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TOWSON UNIVERSITY

Electron-Ion Thermal Equilibration in Collisionless Shocks

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SUPERNOVA REMNANTS
AN ODYSSEY IN SPACE AFTER STELLAR DEATH
6 - 11 JUNE 2016, CHANIA, CRETE, GREECE

Shock Basics

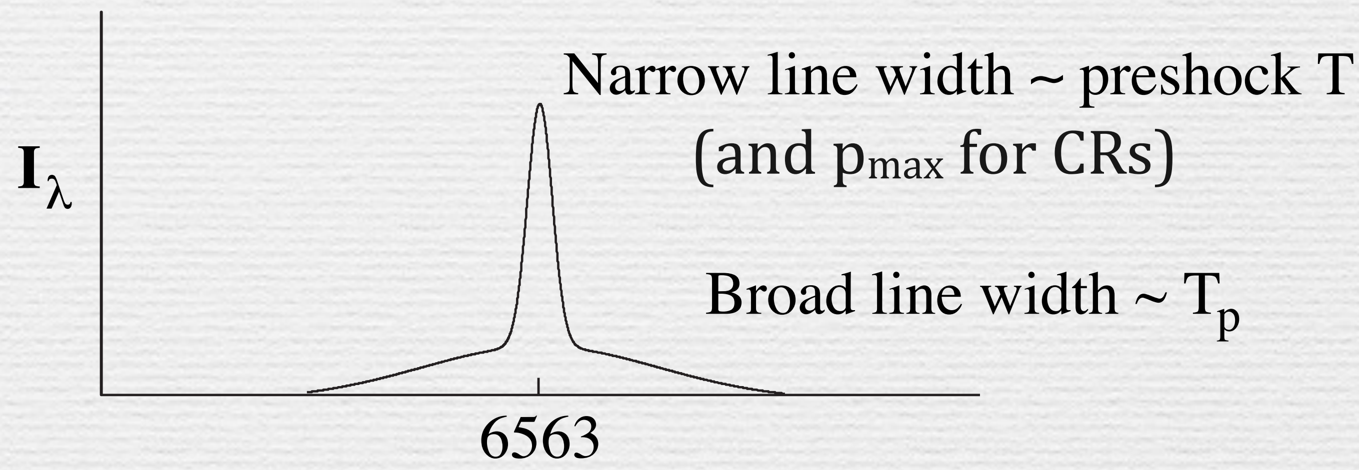
Balmer-Dominated Shocks

- Non-radiative shocks in partially neutral gas produce optical spectra dominated by Balmer lines of H

- Slow, ambient H I rapidly ionized away

- Fast H I forms by charge exchange (pickup ions also formed)

Collisional excitation of fast and slow H I produces *broad* and *narrow* Balmer lines



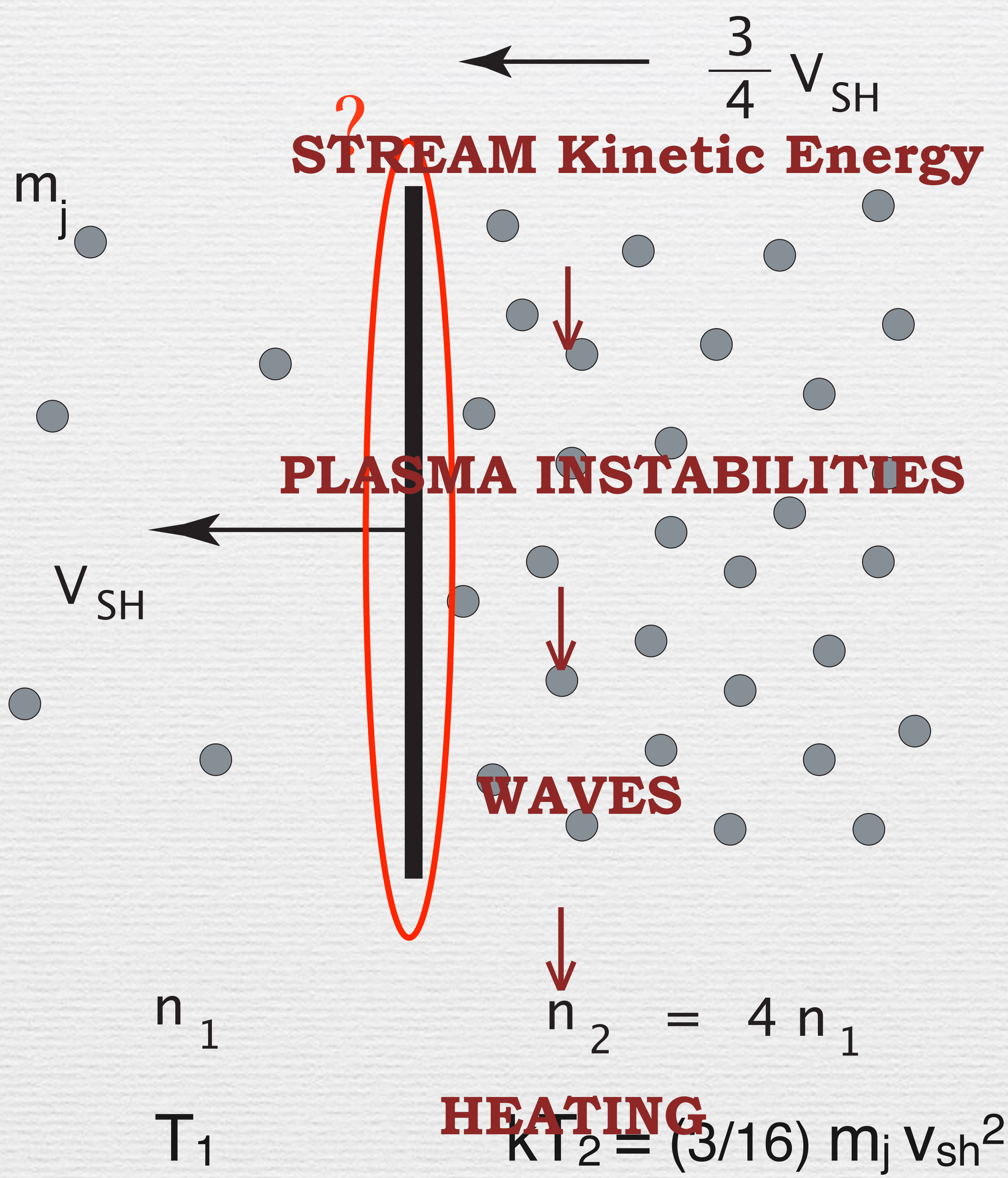
$$I_{H\alpha} = 0.2\,\frac{h\nu_{H\alpha}}{4\pi} n_{HI} V_{SH}$$

$$I_{H\alpha} \sim 5\times10^{-6}\left(\frac{n_{HI}}{1\ \mathrm{cm}^{-3}}\right)\left(\frac{V_{sh}}{1000\ \mathrm{km/s}}\right)$$

ergs cm^{-2} s^{-1} sr^{-1}

(faint!)

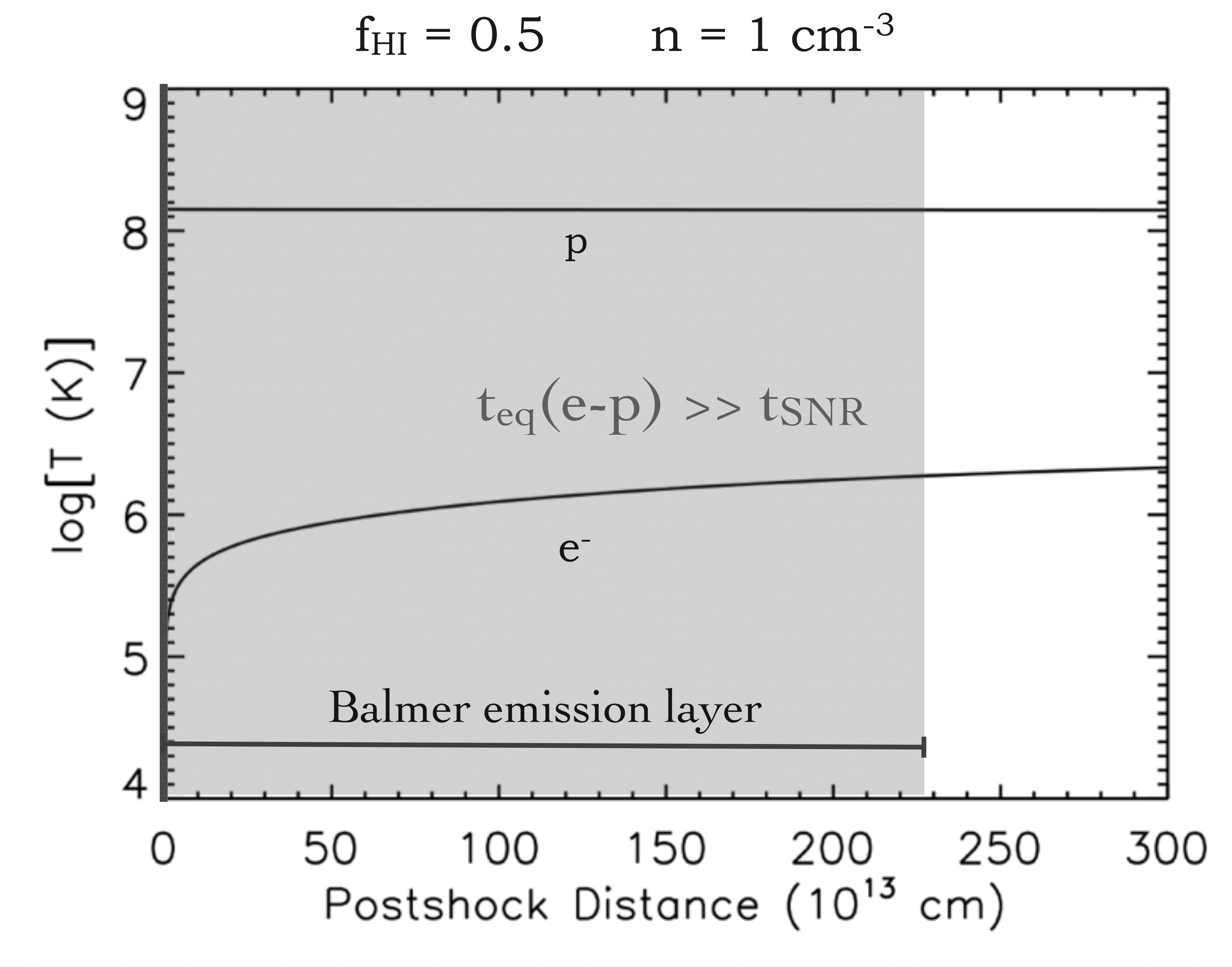
How Are Electrons Heated Relative to Ions?



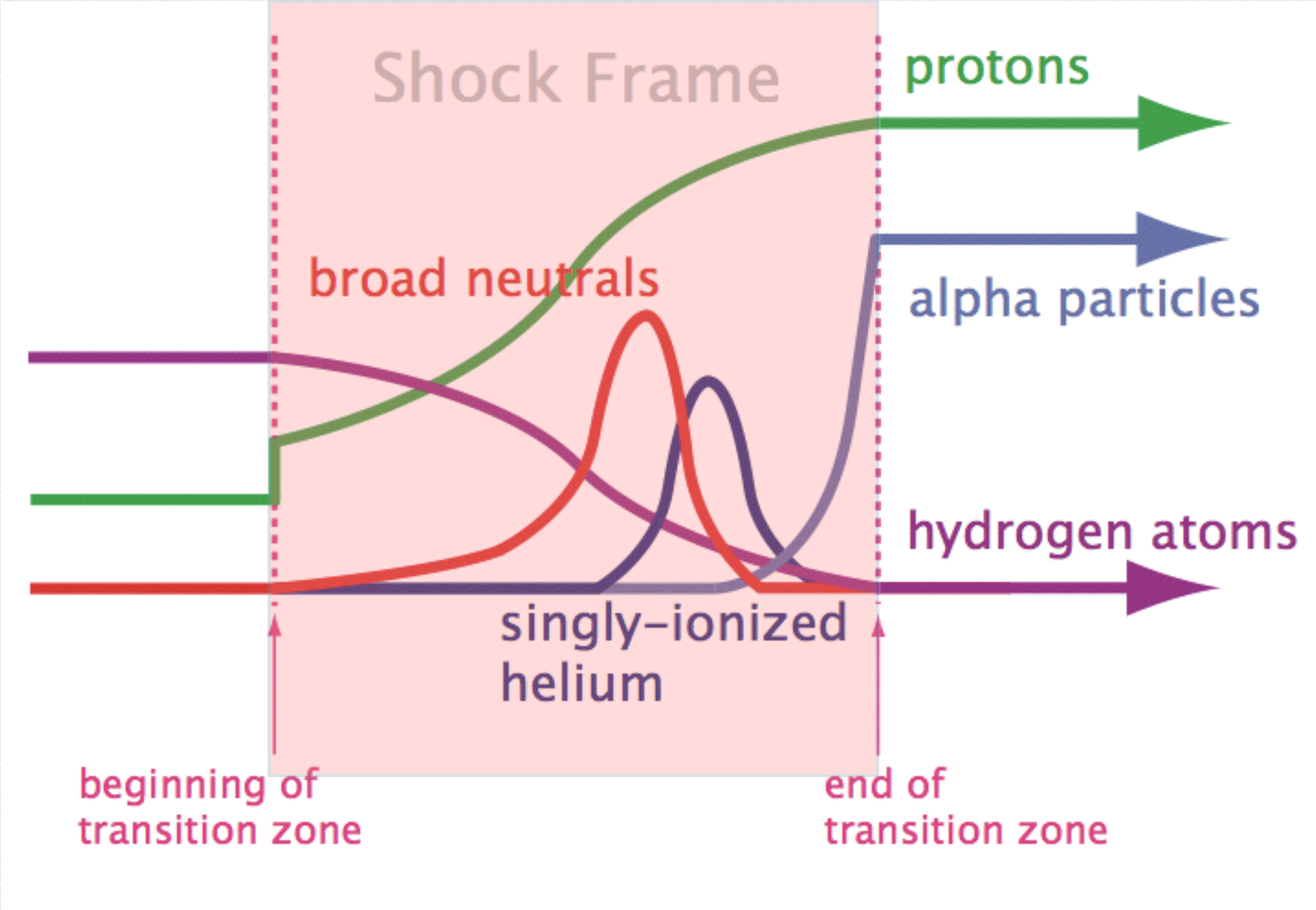
strong shock
jump conditions
for ideal gas

Slow Coulomb Equilibration

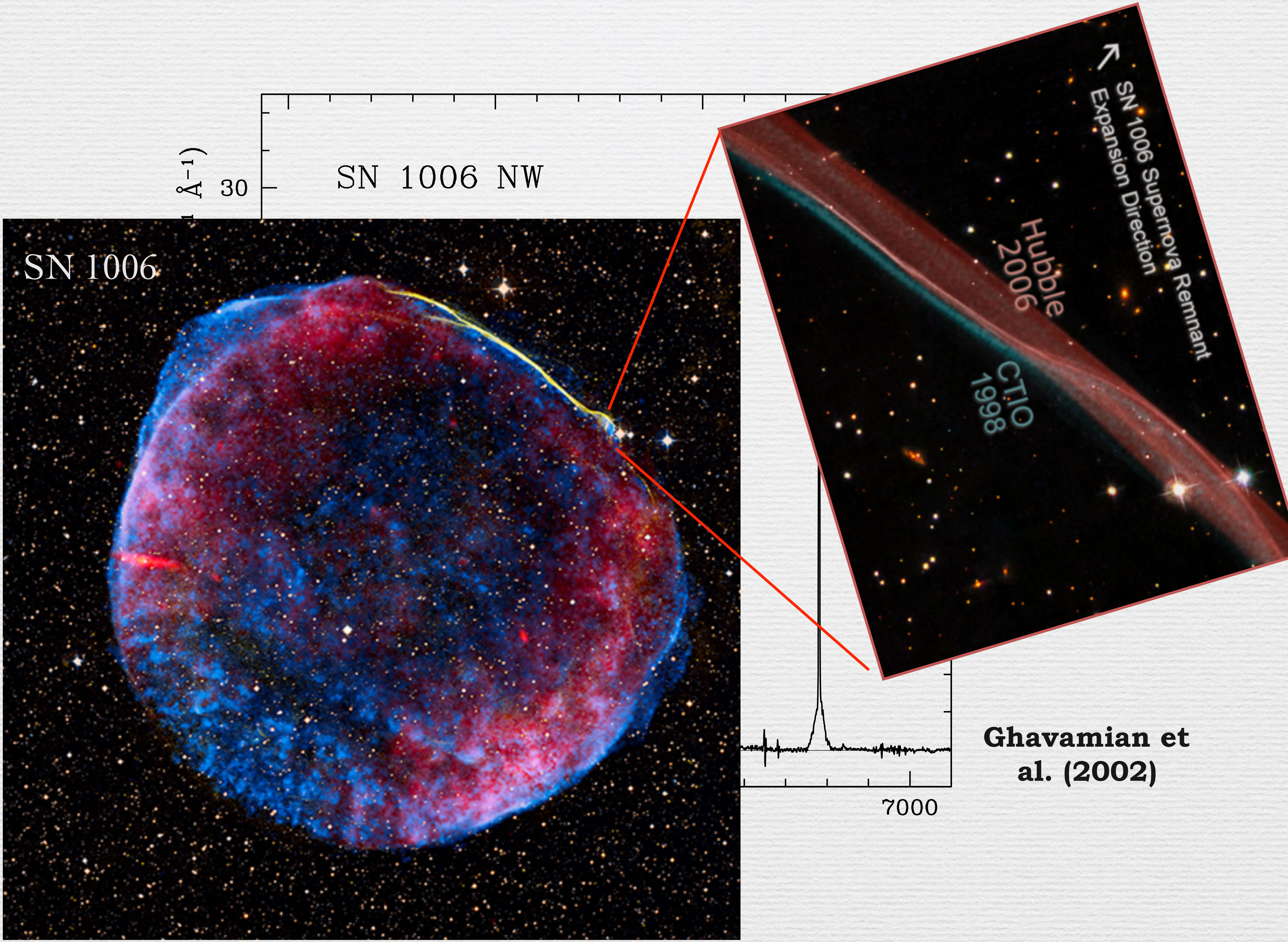
Example: V_{SH} = 2500 km/s, β ($\equiv T_e/T_p$) = m_e/m_p



GHR01



van Adelsberg et al. (2008)

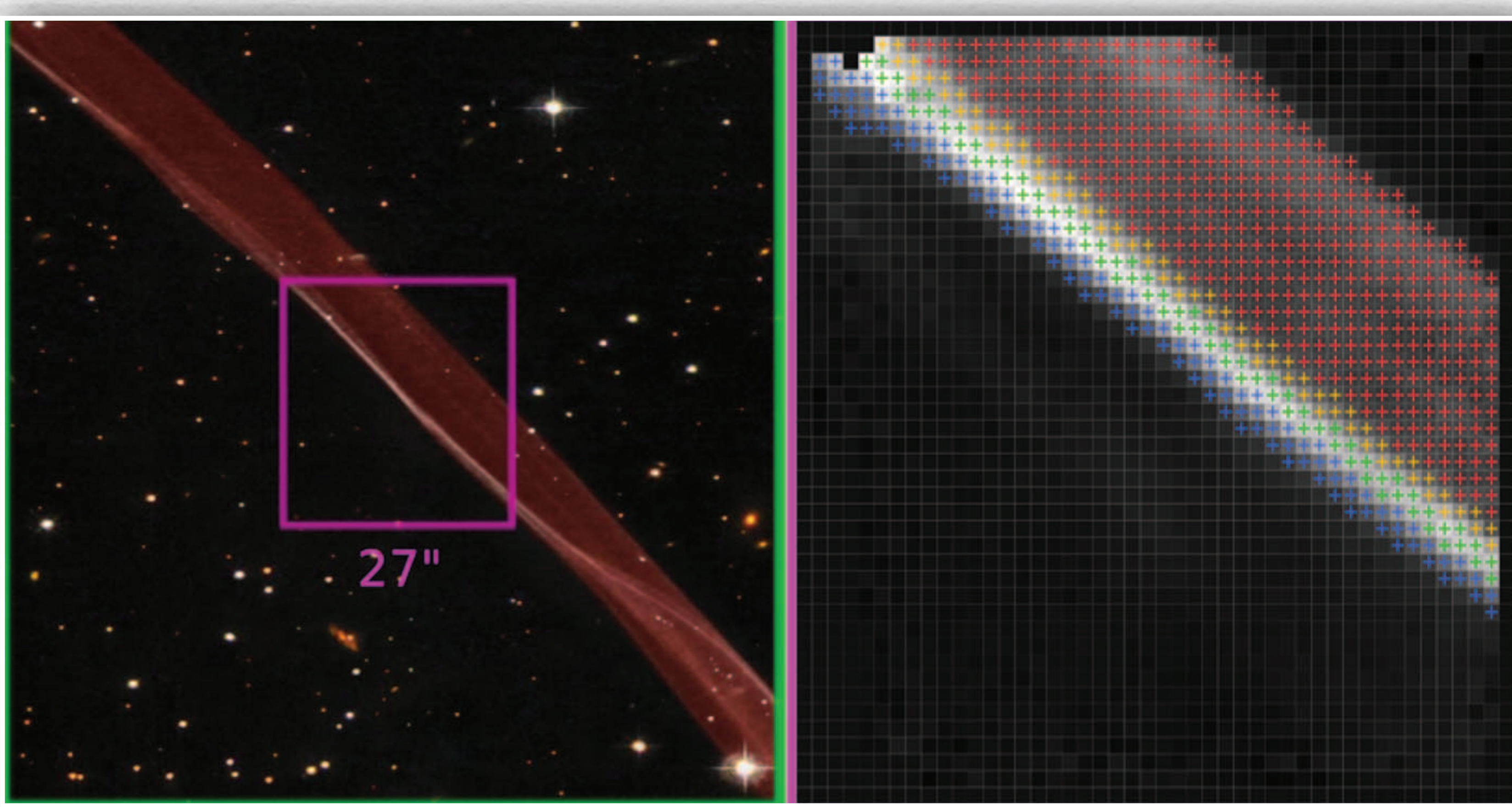


Ghavamian et al. (2002)

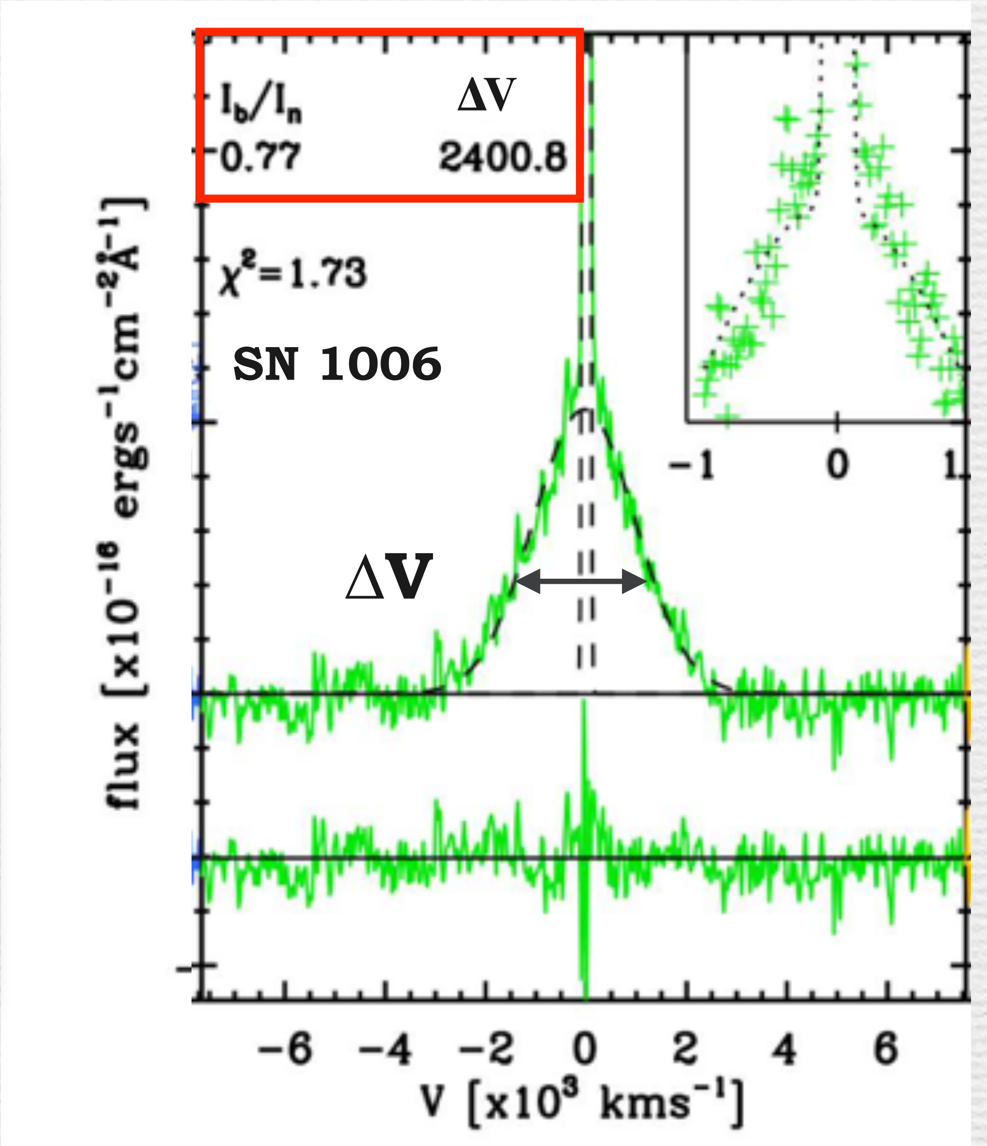
Observables in Balmer-Dominated Spectra

SN 1006

Nikolic et al. (2013)



Nikolic et al. (2013): IFU obs.



$$\Delta V_{\mathrm{broad}}(\mathrm{H}\alpha,\ \mathrm{H}\beta,\ldots) \propto T_p,\ V_{SH},\ \varepsilon_{CR}$$

(Smith et al. 1991; G01, G02, G07, G13, van Adelsberg et al. 2008; Blasi et al 2012; Morlino et al. 2012, 2013)

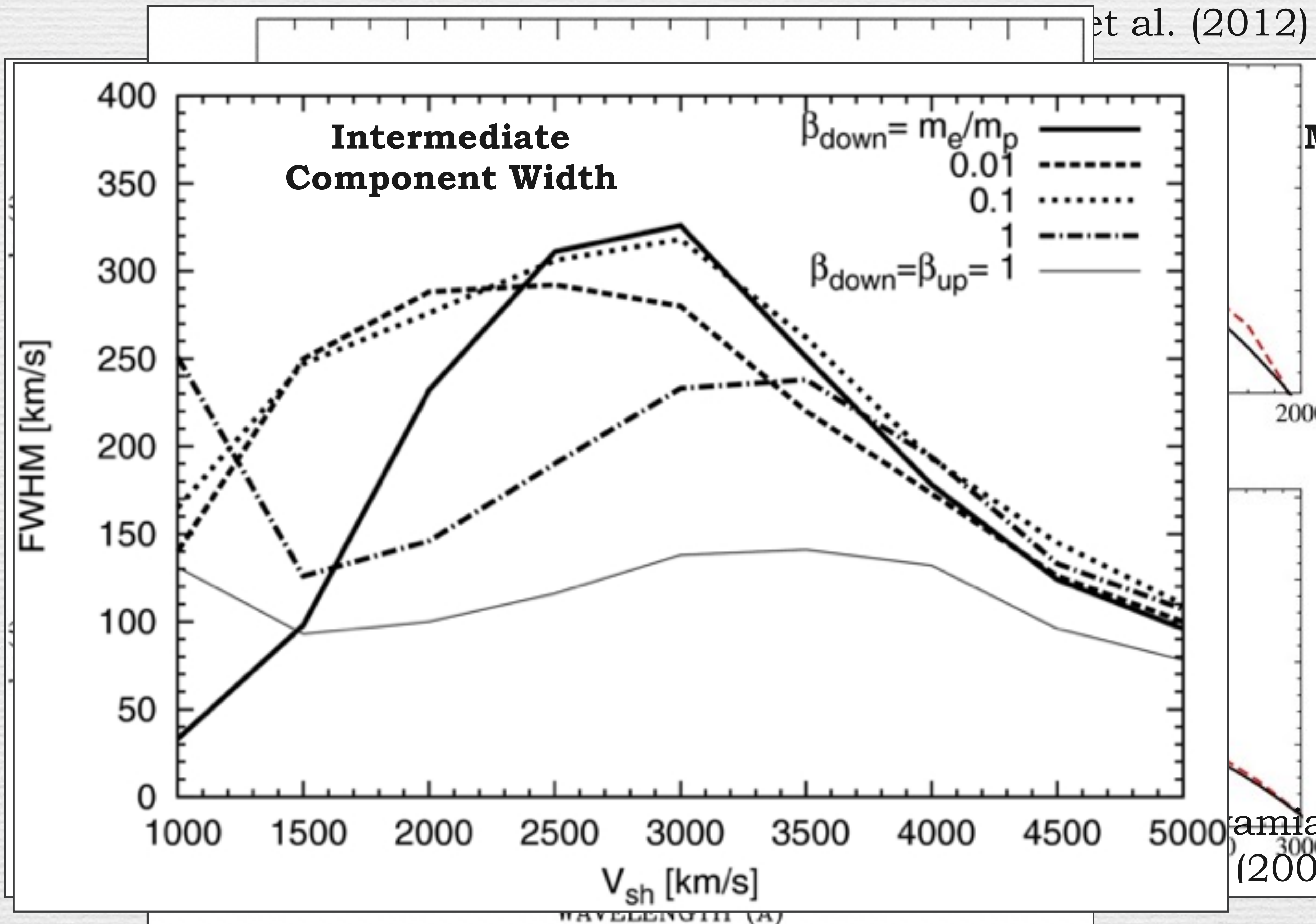
$$\frac{I_b}{I_n} \propto \frac{\langle \sigma_{cx} v \rangle}{\langle \sigma_i\, v \rangle} \rightarrow (\beta_{up},\ \beta_{down},\ V_{SH},\ \varepsilon_{CR})$$

$$(\varepsilon_{CR} \equiv P_{CR}\ /\ \rho_0\ V_{SH}^2)$$

Models

Latest Models Predict a THIRD Hα Component!

- **Neutral return flux** (NRF) upstream deposits energy ahead of shock, creating an intermediate width Hα component
- Typical ΔV_{in} ~ 200-300 km/s: *may be blended with narrow component at low spectral res observations* (Morlino et al 2012)



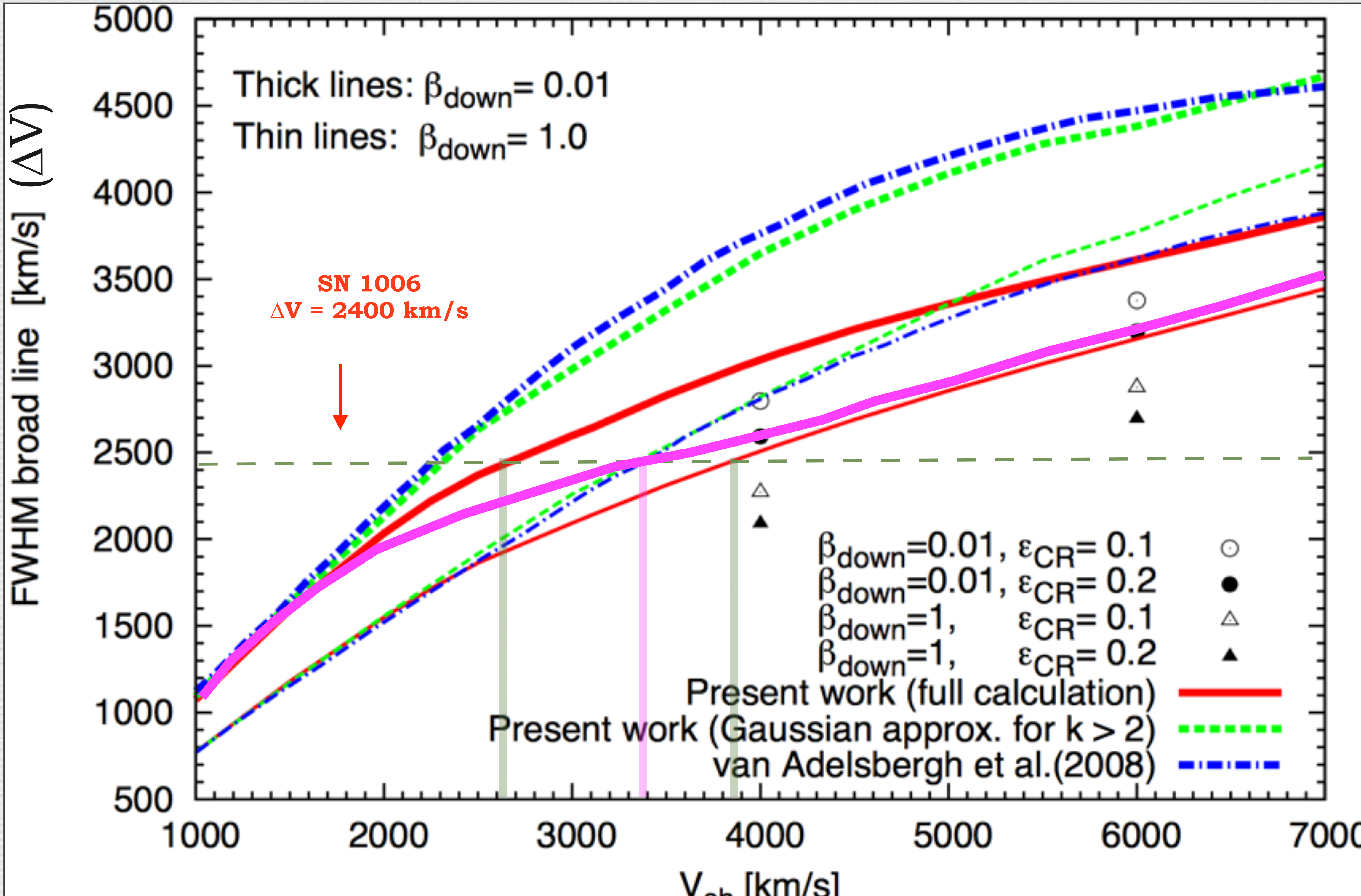
et al. (2012)

Morlino et al. (2012)

amian et al. (2000)

ΔV vs V_{SH} Plot Affected By NRF Too: SN 1006 Again

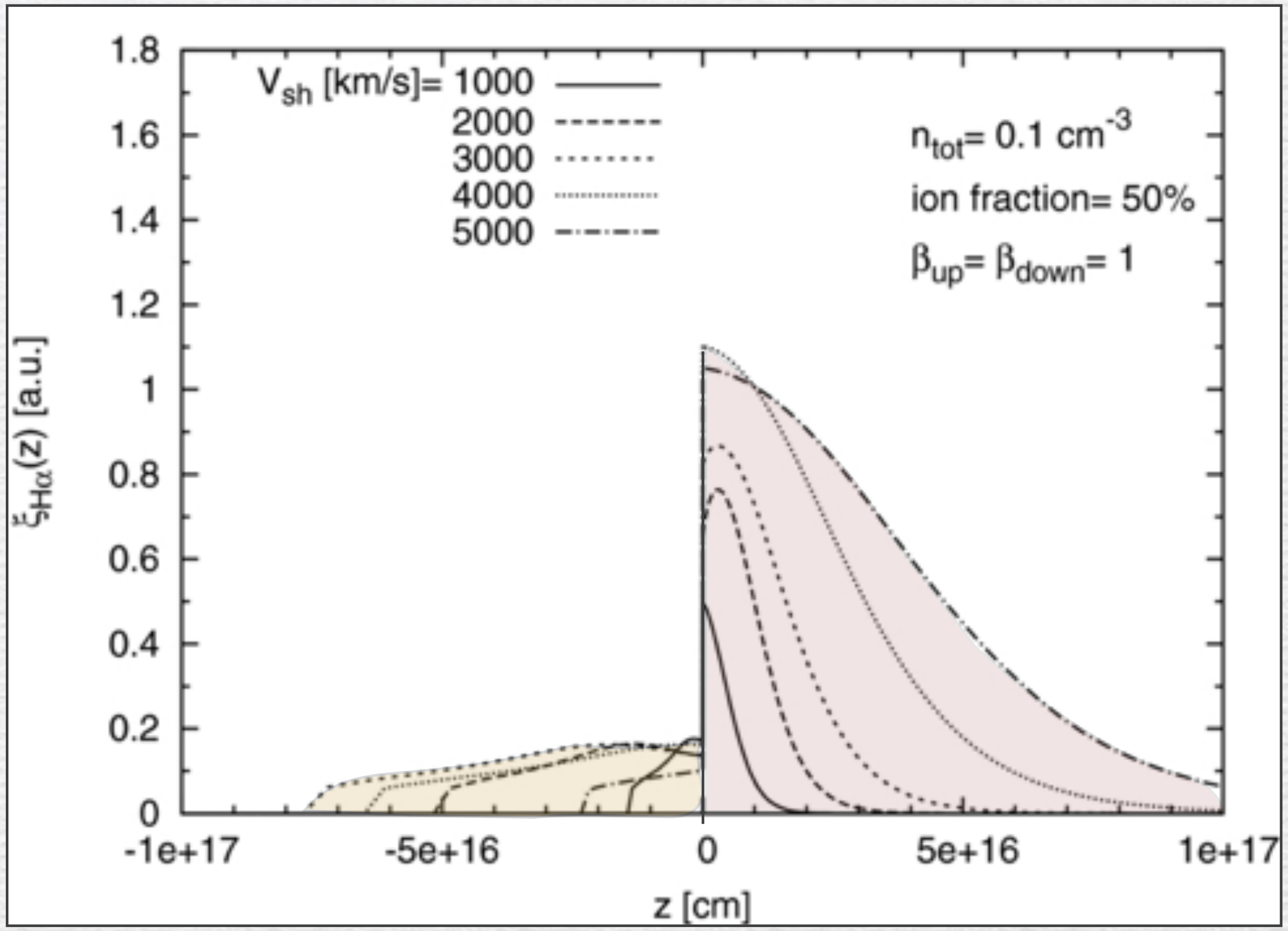
Morlino et al. (2013)

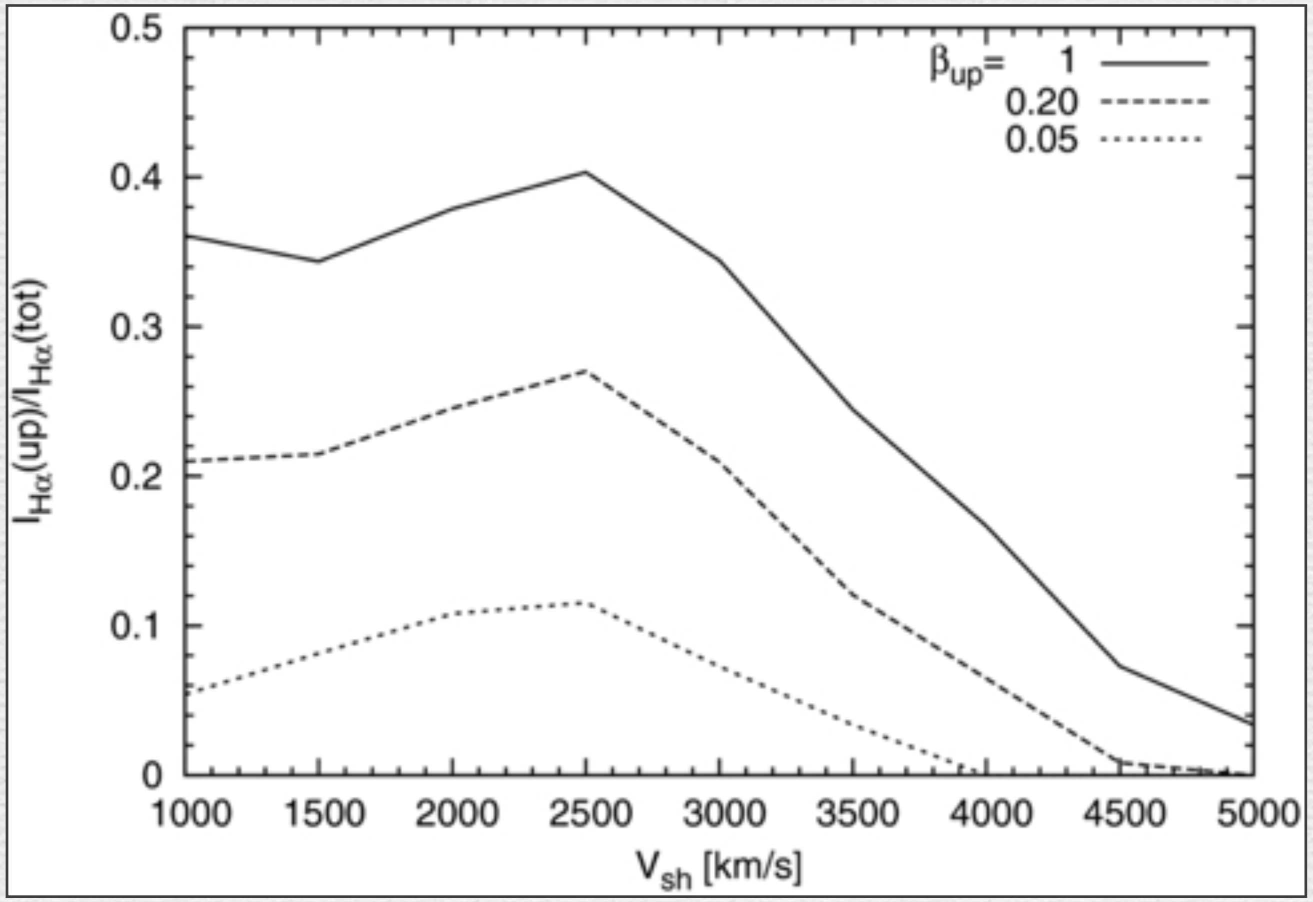


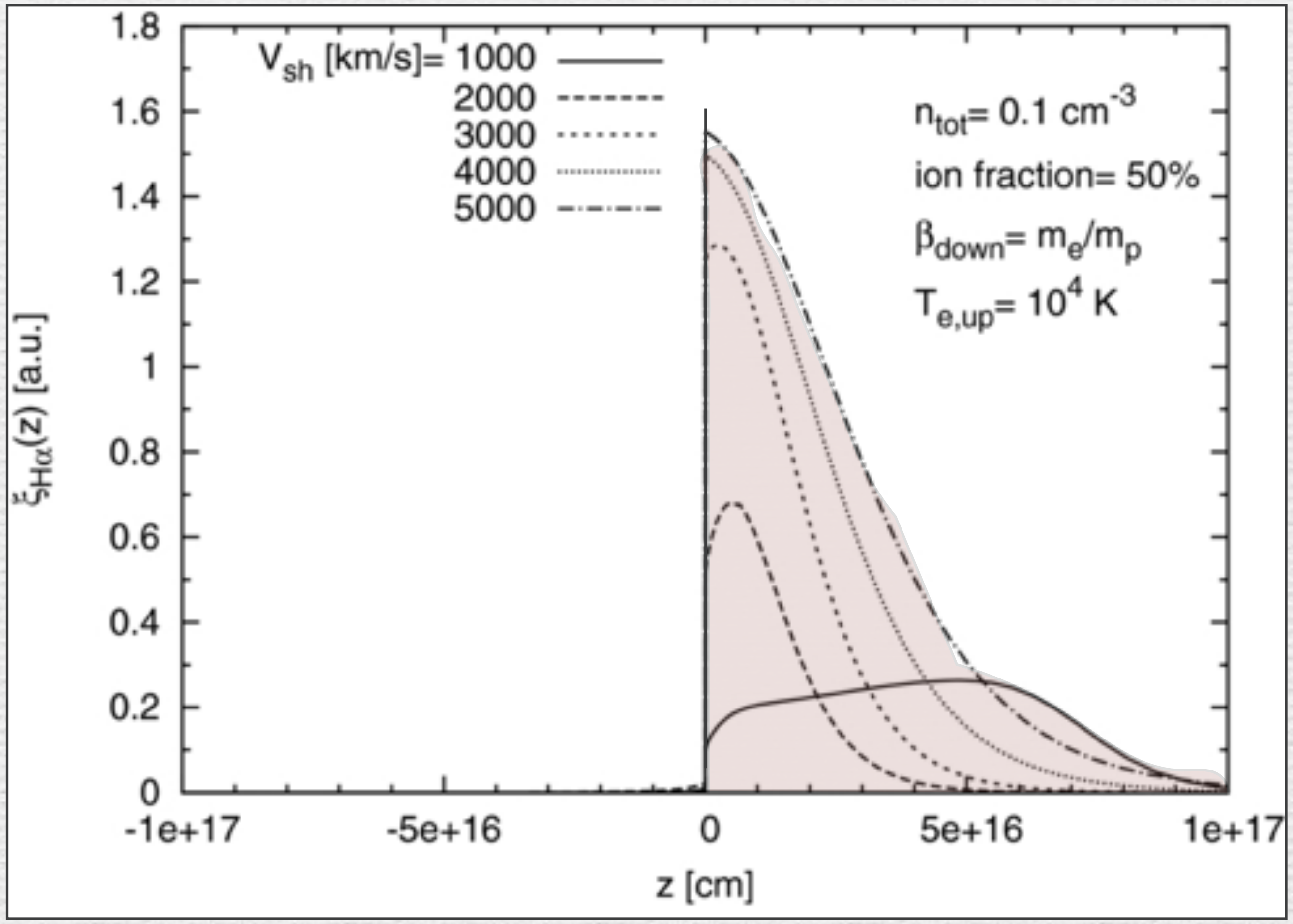
The NRF Also Affects I_b/I_n

- Value of β_{up} substantially affects **F(Hα):** unexpected

- I_b/I_n also strongly affected for low res spectra, where narrow and intermediate components are *unresolved*



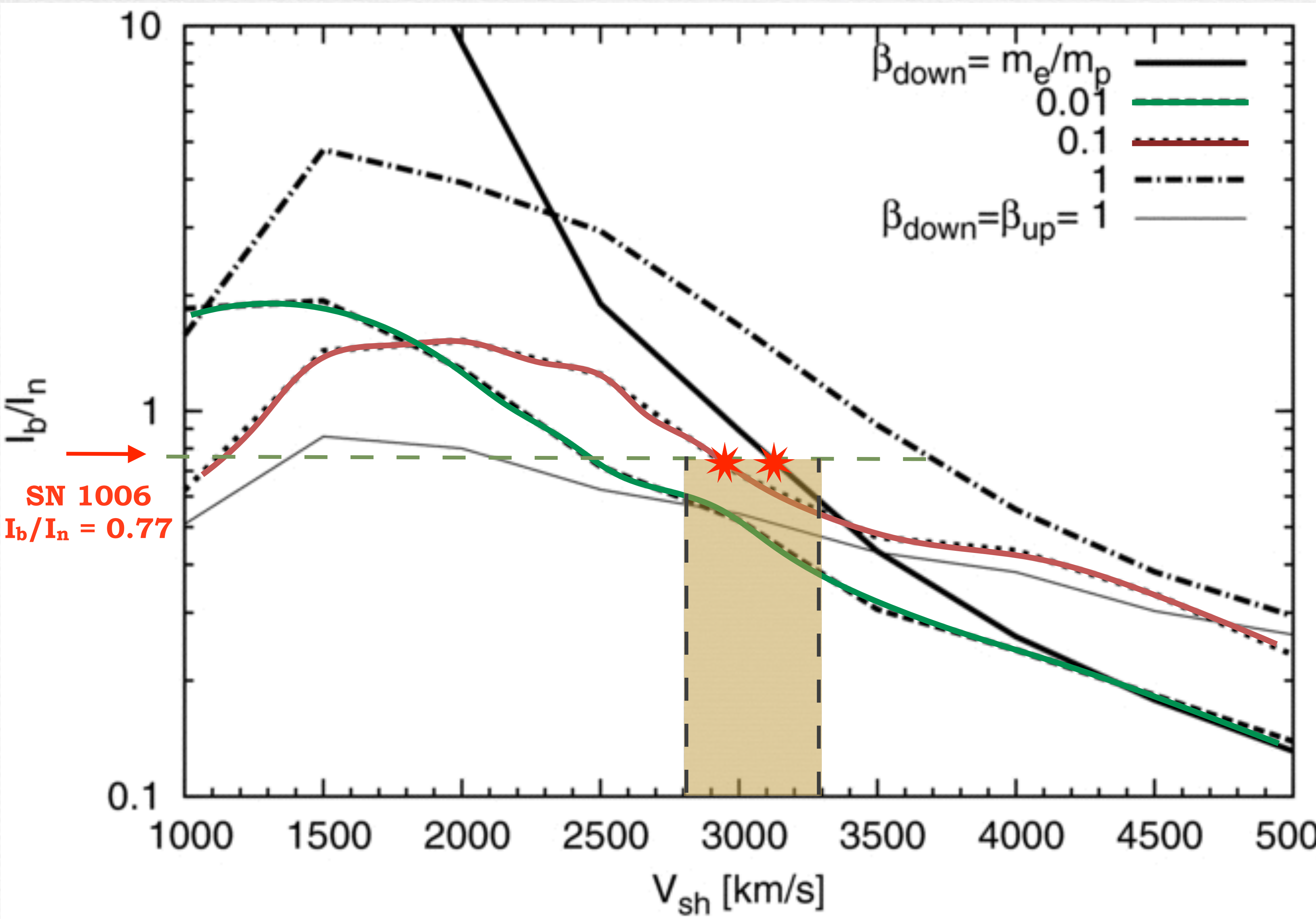




Morlino et al. (2012)

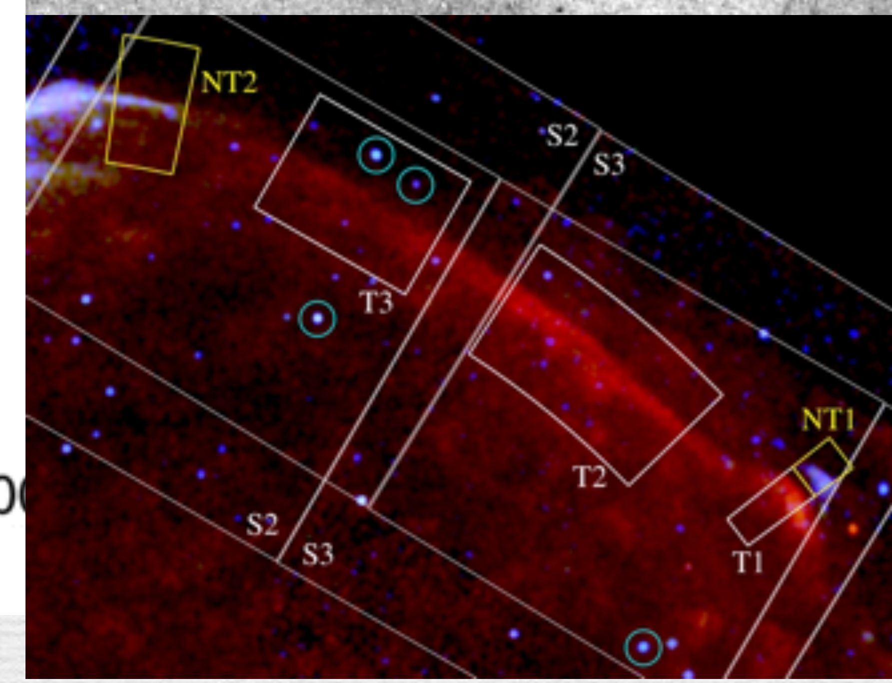
Recent I_b/I_n Calculations Include the Unresolved Intermediate Component

Morlino et al. (2012): NRF but not CR modification



... range of V_{SH} for NW from Chandra proper motions (Katsuda et al. 2013)

Winkler et al. (2003)

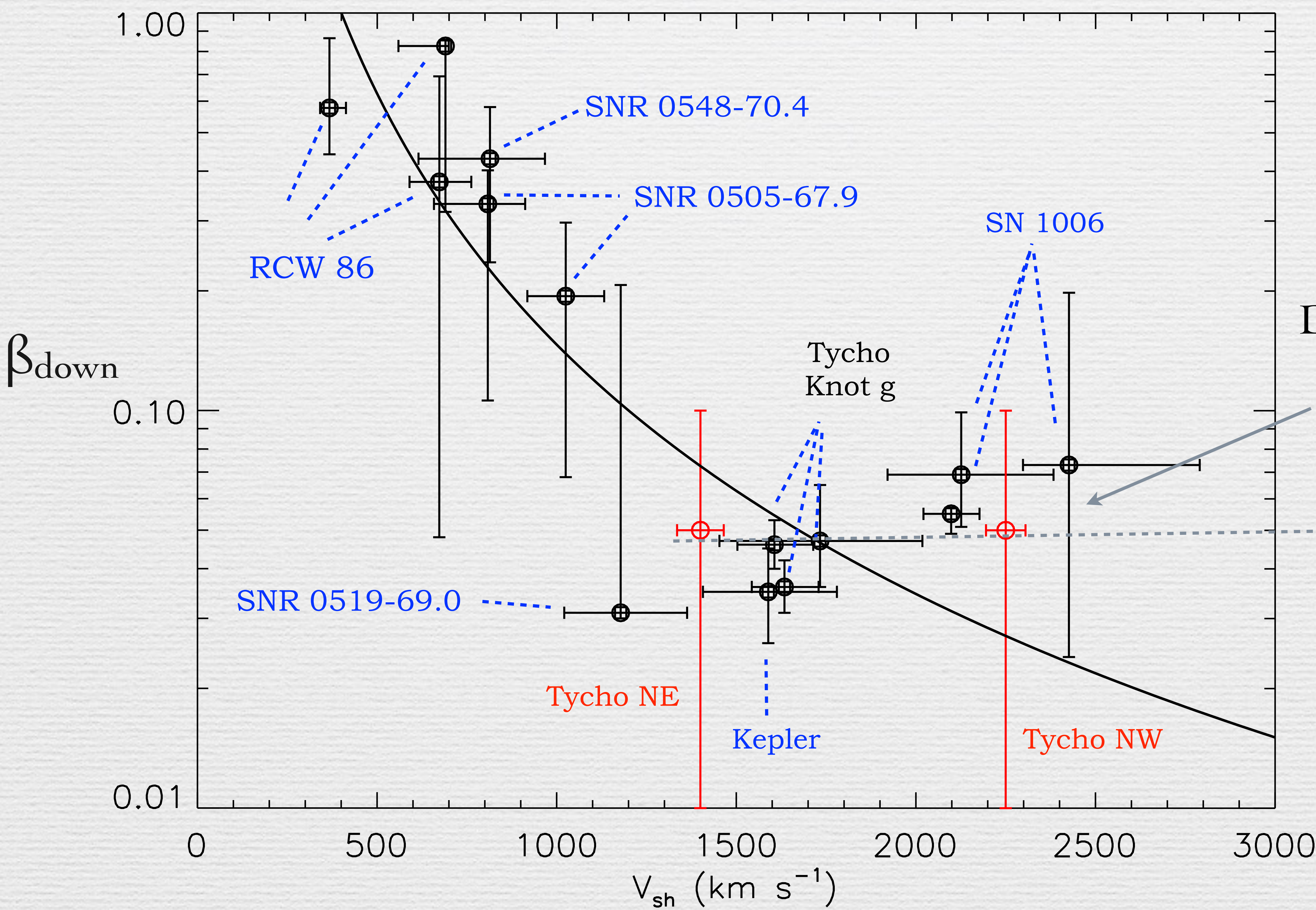


Katsuda et al. (2013)

Trends in T_e/T_p

Observing Many Balmer SNRs Gives $\beta_{down} \sim V_{SH}^{-2}$

van Adelsberg et al 2008; G13



Does T_e/T_p curve change above 2000 km/s ?

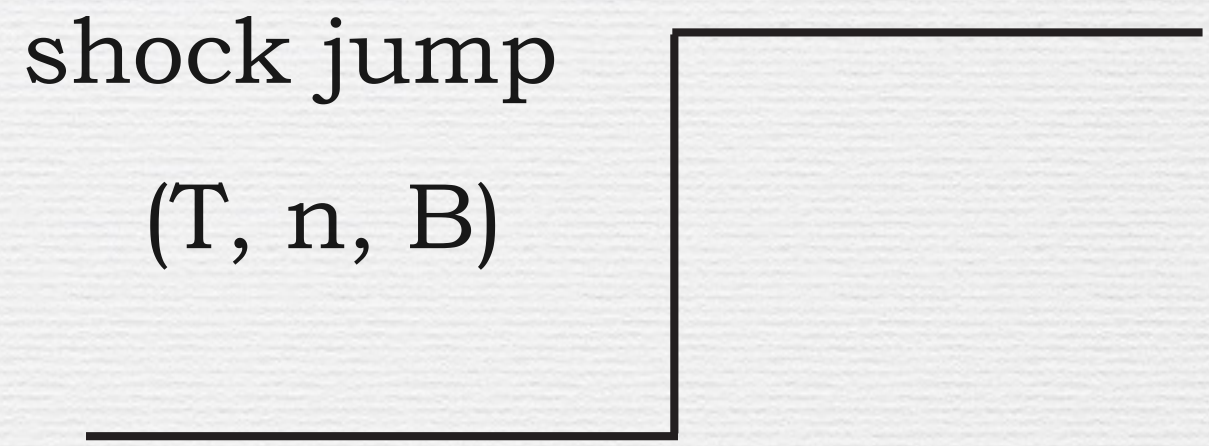
A Possible Explanation May Lie in the CR Pecursor

$$\frac{T_e}{T_p} = \frac{\frac{3}{16} m_e v_{sh}^2 + {\color{red}\Delta E_e}}{\frac{3}{16} m_p v_{sh}^2}$$

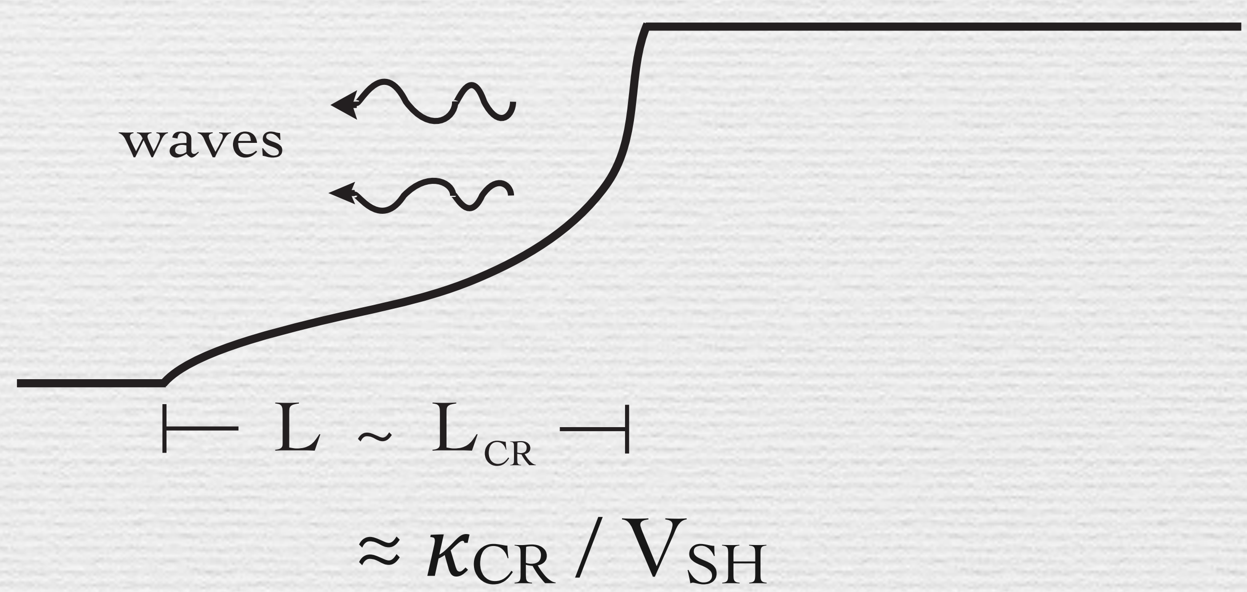
$$\approx \frac{\Delta E_e}{\frac{3}{16} m_p v_{sh}^2}$$

$$\propto \frac{1}{v_{sh}^2}$$

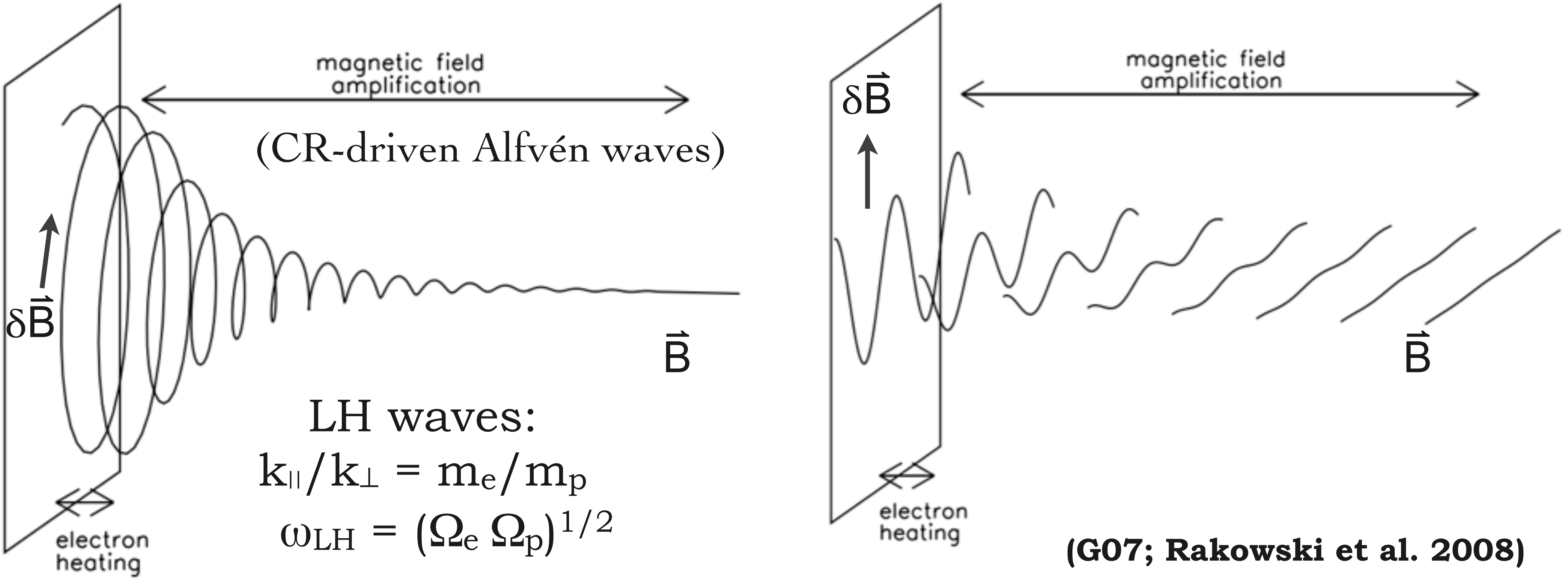
- A constant heating ΔE_e would reproduce what we see
- Suggests a ΔE_e occurs *ahead of the shock...*



With CRs/Reflected Ions



How to Get this Trend?
One Possibility: Lower Hybrid (LH) in the CR Precursor

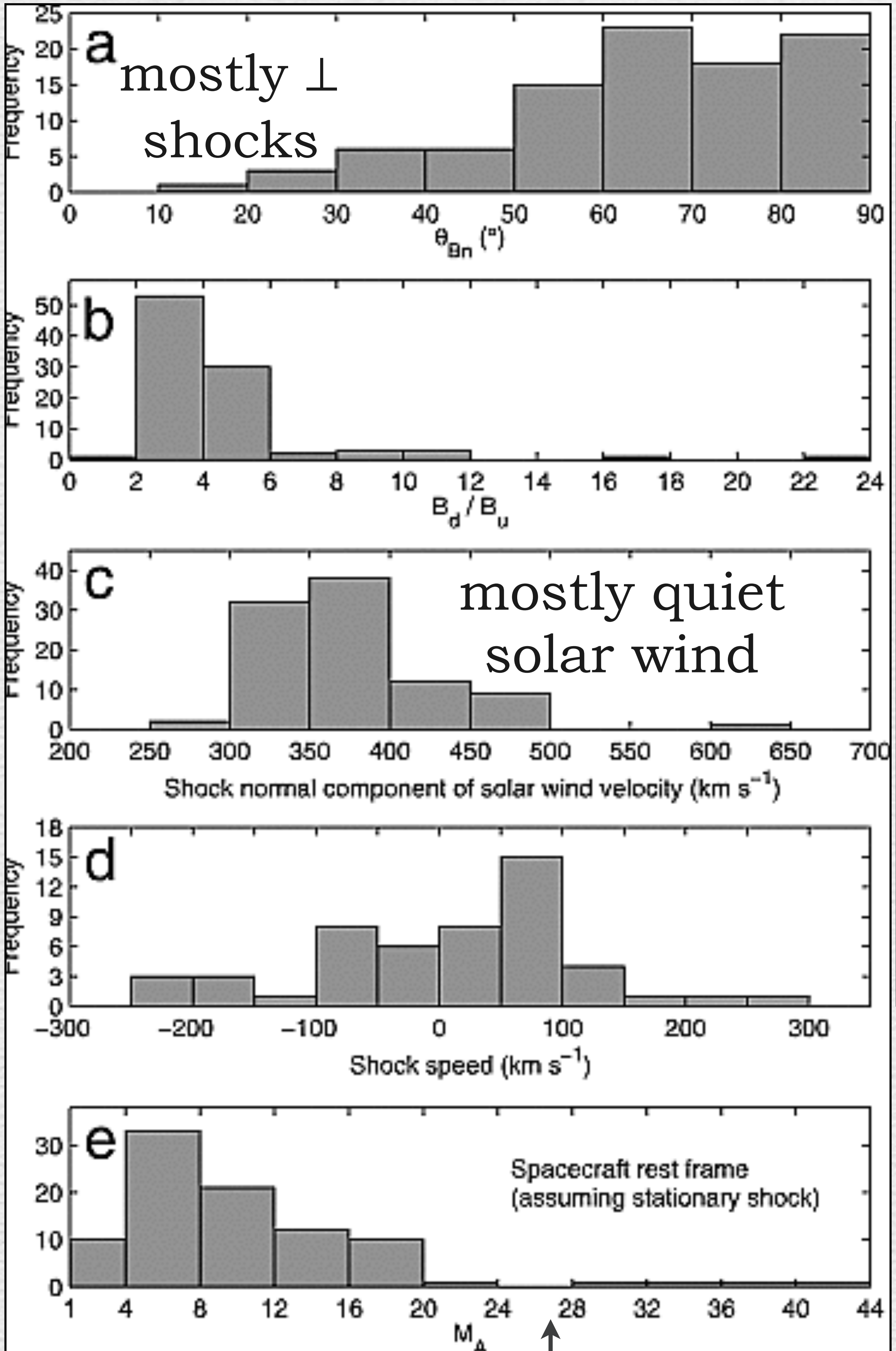


(G07; Rakowski et al. 2008)

- LH waves can bulk heat e^{-}s <u>parallel</u> to δB
- $\Delta E_e = \frac{1}{2} m_e \Delta v_e^2 \propto \Omega_e\, \kappa_{CR}$ ~ constant (for $\kappa \propto 1/B$)

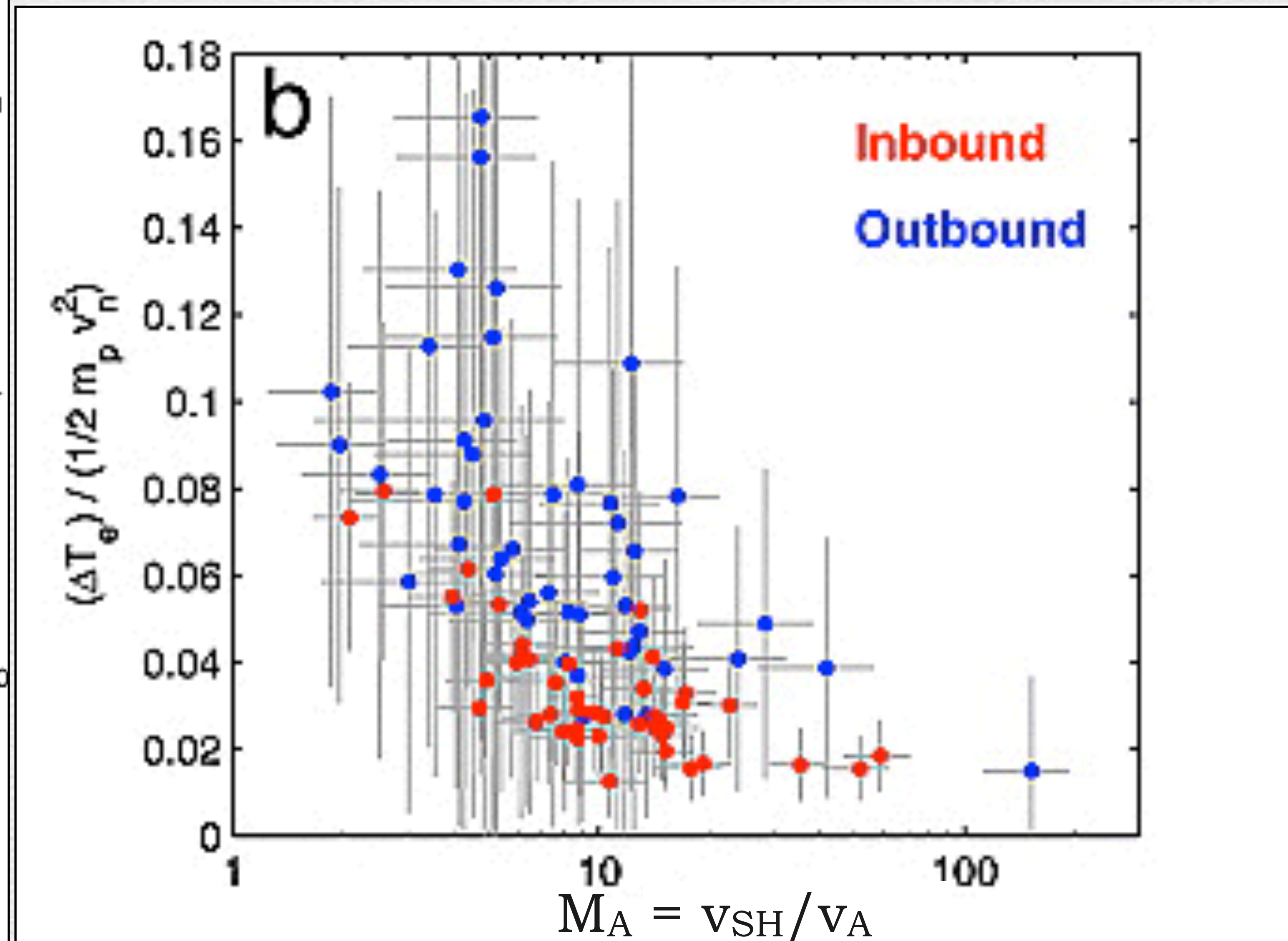
ΔE_e ~ 0.3 keV (const)

β_{down} at Saturn's Bow Shock From Cassini



Masters et al. (2011)

Cygnus Loop

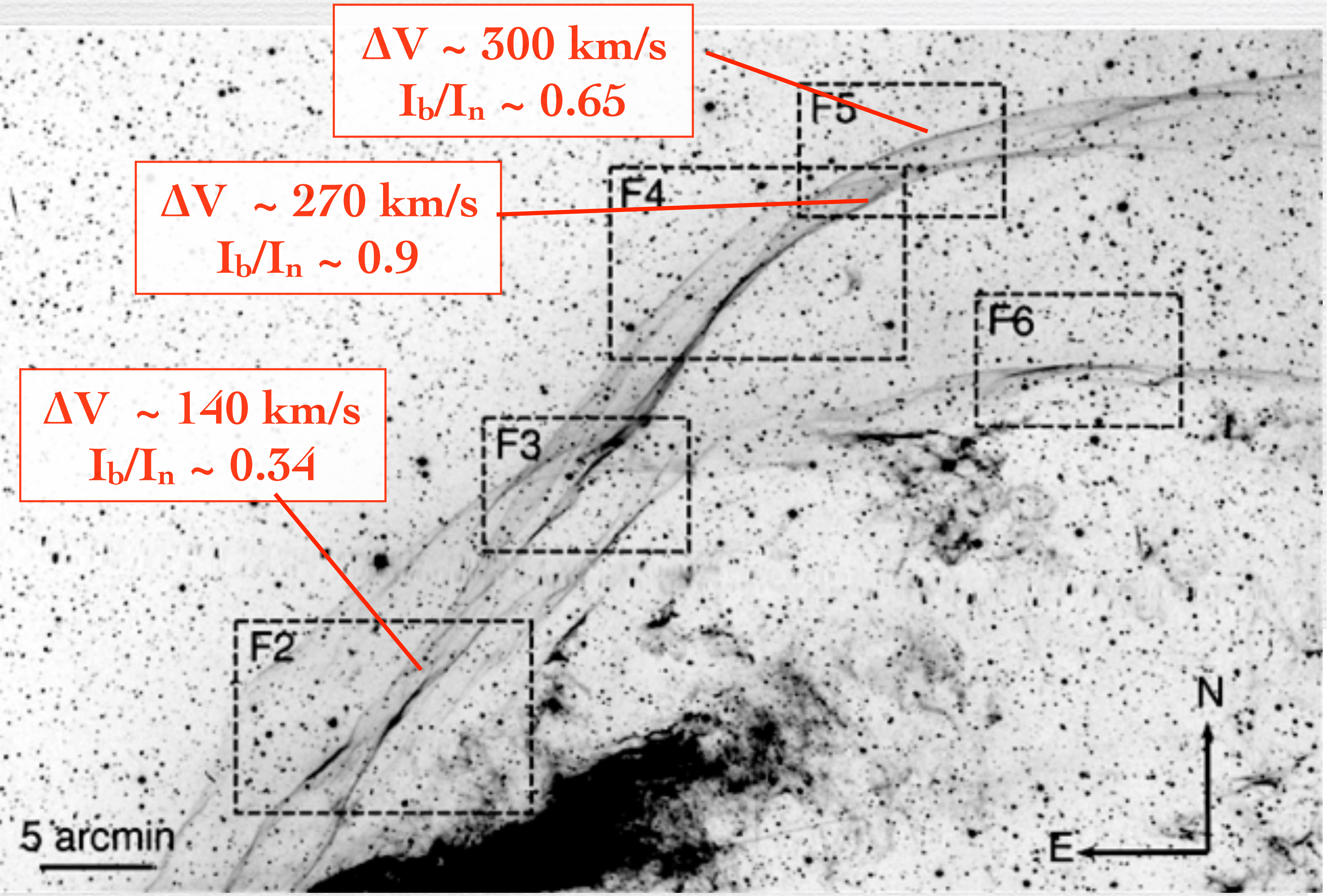


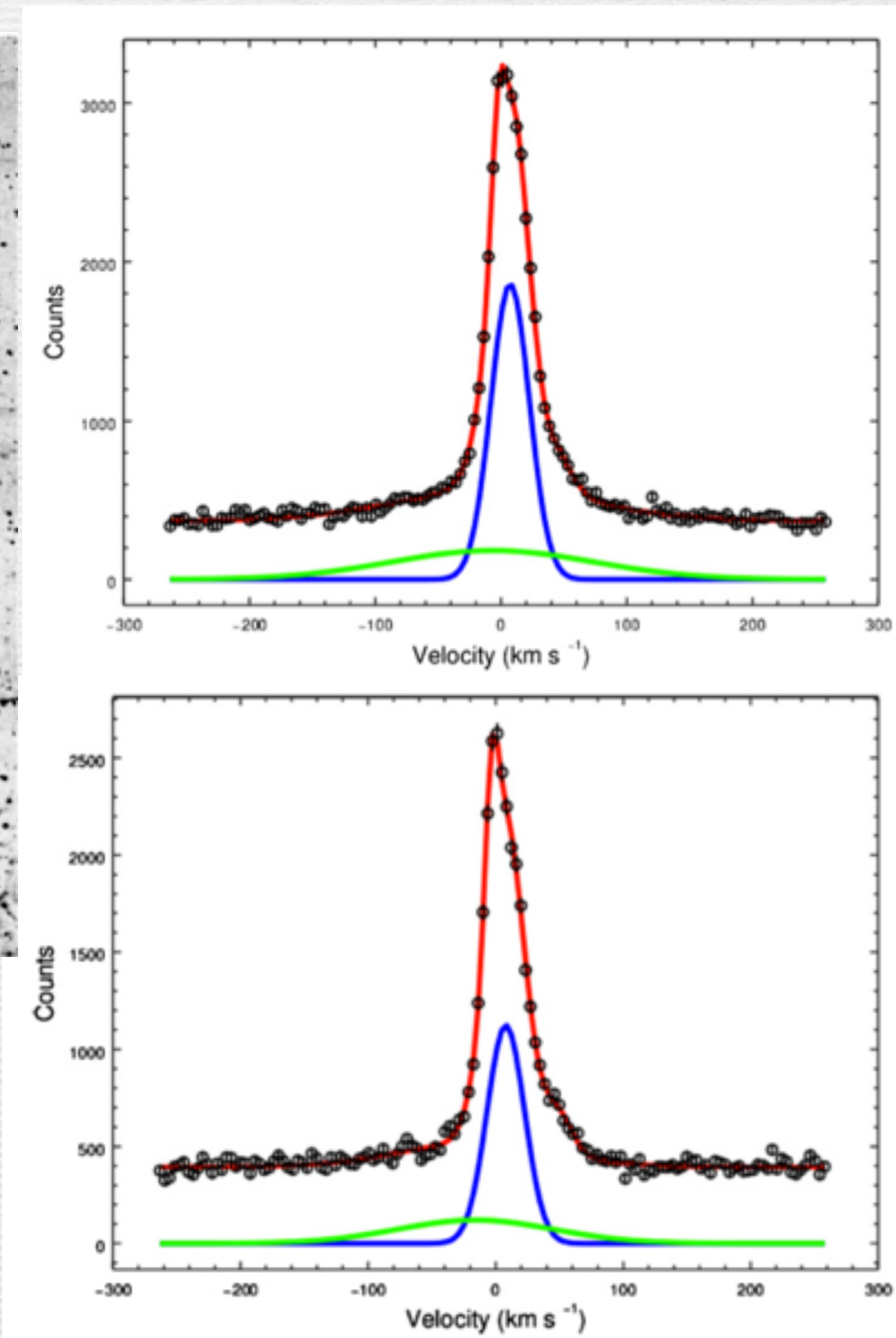
$$\frac{\Delta T_e}{\frac{1}{2} m_p v_n^2} \propto 1/M_A$$

(Schwartz et al. 1988)
(Ghavamian et al. 2013)

New Observations

New Observations of Balmer-Dominated Filaments in the Cygnus Loop



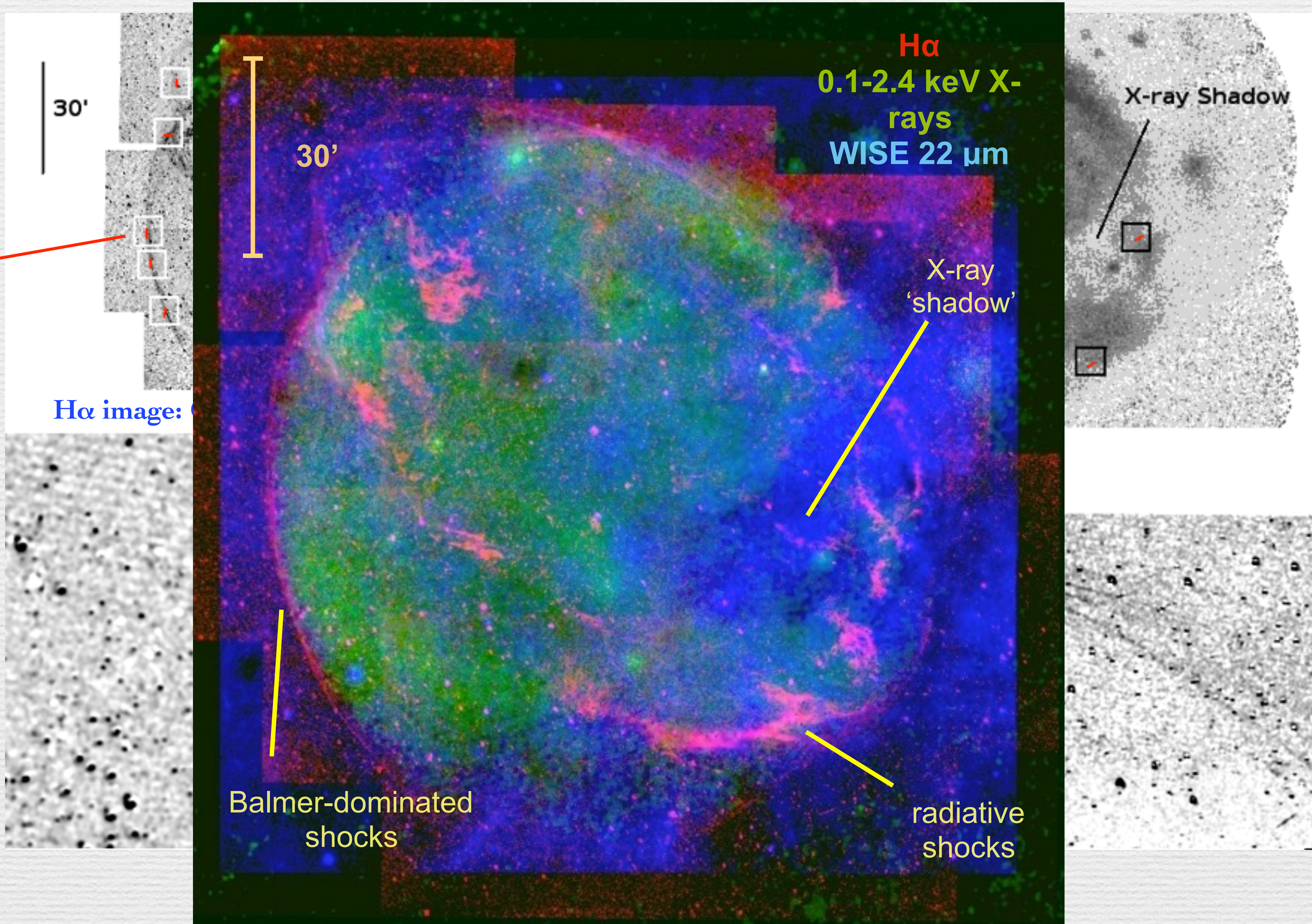


- Comparison to shock models indicates $\beta_{down} \sim 1$
- These I_b/I_n cannot be matched by *any* existing models, and haven't even been calculated in the latest ones (e.g., van Adelsberg et al. 2008, Morlino et al. 2012, 2013)

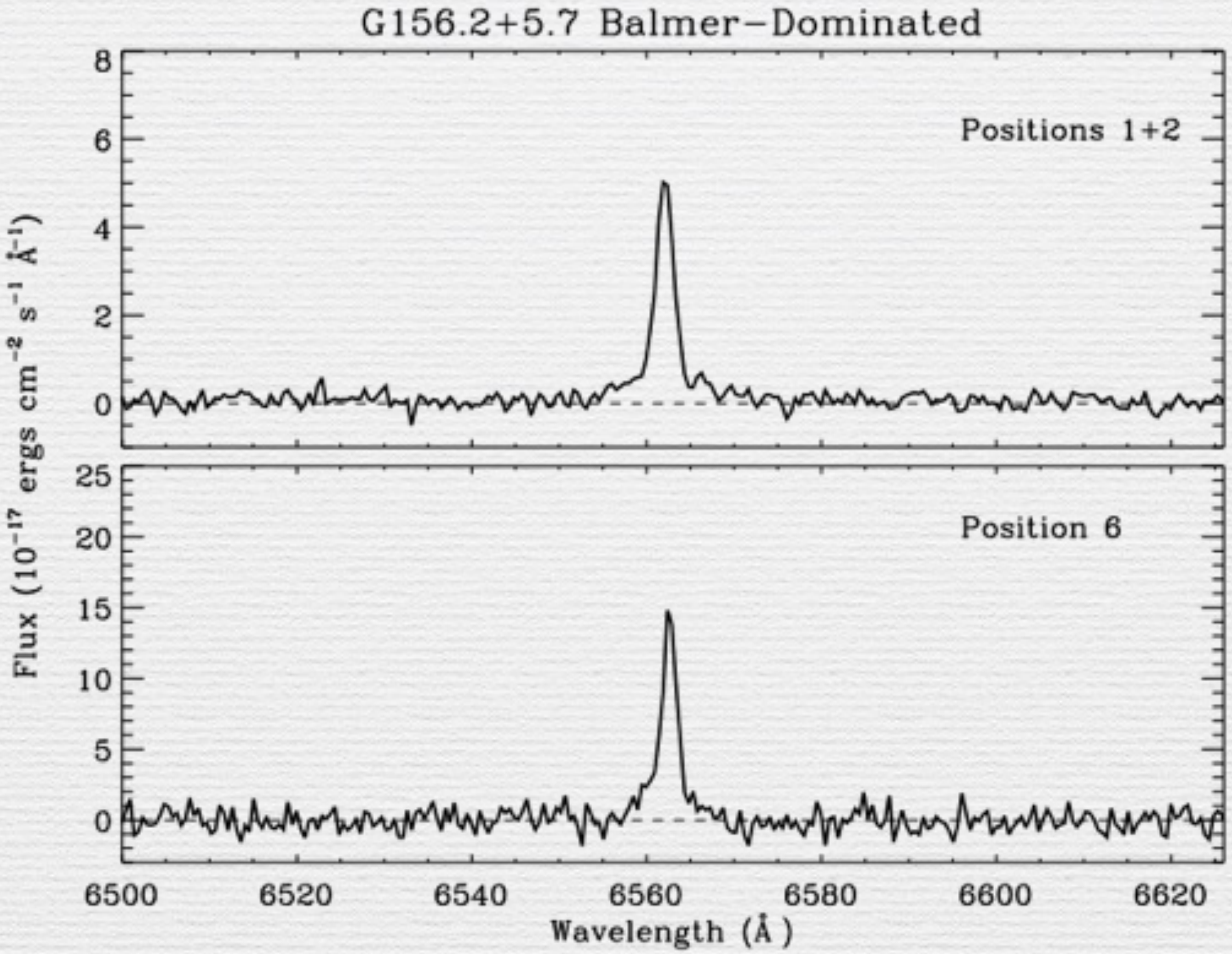
Medina et al. (2014)

First Detection of Broad Hα in the Galactic SNR G156.2+5.7

MMT Blue Channel slit positions



First Detection of Broad Hα in the Galactic SNR G156.2+5.7



Ghavamian & Raymond (2016, in prep)

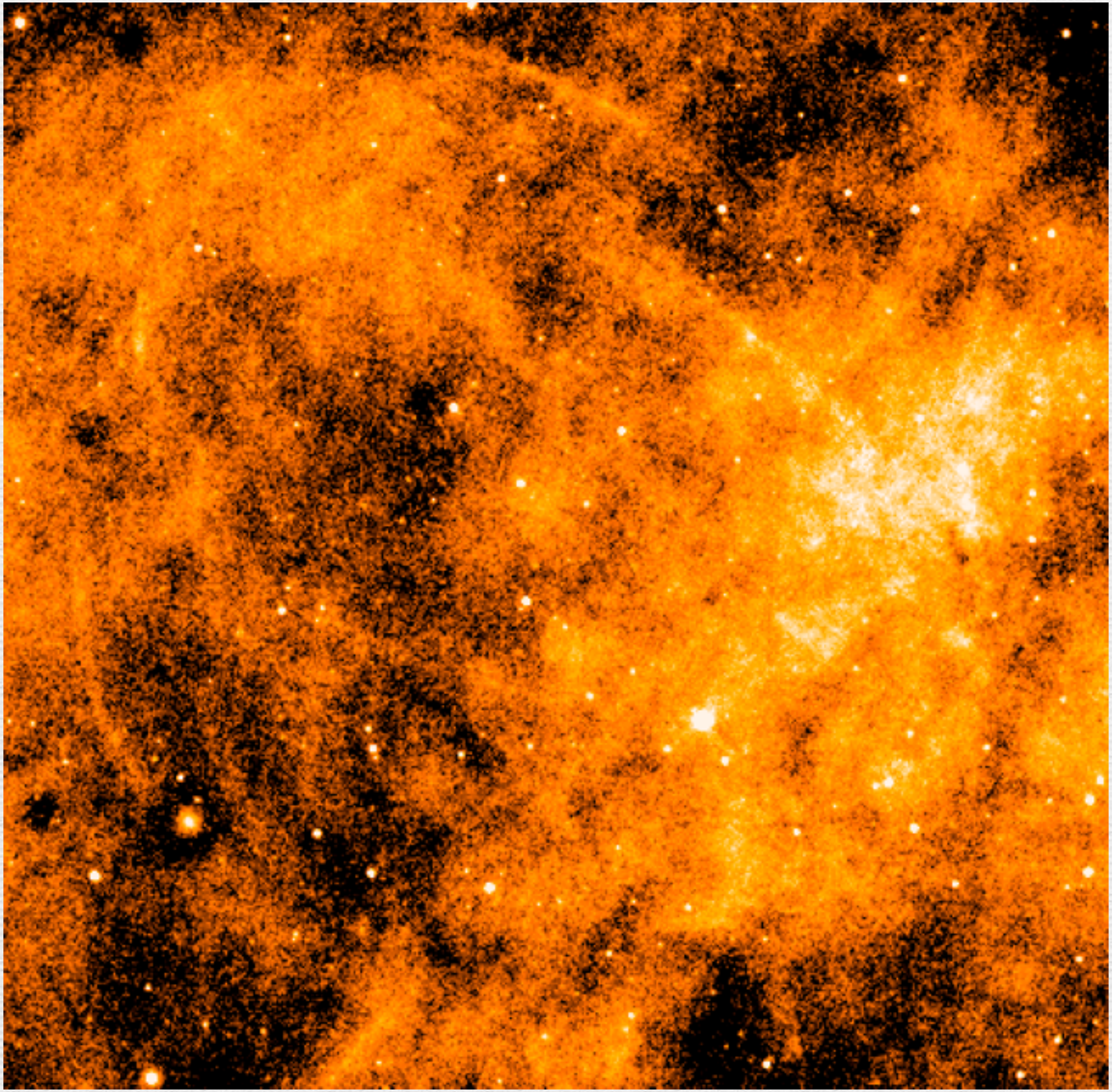
- **ΔV_{1+2} = 490 km/s; I_b/I_n = 0.65**
- **ΔV_6 ~ 235 km/s; I_b/I_n = 1.2**
- Positions 1+2: Measured I_b/I_n <u>too low for shock models</u>

  $470 \leq V_{SH} \leq 600$ km/s

  (Agrees w/V_{SH} from Hα proper motion: **Katsuda et al 2016**)
- Position 6: β_{down} = 1; V_{SH} = 300 km/s

G156.2+5.7 in WISE 22 μm Dust Emission

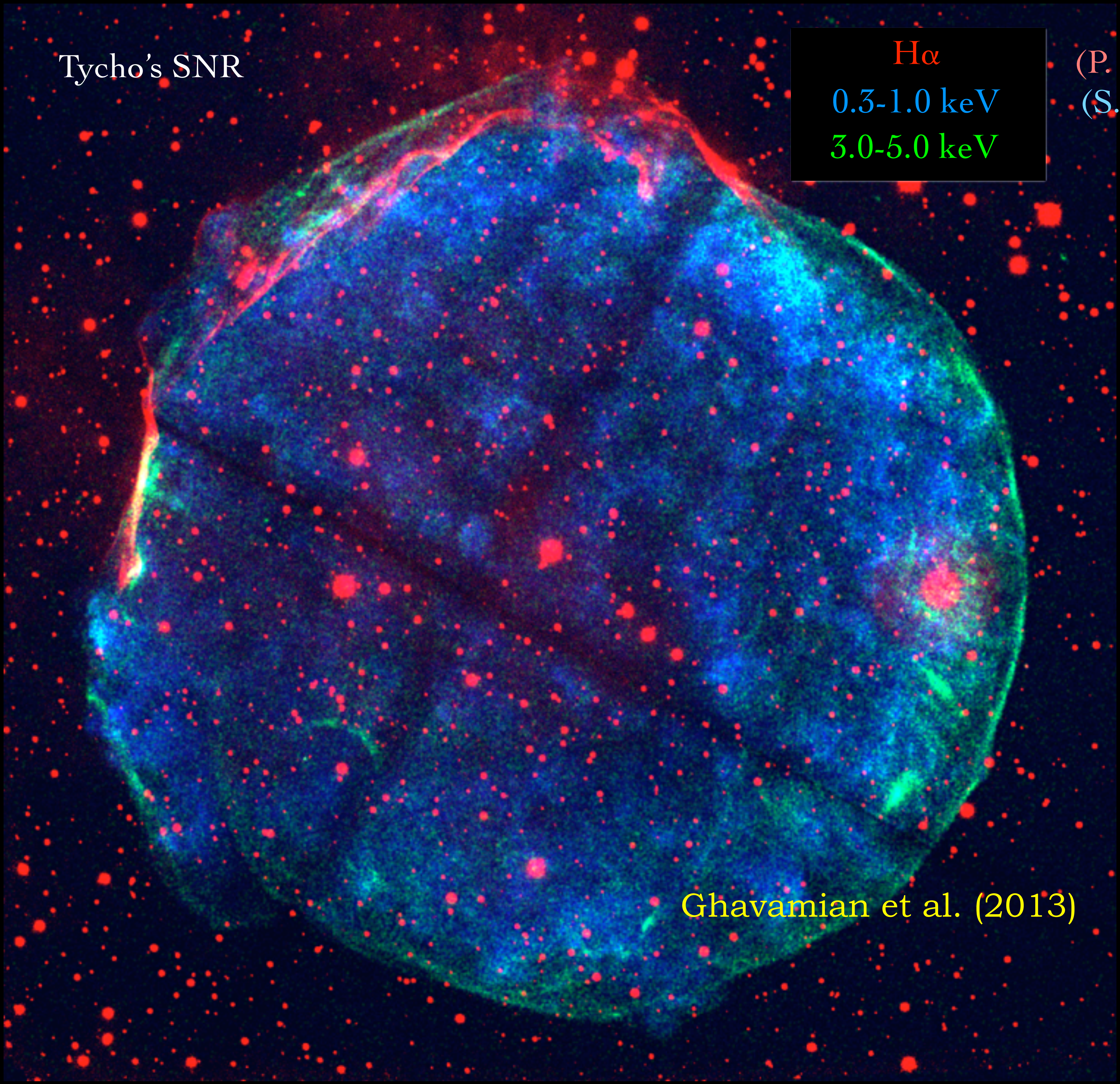
Work by Towson U. undergrad Jason Powell



Ghavamian & Powell (2016, in prep)

Conclusions

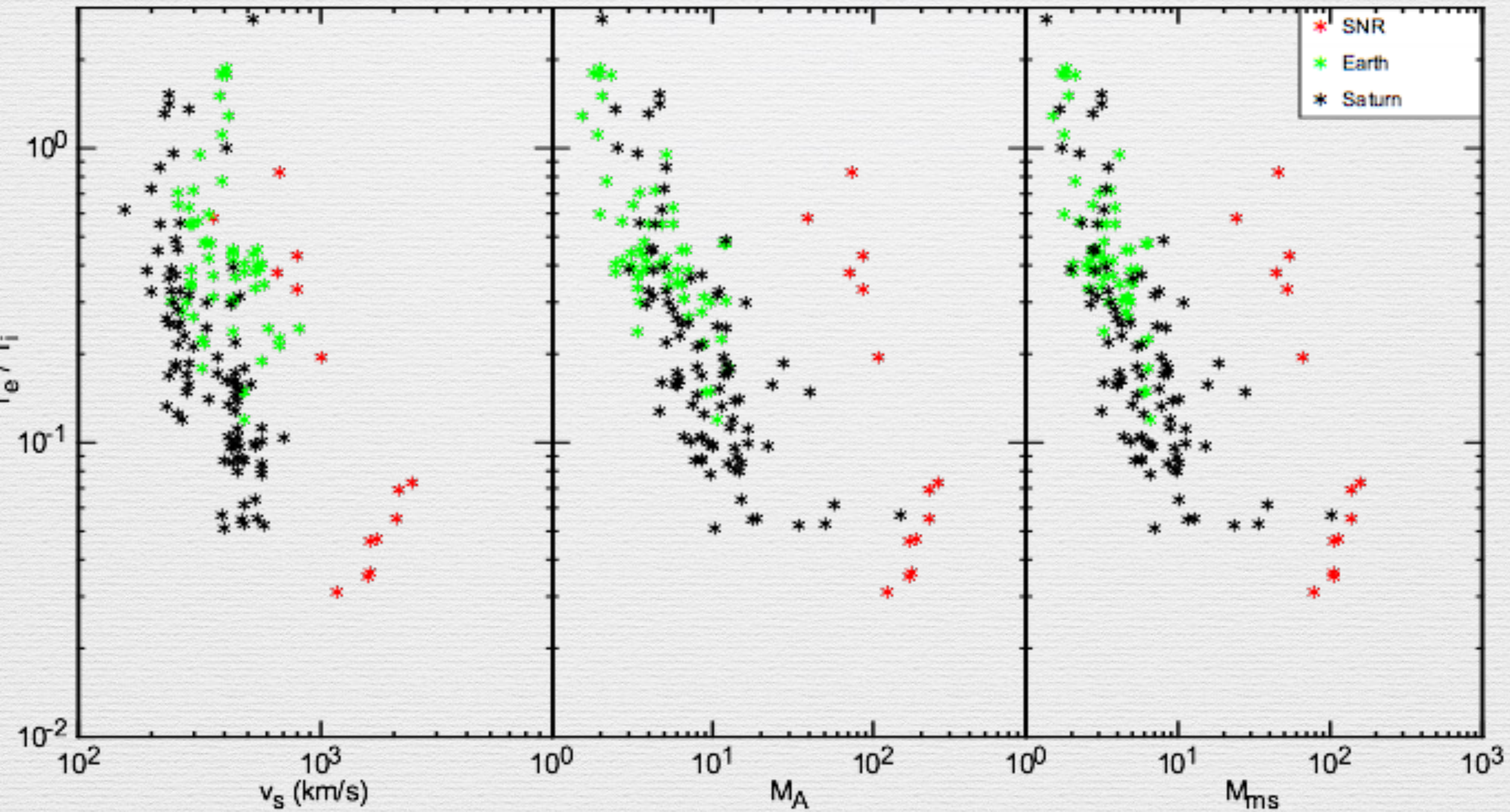
- Balmer-dominated shock models have become <u>much more sophisticated</u>, including momentum feedback from NRF, CR back pressure,…
- This also muddles the picture a bit on measuring T_e/T_p, *though it seems $\varepsilon_{CR} \lesssim 0.2$ can be accommodated*
- I_b/I_n predictions *have not yet been published for NRF + CR modification*
- I_b/I_n for V_{SH} < 1000 km/s have not been attempted since G01. <u>Crucial for interpretation of Balmer spectra in Cygnus Loop, G156.2+5.7,…</u>
- I_b/I_n are <u>problematic</u> at low shock speeds. Often too low.
- *Does the equilibration-shock speed trend hold for fully ionized shocks too?* Need <u>proper motions</u> for SNRs in FULLY PRE-IONIZED gas with well-determined distances (LMC/SMC) to get V_{SH}, along with X-ray spectroscopy (T_e) and UV spectra (T_e and T_i)
- Ion-ion equilibration studies sorely needed too. Needs UV.



(P. F Winkler)
(S. Park et al. 2007)

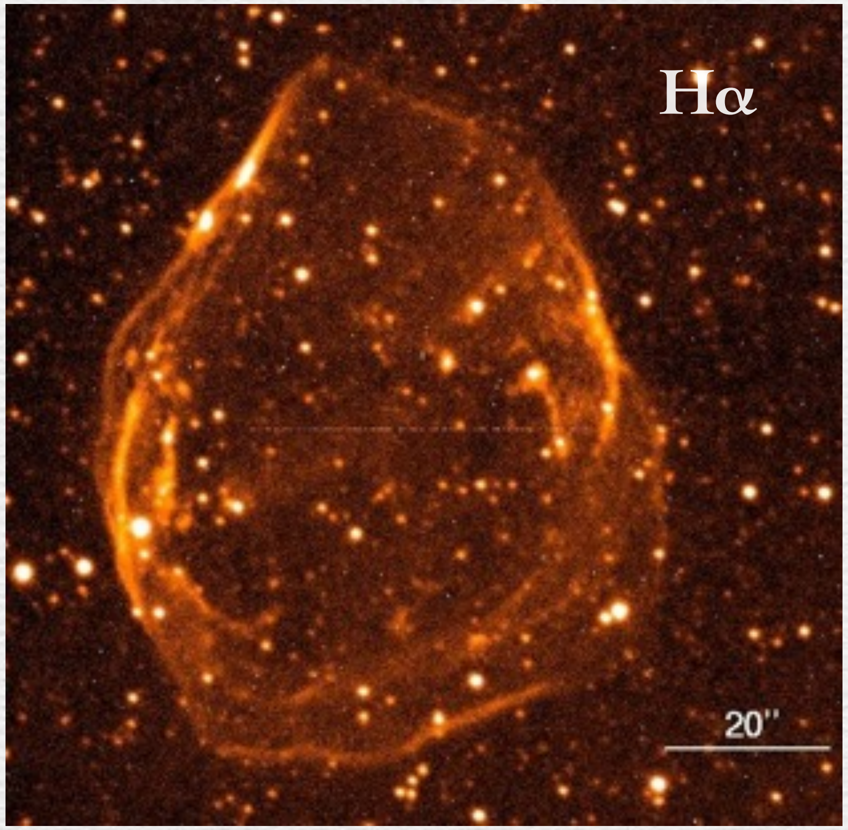
Additional Methods of Estimating T_e/T_p

In Situ Solar Wind Measurements

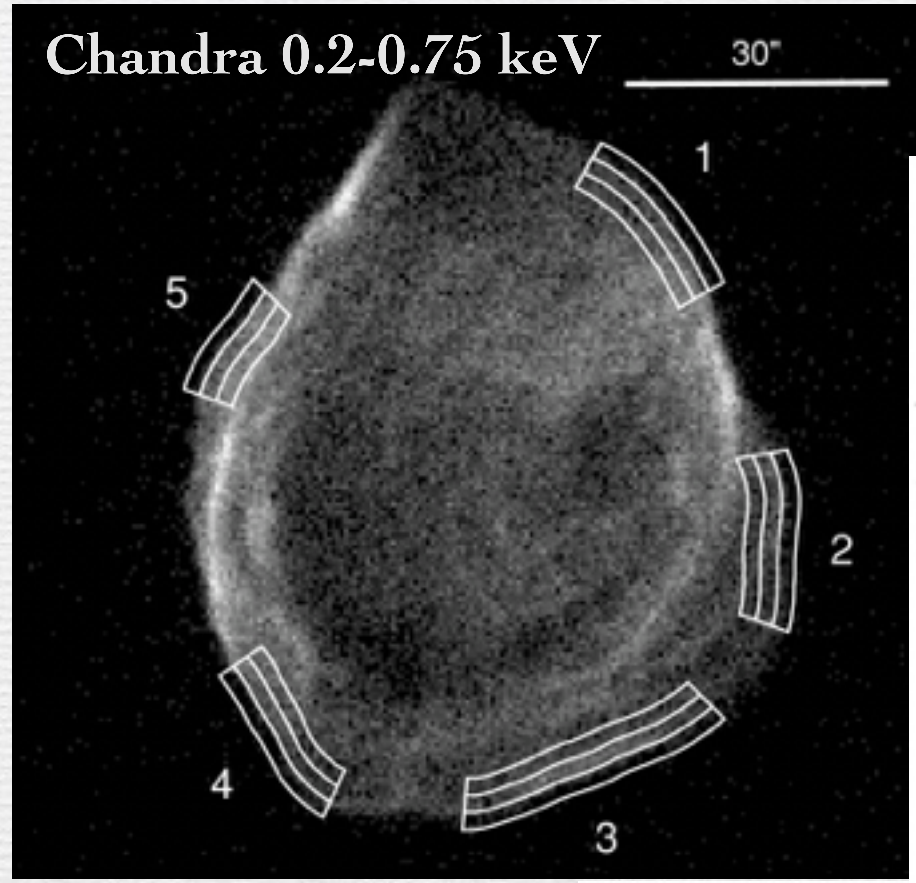


Masters et al (2011), Ghavamian et al. (2013)

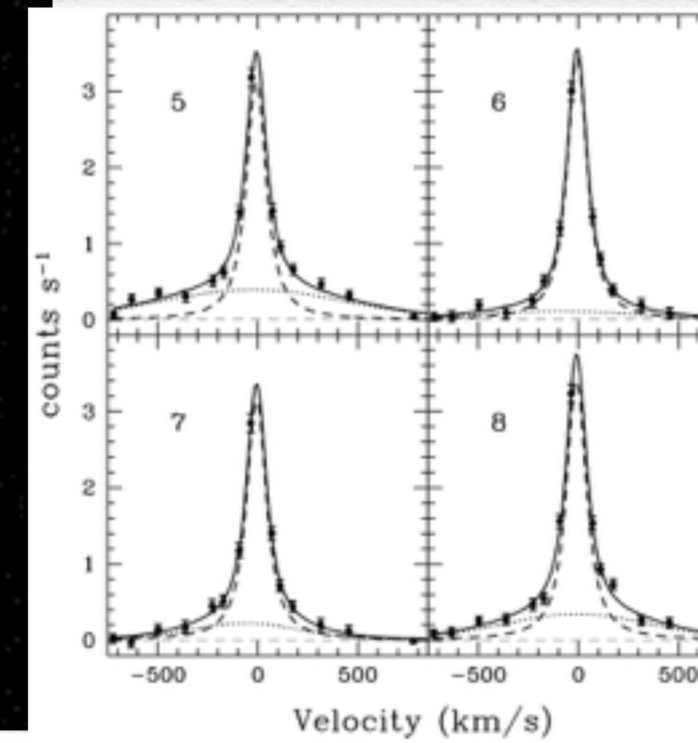
T_e/T_p from Combined Optical/X-ray Studies: DEM L71 in the Large Magellanic Cloud

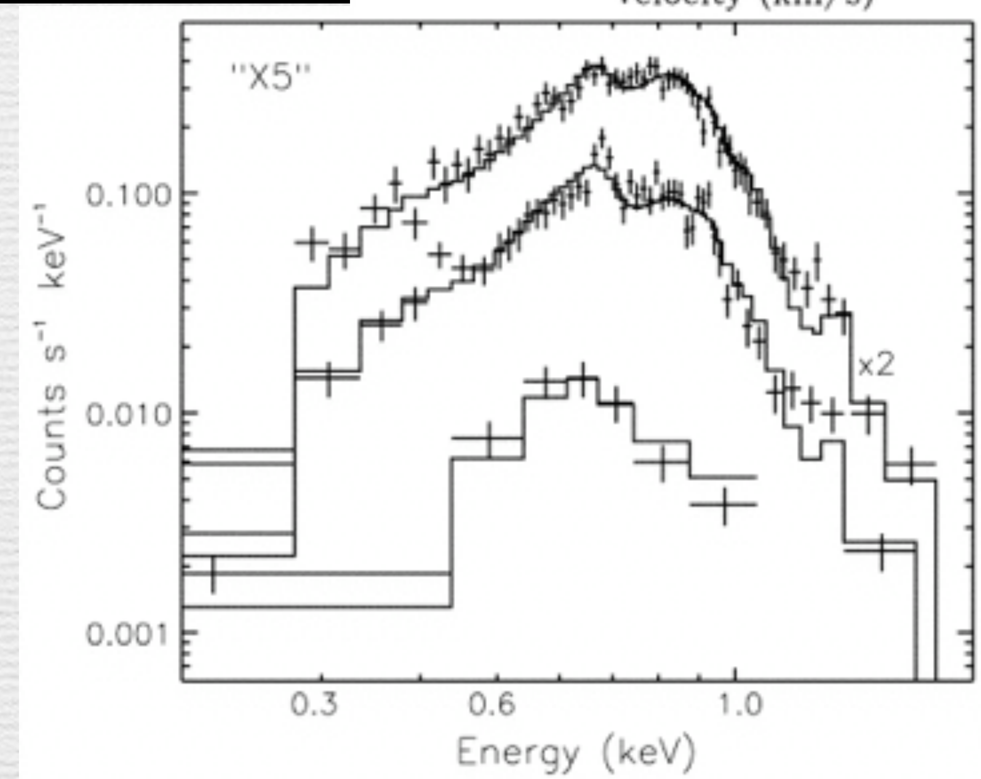


Hughes et al (2003)



Rakowski et al. (2009); G03

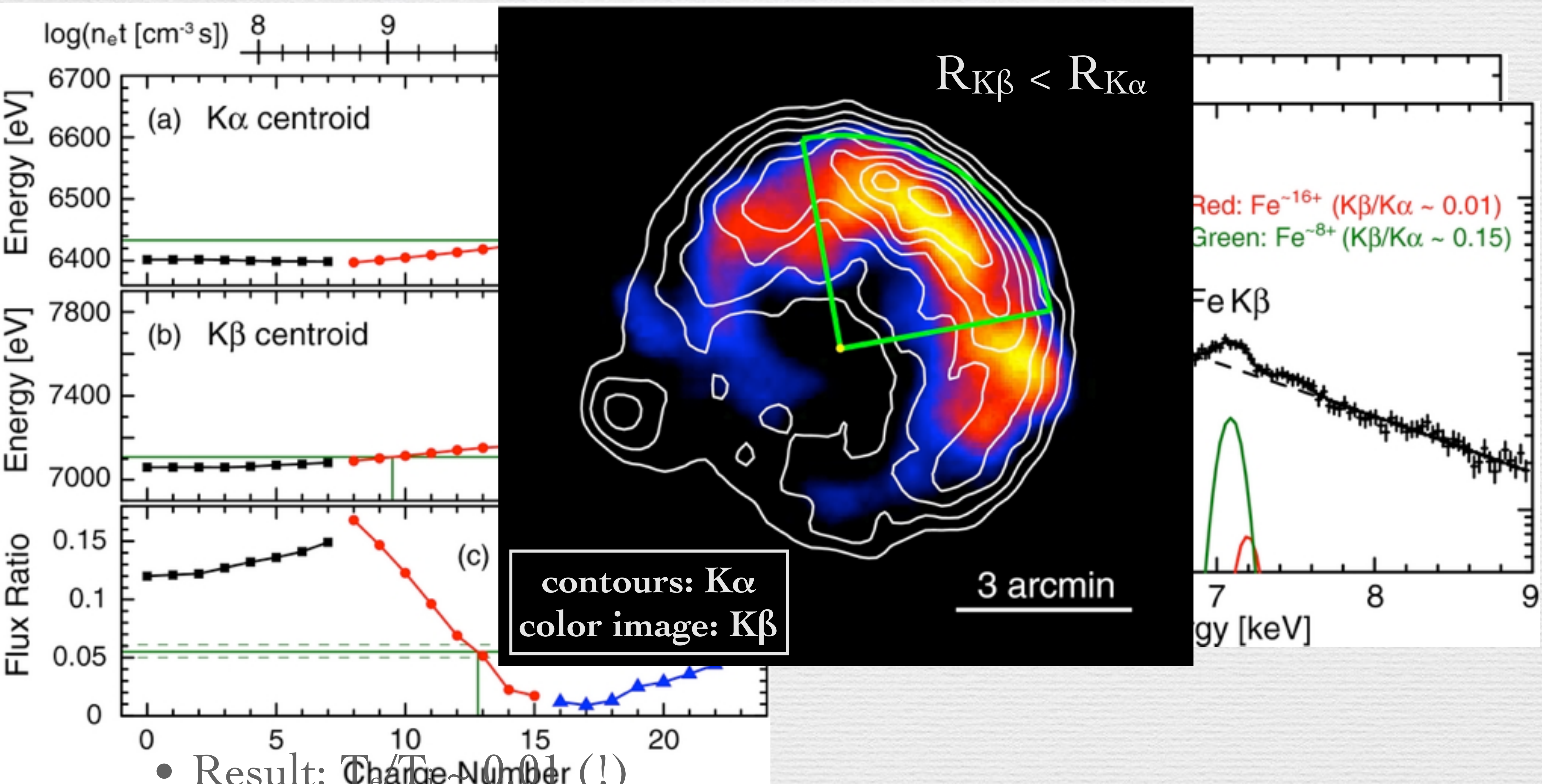




- Optical data give broad Hα FWHM, limiting range of V_{SH}
- X-ray spectra at sequence of positions behind shock gives evolution of T_e due to Coulomb collisions + adiabatic expansion (Rakowski et al. 2003)

First Measurement of T_e/T_i in an Ejecta Shock (Yamaguchi et al. 2014)

Tycho's SNR



- Result: $T_e/T_i \sim 0.01$ (!)
- $V_{rev} \sim 4000$ km/s; Mach number should be ~ 100
- No significant magnetic field expected in expanding Fe-rich ejecta