A Three-Dimensional Kinematic Reconstruction of Supernova Remnant N132D's High-Velocity, Oxygen-rich Ejecta

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Supernova Remnants II, Chania, Crete, Greece – Jun. 7, 2019

Understanding CCSNe explosion asymmetry

- Observations and hydrodynamic models have shown that CCSNe are intrinsically aspherical events with highly clumpy ejecta

  Wang & Wheeler 08, Nordhaus+10, Janka+12, Tanaka+12, 17

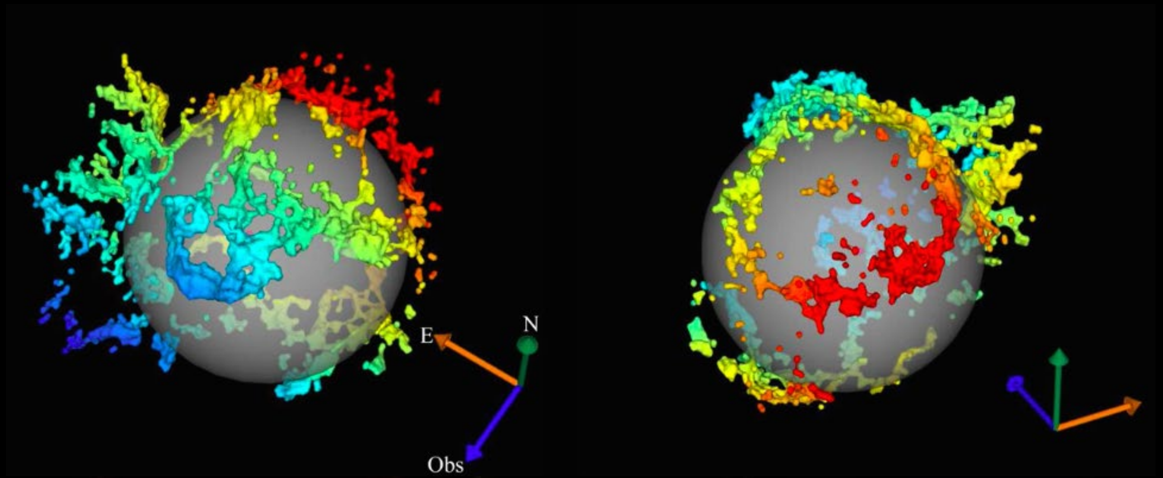
- Late-time (t > 6 months) optical spectra exhibit multi-peaked emission line profiles consistent with aspherical axisymmetric explosions

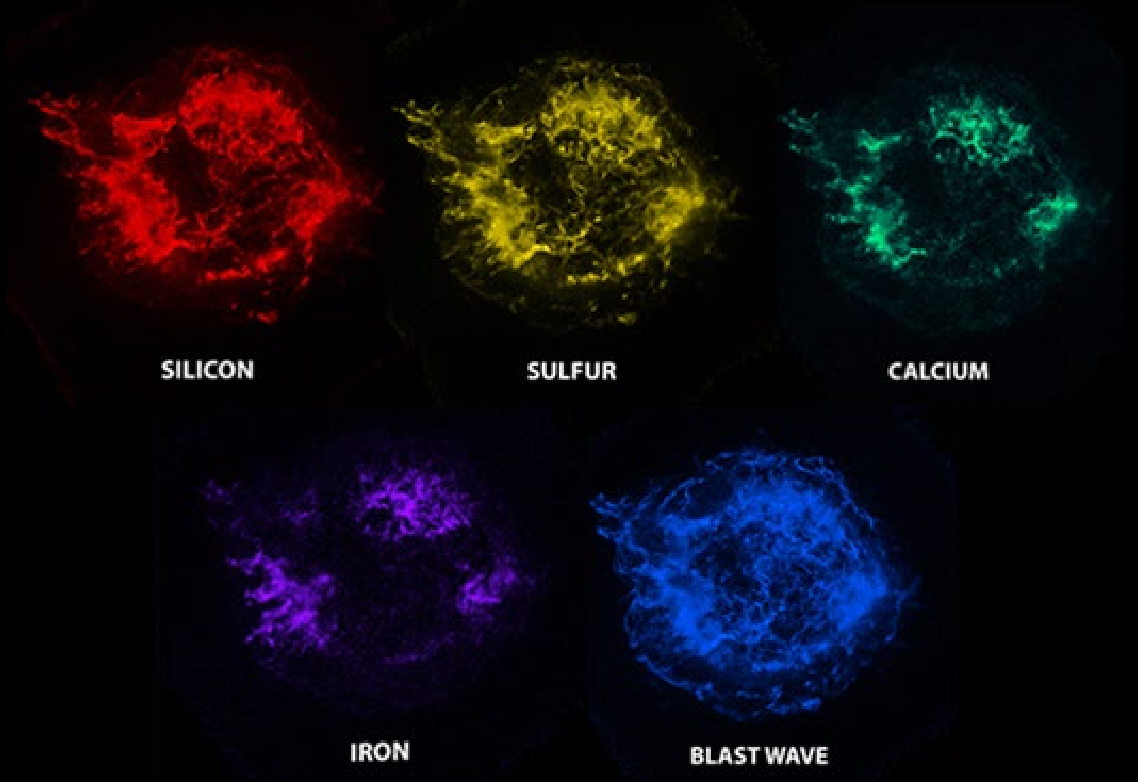
  Mazzali+05, Modjaz+08, Taubenberger+09, Milisavljevic+10

- Spectropolarimetry studies have shown asymmetries in the inner ejecta layers

  Maund+09, Tanaka+08, 12, Bilinski+18, Stevance+18

- Origin of asphericities <u>is still uncertain</u>



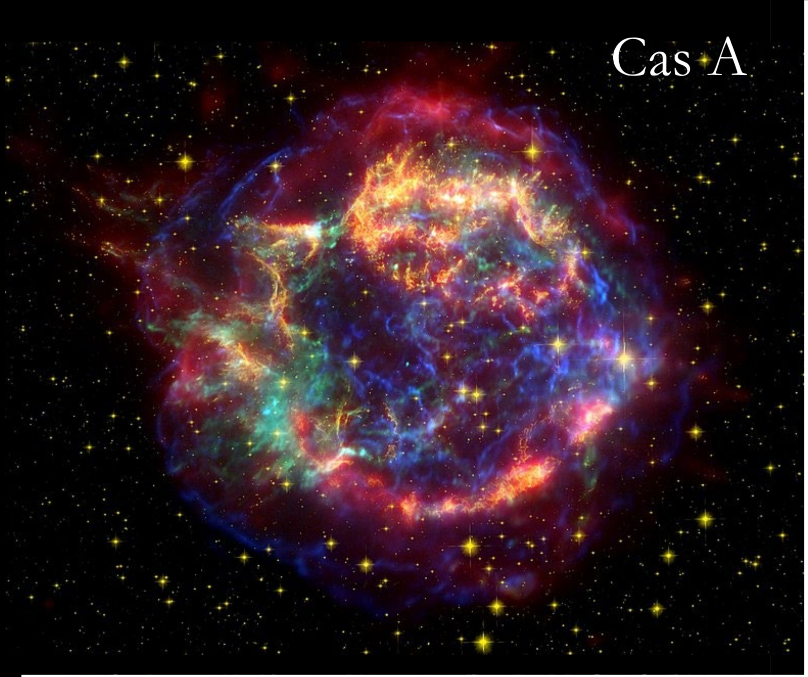


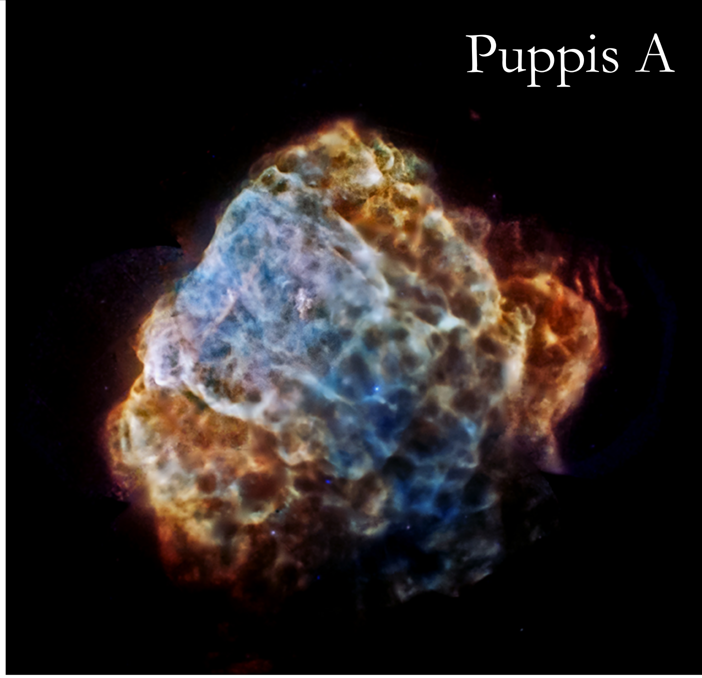
Oxygen-rich SNRs

- Category of young remnants with enhanced abundances of O, Ne, and S with radial velocities > 1000 km/s

- Comprise the ejected stellar interiors from He-burnt layers of massive stars

- Ideal for studies of stellar evolution and core collapse explosion mechanisms

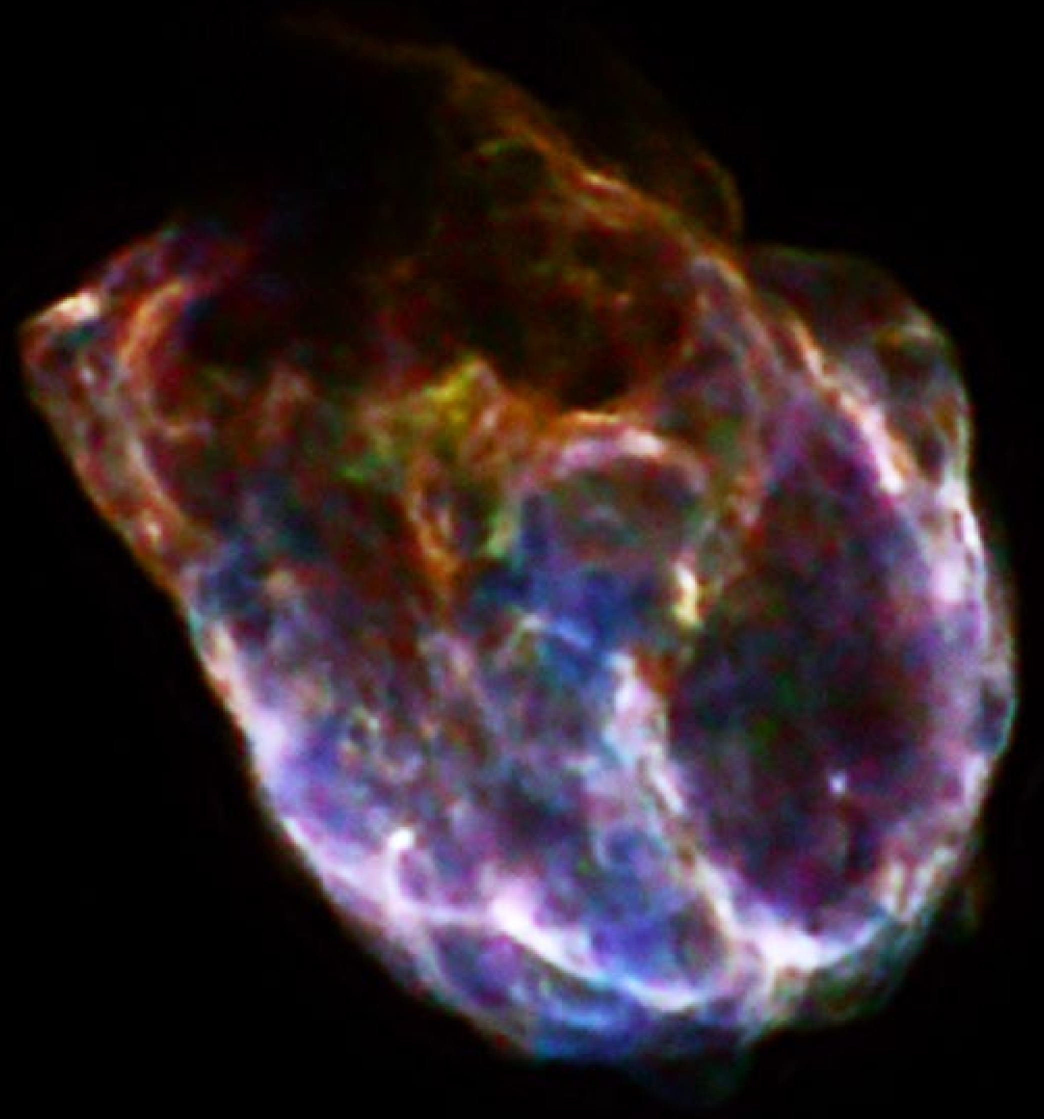




Lasker & Golimowski 91, Morse 03

N132D

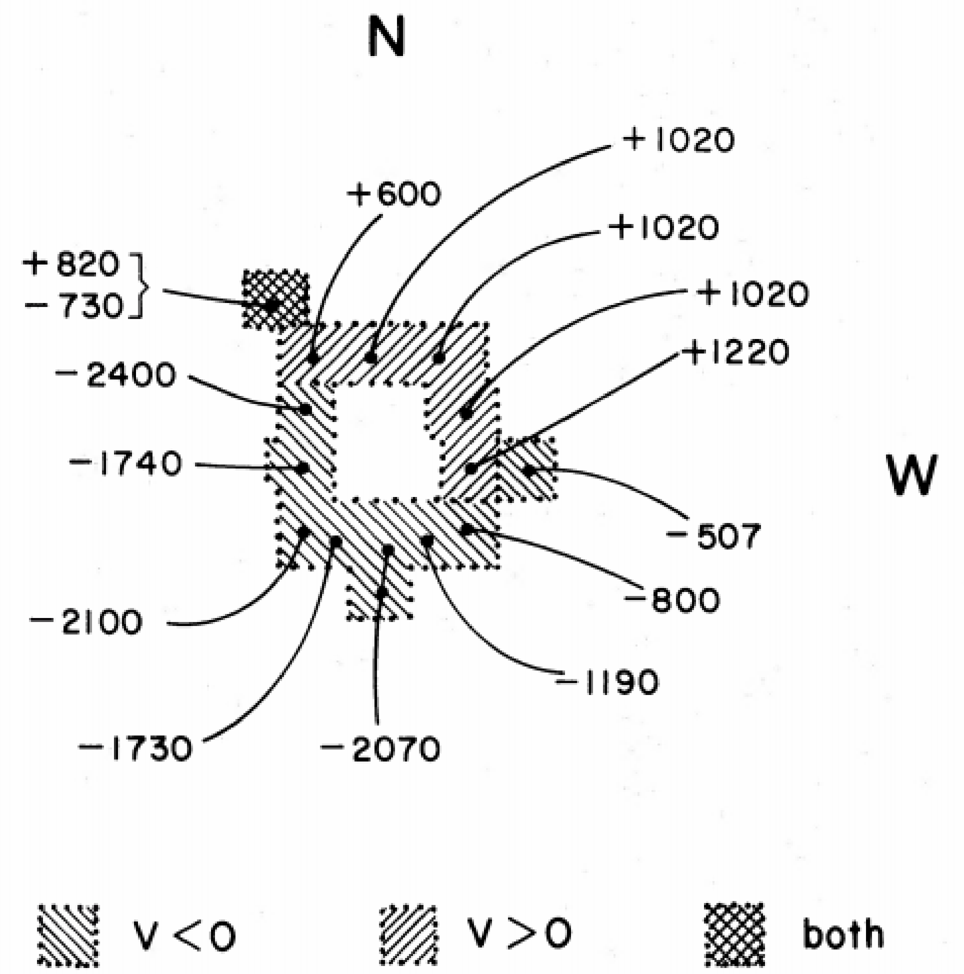
- In stellar bar in LMC
  - d =50 kpc
- Horseshoe-shaped forward shock
- Oxygen-rich ejecta discovered in 1966
  - [O III] 5007 Å line
  - V_r range of 4500 km/s
  - 12 pc diameter ring
- Type Ib (?) CCSN
- SNR Age: 1300 – 3440 yrs



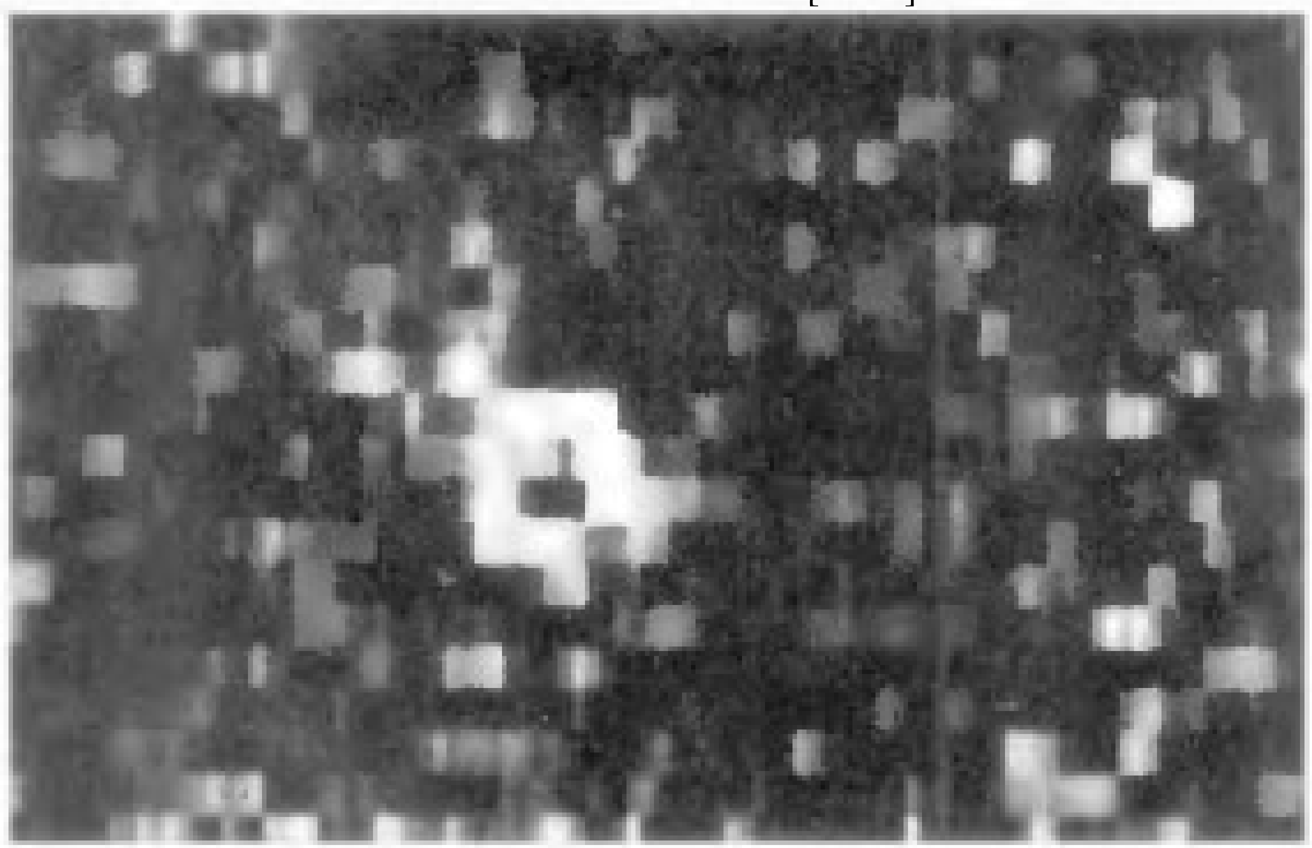
Westerlund & Mathewson 66, Morse+95, Blair+00, Bamba+18, Dopita+18

Initial efforts to map 3D structure of N132D

- Initial observations revealed a thin, inclined ring due to an annular expansion of 2250 km/s in a plane inclined at 45°



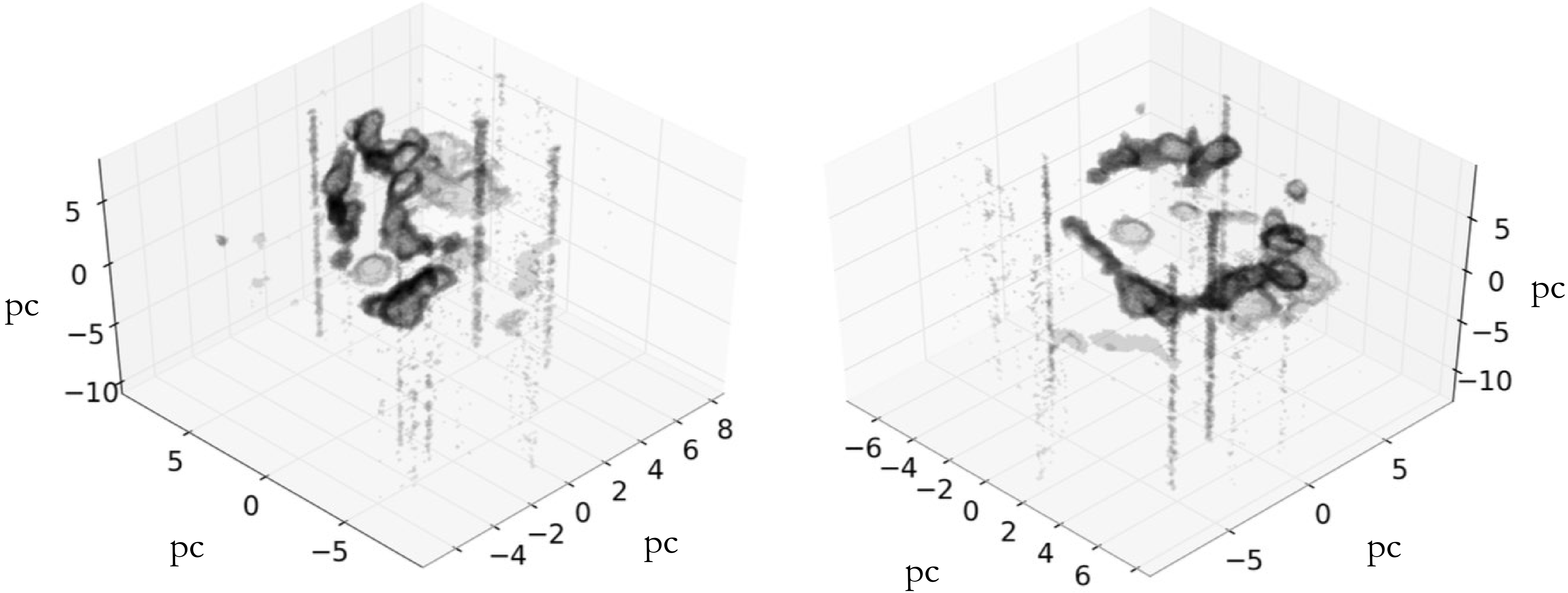
$V_{[O\ III]} > |600\ km/s\ |$



CTIO 1.5 m, Lasker 80

Stereoscopic maps of N132D

- Using observations of [O III] doublet from Siding Spring Observatory, 2.3 m ANU telescope



Vogt & Dopita 11

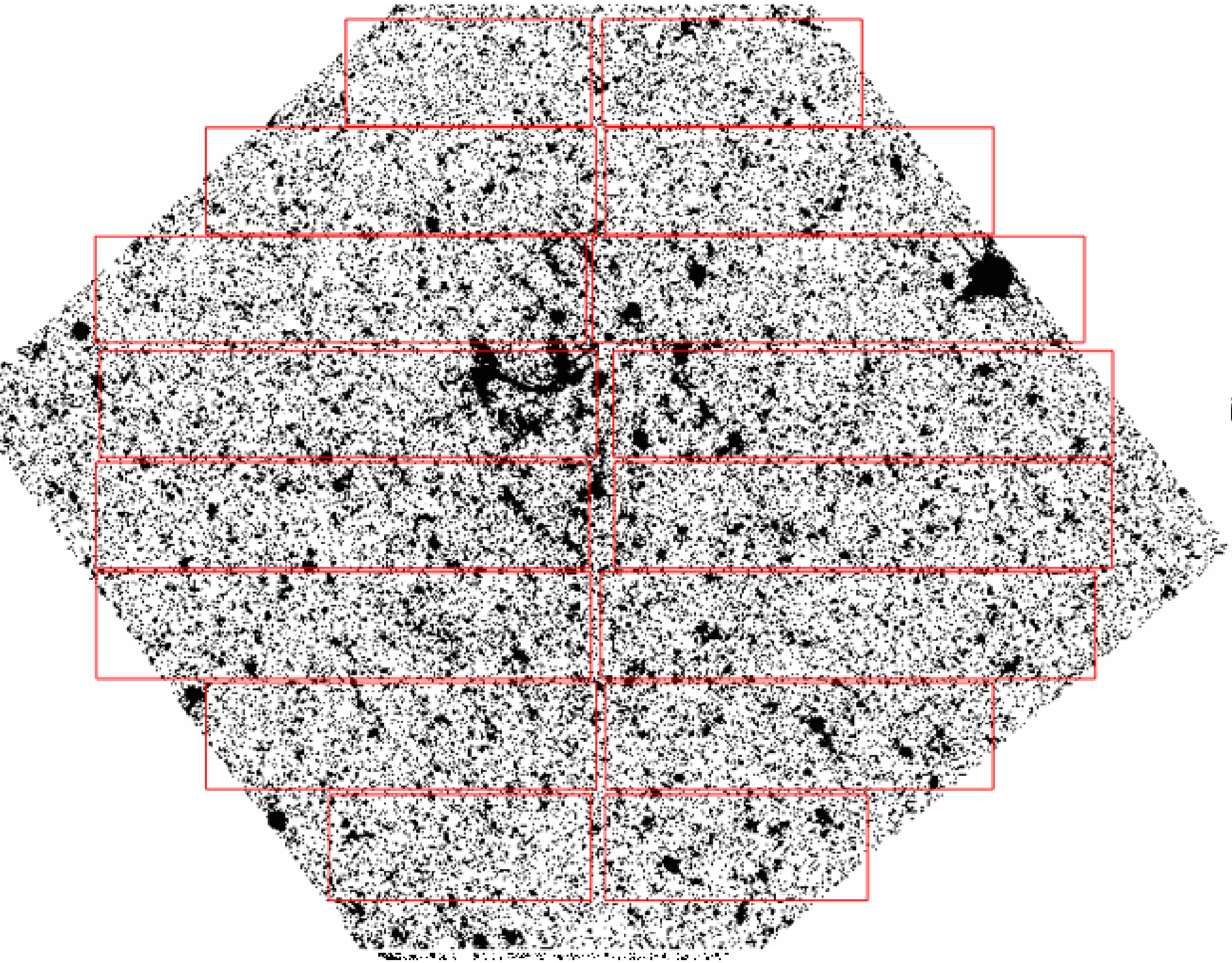
Observations

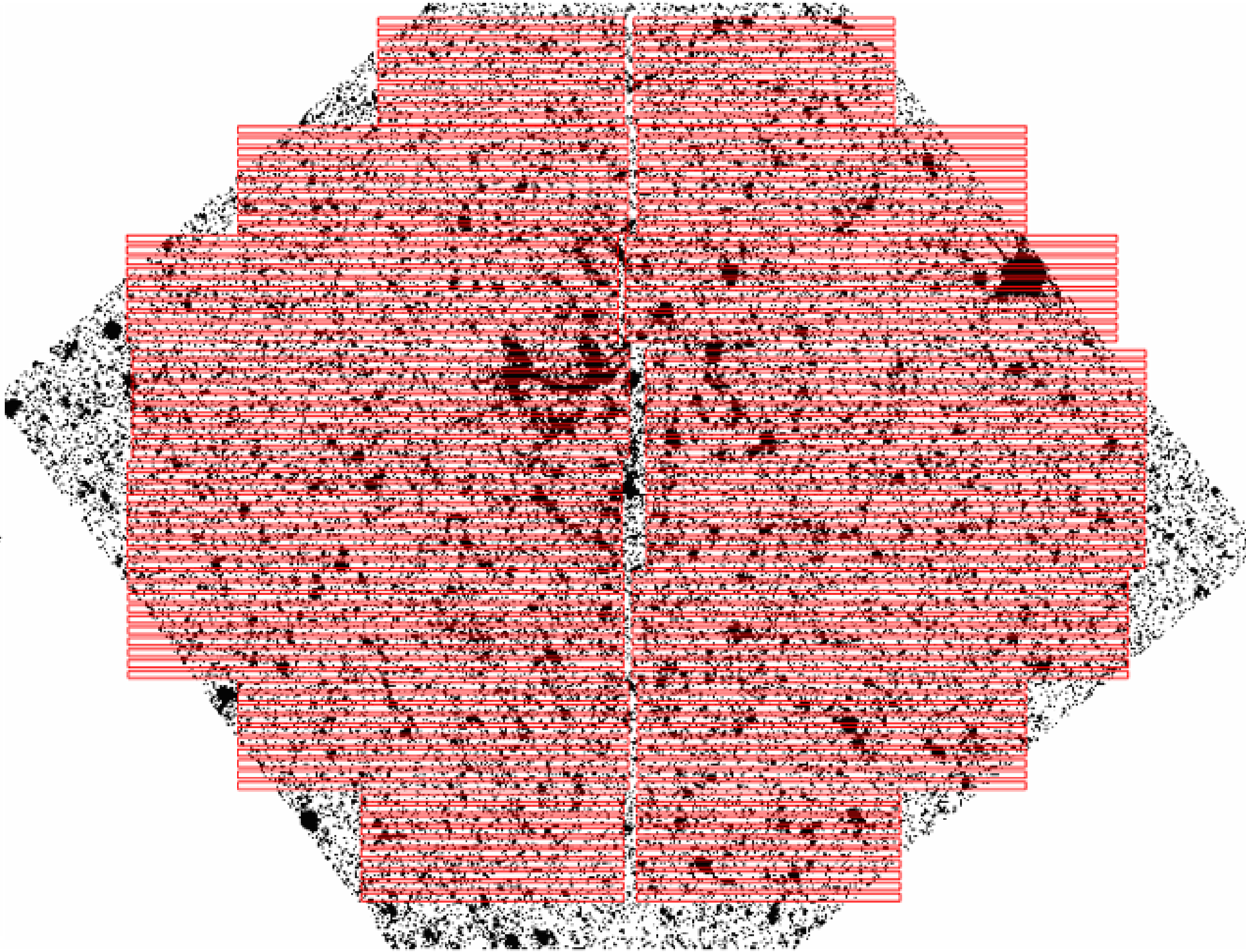
- On Dec 31, 2015 – Jan 1, 2016
- Magellan 6.5 m telescope with IMACS spectrograph + GISMO instrument
  - Coverage: 3650 – 6750 Å
  - Resolution: FWHM 5.5 Å
  - Seeing: 0.7-1.0 arcsec
  - Exposures: 2 x 800 sec
- Used [O III] 4959, 5007 Å emission to map N132D kinematics

PI: D. Milisavljevic

Covered 67% of remnant with long-slit spectroscopy

- 110” x 1.6”, E-S orientation
- Moved in increments of 2.4” in N-S direction





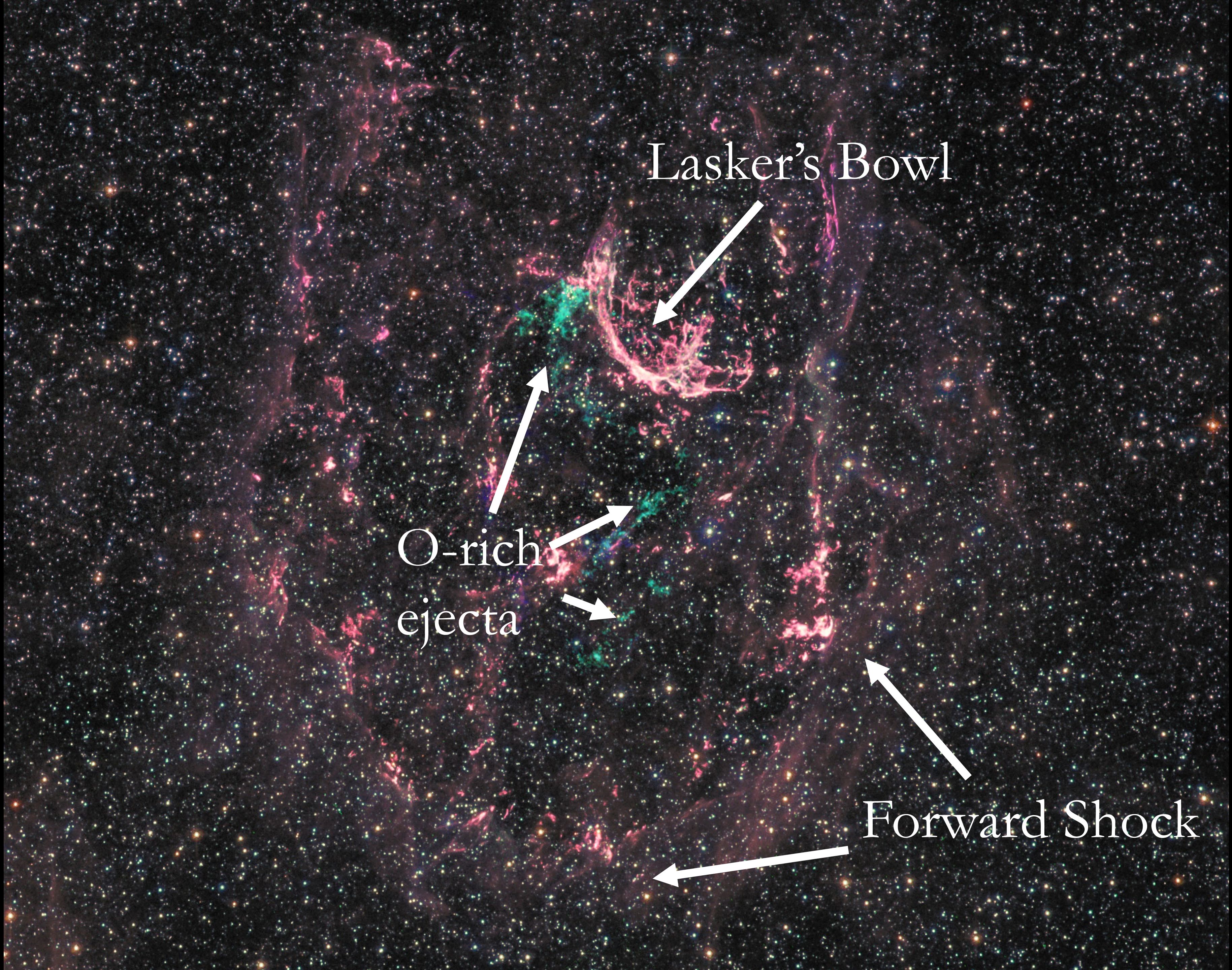
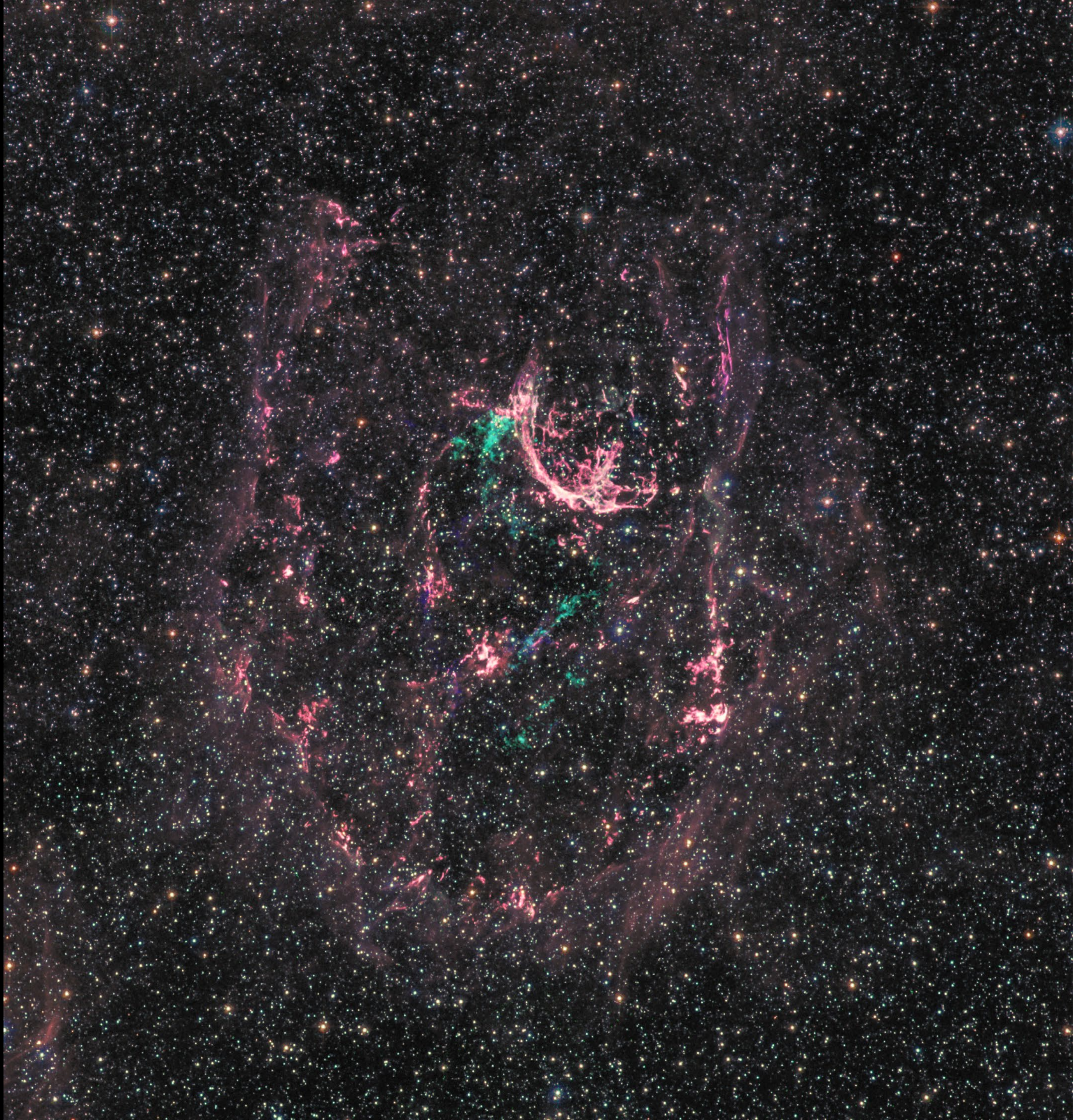
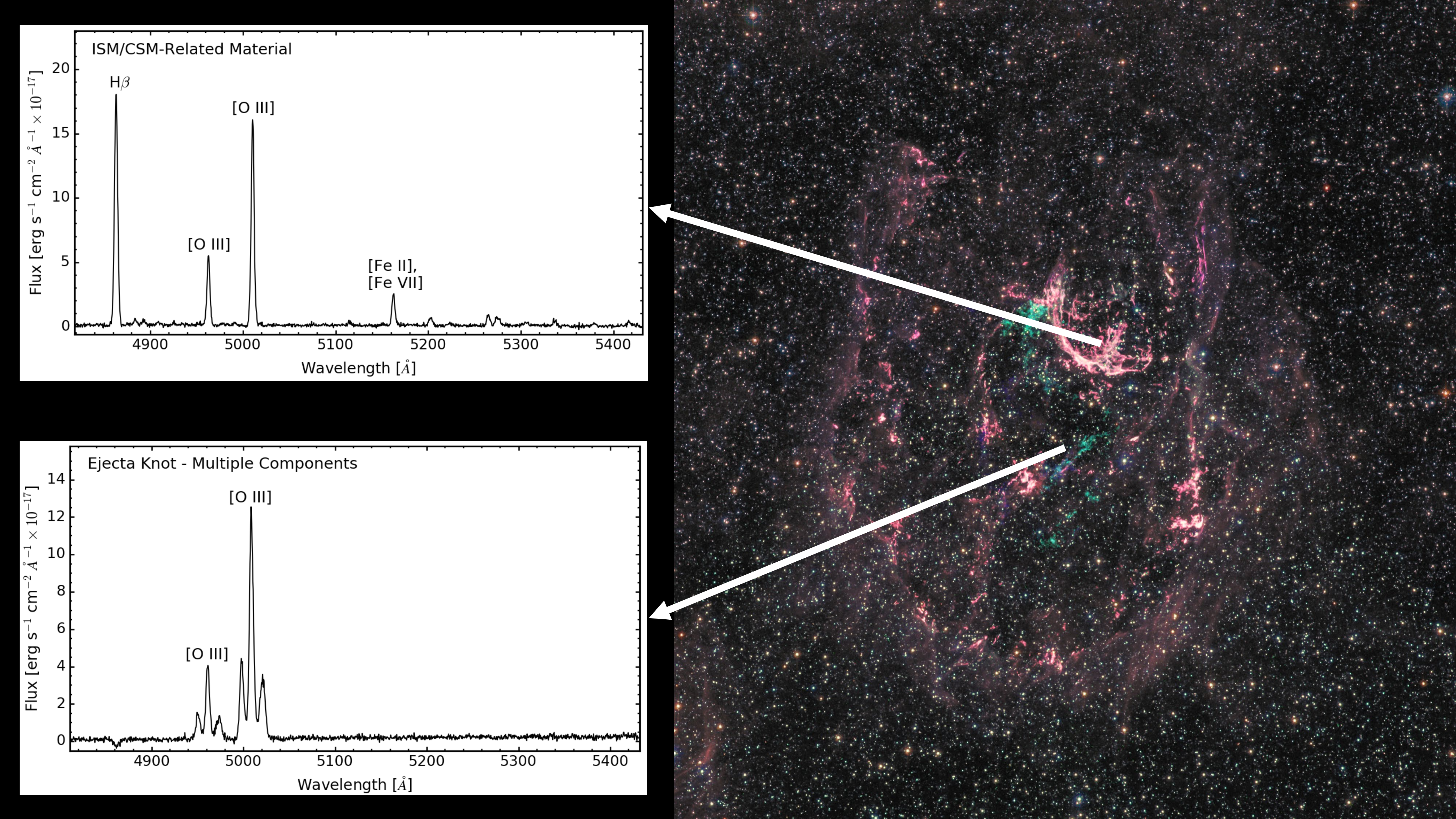


Image Credit:
J. Schmidt

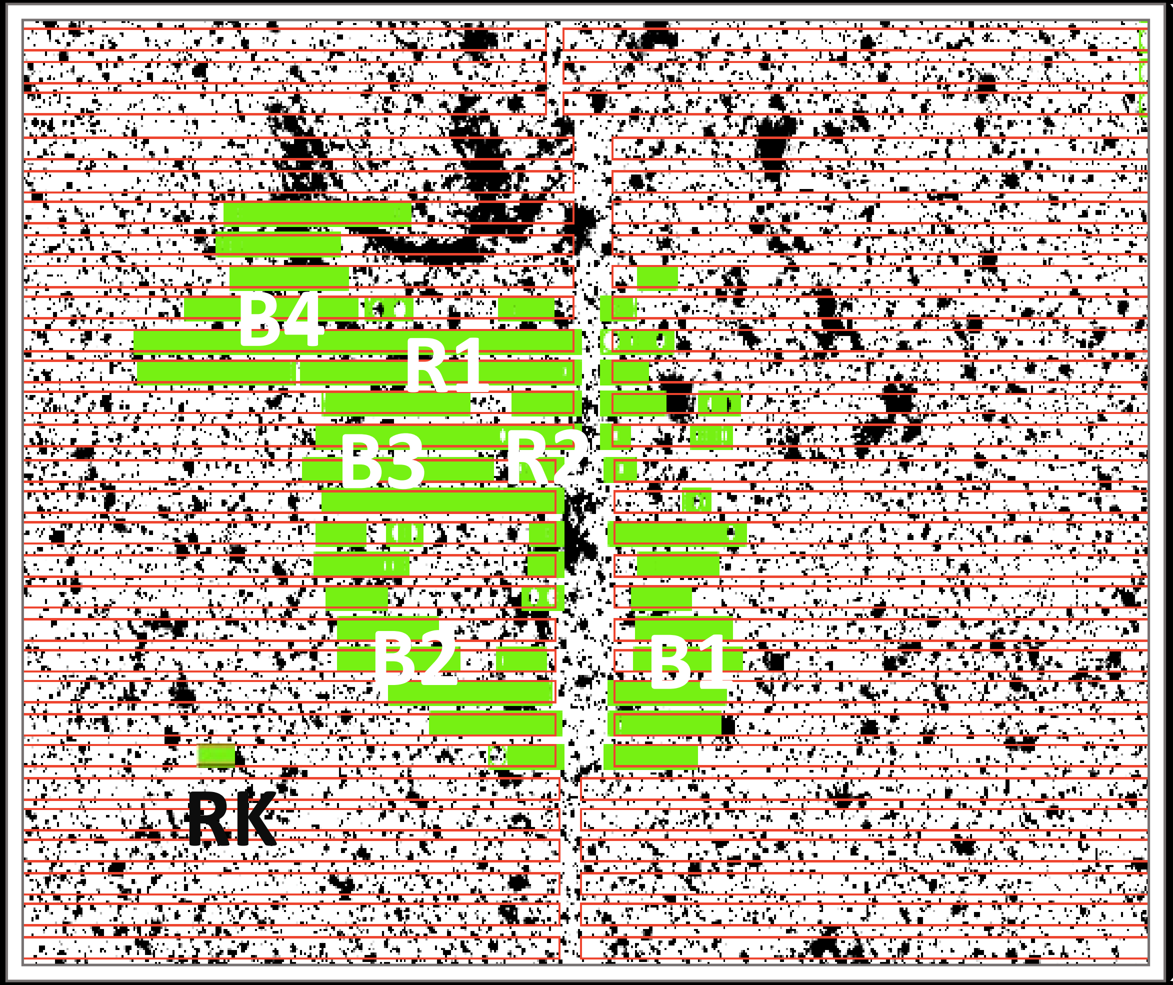
how to identify
true O-rich ejecta?

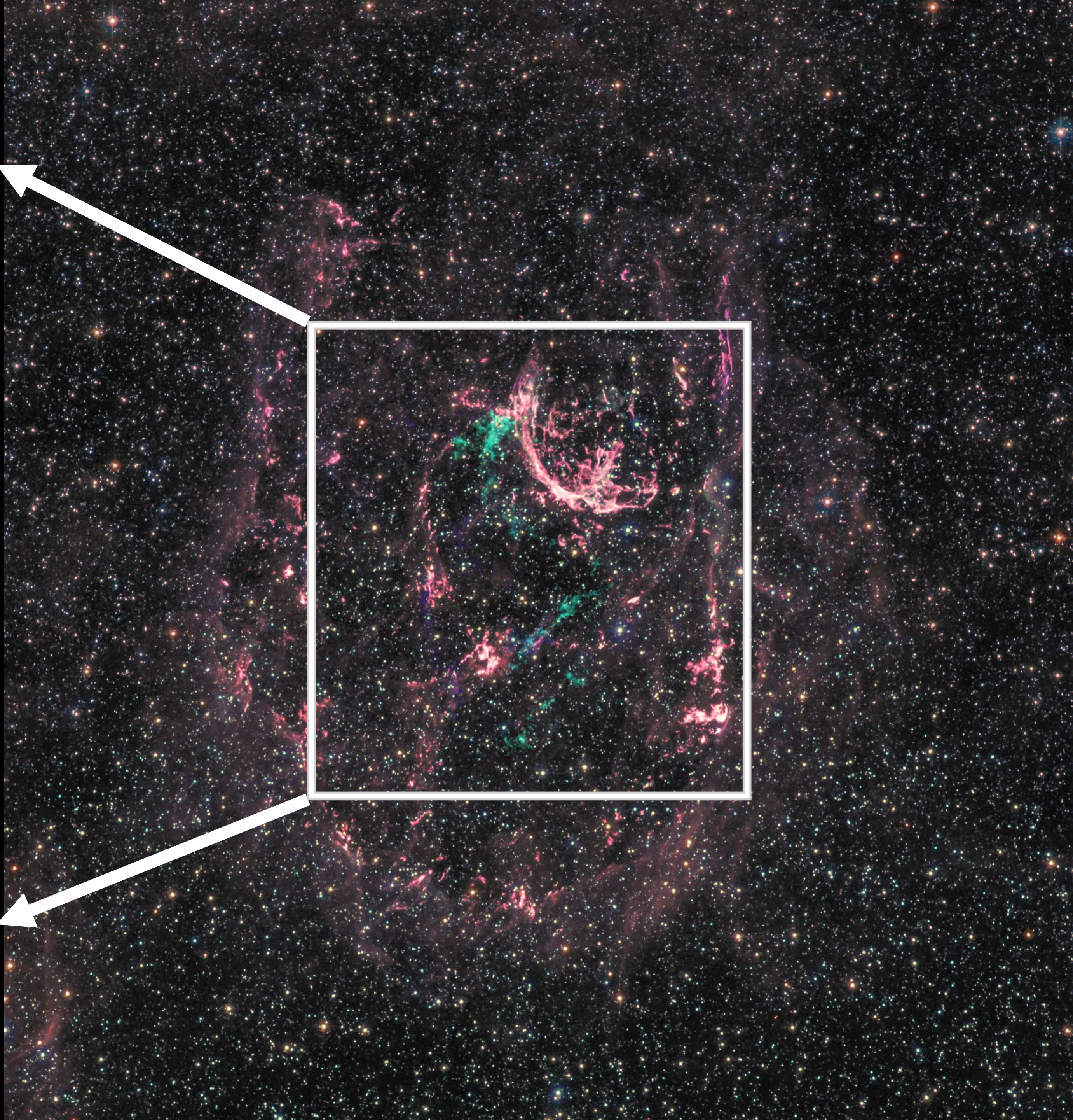




ISM/CSM-Related Material
Hβ
[O III]
[O III]
[Fe II],
[Fe VII]
Flux [erg s^{-1} cm^{-2} Å^{-1} × 10^{-17}]
Wavelength [Å]
Ejecta Knot - Multiple Components
[O III]
[O III]
Flux [erg s^{-1} cm^{-2} Å^{-1} × 10^{-17}]
Wavelength [Å]

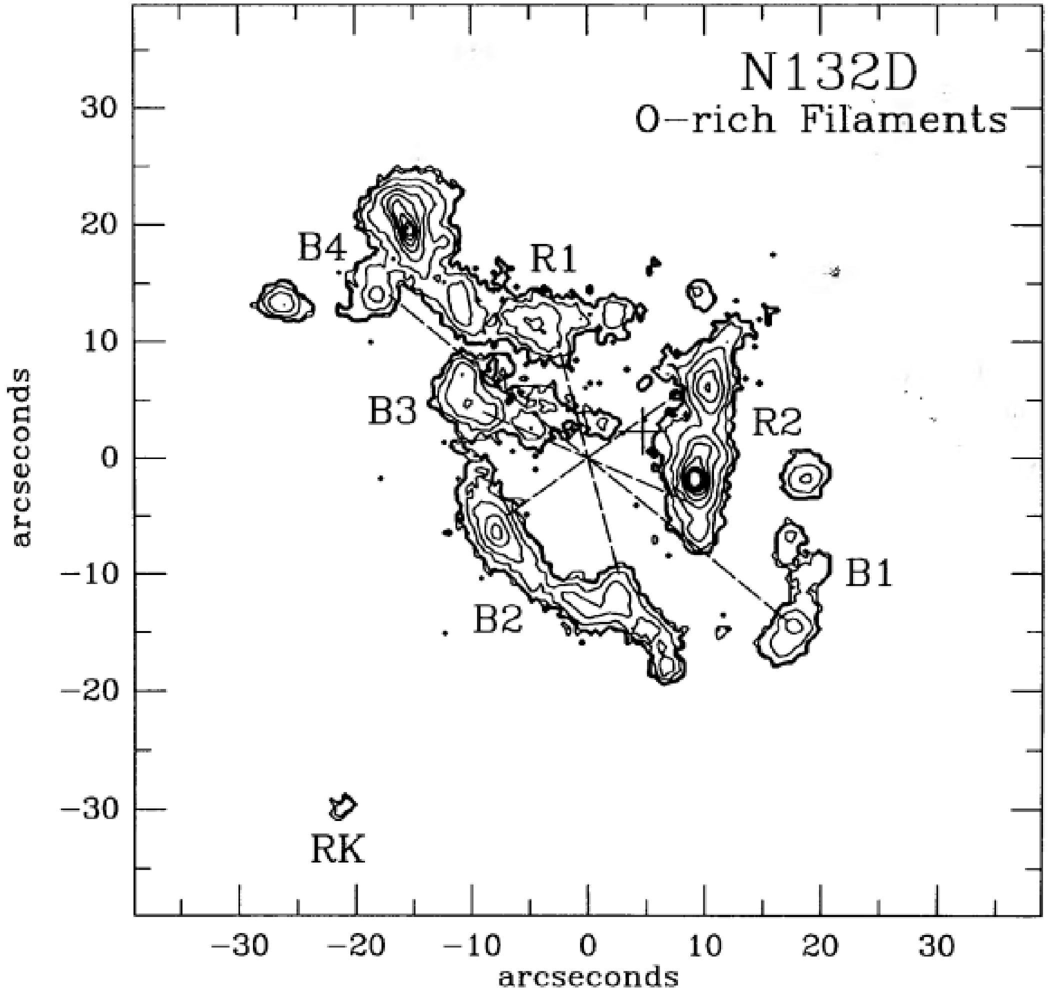
detected O-rich knots



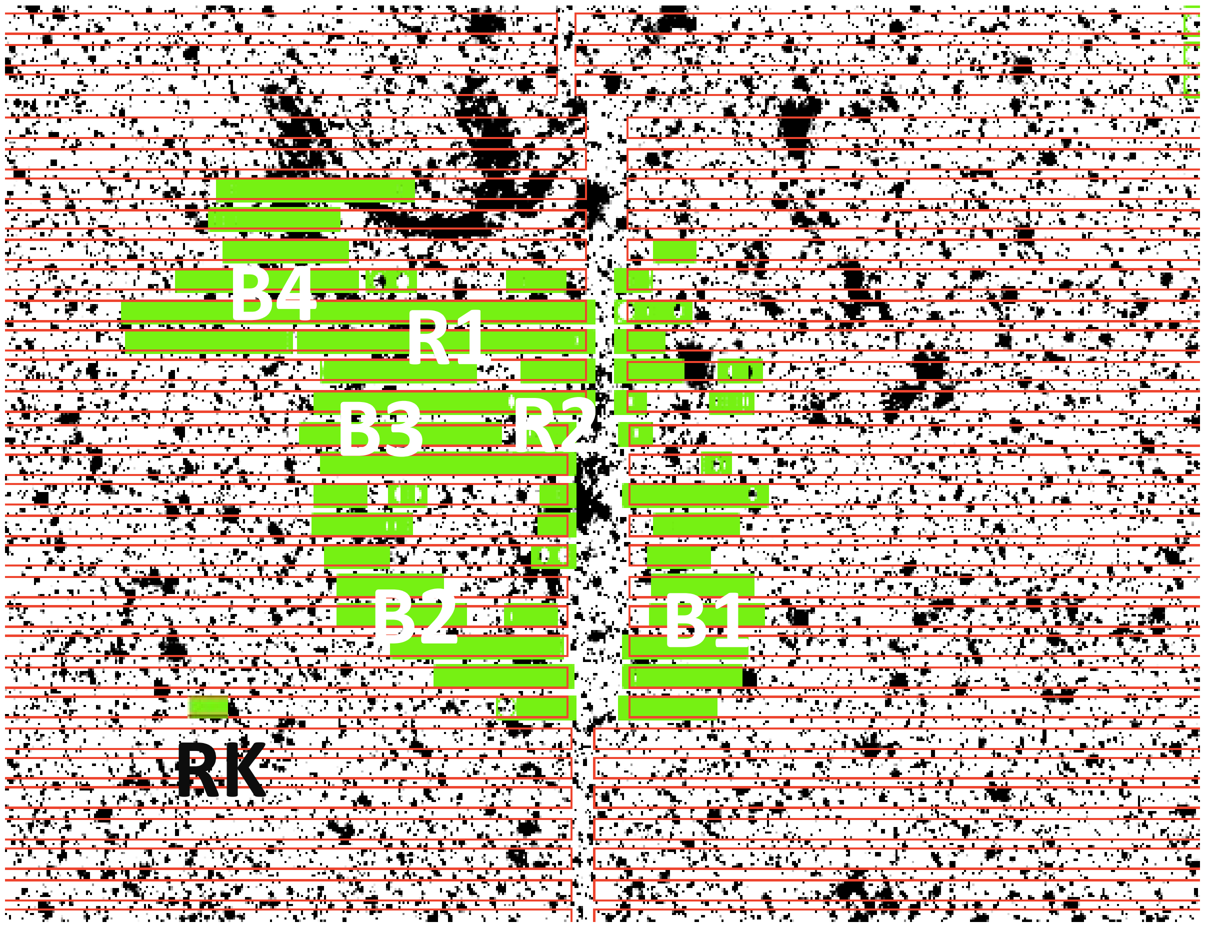


O-rich knots comparison

Morse, Winkler, & Kirshner 1995

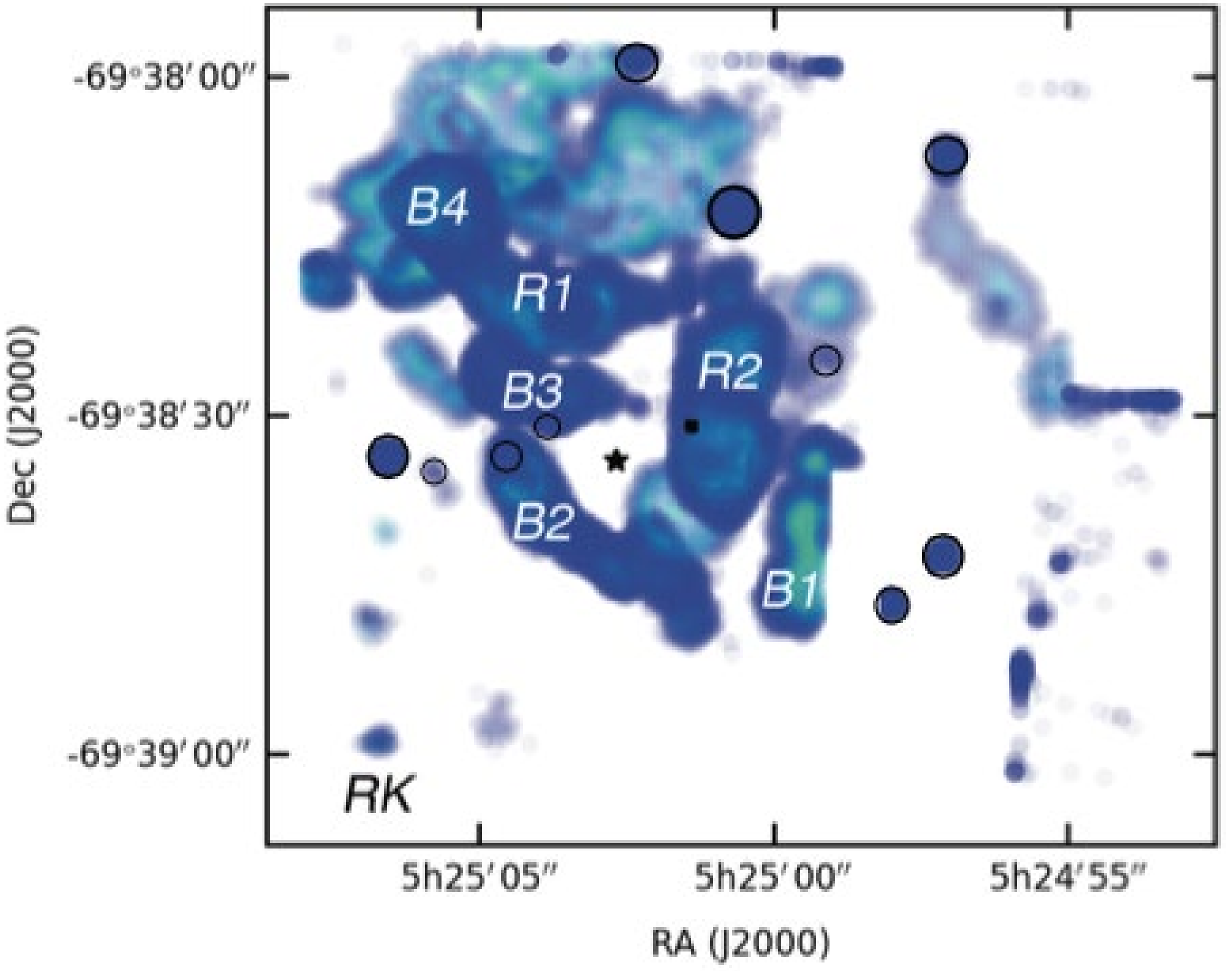


This work



O-rich knots comparison

Vogt & Dopita 2011



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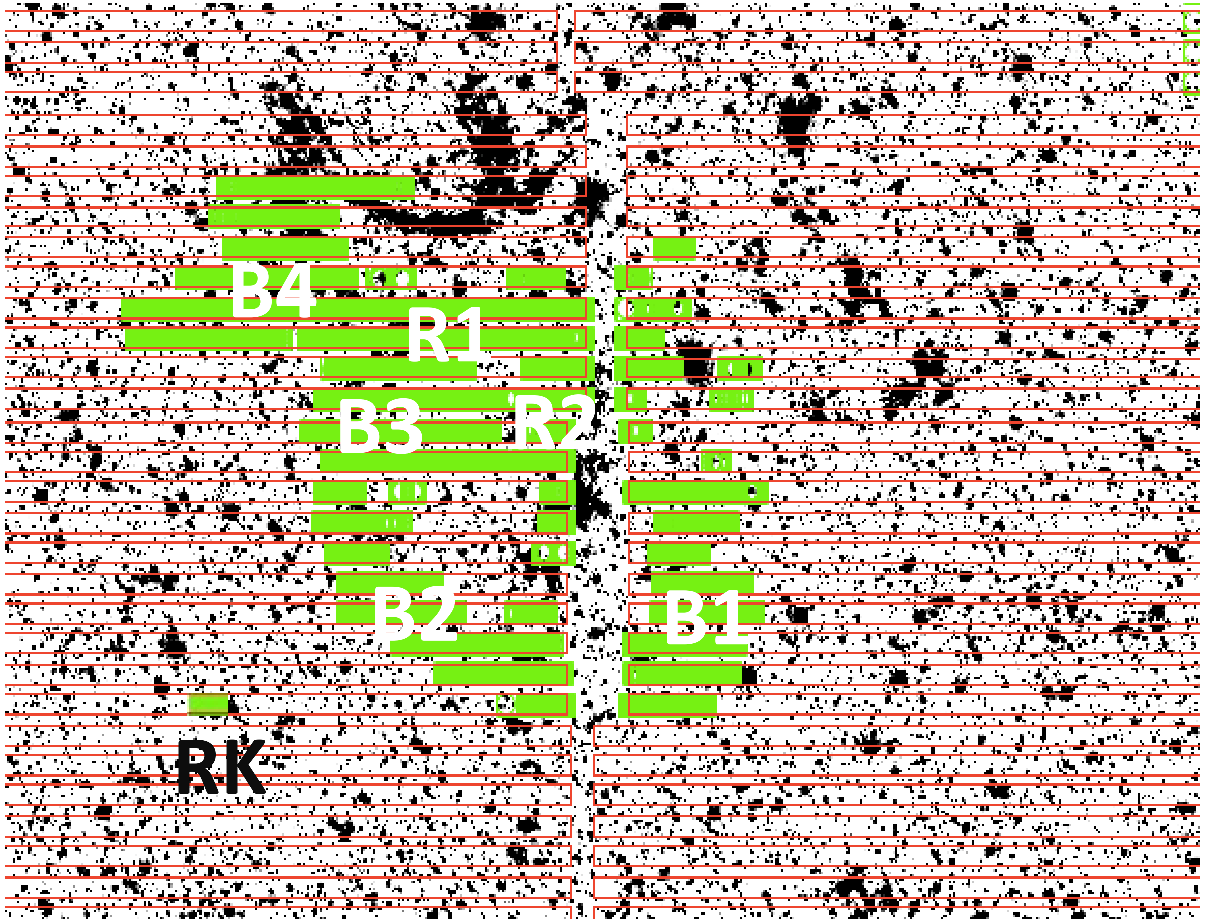
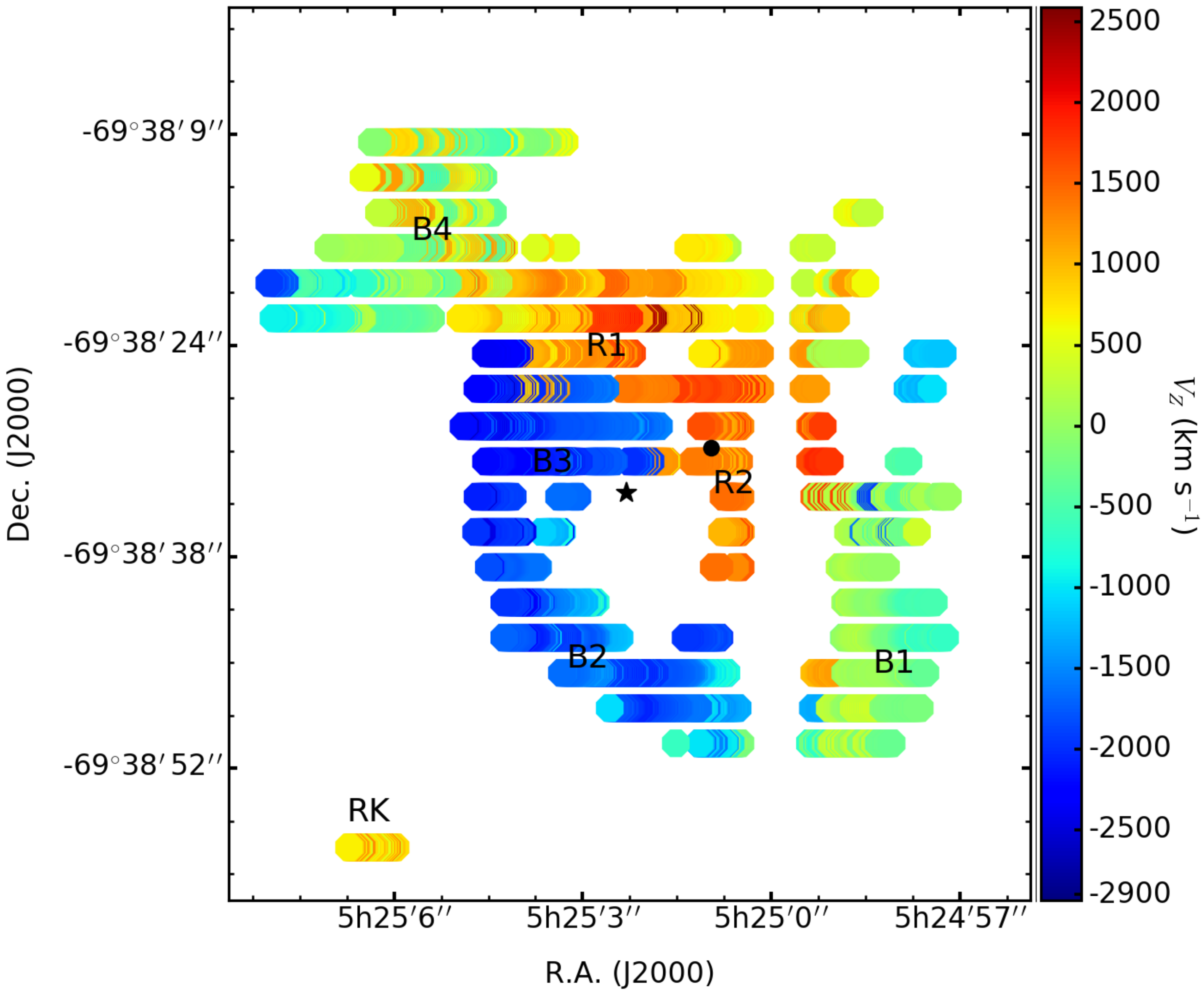


Full RA-Dec-V_r data

- 3D model from secure high-velocity knot detections
  - i.e., *bona fide* O-rich knots
- From our survey:
  - 4126 individual data points
  - >99% from main shell ejecta
- Center of explosion at center of symmetric distribution of O-rich ejecta from Morse+95 [*]



Making the 3D reconstruction

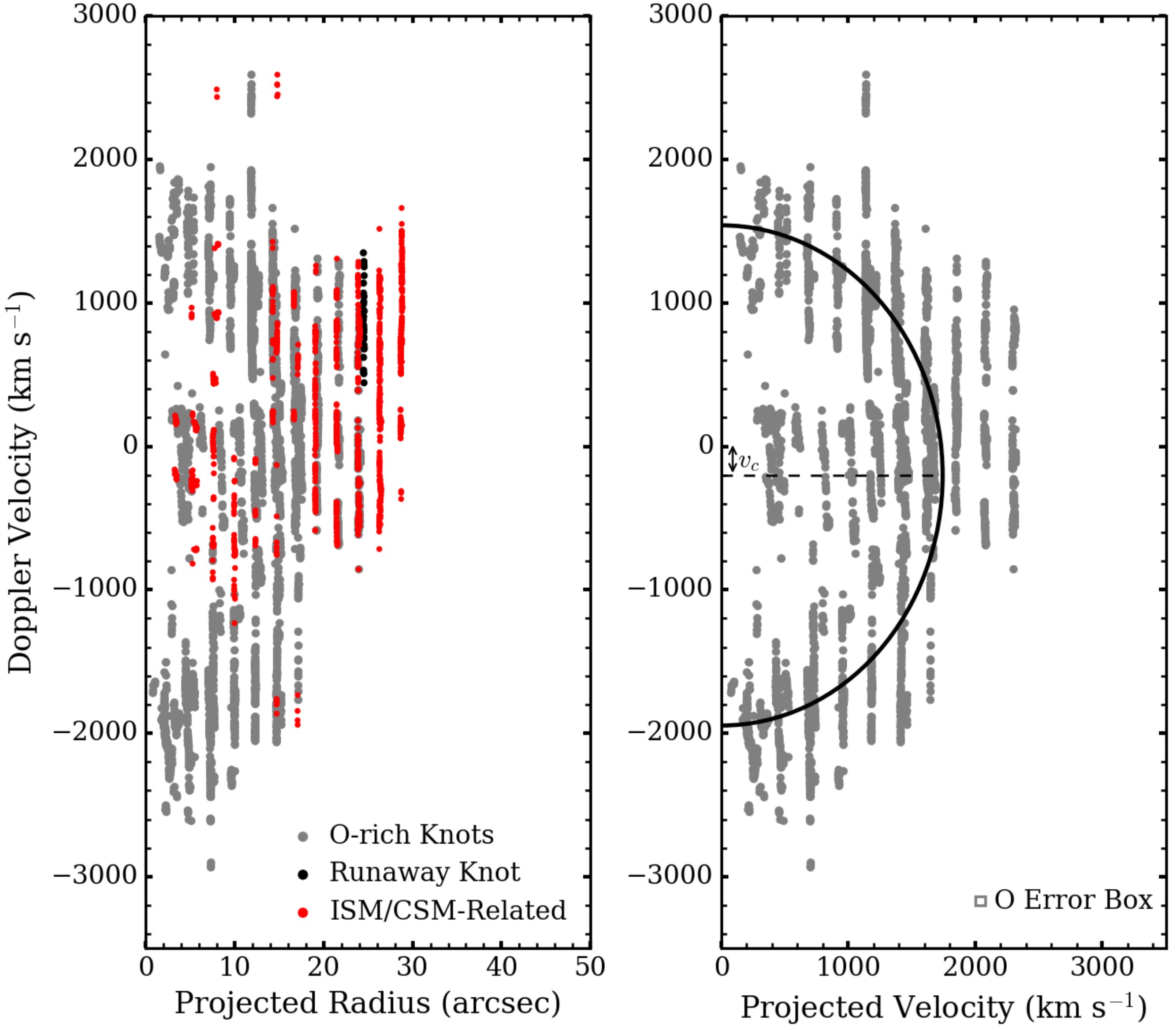
- Assume ballistic trajectories:

$$v = r \times S$$

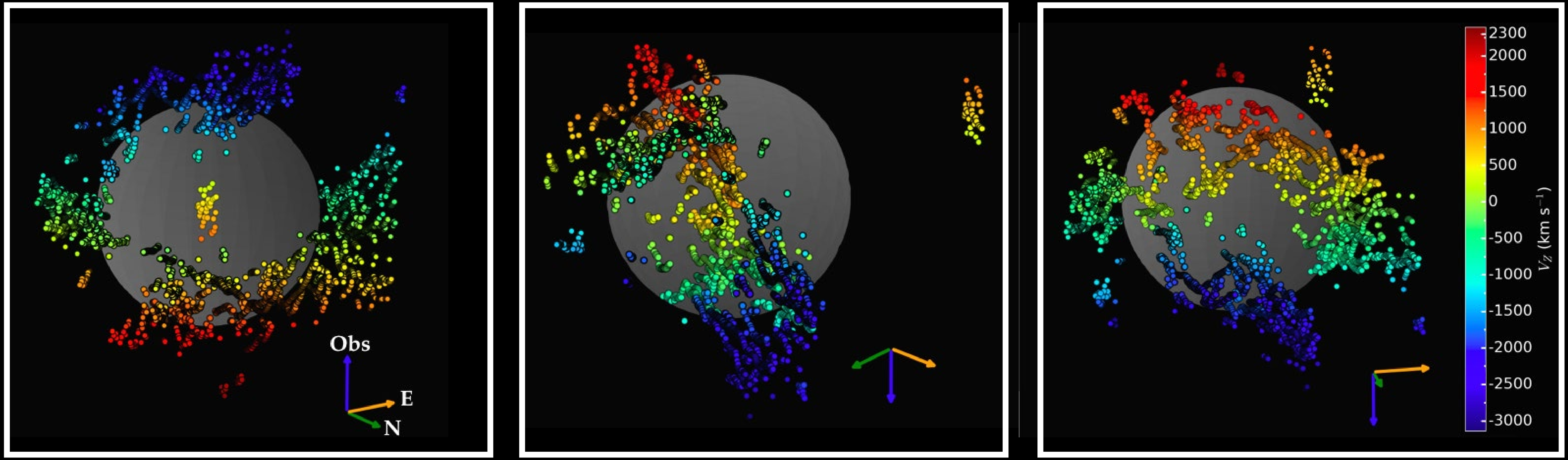
- And spherical expansion model
- Fit semi-circle model to velocity distribution and observed projected radius:

$$(r_p/S)^2 + (v_D - v_c)^2 = (v_c - v_m)^2$$

- S = 96 ± 2 km s^{-1} per arcsec



N132D in 3D velocity space

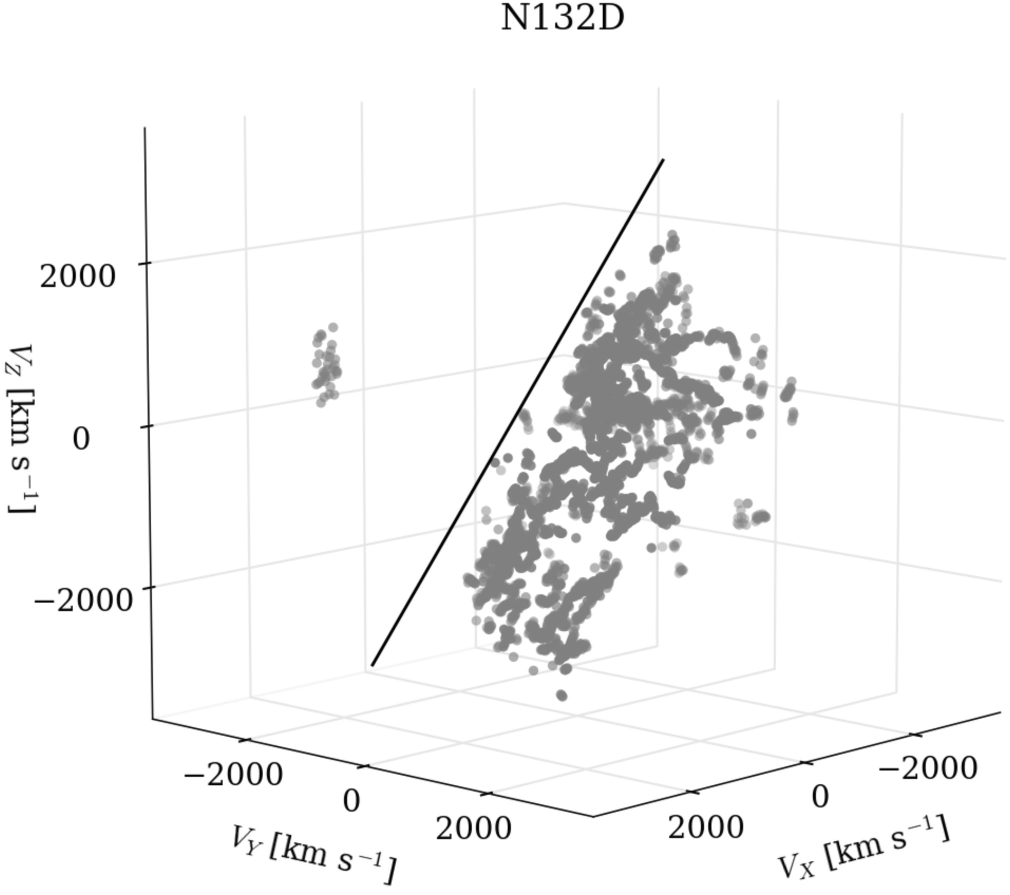


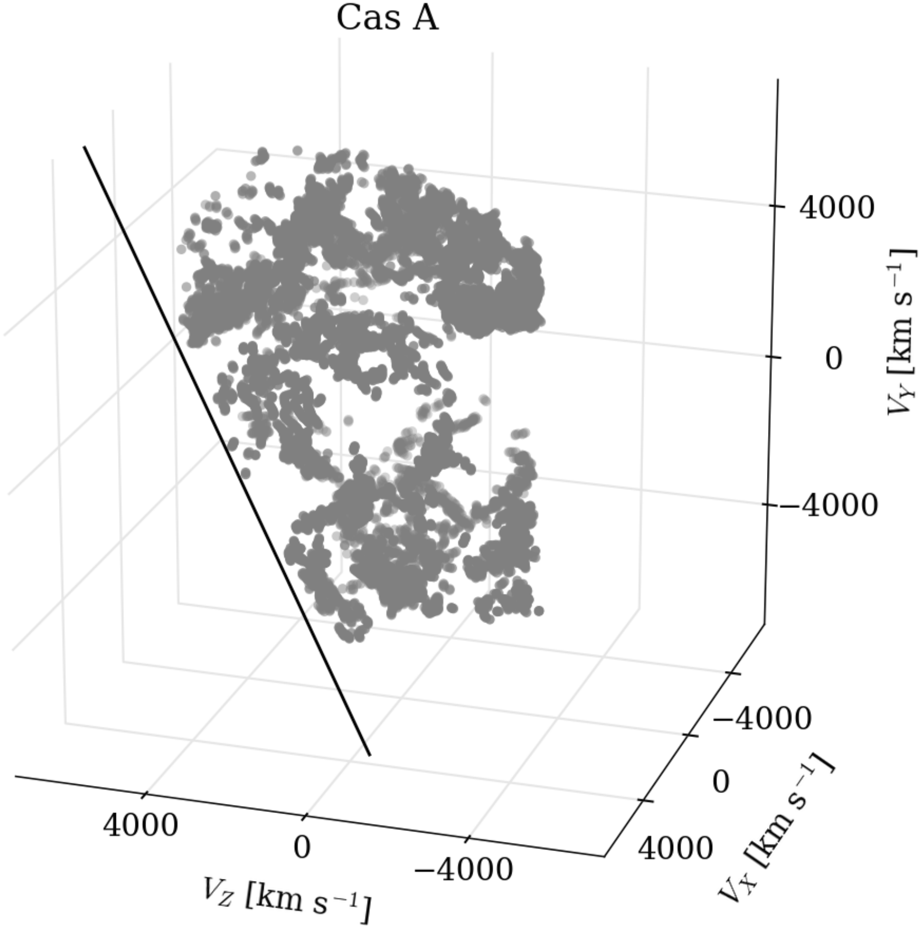
N132D in 3D velocity space

- Identify a tilted ring or torus structure
- Blue-shifted median velocity of -340 km/s with respect to ISM
- Updated remnant age of 2445 ± 195 yrs, which is consistent with Vogt & Dopita 11 estimate

Morphological similarities to Cas A

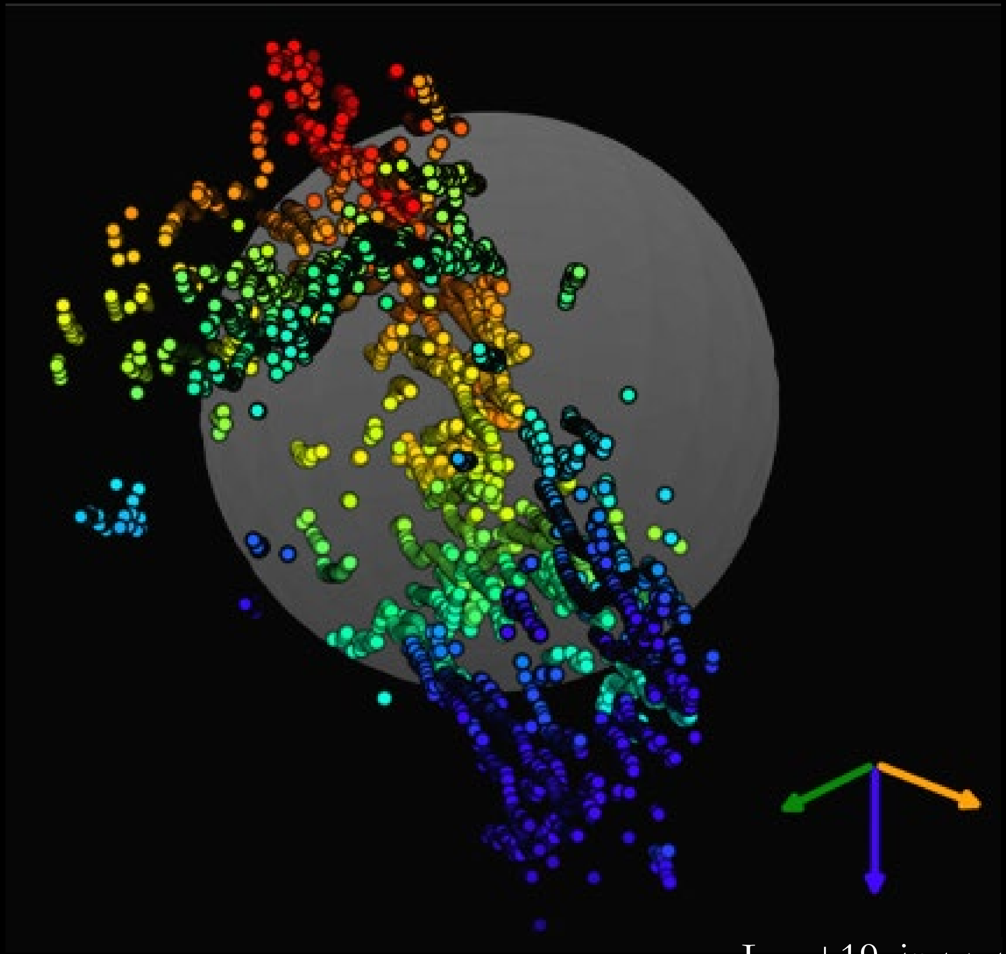
- Nature vs. Nurture:
  - Is the observed morphology due to the explosion dynamics?
    Or influenced by CSM/ISM interaction?



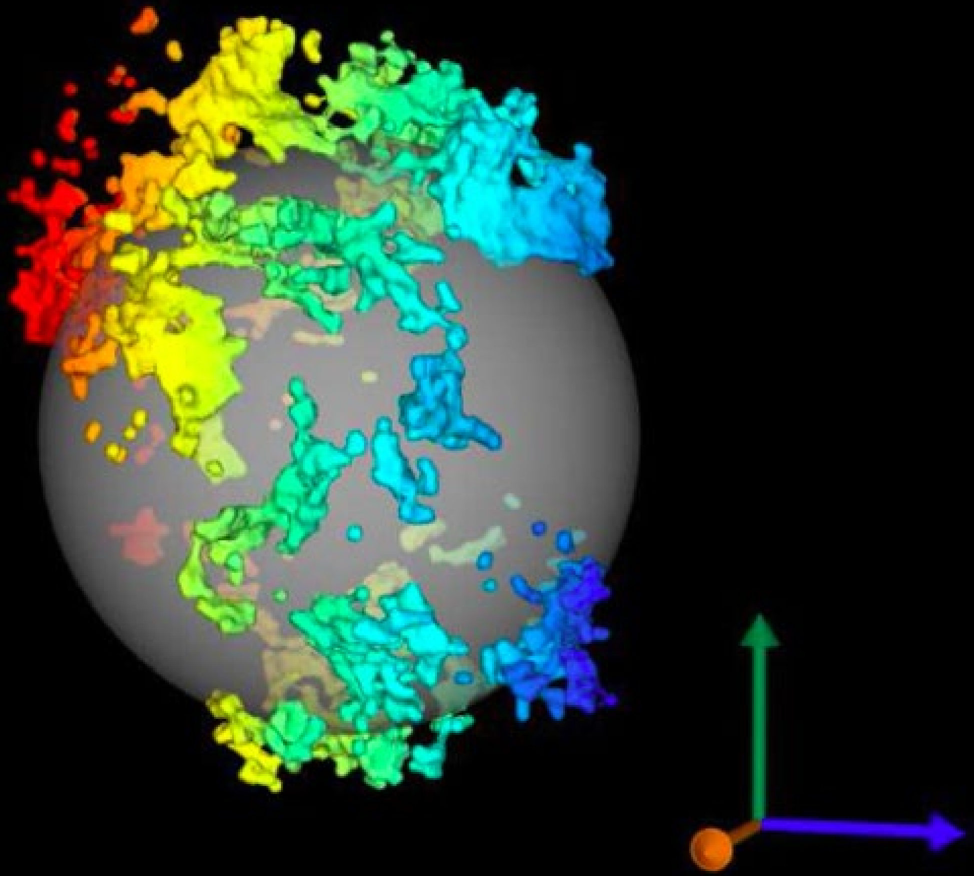


Morphological similarities to Cas A

- Are torus structures common?



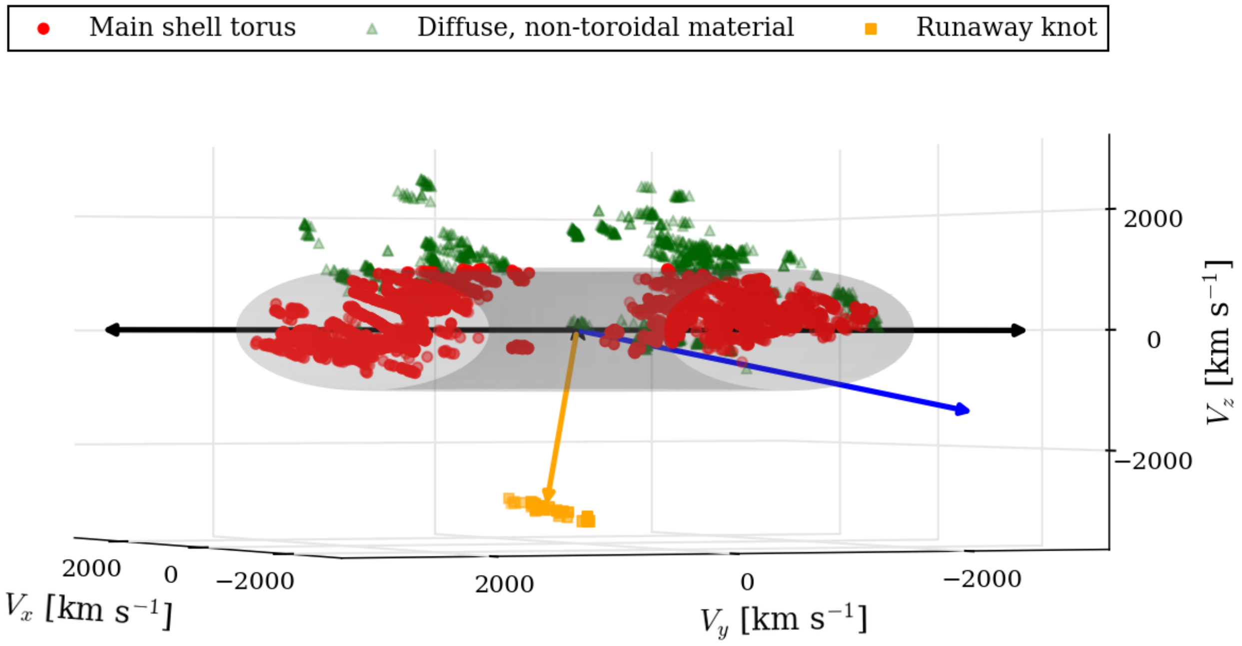
Law+19, in prep.



Milisavljevic & Fesen 13

Runaway knot in N132D

- Define N132D's torus to contain 75% of total main shell ejecta
  - Presence of diffuse non-toroidal material
  - Excludes runaway knot

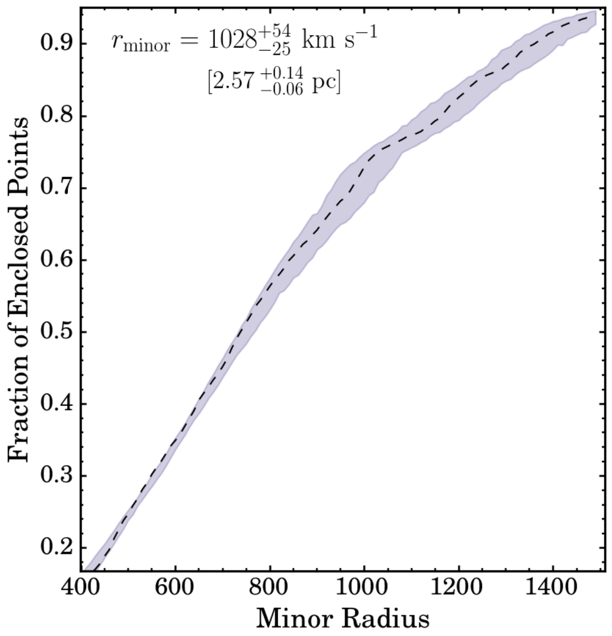


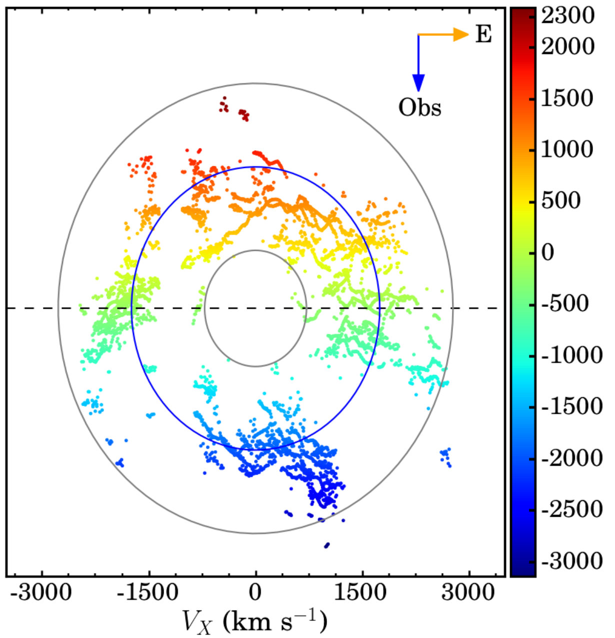
Torus inclination: $\theta_{LOS} = 28° \pm 5°$

Runaway knot: $\theta_{RK} = 89° \pm 2°$

Minor radius: $r_{minor} = 1028^{+54}_{-25}$ km s^{-1}

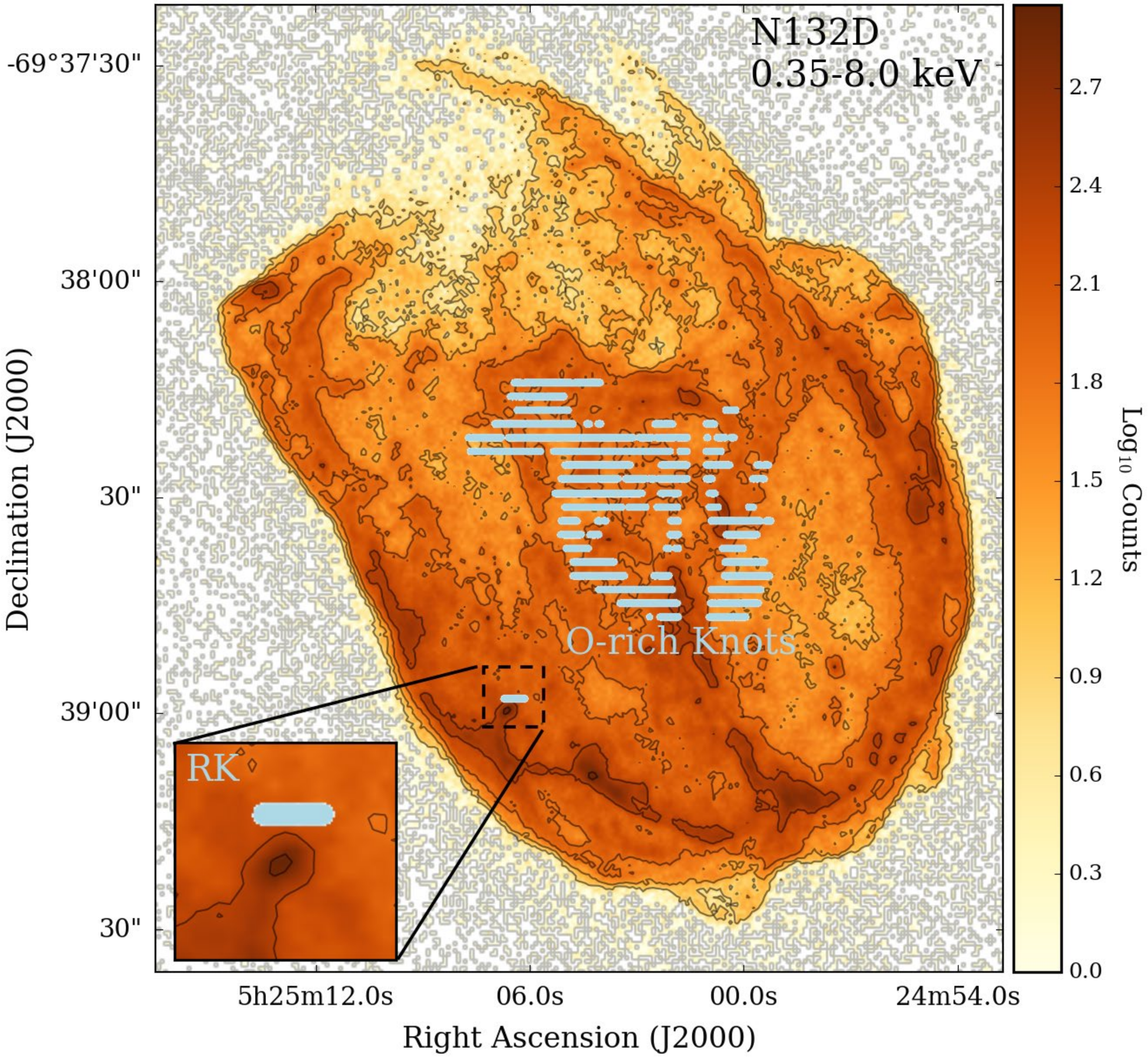
Major radius: $r_{major} = 1744$ km s^{-1}





RK is coincident with X-ray enhancement

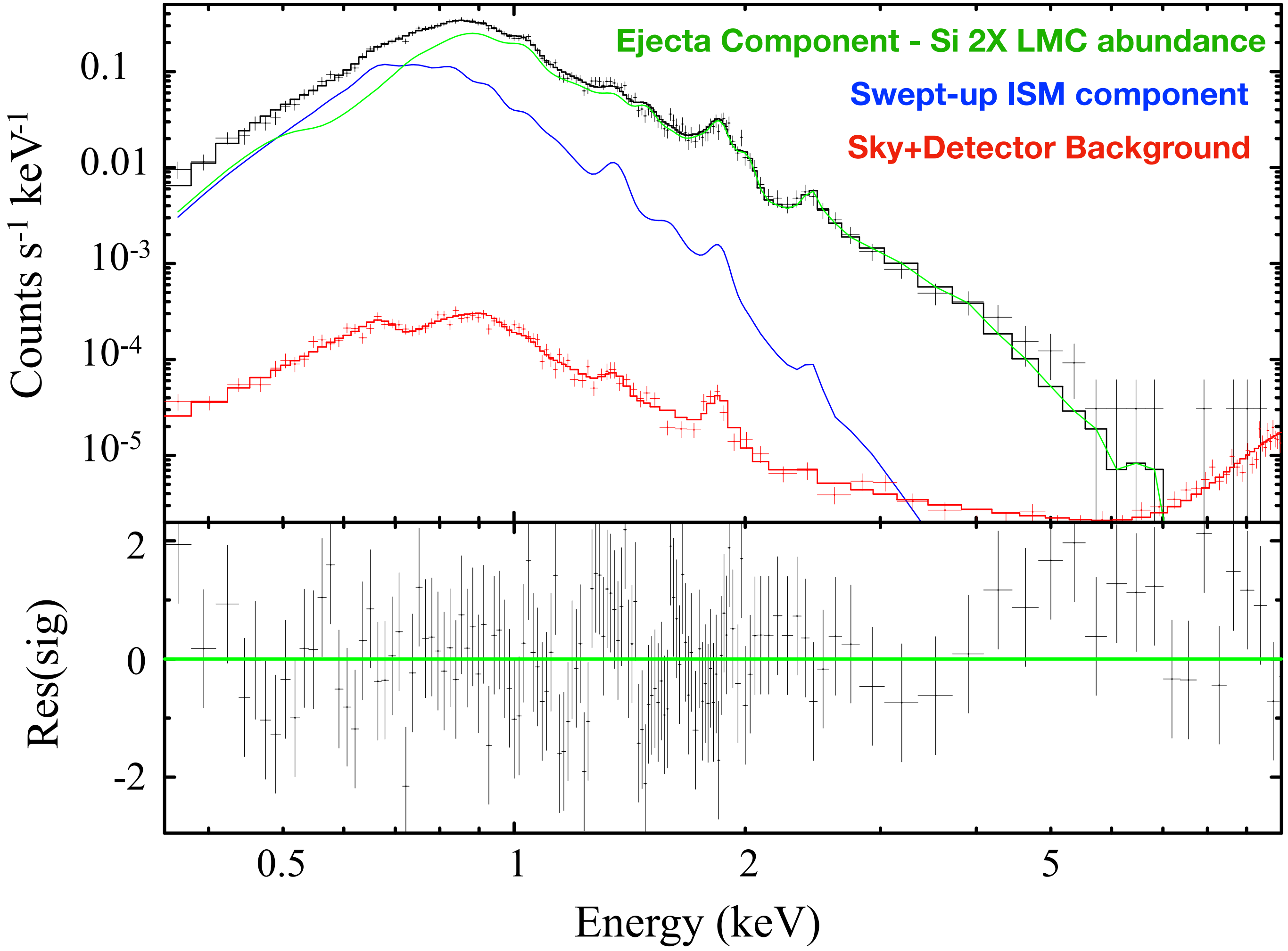
- Small offset observed in X-ray enhancement and optically-emitting runaway knot
  - Consistent with an optical and X-ray brightening time delay
- Displacement of ~few arcseconds observed in Cas A
- Density + temperature effect due to highly inhomogeneous ejecta



Borkowski+07, Patnaude & Fesen 14

Si-rich RK suggests high velocity, near-core origin

- Si abundance is at least 2x in excess of LMC abundance
  - RK is also Si-enriched with respect to main shell ejecta



Schenck+16, Sharda+19, in prep.

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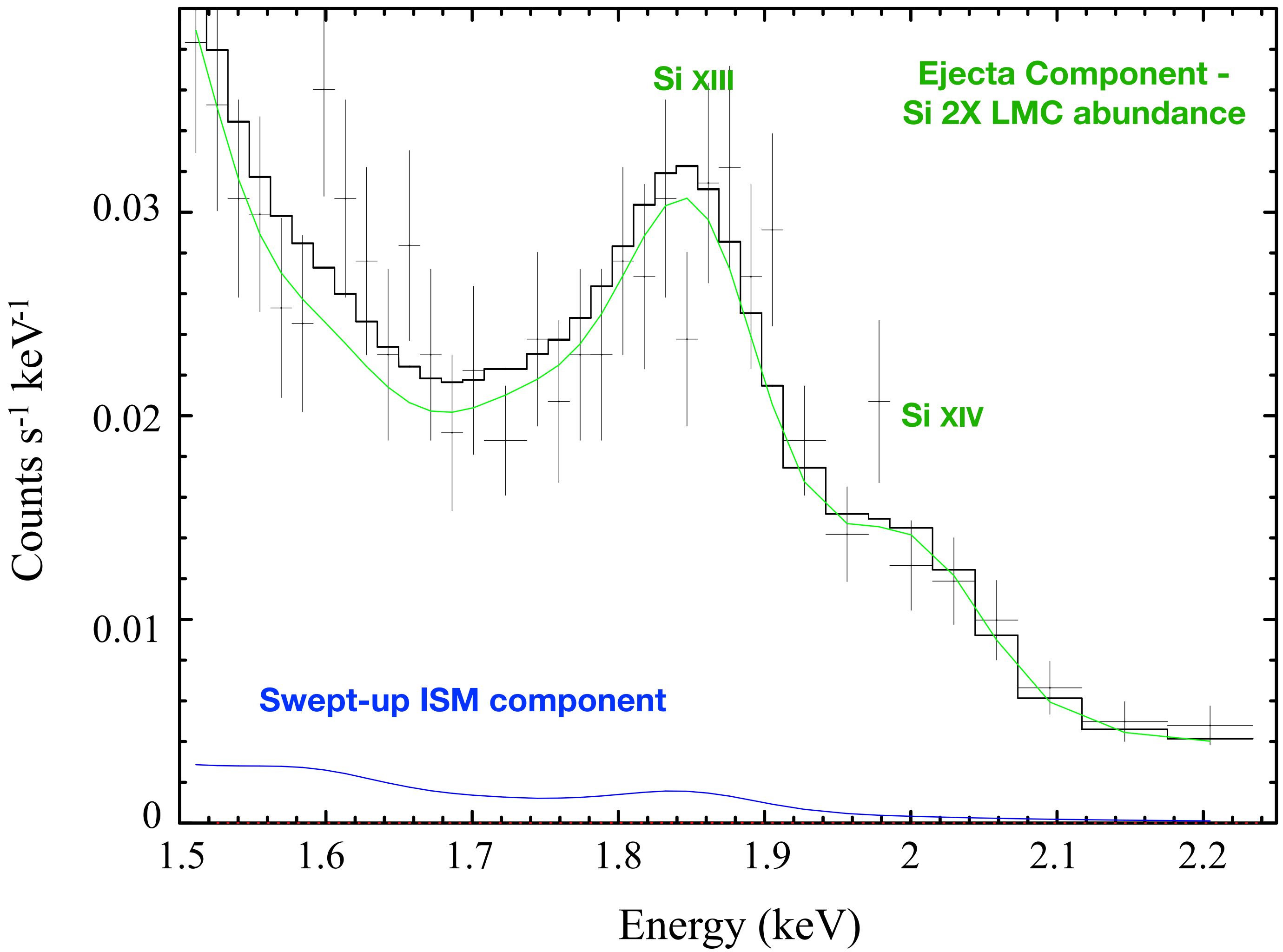

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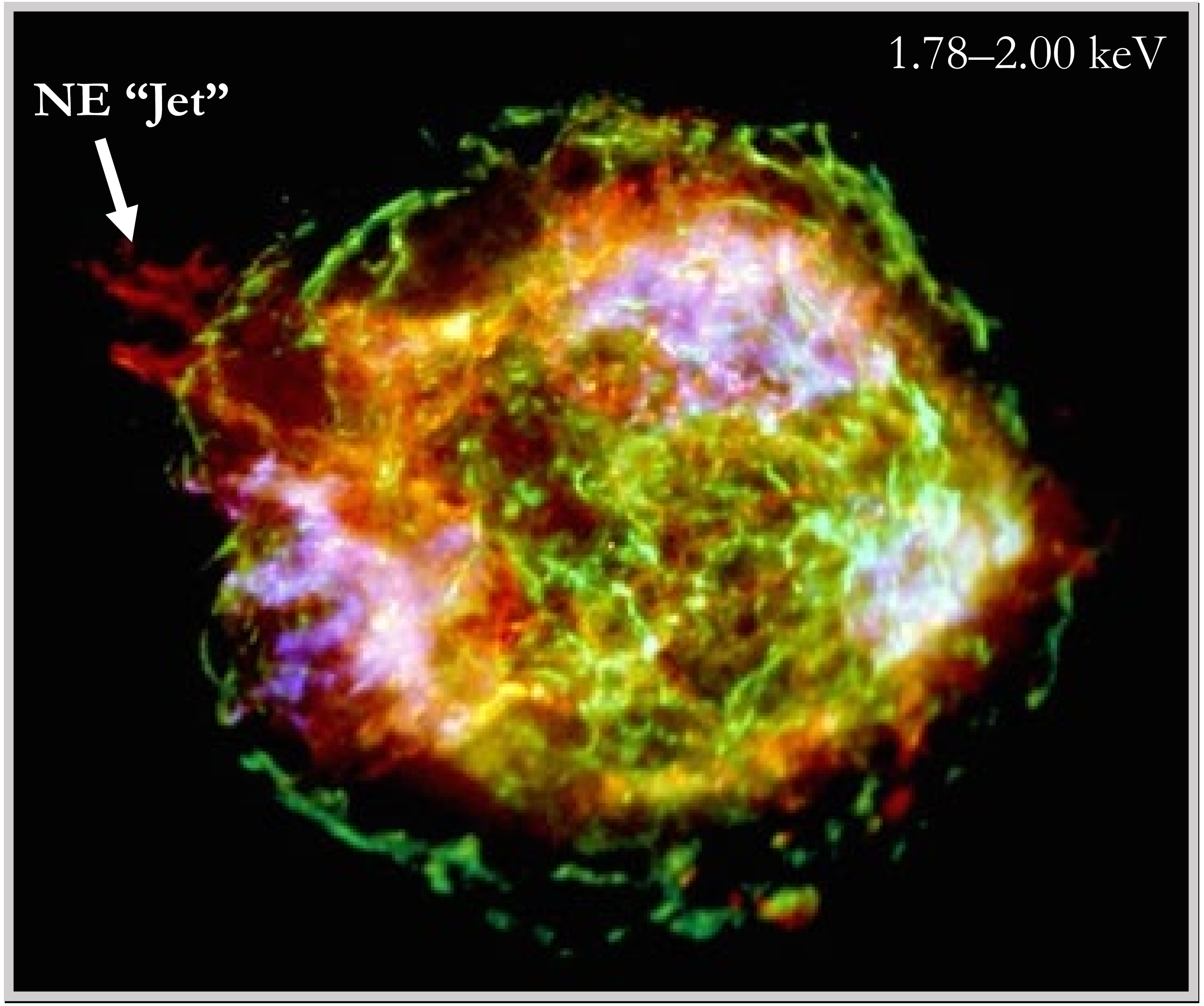

Hwang+04, Tananbaum+14

Si-rich nature of RK hints at a jet-like origin

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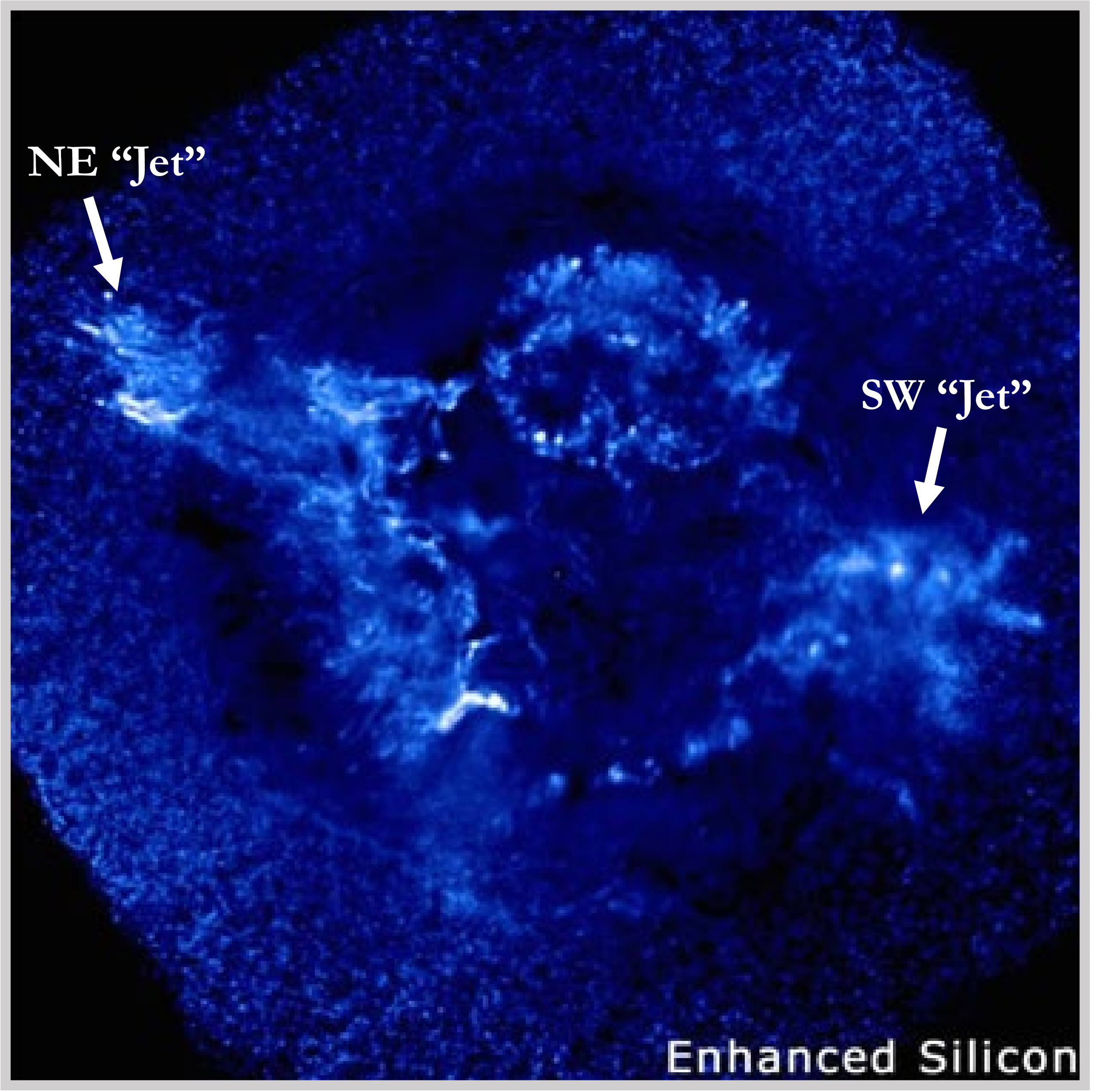

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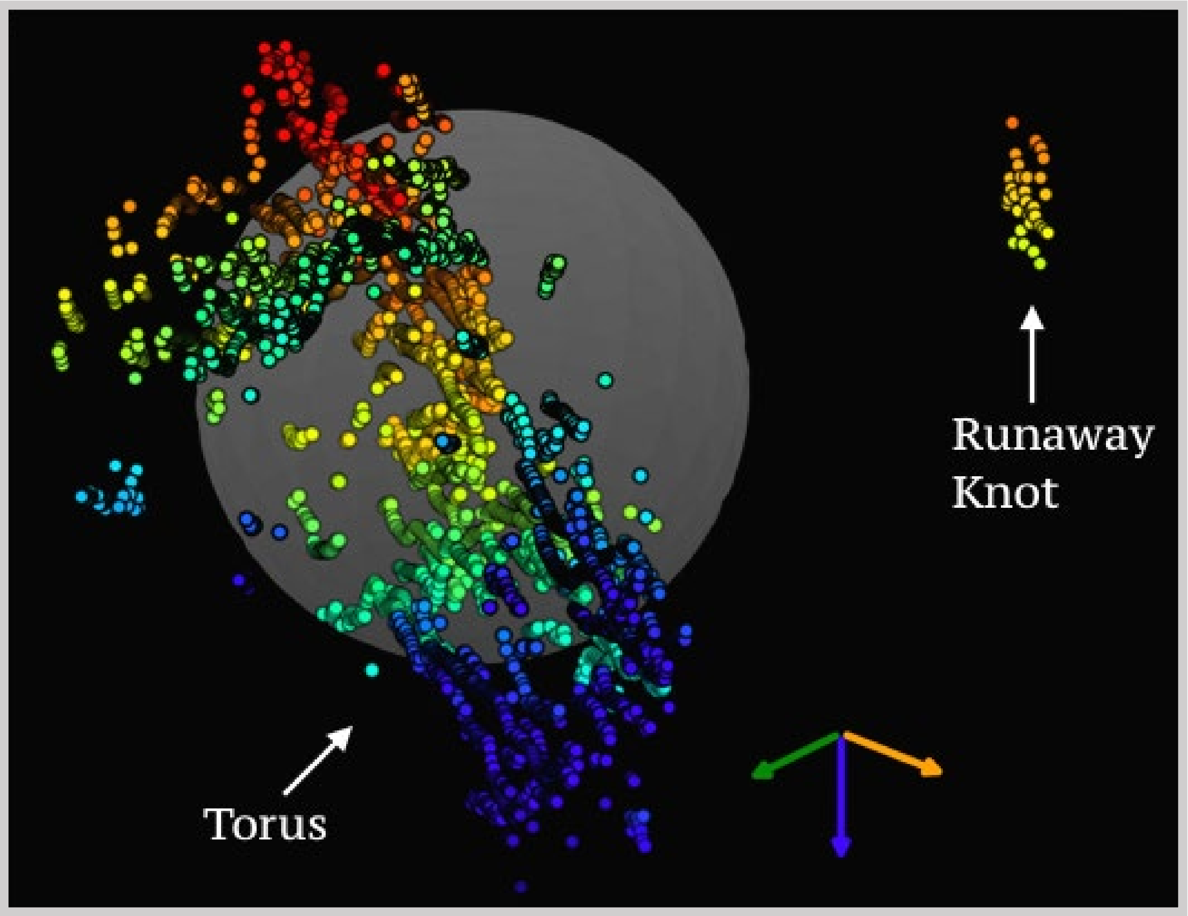
  - RK is also Si-enriched with respect to main shell ejecta
- Similar to Cas A's NE and SW Si-rich high velocity outflows
- Origin of RK may have been deep within progenitor star
  - Evidence that jet-like outflow may have participated in CC explosion



Summary

- N132D has an inclined torus surrounded by diffuse material and shares morphological similarities with Galactic O-rich remnant Cas A

- We confirm the presence of an oxygen-rich "runaway knot" that is coincident with an X-ray point source
  - RK is Si-rich relative to the main ejecta and may be a similar feature as those seen in Cas A's Si-rich NE/SW jets

- Upcoming observations will clarify X-ray morphology
  - Accepted ~1 Ms Chandra program (PI: P. Plucinsky)
  - IR and optical follow-up may detect additional faint RKs

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