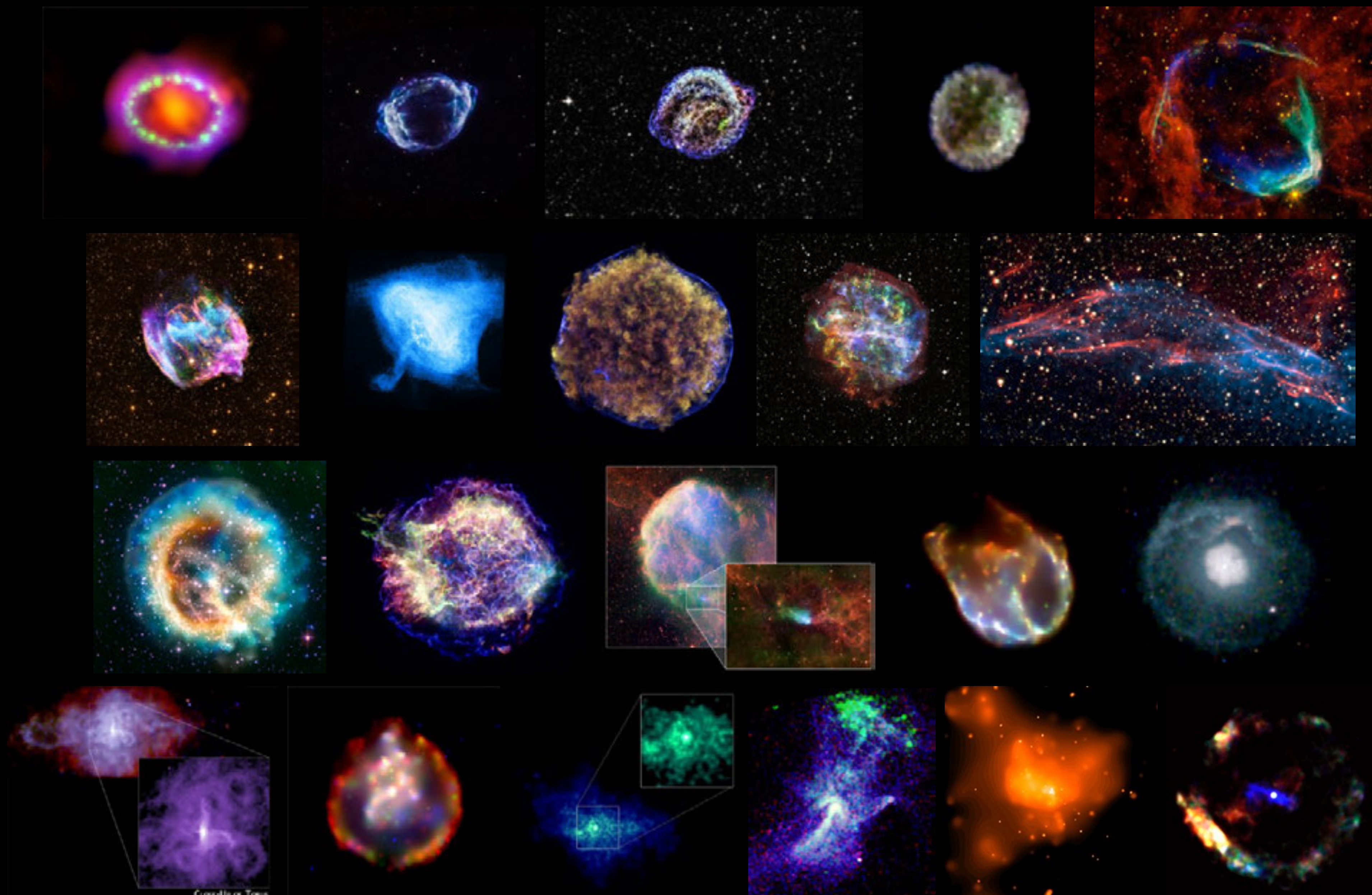
The Morphologies of Supernova Remnants



Laura A. Lopez
(The) Ohio State University
9 June 2019

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Distinct morphologies of different elements useful to constrain explosion/progenitors and origin of neutron star kicks

3D maps of SNRs are even more powerful at revealing asymmetries, microcalorimeters will revolutionize field

Morphological Classification

Shell-type
SNRs

Plerionic
SNRs

Composite
SNRs

Mixed-Morphology
SNRs

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Shell-type
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Type Ia;
Core Collapse

Mixed-Morphology
SNRs

Tying SNRs to their Originating Explosions

Ways to classify explosions of SNRs (Type Ia versus core-collapse):

- Identification of a central neutron star
- Light echoes (Rest et al. 2005, 2008; Krause et al. 2008)
- Metal abundance ratios (e.g., O/Fe)
- Environment (e.g., nearby molecular clouds)
- Nearby stellar populations
- Morphologies (Type Ia SNRs are more circular/symmetric than CC SNRs: Lopez et al. 2009, 2011; Peters et al. 2013)
- Fe line centroid (Type Ia SNRs have lower ionization state Fe than CC SNRs: Yamaguchi et al. 2014)

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Using the Power-Ratio Method to Assess Morphology

Calculate multipole moments of the X-ray image (Buote & Tsai 1995, 1996; Jeltema et al. 2005)

Derived the same as in the expansion of 2D gravitational potential within a radius R (Binney & Tremaine, Section 2.4):

$$\Psi(R,\phi) = -2Ga_0 \ln\left(\frac{1}{R}\right) - 2G\sum_{m=1}^{\infty}\frac{1}{mR^m}\left(a_m \cos m\phi + b_m \sin m\phi\right)$$

$$a_m(R) = \int_{R'\leq R} \Sigma(\vec{x}')\,(R')^m \cos m\phi' \, d^2x'$$

$$b_m(R) = \int_{R'\leq R} \Sigma(\vec{x}')\,(R')^m \sin m\phi' \, d^2x'$$

x\`=(R\`,φ) and Σ is the mass surface density (X-ray surface brightness in our calculation)

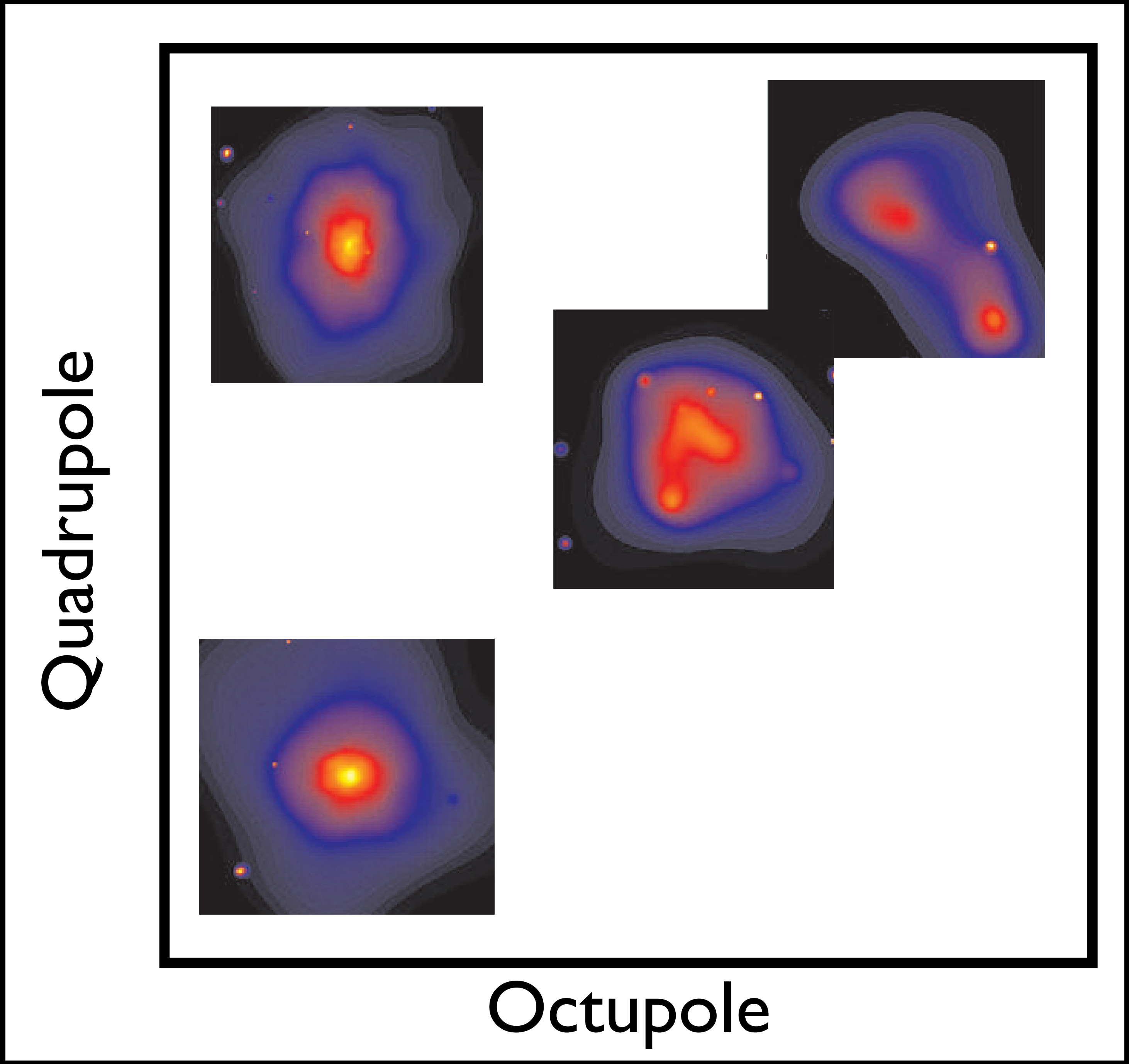
Lopez et al. 2009a/b

Using the Power-Ratio Method to Assess Morphology

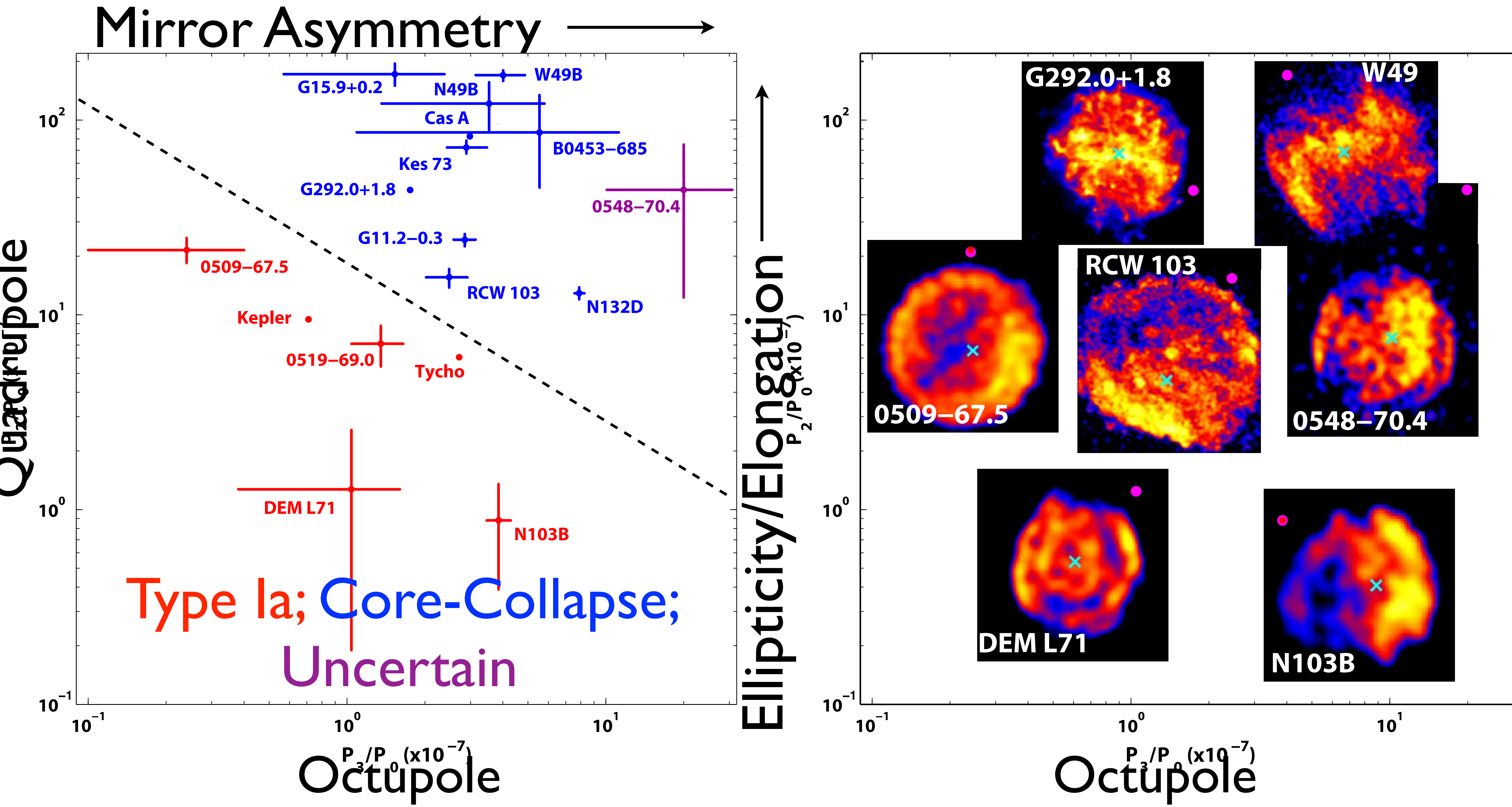
Calculate multipole moments of the X-ray image (Buote & Tsai 1995, 1996; Jeltema et al. 2005)

- Quadrupole:
  measure of ellipticity
  Large for elliptical source, small for circular source

- Octupole:
  measure of mirror asymmetry
  Large for sources with one brighter side; small for homogeneous sources

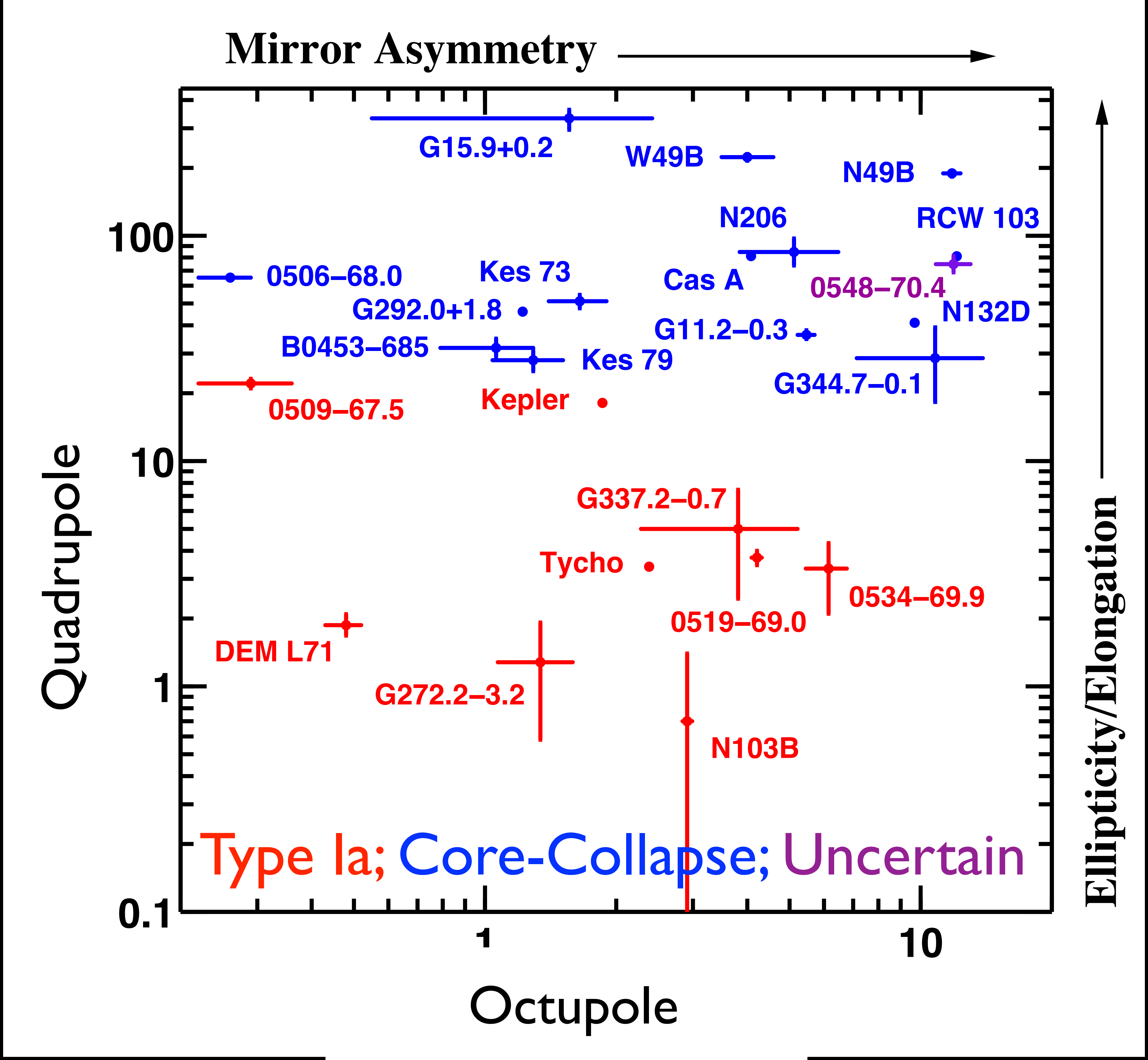


Morphology of Silicon Line Emission in X-rays



Lopez et al. 2009b

Morphology of Thermal X-ray Emission

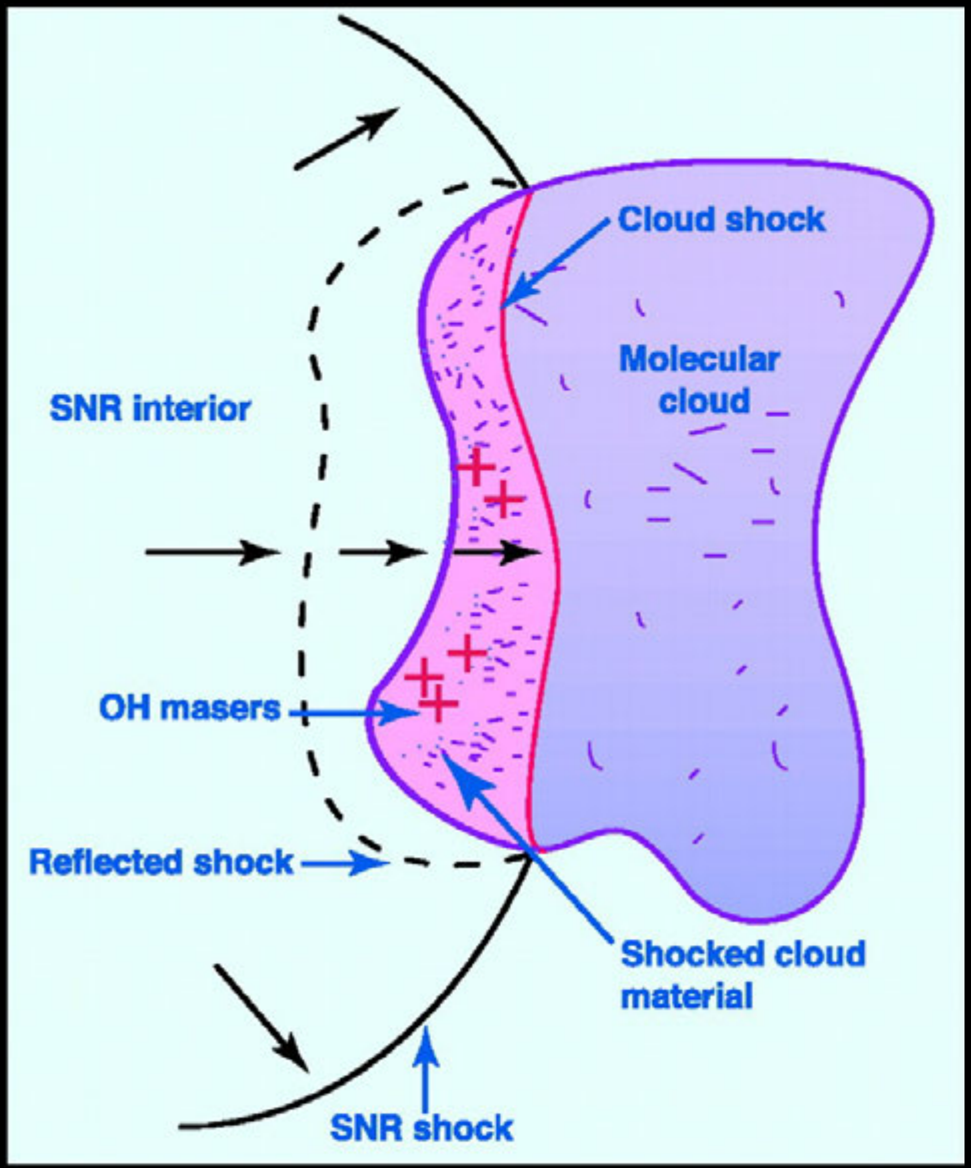


Lopez et al. 2011

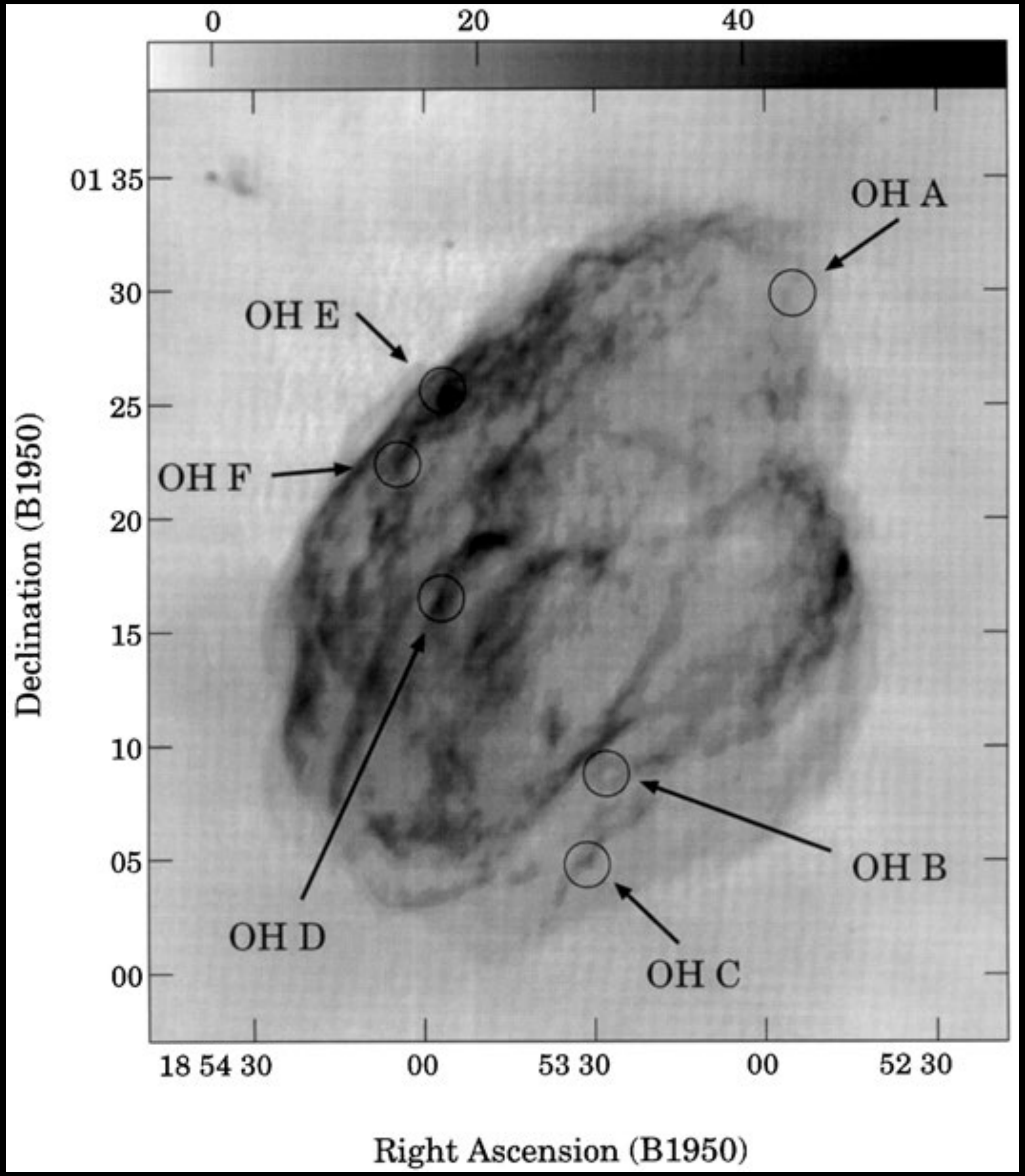
Environment Shapes Morphology

~70 / 300 supernova remnants show signs of interaction with molecular clouds (Jiang et al. 2010)

Signs of interaction: masers, CO or warm H_2, gamma-rays



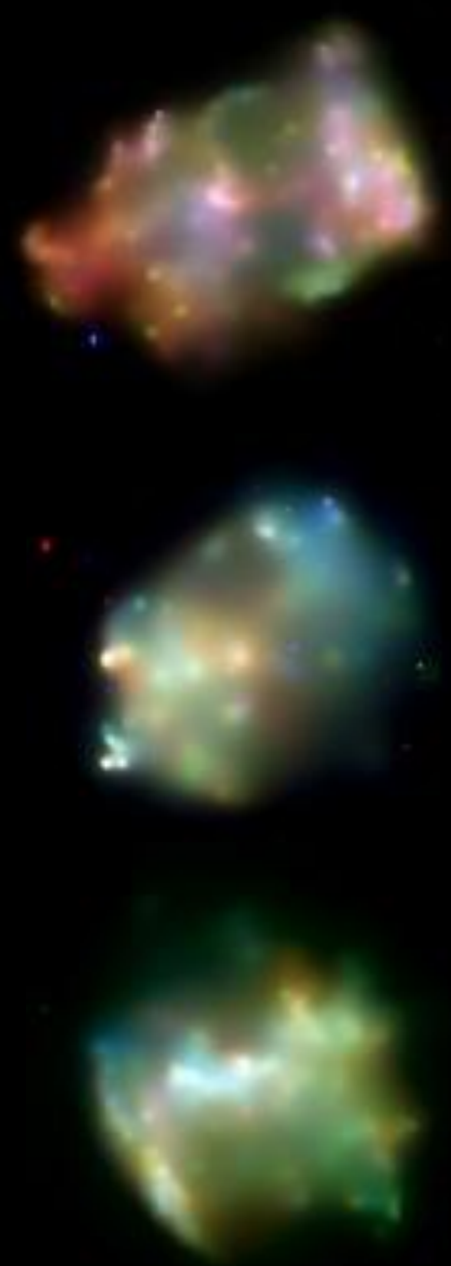
Wardle & Yusef-Zadeh 2002

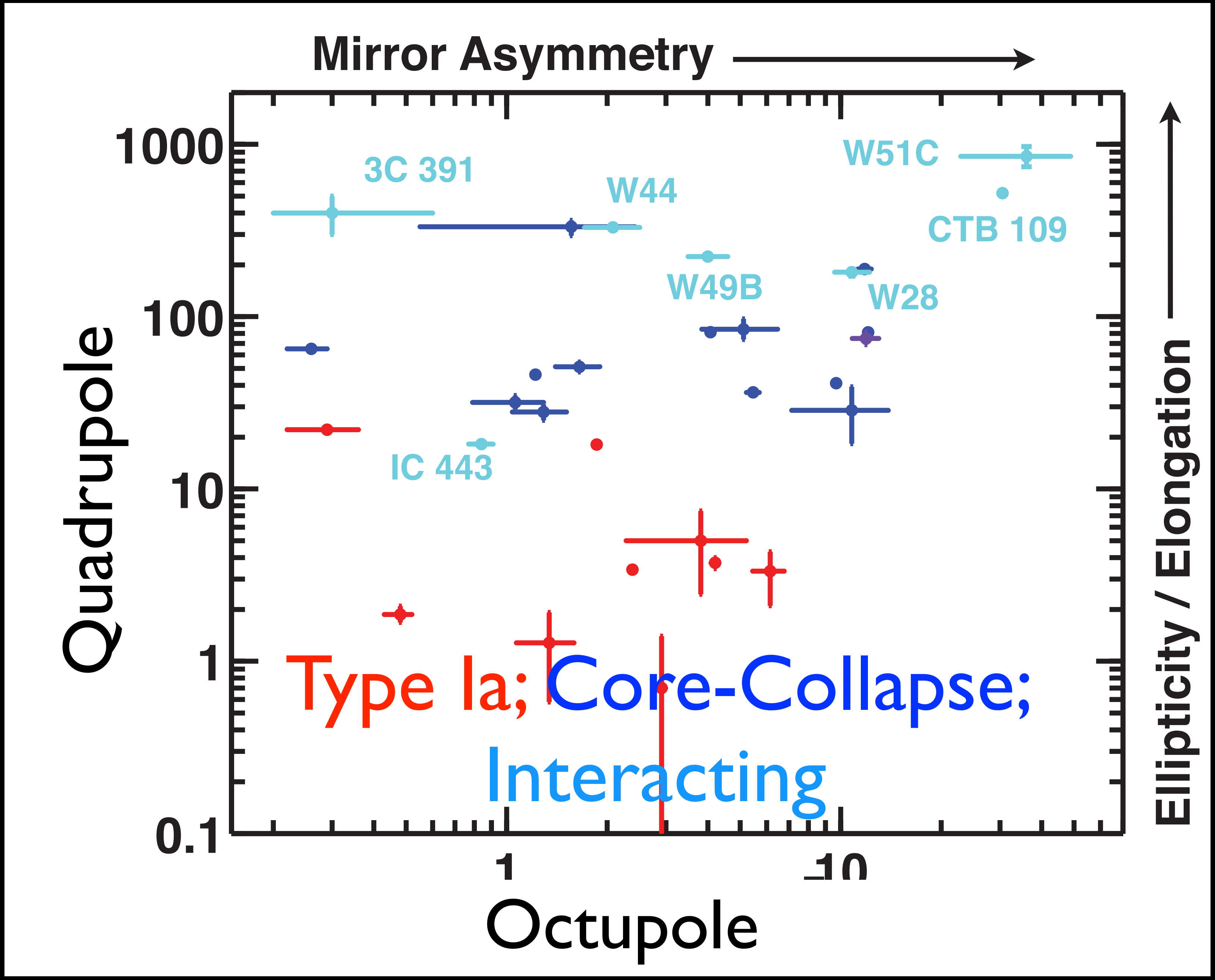


Claussen et al. 1997

Environment Shapes Morphology

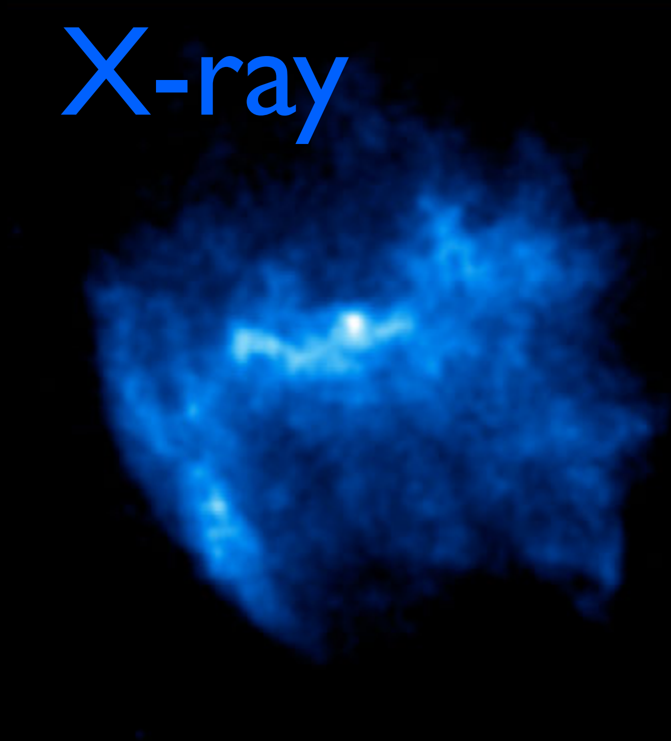
SNRs interacting with molecular clouds tend to be the most elongated/elliptical (Lopez 2014; Holland-Ashford et al. 2017)





Lopez 2014

Other Wavebands?



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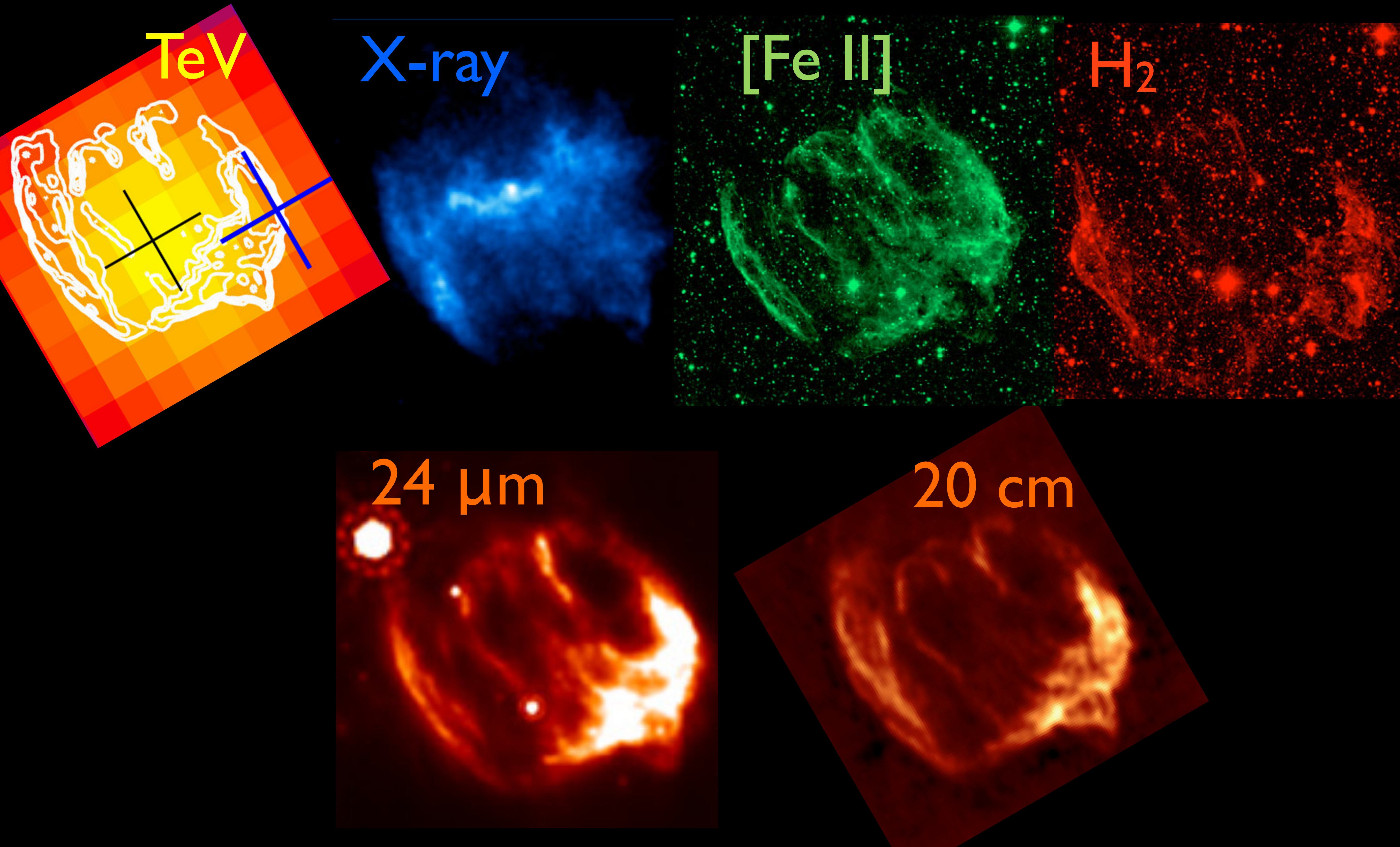
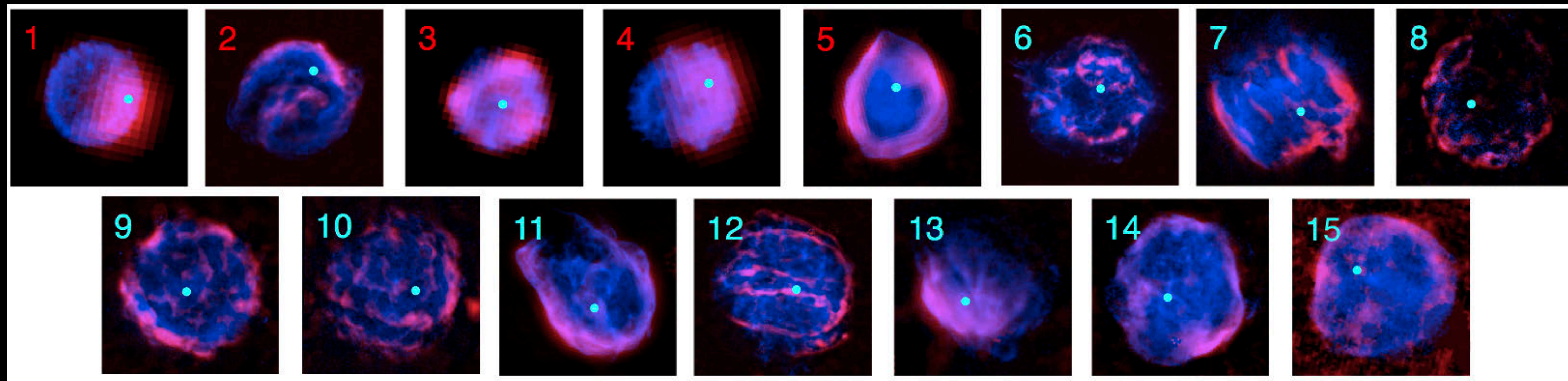


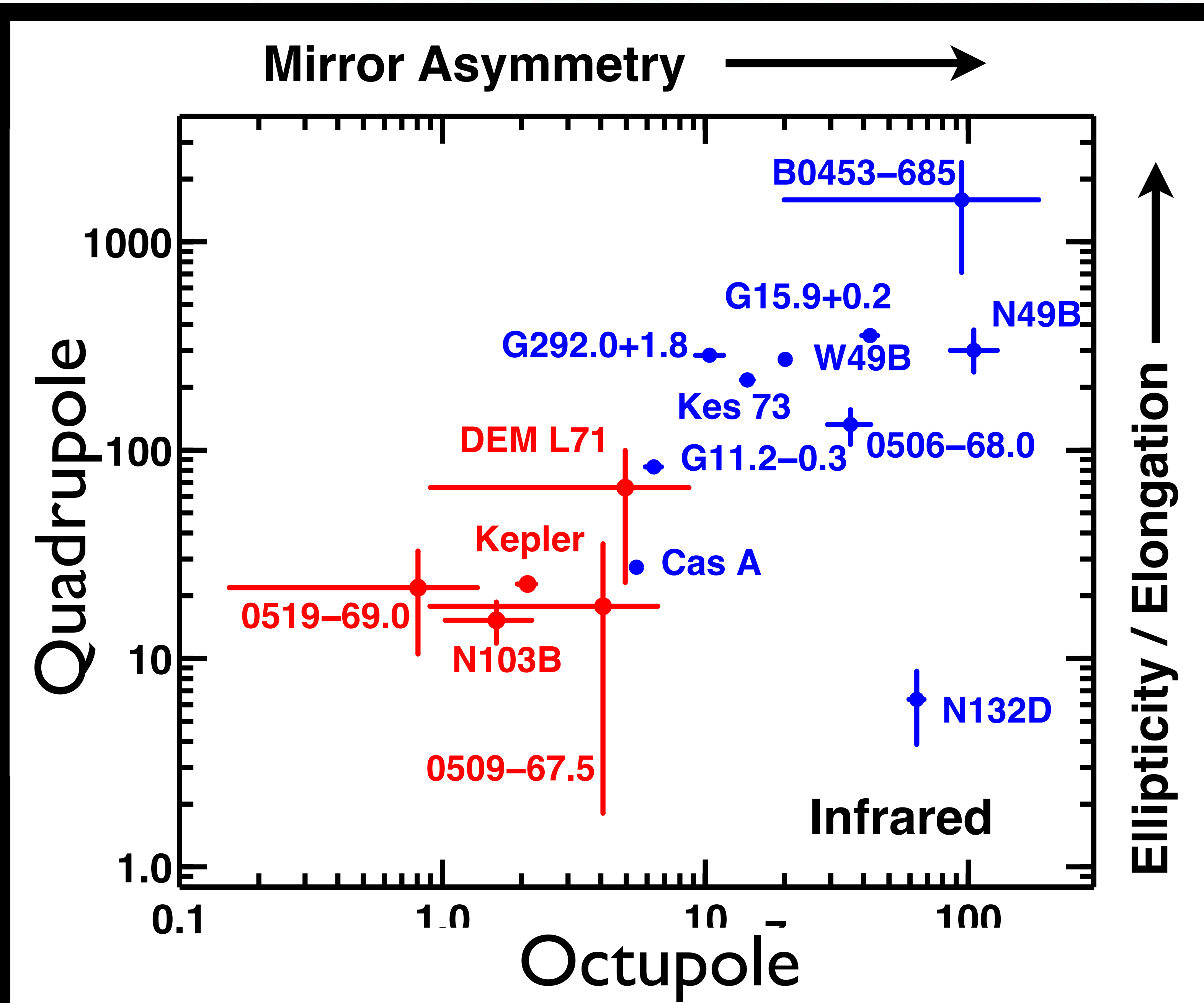
References: TeV: HESS Collaboration 2016; X-ray: Lopez et al. 2013; [Fe II] and H_2: Keohane et al. 2007; 24um: Koo et al. 2016; 20 cm: Helfand et al. 2006

Other Wavebands: Infrared

X-rays
IR



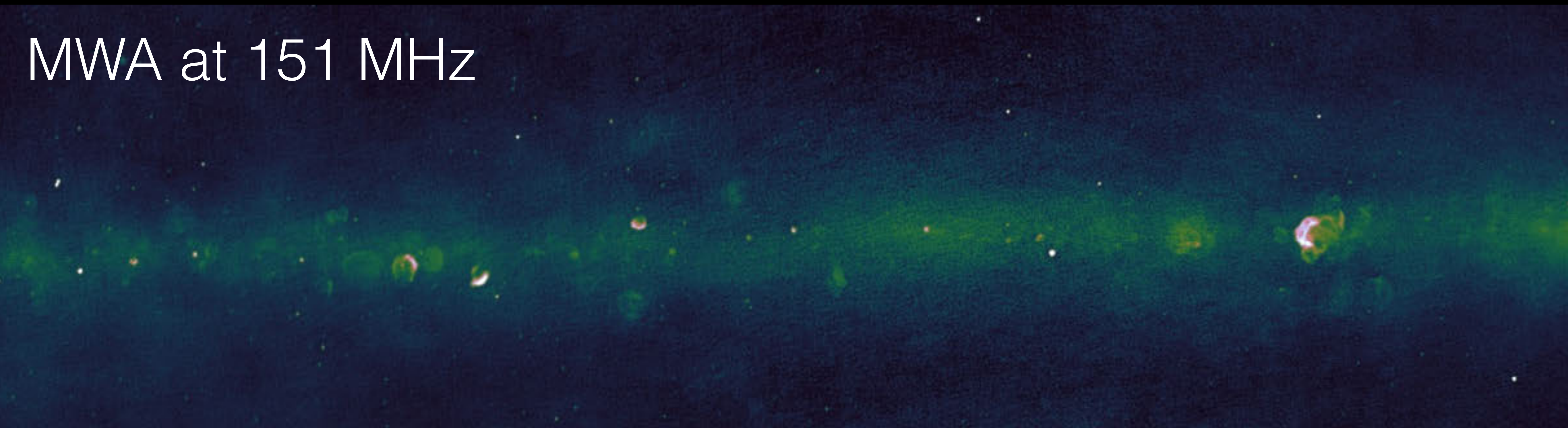
Charee Peters,
U Wisconsin
PhD Student

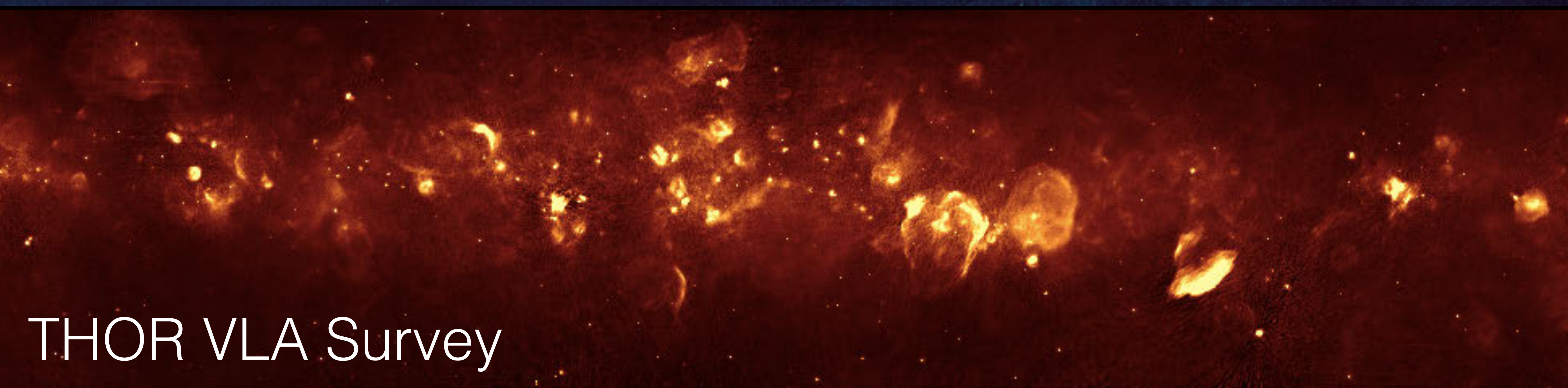


Peters, Lopez et al. 2013

Other Wavebands: Radio

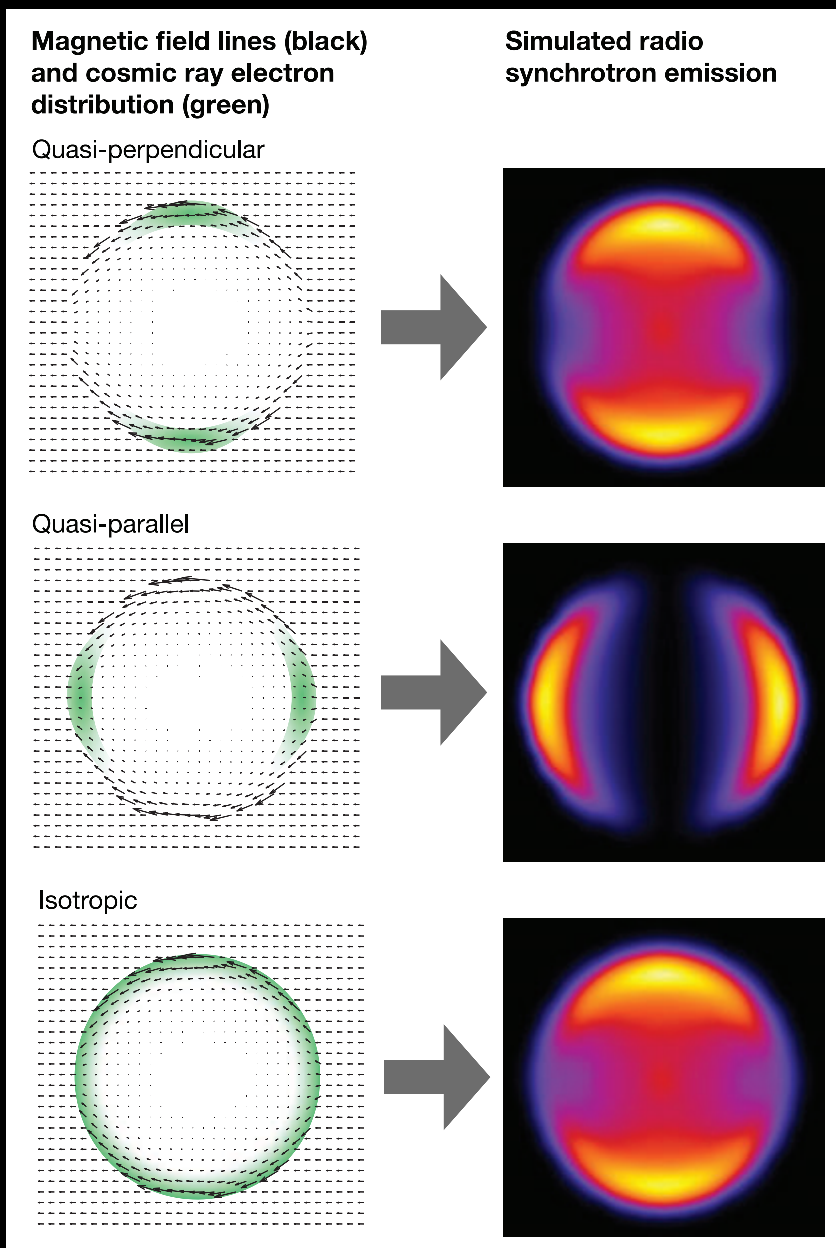
Galactic SNRs are mostly found in the radio

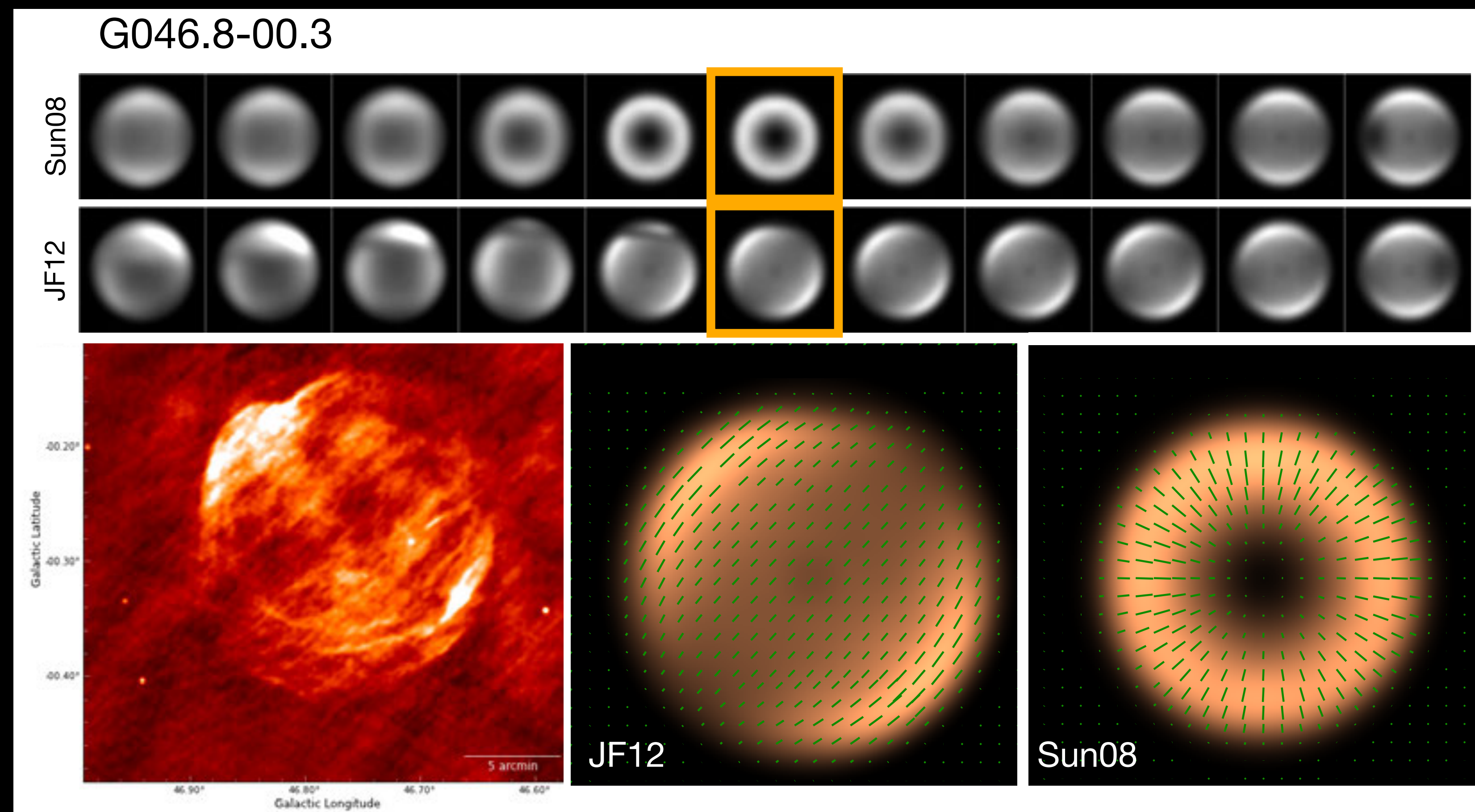




Other Wavebands: Radio

Morphology of synchrotron emission in radio yields information about the ambient density, B-field, and cosmic-ray acceleration





West et al. 2016

See also Orlando et al. 2007, Schneiter et al. 2015, West et al. 2017

Other Wavebands: Radio

Simulations show that degree of asymmetry changes with time in a turbulent/inhomogeneous medium (e.g., Kim & Ostriker 2015, Martizzi et al. 2015, Walch & Naab 2015, Zhang & Chevalier 2019)

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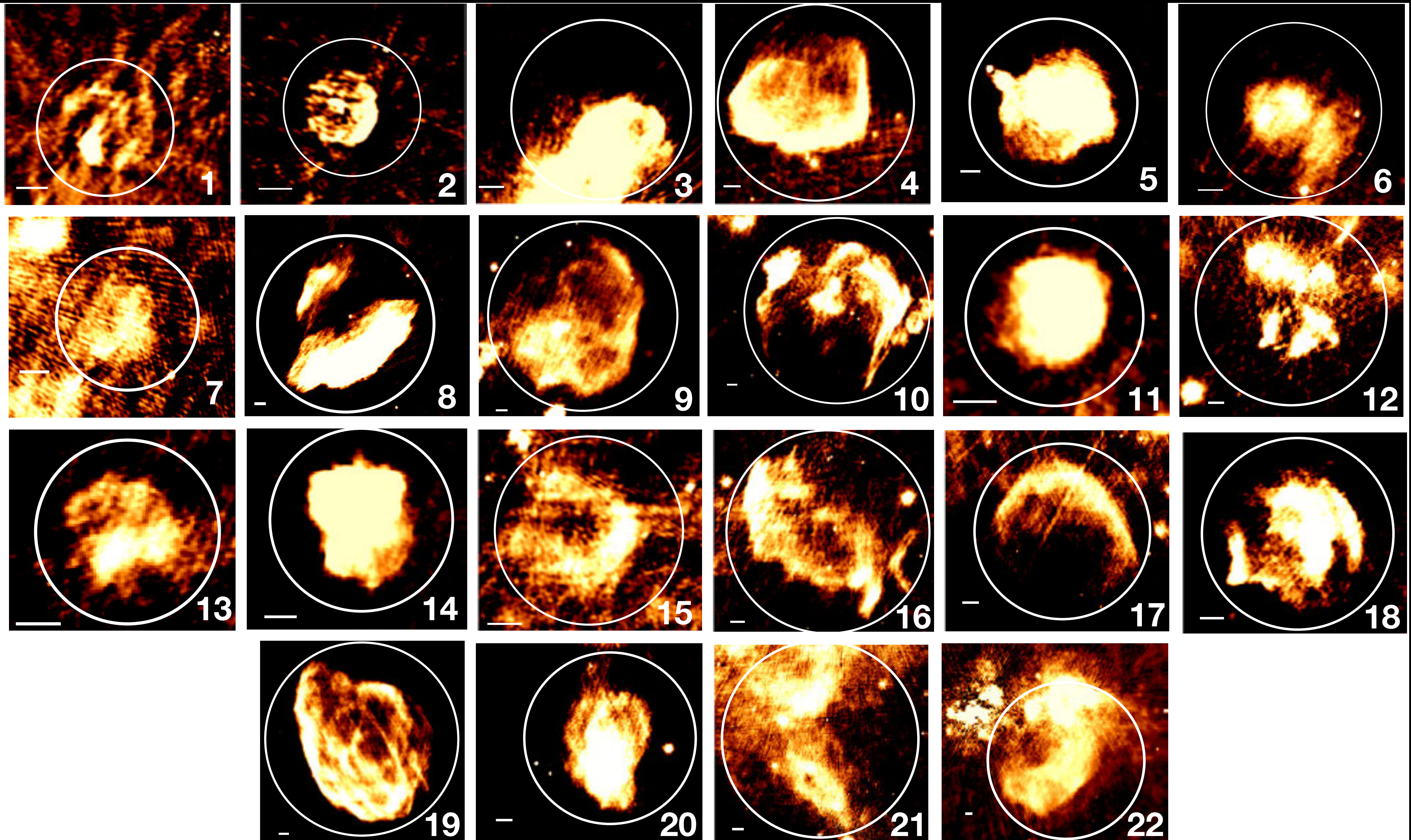
Does radio morphology change with age?

Jennifer Stafford, OSU Undergrad



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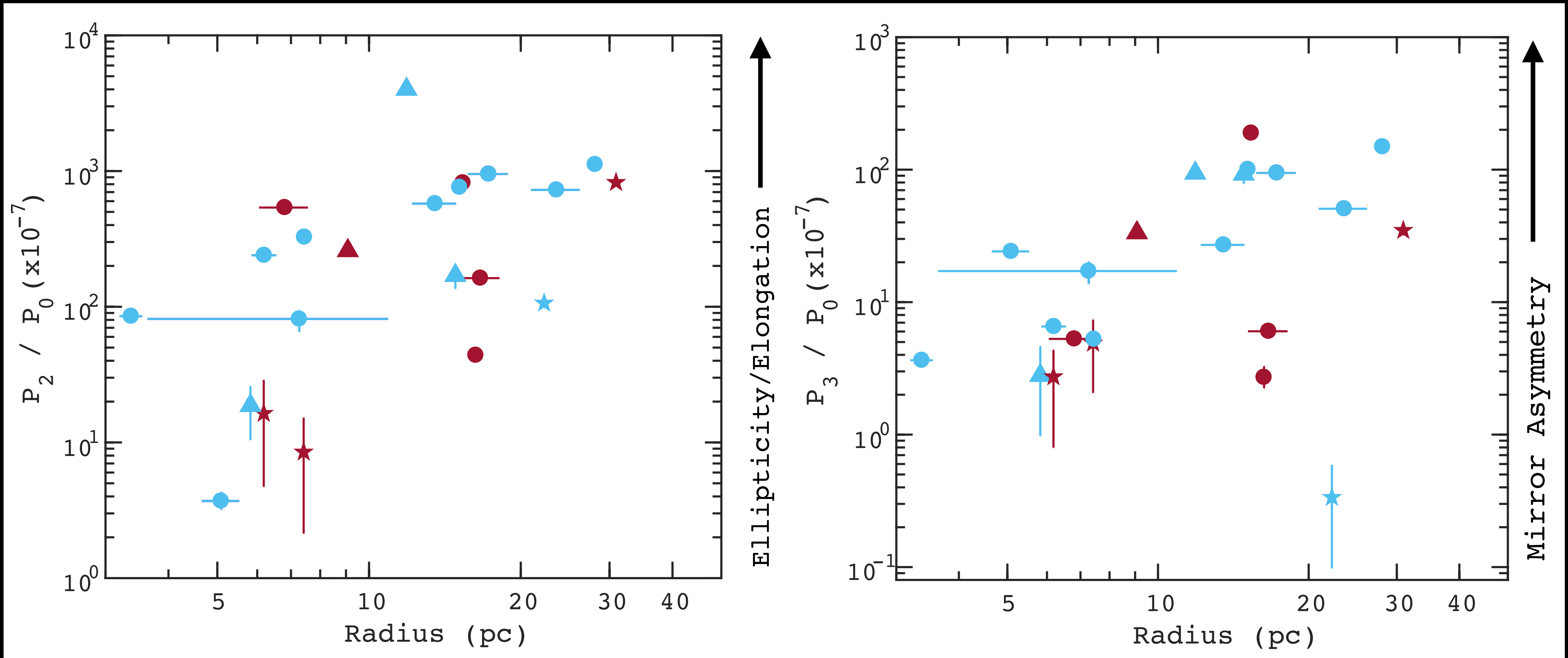
Other Wavebands: Radio

In radio, SNRs get more asymmetric with size/age, consistent with expansion into an inhomogeneous/turbulent ISM

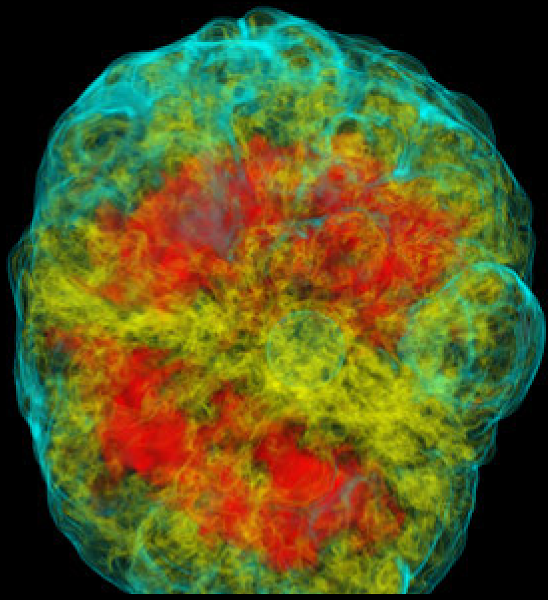
Currently extending this approach to a larger sample (~100 SNRs) in radio

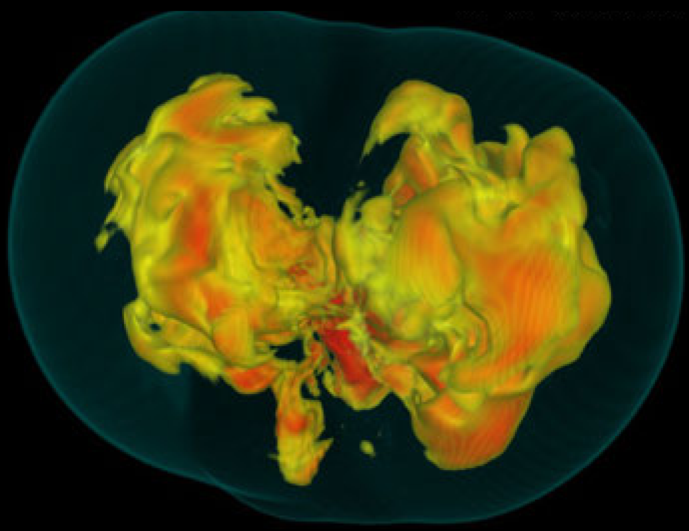


Stafford, Lopez et al. 2019, arXiv: 1808.08234

Tying Morphologies to Originating Explosions

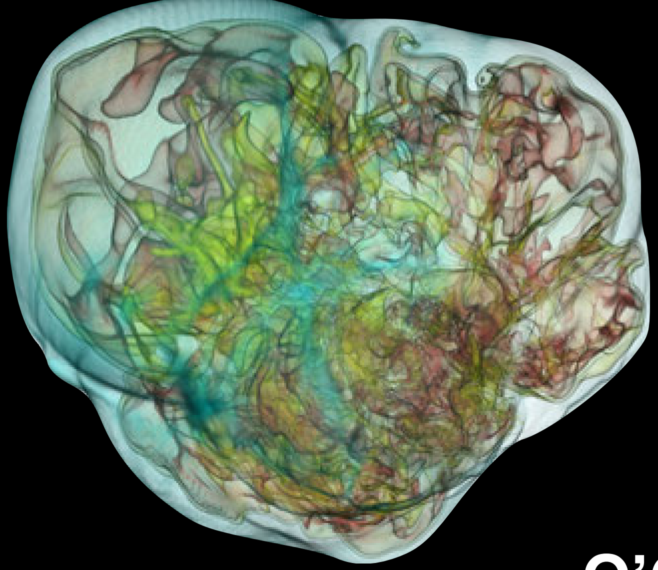
Roberts et al. (2016)

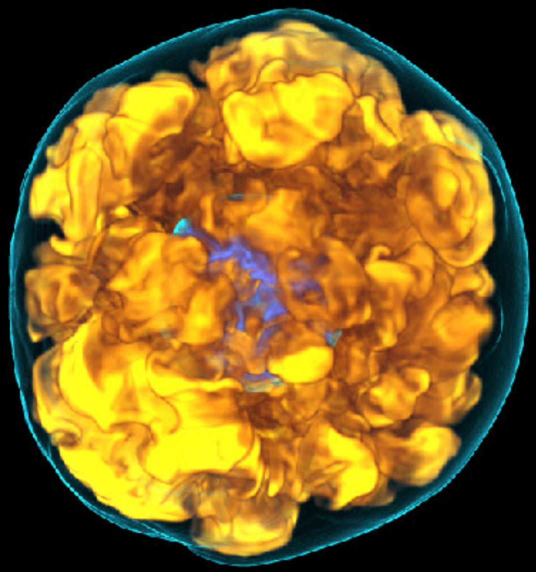




Janka et al. (2016)

Lentz et al. (2016)

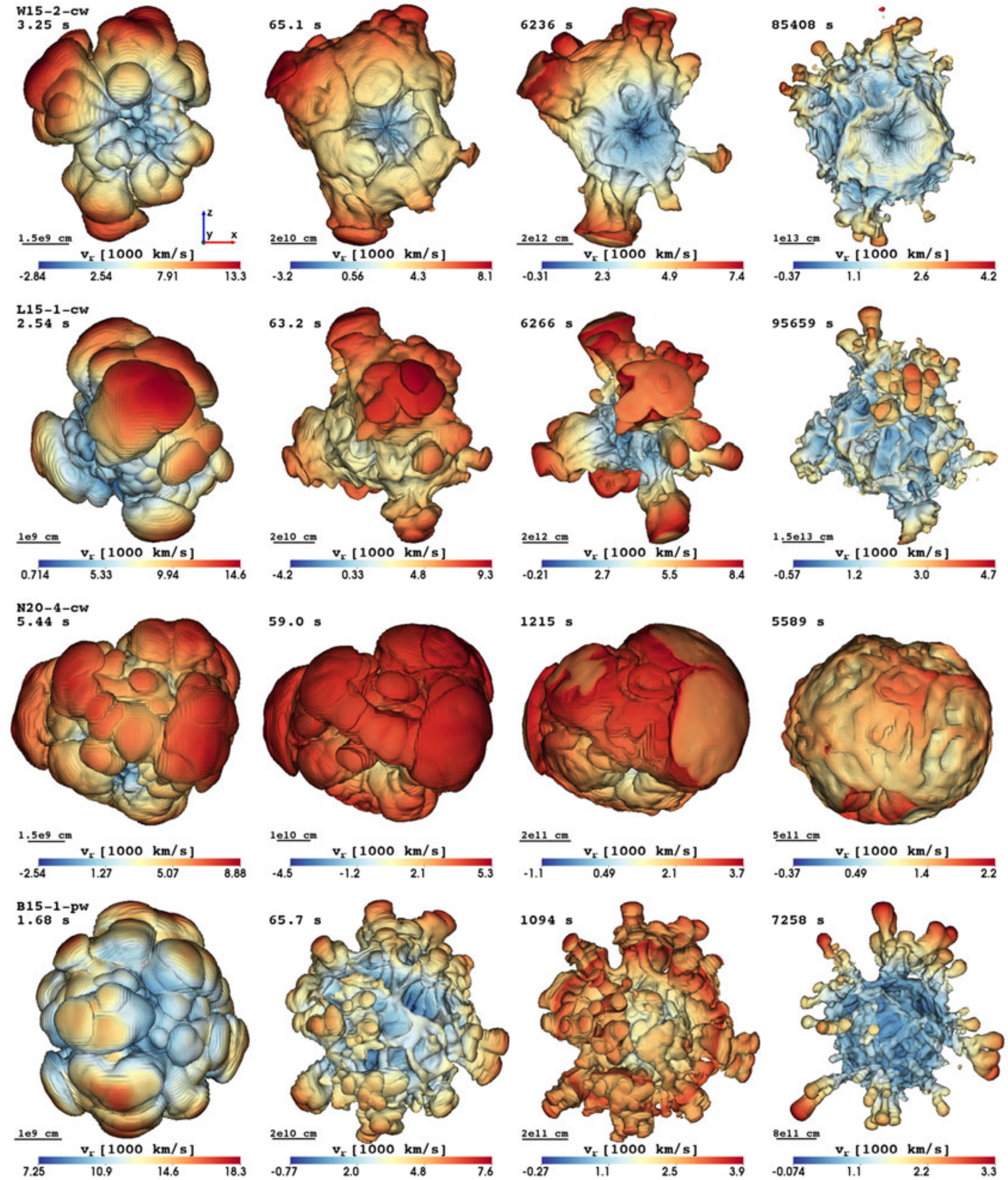




O'Connor & Couch 2018

Simulations are yielding predictions about ejecta distributions, large-scale compositional asymmetries, neutron star kicks that can be compared to observations.

Ni-56 Distribution Depends on Progenitor Structure



Wongwathanarat et al. 2015

Comparing Elemental Spatial Distributions

Do different elements get ejected differently?

Tyler Holland-Ashford, OSU Graduate Student

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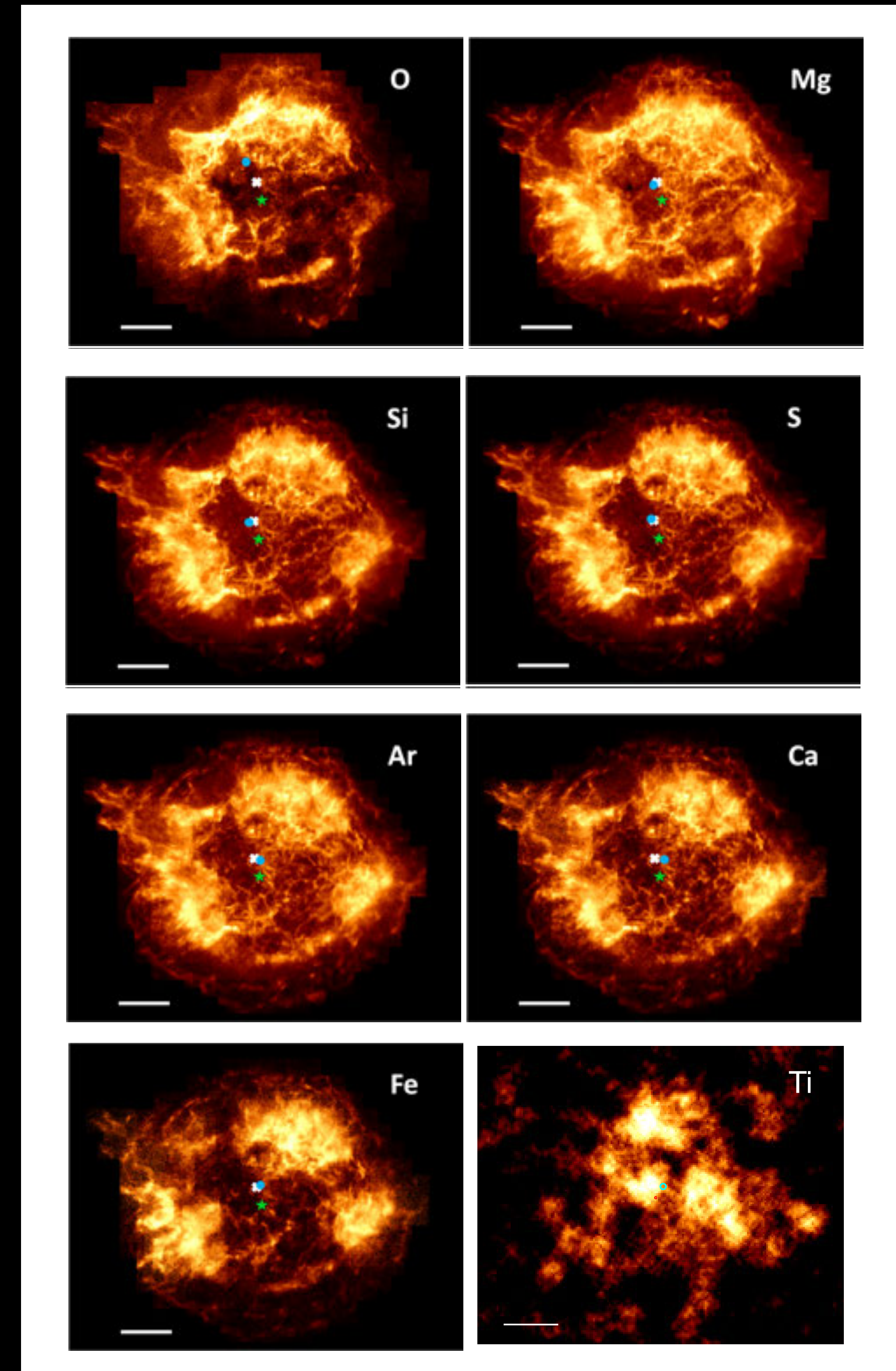

Holland-Ashford, Lopez, & Auchettl 2019, arXiv:1904.06357

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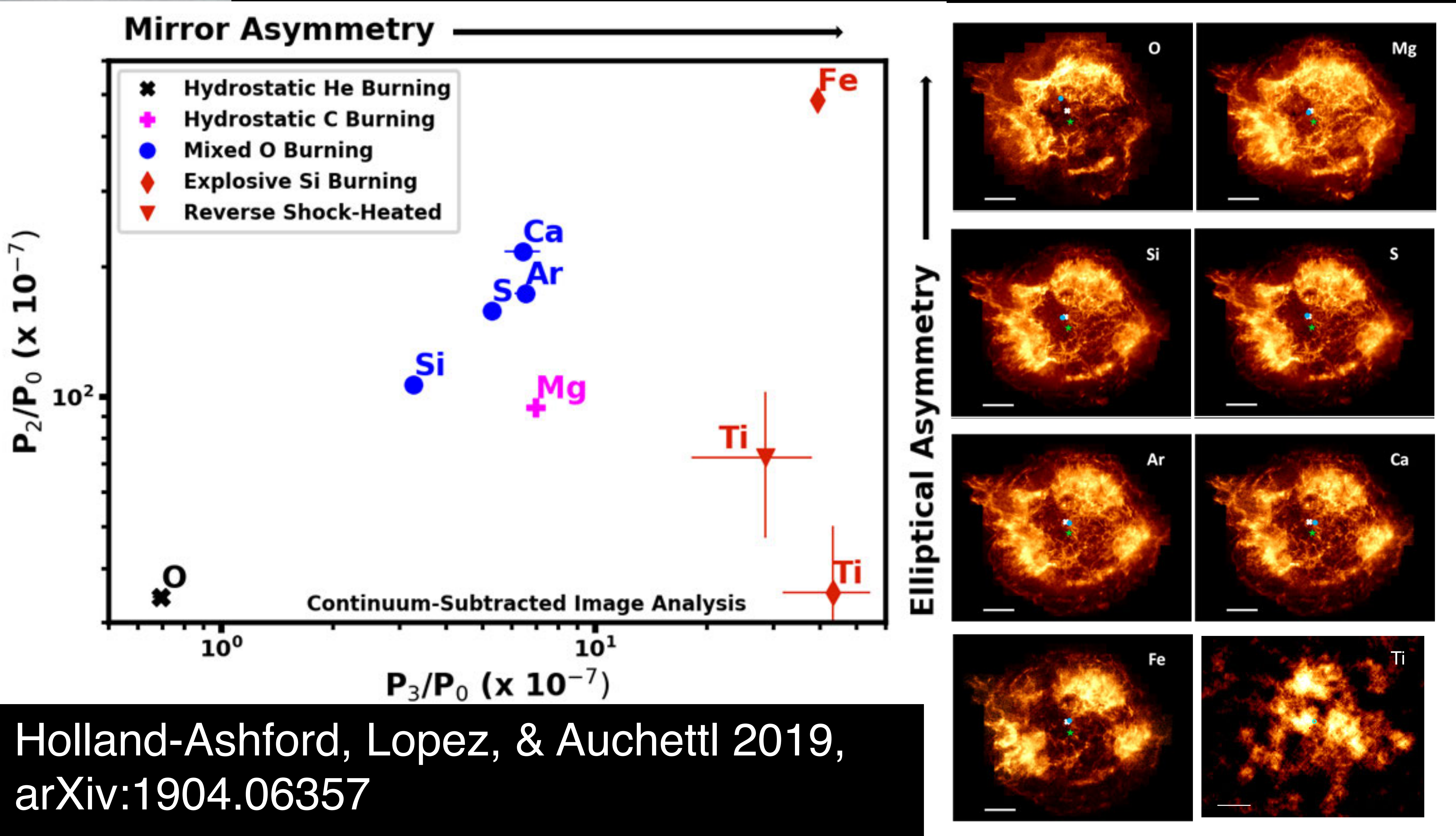
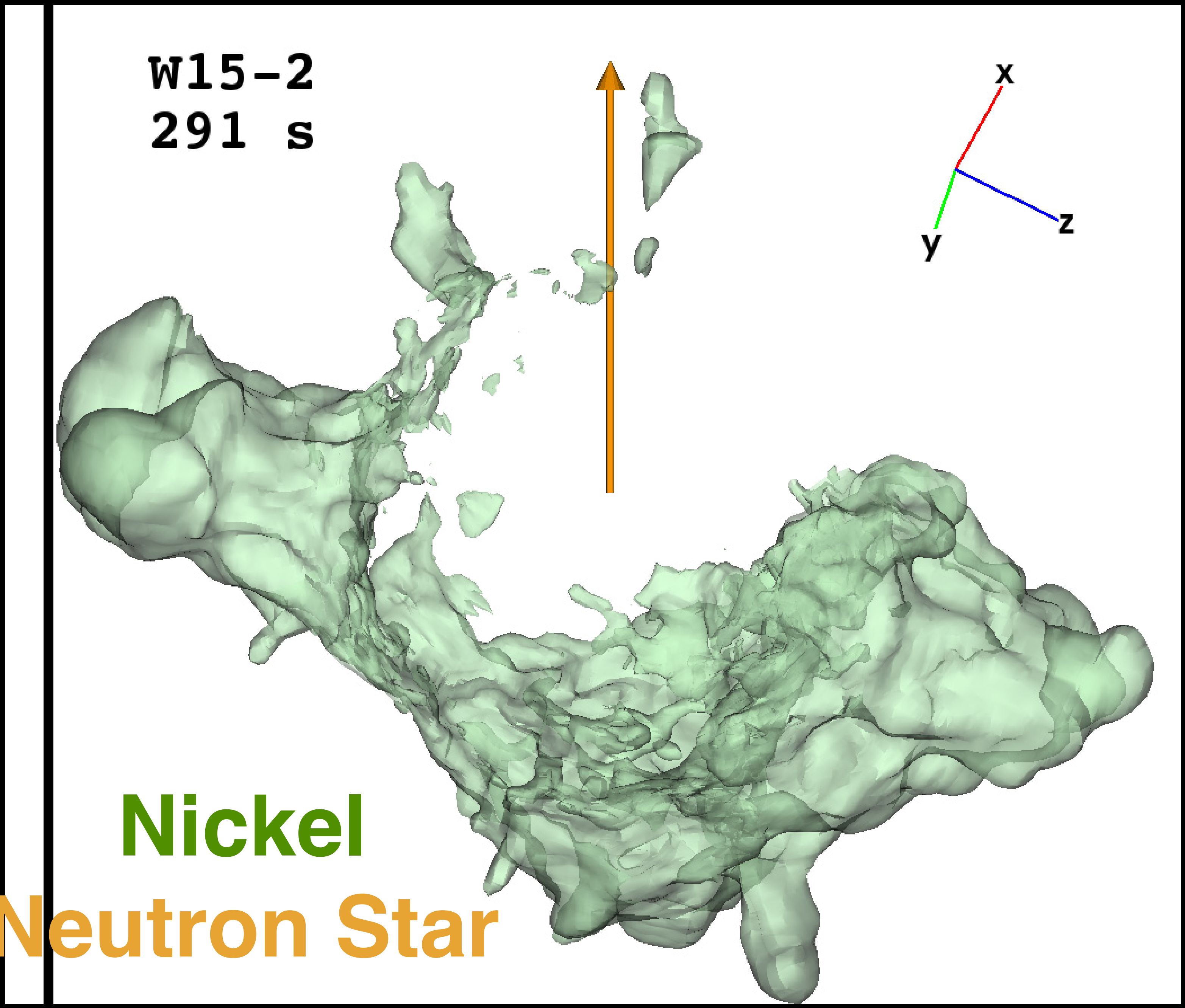


Holland-Ashford, Lopez, & Auchettl 2019, arXiv:1904.06357

Burning processes from Woosley, Heger, Weaver 2002; Curtis et al. 2019

Neutron Star Kicks

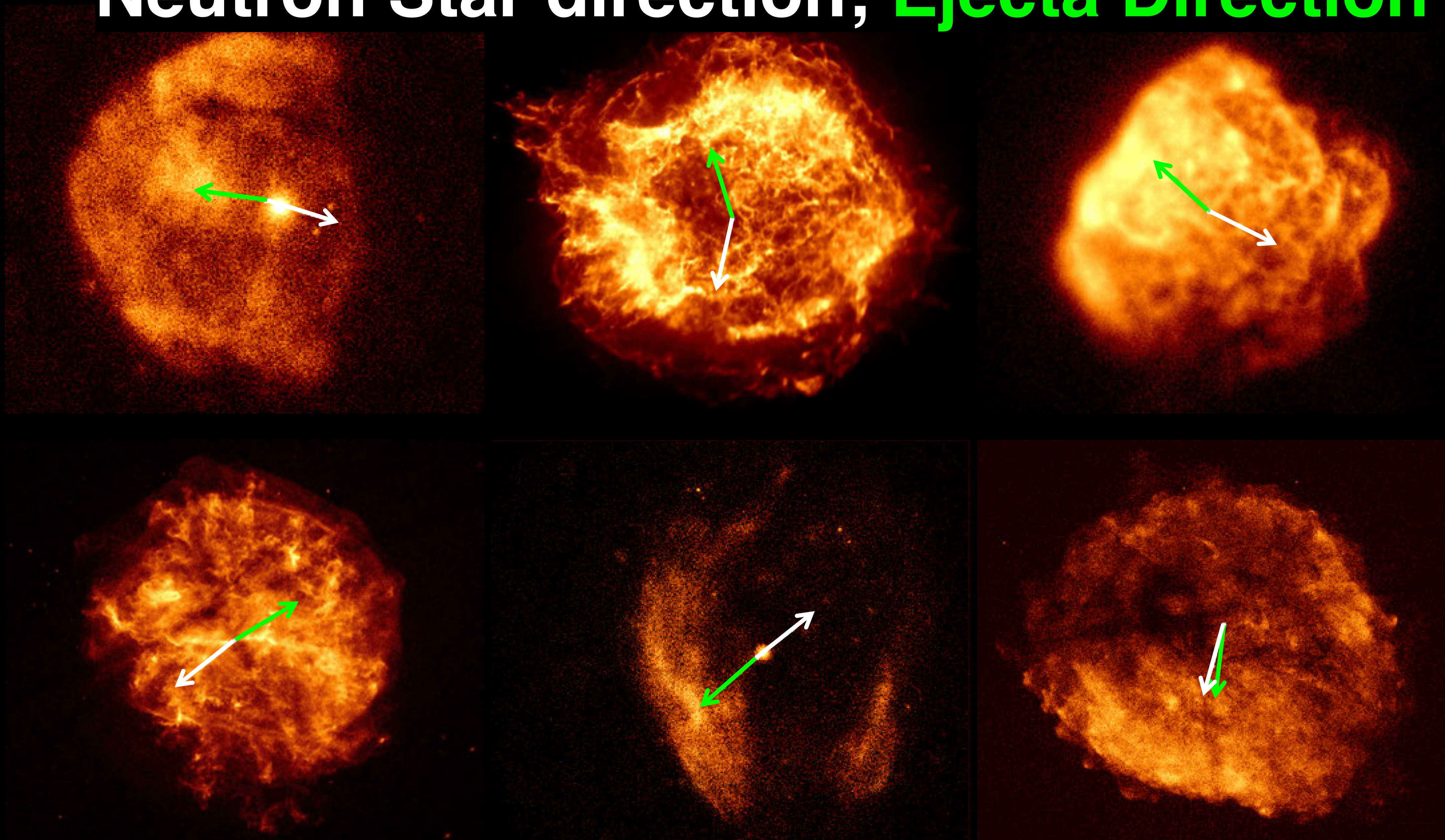


Wongwathanarat et al. 2013

If NS kick arises from asymmetric mass ejection (Scheck et al. 2006, Wongwathanarat et al. 2013, Janka 2017), NS goes opposite to heavy ejecta. If NS arises from anisotropic neutrino emission (Fryer & Kusenko 2006), NS goes in the same direction as heavy ejecta.

Neutron Stars Kicked Opposite to Ejecta

Neutron Star direction; Ejecta Direction



Holland-Ashford, Lopez et al. 2017

Neutron stars are ‘kicked’ by the SN explosion opposite to the ejected material. See also Katsuda et al. 2018

Type Ia Progenitor Systems: the Debate

Ways to distinguish single vs. double degenerate scenarios:

1. Existing populations of potential progenitors
2. Pre-explosion data of SN Ia sites find no companions
3. Observed properties of SNe Ia events themselves
4. Signs of circumstellar medium interaction
5. SNe Ia time delay distribution

Maoz, Mannucci & Nelemans 2014

Type Ia Progenitor Systems: the Debate

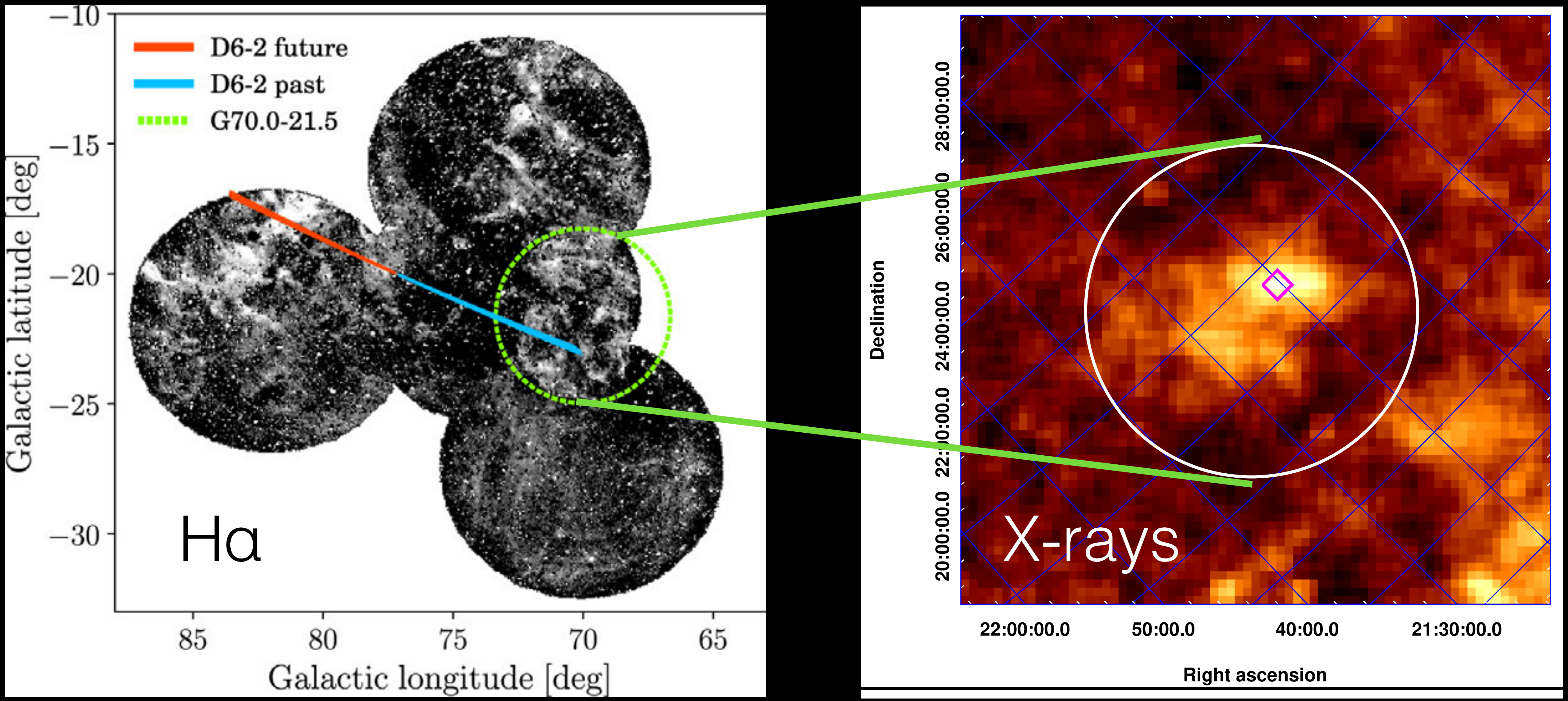
SNRs can offer insights in a variety of ways:

1. Search for surviving companions (e.g., Schaefer & Pagnotta 2012, Kerzendorf et al. 2019) - haven't found any
2. Nucleosynthesis - compare heavy element abundances to yields in different progenitor systems/ignition processes (e.g., Lopez et al. 2015; Yamaguchi et al. 2015)
3. Signs of circumstellar interactions (see reviews by Patnaude & Badenes 2017 and Vink 2017)
4. Hypervelocity white dwarfs originating from SNRs

Type Ia Progenitor Systems: High-Velocity White Dwarfs

Shen+18 searched for hypervelocity WDs in Gaia DR2 and found three.

One traces back to the position of a known SNR, G70.0-21.5 and originated from there ~90,000 years ago.



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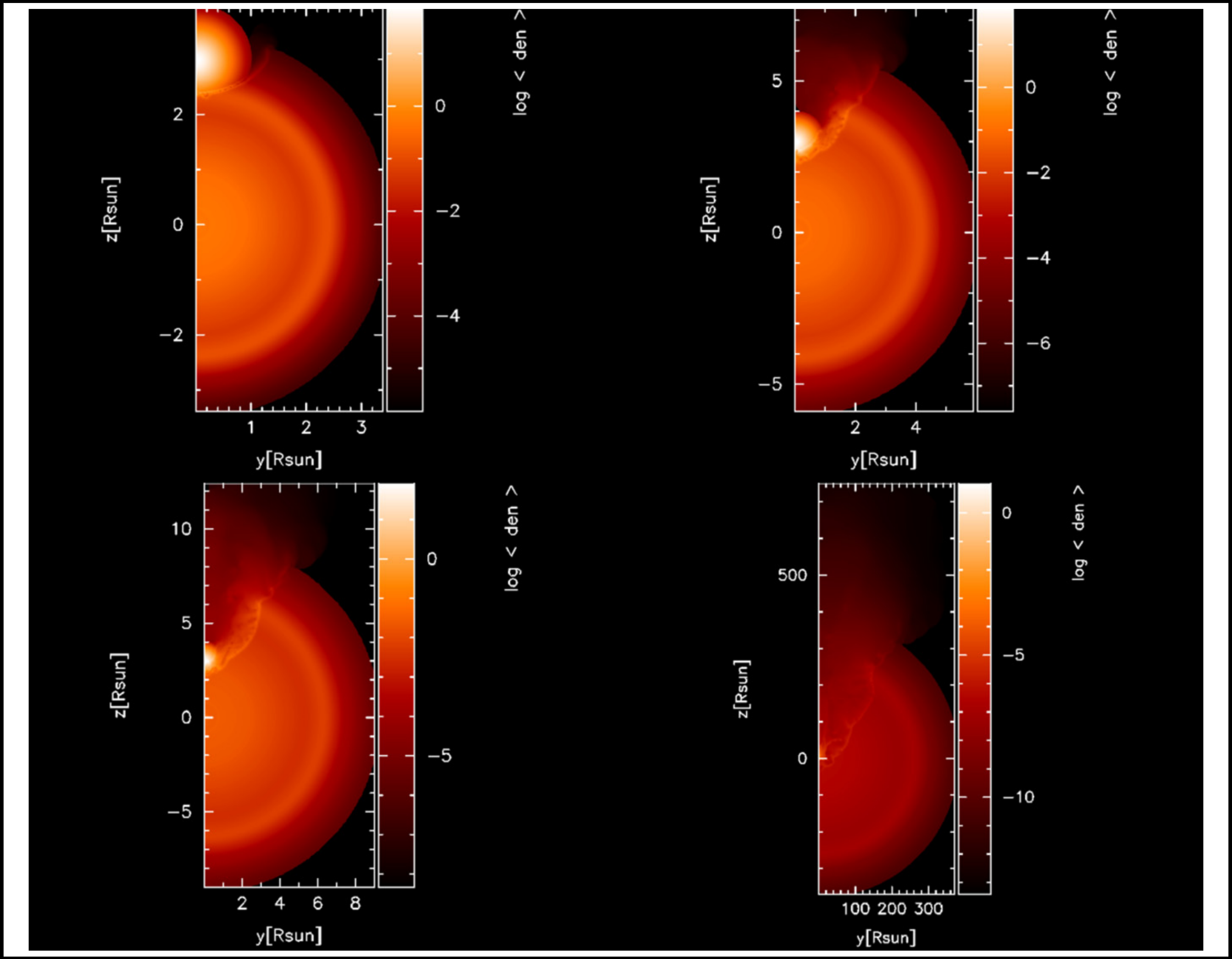
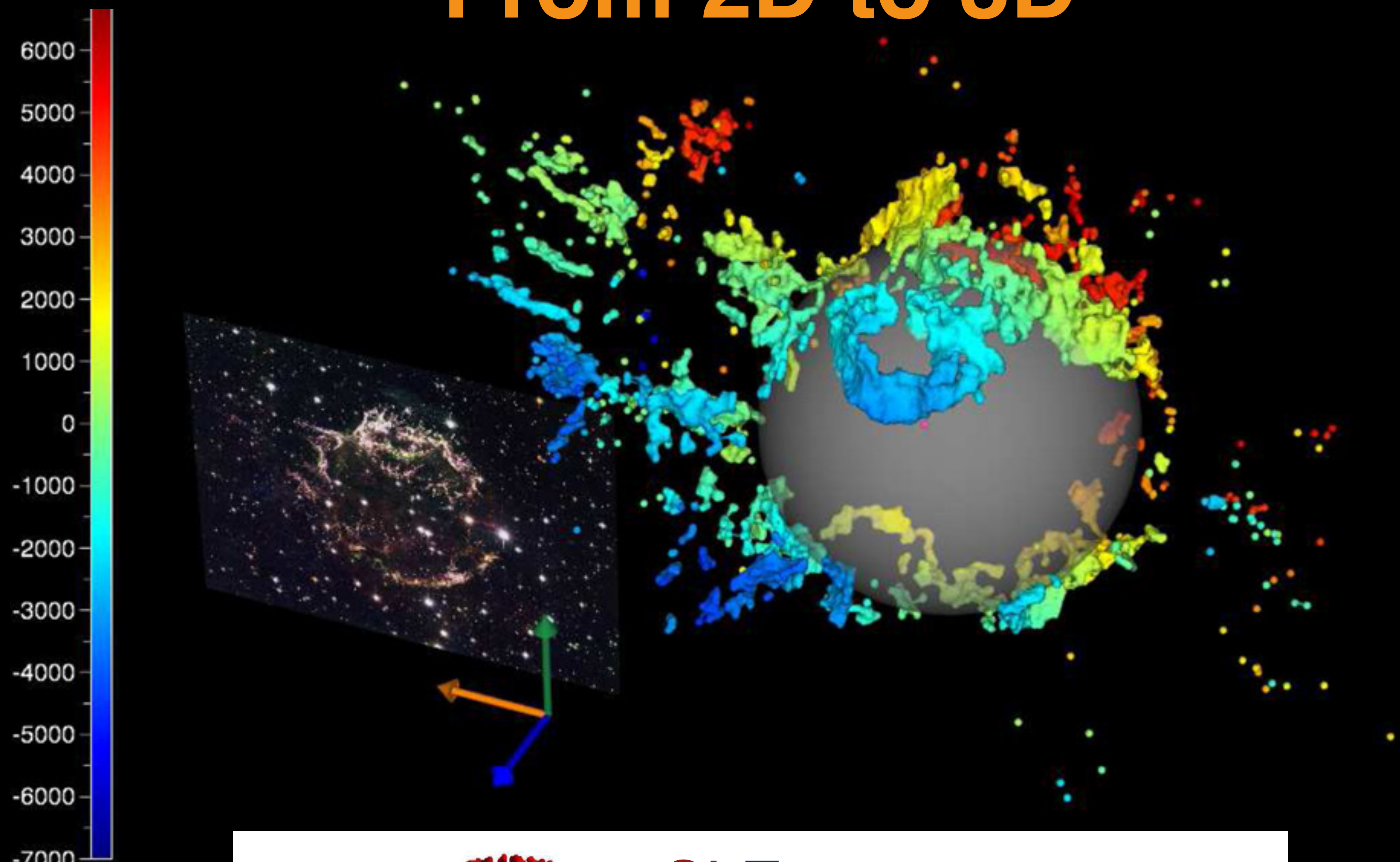
4. Hypervelocity white dwarfs originating from SNRs
5. Morphologies - single vs. double will produce different shapes

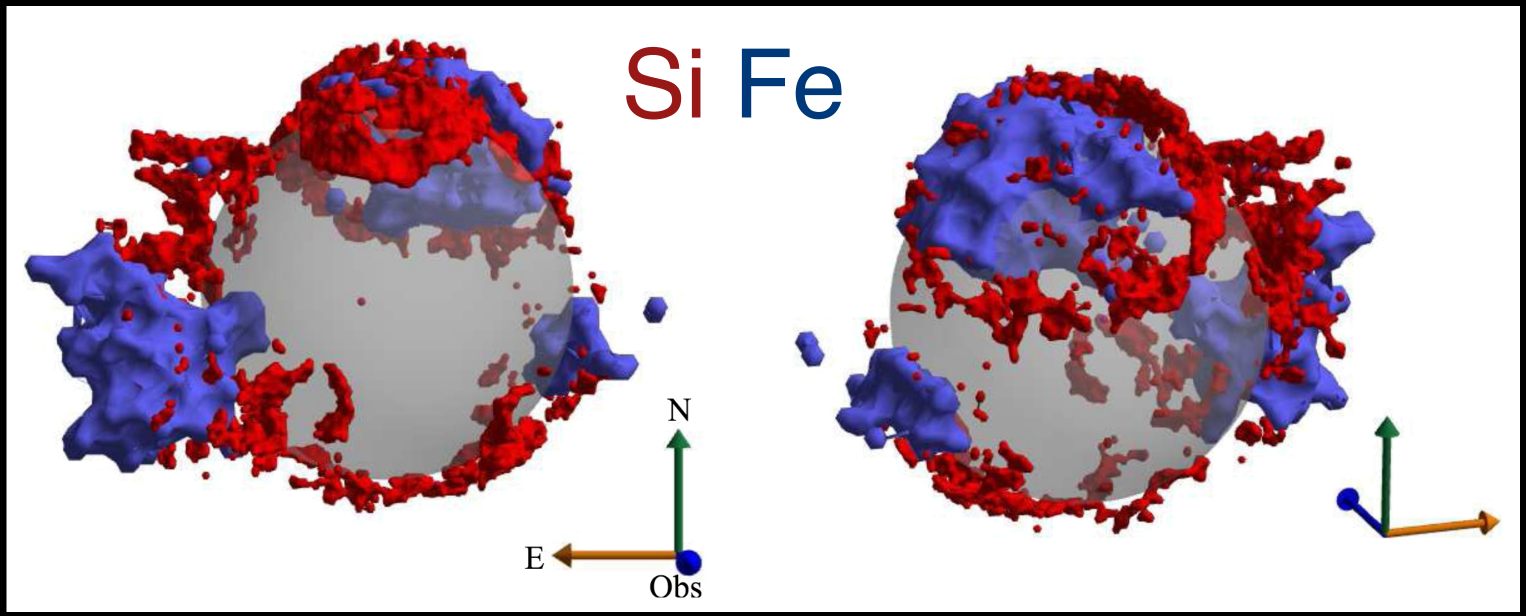
Holes/Gaps in Type Ia SNRs - Possible Signature of Single-Degenerate Scenario



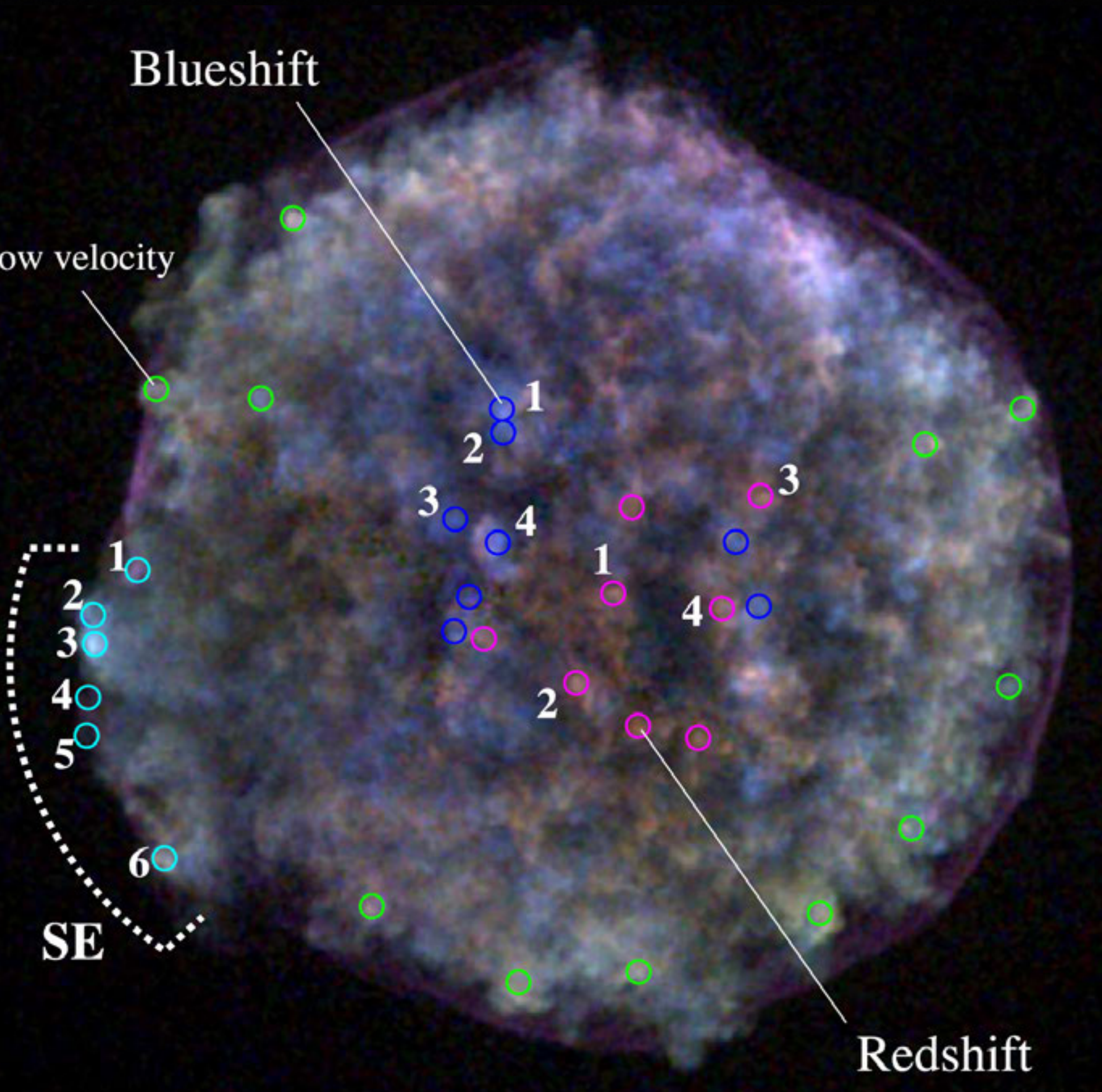
Garcia-Senz et al. 2012

From 2D to 3D





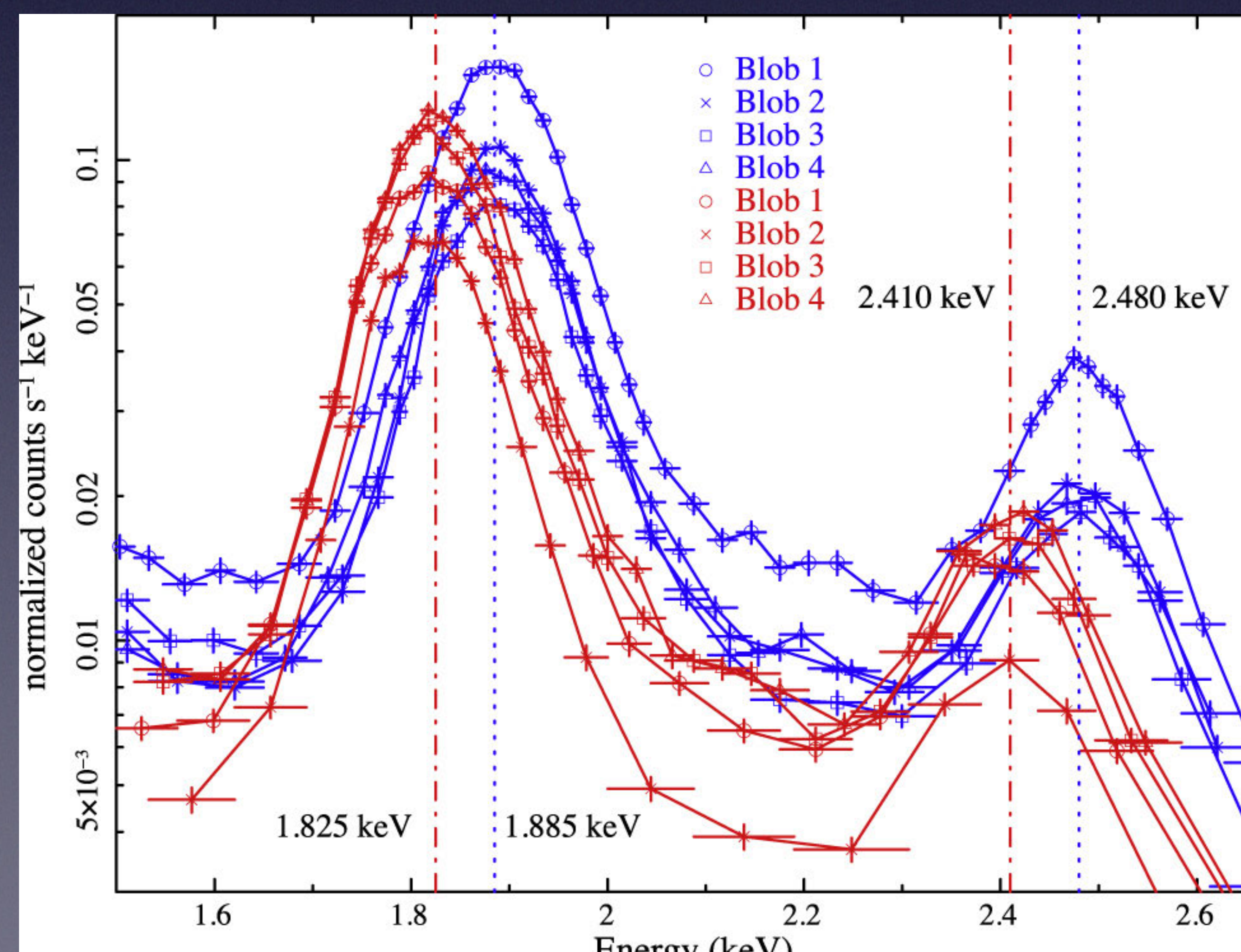
Milisavljevic & Fesen 2013



Tycho's SNR

Spectral analysis of small knots of ejecta in Tycho show very high line-of-sight velocities

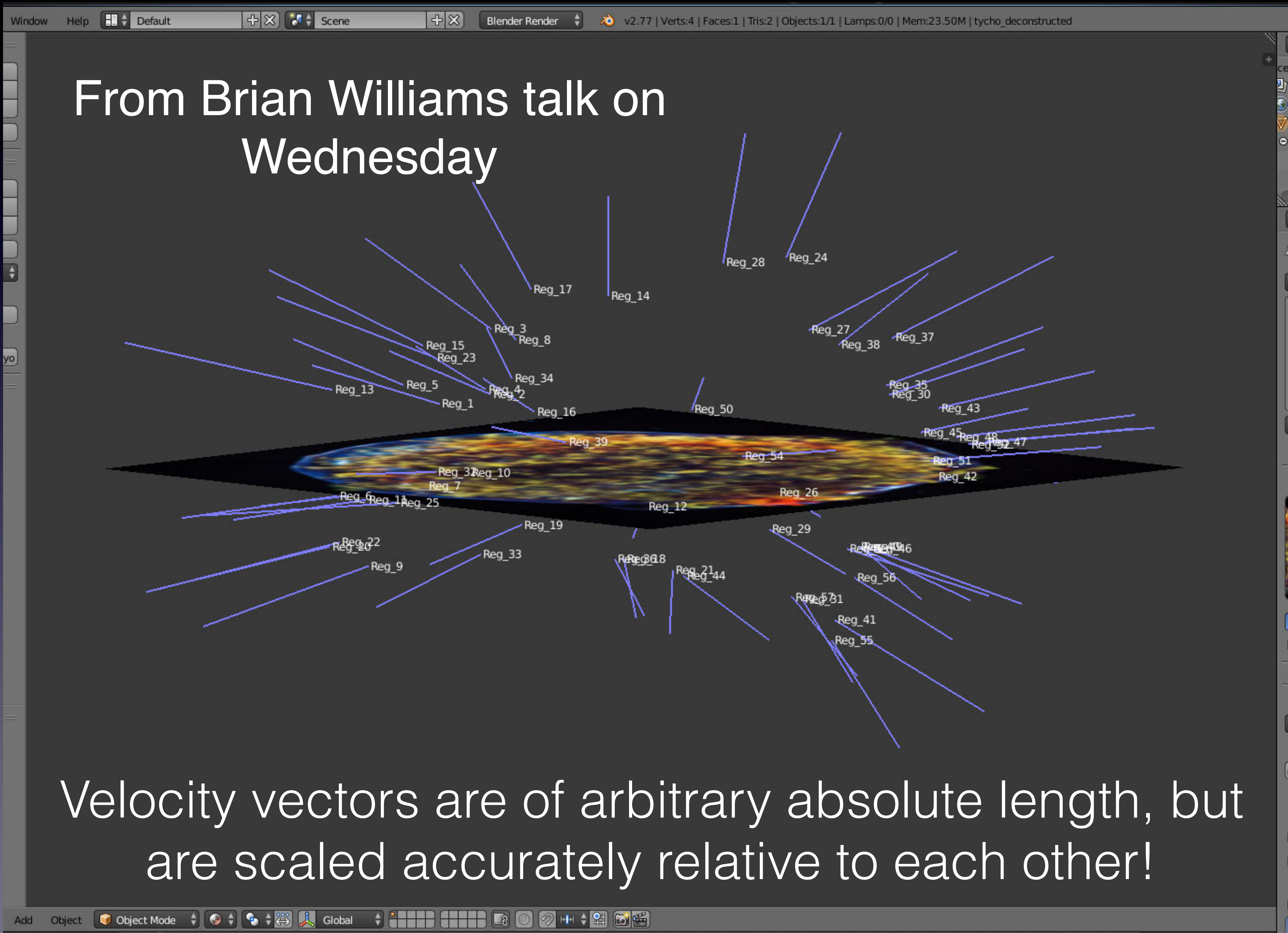
Blueshifted mean = -3220 km/s
Redshifted mean = 4980 km/s



See Sato & Hughes 2017

From Brian Williams talk on Wednesday

Results and 3D visualization

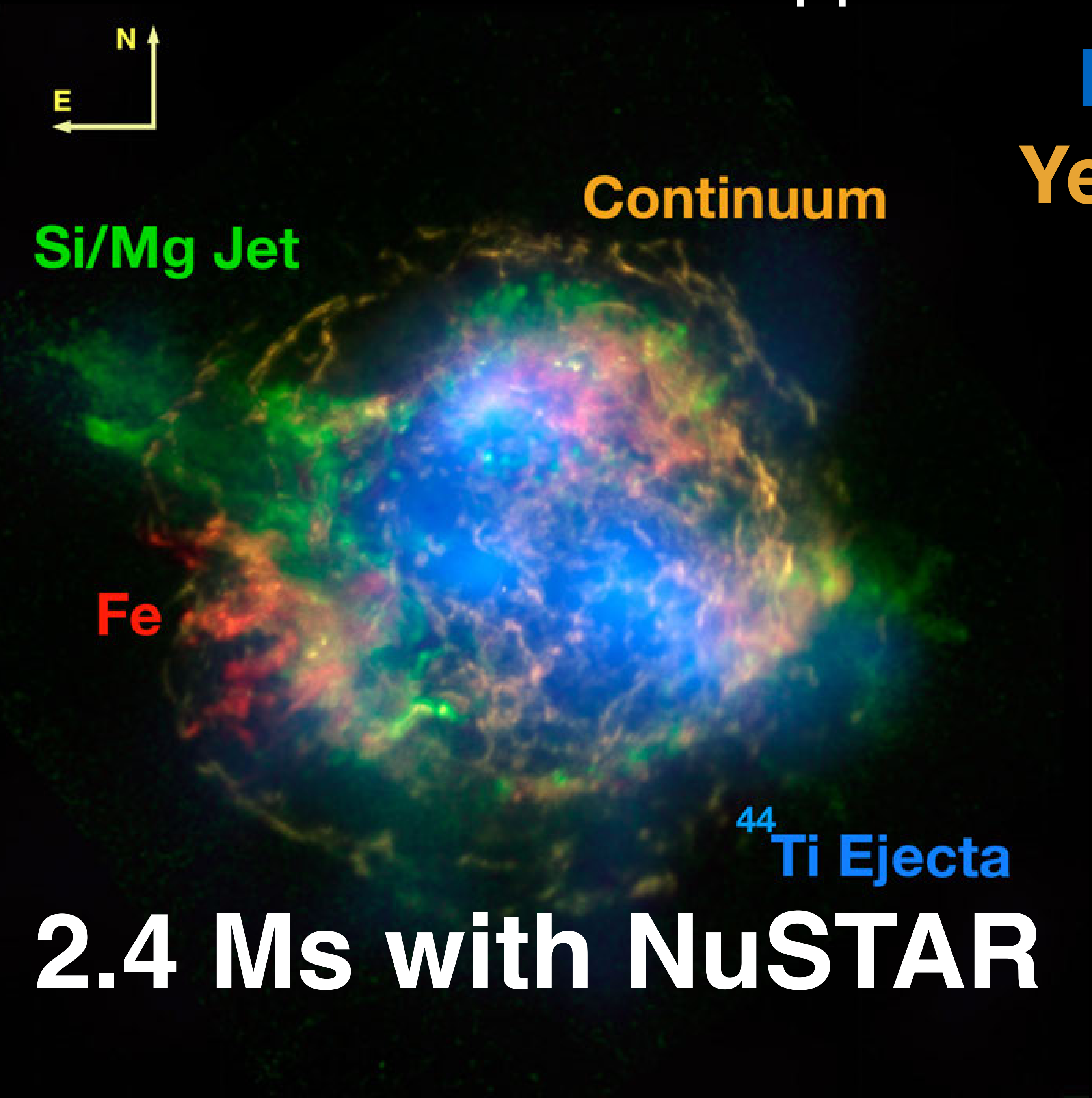


From Brian Williams talk on Wednesday

Velocity vectors are of arbitrary absolute length, but are scaled accurately relative to each other!

From 2D to 3D

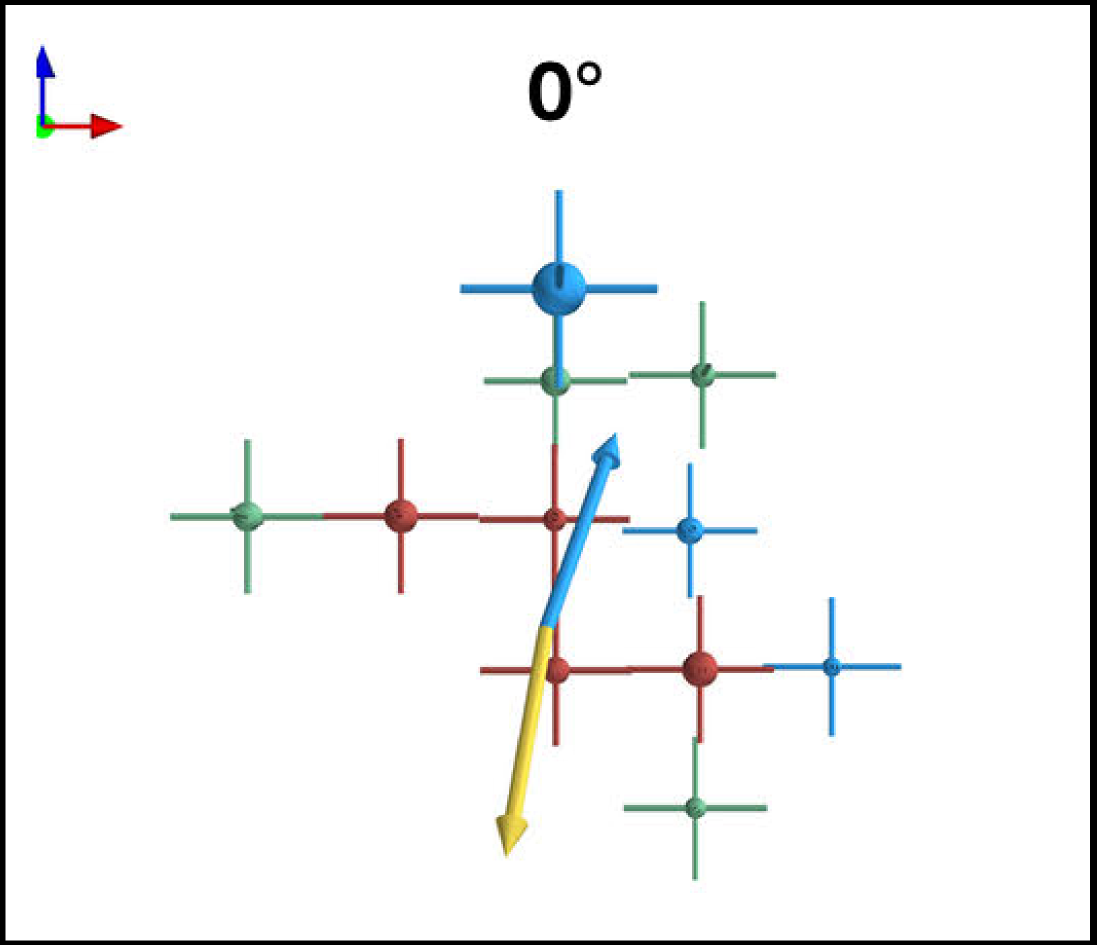
Kinematics of 44-Ti line showed that Ti is opposite to NS motion



Grefenstette et al. 2017

Blue arrow: direction of Ti

Yellow arrow: direction of NS

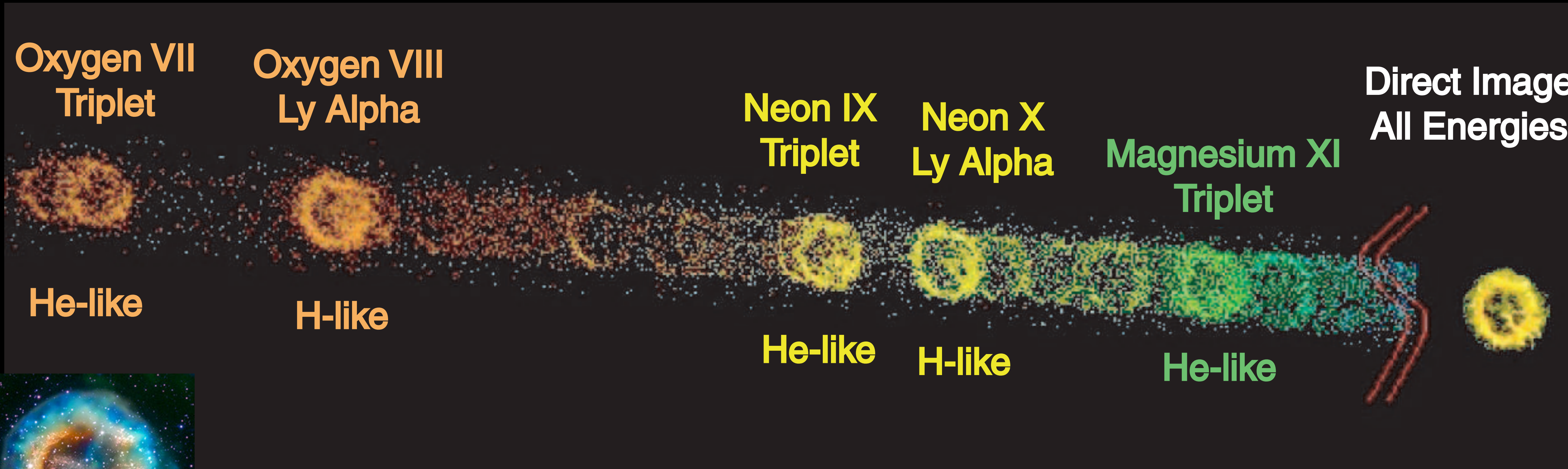


Interior to RS

Near RS

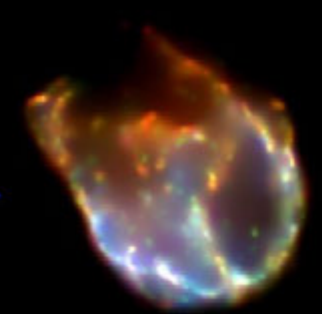
Outside RS

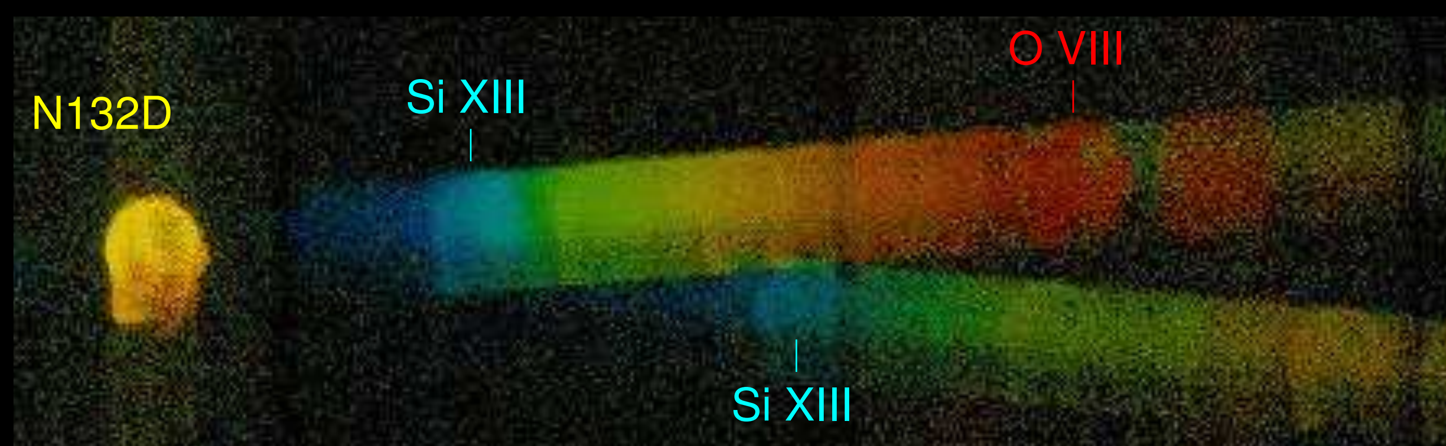
Limitations of Gratings

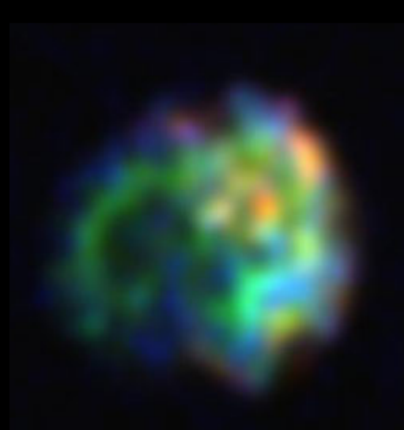


SNR 1E 0102.2-7219

Flanagan et al. 2004





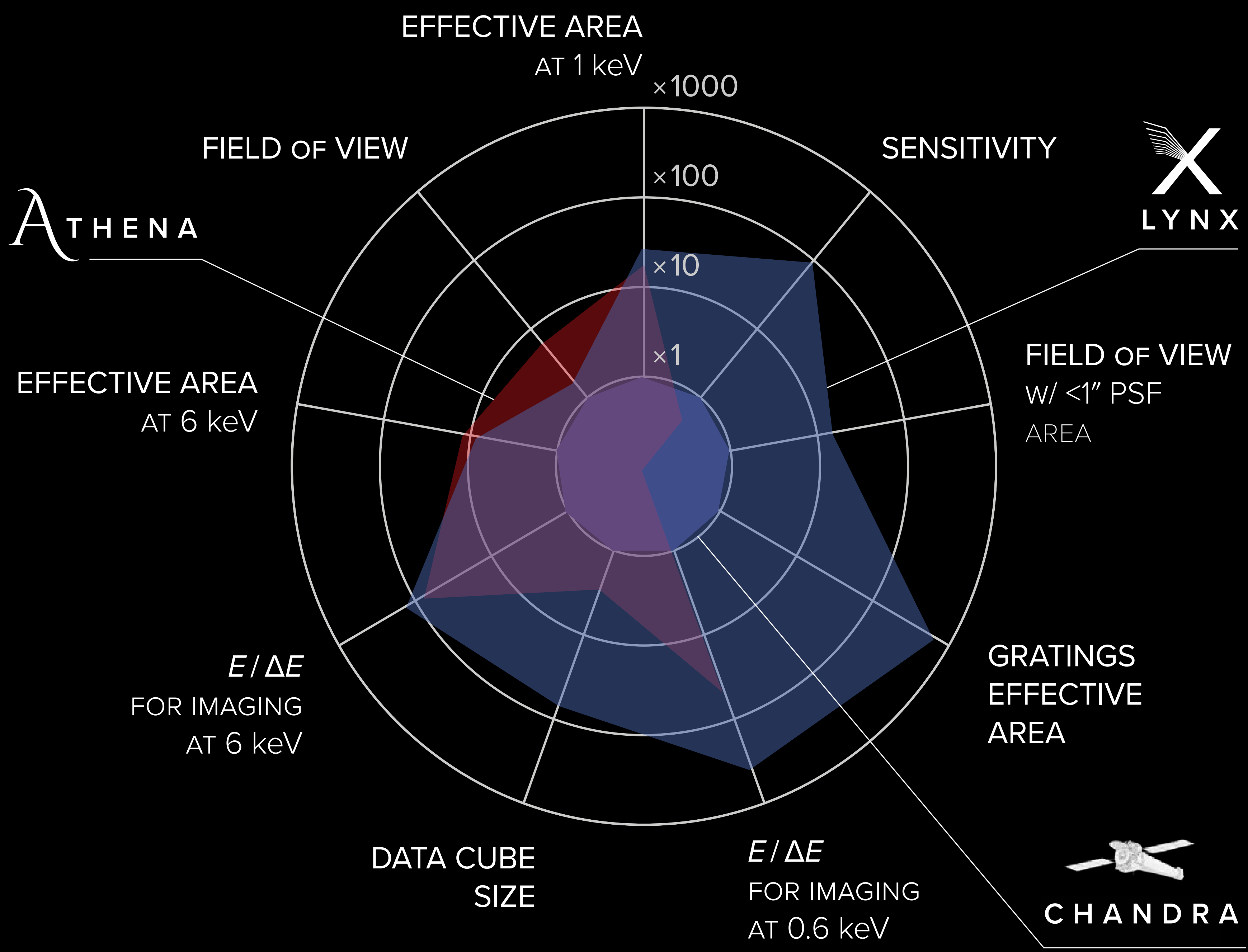


Dewey 2002

Future: Microcalorimeters

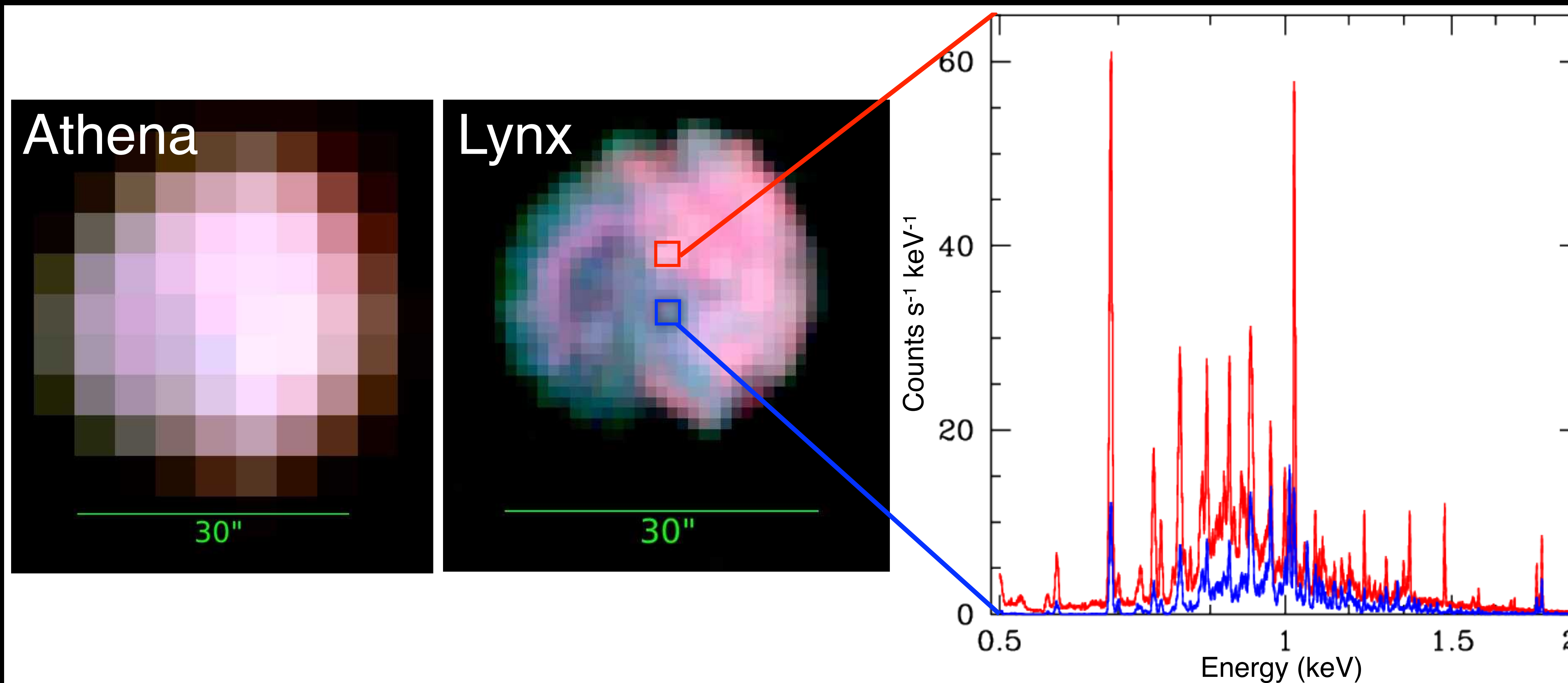
Microcalorimeters on XRISM, Athena, and Lynx are going to revolutionize SNR science, giving a 3D view of ejecta

Lynx is successor mission to Chandra (30x effective area); will have 1” pixel microcalorimeter



Future: Lynx

1” pixels on microcalorimeter reduces confusion between different spectral components to enable precise measures of velocities, ejecta mixing, plasma properties



Lopez et al. 2019, arXiv: 1903.09677

Conclusions

SNR morphologies in different wavebands reflect the explosion asymmetries, the inhomogeneous environments, and the ambient magnetic field/particle acceleration properties

Type Ia SNRs are more circular and symmetric in X-rays and IR, reflecting their distinct explosions & environments.

In radio, morphology reflects ambient density and B-field. Radio morphology becomes increasingly asymmetric with age due to expansion into inhomogeneous medium.

Distinct morphologies of different elements useful to constrain explosion/progenitors and origin of neutron star kicks

3D maps of SNRs are even more powerful at revealing asymmetries, microcalorimeters will revolutionize field