Expansion Measurements of Young Type Ia SNRs and the Physics of Nonradiative Shocks

Supernova Remnants: An Odyssey in Space after Stellar Death, Chania, 2016

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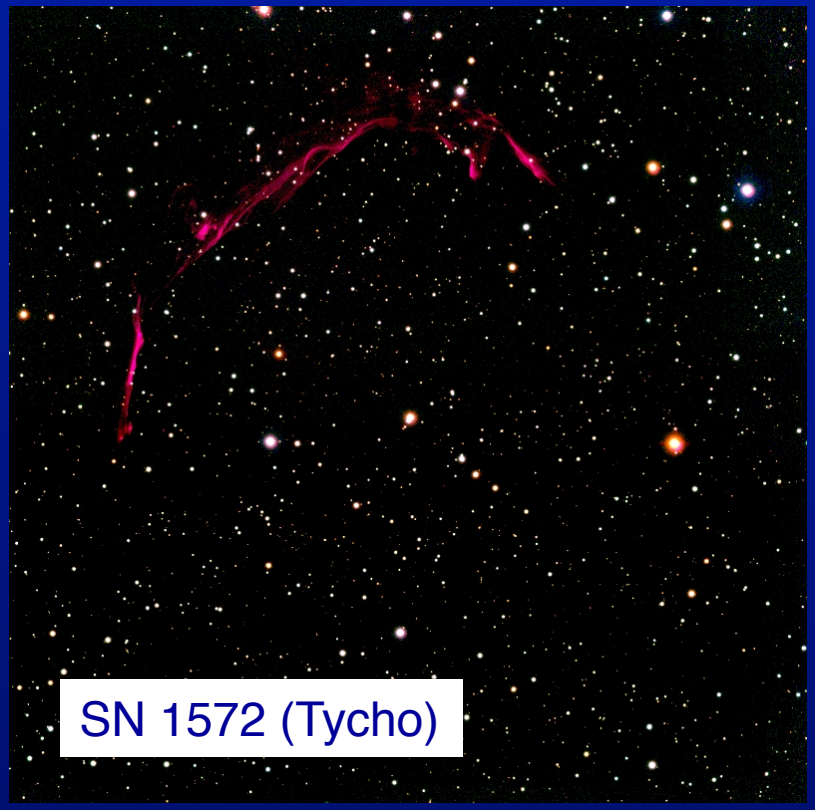
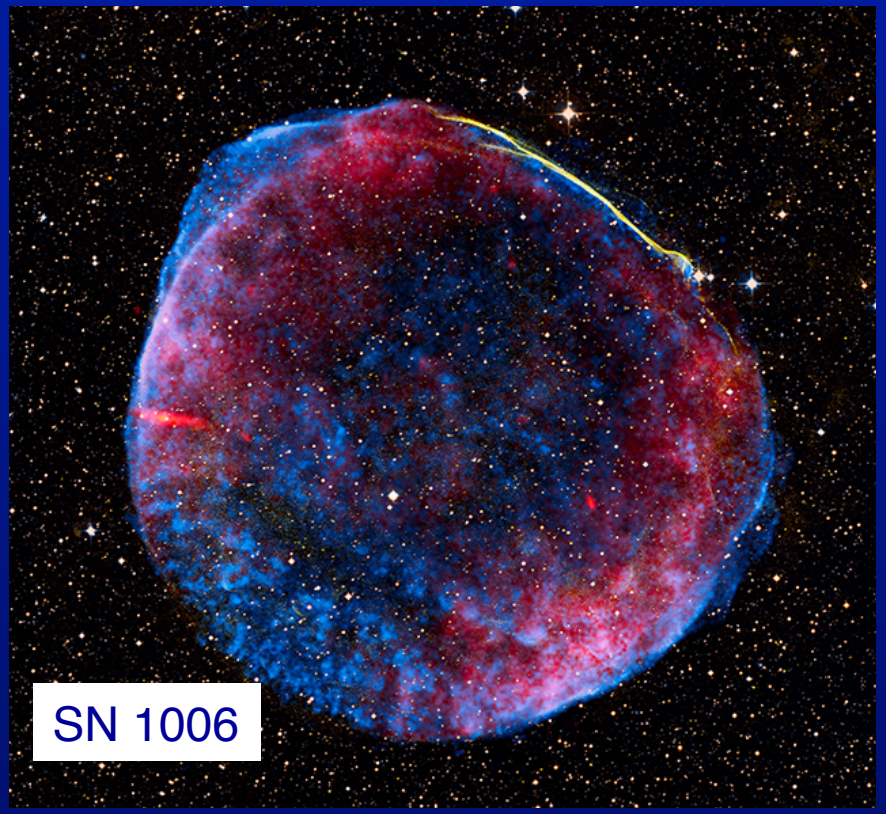
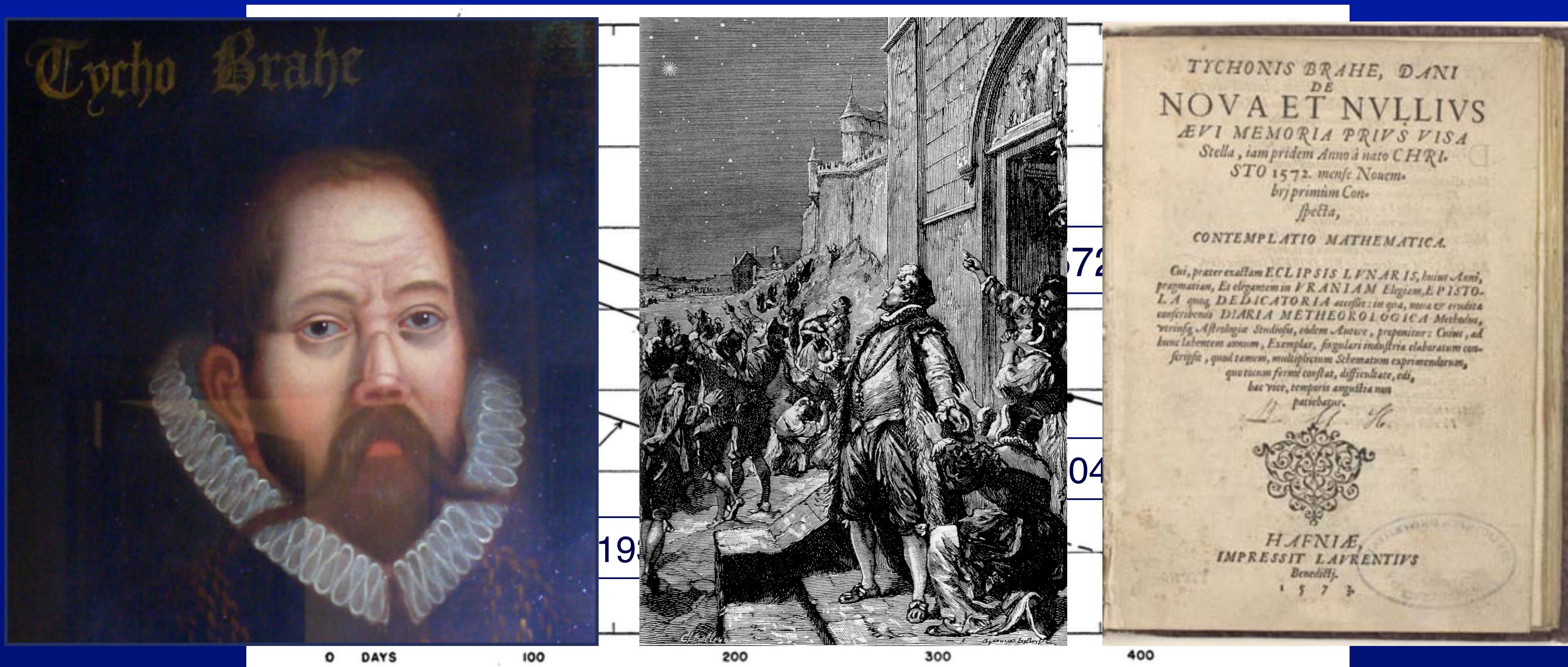
Focus on Optical Measurements of two Historical SNRs





- Both spectacularly bright at outburst
- Both were Type Ia explosions
- Optical emission from both is very faint today; seen only in Balmer lines of H — “Nonradiative shocks” / “Balmer-dominated” SNRs

SN 1572 = Tycho's Supernova

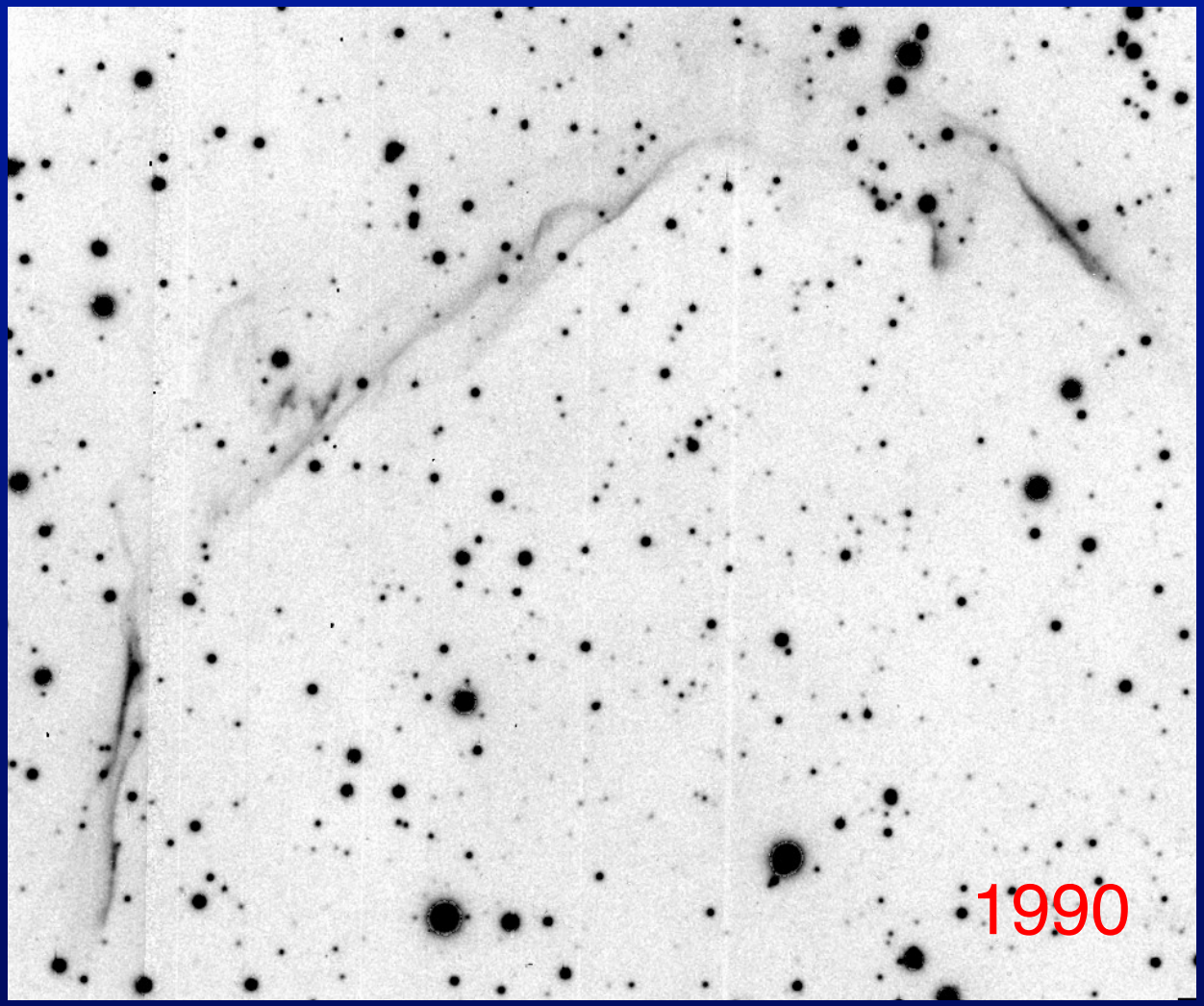


- Appeared ~6 Nov 1572, "equaled Venus at its maximum brightness" / Light curve from Tycho and others is classic SN Ia (Baade 1945)
- Visible to the naked eye until March 1574 / Light echo (discovery Rest+ 2008; spectrum Krause+ 2008) definitively show SN1572 was a Type Ia

Optical Proper Motions in Tycho

CCD Images at 7 epochs: 1986 - 2009

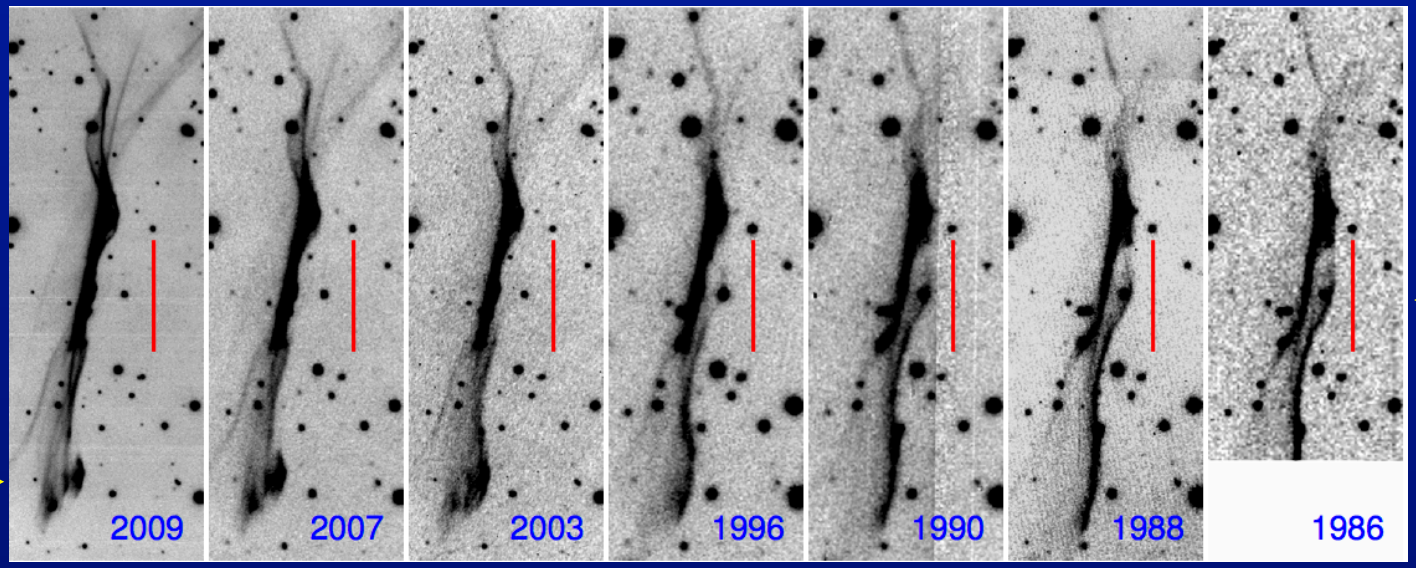
Previous Measurement: Kamper & van den Bergh 1978 (from 5m plates)



Optical Proper Motions in Tycho

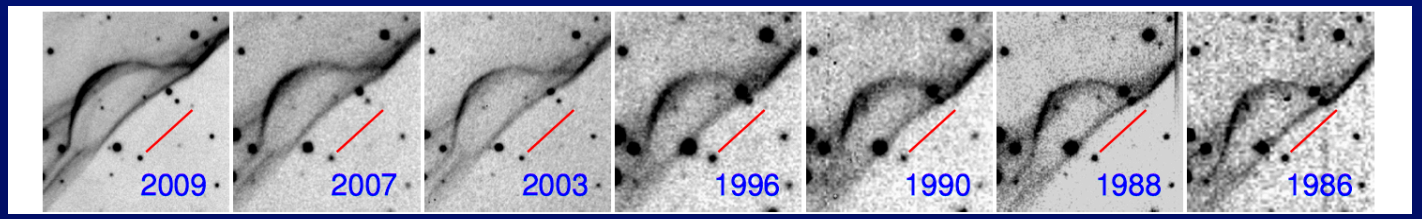
- Not all filaments move continuously
- For proper-motion measurements, we selected only those with coherent motion

One is left behind; another appears here →



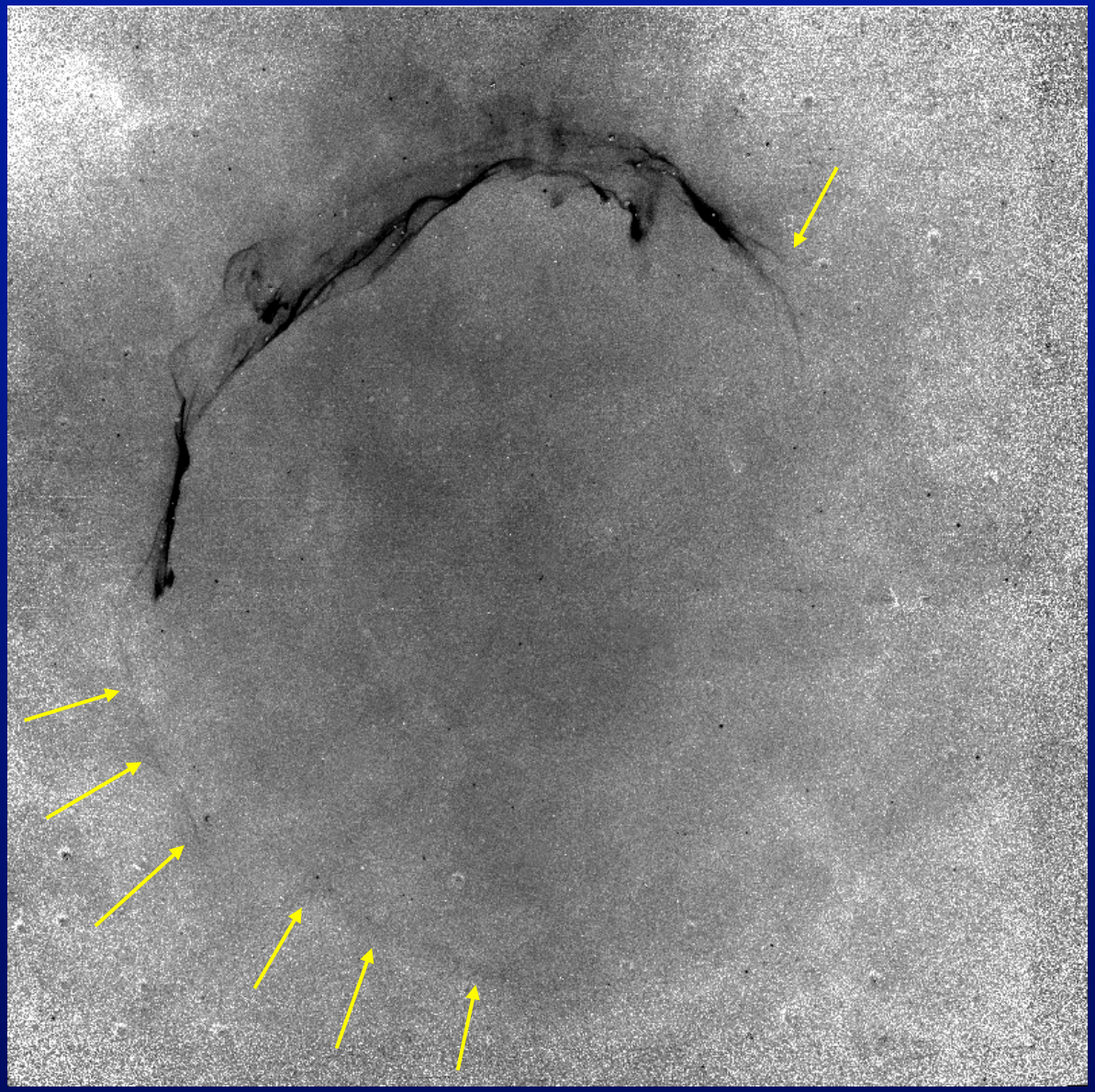
← A filament here disappears

Tycho's brightest filament (including "knot g") on E rim

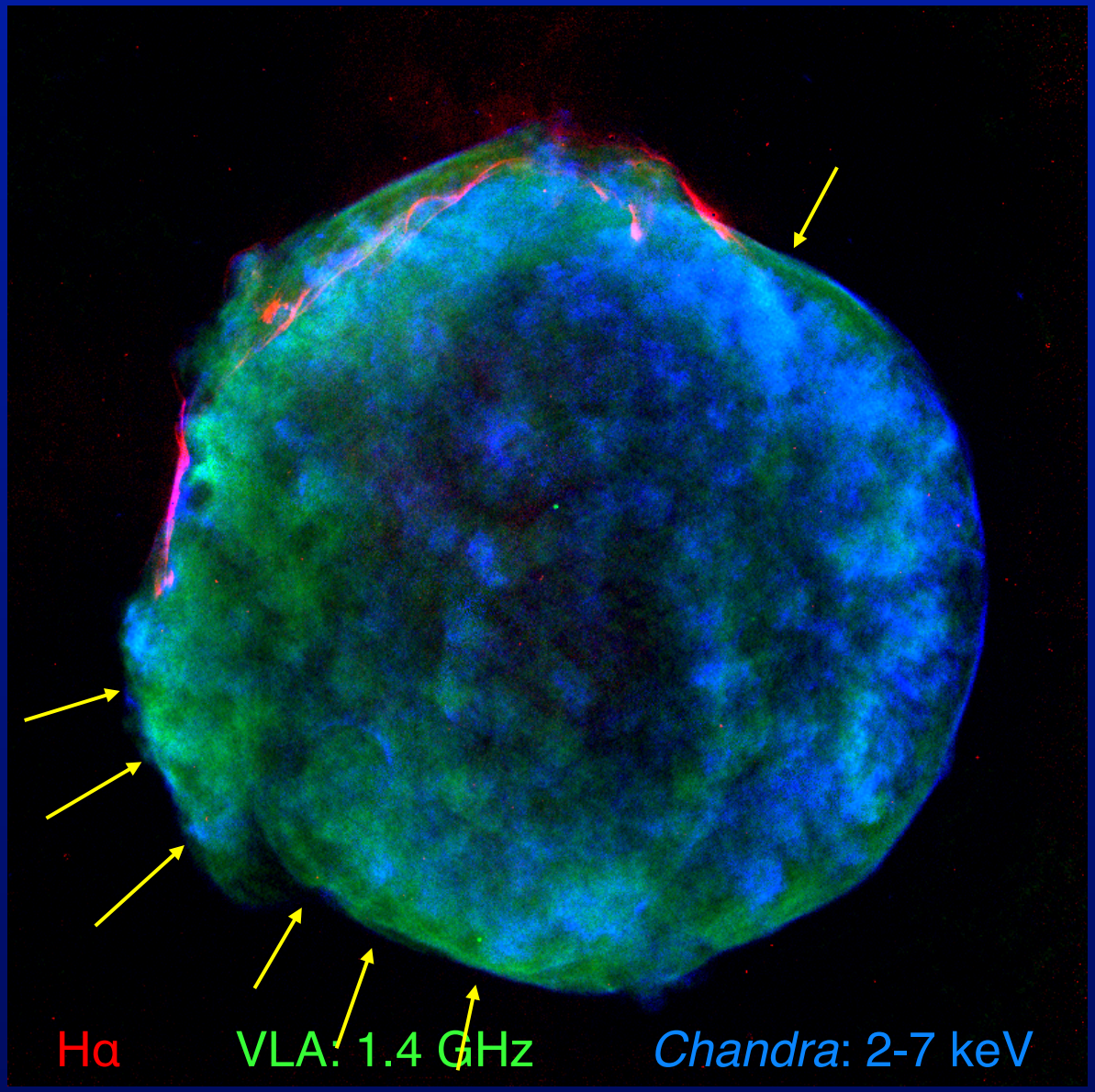


Coherently moving filaments in the NE

Optical Proper Motions in Tycho II: *Faint* Filaments



Optical Proper Motions in Tycho II: *Faint* rim filaments



Hα image: WIYN 2009

VLA image: 1994, extrapolated to 2009 (Reynoso+ 1997)

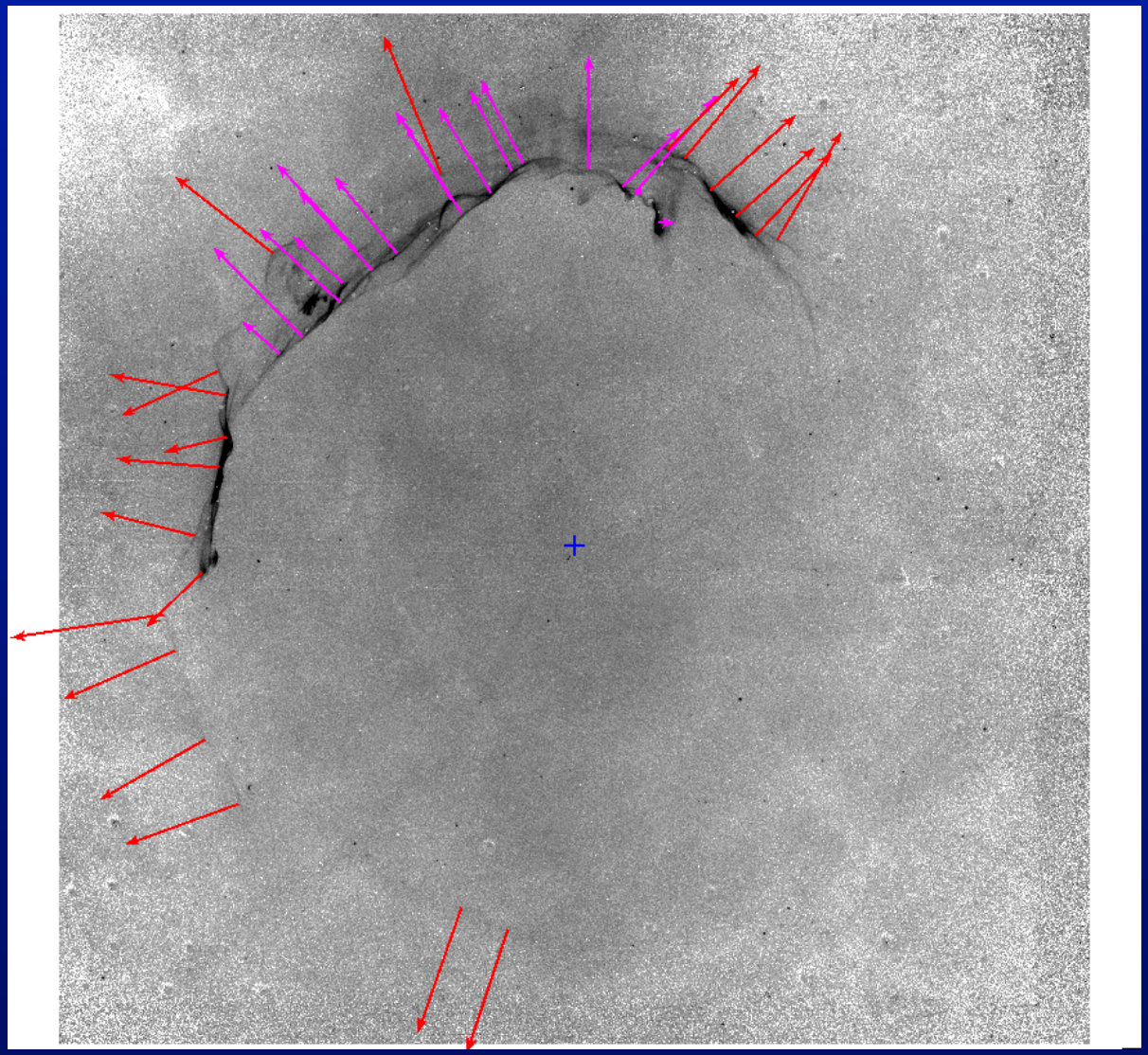
Chandra image 2009 (Eriksen+ 2013)

*(*newer images: Williams+ 2016)

Optical Proper Motions in Tycho

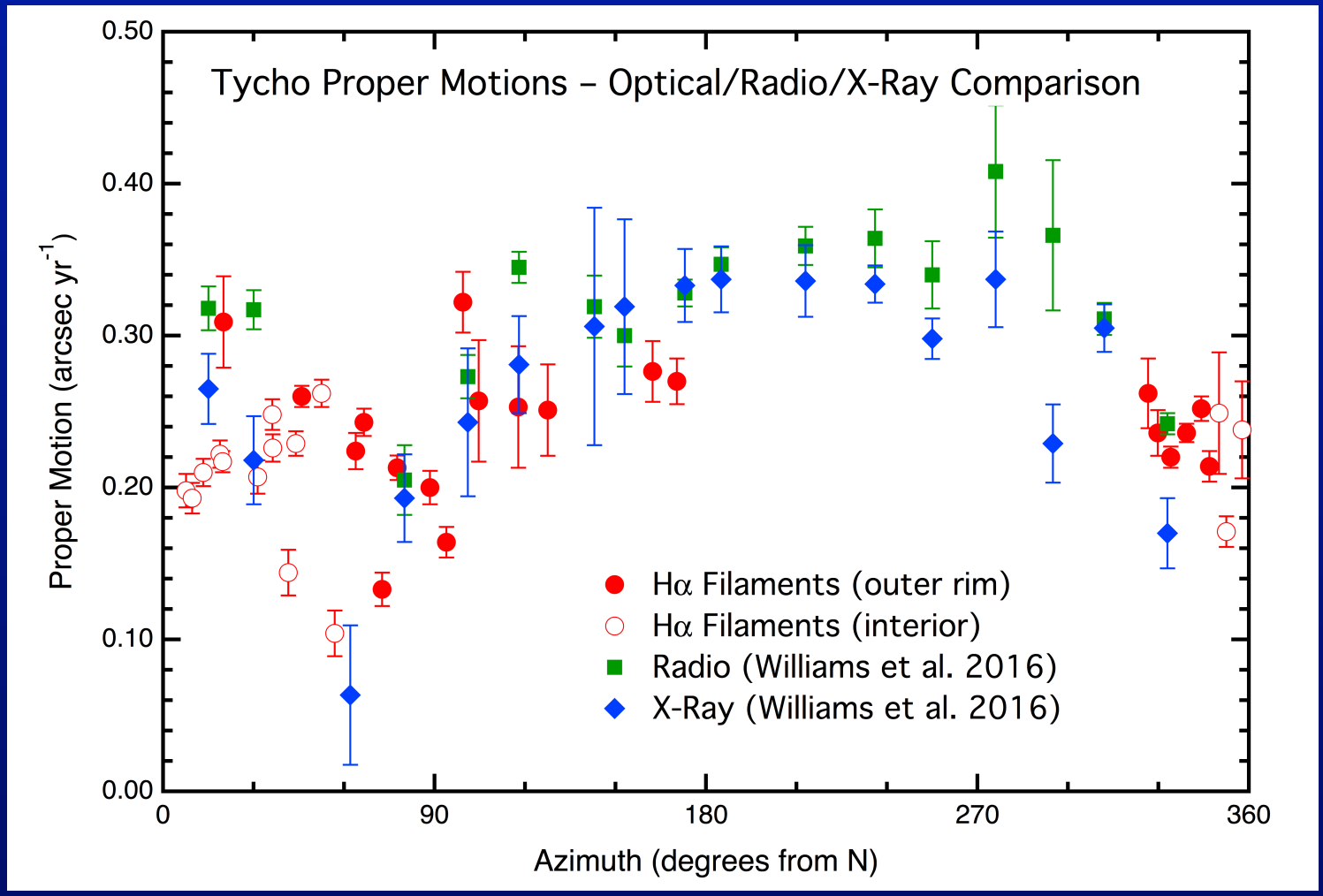
Red: coincide with X-ray/ radio rim

Magenta: interior



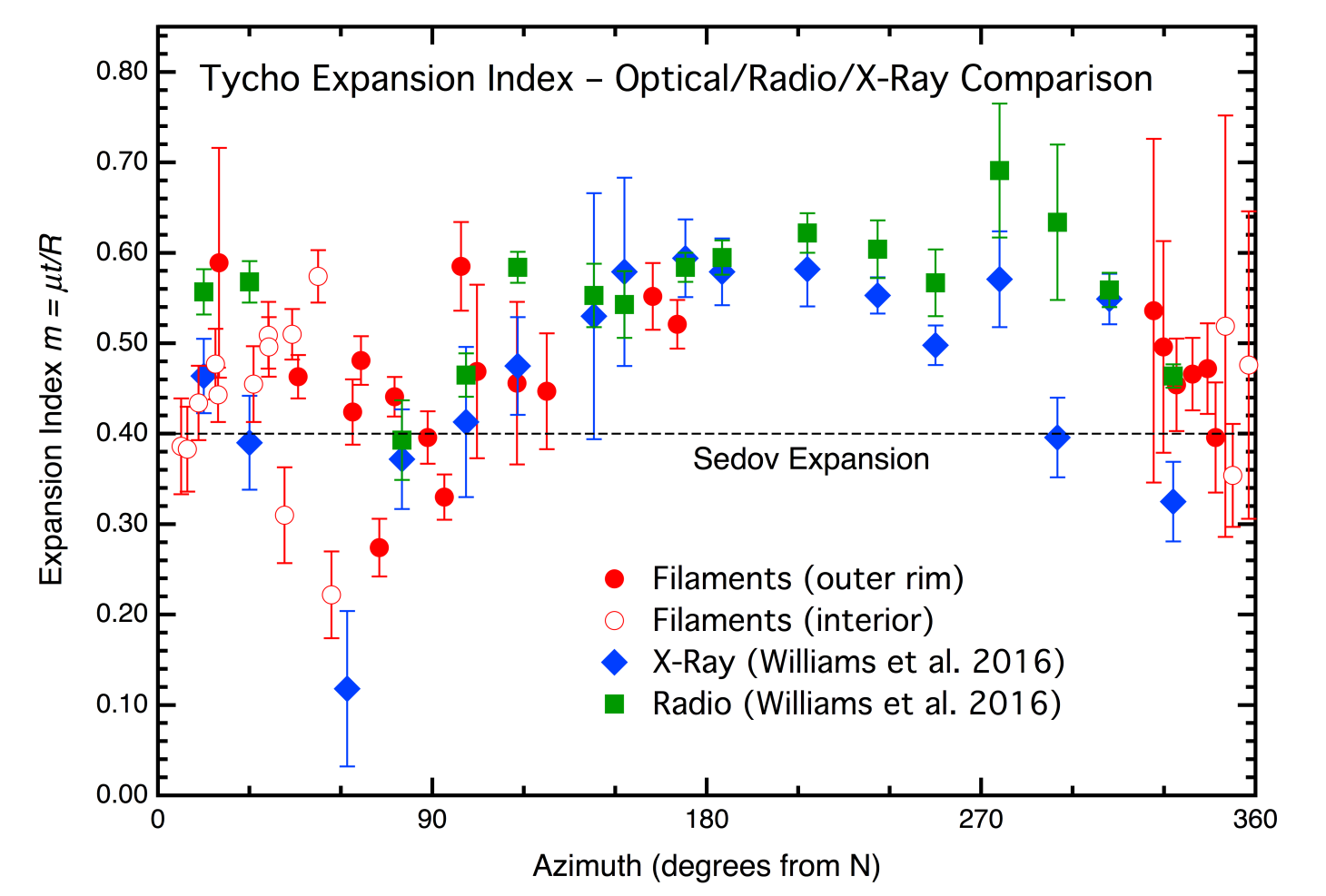
Vectors show proper motions extrapolated 300 years

Proper Motions in Tycho: Multiwavelength Comparison



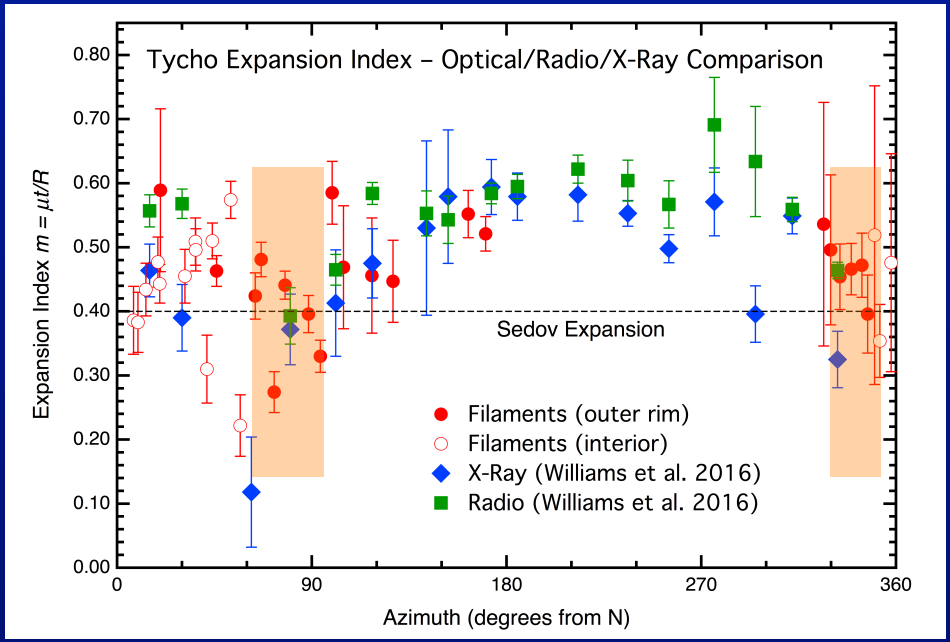
Measurements *at shell rim* are mostly consistent in all three bands

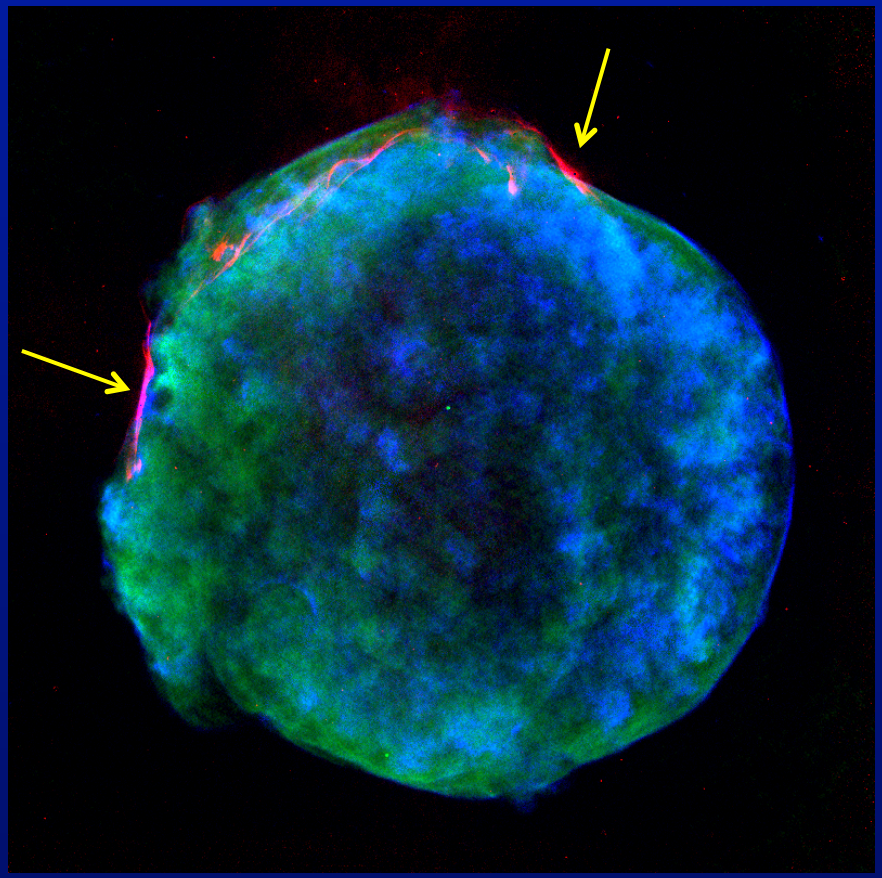
Tycho Expansion Index $m = \frac{\mu}{(R/t)}$



- Expansion at outer rim is mostly faster than Sedov ($m = 0.4$)

Tycho Expansion Index $m=\frac{\mu}{(R/t)}$

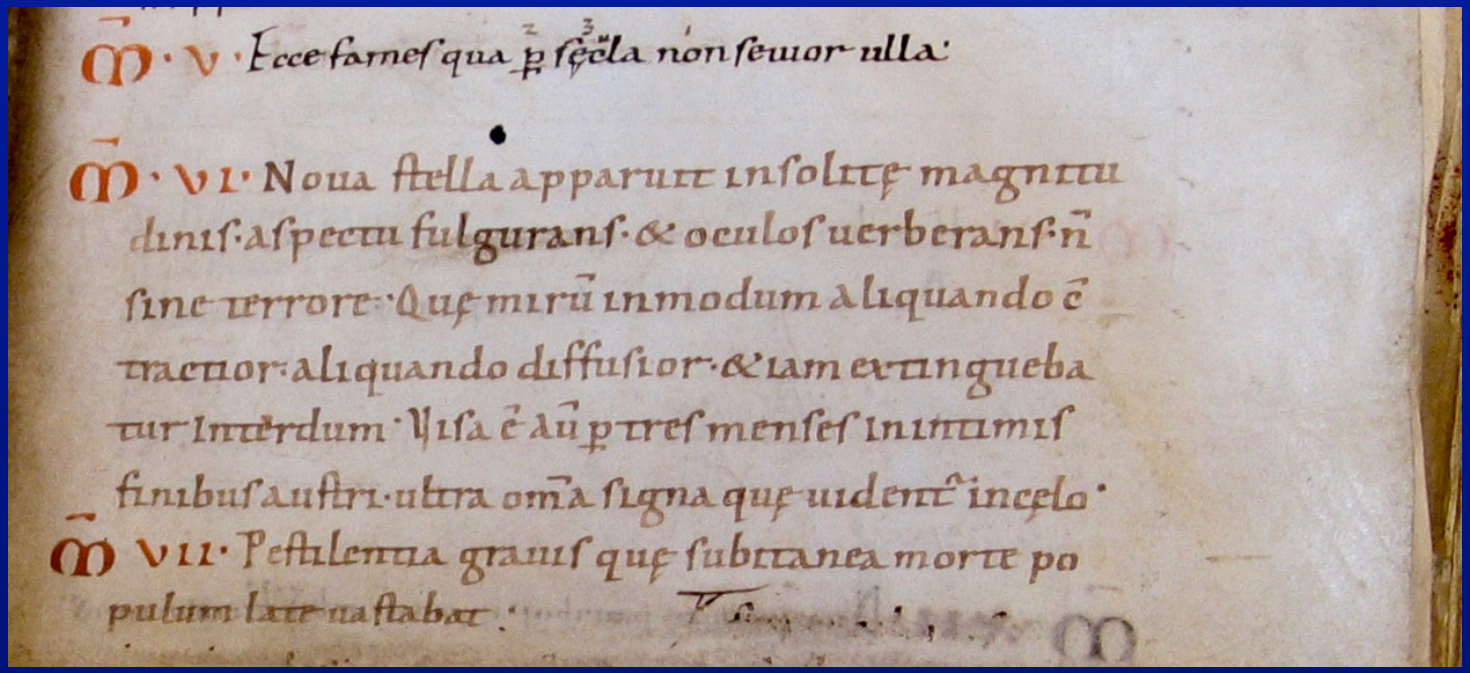




- Expansion at outer rim is mostly faster than Sedov ($m = 0.4$)
- Except in E, NW where Balmer filaments are brightest (and presumably ISM is densest)

SN 1006: Brightest in recorded history

From the Chronicles at Abbey of St. Gallen, Switzerland (where it barely broke the horizon!)

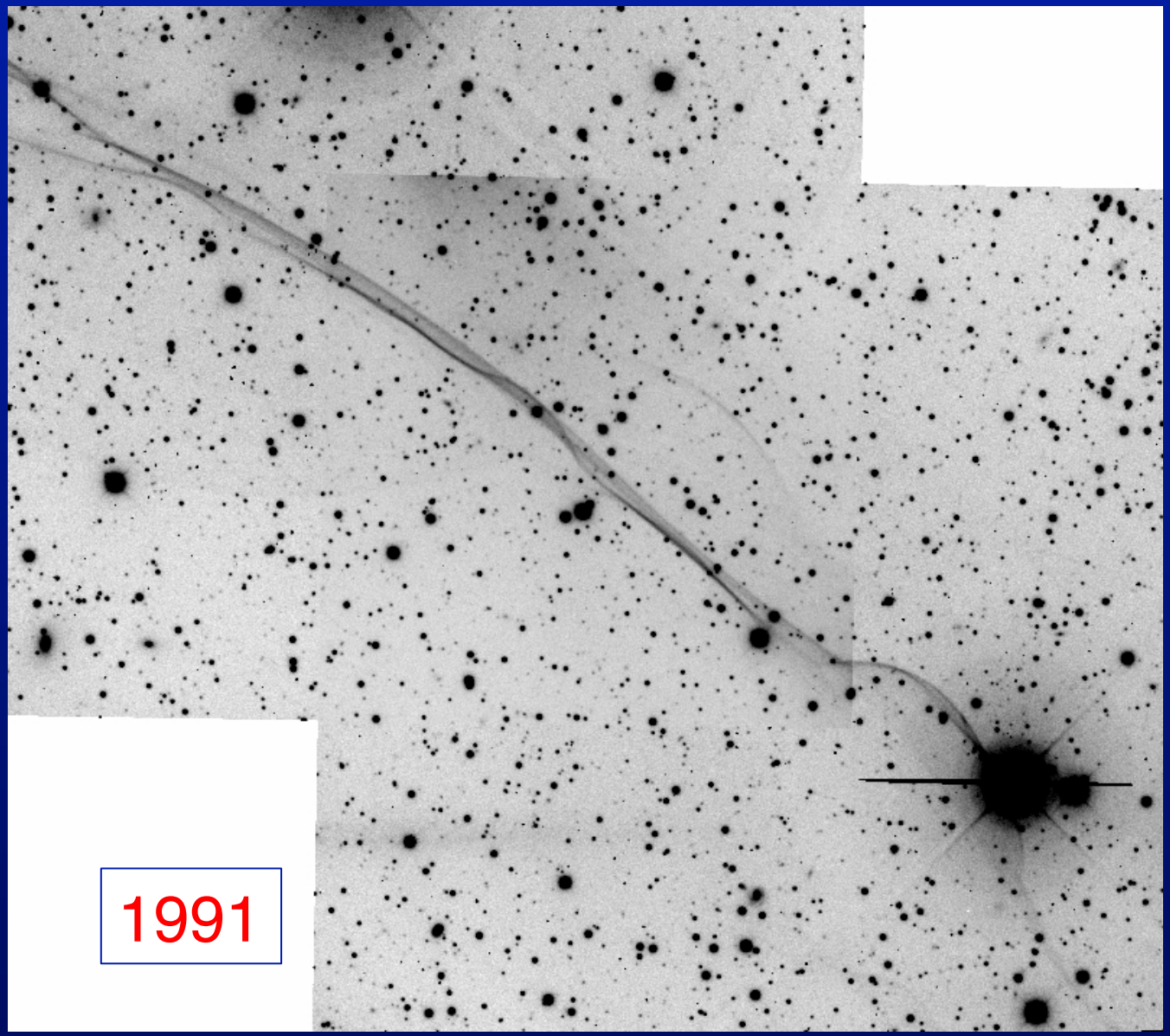


"A new star of unusual size appeared; it was glimmering in appearance and dazzling the eyes, causing alarm. In a wonderful manner it was sometimes contracted, sometimes spread out, and moreover sometimes extinguished. It was seen, nevertheless, for three months in the extreme limits of the south, beyond all the constellations in the sky."

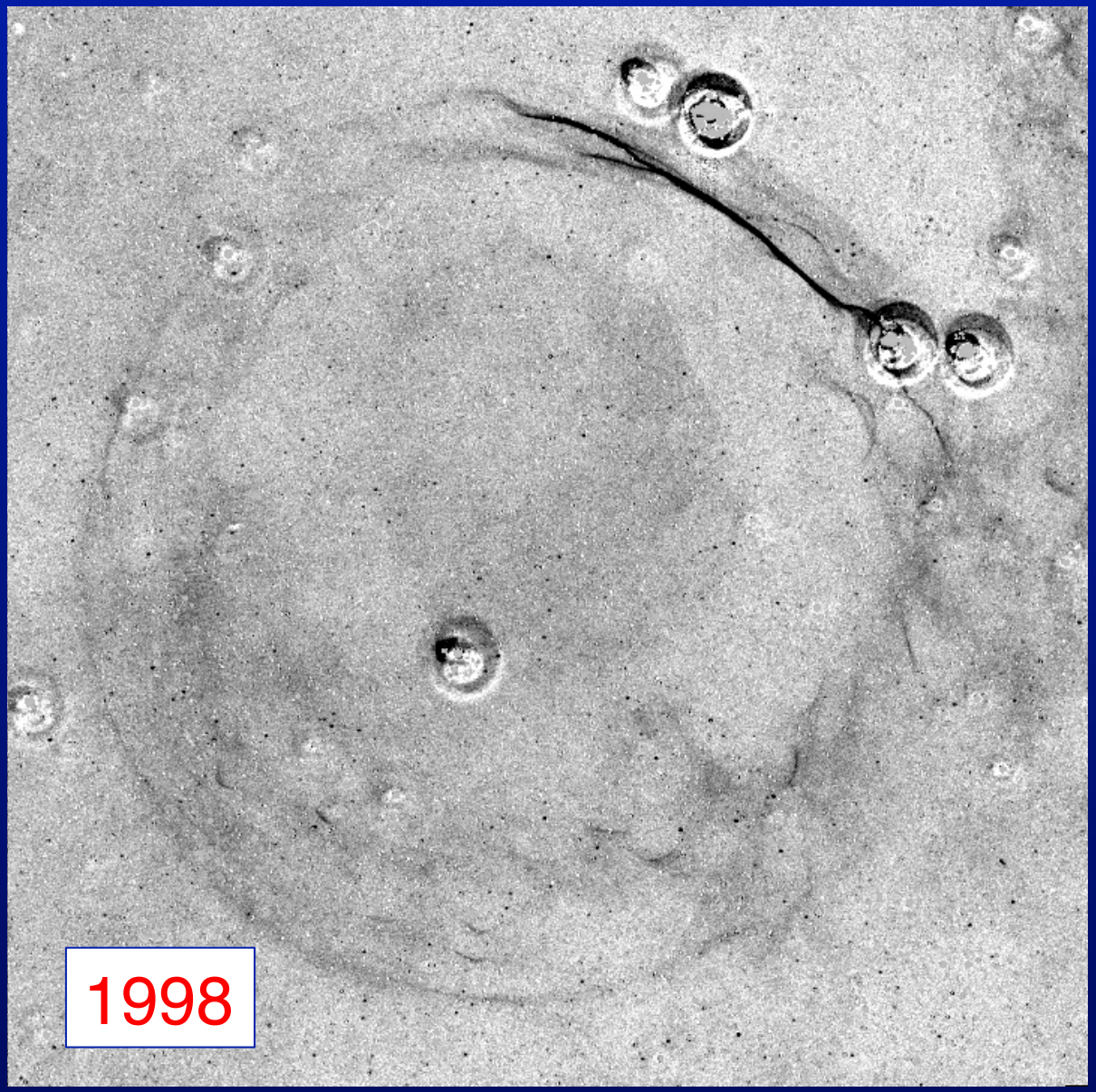
- Peak brightness $V \approx -7.5$ (much brighter than Venus!)
- Visibility accounts somewhat ambiguous; as long as 3 years post-outburst

SN 1006 Expansion: NW “bright” filaments

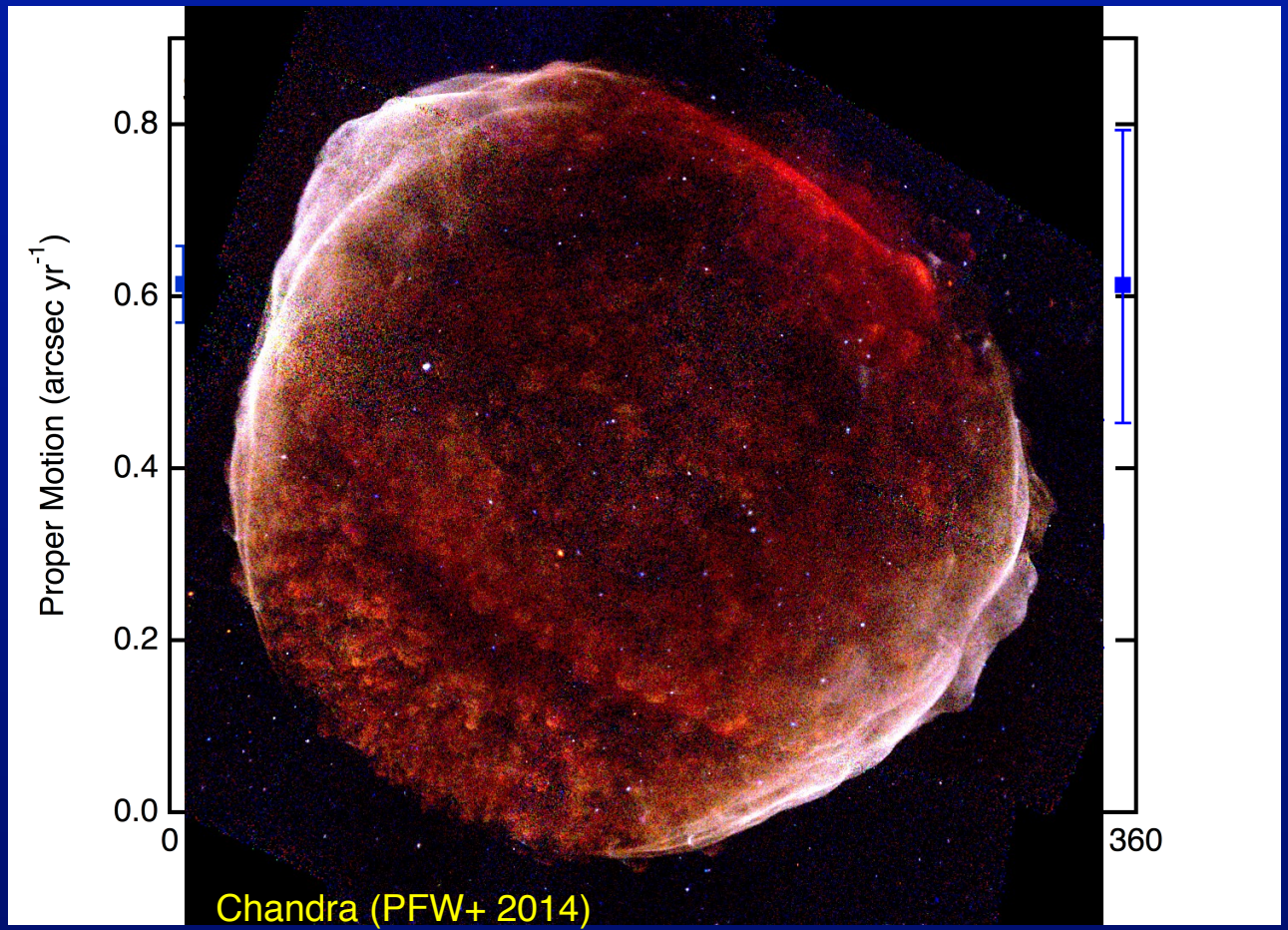
Images at 6 epochs:
1987 - 2016



SN 1006 Expansion: faint filaments surround entire shell



SN 1006 Expansion: optical and X-ray proper motions



- Optical and X-ray proper motions are the same (within errors)
- Faster than Sedov EXCEPT in bright NW where shock meets denser ISM
- High-velocity optical filaments are VERY faint; spectra near impossible

Physics of Nonradiative shocks (much abbreviated)

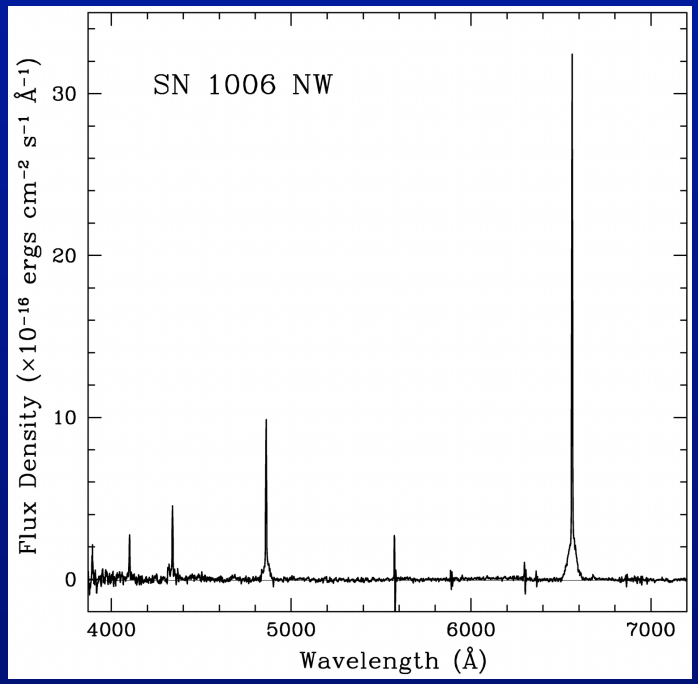
- Fast (300 – 10,000 km/s) shocks propagating into a low-density, partially-neutral medium
- Neutral atoms coast through the shock unaffected, and then …
  - Charge exchange with fast protons ➔ "fast neutrals"; broad emission lines (width ~ shock velocity) *or*
  - Direct collisional excitation ➔ narrow emission lines (width characteristic of *pre*-shock temperature)
  - Hence Balmer lines have both broad and narrow components

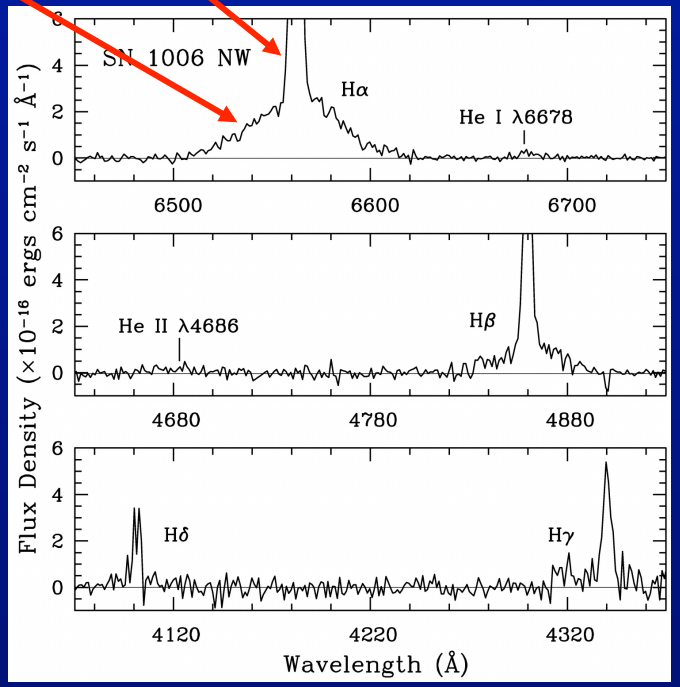
- See talks by Li, Castro, Knezevic, Ghavamian; Hovey poster (S5.1)

- Chevalier et al. 1980, … van Adelsberg et al. 2008, Morlino et al. 2013; see reviews by Heng 2010, Ghavamian et al. 2013

Physics of Nonradiative shocks (much abbreviated)

- Hence Balmer lines have both broad and narrow components (spectra from Ghavamian et al. 2003)





- Lifetime for neutrals in hot environment is SHORT ➔ Optical emission *only immediately* behind the shock
- Linewidth depends *mainly* on shock velocity
- Other factors play a role: electron-ion equilibration; cosmic ray acceleration

Chevalier et al. 1980, … van Adelsberg et al. 2008, Morlino et al. 2013; see reviews by Heng 2010, Ghavamian et al. 2013

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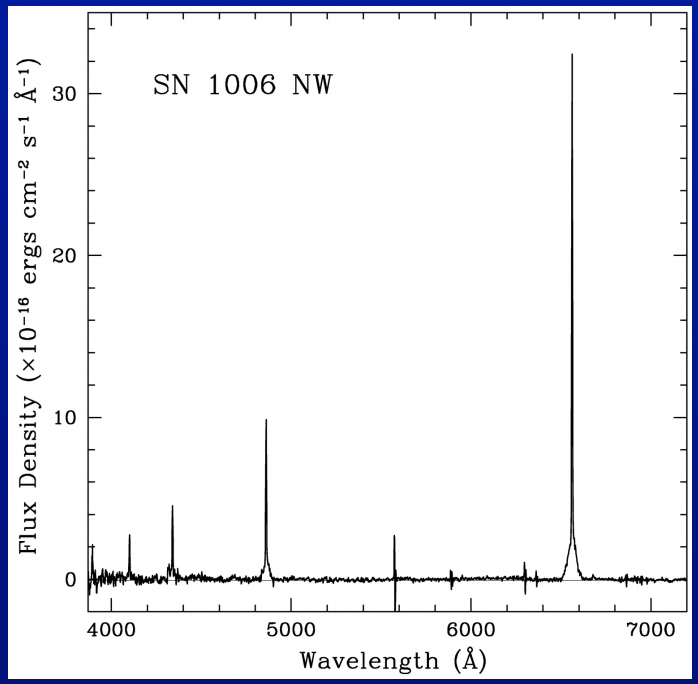
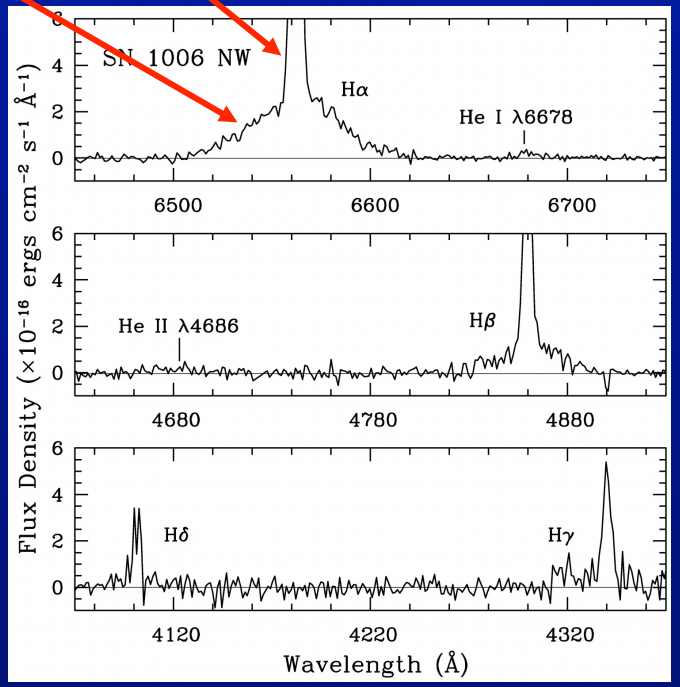
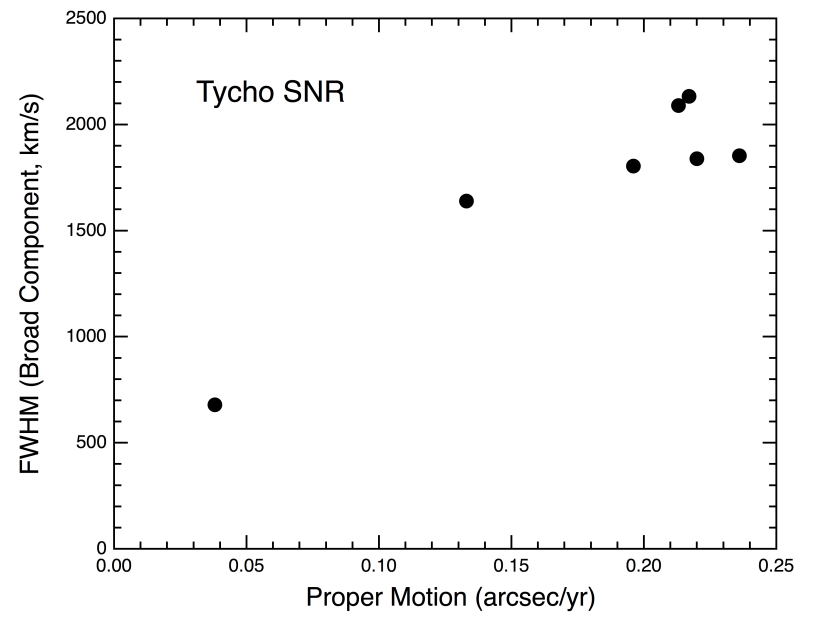


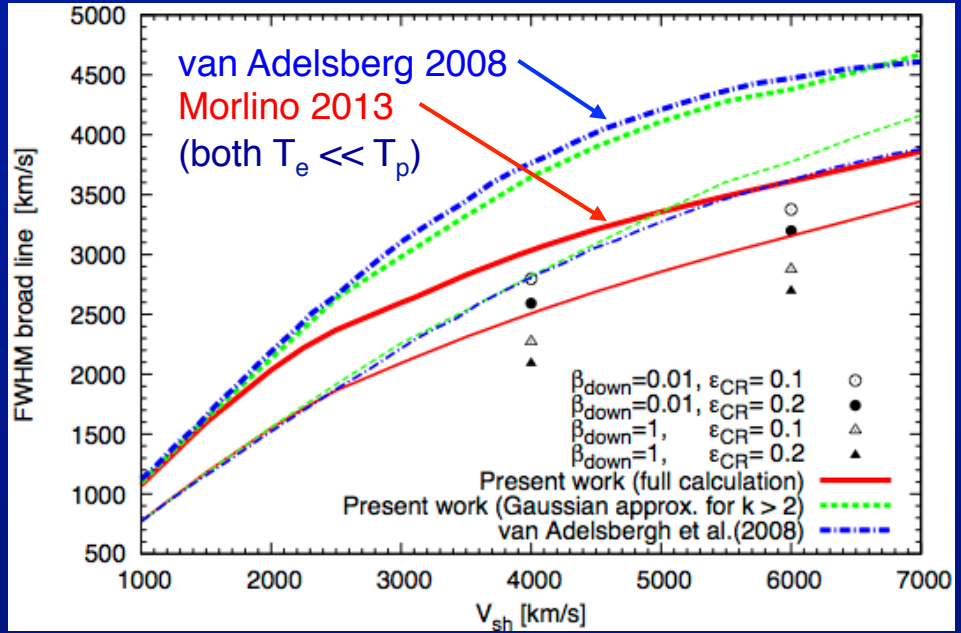


- Proper motions + shock velocity → geometric distance
- BUT getting V_s from broad-component width is model-dependent
- PFW+ 2003: d = 2.2 kpc; BUT more likely value is 1.6 – 1.7 kpc
- More consistent with Scheizer-Middleditch star as a background object

Chevalier et al. 1980, … van Adelsberg et al. 2008, Morlino et al. 2013;
see reviews by Heng 2010, Ghavamian et al. 2013

Tycho line profile measurements

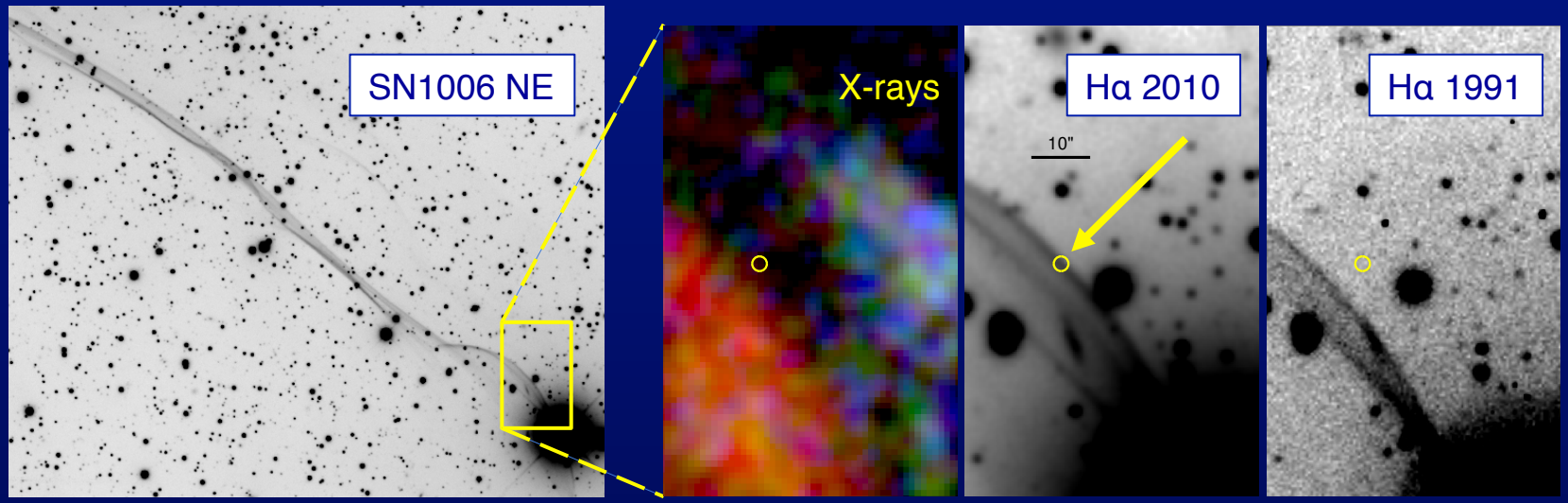




- Measured FWHM of Hα profile for a few filaments with measured proper motions
- Linewidth depends *mainly* on shock velocity
- Other factors play a role: electron-ion equilibration; cosmic ray acceleration
- At least qualitatively similar to models by Morlino et al. 2013
- Measuring profiles at range of velocities (especially fast) is important (Tycho, SN1006, 0509–67.5, etc)

What about heavier ions? Cosmic Rays?

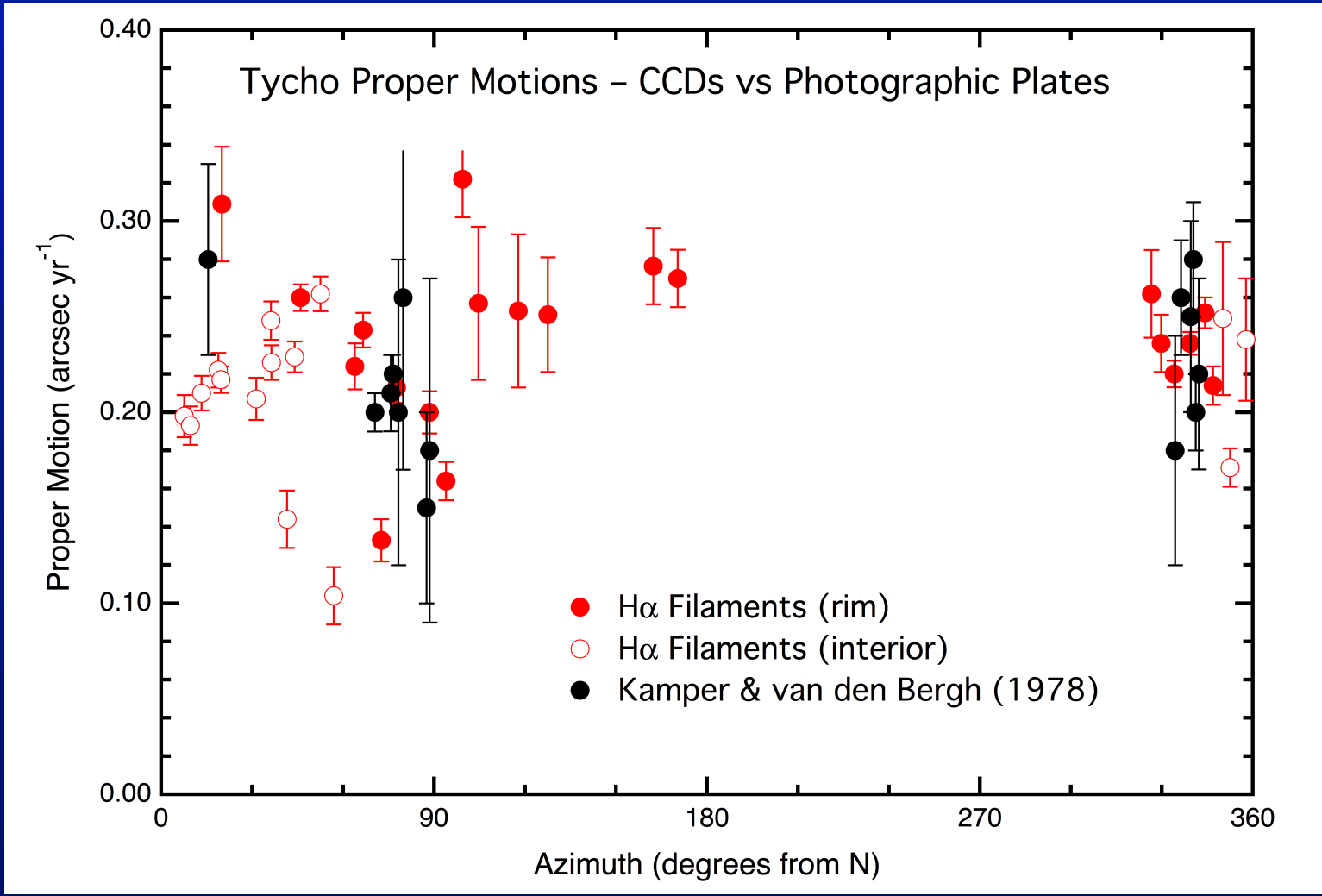
- Simplest picture: collisionless shock heats ions to T proportional to mass: $T_{He} = 4\ T_p$; $T_C = 12\ T_p$, etc.
- Turbulent shocks are (believed to be) responsible for CR acceleration
- Turbulence in shock can also transfer energy among species; inventory of ion temps can assess this
- Measure profiles for He^{+}, C^{+3}, N^{+4} to find ion temps in fastest observable shock in SN1006
- Far UV spectra from HST COS … stay tuned



Summary

- Both Tycho and SN 1006
  - Optical proper motions have been measured around much of shell
  - Measurements *at same azimuth* in optical, radio, X-rays agree
  - Expansion rate is mostly faster than Sedov—except for brightest filaments where shock encounters denser surroundings
- Line profile measurements
  - Measuring profiles for filaments with different proper motions in the same object provides best test for nonradiative shock models and can give reliable distances
  - Measure temperatures for heavier ions is upcoming

Optical Proper Motions in Tycho



Our measurements are consistent with KvdB78, but for far more filaments, with better precision (Putko+, in prep)