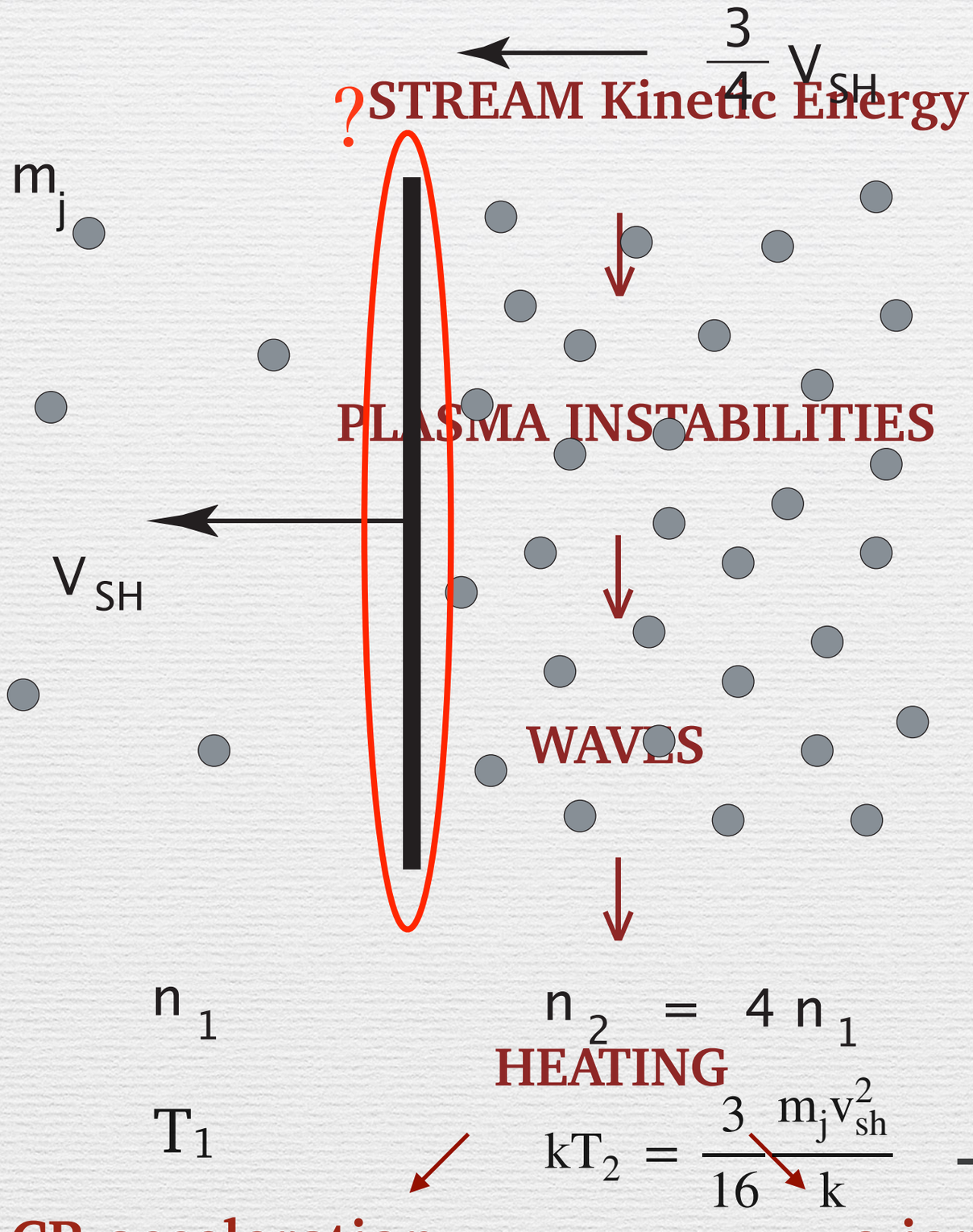
Electron-Ion Equilibration and Cosmic Ray Acceleration in Two Balmer-Dominated SNRs

Parviz Ghavamian
(Towson University, Maryland, U.S.A.)

J. Raymond, I. Seitenzahl, B. Guest, B. Williams, K. Borkowski, R. Reynolds

Supernova Remnants III
An Odyssey in Space after Stellar Death
9-15 June 2024, Chania, Crete, Greece

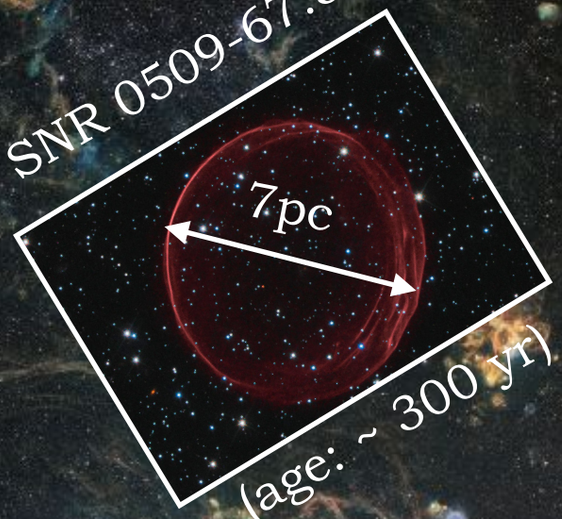
How Are Electrons Heated Relative to Ions?



strong shock jump conditions for ideal gas

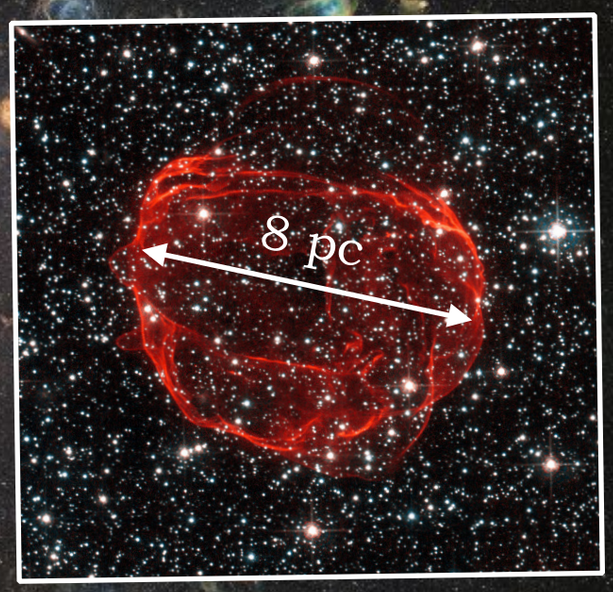
LMC
D = 50 kpc

SNR 0509-67.5



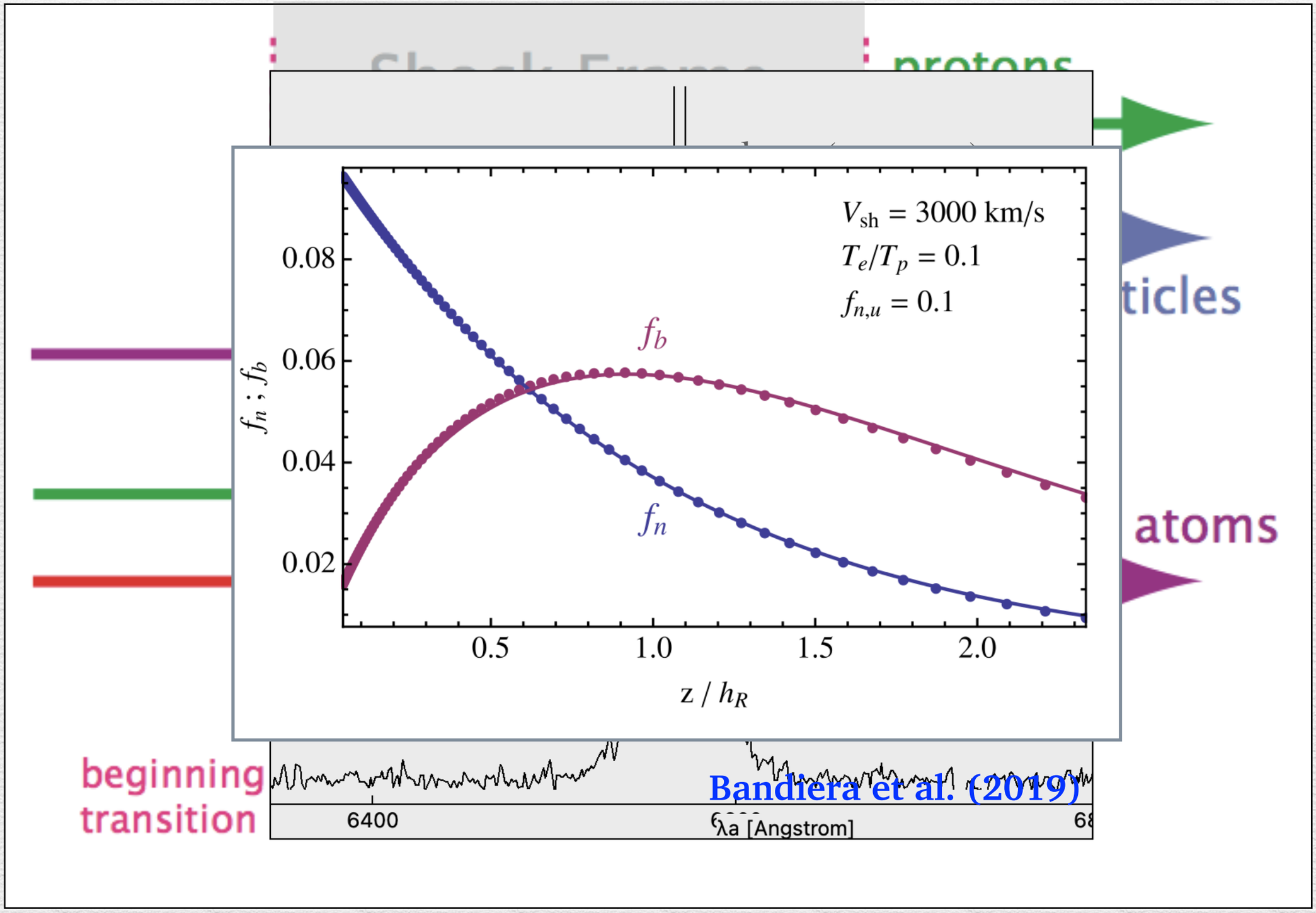
(age: ~ 300 yr)

SNR 0519-69.0



(age: ~ 600 yr)

Balmer-Dominated Shocks

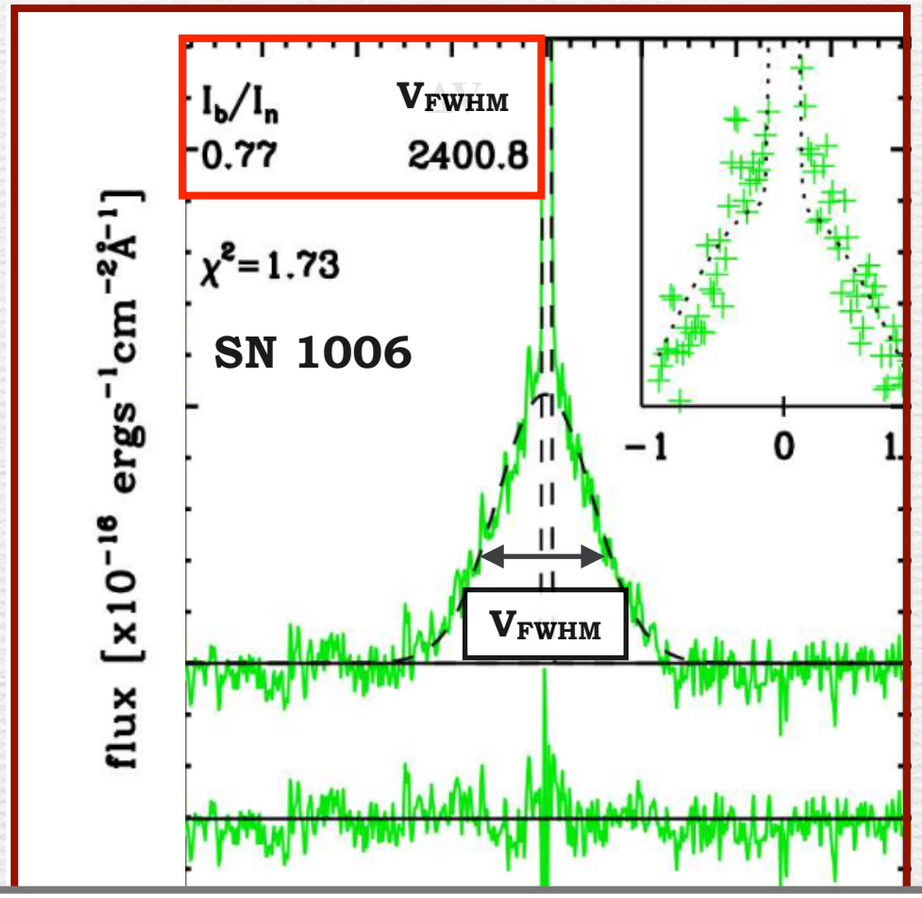


Bandiera et al. (2019)

van Adelsberg et al. (2008)

Measurables in Balmer-Dominated Spectra

SN 1006



Kneževíc et al. (2013)

Reality is not so clean: measured $\frac{I_b}{I_n}$ in SNRs regularly fall <u>below theoretically allowed limit</u>

... Must include contribution to I_n by collisional excitation in CR precursor (Raymond et al. 2011; Morlino et al. 2013)

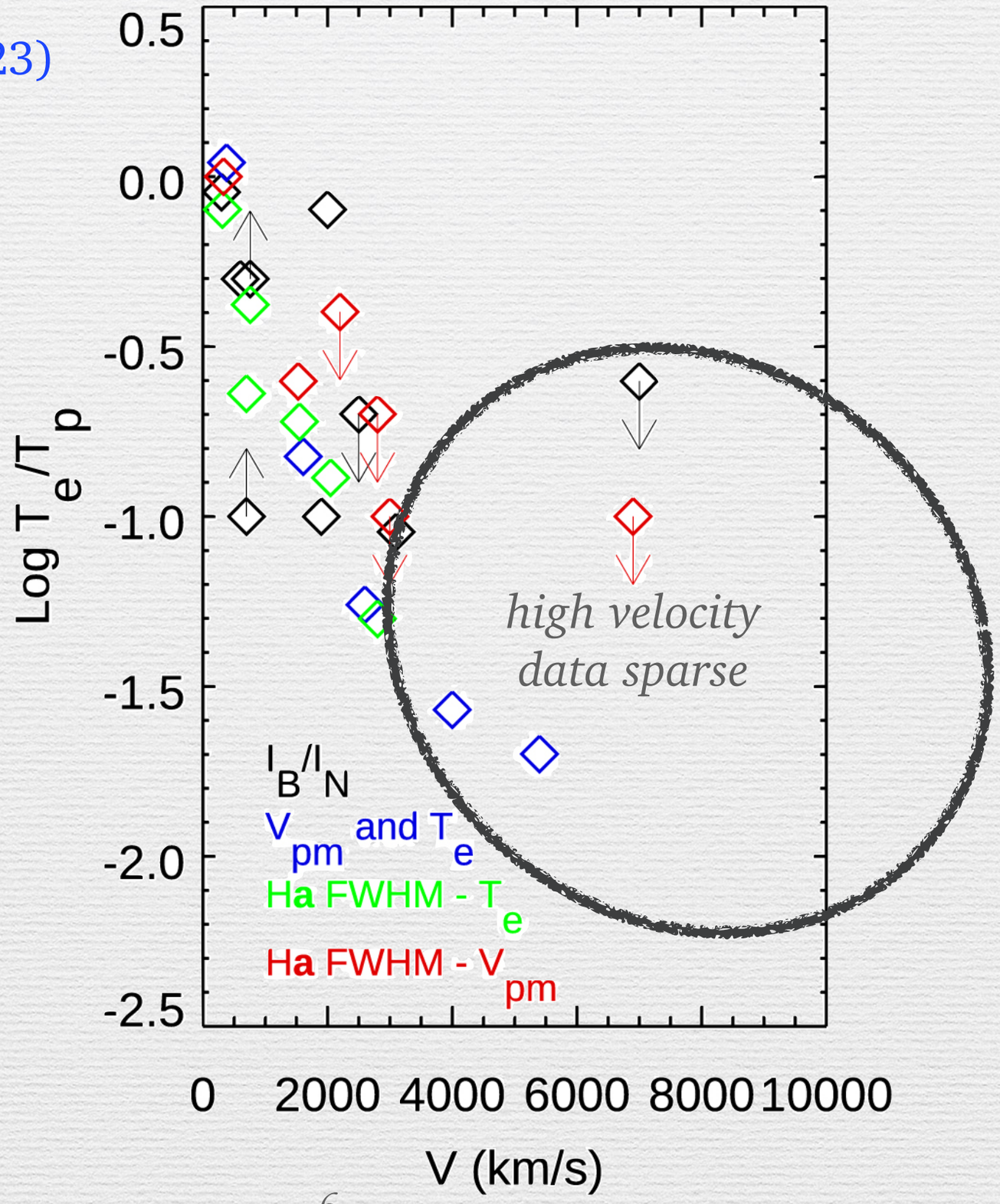
...Energy loss of shock to CR acceleration *not included*

(Smith et al. 1991; (al. 2008; Blasi et al 2012, Morlino et al. 2012, 2013)

bine to self-ently estimate sh, T_e/T_p

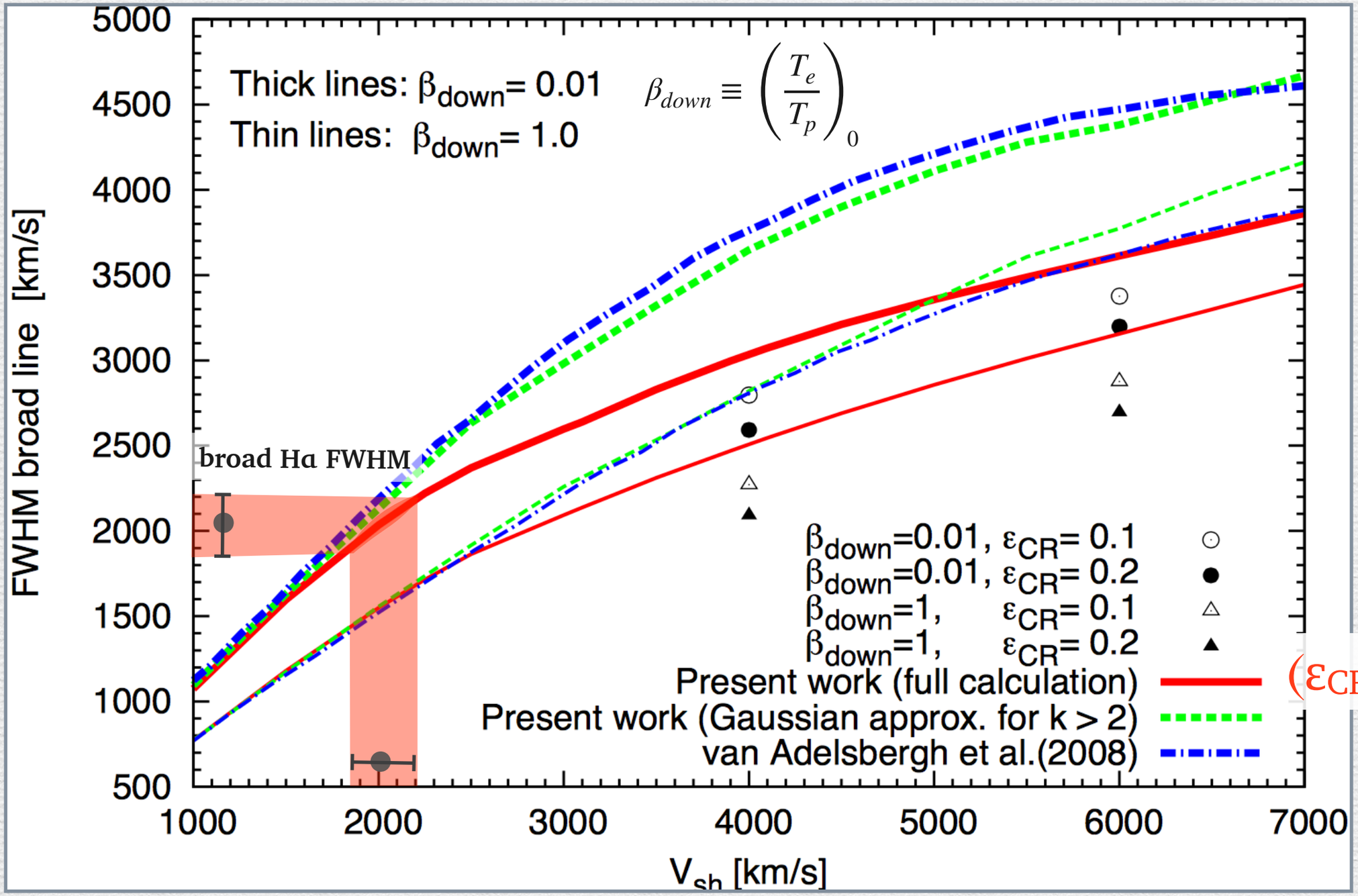
Measurements of Electron-Ion Equilibration

Raymond et al (2023)



Proper Motion-Determined V_{sh} vs Broad Hα FWHM

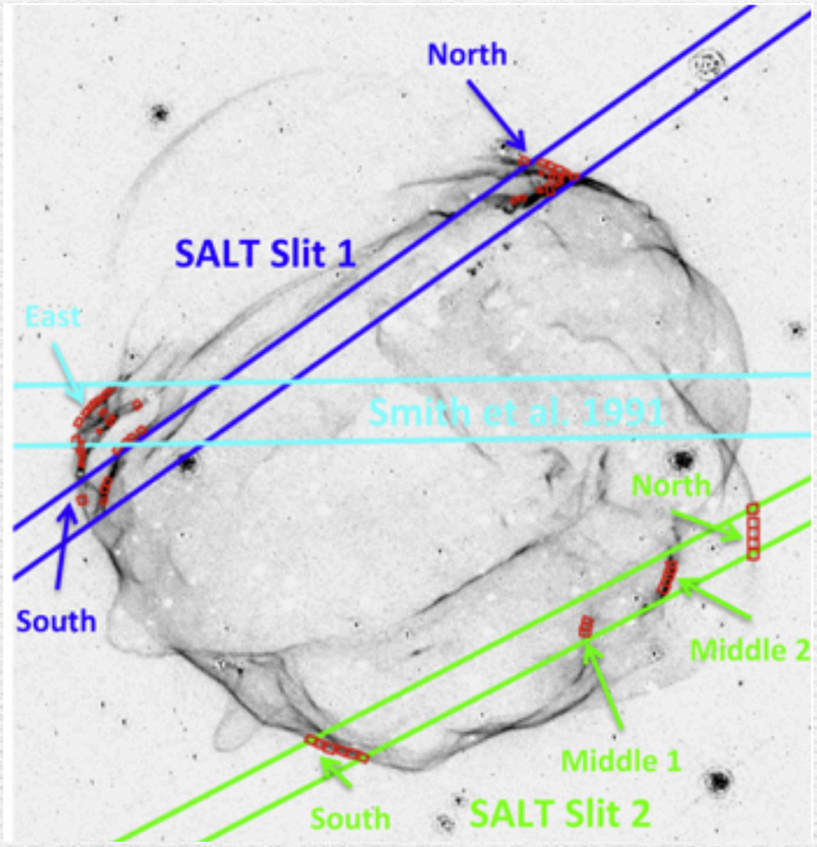
(Semi-analytical models of Morlino et al. 2013)

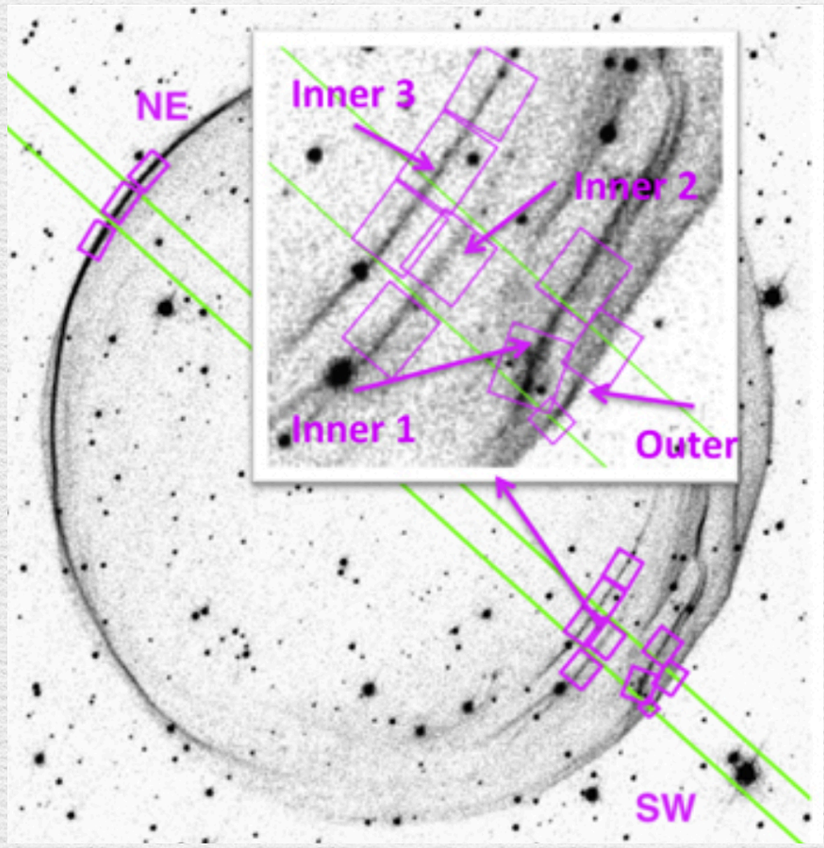


$$\varepsilon_{CR} \equiv \frac{P_{CR}}{\rho_0 v_{sh}^2}$$

$(\varepsilon_{CR} = 0)$

First HST Proper-Motion vs Broad Hα FWHM Study: Hovey et al. (2018)

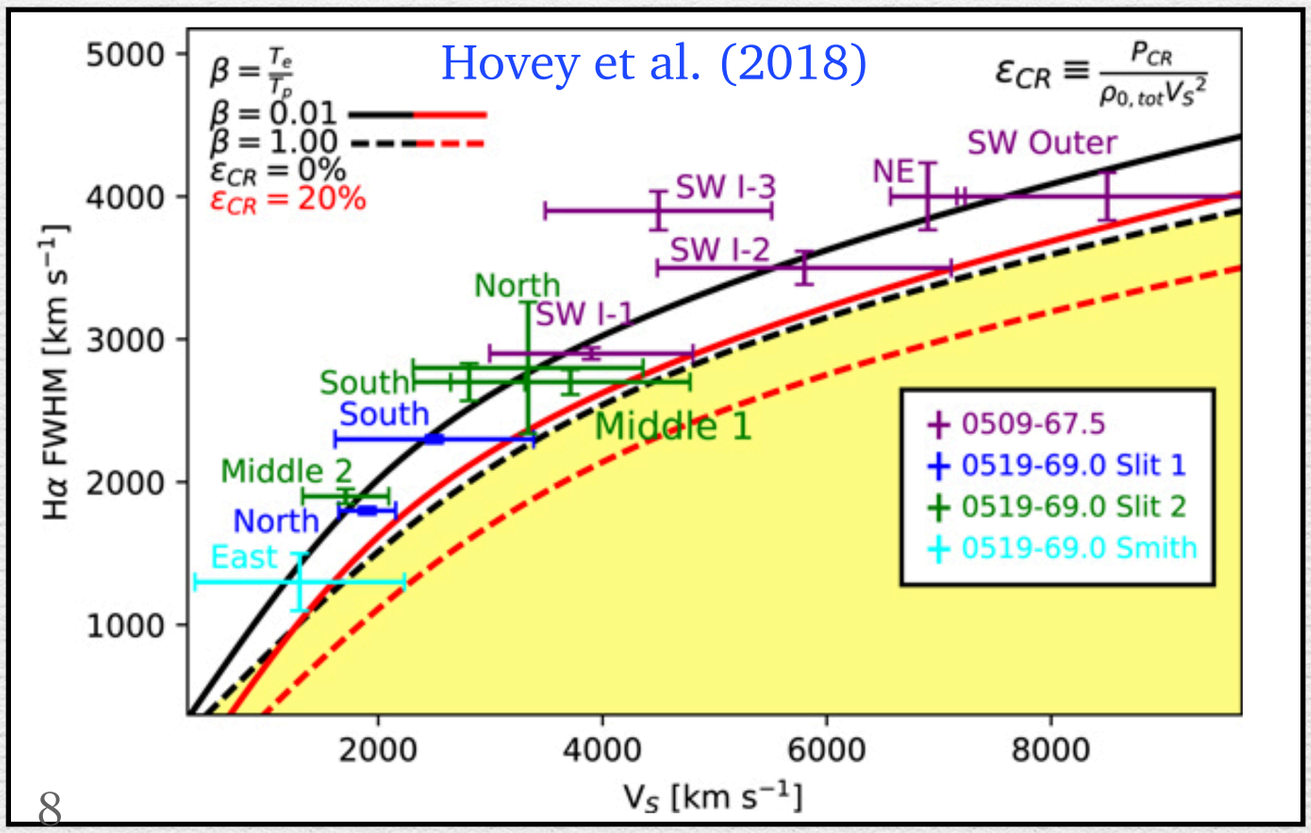




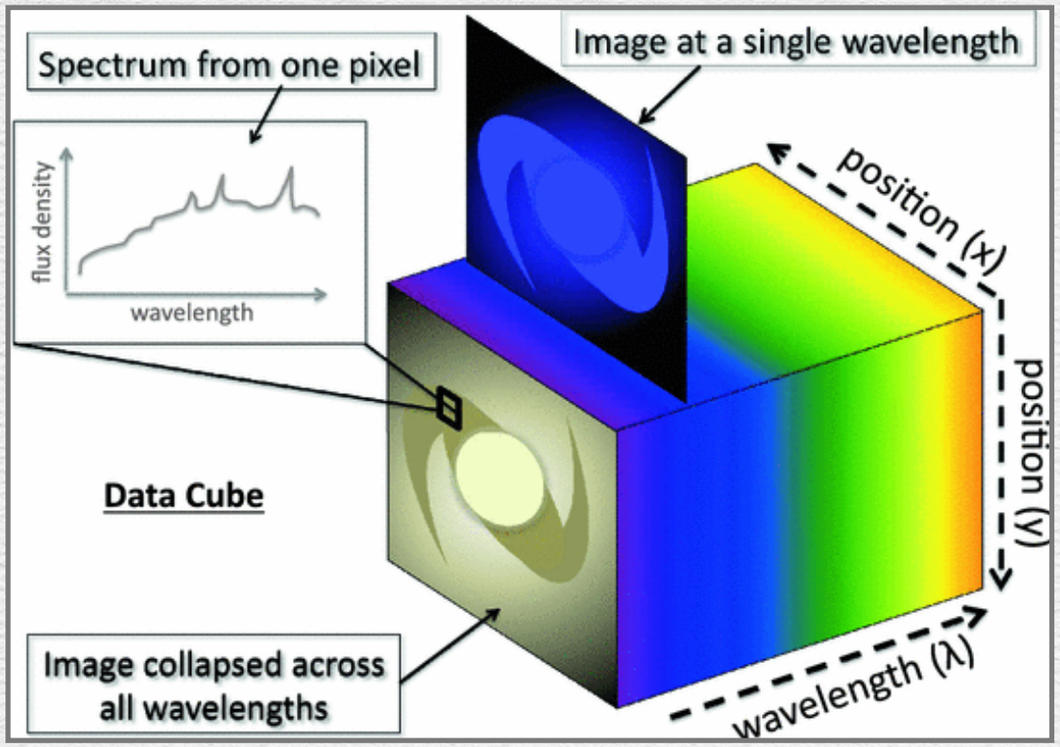
- Longslit spectroscopy at several locations around each SNR rim
- Measured Hα proper motions around rim at 5-6 places using HST/ACS

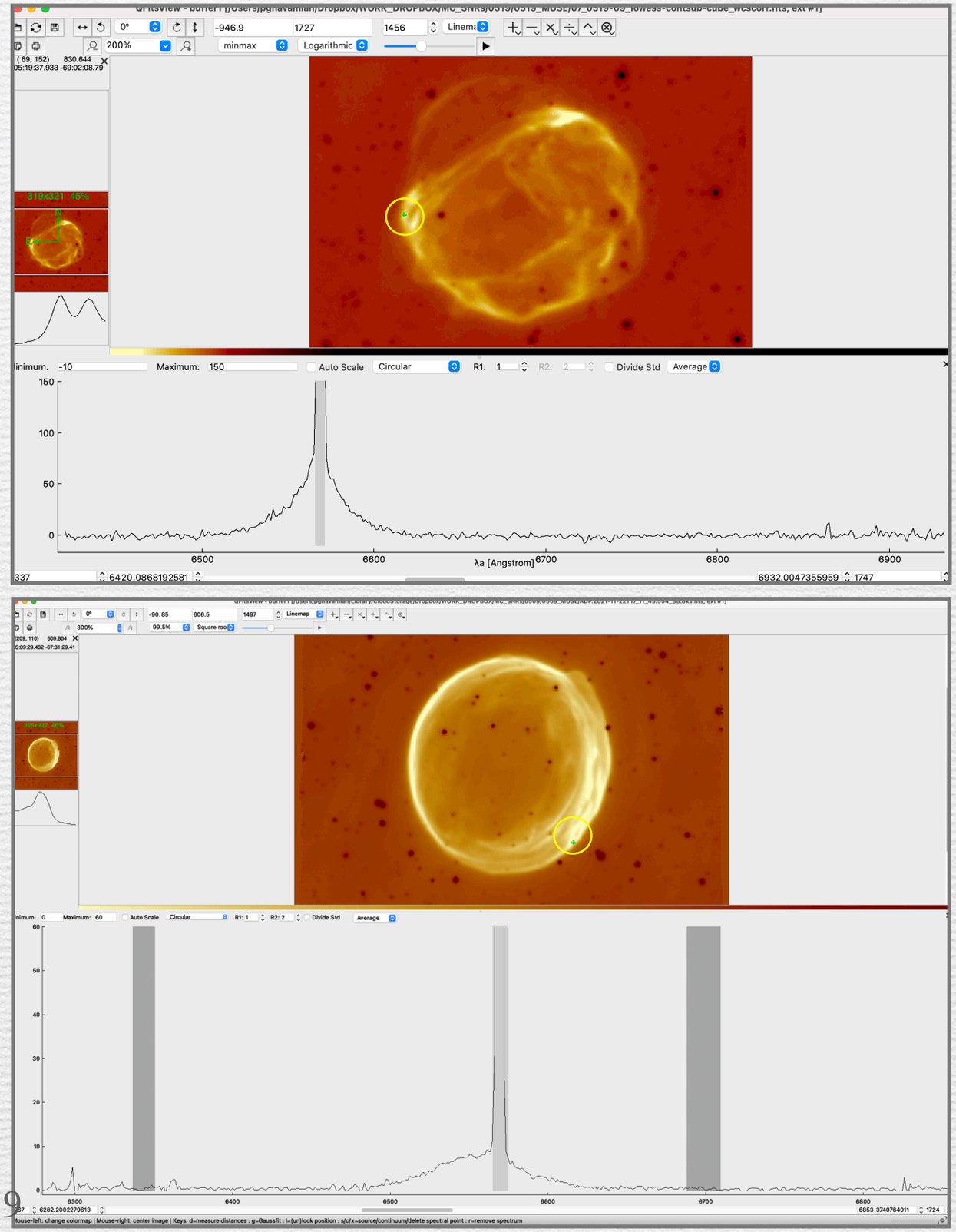
$$v_{sh}(\mathrm{km/s}) = 4760\ \omega(''\mathrm{yr}^{-1})\ D_{\mathrm{kpc}}$$

- *Only 1 year HST baseline in 2018, so large error bars on* v_{sh}
- Conclusion: CR acceleration effects small in both SNRs ($\varepsilon_{CR} \lesssim 11\%$)



New Data: IFU Spectroscopy



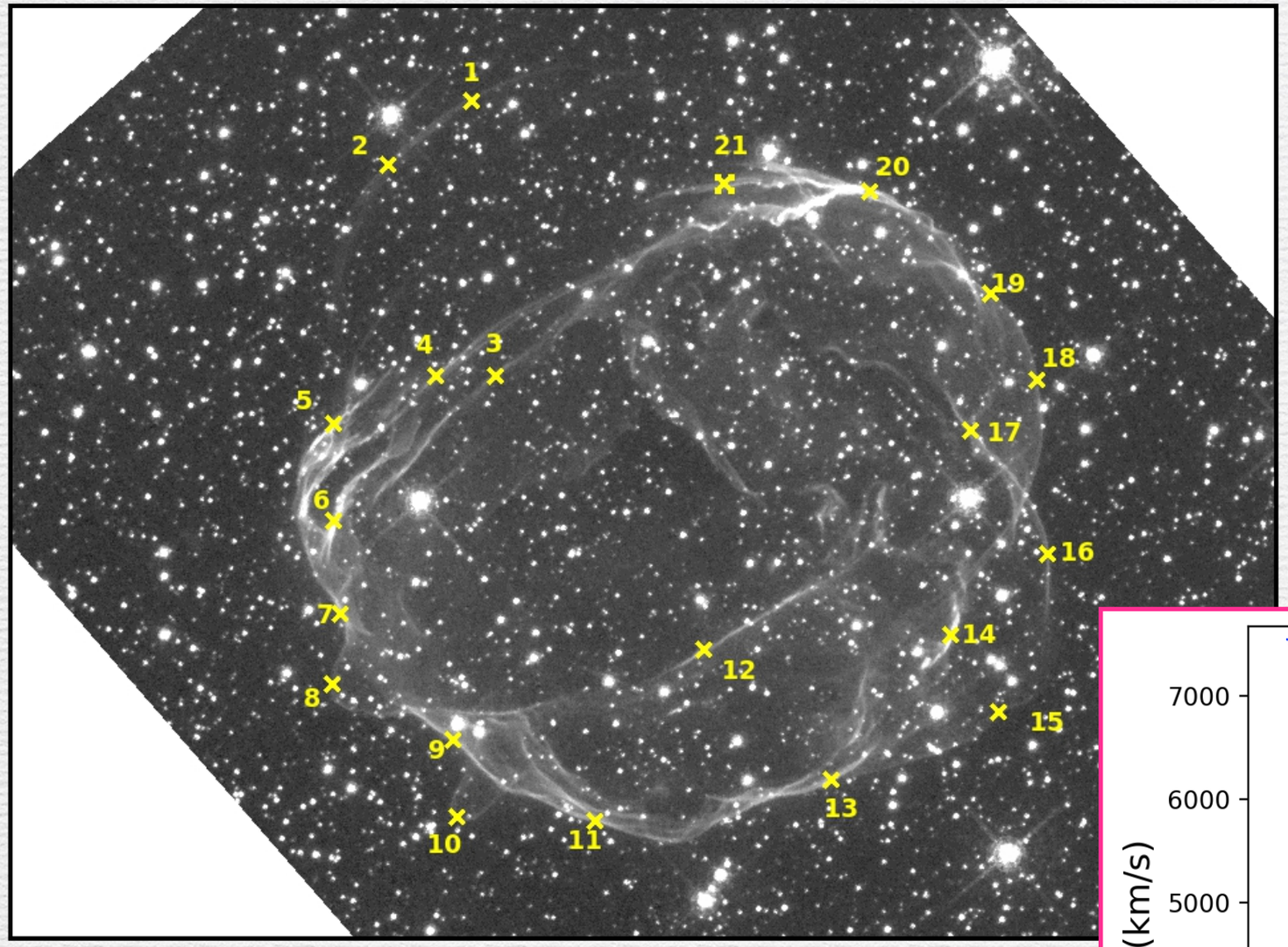


- 3 of the 4 Balmer-dominated LMC SNRs have been observed with HST, with ACS imaging available for 0509 and ACS/WFC3 fo 0519

- Deep ESO/VLT MUSE data of 0509 (**24 hrs in AO mode (!)** PI: I. Seitenzahl) and 0519 (**1.4 hrs** PI: B. Leibundgut) are now available

SNR 0519-69.0

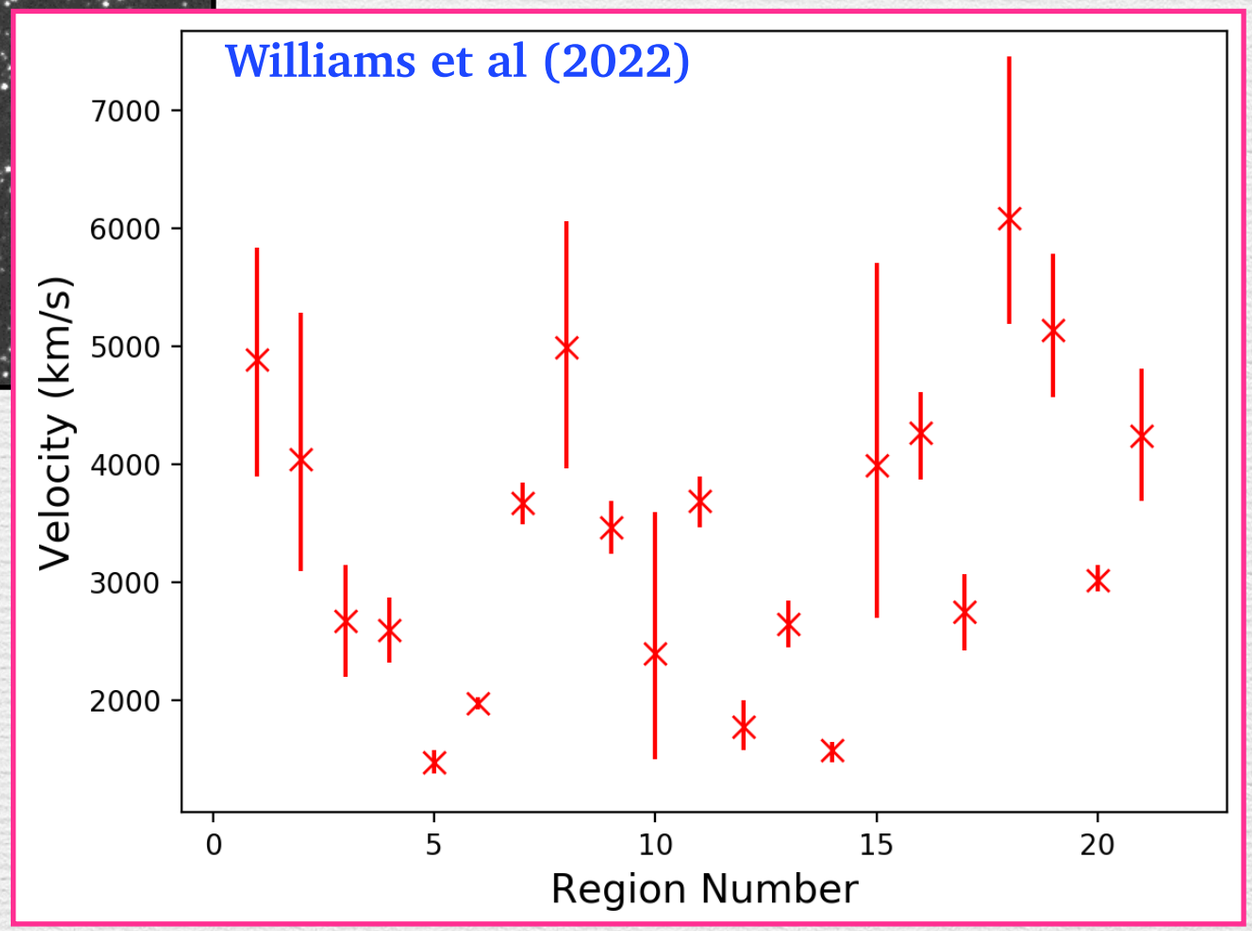
10-year Proper Motion v_{sh} With Hα FWHM from MUSE



Williams et al (2022)

1 ACS pixel = 0.04"
(3×10^{16} cm @D = 50 kpc)

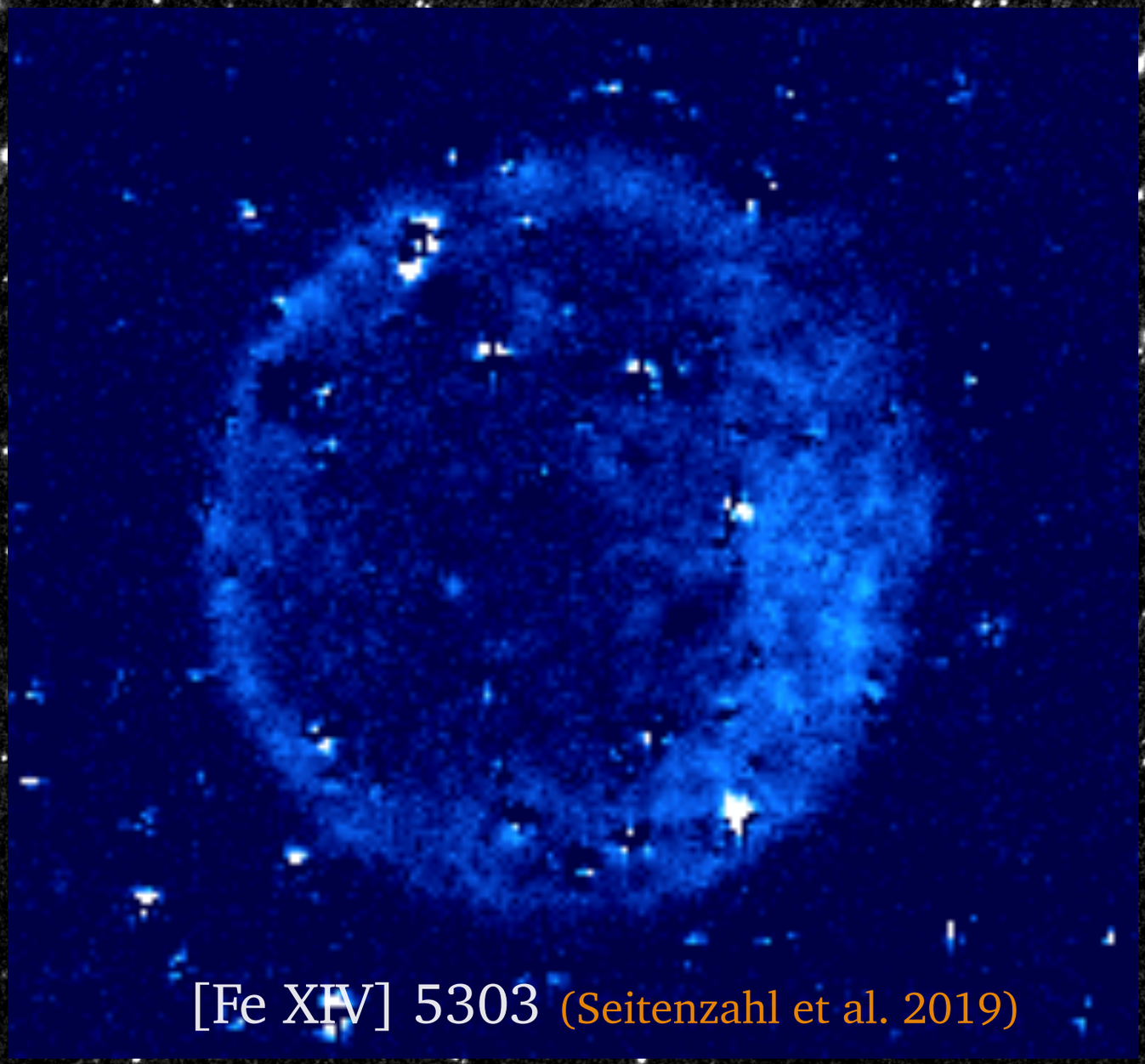
filament proper motions ~ 4 - 5 pixels over 10 years



- Localized [O III], [S II] knots in NW (n_e ~ 1500 -10^4 cm^{-3}): not ISM, likely circumstellar wind material (Li et al. 2021) (see Chiotellis talk)

Position Angle →

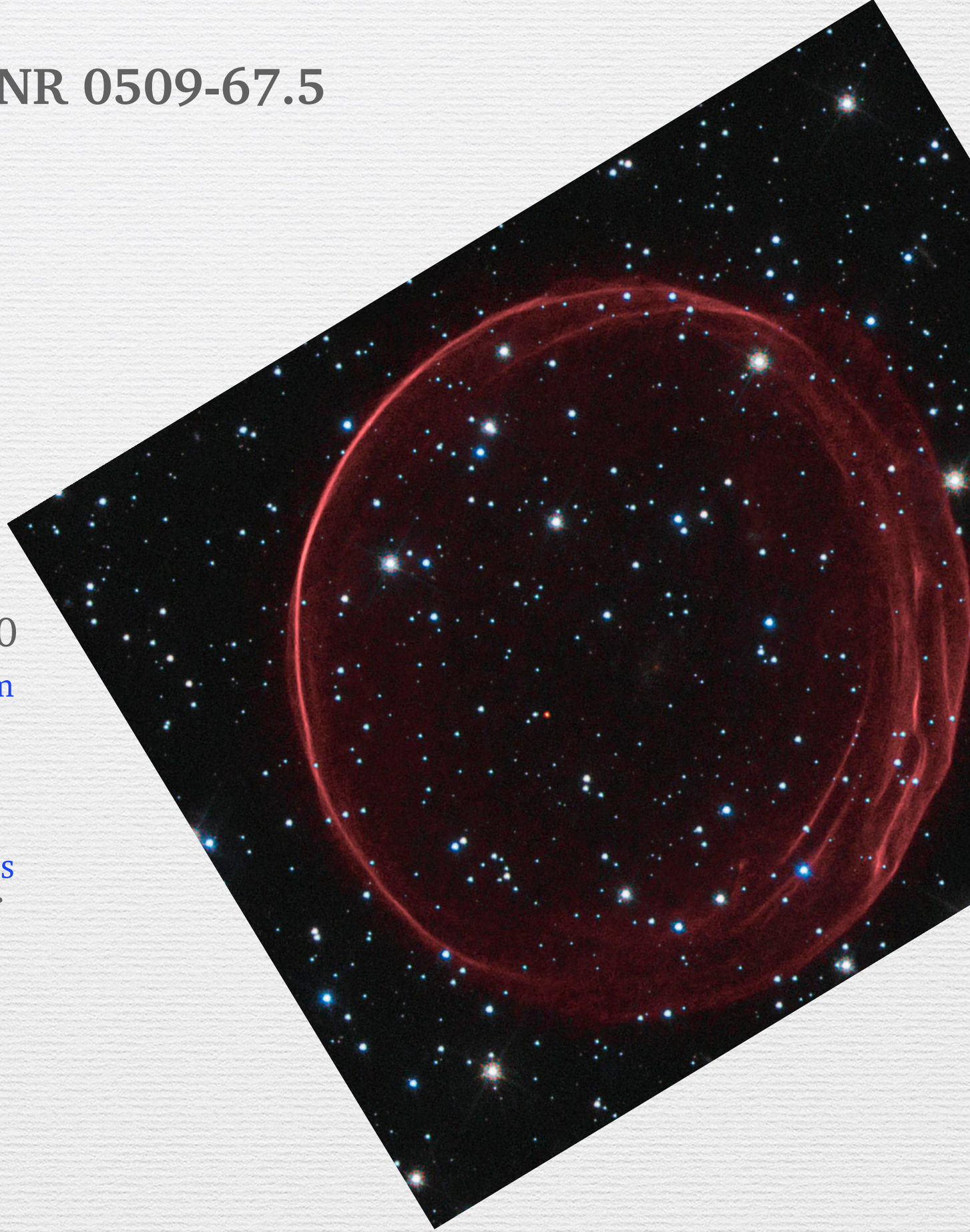
SNR 0509-67.5 HST/ACS 2006-2016



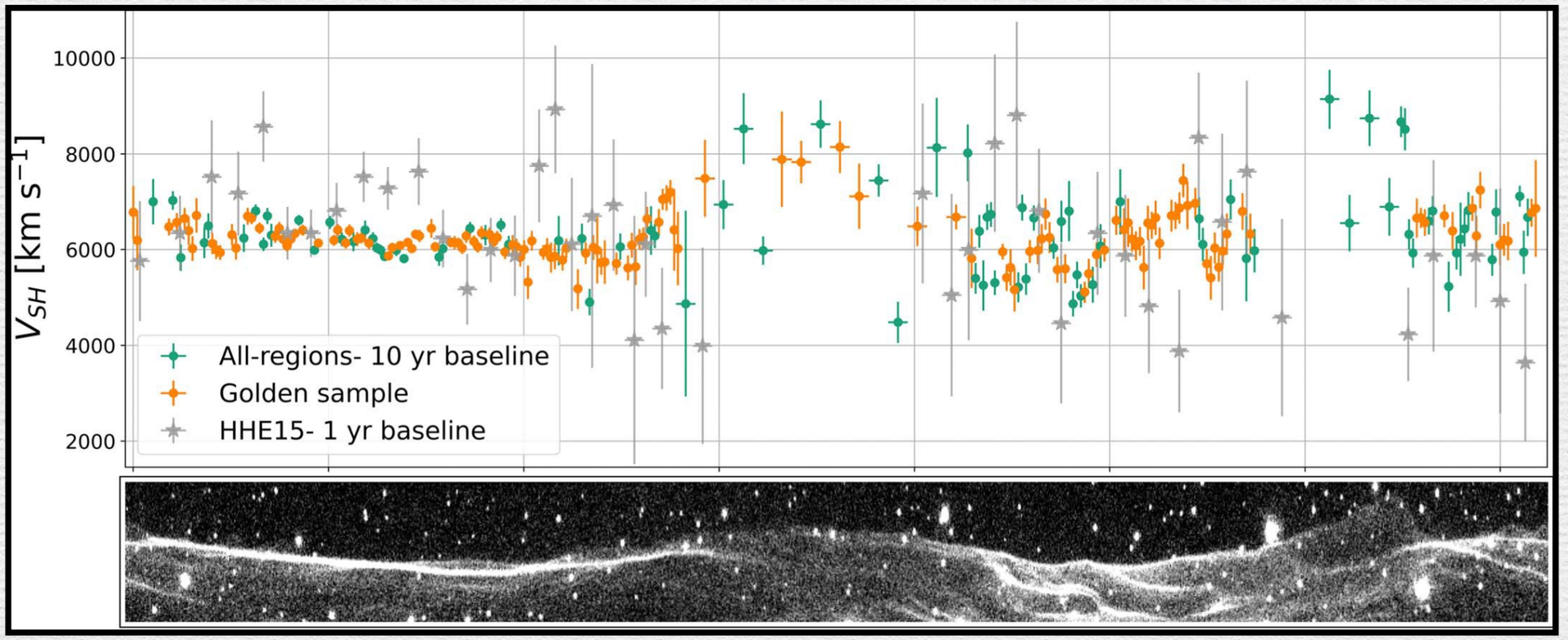
[Fe XIV] 5303 (Seitenzahl et al. 2019)

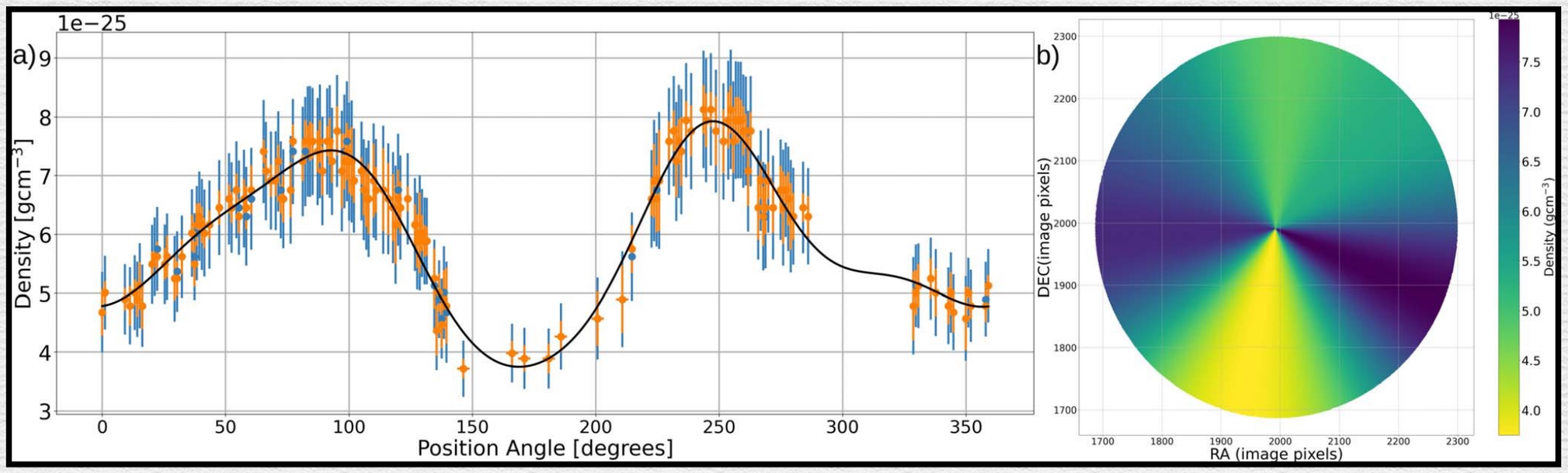
SNR 0509-67.5

- Luminous Type Ia (Rest et al 2005; Kosenko et al. 2008); M ~ 1.0-1.3 $M_{\odot}$
- Balmer-dominated shocks (Tuohy et al. 1982)
- Proper motion gives v_{sh} ~ 5500-7500 km/s (Hovey et al. 2015, 2018, Arunachalam 2022)
- DDT explosion gives best fit (Badenes et al 2008) **(though see the poster of Priyam Das: S4.6)**



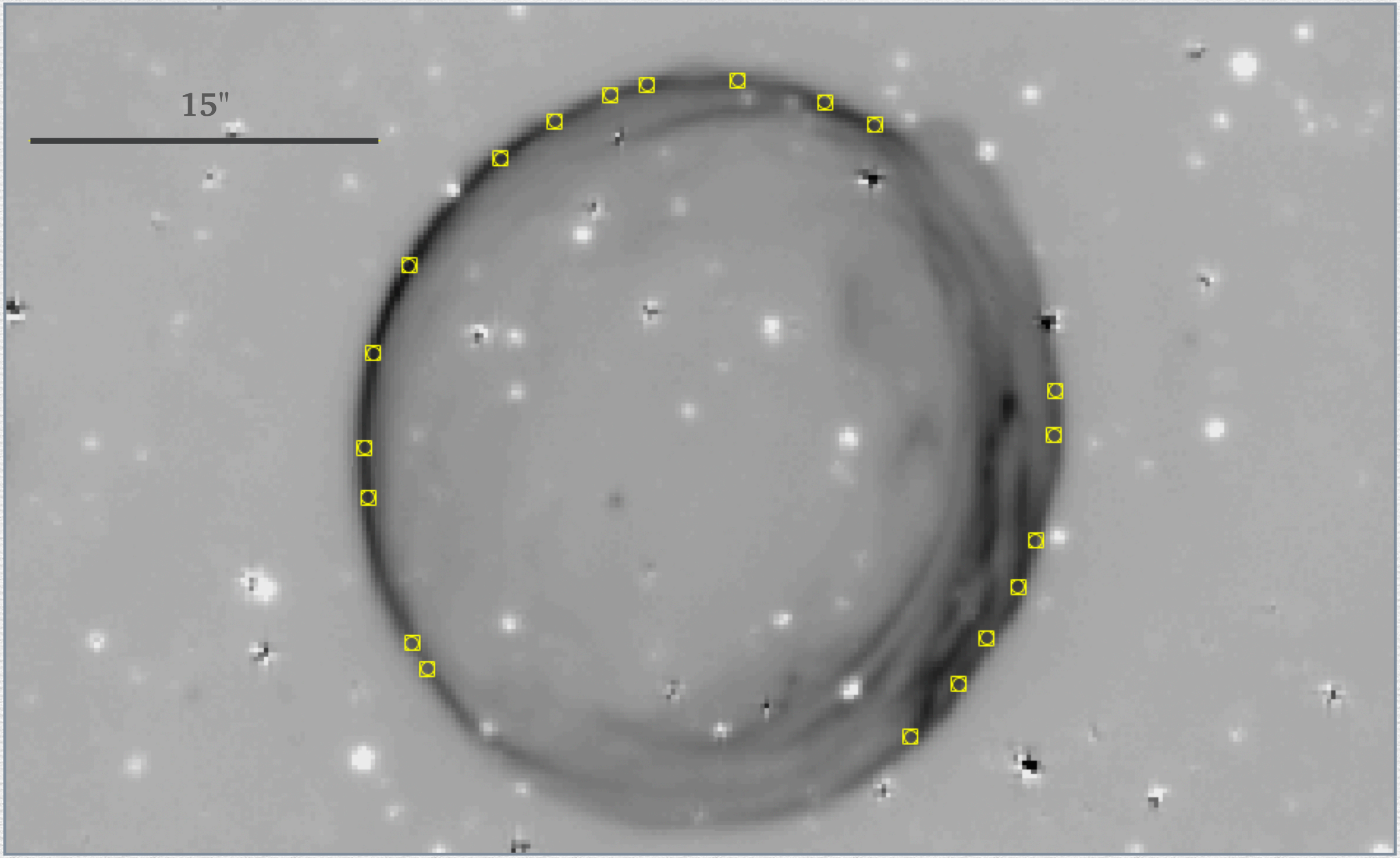
SNR 0509-67.5 Proper Motions (HST 10-yr Baseline) (Arunachalam et al. 2022)



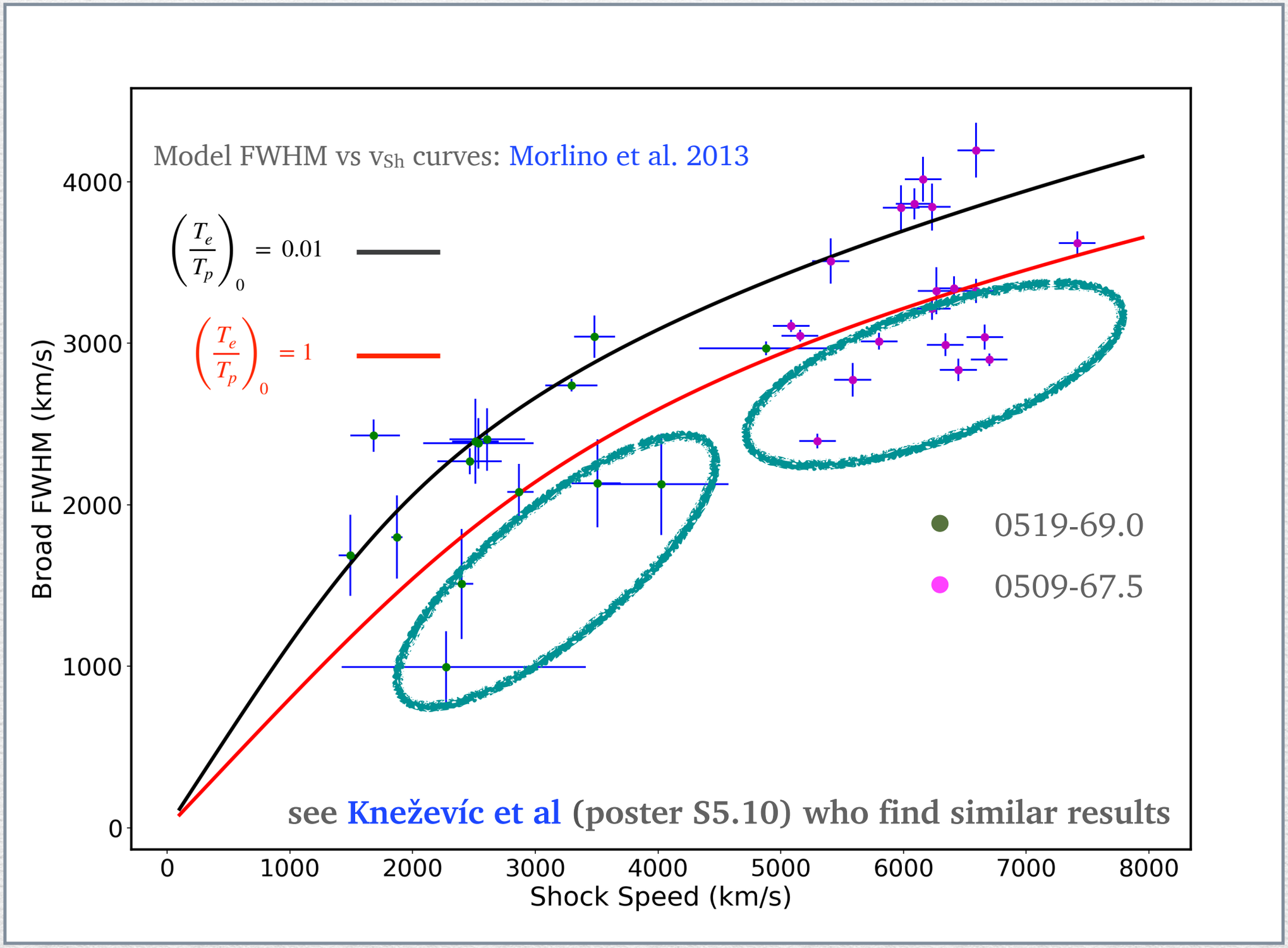


Sinusoidal density variation: evidence of CS wind? (e.g., Chiotellis talk)

MUSE Spectral Extraction windows (0.6"×0.6")

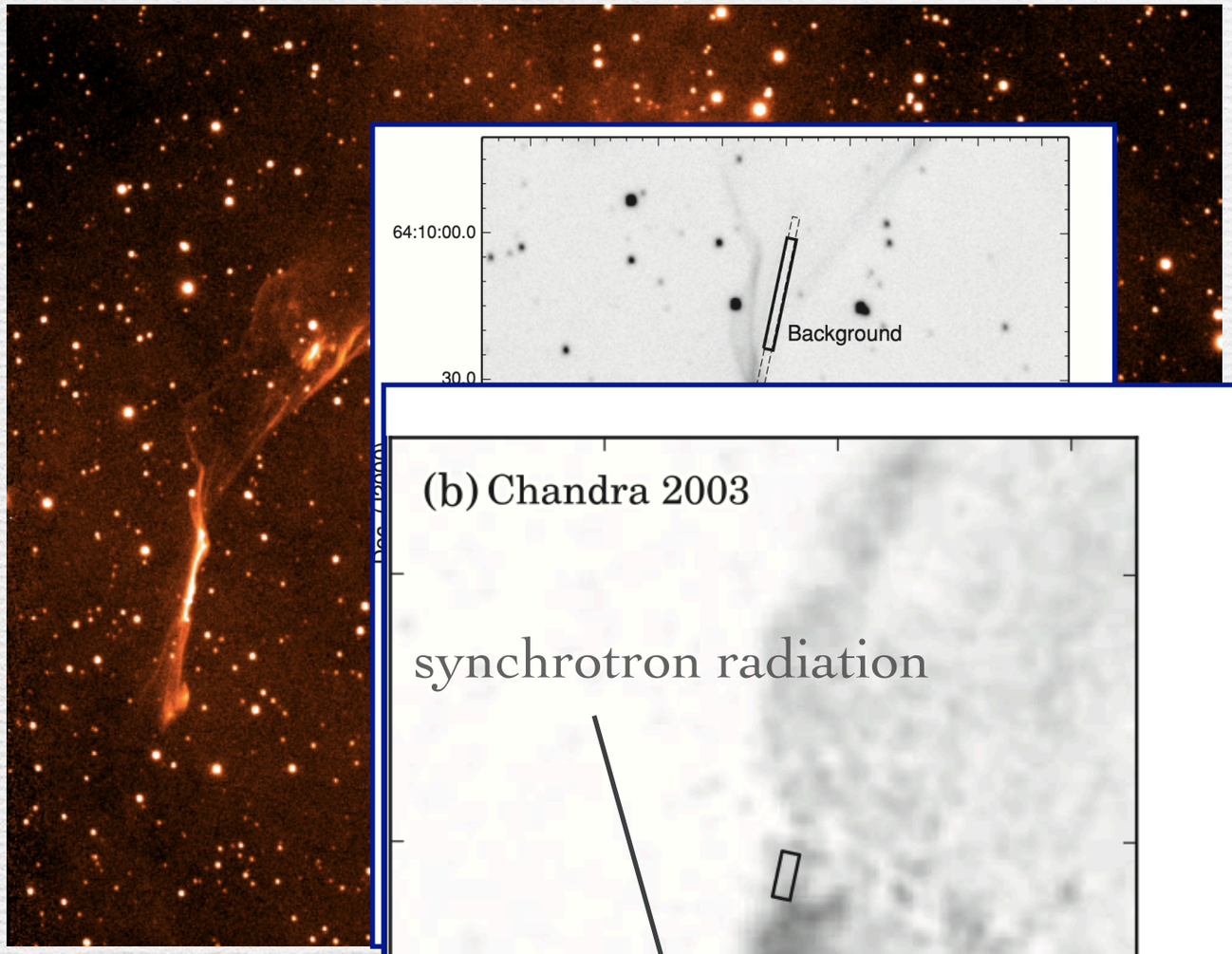


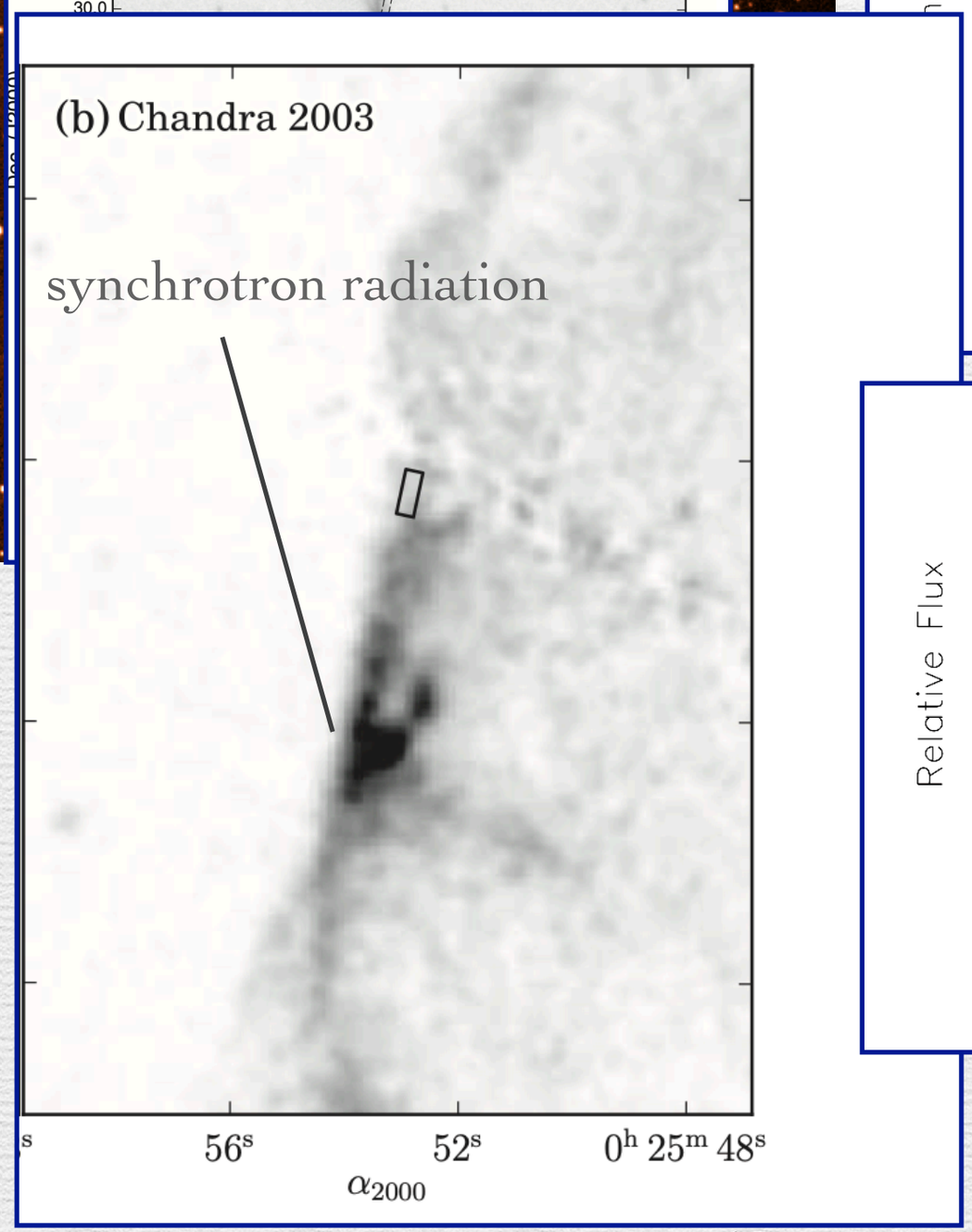
Results for SNR 0509-67.5 and 0519-69.0

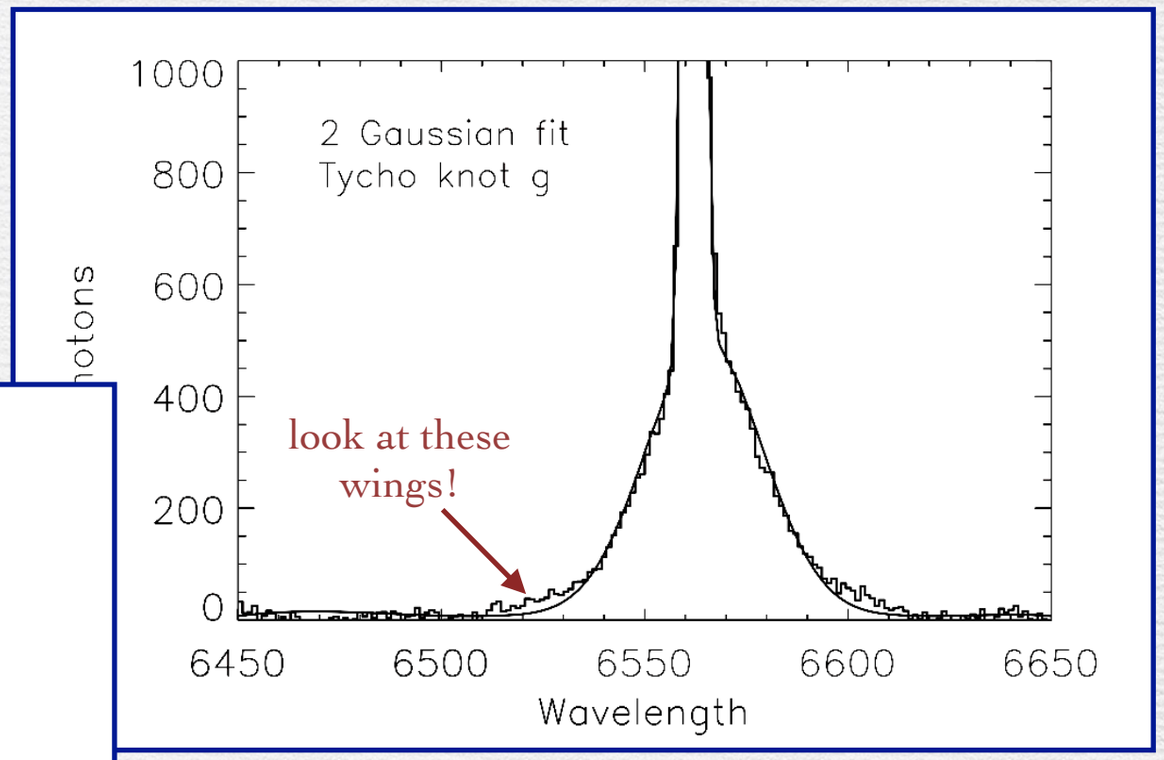


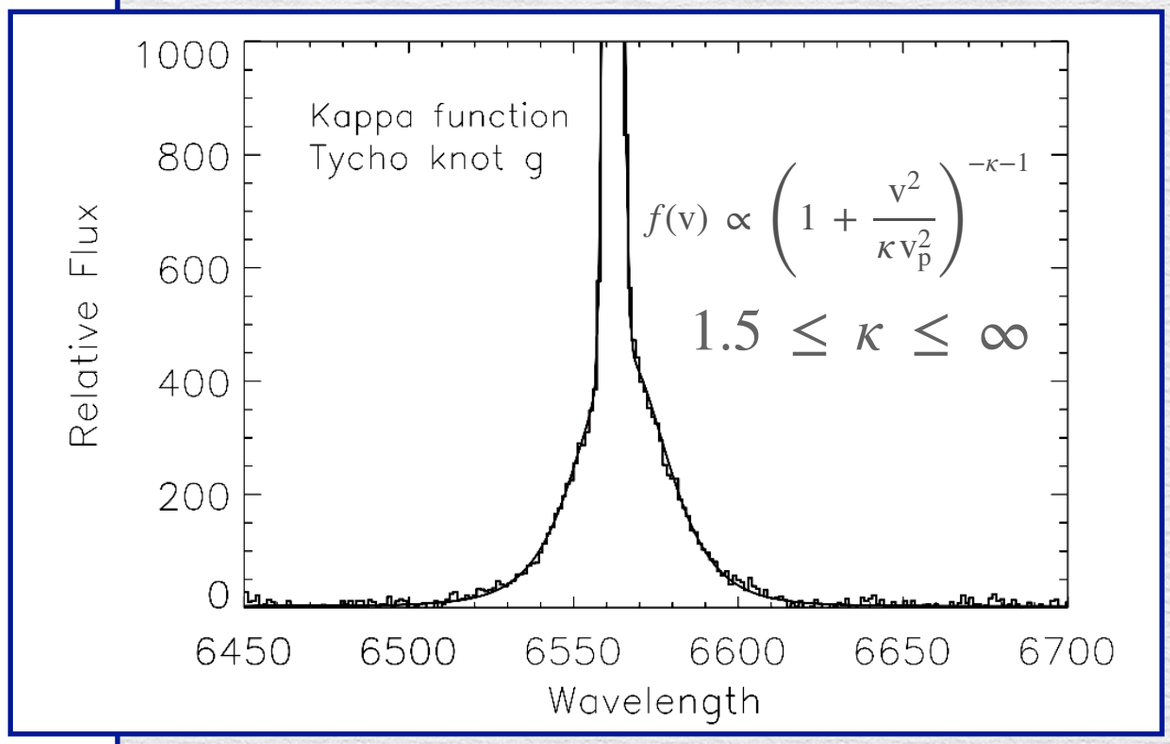
Proper motion shock speeds: Williams et al. 2022, Arunachalam et al. 2022

Non-Gaussian Wings on Broad Hα: Tycho



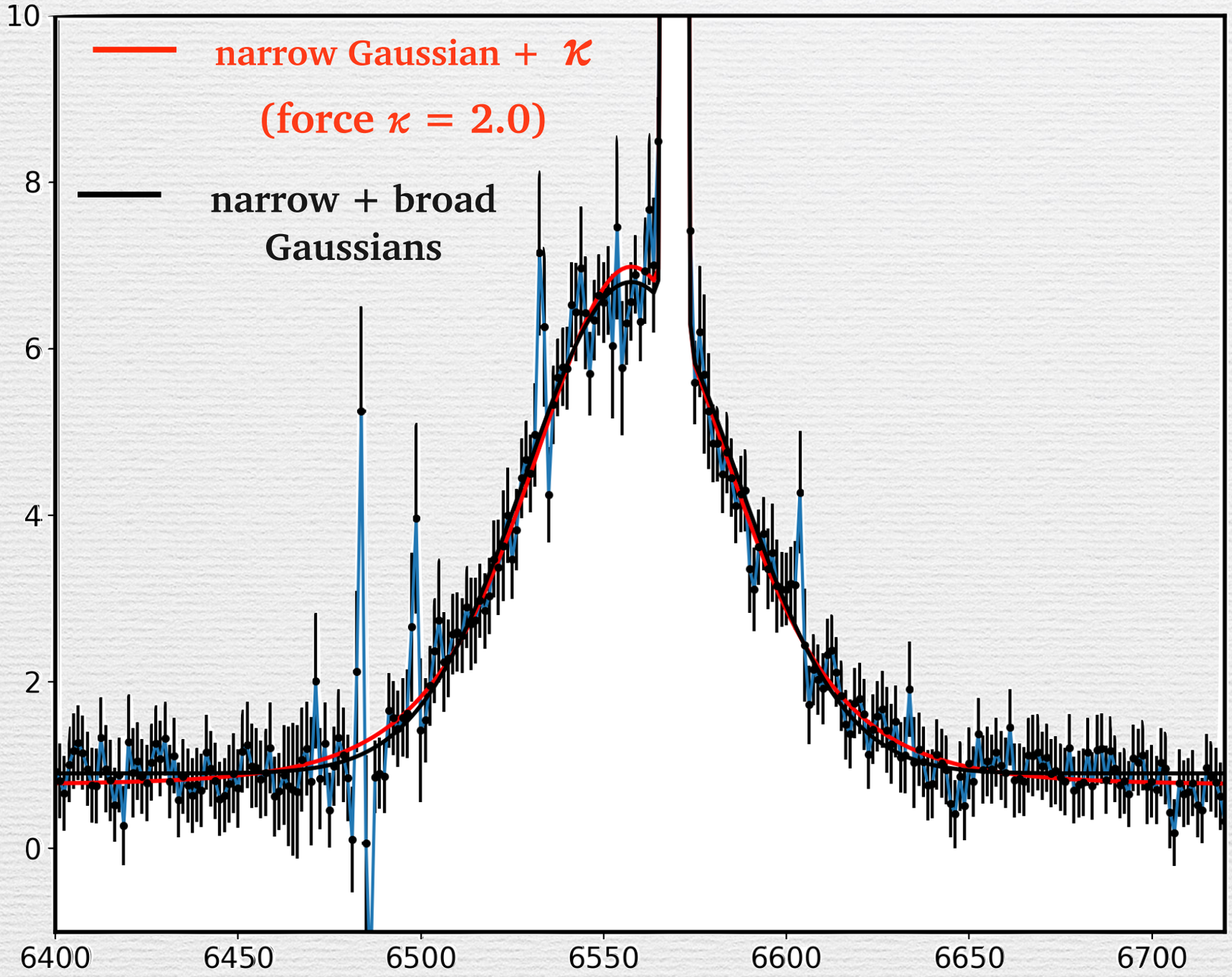


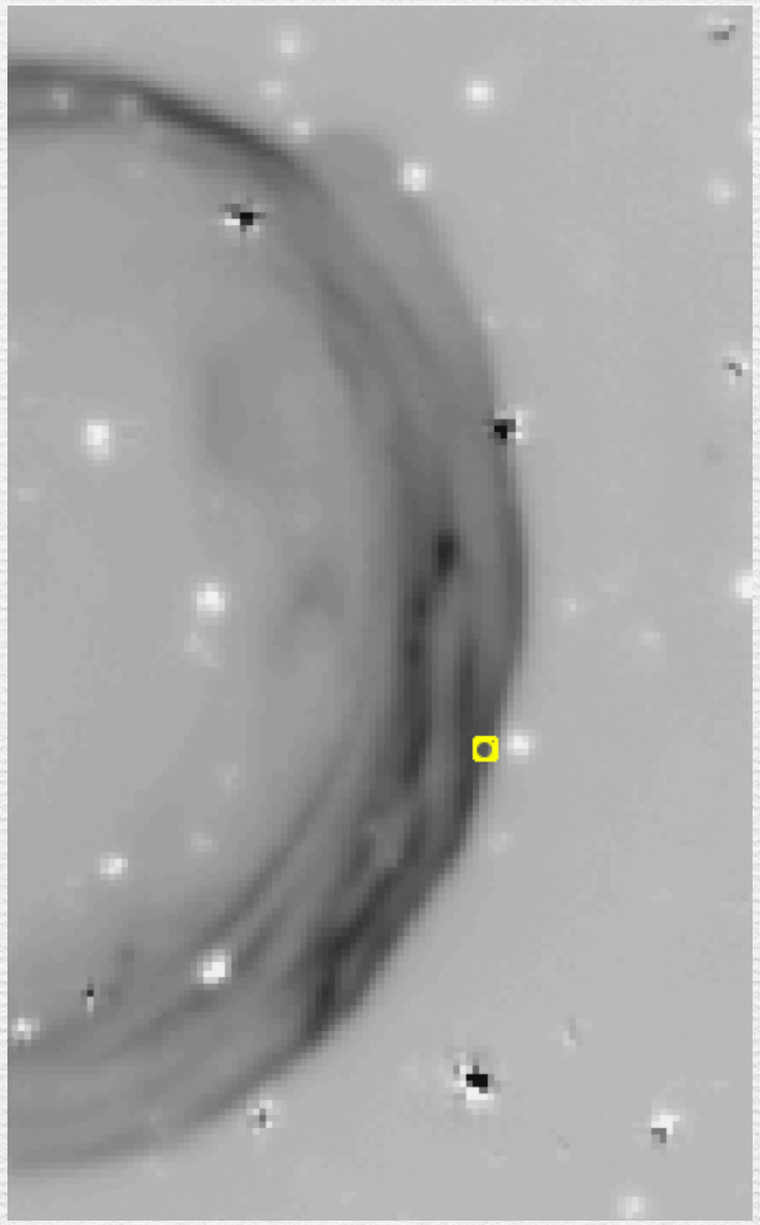




Best Fit: $\kappa = 2.0^{+1.6}_{-0.15}$

Kappa Profile Fits: 0509-67.5





(fits are statistically indistinguishable): no clear evidence for non-Maxwellian wings on the broad component

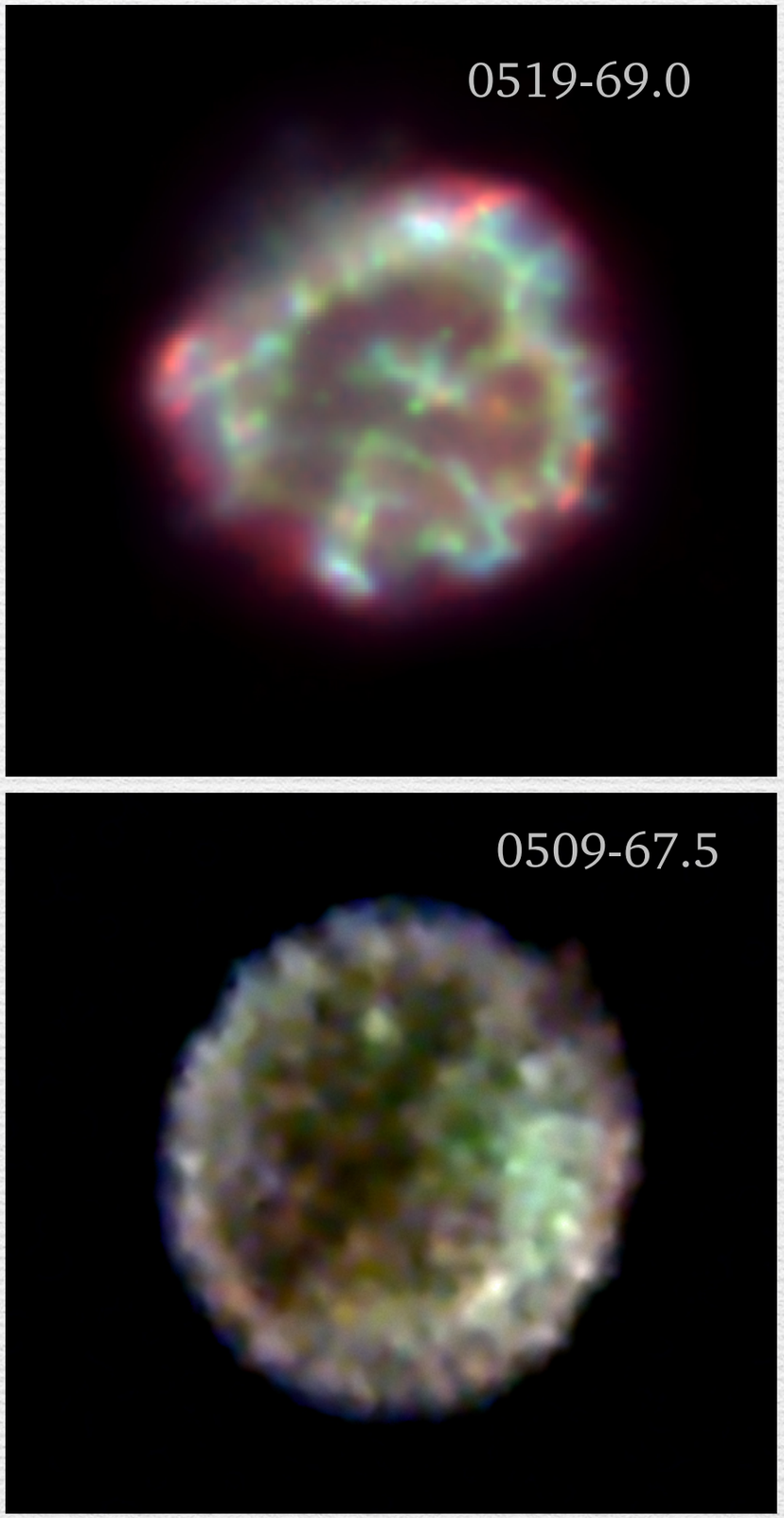
X-ray Spectra of Both SNRs Rule Out $\left(\frac{T_e}{T_p}\right)_0 \sim 1.0$

- Chandra X-ray spectroscopy of the forward shock in 0519-69.0 give $T_e \approx 1.43^{+0.12}_{-0.15}$ keV, with little variation around the rim (Schenck et al. 2016)

- Substantial variation in equilibration would produce substantial variations in X-ray volume emissivity: none seen (except for those caused by density fluctuations, e.g., 0519-69.0)

- Global X-ray spectral fits of 0509-67.5 show $\left(\frac{T_e}{T_p}\right)_0 \sim 0.01$ (Kosenko et al. 2008)

- Even degree of ion-ion equilibration in 0509-67.5 is low (FUSE spectroscopy; Ghavamian et al. 2007)



Density Fluctuation Model of ISM (Shimoda et al. 2015)

$$(T_n)_0 \approx \frac{3}{16}\frac{m_p V_n^2}{k} \qquad (T_{pm})_0 \approx \frac{3}{16}\frac{m_p V_{pm}^2}{k}$$

(...if minimal equilibration)

$$\eta \equiv \frac{(T_{pm})_0 - (T_n)_0}{(T_{pm})_0} \quad \text{(S15)}$$

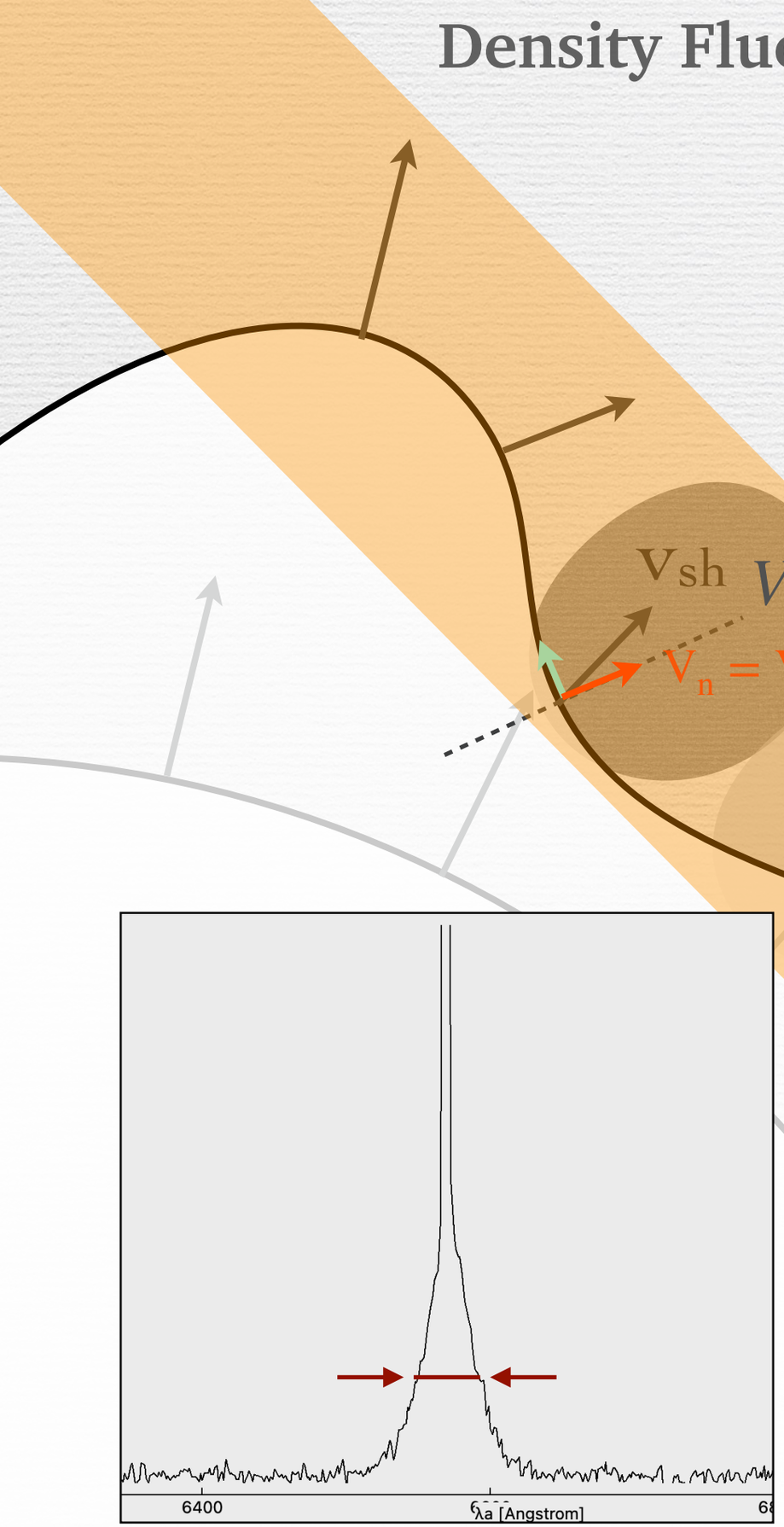
$$(\langle\rho\rangle_0 + \Delta\rho)V_+^2 \approx (\langle\rho\rangle_0 - \Delta\rho)V_-^2$$

ram pressure conservation

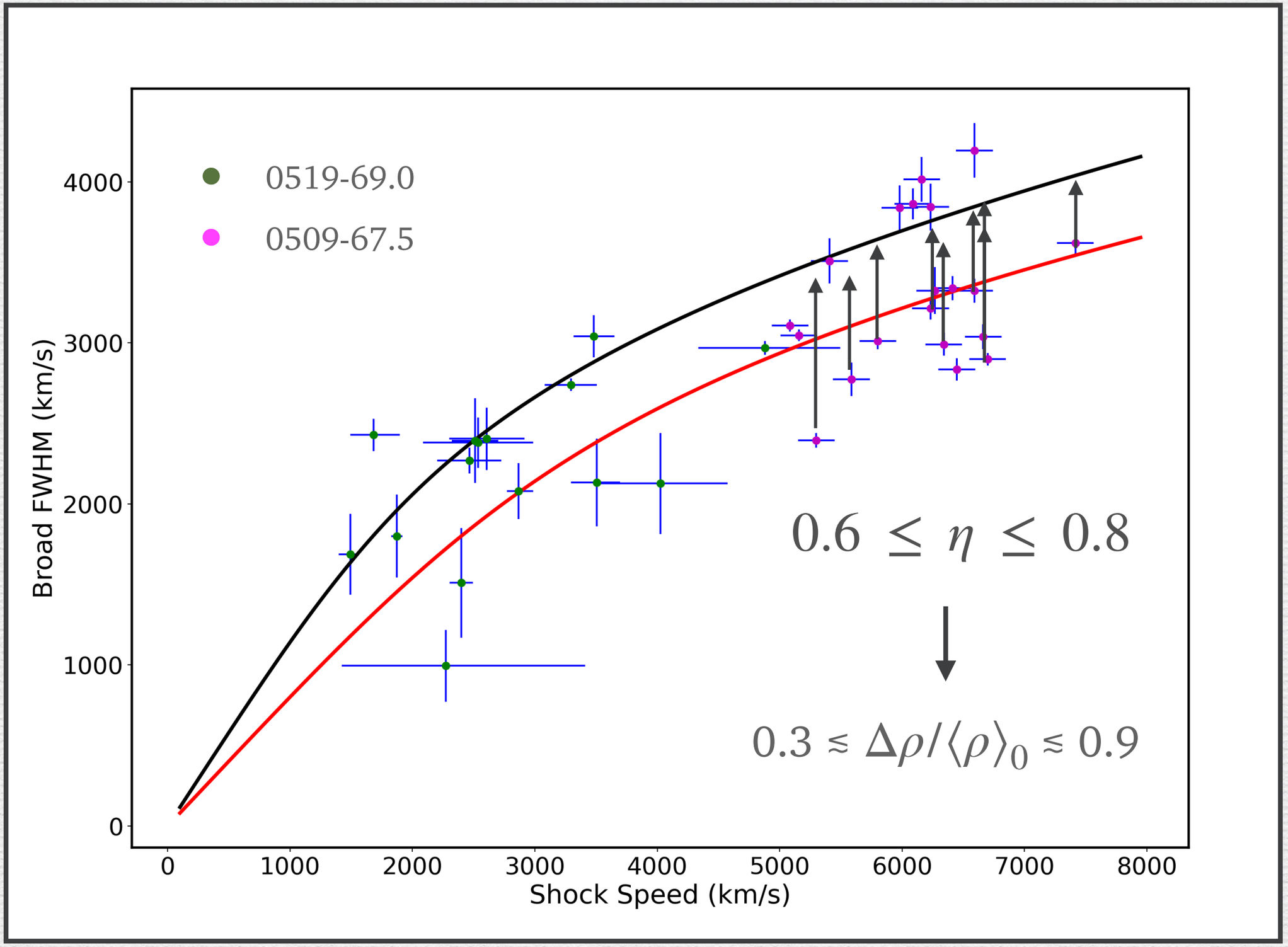
$$2\left(\frac{\Delta\rho}{\langle\rho\rangle_0}\right) \lesssim \eta \lesssim \left(\frac{\Delta\rho}{\langle\rho\rangle_0}\right)^2 \quad \textbf{(S15)}$$

$$\downarrow$$

$$\frac{\eta}{2} \lesssim \frac{\Delta\rho}{\langle\rho\rangle_0} \lesssim \sqrt{\eta}$$



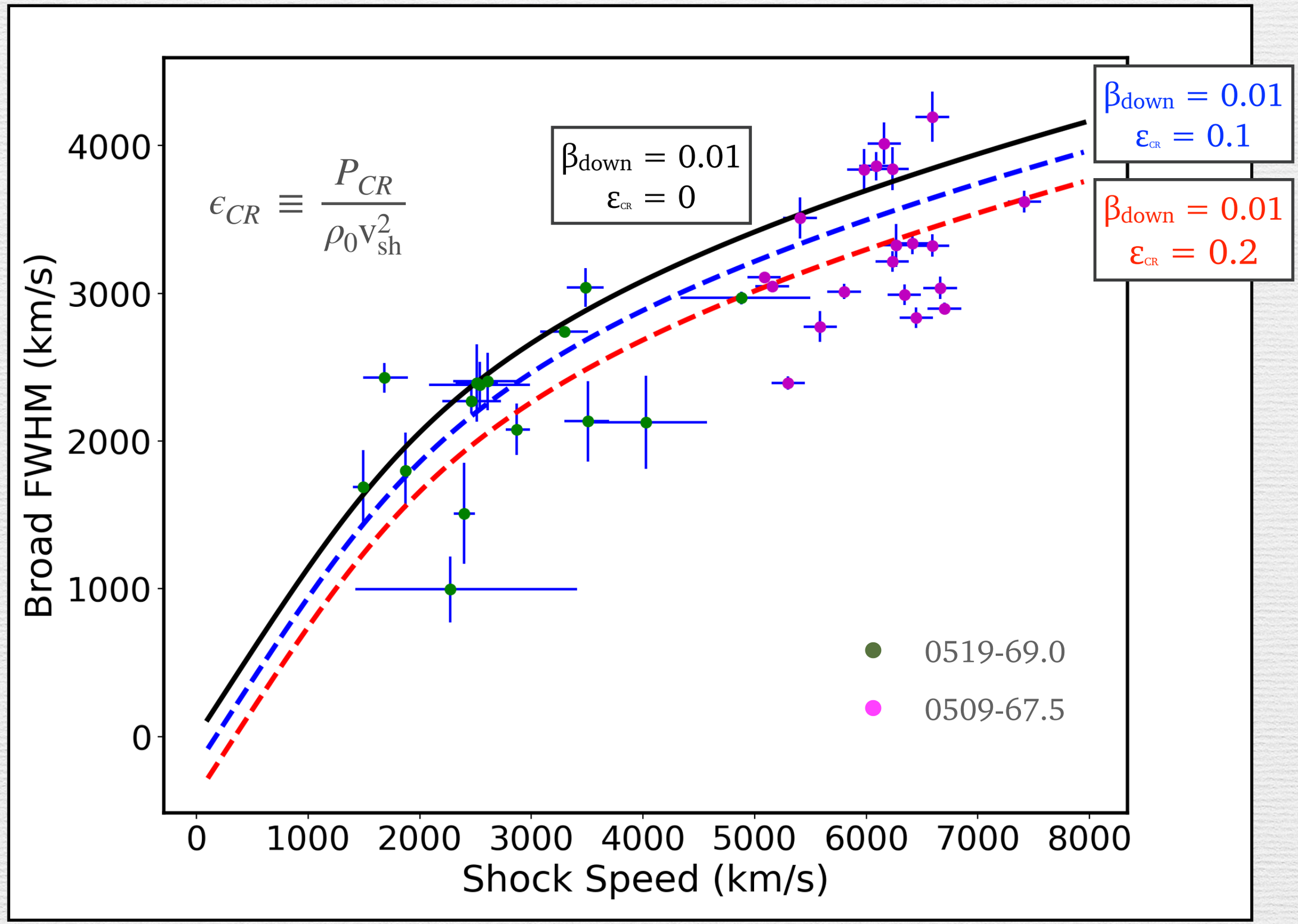
Estimating η for 0509-67.5



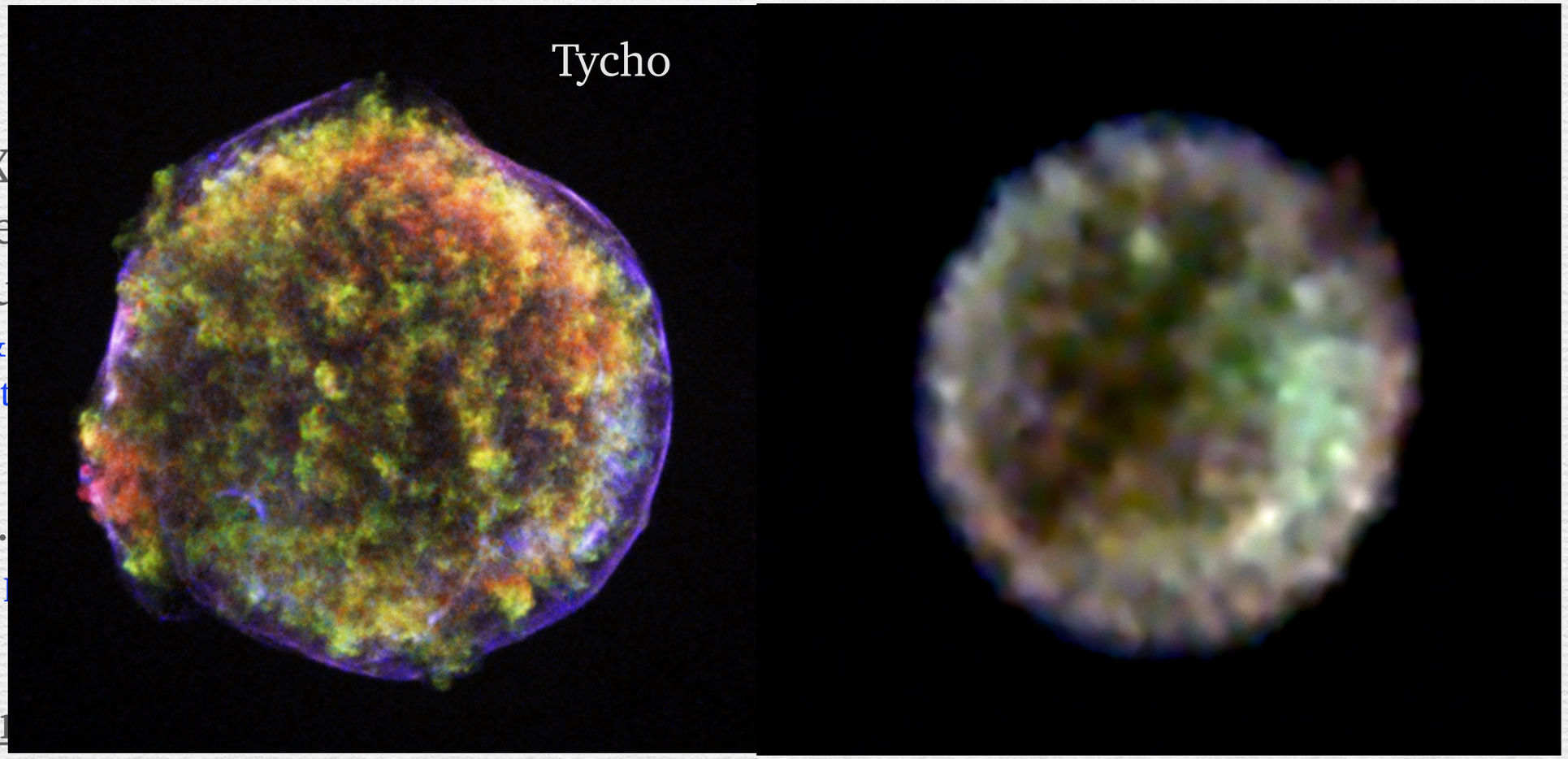
$\Delta\rho/\langle\rho\rangle_0 \sim 0.3$ broadly consistent with with decay of SN-driven turbulence (P(k) $\propto k^{-5/3}$; L ~ 100 pc) down to parsec scales (e.g., de Avillez & Breitschwerdt 2007; Inoue et al. 2013; Shimoda et al. 2015)

$\varepsilon_{CR} \neq 0$ Still Doesn't Solve The Broad FWHM Problem

(Morlino et al. 2013)



BUT: There is Evidence for Cosmic Ray Acceleration in 0509-67.5

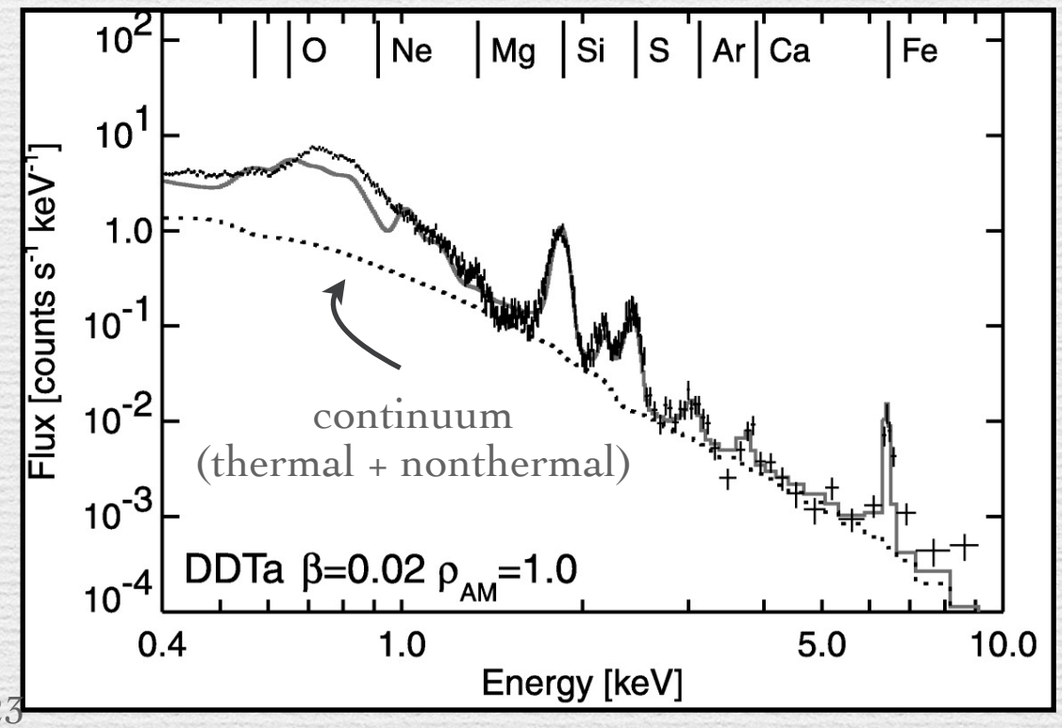


- Global X
  presence
  continuu
  (Warren &
  Kosenko et

- $E_{roll} \sim 0.$
  (Warren &

- But: no
  filaments (consistent with expected ion-neutral damping; Drury et al. 1996; Reville et al 2008; Ghavamian et al. 2012)

- Feeble radio emission (as with the other three LMC Balmer SNRs; Seok et al. 2013)



Badenes et al. 2008

Conclusions

- New, longer baseline Hα proper motions (≳ 10 yrs) are possible for LMC Balmer-dominated SNRs, giving tighter shock speed constraints

- Deep MUSE IFU datacubes are also available, enabling high S/N Hα line profile measurements for each entire SNR

- FWHM vs v_{sh} measurements strongly deviate from the best model predictions, falling well below $\left(T_e/T_p\right)_0 = 1$. Other datapoints fall well above $\left(T_e/T_p\right)_0 \sim \frac{m_e}{m_p}$, <u>greatly complicating equilibration measurements</u>

- **Why?** Likely do to some combination of:

  1. *Density fluctuations/shock geometry*

  2. *Energy loss to cosmic ray acceleration*

  3. *Coupling between fast neutrals and protons (models need to catch up with observations)*