On Measuring the CR Production Rate in SNR Shocks by Polarized Balmer Line Emission

cf.: Shimoda et al. 2018, MNRAS, 473
Shimoda & Laming 2019, MNRAS, 485
Shimoda et al., ICRC 2019, PoS 424

Jiro Shimoda[1]

Yutaka Ohira[2]
Ryo Yamazaki[2]
J. Martin Laming[3]
Satoru Katsuda[4]

1. Tohoku Univ.
2. Aoyama Gakuin Univ.
3. NRL
4. Saitama Univ.

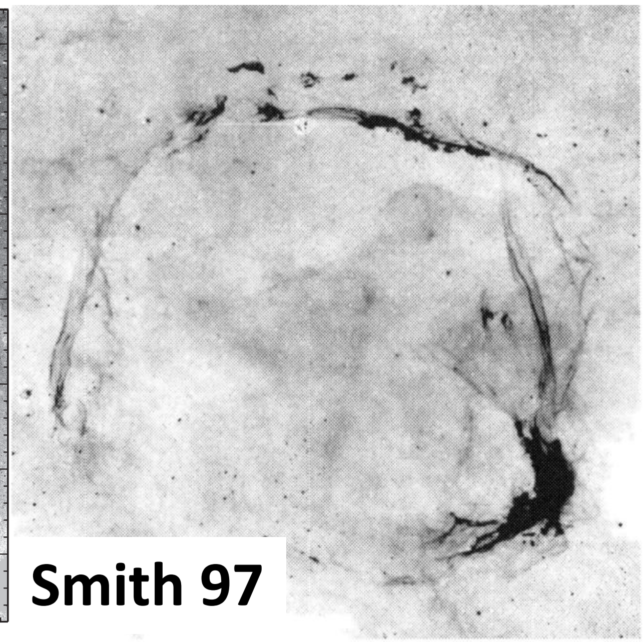
ICRC 2019, Wisconsin, July 30

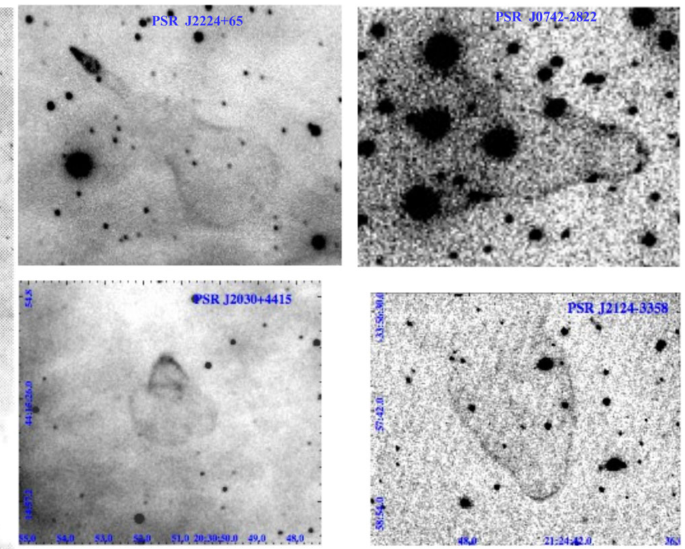
Summary of this work

- We have calculated the polarized Balmer line emissions from the collisionless shocks efficiently accelerating CRs.
- **<u>The energy loss rate of the shocks due to the CR acceleration</u>** can be measured by the polarization degree.
- Our results suggest a sizable loss rate for SN 1006.

Balmer Line Emissions from Collisionless Shocks


Winkler+14


Smith 97



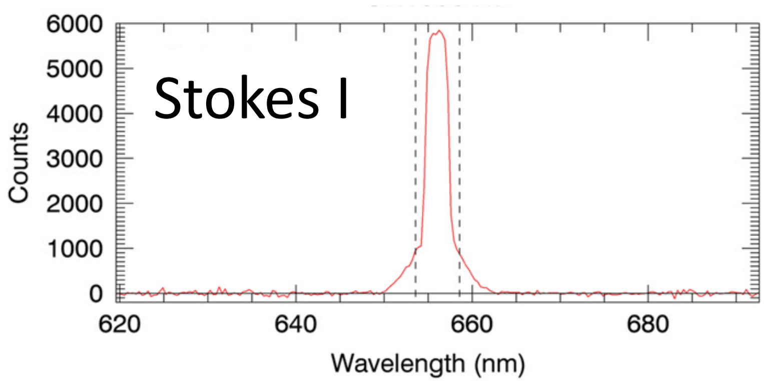
Figures from Morlino+15

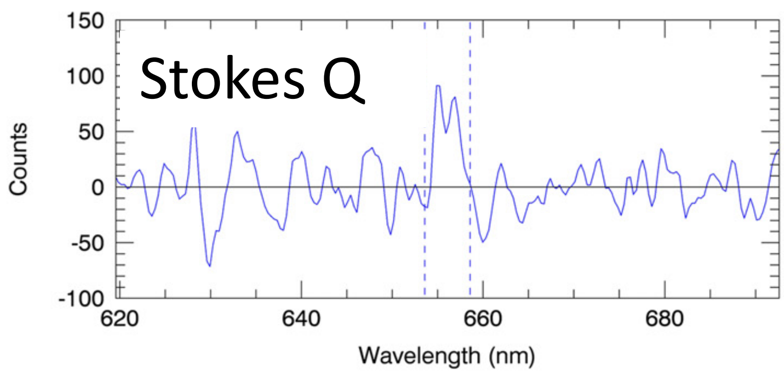
Supernova Remnants (SNRs)

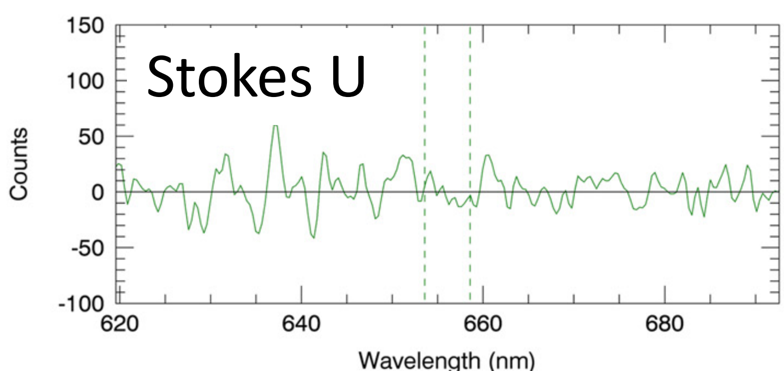
Pulsar Wind Nebulae

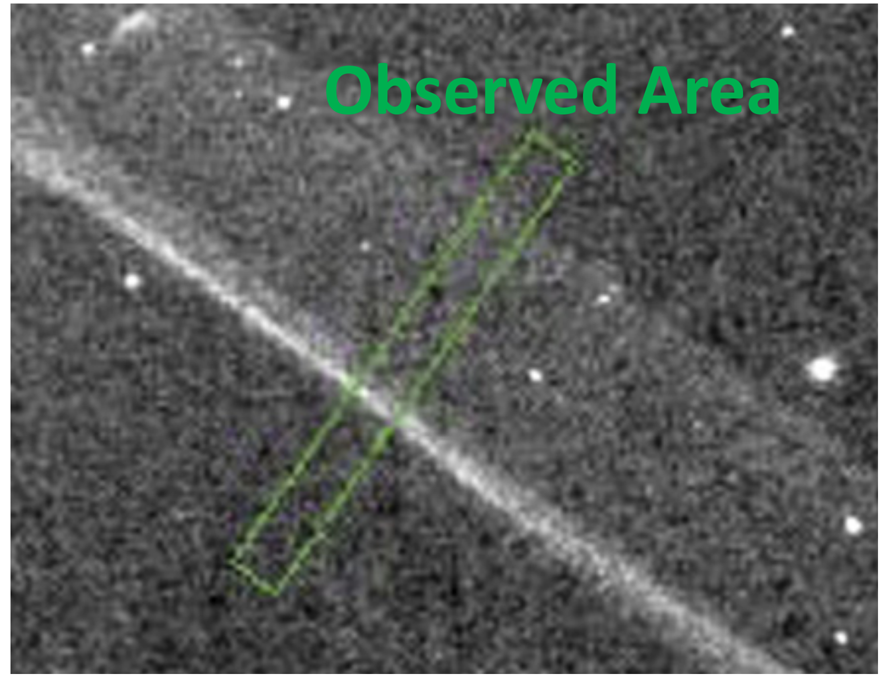
Balmer line emissions (especially Hα) are ubiquitously seen in collisionless shocks propagating into the ISM.

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



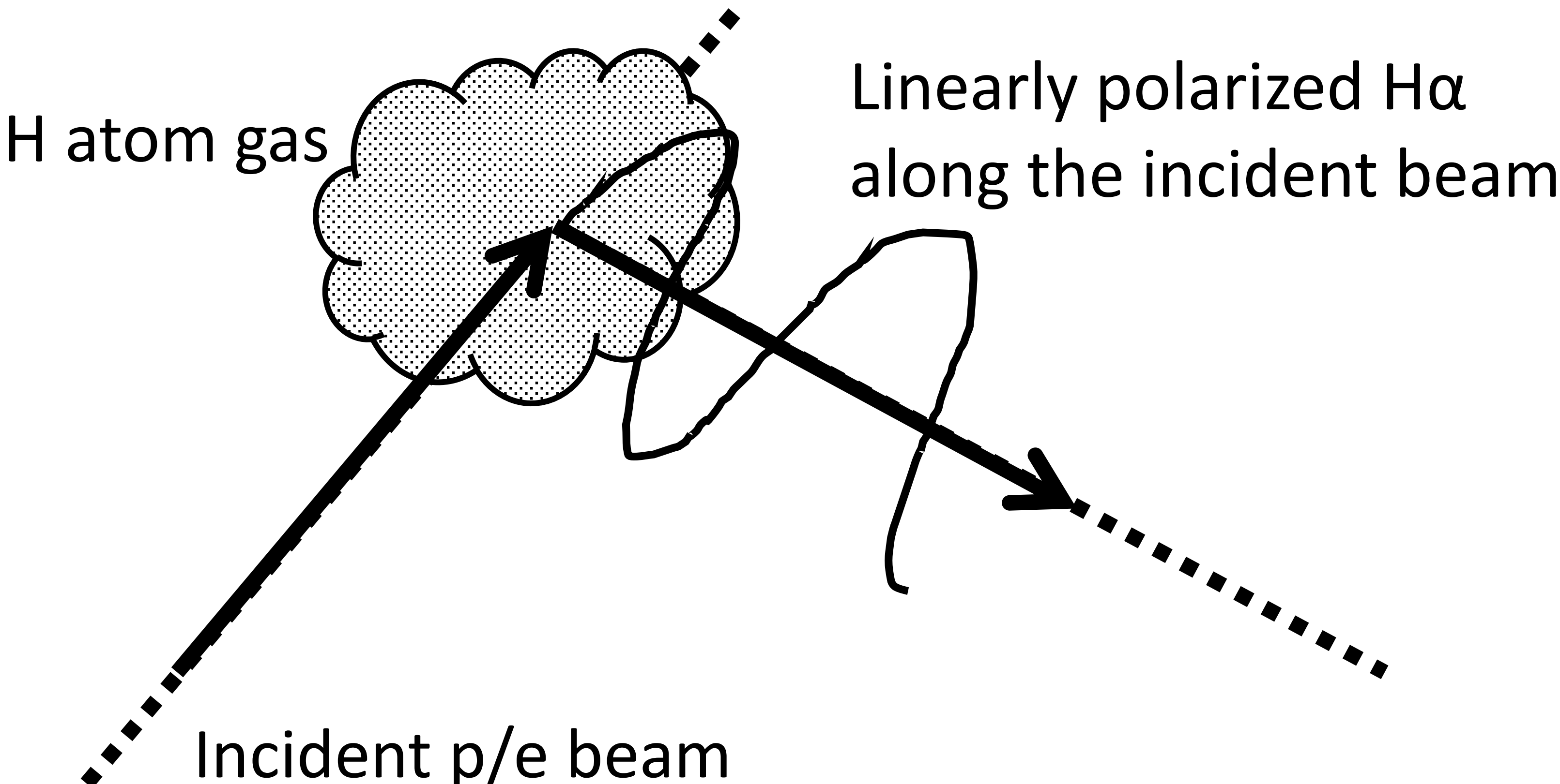






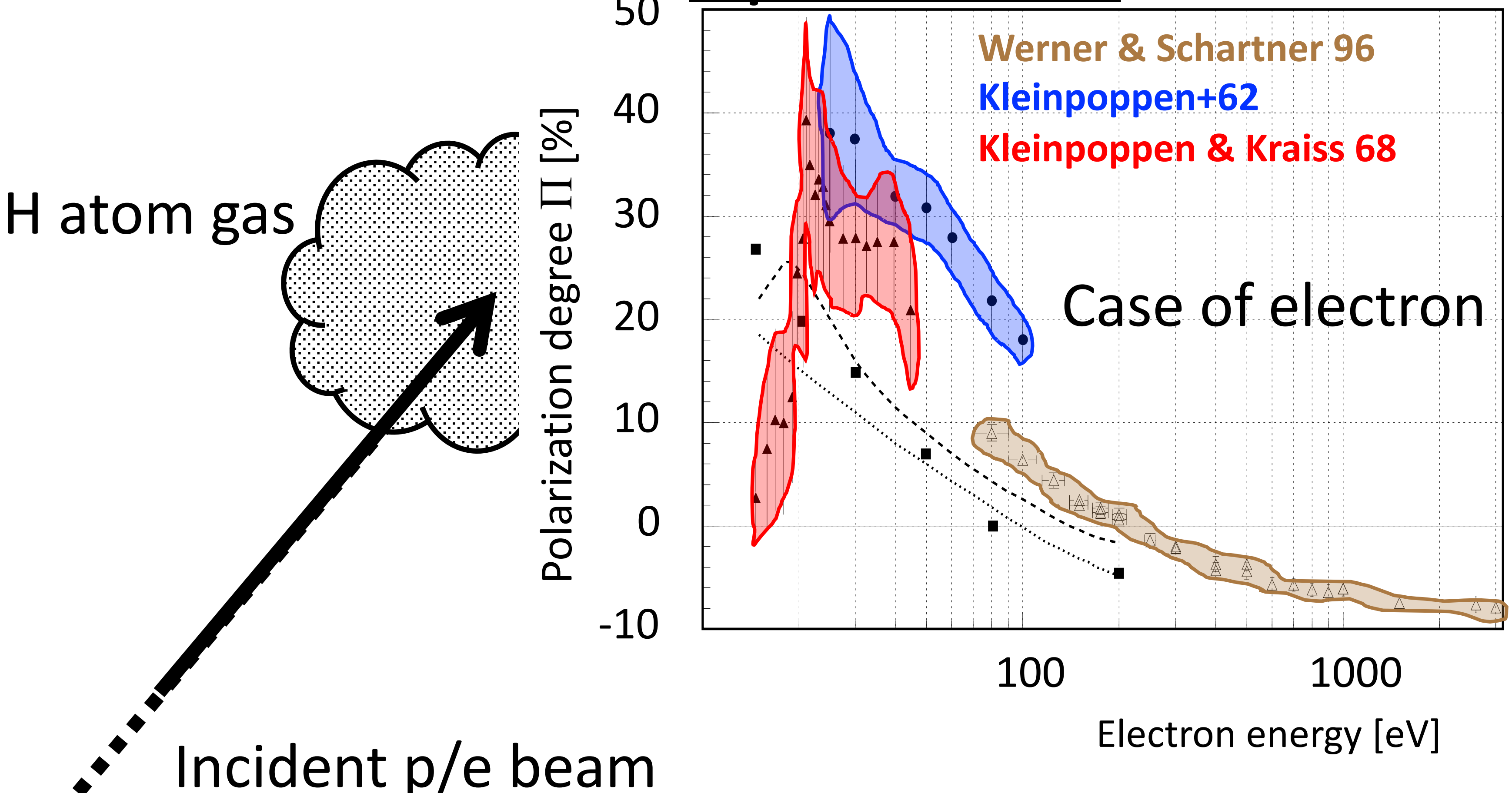
- **Linear Polarization**
- **Polarization angle： perpendicular to the shock**
- **Degree： 2.0 ± 0.4 %**

Polarized Hα in **Experiment**



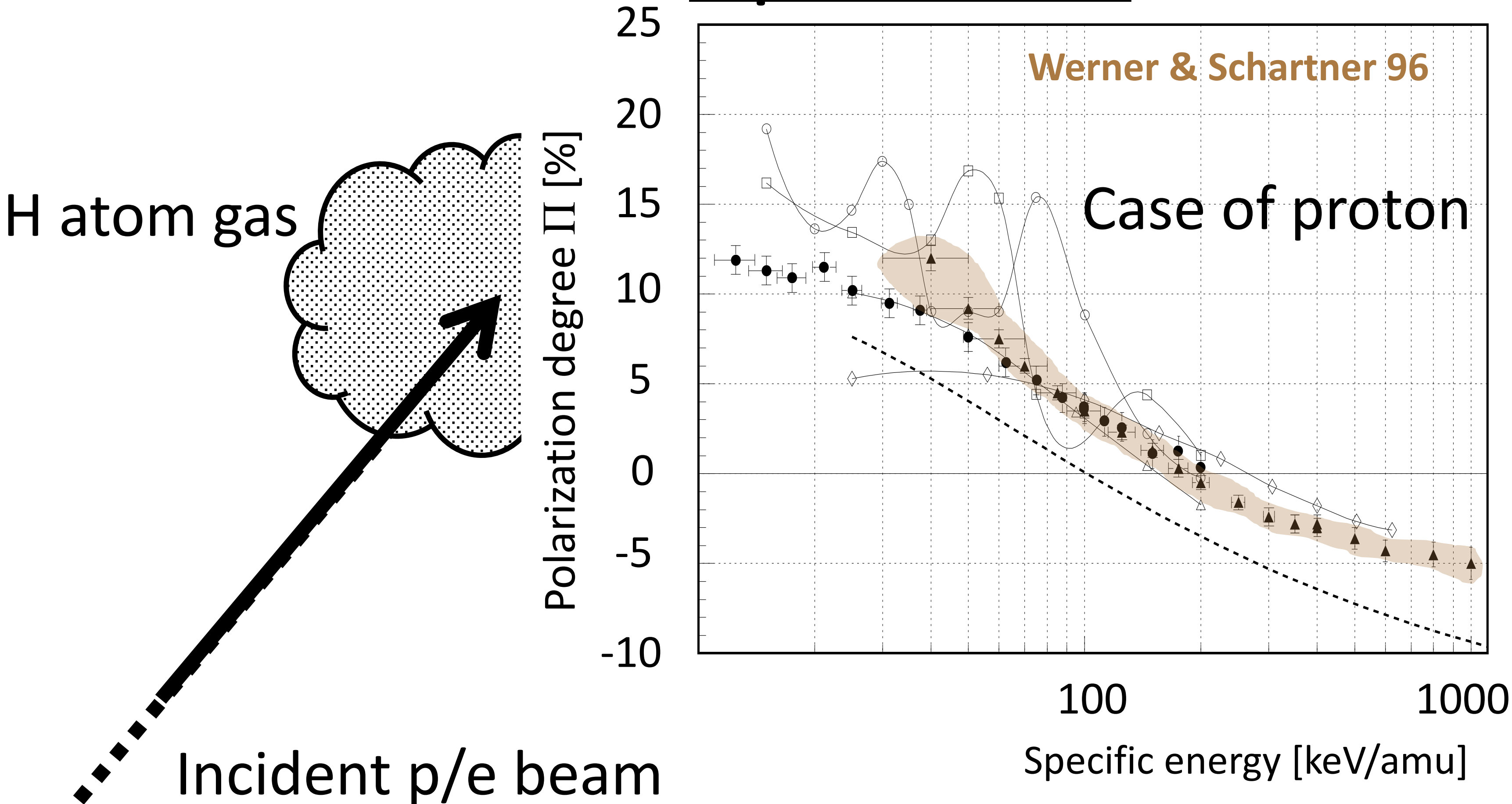
In the experiments, the proton/electron beam excites the H atoms, resulting in linearly polarized Hα along the incident beam direction.

Polarized Hα in Experiment



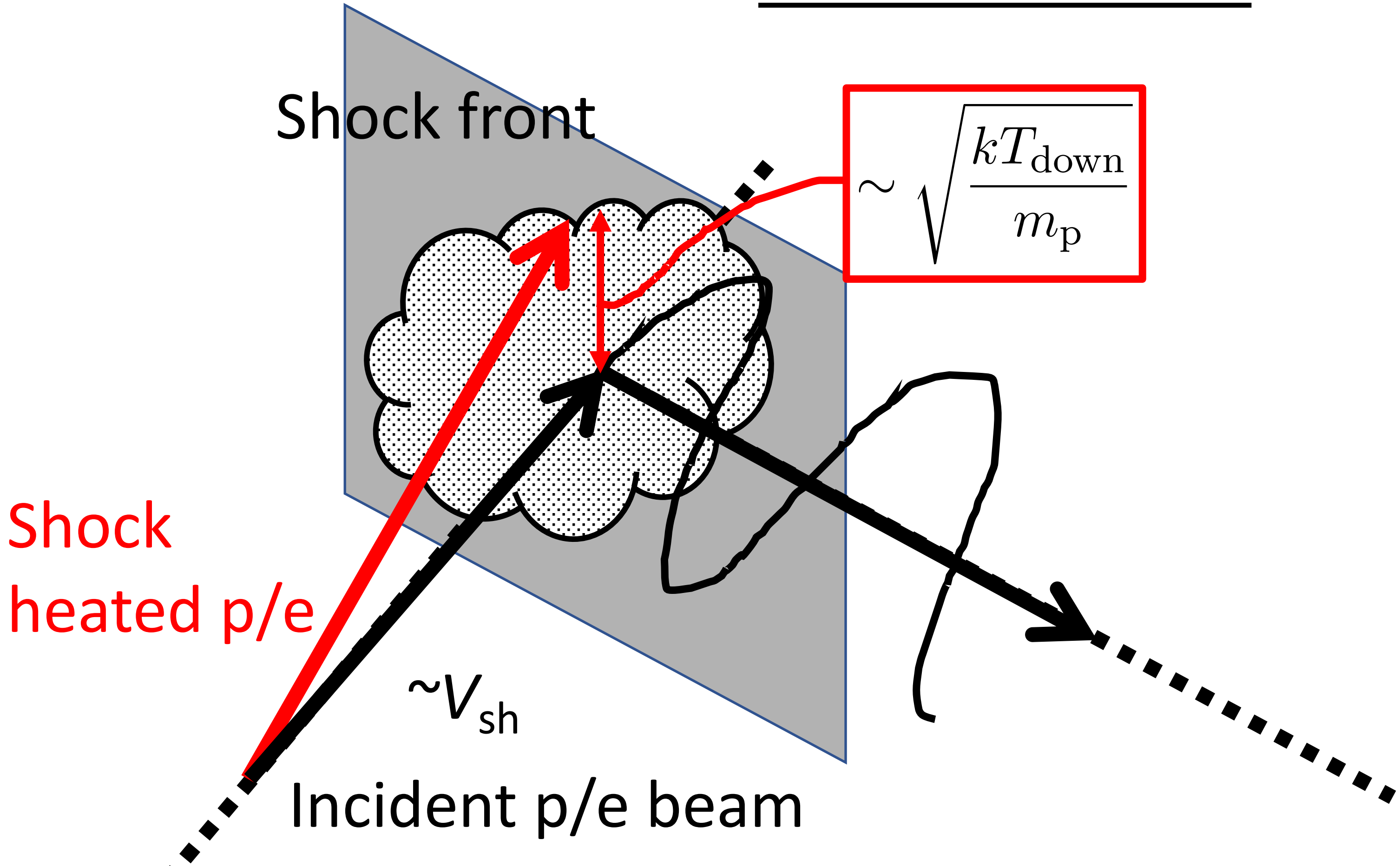
In the experiments, the proton/electron beam excites the H atoms, resulting in linearly polarized Hα along the incident beam direction.

Polarized Hα in Experiment



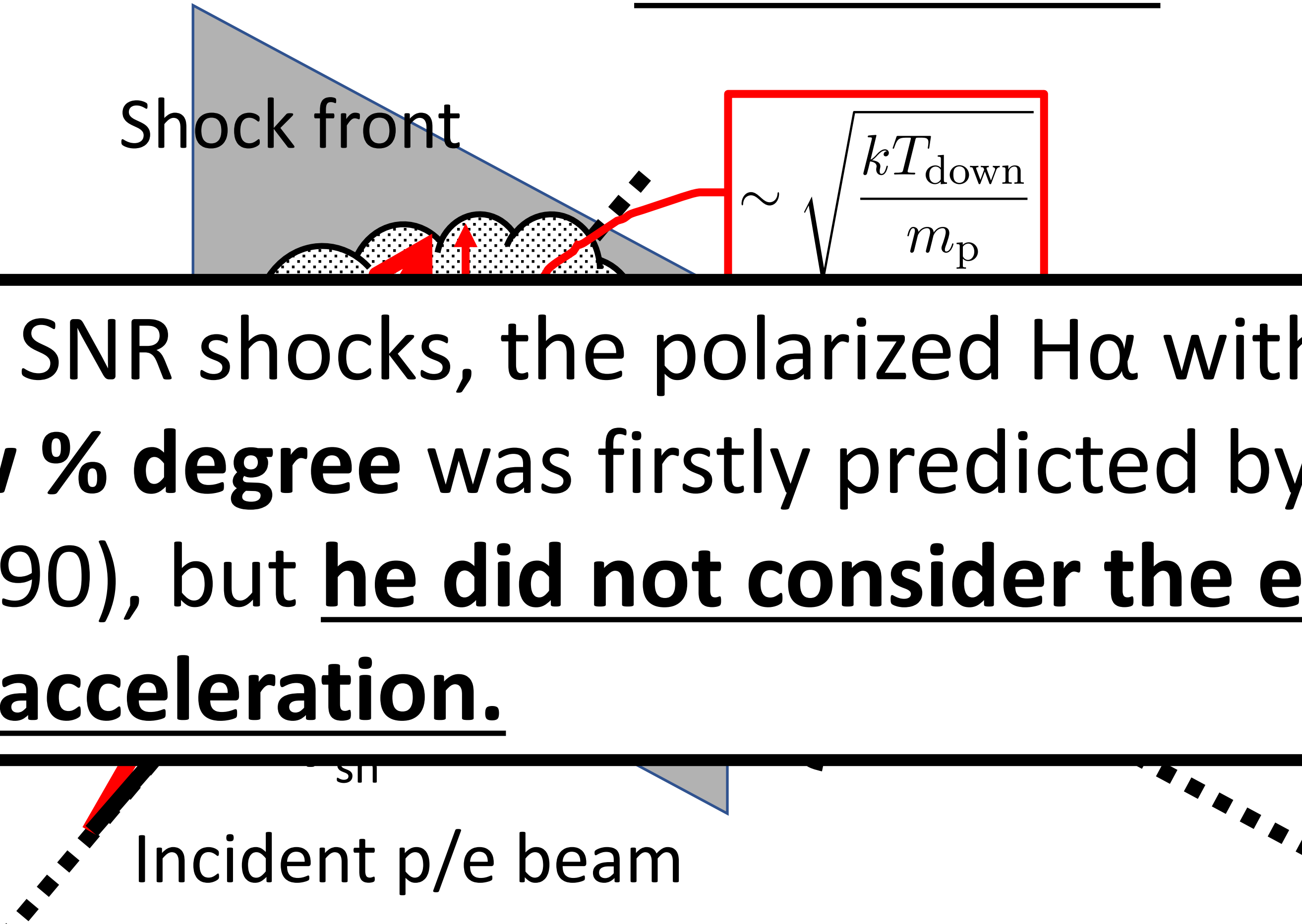
In the experiments, the proton/electron beam excites the H atoms, resulting in linearly polarized Hα along the incident beam direction.

Polarized Hα in SNR shocks



- In the SNR shocks, since the shock heated proton/electron also excites the H atoms, **the net linear polarization of Hα is depolarized**.

Polarized Hα in **SNR shocks**

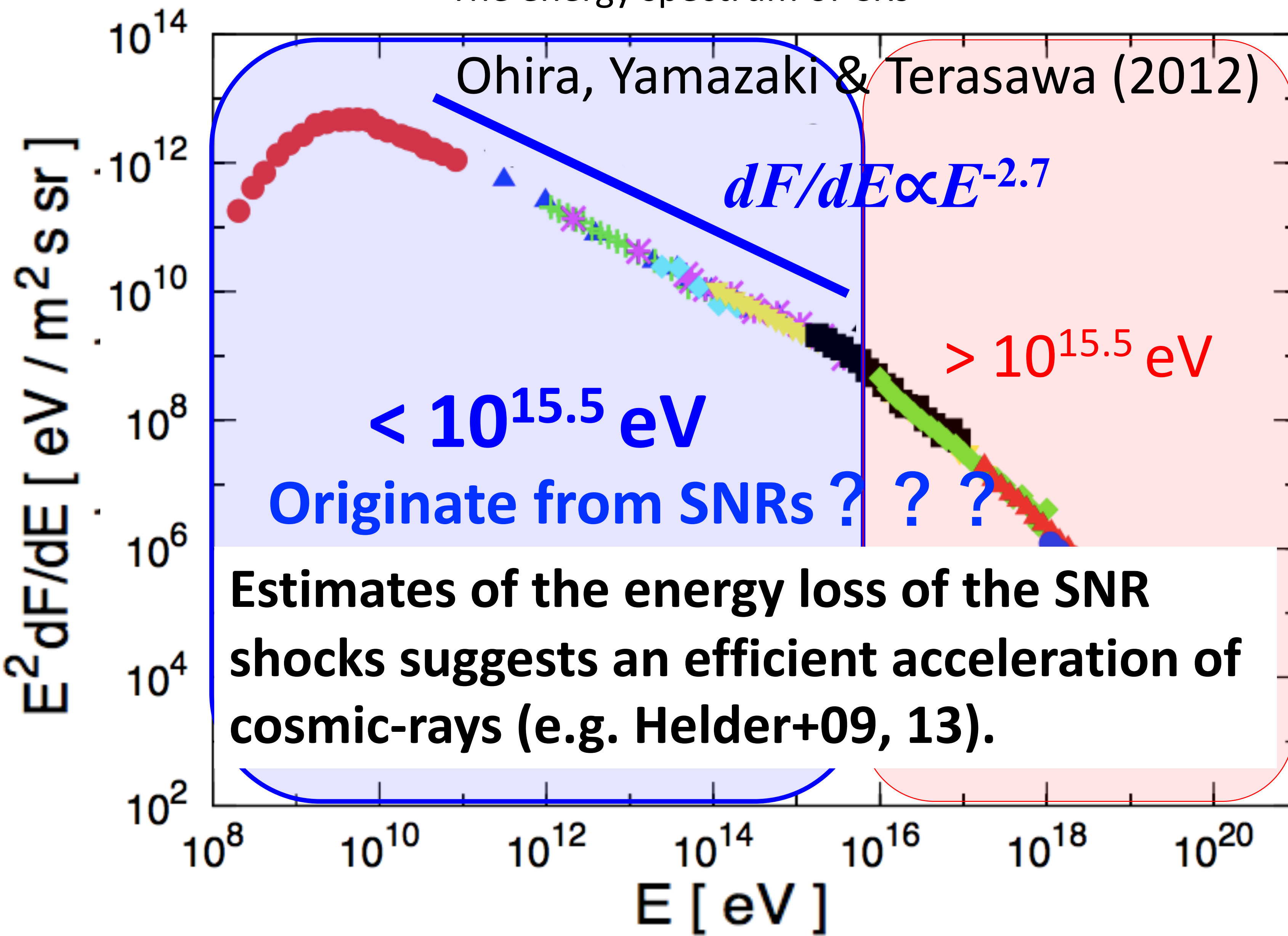


- For SNR shocks, the polarized Hα with **a few % degree** was firstly predicted by Laming (1990), but **he did not consider the effects of CR acceleration.**

- In the SNR shocks, since the shock heated proton/electron also excites the H atoms, **the net linear polarization of Hα is depolarized**.

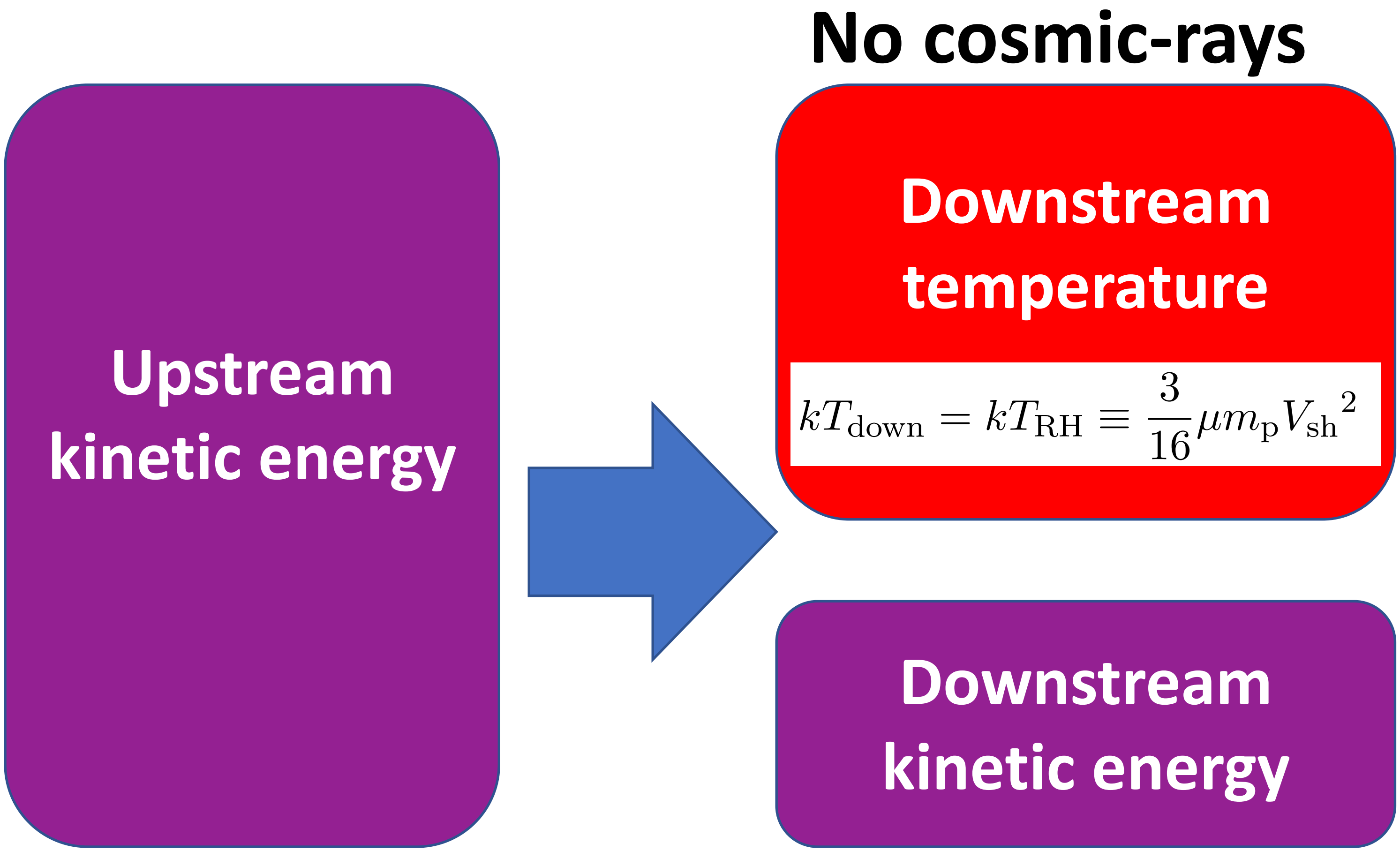
Cosmic Rays

The energy spectrum of CRs



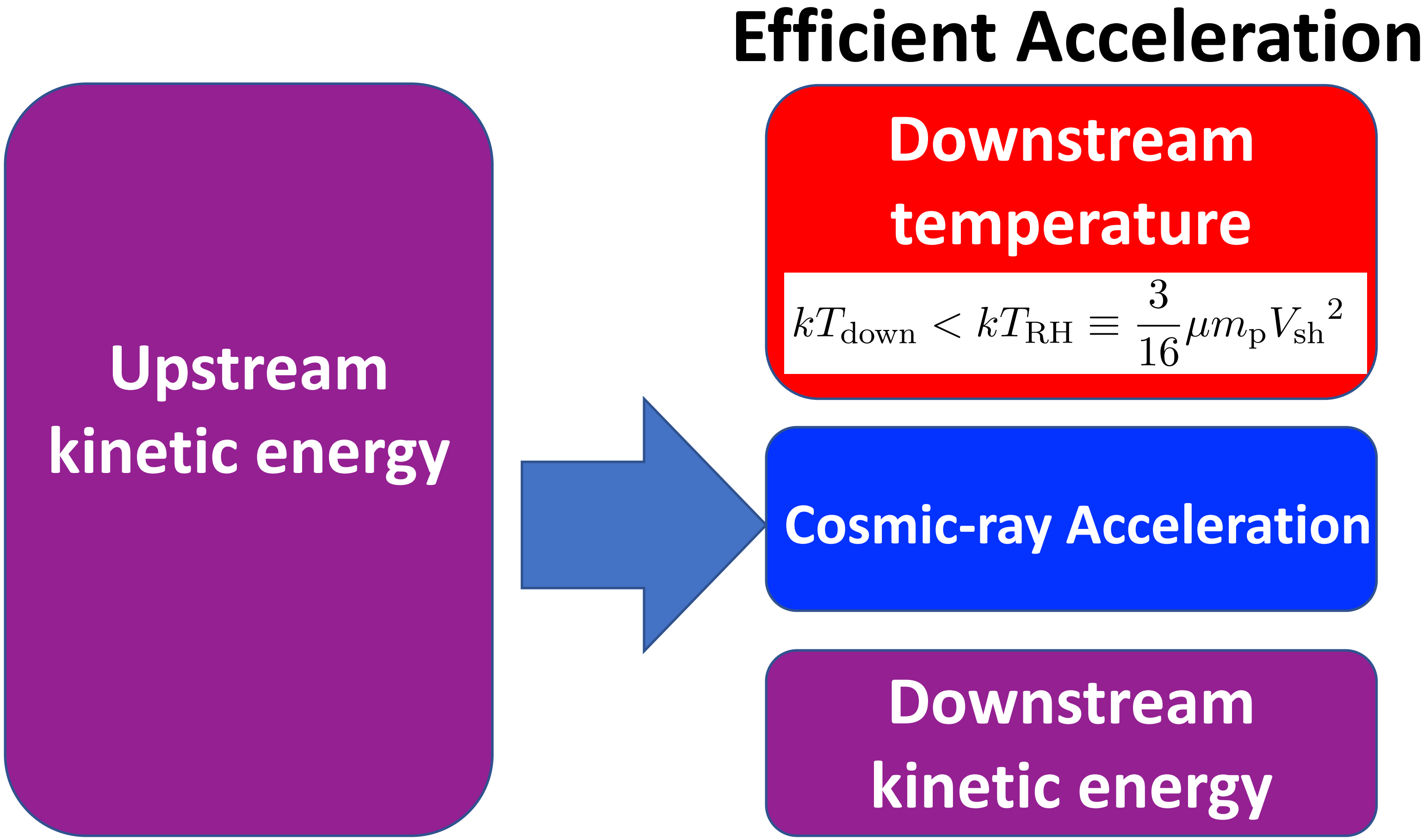
Estimates of the energy loss of the SNR shocks suggests an efficient acceleration of cosmic-rays (e.g. Helder+09, 13).

On the energy loss of the shocks



If the shock accelerates cosmic-ray, …

On the energy loss of the shocks

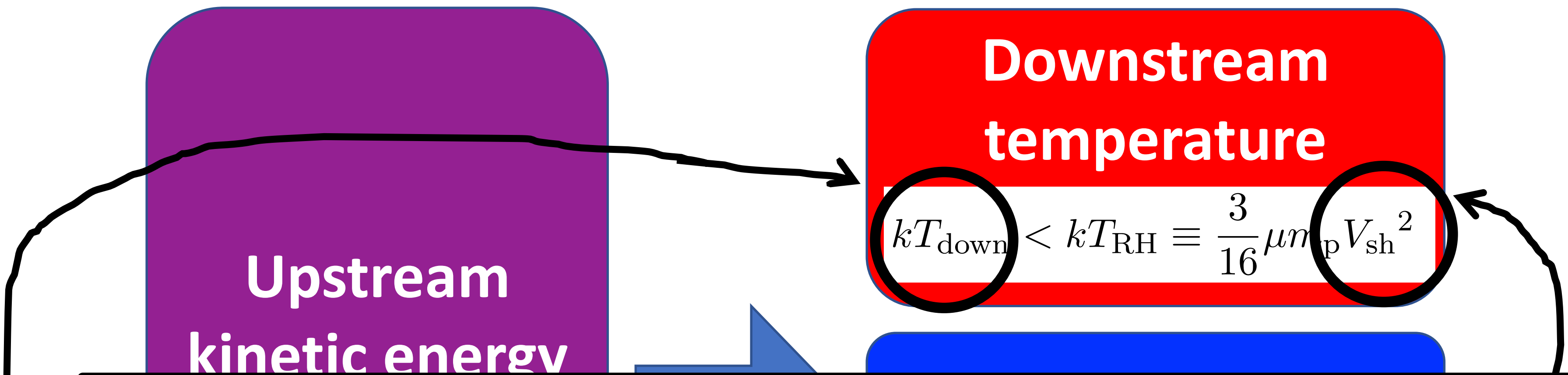


Energy loss rate (Shimoda+ 15)：

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

On the energy loss of the shocks

Efficient Acceleration

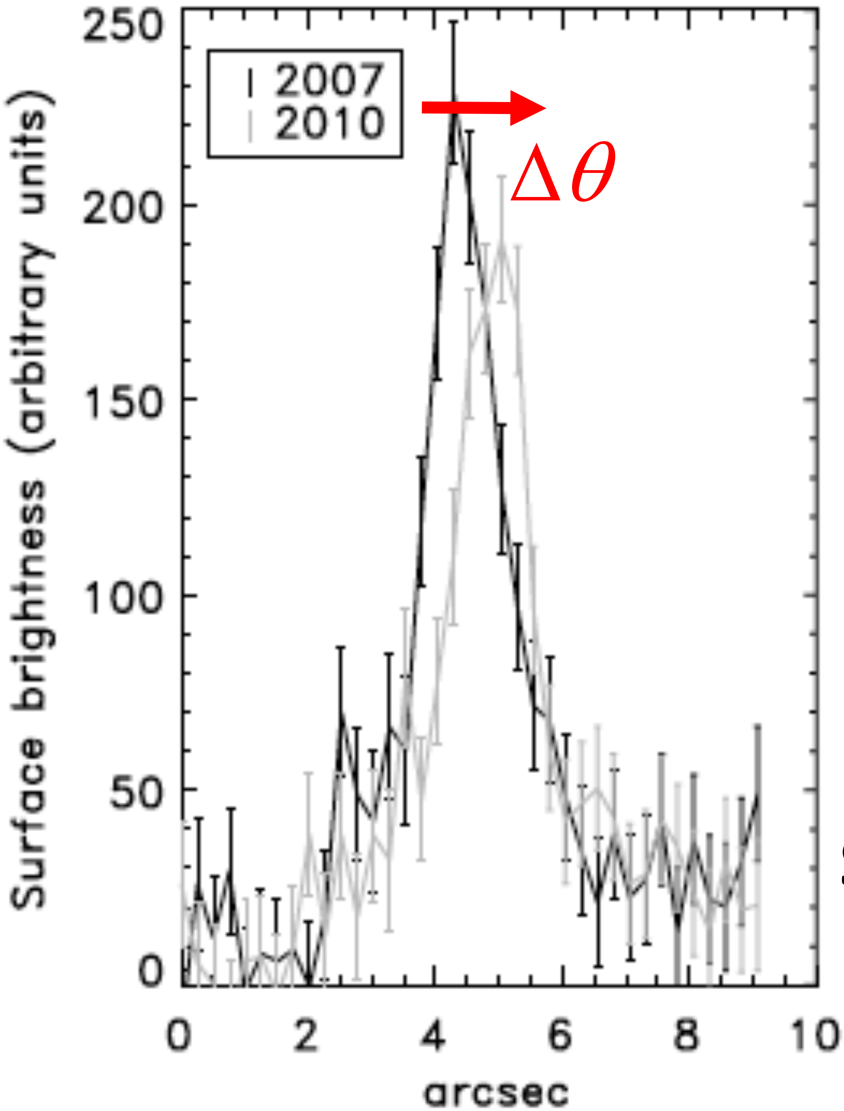


If we measure independently the downstream temperature T_{down} and the shock velocity V_{sh}, we can estimate **the energy loss rate as a missing thermal energy.**

Energy loss rate (Shimoda+ 15)：

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

Previous estimates of the loss rate



Helder+ 13 for SNR RCW 86

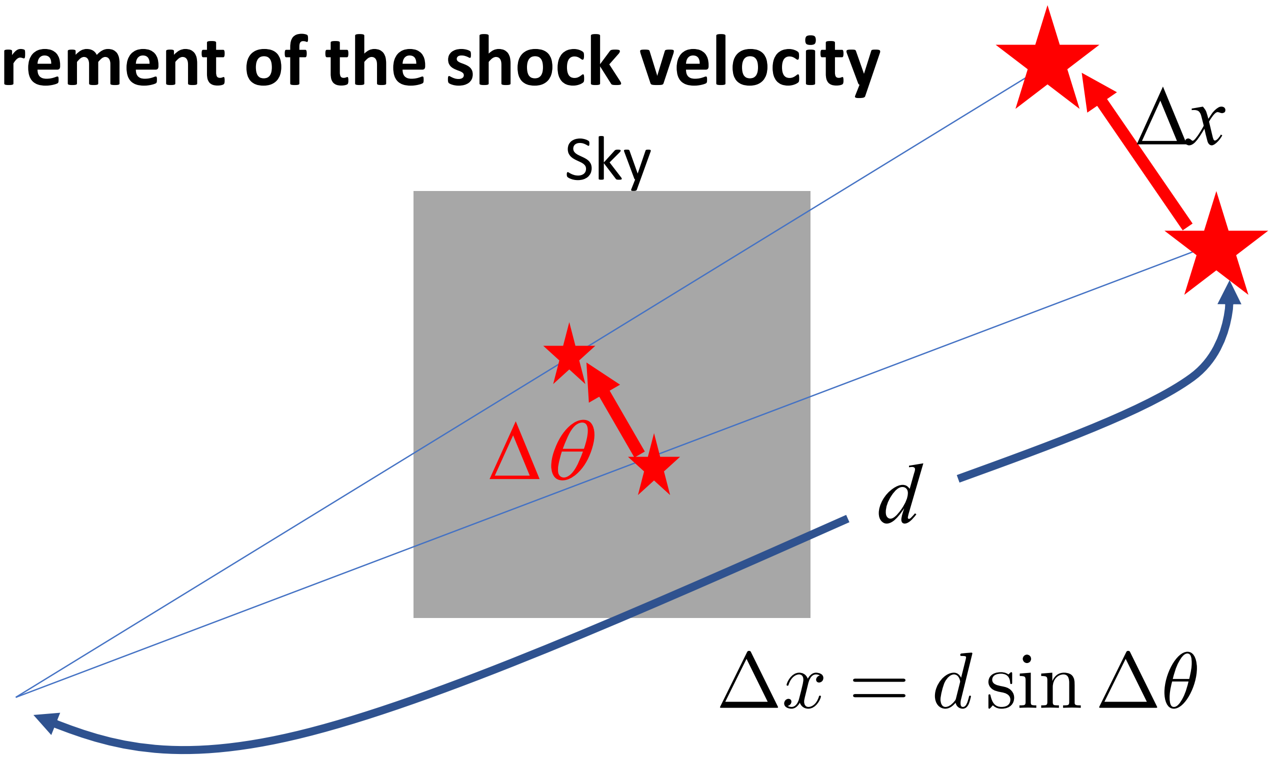
Shock velocity is measured by **the expansion speed of SNR** (the proper motion $\Delta\theta$).

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

Suggesting the significant energy loss @ RCW 86 (e.g. Helder+ 09, 13, Shimoda+15, 18)

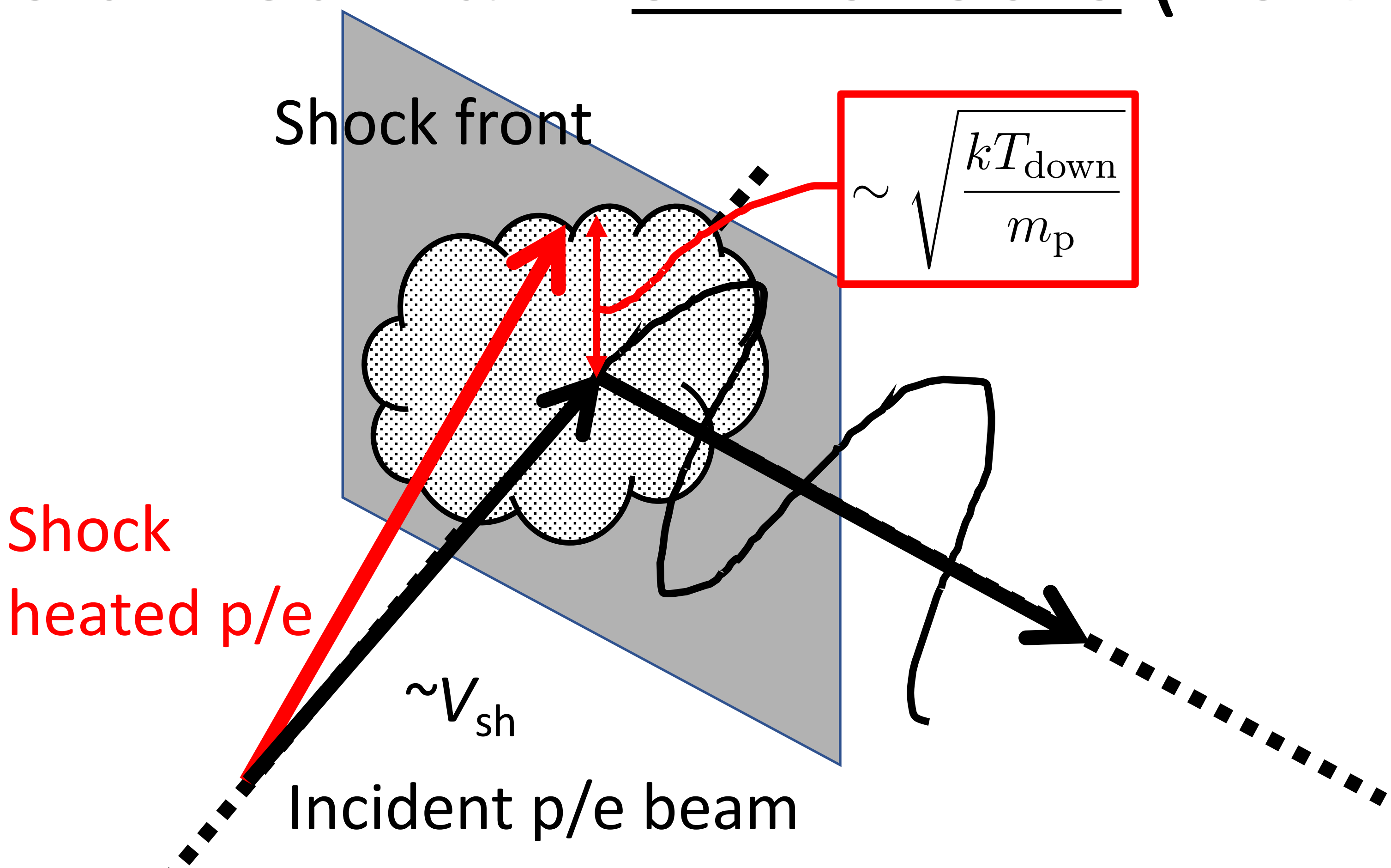
Problem in the previous estimates

□Measurement of the shock velocity



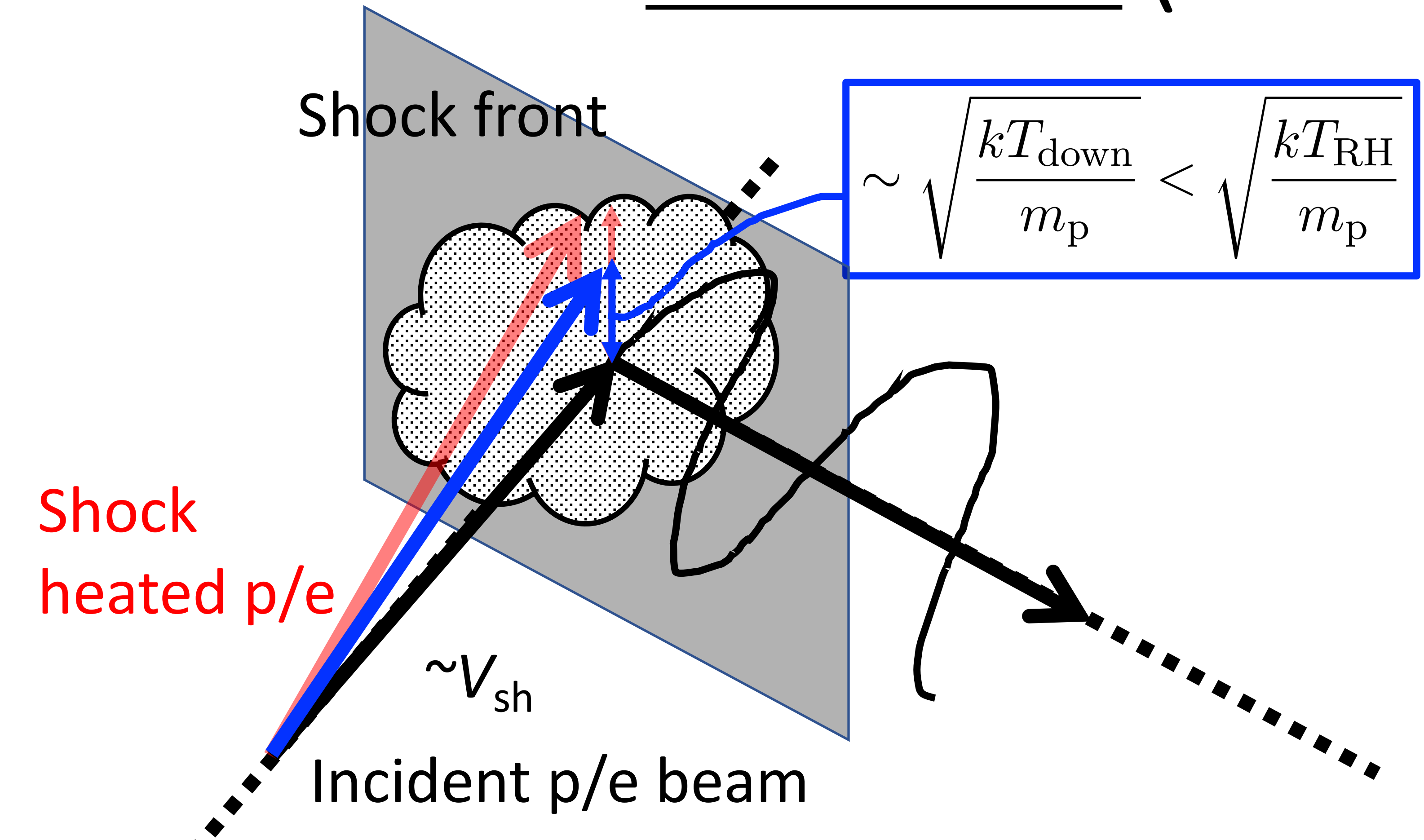
✓<u>In order to derive the shock velocity from the proper motion, **we need a distance to the SNR with high accuracy** (with errors less than 1 %).</u>

Polarized Hα in SNR shocks (no CRs)



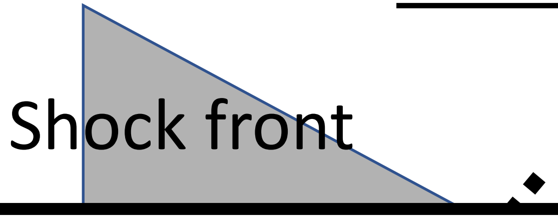
- In the SNR shocks, since the shock heated proton/electron also excites the H atoms, **the net linear polarization of Hα is depolarized**.

Polarized Hα in SNR shocks (with CRs)



- **When the shock efficiently accelerates CRs, the downstream temperature becomes lower, resulting in a higher polarization of Hα.**

Polarized Hα in SNR shocks (with CRs)



$\simeq \sqrt{\frac{kT_{\mathrm{down}}}{\cdots}} < \sqrt{\frac{kT_{\mathrm{RH}}}{\cdots}}$

- **In the previous study**, Laming (1990) considered **only Hα emission from shocks without CRs.**
- **In this work**, **updating the atomic data** (e.g. cross sections), we calculate **polarized Hα emissions from shocks efficiently accelerating CRs** based on the latest radiation line transfer model constructed by Shimoda & Laming (2019).

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**.

We derive the downstream velocity from the jump conditions for the shock loosing an energy (like a radiative shock, 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

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

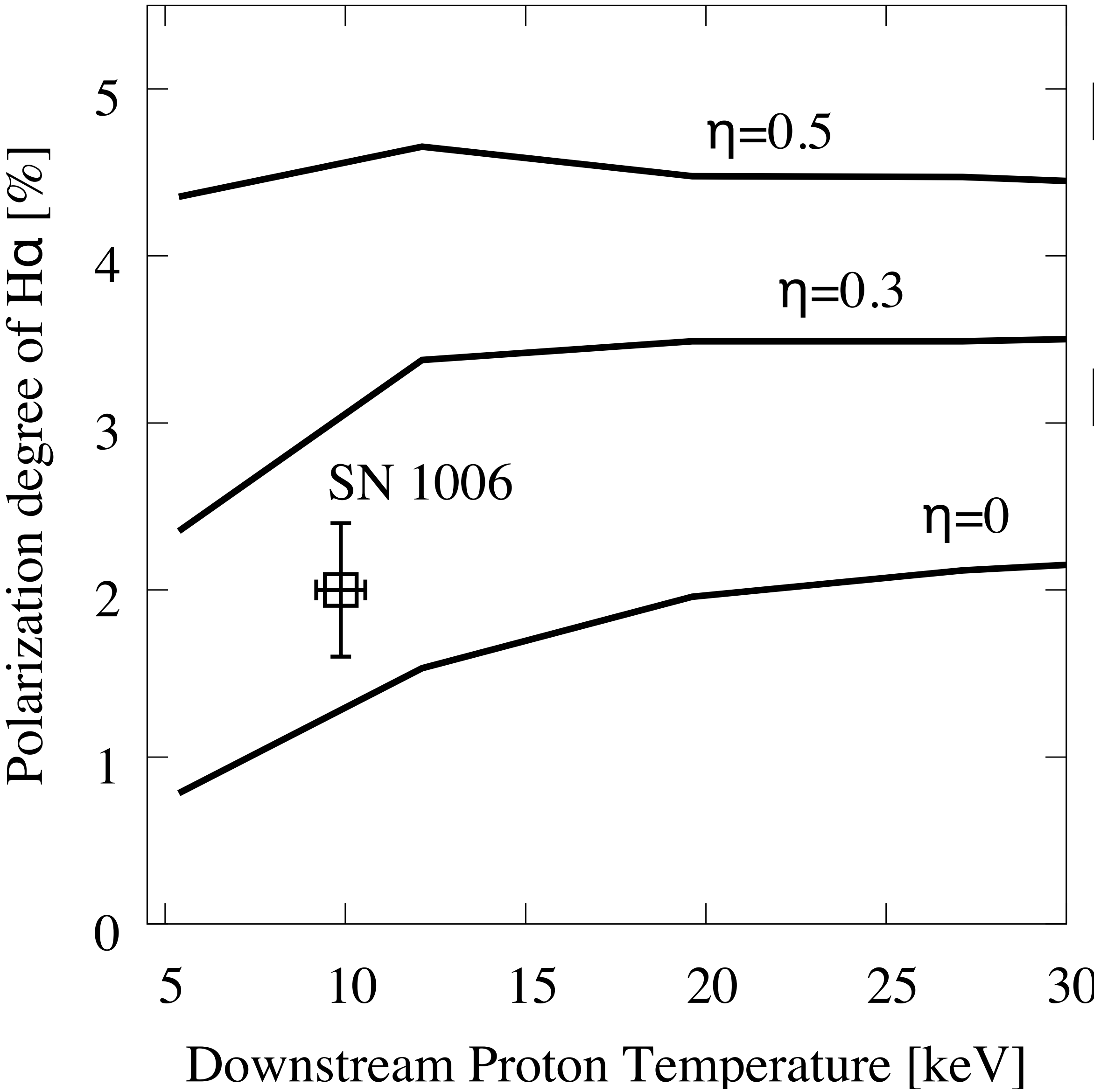
$$Q \equiv I_{\parallel} - I_{\perp}$$

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

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

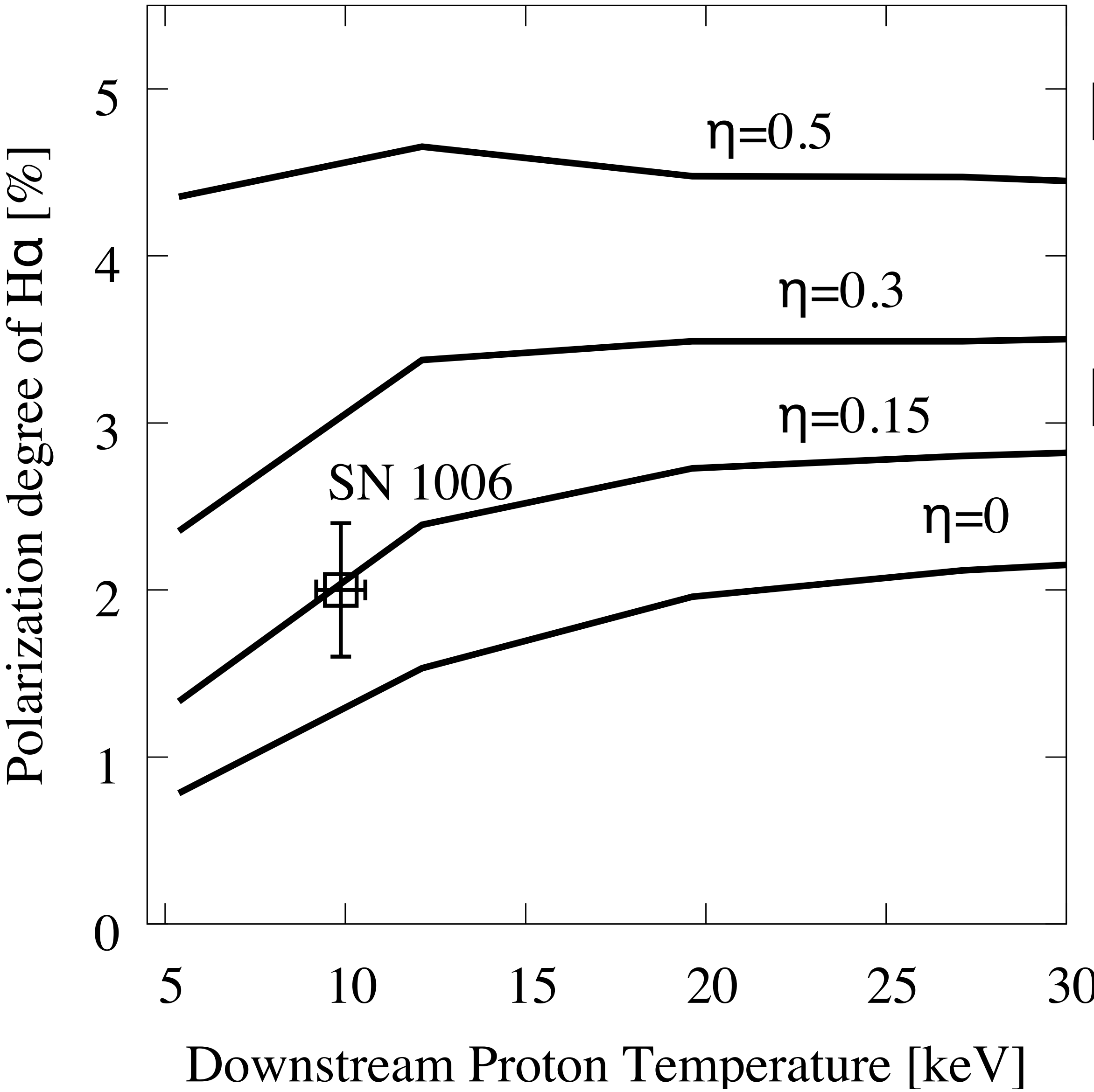
※ Parallel and Perpendicular are defined respecting to the shock velocity.

Polarization degree of Hα



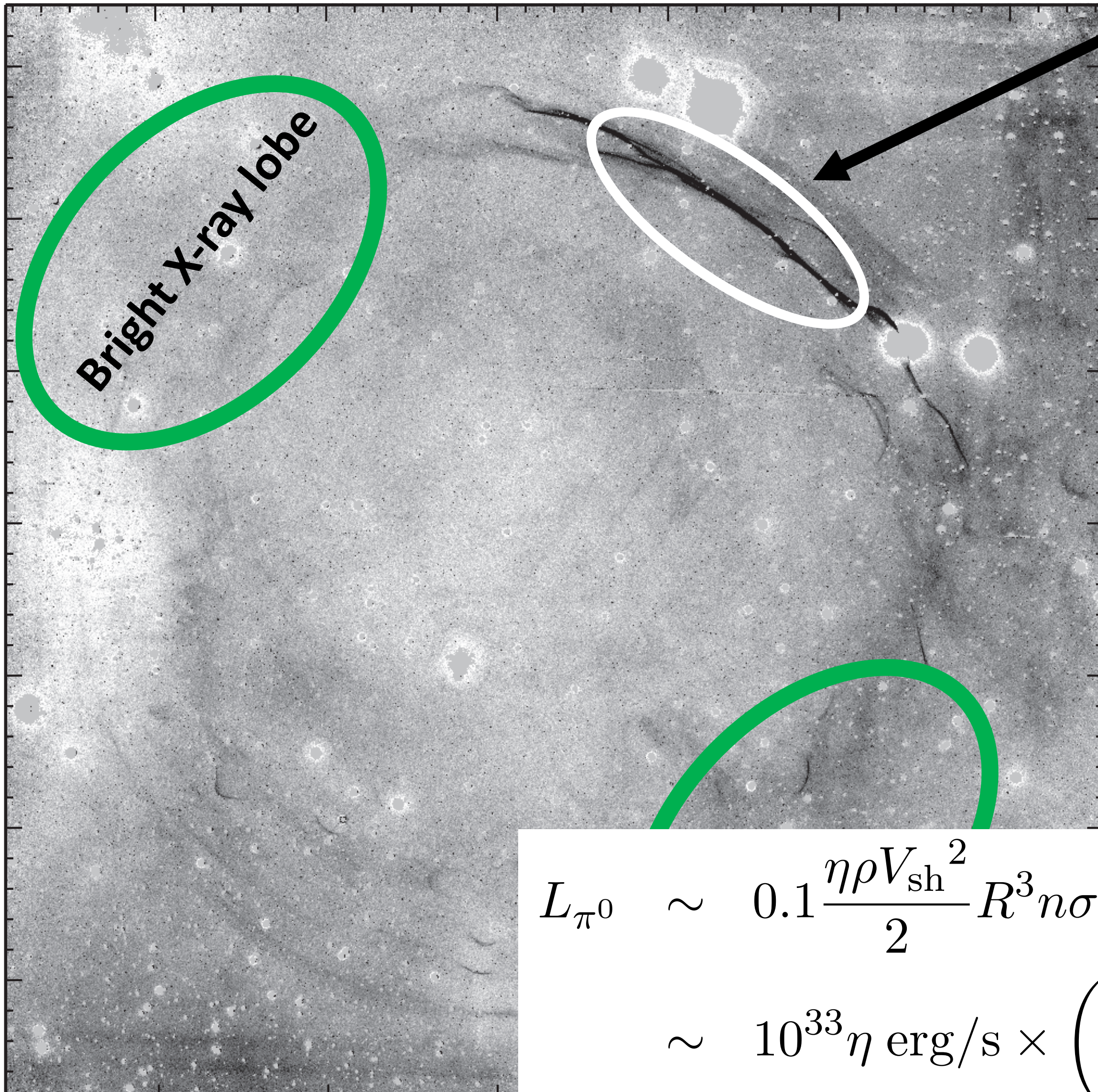
- The degree depends on the loss rate η.
- The observation of SN 1006 implies $\eta \approx 0.15$

Polarization degree of Hα



- The degree depends on the loss rate η.
- The observation of SN 1006 implies $\eta \approx 0.15$

SN 1006



η ~ 0.1 ? (this work)

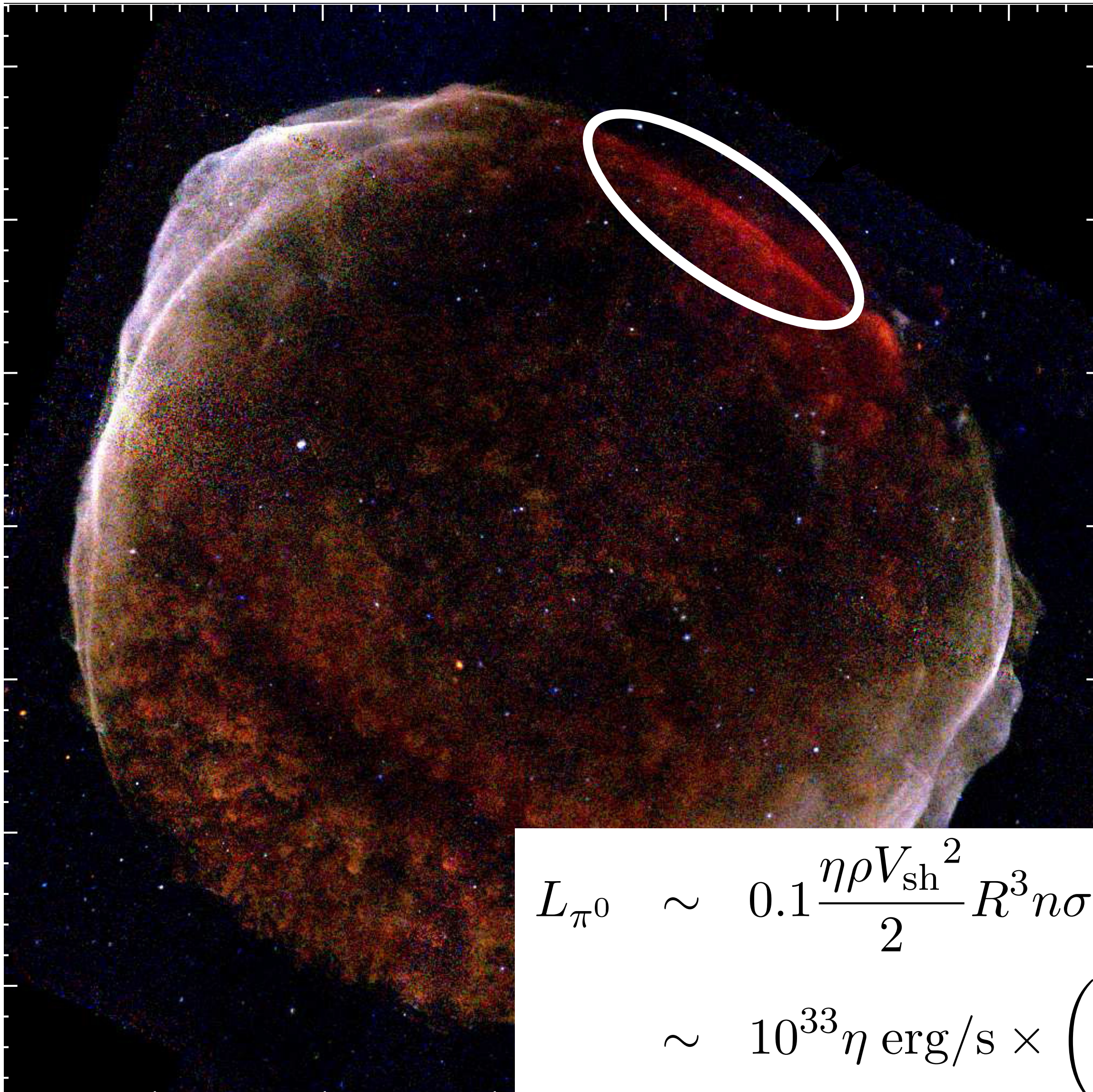
- ✓ density ~ 0.3 cm^{-3}
- ✓ V_{sh} ~ 3000 km/s @ 2.2 kpc

(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



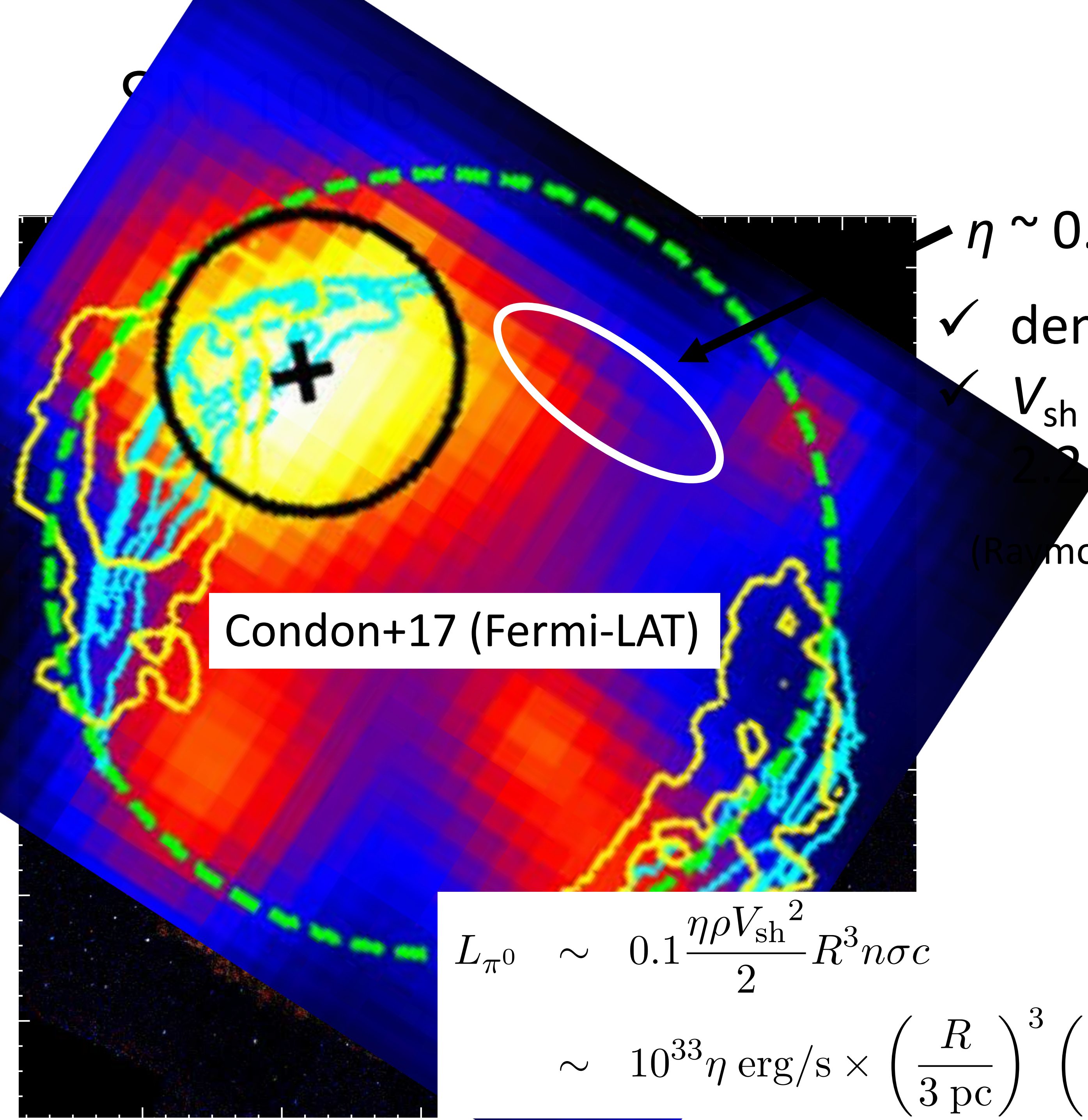
η ~ 0.1 ? (this work)

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

(Raymond+ 07; Katsuda+12)

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

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



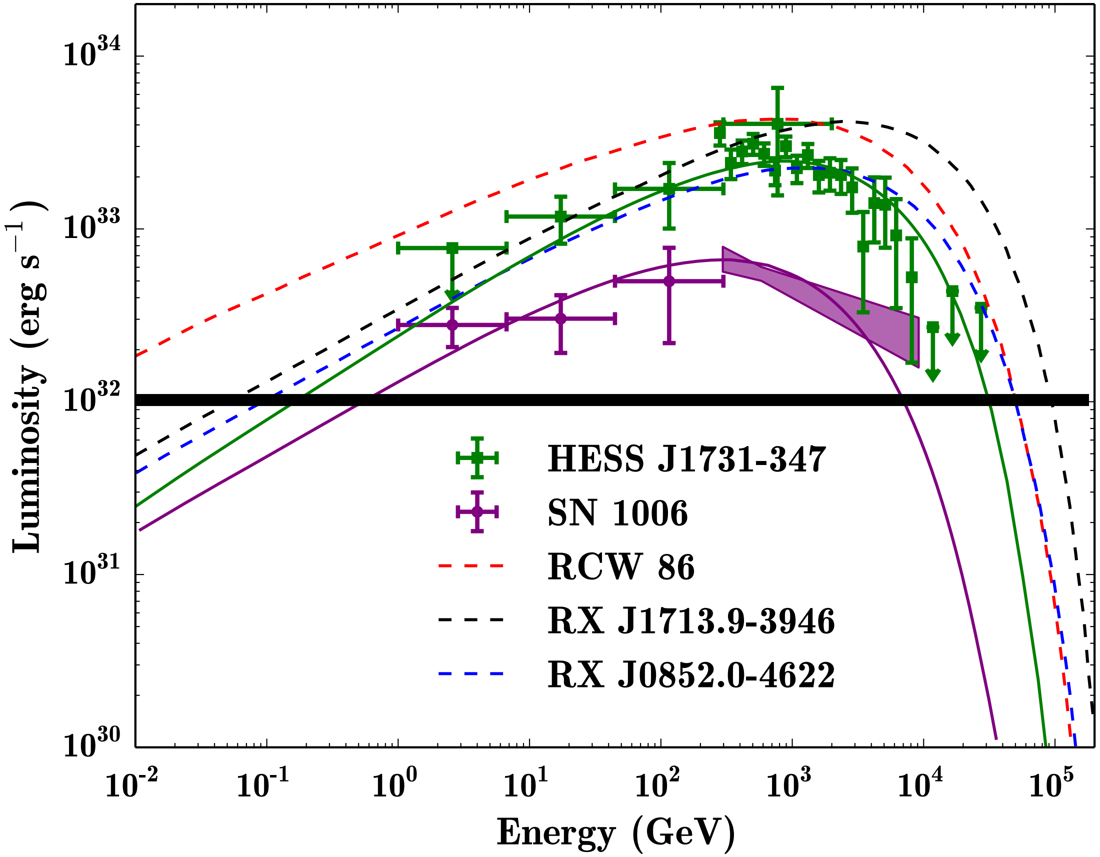
η ~ 0.1 ? (this work)

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

(Raymond+ 07; Katsuda+12)

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

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

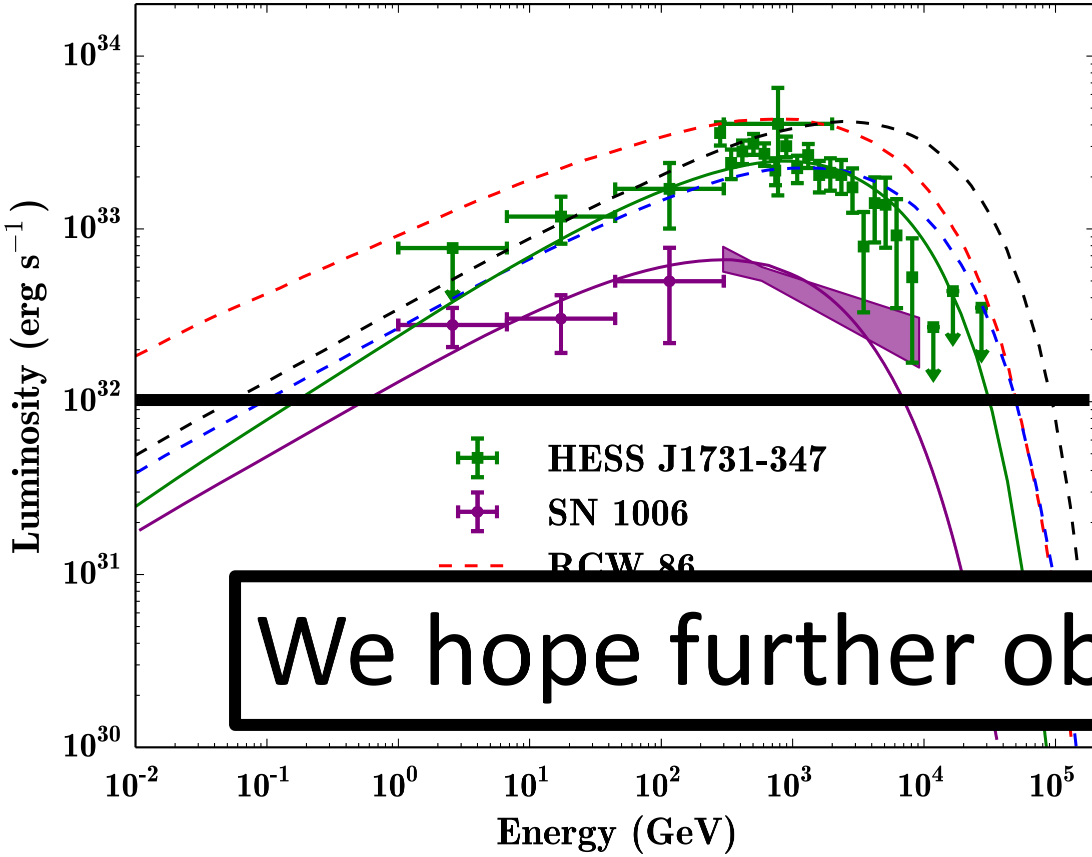


- η ~ 0.1 ? (this work)
- ✓ density ~ 0.3 cm^{-3}
- ✓ V_{sh} ~ 3000 km/s @ 2.2 kpc

(Raymond+ 07; Katsuda+12)

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

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



- η ~ 0.1 ? (this work)
- ✓ density ~ 0.3 cm^{-3}
- ✓ V_{sh} ~ 3000 km/s @ 2.2 kpc

(Raymond+ 07; Katsuda+12)

We hope further observations!

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

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

Summary of this work

- We have calculated the polarized Balmer line emissions from the collisionless shocks efficiently accelerating CRs.
- **The energy loss rate of the shocks due to the CR acceleration** can be measured by the polarization degree.
- Our results suggest a sizable loss rate for SN 1006.

→ **Hadronic dominated γ-rays will be detected ?**

Once we determine the η and distance

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 : $\eta_{\rm p}$

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

Number of thermal nuclei can be derived from Hα surface brightness (e.g. Raymond+07).

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

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

known

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

Related to Synchrotron surface brightness L_{syn}

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

Once we determine the η and distance

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

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

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

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

$$= a\eta_{\rm e} + b\eta_{\rm p}$$

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

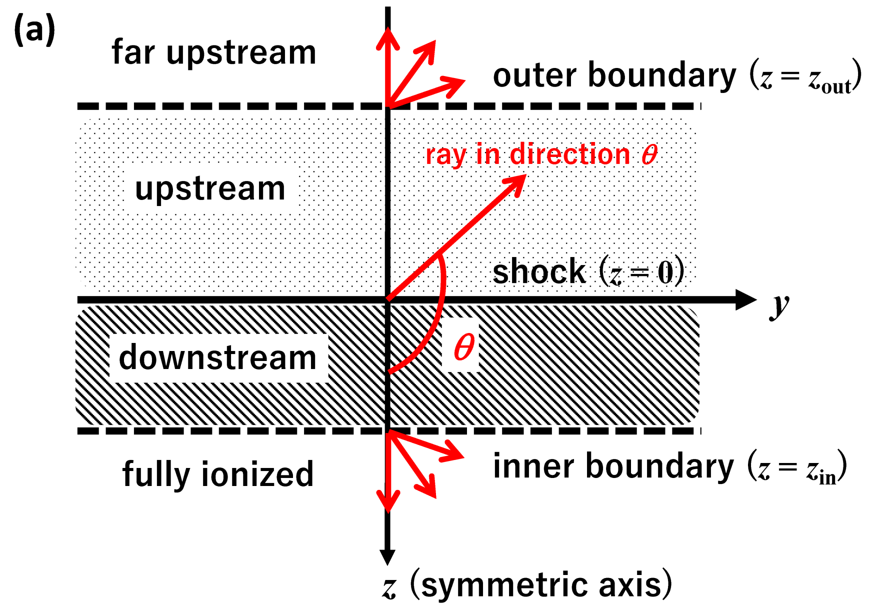
Surface brightness are detectable

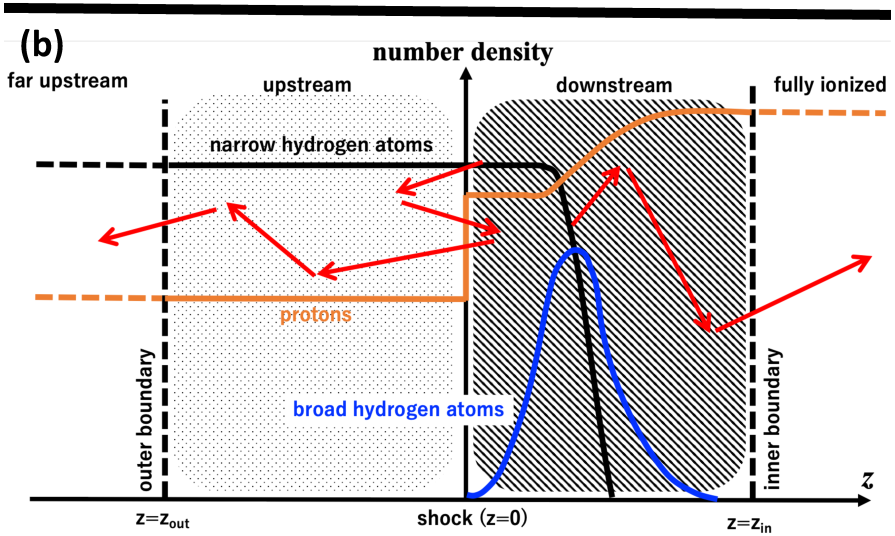
η and coefficients a, b, and c are known

We have three unknowns and three equations!

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

Line Transfer Model





Parameters:

① Upstream number density $n_{\mathrm{tot},0}$

② Upstream ionization degree χ_0

③ Downstream proton temperature T_{down}

④ Downstream electron temperature $T_e = \beta T_p$

⑤ Energy loss rate η

Shock jump condition:

Cohen+98 (like a radiative shock)

Pure hydrogen plasma.

Excitation level is solved up to 4f.

Polarization is estimated only for the downside of shock.

Applications of Hα

1980~

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

2000~

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

present

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