Recent Progress in Young Galactic* SNRs

Brian J. Williams (NASA GSFC / USRA)
@bjwilli2

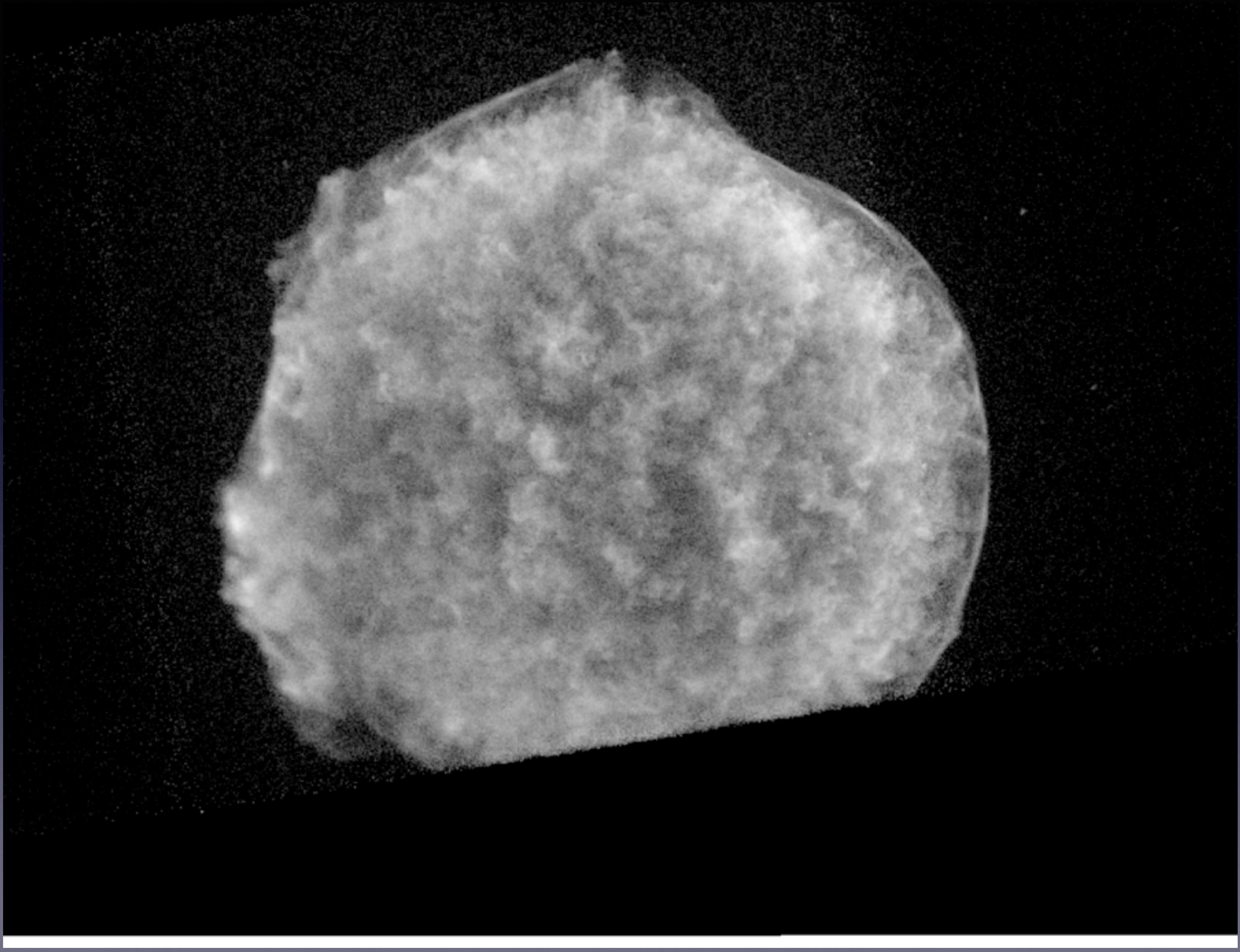
**(plus some LMC stuff, too)*

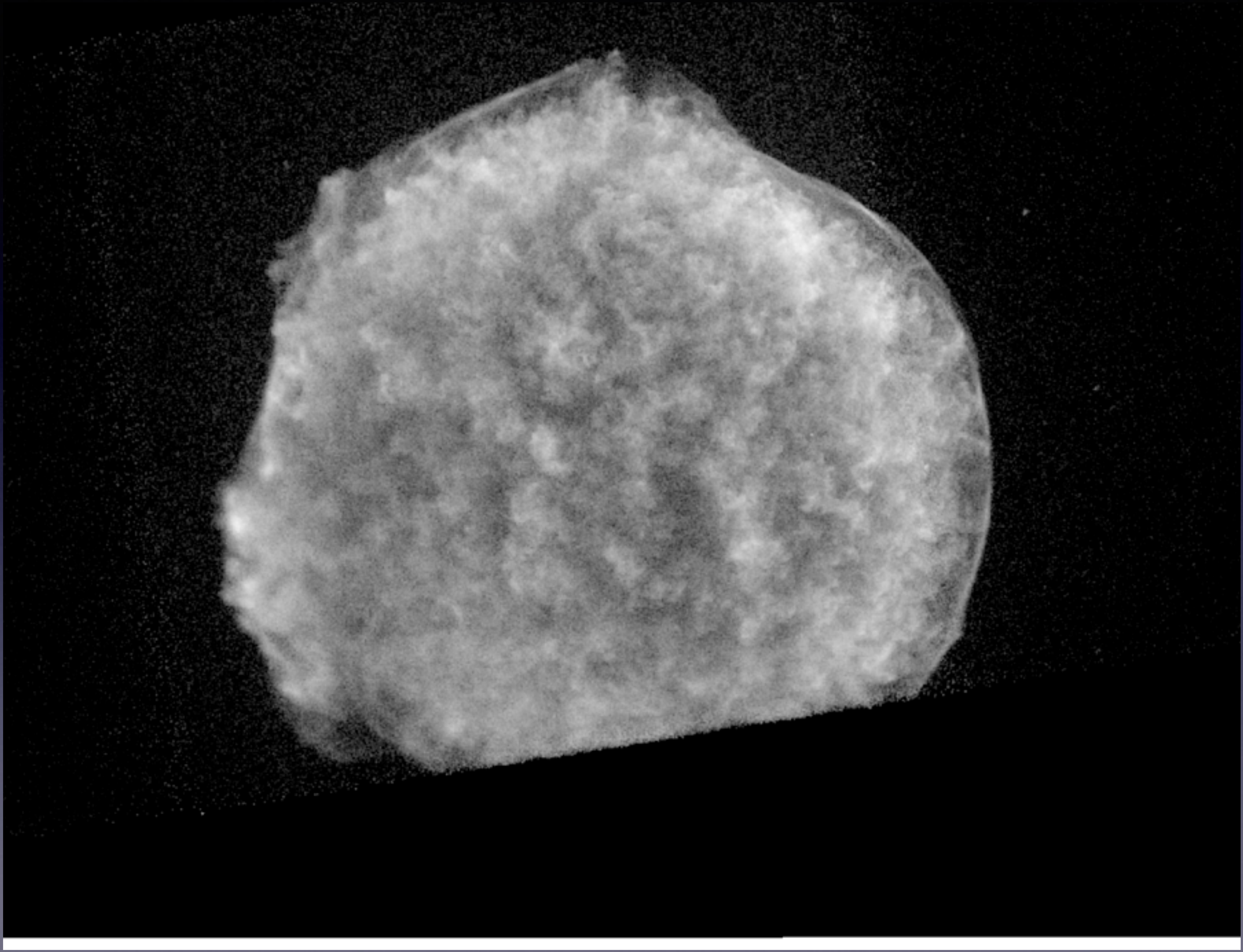
I. Kinematics of SNRs

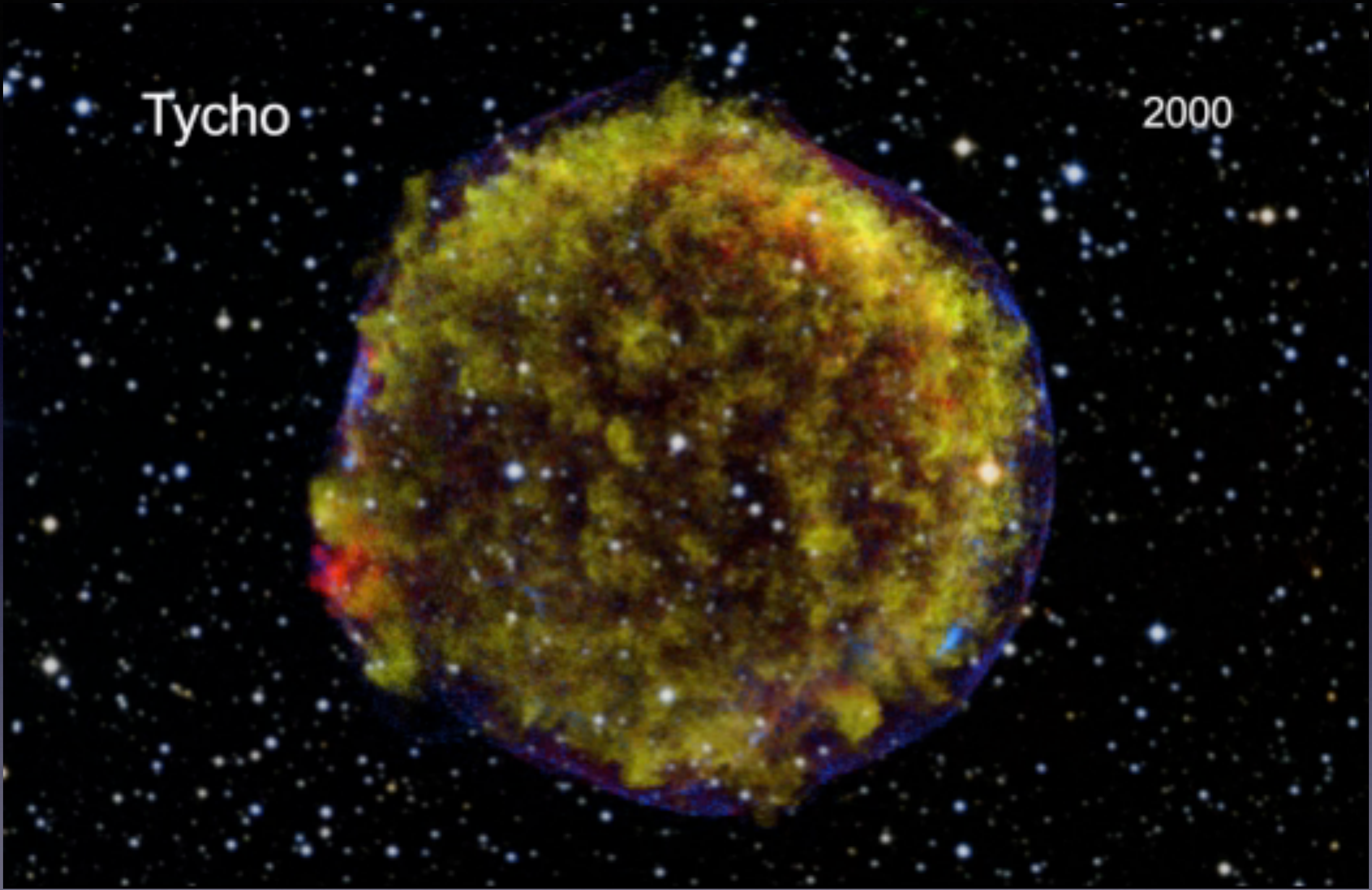
- More and more papers coming out on proper motions from SNRs
- As t increases, this gets easier and easier to do in the era of high spatial resolution astronomy (JVLA, Hubble, ground-based optical, Chandra)
- But not just proper motions! Spectral information gives info on line-of-sight velocity as well…
- How does all of this translate into increased knowledge of SNRs and their progenitors?

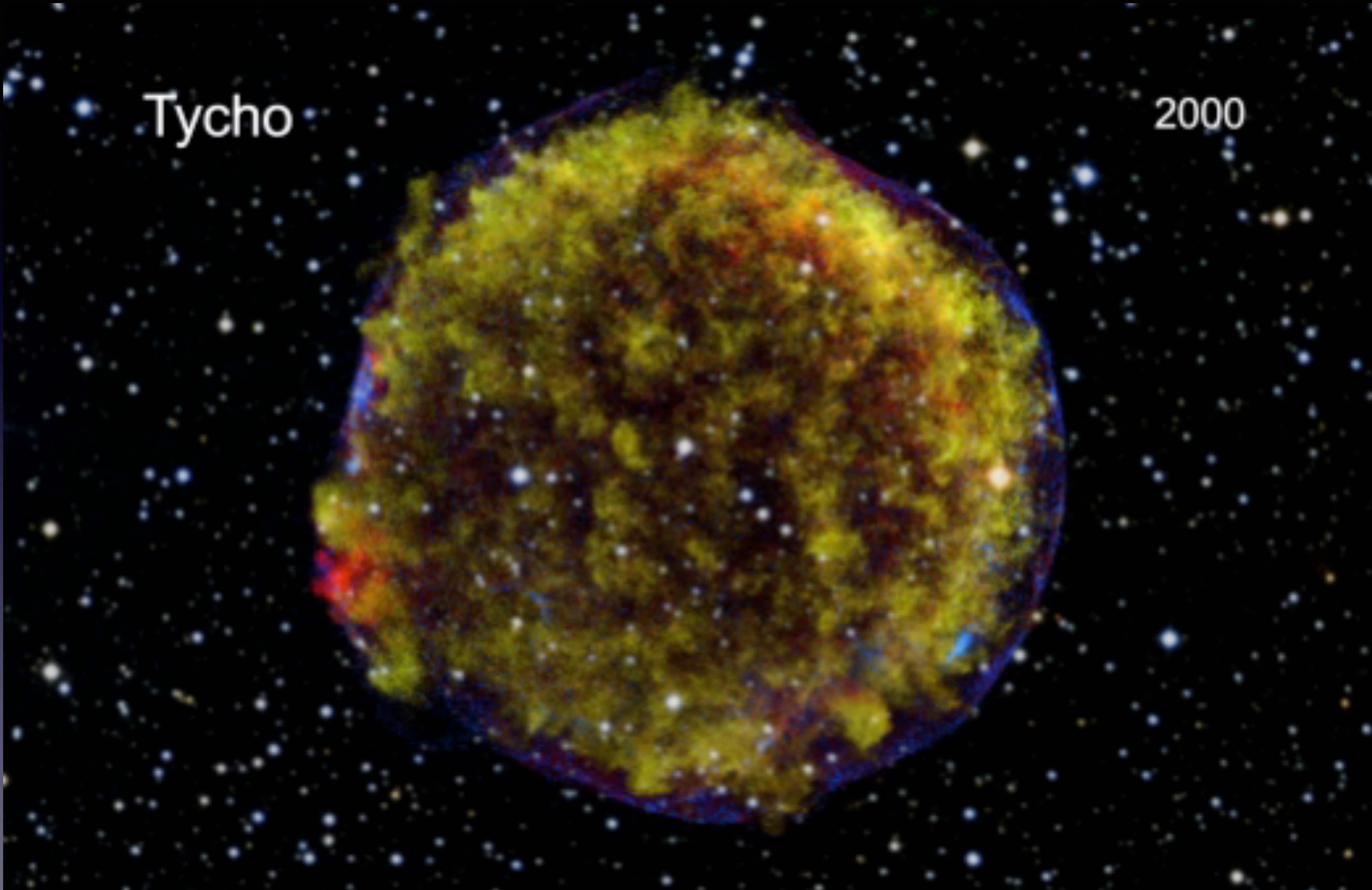
Tycho’s SNR

Chandra - 2000, 2003, 2007, 2009, *<u>2015</u>*

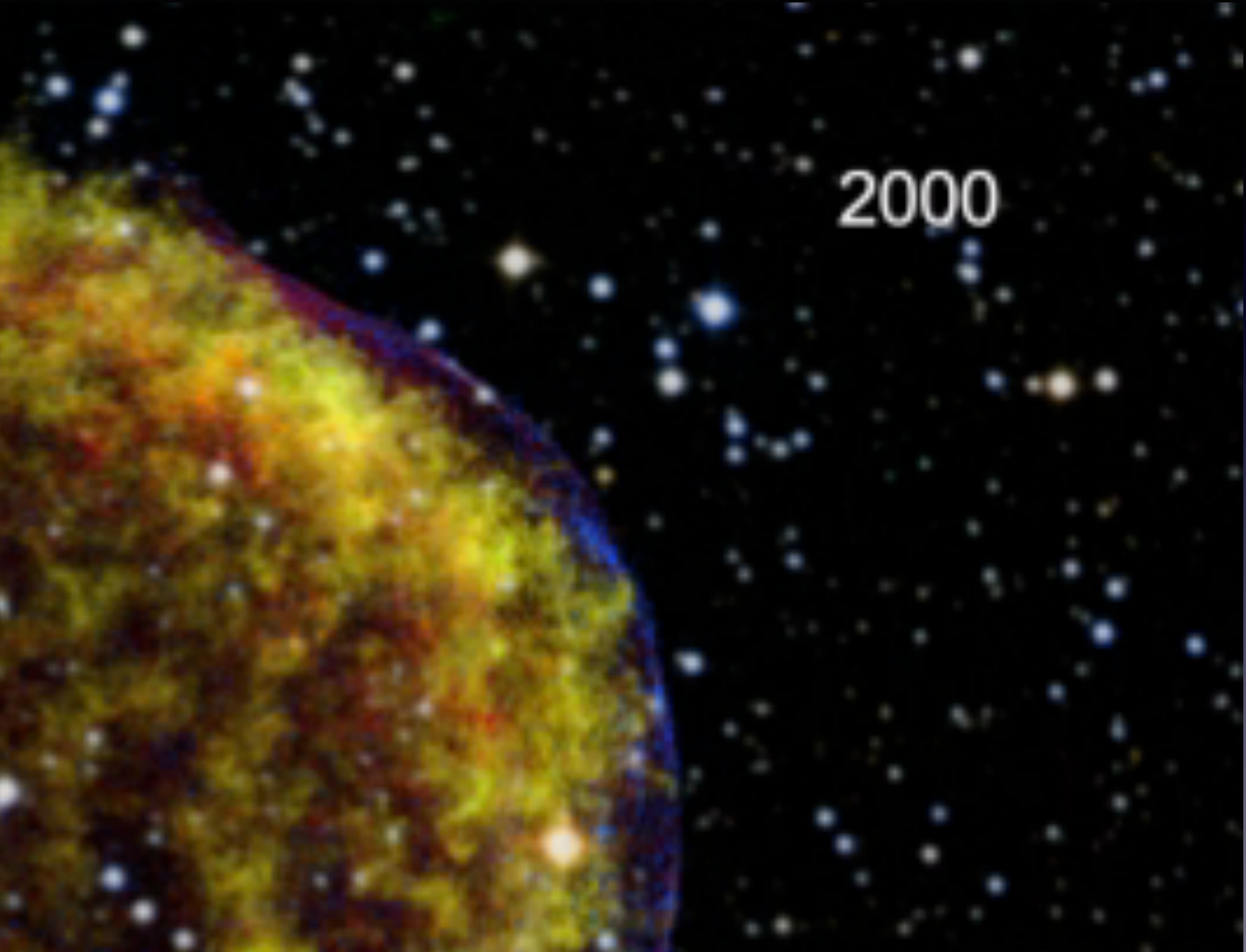


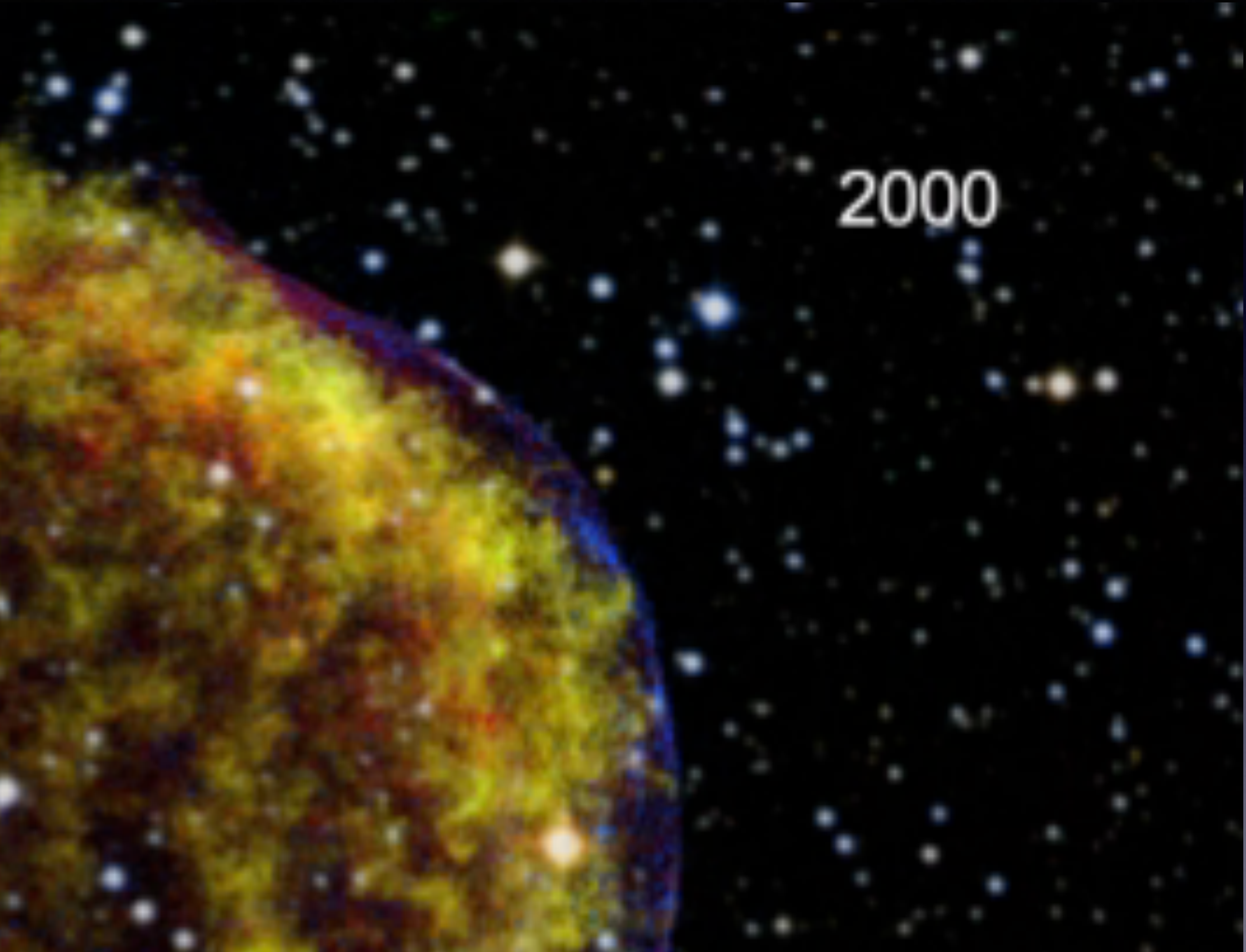


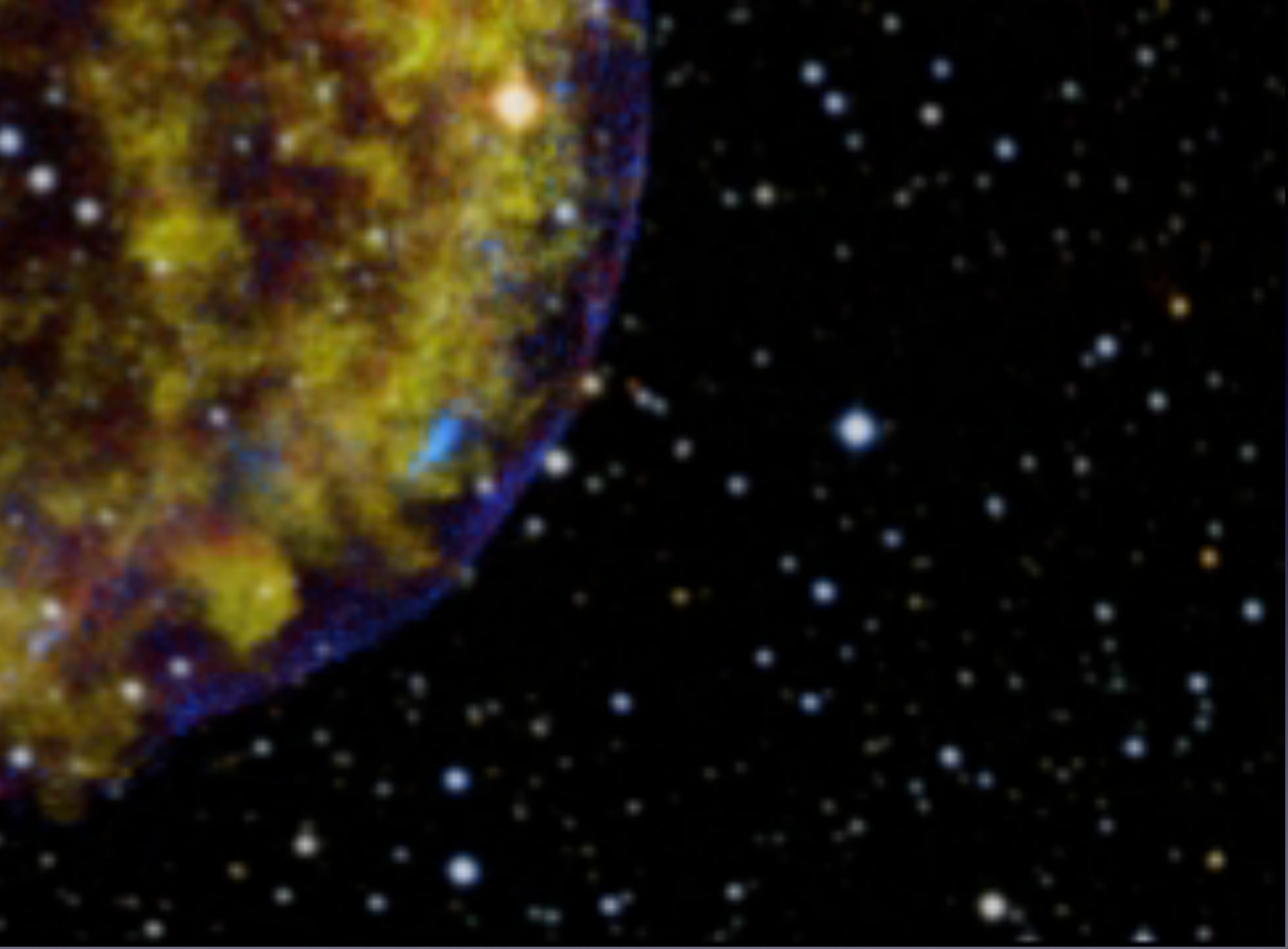

Tycho
2000

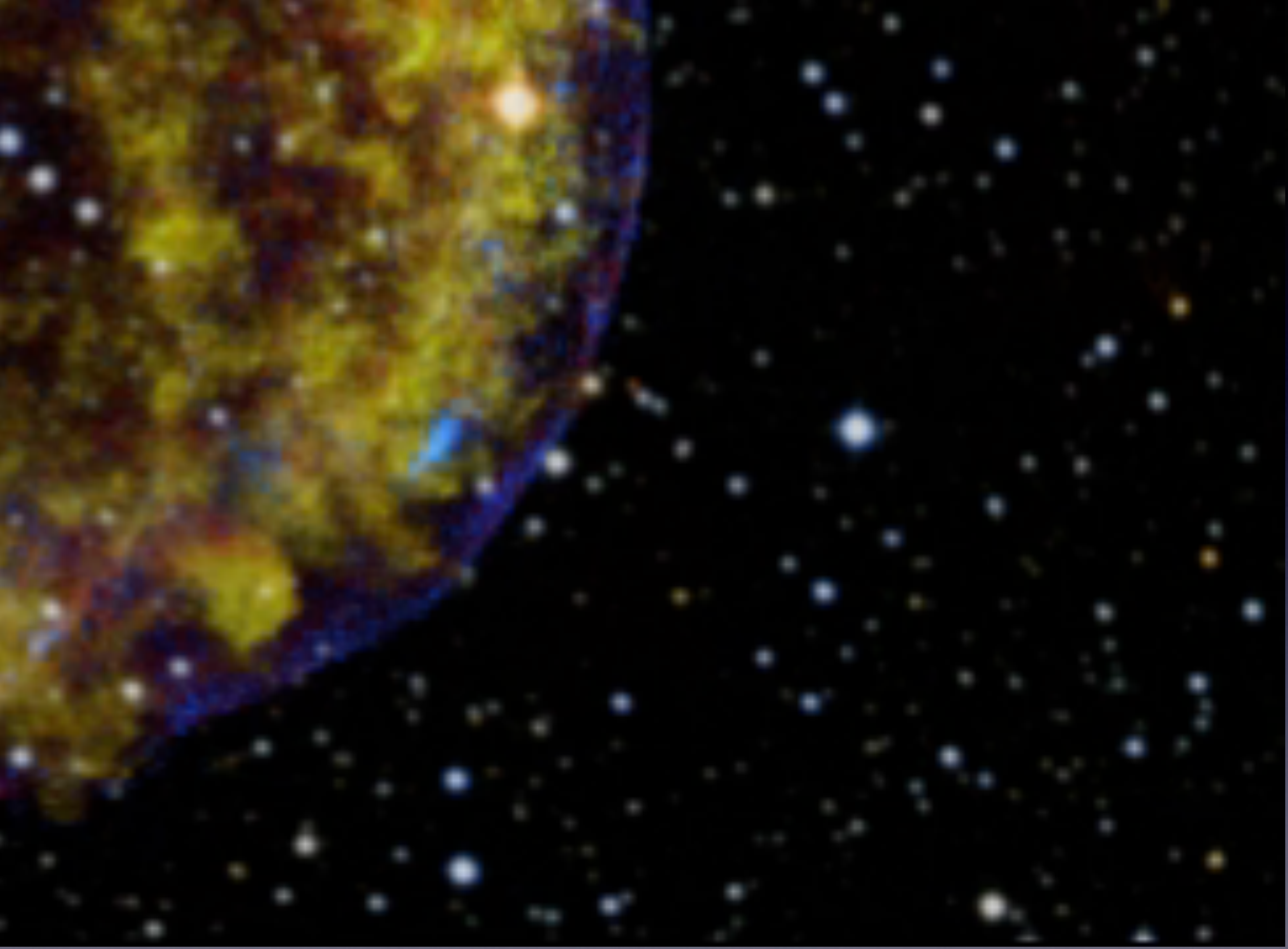


Tycho
2000


2000


2000






Tycho


Tycho

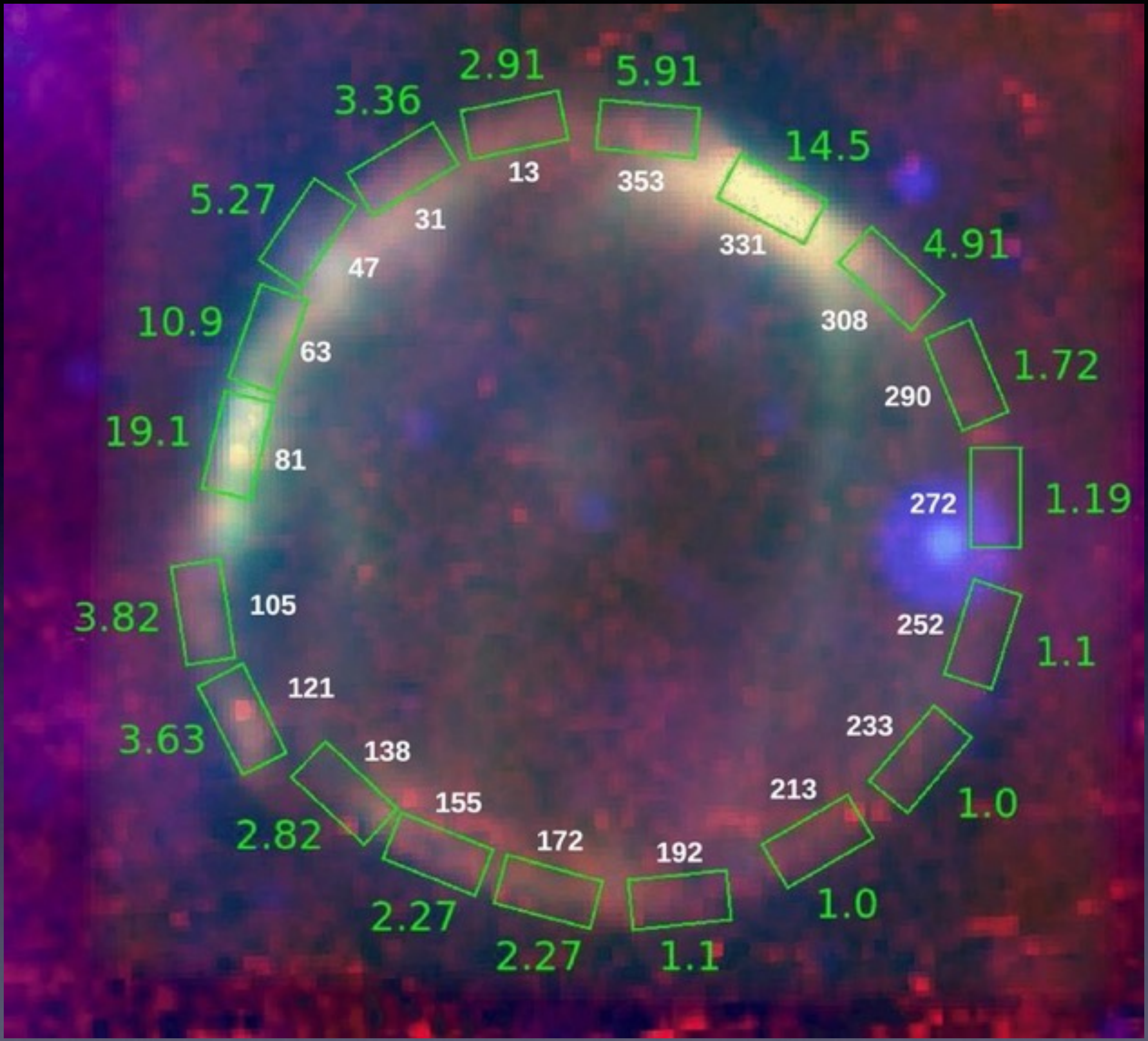
Tycho’s SNR

Chandra - 2000, 2003, 2007, 2009, *2015*

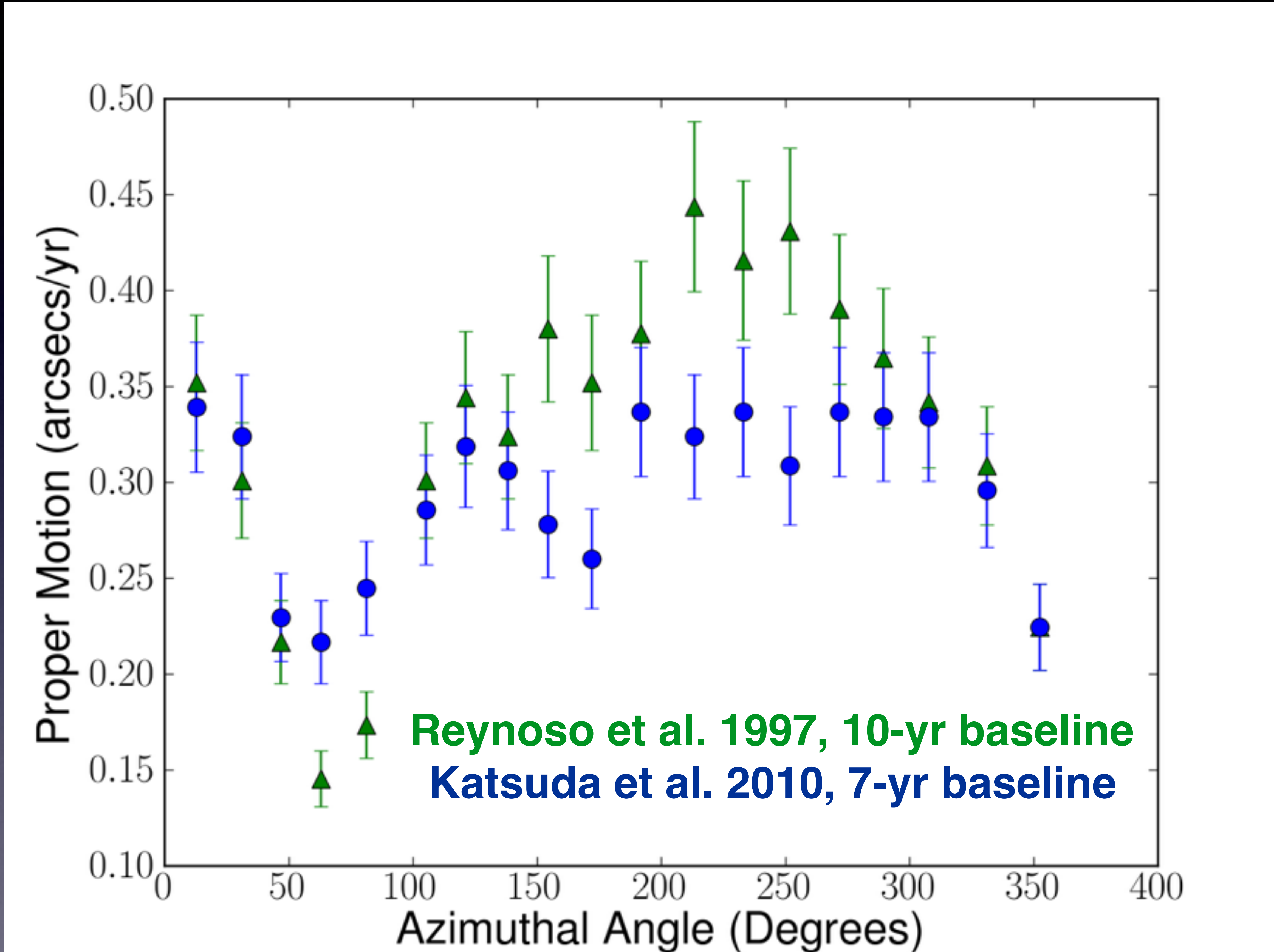
Tycho's SNR

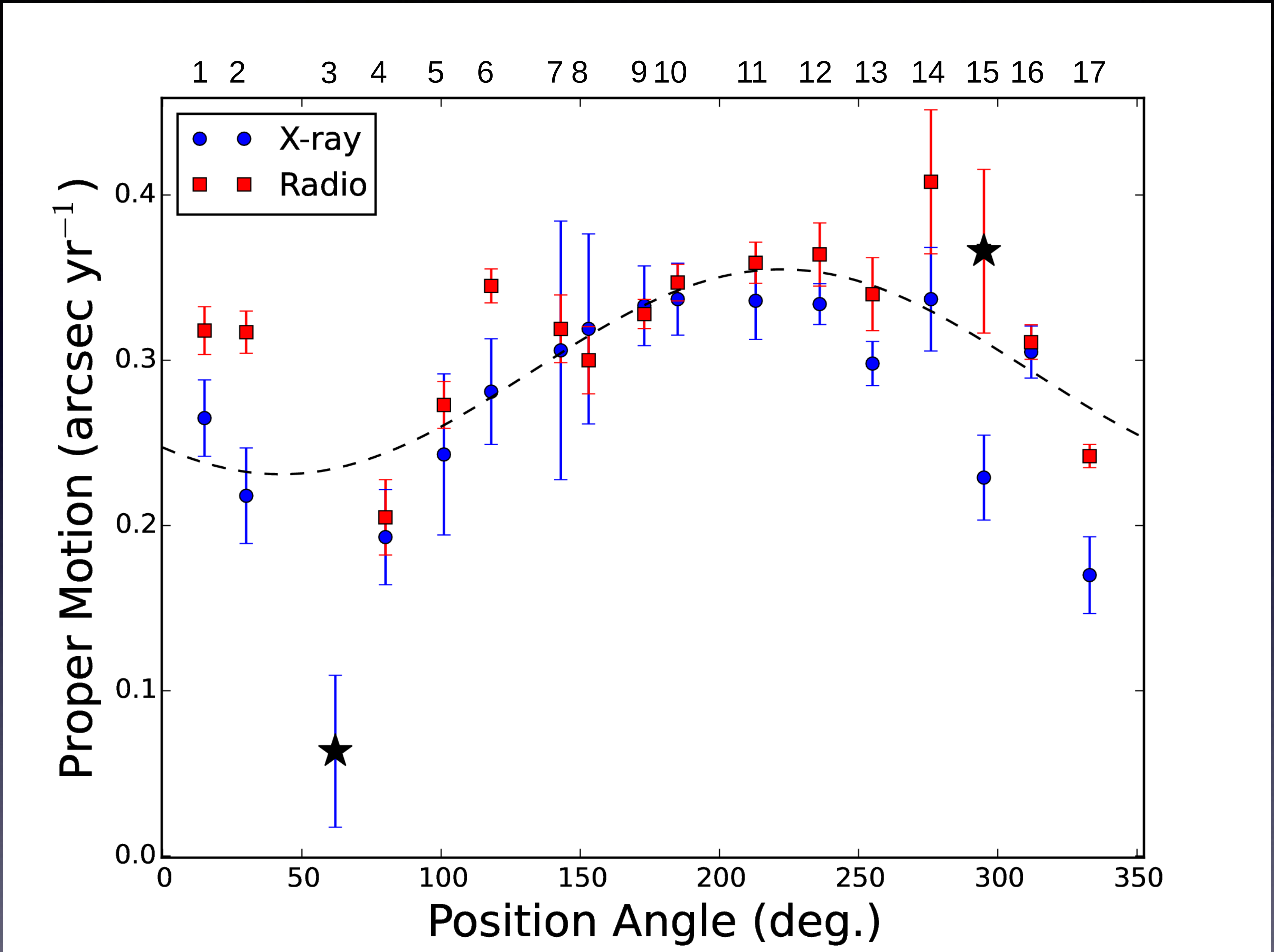
Chandra - 2000, 2003, 2007, 2009, <u>*2015*</u>

VLA - 1984, 1993, 2002, *2014*

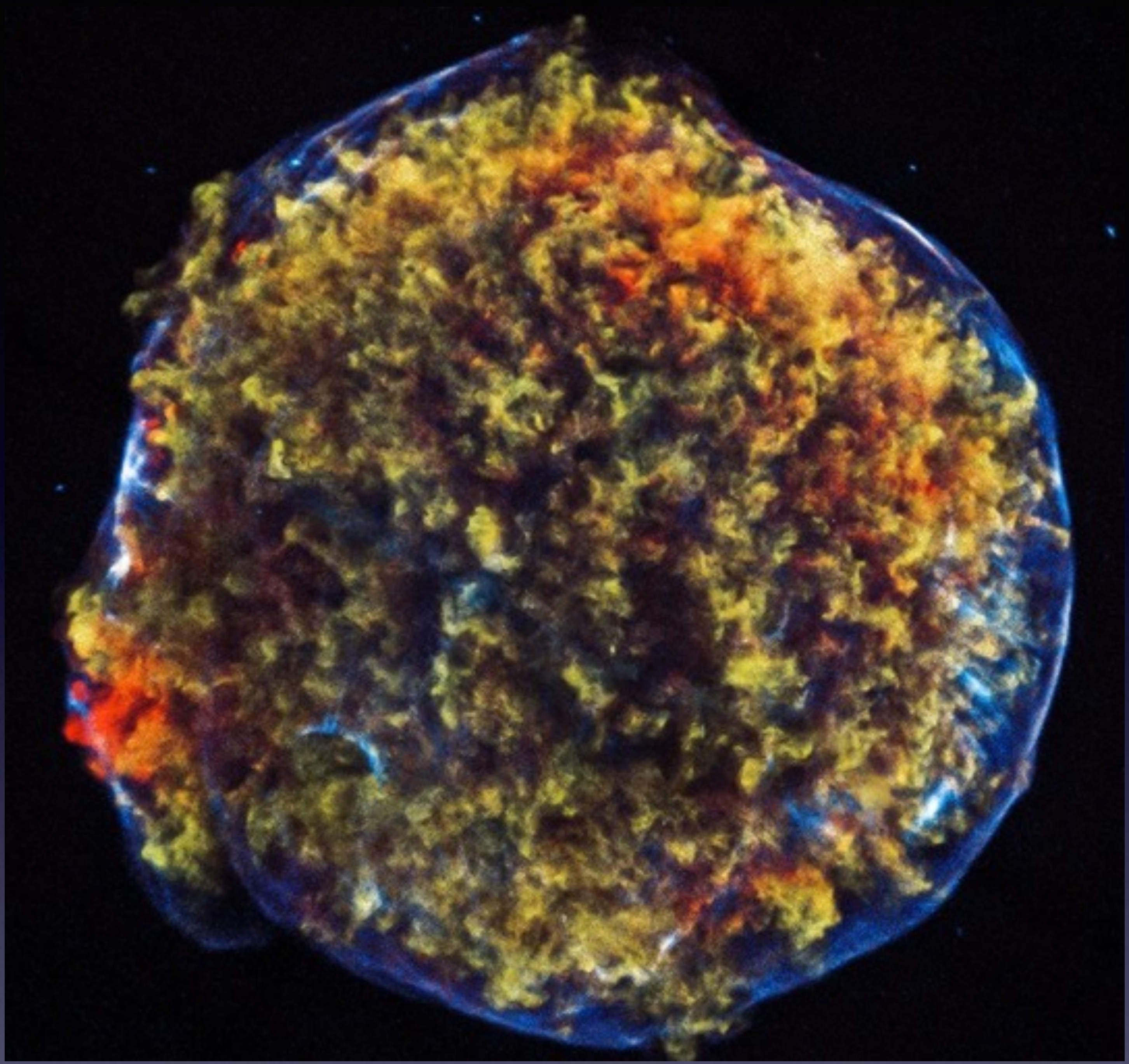


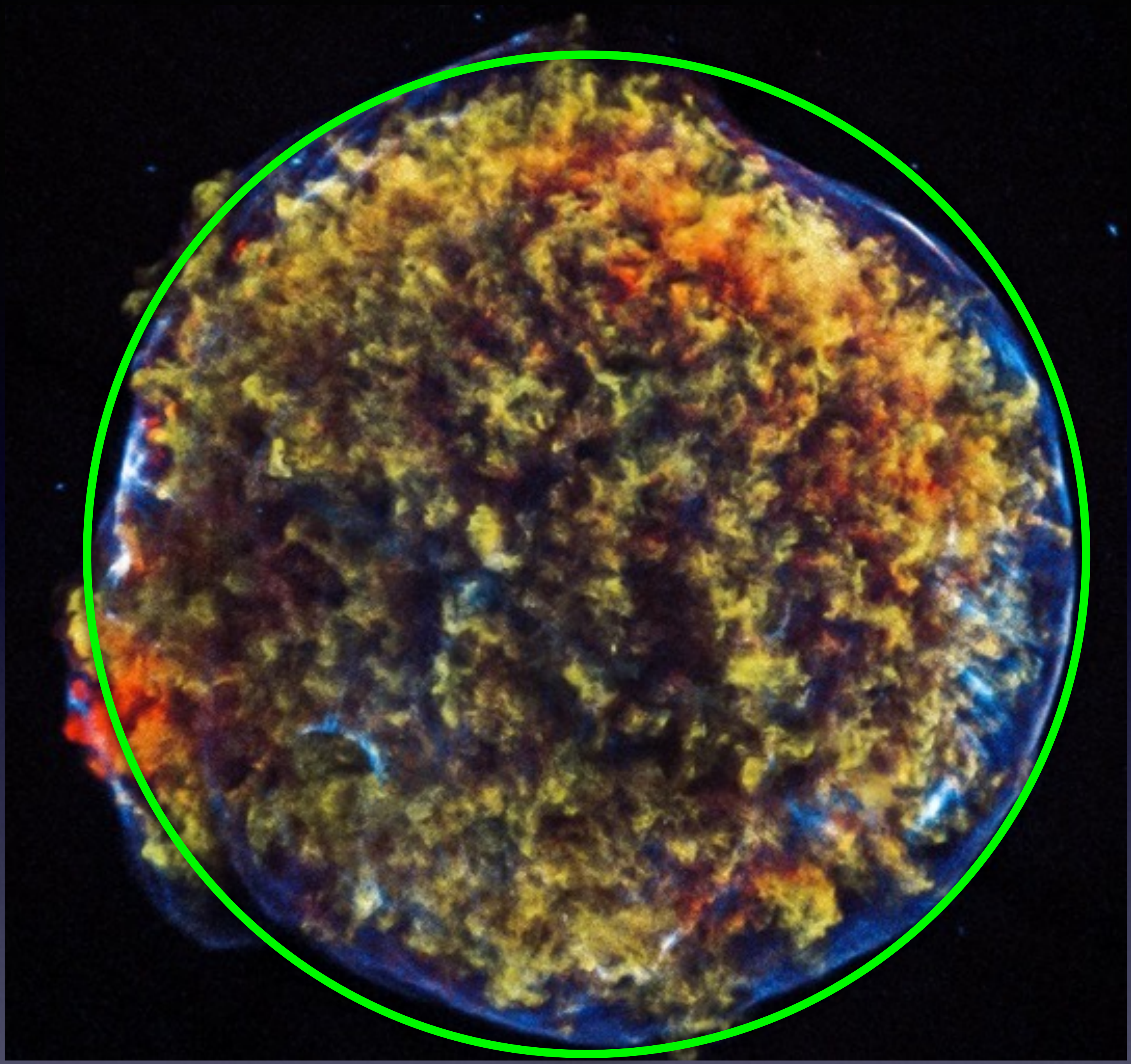
Williams et al. 2013 measured densities of surrounding ISM, found evidence of density gradient


0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
Proper Motion (arcsecs/yr)
0
50
100
150
200
250
300
350
400
Azimuthal Angle (Degrees)
Reynoso et al. 1997, 10-yr baseline
Katsuda et al. 2010, 7-yr baseline

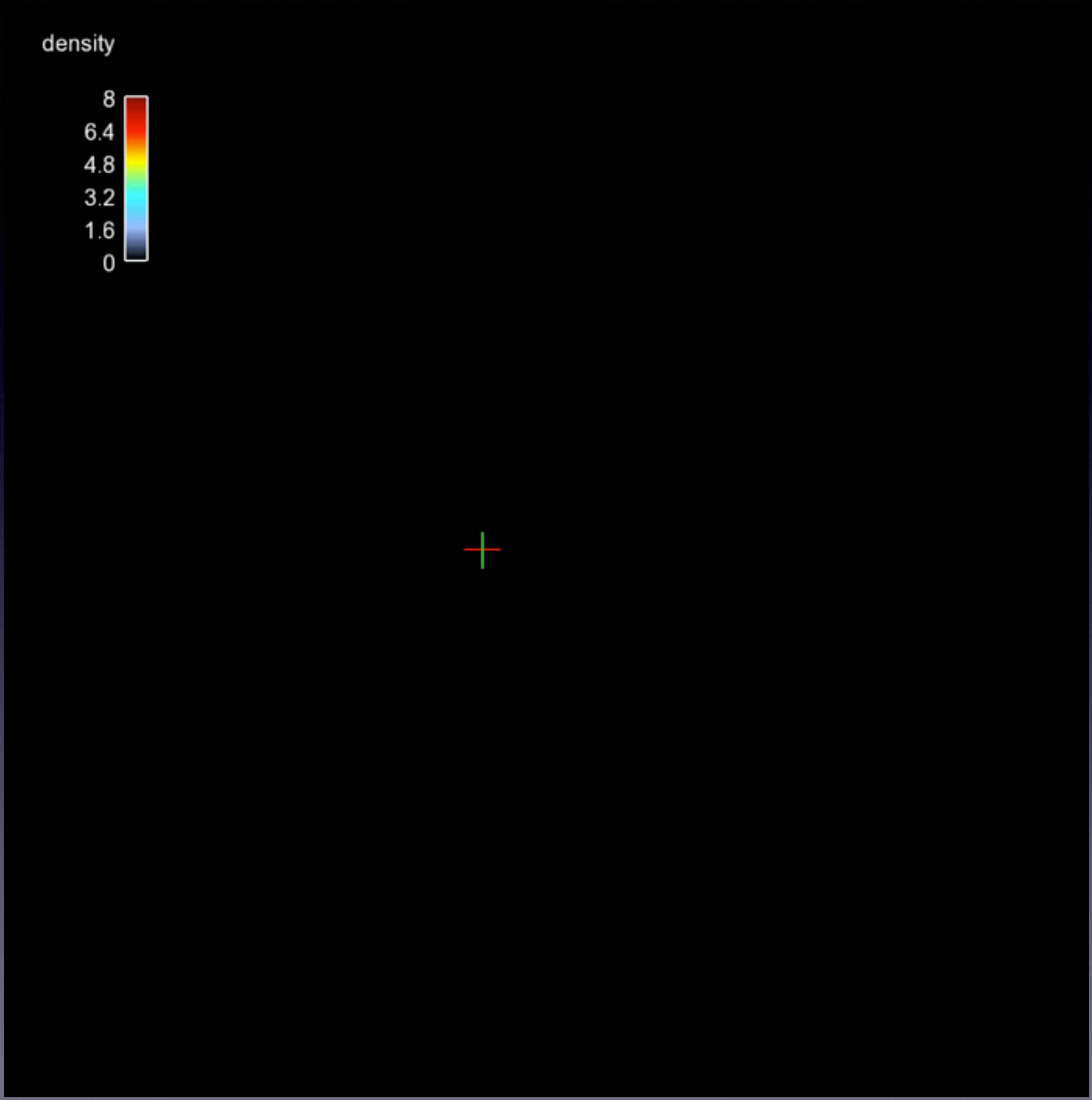


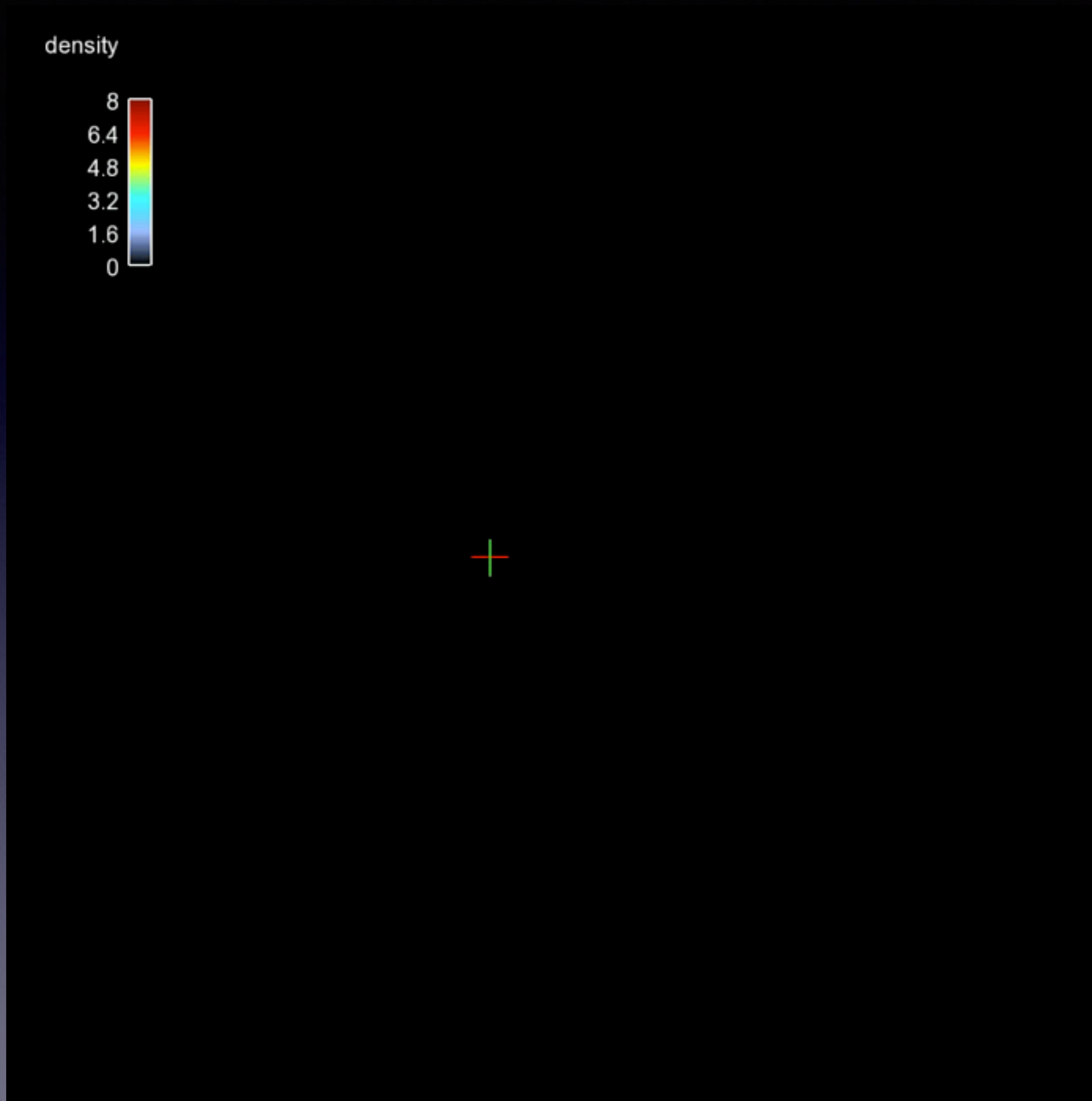
Plot from Williams et al. 2016, 15-yr baseline in X-rays, 30-yr in radio!

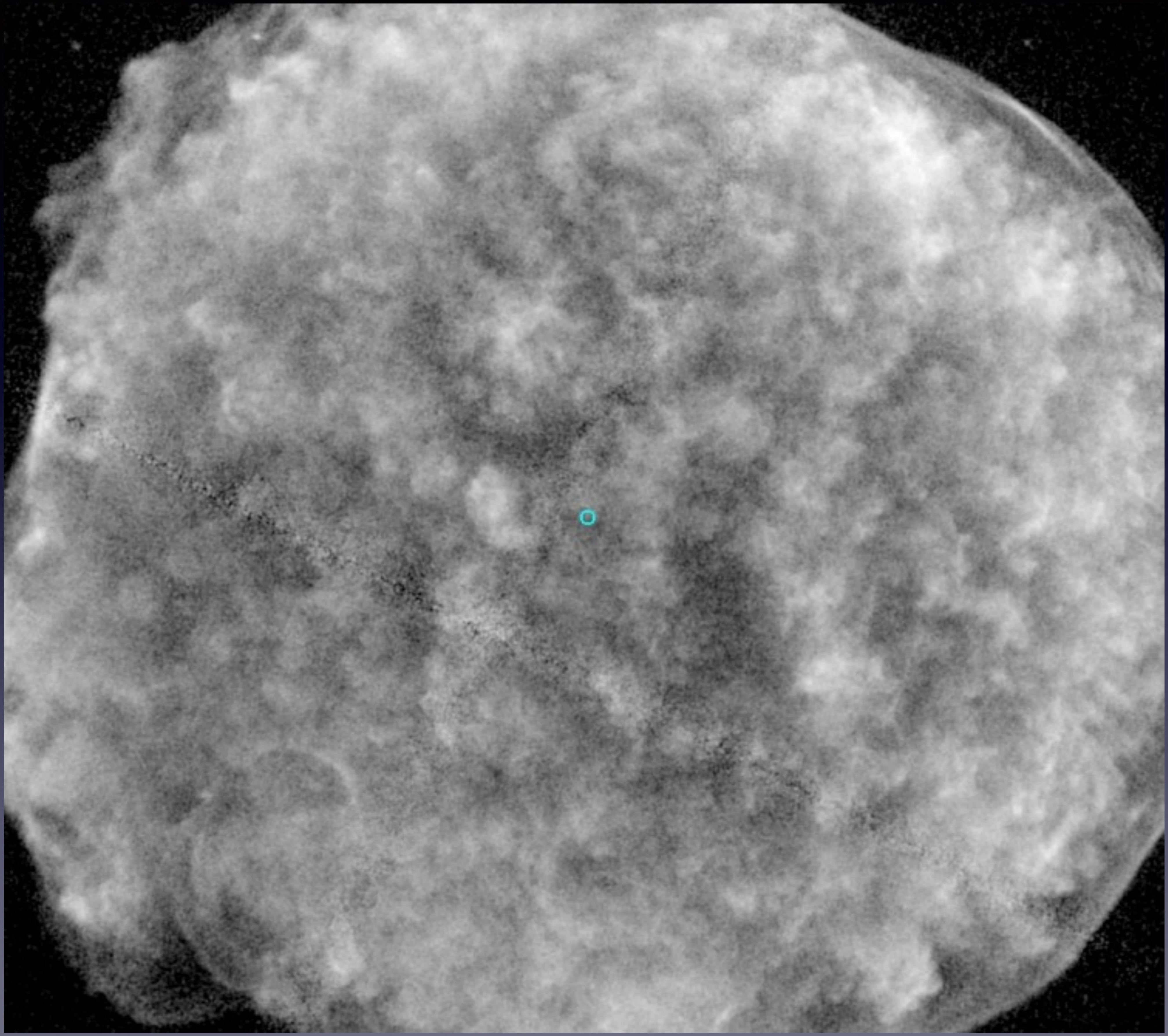




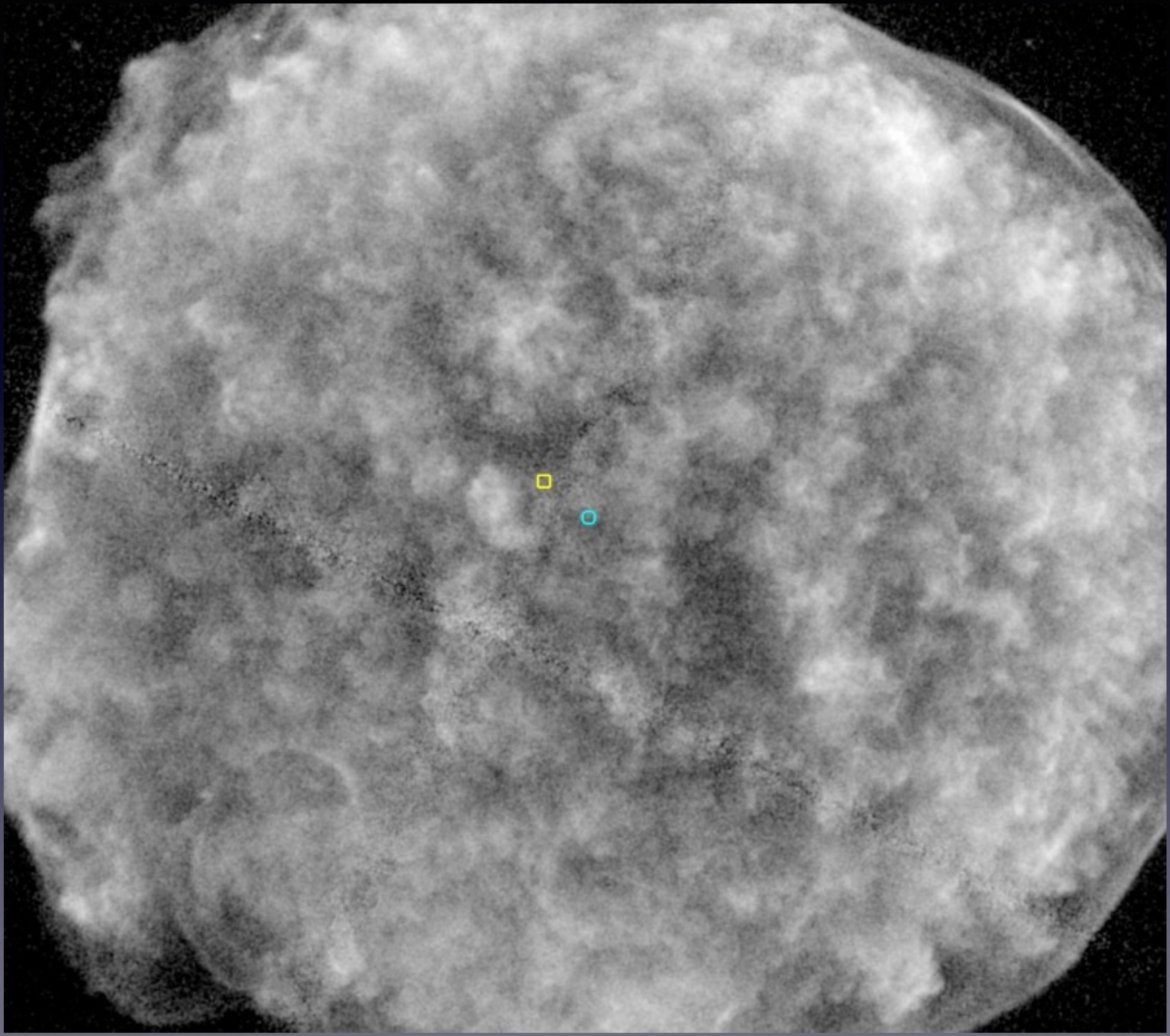
“But wait! Tycho is circular…”


density
8
6.4
4.8
3.2
1.6
0


density
8
6.4
4.8
3.2
1.6
0

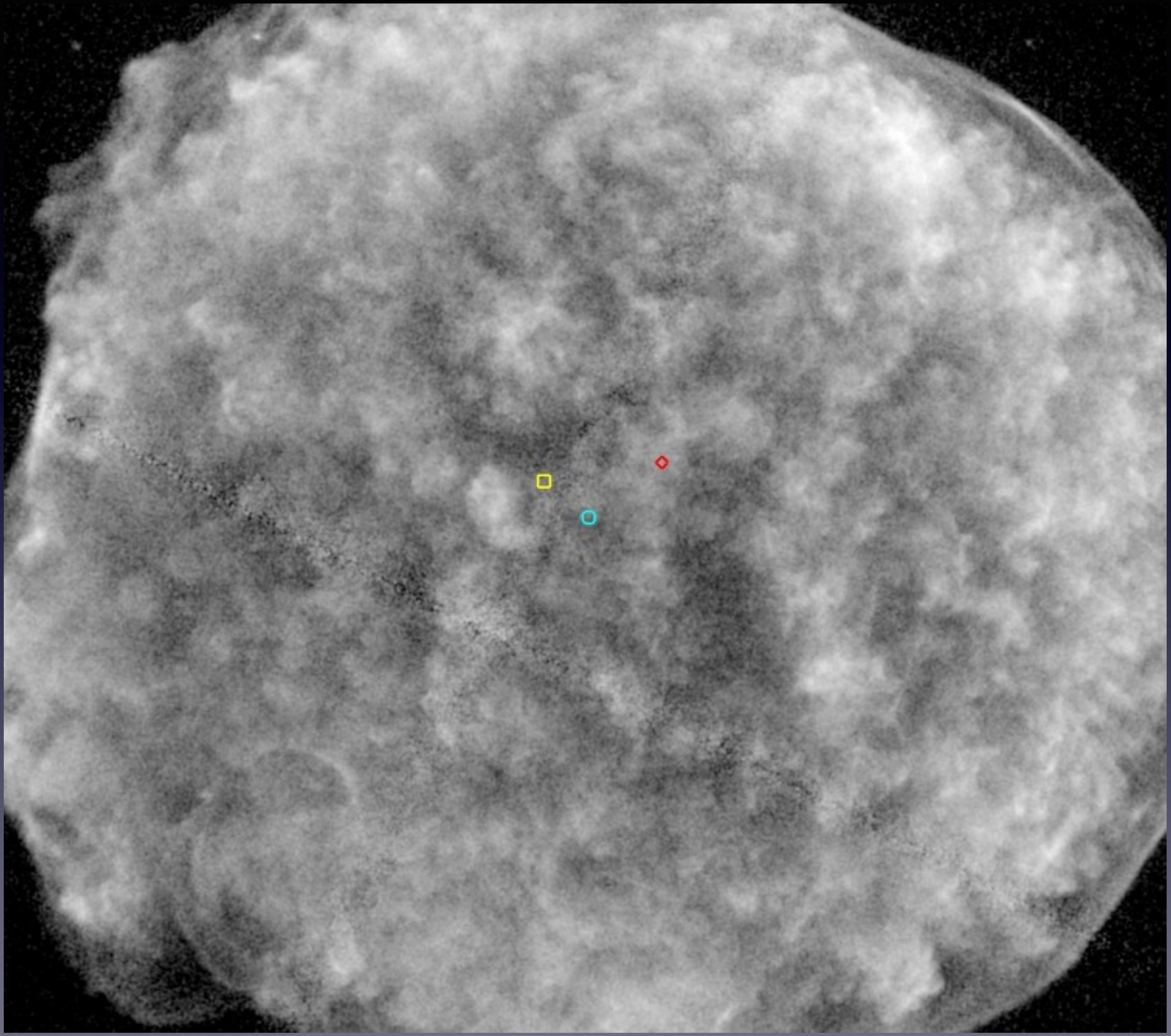


Center, Ruiz-Lapuente et al. 2004



Center, Ruiz-Lapuente et al. 2004

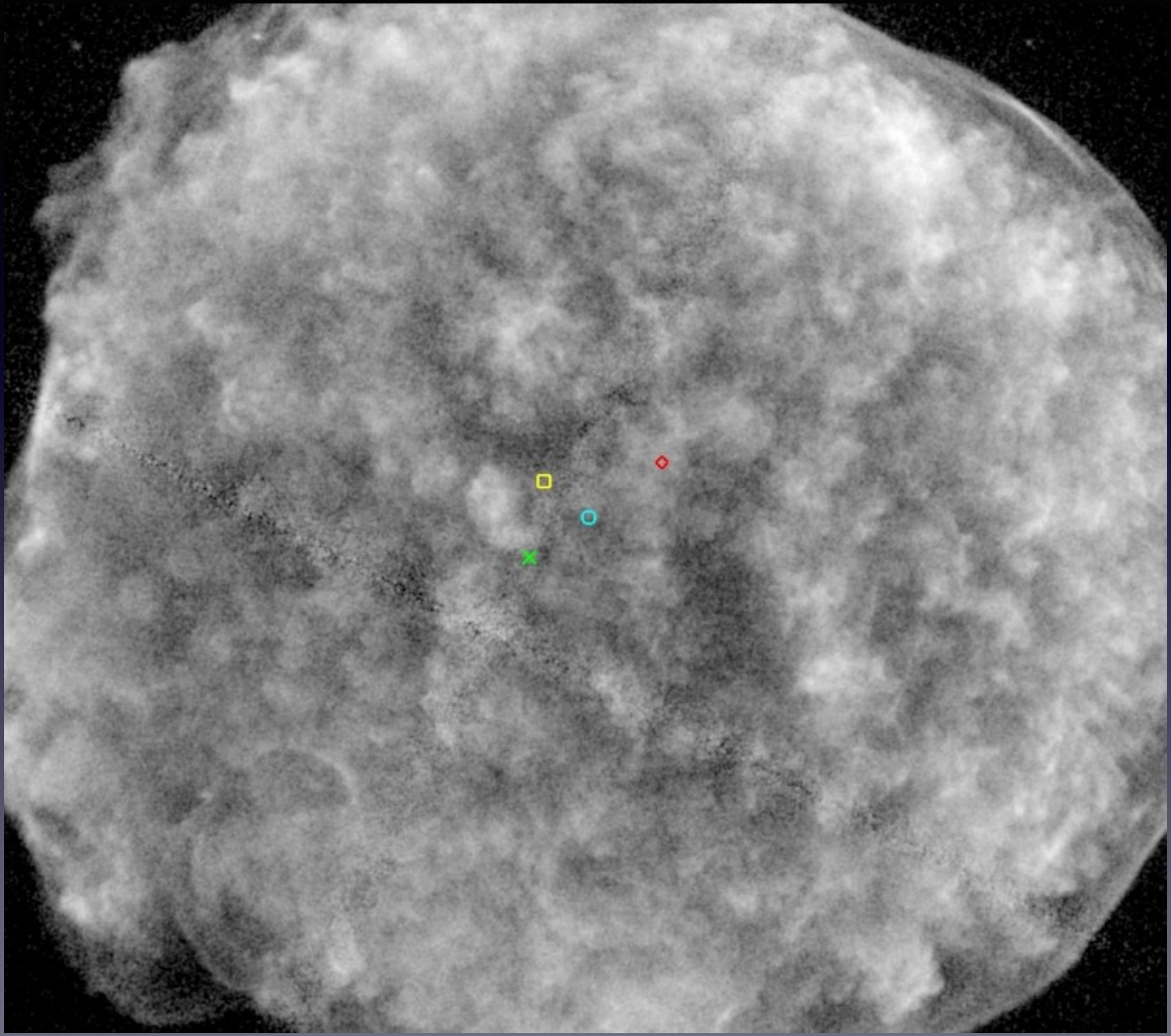
Explosion site, Williams et al. 2016



Center, Ruiz-Lapuente et al. 2004

Explosion site, Williams et al. 2016

Explosion site, Xue & Schaefer 2015



Center, Ruiz-Lapuente et al. 2004

Explosion site, Williams et al. 2016

Explosion site, Xue & Schaefer 2015

“Star G,” Ruiz-Lapuente et al. 2004

- Just because a remnant is circular, doesn’t mean the explosion site and geometric center are the same

- Effect is “only” ~10% for Tycho, but Tycho is dynamically young! Older remnants will show larger effects…

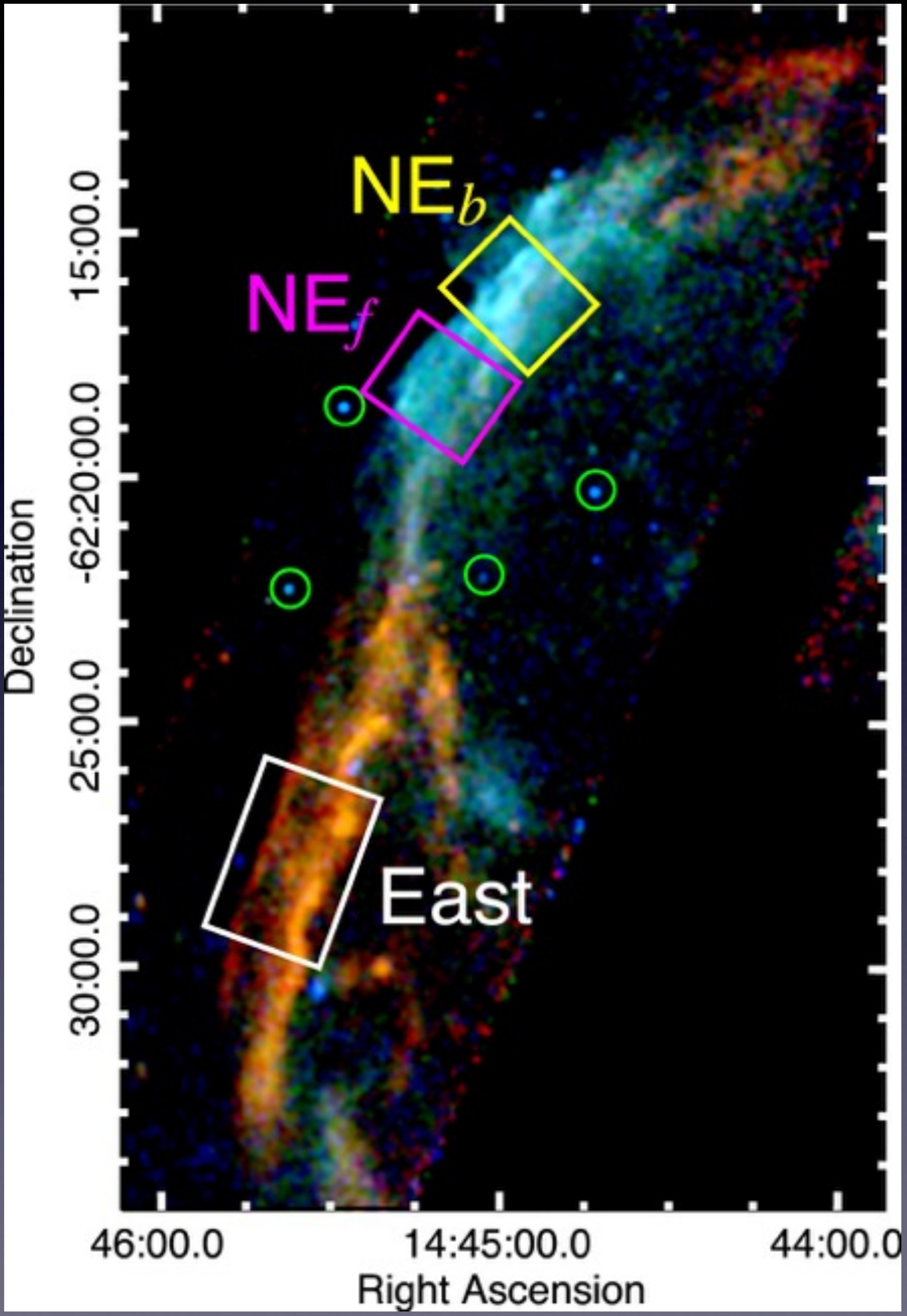
- See further talks on Tycho kinematics by Frank Winkler and Jack Hughes

RCW 86

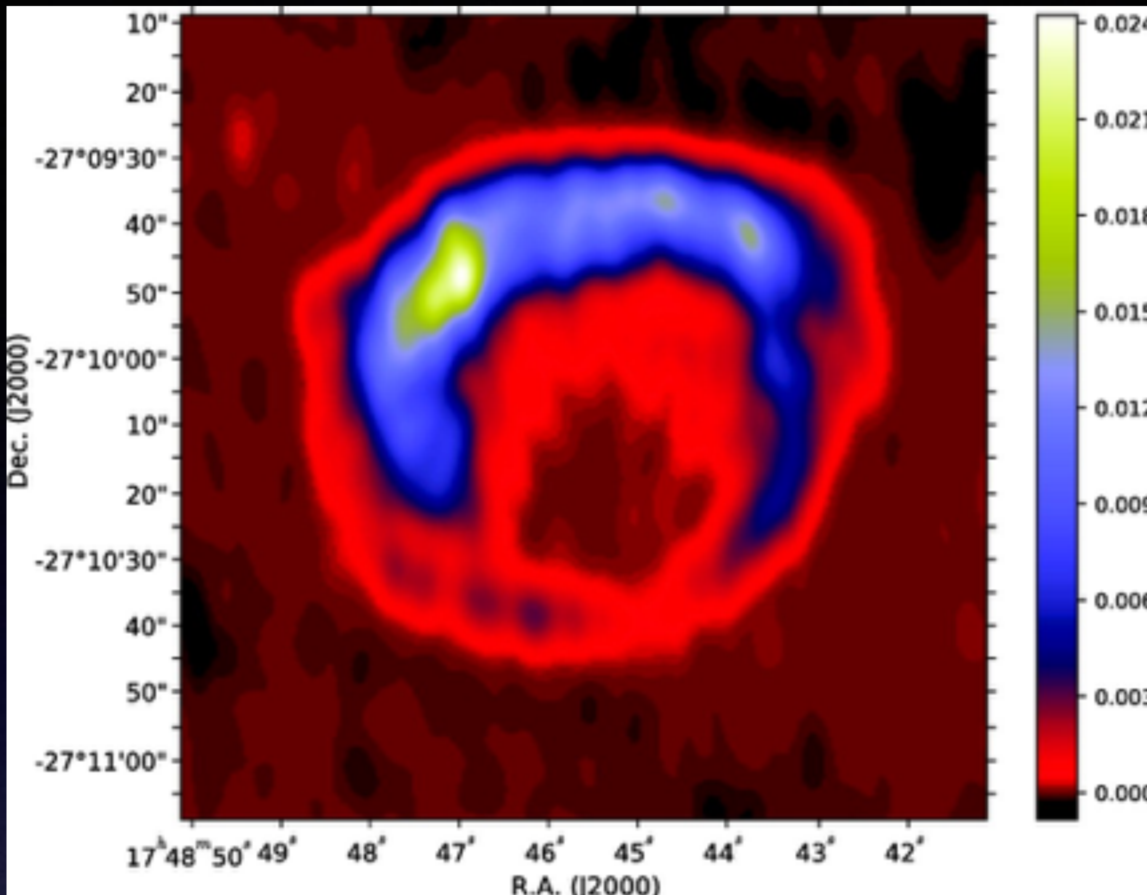
- Recent paper by Yamaguchi et al. 2016 derives proper motions for nonthermal (1800-3000 km/s) and thermal filaments (720 km/s)

- thermal velocities comparable to those reported by Helder et al. 2013 for optical Hα filaments

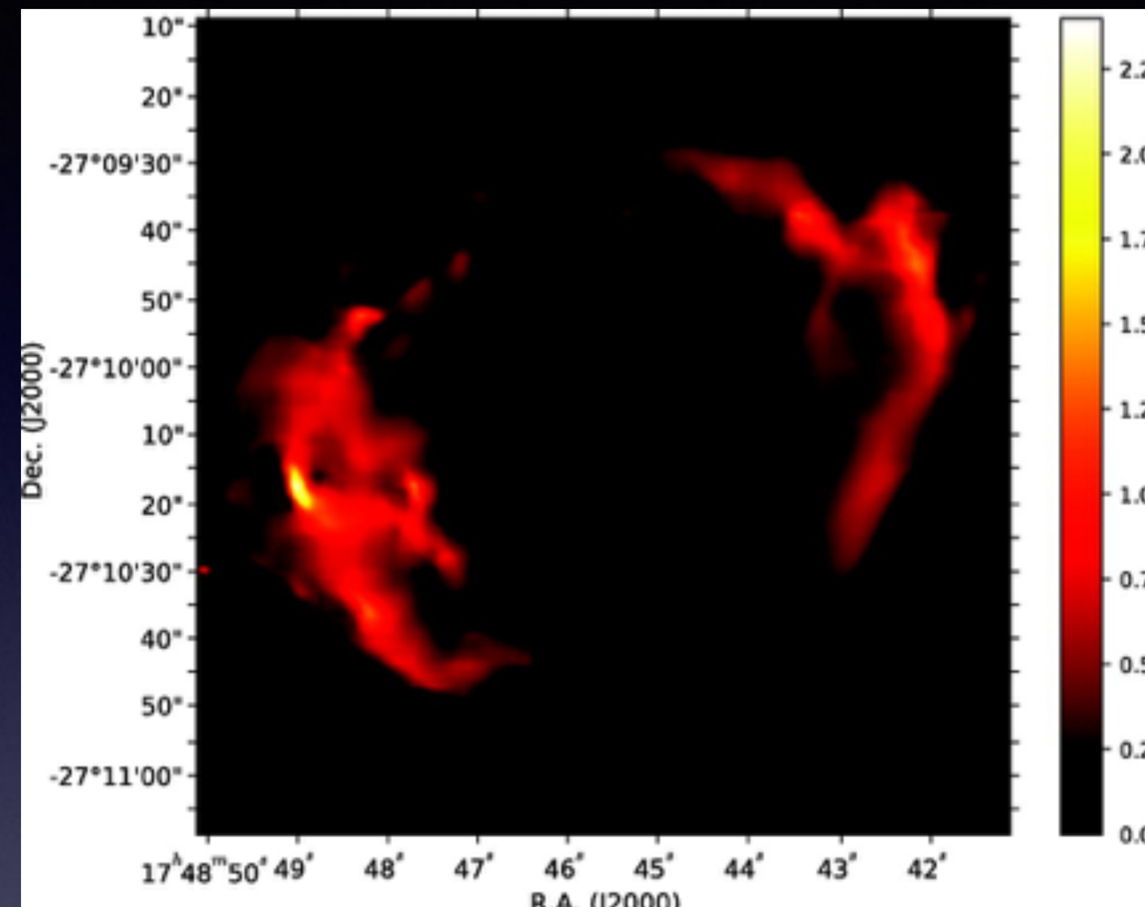
- consistent with predictions of Williams et al. 2011 that RCW 86 exploded in bubble, nonthermal rims are where shock hasn't yet hit bubble wall; see D. Castro talk for physics of synchrotron emission



G1.9+0.3

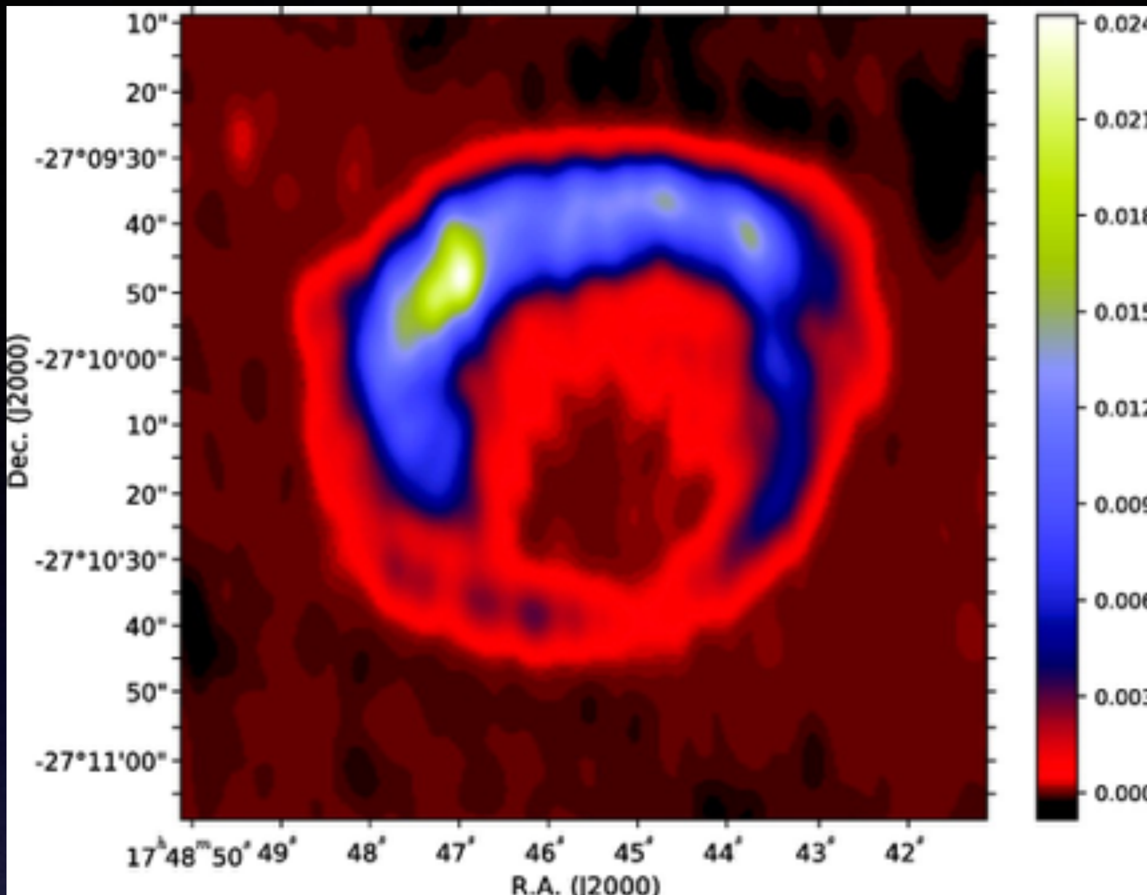


Radio image, 1984

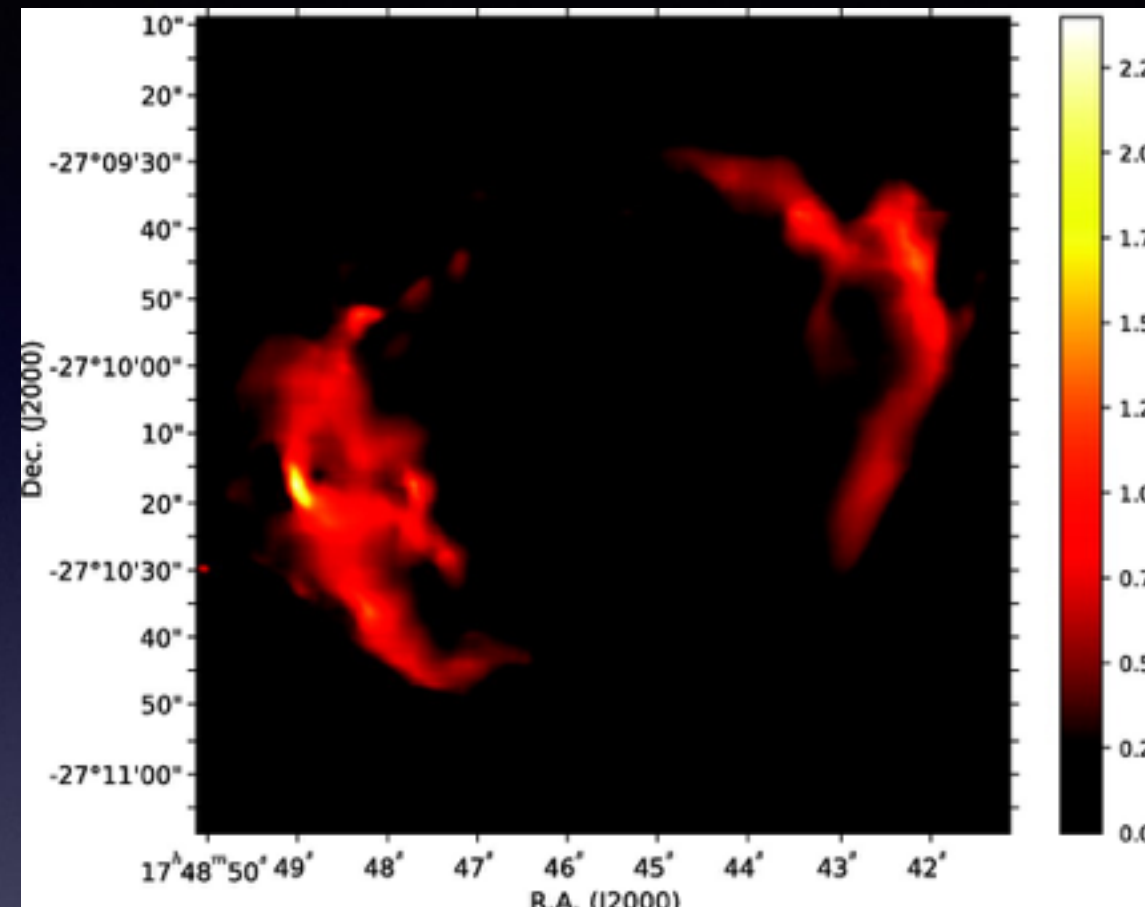


X-ray image, 2007

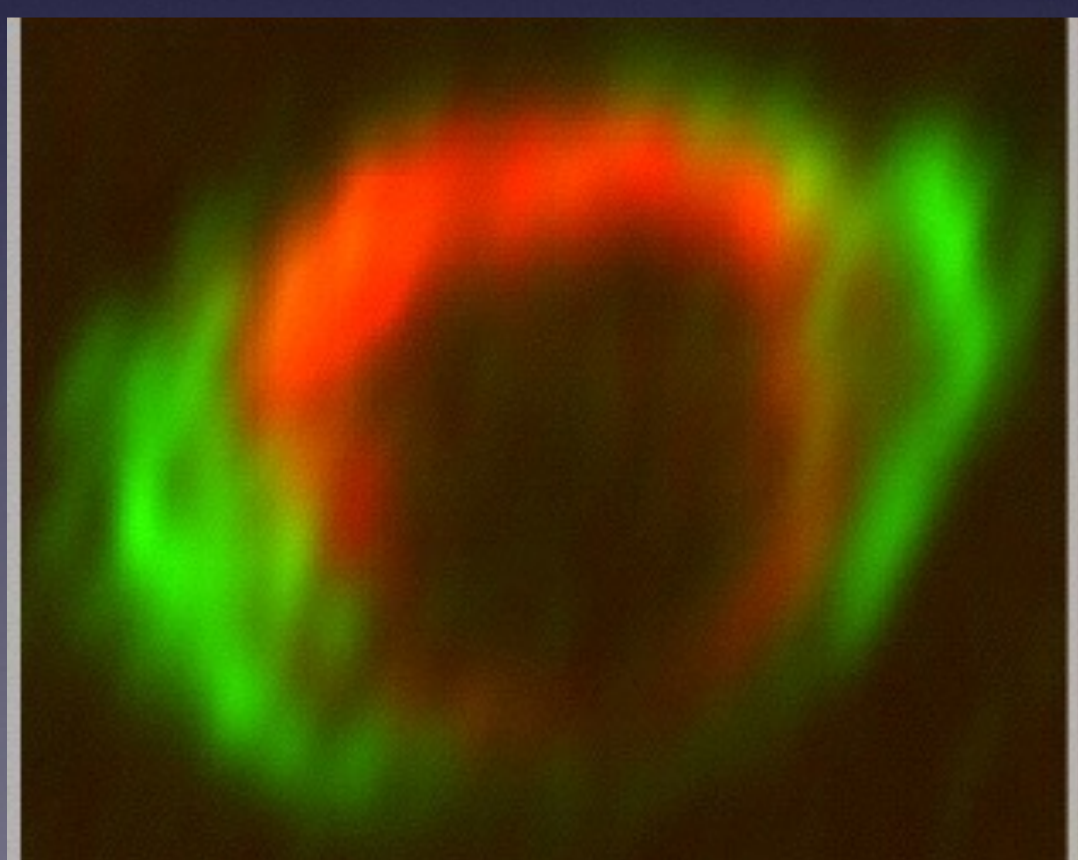
G1.9+0.3



Radio image, 1984



X-ray image, 2007



Reynolds et al. 2008

G1.9+0.3 is by far the youngest remnant in the Milky Way, age ~120 years (but no way it could have been seen from Earth at that time)

G1.9+0.3 is by far the youngest remnant in the Milky Way, age ~120 years (but no way it could have been seen from Earth at that time)

Lots of great science…

- Radio flux is still *brightening,* (Green et al. 2008)
- Overwhelmingly synchrotron-dominated, but spectral variations from place to place (Reynolds et al. 2009)
- Ejecta detected, asymmetrically-distributed, moving up to 18,000 km/s (Borkowski et al. 2009)
- Detected with NuSTAR up to 30 keV (Zoglauer et al. 2015)
- Expansion is asymmetric; see poster by S. Reynolds

Kepler's SNR

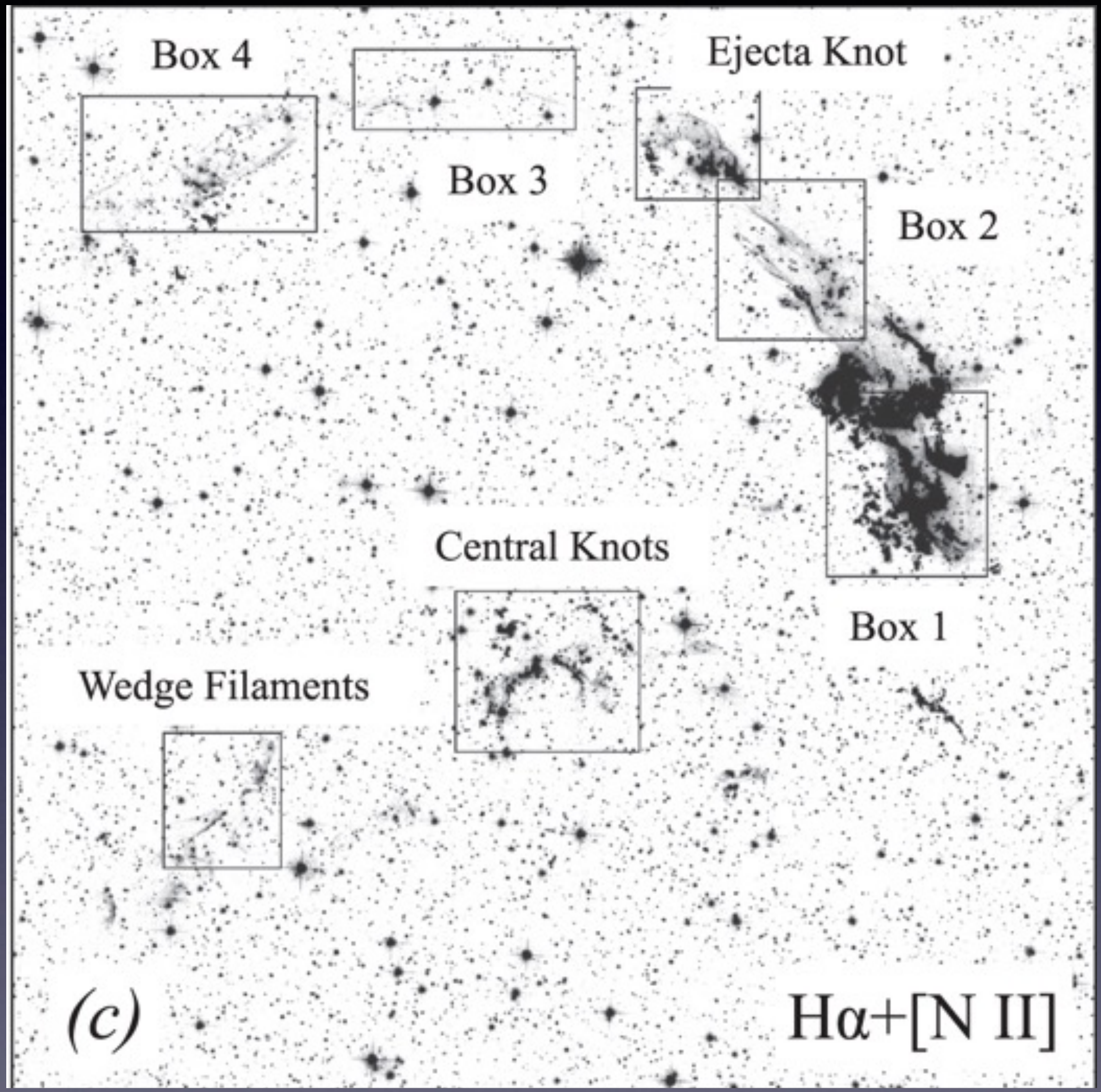
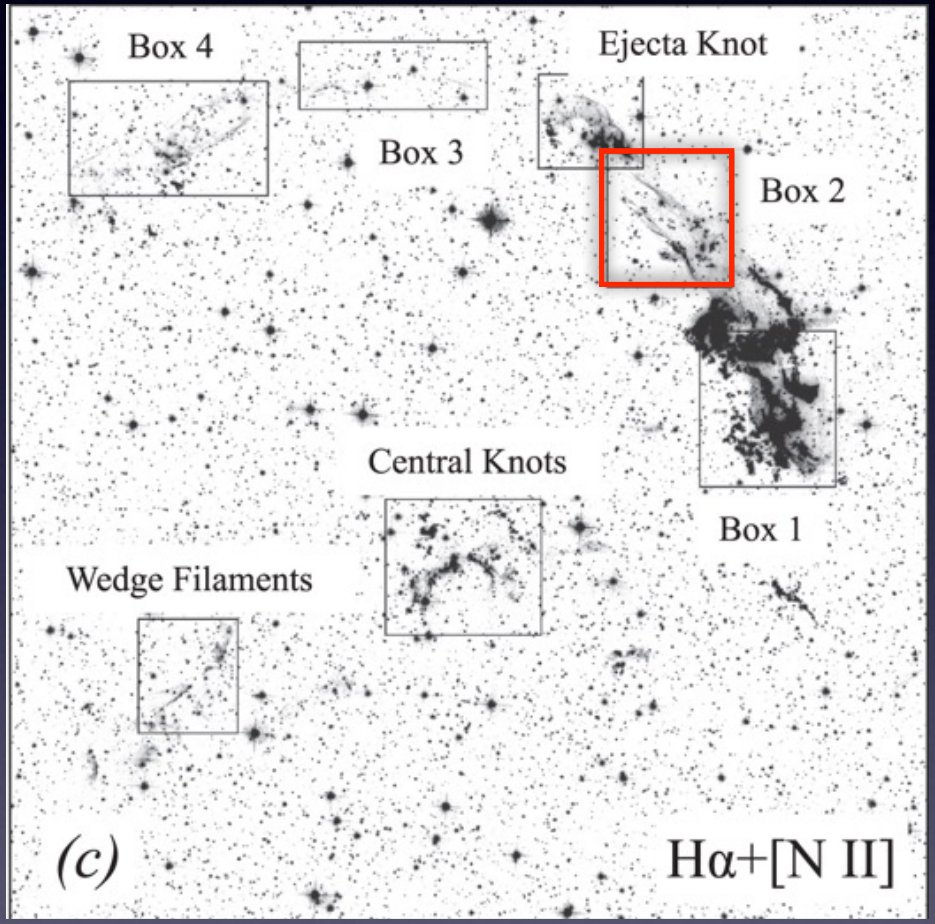
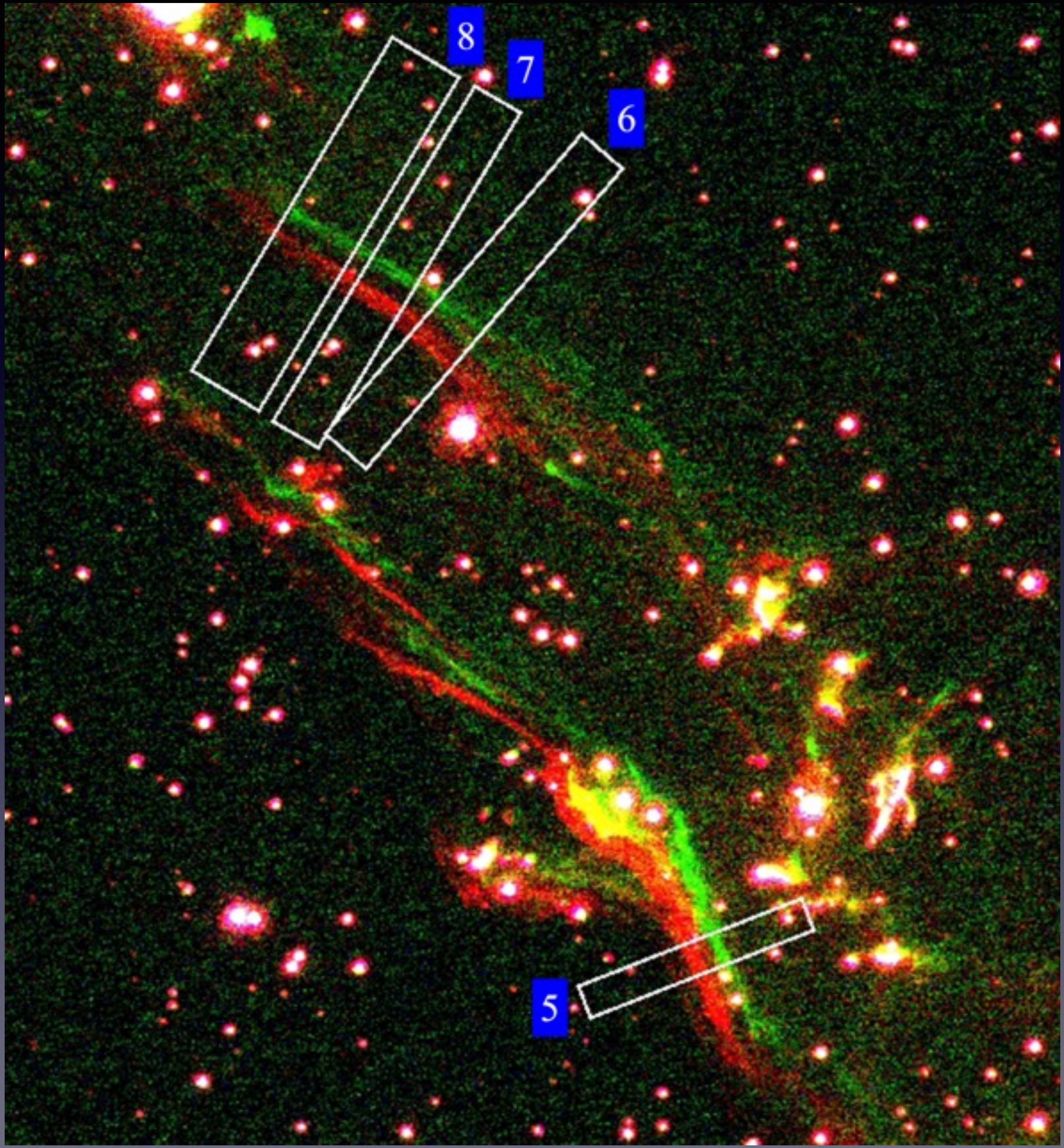
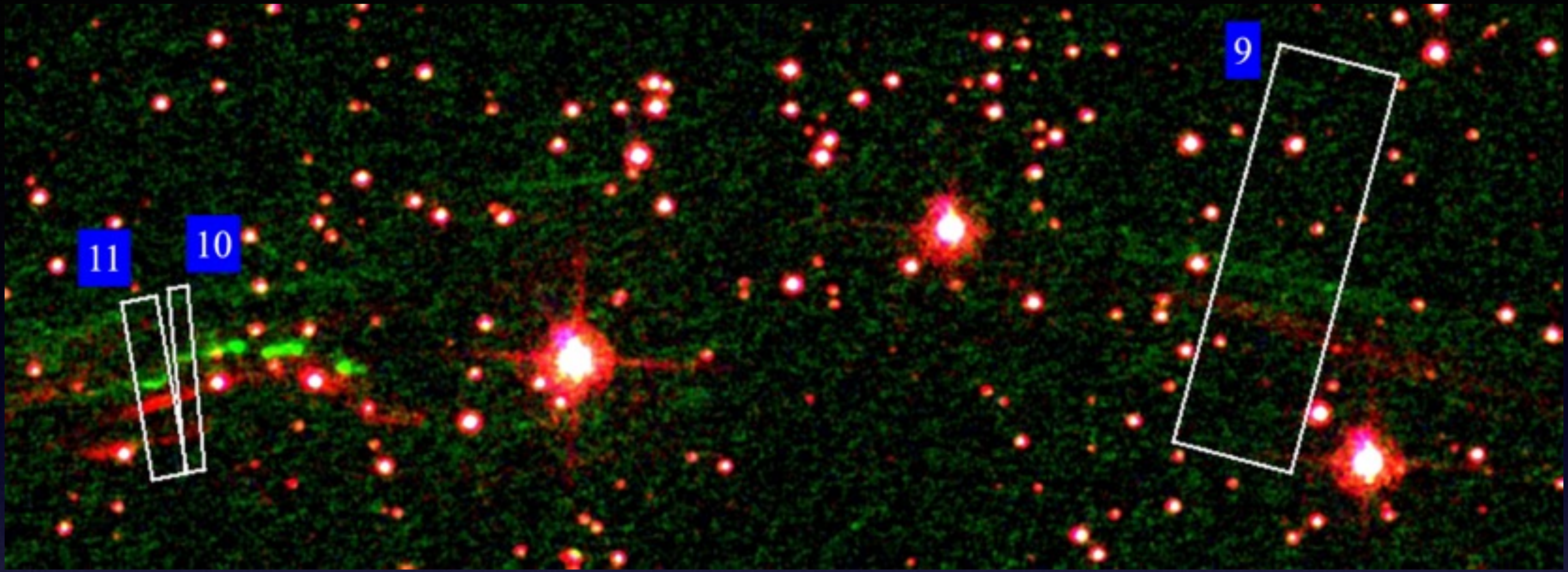


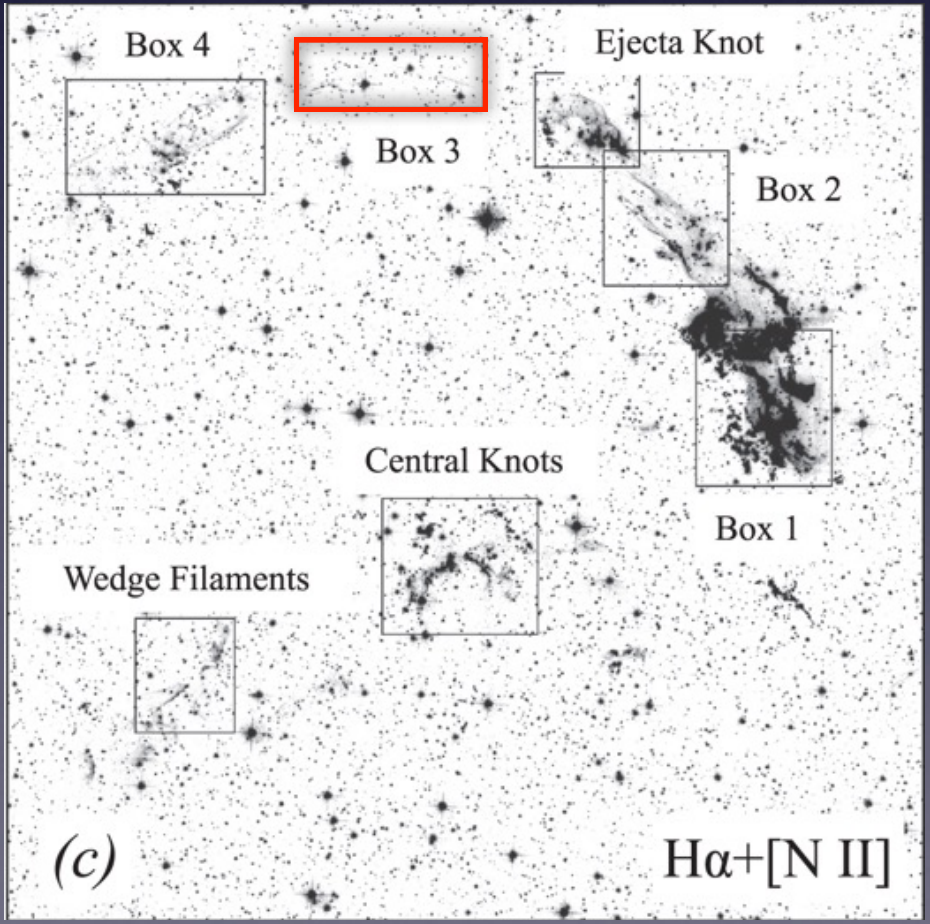
Figure 1(c) from Sankrit et al. 2015


Box 4
Ejecta Knot
Box 3
Box 2
Central Knots
Box 1
Wedge Filaments
(c)
Hα+[N II]

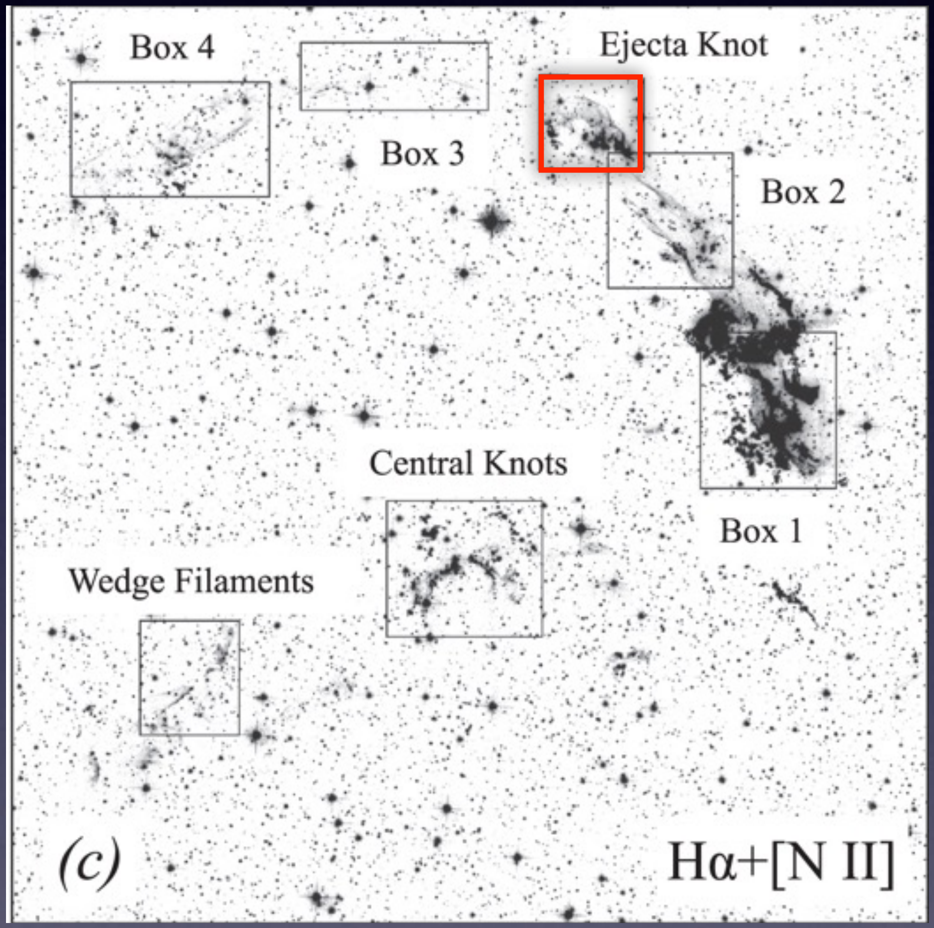

8
7
6
5

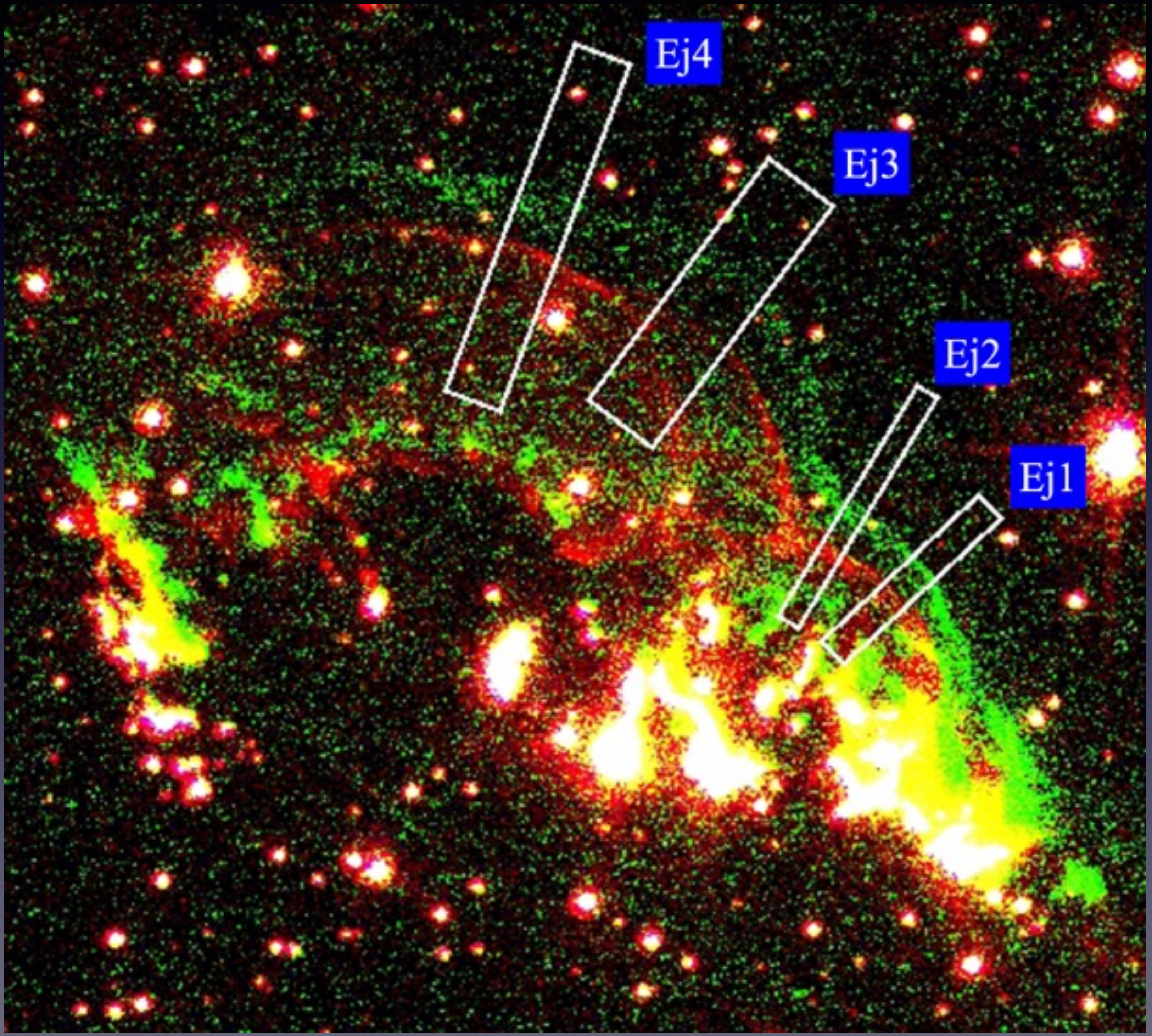


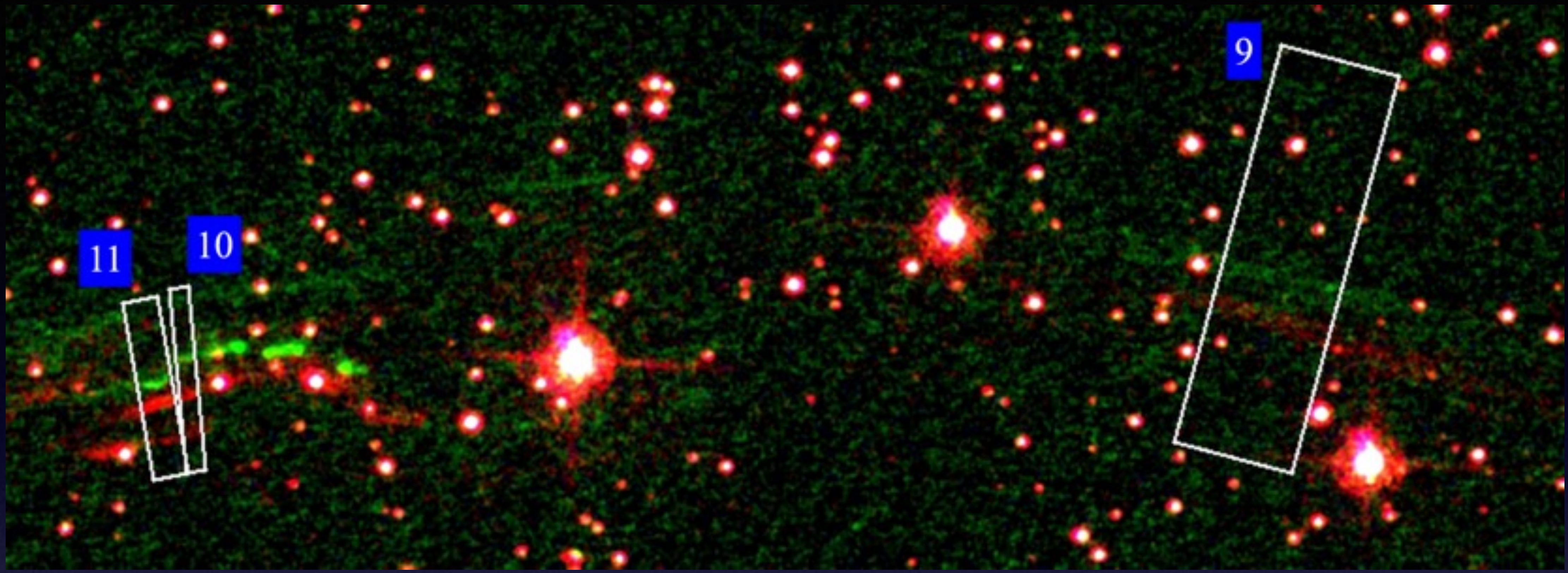
9
11
10

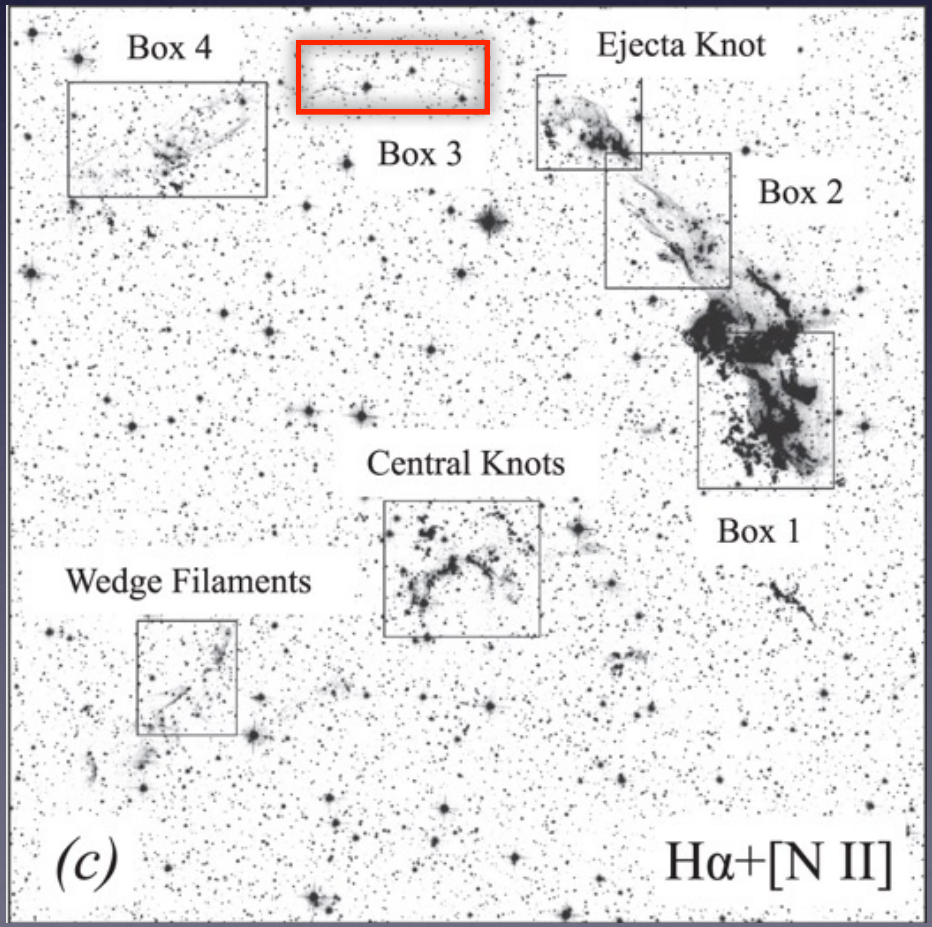


Box 4
Ejecta Knot
Box 3
Box 2
Central Knots
Box 1
Wedge Filaments
(c)
Hα+[N II]


Box 4
Box 3
Ejecta Knot
Box 2
Central Knots
Box 1
Wedge Filaments
(c)
Hα+[N II]

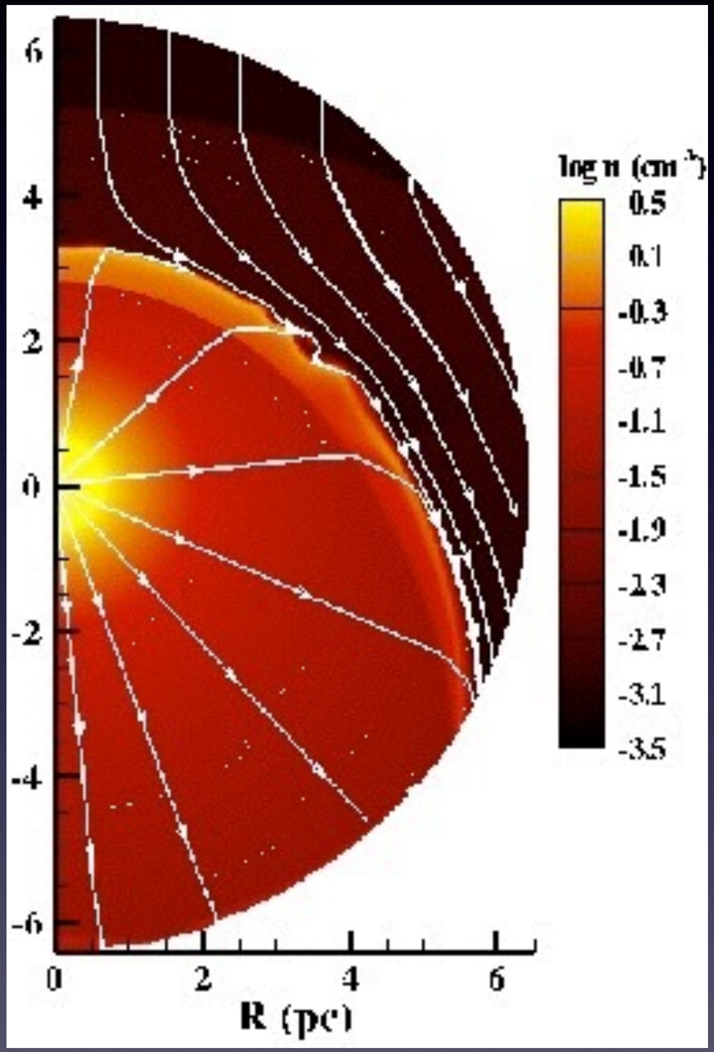

Ej4
Ej3
Ej2
Ej1





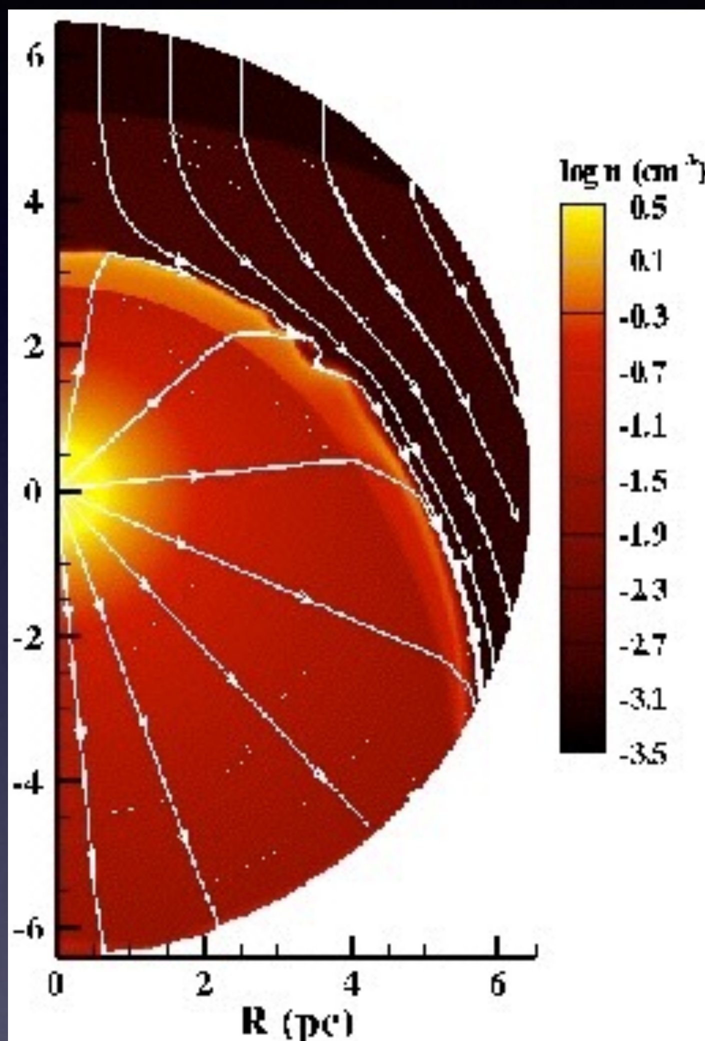
- Shock velocities vary by a factor of 2
- Comparing proper motions to shock velocities derived from Hα spectroscopy, we get distance of 5.1 ± 0.8 kpc
- At this distance, mean shock velocity in north rim is 1690 km/s, pre-shock density ~8 cm^{-3}

A few recent papers on Kepler…

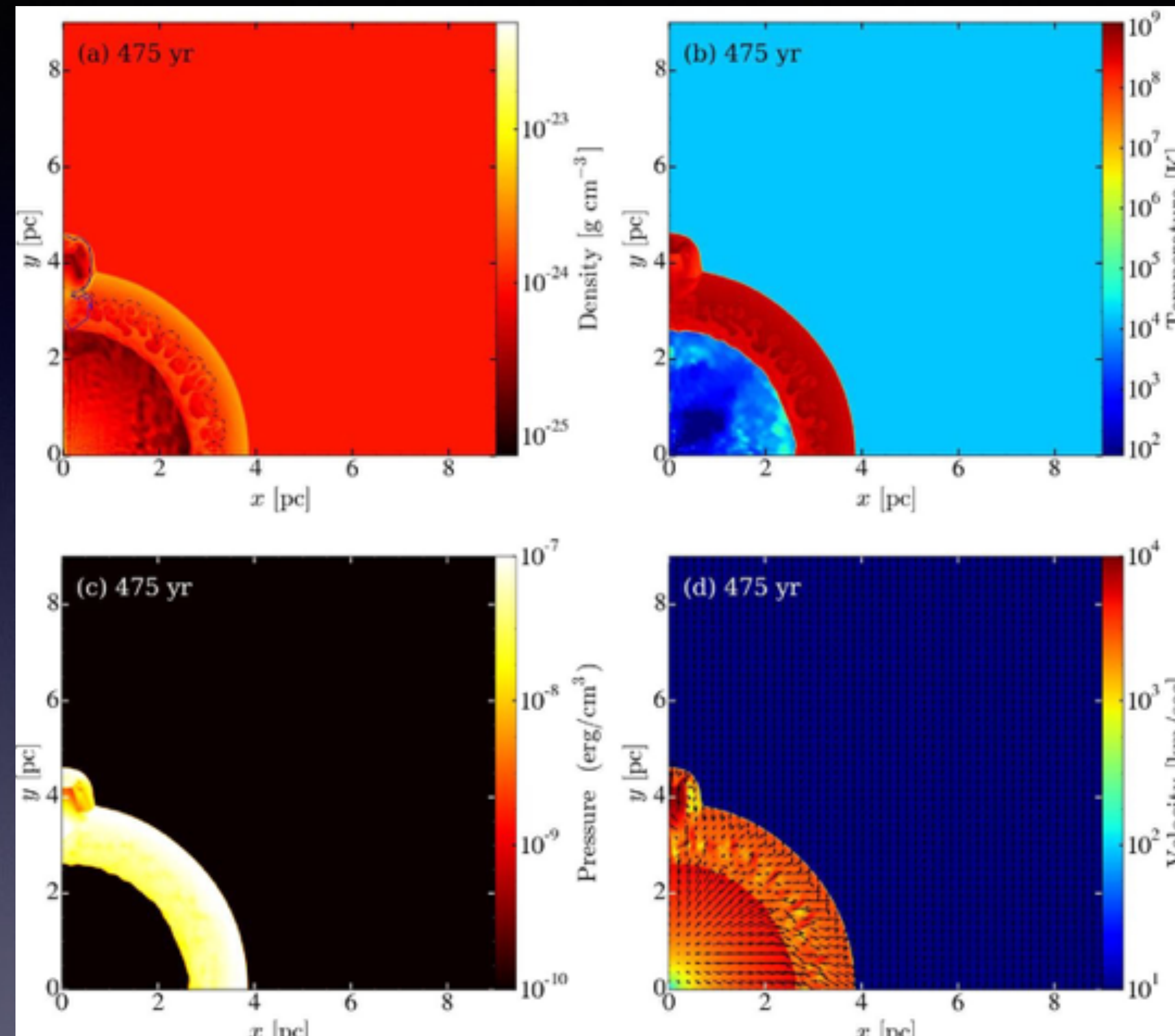


Chiotellis+ 2012 find Kepler is consistent with a symbiotic binary progenitor (i.e. single-degenerate) of WD + 4-5 M_{sun} AGB star, favor large (> 6 kpc) distance

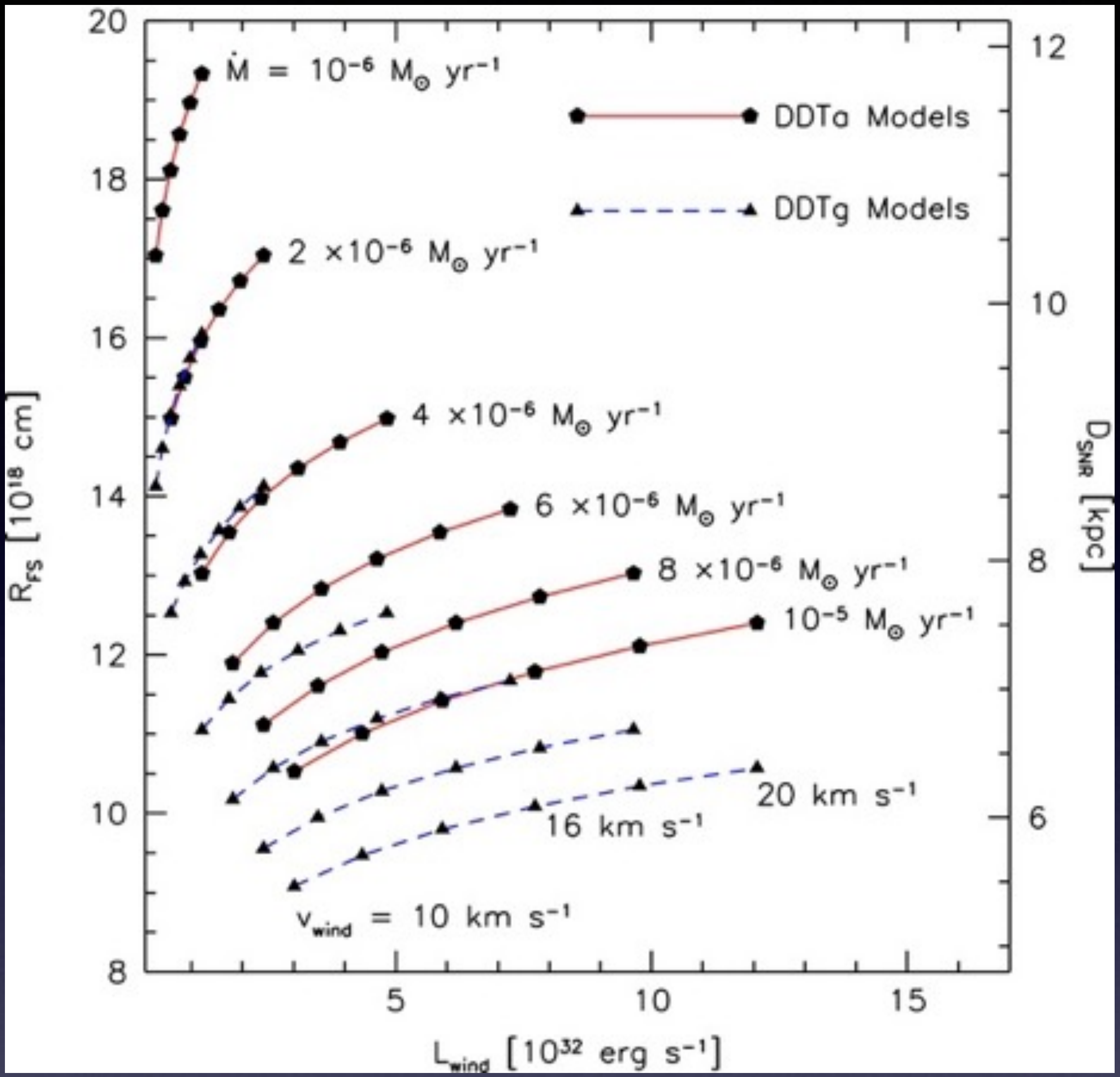
A few recent papers on Kepler…



Chiotellis+ 2012 find Kepler is consistent with a symbiotic binary progenitor (i.e. single-degenerate) of WD + 4-5 M_{sun} AGB star, favor large (> 6 kpc) distance

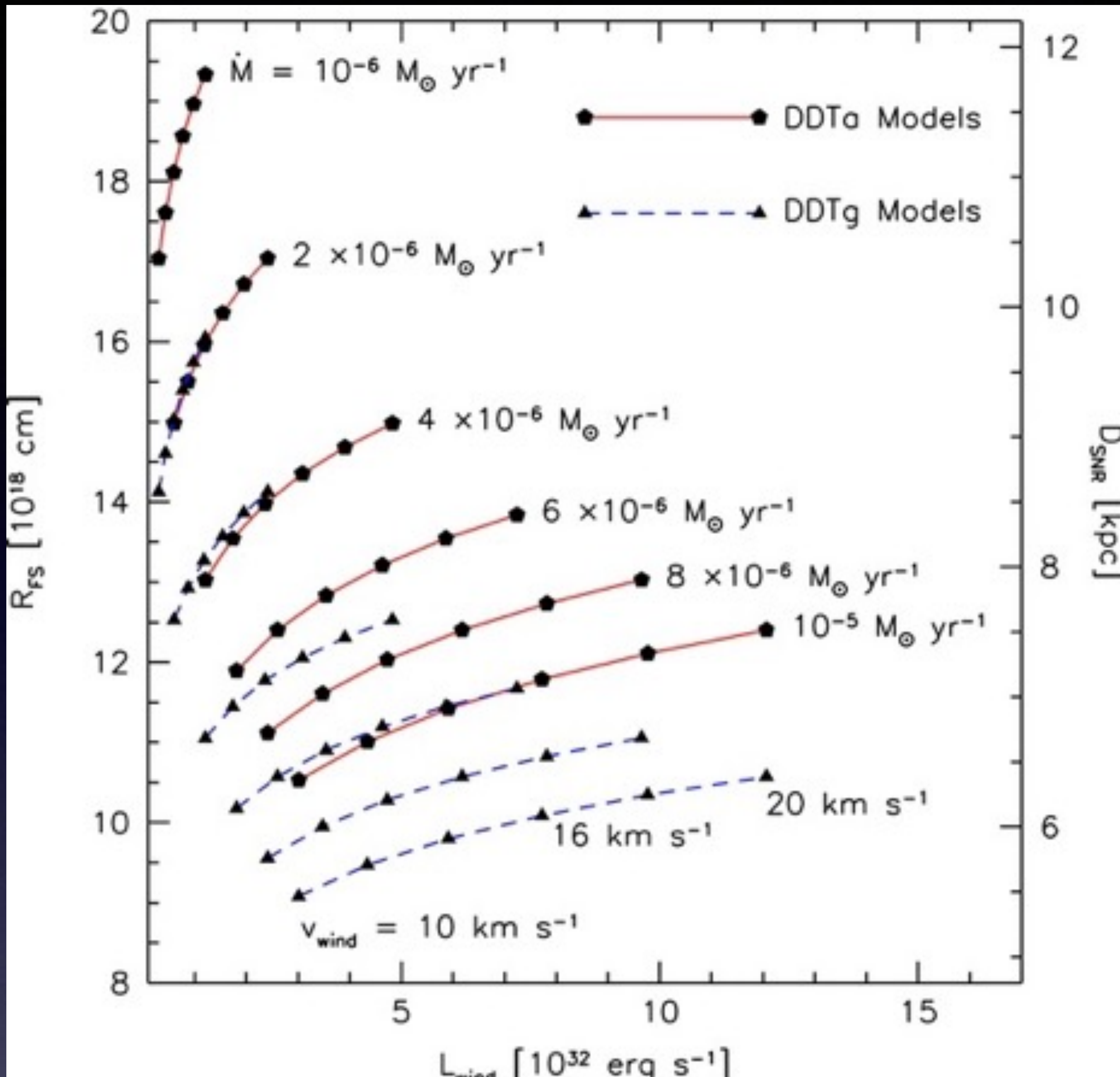


Tsebrenko & Soker 2015 use an "iron bullet" model to explain the "ears" in Kepler



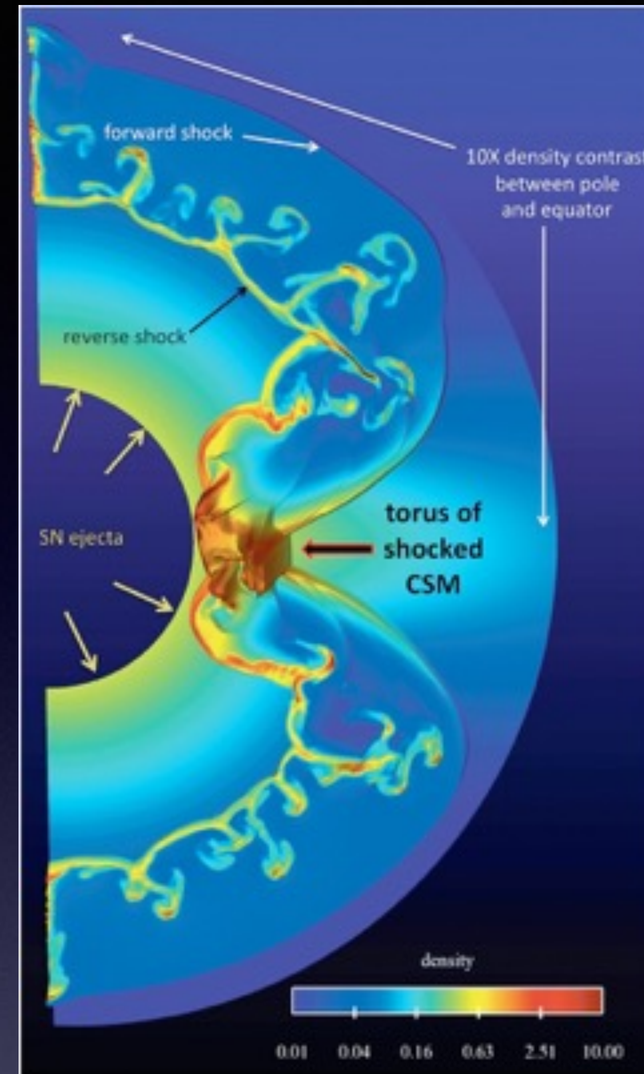
Patnaude+ 2012

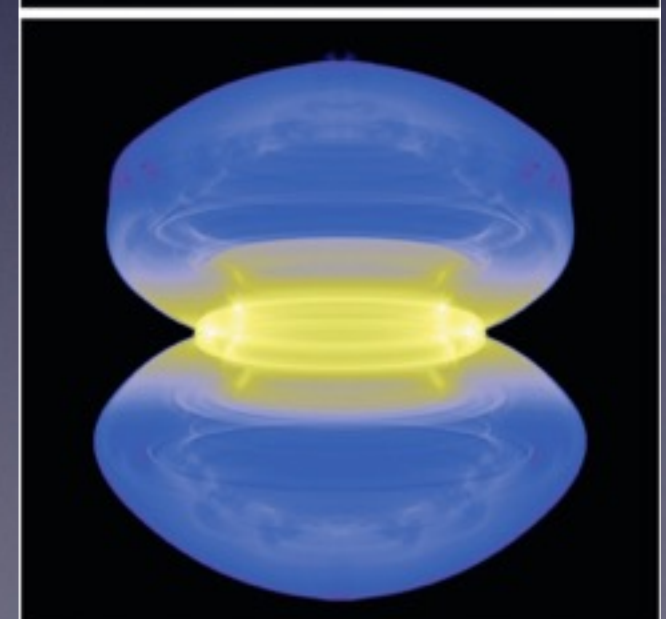
- Interacting with slow (10-20 km/s) wind, mass loss rate > 4 x 10^{-6} $M_\odot$ yr^{-1}
- Low-density cavity near SN prior to explosion
- ~~Subenergetic explosions~~, large distances (> 7 kpc) required



Patnaude+ 2012

- Interacting with slow (10-20 km/s) wind, mass loss rate > 4 x 10^{-6} $M_{\odot}$ yr^{-1}
- Low-density cavity near SN prior to explosion
- ~~Subenergetic explosions~~, large distances (> 7 kpc) required



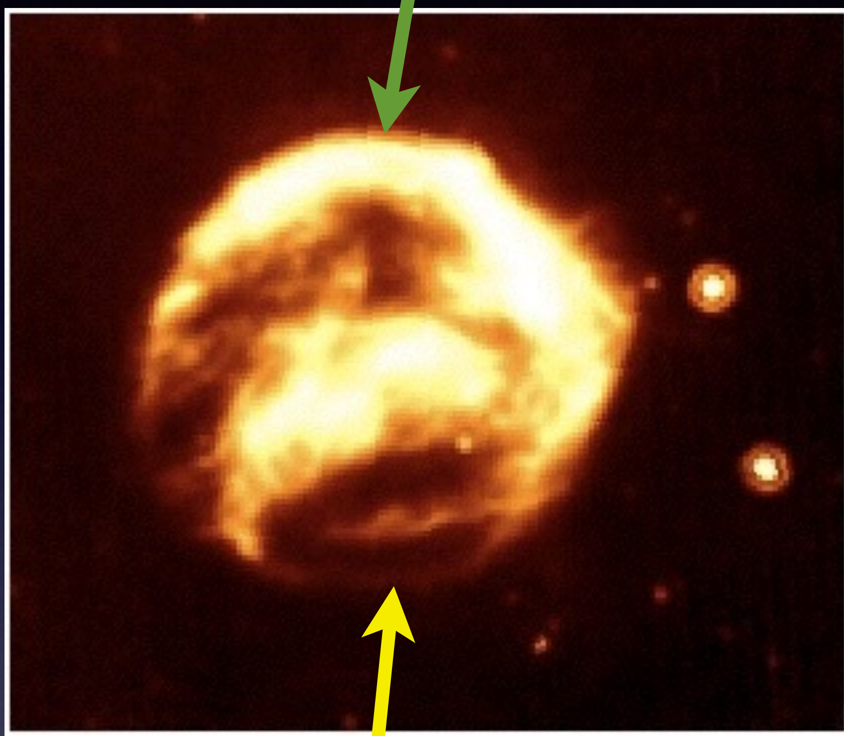


- Burkey+ 2013 confirm that Kepler is most consistent with SD scenario

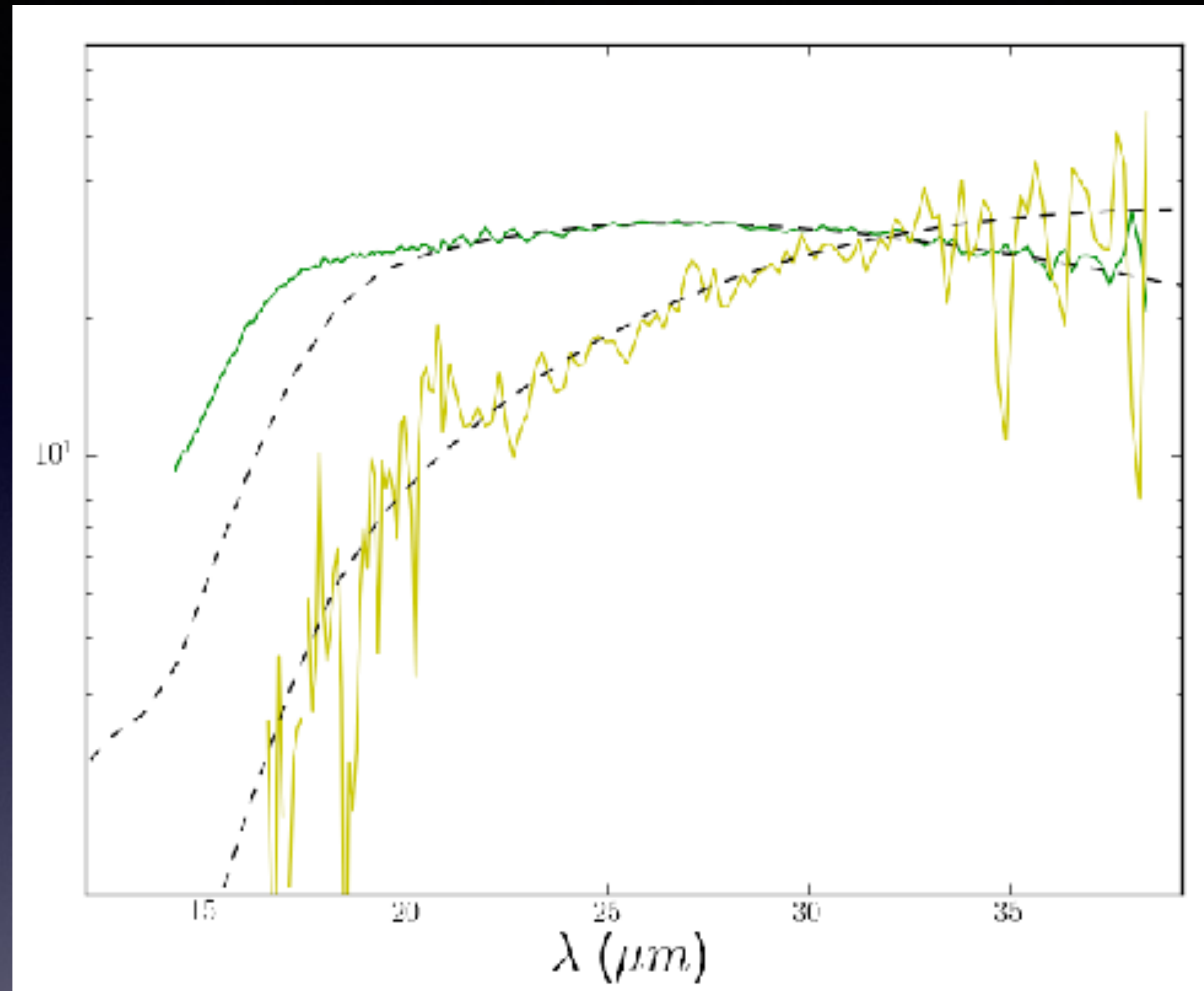
- Spatial morphology explained by dense equatorial wind

- North/south density gradient explained by system's movement in northward direction

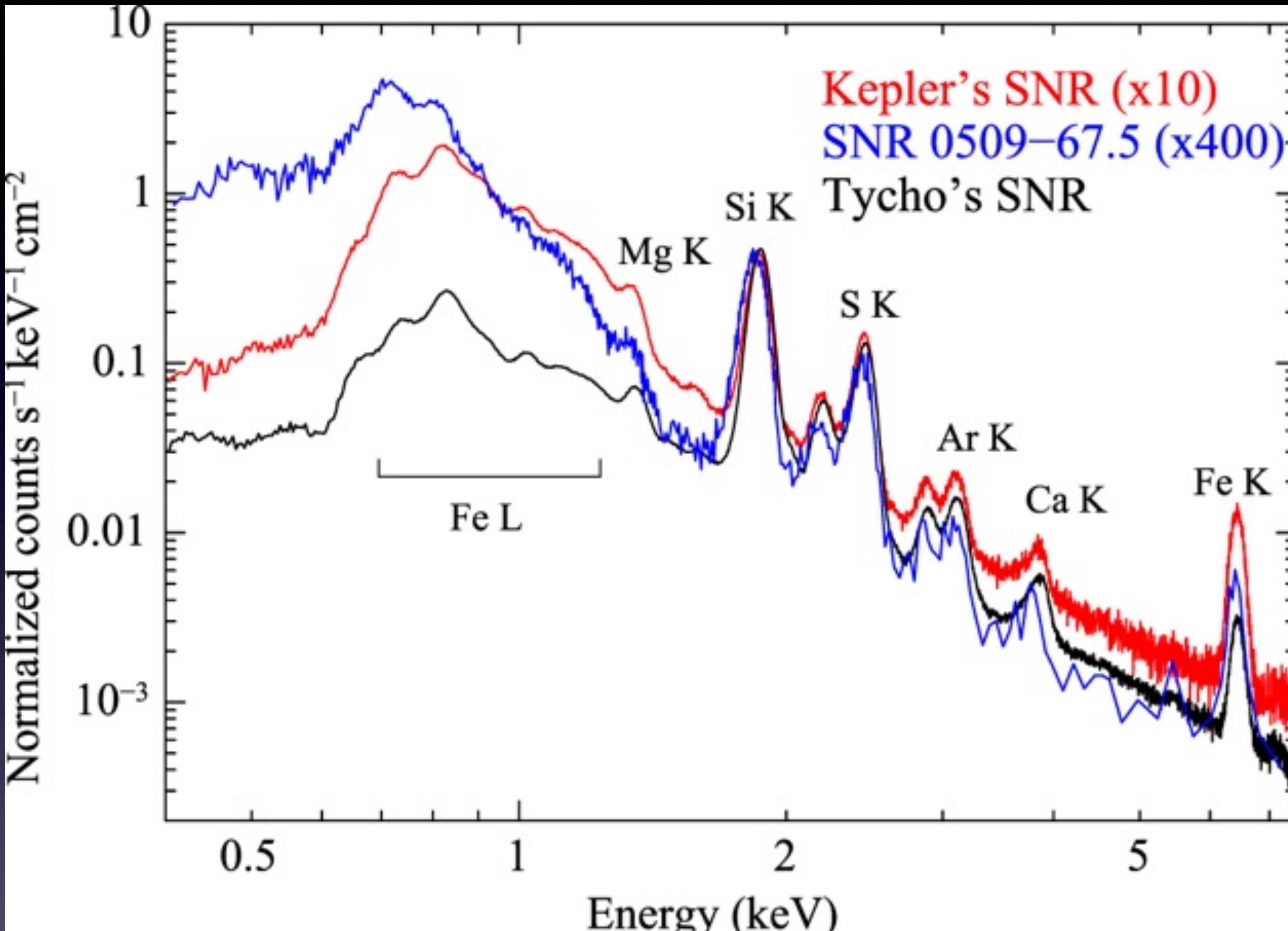
Green spectrum from north rim



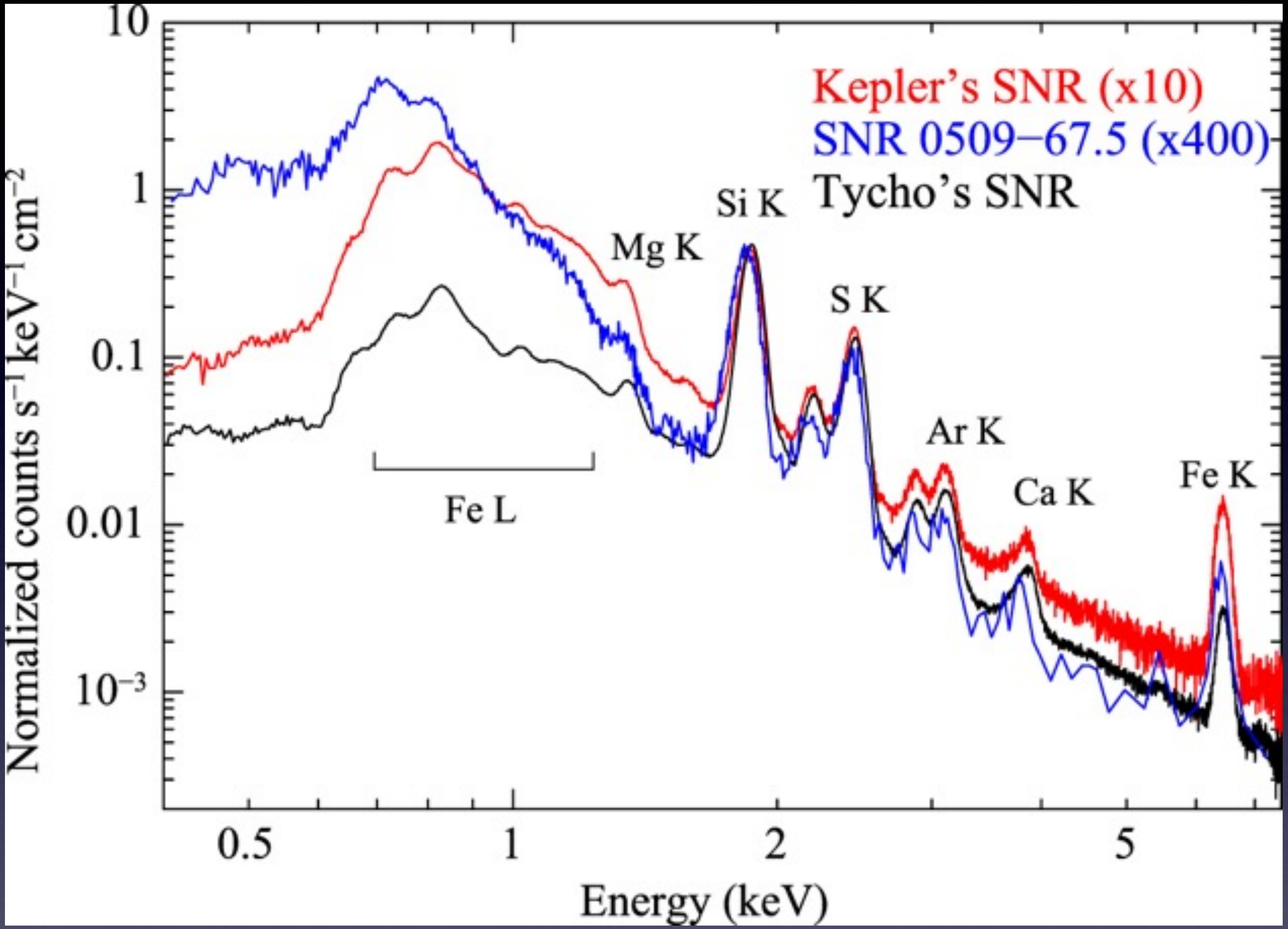
Yellow spectrum from south rim



Spectroscopic confirmation of much hotter dust in north than in south, density gradient required to produce this factor of 10-20 (Williams+ 2012)

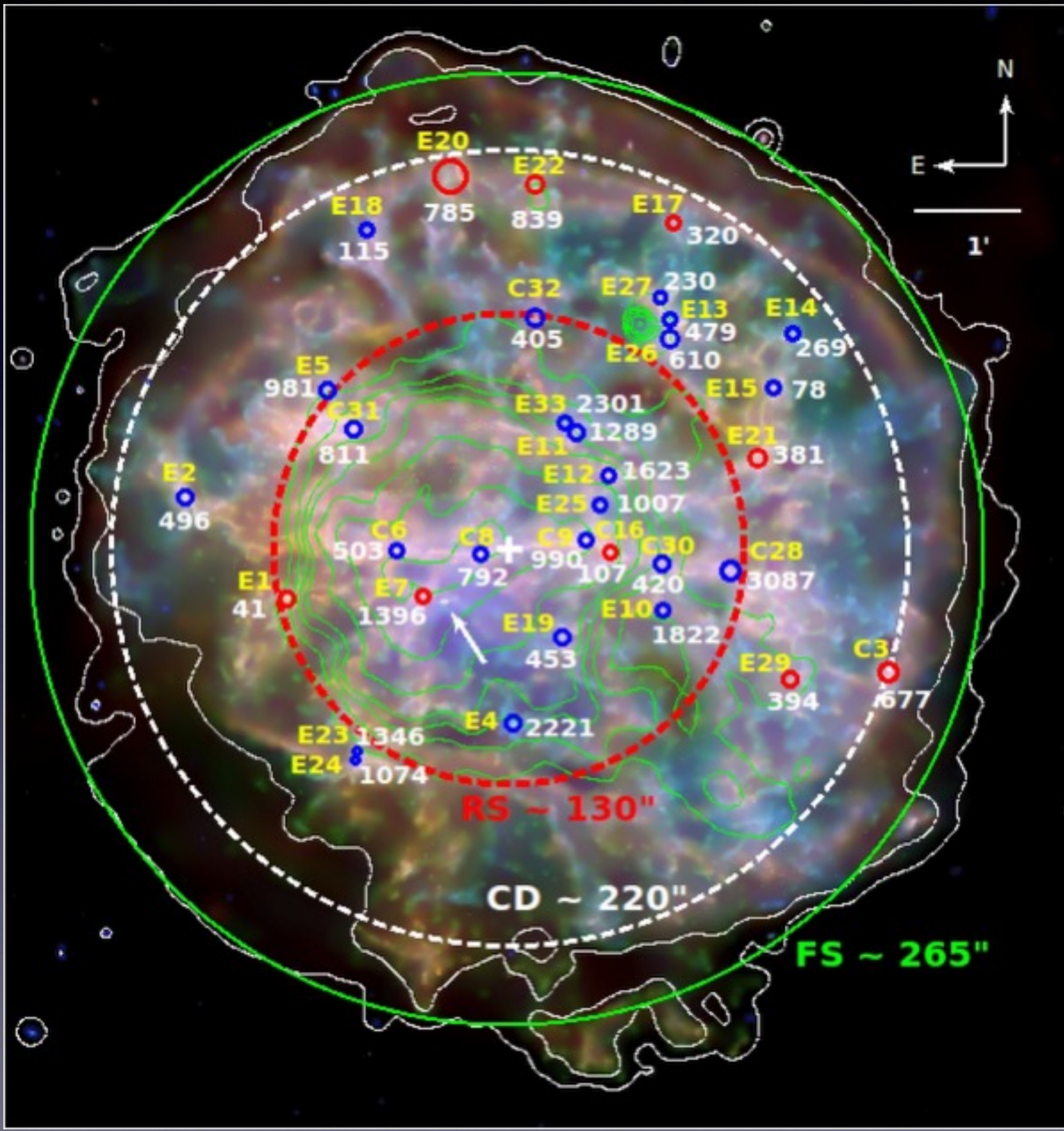


- **Katsuda et al. 2015 find that Kepler is "An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…," a 91T-like SN**



- Katsuda et al. 2015 find that Kepler is "An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…," a 91T-like SN

Is there a link between Kepler and "Ia-CSM" SNe?



G292.0+1.8

- Bhalerao et al. 2015 used Chandra HETG spectra of several dozen knots to measure the red/blueshift of lines and get radial velocities
- Ejecta knots vary from -2300 to +1400 km/s
- Dynamics limit ejecta mass to <8 $M_\odot$ and progenitor mass to <35 $M_\odot$

II. What can SNRs tell us about SN progenitors?

Stars

Supernovae

Supernova Remnants

II. What can SNRs tell us about SN progenitors?

Stars

?

Supernovae

?

Supernova Remnants

II. What can SNRs tell us about SN progenitors?

Conceptually easy…
but practically *impossible*!

Stars

?

Supernovae

?

Supernova Remnants

One approach… reverse the problem

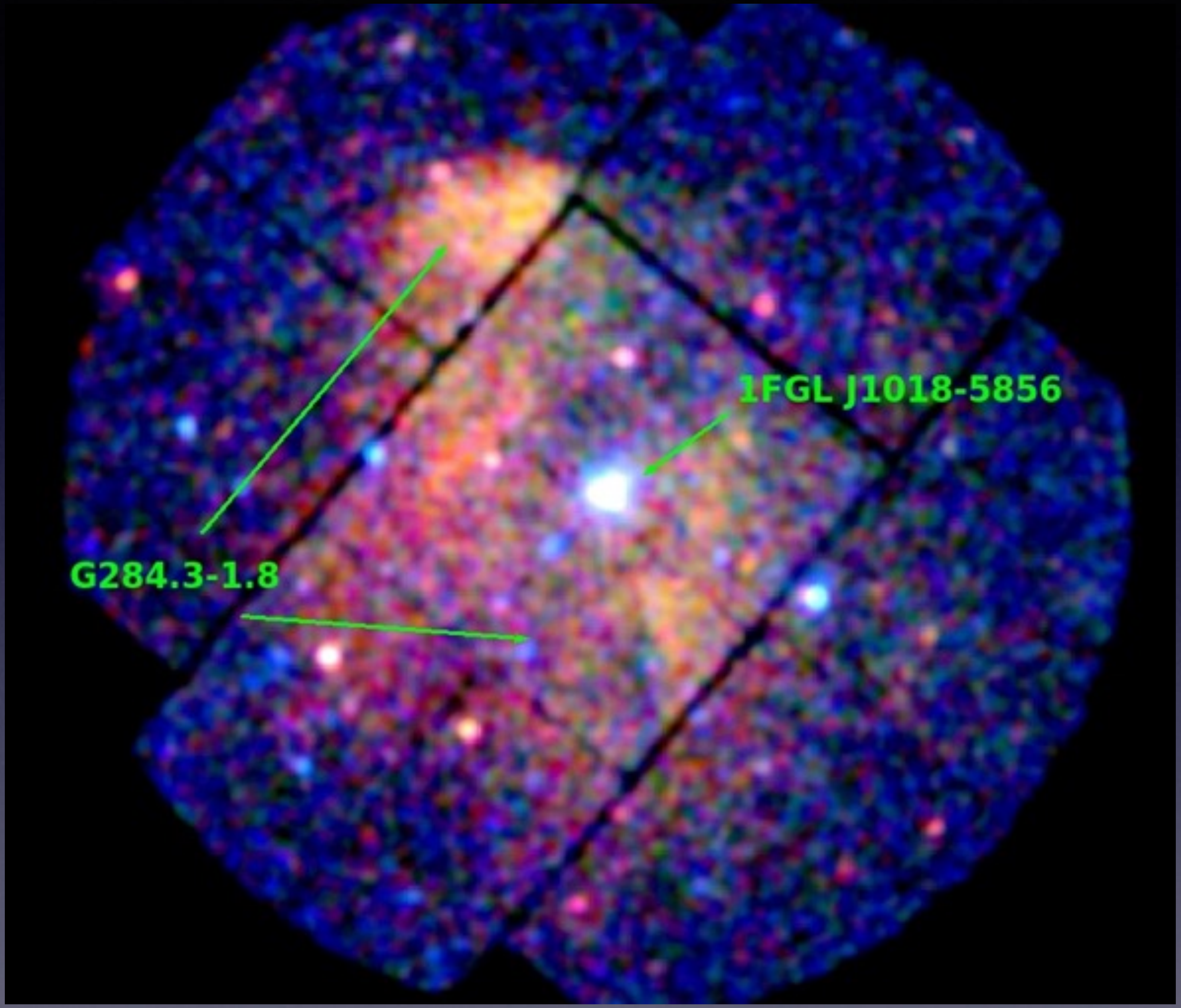
?

?

Solvable, though not easy

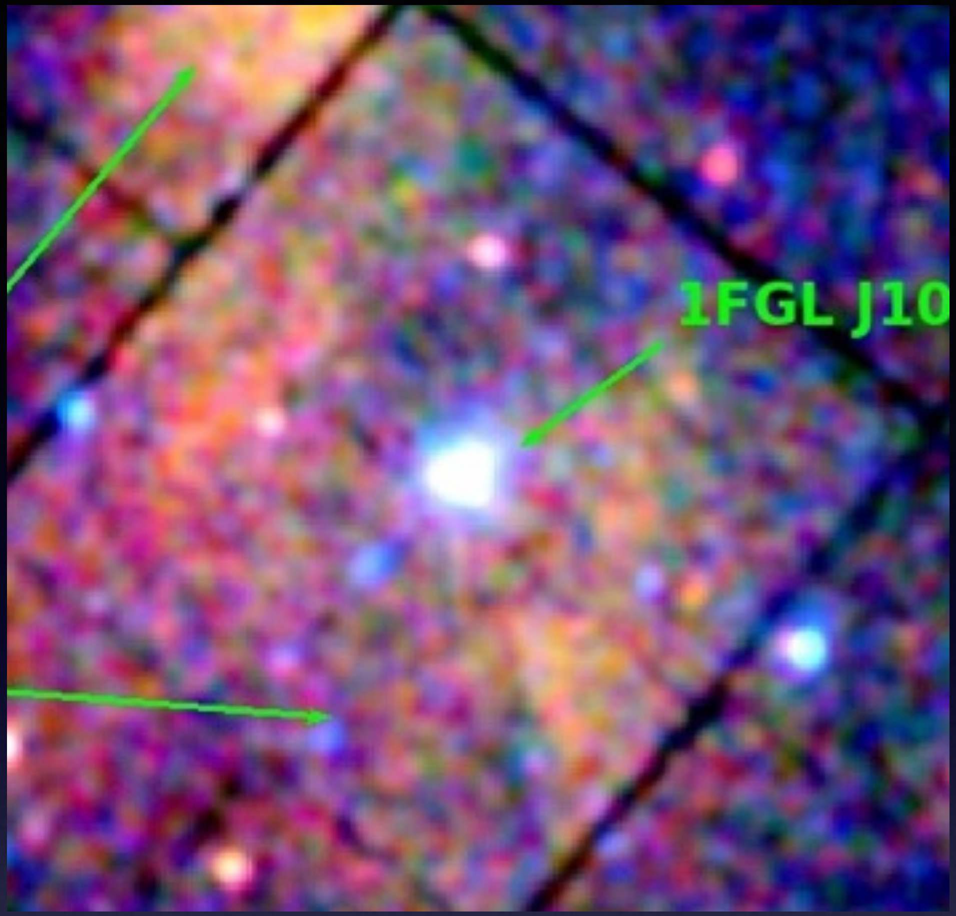
G284.3-1.8

See Williams et al. 2015



XMM-Newton image

1FGL J1018.6-5856

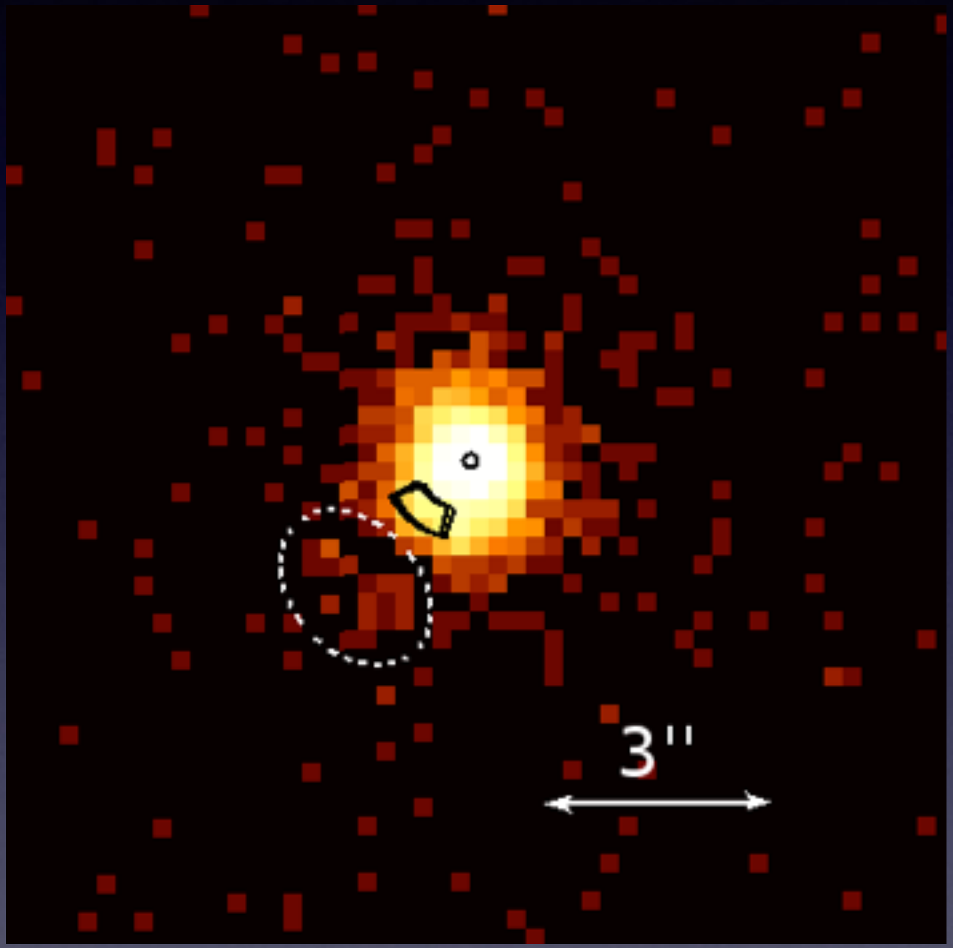


XMM

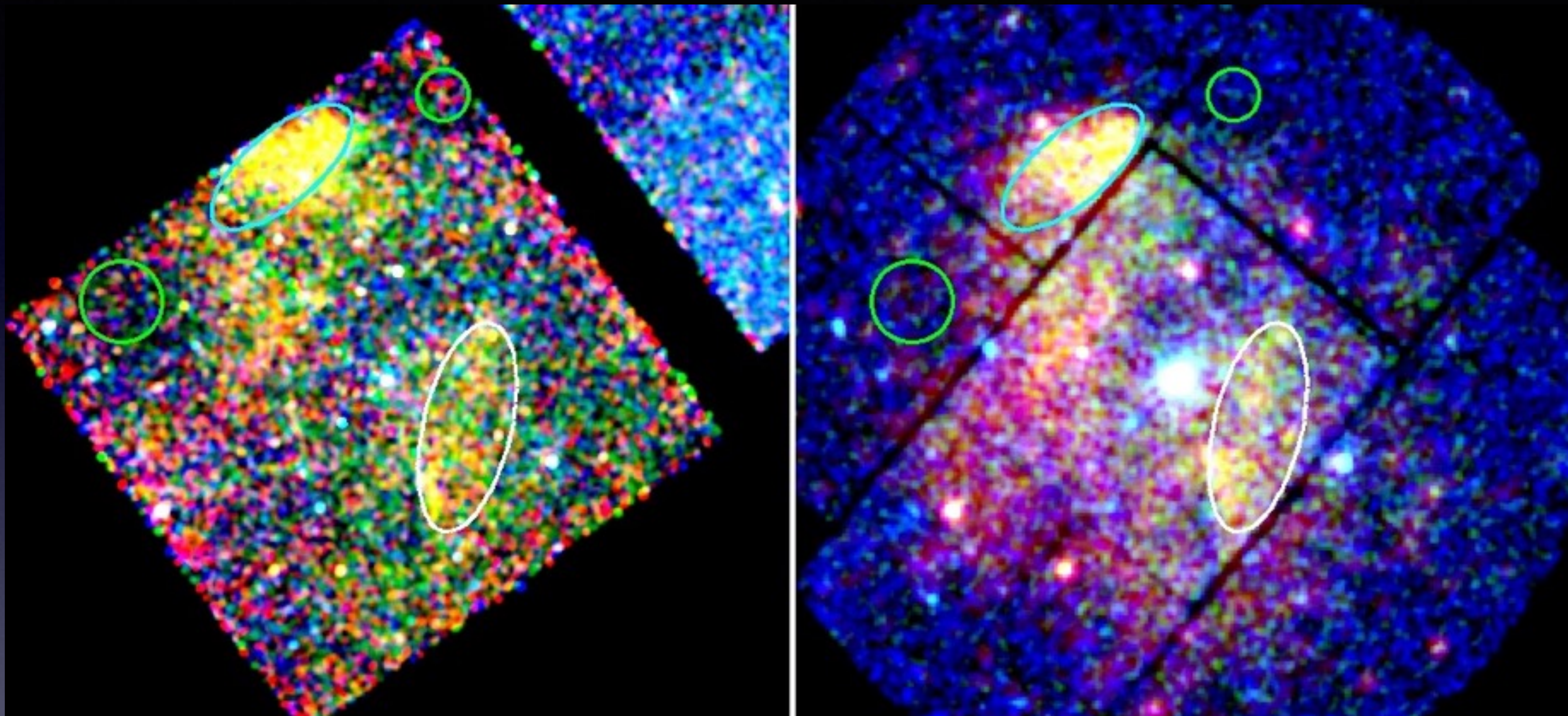
- It's a binary! 16.6d period confirmed in X-rays and ɣ-rays

- Optical counterpart identified: 30 $M_{\odot}$ O6V((f)) star

- One of only two high-mass ɣ-ray binaries inside an SNR (SS 433 in W50)



Chandra image, consistent with point source

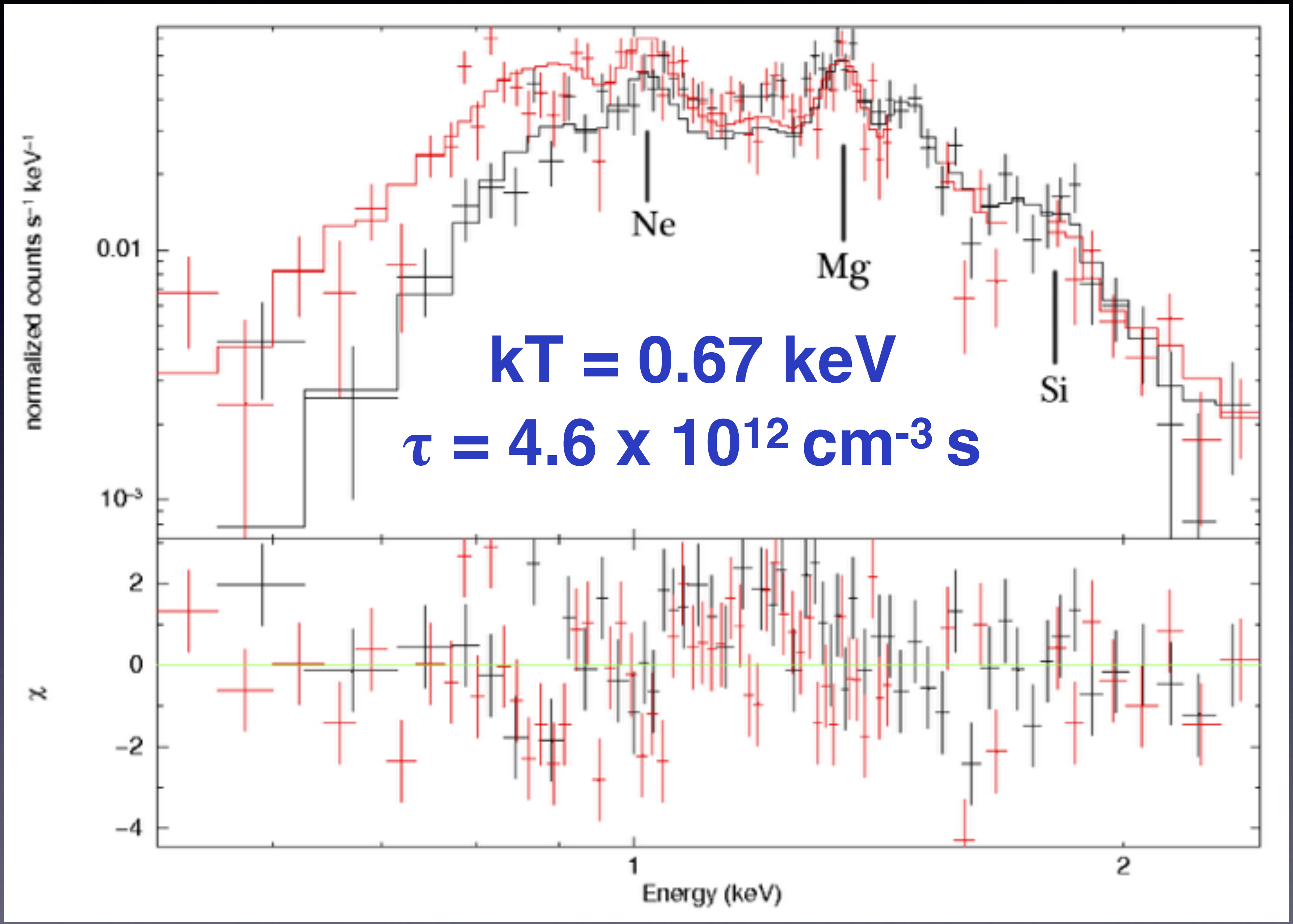


72 ks Chandra Obs. (ours)

105 ks XMM Obs. (PI: De Luca)

Selected two bright regions for analysis: North & West

North region spectrum



Chandra, XMM MOS 2

Model:
phabs x *vpshock*

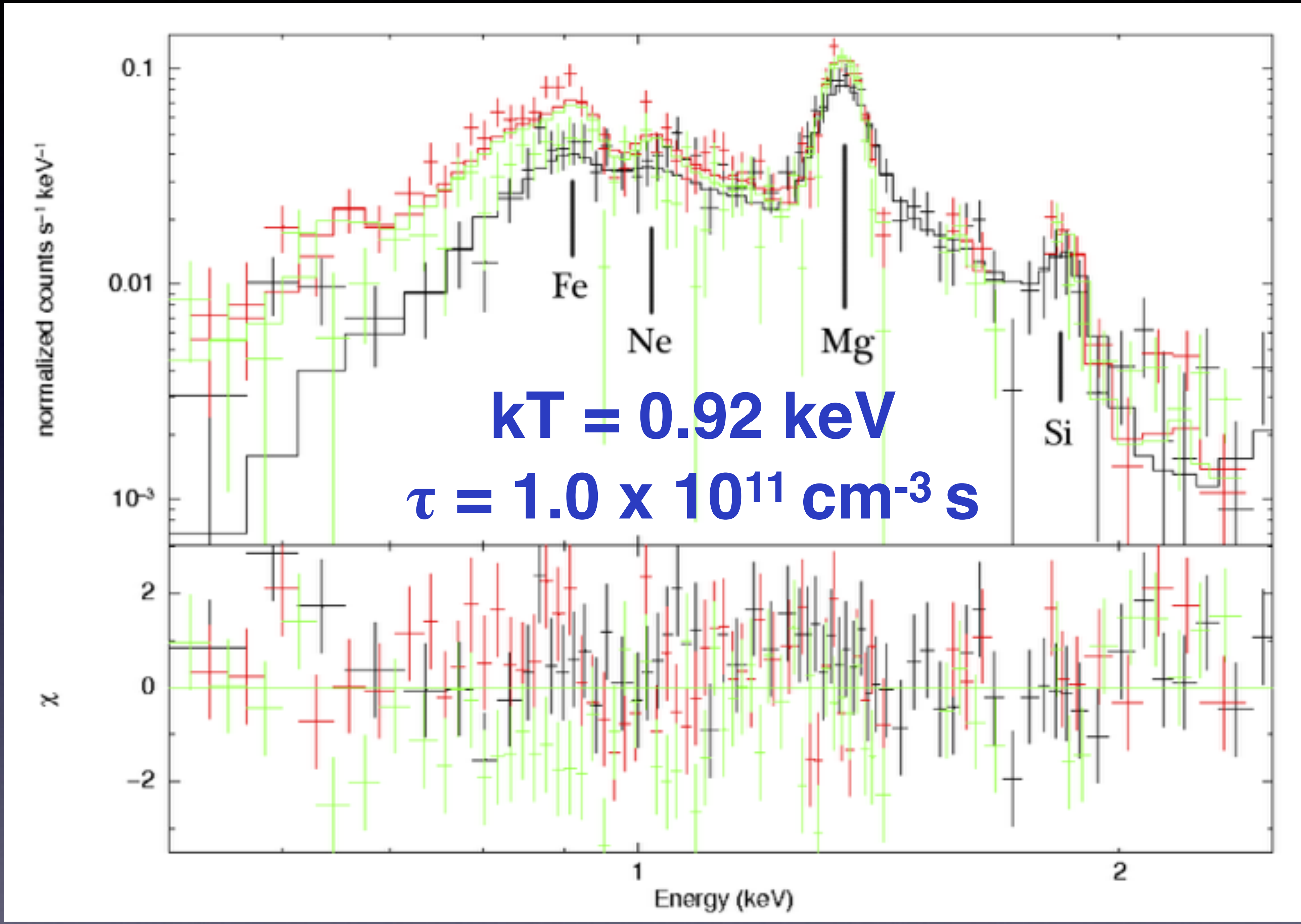
Abundances:

O ≡ 1
Ne = 1.19
Mg = 1.06
Si = 0.19
Fe = 0.24

West region spectrum

Abundances:

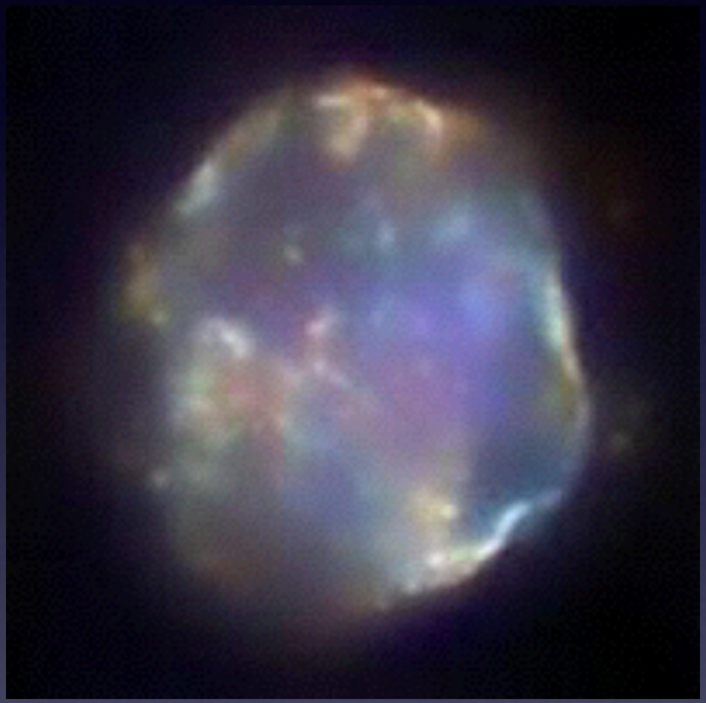
O ≡ 1
Ne = 1.30
Mg = 4.53
Si = 1.50
Fe = 0.97



Chandra, XMM MOS 1, XMM MOS 2

West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta

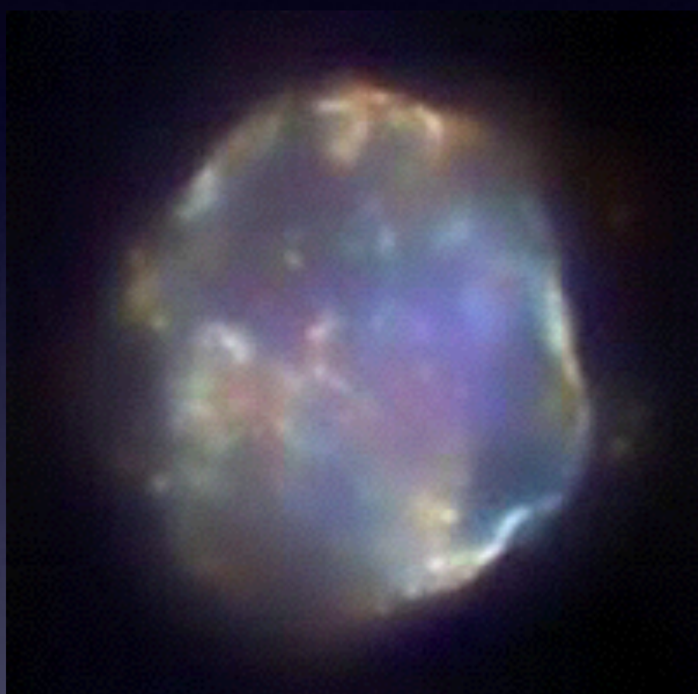
Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 $M_\odot$) (Thielemann+ 1996)



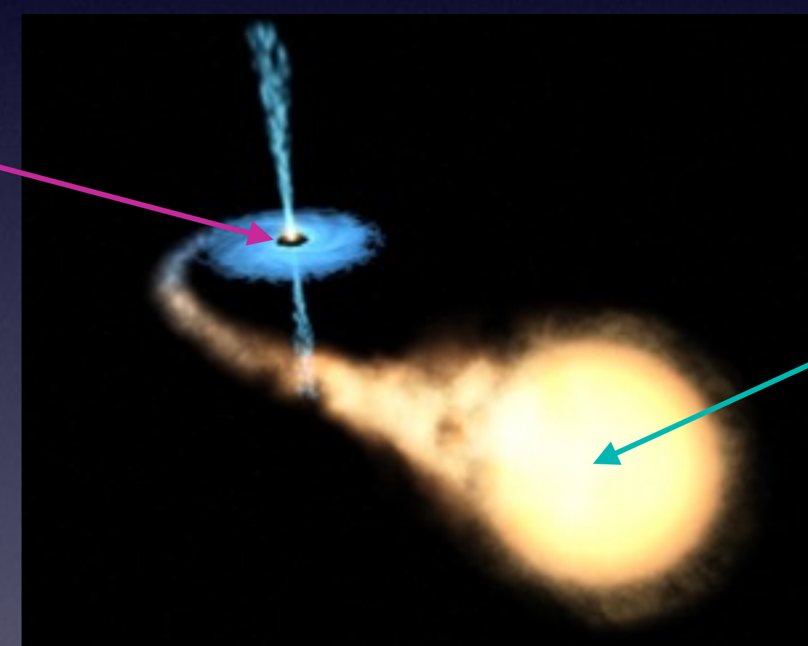
SNR N49B

West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta

Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 $M_\odot$) (Thielemann+ 1996)

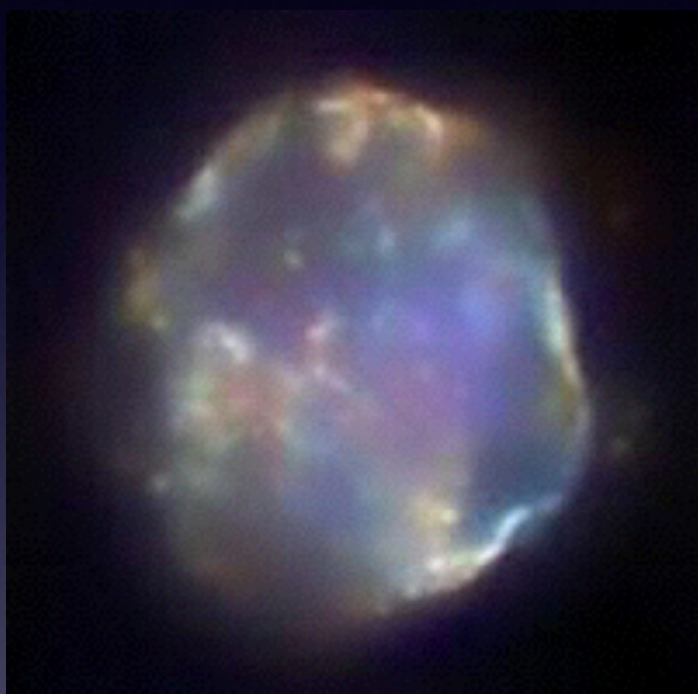


SNR N49B



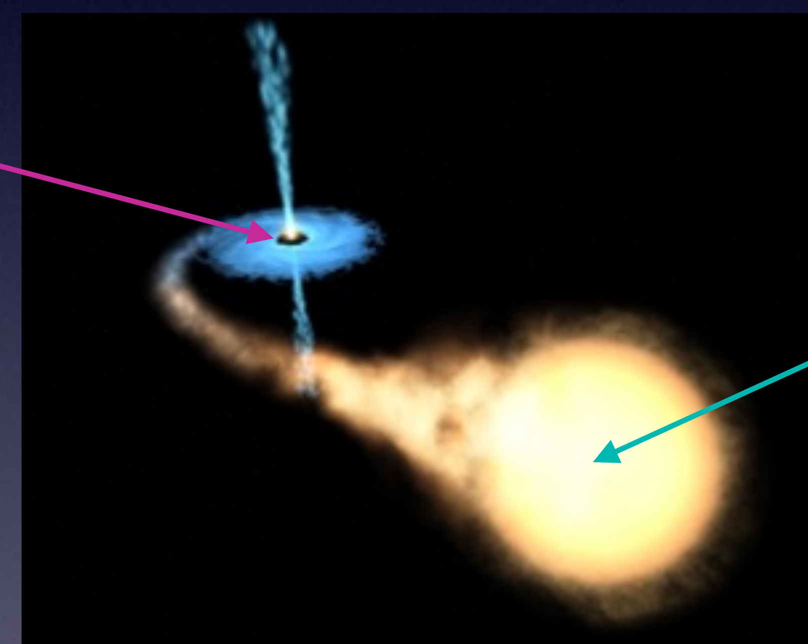
West region rich in Mg, spectra and abundances similar to N49B in LMC (Park et al. 2003), another SNR with Mg-rich ejecta

Nucleosynthesis models produce significant amounts of Mg in explosions of massive (> 25 $M_\odot$) (Thielemann+ 1996)



SNR N49B

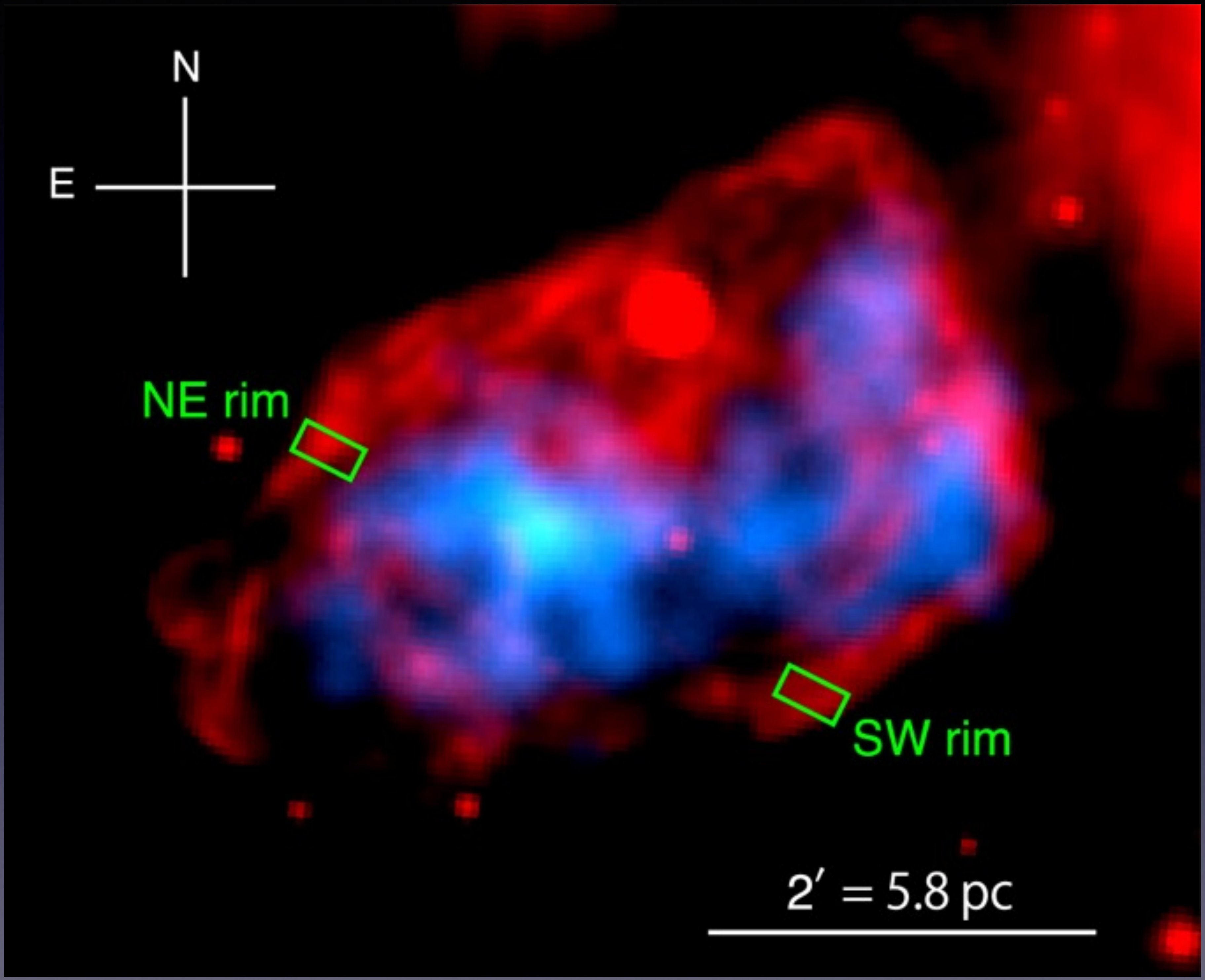
Star 2



Star 1

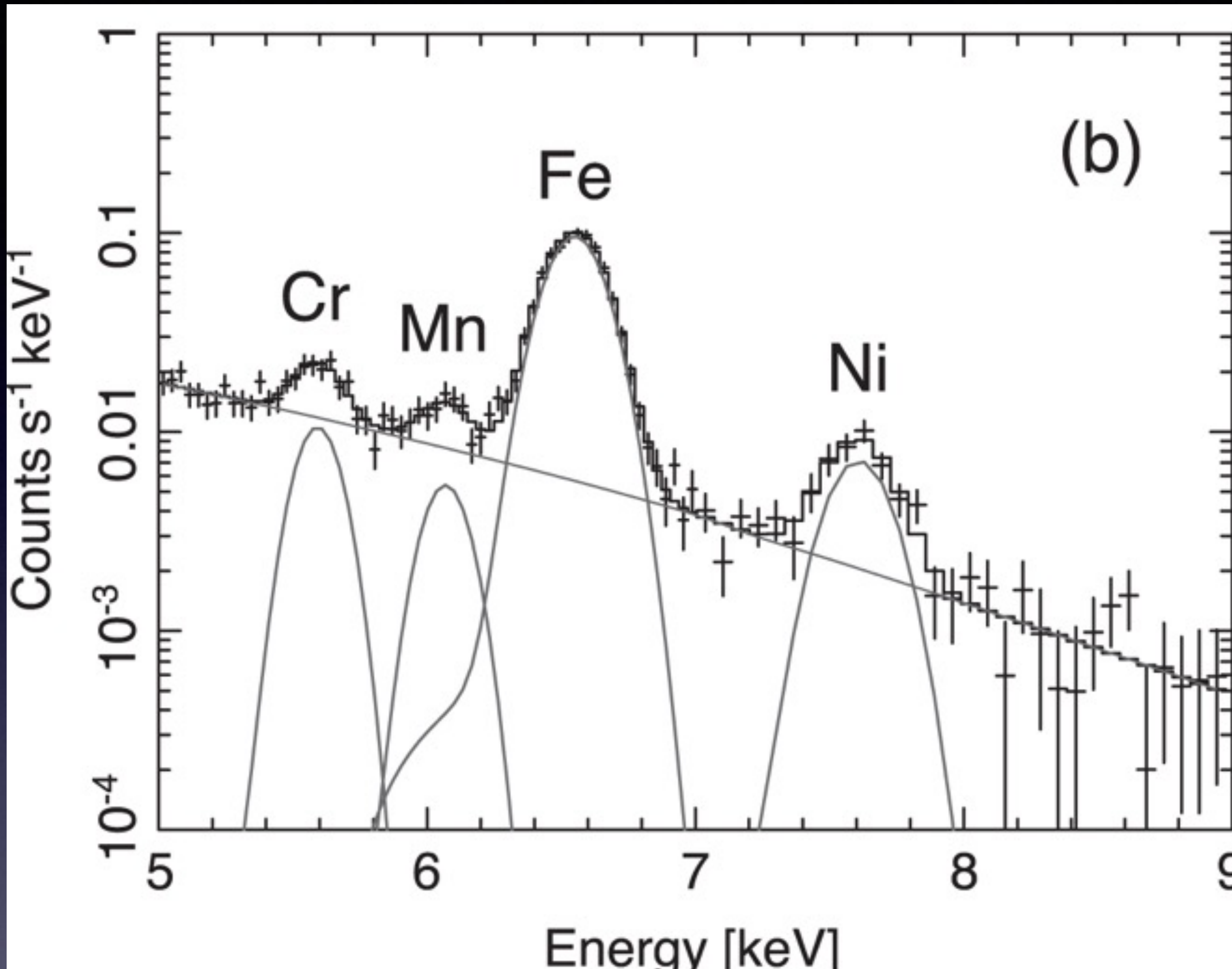
To reproduce observed properties, best fit binary evolution models have Star 2 with 27 $M_\odot$ initial mass

3C 397

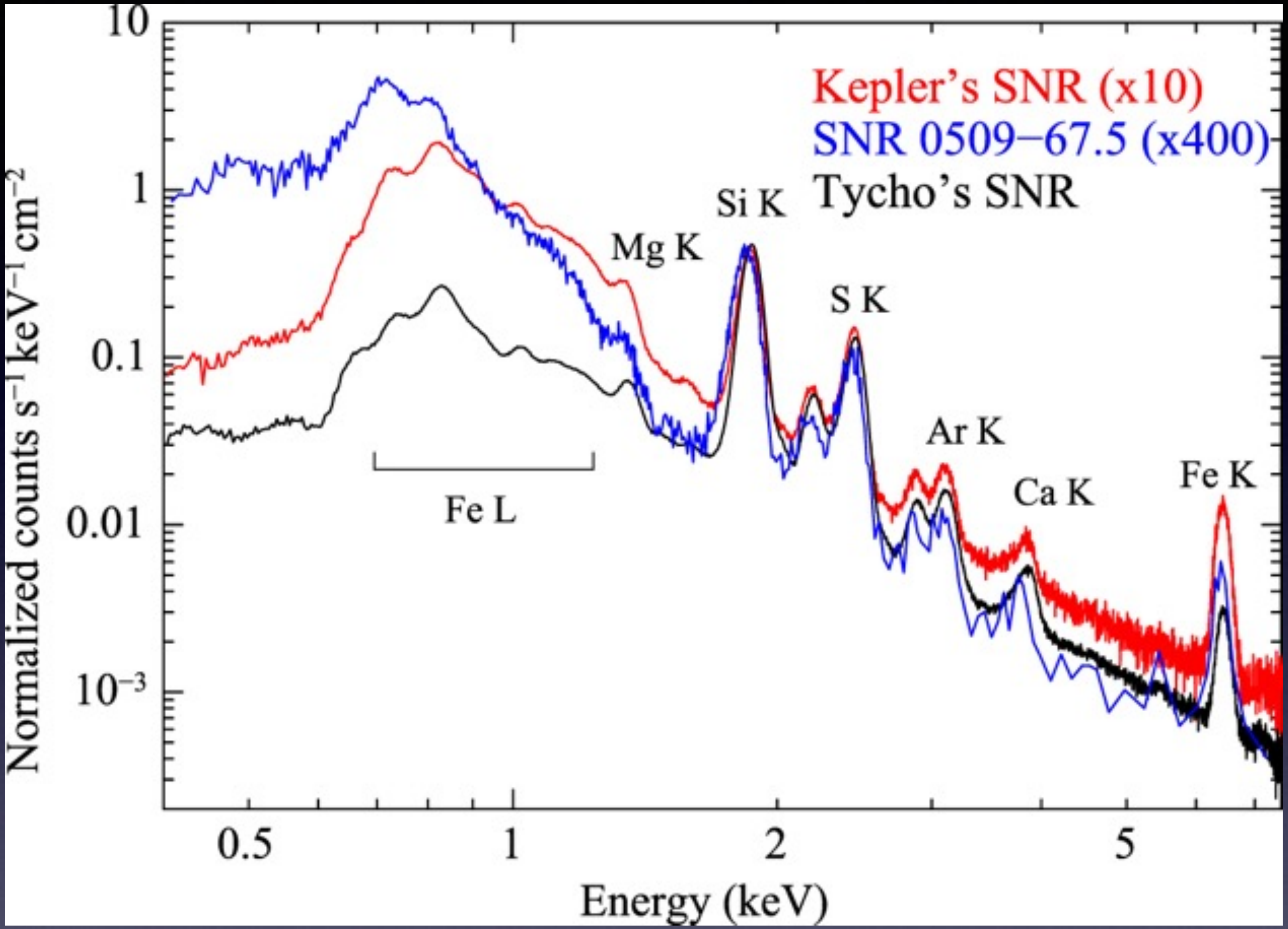


Yamaguchi et al. 2015

Spitzer (IR) & Suzaku (X-ray)



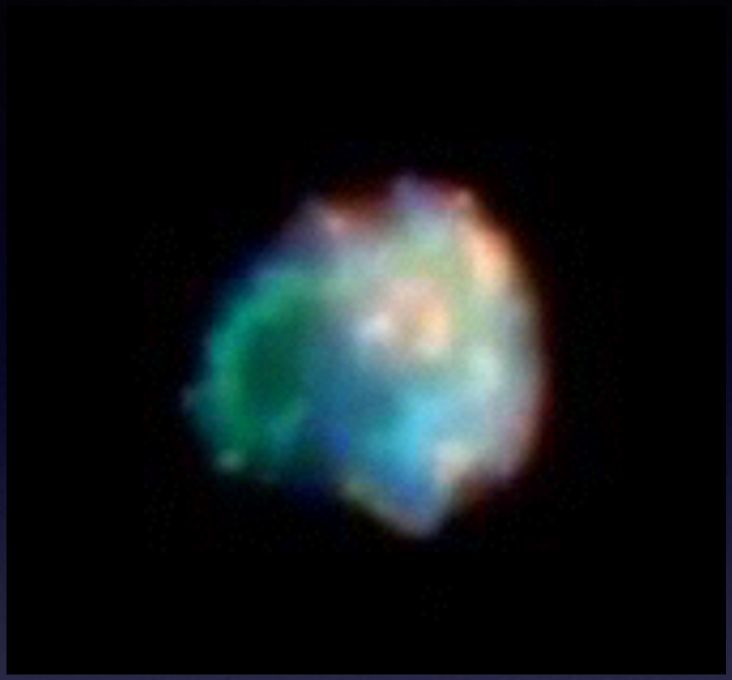
High Mn/Fe and Ni/Fe ratios imply high density in the WD core… which implies near Chandrasekhar mass WD… which implies single-degenerate progenitor



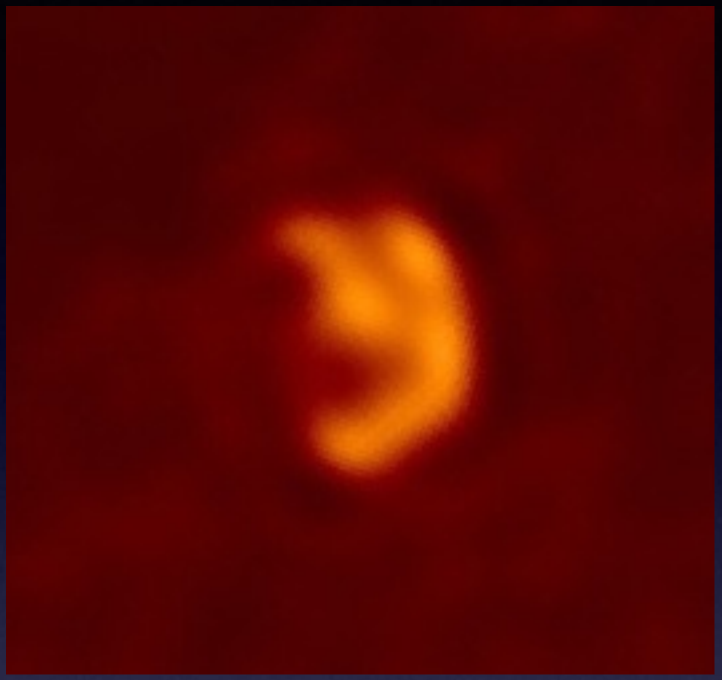
- Katsuda et al. 2015 find that Kepler is "An Overluminous Type Ia Event Interacting with a Massive Circumstellar Medium…," a 91T-like SN

Is there a link between Kepler and "Ia-CSM" SNe?

N103B (0509-68.7)

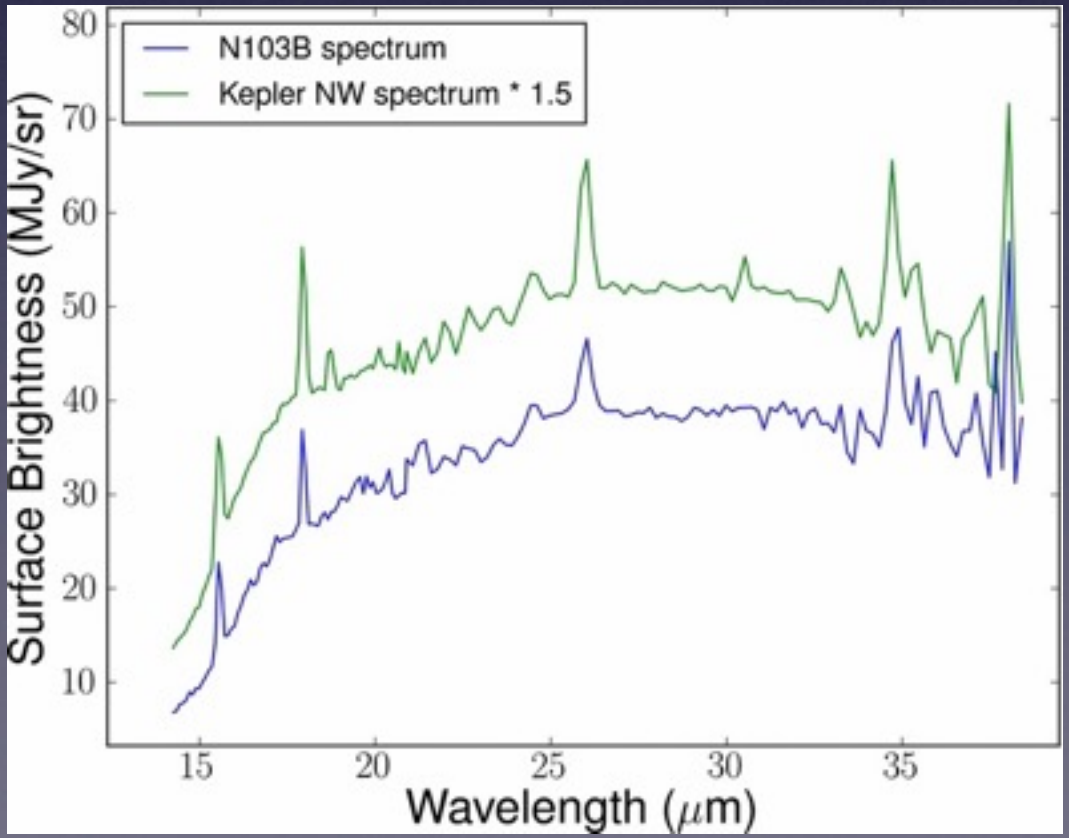


Chandra

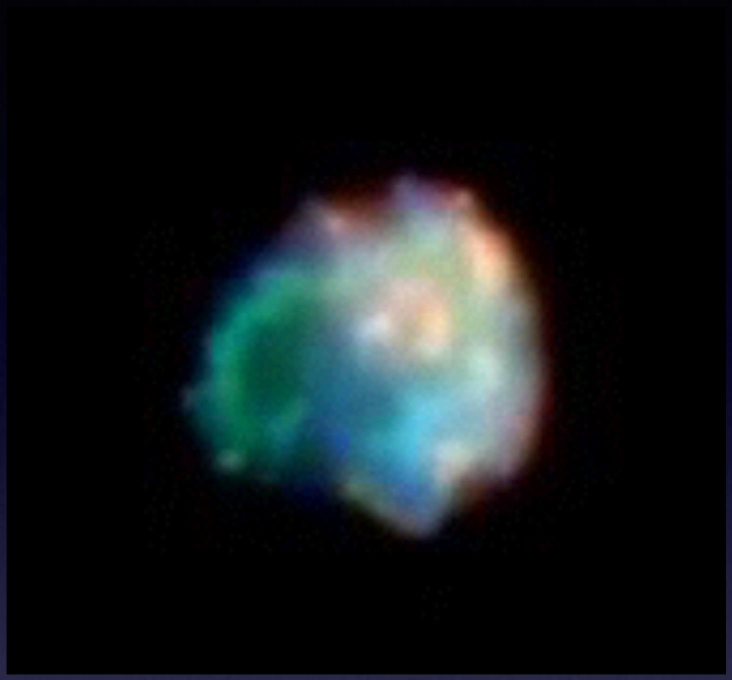


Spitzer

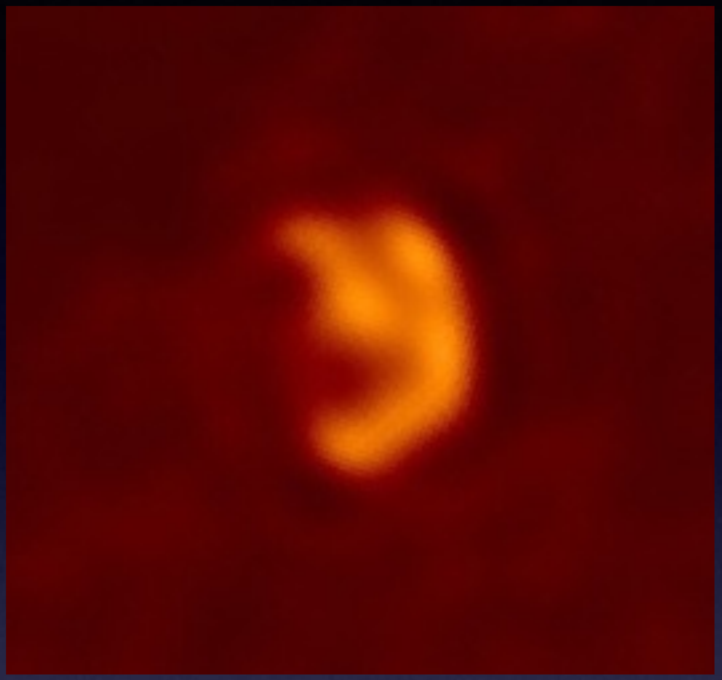
N103B appears to be ***second*** member of class of Type Ia SNRs with dense CSM, long after explosion (BJW+ 2014)



N103B (0509-68.7)

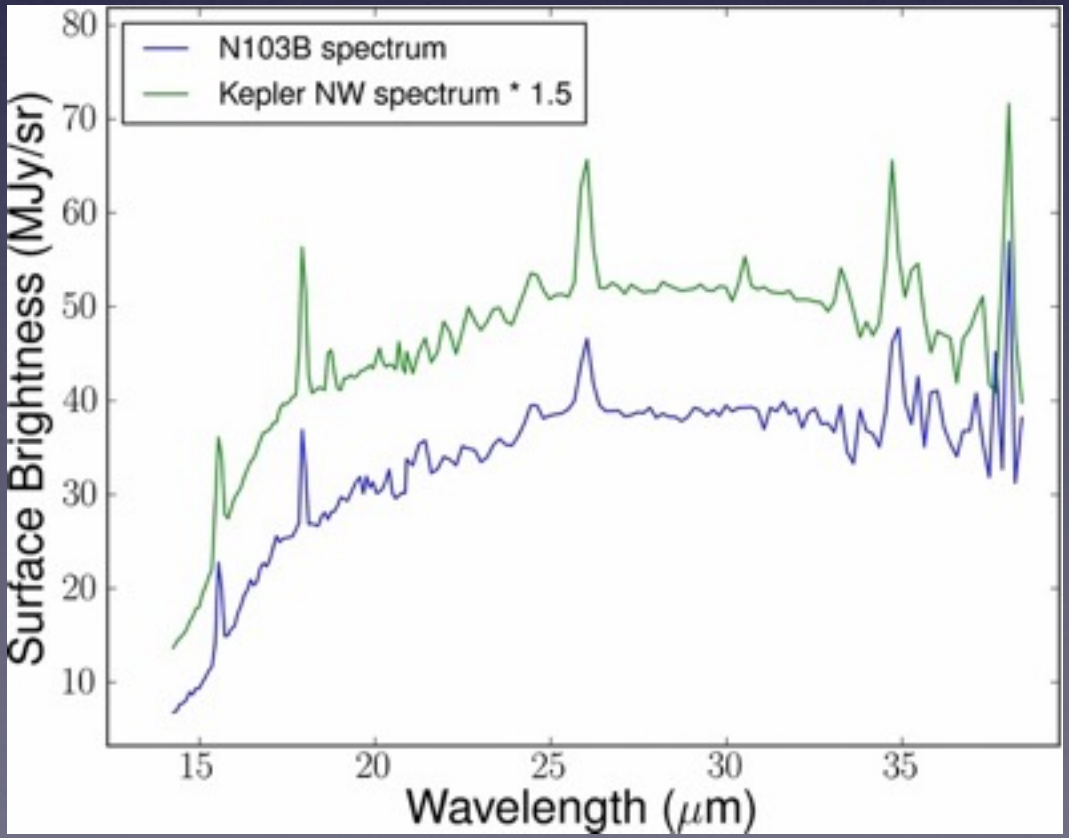


Chandra



Spitzer

N103B appears to be ***second*** member of class of Type Ia SNRs with dense CSM, long after explosion (BJW+ 2014)



Stay tuned… approved for 400 ks with Chandra, plus 5 orbits HST