Polarized Balmer Line Emissions from Collisionless Shock Waves: On Measurements of the Energy Loss of the Shocks due to the Production of Non-thermal Particles

Ref: Shimoda et al. 2018, MNRAS, 473

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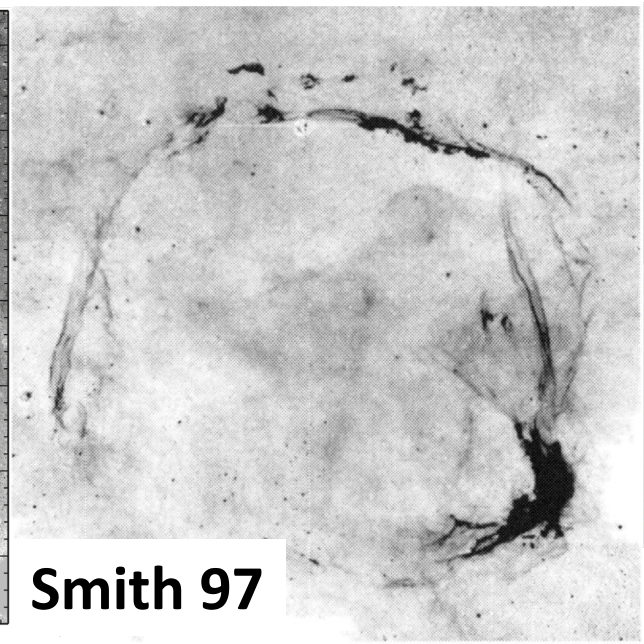
Summary of this work

- We have calculated the polarized Balmer line emissions from the shocks efficiently accelerating non-thermal particles.
- We have shown that **the energy loss rate of the shocks resulting from the particle acceleration** can be measured by the polarization degree.
- Our calculation will be applied for **an estimation of a distance from the acceleration sites**.

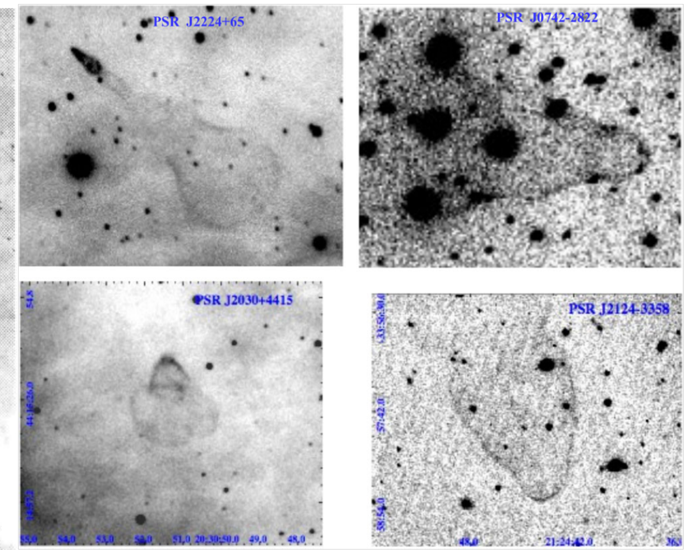
Balmer Line Emissions from Collisionless Shocks

Winkler+14



Smith 97

Supernova Remnants (SNRs)



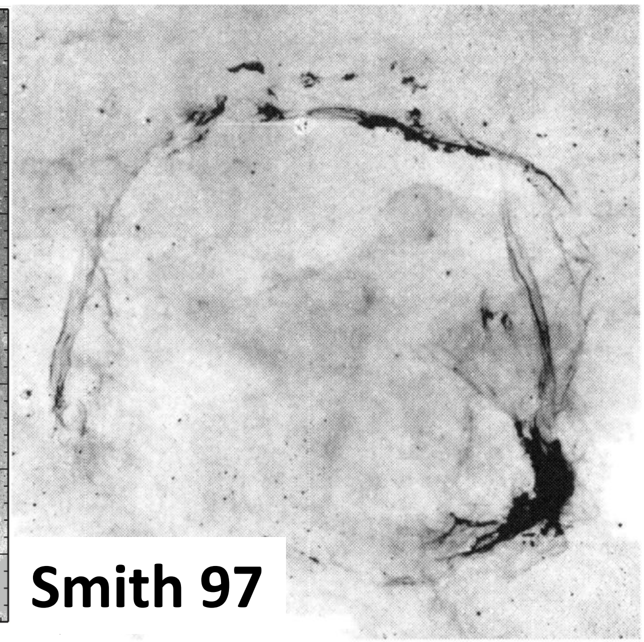
Figures from Morlino+15

Palsar 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



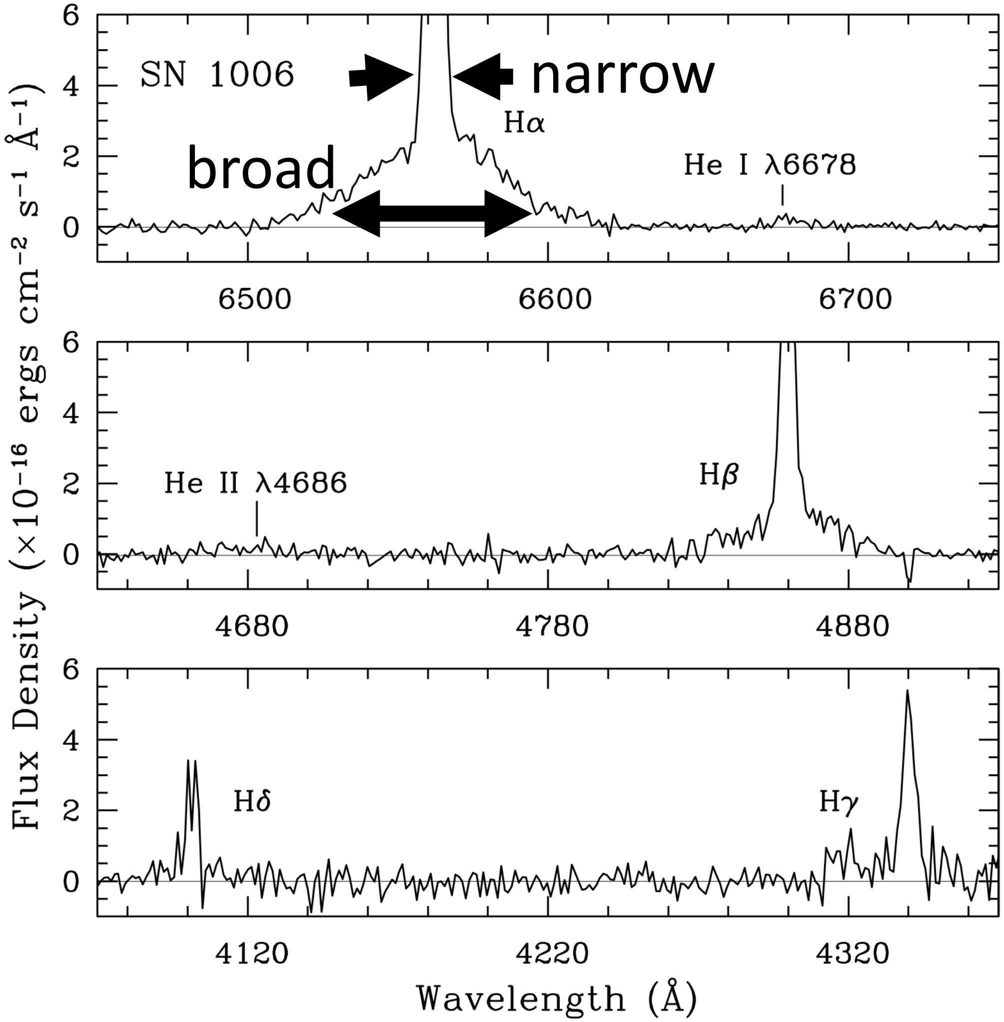
Smith 97

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

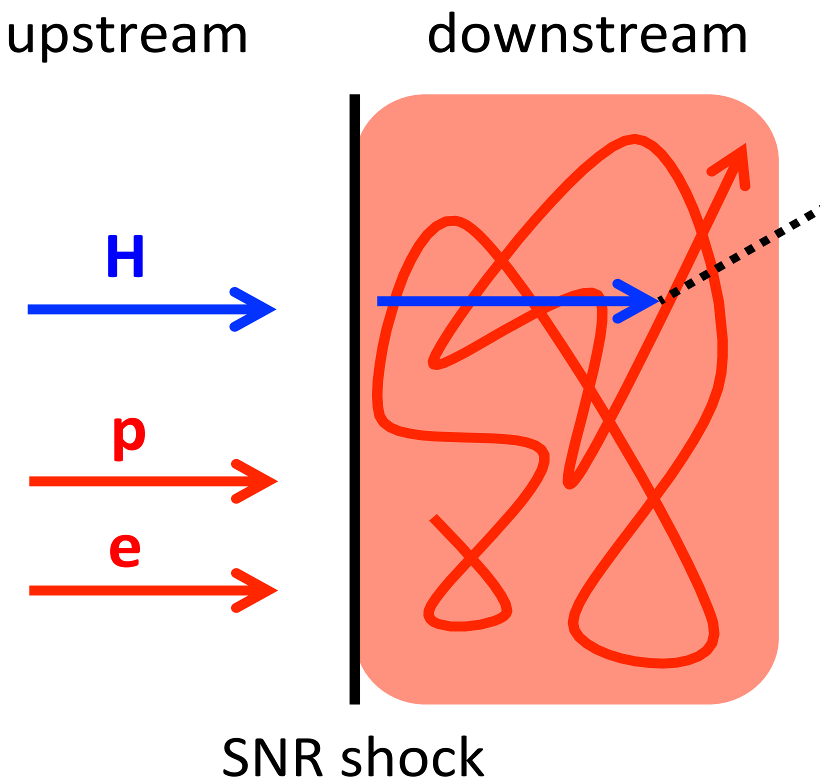


Spectrum of Balmer line Emissions
(Ghavamian+02, for SNR SN 1006)

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

Balmer Line Emissions from Collisionless Shocks

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



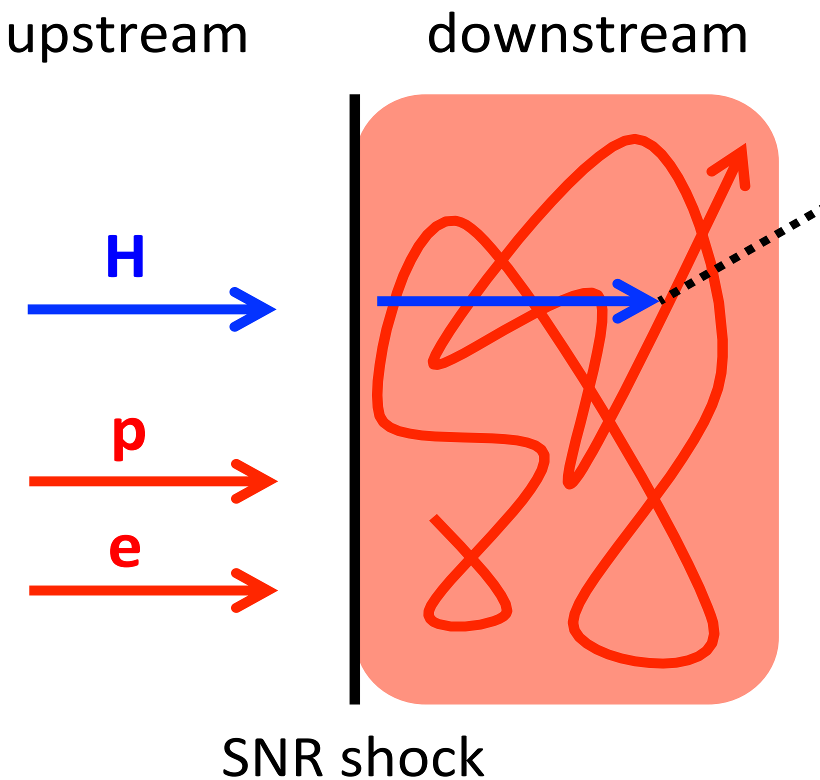
- The collisionless shock is formed by the interaction between charged particles and plasma waves rather than Coulomb collision.
- **The neutral particles (e.g. hydrogen atoms) are not affected.**

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**

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

Emits "narrow" comp.

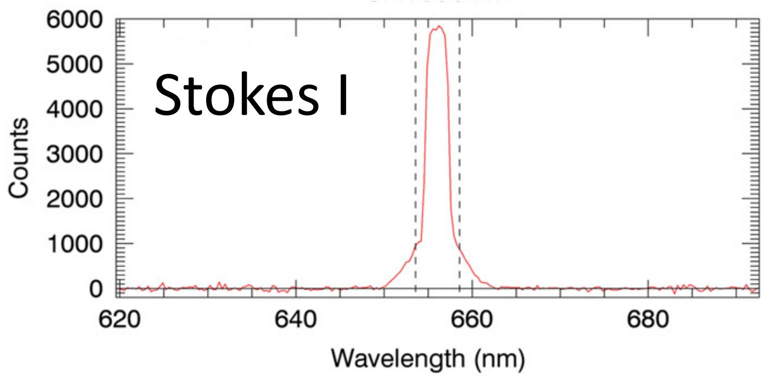
- ☐ **Charge Transfer**

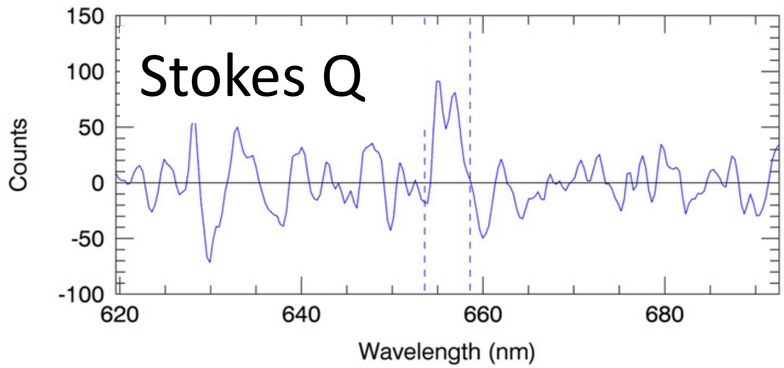
$$\mathrm{H} + \mathrm{p} \longrightarrow \mathrm{p} + \underline{\mathrm{H}^*}$$

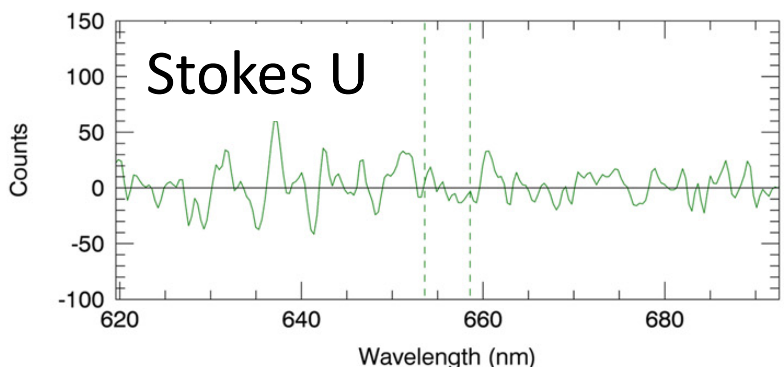
Emits "broad" comp.

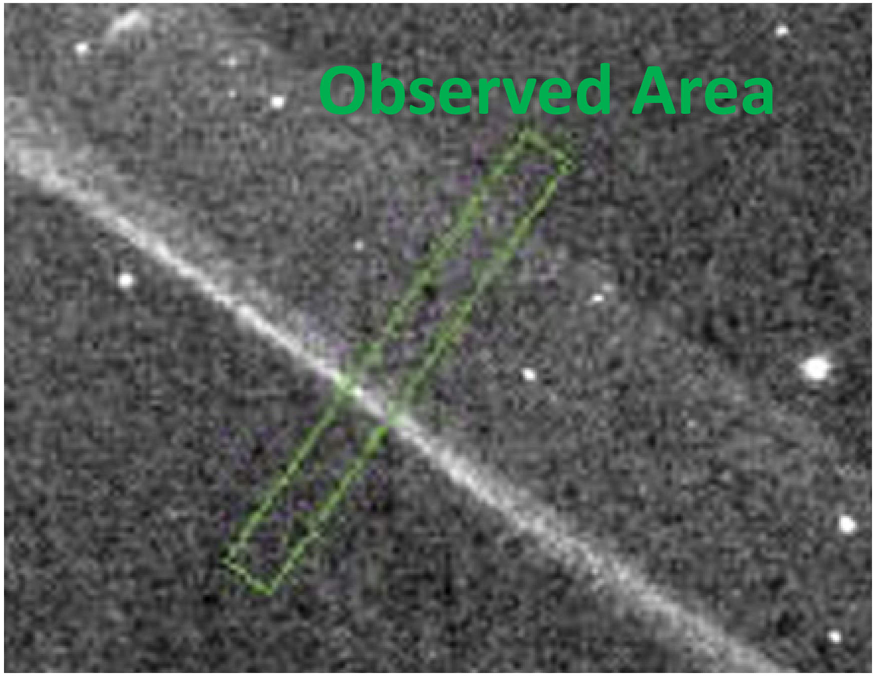
The "broad" component reflects the downstream temperature of protons.

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



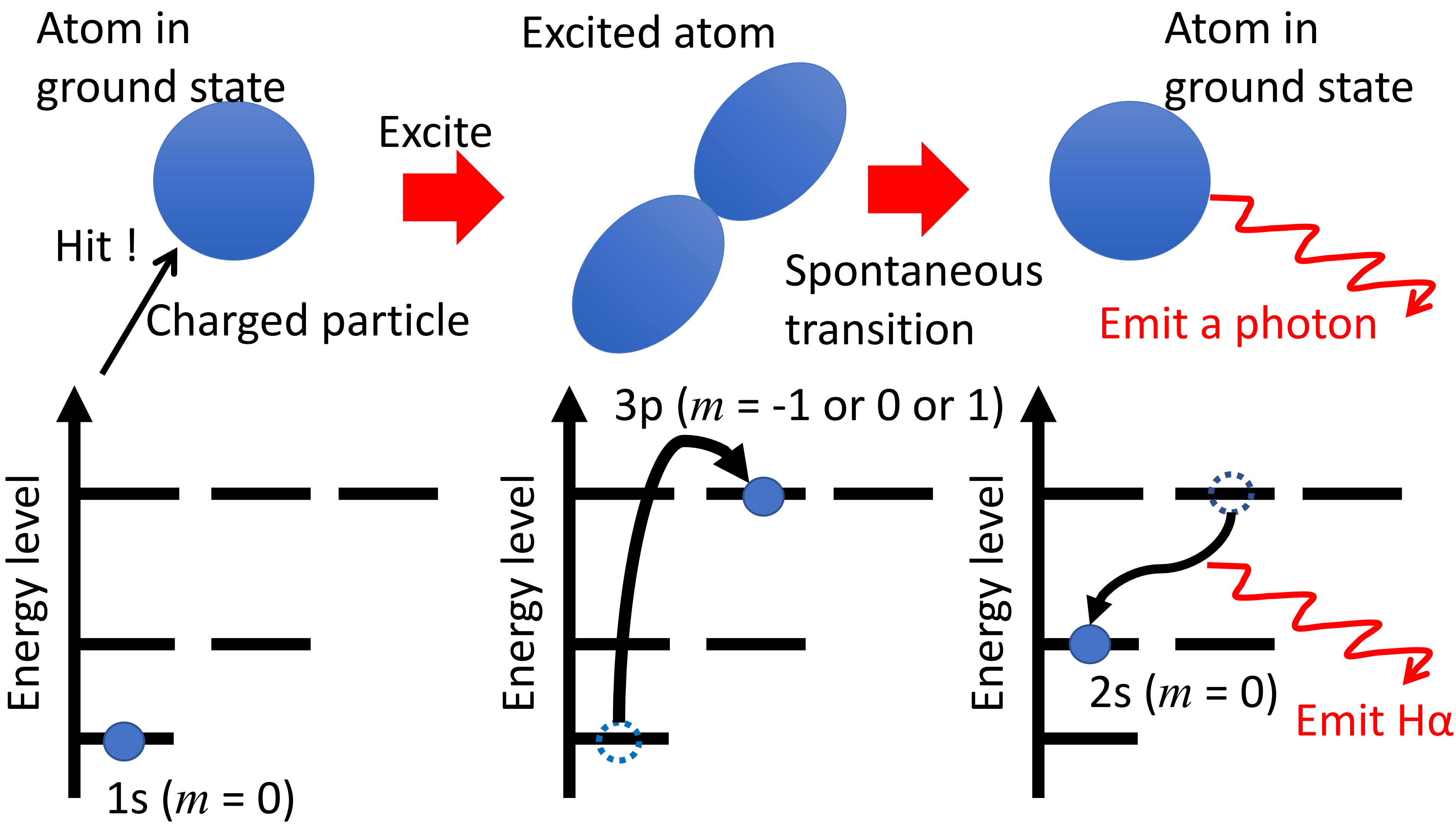






- **Linear Polarization**
- **Polarization angle：perpendicular to the shock**
- **Degree： 2.0 ± 0.4 %**

On polarization of atomic line

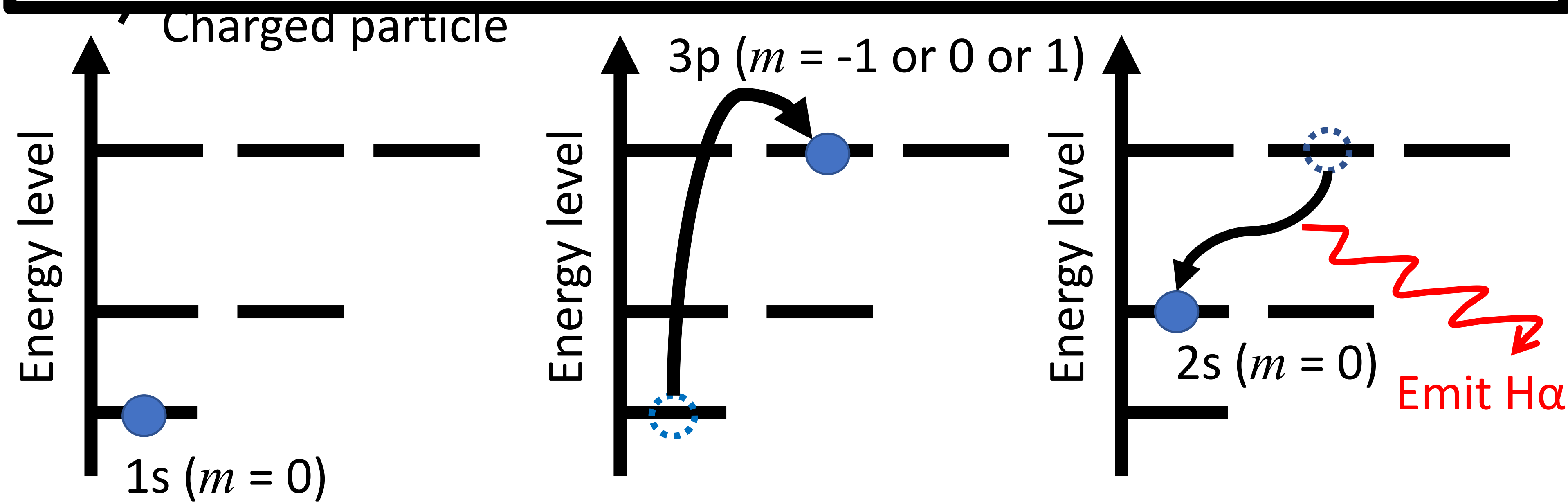


On polarization of atomic line

Polarization of photon is characterized by the variation of m before and after the transition:

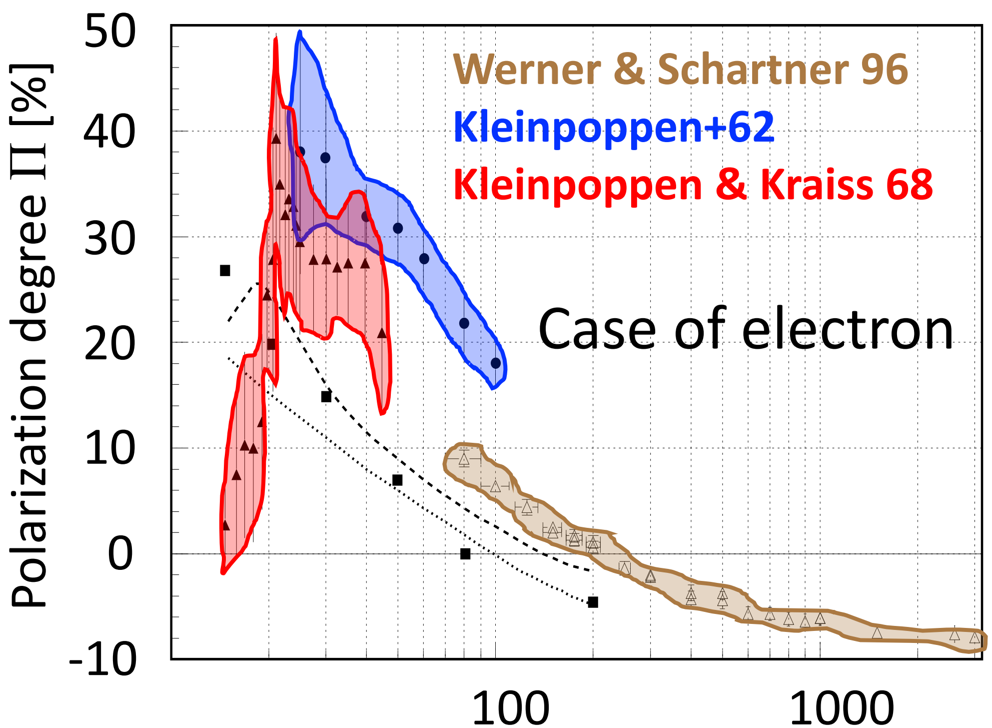
$\Delta m = 0 \rightarrow$ Linear

$\Delta m = \pm 1 \rightarrow$ Circular



Polarized Hα

☐Experiments: Hydrogen atoms in electron/proton beam



degree: $\Pi \equiv \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}$

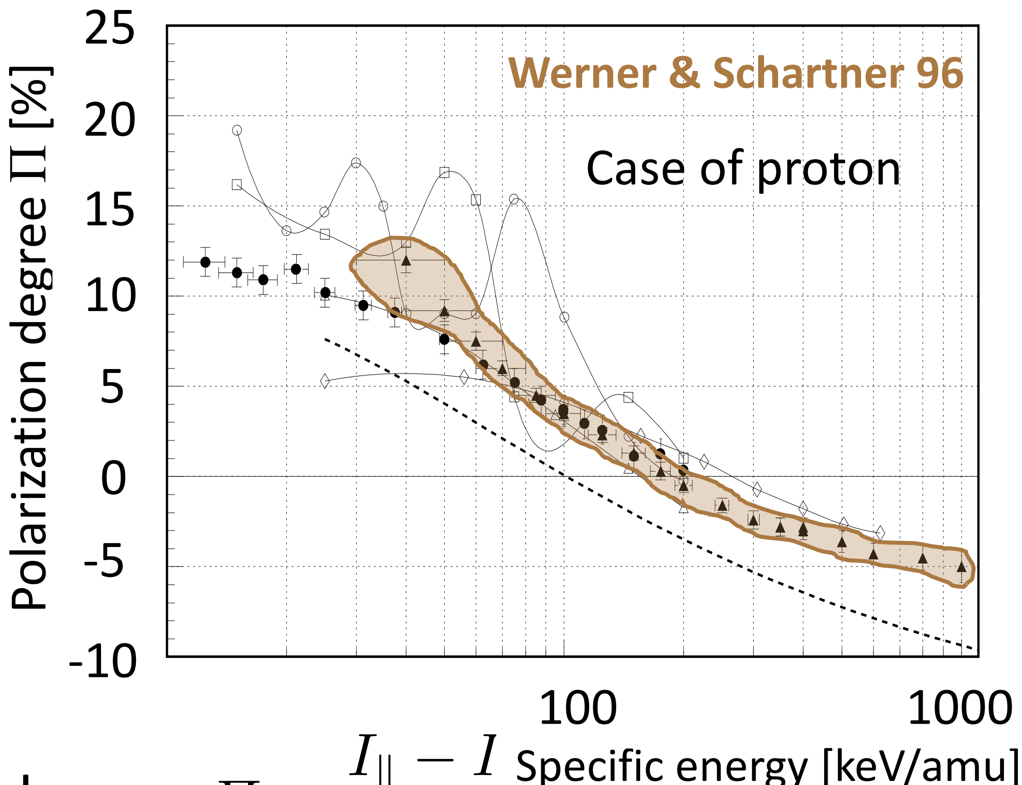
parallel to the beam : $I_{\parallel}$

perpendicular to the beam : $I_{\perp}$

- ✓Hydrogen atoms in electron (proton) beam emit polarized Hα with ～40 % (20 %) degree.
- ✓**<u>Polarization direction is parallel to the incident beam.</u>**

Polarized Hα

☐Experiments: Hydrogen atoms in electron/proton beam



degree: $\Pi \equiv \frac{I_{\|} - I_{\perp}}{I_{\|} + I_{\perp}}$

parallel to the beam : $I_{\|}$

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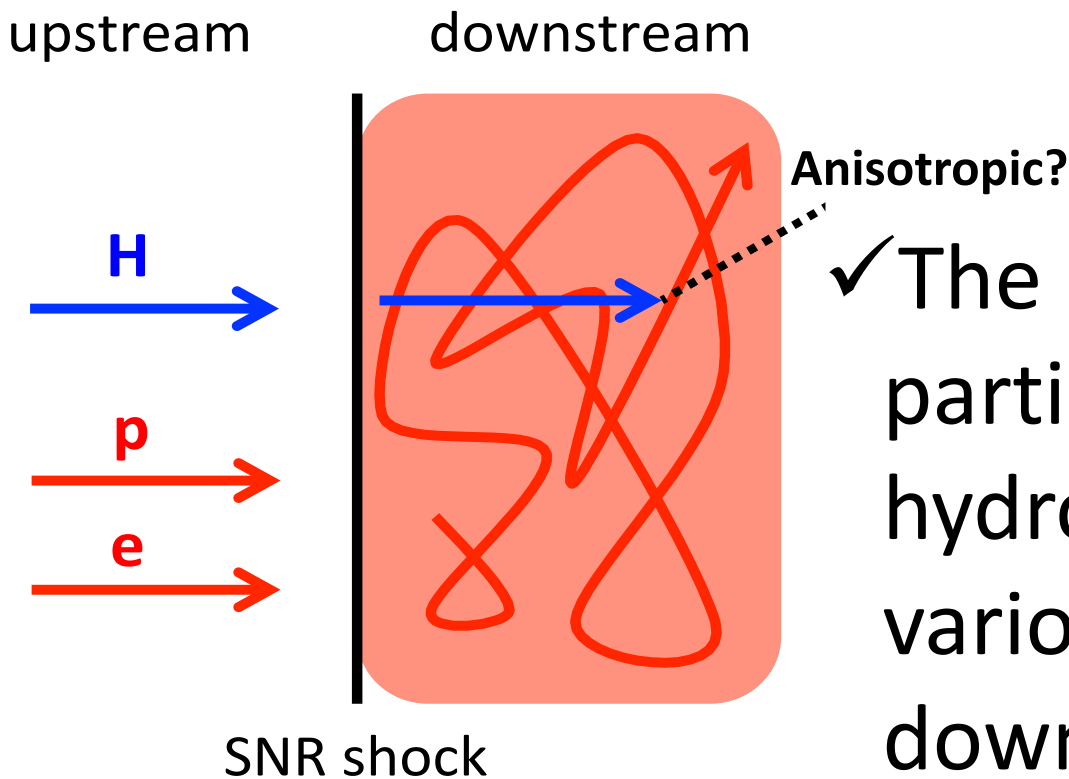
✓Hydrogen atoms in electron (proton) beam emit polarized Hα with ～40 % (20 %) degree.

✓**<u>Polarization direction is parallel to the incident beam.</u>**

Polarized Hα

☐For the case of shocks



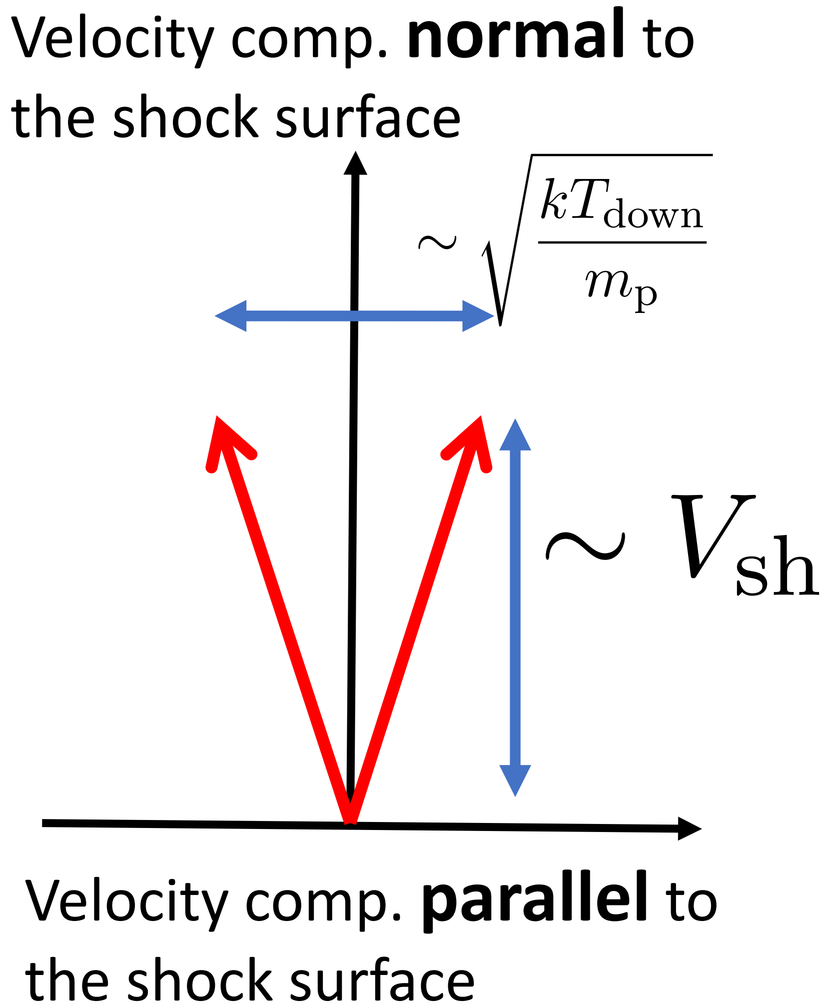
✓The hot charged particles hit the cold hydrogen atoms from various direction in the downstream region.

Charged particles → shock heating

Hydrogen atoms → no dissipation

Polarized Hα

✓ **Collision direction seen in the rest frame of hydrogen atoms**



- In the rest frame of hydrogen atoms (i.e. the upstream frame), the colliding charged particles are seen as a "mildly collimated beam".
- **<u>The "width" of beam is determined by the downstream temperature.</u>**
- The anisotropy of collision yields polarized Hα with a few % degree.

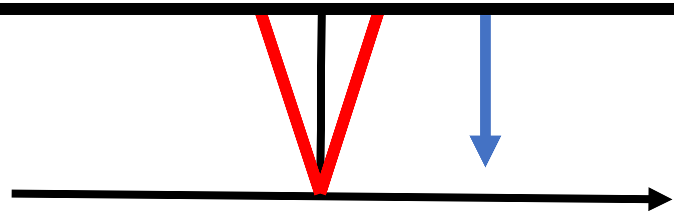
Polarized Hα

✓ **Collision direction seen in the rest frame of hydrogen atoms**

Velocity comp. **normal** to

- In the rest frame of hydrogen

☐ The polarized Hα with a few % degree was firstly predicted by Laming (1990) for SNR shocks, but **he did not consider the acceleration of non-thermal particles (i.e. cosmic-rays).**

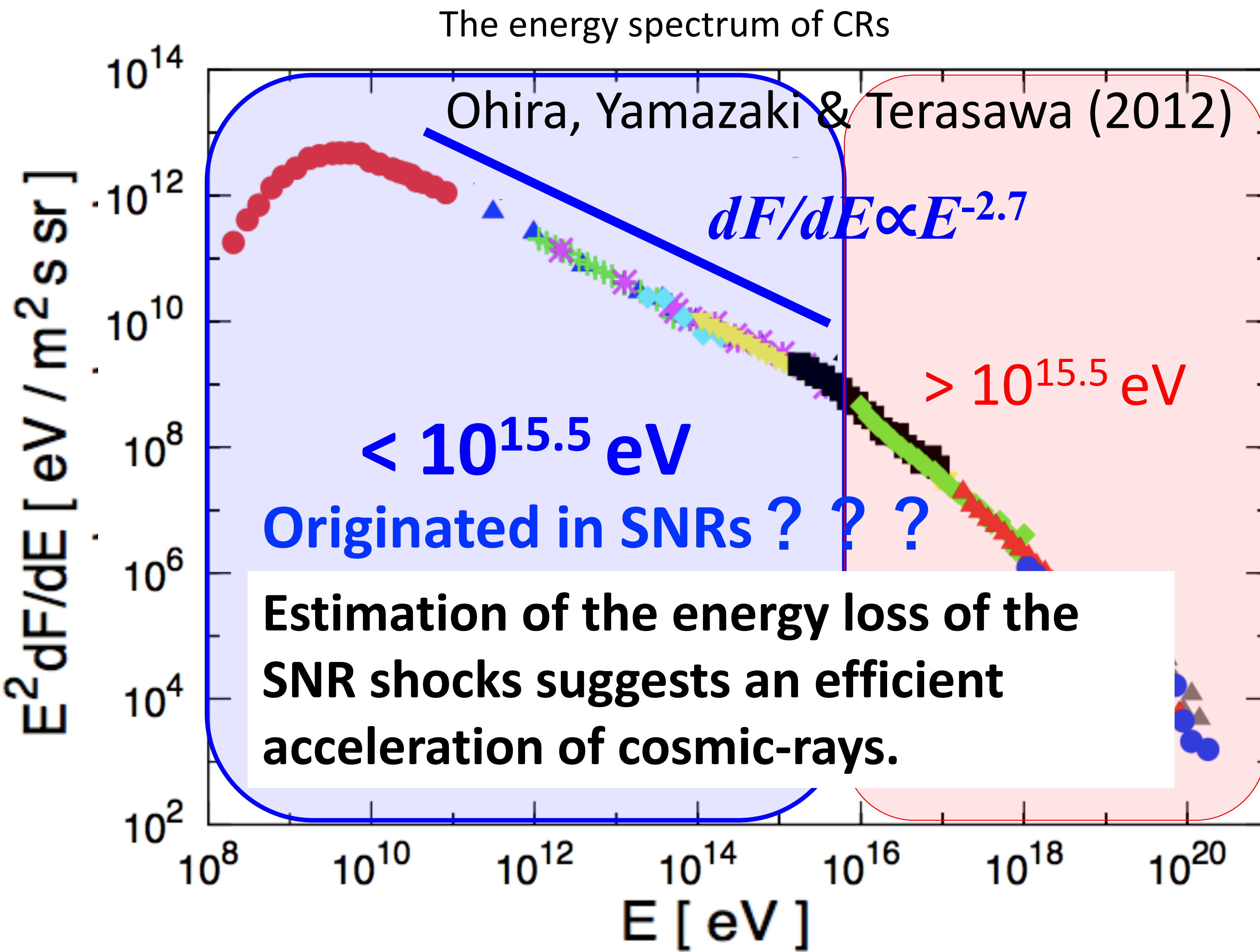


Velocity comp. **parallel** to the shock surface

downstream temperature.

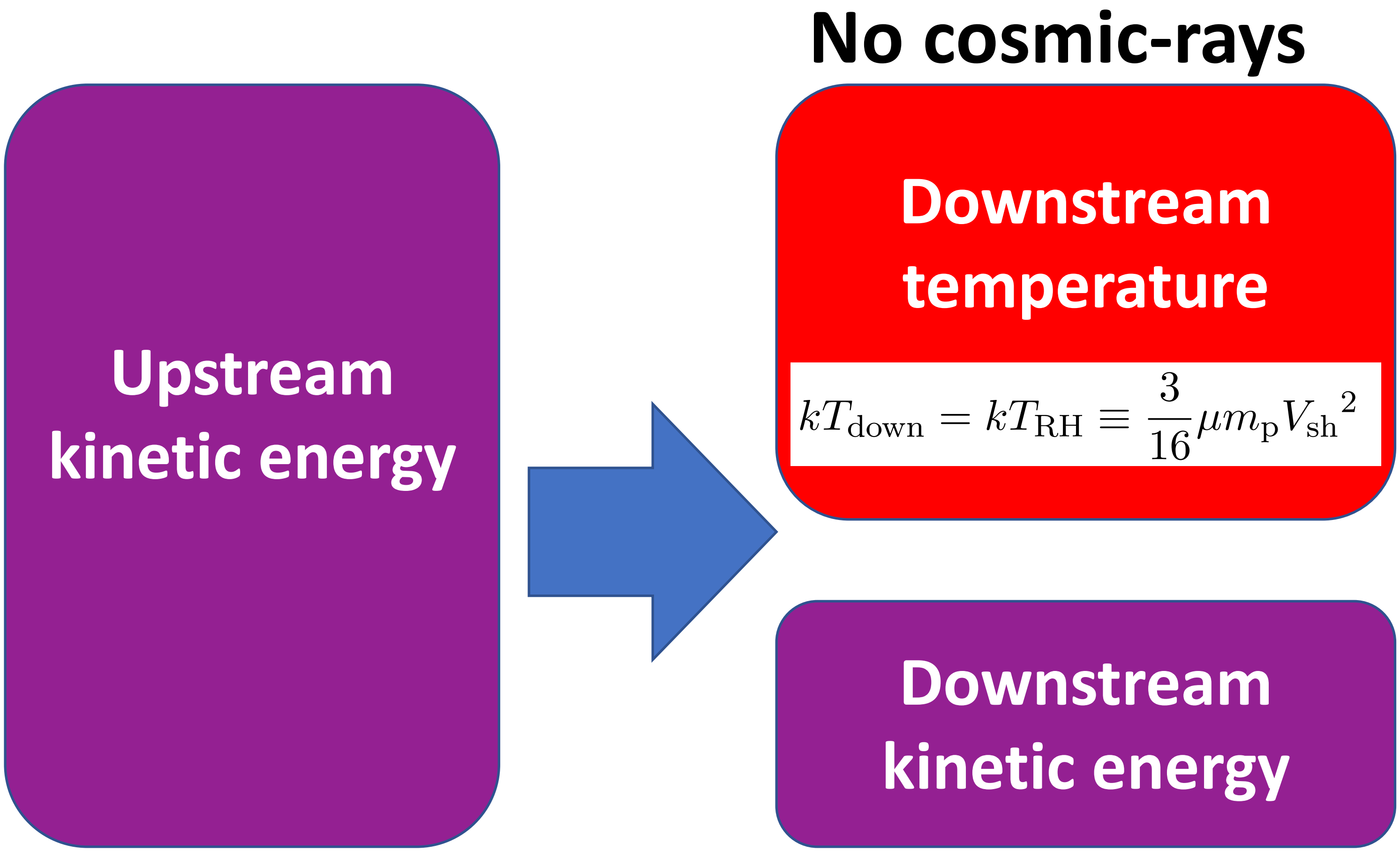
- The anisotropy of collision yields polarized Hα with a few % degree.

Cosmic Rays



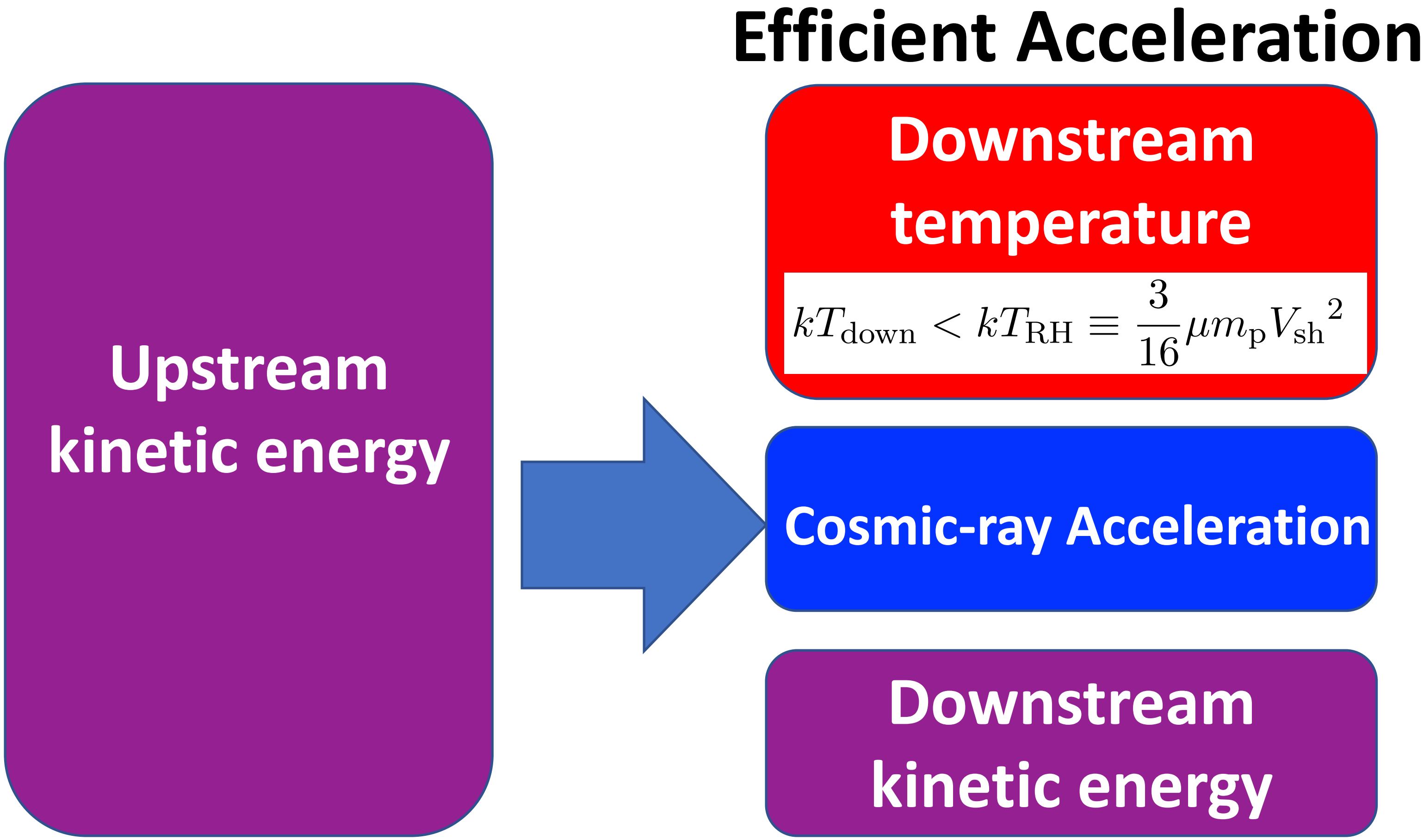
The energy spectrum of CRs
Ohira, Yamazaki & Terasawa (2012)
dF/dE∝E^-2.7
< 10^15.5 eV
Originated in SNRs？？？
> 10^15.5 eV
Estimation of the energy loss of the SNR shocks suggests an efficient acceleration of cosmic-rays.
E^2dF/dE [eV / m^2 s sr]
E [eV]
10^14
10^12
10^10
10^8
10^6
10^4
10^2
10^8
10^10
10^12
10^14
10^16
10^18
10^20

On the energy loss of the shocks



If the shock accelerates cosmic-ray, ...

On the energy loss of the shocks

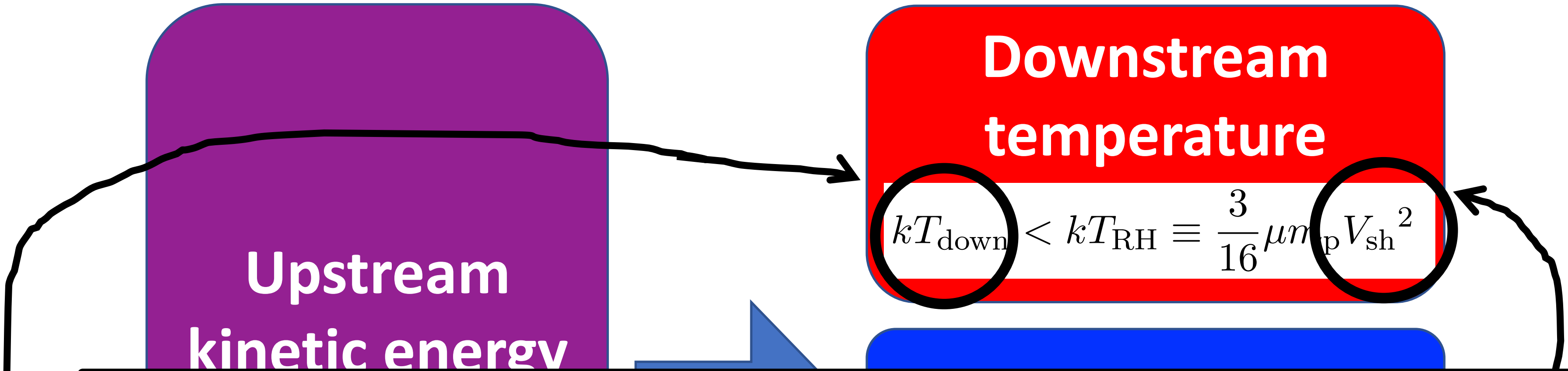


Energy loss rate (Shimoda+ 15)：

$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}}$$

On the energy loss of the shocks

Efficient Acceleration

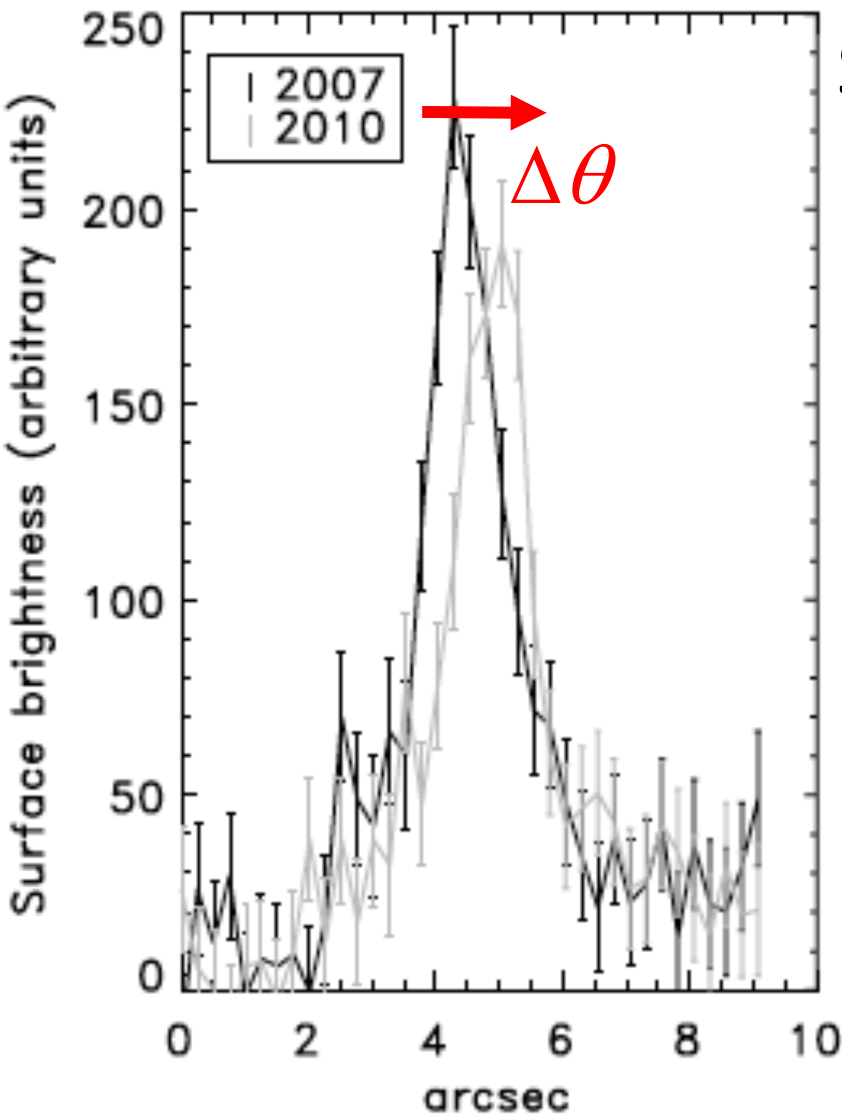


If we measure independently the downstream temperature $T_{\rm down}$ and the shock velocity $V_{\rm sh}$, <u>we can estimate **the energy loss rate as a missing thermal energy.**</u>

Energy loss rate (Shimoda+ 15)：

$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}}$$

Previous works of the loss rate



Helder+ 13 for SNR RCW 86

Shock velocity is measured by **the proper motion $\Delta\theta$.**

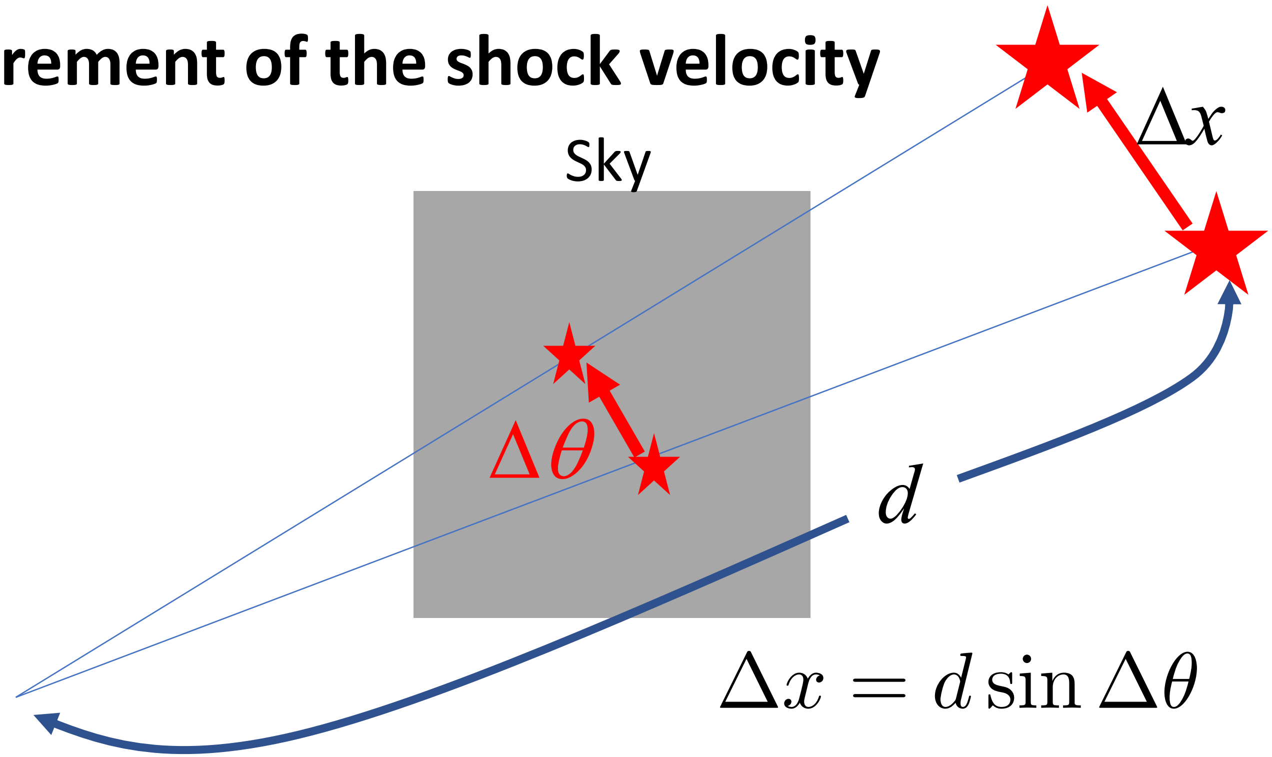
Downstream temperature is measured by the broad Hα.

$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}} = 0.5 \pm 0.3$$

Suggesting the significant energy loss (e.g. Helder+ 09, 13, Shimoda+15, 18)

Problem in the previous estimation

☐Measurement of the shock velocity

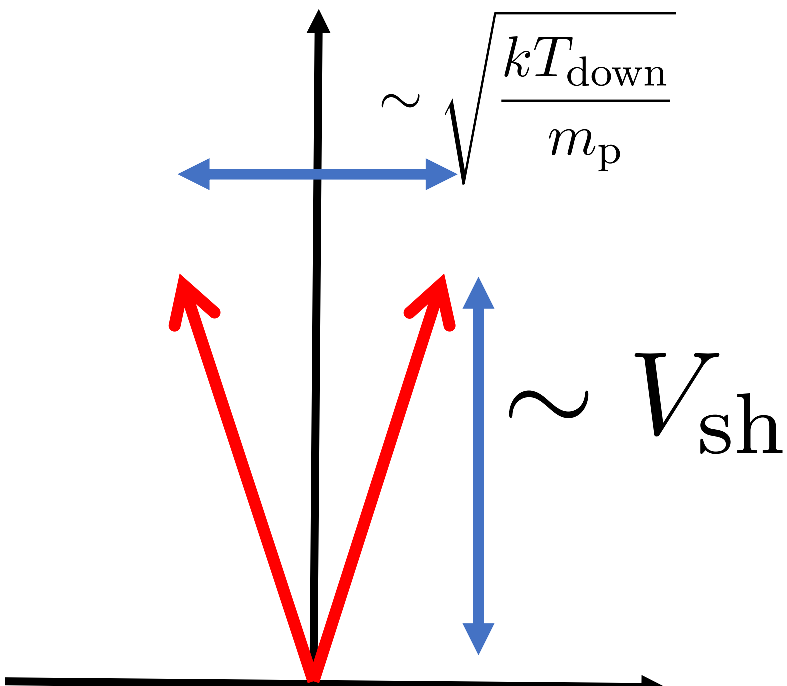


✓<u>In order to derive the shock velocity from the proper motion, **we need a distance to the SNR with high accuracy** (with errors less than 1 %).</u>

Polarized Hα (No cosmic-ray)

✓ **Collision direction seen in the rest frame of hydrogen atoms**

Velocity comp. **normal** to the shock surface



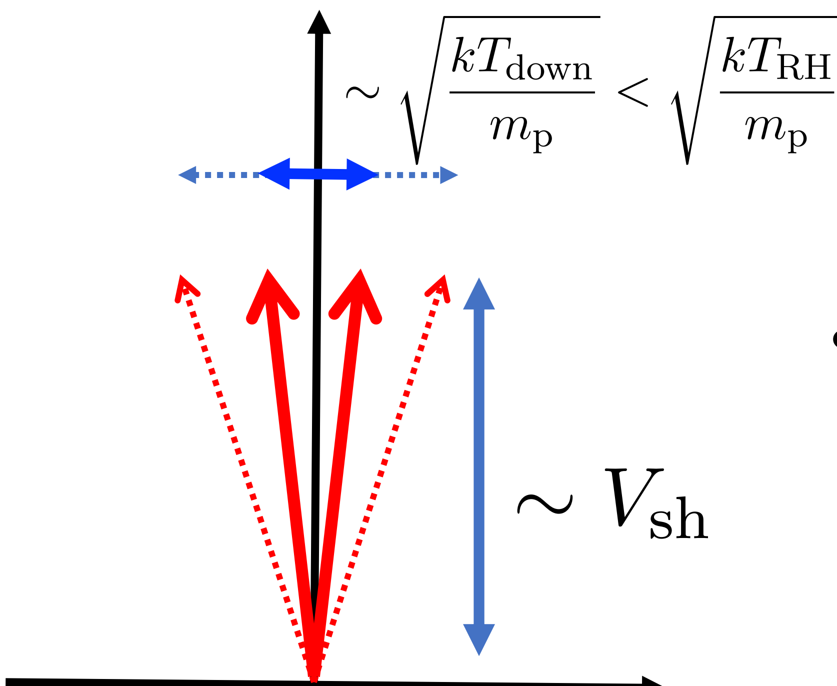
Velocity comp. **parallel** to the shock surface

- In the rest frame of hydrogen atoms (i.e. the upstream frame), the colliding charged particles are seen as a "mildly collimated beam".
- <u>**The "width" of beam is determined by the downstream temperature.**</u>
- The anisotropy of collision yields polarized Hα with a few % degree.

Polarized Hα (with cosmic-ray)

✓ **Collision direction seen in the rest frame of hydrogen atoms**

Velocity comp. **normal** to the shock surface



Velocity comp. **parallel** to the shock surface

- If the shock efficiently accelerates cosmic-rays, then they can escape from the shock, carrying away significant energy.
- As a result, the downstream temperature becomes lower than the adiabatic case, yielding larger anisotropy of collision.
- **Polarization degree increases!**

Polarized Hα (with cosmic-ray)

✓ **Collision direction seen in the rest frame of hydrogen atoms**

Velocity comp. **normal** to

- If the shock efficiently

☐ **In the previous study**, Laming (1990) considered **only Hα emission from shocks without cosmic-rays.**

☐ **In this work**, **updating the atomic data** (e.g. cross sections), we calculate **Hα and Hβ emissions from shocks efficiently accelerating cosmic-rays.**

Velocity comp. **parallel** to the shock surface

- **Polarization degree increases!**

Calculation diagram

Downstream temperatures

$$kT_{\rm p} = \frac{3}{16}(1-\eta)\mu m_{\rm p} V_{\rm sh}^2$$

$$kT_{\rm e} = \beta k T_{\rm p}$$

The downstream proton and electron temperatures are **observable**.

Setting the downstream proton and electron temperatures, and the energy loss rate η, we derive the downstream velocity from the jump conditions for the shock loosing an energy (Cohen+98).

Downstream velocity in the upstream frame

$$u_2 = \left(1 - \frac{1}{R_c}\right)\sqrt{\frac{16}{3}\frac{kT_{\rm p}}{(1-\eta)\mu m_{\rm p}}}$$

Distribution function of protons and electrons

$$f_q(\boldsymbol{v_q}, \boldsymbol{u_2}) = \left(\frac{m_q}{2\pi k T_q}\right)^{\frac{3}{2}} \exp\left(-\frac{m_q(\boldsymbol{v_q}-\boldsymbol{u_2})^2}{2kT_q}\right)$$

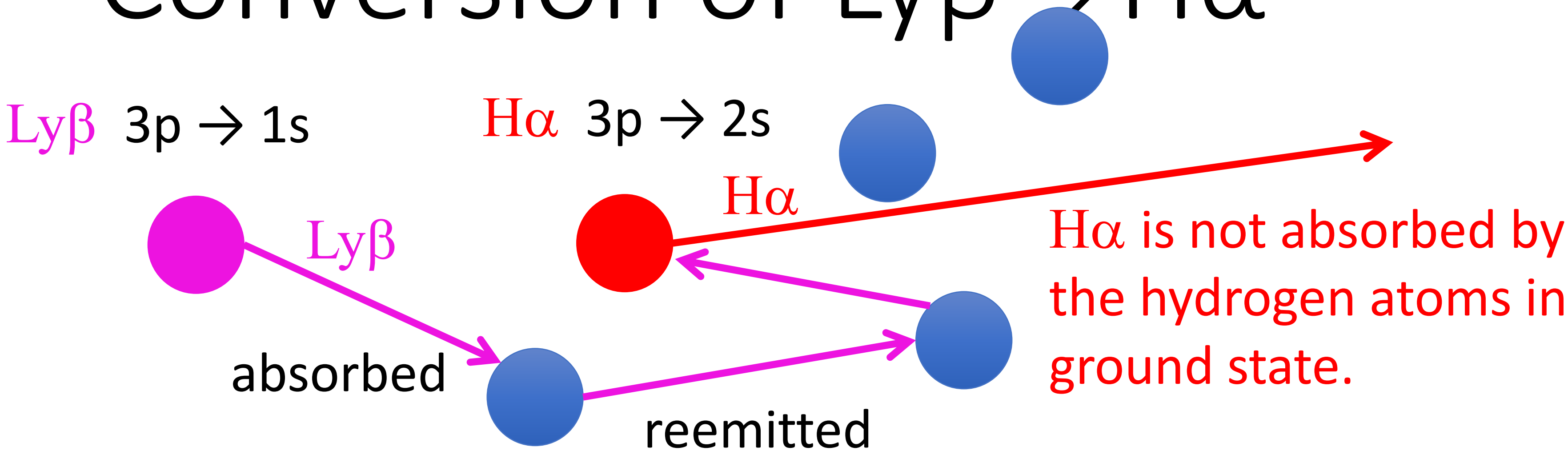
$$Q \equiv I_{\parallel} - I_{\perp}$$

$$I \equiv I_{\parallel} + I_{\perp}$$

$$\Pi \equiv \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}}$$

※ Parallel and Perpendicular are defined respecting to the shock surface.

Conversion of Lyβ→Hα



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

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

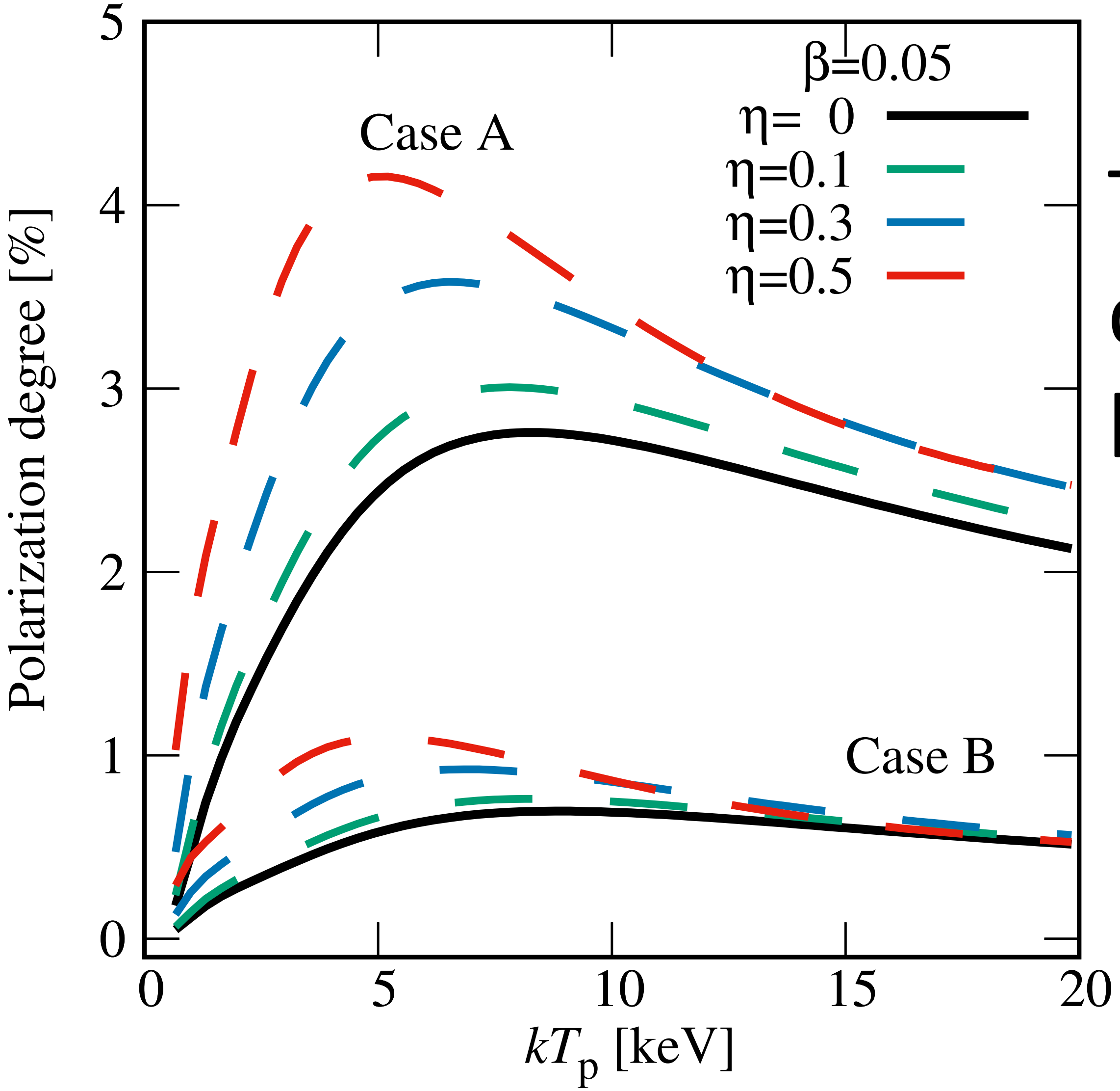
c) Eventually, Lyβ is converted to <u>**Hα** due to 3p to 2s transition</u>.

Optically thin for Lyβ is "Case A"

Optically thick for Lyβ is "Case B"

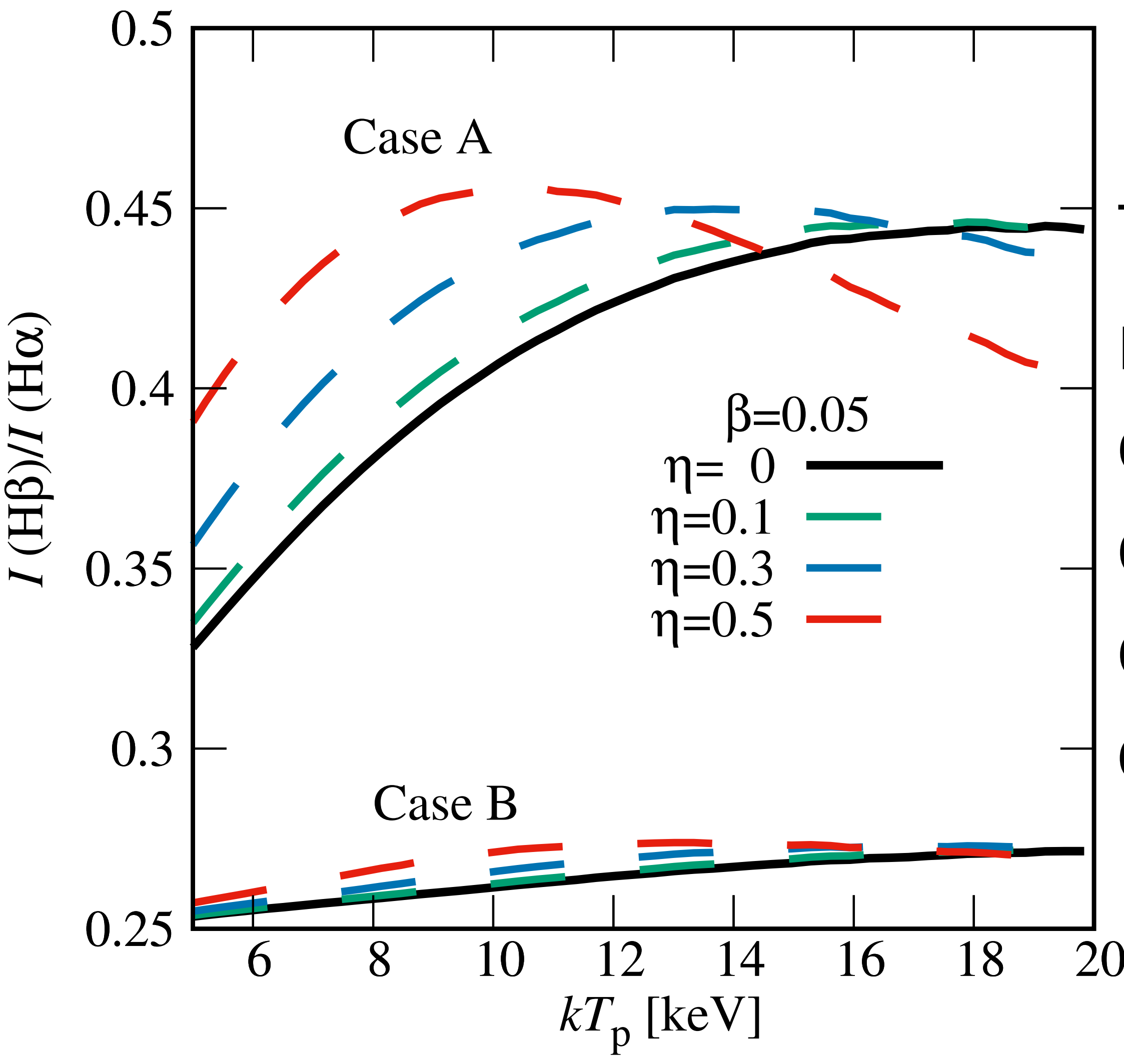
We assume the converted Hα photons are **<u>unpolarized</u>**.

Polarization of Hα: Q(Hα)/I(Hα)



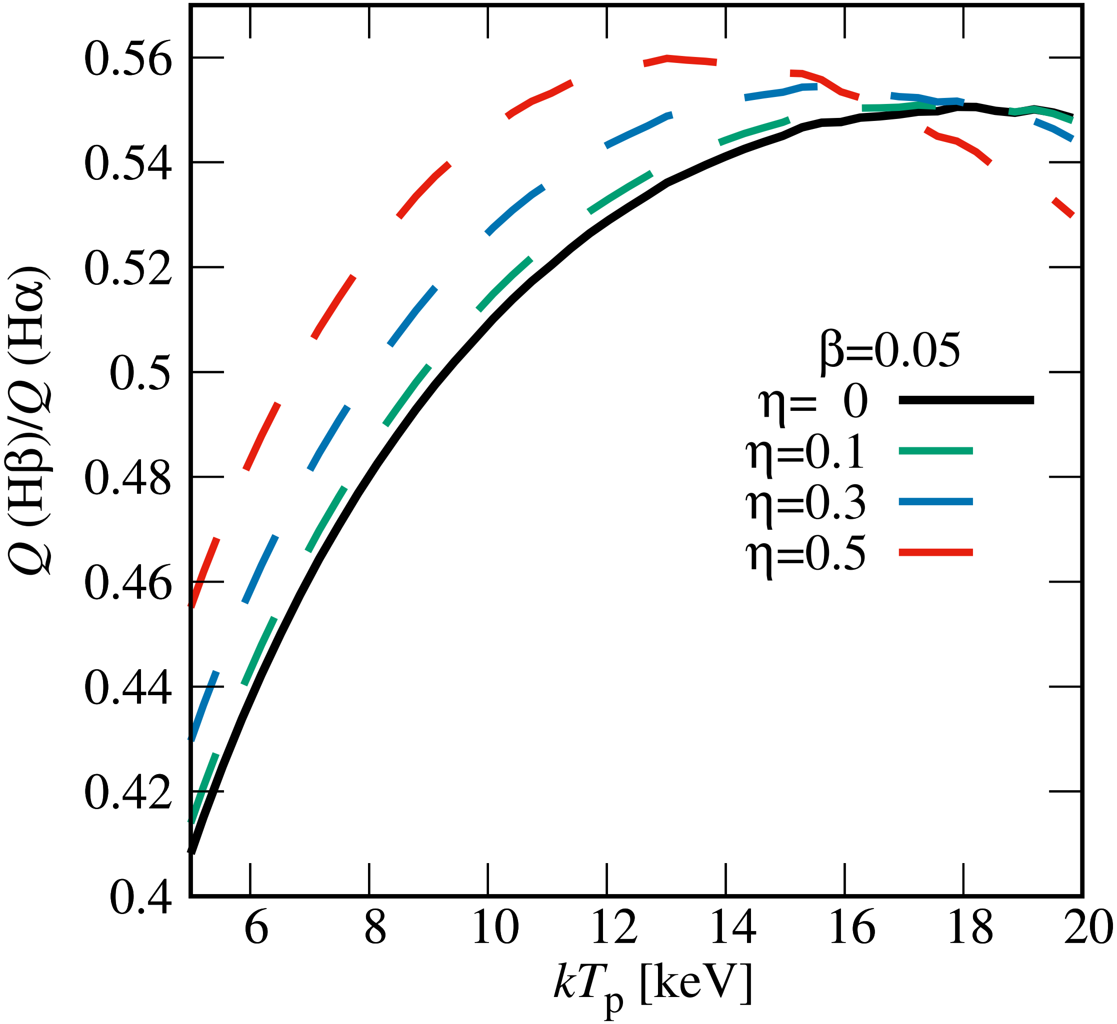
The degree depends on the loss rate η.

Ratio of total intensity: $I(\mathrm{H}\beta)/I(\mathrm{H}\alpha)$



The total intensity ratio depends also on the loss rate due to the difference of cross sections.

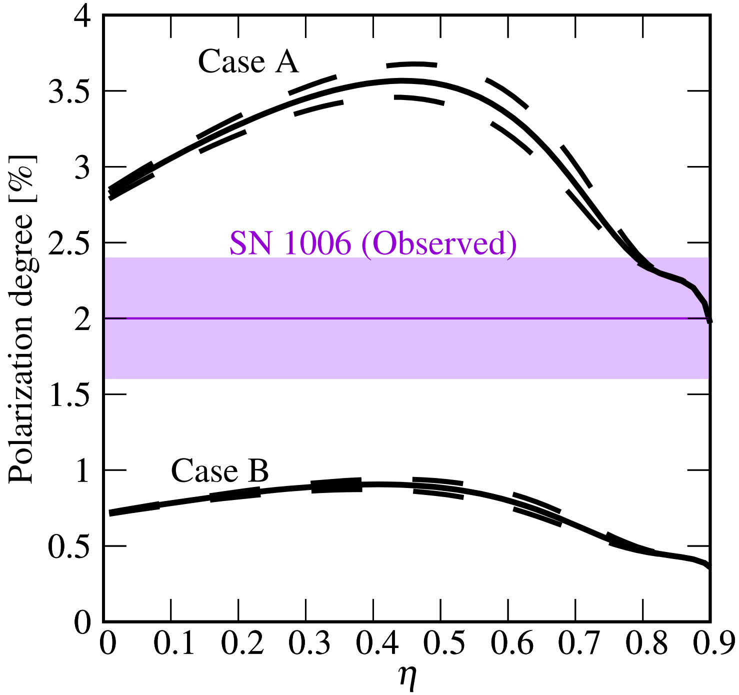
Ratio of polarized intensity: $Q(\mathrm{H\beta})/Q(\mathrm{H\alpha})$



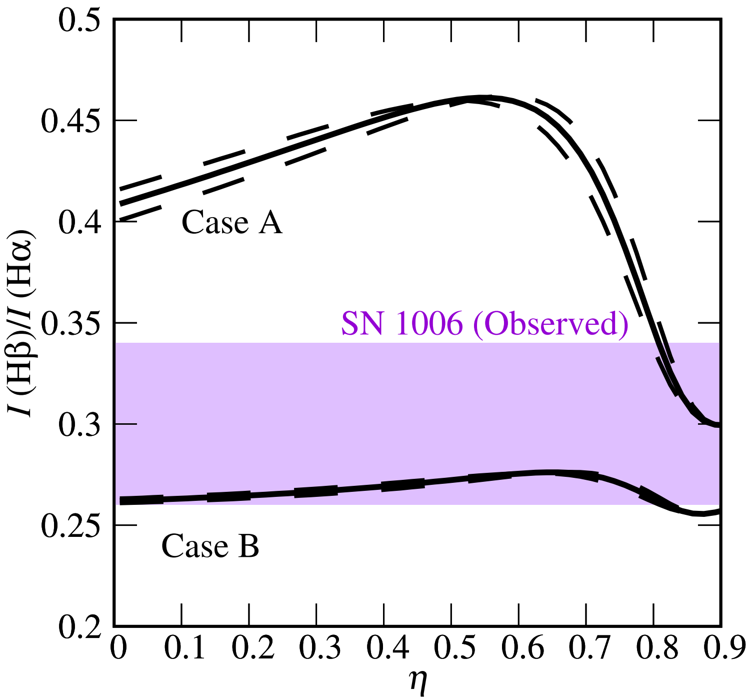
The polarized intensity ratio depends also on the loss rate due to the difference of cross sections.

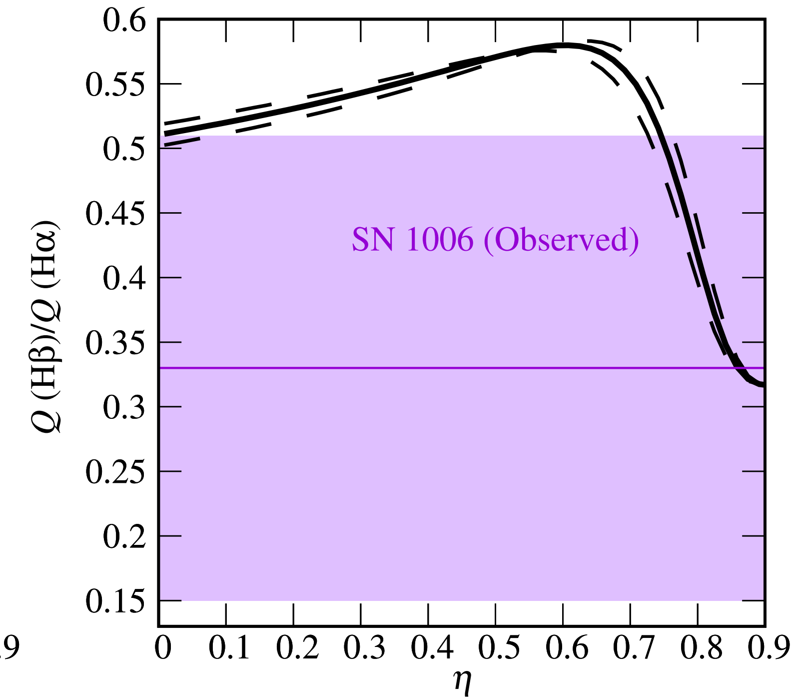
<u>**It does not depend on Case A or B.**</u>

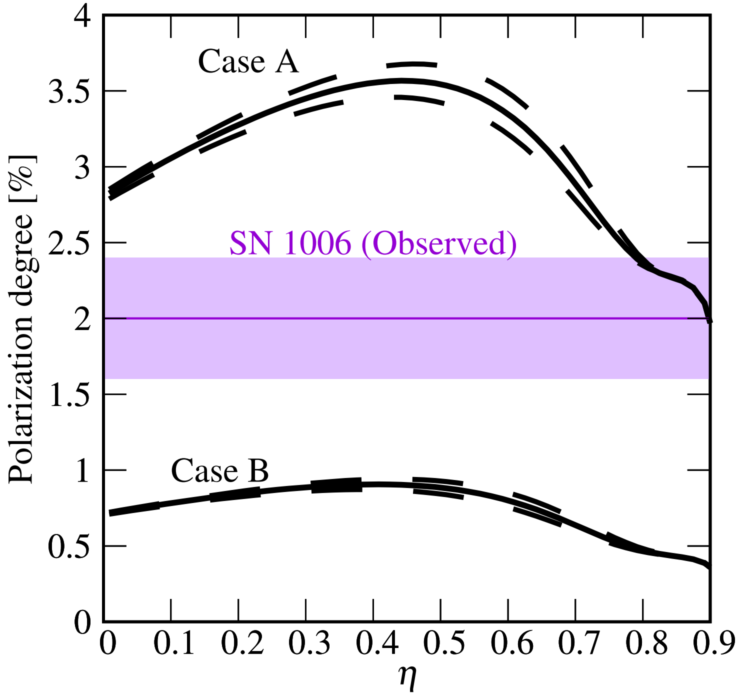
Comparison with the observation: vs. η



The loss rate is not constrained due to the errors of observations.







Comparison with the observation: vs. η

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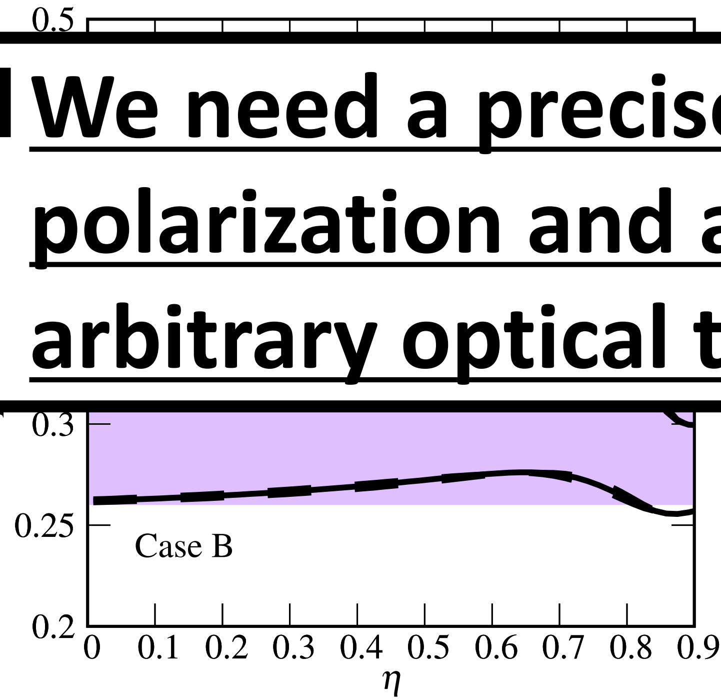

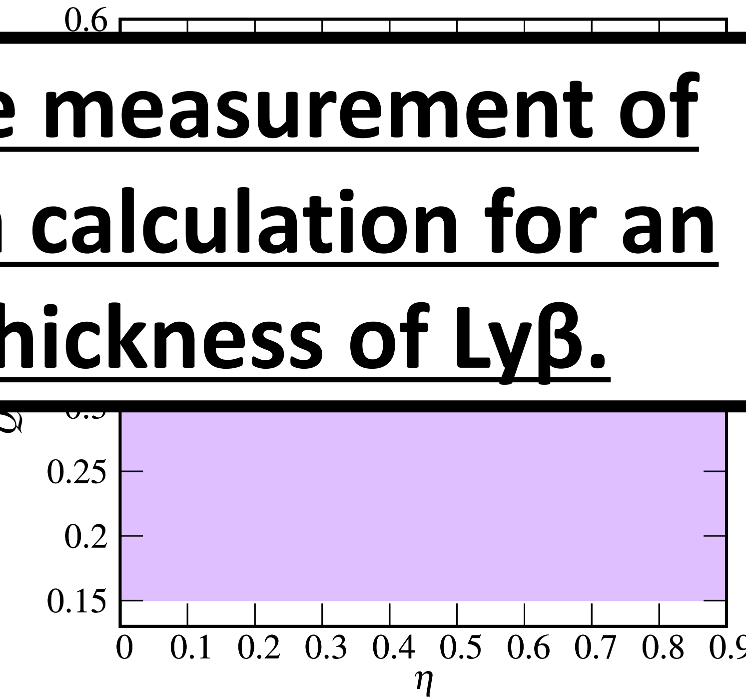

- ☐ <u>**We need a precise measurement of polarization and a calculation for an arbitrary optical thickness of Lyβ.**</u>

Applications

Comparison of the proper motion and the downstream temperature **had been relied on for an estimation of distance to the SNR (Chevalier+80).**

1980~

The significant energy loss of shock was suggested (e.g. Hughes+00, Warren+05, Helder+09,13). **The previous estimation of distance became suspicious.**

2000~

We can estimate the distance by combination of the loss rate by polarization and the proper motion.

present

Once we determine the distance and η

Downstream temperature

$$kT_{\rm down} < kT_{\rm RH} \equiv \frac{3}{16}\mu m_{\rm p} {V_{\rm sh}}^2$$

Cosmic-ray Acceleration

Downstream kinetic energy

$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}}$$

- Cosmic-ray protons : $\eta_{\rm p}$

$$p_{\rm CR} + p_{\rm thermal} \rightarrow \pi^0 \rightarrow 2\gamma$$

Number of thermal nuclei can be derived from Hα surface brightness with the calculation for an arbitrary optical thickness of Lyβ (e.g. Chevalier+80).

- Cosmic-ray electrons : $\eta_{\rm e}$

$$e_{\rm CR} + \gamma_{\rm CMB} \rightarrow \gamma_{\rm IC}$$

known

- Generation of Magnetic field: $\eta_{\rm B}$

Related to Synchrotron surface brightness $L_{\rm syn}$

We can **observationally** constraint the energy budget of collisionless shock in detail.

Once we determine the distance and η

Downstream temperature

$$kT_{\rm down} < kT_{\rm RH} \equiv \frac{3}{16}\mu m_{\rm p} {V_{\rm sh}}^2$$

Cosmic-ray Acceleration

Downstream kinetic energy

$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}}$$

$$\eta = \eta_{\rm e} + \eta_{\rm p} + \eta_{\rm B}$$

$$L_\gamma = L_{\rm IC}(\eta_{\rm e}) + L_{\pi^0}(\eta_{\rm p}) = a\eta_{\rm e} + b\eta_{\rm p}$$

$$L_{\rm syn} = c\eta_{\rm e}\eta_{\rm B}$$

Surface brightness are detectable

η and coefficients a, b, and c are known

We have three equations with three unknowns!

We can **observationally** constraint the energy budget of collisionless shock in detail.

Summary of this work

- We have calculated the polarized Balmer line emissions from the shocks efficiently accelerating non-thermal particles.
- We have shown that **the energy loss rate of the shocks resulting from the particle acceleration** can be measured by the polarization degree.
- Our calculation will be applied for **an estimation of a distance from the acceleration sites**.