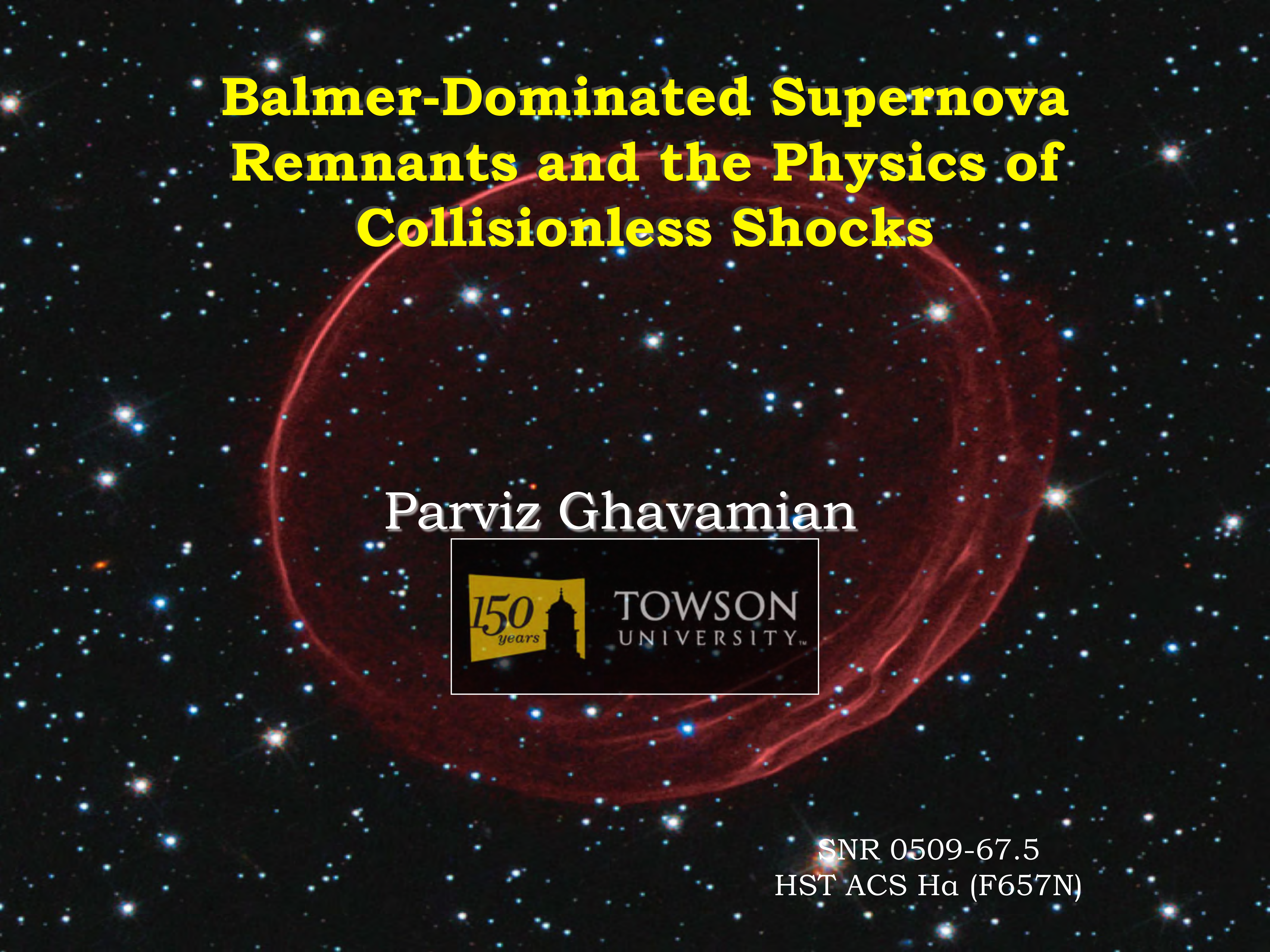

Balmer-Dominated Supernova Remnants and the Physics of Collisionless Shocks

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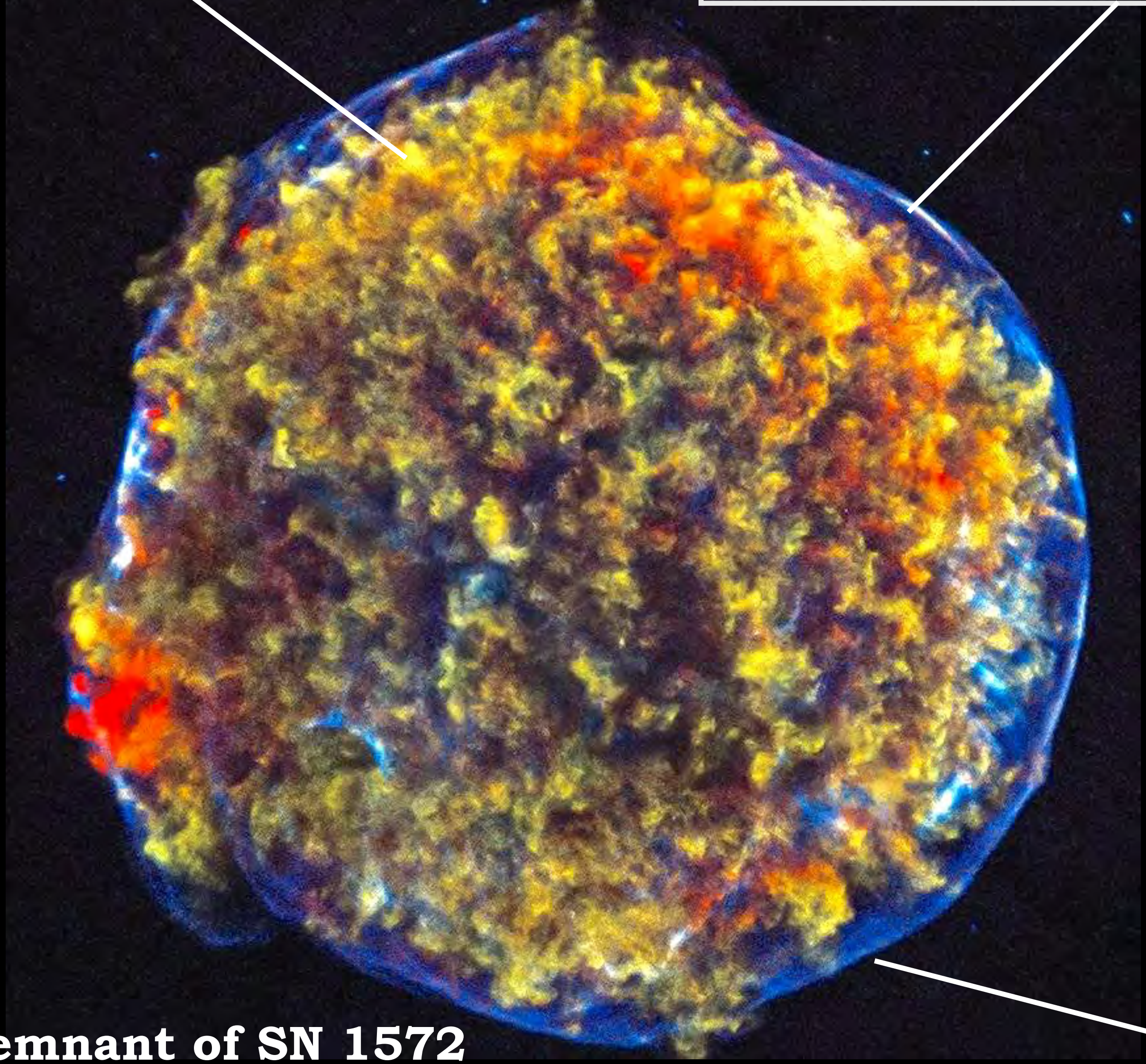
150 years TOWSON UNIVERSITY

SNR 0509-67.5
HST ACS Hα (F657N)

Supernova Remnants Heat and Enrich the ISM and Accelerate Cosmic Rays

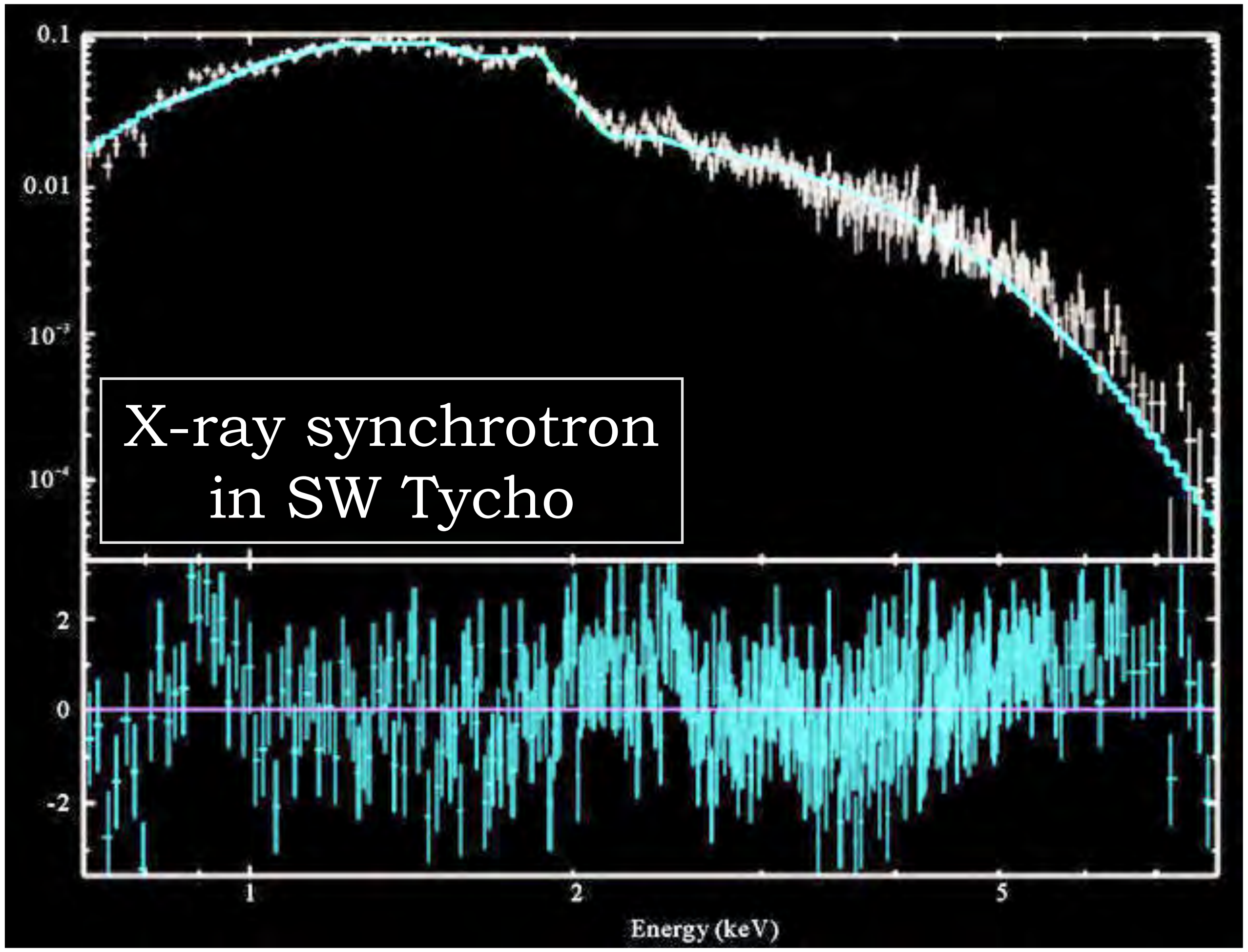
reverse-shocked Si-Rich and Fe-Rich SN ejecta
$T \sim 5 \times 10^7$ K

blast wave (~5000 km s^{-1})
(X-ray synchrotron radiation from e^- CRs ~ 10 TeV)



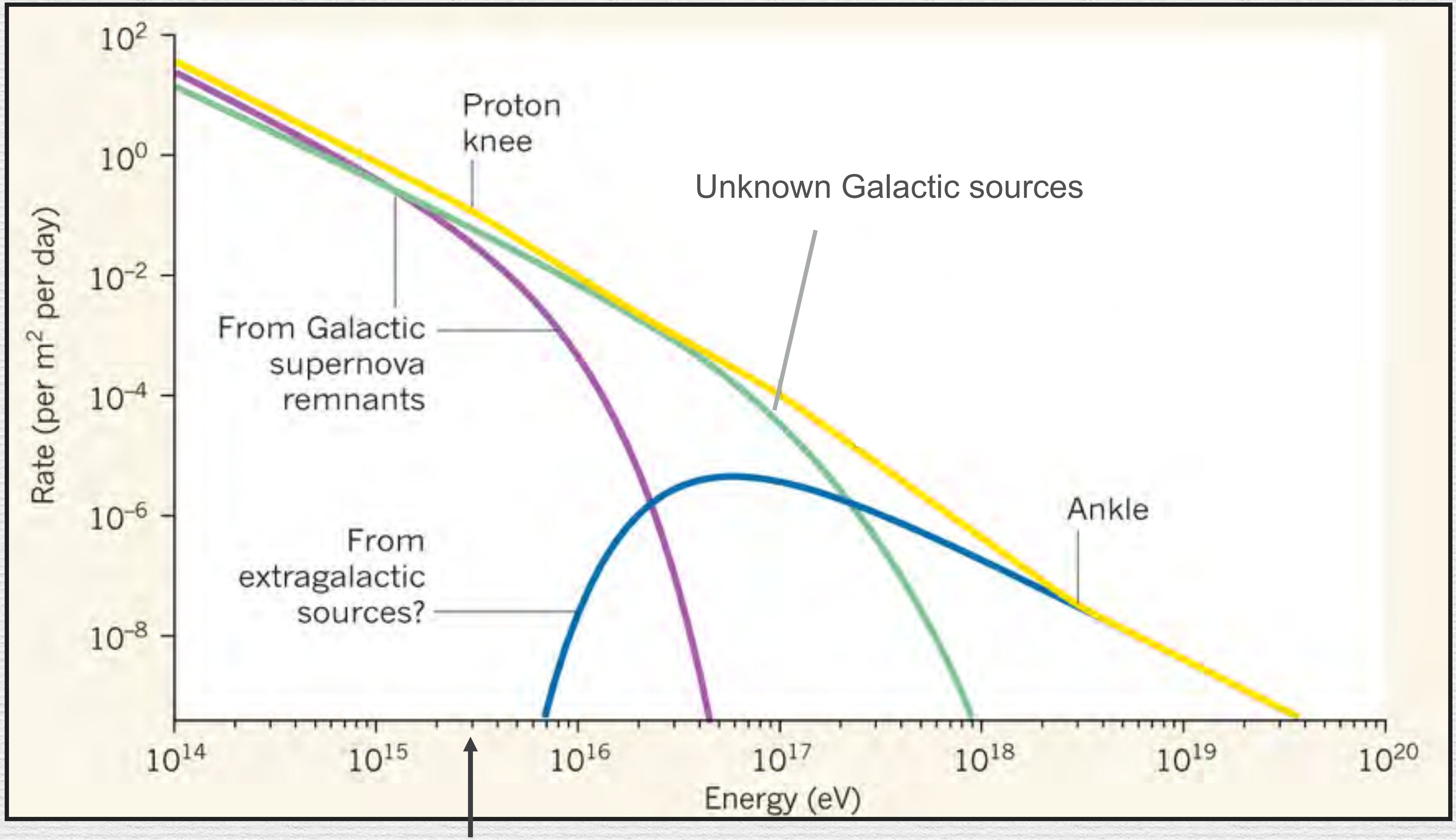
Remnant of SN 1572
(Tycho's SNR)
(CXC/NASA)

Bozkurt et al. (2013)



X-ray synchrotron in SW Tycho

SNRs Are Believed to Generate Cosmic Rays Up to the Proton ‘Knee’ near 10^{15} eV



(Taylor 2016)

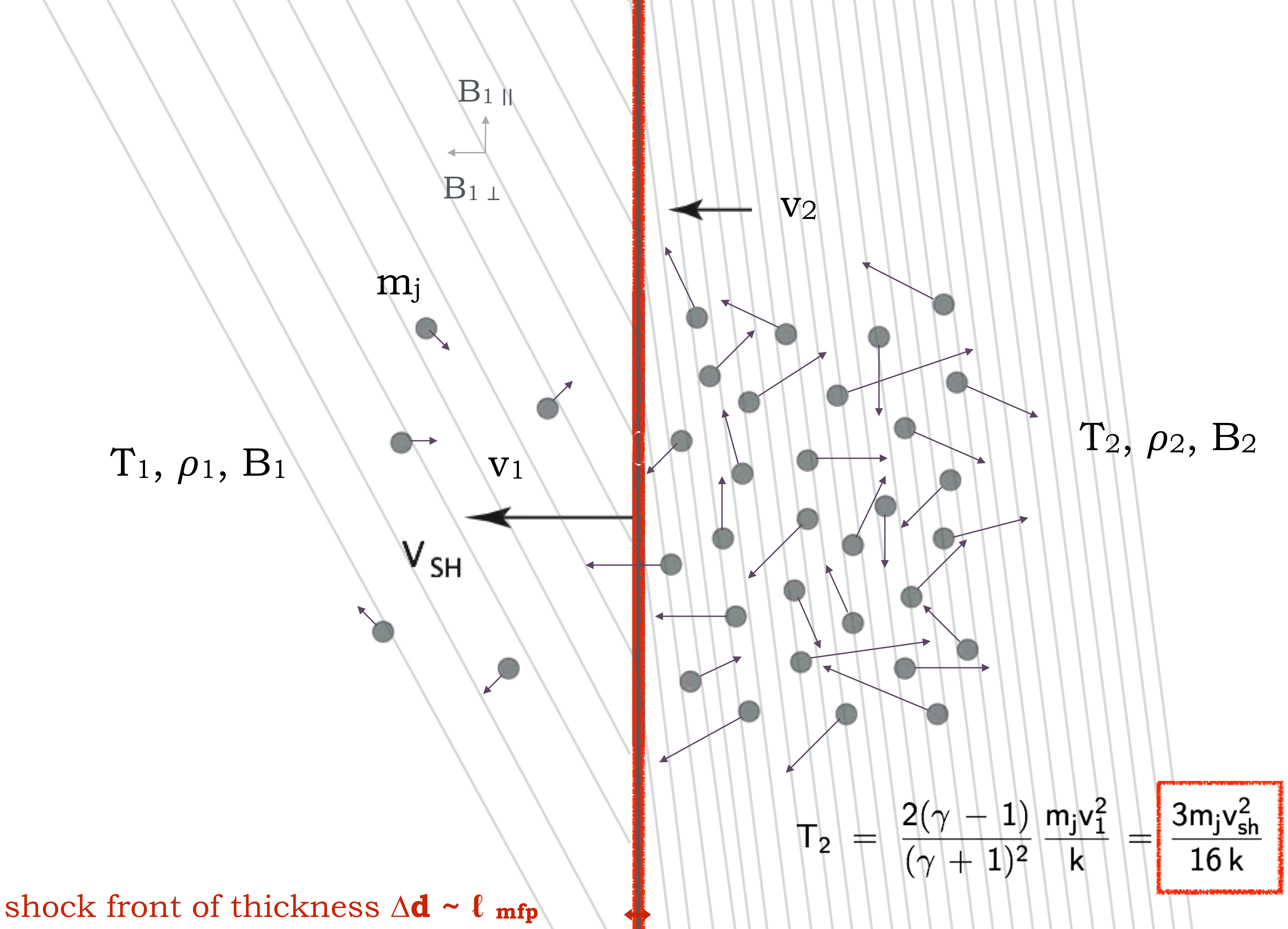
Why Study Supernova Remnant Shocks?

I. They Accelerate Cosmic Rays

II. They are Collisionless Shocks, Whose Physics is Poorly Understood

III. These shocks occur in many places in astrophysics (Galaxy clusters, star forming regions, large scale structure formation…), so understanding them is important!

The Shock Jump Conditions in a Plasma



$$T_2 = \frac{2(\gamma - 1)}{(\gamma + 1)^2}\frac{m_j v_1^2}{k} = \boxed{\frac{3 m_j v_{sh}^2}{16\, k}}$$

shock front of thickness $\Delta \mathbf{d} \sim \ell_{\mathbf{mfp}}$

Why Collisionless?

- Average distance a proton of velocity **v** (cm/s) travels before suffering a hard 90º deflection is

$$\boxed{d_{90^\circ} = 7.5 \left(\frac{v}{1000\,km\,s^{-1}}\right)^4 \left(\frac{n_i}{1\,cm^{-3}}\right)^{-1} \text{ L.Y.}}$$ **(Spitzer 1962)**

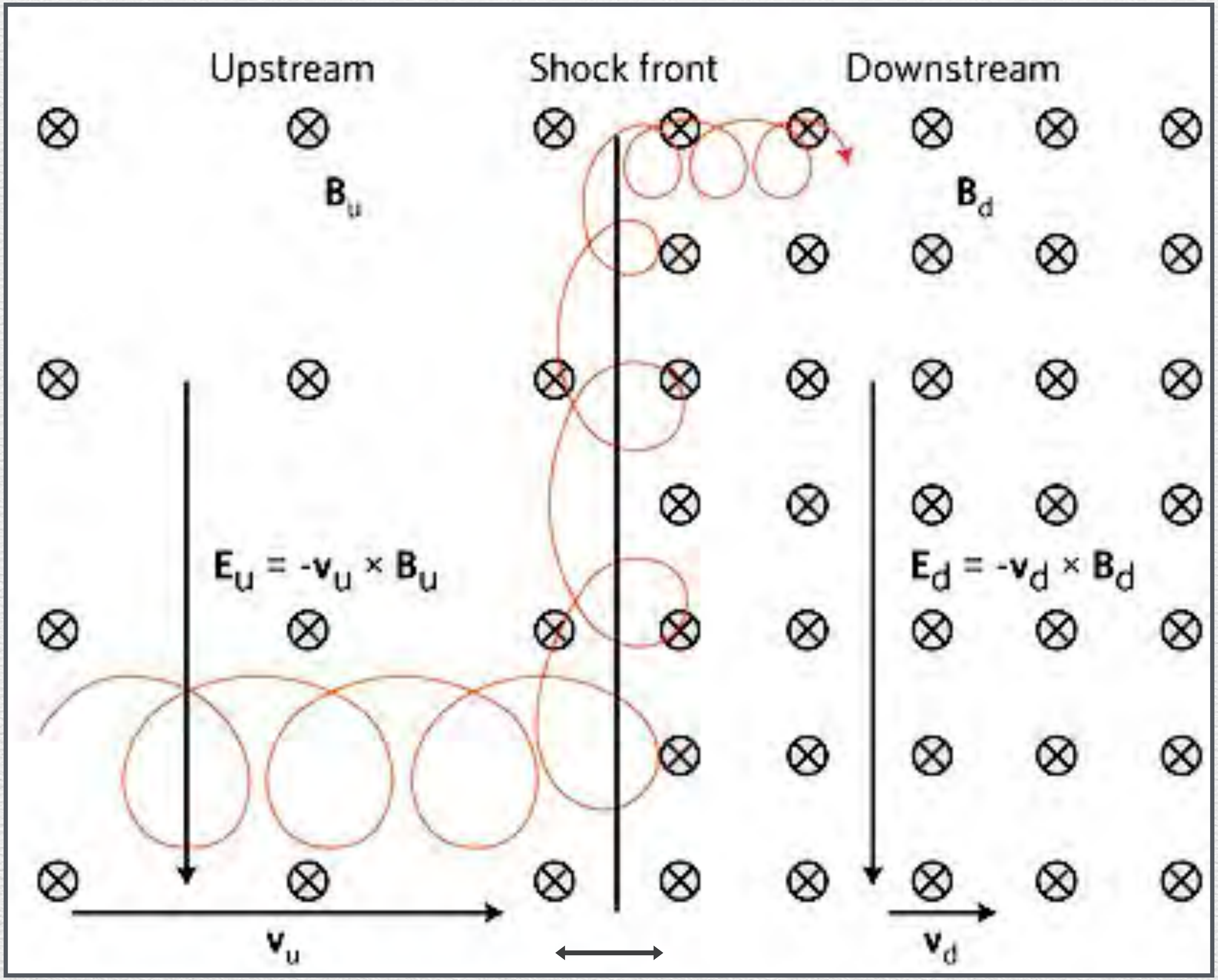
- For protons in a SNR shock, v ~ 2000-10^4 km s^{-1}, and n_i ~ 0.1-1.0 cm^{-3}, so

$$\mathbf{100\ L.Y.} \lesssim \mathbf{d_{90^\circ}} \lesssim \mathbf{1000\ L.Y.} \sim \Delta\mathbf{d} \gg \mathbf{R_{SNR}}$$

...Shock jump *CANNOT* be one collision mean free path!

- Instead, scattering and heating of charged particles at the shock front occurs via <u>plasma waves</u> and <u>MHD turbulence</u>

Quasi-Perpendicular Collisionless Shock



Δd

$\Delta d \approx r_{L,i}$
$= m_i v_\perp / eB$

Broad Physics of a Collisionless Shock

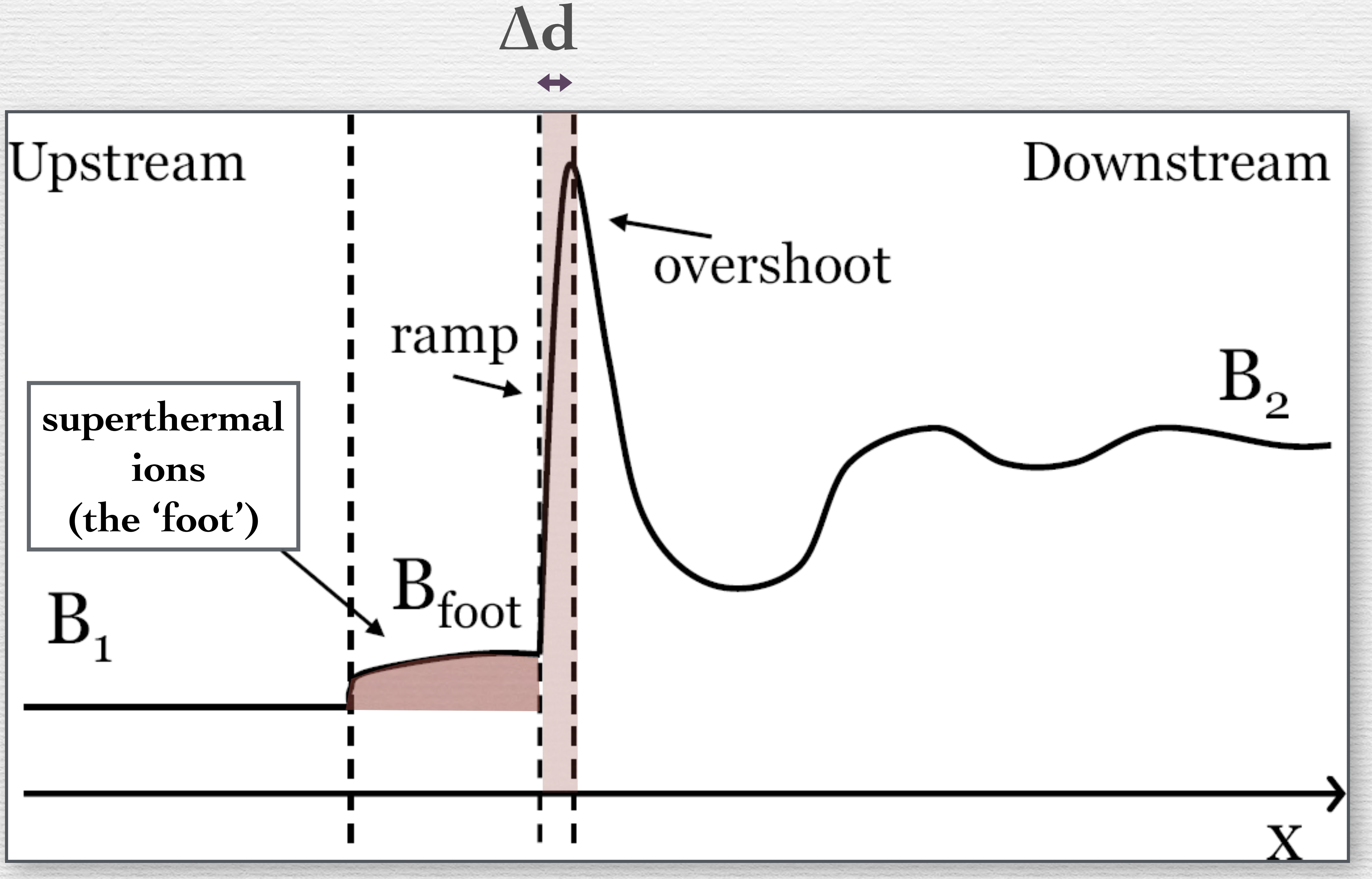
STREAM Kinetic Energy Entering Shock
(e^-s and ions in interstellar B-field)

Plasma Instabilities
(2-stream, firehose, Weibel….)

Plasma Waves
(Alfvén, lower hybrid, whistler)

Heating of Ions
(resonant/non-resonant scattering of ions and e^-s)

Perpendicular Shocks Have Pre-Shock Wave Activity!



Degree of Electron-Ion (Ion-Ion) Temperature Equilibration is Unknown

- Electron and ion heating at shock transition depends on complicated microphysics of the plasma, so:

$$\mathbf{(m_e/m_p) \le (T_e / T_p)_0 \le 1}$$

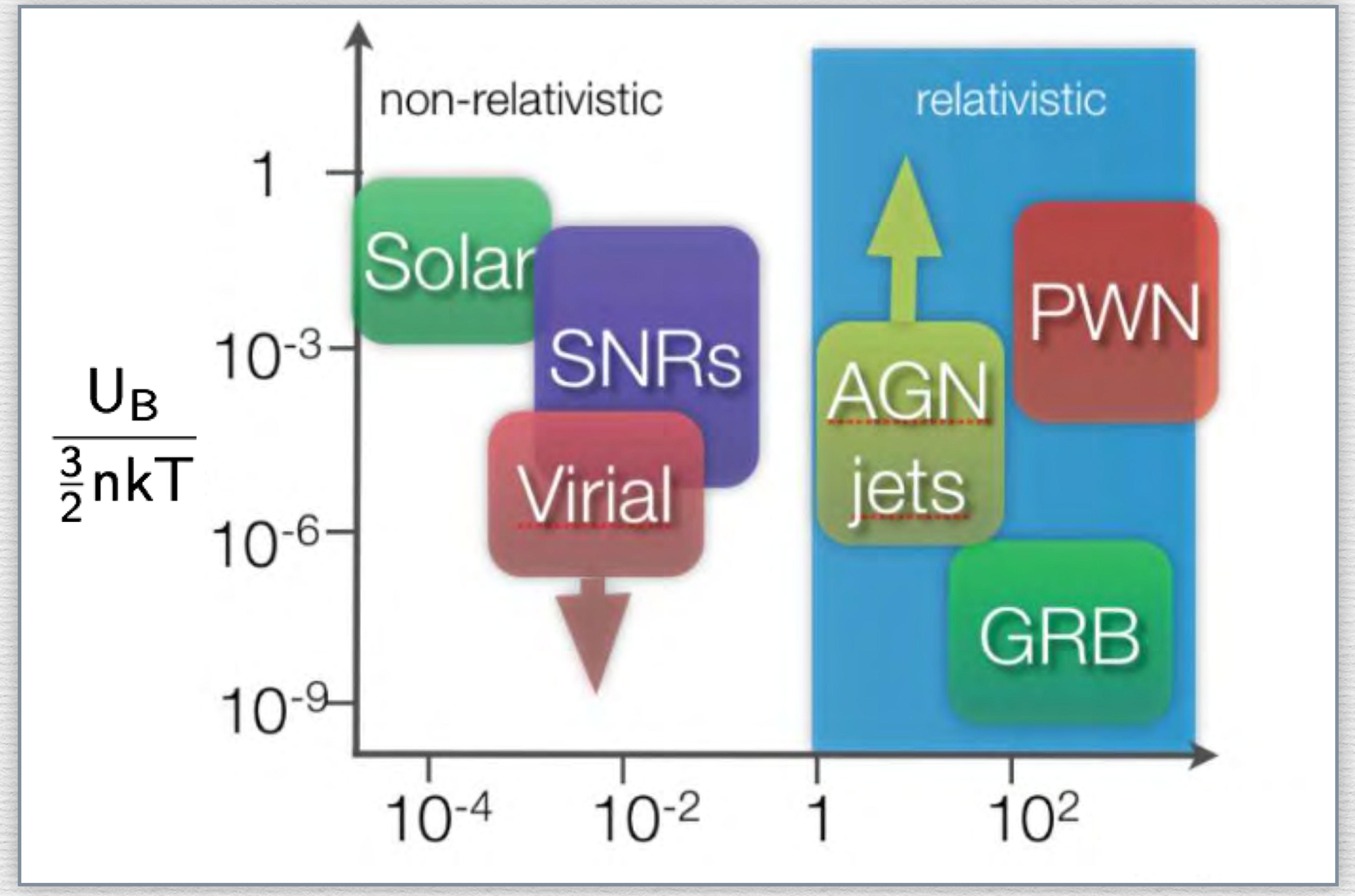
minimal from jump cond (~ 1/1836 for e-, p)

maximum (efficient collisionless heating)

- Observational probes of <u>conditions in the immediate postshock gas are needed</u>

Parameter Space of Collisionless Shocks

magnetization parameter

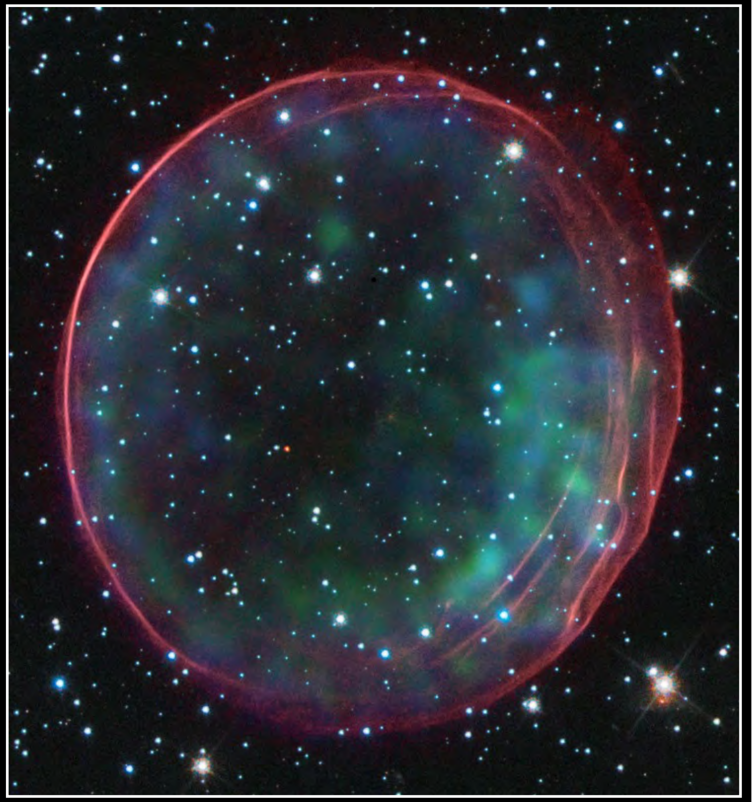


(courtesy A. Spitkovsky)

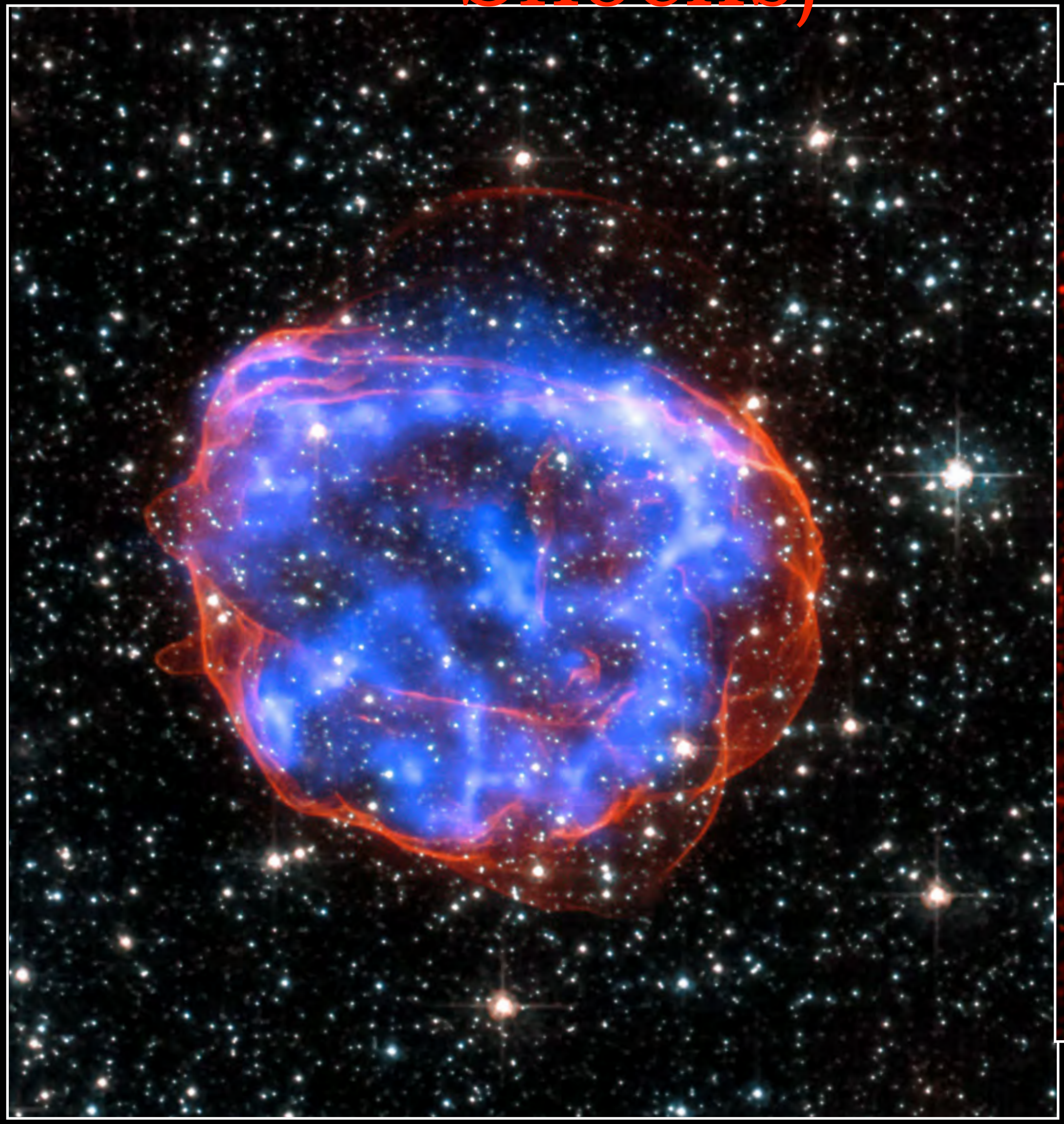
$\Gamma v_{SH}/c$

(relativistically correct shock speed)

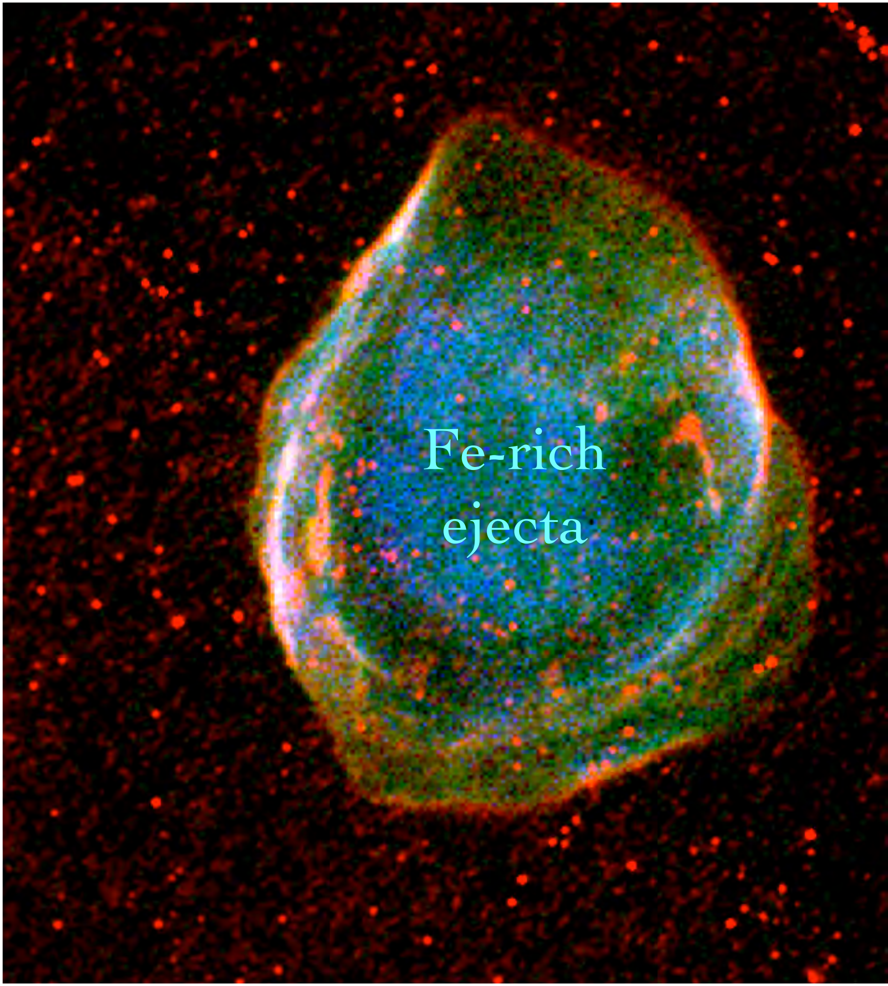
One Tool: Non-Radiative Shocks in Warm Partially Ionized Gas (Balmer-Dominated Shocks)



SNR 0509-67.5
(HST/ACS)



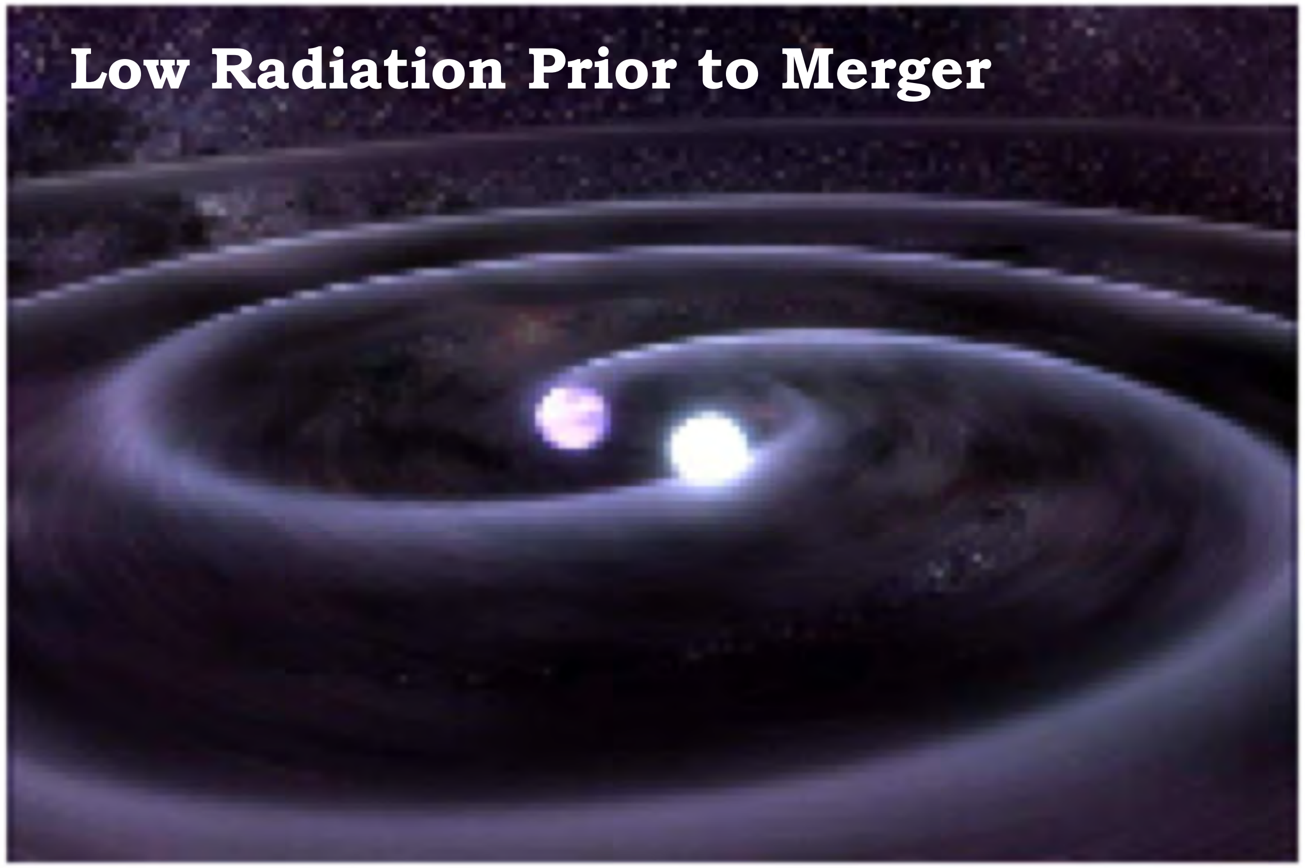
SNR 0519-69.0



SNR 0505-67.9
(DEM L 71)
(HST/WFC3)

Blue+Green: X-rays (Chandra)
Red: Hα

Most Balmer-Dominated SNRs Result from Type Ia SNe (Detonation of a C/O or O/Ne WD)



Single Degenerate

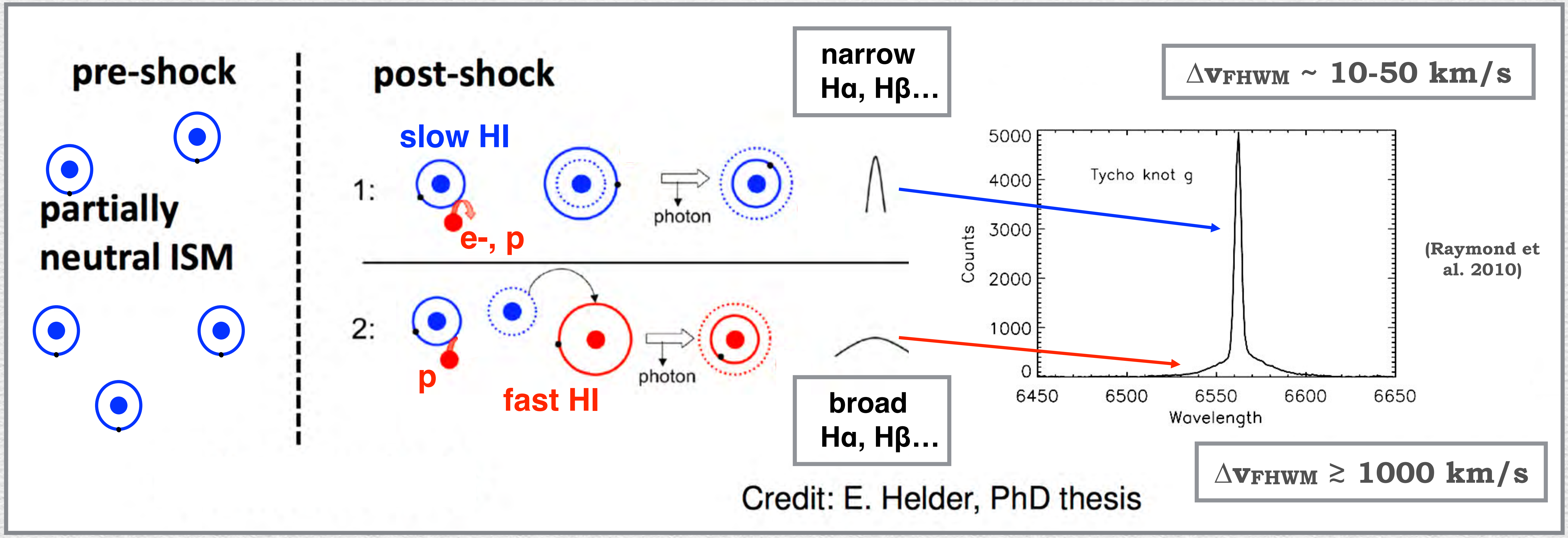
Double Degenerate

Whelan & Iben (1973)
Shen & Bildsten (2009)

Webbink (1984)
Ilkov & Soker (2012)

What Are Balmer-Dominated Shocks?

- Nonradiative shocks in warm, partially neutral ISM produce spectra dominated by collisionally excited H I (T ~ 10^7-10^8 K)



Δv_{FWHM} ~ 10-50 km/s

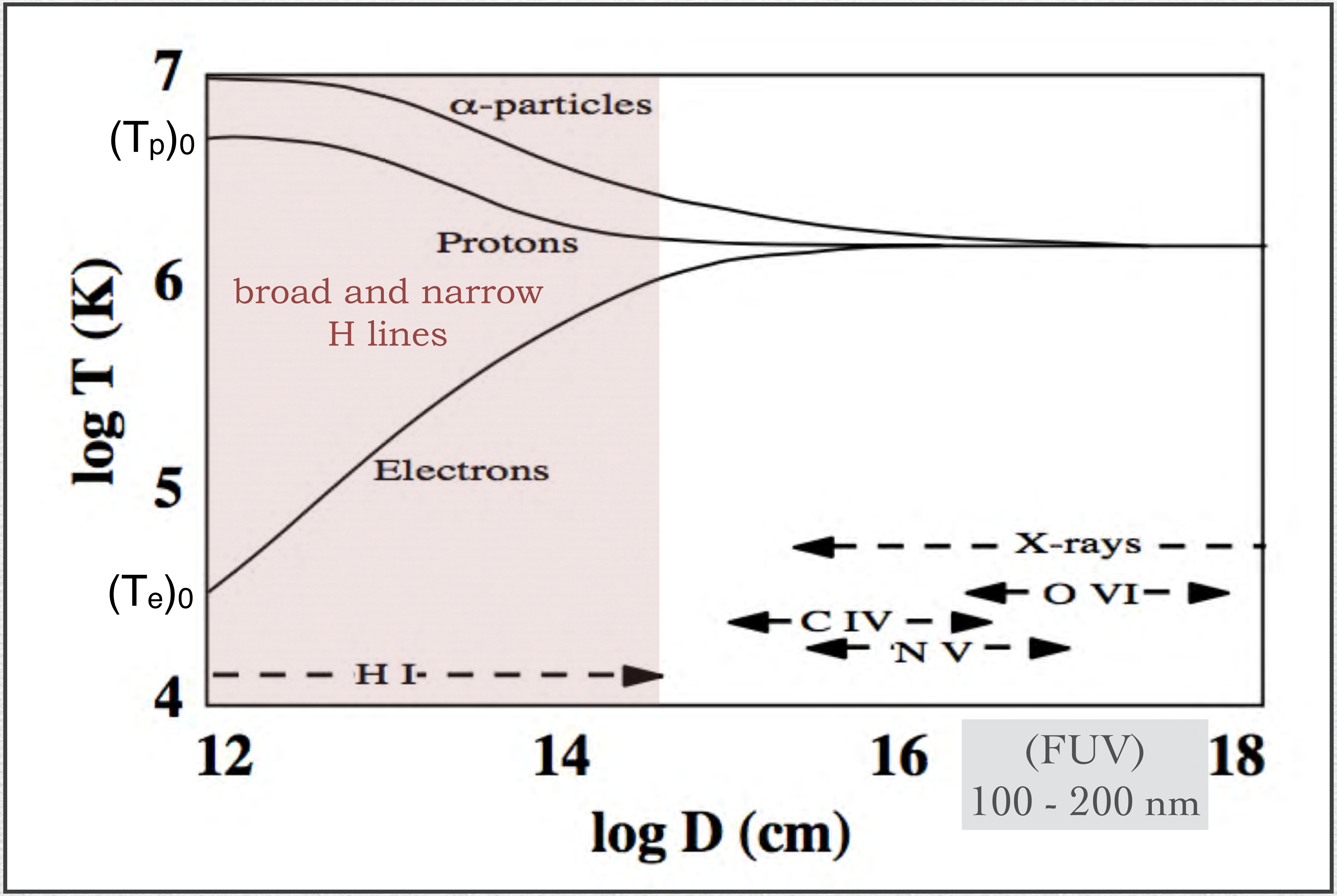
$\Delta v_{FWHM} \gtrsim 1000$ km/s

(Raymond et al. 2010)

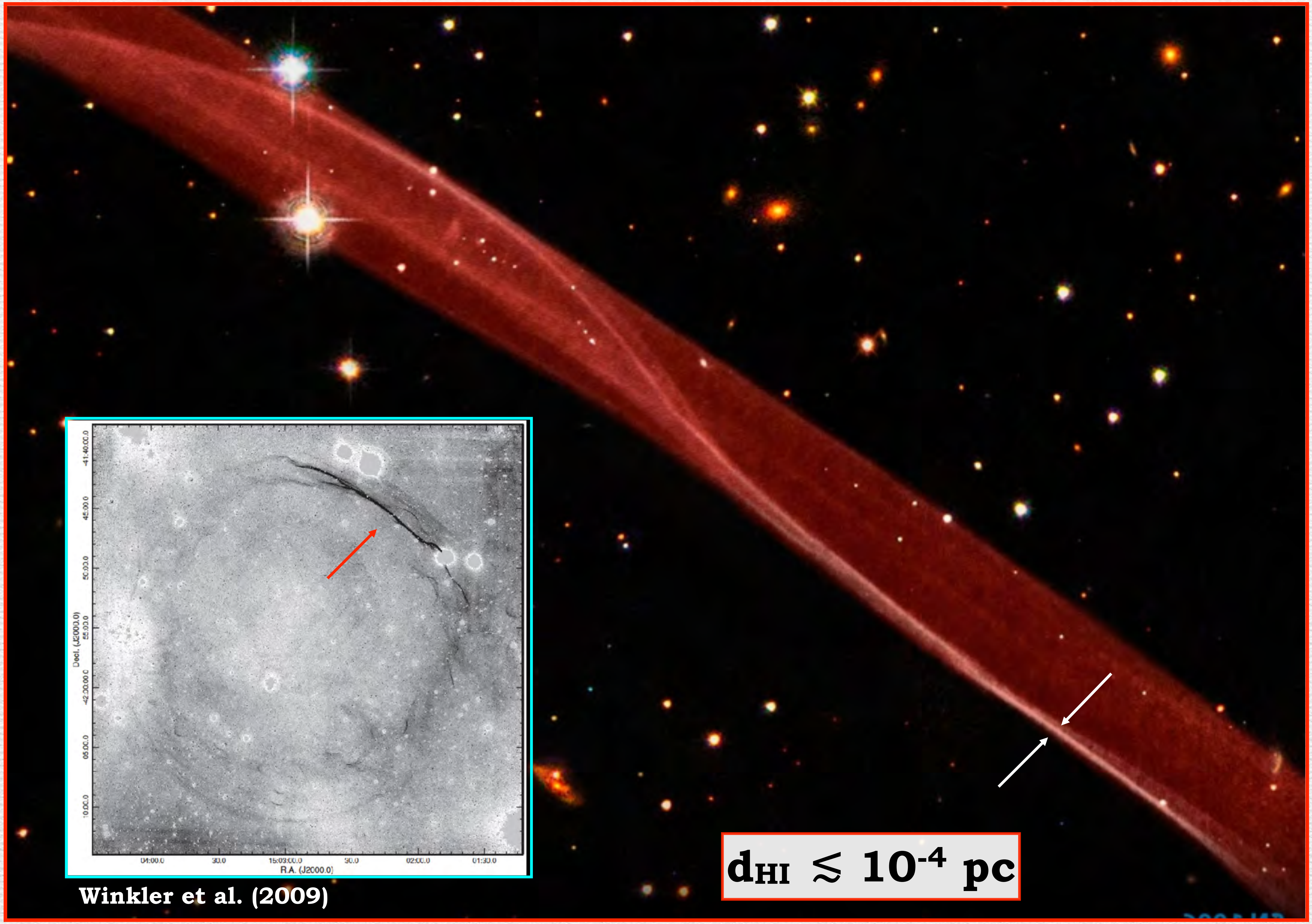
Credit: E. Helder, PhD thesis

- **Faint:** n_{ISM} ~ 1 cm^{-3}; only factor of 4 post-shock compression
- Hard to detect, requires deep narrowband Hα imagery

Broad and Narrow Hα Emission is Sensitive to The Initial Electron-Ion Equilibration



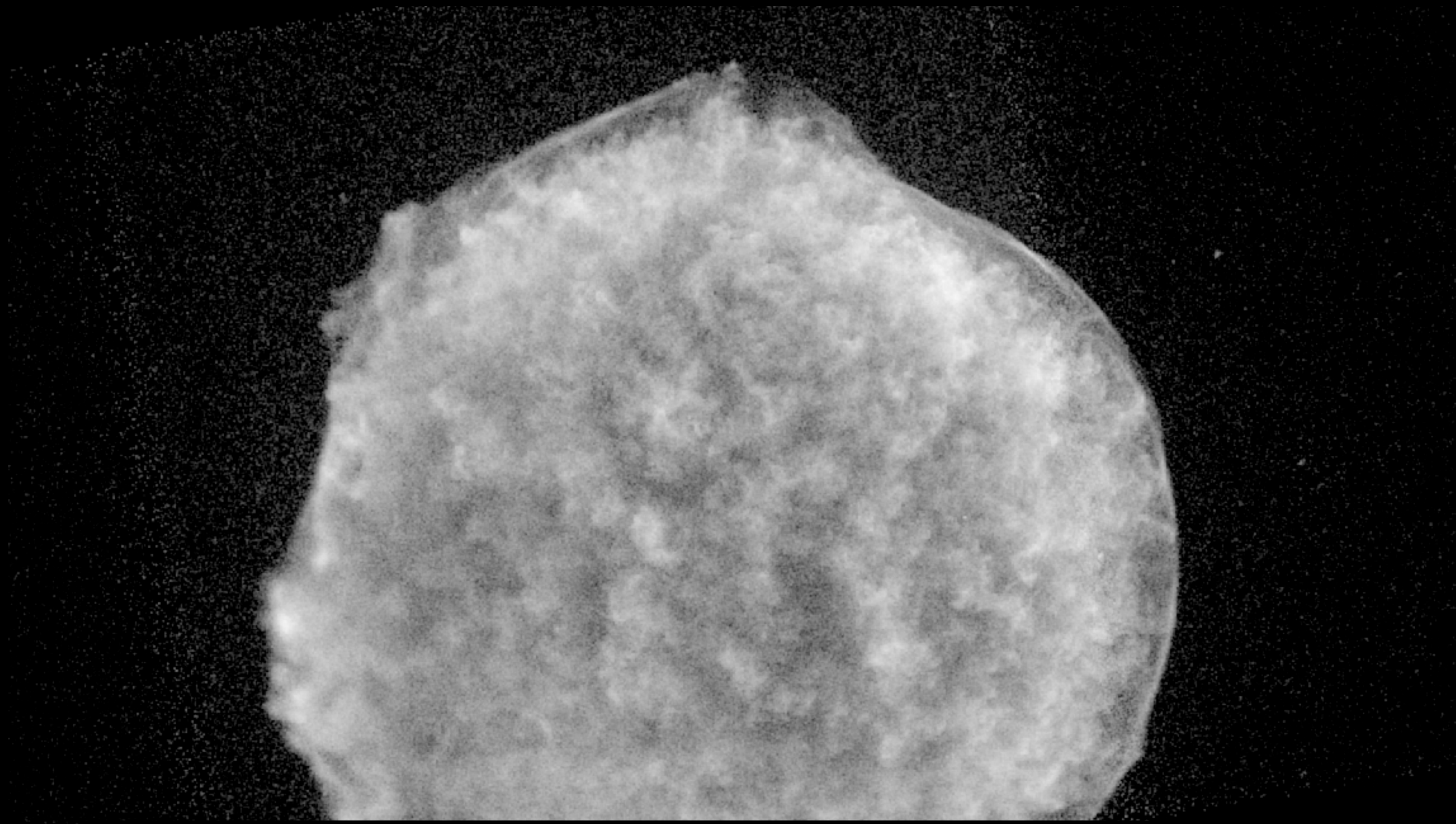
SN 1006: Edge-on Sheet Geometry



Winkler et al. (2009)

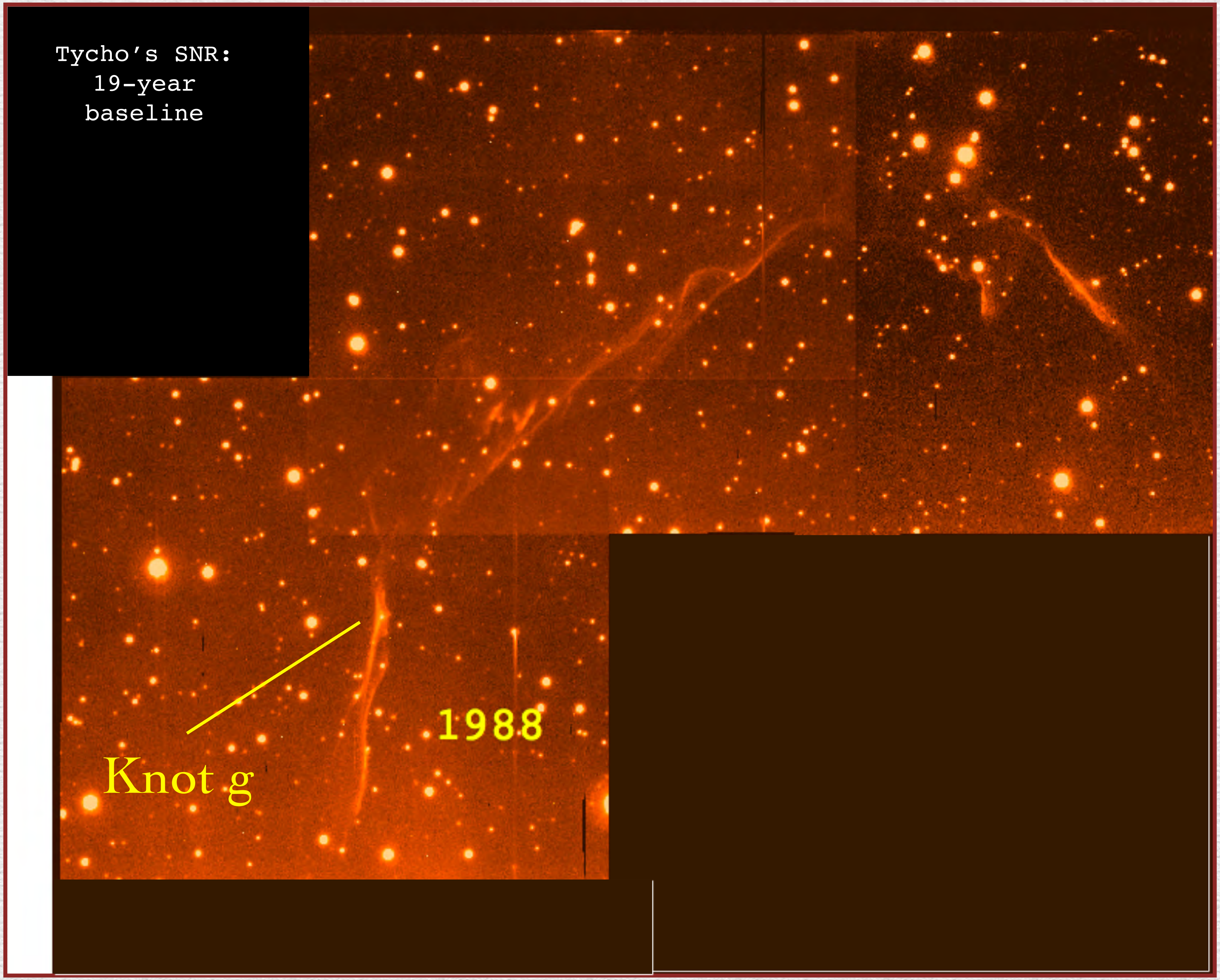
$d_{HI} \lesssim 10^{-4}$ pc

15-yr X-ray Expansion of Tycho's SNR (Chandra)

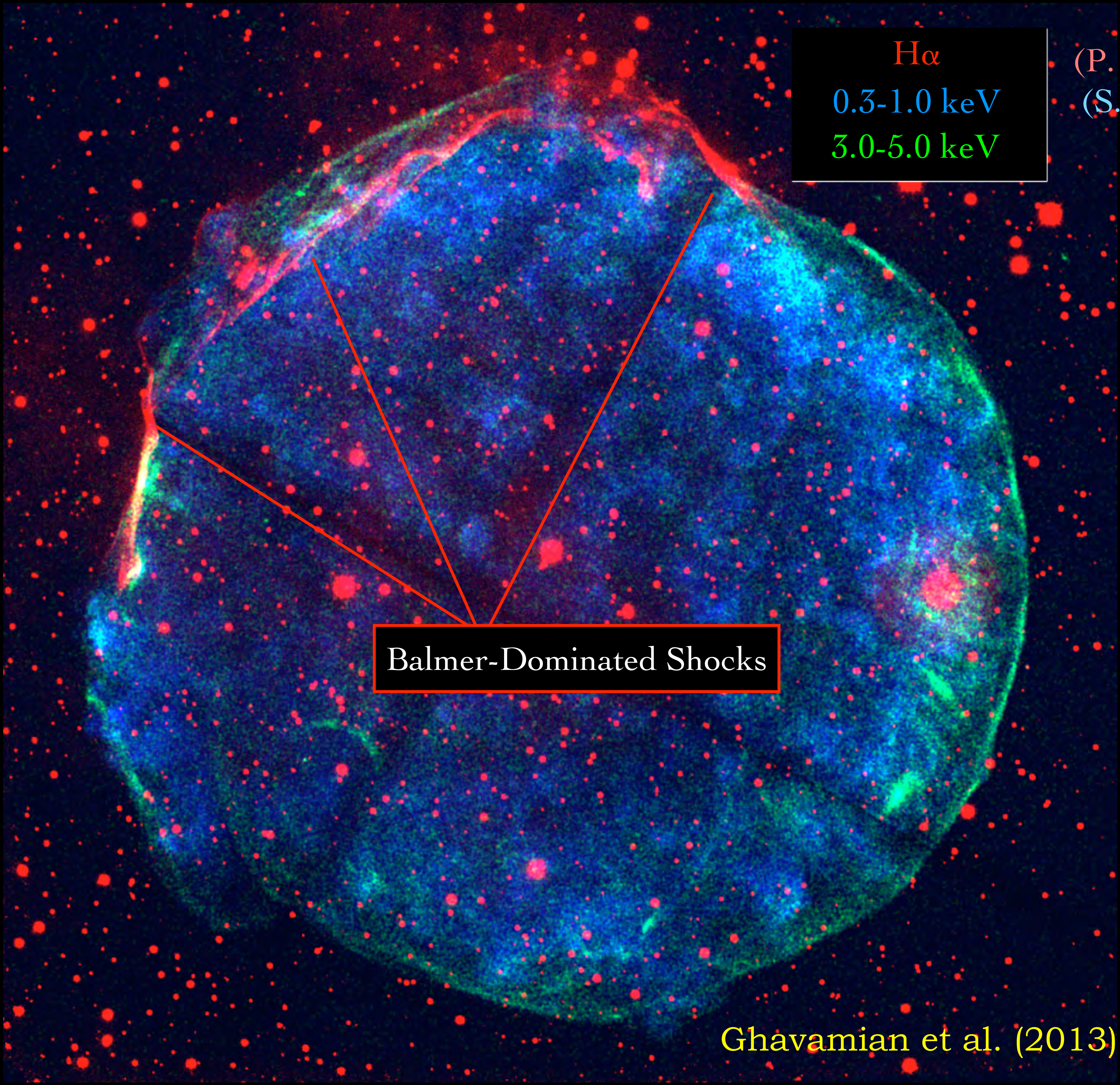


(**1-3 keV (soft X-rays)**: shows thermal emission only)

Tycho's SNR: The Movie



Winkler, Blair & Fesen (KPNO 4m data)



Balmer-Dominated Shocks

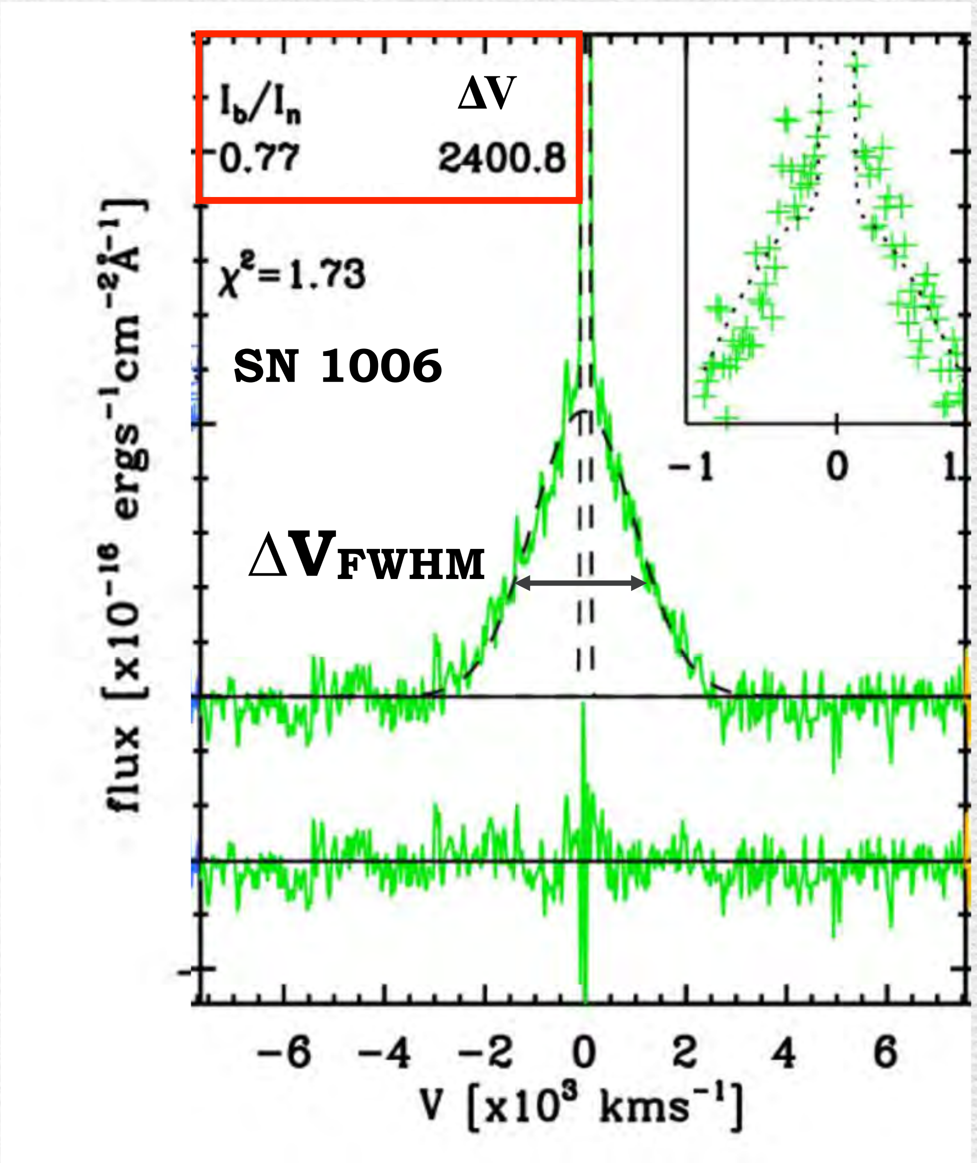
(P. F Winkler)
(S. Park et al. 2007)

Ghavamian et al. (2013)

Observables in Balmer-Dominated Spectra

SN 1006

Nikolic et al. (2013): IFU obs.



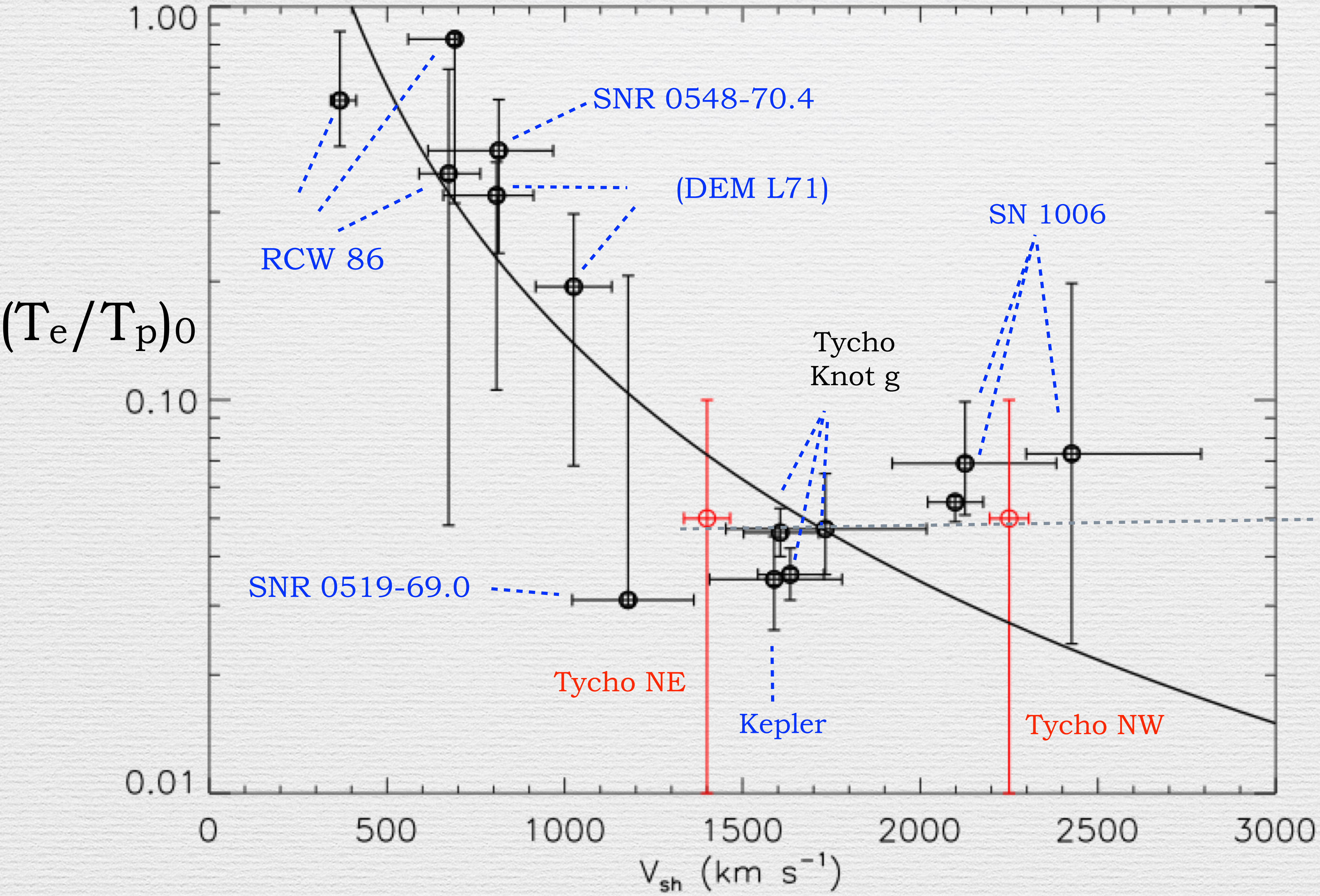
$$\Delta V_{FWHM}(H\alpha, H\beta, \ldots) \propto T_p, V_{SH}$$

$$\frac{I_b}{I_n} \propto \frac{\langle \sigma_{cx} v \rangle}{\langle \sigma_i v \rangle} \Rightarrow \left(V_{SH}, \left(\frac{T_e}{T_p}\right)_0, f_{HI}\right)$$

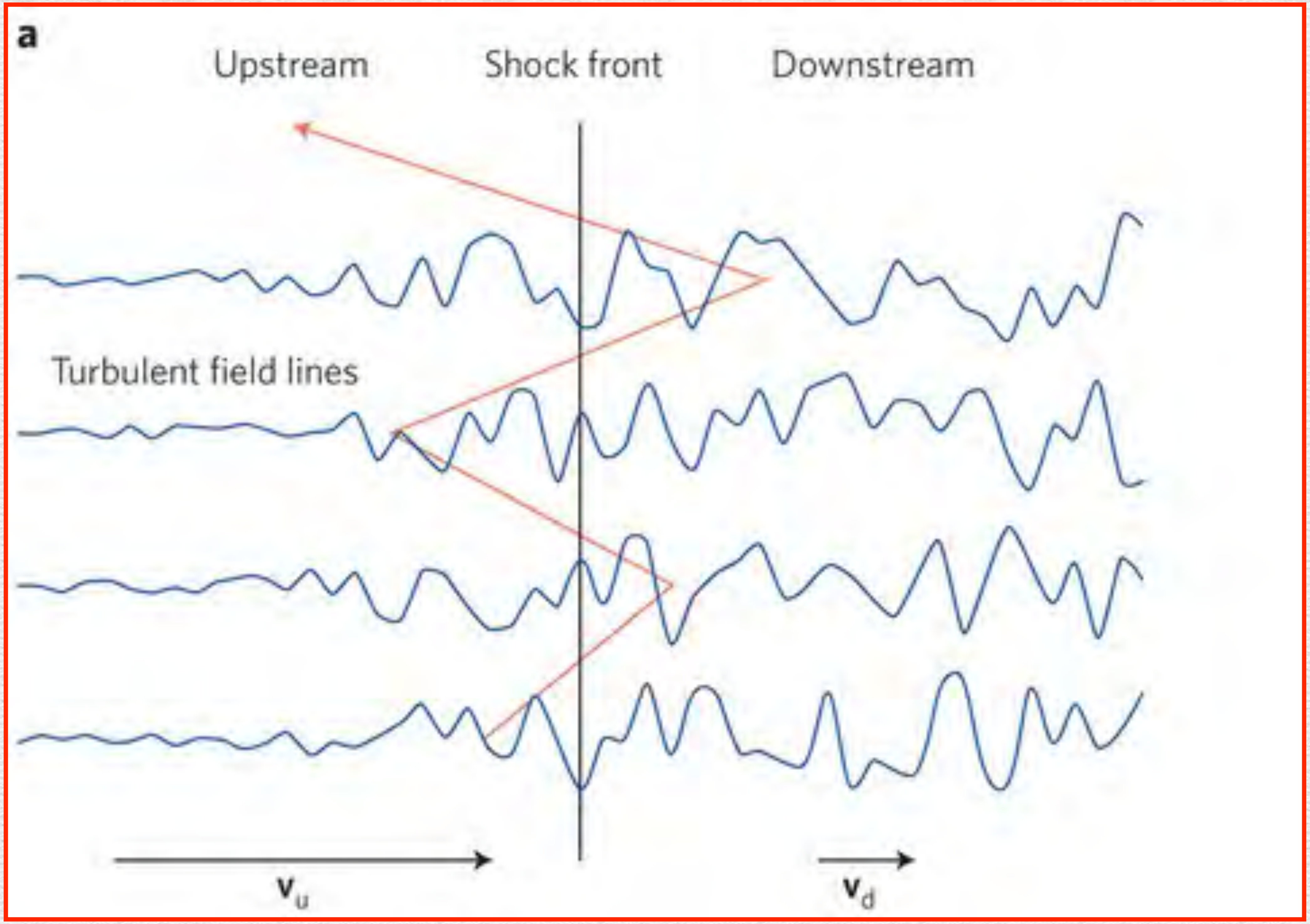
(Smith et al. 1991; G01, G02, G07, G13, van Adelsberg et al. 2008)

Many Balmer SNRs Reveals a Distinct Trend: (T_e/T_p)

van Adelsberg et al 2008; G13



Cosmic Ray Acceleration



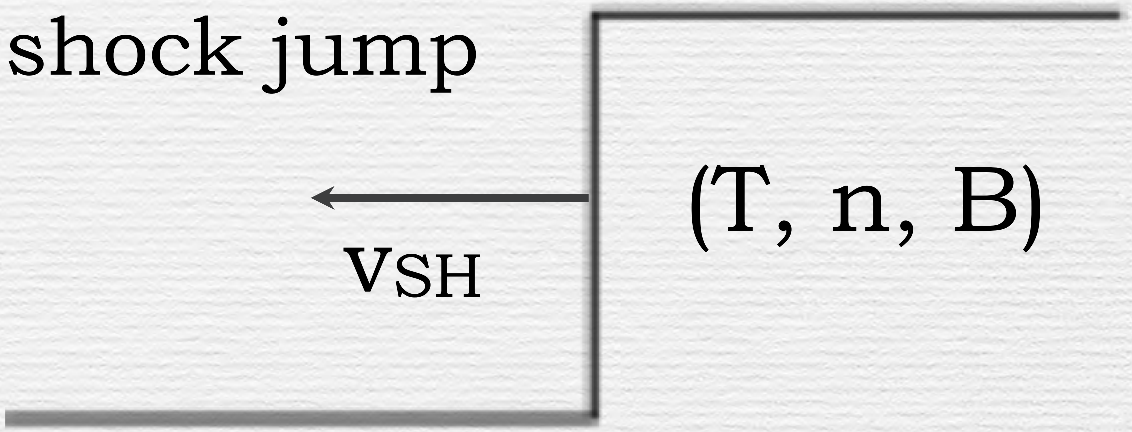
A Possible Explanation For $T_e/T_p \propto 1/V_{SH}^2$

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

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

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

- A constant heating ΔE_e would reproduce what we see
- Likely occurs *ahead of the shock*
- *Likely candidate: cosmic ray precursor*

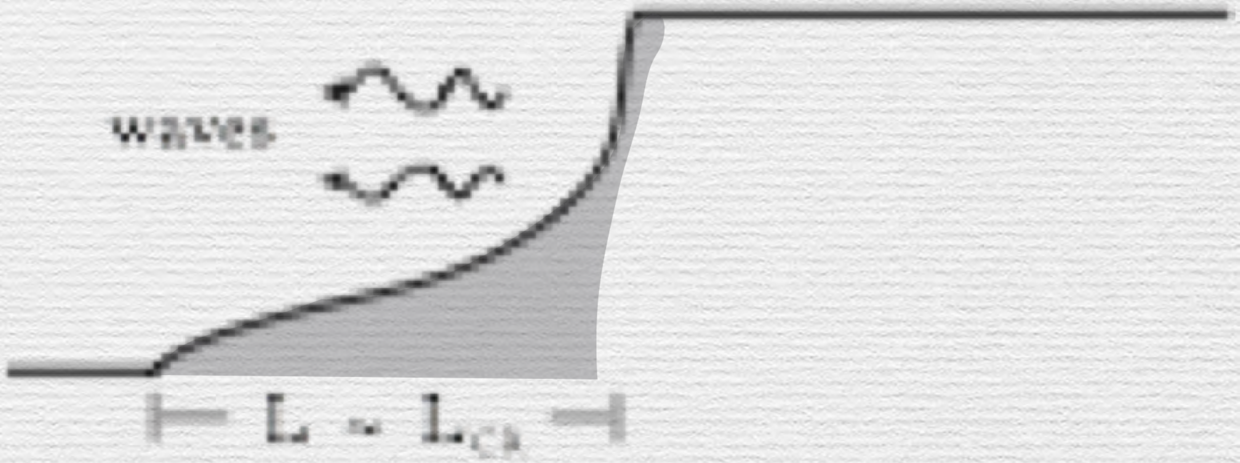


shock jump

v_{SH}

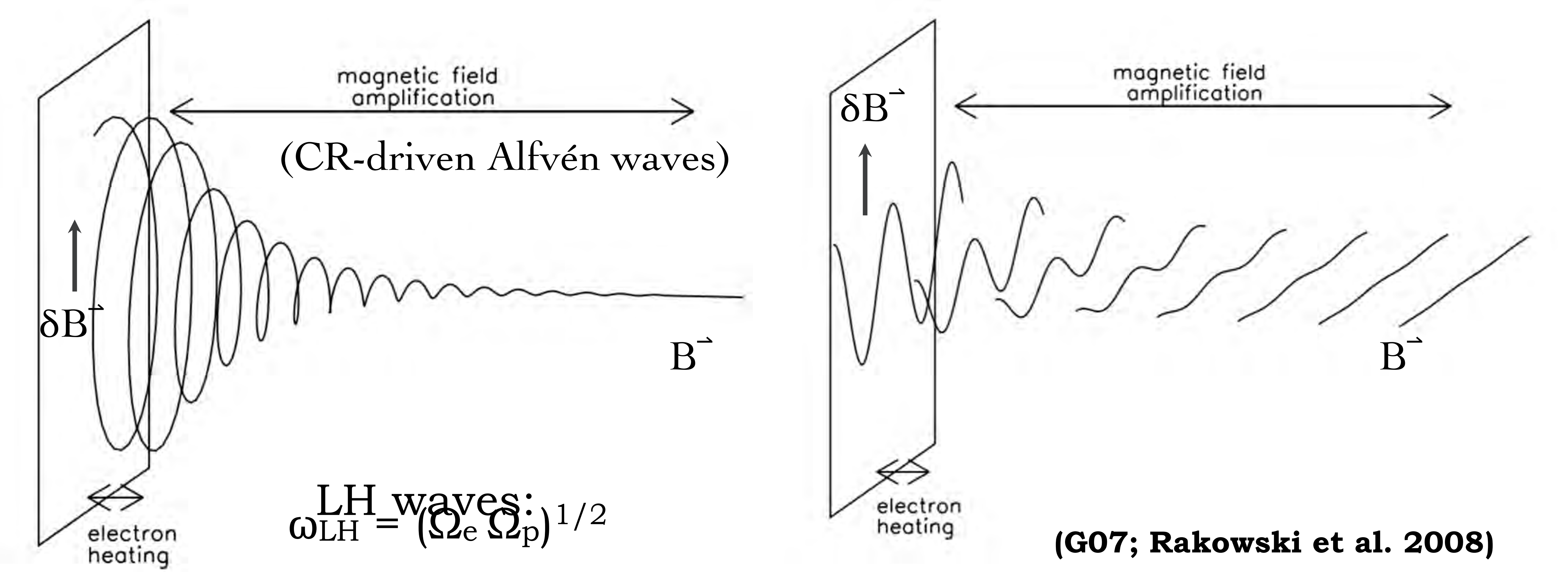
(T, n, B)

With CRs/Reflected Ions



$\propto p_{CR}(\max)$

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



(CR-driven Alfvén waves)

LH waves: $\omega_{LH} = (\Omega_e \, \Omega_p)^{1/2}$

(G07; Rakowski et al. 2008)

- LH waves can bulk heat e⁻s parallel to δB
- $\Delta E_e = \frac{1}{2} m_e \Delta v_e^2 \propto \Omega_e \, \kappa_{CR}$

$\Delta E_e \sim 0.3$ keV (const)