Observations of Balmer-dominated Filaments in Supernova Remnants

Jae-Joon Lee

Korea Astronomy & Space Science Institute (KASI)

Shock Waves

Physics of Interstellar Shock Waves

Non-Radiative

Shock Waves

Non-Radiative

Shock Waves

where Radiative Loss is Negligible

Shock Jump Condition

$$\begin{aligned} \rho_2 &= 4\rho_1 \\ T_2 &= \frac{3}{16}\frac{\mu v_s^2}{k} \end{aligned}$$

Shock Jump Condition

$$\rho_2 \stackrel{?}{=} 4\rho_1$$

$$T_2 \stackrel{?}{=} \frac{3}{16}\frac{\mu v_s^2}{k}$$

A Key Characteristics of interstellar shocks is,

A Key Characteristics of interstellar shocks is,

they are

Collisionless

A Key Characteristics of interstellar shocks is,

they are

Collisionless

- The shock dissipation is not by collisions but by collective motions of plasma (MHD turbulence, etc.)

A Key Characteristics of interstellar shocks is,

they are

Collisionless

- The shock dissipation is not by collisions but by collective motions of plasma (MHD turbulence, etc.)

- The shock transition process, that converts the bulk-motion of preshock gas into the random motion of postshock gas, is collisionless

Shock Jump Condition

$$\rho_2 \stackrel{?}{=} 4\rho_1$$

$$T_2 \stackrel{?}{=} \frac{3}{16}\frac{\mu v_s^2}{k}$$

Collisionless shocks

Collisionless shocks

- do not partition energy equally among different species

$$T_p \neq T_e \neq T_{ion}$$

Collisionless shocks

- do not partition energy equally among different species

$$T_p \neq T_e \neq T_{ion}$$

- accelerate cosmic rays

$$\begin{aligned} \rho_2 &> 4\rho_1 \\ T_2 &< \frac{3}{16}\frac{\mu v_s^2}{k} \end{aligned}$$

We want to Constrain

We want to Constrain

Physics of Collisionless Shocks

We want to Constrain

Physics of Collisionless Shocks

by

Observations

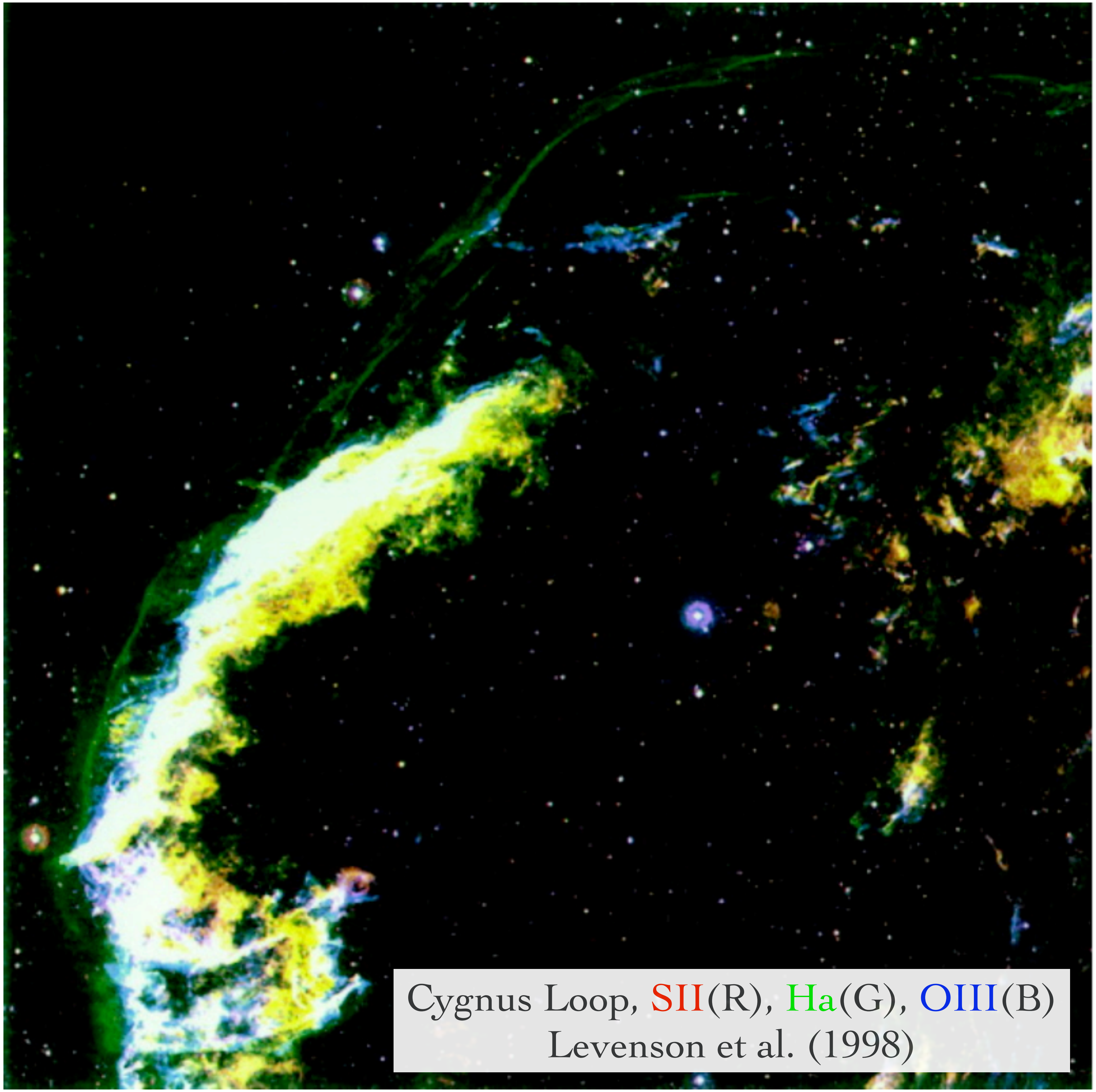
of

Balmer-dominated filaments

Balmer-dominated filaments

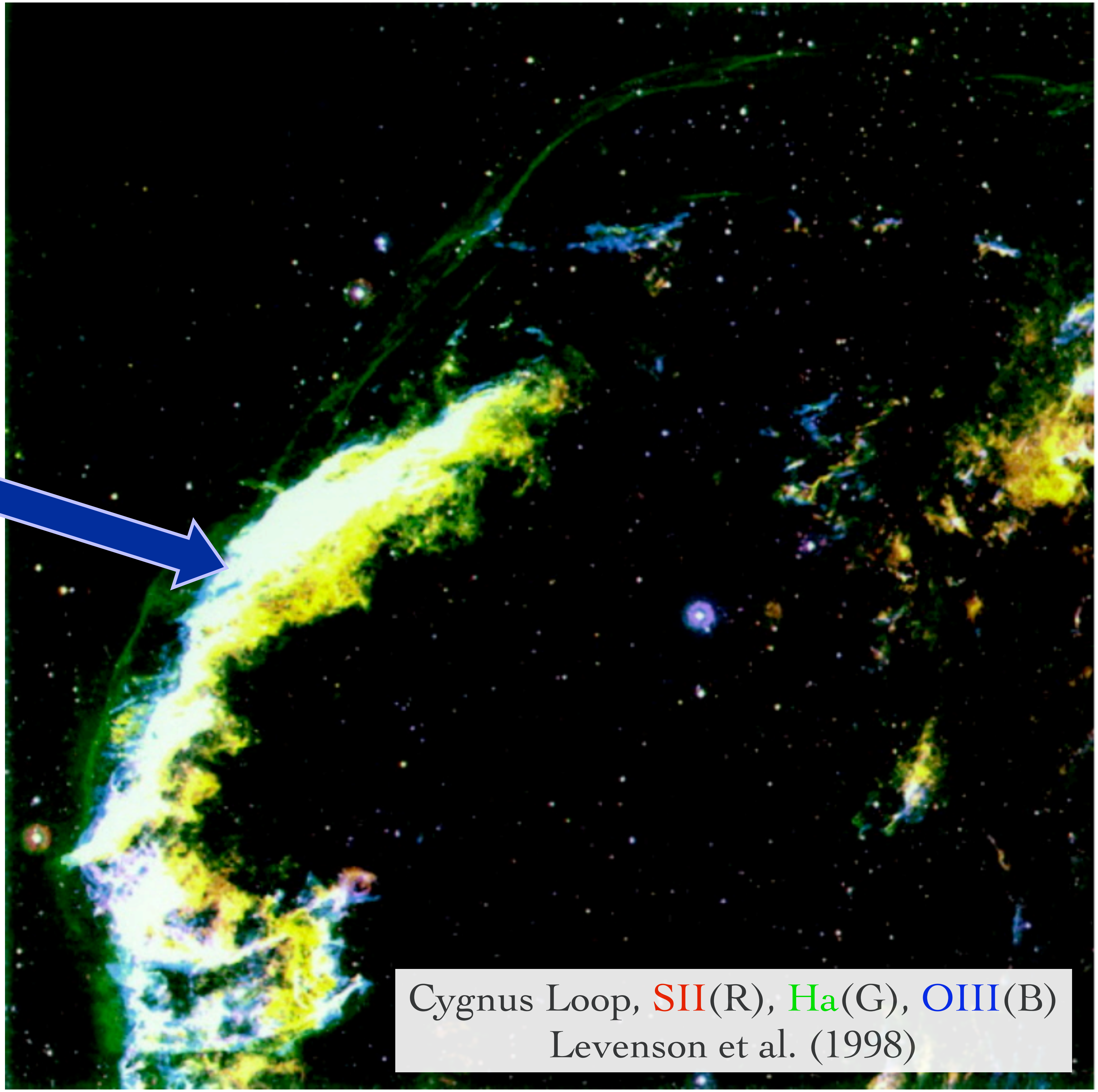
What are Balmer-dominated filaments ?

Balmer-dominated filaments



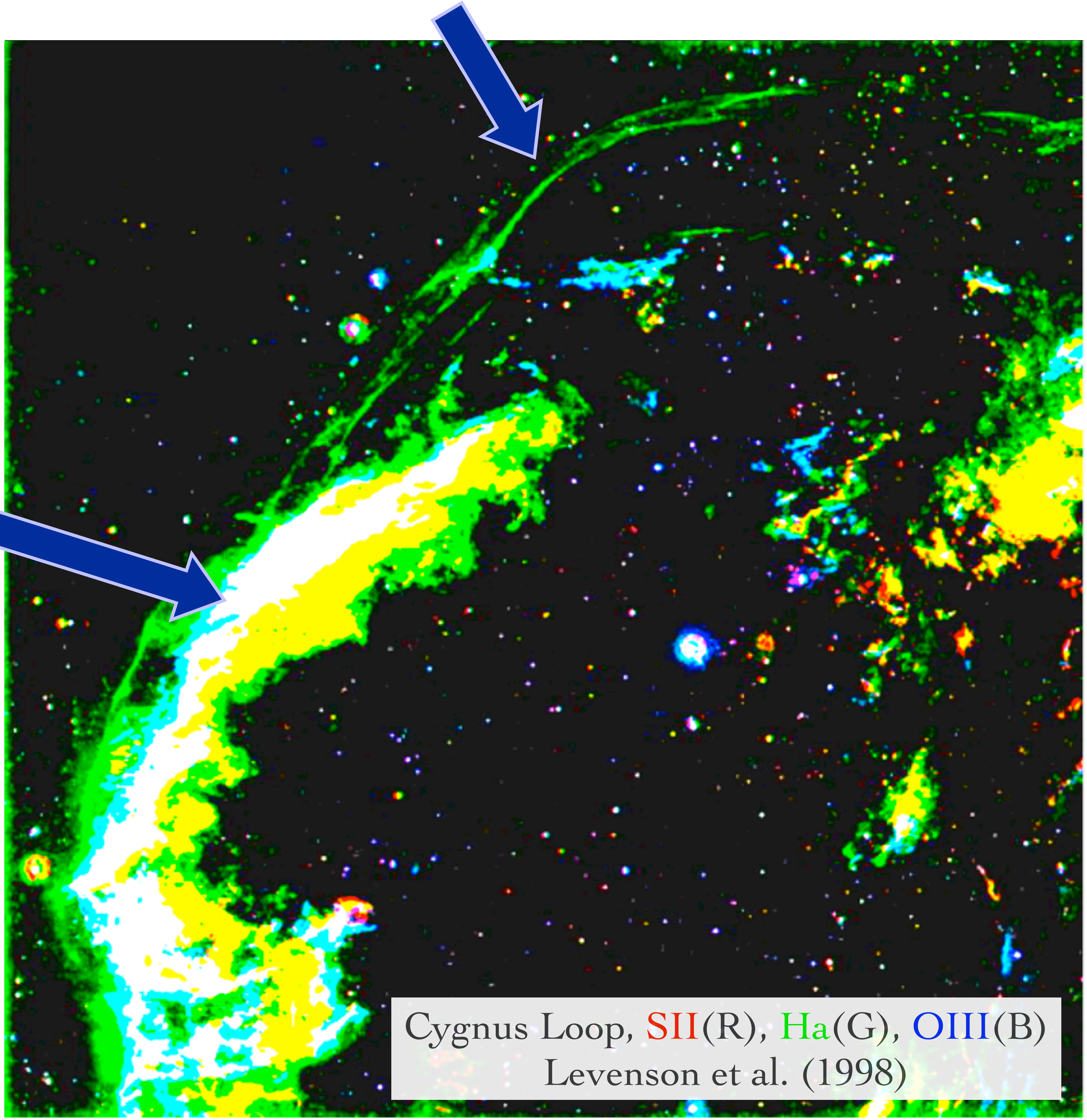
Balmer-dominated filaments

Radiative filament



Balmer-dominated filaments

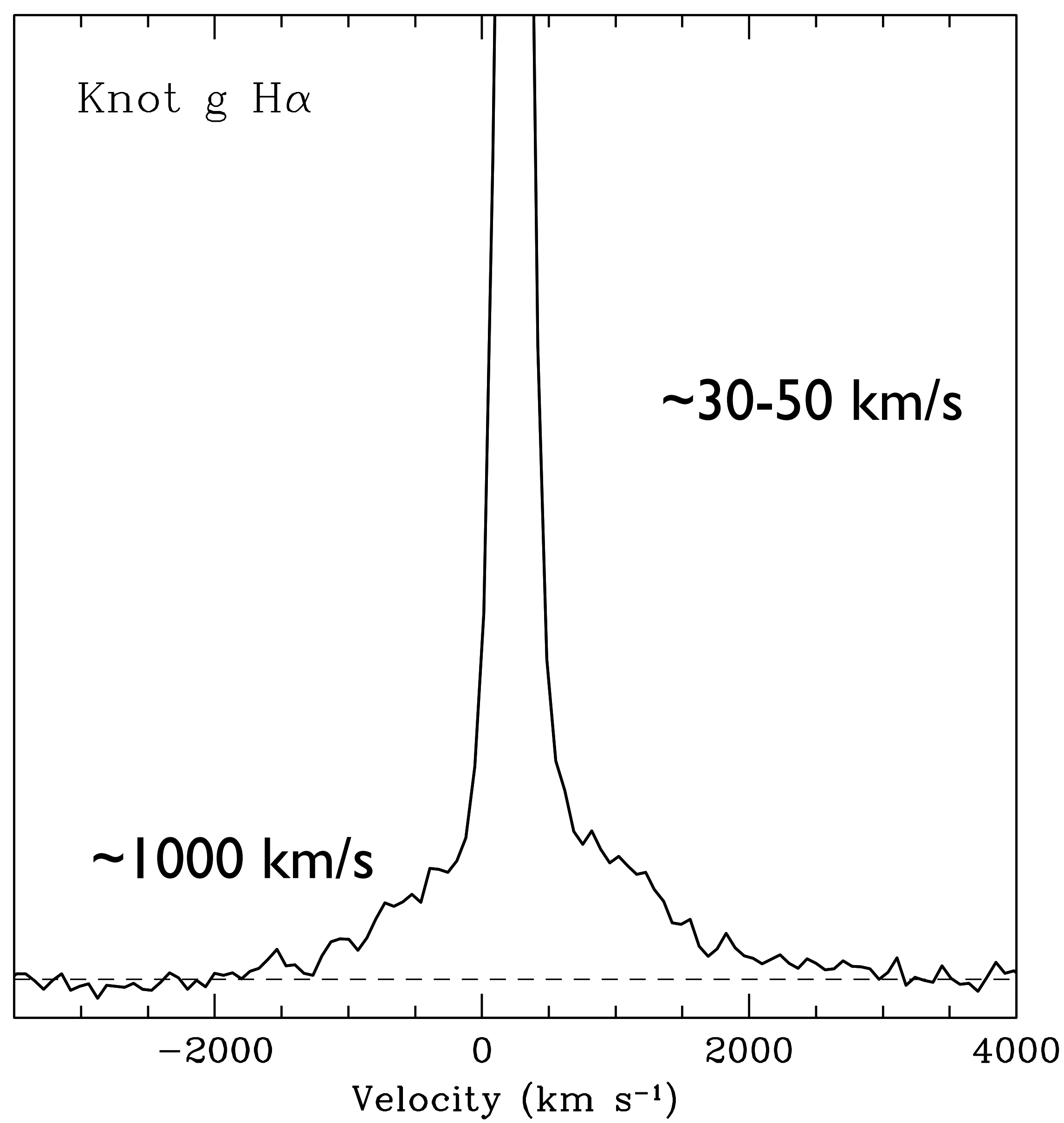
Radiative filament



Faint optical filaments whose line emission is dominated by Hydrogen Balmer lines.

- Usually found in young (Type Ia) SNRs (Vs > 500 km/s)
  - Tycho, Kepler, SN1006 etc.
- Represent fast non-radiative shocks into partially neutral medium (Chevalier & Raymond, 1978)
  - Ha emission is from just behind the shock front

Unique Line Profile

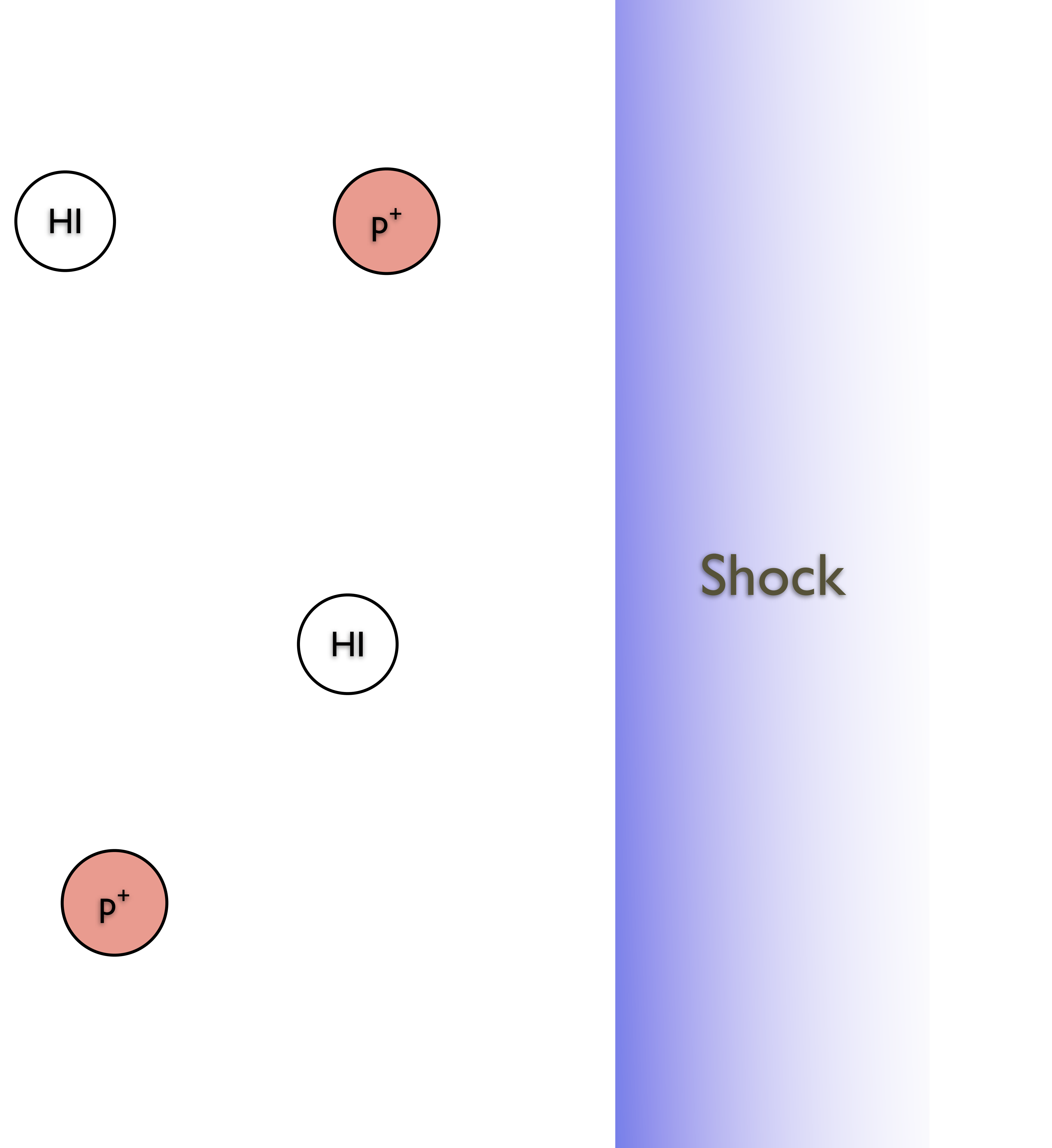


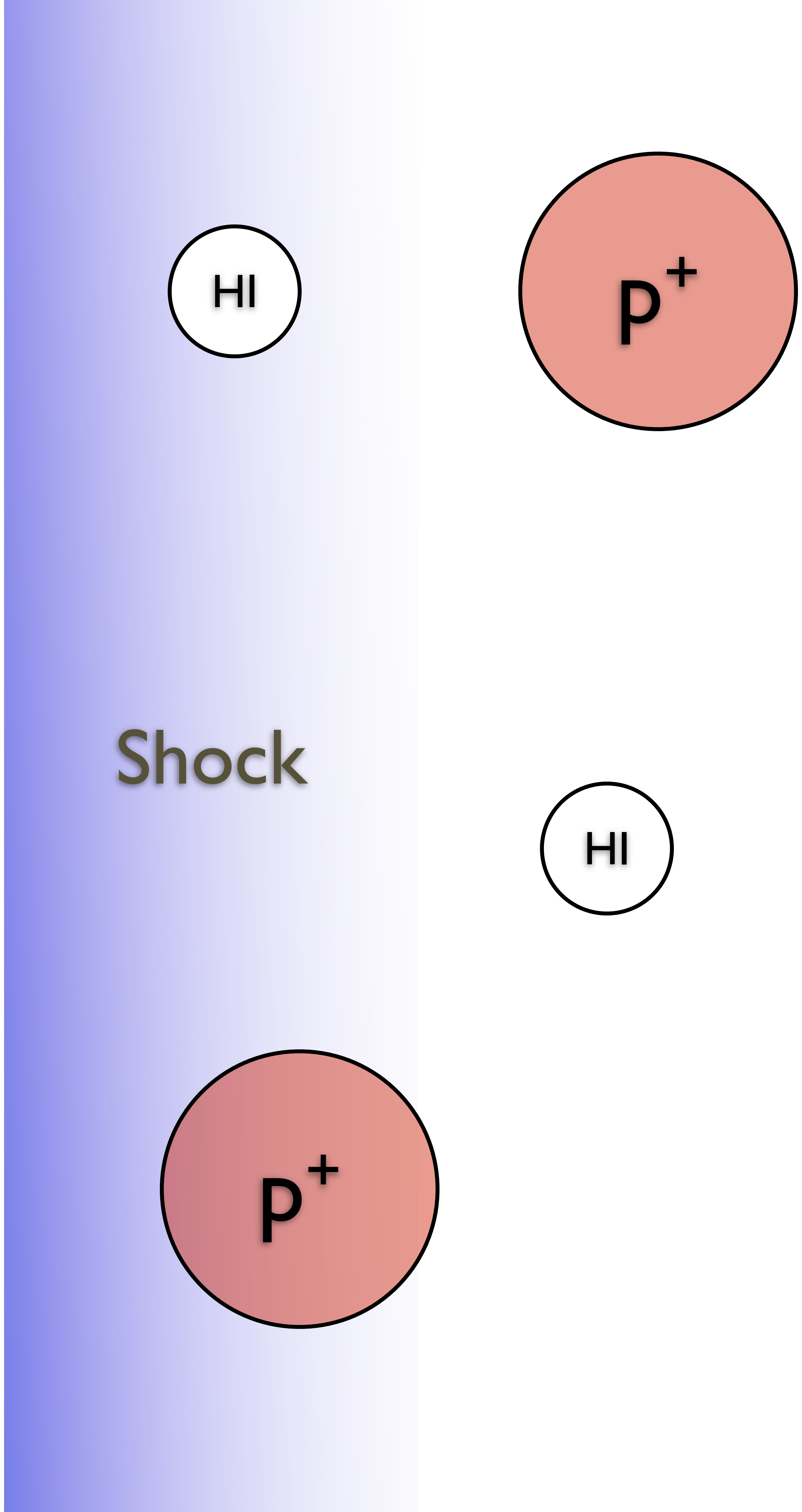
Ha profile of Tycho (Ghavamian, 2001)

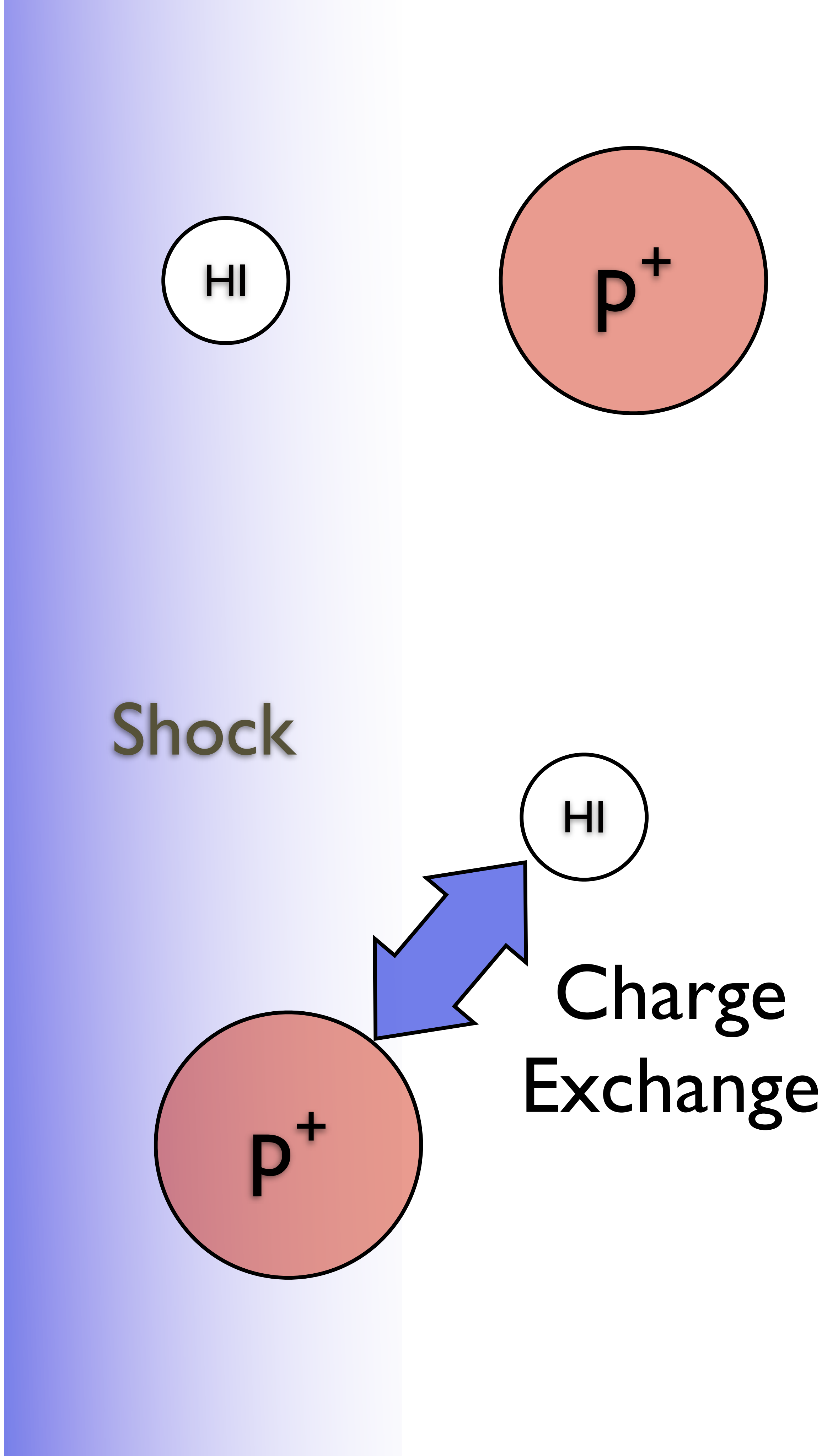
Collisionless Shocks

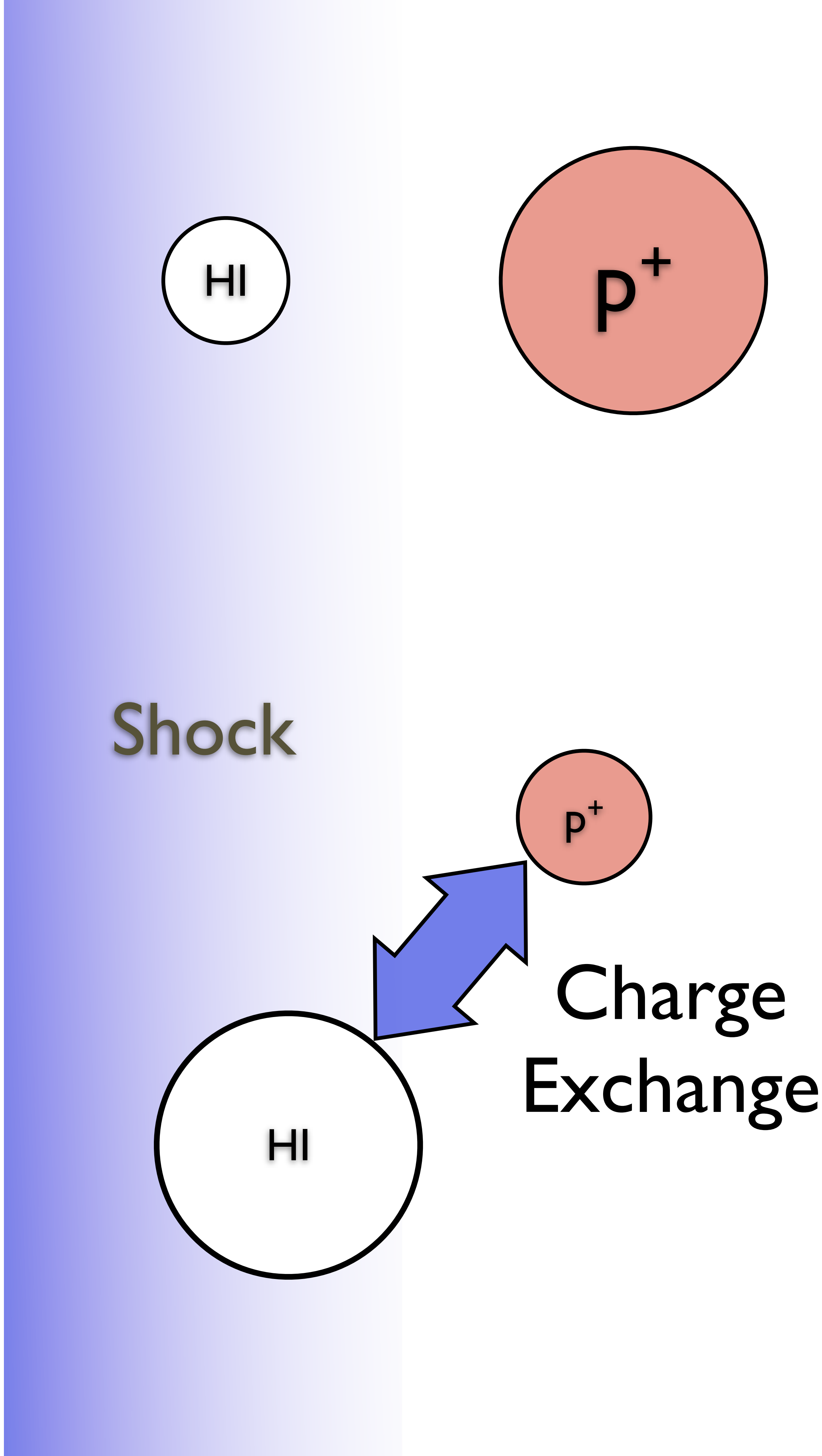
into

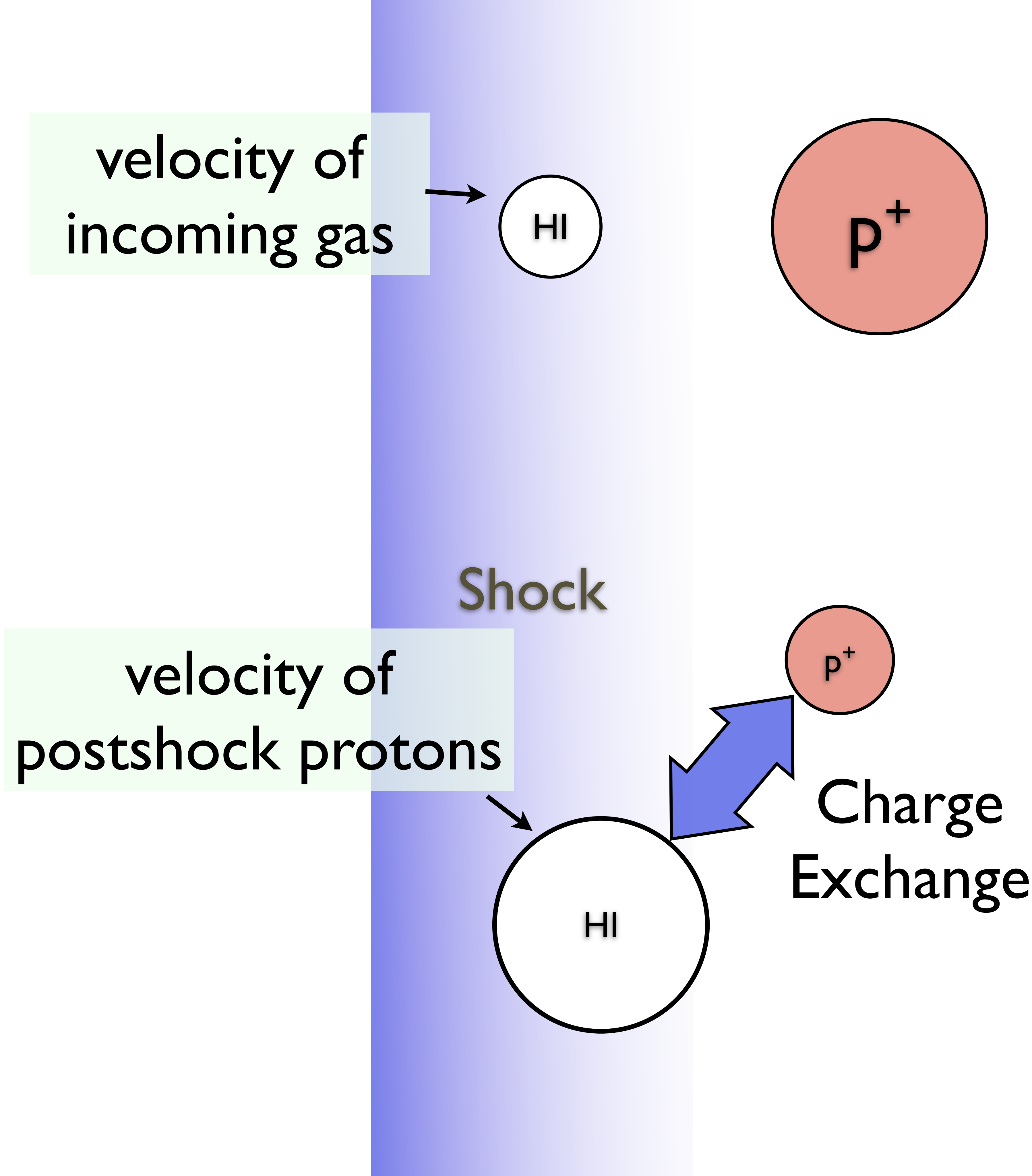
Partially Neutral Medium

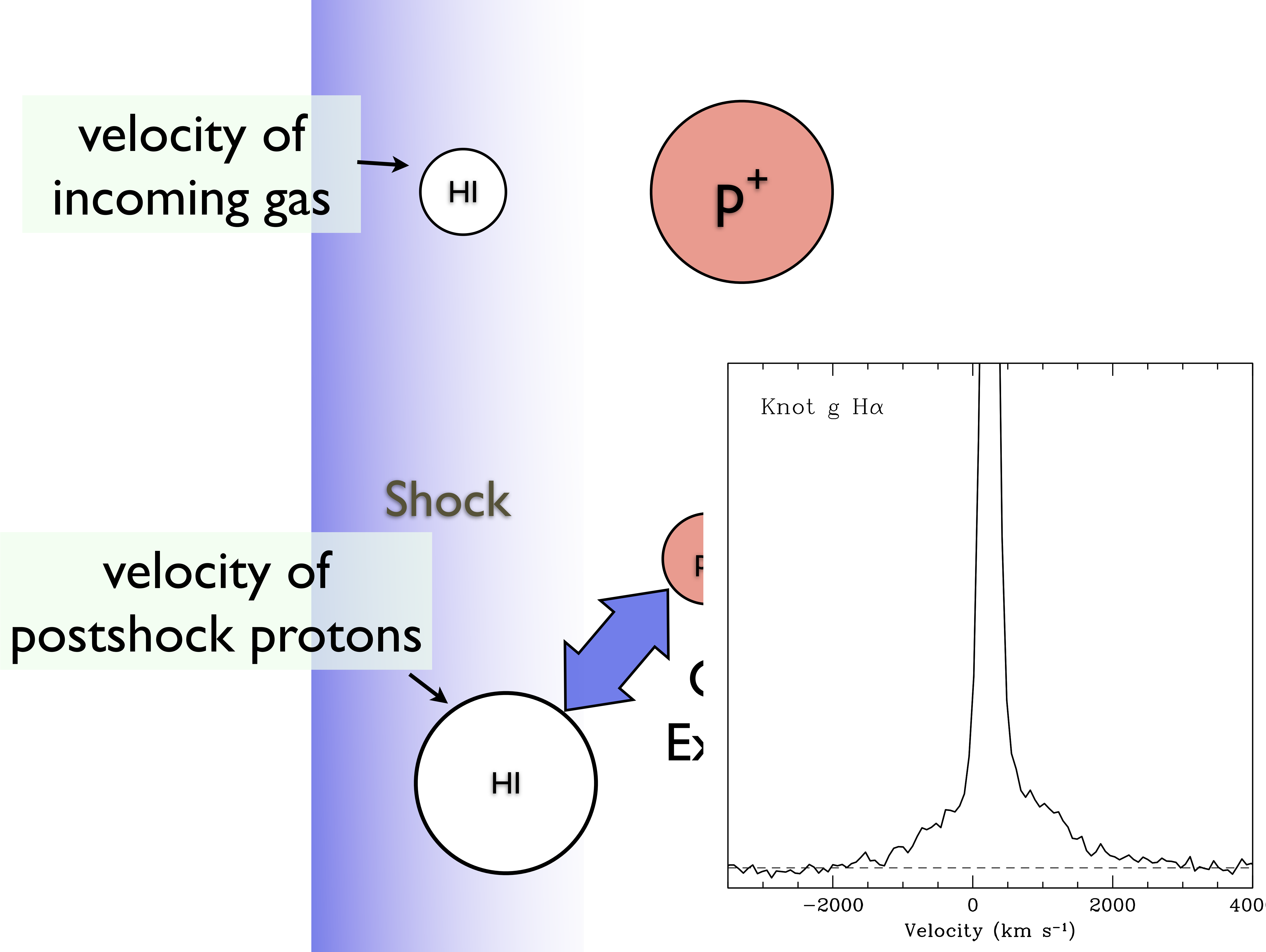

HI
p+
Shock
HI
p+

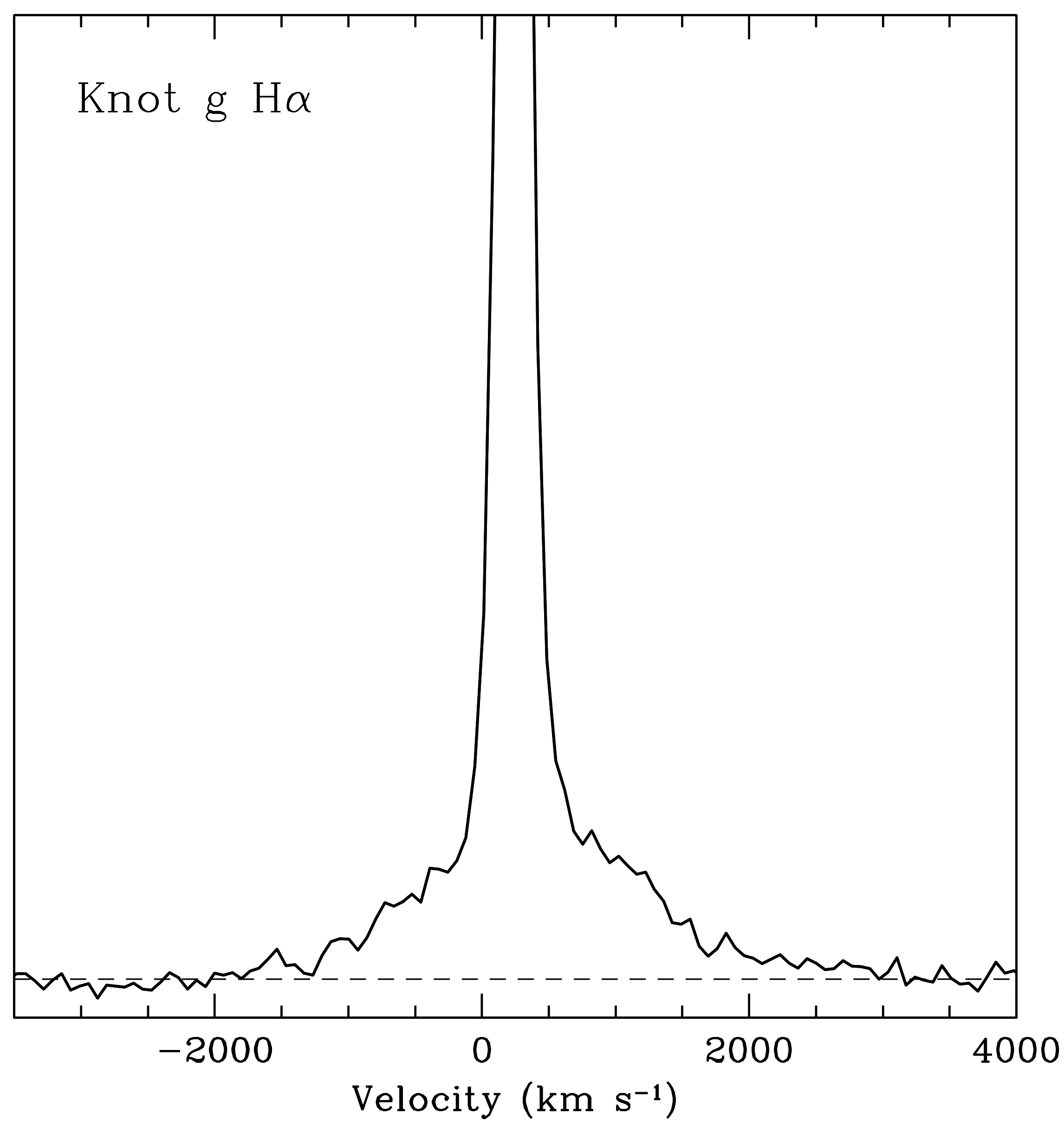

HI
p+
Shock
HI
p+


HI
p+
Shock
HI
Charge
Exchange
p+

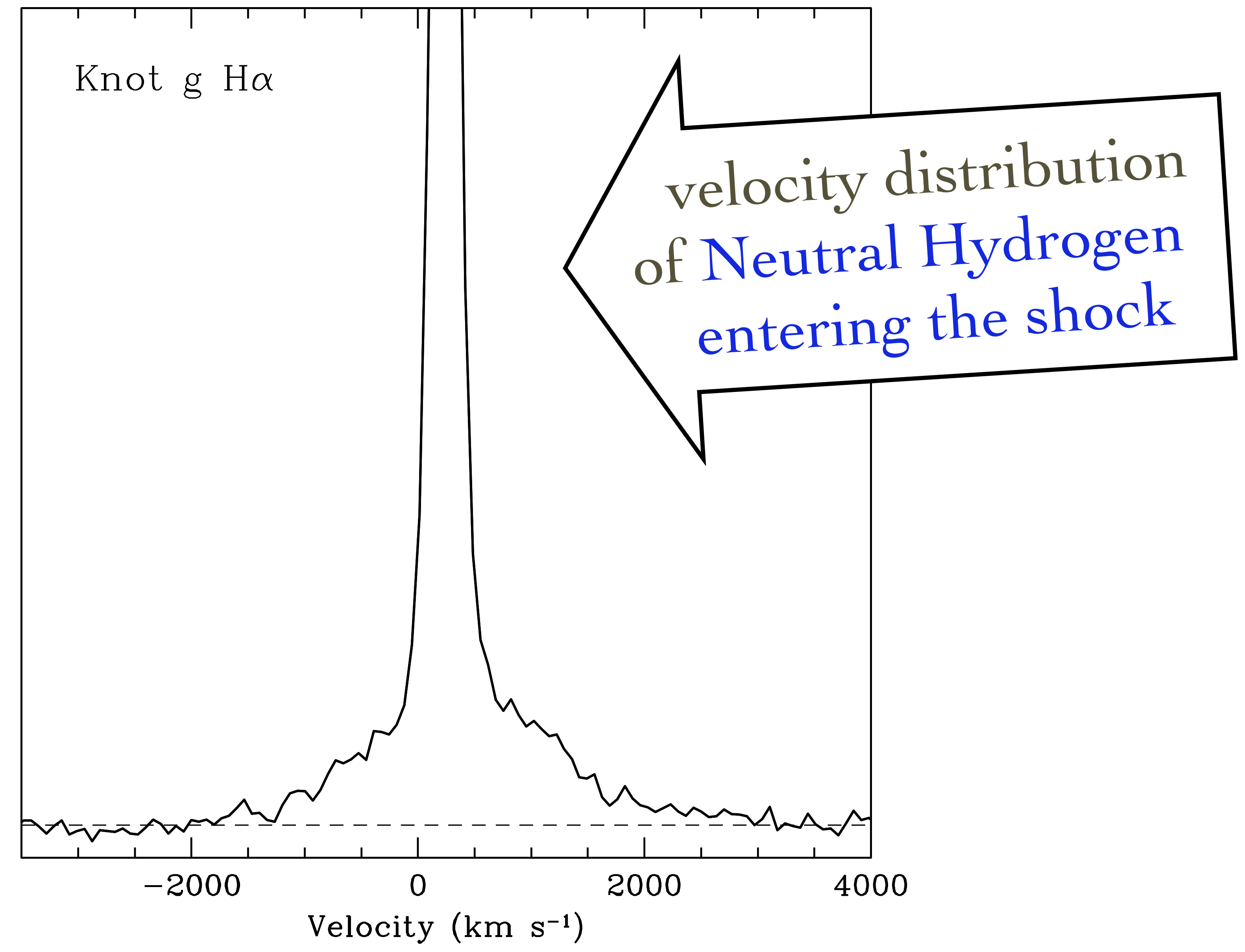

HI
p+
Shock
p+
Charge
Exchange
HI


velocity of
incoming gas
HI
p+
Shock
velocity of
postshock protons
p+
HI
Charge
Exchange

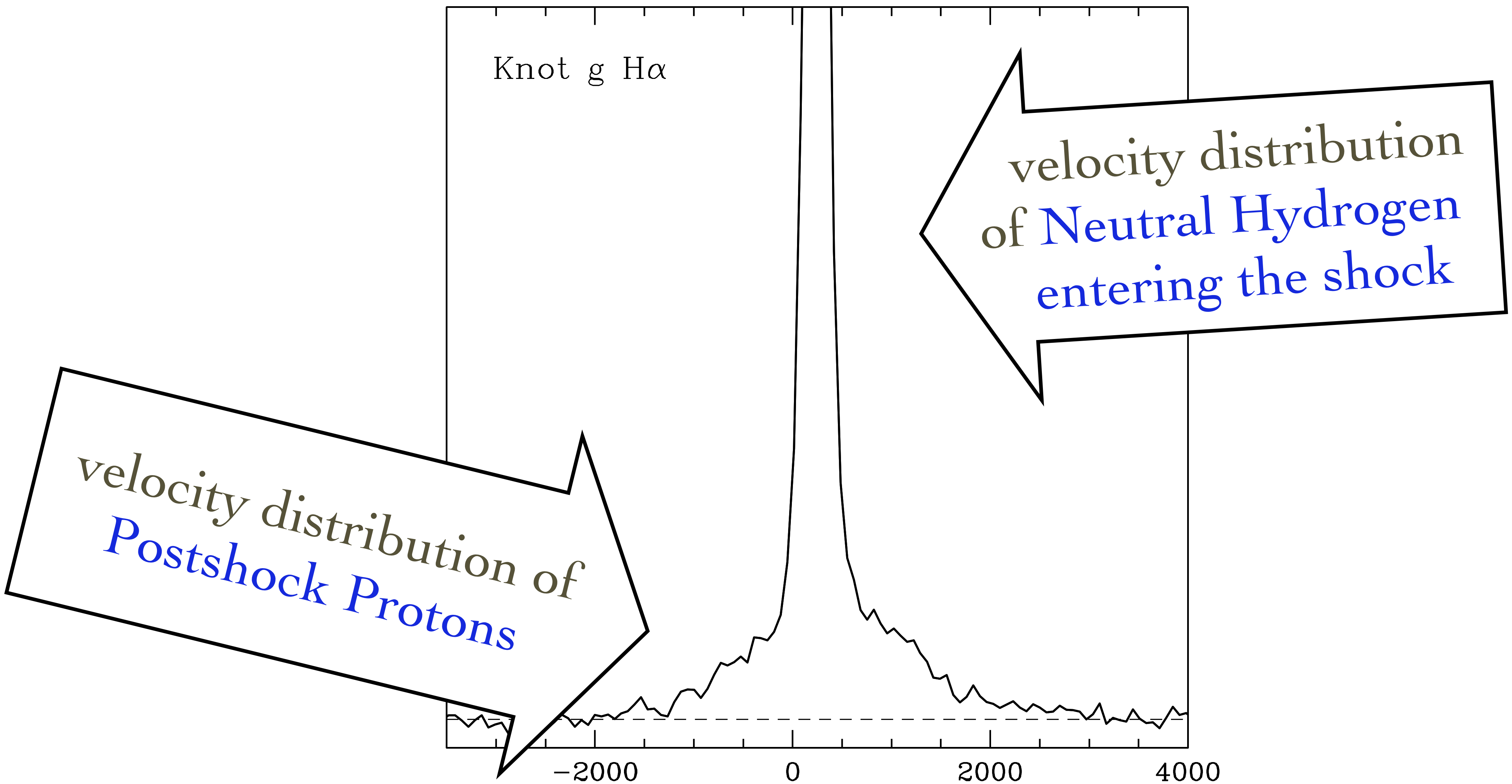

velocity of
incoming gas
HI
p+
Shock
velocity of
postshock protons
HI
Knot g Hα
−2000
0
2000
4000
Velocity (km s⁻¹)



Ha profile of Tycho (Ghavamian, 2001)



Ha profile of Tycho (Ghavamian, 2001)



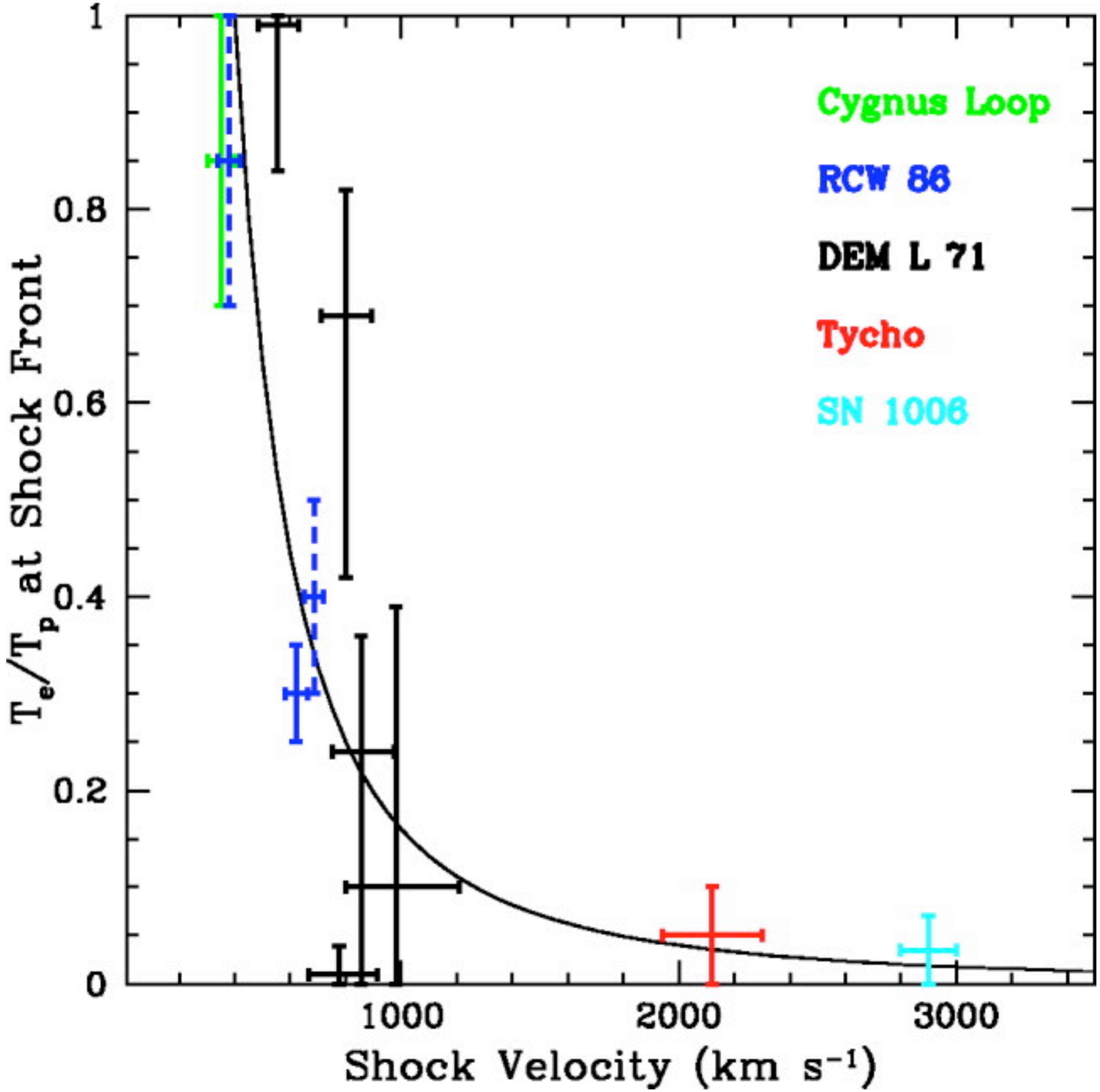
Ha profile of Tycho (Ghavamian, 2001)

Temperature Equilibration

- Broad component Line width : Tp
- Flux ratio of Broad to Narrow Components : Te

Temperature Equilibration

Te / Tp



Ghavamian et al. (2007)

Cosmic Ray Acceleration

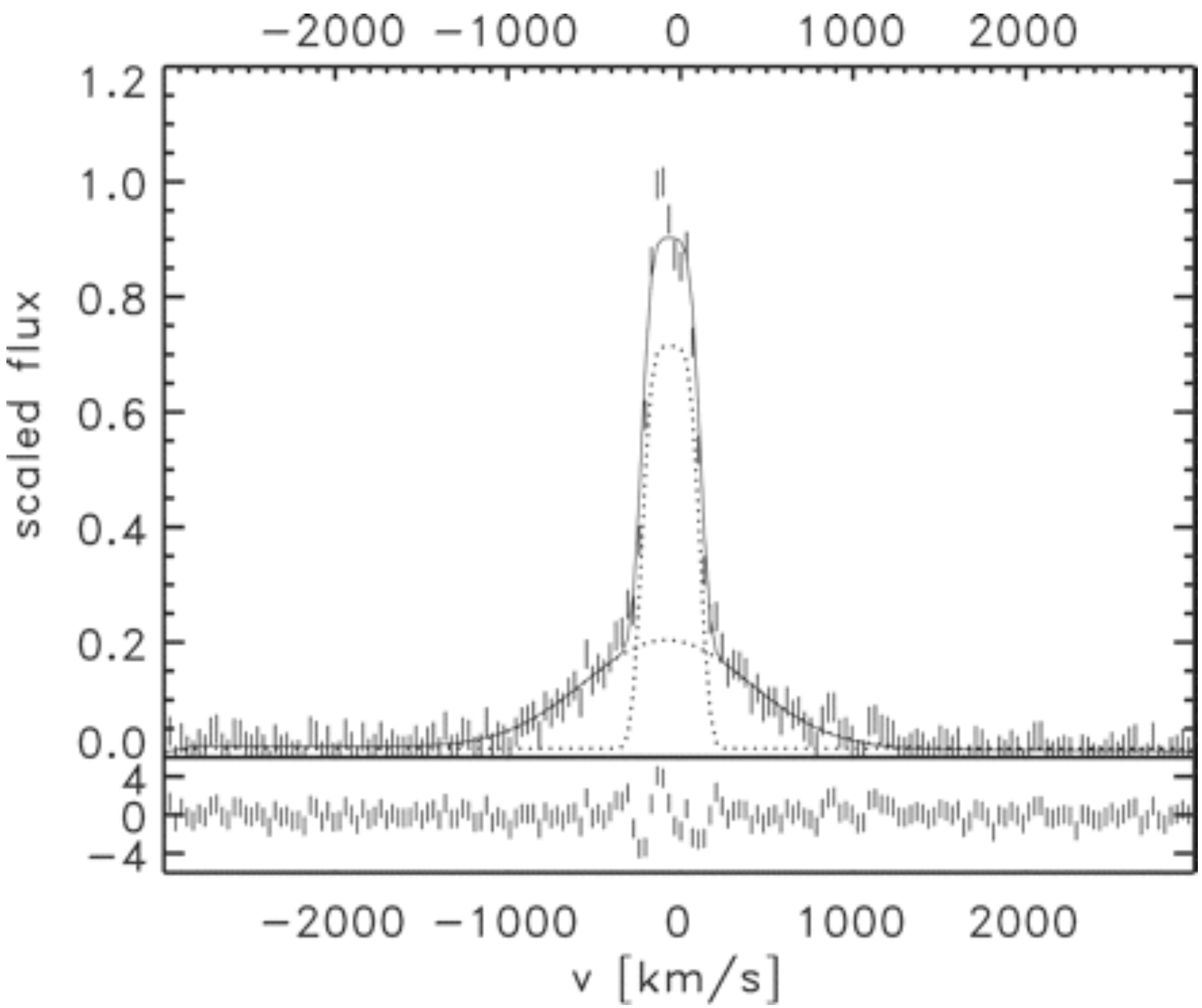
- Do SNR shocks accelerate Cosmic ray protons? How efficient?
    - Gamma-ray Observations

Do SNR shocks accelerate Cosmic ray protons?

$$T_2 = \frac{3}{16}\frac{\mu v_s^2}{k}$$

- T_p(obs) << $T(v_s)$

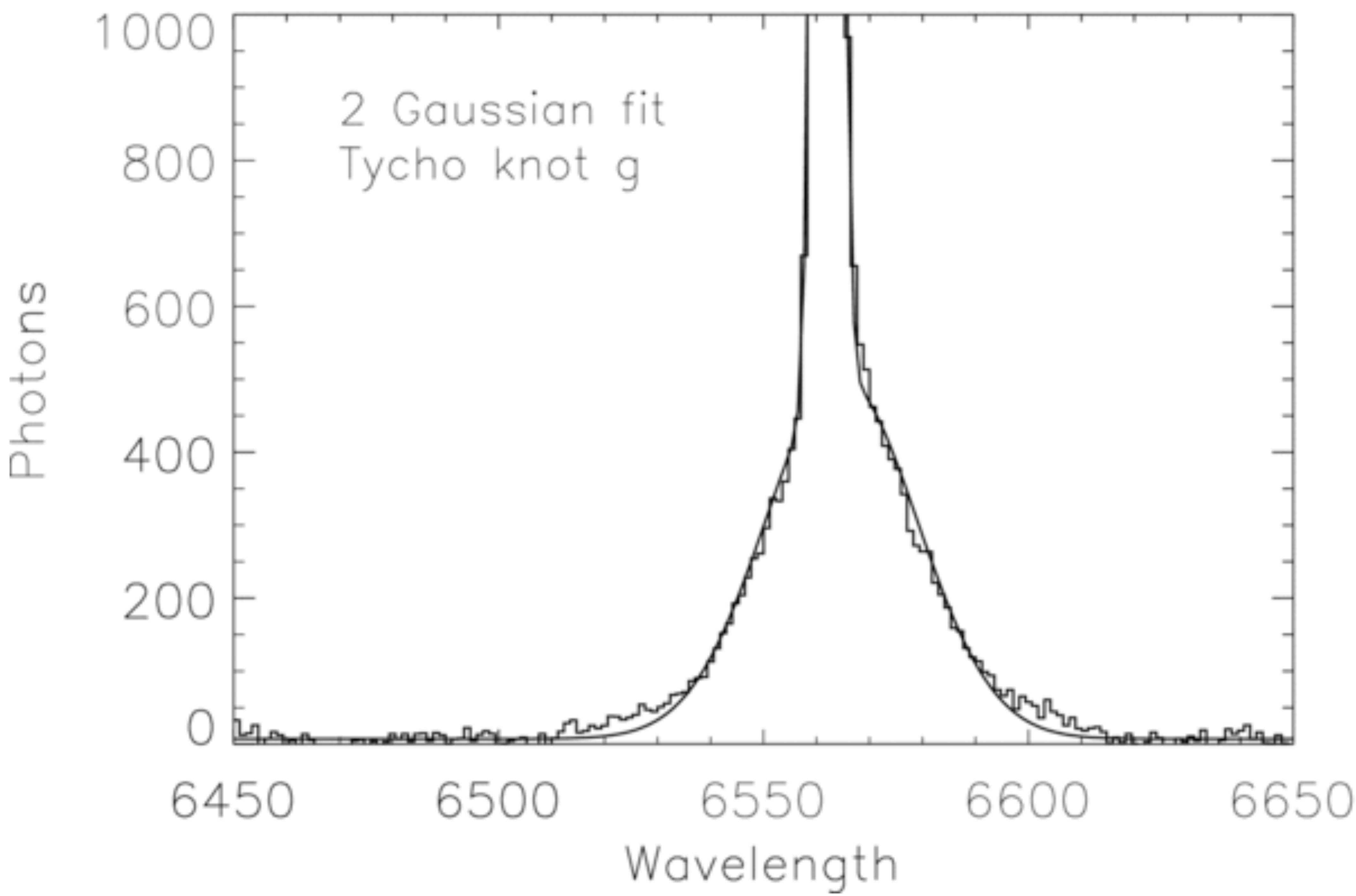
RCW 86 : measured shock velocity ~ 6000 km/s



Helder et al. (2009)

Non-Gaussian Line Profiles

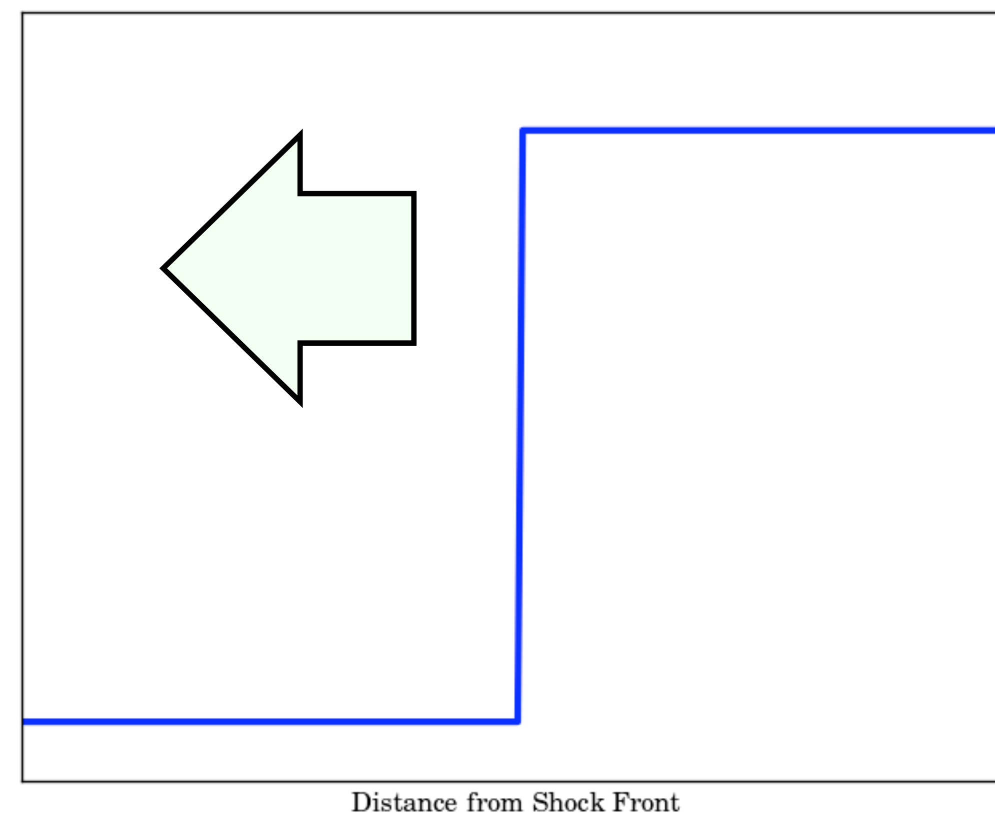
- With cosmic ray protons (i.e., nonthermal protons), line profiles of the broad component deviate from Gaussian



Raymond et al. (2010)

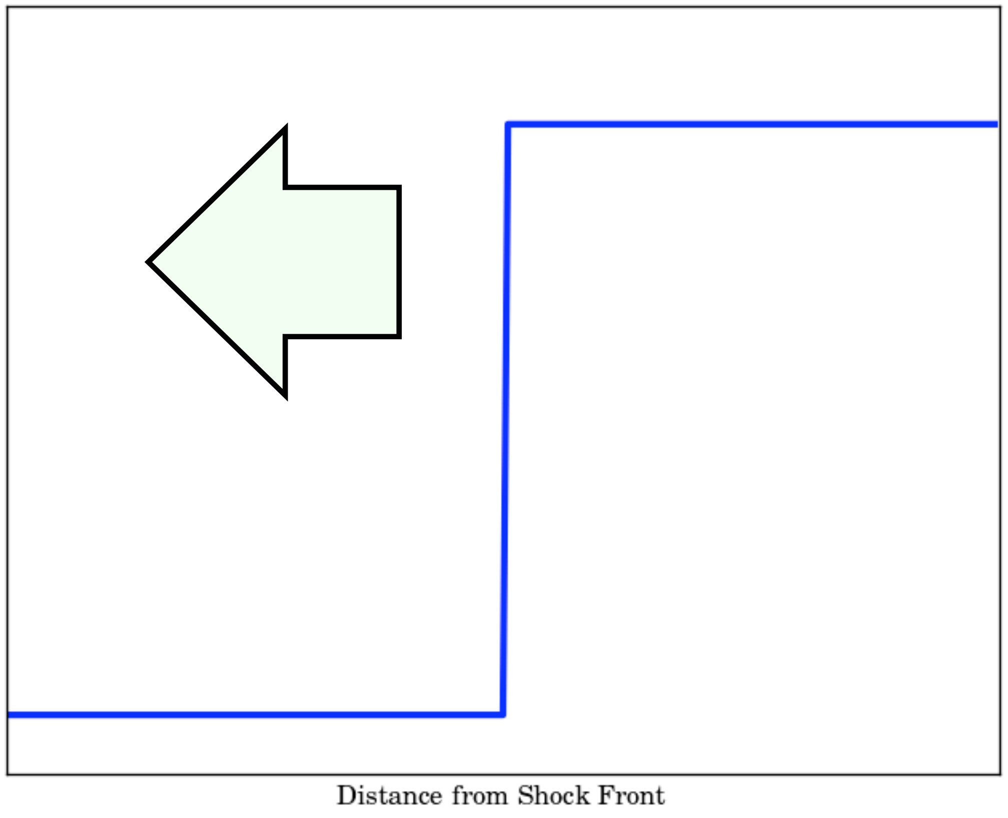
Cosmic Ray Precursor

- Shock
  - Discontinuous
  - Supersonic motion



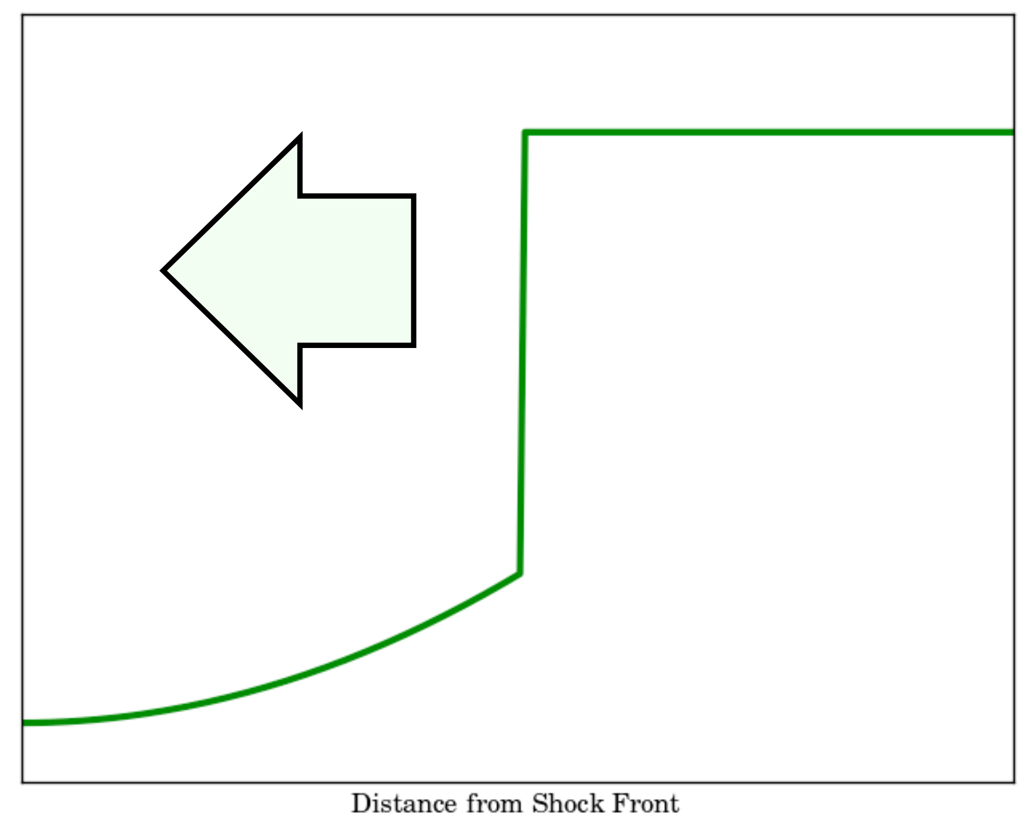
Cosmic Ray Precursor

- Shock
  - Discontinuous
  - Supersonic motion
- Shock Precursor
  - radiative precursor
  - cosmic ray precursor

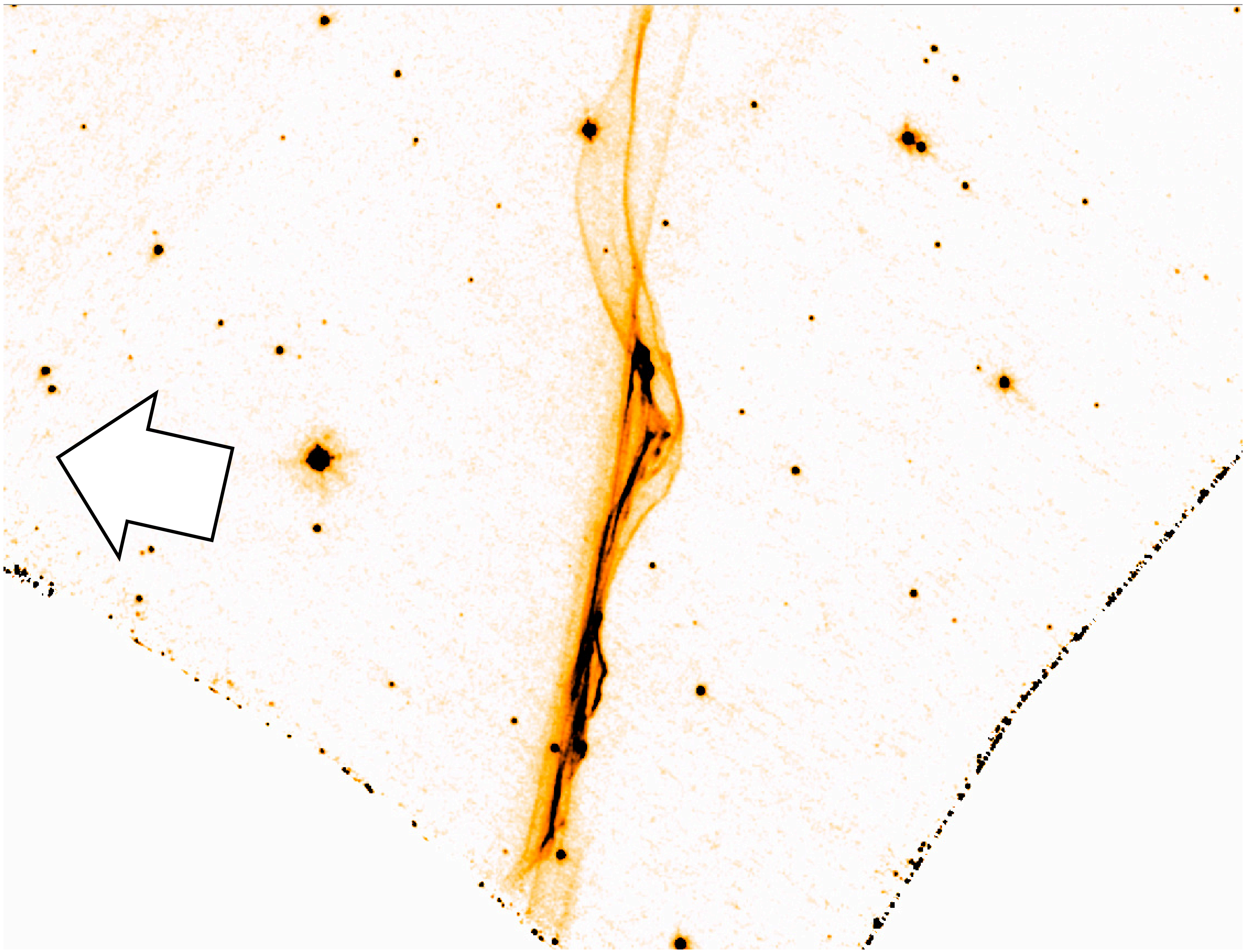


Cosmic Ray Precursor

- Shock
  - Discontinuous
  - Supersonic motion
- Shock Precursor
  - radiative precursor
  - cosmic ray precursor

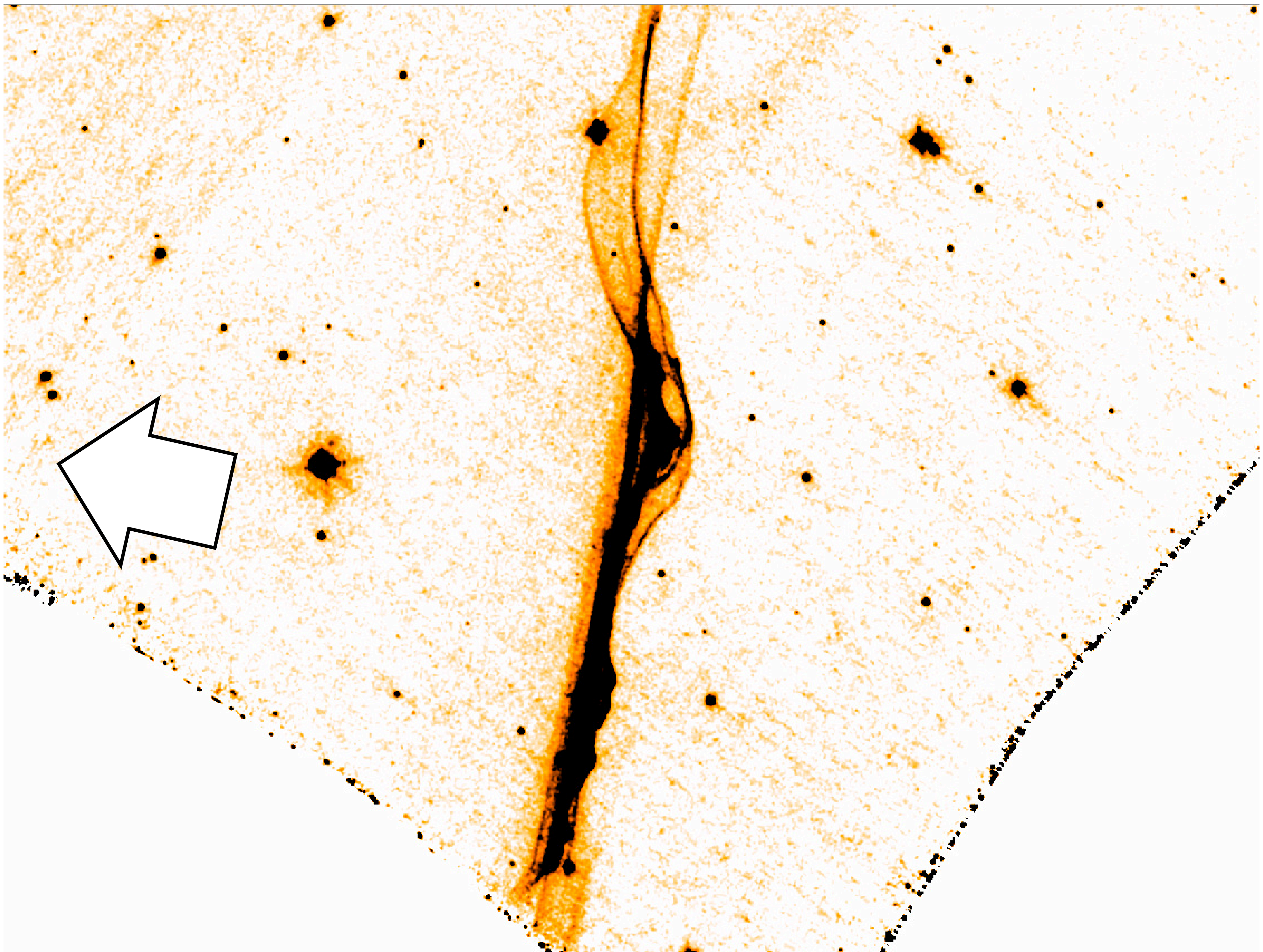


HST Imaging of Tycho



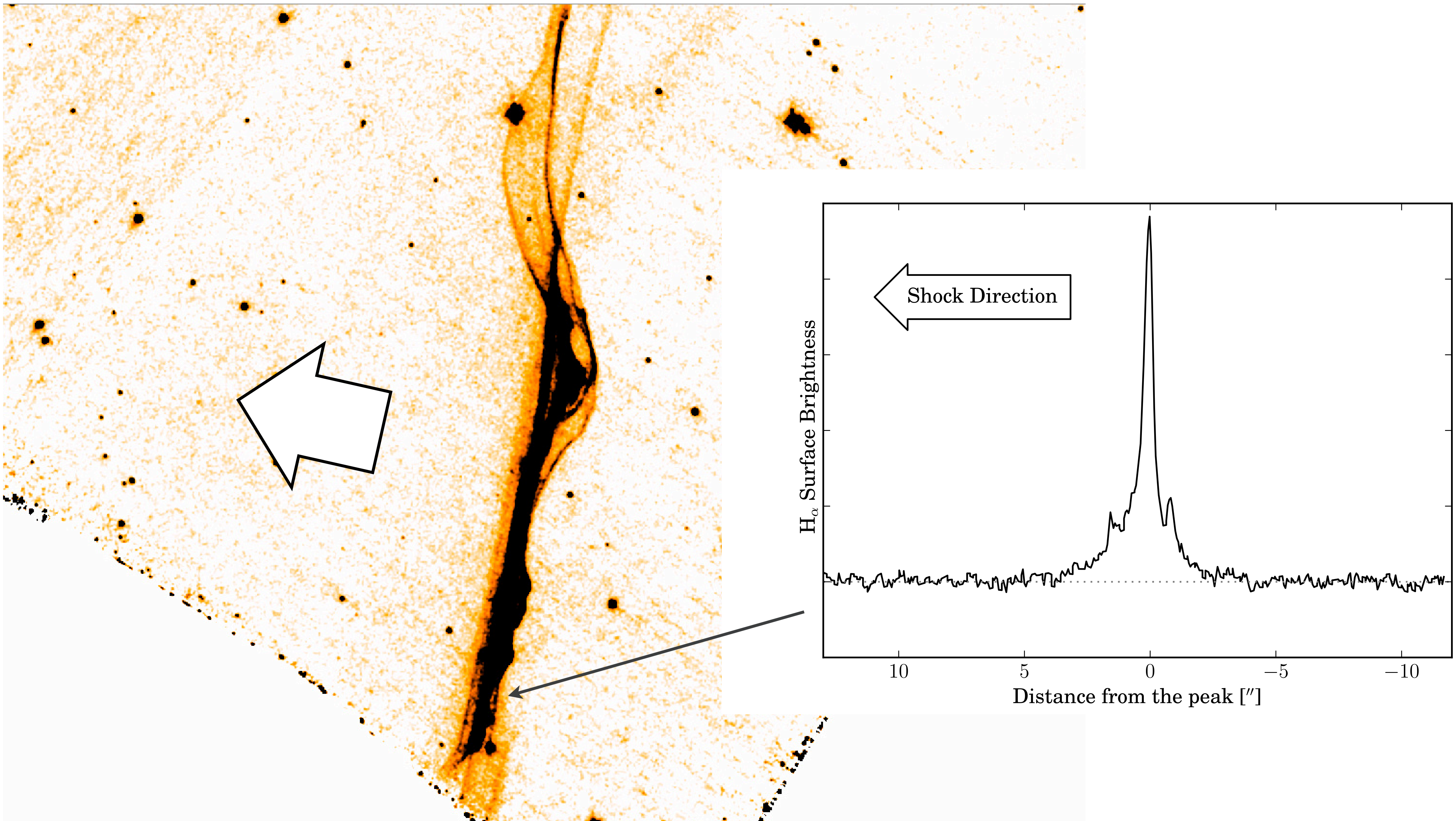
Lee et al. (2010)

HST Imaging of Tycho

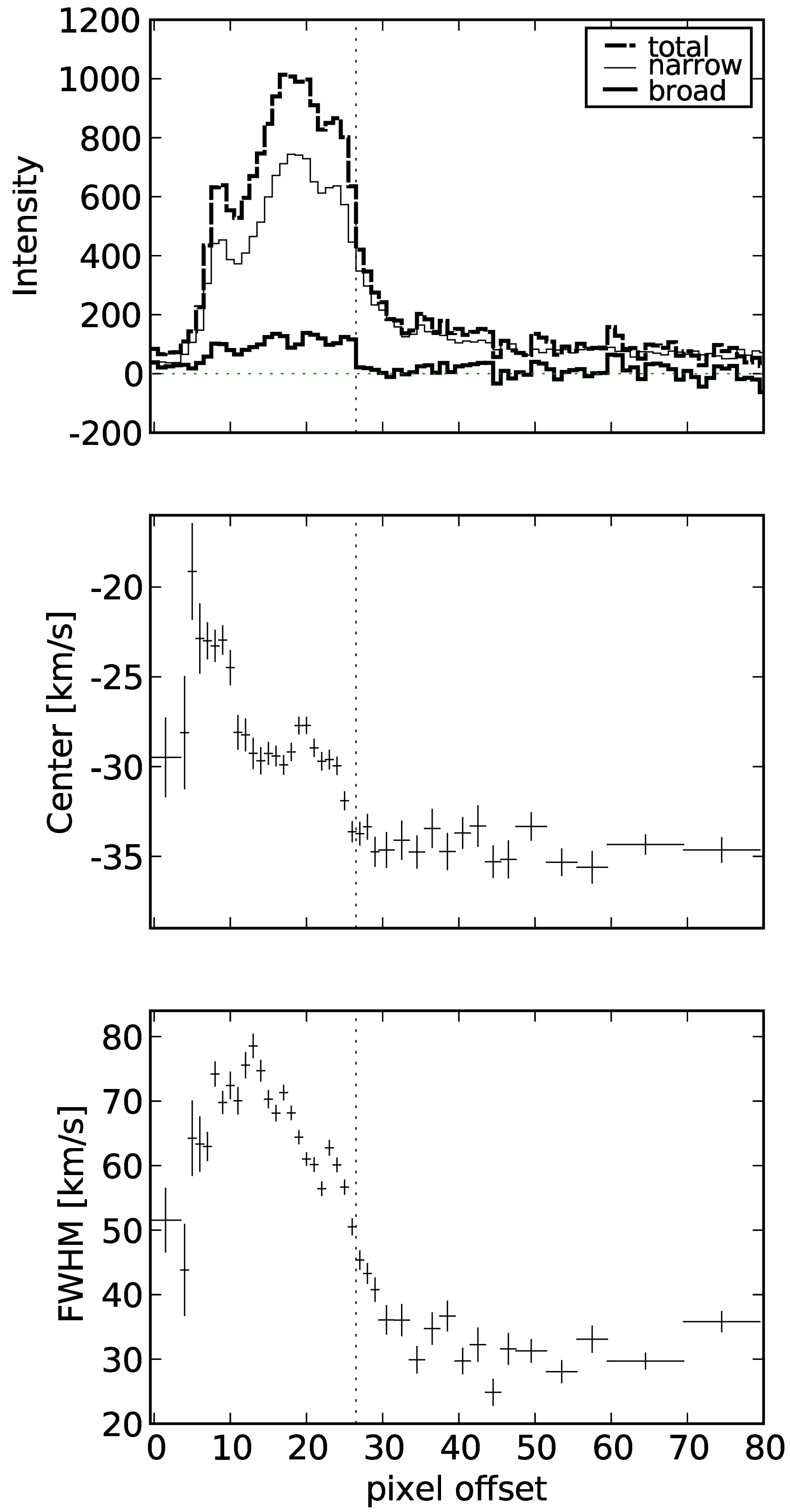


Lee et al. (2010)

HST Imaging of Tycho



Lee et al. (2010)



- Deceleration of preshock gas
- Radial velocity difference in precursor and postshock area (Lee et al., 2007)

Modeling CR Precursor

Modeling CR Precursor

- From observation:

Modeling CR Precursor

- From observation:
  - precursor temperature (Tpeak)

Modeling CR Precursor

- From observation:
  - precursor temperature (Tpeak)
  - Amount of gas deceleration (ΔV ~100 km/s)

Modeling CR Precursor

- From observation:
  - precursor temperature (Tpeak)
  - Amount of gas deceleration (ΔV ~100 km/s)
  - precursor width (L)

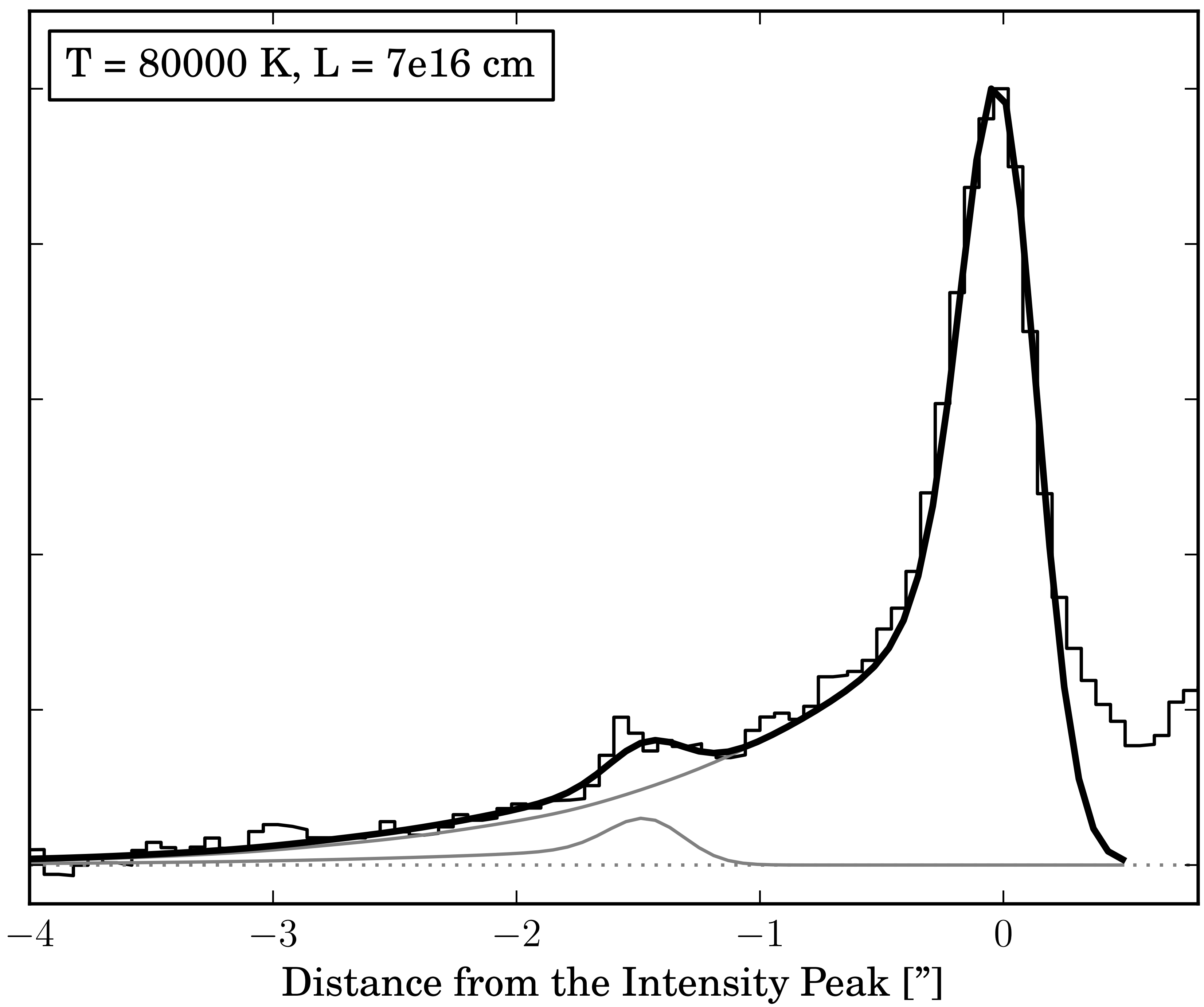
Modeling CR Precursor

- From observation:
    - precursor temperature (Tpeak)
    - Amount of gas deceleration (ΔV ~100 km/s)
    - precursor width (L)
- Hα emission model w/ radiative transfer (Lee et al., in prep)

Modeling CR Precursor

- From observation:
  - precursor temperature (Tpeak)
  - Amount of gas deceleration (ΔV ~100 km/s)
  - precursor width (L)
- Hα emission model w/ radiative transfer (Lee et al., in prep)
- A time-dependent cosmic-ray (CR) modified shock model (Wagner et al., 2009)

Modeling CR Precursor



Cosmic ray Diffusion Coefficient

Cosmic ray Injection Rate

Cosmic ray Diffusion Coefficient

Cosmic ray Injection Rate

Cosmic ray Diffusion Coefficient

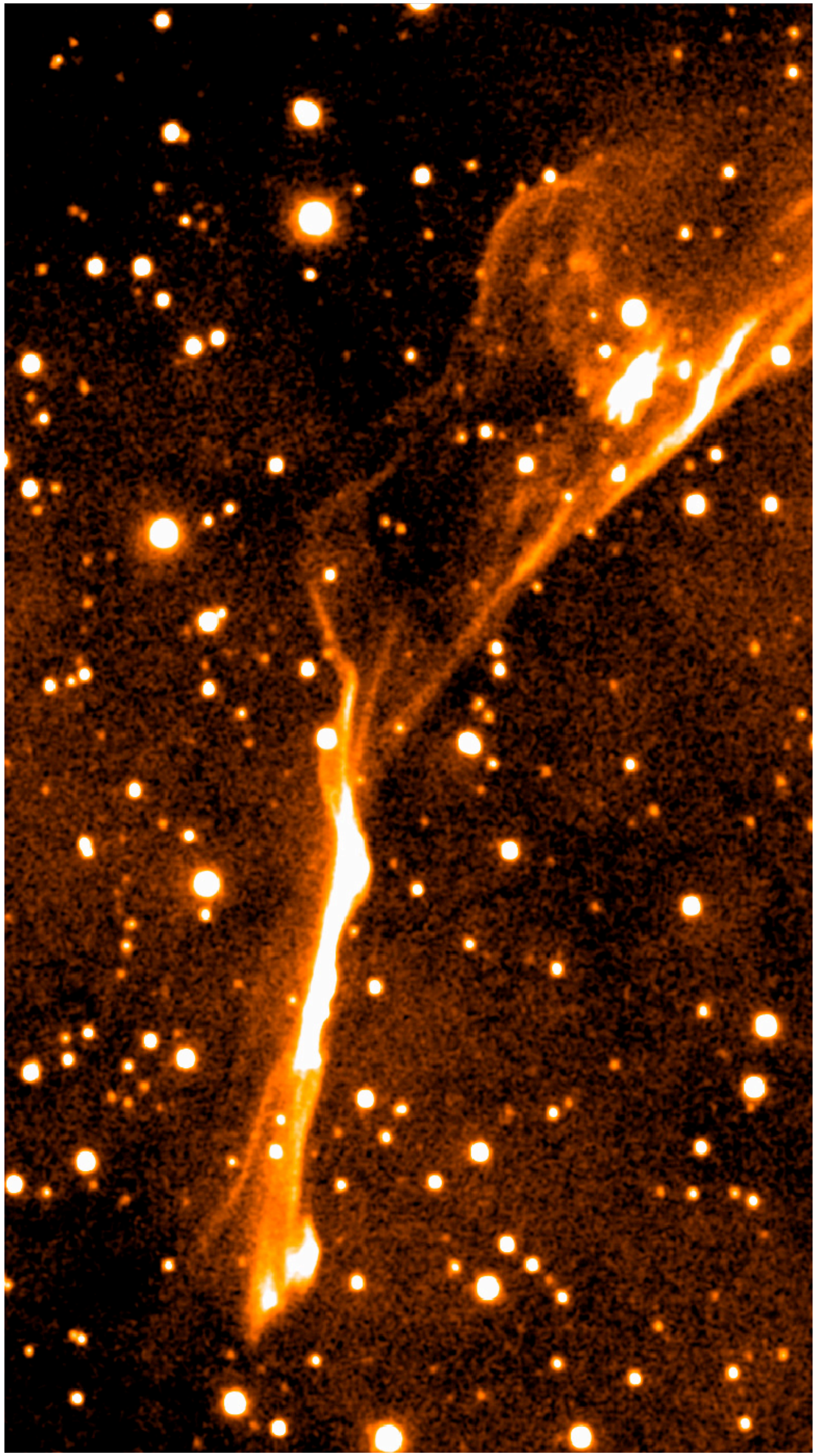
Cosmic ray Injection Rate

Summary

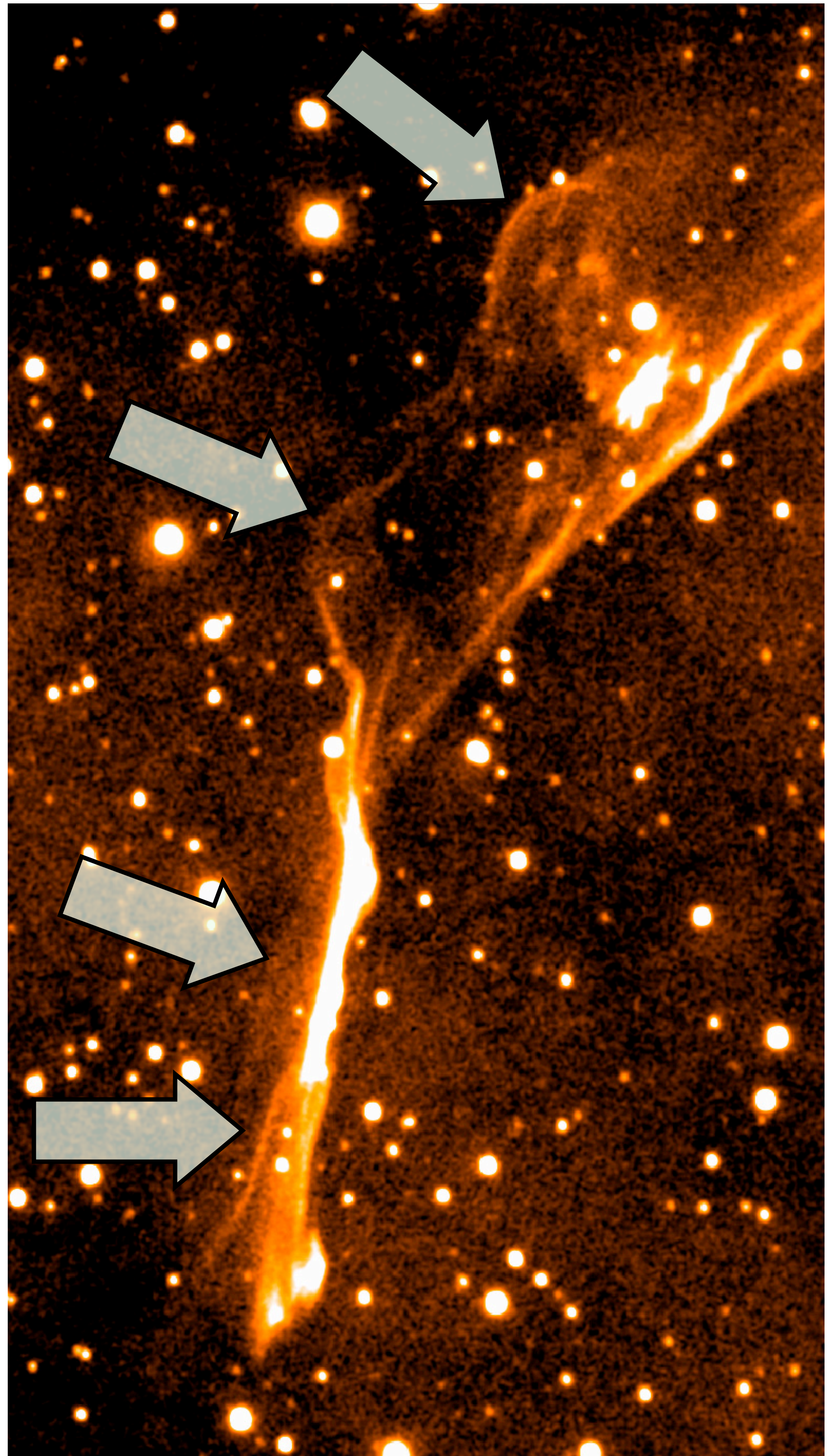
- w/ Balmer-Dominated Filaments,
  - Tp + Te
  - key parameters of CR acceleration: diffusion coeff., injection rate, etc...
- Applications of Balmer-Dominated filaments are not fully realized!

Current Status

- Even with ~10 m class telescopes currently available (MMT, SUBARU, VLT, etc.), we're only observing brightest (i.e., slowest) filaments.
  - brightness $\propto \varrho v$
  - $\varrho \propto v^{-2}$ (w/ constant ram pressure)
  - brightness $\propto v^{-1}$

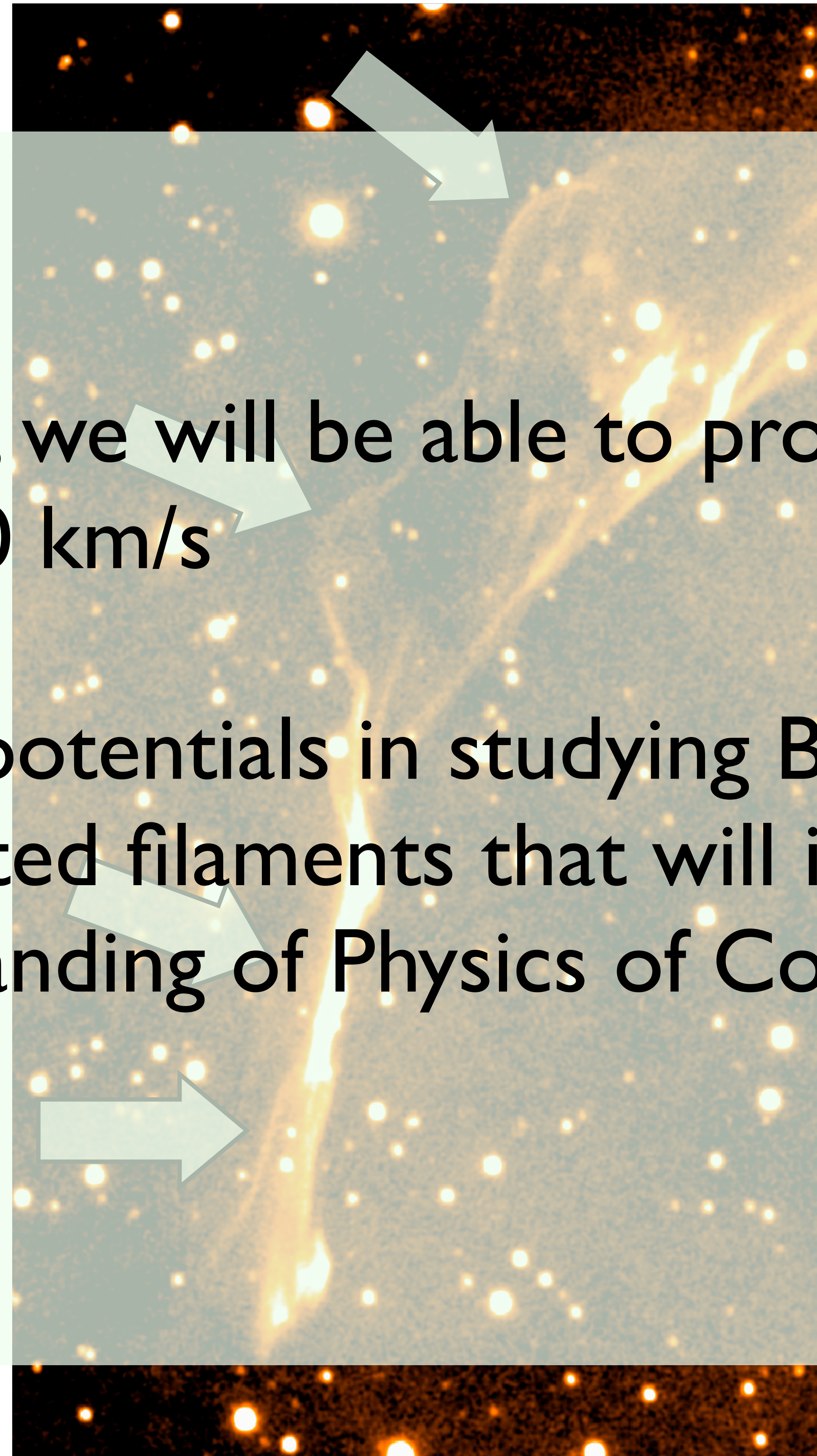


Tycho w/ KPNO (courtesy of F. Winkler)



Tycho w/ KPNO (courtesy of F. Winkler)

- w/ GMT, we will be able to probe shocks of v > 3000 km/s
- Lots of potentials in studying Balmer-Dominated filaments that will improve our understanding of Physics of Collisionless shocks.



Tycho w/ KPNO (courtesy of F. Winkler)