Hα polarimetry as a powerful diagnostics of cosmic-ray modified shock

Cf.) Shimoda & Laming 2019a, MNRAS, 485
Shimoda & Laming 2019b, MNRAS, 489

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ICRC, 2021, July

Summary

- Cosmic-Ray Modified Shocks (CRMSs) are one of an essential prediction of the diffusive shock acceleration.
- We must examine a velocity modification of plasma with $\sim 10\ \%$ level around the SNR shock.
- The polarization direction of Hα responds ***sensitively*** whether the shock is modified.

Supernova Remnant (SNR)

SNR 0509-67.5 (Chandra & HST)
Blue: 1.5 – 7.0 keV
Green: 0.2 – 1.5 keV
Red: Hα

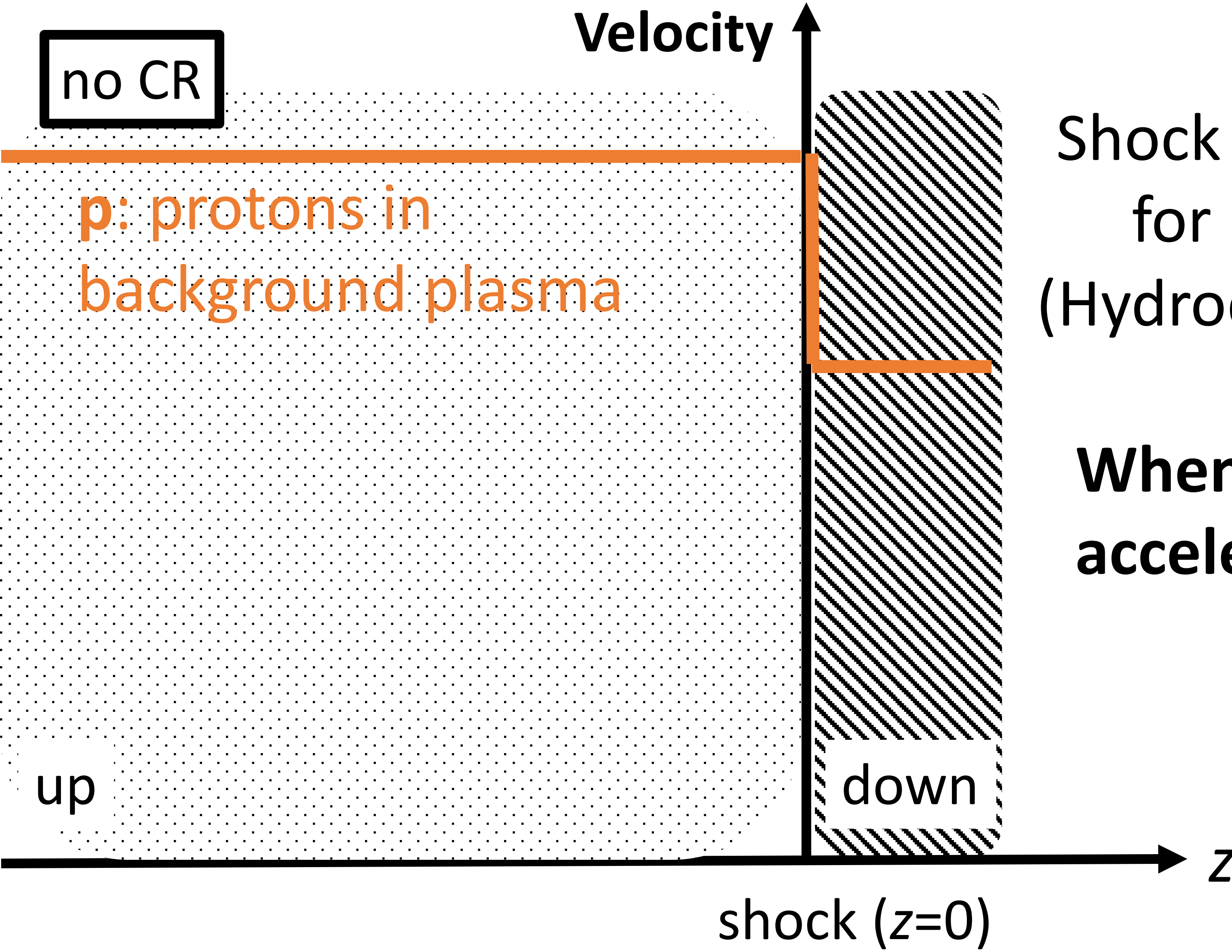
γ-ray: electron or proton?

X-ray: ~TeV CR electrons
Supernova ejecta

Hα: useful tracer of shock condition & physics.

SNR shock is considered as the best candidate of CR origin.

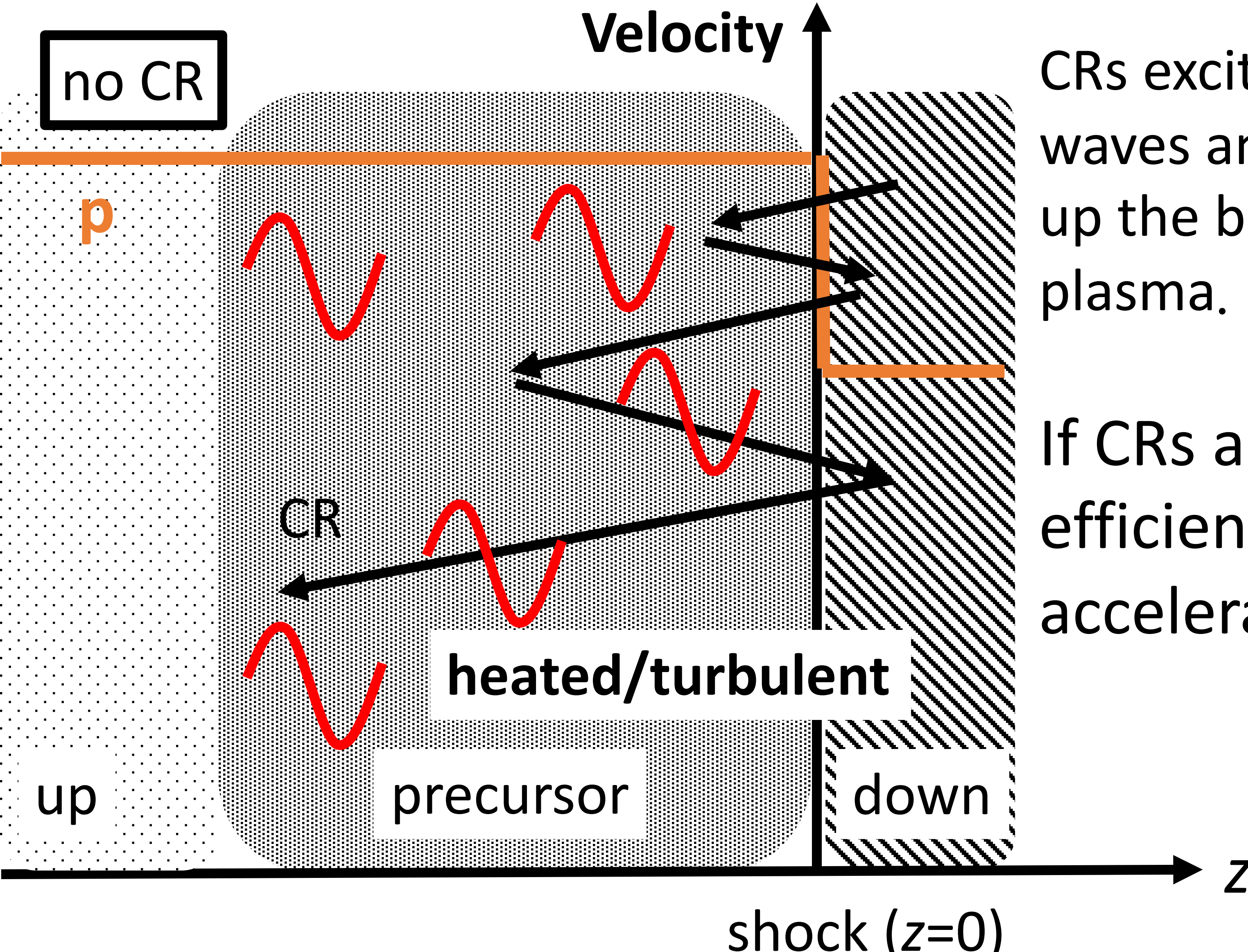
Shock Structure with CRs



Shock structure
for no CRs
(Hydrodynamics)

When CRs are accelerated？

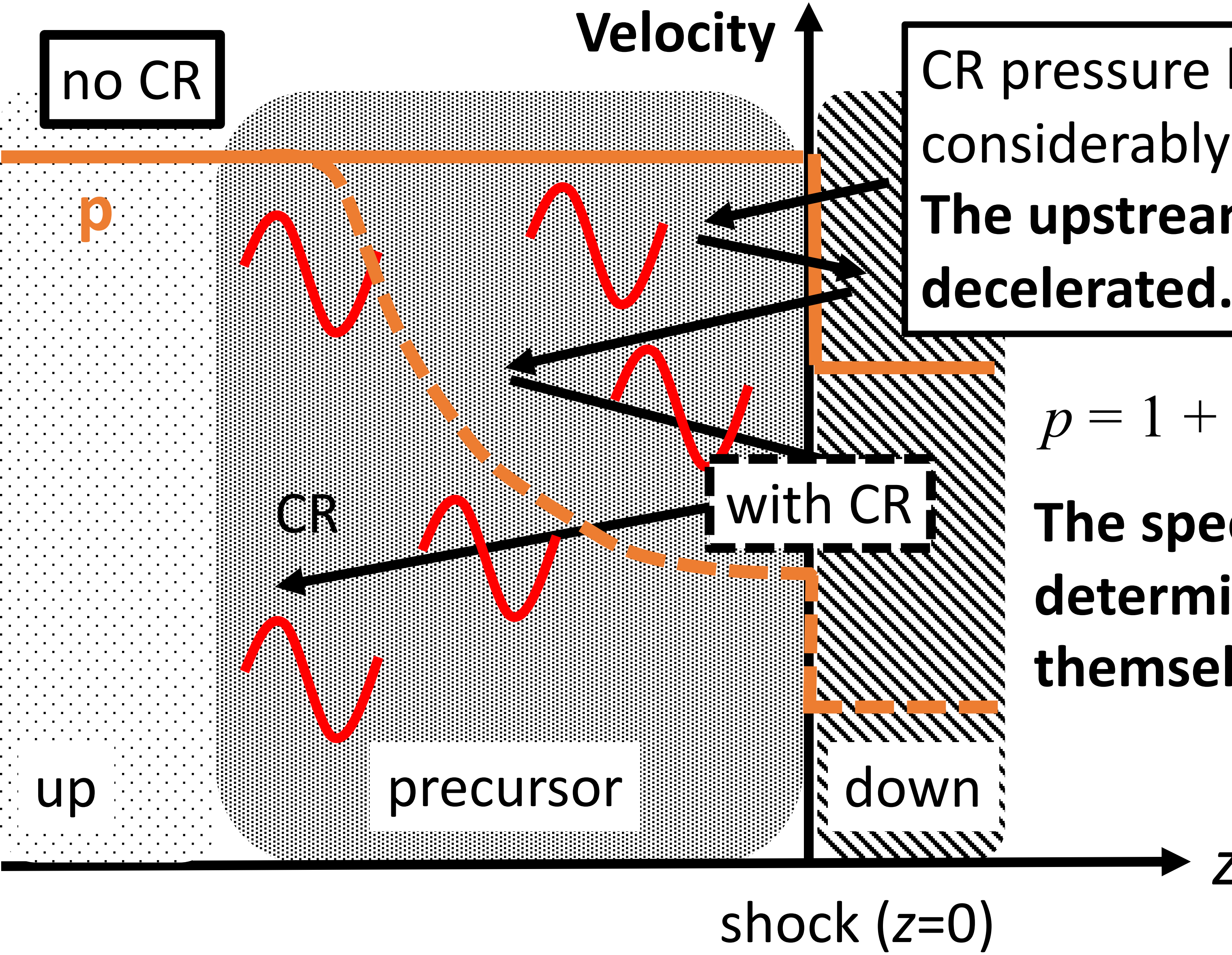
Shock Structure with CRs



CRs excite plasma waves and/or heat up the background plasma.

If CRs are more efficiently accelerated, …

Shock Structure with CRs

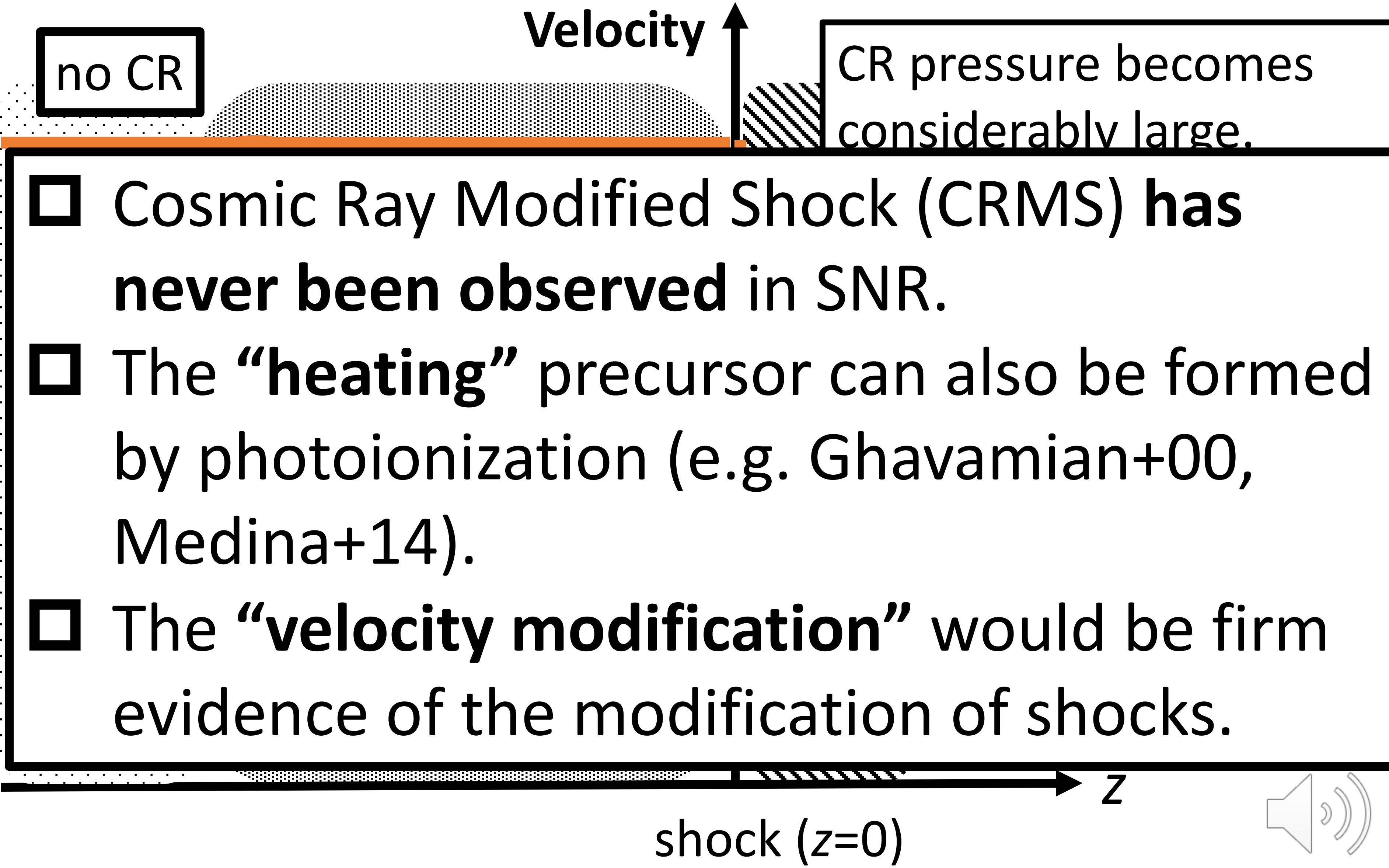


CR pressure becomes considerably large.
The upstream plasma is decelerated.

$$p = 1 + 3u_2 / (u_0\text{-}u_2)$$

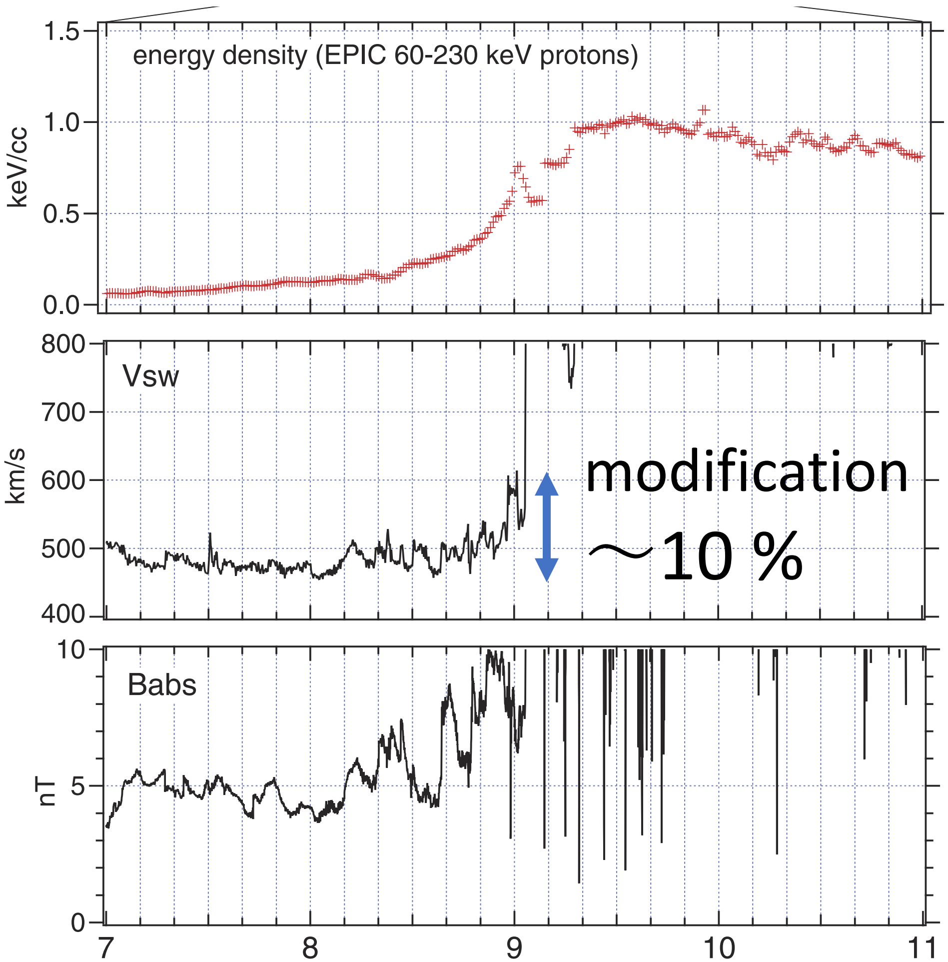
The spectrum is determined by CRs themselves!

Shock Structure with CRs



- Cosmic Ray Modified Shock (CRMS) **has never been observed** in SNR.
- The “**heating**” precursor can also be formed by photoionization (e.g. Ghavamian+00, Medina+14).
- The “**velocity modification**” would be firm evidence of the modification of shocks.

Cosmic-Ray Modified Shock (CRMS)



Terasawa 2006

~20 % of shock energy (flux) converted to non-thermal particles

- *In situ.* observation

Solar wind

V_{sh} ~ 100 km/s

E_{CR} ~ 10 keV - MeV

B ~ 10 μG (M_A ~ 5)

Age ~ day

Young SNR

V_{sh} > 1000 km/s

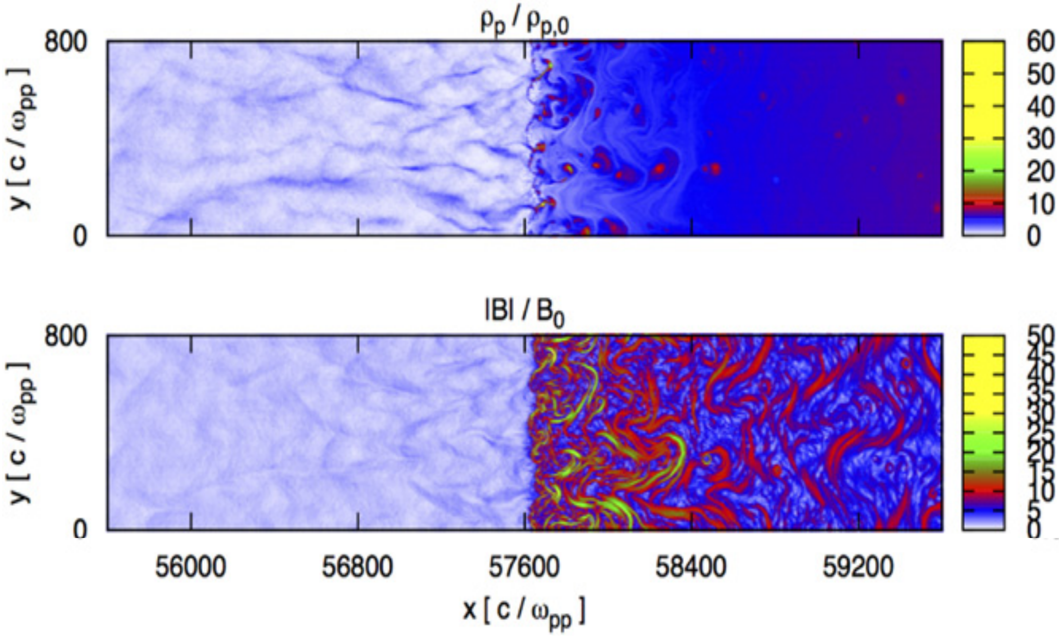
E_{CR} ~ 1 GeV – 3 PeV ?

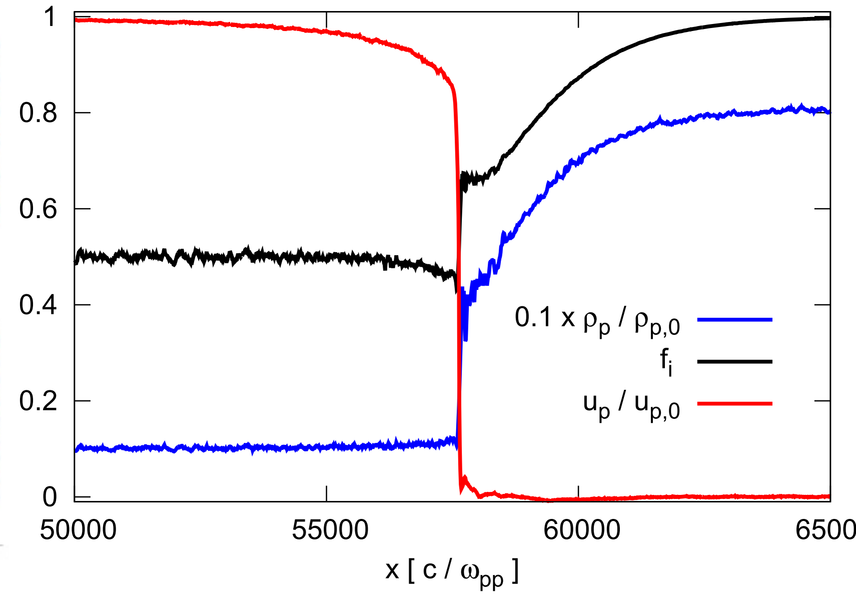
B ~ 1 - 100 μG ?

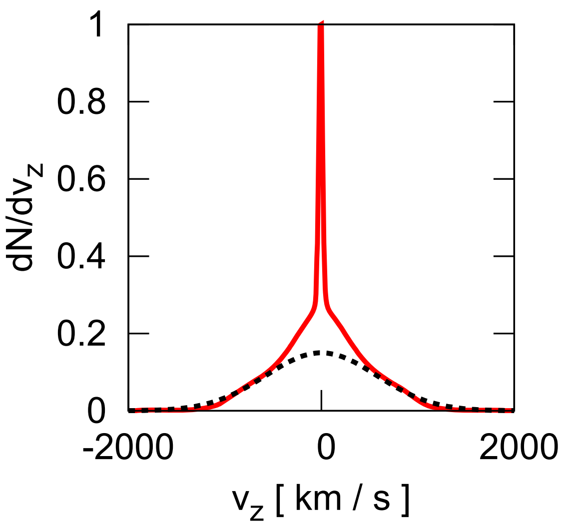
(M_A ~ 1 – 100 ?)

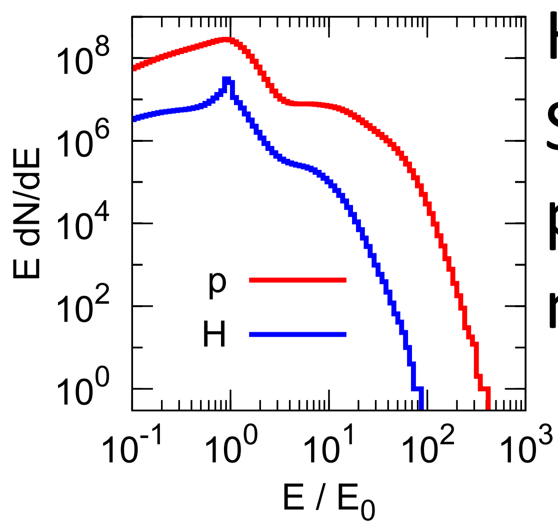
Age ~ 100 – 1000 yr.

Cosmic-Ray Modified Shock (CRMS)





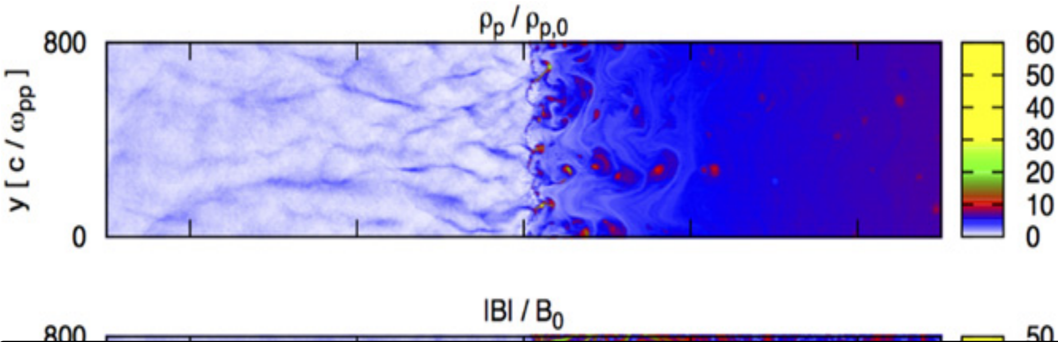


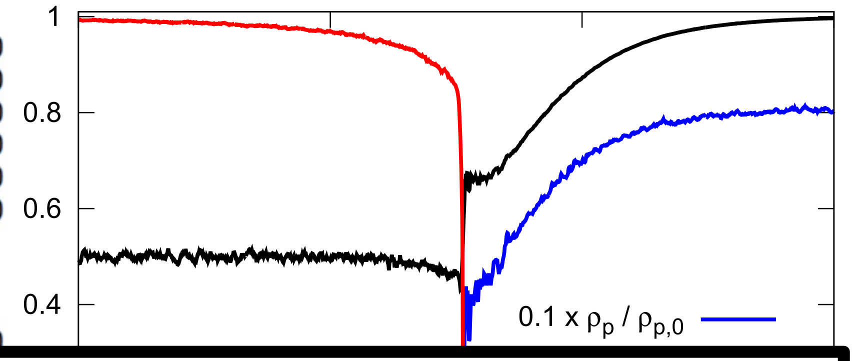


Hybrid simulation of SNR shocks traveling in partially ionized medium by Ohira 16.

Age ～ 0.1 day

Cosmic-Ray Modified Shock (CRMS)

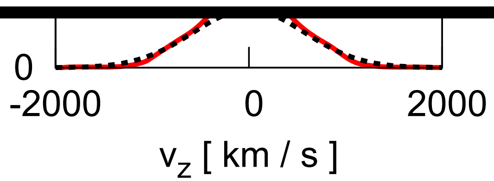


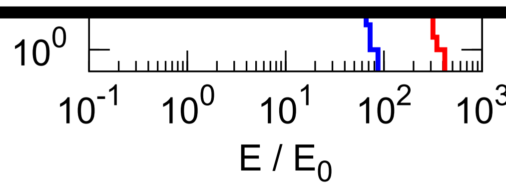


- The implied modification is about 10 %.

We must examine such modification of plasma located at a distance of <u>kpc scale</u>.

Challenging!





Age ～ 0.1 day

Supernova Remnant (SNR)

γ-ray: electron or proton?

X-ray: ~TeV CR electrons
Supernova ejecta

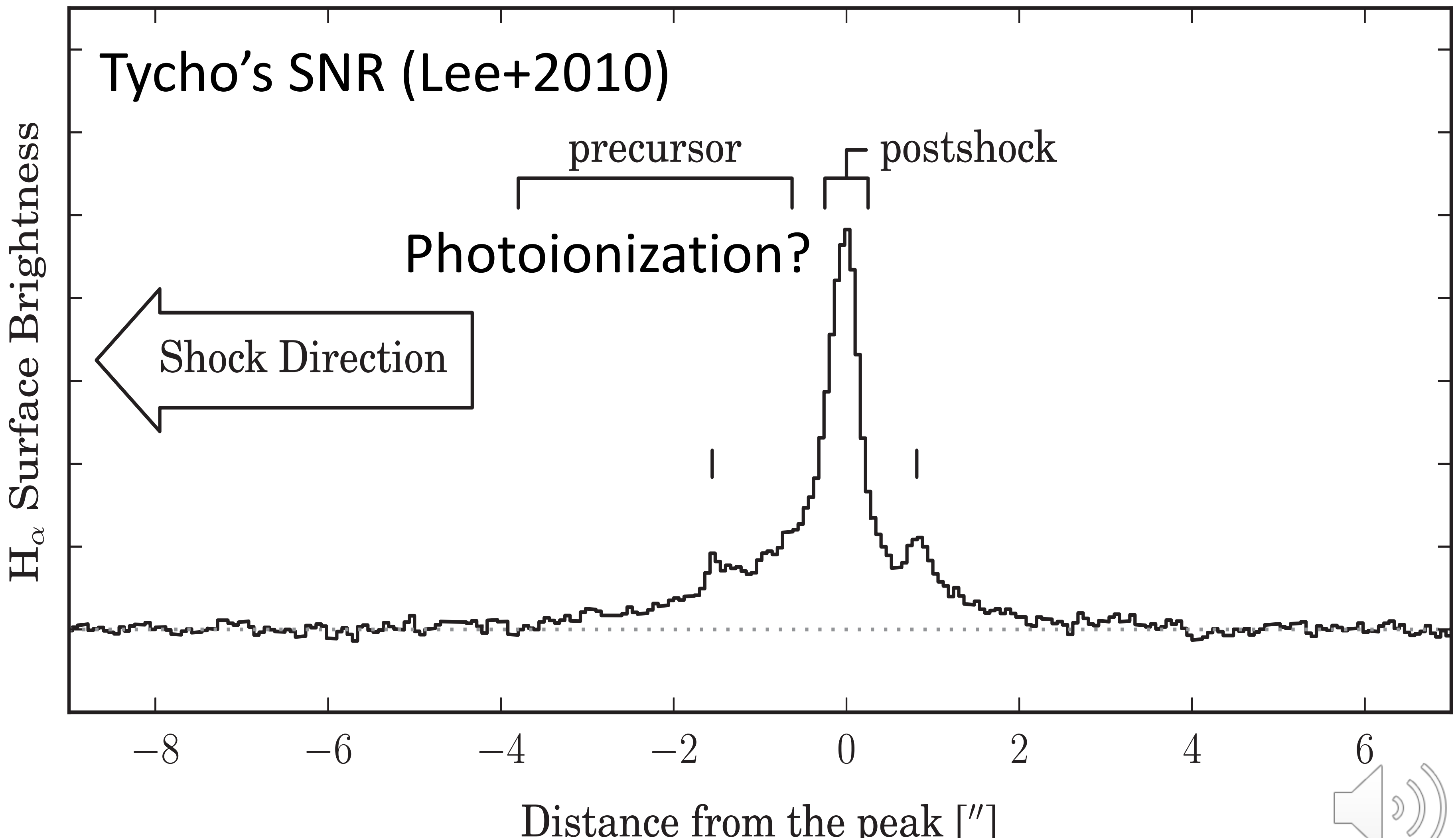
Hα: useful tracer of shock condition & physics.

Hα emissions reflect a plasma condition around the shock (e.g. Raymond 91 for review).

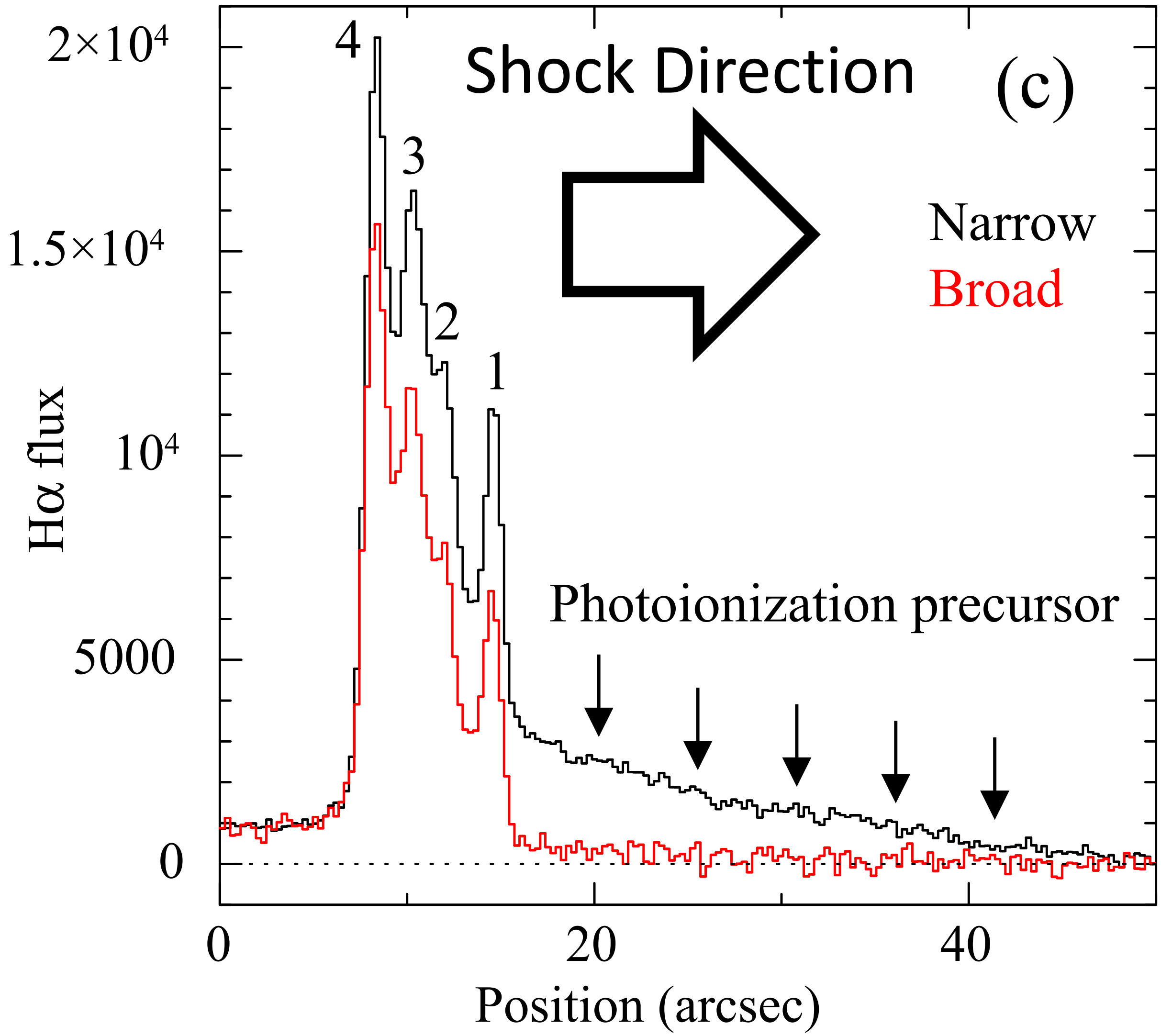
Red: Hα

best candidate of CR origin.

Hα emission from upstream

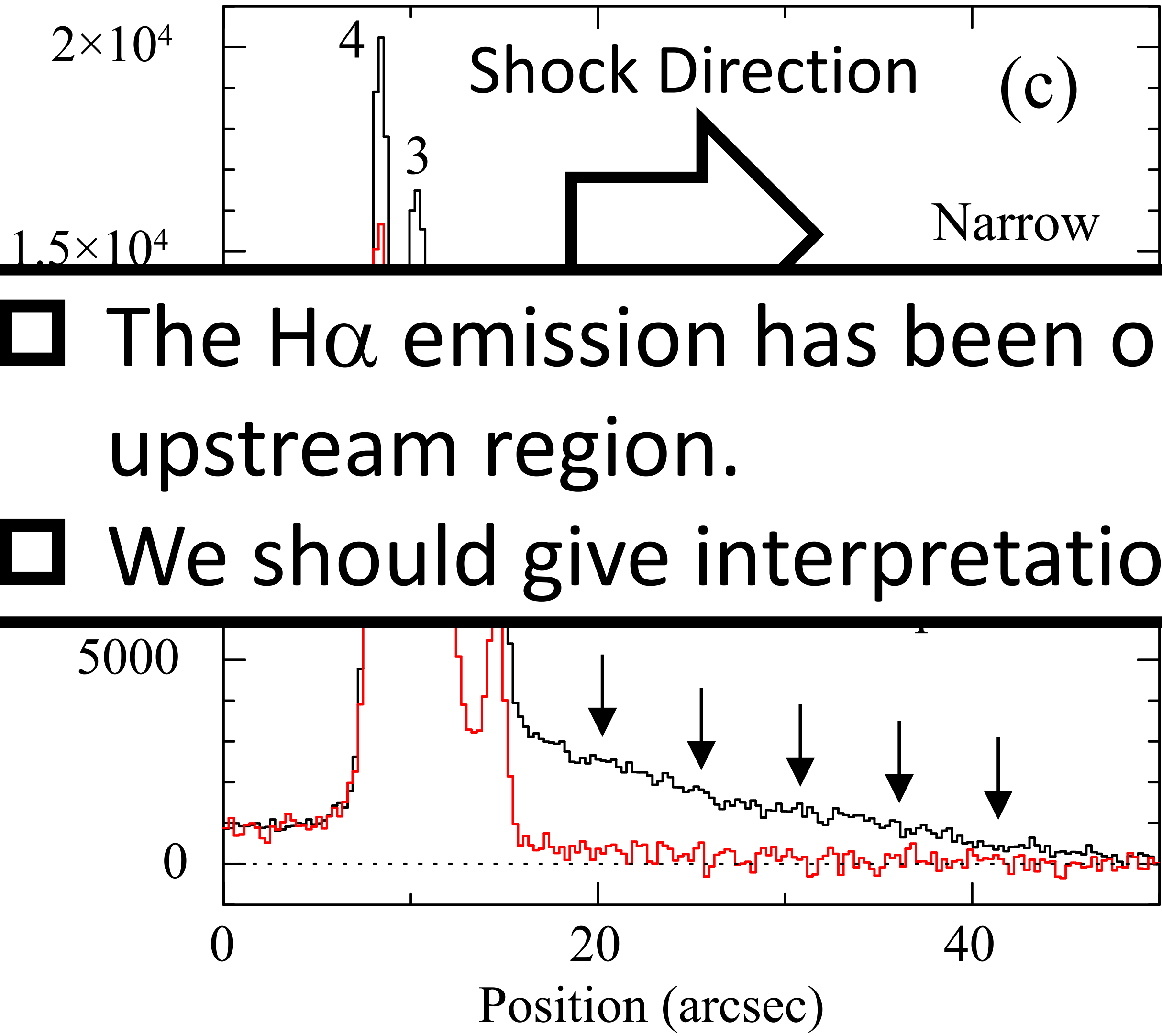


Hα emission from upstream



SNR Cygnus Loop
(Katsuda+2016)

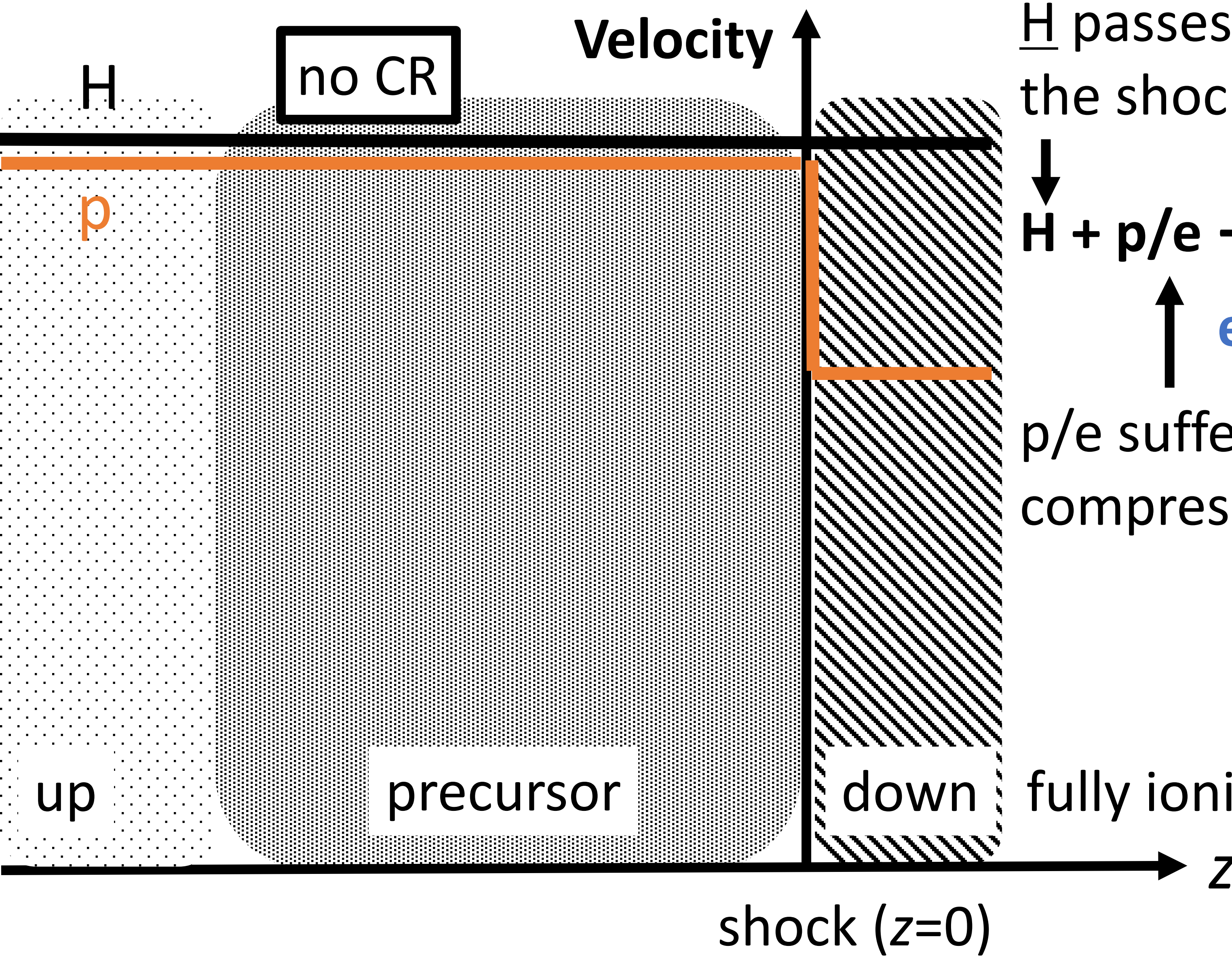
Hα emission from upstream



SNR Cygnus Loop (Katsuda+2016)

- The Hα emission has been observed at the upstream region.
- We should give interpretations.

Hα emission from upstream



H passes through the shock front

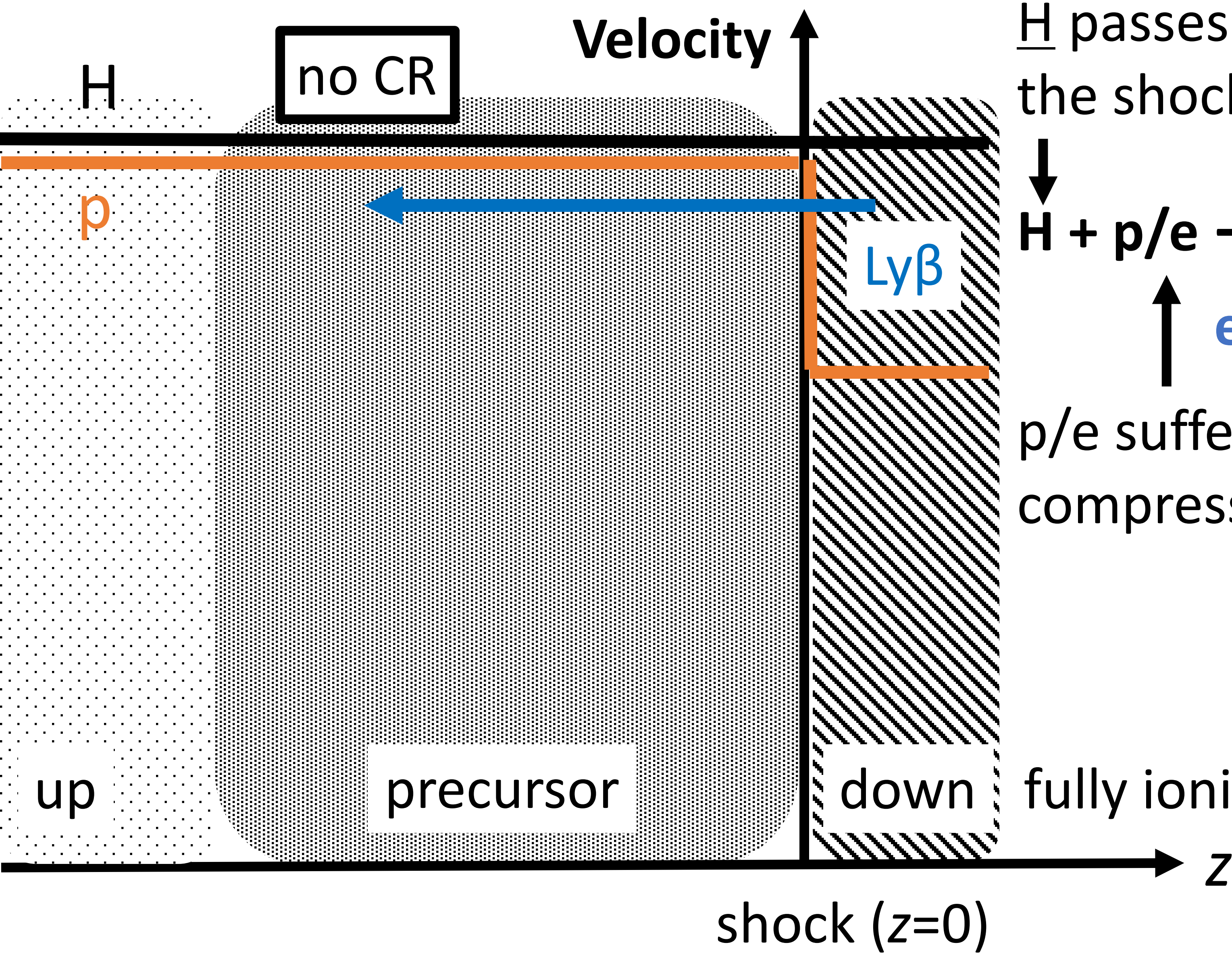
H + p/e → H* + p/e

emits Lyβ

p/e suffers the shock compression

fully ionized

Hα emission from upstream



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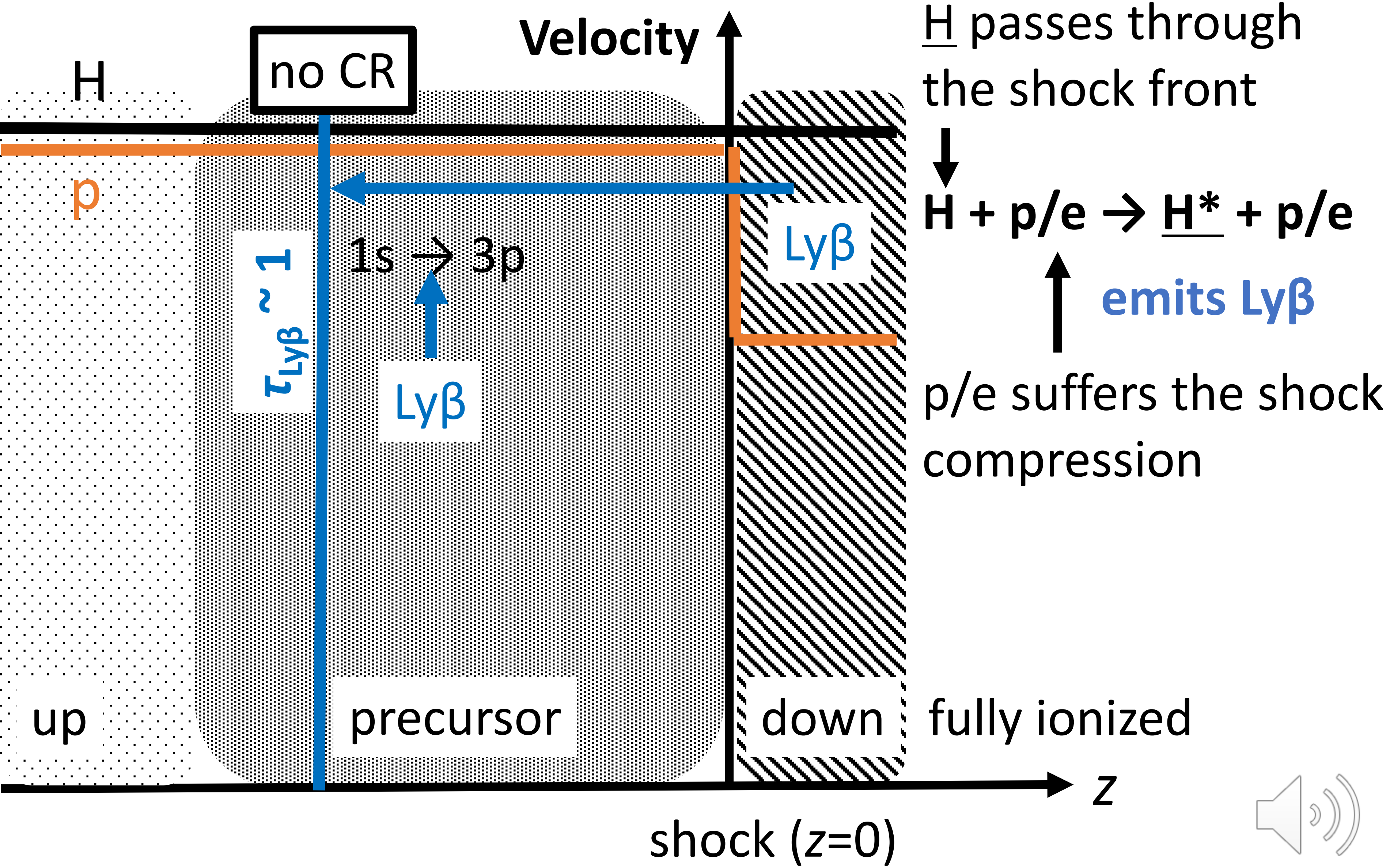
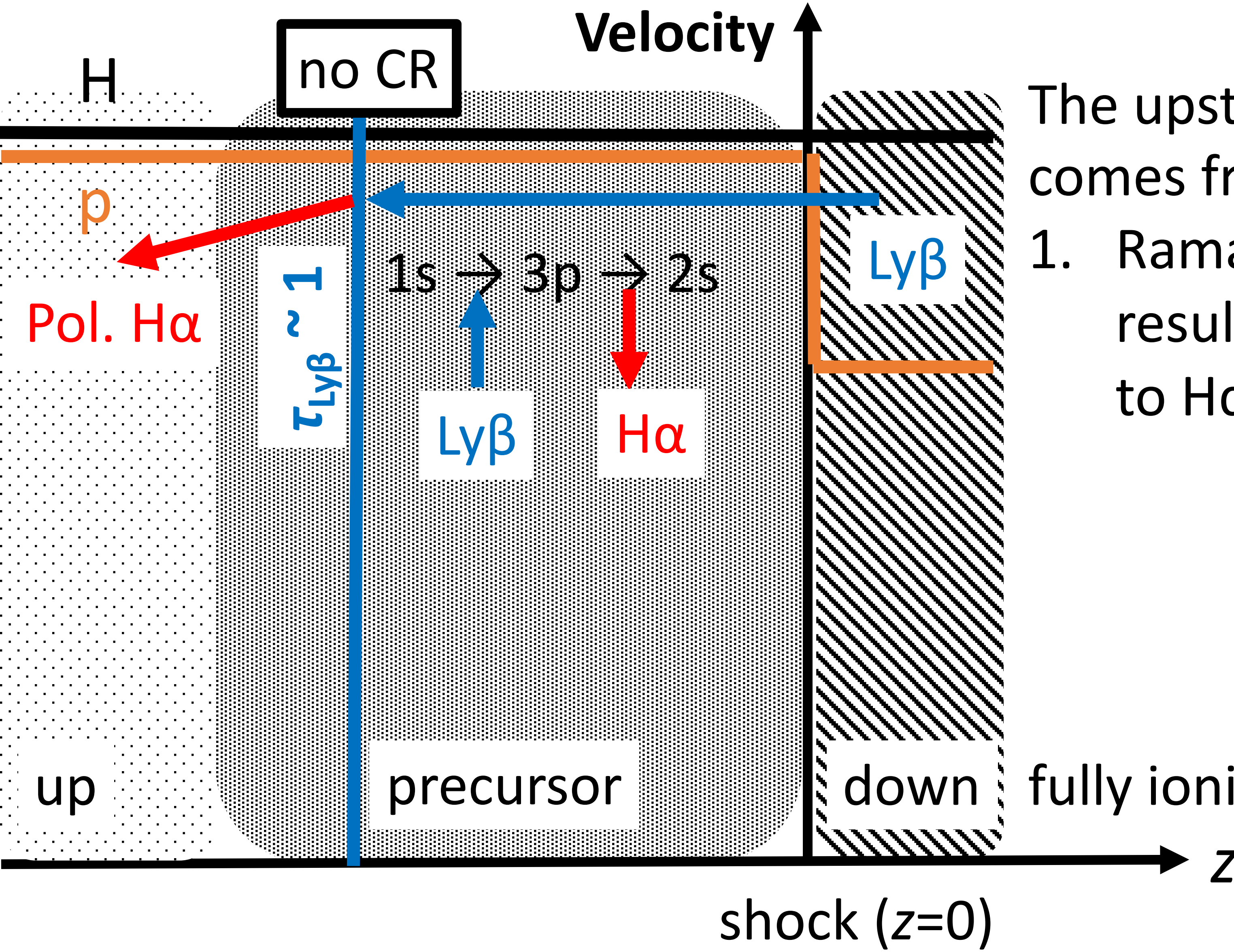


Hα emission from upstream

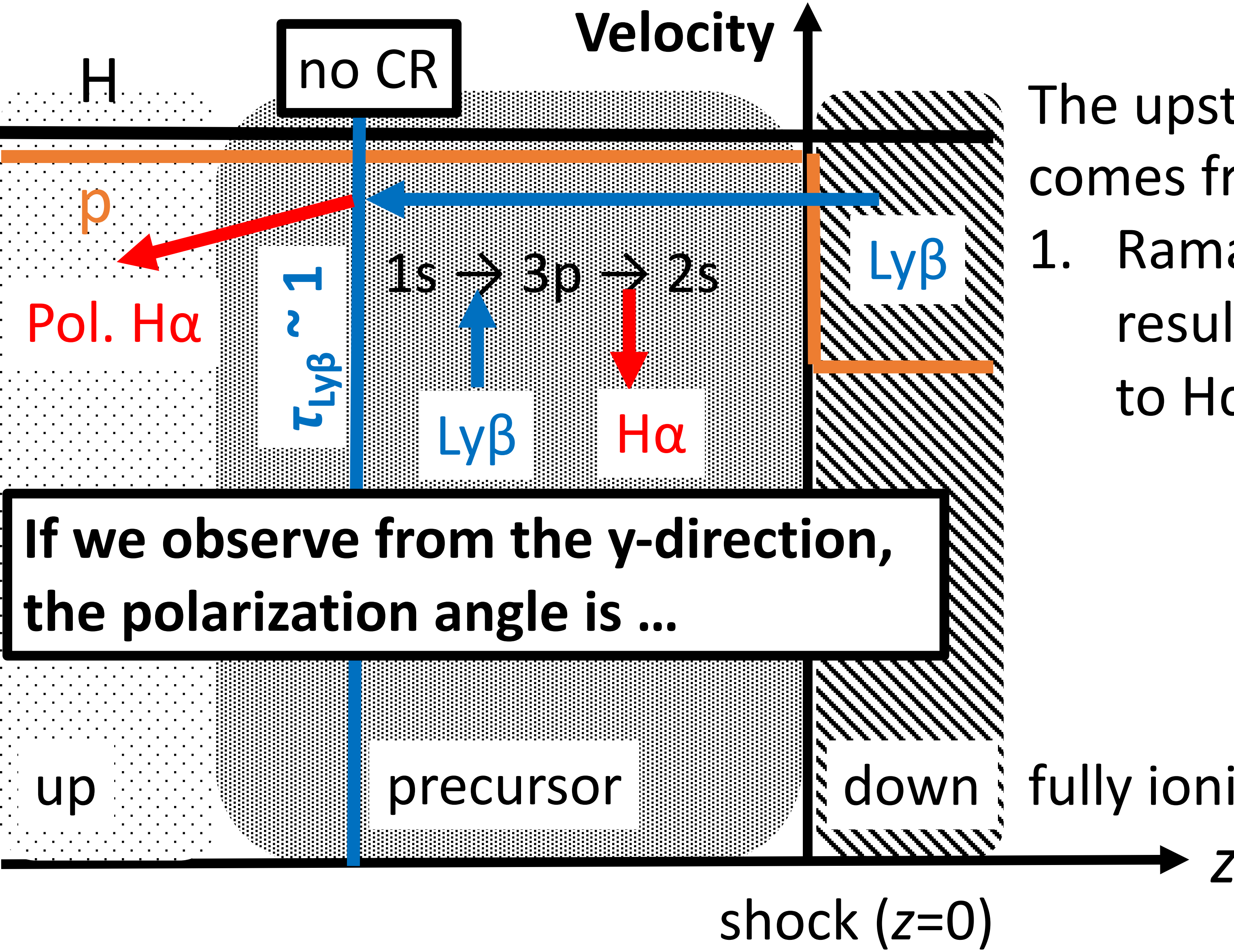


The upstream Hα comes from：

1. Raman scattering resulting in Lyβ to Hα

fully ionized

Hα emission from upstream



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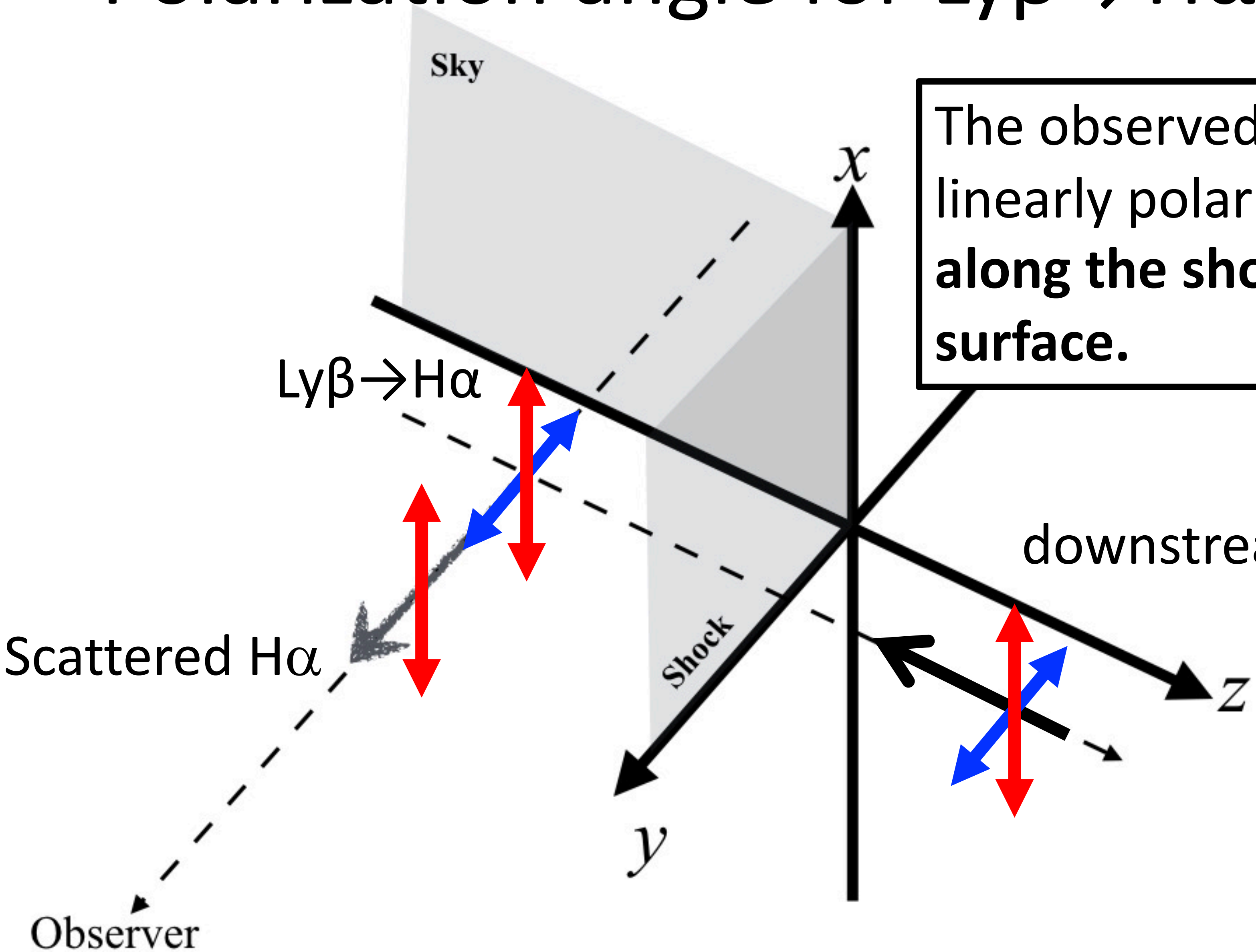
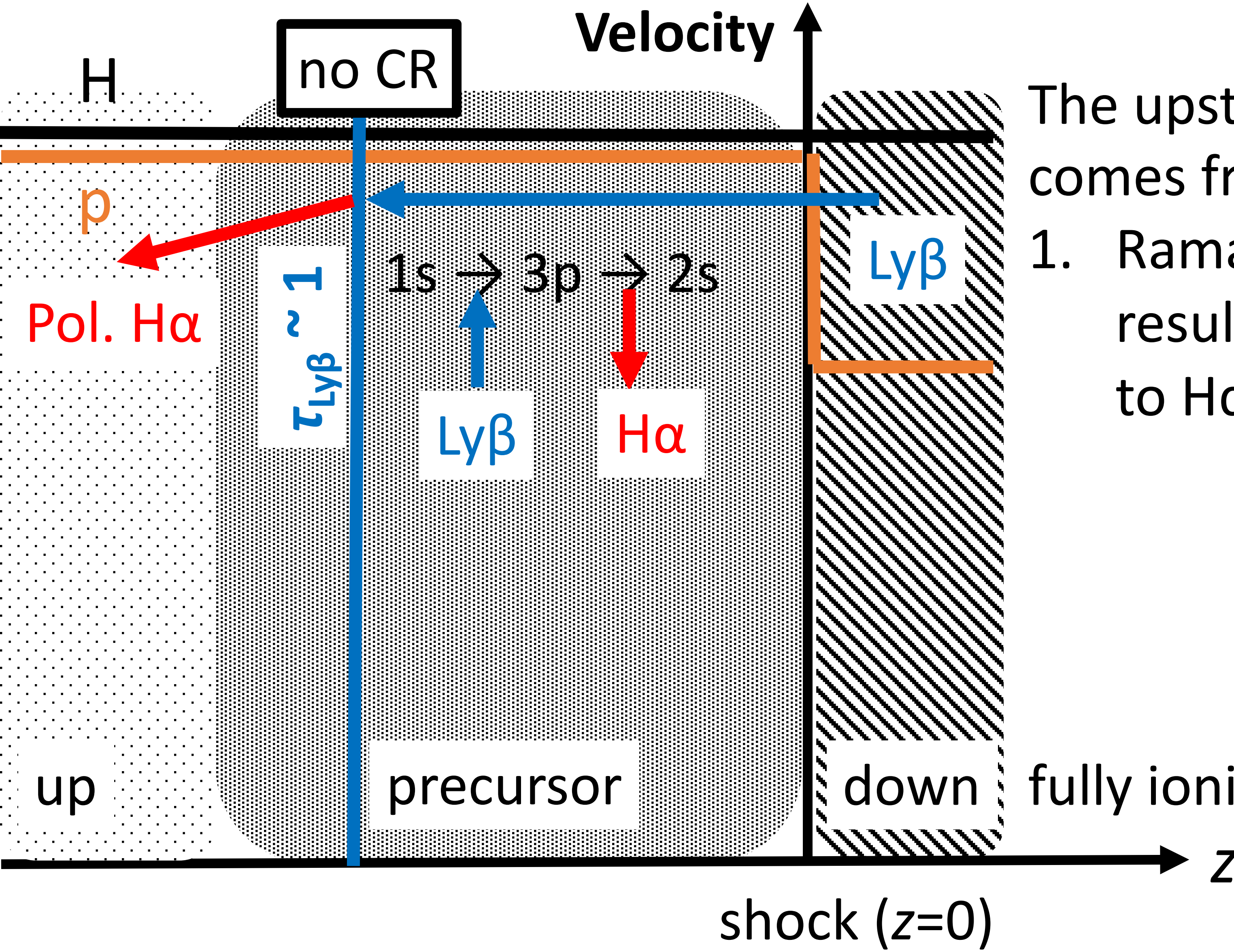
Polarization angle for Lyβ→Hα



The observed Hα is linearly polarized **along the shock surface.**

Hα emission from upstream



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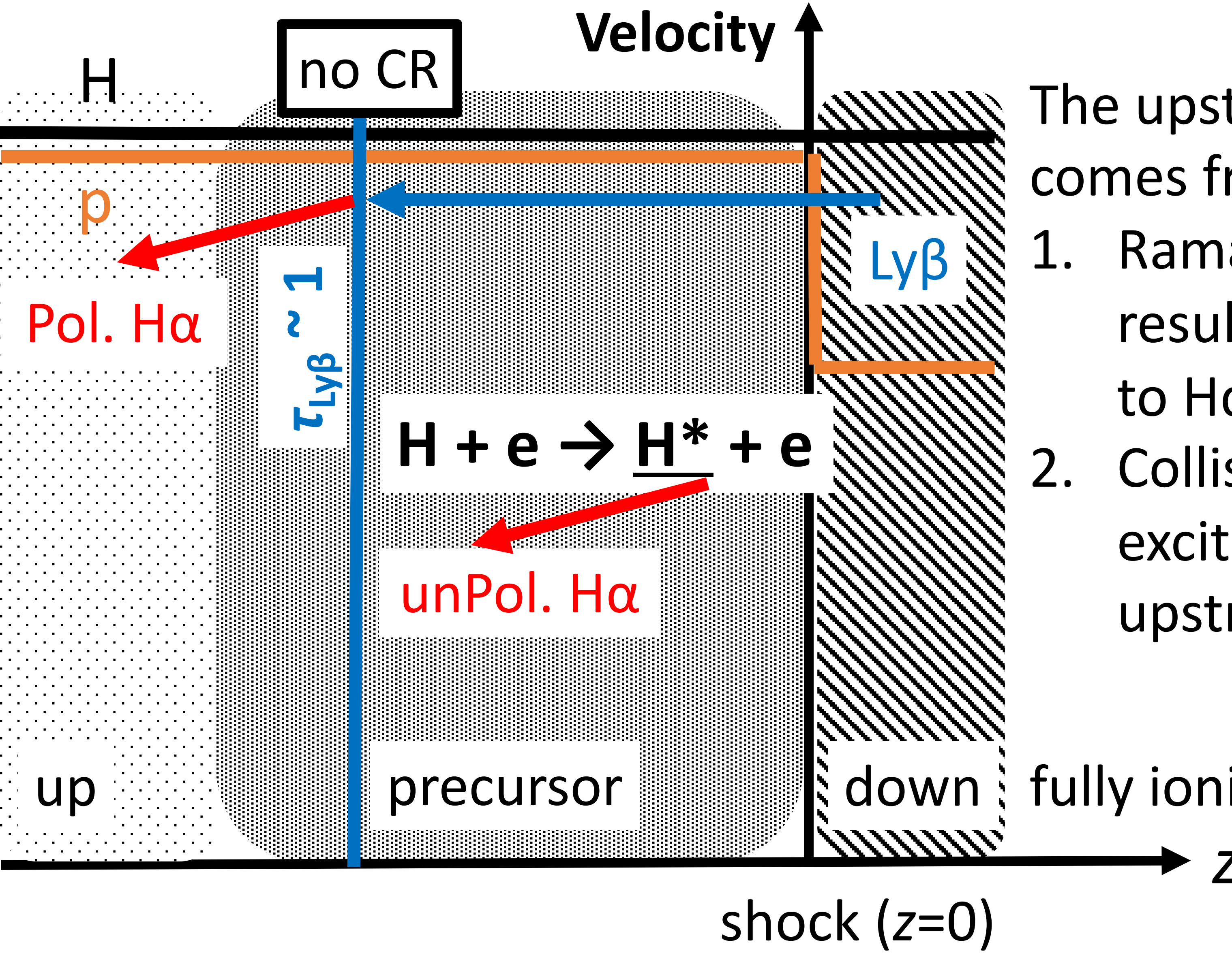
Hα emission from upstream

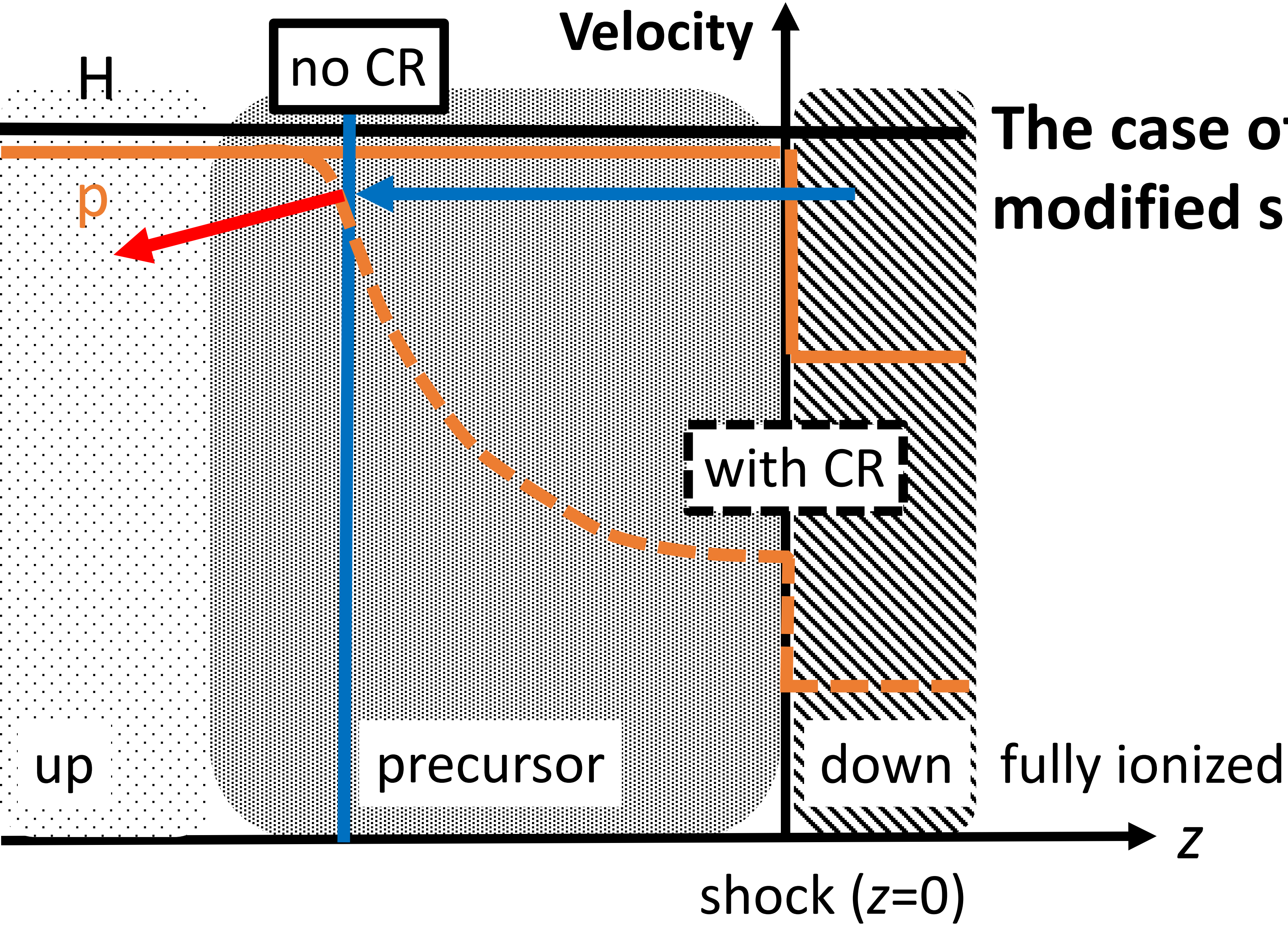


The upstream Hα comes from：

1. Raman scattering resulting in Lyβ to Hα
2. Collisional excitation in the upstream region.

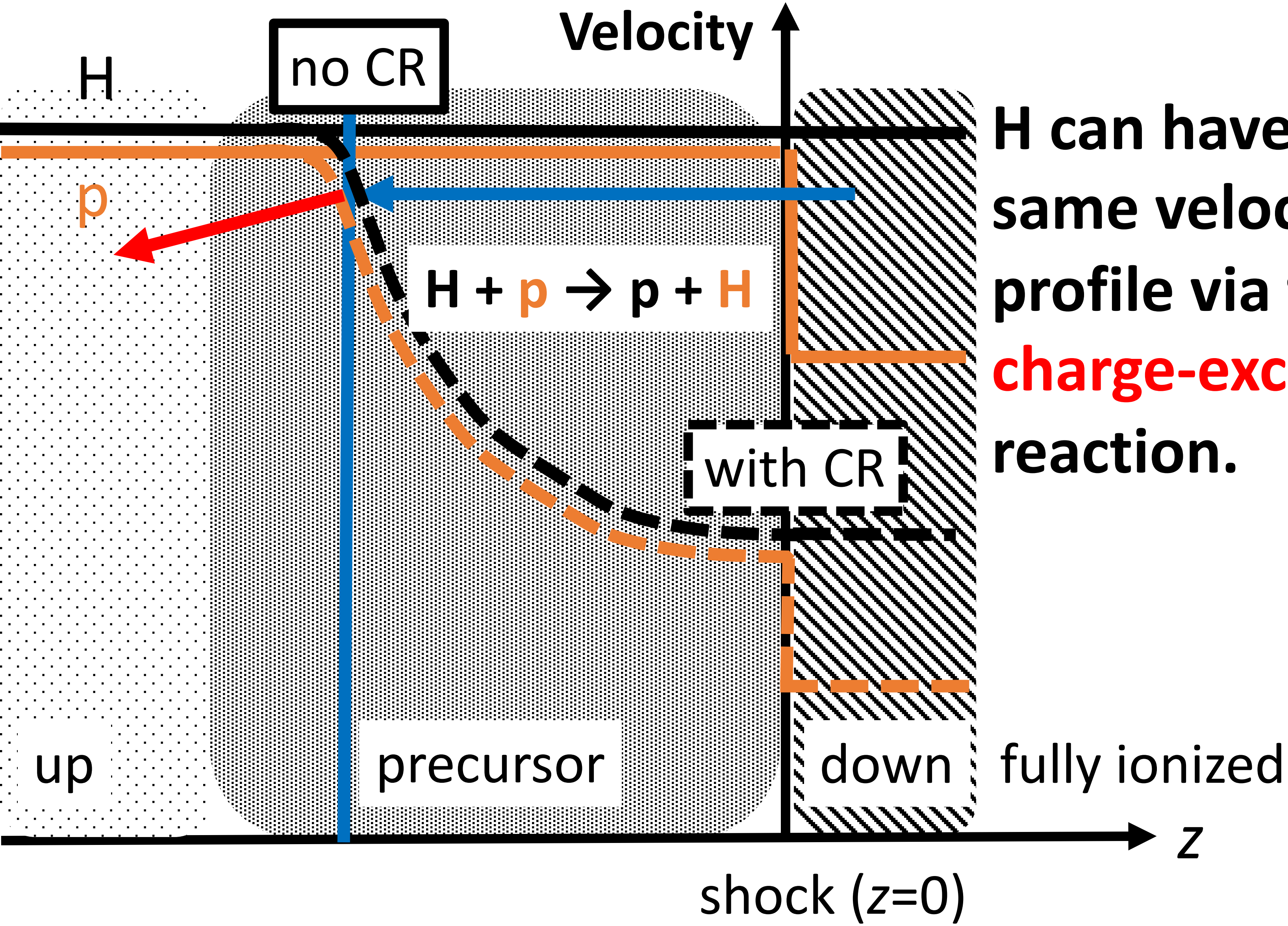
fully ionized

Hα emission from upstream



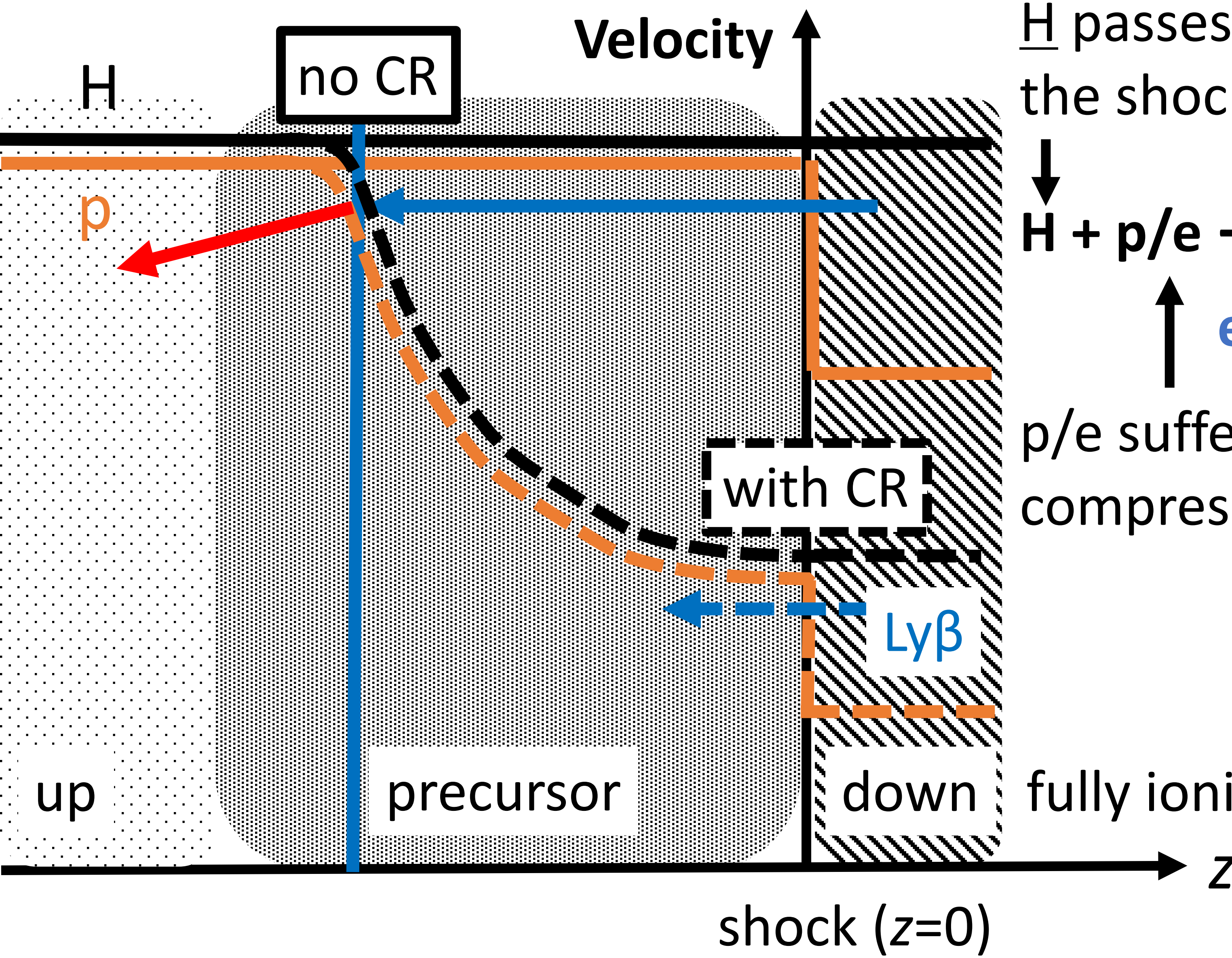
The case of CR modified shock.

Hα emission from upstream



H can have the same velocity profile via the charge-exchange reaction.

Hα emission from upstream



H passes through the shock front

↓

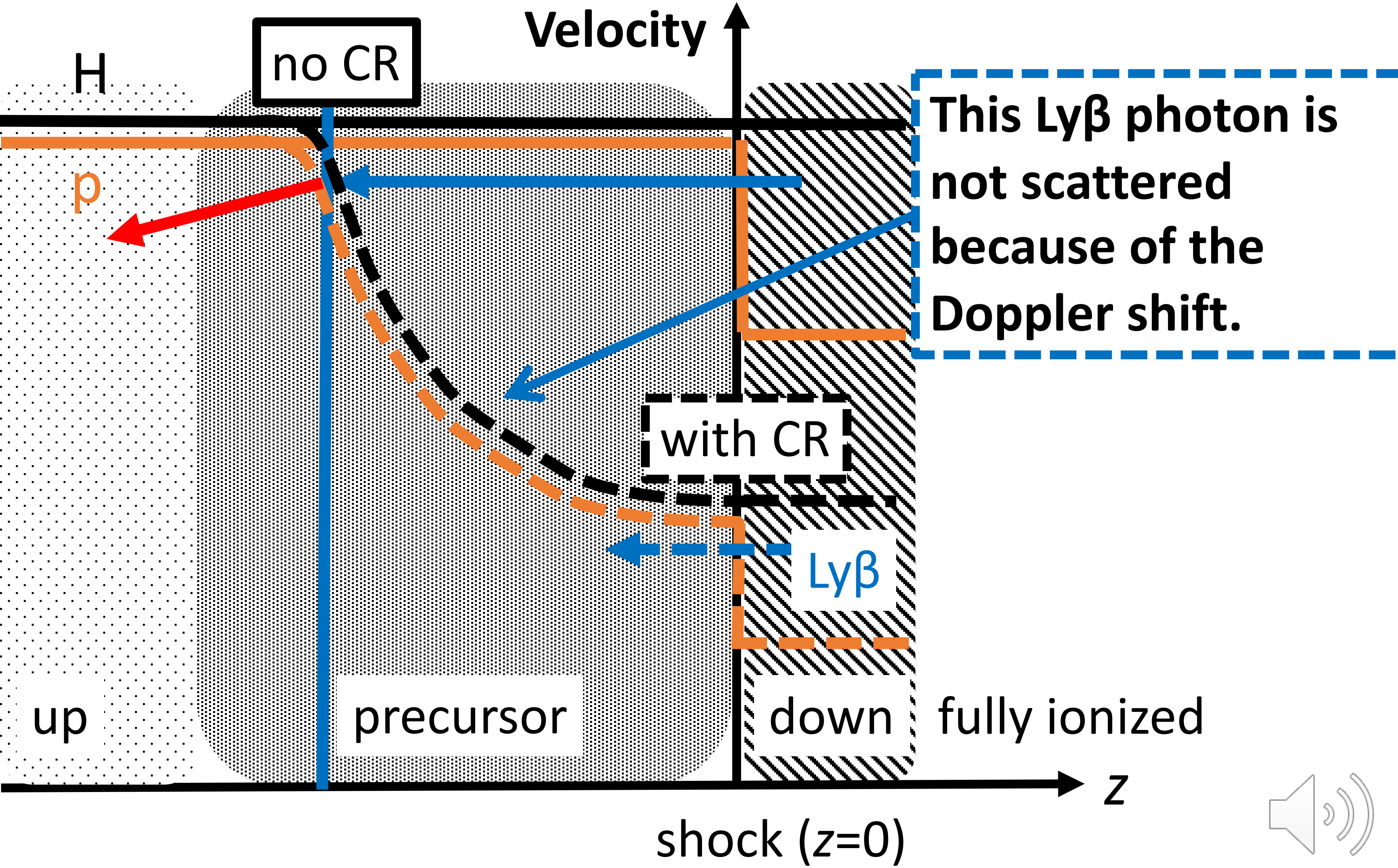
H + p/e → H* + p/e

↑ **emits Lyβ**

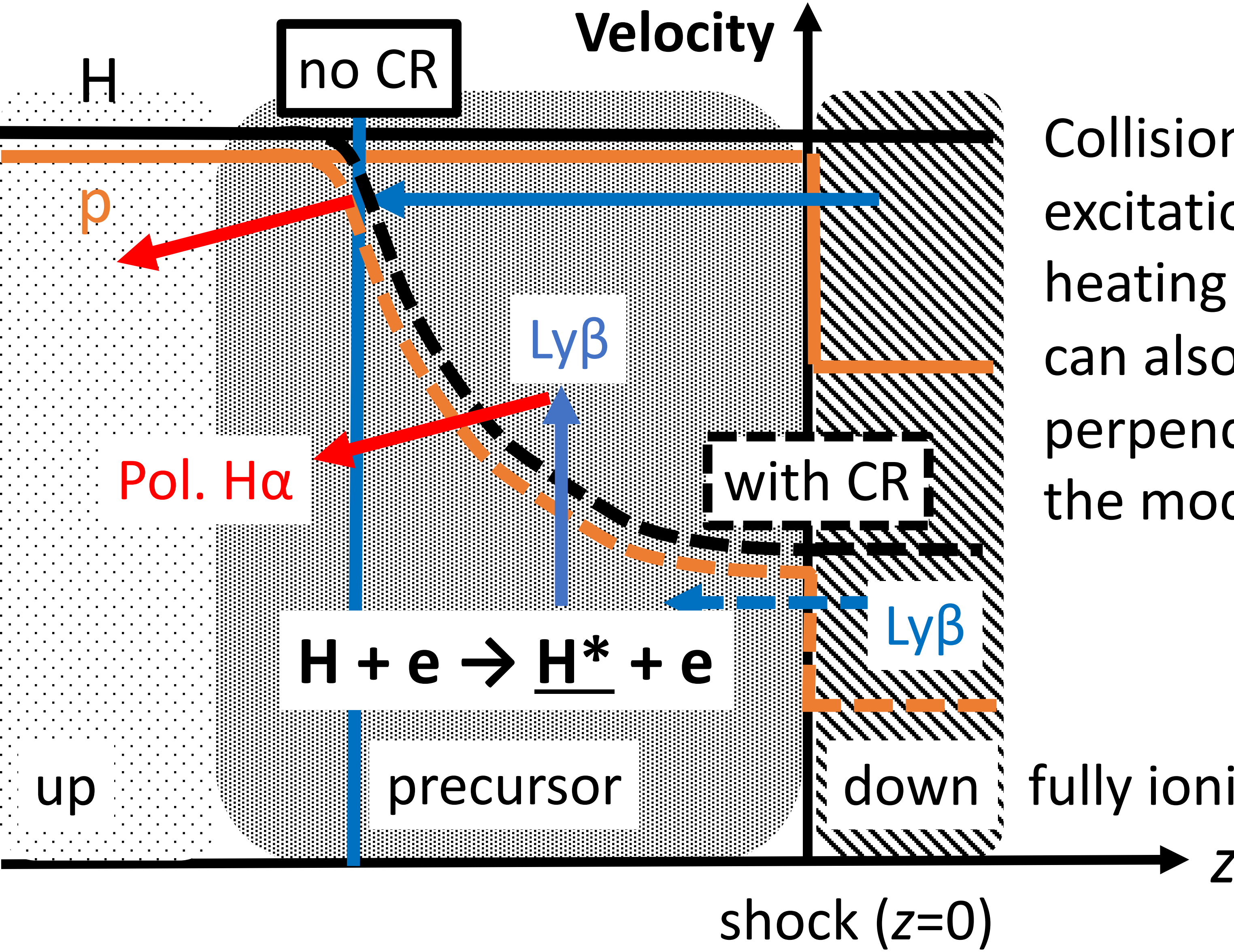
p/e suffers the shock compression

fully ionized

Hα emission from upstream



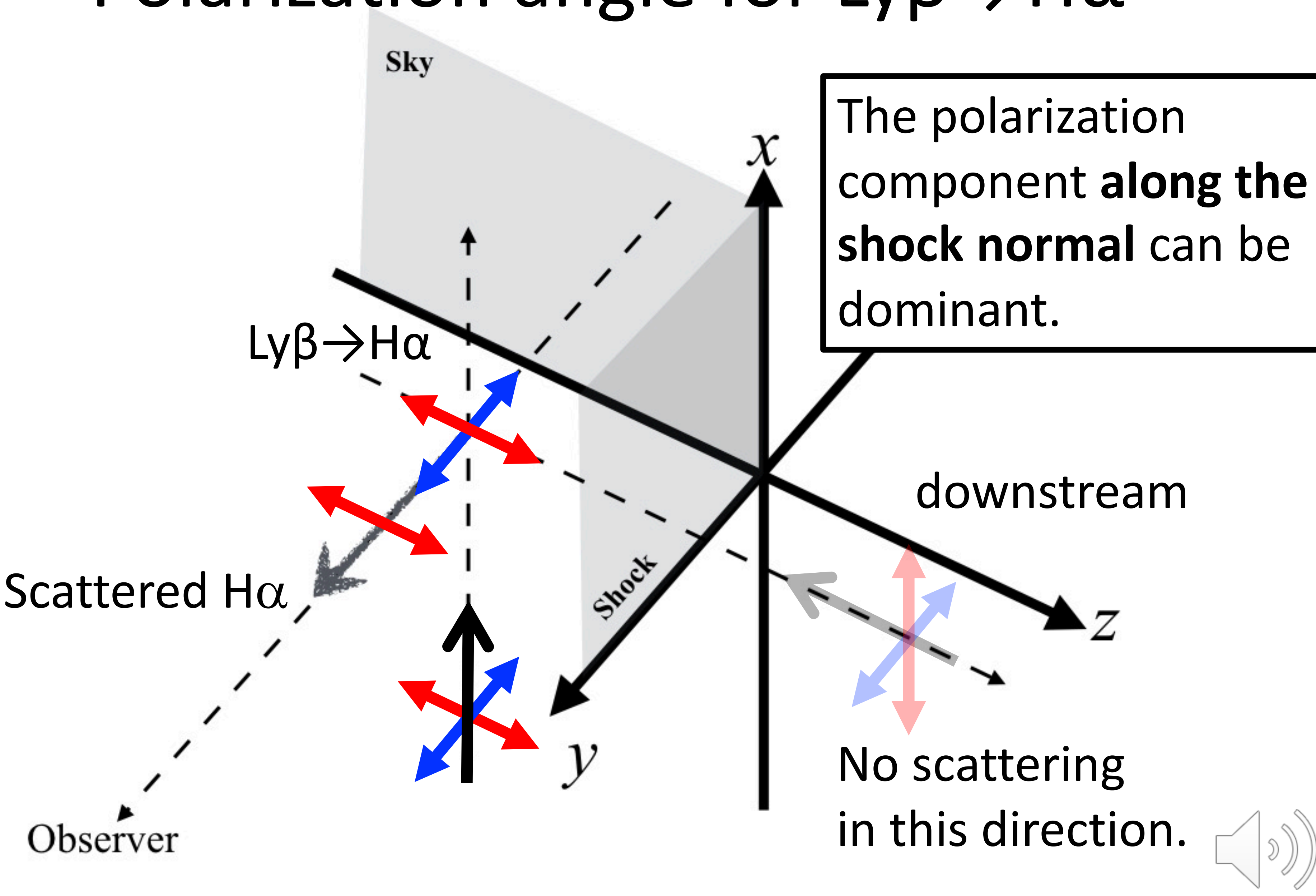
Hα emission from upstream



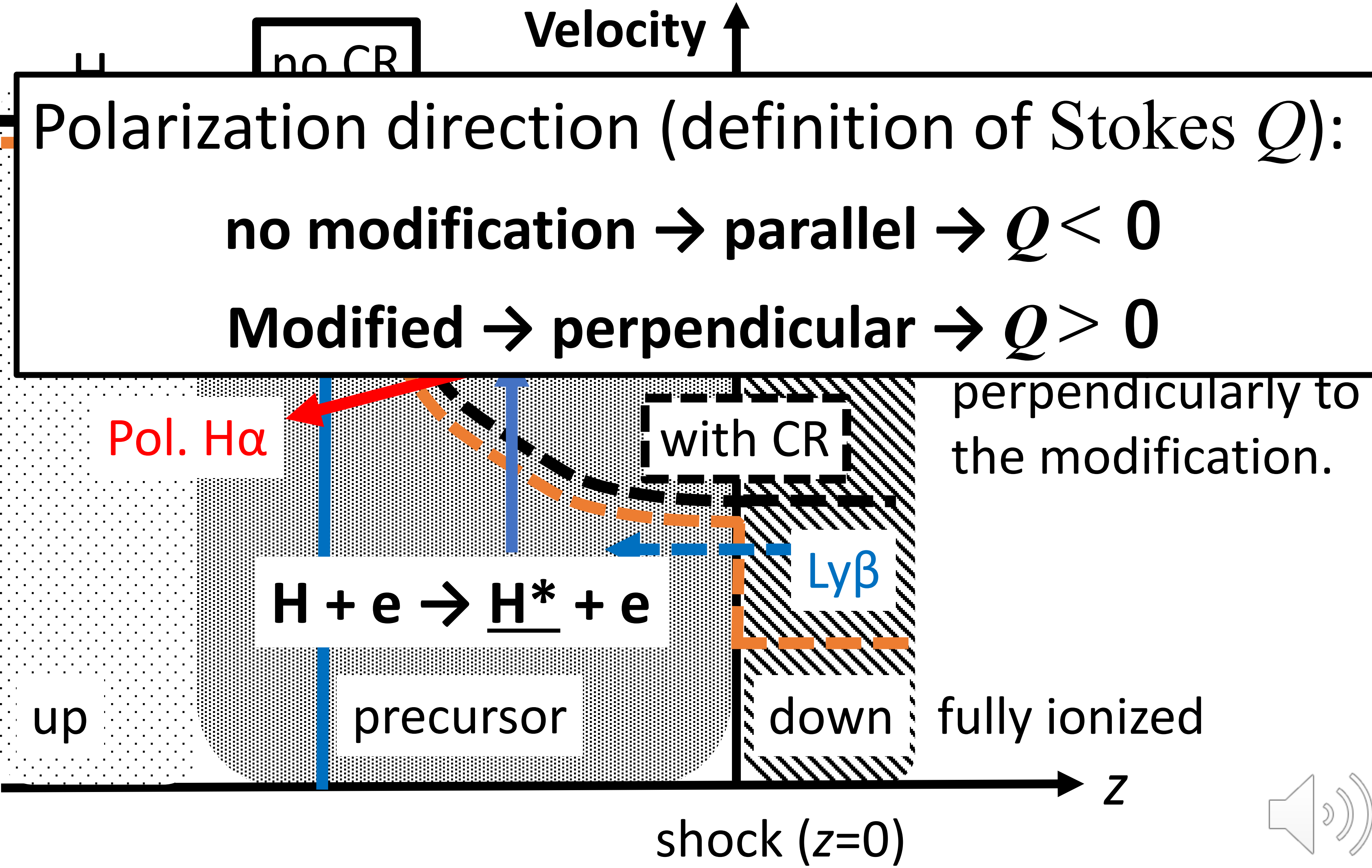
Collisional excitation in the heating precursor can also yield Lyβ perpendicularly to the modification.

Polarization angle for Lyβ→Hα

The polarization component **along the shock normal** can be dominant.



Hα emission from upstream



Polarization direction (definition of Stokes Q):

no modification → parallel → $Q < 0$

Modified → perpendicular → $Q > 0$

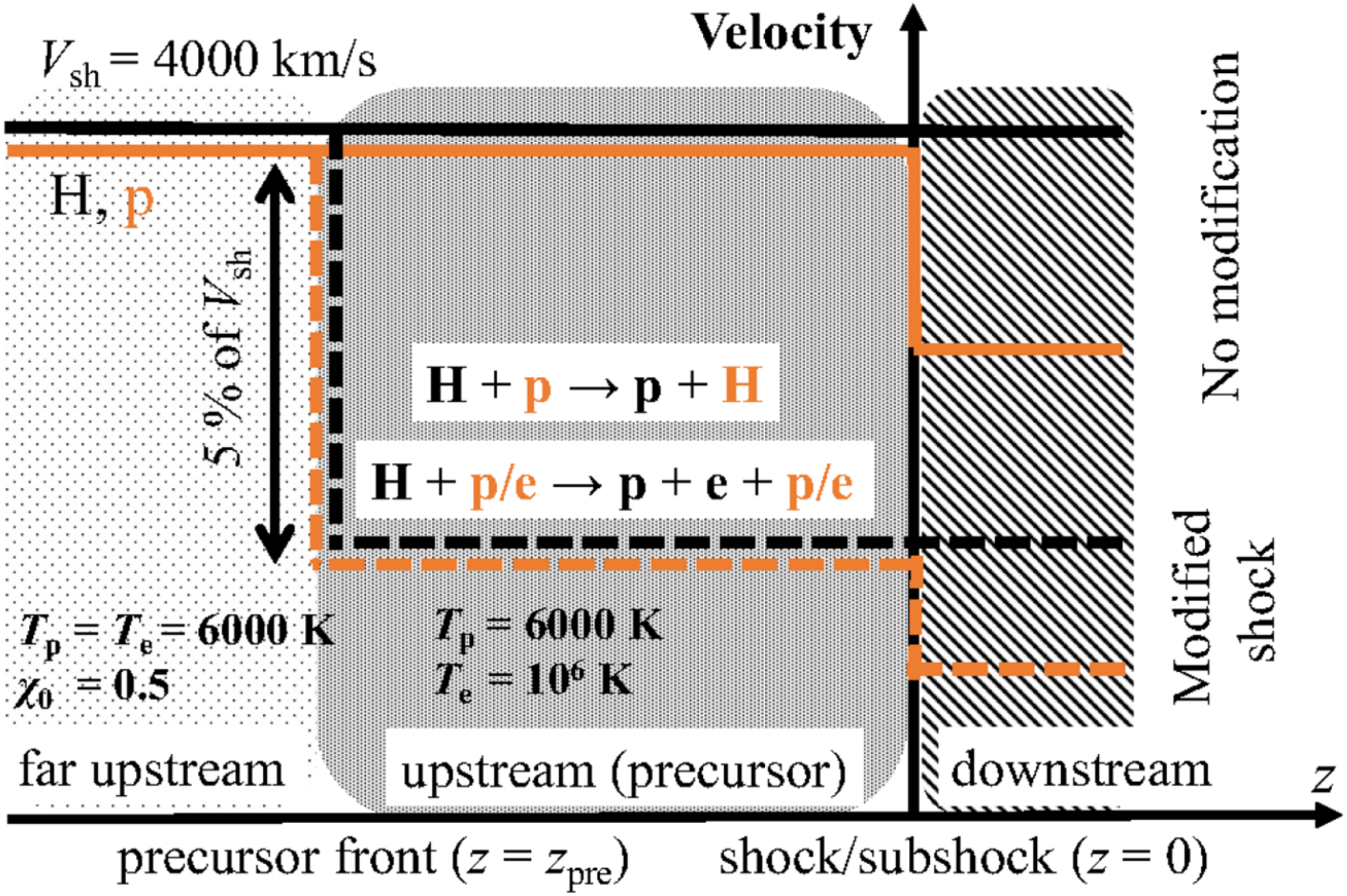
Hα emission from upstream

- Radiation line transfer & atomic population with polarized light → quite complex!
- **We make simplifications:**

1. Omitting the polarization in atomic population calculations (SJ & Laming 19a). Stokes I is OK.
2. Completely unpolarized Lyβ is supposed.
3. For the Stokes Q, the $3p_{3/2}$ state only results from the radiative excitation in the upstream region.

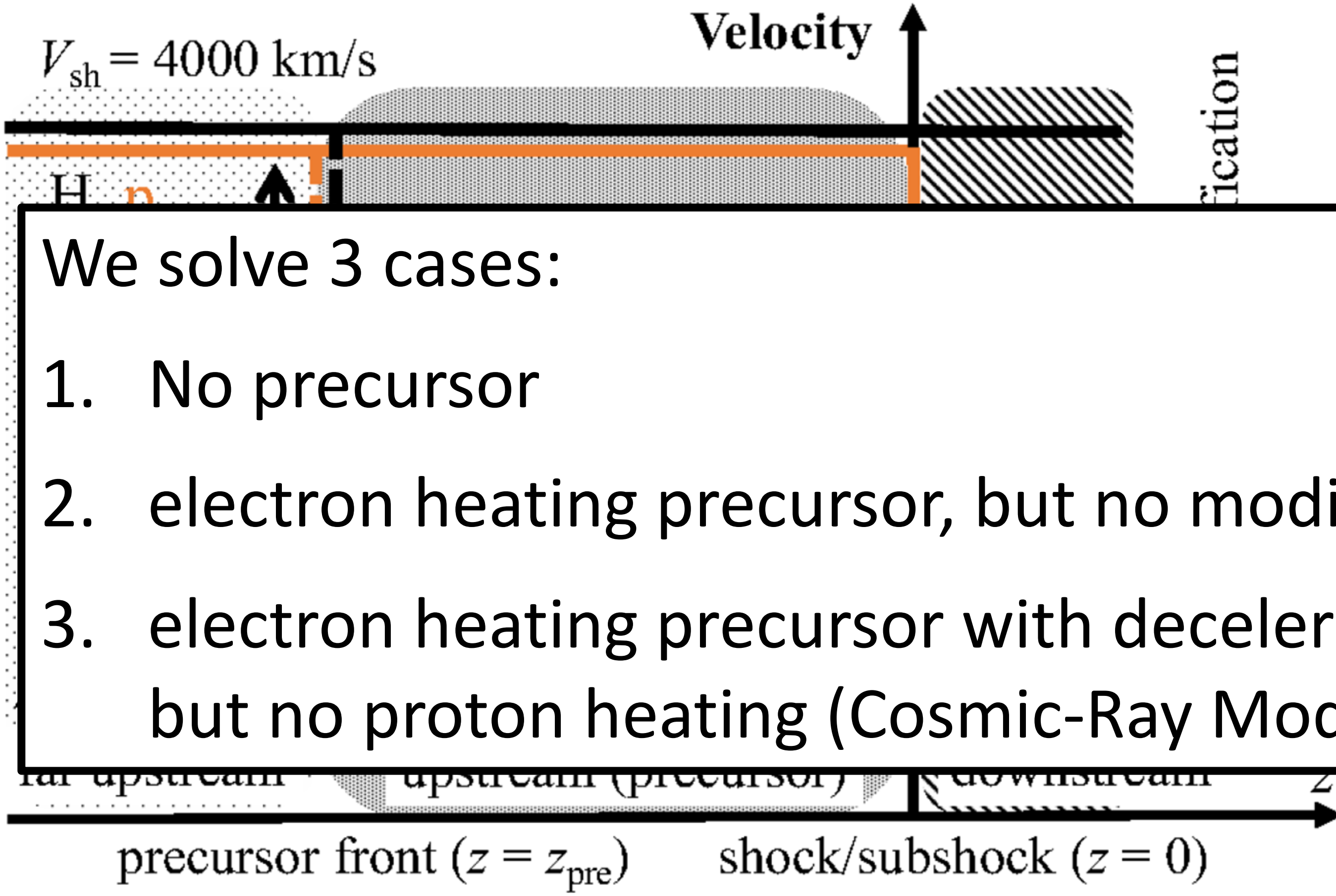
See, SJ & Laming 19b for details

Model set up for the shock



Downstream value is given by usual Rankine-Hugoniot relations with $T_e = 0.1\ T_p$ (incomplete ion-electron temperature equilibrium).

Model set up for the shock

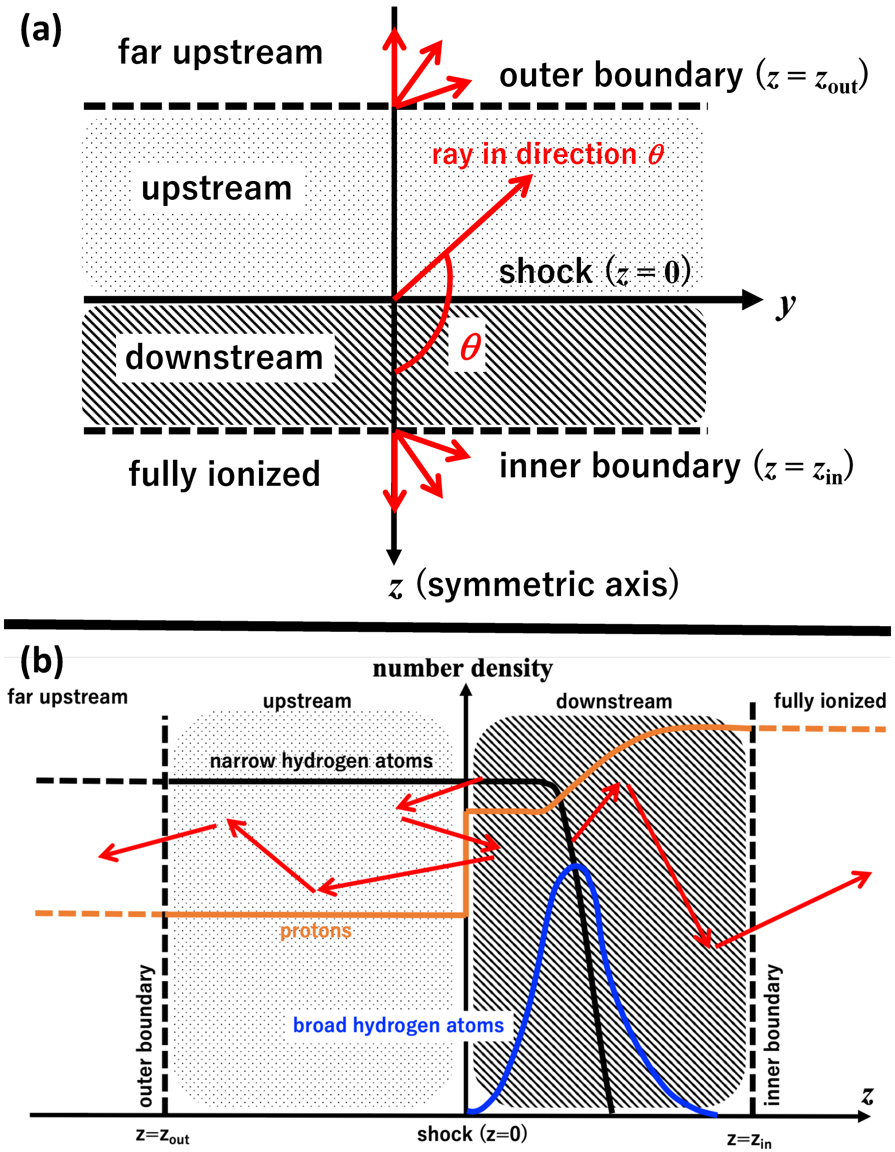


We solve 3 cases:

1. No precursor
2. electron heating precursor, but no modification
3. electron heating precursor with decelerated protons, but no proton heating (Cosmic-Ray Modified Shock)

Downstream value is given by usual Rankine-Hugoniot relations with $T_e = 0.1\ T_p$ (incomplete ion-electron temperature equilibrium).

Line Transfer Model



Parameters:

① Shock velocity V_{sh}

② Upstream number density $n_{tot,0}$

③ proton fraction χ_0

④ Upstream electron temp

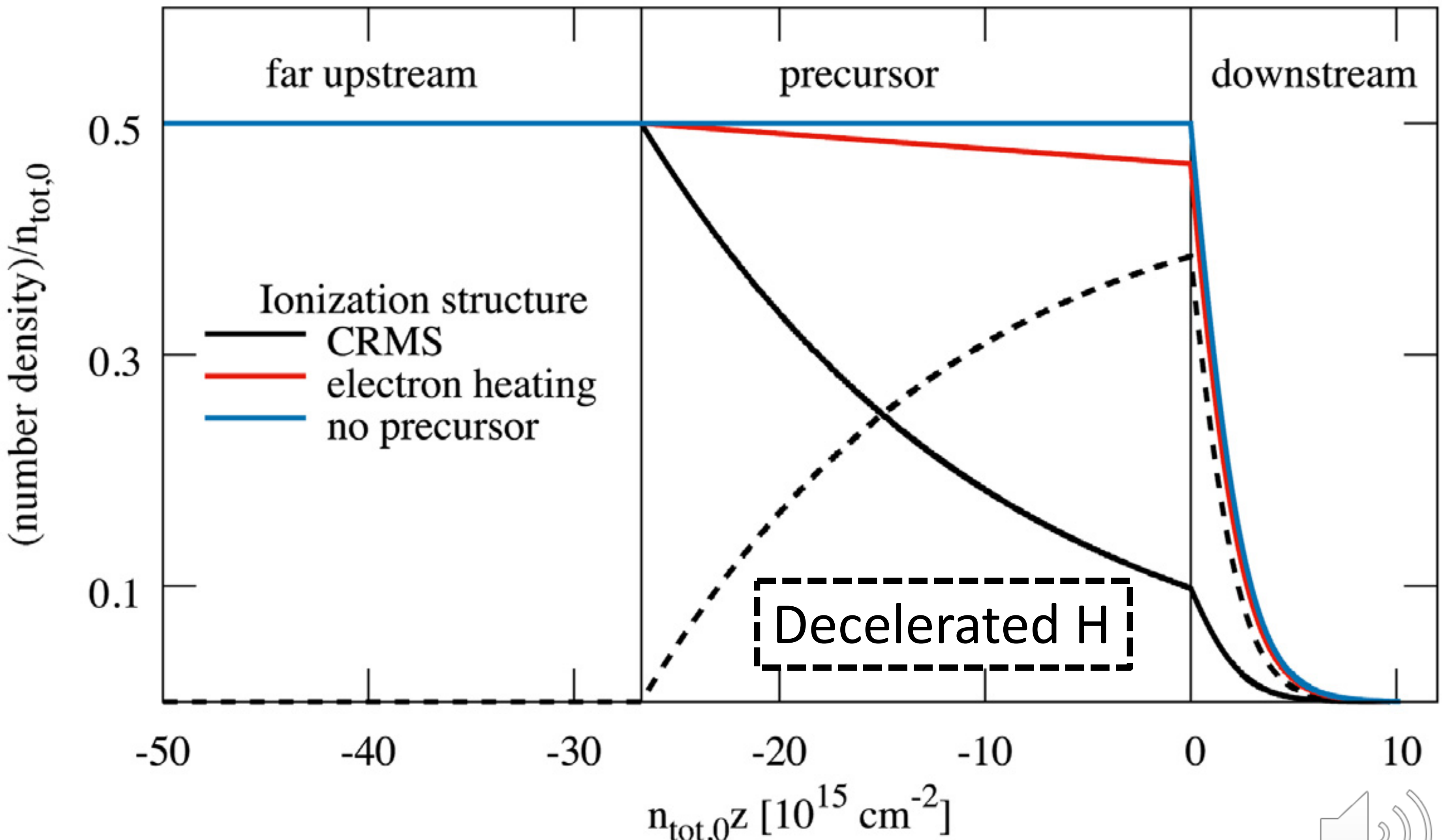
⑤ Downstream electron temp $T_e = \beta T_{down}$

Pure hydrogen plasma.

We solve the excited states up to 4f.

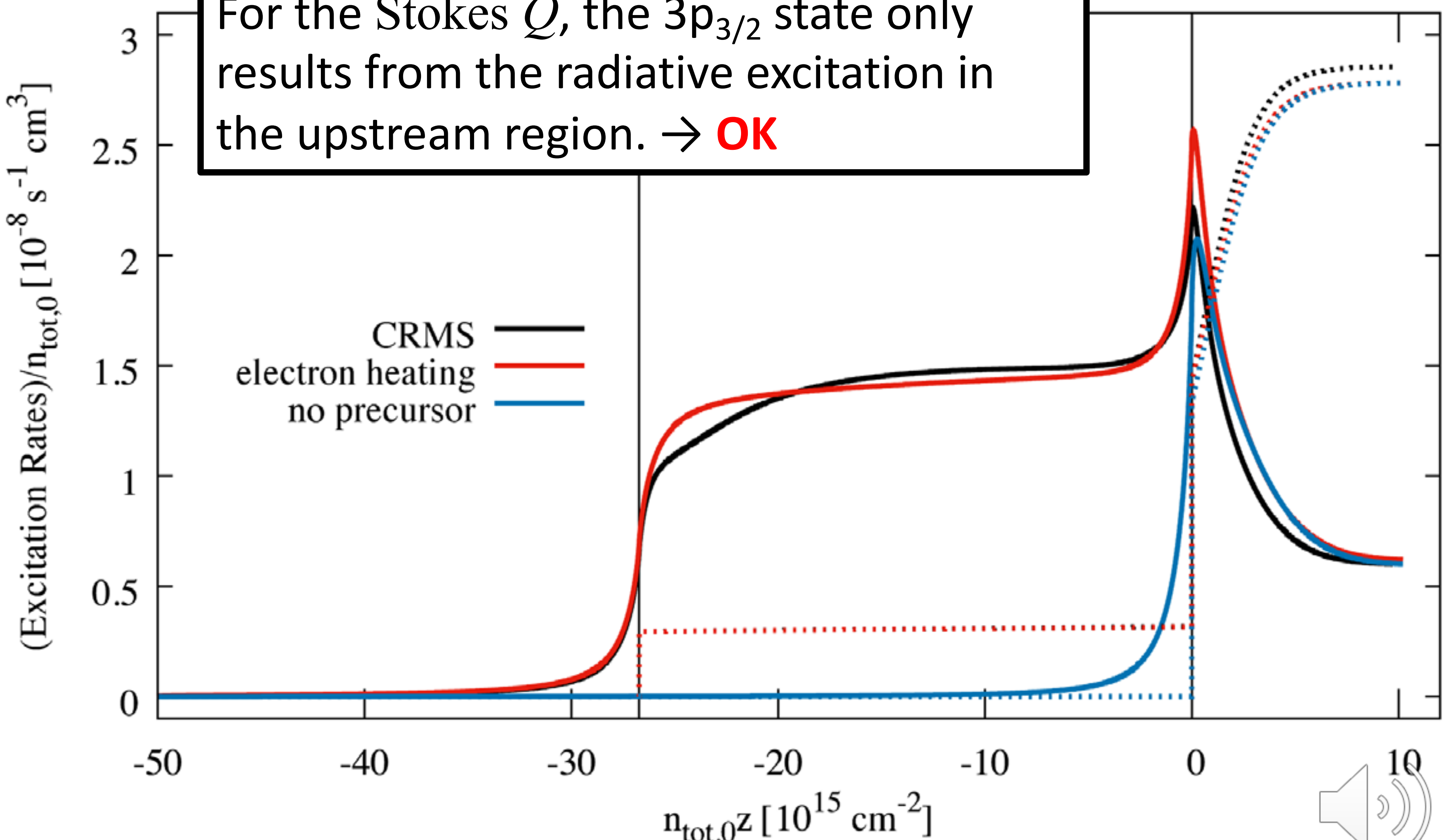
(SJ & Laming 19a)

Results: Ionization Structure of H



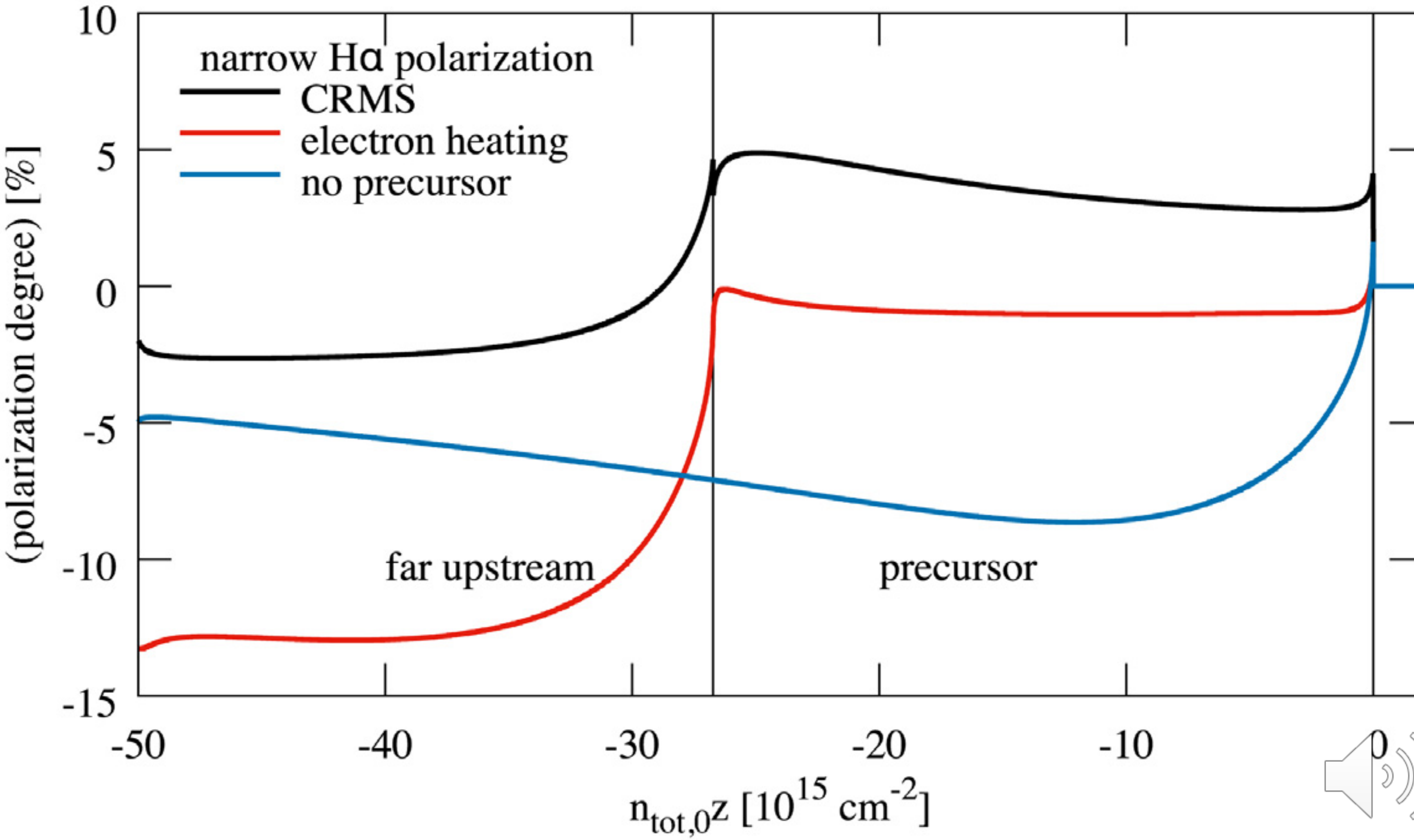
Results: Radiative vs. Collisional

For the Stokes Q, the $3p_{3/2}$ state only results from the radiative excitation in the upstream region. → **OK**



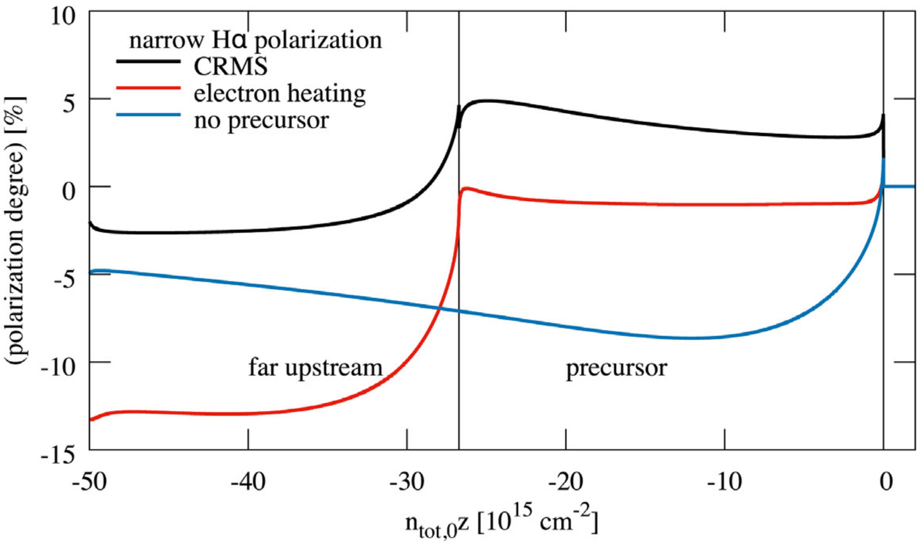
Results: Polarization of Hα

The sign of degree indicates the polarization angle (Stokes Q).

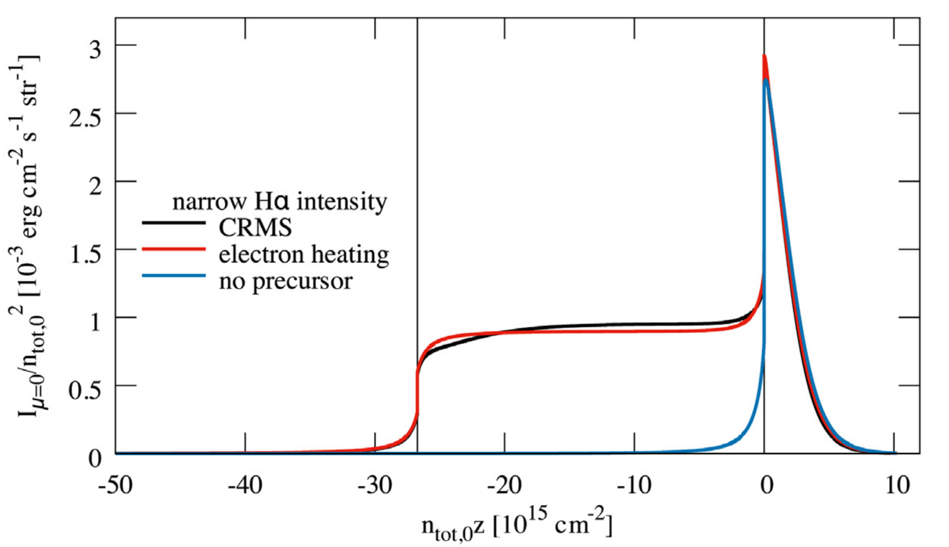


Results: Polarization of Hα

Polarization degree



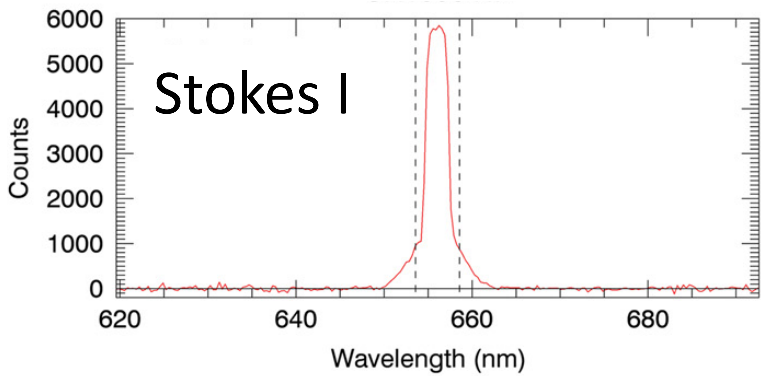
Surface brightness

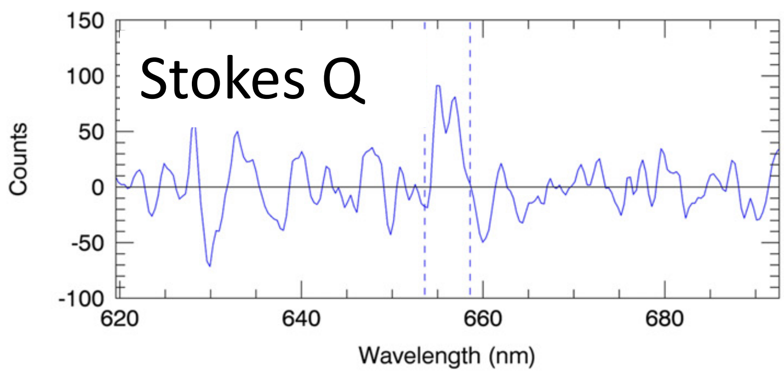


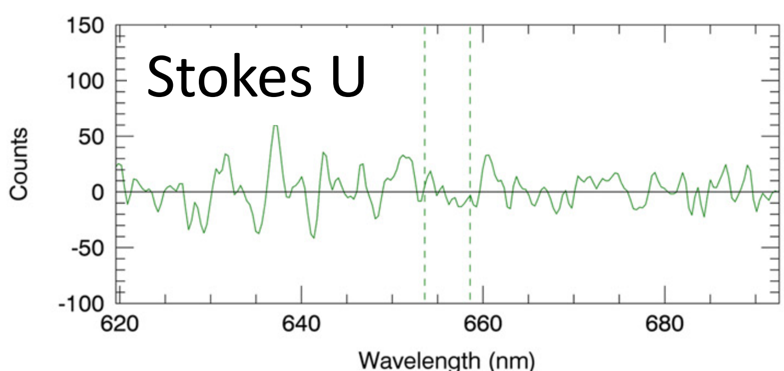
The polarization direction can respond whether the shock is modified.

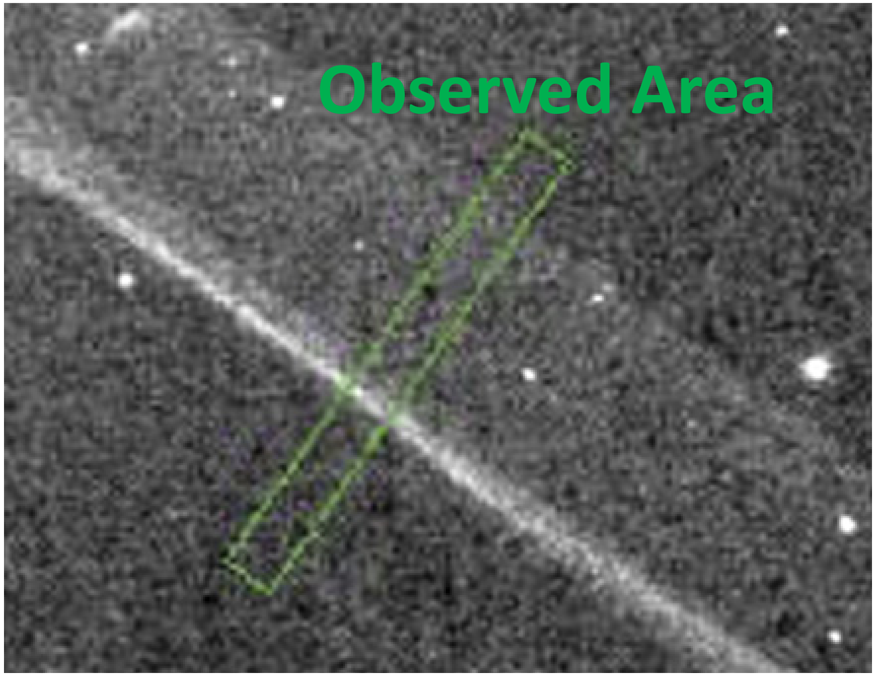
The degree of a few per cent is measurable (Sparks+ 15).

Discovery of polarized Hα emission @ bright filament of SN 1006 (Sparks+ 15)



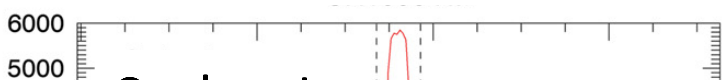


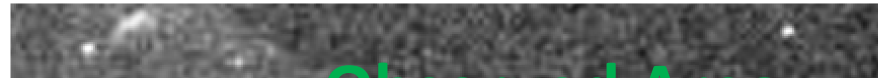




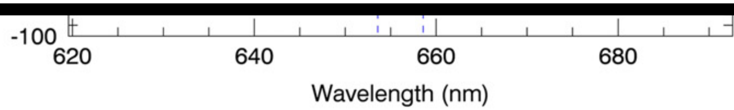
- **Linear Polarization**
- **Polarization angle：perpendicular to the shock**
- **Degree： 2.0 ± 0.4 %**

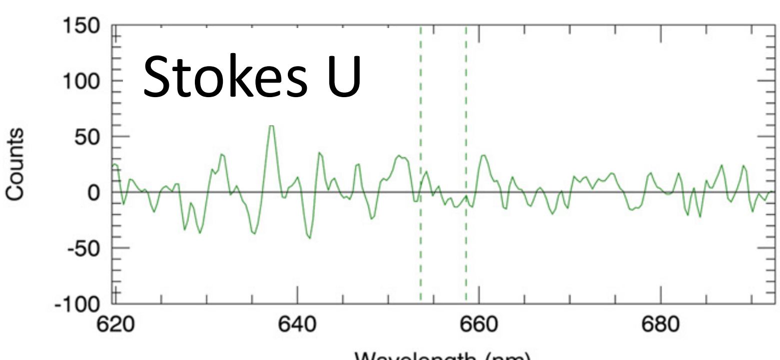
Discovery of polarized Hα emission @ bright filament of SN 1006 (Sparks+ 15)





- ✓ Our calculation is consistent with the observation.
- ✓ Polarized Hα has been reported by Sparks+15, **but this is not spatially resolved…**
- ✓ Further observations of Hα polarimetry will bring new insights to particle acceleration!





- **Linear Polarization**
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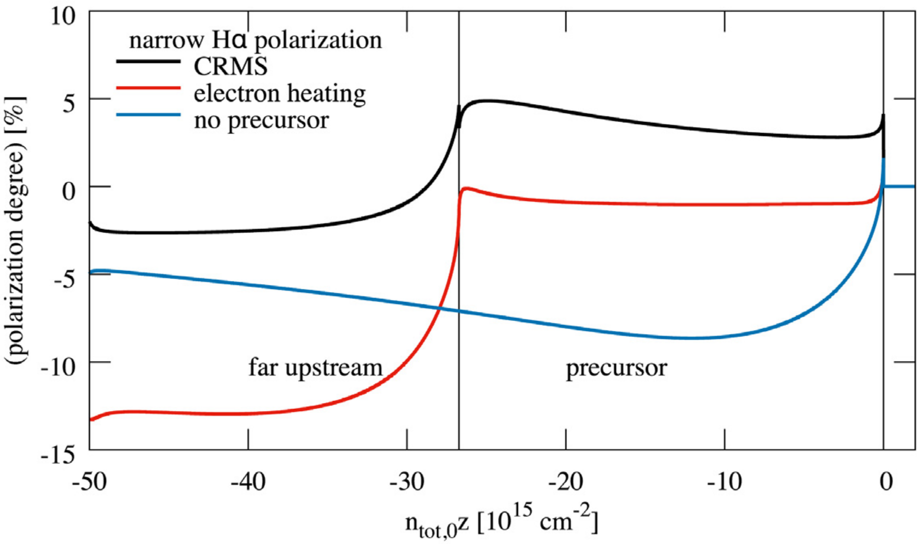
Polarization of Hα vs others

Polarization degree



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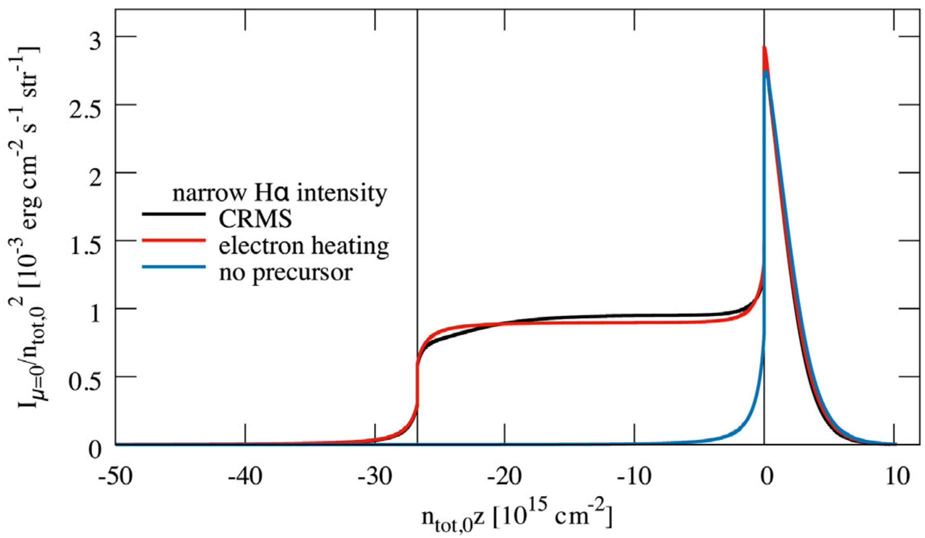
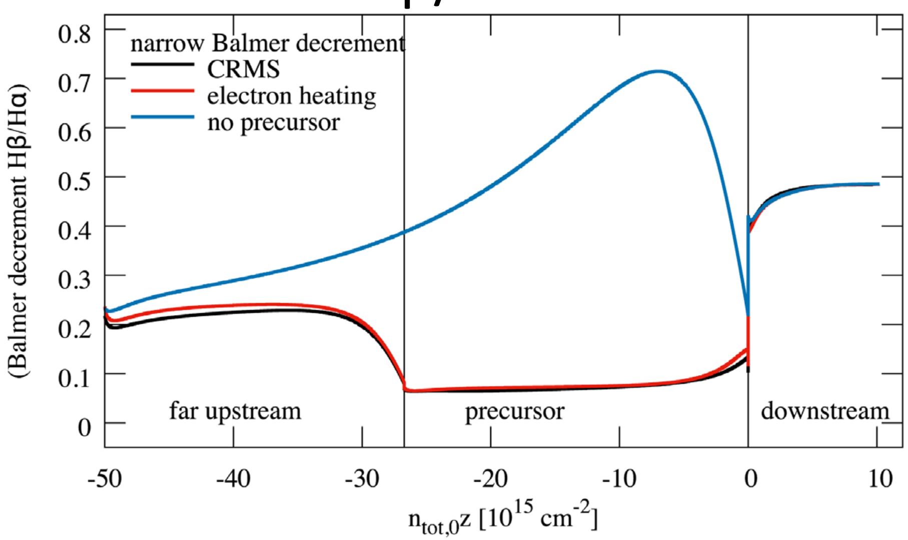


Hβ/Hα

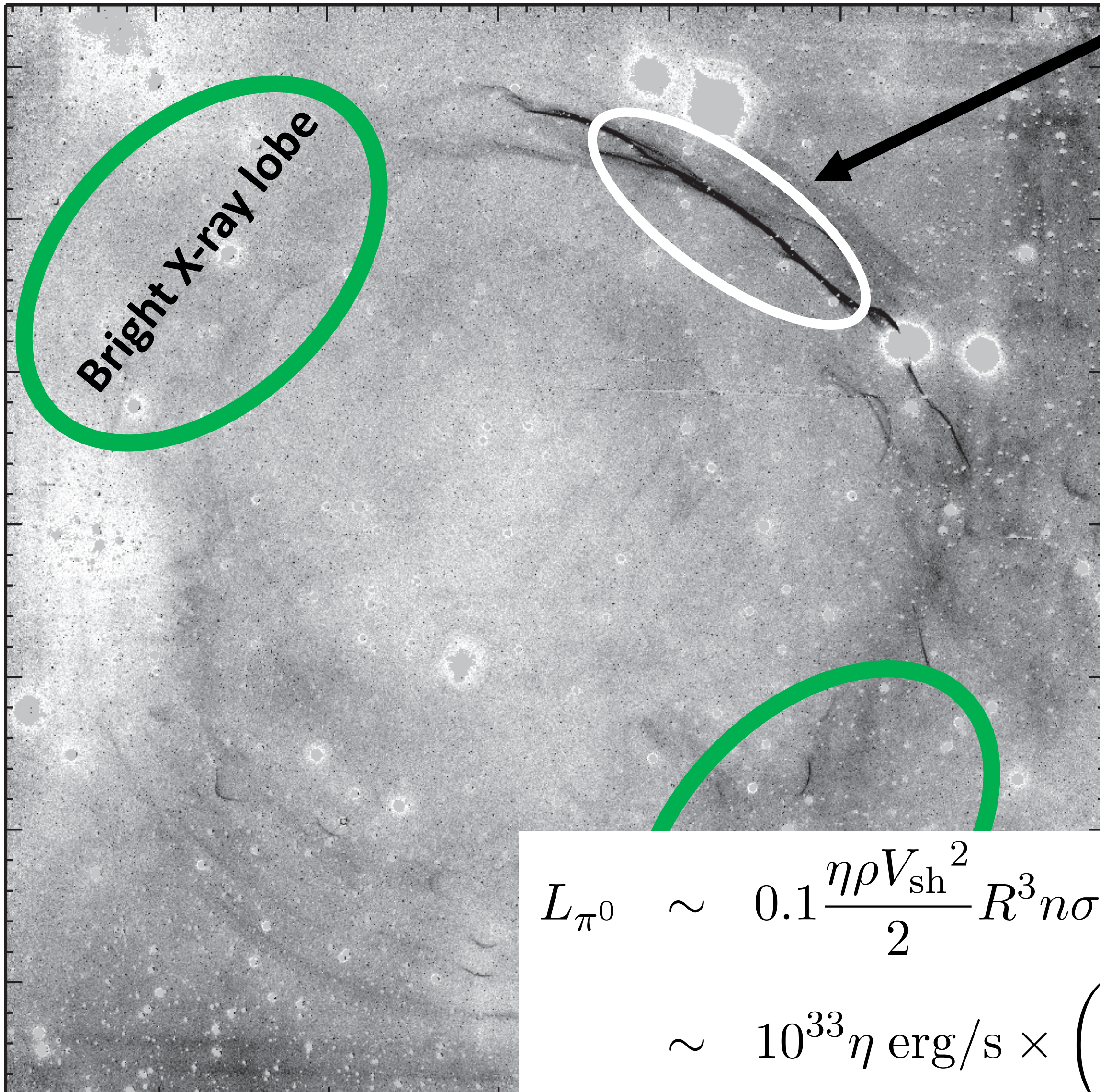


Only polarization can catch the velocity modification!

Summary

- Cosmic-Ray Modified Shocks (CRMSs) are one of essential prediction of the diffusive shock acceleration.
- We must examine a velocity modification of plasma with $\sim 10\ \%$ level around the SNR shock.
- The polarization direction of Hα responds ***sensitively*** whether the shock is modified.

SN 1006



η ~ 0.1 ?

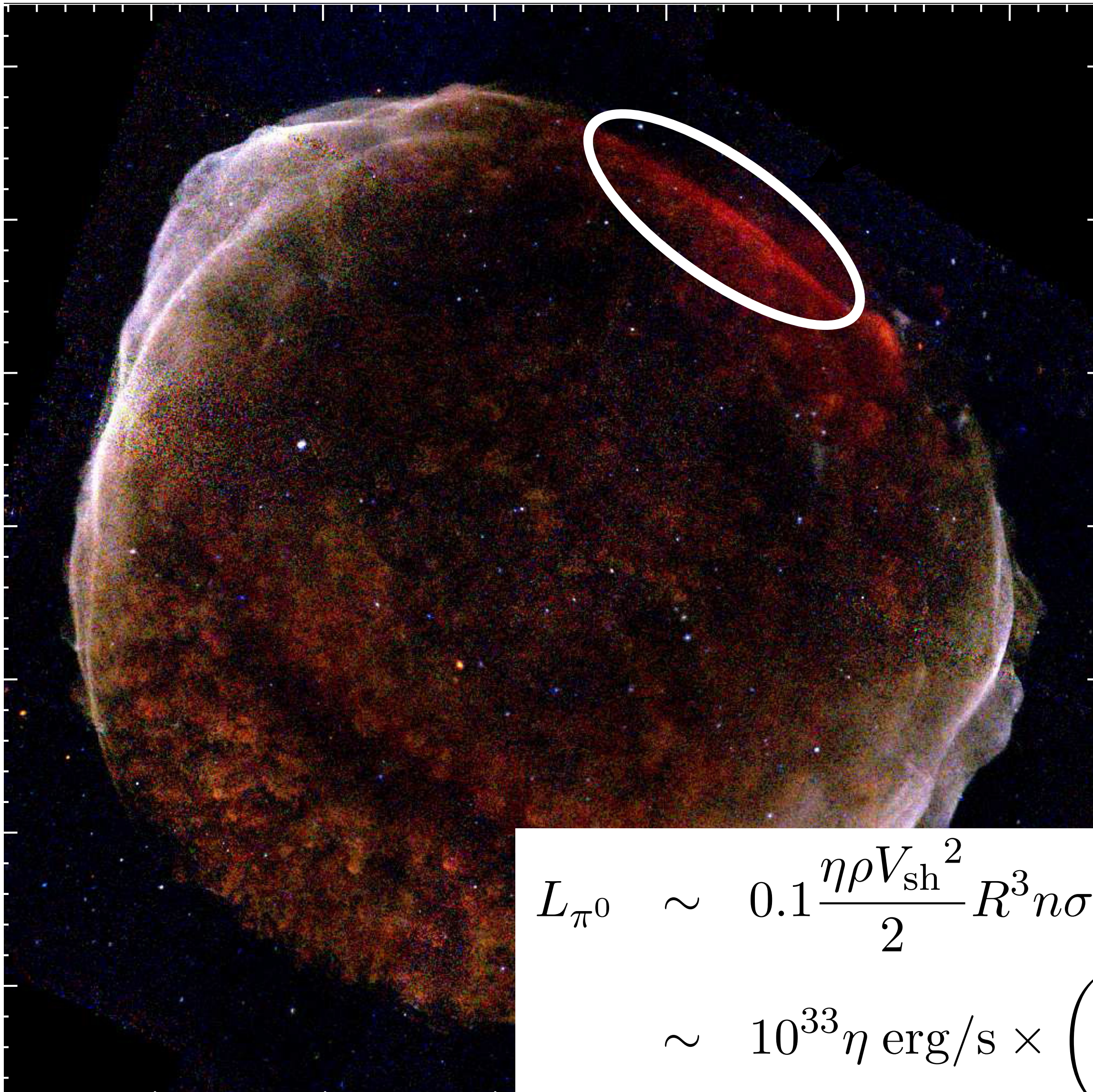
- ✓ density ~ 0.3 cm^{-3}
- ✓ V_{sh} ~ 3000 km/s @ 2.2 kpc

(Raymond+ 07; Katsuda+12)

$$L_{\pi^0} \sim 0.1 \frac{\eta \rho {V_{\rm sh}}^2}{2} R^3 n \sigma c$$

$$\sim 10^{33} \eta \ {\rm erg/s} \times \left(\frac{R}{3 \ {\rm pc}}\right)^3 \left(\frac{V_{\rm sh}}{0.01c}\right)^2 \left(\frac{n}{0.3 \ {\rm cm}^{-3}}\right)^2$$

SN 1006



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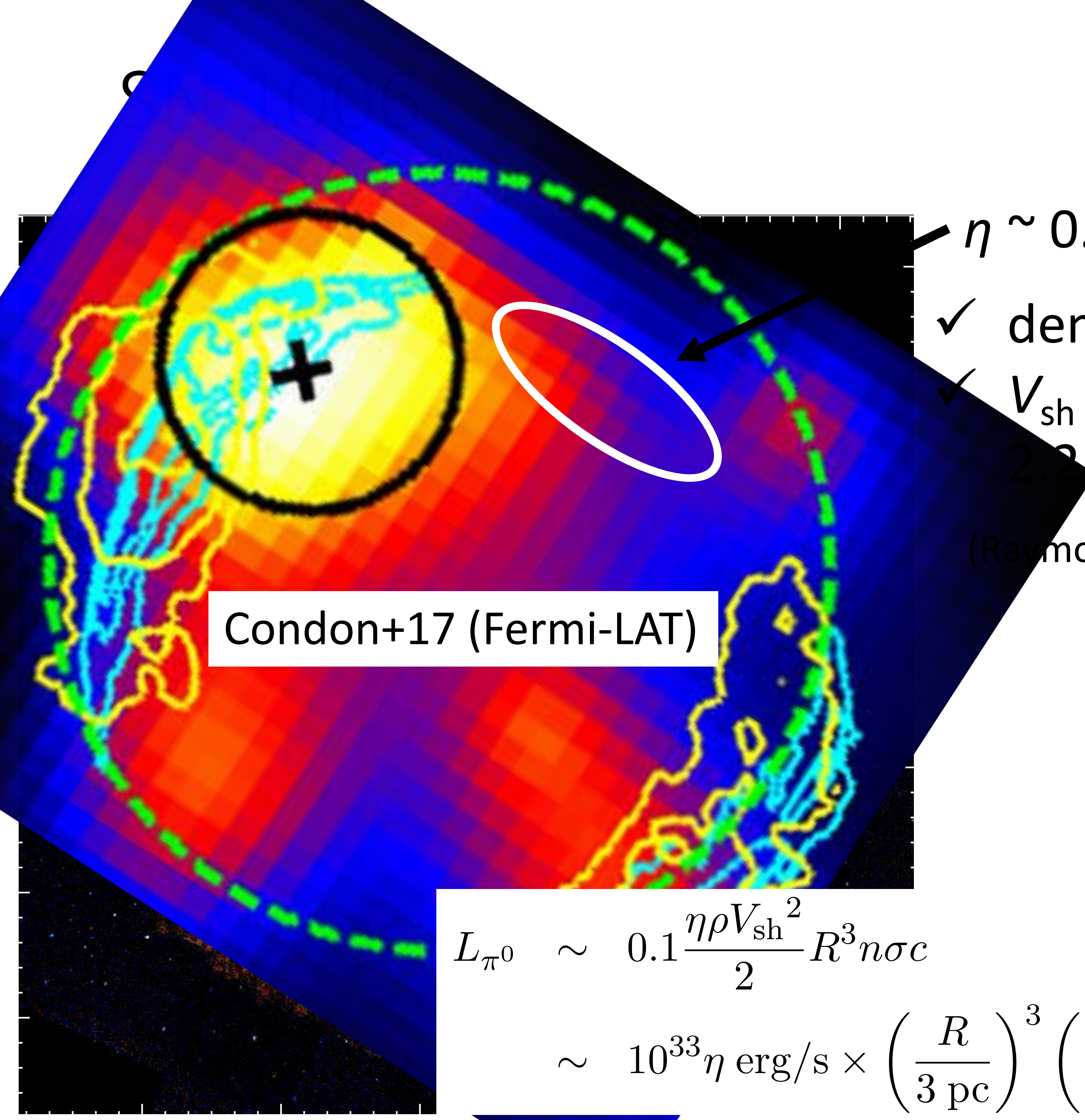

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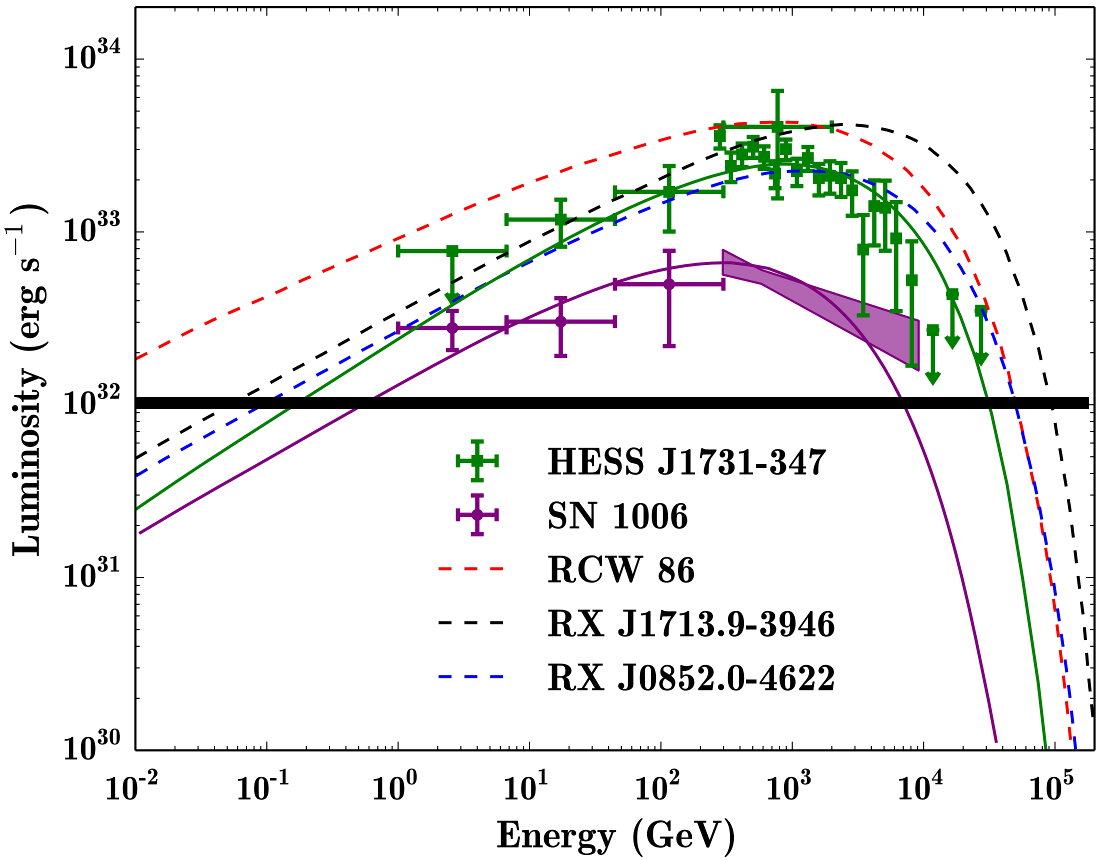
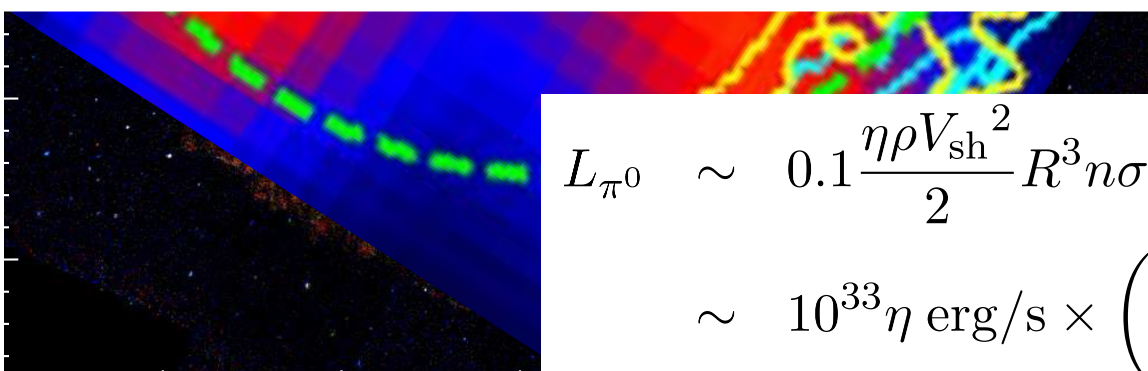
$$\sim 10^{33} \eta \ {\rm erg/s} \times \left(\frac{R}{3\ {\rm pc}}\right)^3 \left(\frac{V_{\rm sh}}{0.01c}\right)^2 \left(\frac{n}{0.3\ {\rm cm}^{-3}}\right)^2$$



- $\eta \sim 0.1$
- ✓ density ~ 0.3 cm^{-3}
- ✓ V_{sh} ~ 3000 km/s @ 2.2 kpc

(Raymond+ 07; Katsuda+12)



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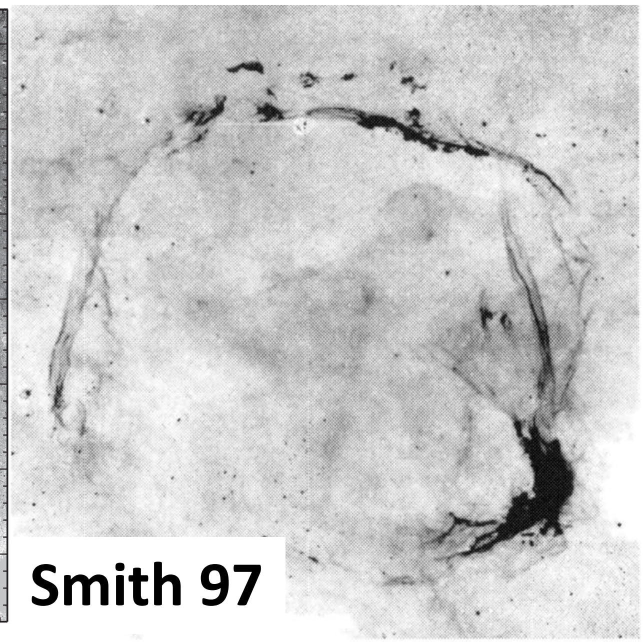
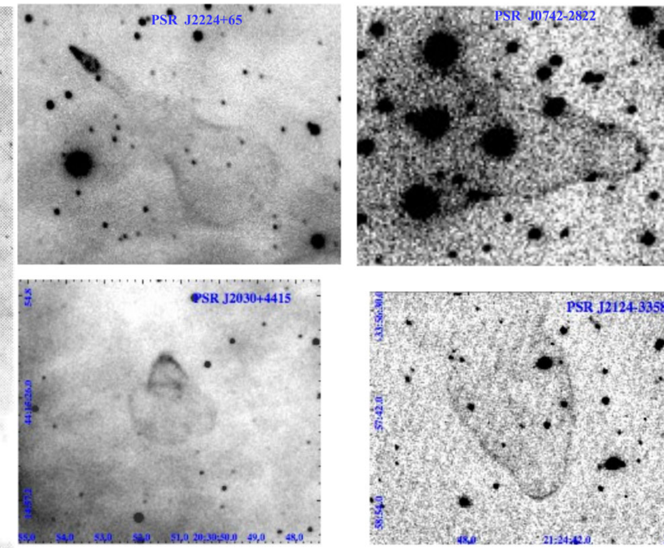
Balmer Line Emissions from Collisionless Shocks

Winkler+14



Smith 97



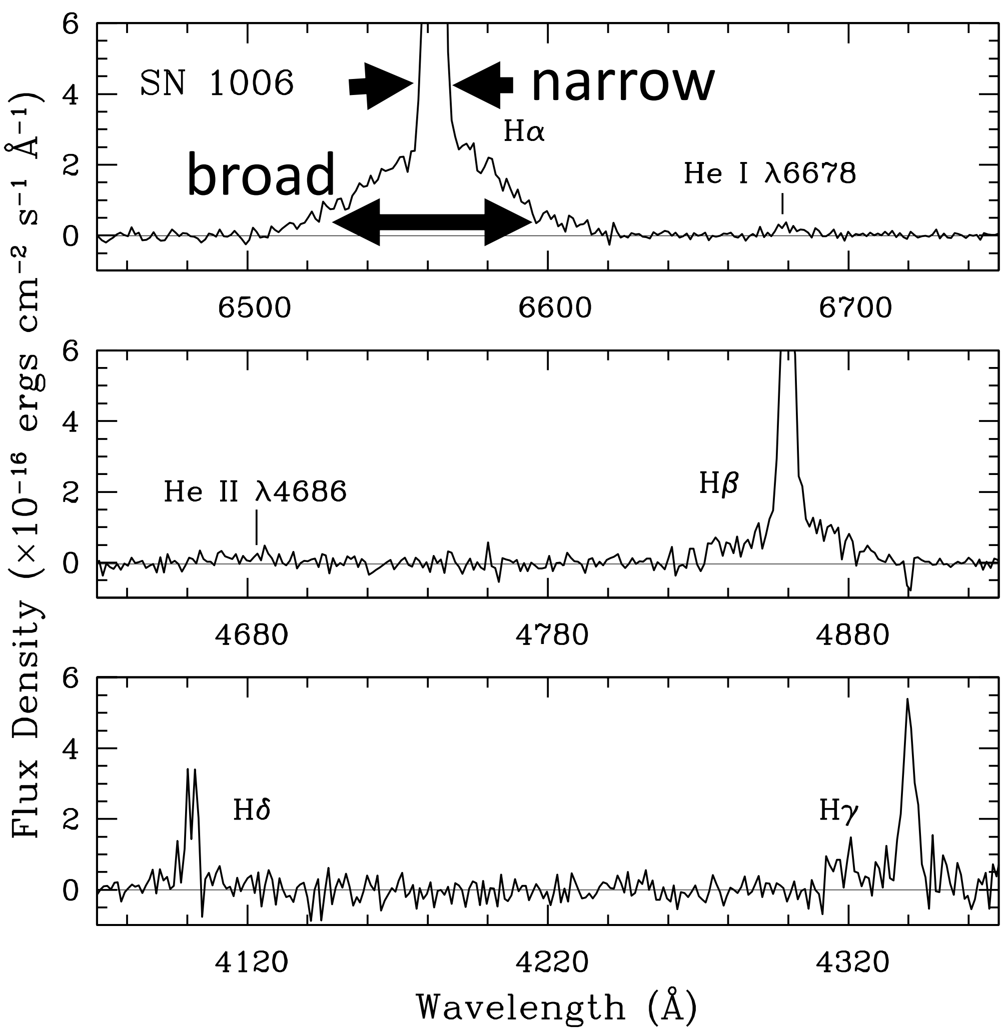
Figures from Morlino+15

Supernova Remnants (SNRs)

Pulsar Wind Nebulae

Balmer line emissions (especially Hα) are ubiquitously seen in collisionless shocks propagating into the ISM.

Balmer Line Emissions from Collisionless Shocks



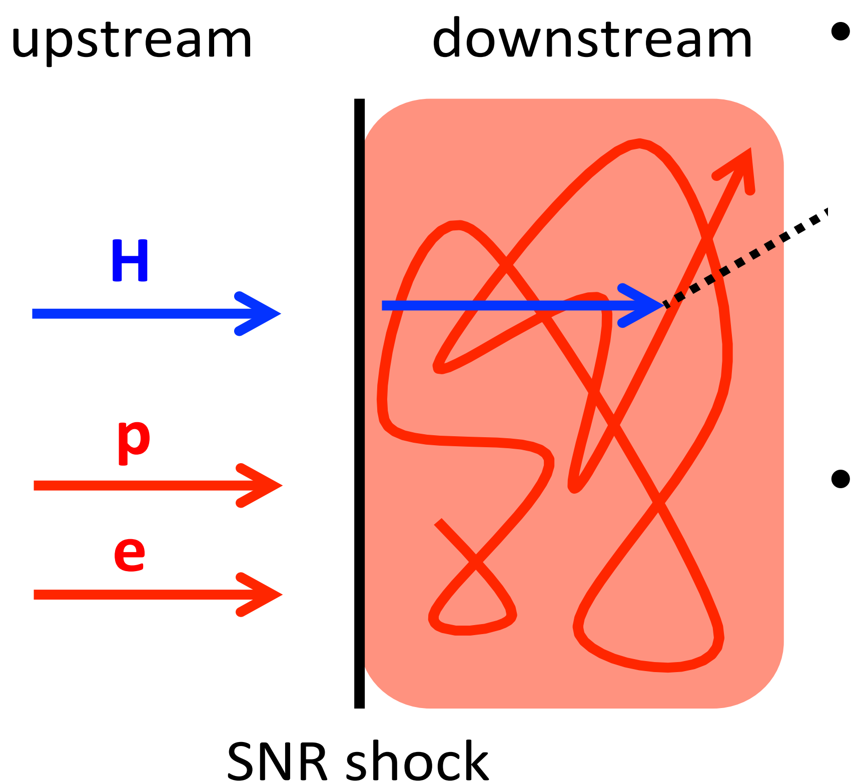
Spectrum of Balmer line Emissions

(Ghavamian+02, for SNR SN 1006)

<u>The lines consist of **“narrow”** and **”broad”** components.</u>

Balmer Line Emissions from Collisionless Shocks

✓ **Emission Mechanism** (e.g. Chevalier+80)



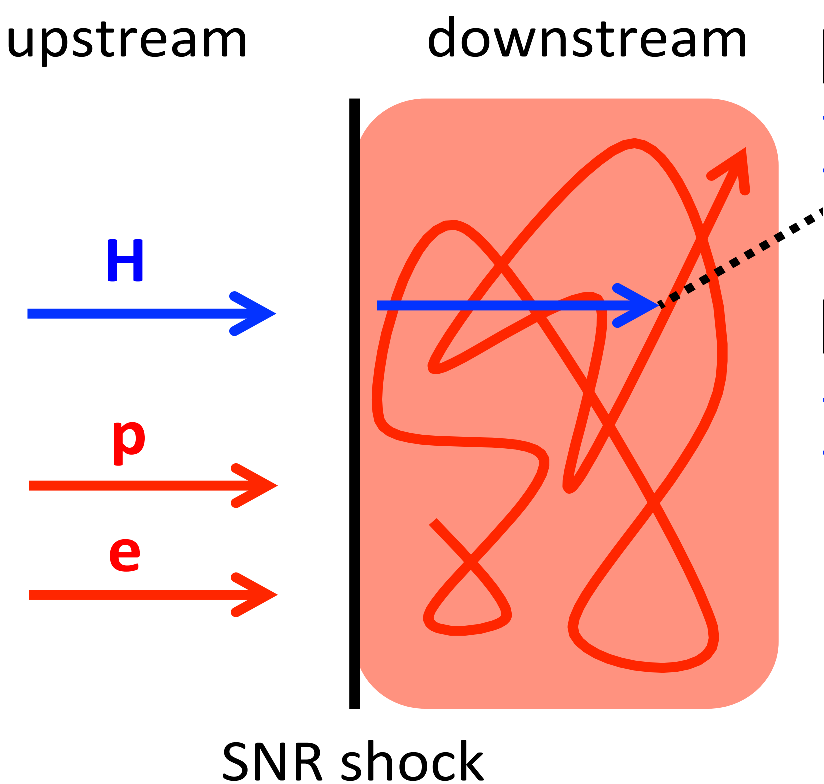
- The collisionless shock is formed by the interaction between **charged particles and plasma waves.**
- **The neutral particles (e.g. hydrogen atoms) are not affected.**

Charged particles → shock heating

Hydrogen atoms → no dissipation

Balmer Line Emissions from Collisionless Shocks

✓ **Emission Mechanism** (e.g. Chevalier+80)



Charged particles → shock heating

Hydrogen atoms → no dissipation

☐ **Collisional Excitation**

$$\mathrm{H} + \mathrm{p}\ (\mathrm{or}\ \mathrm{e}) \longrightarrow \underline{\mathrm{H}^*} + \mathrm{p}\ (\mathrm{or}\ \mathrm{e})$$

Emits "narrow" comp.

☐ **Charge Transfer**

$$\mathrm{H} + \mathrm{p} \longrightarrow \mathrm{p} + \underline{\mathrm{H}^*}$$

Emits "broad" comp.

The "broad" component reflects the downstream temperature of protons.