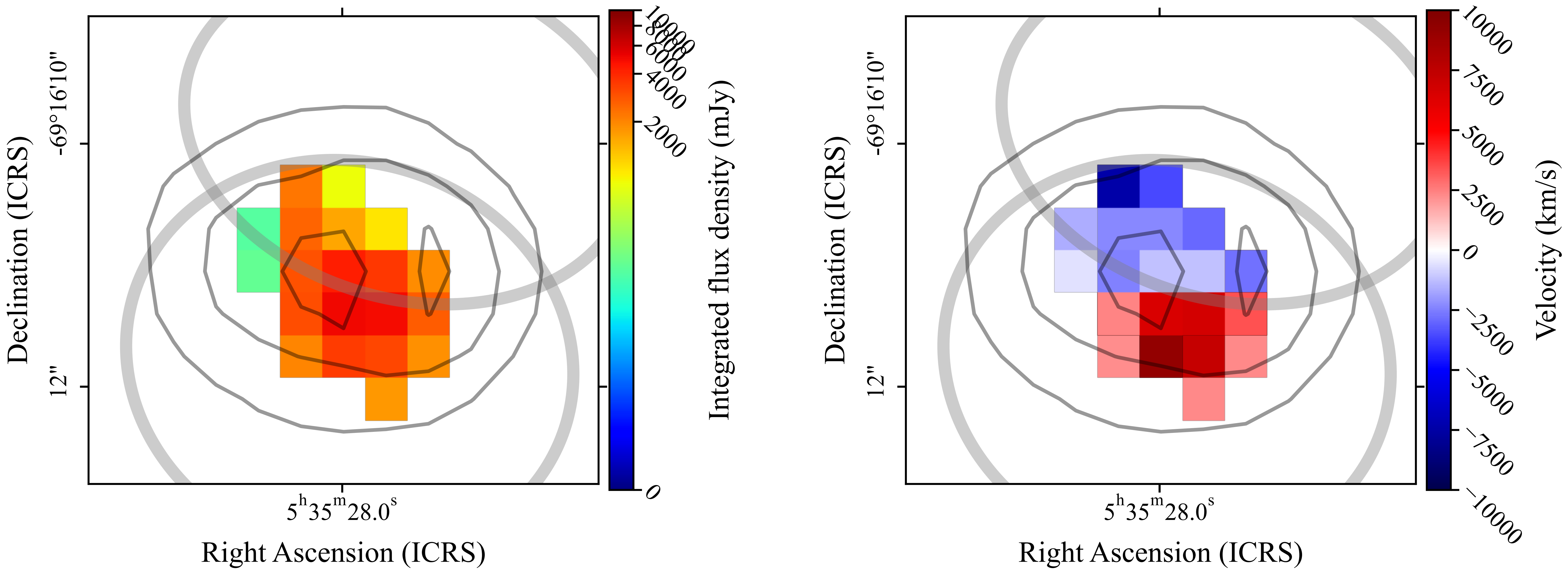
(Arendt+23, Matsuura+23)

The “broken dipole” in other lines/elements

Hα

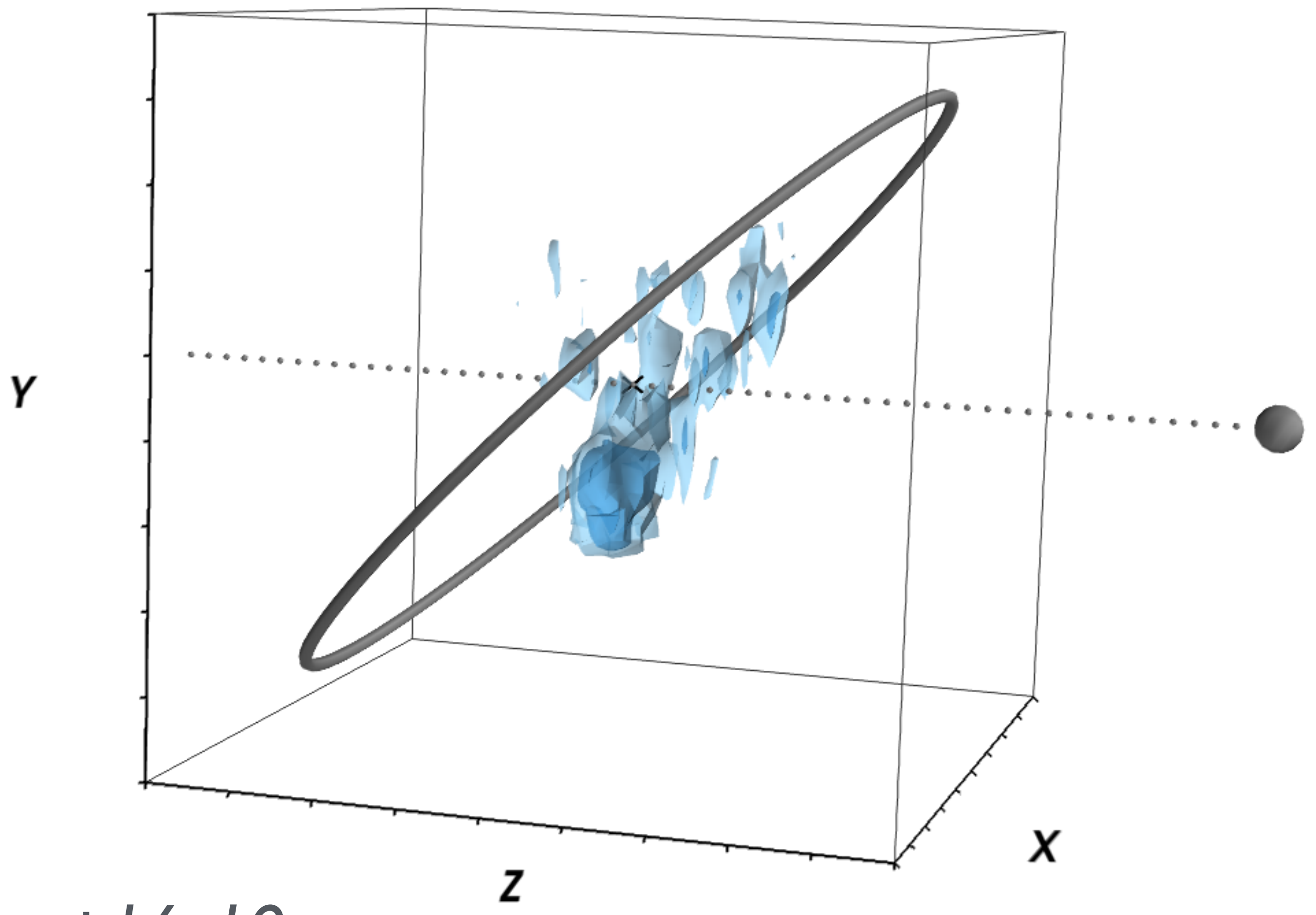


[Fe II] 25.98829 μm

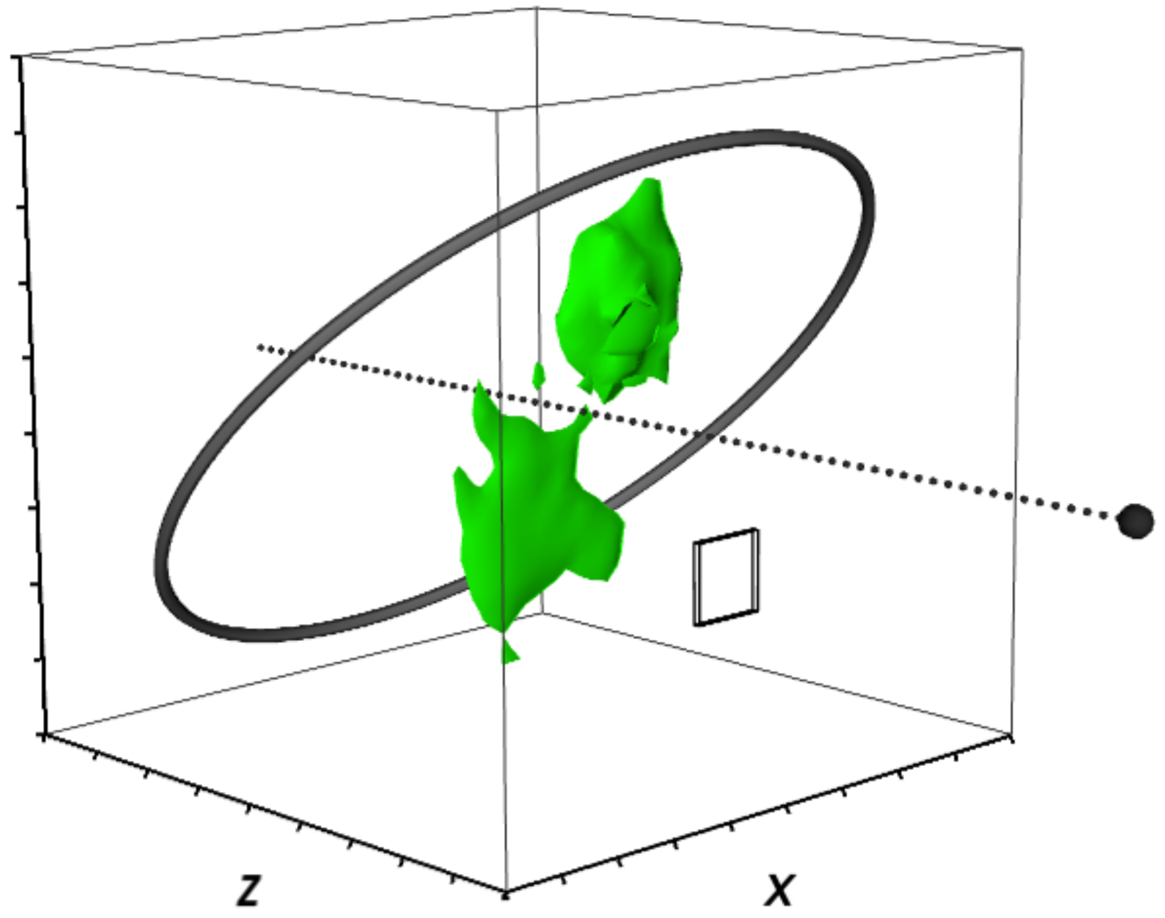


(Jones+23)

H_2



Fe+Si



Similar global large-scale asymmetry in all atomic lines:

“broken dipole” with brightest ejecta close to the ring plane in the north and closer to the sky plane in the south (*Kjaer+10, Larsson+13,16,19, Kangas+22*).

Larsson+16, 19

Origin of the asymmetries?

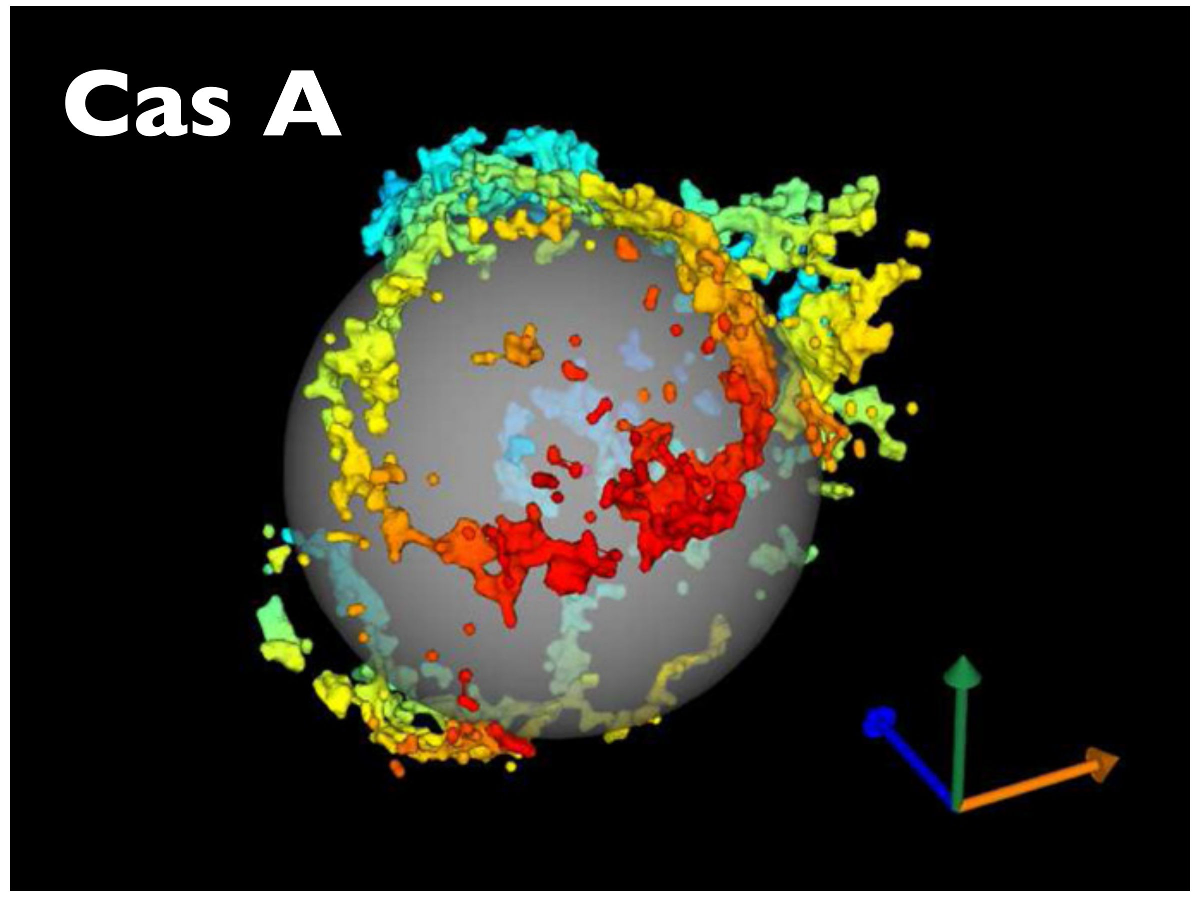
Are the rings intrinsic ejecta structures, or caused by the energy sources and/or dust?

Can the neutrino-driven mechanism explain the large-scale ejecta asymmetries?

Contribution of magnetorotational effects?

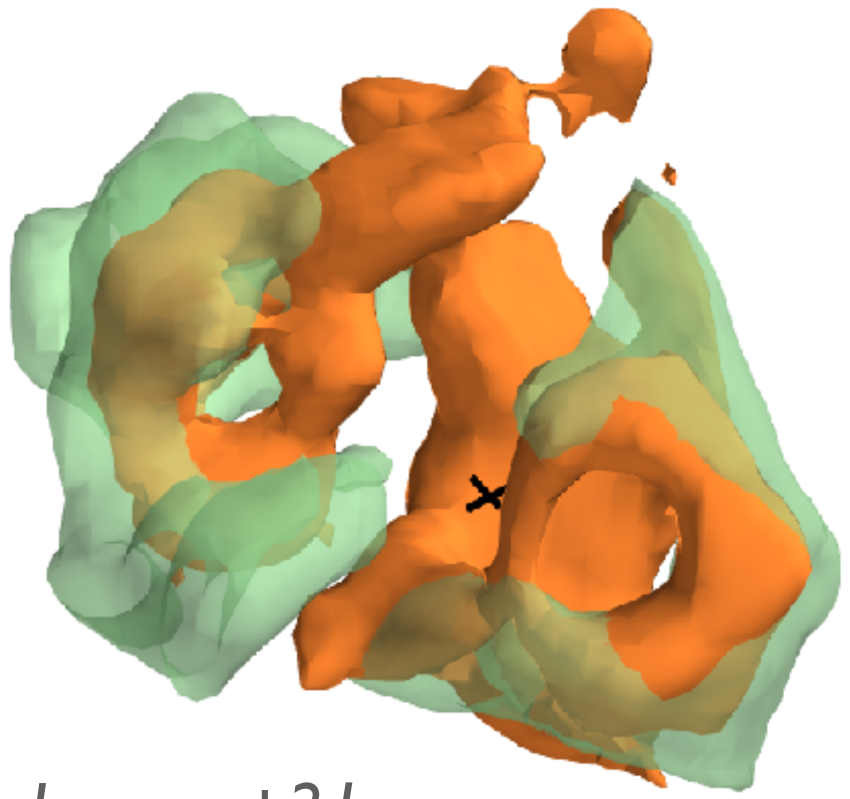
The NIRSpec observations will provide 3D maps of Fe, Si, He, H & H_2. …..

Rings and asymmetries everywhere



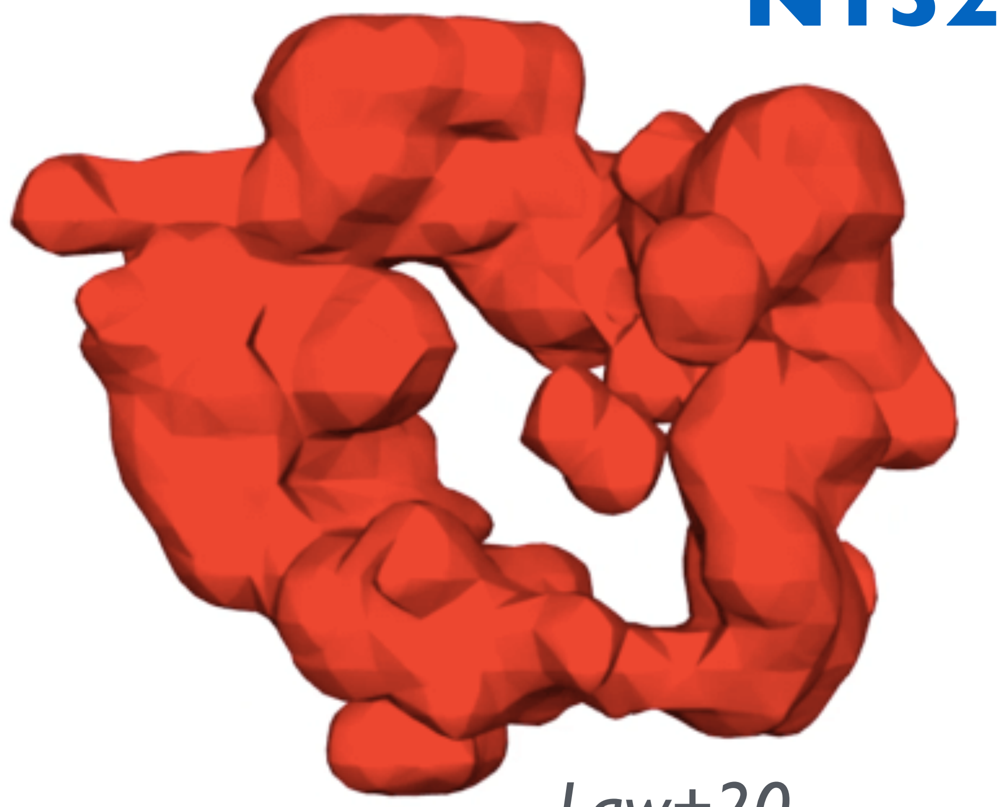
Milisavljevic & Fesen (2013)

SNR 0540



Larsson+21

N132D

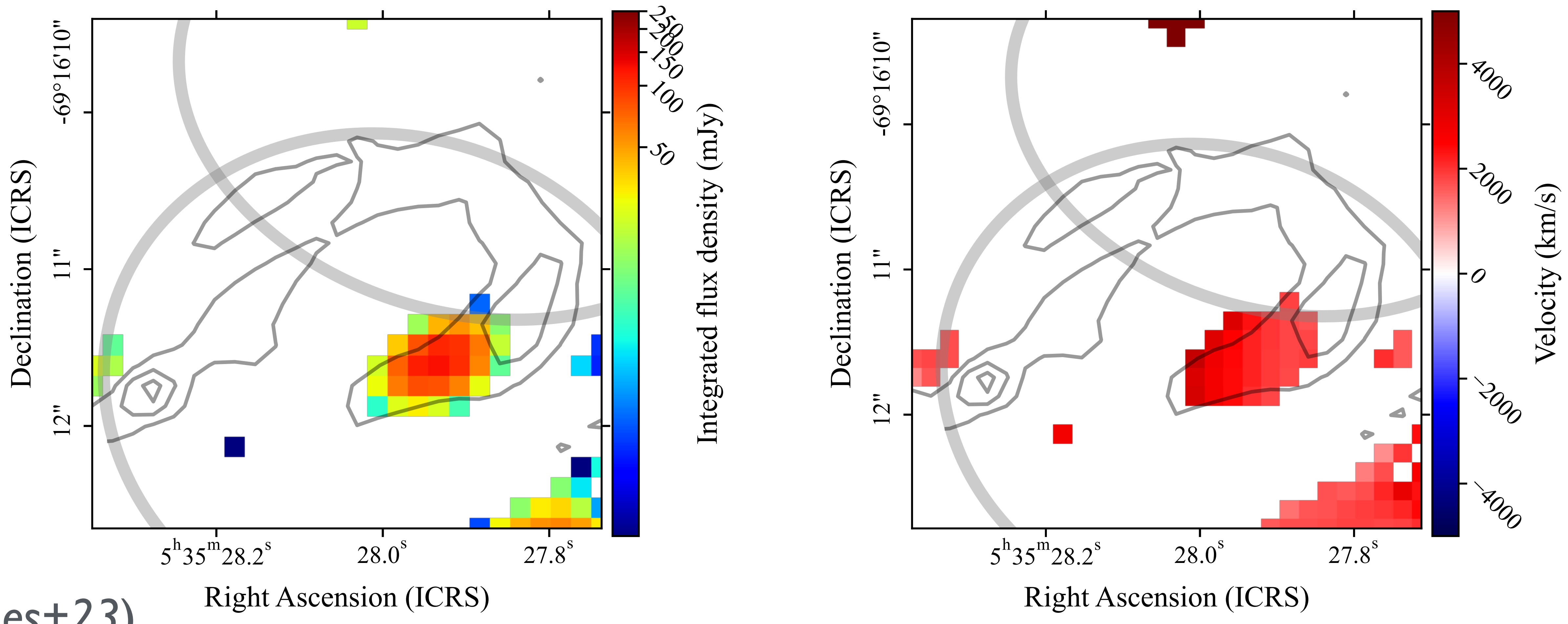


Law+20

Interaction with the Fe-rich inner ejecta

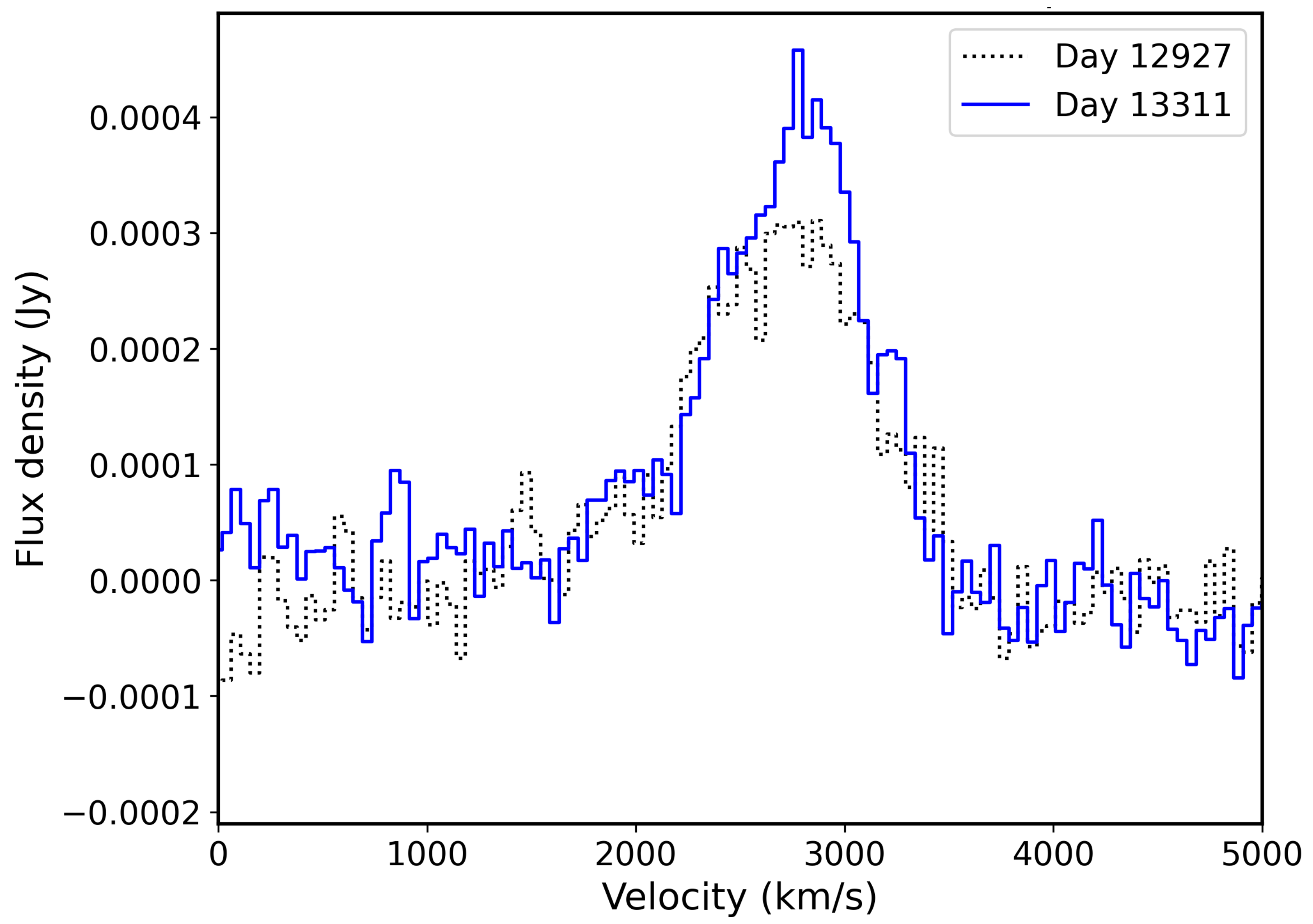
Increase between Cycles 1 & 2!

[Fe II] 5.340 μm, day 12927

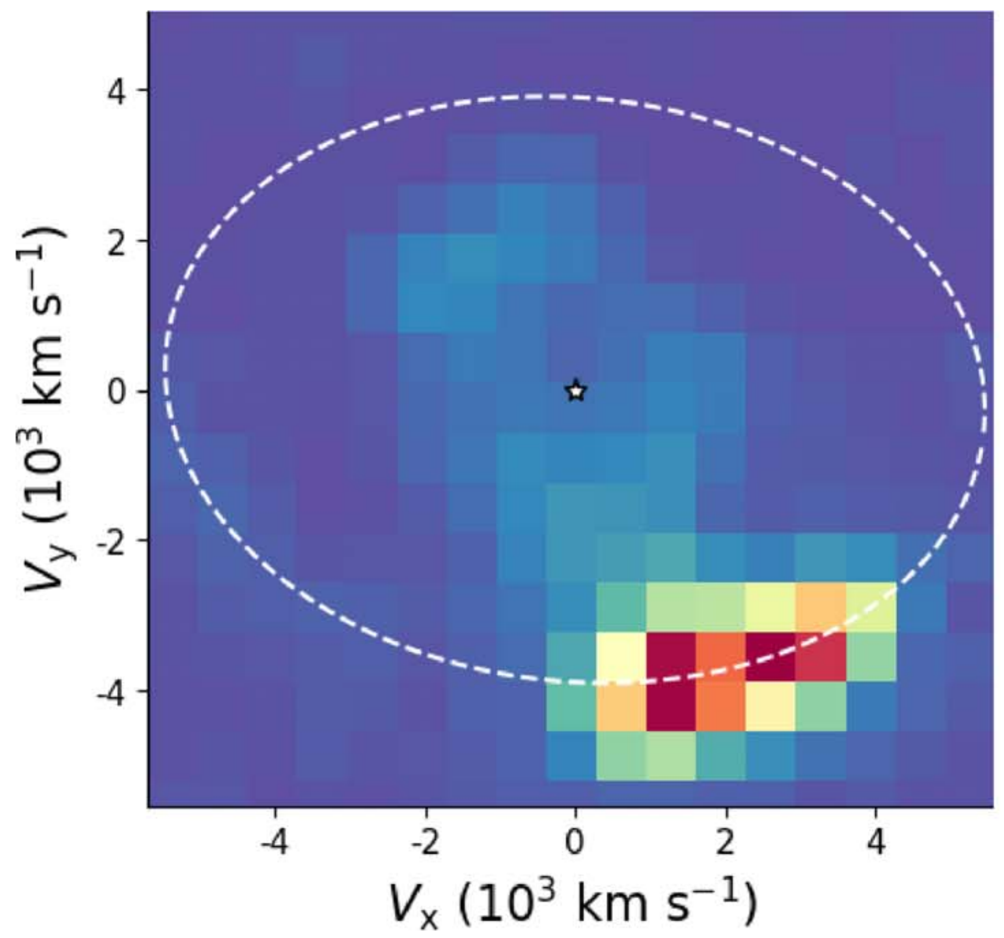


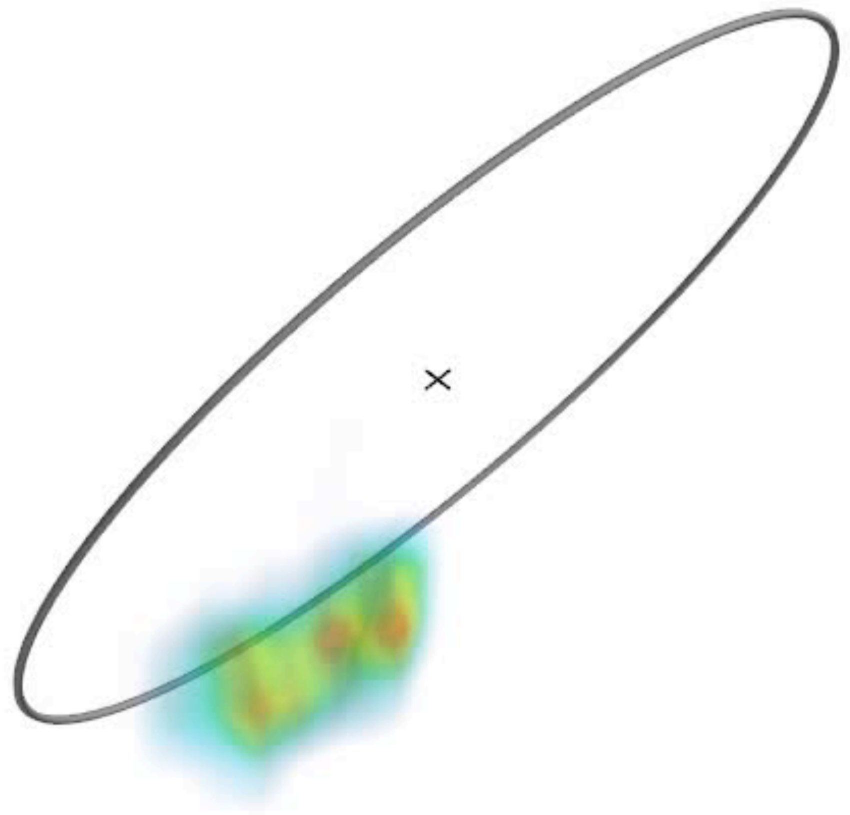
(Jones+23)

[Fe II] 5.340 μm, south



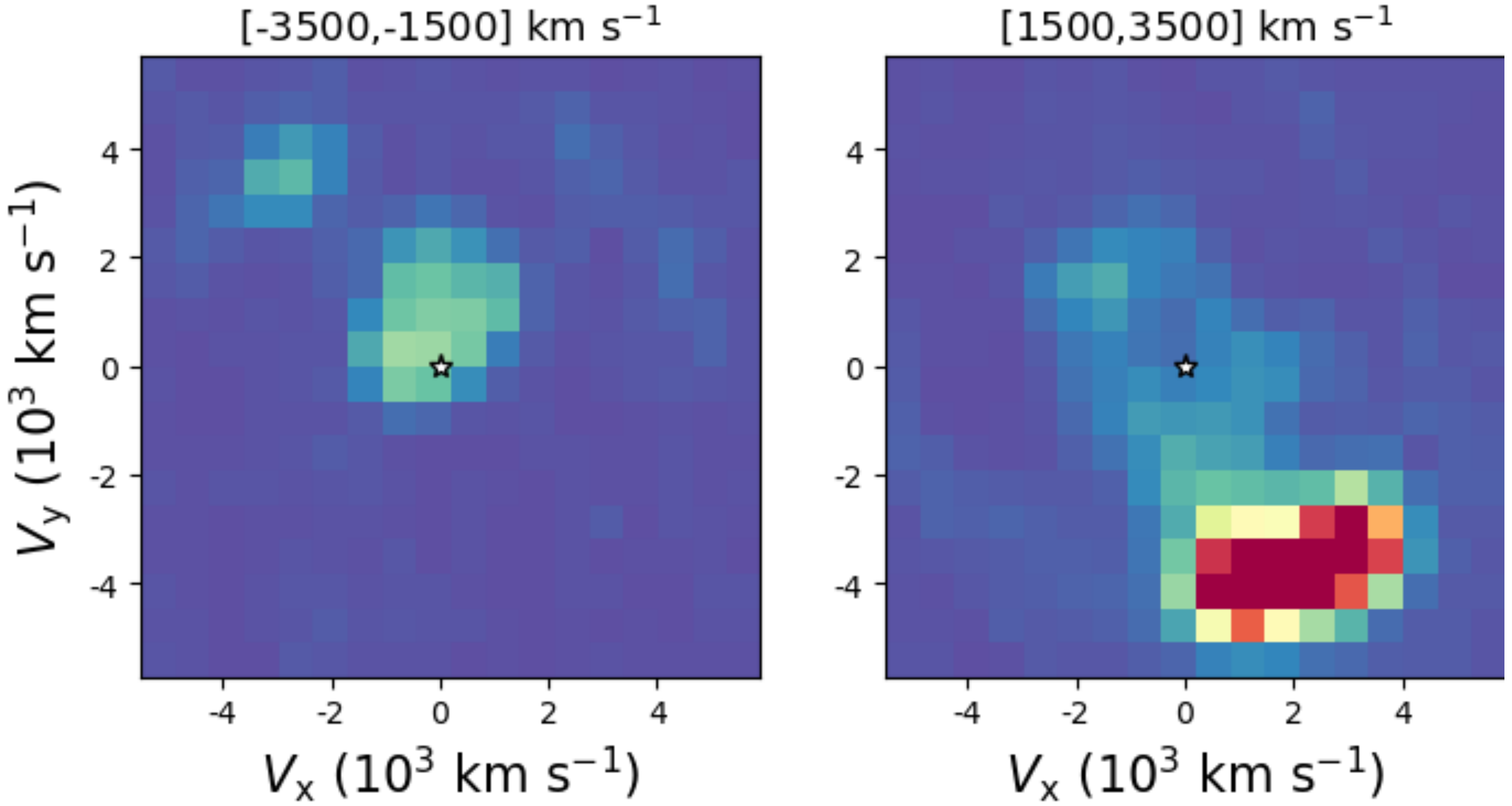
[Fe II] 1.644 μm, redshifts > 1500 km s^{-1} , day 12927





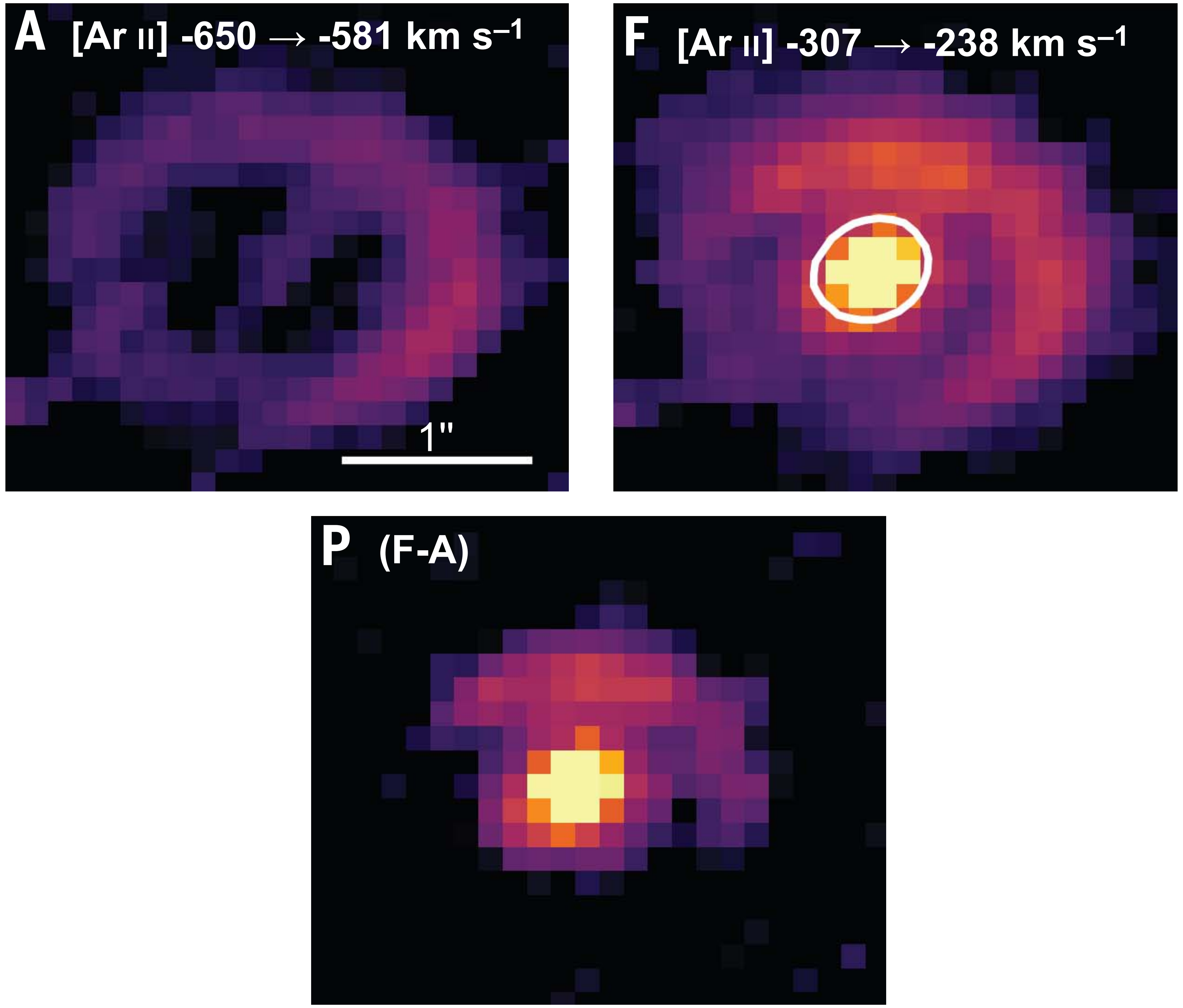
(Larsson+23)

[Fe II] 1.644 μm, day 13511

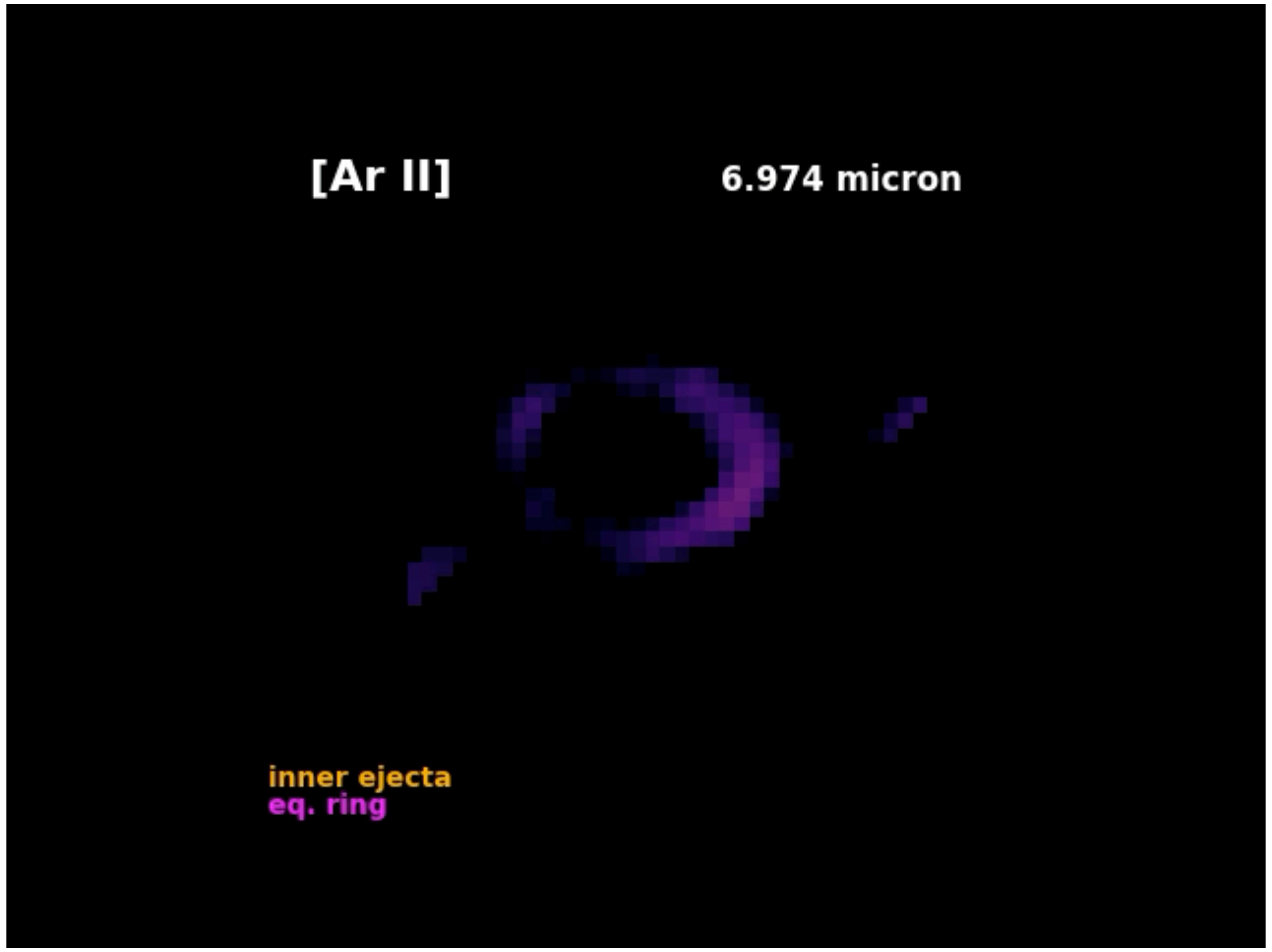


THE INNERMOST EJECTA & COMPACT OBJECT

A bright, narrow [Ar II] 6.985 μm line from the central ejecta



(Fransson+24)

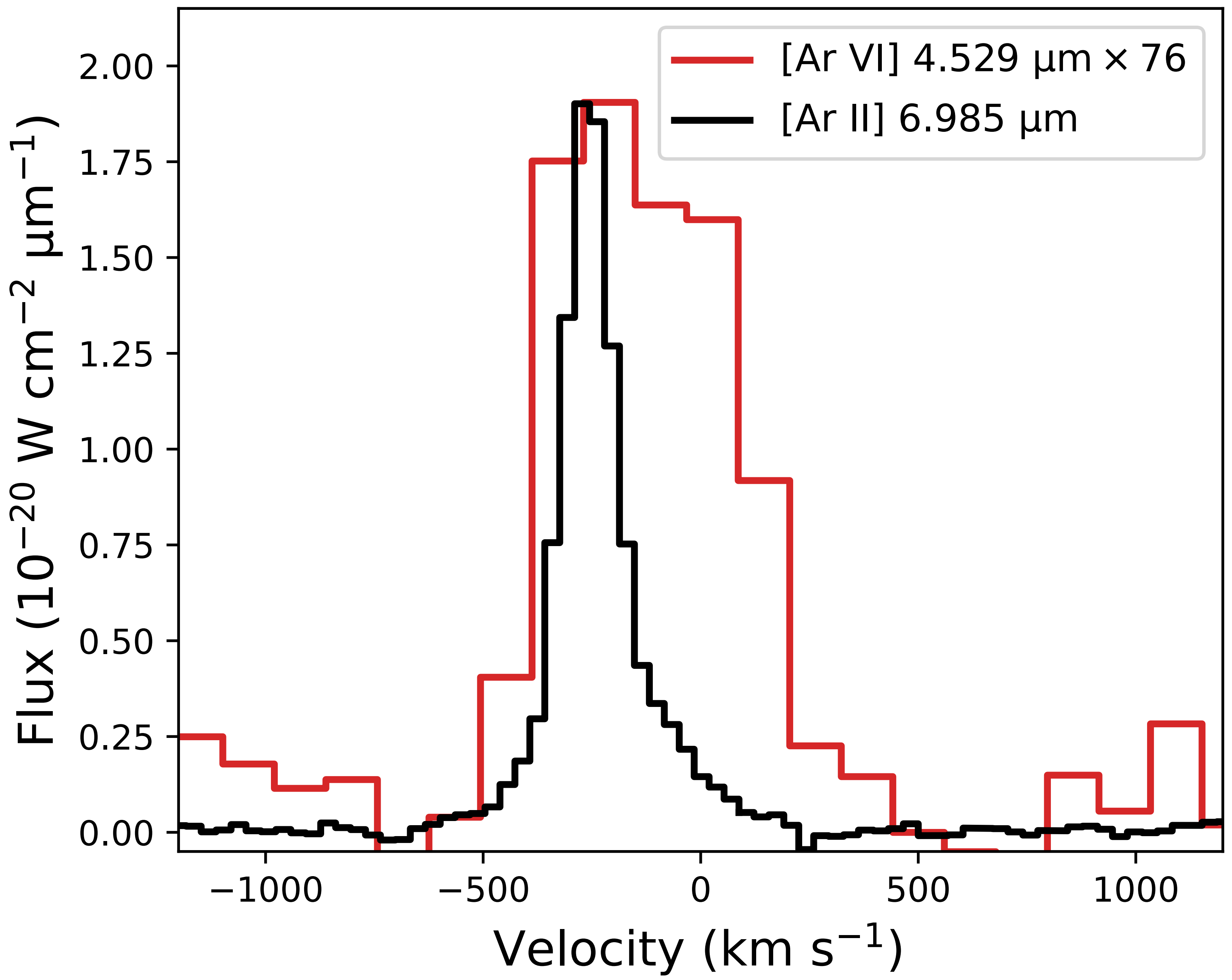


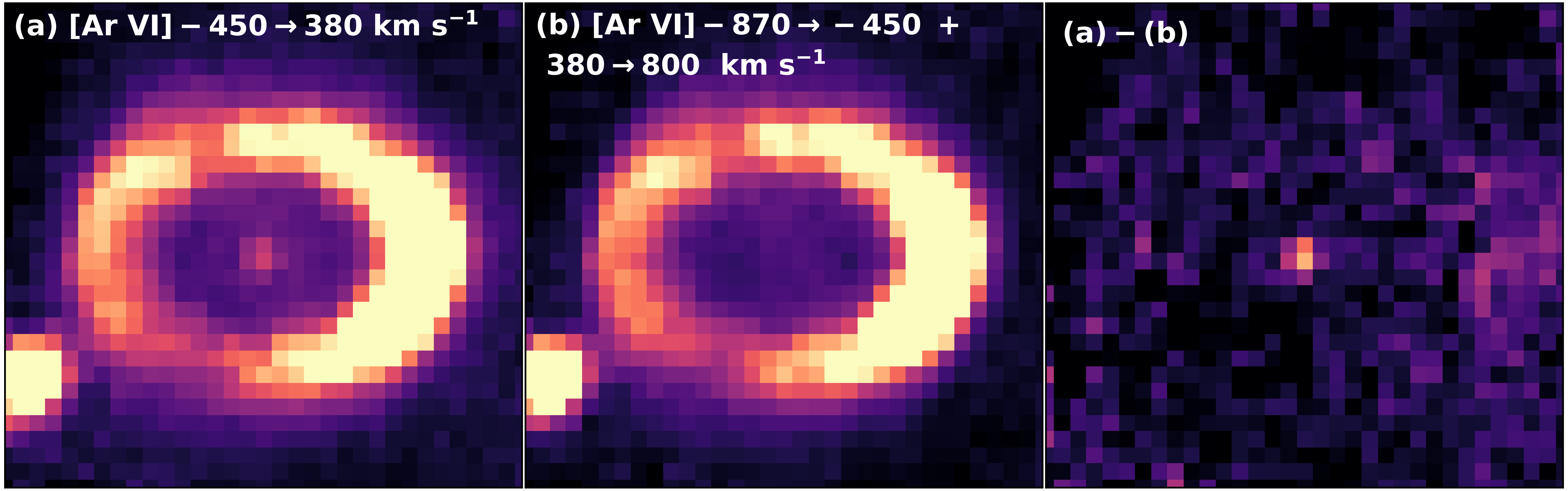
Credit: P. Kavanagh

Other lines lines with similar properties detected at the centre

[Ar VI] 4.529 µm , [Ar III] 8.991 µm , [S IV] 10.51 µm, [S III] 18.71 µm.

Focus on [Ar II] (brightest, best spectral resolution) and [Ar VI] (best spatial resolution).





(Fransson+24)

Properties of the emission lines

- Lines blueshifted by ~260 km s^{-1}.

- Narrow widths (FWHM ~100 km s^{-1}).

- Spatial position consistent with the centre of the ring.

- Emission region spatially unresolved.

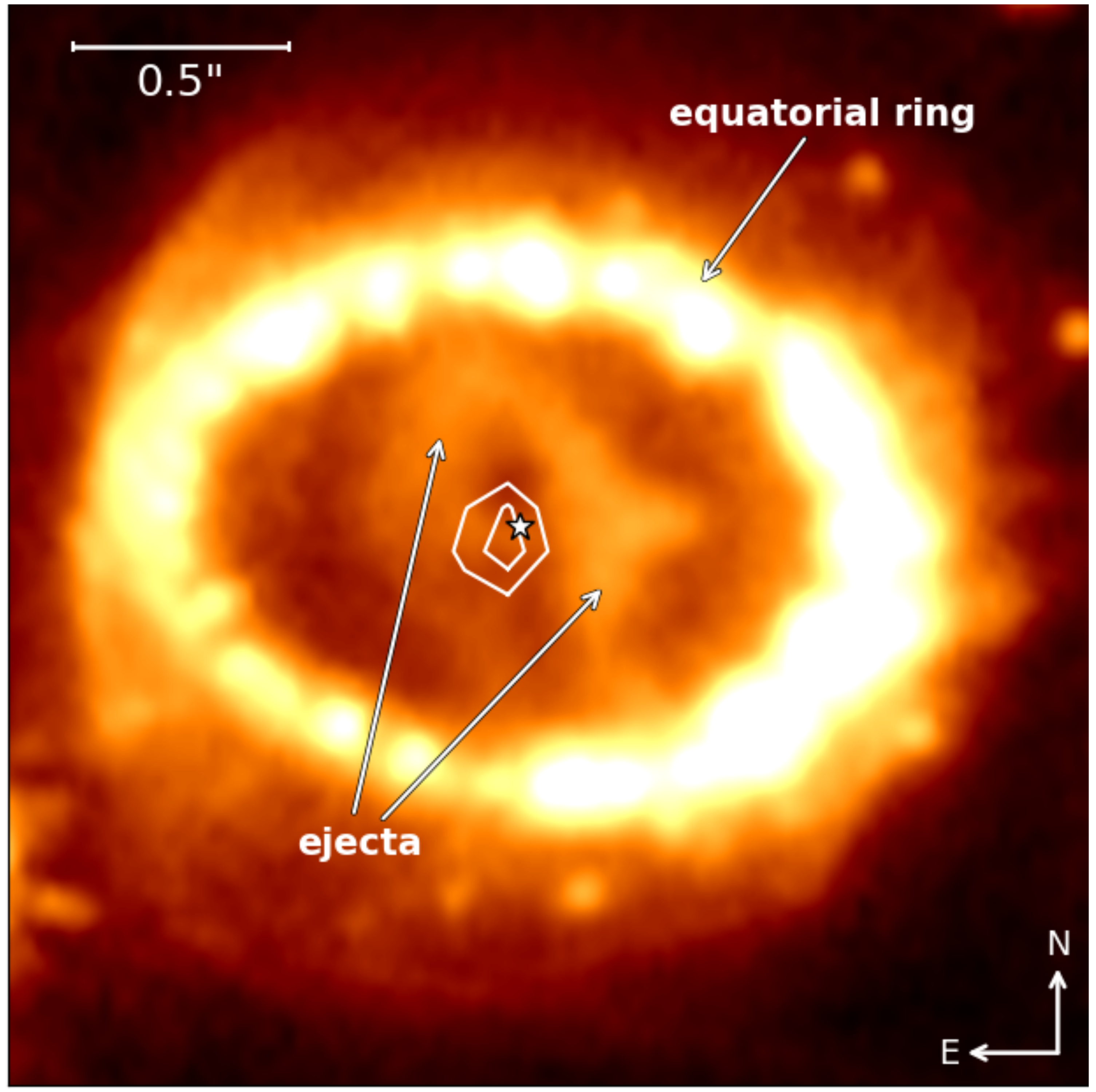
Strong indication of ionisation of the central ejecta by a compact object

✓ Small, highly ionised emission region at the centre.

✓ Ar and S expected at the core of the exploded star.

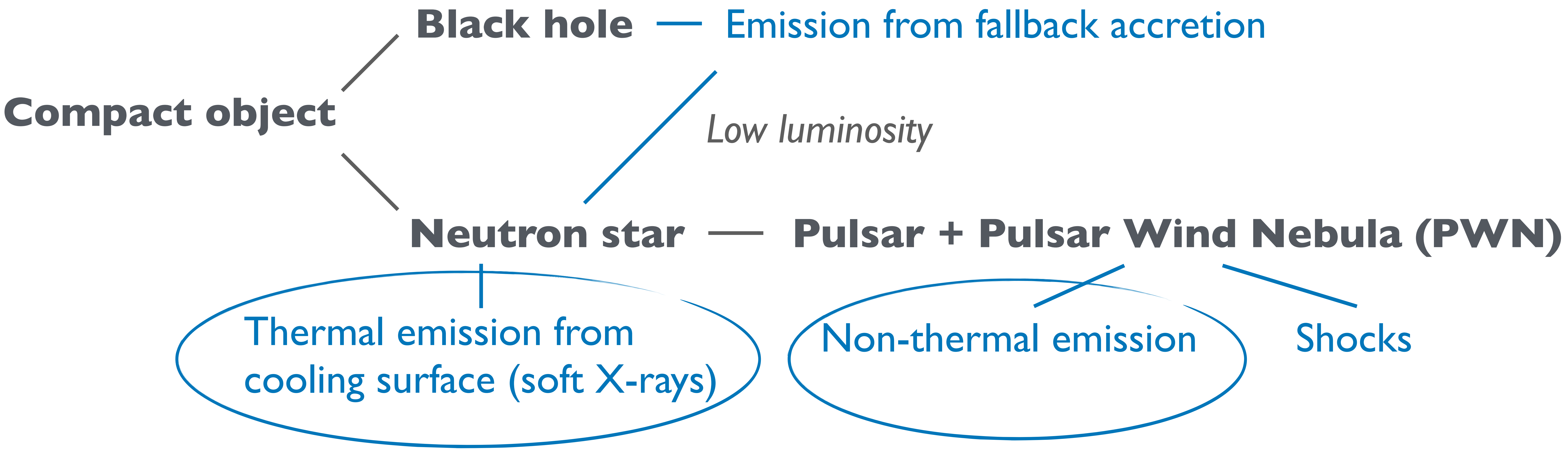
✓ Other explanations ruled out (excitation by reverse shock, X-rays, ^{44}Ti, dust reflection).

HST/F625W + [Ar VI] contours



(*Fransson+24*)

What kind of compact object?



Compact object

Black hole — Emission from fallback accretion

Low luminosity

Neutron star — **Pulsar + Pulsar Wind Nebula (PWN)**

Thermal emission from cooling surface (soft X-rays)

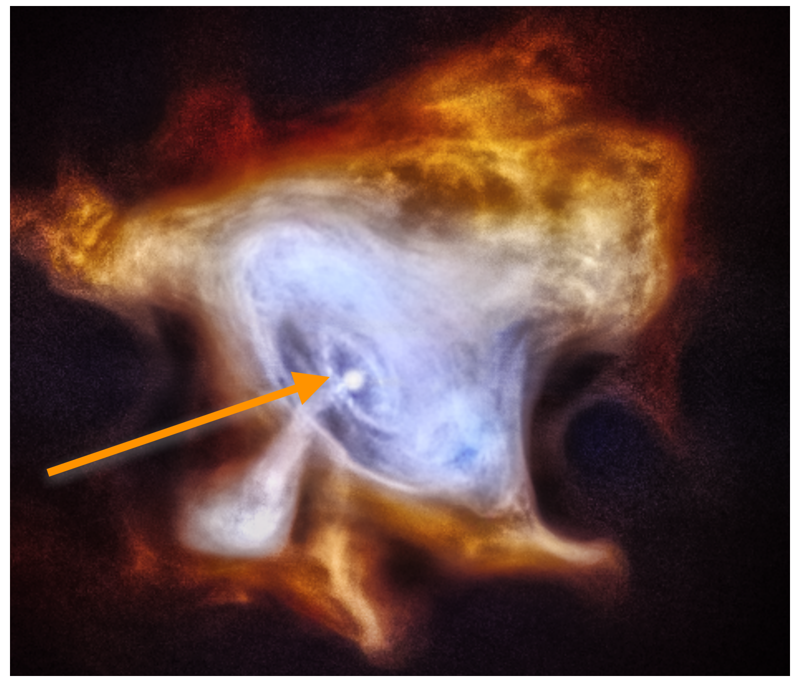
Non-thermal emission

Shocks

Black hole unlikely based on progenitor properties. Core mass too low.

Shock models underpredict the high ionisation lines compared to [Ar II], but cannot be completely ruled out.

Similar to Cas A?



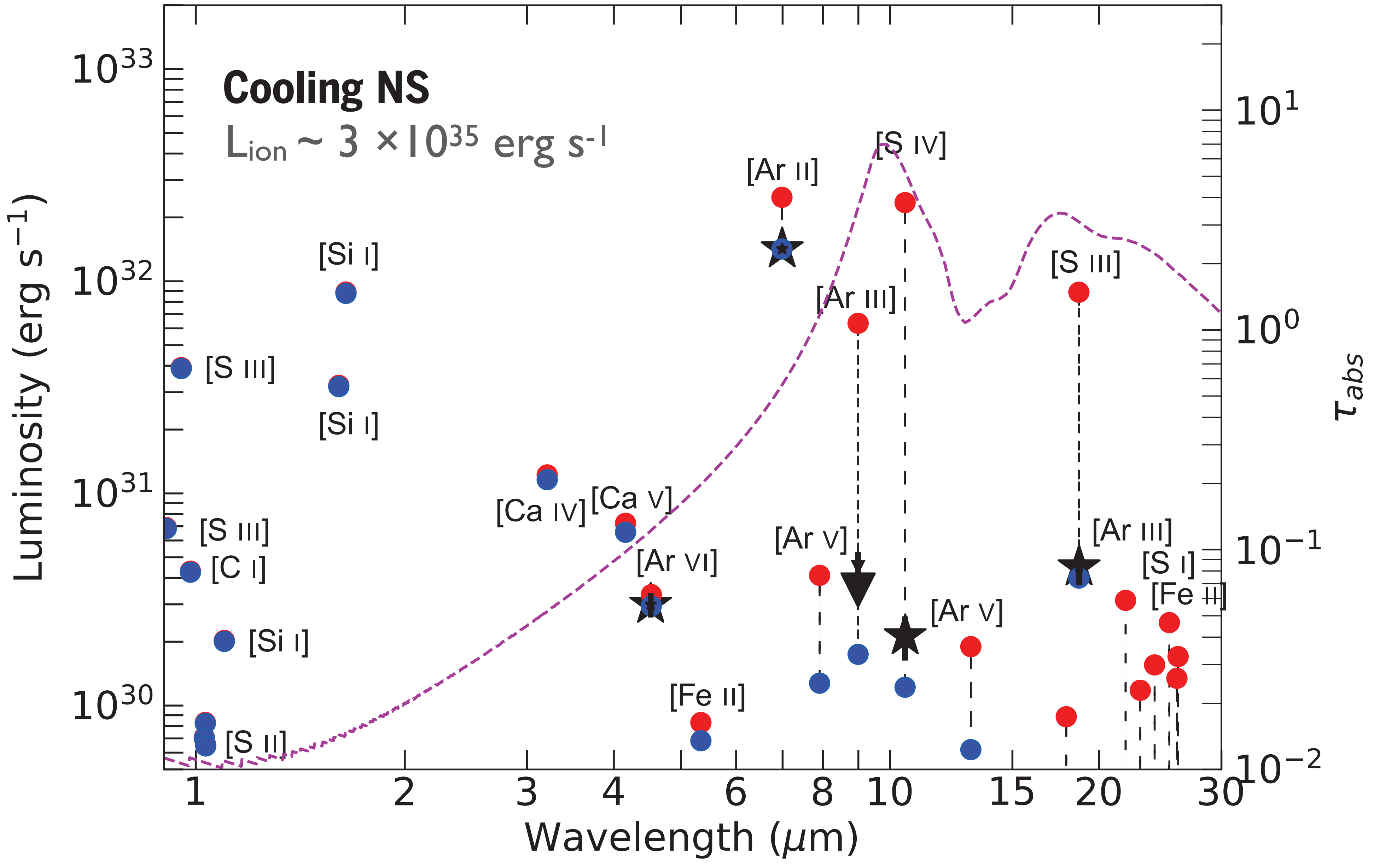
A "mini-Crab"?

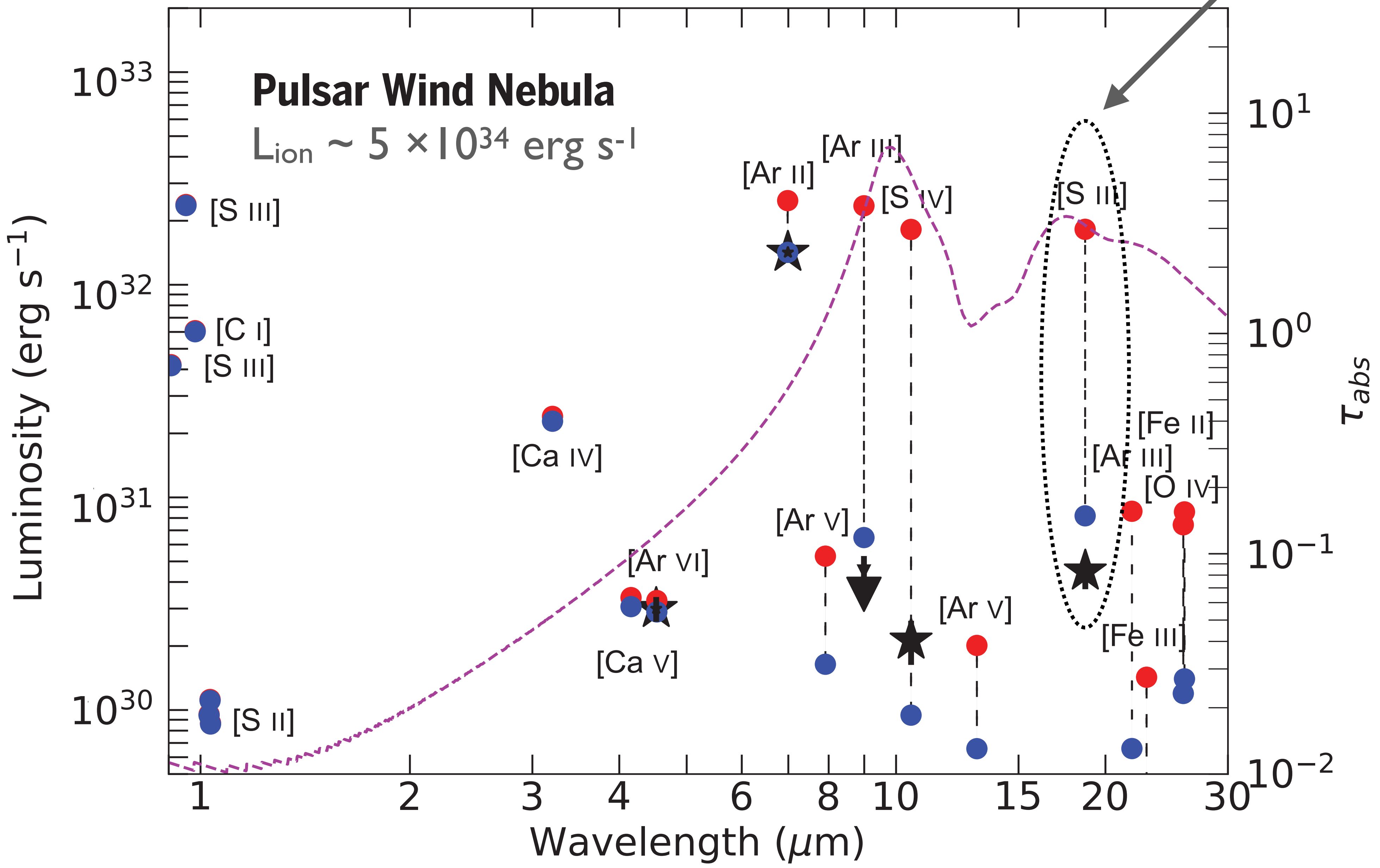
Observations affected by dust

- Dust is known to exist in the ejecta (*Wooden+93, Matsuura+11, 15, Cigan+19*).
- Silicates likely dominate in the central regions.
- Sharp rise in absorption longwards of ~ 8 μm.

Photoionisation models

Photoionisation modelling based on major update of code in Chevalier & Fransson (1992)





Effect of dust absorption
(assuming Mg_2SiO_4)

Model results assuming abundances typical of explosive O-burning and density $n_{ion} = 2.6 \times 10^4$ cm^{-3}.

Line ratios sensitive to the ionisation parameter $\xi = L_{ion}/n_{ion}r^2 \sim 0.3$.

Covering factor of ~0.5-2%, strong asymmetry/clumping and dust.

Conclusions and open questions

- ✦ Both a cooling neutron star and a PWN (and combinations) can explain the line emission.
- ✦ Blueshift and position may imply a kick of ~400±200 km s^{-1} (especially if just a neutron star).

Physical properties of the compact object?

Properties of dust in the central ejecta? How are the lines affected by absorption and scattering?

Abundances and physical conditions in the line emitting ejecta?

?

Time evolution?

What about other emission lines?

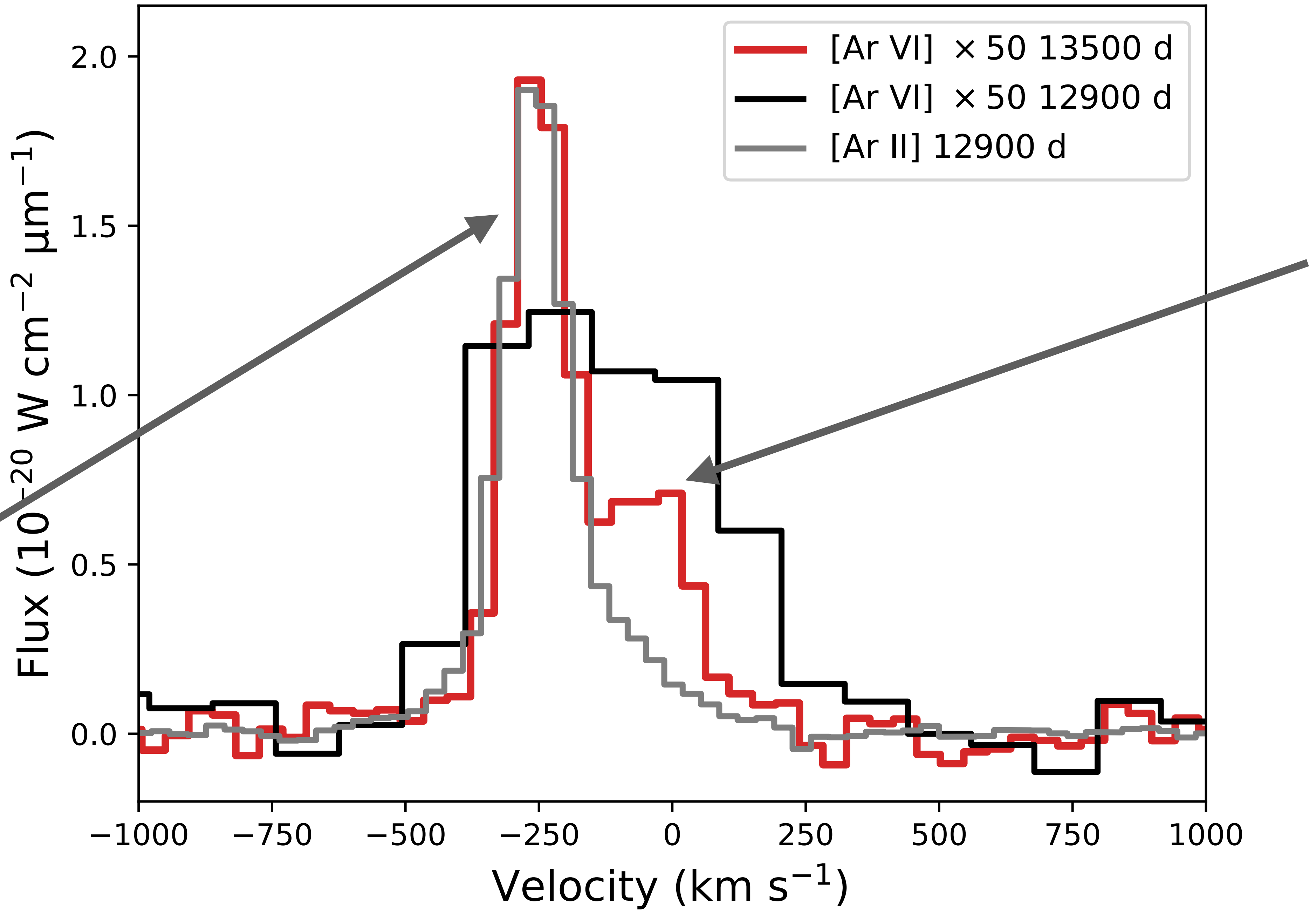
Connection with other multiwavelength observations (sub-mm & X-rays)?

Non-detection of [O III] in HST imaging *(Rosu+24)*.

- ➡ Dust scattering/absorption important.
- ➡ Ejecta region with low O abundance (inner part of S- and Ar-rich zone).

A preview of JWST Cycle 2 data

NIRSpec data with higher spectral resolution.

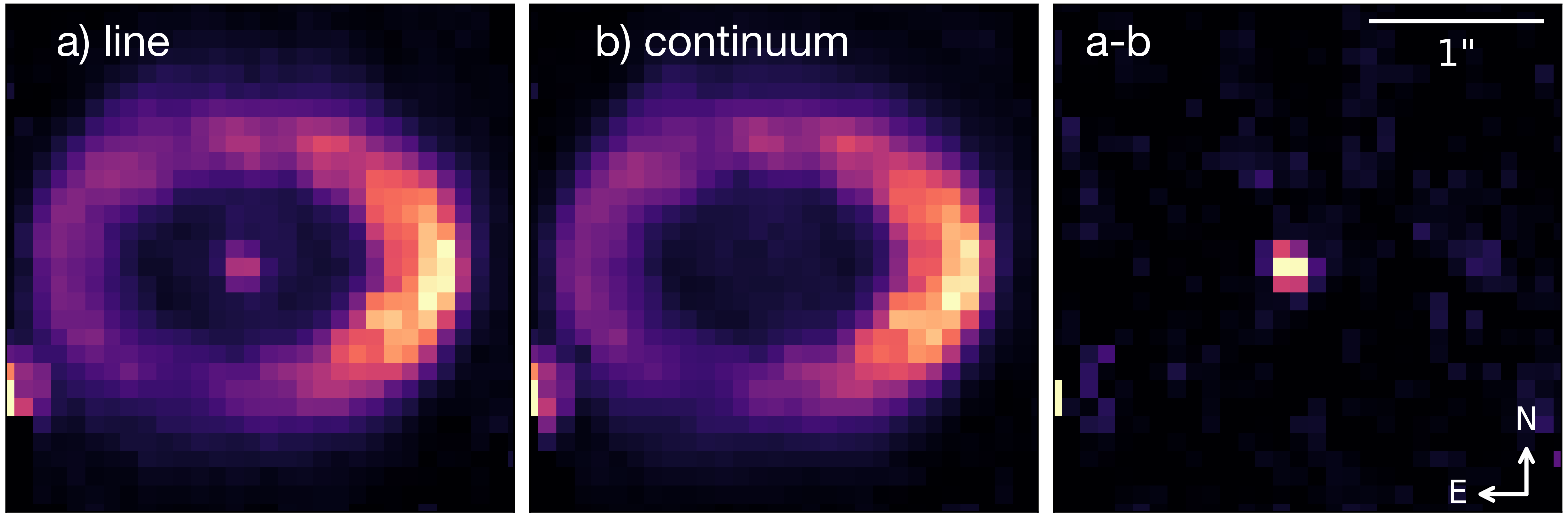


Clear diffuse component at ~0 km s^{-1}, similar to other high-ionisation lines seen with MRS.

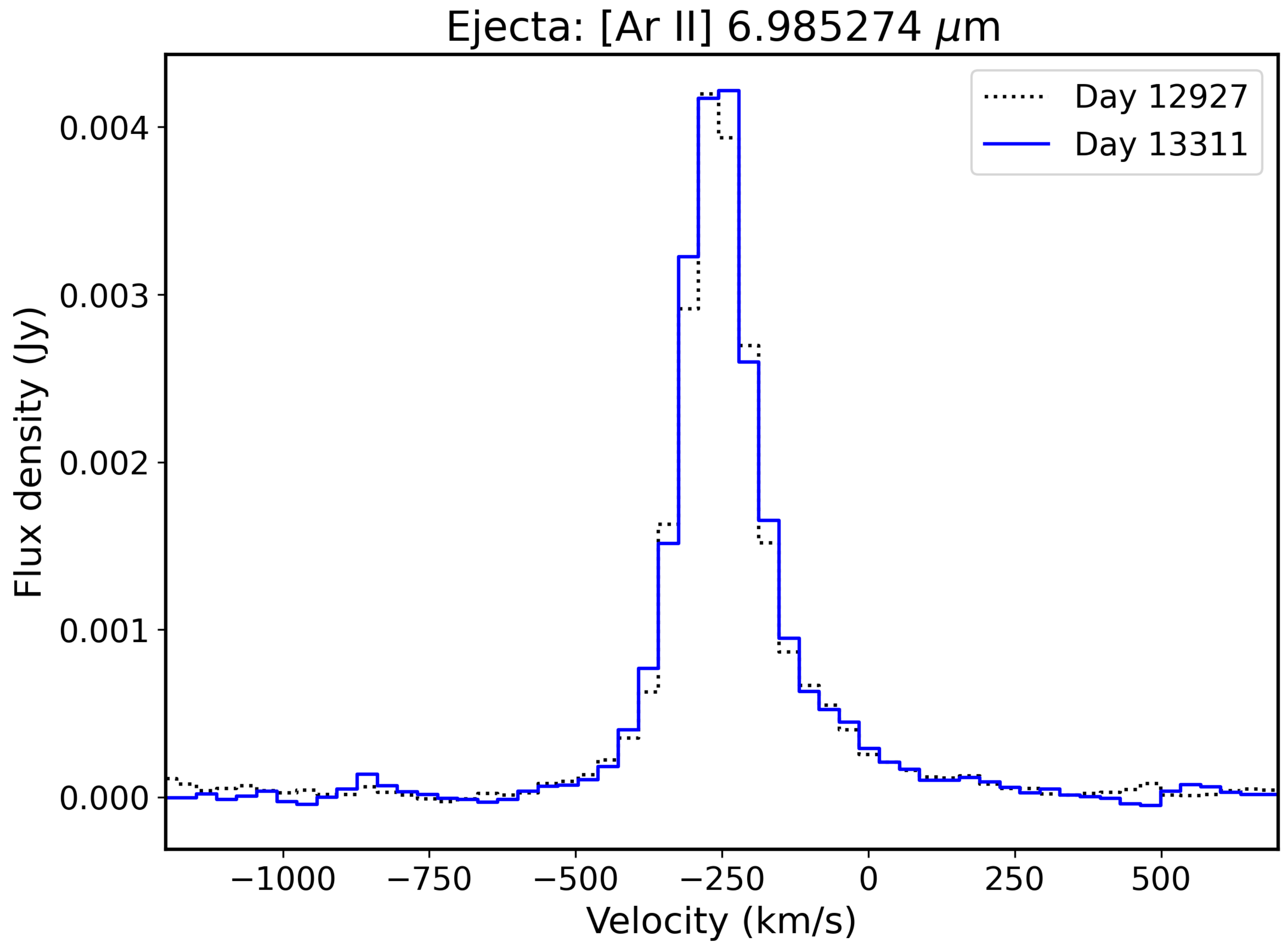
Surrounding gas flash-ionised by the SN and/or ring?

Blue component consistent with [Ar II] line.

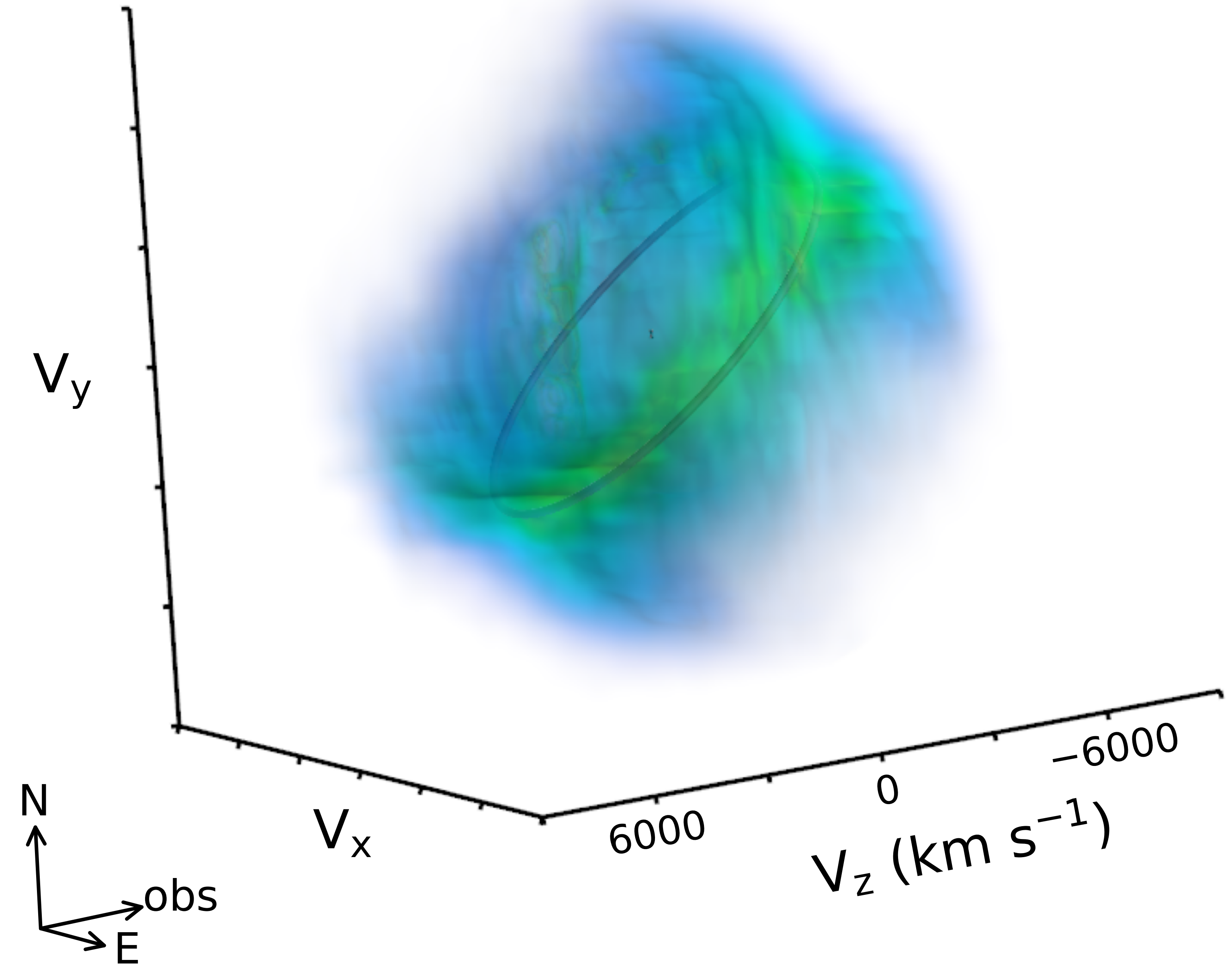
[Ar VI] 13500 days



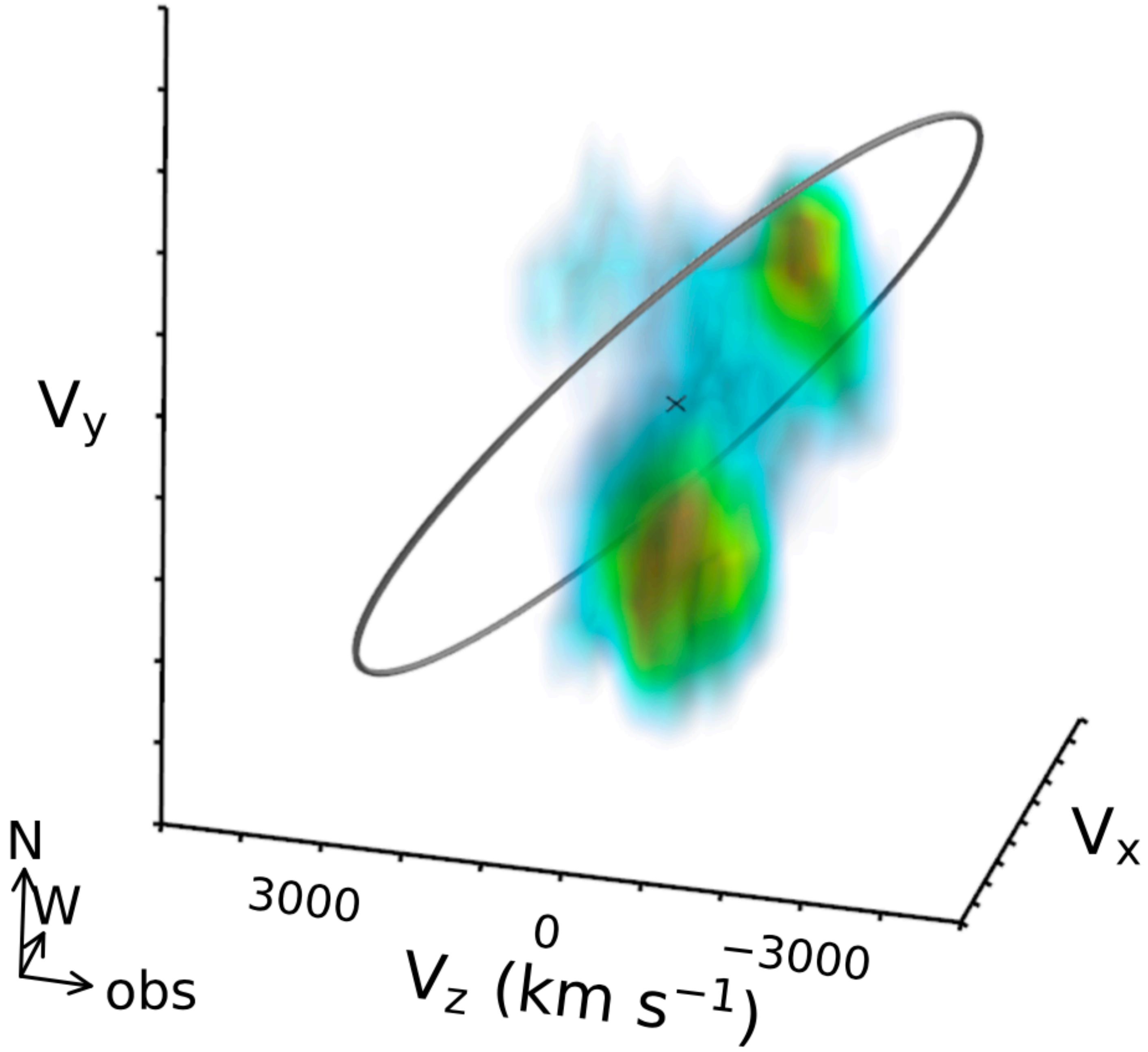
MRS cycle 2 data of [Ar II] line shows no significant change.



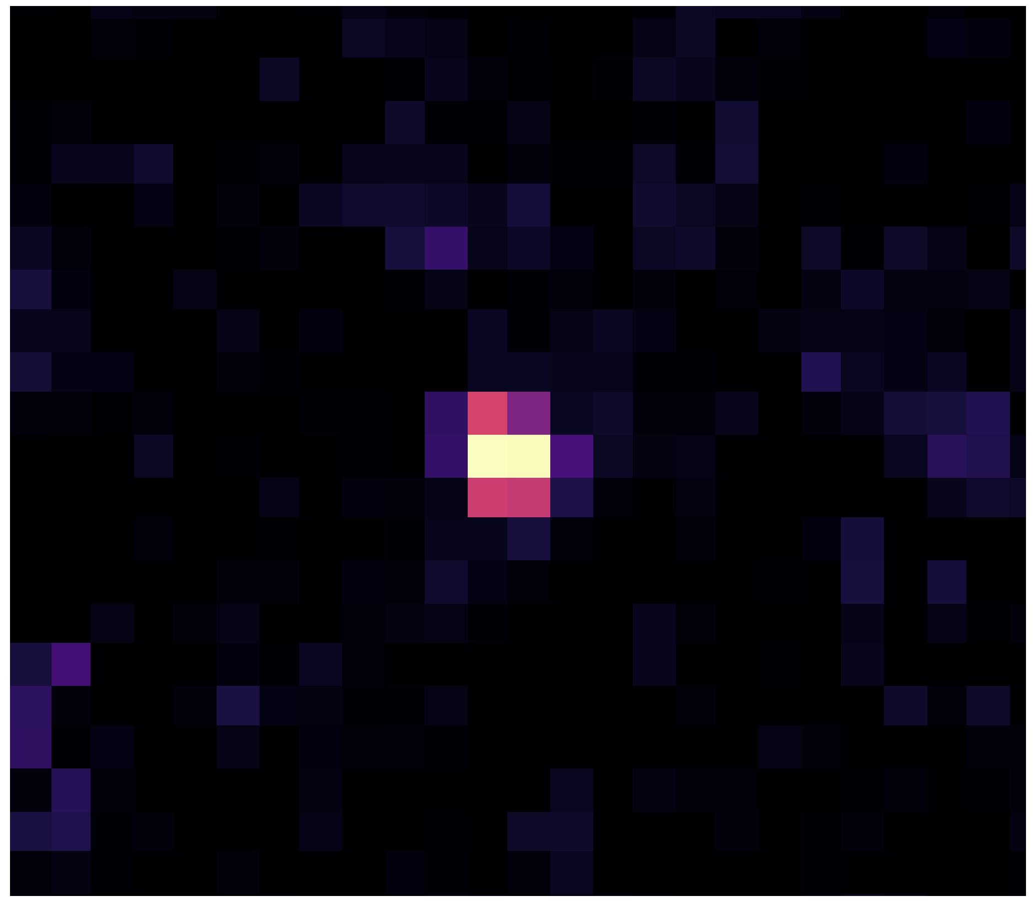
Summary



I. Outer ejecta interacting with the reverse shock - bubble-like CSM.



II. Highly asymmetric Fe-rich inner ejecta.



III. A small clump of ejecta ionised by the compact object.

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