# High-Resolution Hα Spectroscopy of Balmer-Dominated Shocks in Supernova Remnants

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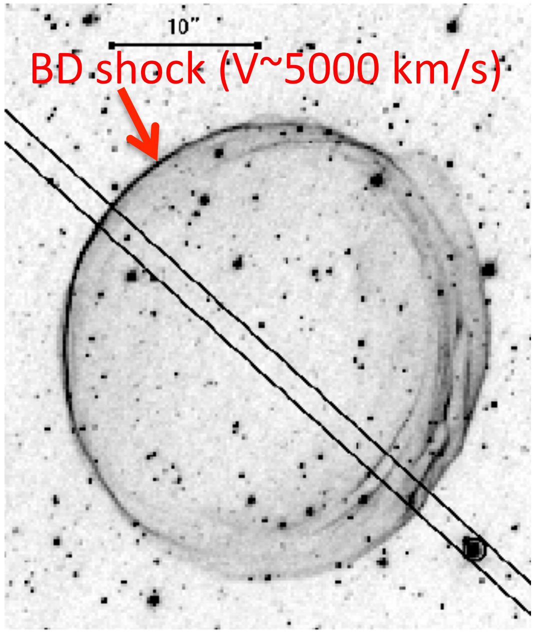
# Balmer-Dominated (BD) Shock

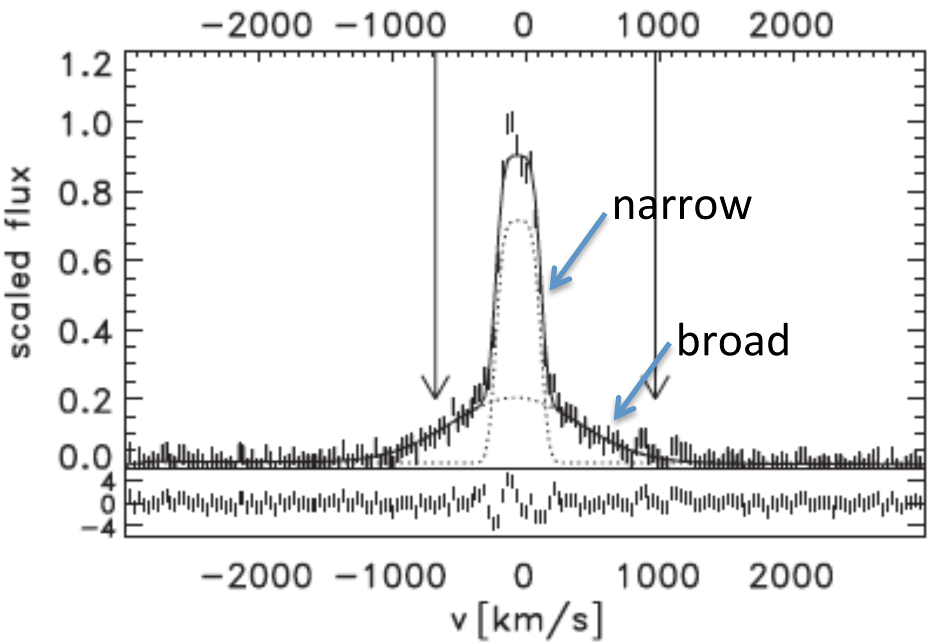
- Relatively fast (>100 km/s) shock seen in ~10 SNRs.
- Presence of strong Hα lines with broad + narrow components.
  → The shock must propagate into (partially) neutral gas.
- Absence of (or little) forbidden lines from metals.
  → The plasma is not recombining but ionizing.
- BD shocks are the only sites to see fast SNR shocks in optical.

Hα image of SNR 0509 in LMC




Helder et al. (2010)

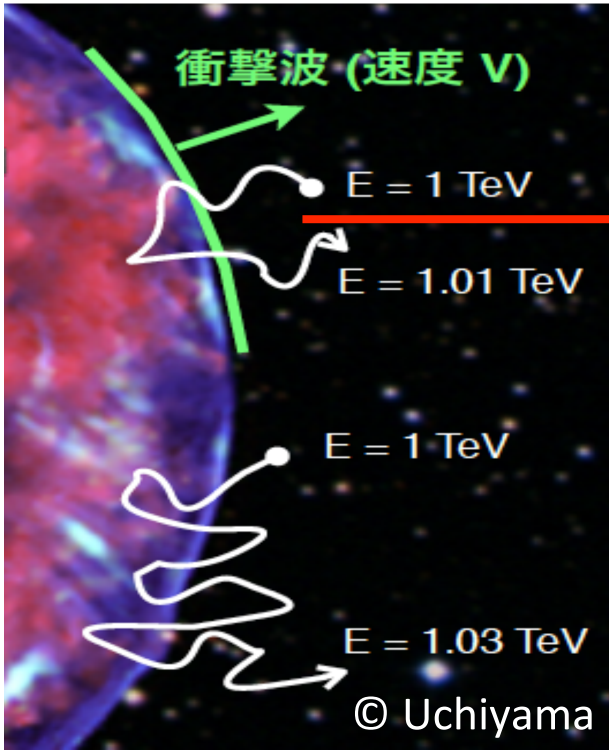
Hα line profile



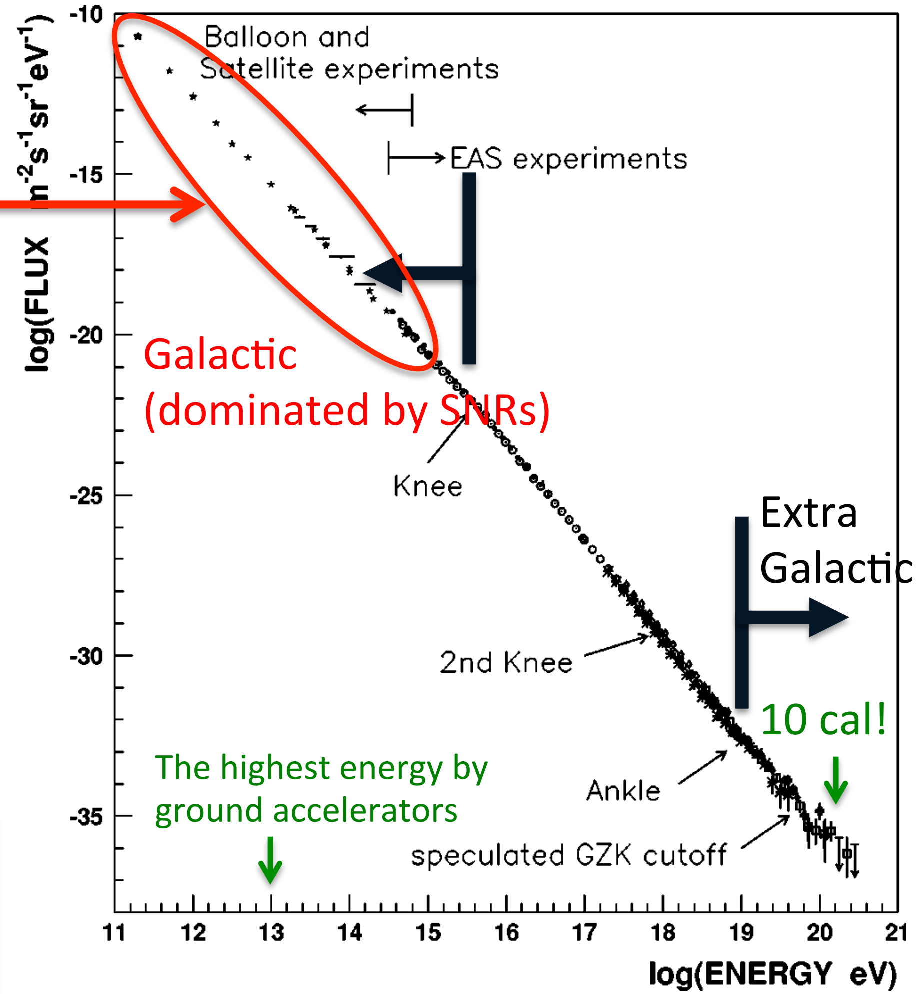

Heng (2010)

# SNR Shocks Are Accelerating Cosmic Rays

SNR shock accelerating CRs



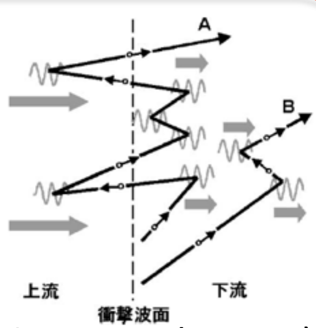

Energy distribution of CRs




Nagano & Watson (2000)

What is the mechanism of the acceleration?

→ A promising scenario is the diffusive shock acceleration (DSA) theory.

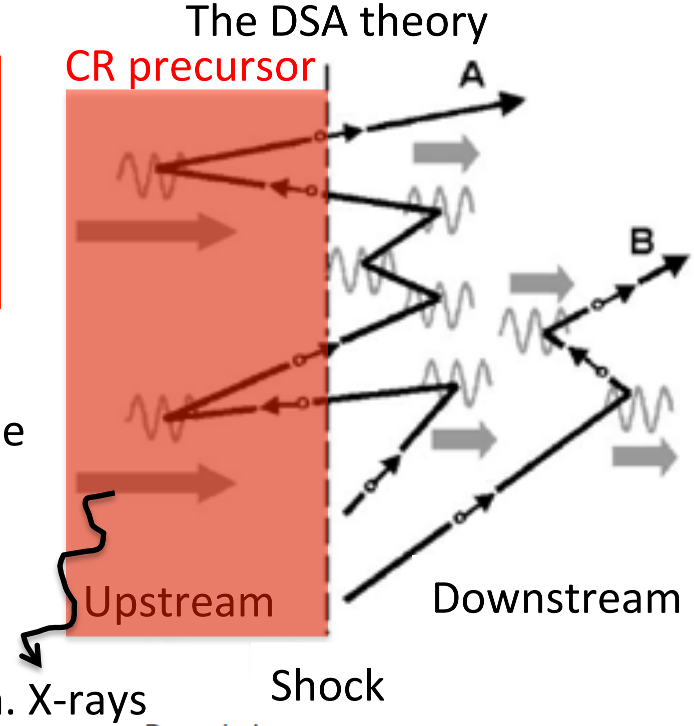



(Cf. Bamba & Yamazaki 2004)

# An Imprint of DSA: Cosmic-Ray Precursor

The DSA theory predicts a cosmic-ray (CR) precursors, whose length scale is ~$\kappa/V_s$ ($\kappa$ is the diffusion coefficient).

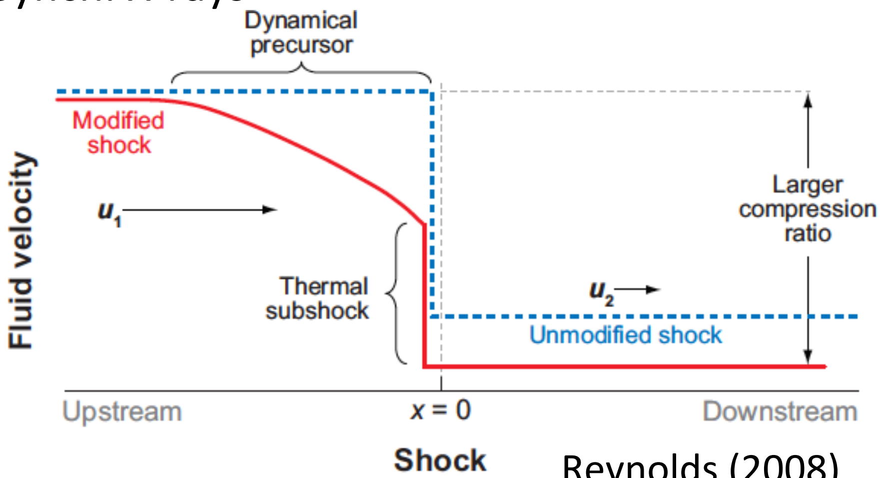
A: accelerated particle
B: non-accelerated particle




However, it's not yet detected.

The CR precursor could be detected in H$\alpha$ emission ahead of the BD shocks, as the gas slows down (wrt. a shock) and is heated in the precursor.

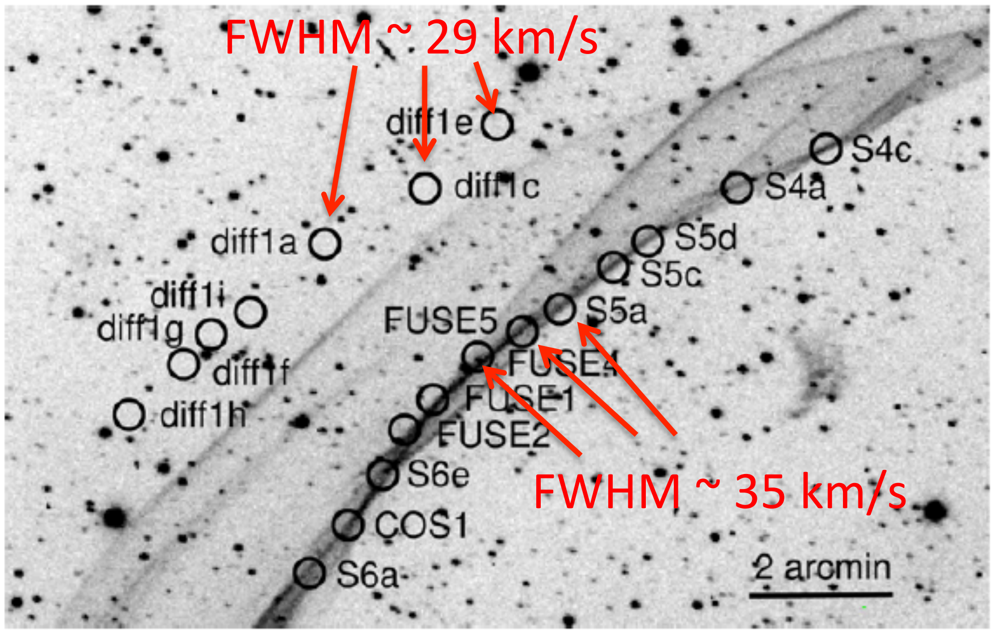
□ The effect of efficient CR acceleration →




Reynolds (2008)

# A Hint of CR Precursors in the Cygnus Loop

Hα image of the NE limb of the Cygnus Loop (Medina et al. 2014)




[The Cygnus Loop]

Distance: 540 pc → 1" = $2.6 \times 10^{-3}$ pc

The nearest SNR with BD shocks

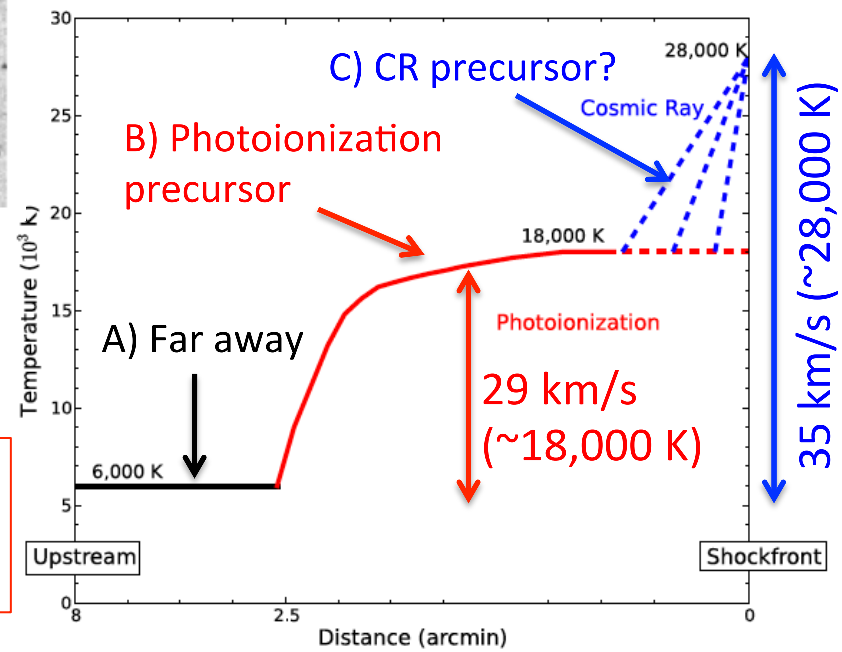
[The width of the Hα narrow component]

A) 21 km/s far away (expected)

B) 29 km/s in the photoionization precursor

↓ Increase!

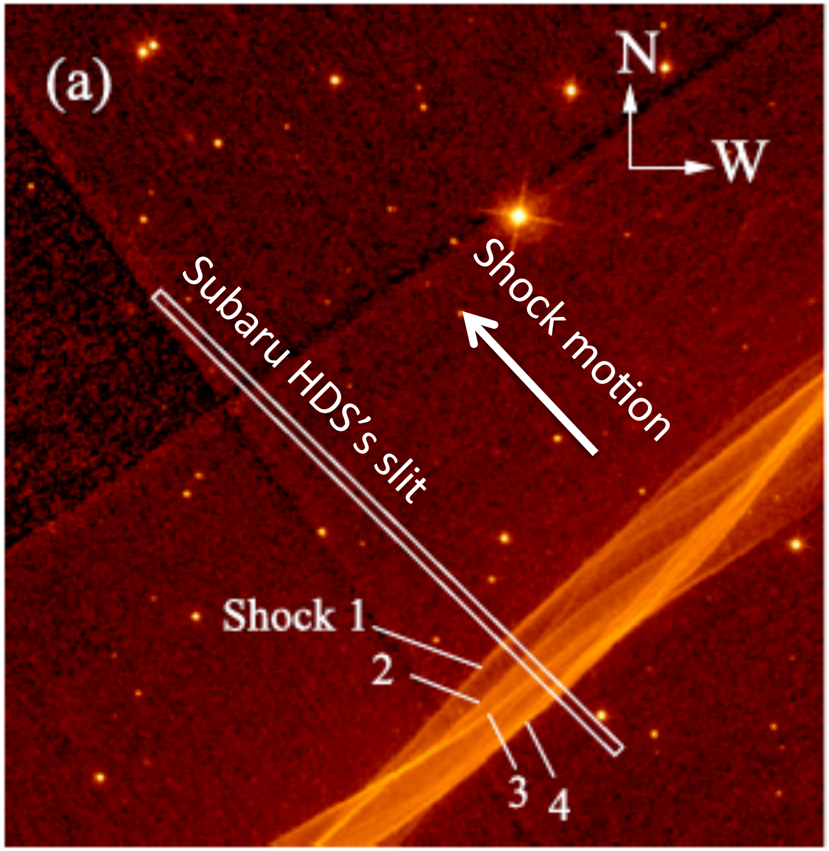
C) 35 km/s at the BD shocks



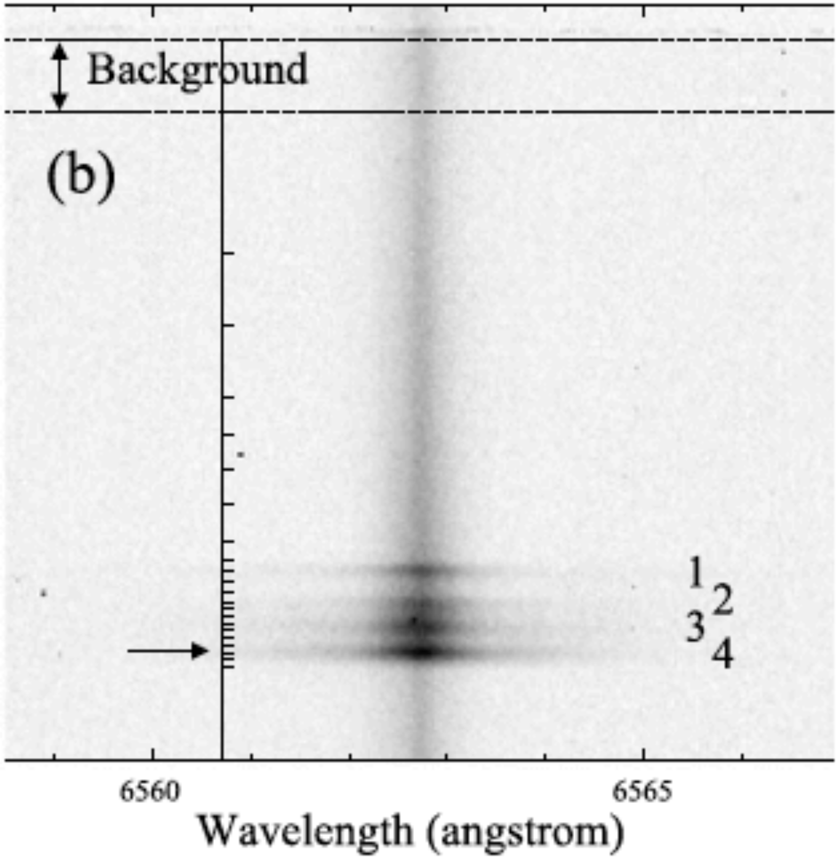

We want to detect the CR precursor and measure its length scale!

# High-Resolution Spectroscopy with Subaru/HDS

HST image

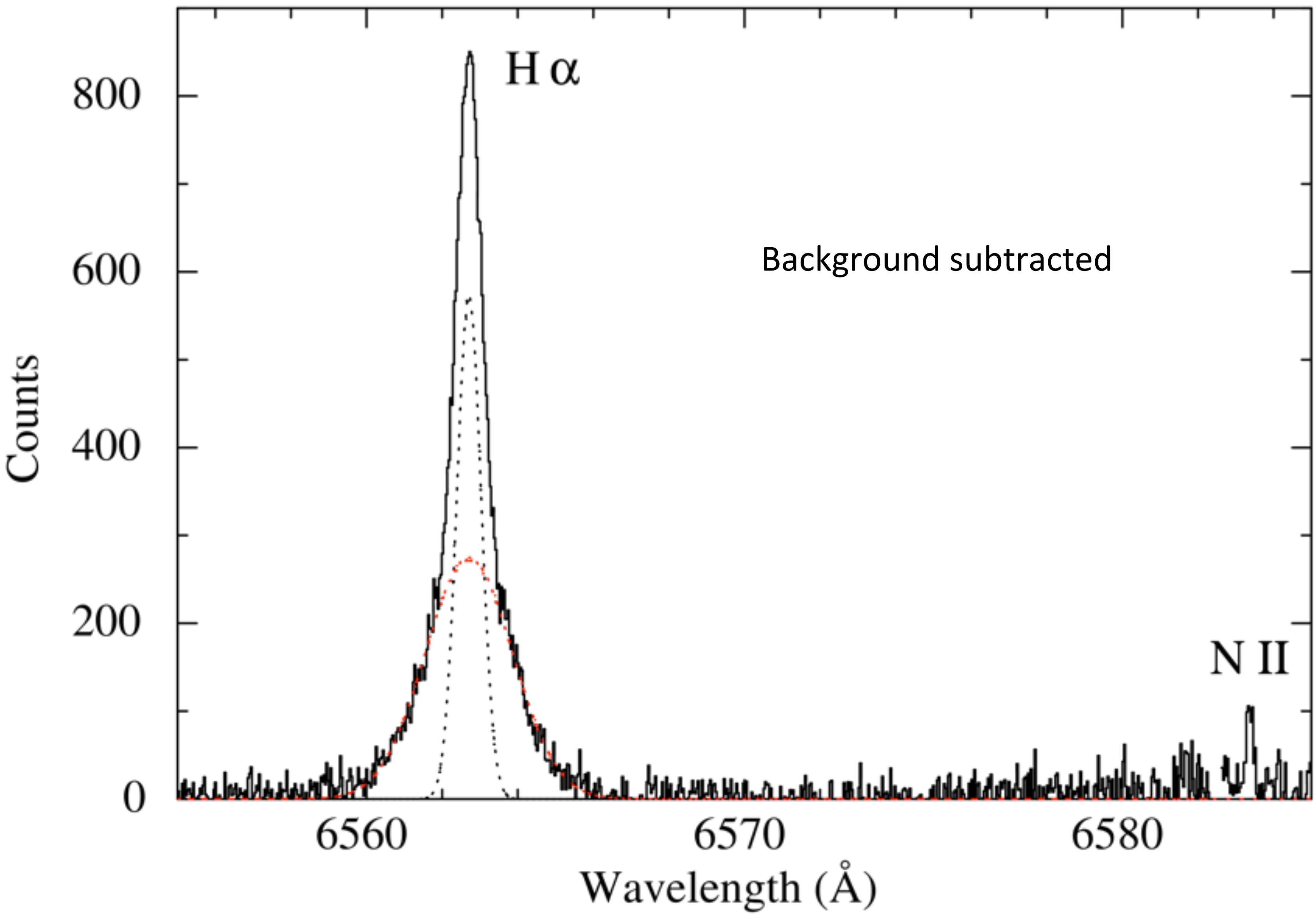



2D spectrum of Hα with the HDS

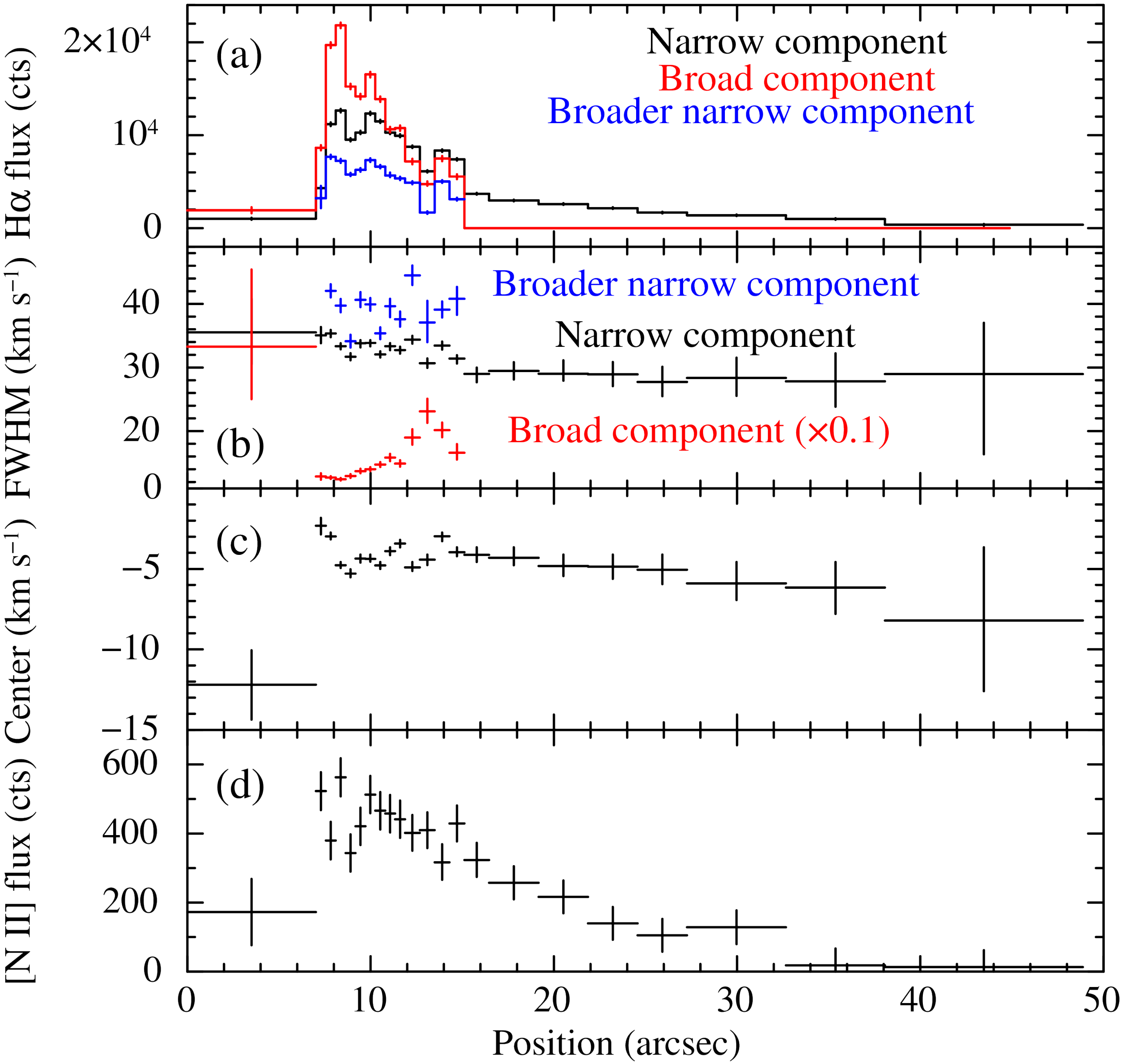



Observation: Aug. 31, 2015
Exposure time: 2.5 hrs

# Example Spectrum



# Radial Profiles of Gaussian Parameters




[The Hα line width]

- □ 29 km/s in the photoionization precursor
- □ 33 km/s at the BD shock

We found that the transition zone from 29 km/s to 33 km/s (possible CR precursor) is extremely thin: < 0.5" ~ 0.001 pc

# The Origin of the Sudden Broadening

- Energy source: A) Sound wave or B) Alfven wave?

Timescale for the waves to develop — Crossing time for the shock

(A) $t_s \sim 5\times10^8\, s\left(\frac{V_{sound}}{30\, km\, s^{-1}}\right)\left(\frac{L_{cr}}{0.001\, pc}\right)\left(\frac{V_s}{200\, km\, s^{-1}}\right)^{-1}\left(\frac{\eta_{cr}}{0.1}\right)^{-1} > t_{cross} \sim 2\times10^8\, s\left(\frac{L_{cr}}{0.001\, pc}\right)\left(\frac{V_s}{200\, km\, s^{-1}}\right)^{-1}$

(B) $t_a \sim 5\times10^7\, s\left(\frac{V_a}{6.6\, km\, s^{-1}}\right)\left(\frac{L_{cr}}{0.001\, pc}\right)\left(\frac{V_s}{200\, km\, s^{-1}}\right)^{-1}\left(\frac{\eta_{cr}}{0.1}\right)^{-1} < t_{cross} \sim 2\times10^8\, s\left(\frac{L_{cr}}{0.001\, pc}\right)\left(\frac{V_s}{200\, km\, s^{-1}}\right)^{-1}$

- Nature of broadening: A) Turbulence or B) Heating?

(A) Turbulent velocity

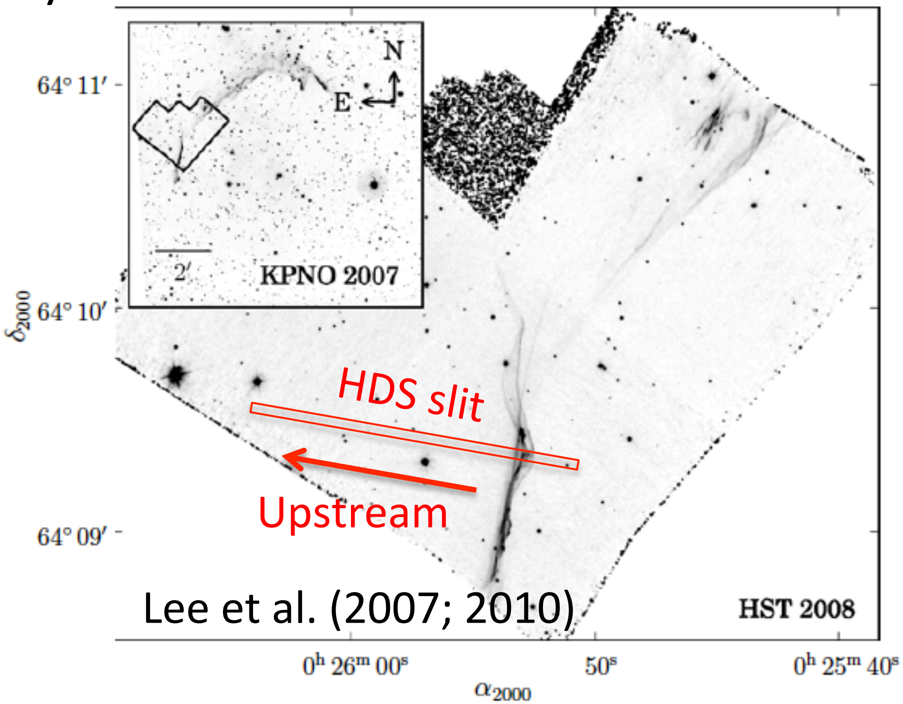
$$\delta V \sim 2.7\, km\, s^{-1}\left(\frac{V_a}{6.6\, km\, s^{-1}}\right)\left(\frac{\delta B / B}{0.4}\right) \qquad \frac{\delta B}{B} \sim 0.4\left(\frac{L_{cr}}{0.001\, pc}\right)^{-0.5}\left(\frac{V_s}{200\, km\, s^{-1}}\right)^{-0.5}\left(\frac{B}{3\, \mu G}\right)^{-0.5}\left(\frac{p}{m_p c}\right)^{0.5}$$

→ Impossible to explain the data

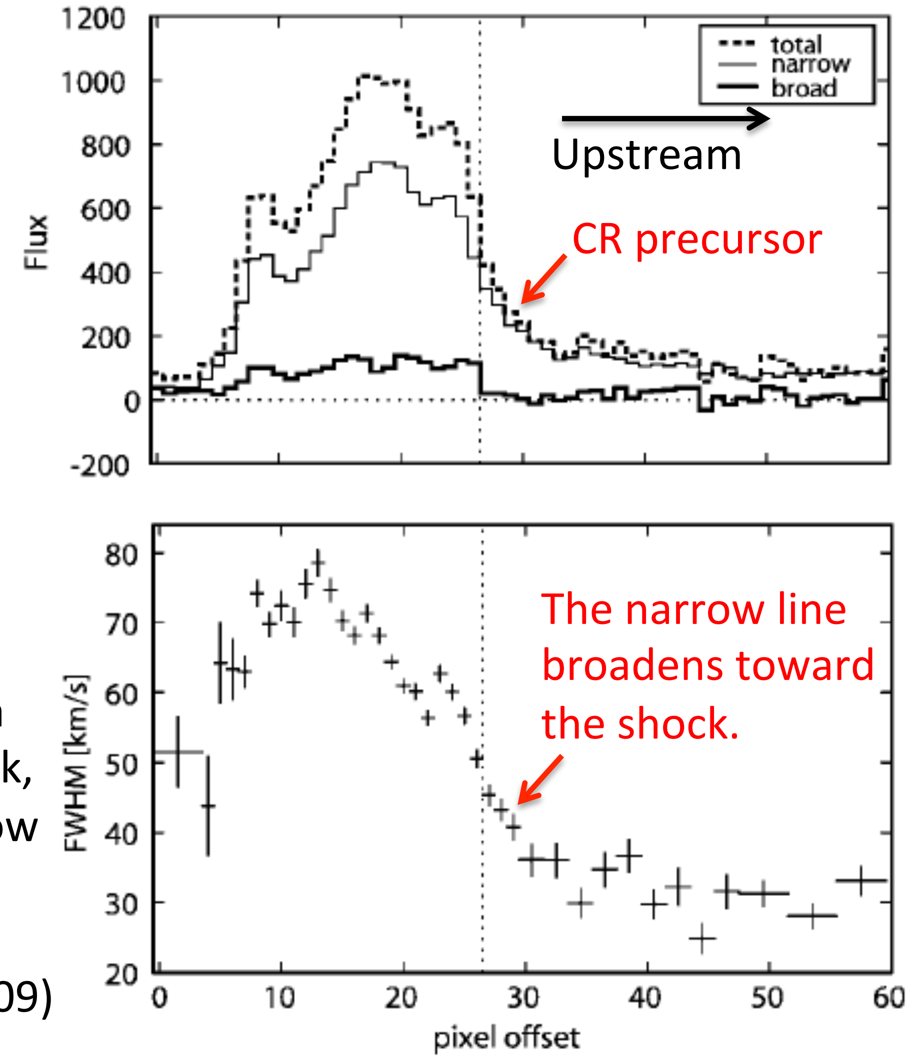
(B) Heating can explain the width (Boulares & Cox 1988), with fine tuning of the parameters.

# Another CR Precursor in Tycho's SNR

Tycho's SNR



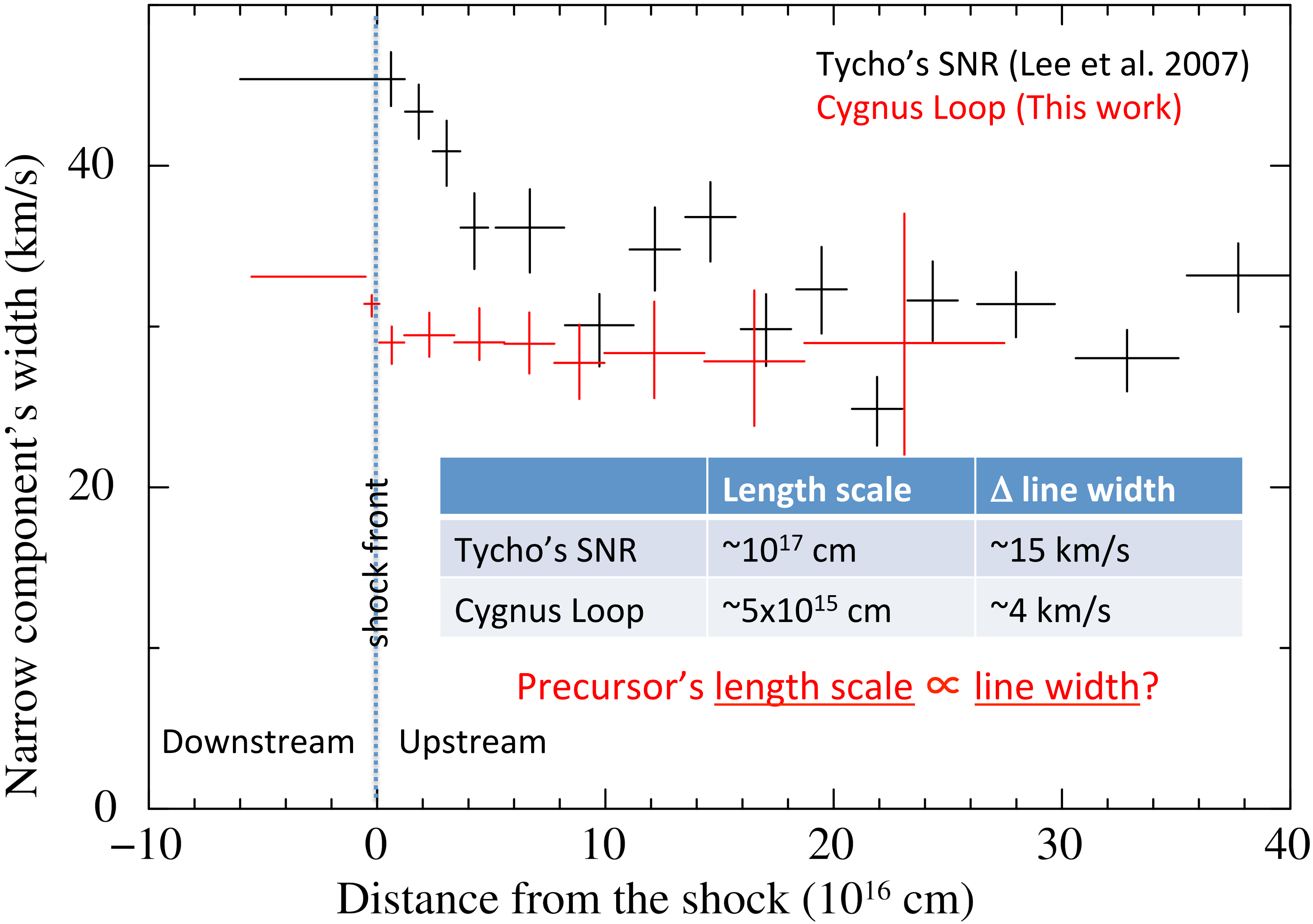

## H$\alpha$ emission & width profiles




In the NE rim of Tycho's SNR, Lee et al. found a thin precursor (l ~ $10^{17}$ cm) in front of the shock, where they found a rapid increase of the narrow line width: 30 km/s → 45 km/s.

→ argues for a CR precursor (Wagner et al. 2009)

# Length Scale ∝ Line Width?

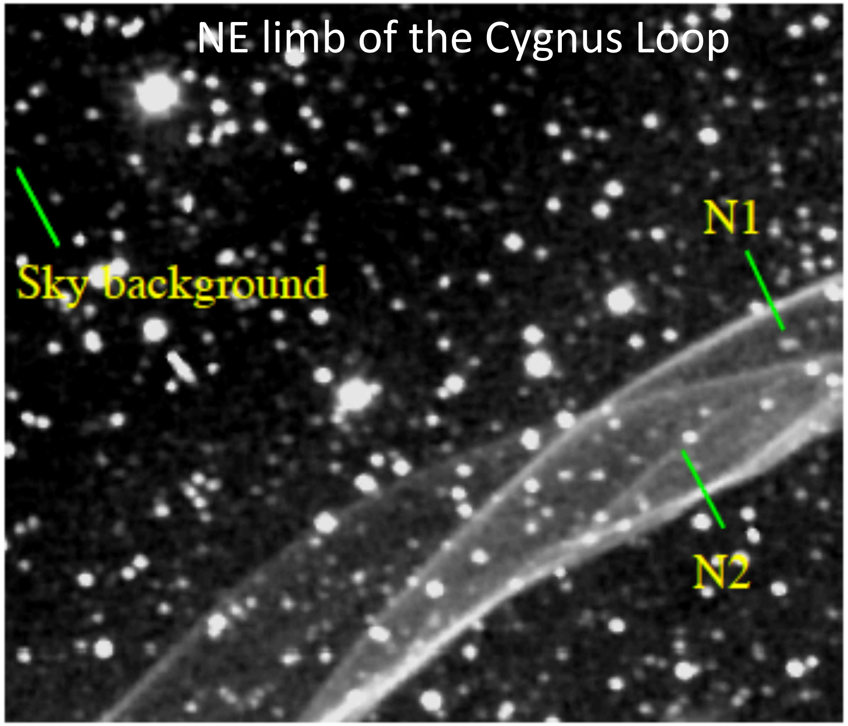


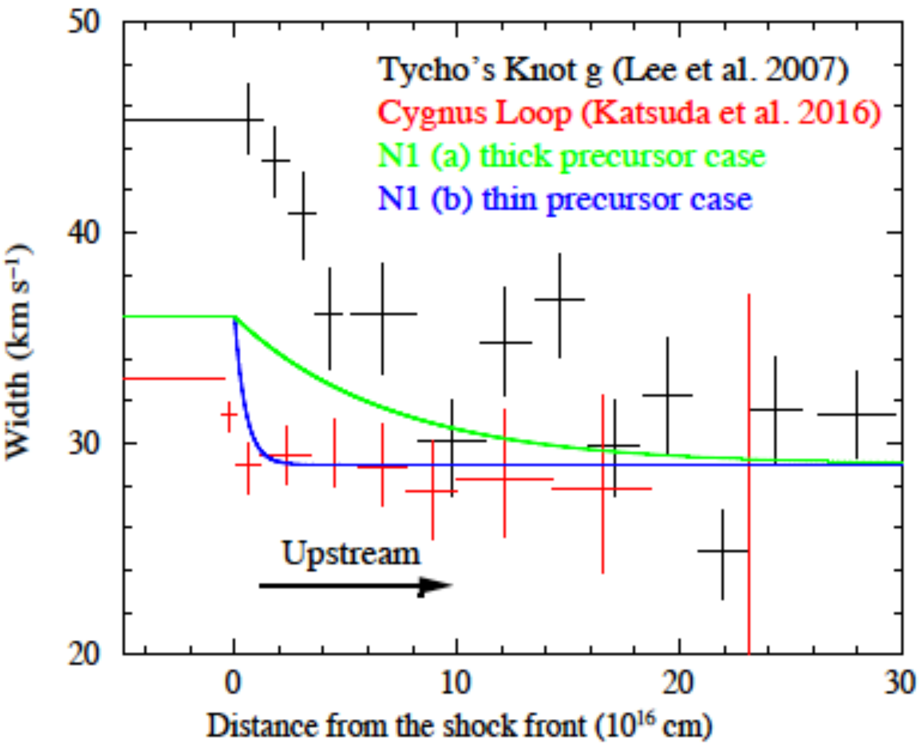

| | Length scale | Δ line width |
|---|---|---|
| Tycho's SNR | ~$10^{17}$ cm | ~15 km/s |
| Cygnus Loop | ~$5\times10^{15}$ cm | ~4 km/s |

Precursor's length scale ∝ line width?

# Future Prospects

- So far, spatially-resolved H$\alpha$ spectroscopy has been performed only for Tycho and Cygnus. Similar analyses for many BD shocks are important to testify the possible correlation between the length scale and the line width. This is an important step to establish the DSA theory.

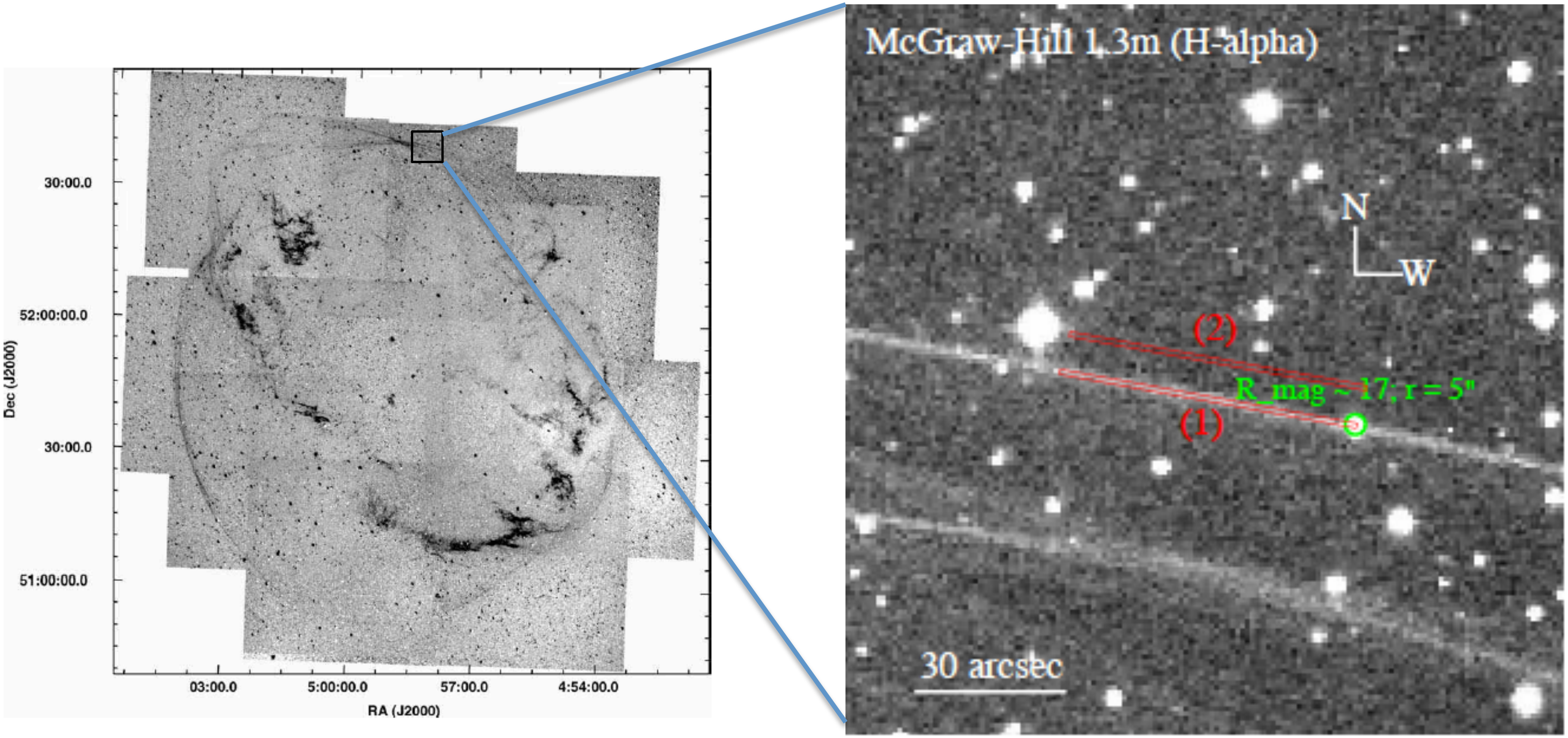


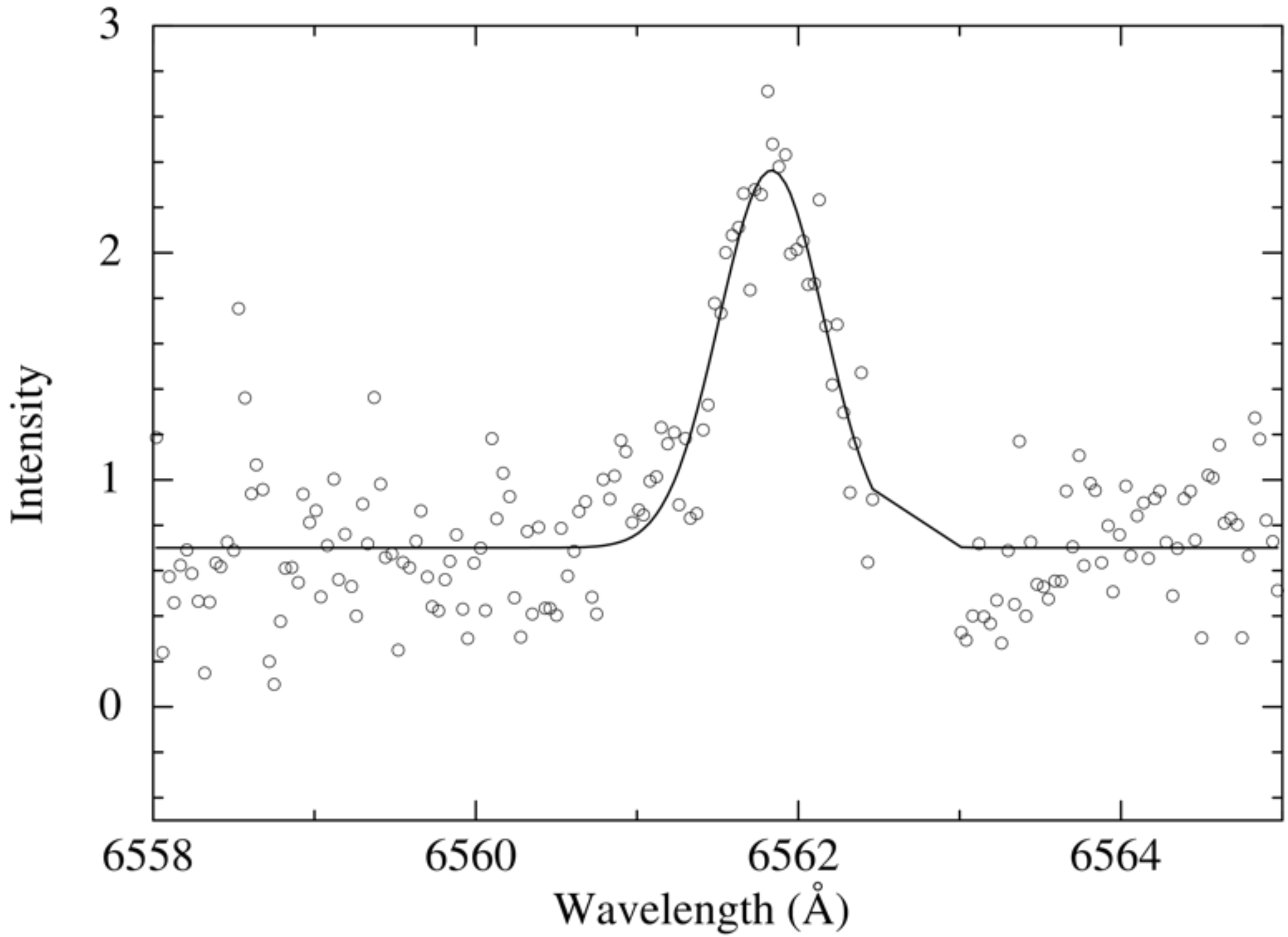
# Searching for Other Targets: Subaru/HDS Observation of G156.2+5.7

| Observation date | 2016-11-15 |
|---|---|
| Exposure | 2 hr each for source and BG |

We aim at detecting an Hα broad component (for the first time), and deriving proton temperature.



# Hα Profile Fitting (Preliminary)




□ Line center: 6561.8Å → Heliocentric l.o.s velocity of -33 km/s

□ FWHM: 33.5 km/s → Broader than expected in the ISM, implying heating in a CR precursor

# Summary

- We performed spatially-resolved high-resolution spectroscopy of a bright nonradiative filament in the northeastern Cygnus Loop, by using the Subaru HDS.
- We found that the H$\alpha$ narrow component's width abruptly increases at the shock within a thin layer (< 0.5" → ~0.001 pc) just in front of the shock.
- We attribute the broadening to the heating due to damping of the Alfven waves in a thin CR precursor.
- So far, the precursor's length scale is measured only for Tycho and the Cygnus Loop. More observations are important to understand the nature of the precursor and to establish the DSA theory.
- We presented preliminary results of Subaru/HDS spectroscopy of G156.2+5.7.