超新星残骸衝撃波でのライマン輝線捕獲を考慮した水素原子輝線放射モデルについて

（On modeling of hydrogen line emission from supernova remnant shocks: the effect of Lyman line trapping）

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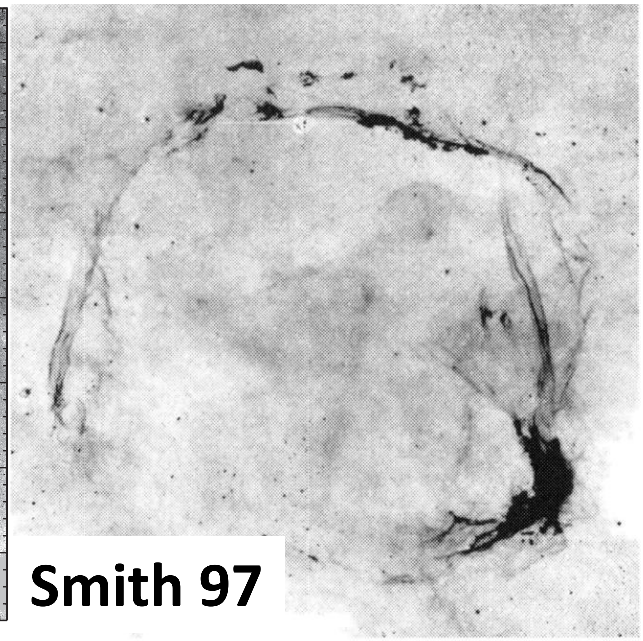
Summary of this work

- We study the hydrogen line emission from SNR shocks including the effects of Lyman line trapping.
- We find that the $\mathrm{H}\alpha$ emission can be mildly absorbed by hydrogen atoms in the 2s state at the realistic SNRs.
- Our calculation will explain **the anomalous width of $\mathrm{H}\alpha$ line with no cosmic-ray**.

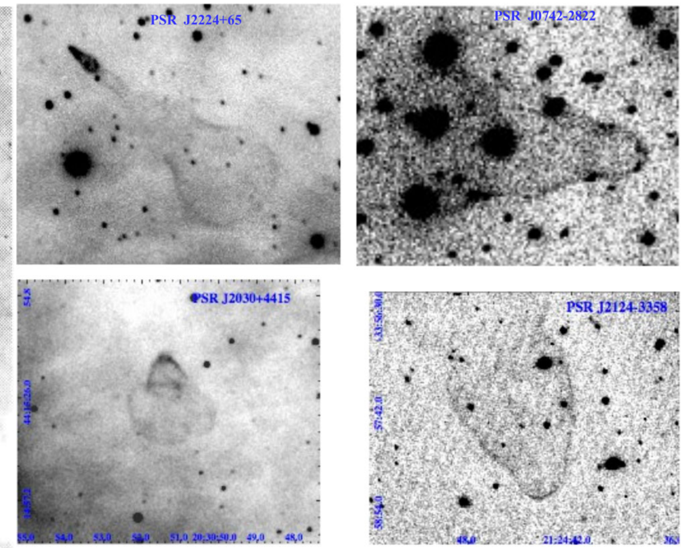
Balmer Line Emissions from Collisionless Shocks

Winkler+14



Smith 97

Supernova Remnants (SNRs)



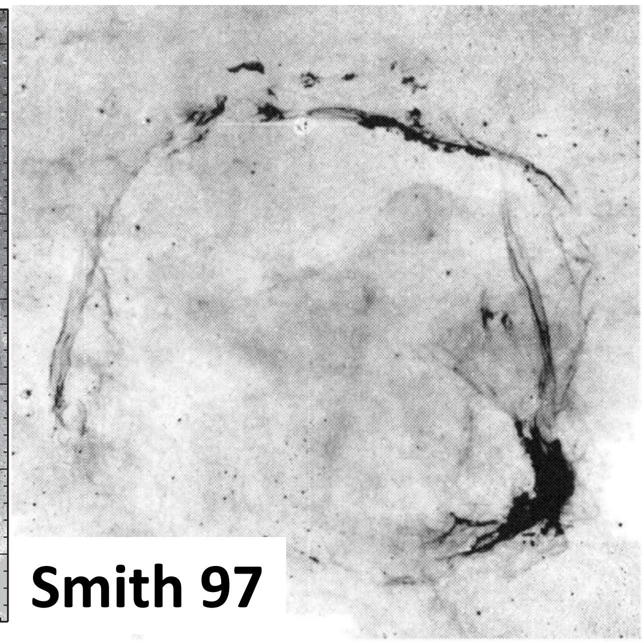
Figures from Morlino+15

Pulsar Wind Nebulae

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

Balmer Line Emissions from Collisionless Shocks

Winkler+14



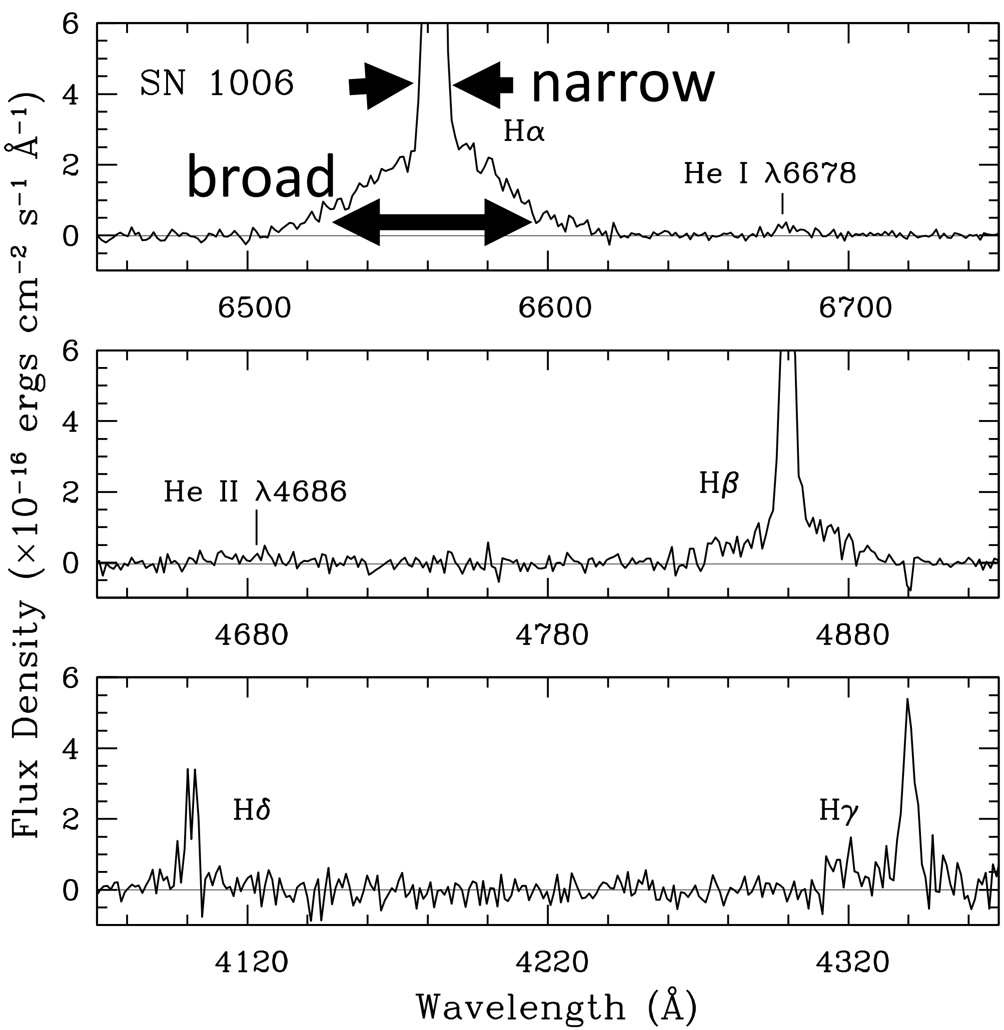
Smith 97

Supernova Remnants (SNRs)

Hereafter, we focus on the SNRs. (although our study is applicable to other objects)

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

Balmer Line Emissions from Collisionless Shocks

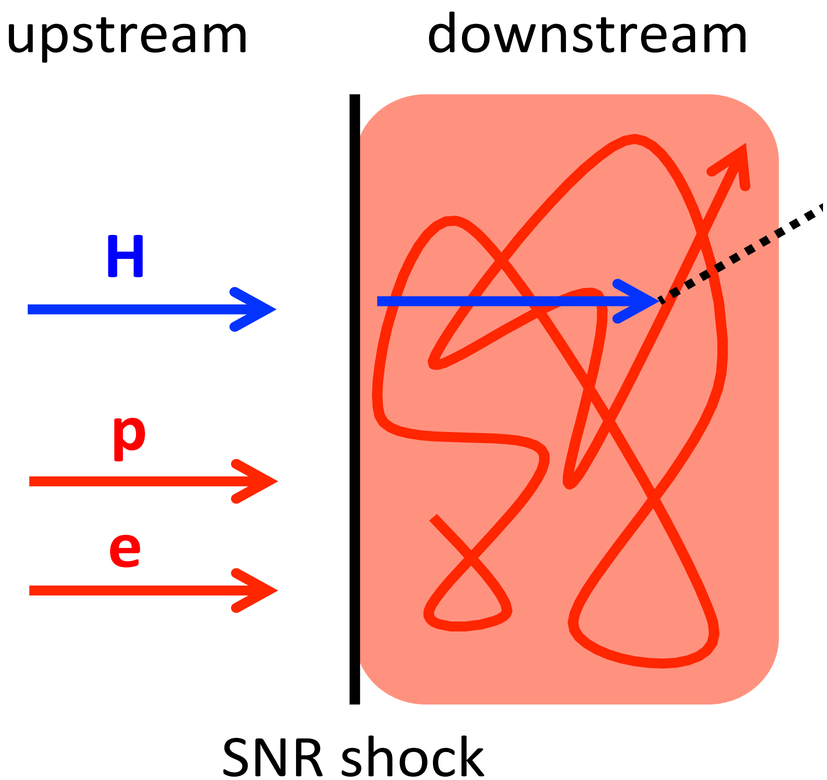


Spectrum of Balmer line Emissions (Ghavamian+02, for SNR SN 1006)

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

Balmer Line Emissions from Collisionless Shocks

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



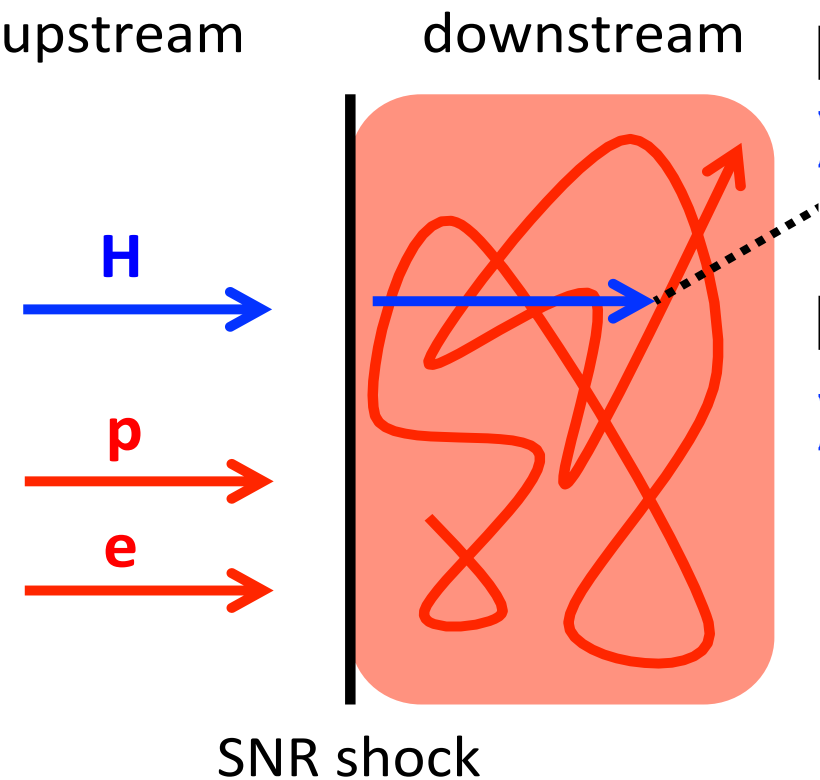
Charged particles → shock heating

Hydrogen atoms → no dissipation

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

Balmer Line Emissions from Collisionless Shocks

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



☐ **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**

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

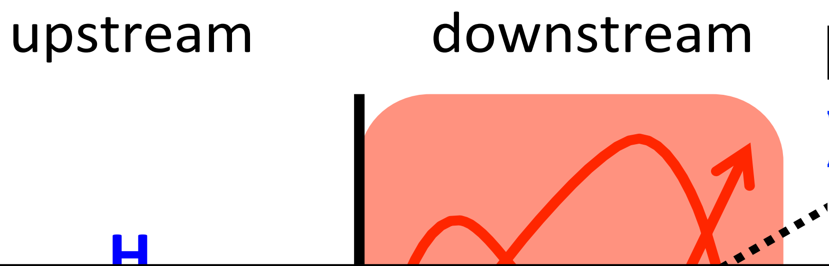
Emits "broad" comp.

Charged particles → shock heating

Hydrogen atoms → no dissipation

Balmer Line Emissions from Collisionless Shocks

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



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

Emits "narrow" comp.

✓ The width of <u>**"narrow"**</u> reflects <u>**the upstream temperature of hydrogen atoms.**</u>

✓ The width of **"broad"** reflects **the downstream proton temperature**.

The width of narrow is “too broad”

SNR	Shock velocity (km s^{-1})	Narrow component *FWHM* (km s^{-1})
Cygnus Loop	300–400	28–35
RCW 86 SW	580–660	32 ± 2
RCW 86 W	580–660	32 ± 5
RCW 86 NW	580–660	40 ± 2
Kepler D49 & D50	2000–2500	42 ± 3
0505-67.9	440–880	32–43
0548-70.4	700–950	32–58
0519-69.0	1100–1500	39–42
0509-67.5	–	25–31
Tycho	1940–2300	44 ± 4
SN 1006	2890 ± 100	21 ± 3

Sollerman+2003

- ✓ The width of narrow component is in the **30-50 km/s range (equivalently, 2.5-5.6 eV).**

* 1 eV ←→ 21 km/s

- ✓ If these were the ISM equilibrium temperatures, then **all of hydrogen atoms would be completely ionized!**

The width of narrow is “too broad”

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Sollerman+2003

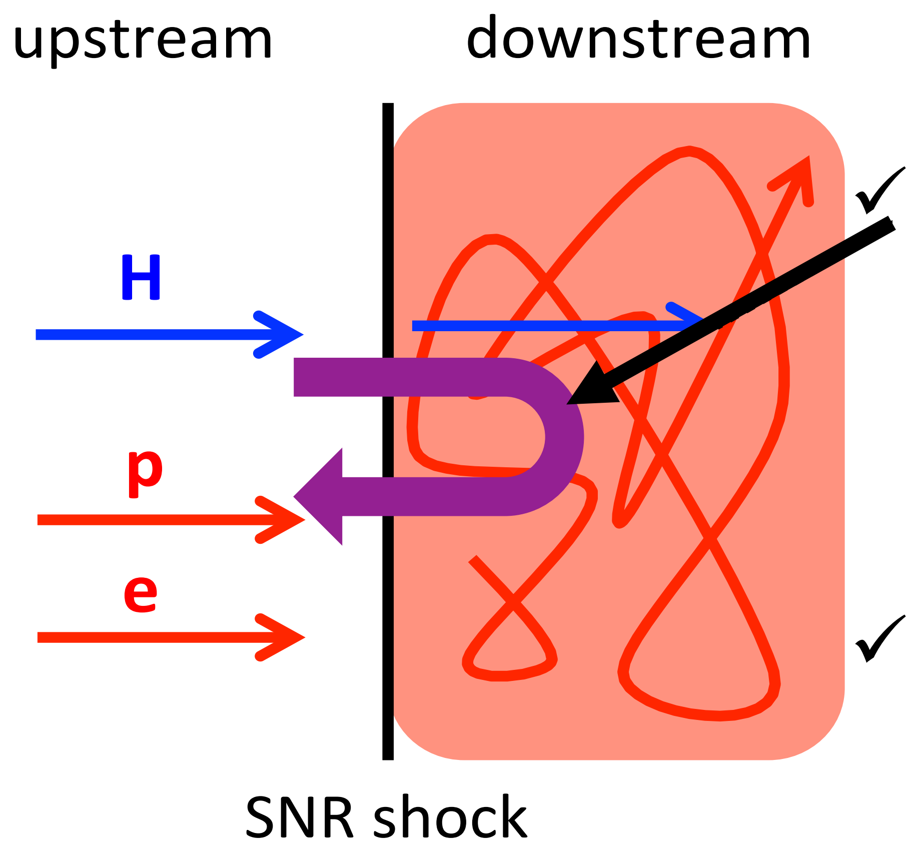
✓ The width of narrow component is in the **<u>30-50 km/s range (equivalently, 2.5-5.6 eV).</u>**

* 1 eV ←→ 21 km/s

<u>ionized!</u>

✓ The anomalous width of narrow component implies **<u>a pre-shock heating of the upstream hydrogen atoms</u>** at the vicinity of the shock (e.g. Smith+94).

Possible upstream heating: (i) neutral precursor



Charged particles → shock heating

Hydrogen atoms → no dissipation

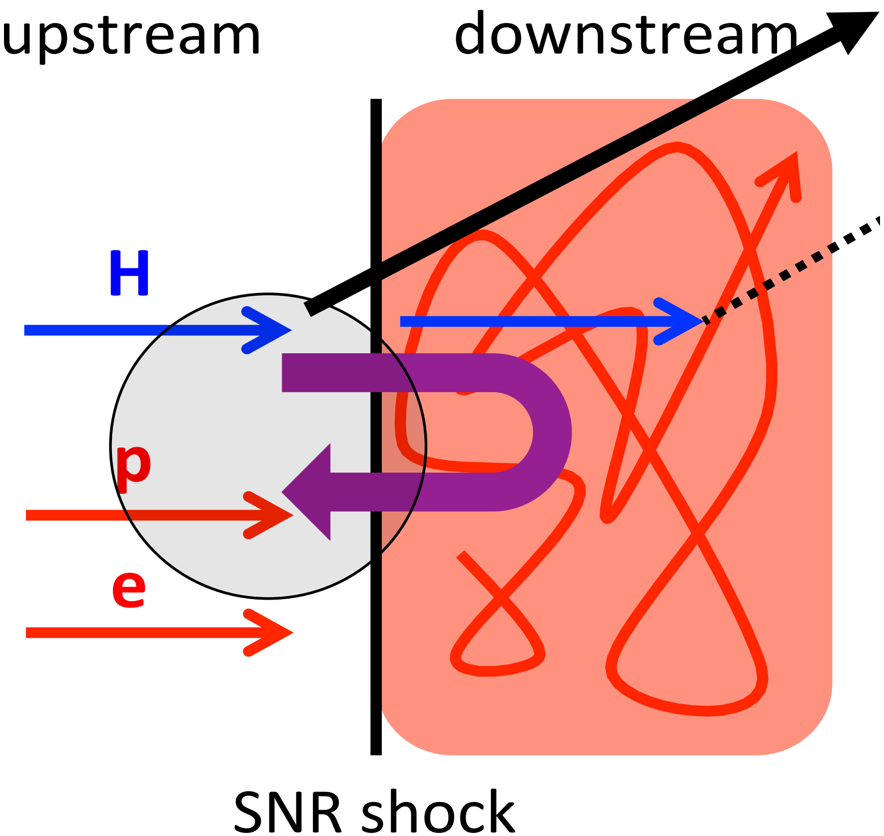
- **Charge Transfer**

$$H + p \rightarrow p + \underline{H^*}$$

✓ A part of downstream hydrogen atoms **can be back to the upstream region** (e.g. Smith+94).

✓ The leaking hydrogen **<u>can deposit some energy flux to the upstream fluid</u>** via several atomic/plasma processes.

Possible upstream heating: (i) neutral precursor



Charged particles → shock heating

Hydrogen atoms → no dissipation

- **Ionization of fast neutrals**

$$H + p/e \rightarrow \underline{p + e} + p/e$$

heat up

- **Charge Transfer**

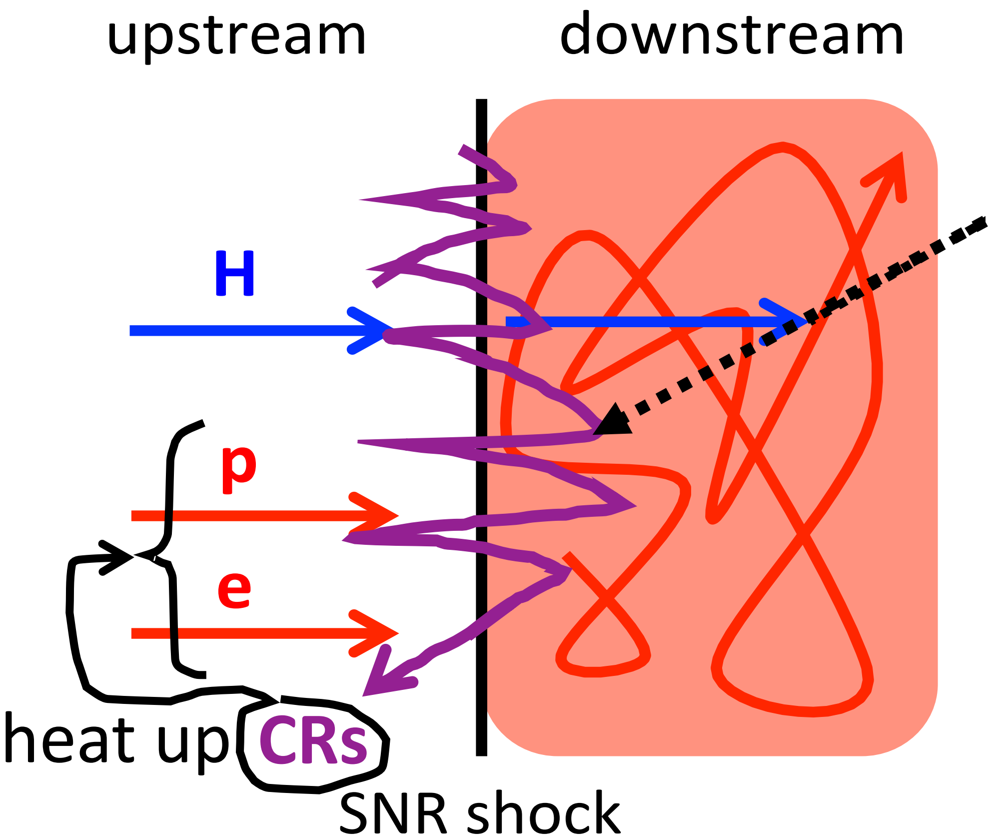
$$H + p \rightarrow p + \underline{H^*}$$

Emits the anomalous narrow component with the width of 30-50 km/s

Possible upstream heating: (i) neutral precursor

- ✓ Smith+94 doubted that there is enough time for the heating until the fast protons swept up by the shock again.
- ✓ The neutral precursor scenario has been studied in the literatures: e.g. Blasi+12; Ohira 12, 13, 14, 16; Morlino+12, 13.
- ✓ Recent hybrid simulations suggested **no significant broadening** (Ohira 16).

Possible upstream heating:
(ii) cosmic-ray precursor



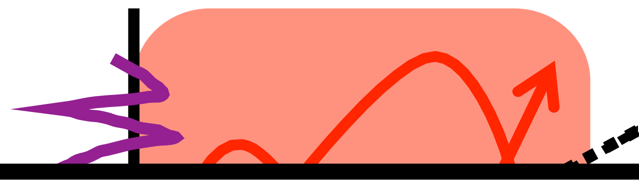
Charged particles → shock heating

Hydrogen atoms → no dissipation

The CRs accelerating via DSA mechanism can also affect the upstream plasma (or can generate Alfvenic turbulence in the upstream region).

The formation of the anomalous narrow component is similar to the neutral precursor case.

Possible upstream heating: (ii) cosmic-ray precursor

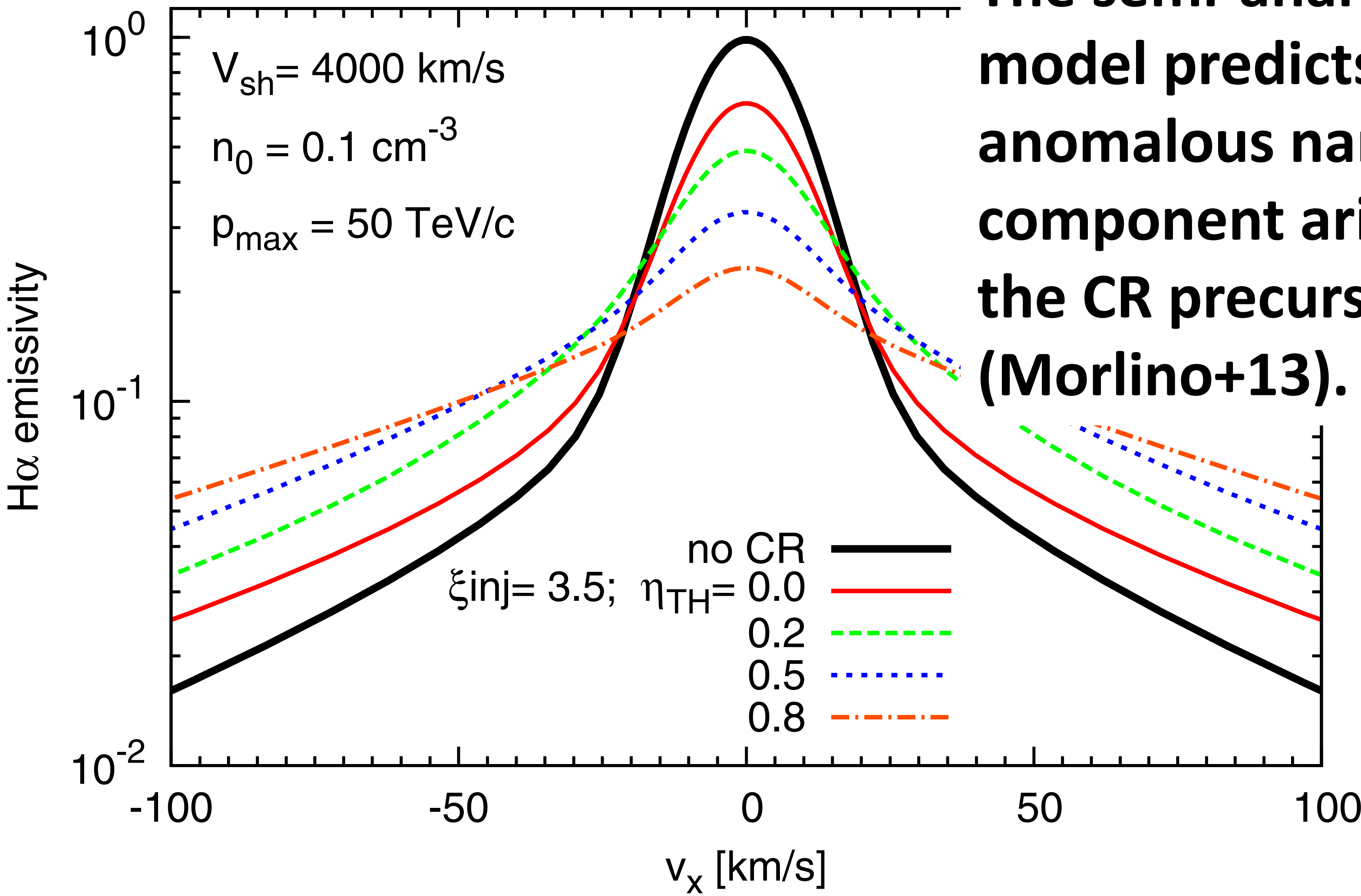


The CRs accelerating via DSA mechanism can also affect

- ✓ Morlino+13 provided the Hα emission model based on this CR-precursor scenario.
- ✓ **Their model is now accepted as ”the standard model”** of the Hα emission from the SNR shocks.

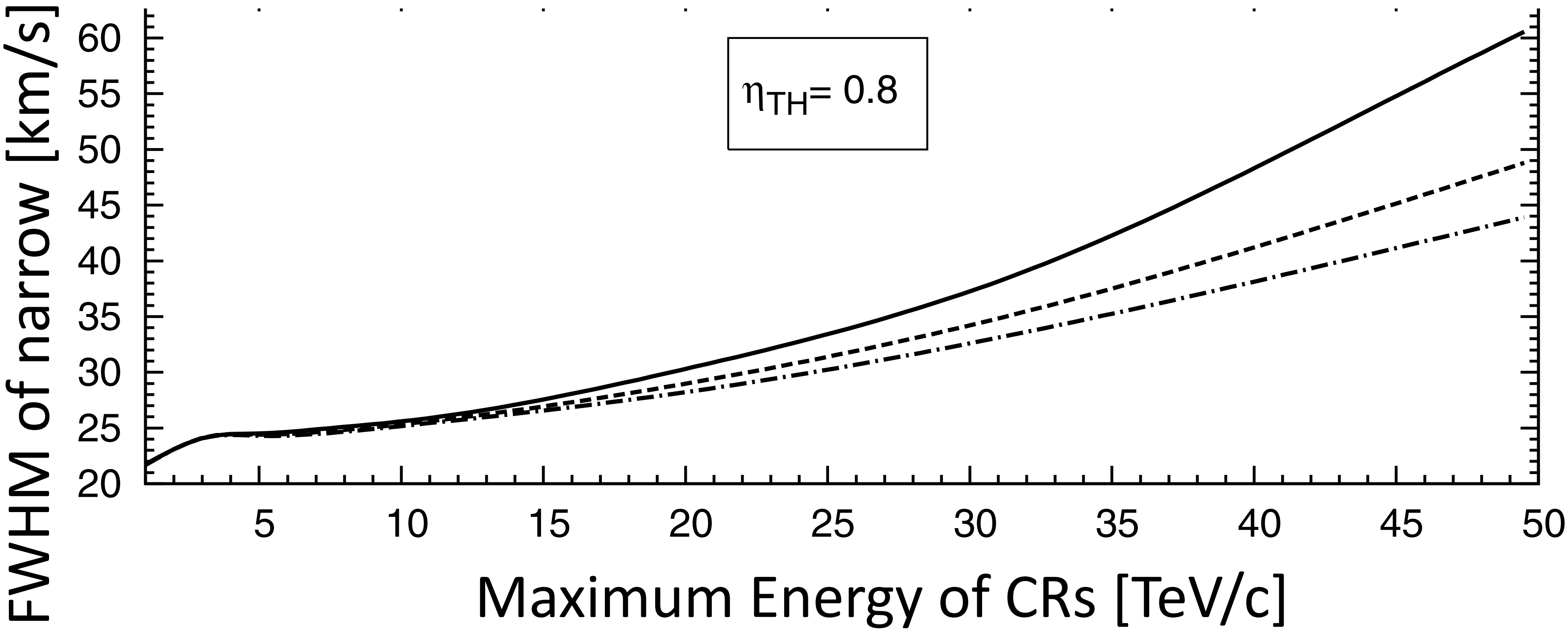
Hydrogen atoms → no dissipation

Possible upstream heating: (ii) cosmic-ray precursor



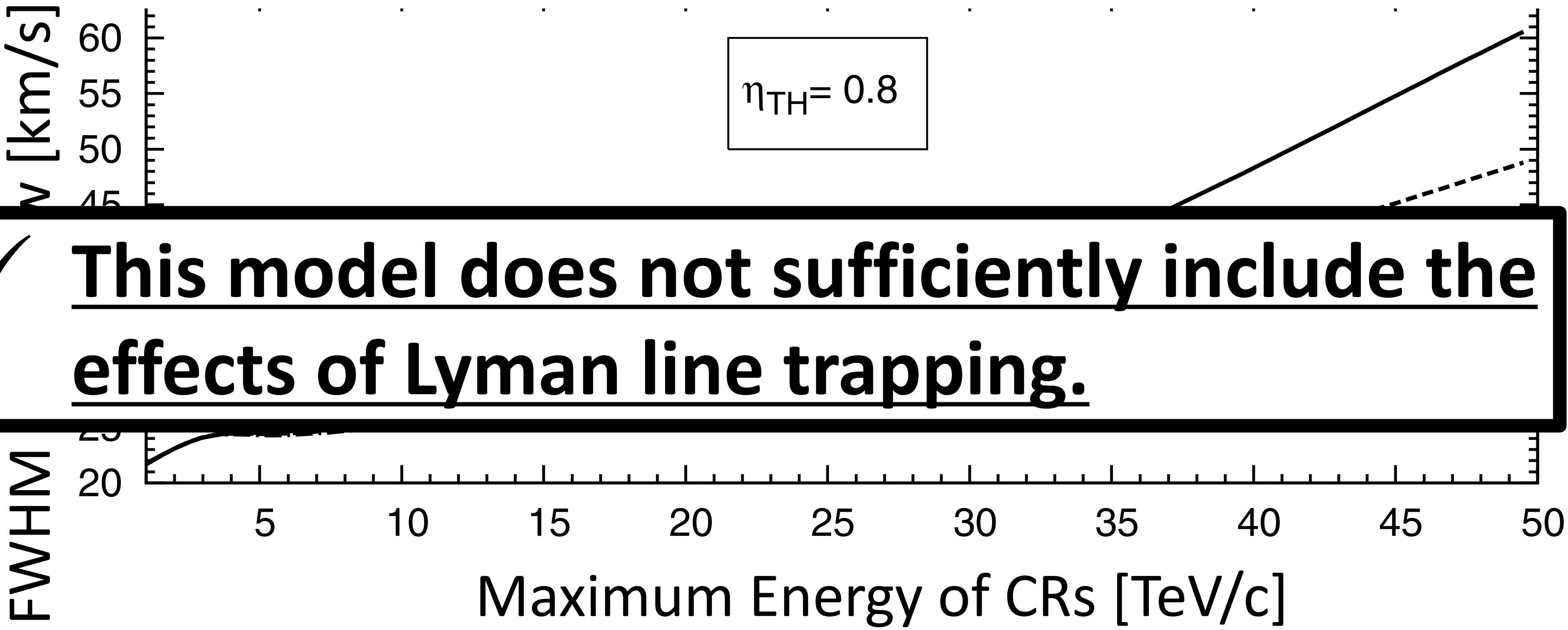
The semi-analytical model predicts the anomalous narrow component arising from the CR precursor (Morlino+13).

Possible upstream heating: (ii) cosmic-ray precursor



FWHM of the narrow component depends on the Maximum energy of CRs (Morlino+13).

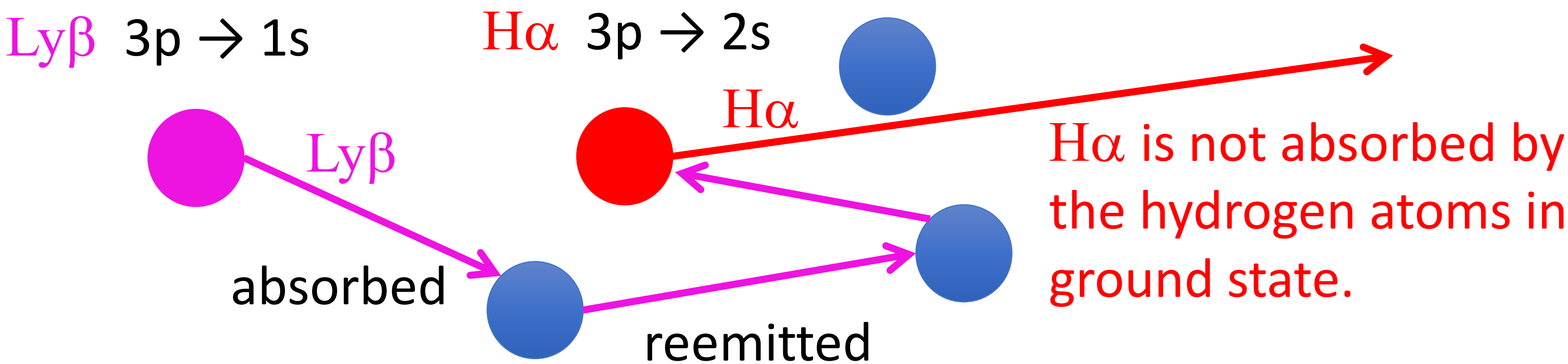
Possible upstream heating: (ii) cosmic-ray precursor



✓ **<u>This model does not sufficiently include the effects of Lyman line trapping.</u>**

FWHM of the narrow component depends on the Maximum energy of CRs (Morlino+13).

Lyman line trapping Lyβ→Hα



a) **A part of hydrogen atoms in n=3 emit Lyβ due to 3p to 1s transition.**

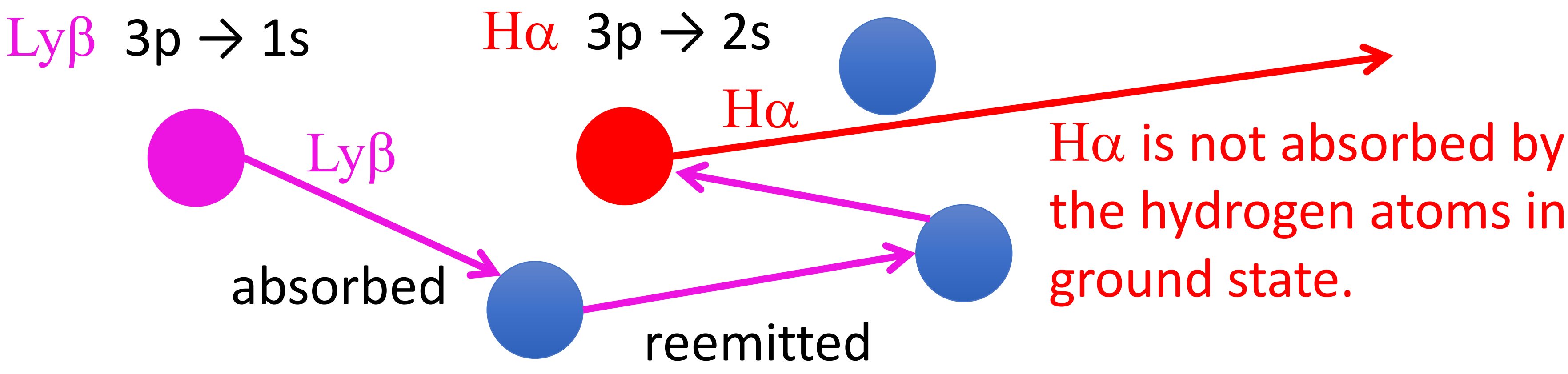
b) **The emitted Lyβ** is absorbed by the hydrogen atoms in ground state.

c) Eventually, Lyβ is converted to **Hα** due to 3p to 2s transition.

Optically thin for Lyβ is "Case A"

Optically thick for Lyβ is "Case B"

Lyman line trapping Lyβ→Hα



When the SNR shocks are in Case B, **<u>the efficient conversion of Lyβ to Hα yields “2s” hydrogen atoms, which absorb the Hα photons.</u>**

Optical thickness of $\mathrm{H\alpha}$ in the realistic SNR shocks

- The number density of "2s" hydrogen atoms:

$$n_{\mathrm{H}}(2\mathrm{s}) \gtrsim n_{\mathrm{H}}(1\mathrm{s}) \frac{C_{1\mathrm{s},2\mathrm{s}}}{A_{2\mathrm{s},1\mathrm{s}}} \sim 10^{-8}\text{-}10^{-7} \times n_{\mathrm{H}}(1\mathrm{s})$$

Spontaneous transition rate: $A_{2\mathrm{s},1\mathrm{s}} \approx 8.2\ \mathrm{s}^{-1}$

Collisional excitation rate: $C_{1\mathrm{s},2\mathrm{s}} \sim 10^{-7}\text{-}10^{-6}\ \mathrm{s}^{-1}$

- Optical thickness of the $\mathrm{H\alpha}$ photons:

$$\tau \sim \sigma_\nu n_{\mathrm{H}}(2\mathrm{s}) L \gtrsim 0.1 \left(\frac{n_{\mathrm{H}}(2\mathrm{s})}{10^{-7}\ \mathrm{cm}^{-3}} \right) \left(\frac{L}{10^{18}\ \mathrm{cm}} \right)$$

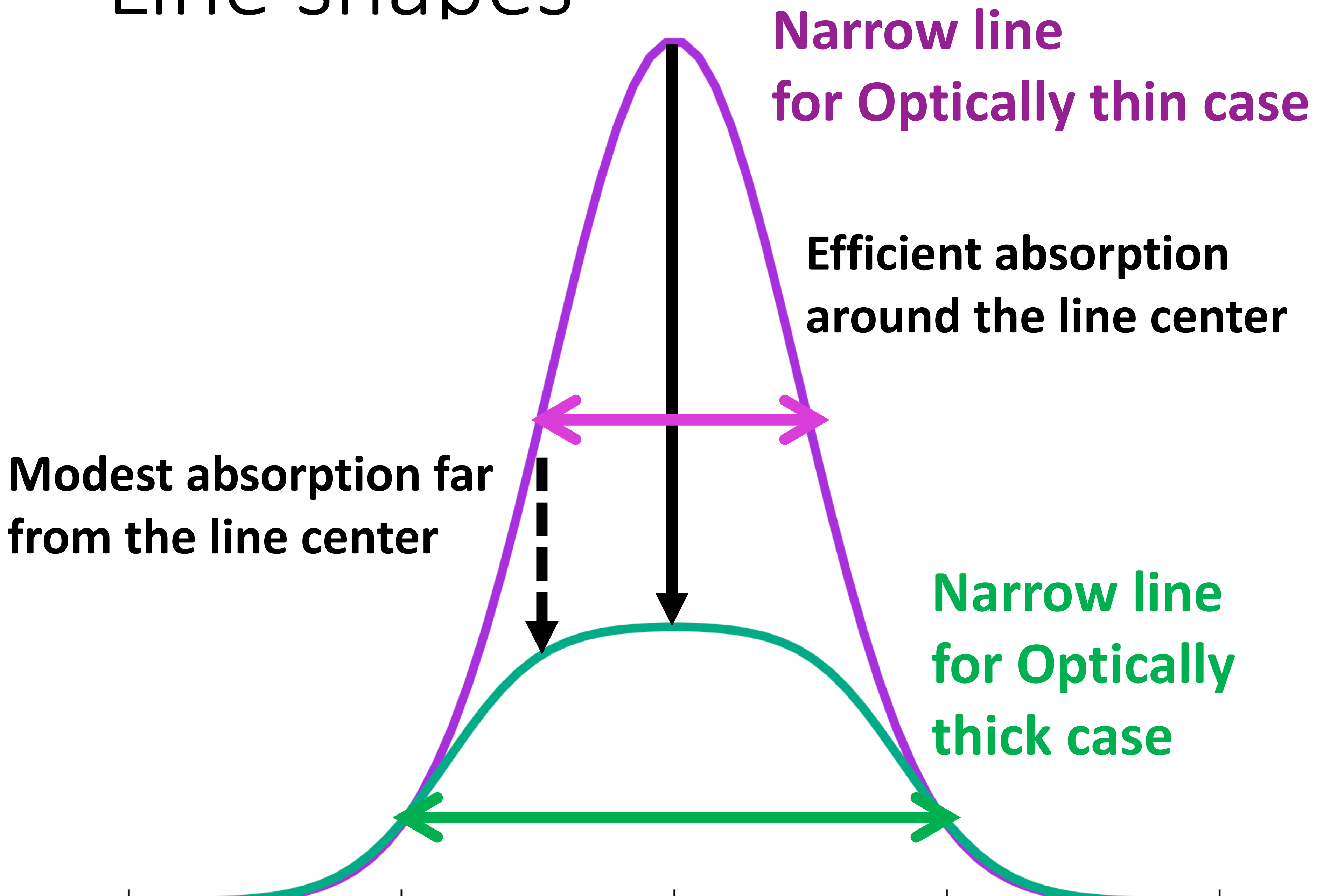
Optical thickness of Hα in the realistic SNR shocks

✓ **The Hα photons can be absorbed in the realistic SNR shocks.**

- Optical thickness of the Hα photons:

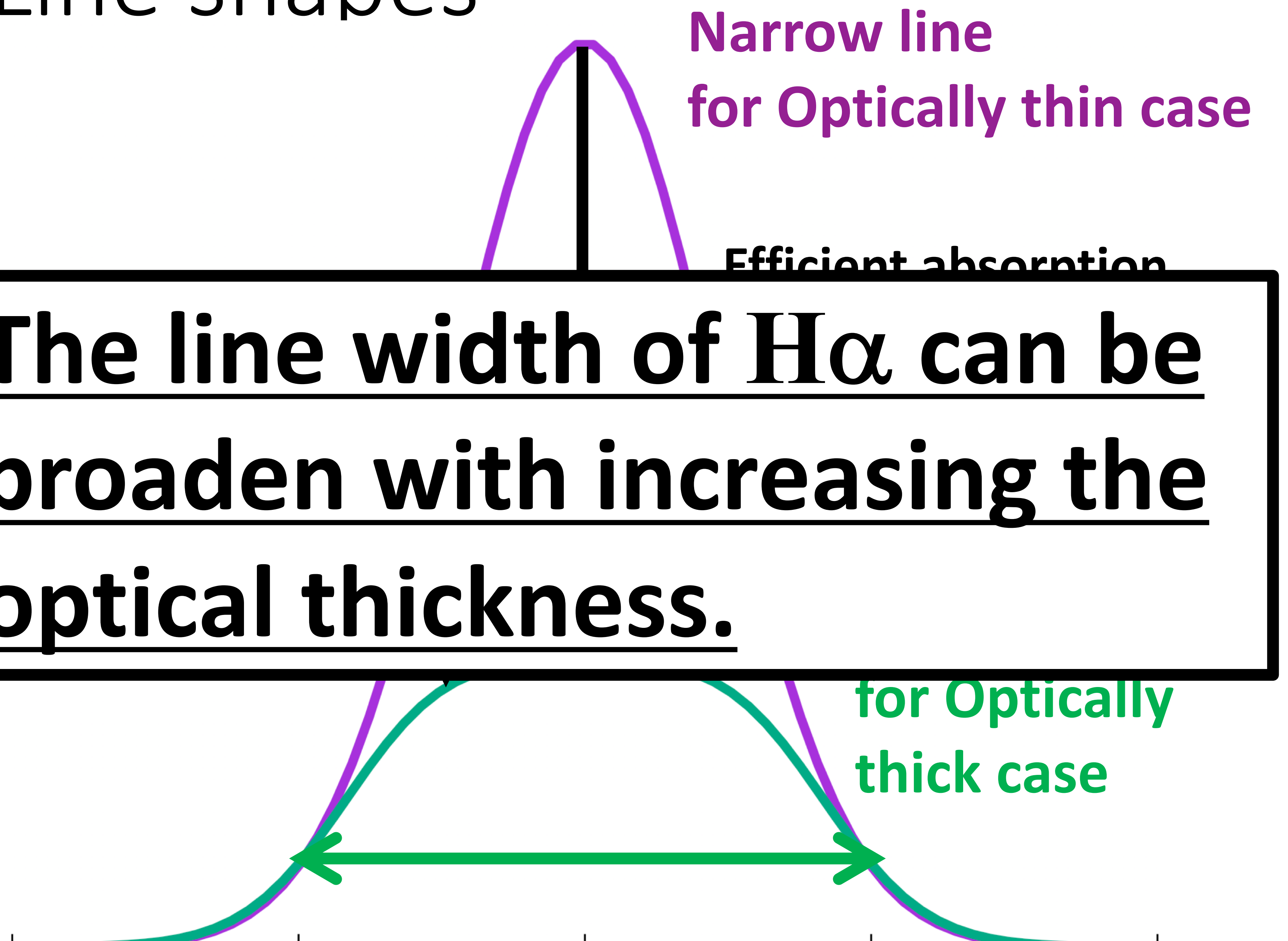
$$\tau \sim \sigma_\nu n_{\rm H}(2{\rm s}) L \gtrsim 0.1 \left(\frac{n_{\rm H}(2{\rm s})}{10^{-7}\ {\rm cm}^{-3}} \right) \left(\frac{L}{10^{18}\ {\rm cm}} \right)$$

Line shapes



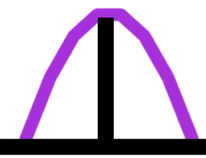
Narrow line
for Optically thin case
Efficient absorption
around the line center
Modest absorption far
from the line center
Narrow line
for Optically
thick case

Line shapes

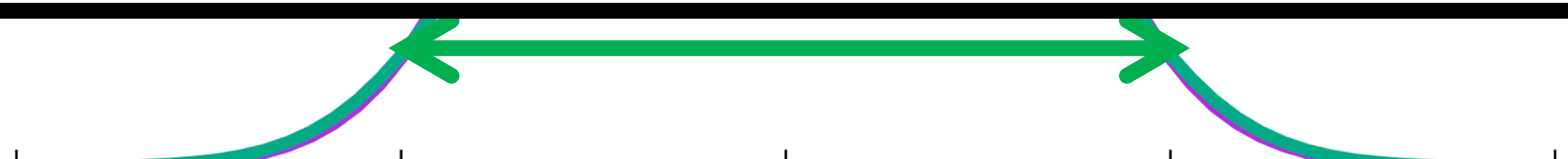


✓ **<u>The line width of Hα can be broaden with increasing the optical thickness.</u>**

Line shapes



- ✓ Morlino+13 considered “Case B”.
- ✓ **They neglected the production of “2s” hydrogen atoms.**
- ✓ We are now constructing the emission model including the radiative line transfer.



Emission model (preliminary)

1. Rate equation for the statistical equilibrium

$$\sum_k \left[n_{\mathrm{H}}(k)\left(P_{k,j}+C_{k,j}\right)-n_{\mathrm{H}}(j)\left(P_{j,k}+C_{j,k}\right)\right]=0$$

$n_{\mathrm{H}}(k)$: the number density of hydrogen atom at the state k

$P_{k,j}$: the radiative transition rate for k to j

$C_{k,j}$: the collisional rate for k to j

Here, <u>we only consider the collisional rate from 1s</u> because the mean collision time is very longer than the radiative decay time.

Emission model (preliminary)

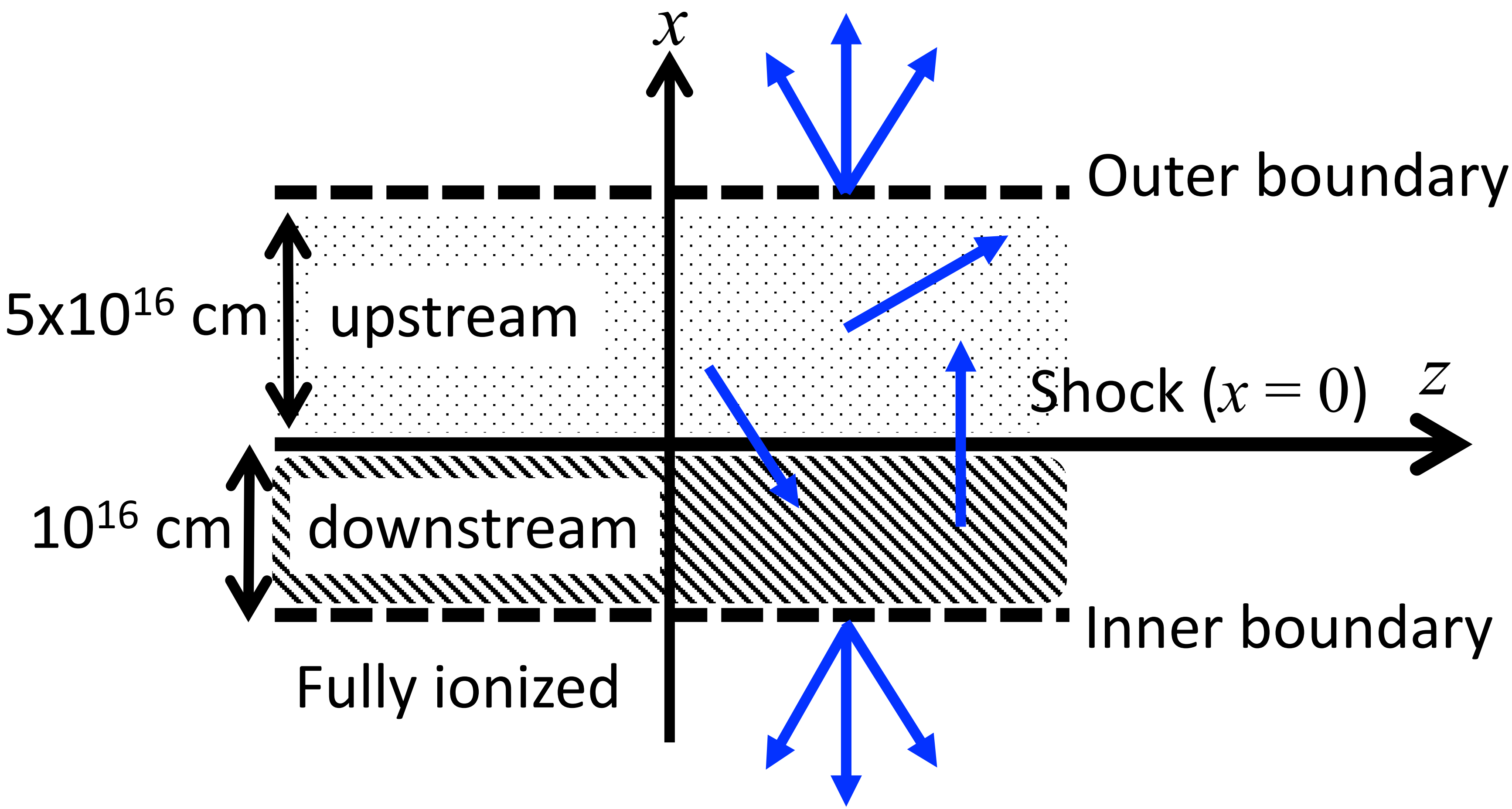
1. Rate equation for the statistical equilibrium

$$
\begin{aligned}
P_{k,j} &= A_{k,j} + \frac{g_j}{g_k}\int \frac{4\pi\sigma_\nu}{h\nu} J_\nu d\nu \\
P_{j,k} &= \int \frac{4\pi\sigma_\nu}{h\nu} J_\nu d\nu, \\
J_\nu &= \frac{1}{4\pi}\int I_\nu d\Omega
\end{aligned}
$$

In order to evaluate the radiative rate, we need to calculate the mean intensity J_ν, that is, the specific intensity I_ν.

Emission model (preliminary)

- As the first step, we consider the radiative line transfer and the atomic population problem for the plane parallel shock.

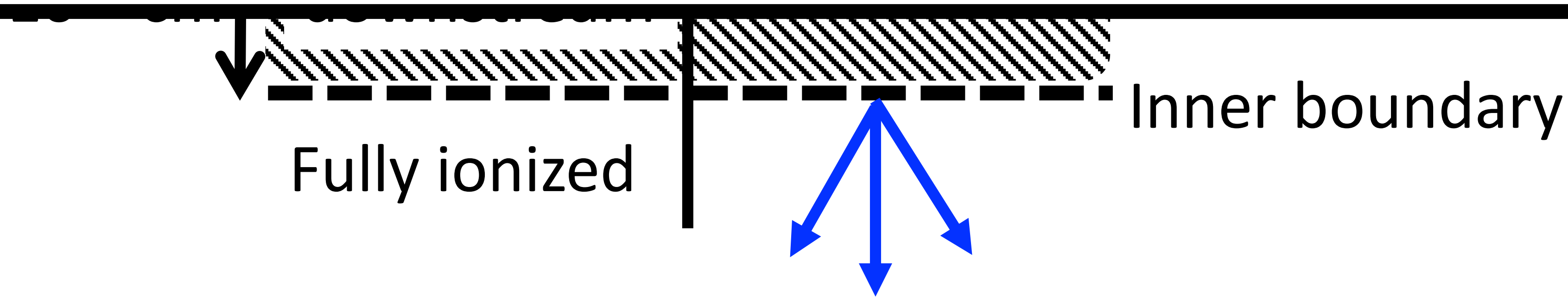


Emission model (preliminary)

- As the first step, we consider the radiative line transfer and

✓ We assume the axial symmetry.

✓ Setting the distribution function of particles, then we can derive the population of atomic states for 1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p, 4d and 4f.



distribution functions @ shock rest

upstream: shifted Maxwellian with temperature T_0 = 1 eV and bulk velocity $V_{sh} \approx 2000$ km/s with assuming the temperature equilibrium.

$$
\begin{aligned}
f_{\mathrm{H},0}(\boldsymbol{v}_{\mathbf{H}}) &= n_{\mathrm{H},0}\left(\frac{m_{\mathrm{H}}}{2\pi k T_0}\right)^{3/2} \exp\left[-\frac{m_{\mathrm{H}}\left(\boldsymbol{v}_{\mathbf{H}}-\boldsymbol{V}_{\mathbf{sh}}\right)^2}{2kT_0}\right] \\
f_{\mathrm{p},0}(\boldsymbol{v}_{\mathbf{p}}) &= n_{\mathrm{p},0}\left(\frac{m_{\mathrm{p}}}{2\pi k T_0}\right)^{3/2} \exp\left[-\frac{m_{\mathrm{p}}\left(\boldsymbol{v}_{\mathbf{p}}-\boldsymbol{V}_{\mathbf{sh}}\right)^2}{2kT_0}\right] \\
f_{\mathrm{e},0}(\boldsymbol{v}_{\mathbf{e}}) &= n_{\mathrm{e},0}\left(\frac{m_{\mathrm{e}}}{2\pi k T_0}\right)^{3/2} \exp\left[-\frac{m_{\mathrm{e}}\left(\boldsymbol{v}_{\mathbf{e}}-\boldsymbol{V}_{\mathbf{sh}}\right)^2}{2kT_0}\right]
\end{aligned}
$$

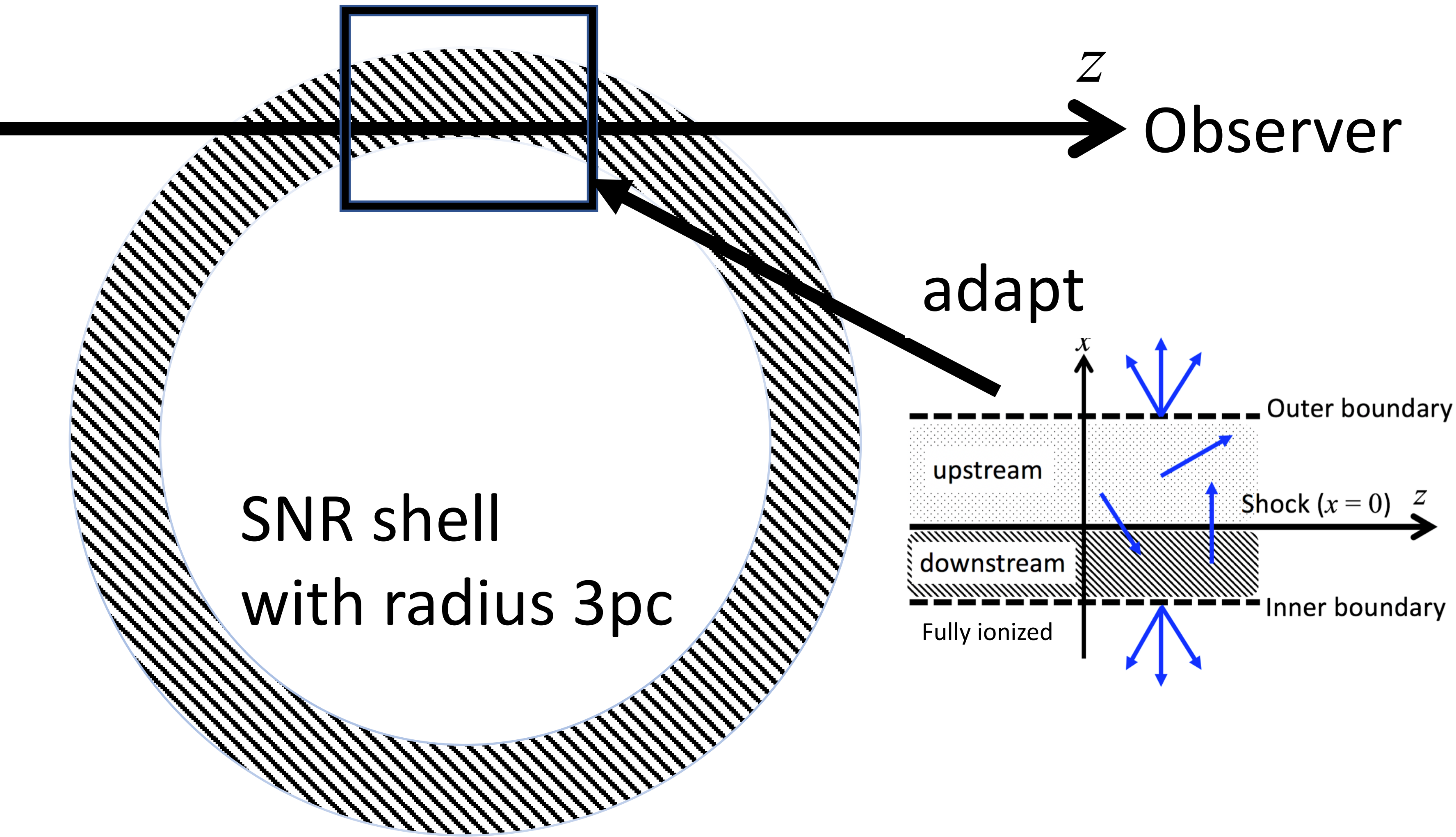
$$n_{\mathrm{H},0} = n_{\mathrm{p},0}$$

distribution functions @ shock rest

downstream: $\xi_n = 0.3,\ \xi_b = 0.7, T_{\rm e,2} = 0.05 T_{\rm p,2}$

$$
\begin{aligned}
f_{\rm H,2}(\boldsymbol{v}_{\mathbf{H}}) &= n_{\rm H,0}\xi_n \left(\frac{m_{\rm H}}{2\pi k T_0}\right)^{3/2} \exp\left[-\frac{m_{\rm H}\left(\boldsymbol{v}_{\mathbf{H}} - \boldsymbol{V}_{\mathbf{sh}}\right)^2}{2kT_0}\right] \\
&+ n_{\rm H,0}\xi_b \left(\frac{m_{\rm H}}{2\pi k T_{\rm p,2}}\right)^{3/2} \exp\left[-\frac{m_{\rm H}\left(\boldsymbol{v}_{\mathbf{H}} - \boldsymbol{u}_{\mathbf{2}}\right)^2}{2kT_{\rm p,2}}\right] \\
f_{\rm p,2}(\boldsymbol{v}_{\mathbf{p}}) &= n_{\rm p,2} \left(\frac{m_{\rm p}}{2\pi k T_{\rm p,2}}\right)^{3/2} \exp\left[-\frac{m_{\rm p}\left(\boldsymbol{v}_{\mathbf{p}} - \boldsymbol{u}_{\mathbf{2}}\right)^2}{2kT_{\rm p,2}}\right] \\
f_{\rm e,2}(\boldsymbol{v}_{\mathbf{e}}) &= n_{\rm e,2} \left(\frac{m_{\rm e}}{2\pi k T_{\rm e,2}}\right)^{3/2} \exp\left[-\frac{m_{\rm e}\left(\boldsymbol{v}_{\mathbf{e}} - \boldsymbol{u}_{\mathbf{2}}\right)^2}{2kT_{\rm e,2}}\right]
\end{aligned}
$$

Plane parallel → Spherical Shell



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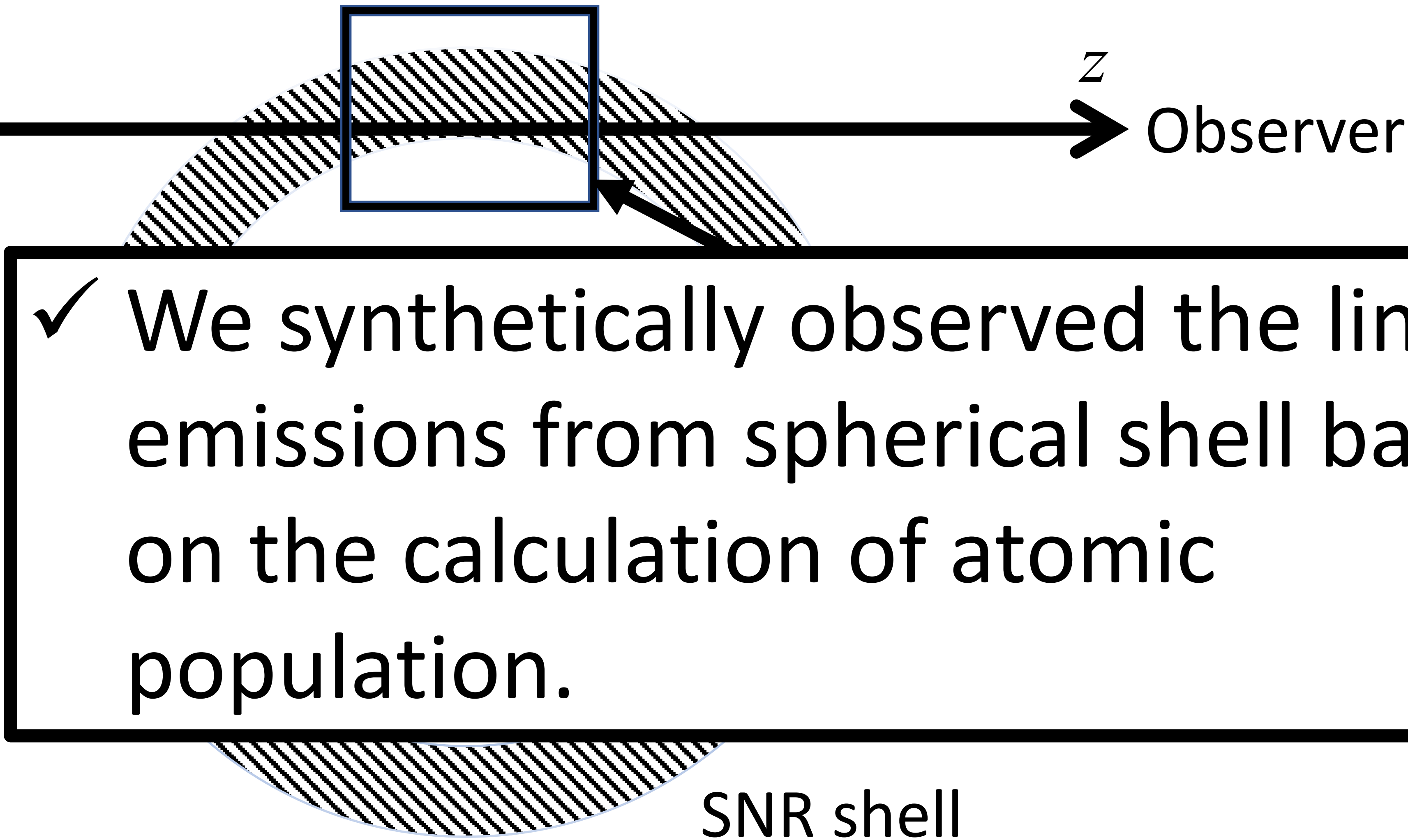
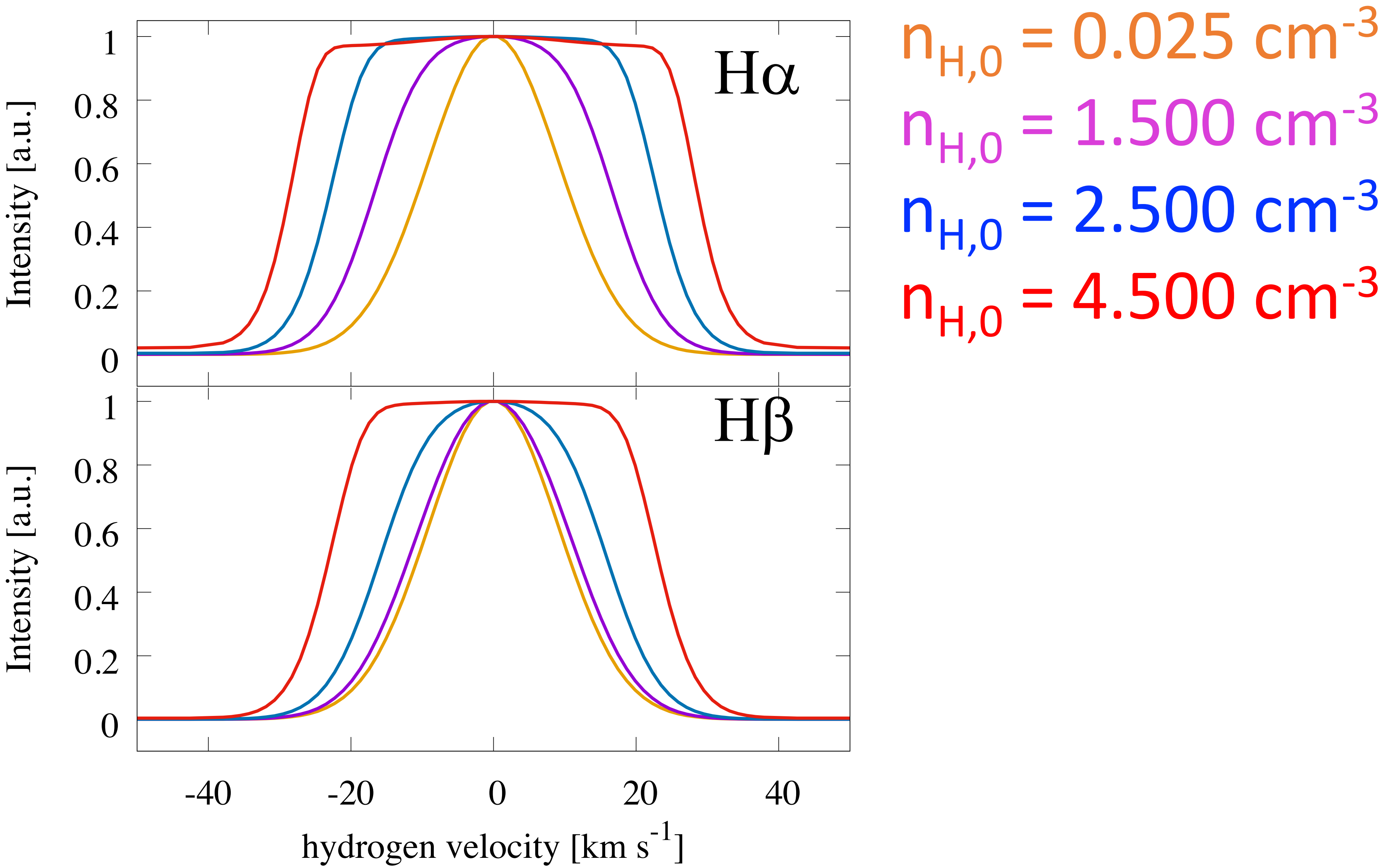
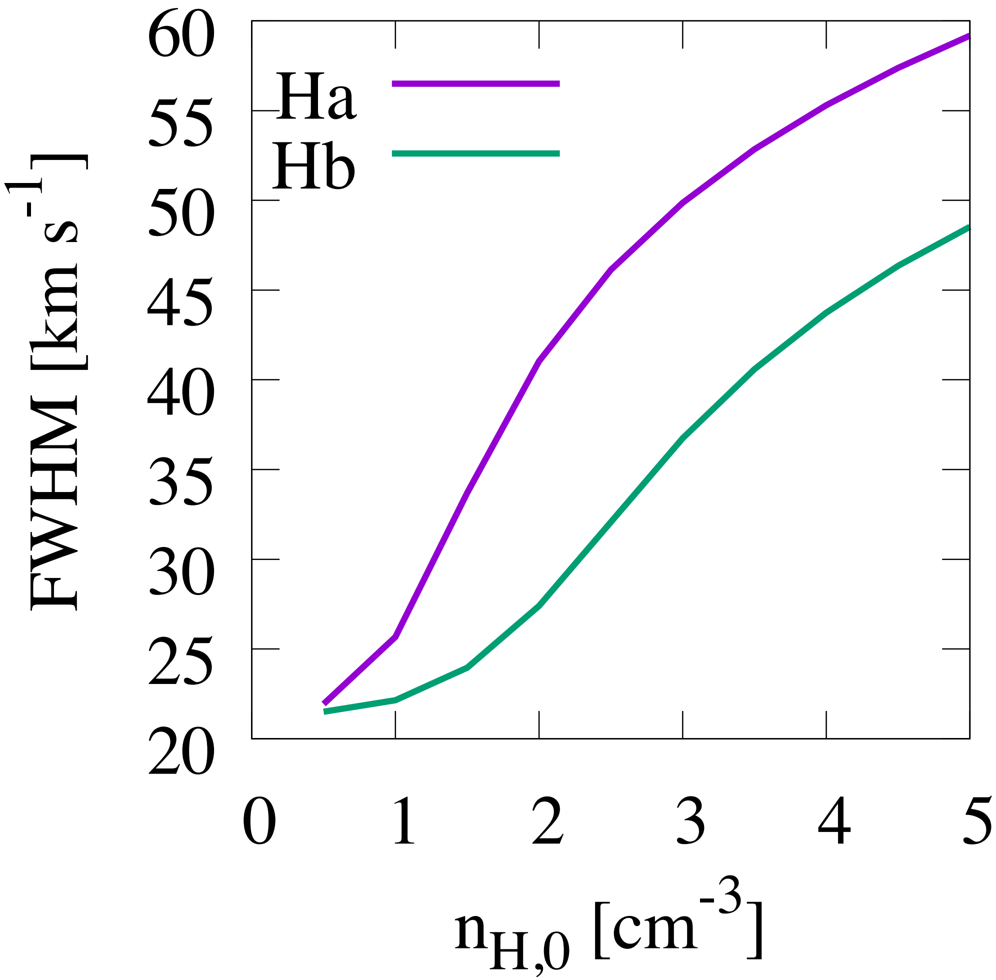


- ✓ We synthetically observed the line emissions from spherical shell based on the calculation of atomic population.

Observed Spectrum



FWHM: vs. Observations (Hα)



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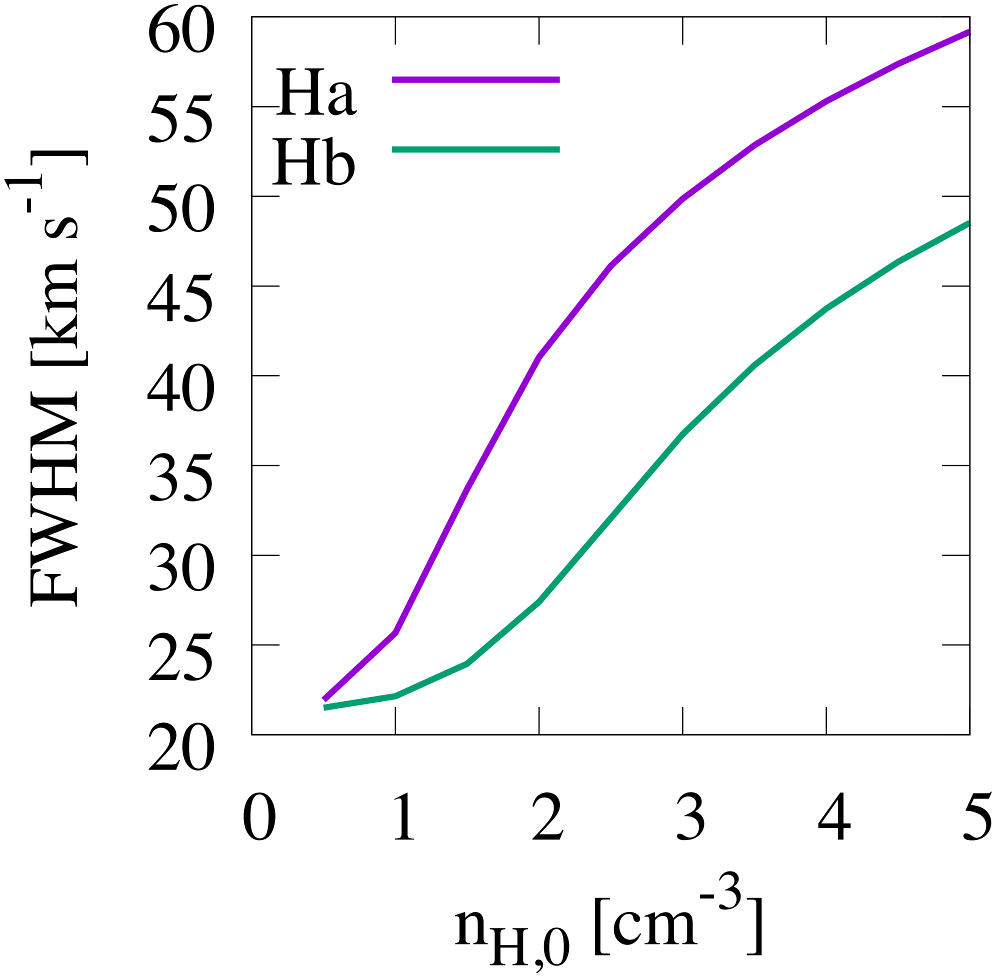

The anomalous narrow component comes from the atomic processes without CR acceleration!

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- We find that the Hα emission can be mildly absorbed by hydrogen atoms in the 2s state at the realistic SNRs.
- Our calculation will explain **<u>the anomalous width of Hα line with no cosmic-ray</u>**.