Expansion of Young Galactic Supernova Remnants in X-rays

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2016 Chandra Science for the Next Decade

Young Supernova Remnants

- Learn how stars explode by examining SN ejecta (dynamics, asymmetries, nucleosynthetic products)
- Learn about progenitors by tracing mass lost by them (core-collapse and Type Ia-CSM)
- Study particle acceleration in very fast shocks
- Relate compact objects to supernovae that produced them

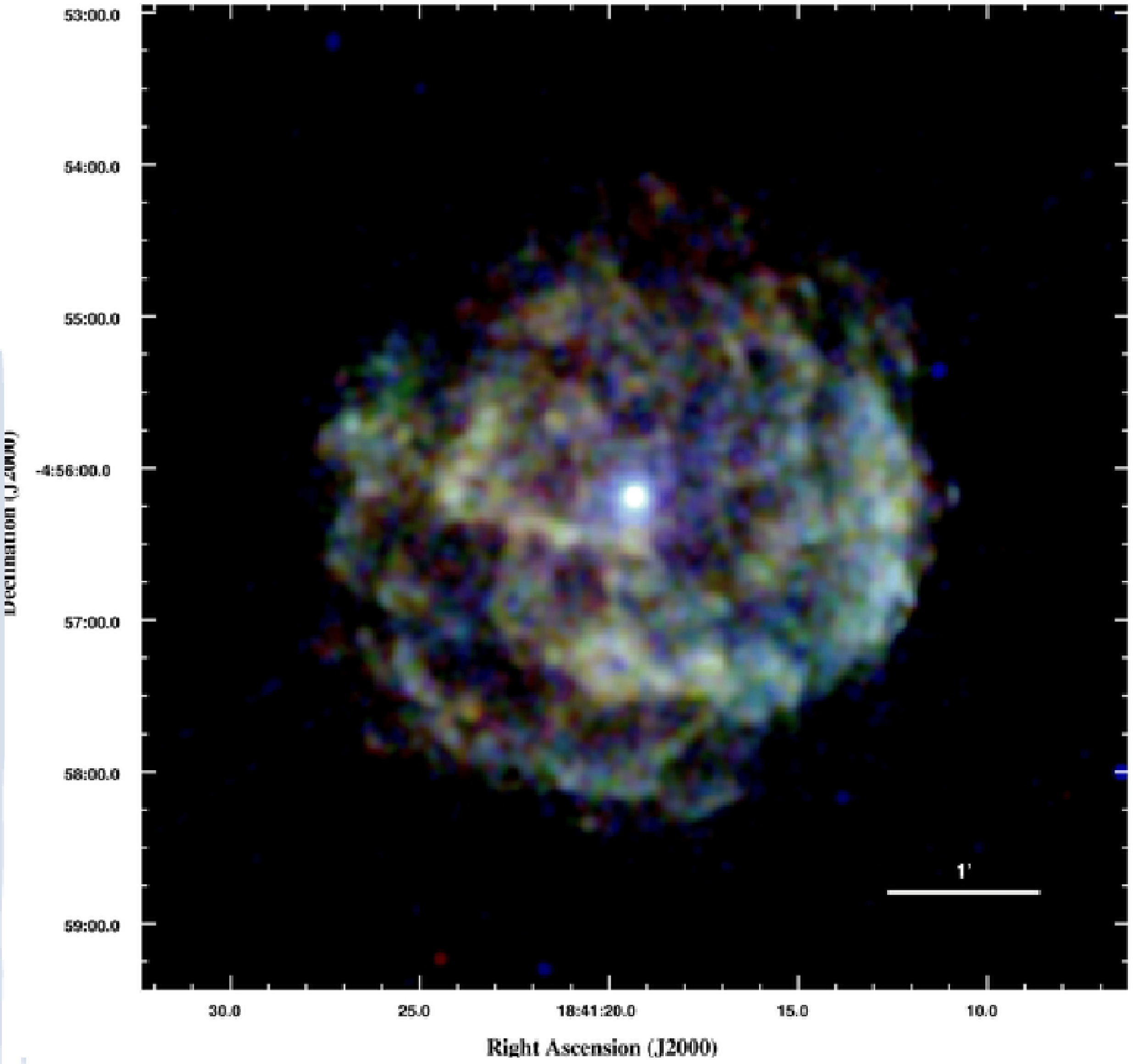
Youngest Galactic Shell Remnants

G1.9+0.3	SN Ia?	1900
Cas A (circumstellar medium)	SN IIb	1680
Kepler's SNR (SN 1604, CSM)	SN Ia	1604
Tycho's SNR (SN 1572)	SN Ia	1572
Kes 75	CC SN	< 1000 yr
SN 1006	SN Ia	1006
RCW 86 (SN 185)	SN Ia	185
G11.2-0.3 (pulsar/PWN, CSM)	CC SN	
G292.0+1.8 (pulsar/PWN, O-rich)	Type IIL/b	3000 yr
Kes 73 (magnetar, CSM)	CC SN	

Expansion and Age

- $R = Ct^m$
- $V = dR/dt = mR/t$
- $t_{SNR} = m/(d\ln R/dt)$, distance independent
- m=1, undecelerated optically-emitting ejecta (center of expansion = explosion site)
- m=2/3, Sedov wind dynamics
- m=2/5, standard Sedov dynamics
- If radial velocities are known, distance can be estimated

Kes 73: CC SNR with a Magnetar



Chandra X-ray image from Kumar et al. (2014)

Magnetar, P=12s

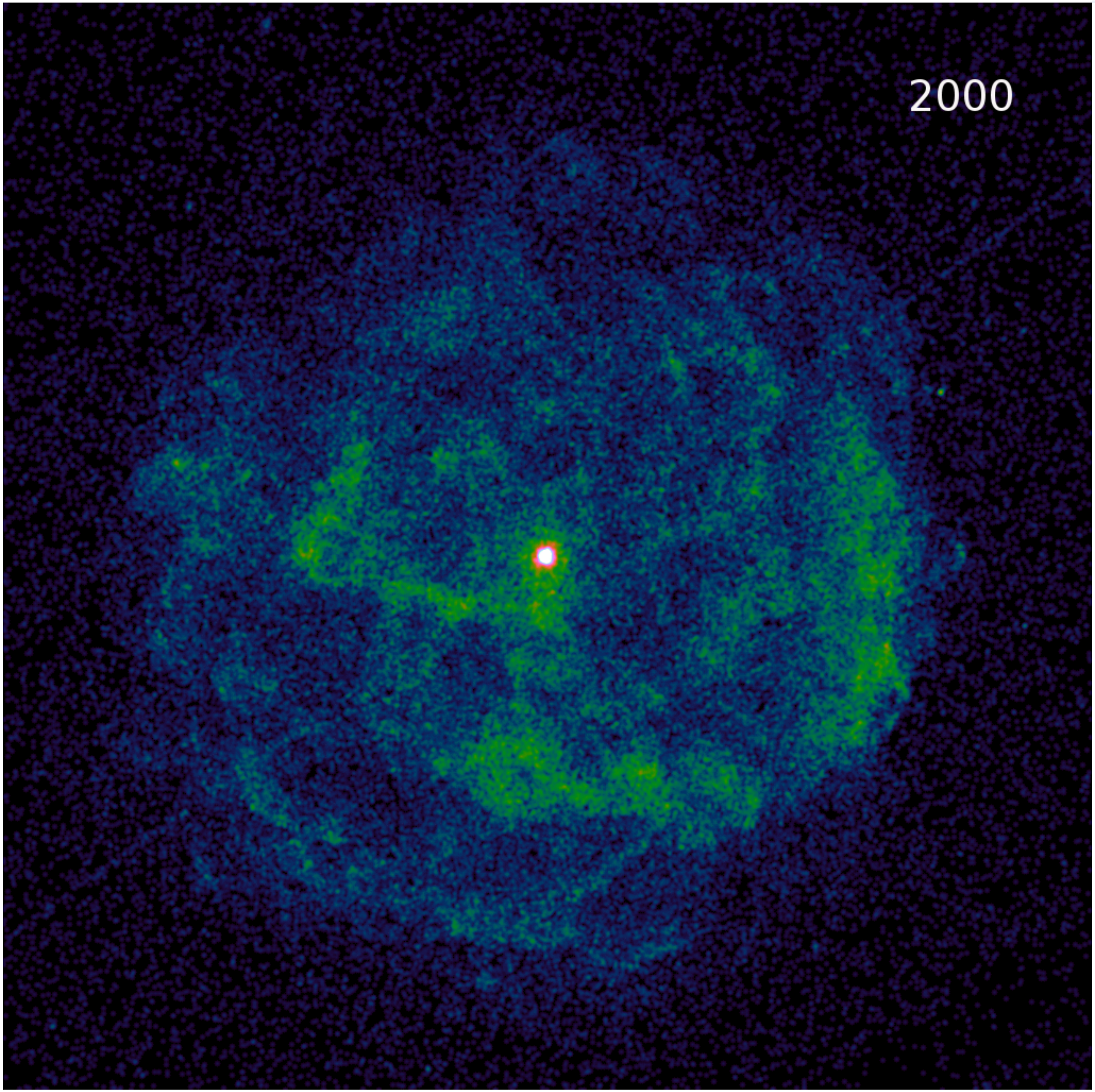
Distance 8.5 kpc

CSM, SN IIL/IIb (Chevalier 2005)

Ages quoted in literature ≤ 2000 yr

Heavy-element ejecta might be present (Kumar et al. 2014)

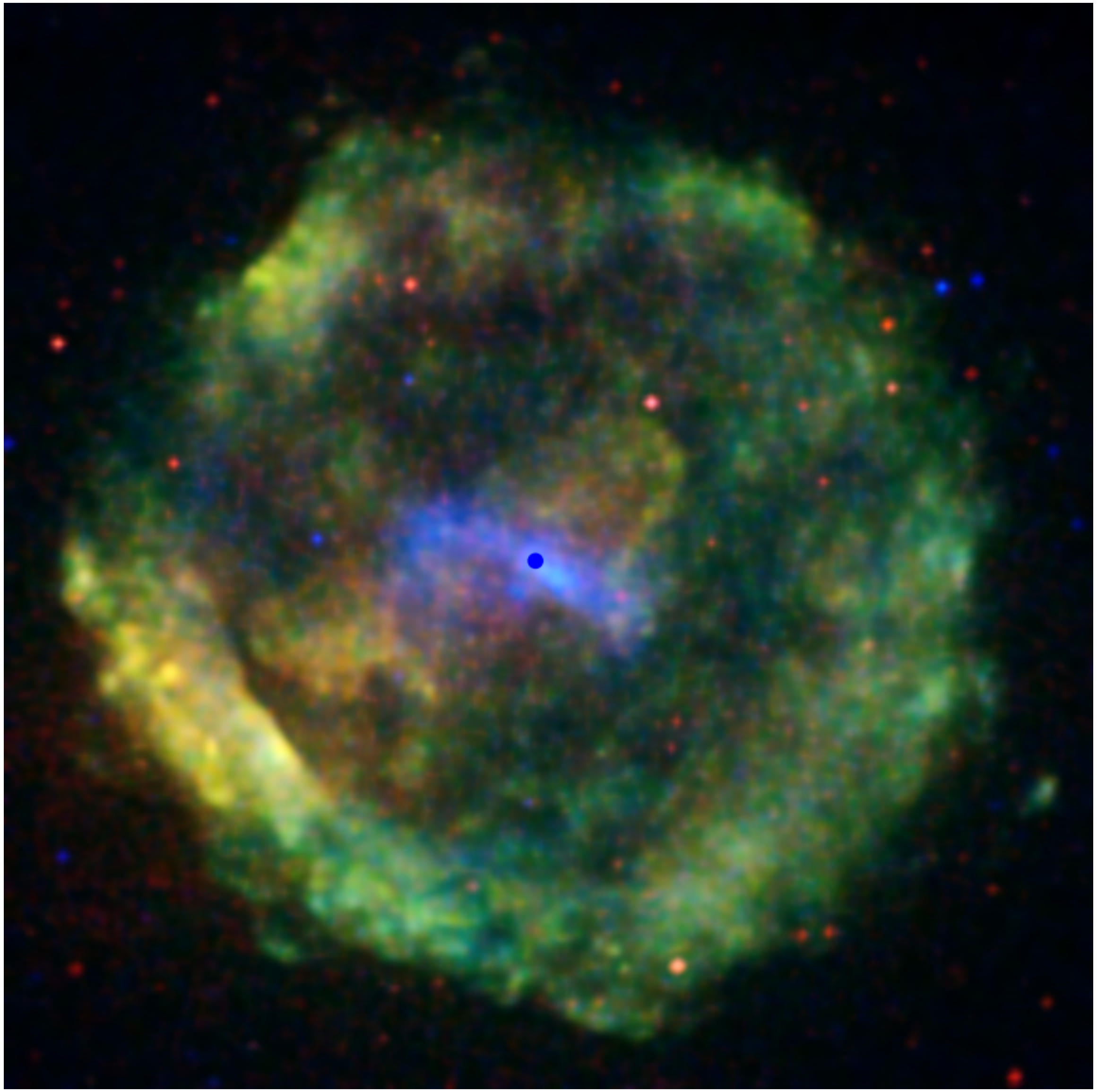
Kes 73



Kes 73: Expansion and Age

- In 15 yr, expanded by 0.34% +/- 0.05%
- dlnR/dt = 0.023% +/- 0.003% per yr
- Undecelerated age 4400 yr
- m=2/3, 2900 yr
- m=2/5, 1700 yr
- Spin-down age of magnetar 4800 yr
- Age determination possible for several thousand year-old remnants

G11.2-0.3



Expansion rate 0.028%+/-0.002% yr^{-1} (based on 2000, 2003, and 2013 Chandra observations)

Age 1400-2400 yr

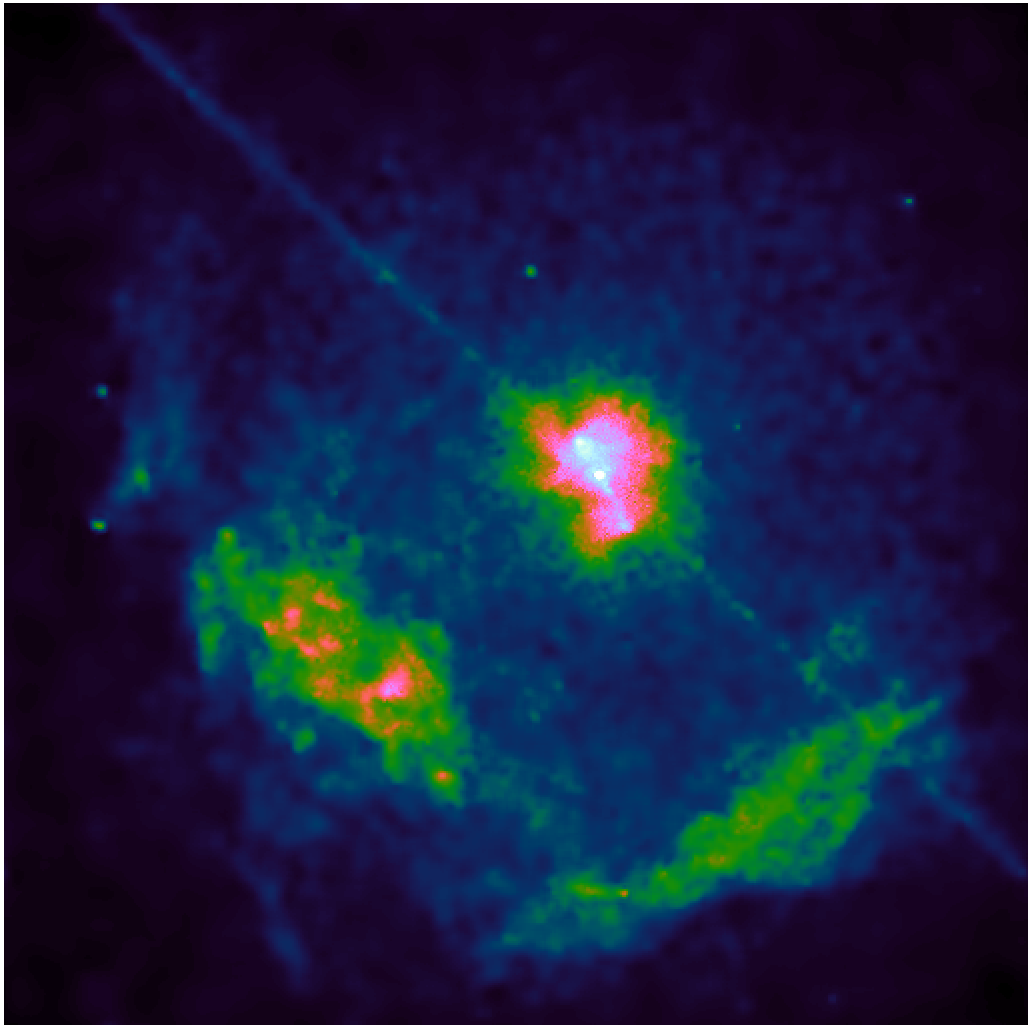
Not the remnant of a possible SN in 386 CE (16^{m} of extinction)

Circumstellar medium

SN cIIb/Ibc – the entire stellar envelope was lost prior to the explosion

Borkowski, Reynolds, & Roberts (2016)

Kes 75



Kes 75 in 2006. Image size 3.7 x 3.7 arcmin.

Pulsar, P=326 ms, spindown age 884 yr

Distance 6 kpc

Age uncertain, could be as young as 430 yr (Gelfand et al. 2014)

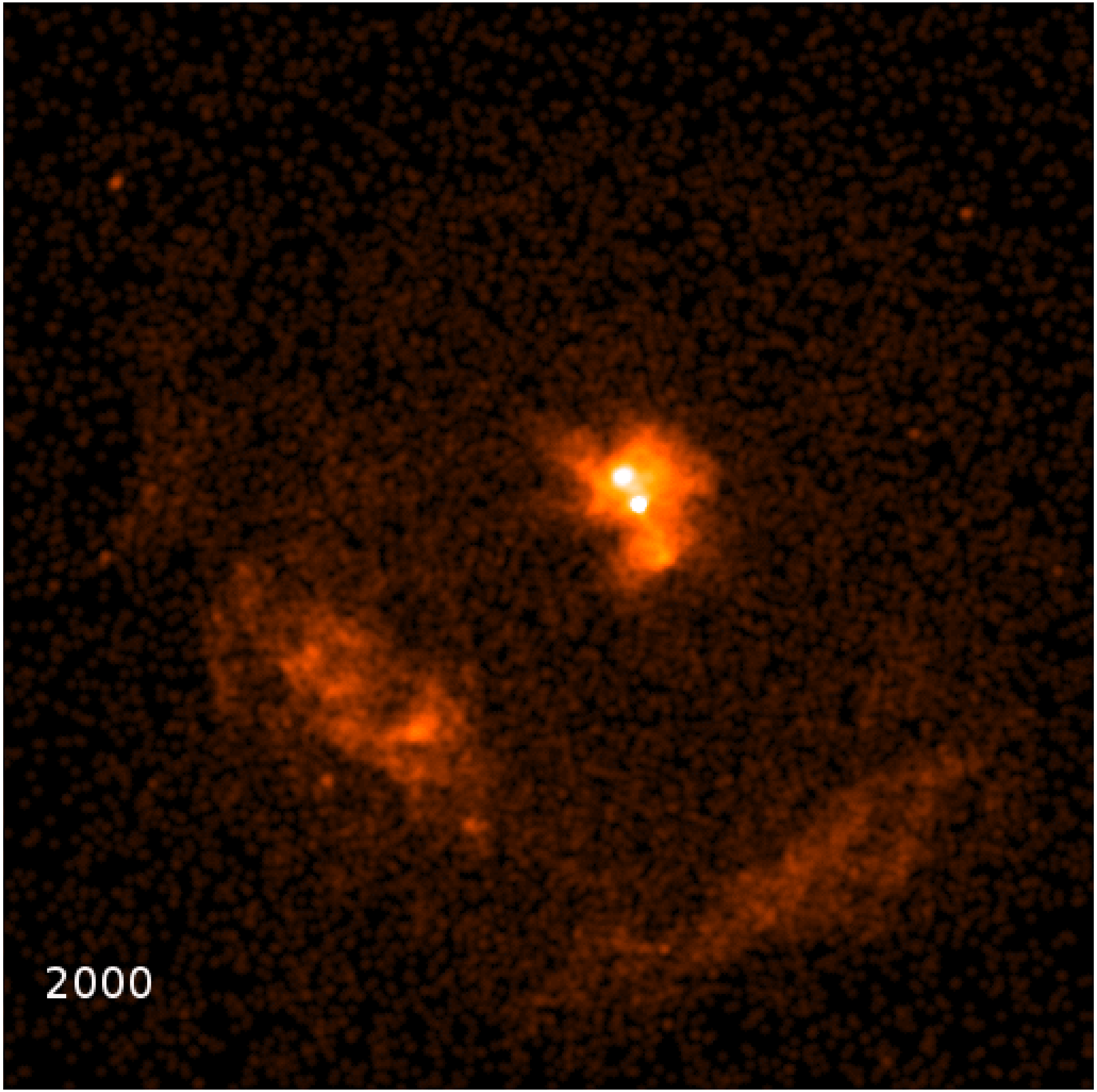
Youngest CC/PWN combination, second youngest (after Cas A) CC remnant in the Galaxy

High absorption, SN not seen

Heavy-element ejecta detected

Very asymmetric (incomplete?) shell, dynamics of the remnant not understood.

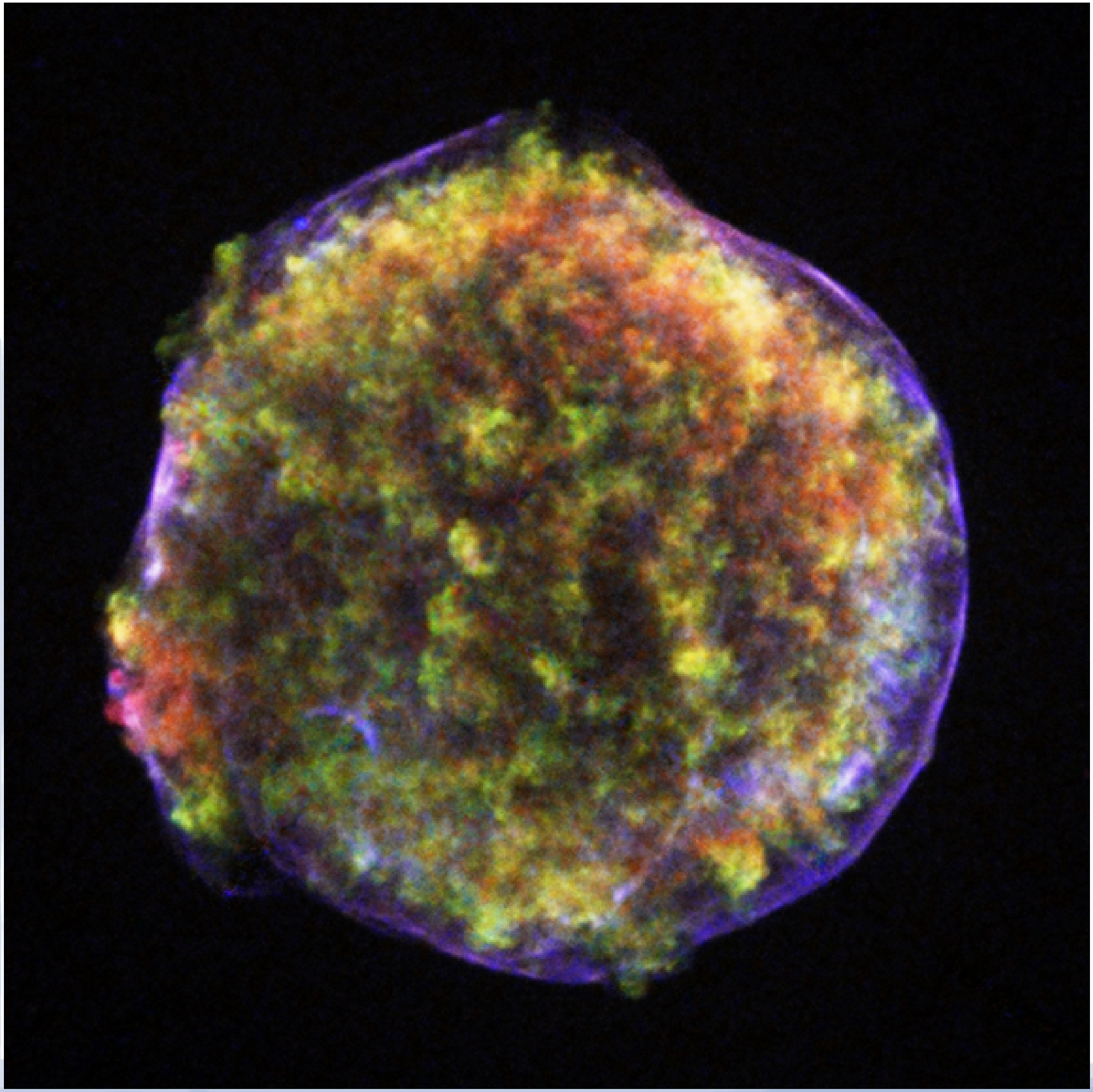
Kes 75



Kes 75: Expansion and Age

- Shell expanded by 0.50%+/-0.06% between 2006 and 2016 (uniform expansion assumed – not realistic)
- Expansion rate 0.050%+/-0.006% yr^{-1}, undecelerated age of 2000 yr
- Outermost parts of the PWN expand with rate of 0.13%+/-0.04% yr^{-1} (errors are 90% confidence intervals, more accurate measurements under way). Lower limit to age is ~800 yr, consistent with the pulsar spindown age.
- Significant (m=2/5) deceleration of the blast wave implied.

Tycho's SNR



SN 1572

Normal Type Ia (spectra of light echos)

2.3 kpc distance

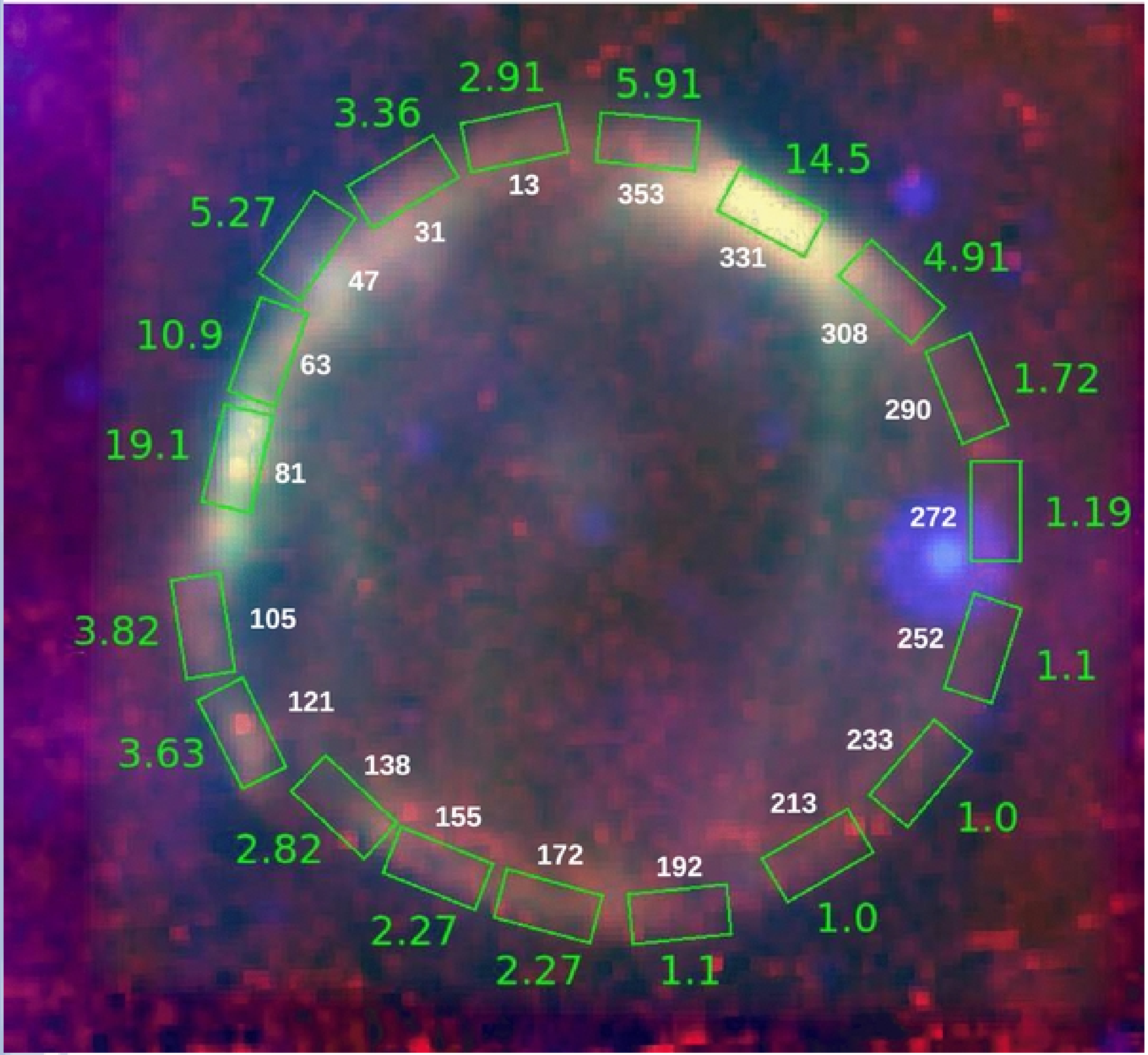
Nonthermal X-rays

Strong Fe lines (ejecta)

Strong Si, S, Ar, Ca (ejecta)

Companion found (Star G; Ruiz-Lapuente et al. 2004)?

Tycho's SNR: Density Gradient



IR color image showing variations in postshock density (Williams et al. 2013).

Dust heated by collisions with electron and ions behind the blast wave

Density diagnostic in young SNRs (e.g. Dwek & Arendt 1992).

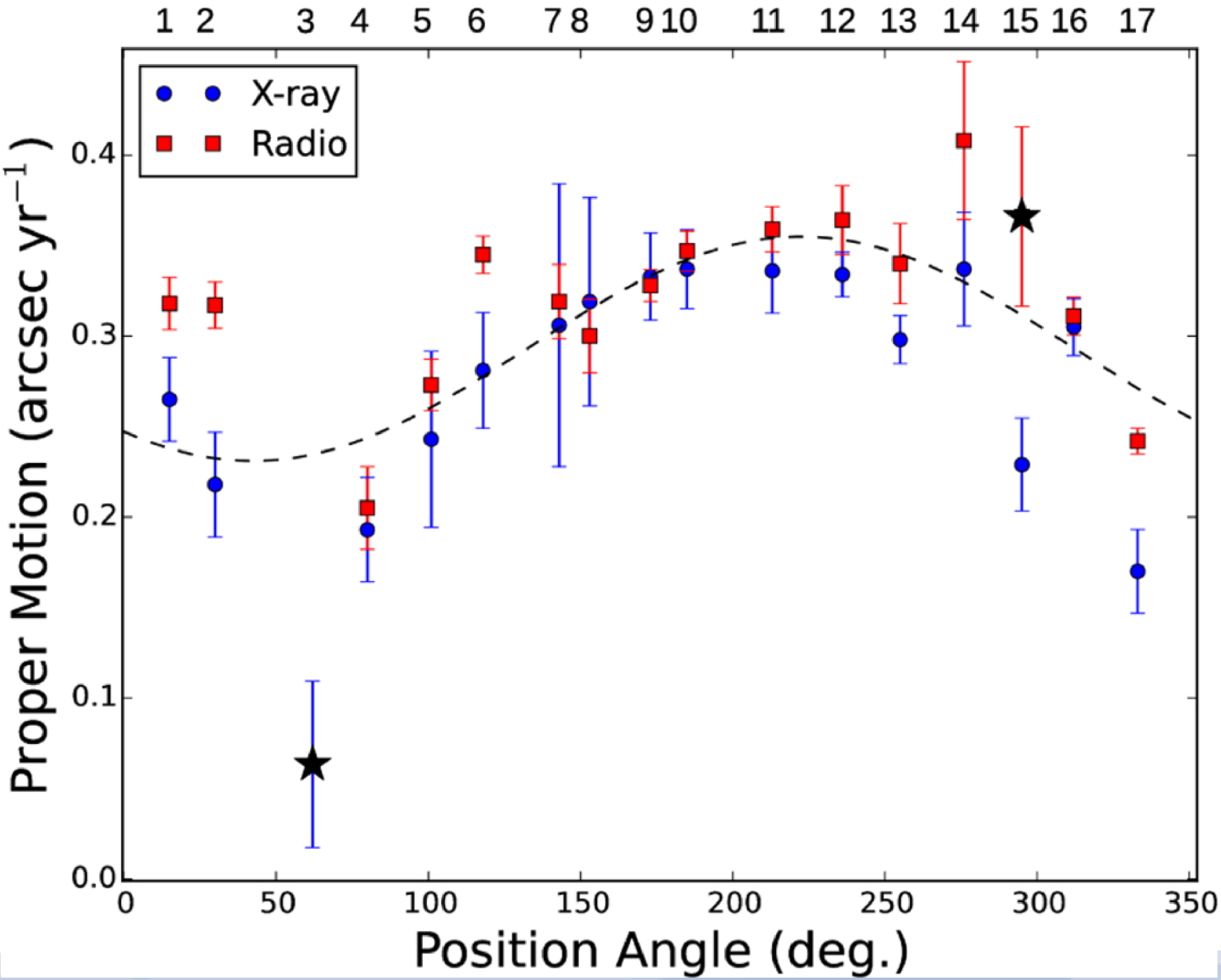
Order of magnitude variation in density

Asymmetric expansion

Remnant spherical but its center displaced from the explosion center.

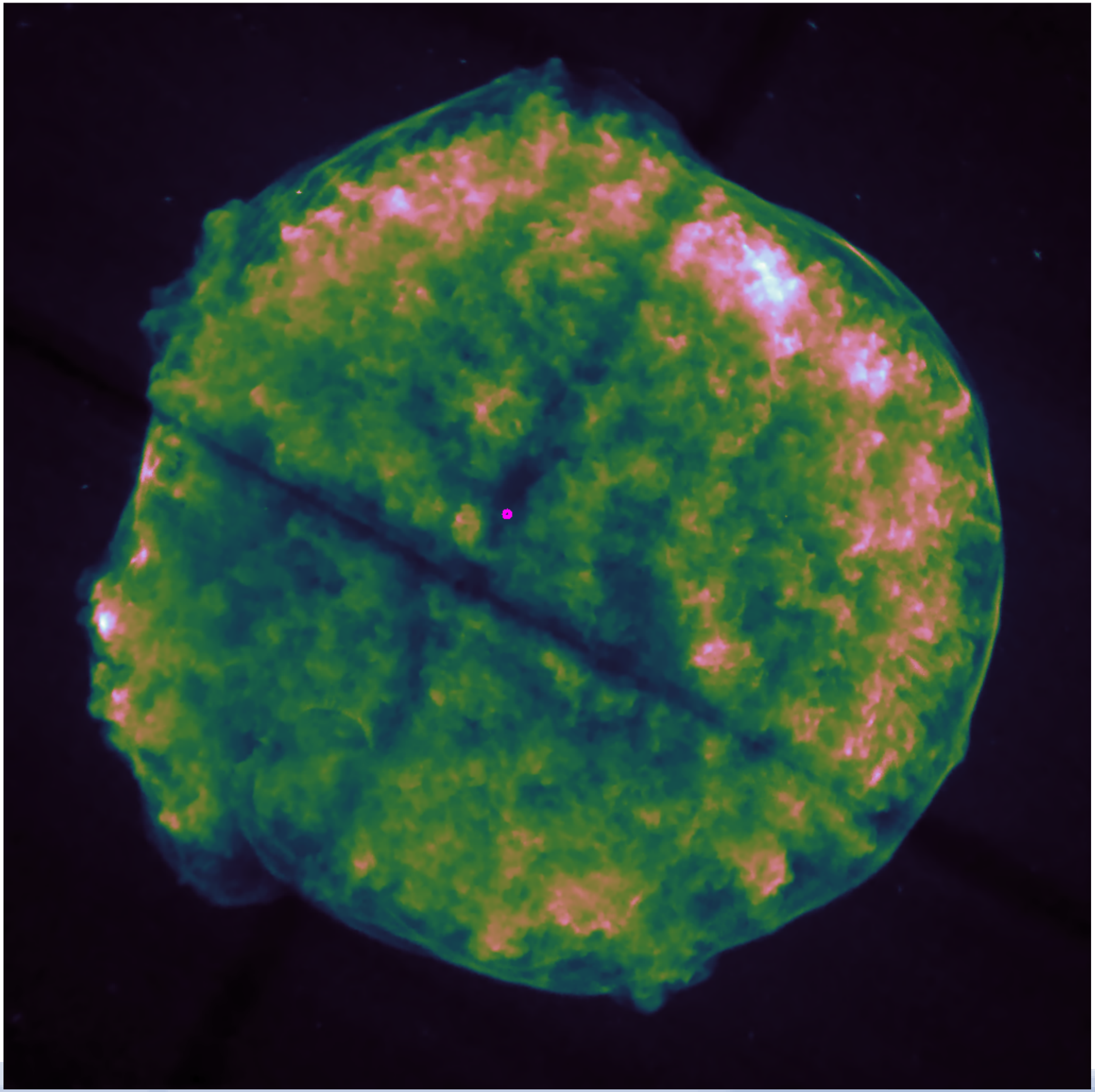
No ejecta dust detected.

Tycho SNR: Blast Wave Expansion



Williams et al.
2016

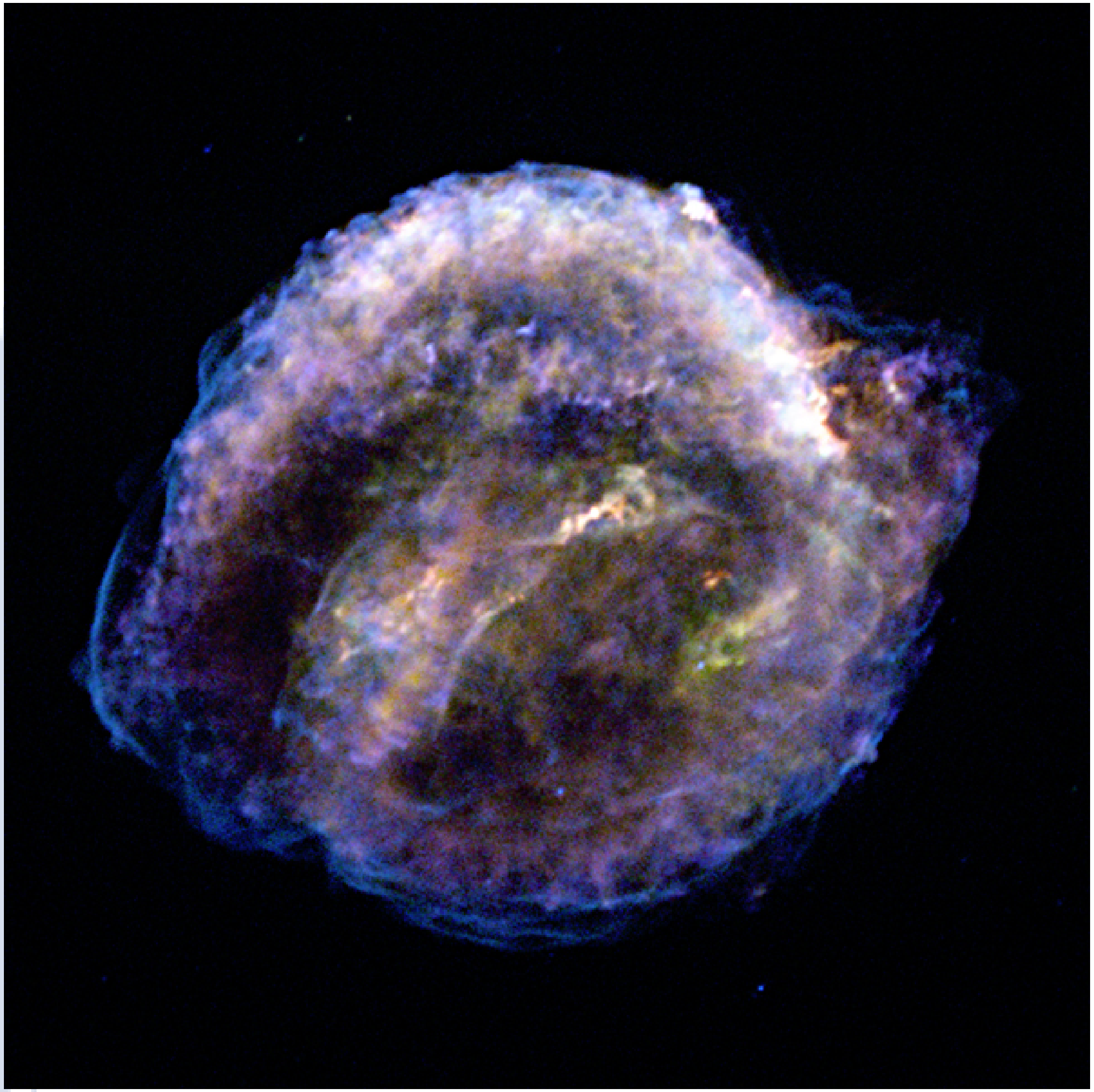
Tycho SNR: Explosion Site



Explosion site displaced NE away from the geometrical center.

Star G not close to the explosion site shown here.

Kepler's SNR: Type Ia with CSM



SN 1604

3' diameter

5 kpc distance

Strong Fe lines (ejecta)

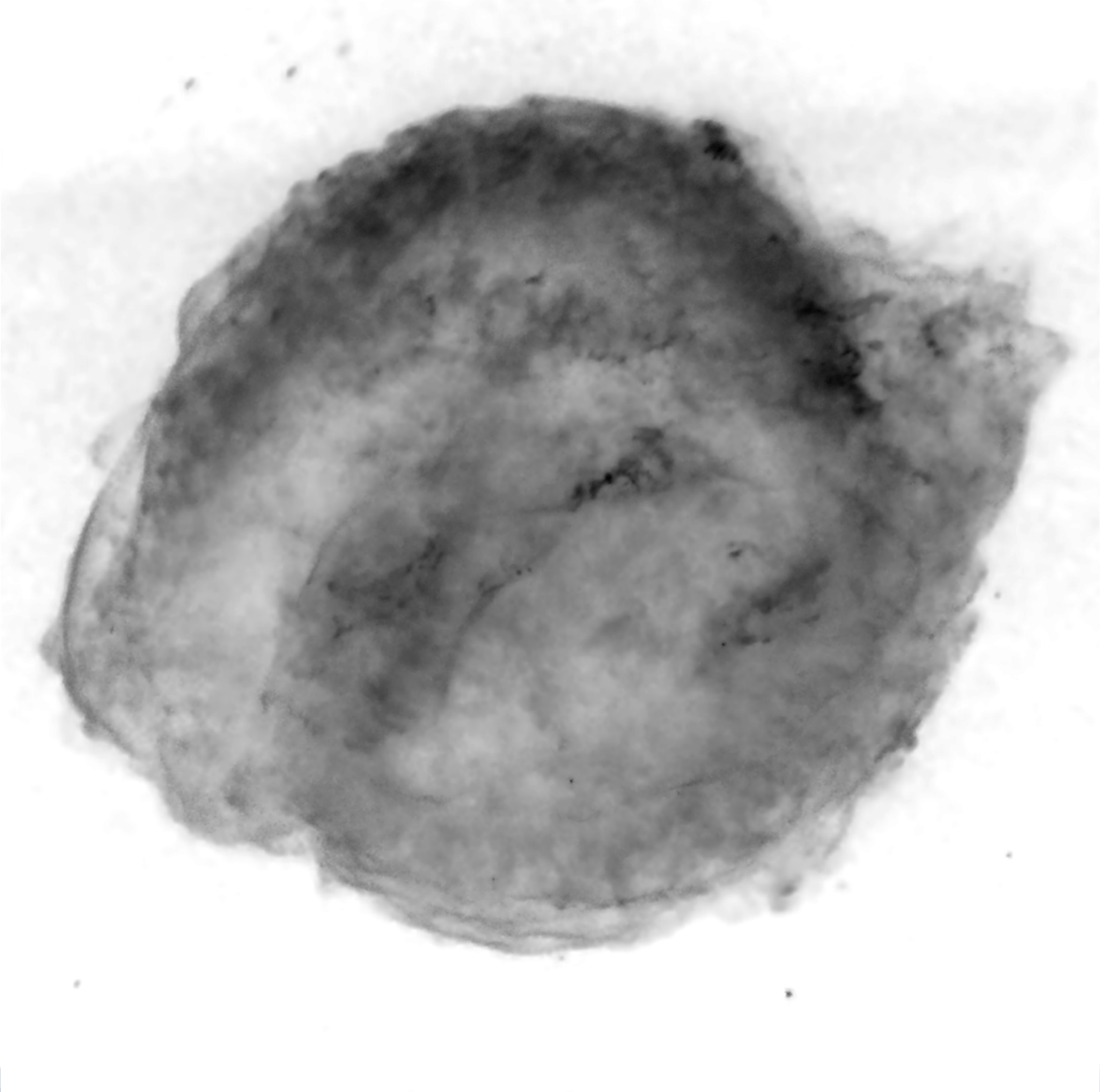
Strong Si, S, Ar, Ca (ejecta)

Weak O, Mg (CSM)

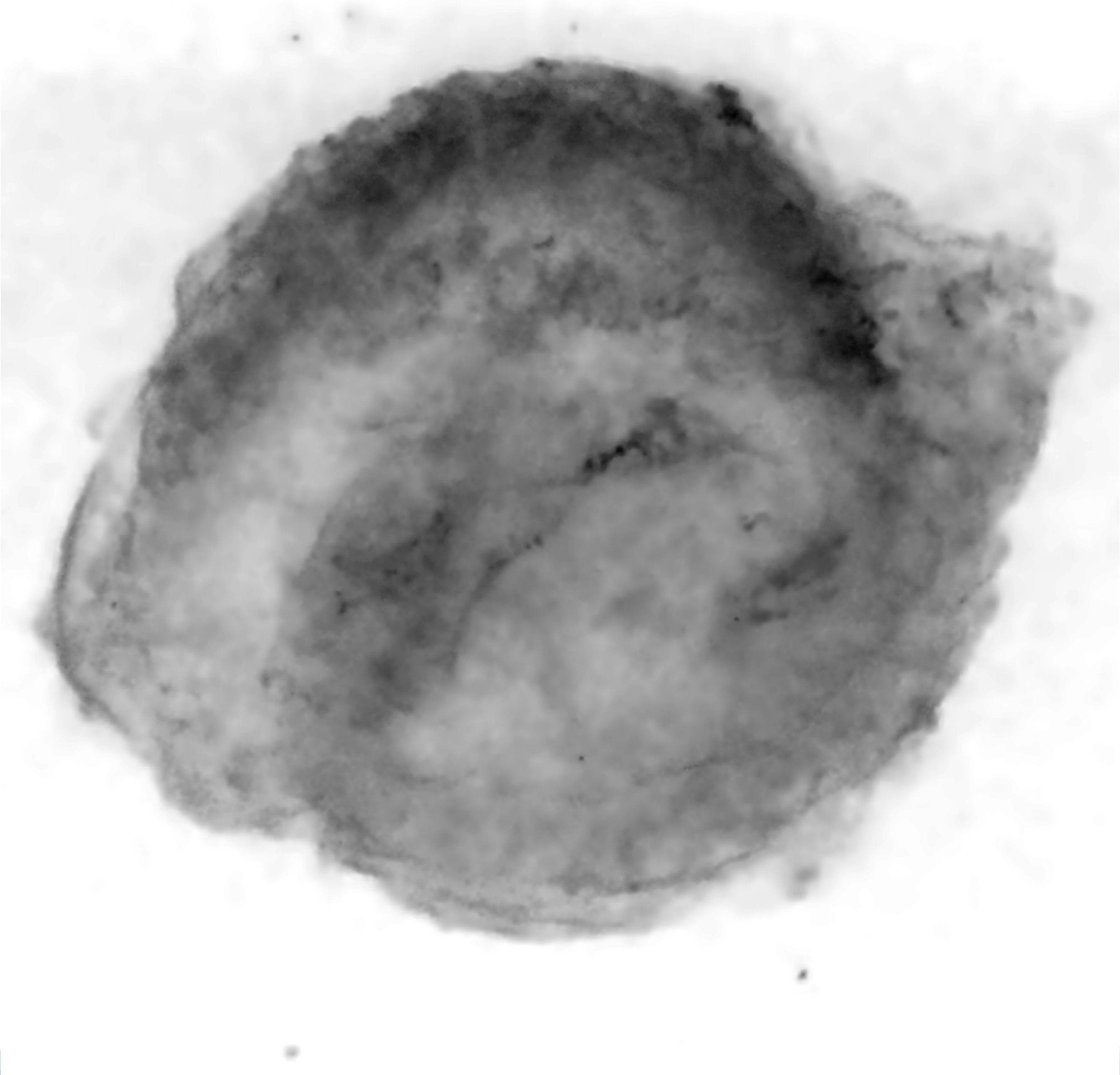
Enhanced N in the CSM (from optical)

Asymmetric mass loss

2006



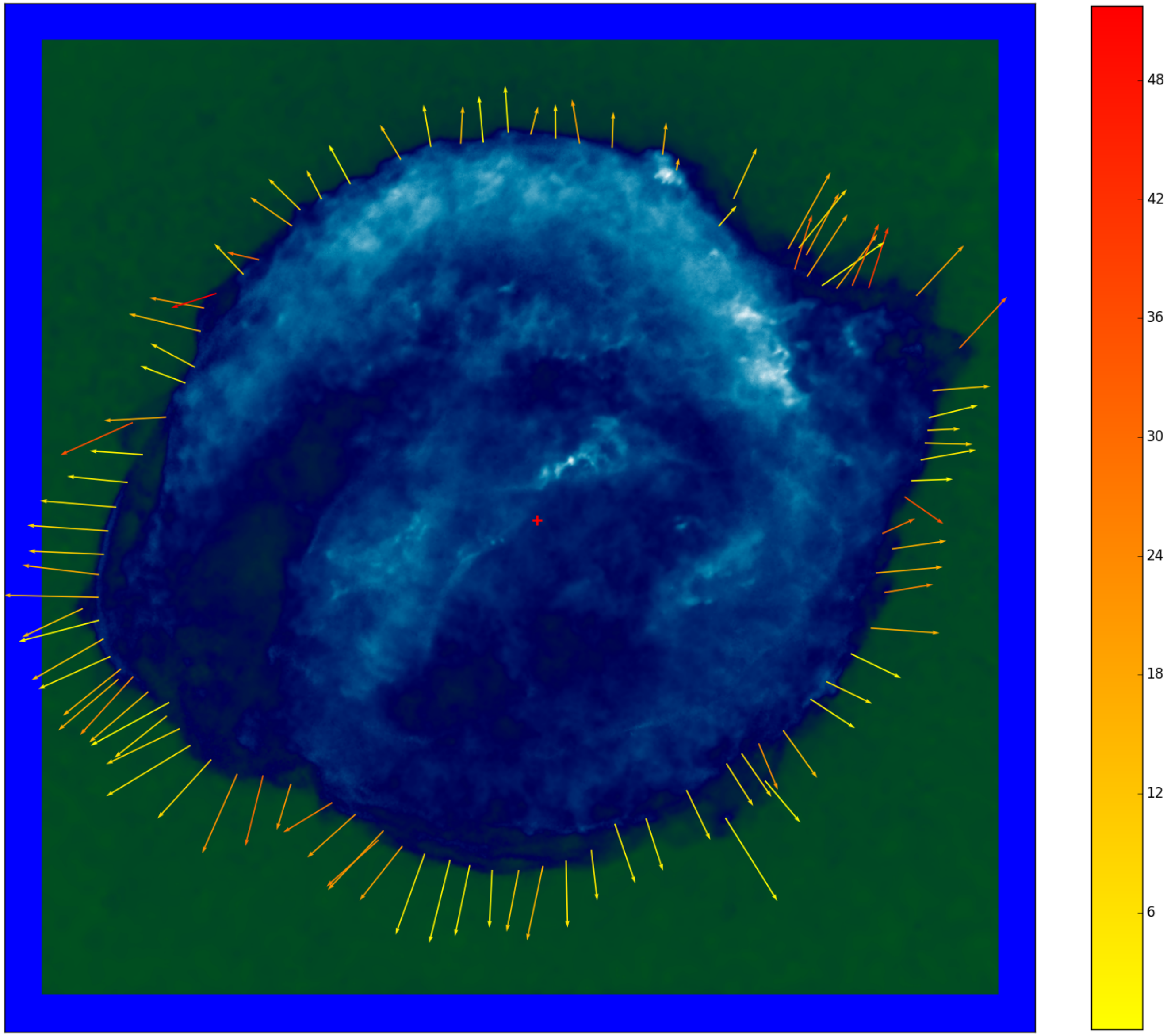
2014



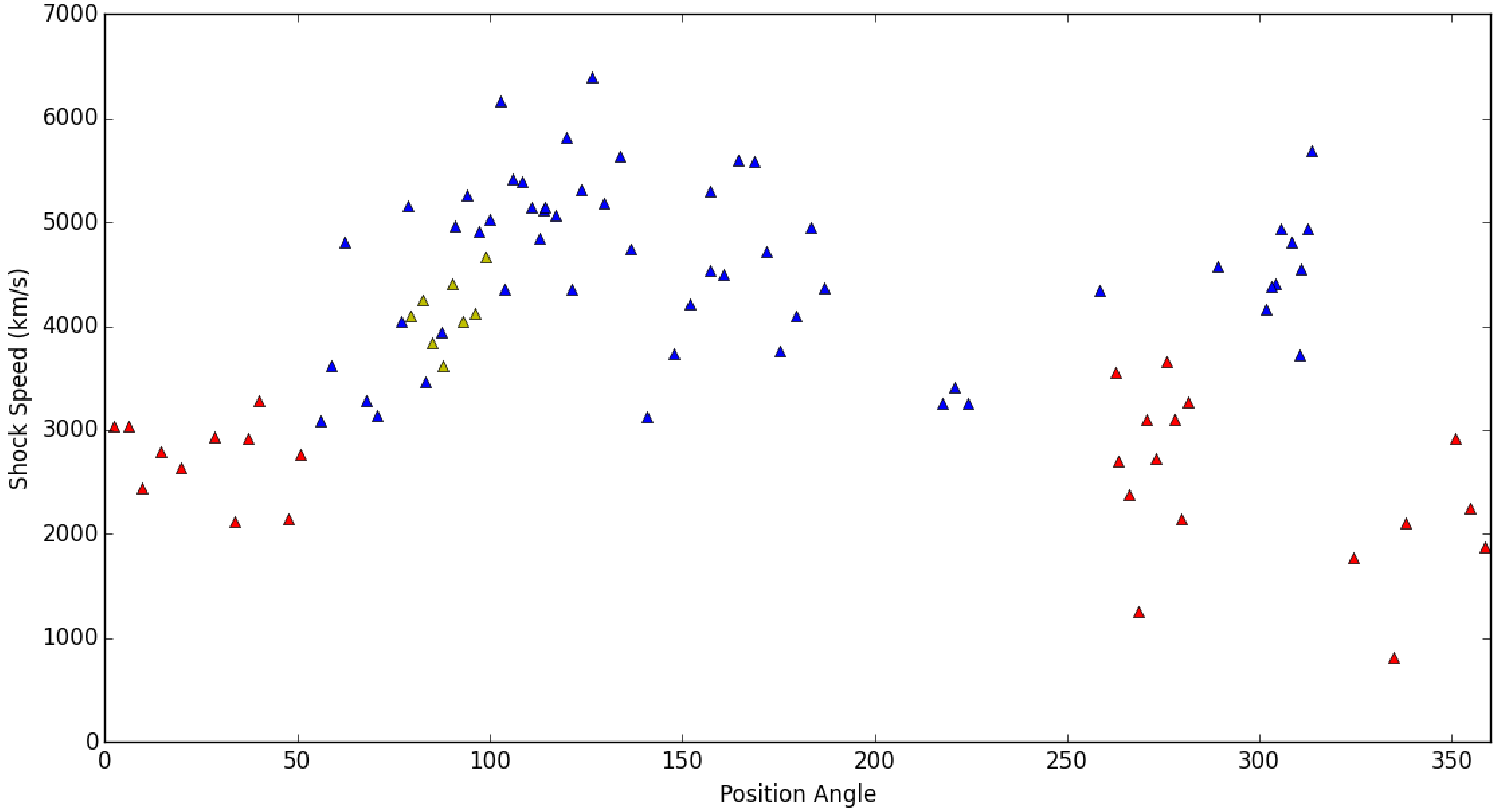
Expansion Measurement Method

- Intensity-based deformable image registration technique (commonly used in medical imaging)
- Nonparametric
- “Demons” method of Thirion (1998)
- Diffeomorphic (one-to-one transformation) variation of the Demons method
- Limitations: hard to estimate errors when applied to Chandra data, potential problems in presence of large spatial gradients in shock speeds.

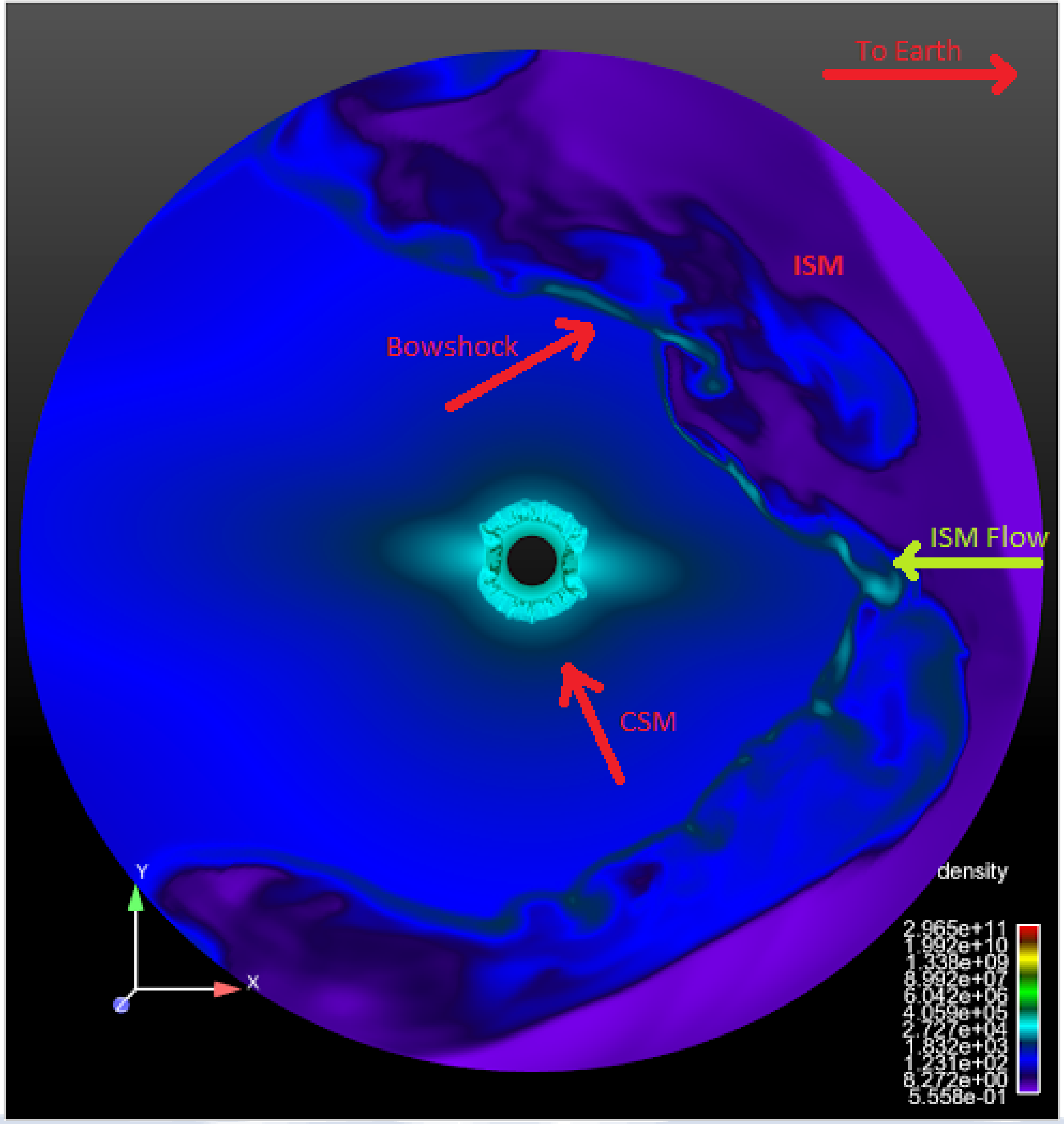
Kepler's SNR: Blast Wave Motion



Kepler's SNR: Blast Wave Speed



Kepler's SNR: 3D Hydro

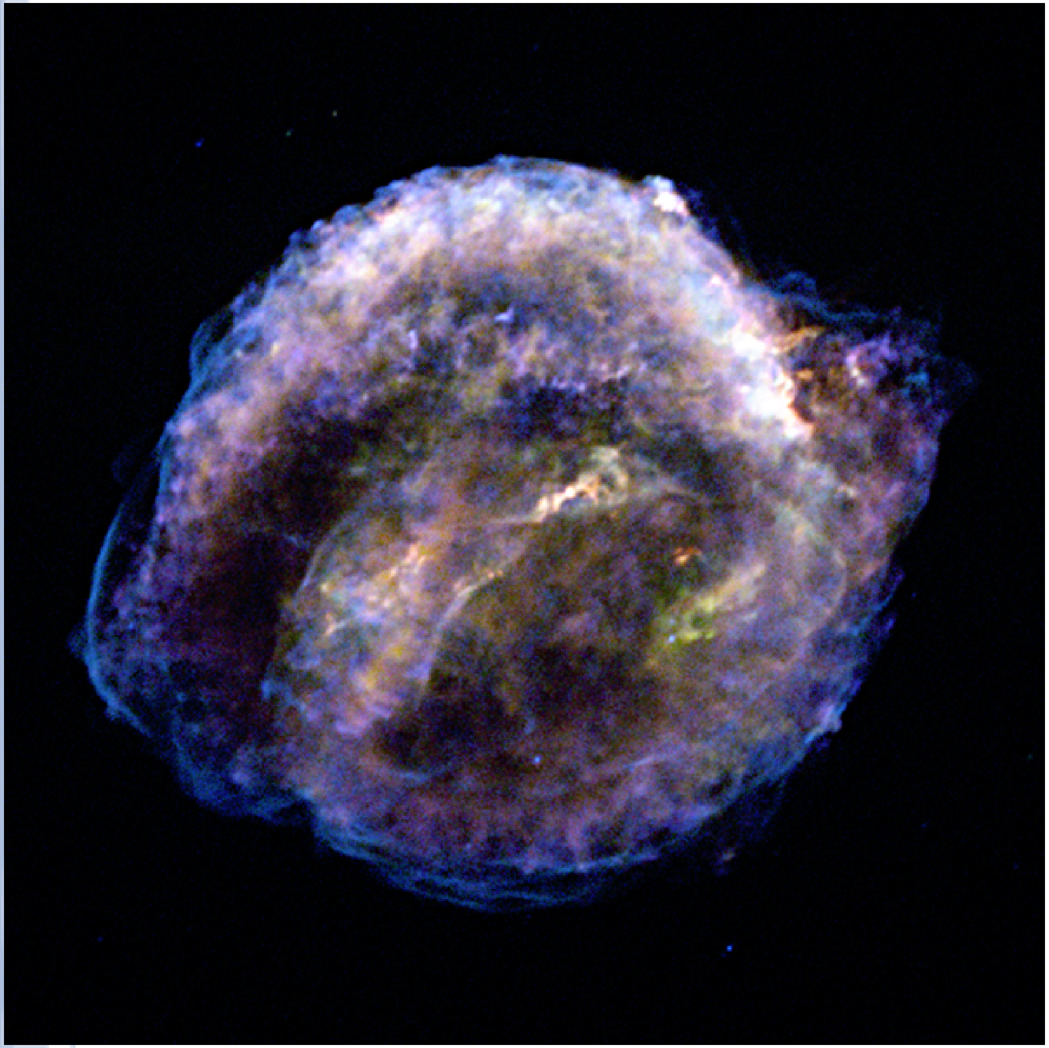


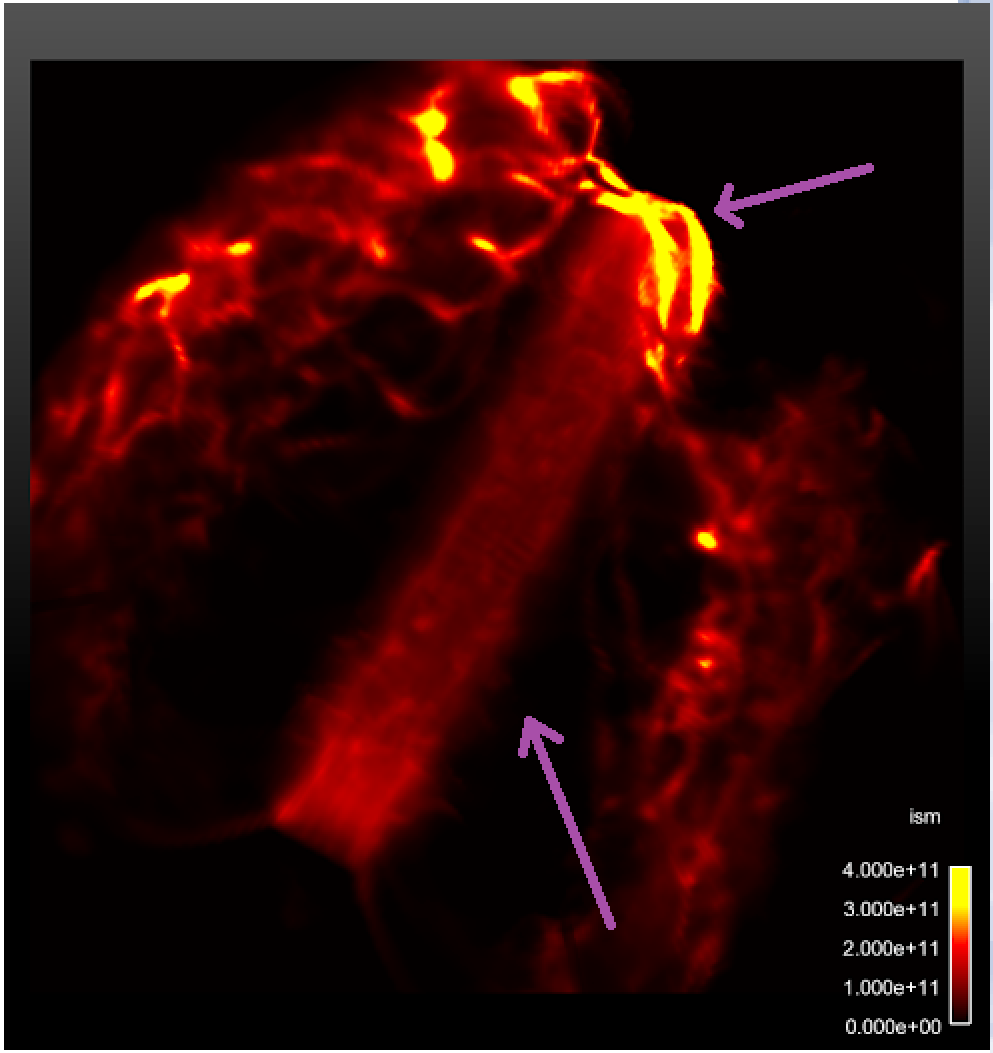
Fast-moving Type Ia progenitor with asymmetric stellar wind

VH-1 hydro code used

Simulations done by undergraduate student Jessica Sullivan

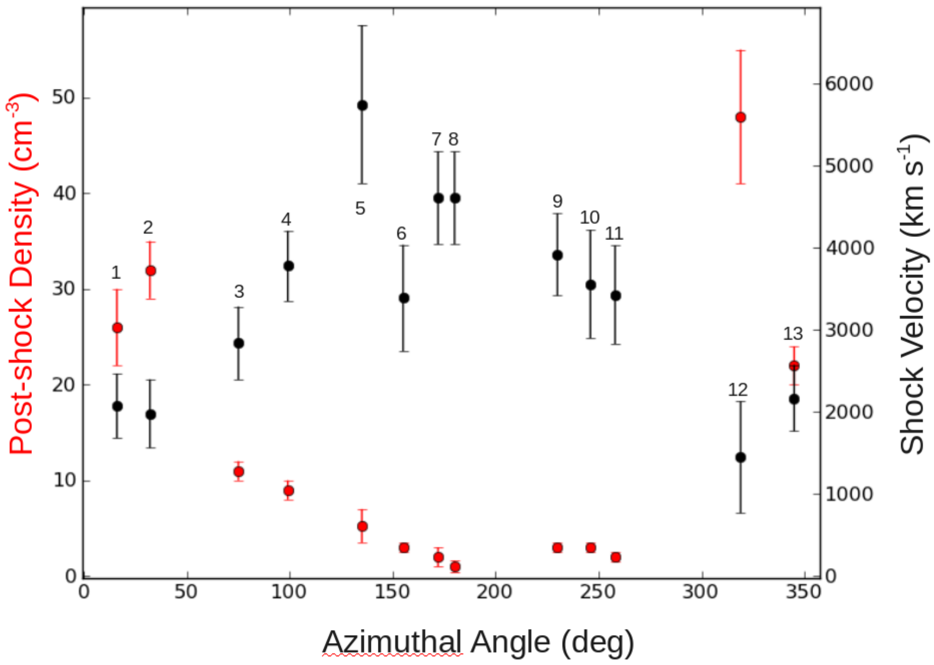
Kepler's SNR: 3D Hydro Model



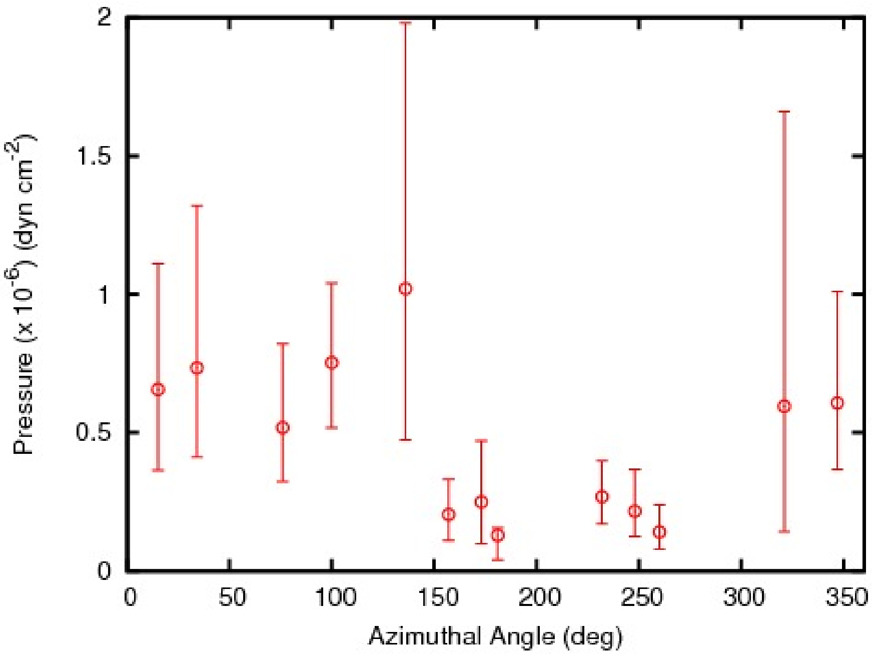


Simulations done by Jessica Sullivan

Kepler's SNR: Density, Pressure

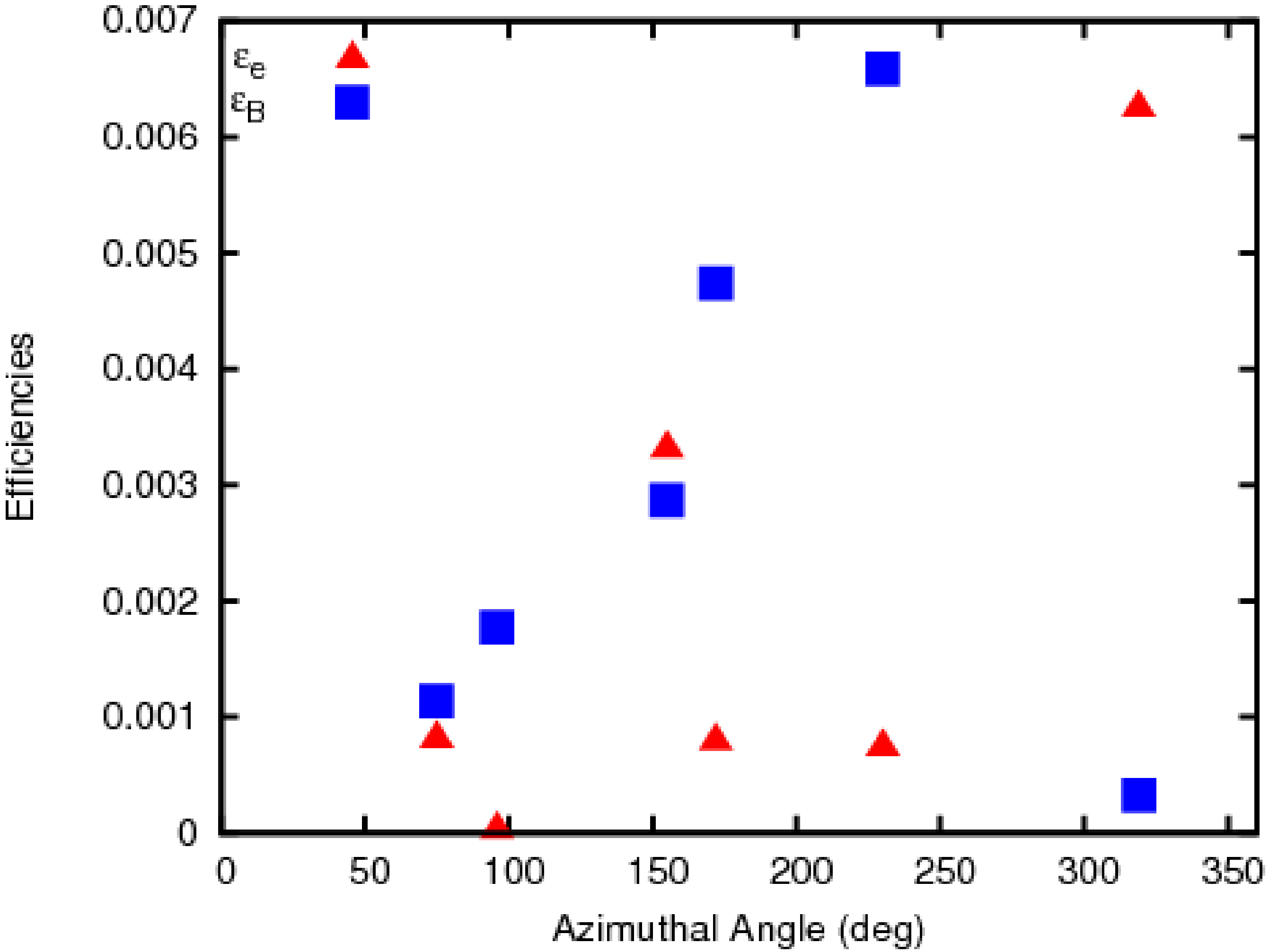


Density varies by a factor of at least 45



N-S pressure difference (factor of 3)

Electron and Magnetic Efficiencies for Relativistic Component



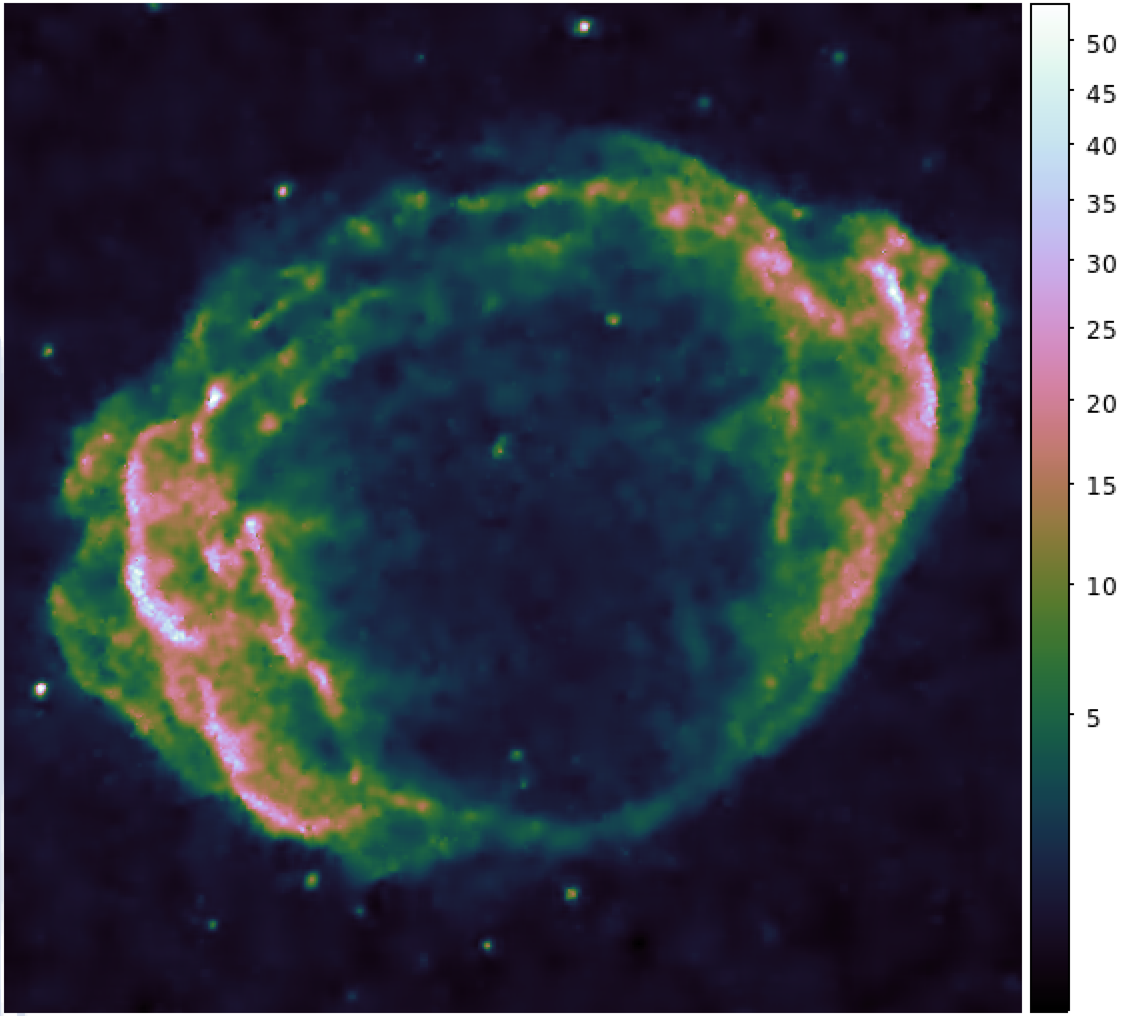
G1.9+0.3: The Youngest Galactic Supernova Remnant

In collaboration with Stephen Reynolds and Peter Gwynne (North Carolina State University), David Green (Cambridge University), Una Hwang (University of Maryland), Robert Petre (NASA/Goddard Space Flight Center), Rebecca Willett (University of Wisconsin-Madison)

Age, Distance, Velocities, Time Variability

- Radio and X-ray expansion imply age of about 100 yr (Reynolds et al. 2008; Green et al. 2008; Carlton et al. 2011). G1.9+0.3 is the youngest known Galactic supernova remnant.
- Extremely high absorption and location near the Galactic Center (300 pc away in projection) suggest 8.5 kpc distance. An even larger (10 kpc or more) distance has been inferred from HI absorption (Roy & Pal 2014).
- Average blast wave speed of 12,000 - 14,000 km/s from X-rays and radio.
- Radio and X-ray fluxes increasing with time. Radio: 2% per yr (Green et al. 2008), 1.2% per yr (Murphy et al. 2008). X-rays: 1.9% per yr (Borkowski et al. 2014).
- Radio morphology changed significantly between 1985 and 2008, implying strong departures from homologous expansion.

2011 Chandra Observations of G1.9+0.3



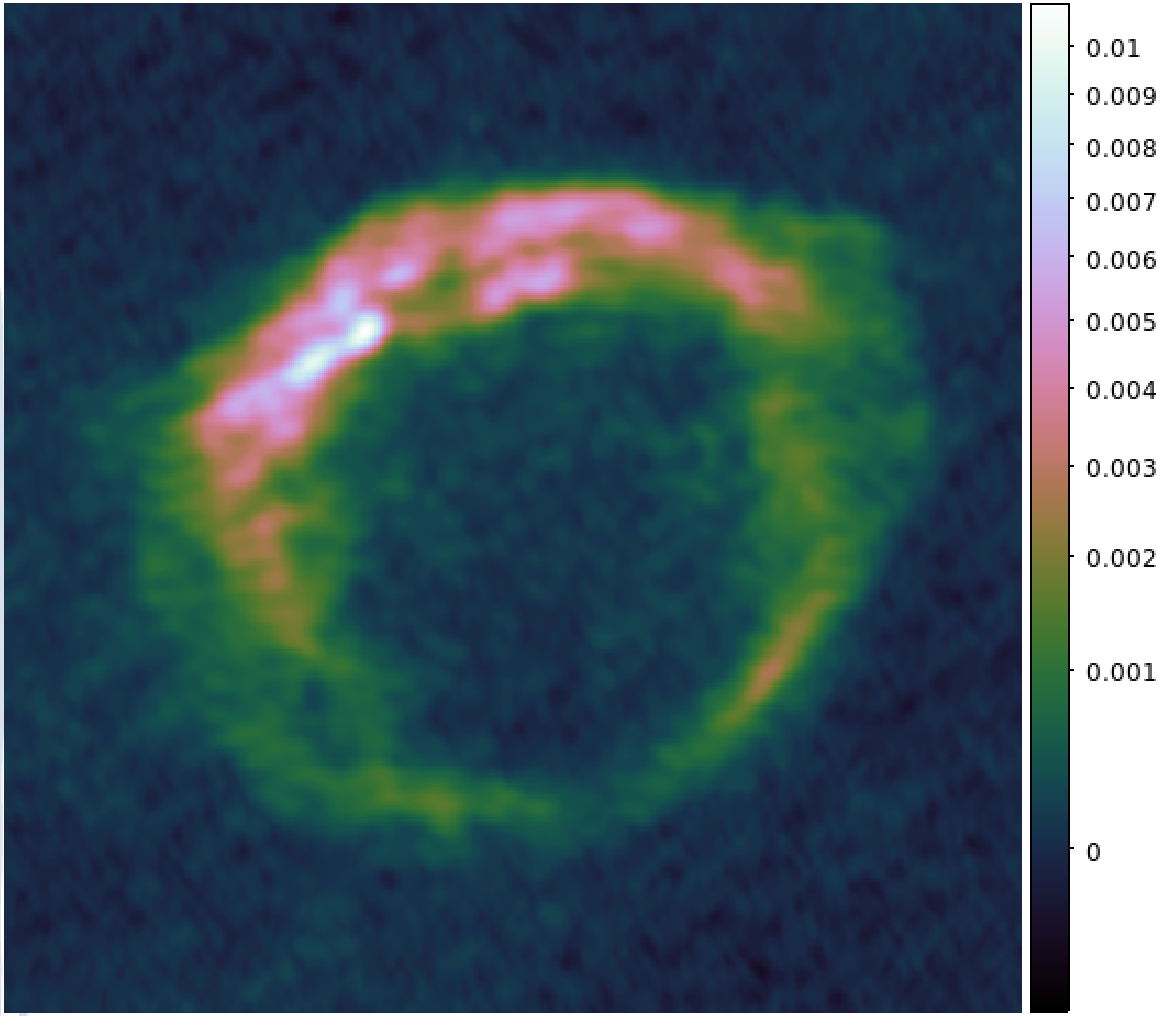
- Observed by Chandra in 2011 for 980 ks (Borkowski et al. 2013)

  Much shorter Chandra observations in 2007 (50 ks) and 2009 (240 ks)

  392 ks observation in 2015

  Image smoothed with the method of Krishnamurthy et al. 2010
- Scale in counts per ACIS S3 pixel

1.4 GHz VLA Image of G1.9+0.3

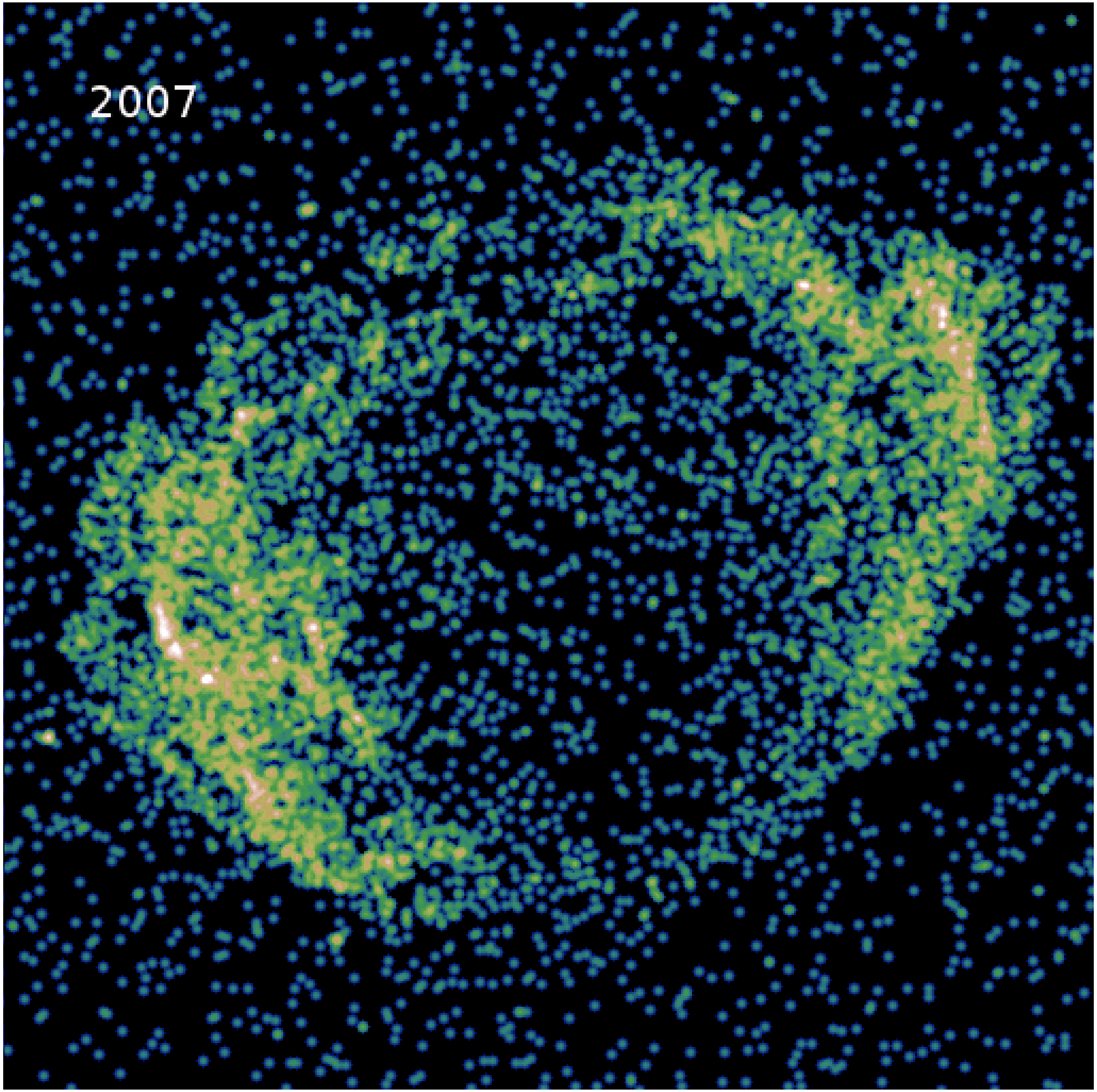


VLA image from 2008 December

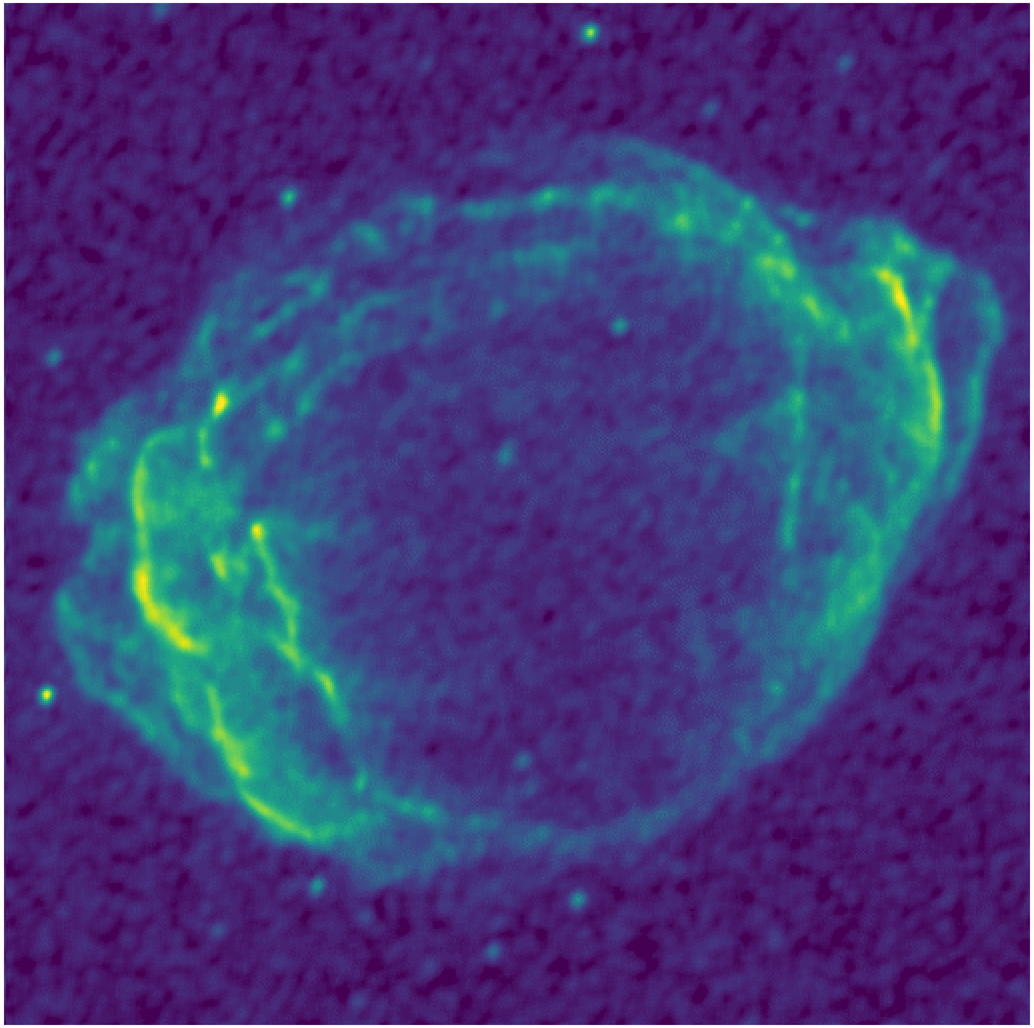
Resolution 2.3" x 1.4'

Scale in Jy per beam

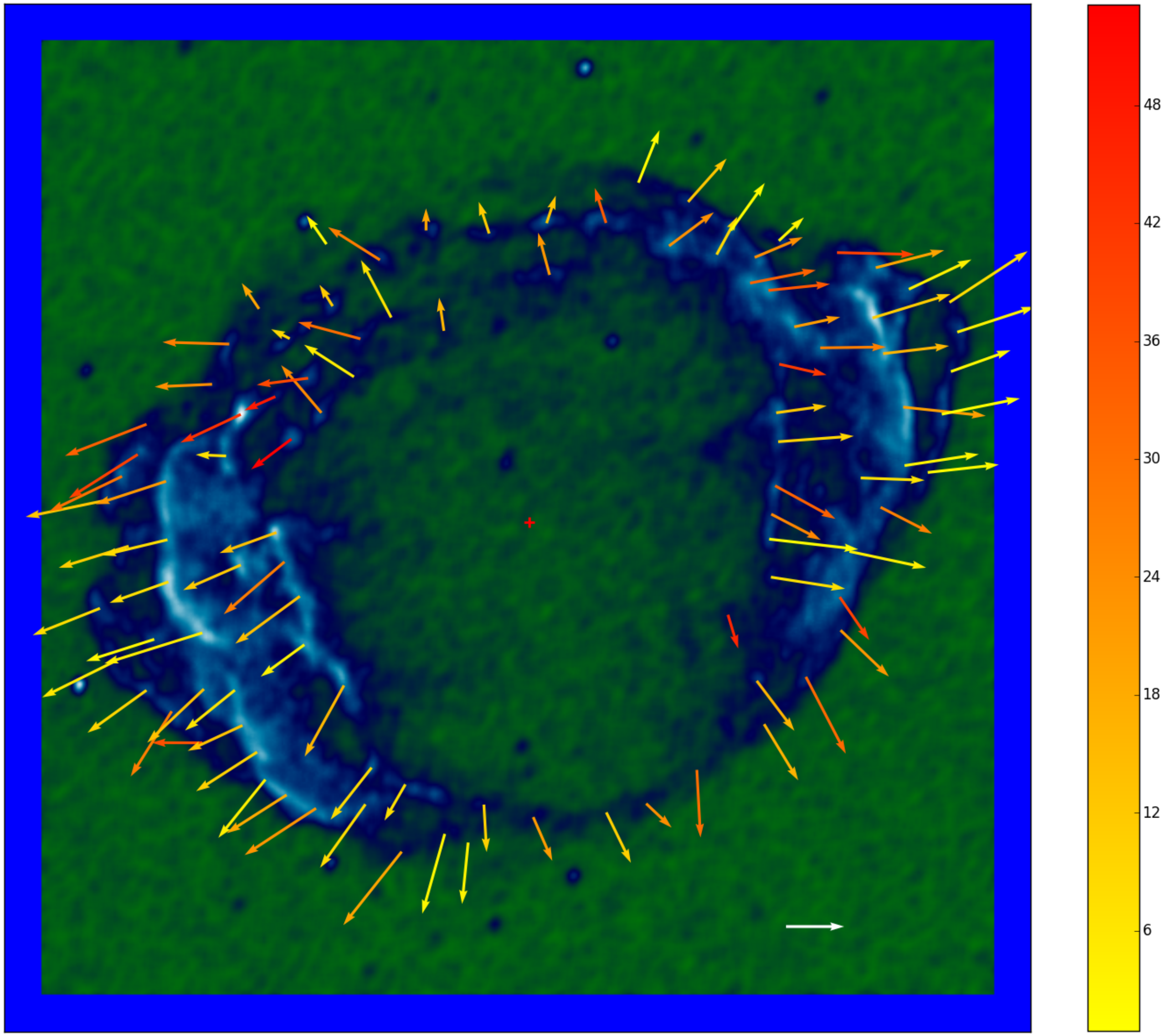
G1.9+0.3



G1.9+0.3 in 2011 and 2015



G1.9+0.3: Proper Motions



Proper motion vectors color coded according to the deviations in direction from radial (with respect to the geometrical center of the remnant, marked by the red cross), in degrees according to the vertical scale. The white arrow indicates 0.25"/yr (10,100 km/s at 8.5 kpc).

G1.9+0.3: Summary

1. Expansion of G1.9+0.3 is extremely asymmetric, varying in magnitude by a factor of up to 5 and strongly deviating from radial motions.

2. The measured proper motions, ranging from 0.09'' to 0.44'' per yr, correspond to shock speeds between 3,600 km/s and 18,000 km/s (at 8.5 kpc). This offers us a unique opportunity to study how particle acceleration varies with the shock speed. Age-limited acceleration.

3. Shock velocities are slowest toward the north where radio emission is bright and thermal ejecta emission is most prominent. Such strong deceleration of the northern blast wave most likely arises from the collision of SN ejecta with much denser than average ambient medium there. The presence of the asymmetric ambient medium naturally explains the radio asymmetry.

4. The SN ejecta have also been strongly decelerated in the north, but they expand faster than the blast wave.

5. As with Kepler's SN - the most recent historical SN in the Galaxy - the SN ejecta are likely colliding with the asymmetric circumstellar medium (CSM) ejected by the SN progenitor prior to its explosion. G1.9+0.3 fills the gap between distant Type Ia-CSM SNe (e.g., Silverman et al. 2013) and older Type Ia-CSM SNRs such as Kepler's SNR (e.g., Burkey et al. 2013), providing us with a unique opportunity to learn about mysterious Type Ia progenitors.

Expansion of Young SNRs in X-rays

- G292.0+1.8 (3000 yr) and G310.6-1.6 (~1000 yr?) scheduled for observations in a few months
- G330.2+1.0 and RCW 89 (1000-2000 yr old) next year
- Sizable sample becoming available (other remnants not discussed here include Cas A and SN 1006)
- Increasing time baseline
- The counting noise is a big problem for expansion measurements, longer exposures (plus improvements in statistical techniques) are needed.
- Measurements of temporal variations in brightness are even more affected by the counting noise
- The youngest remnants change rapidly in shape and brightness, they will be different when observed with the XRS.
- Type Ia explosions, particle acceleration: G1.9+0.3, Kepler, Tycho