X-ray Line Diagnostics of the Cosmic-Ray Accelerating Shock by XRISM and Athena

Ref: Shimoda et al. (2201.07607, https://arxiv.org/pdf/2201.07607.pdf)

Jiro Shimoda[1]

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European Astronomical Society 2022, 6/28

XRISM mission

- ✓ **New X-ray space telescope**
- ✓ **Imaging spectroscopy with amazing energy resolution!**

Dear XRISM users.

X-Ray Imaging and Spectroscopy Mission (XRISM) is the seventh Japanese X-ray observatory exploring the world of X-ray imaging and high-resolution spectroscopy, following ASTRO-H “Hitomi.” XRISM is a flower equipped with a long-waited X-ray micro-calorimeter and a conventional and reliable X-ray wide-field CCD camera on the focal plane of X-ray Mirrors. We believe the combination will bring the epoch-making and reliable results to you, XRISM users. The new vision of astrophysics you encounter may be too novel to cook only with the tools we prepare. We want to encourage the XRISM user community to develop new analysis tools or methods to explore the world of XRISM.

Enjoy the new space!

Tashiro, Makoto (XRISM PI)

田代 信

https://xrism.isas.jaxa.jp/research/

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arXiv:1412.1169

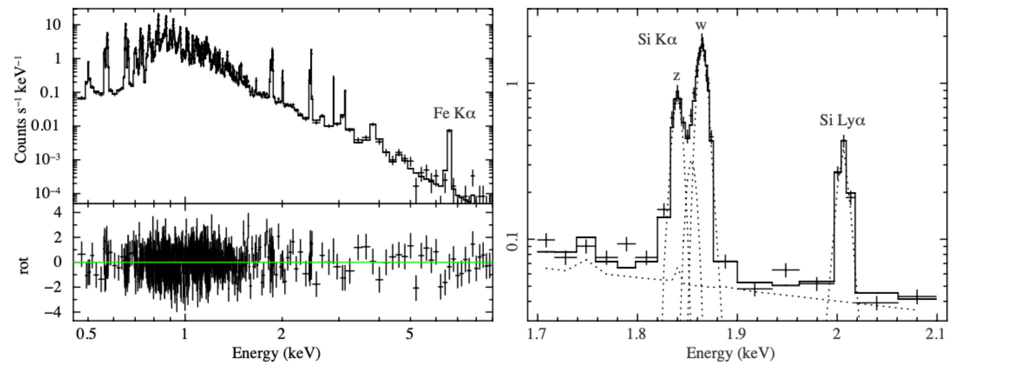
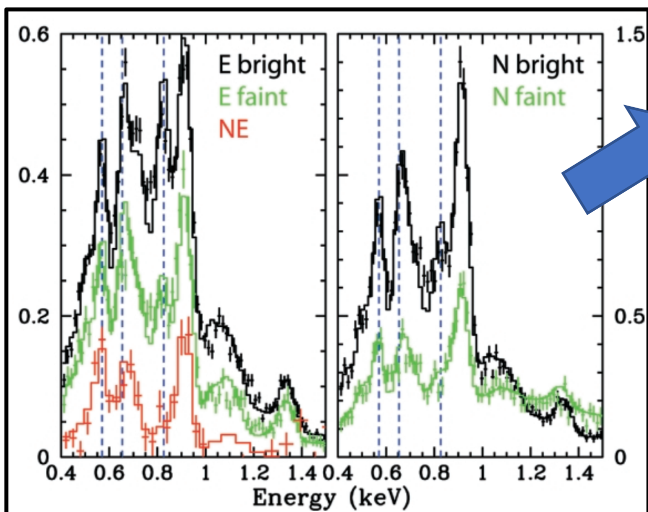


Figure 16: Simulated SXS spectrum of SNR 0519–69.0 with an exposure of 60 ksec. The widths of Si lines can be determined with an error of ~10%.



Previous spectrum
(XMM-Newton, Vink+06, RCW 86)

- ➢ **The energy resolution is a few eV.**

→ We can resolve individual line!

- ➢ The ion temperature can be measured by the line width.

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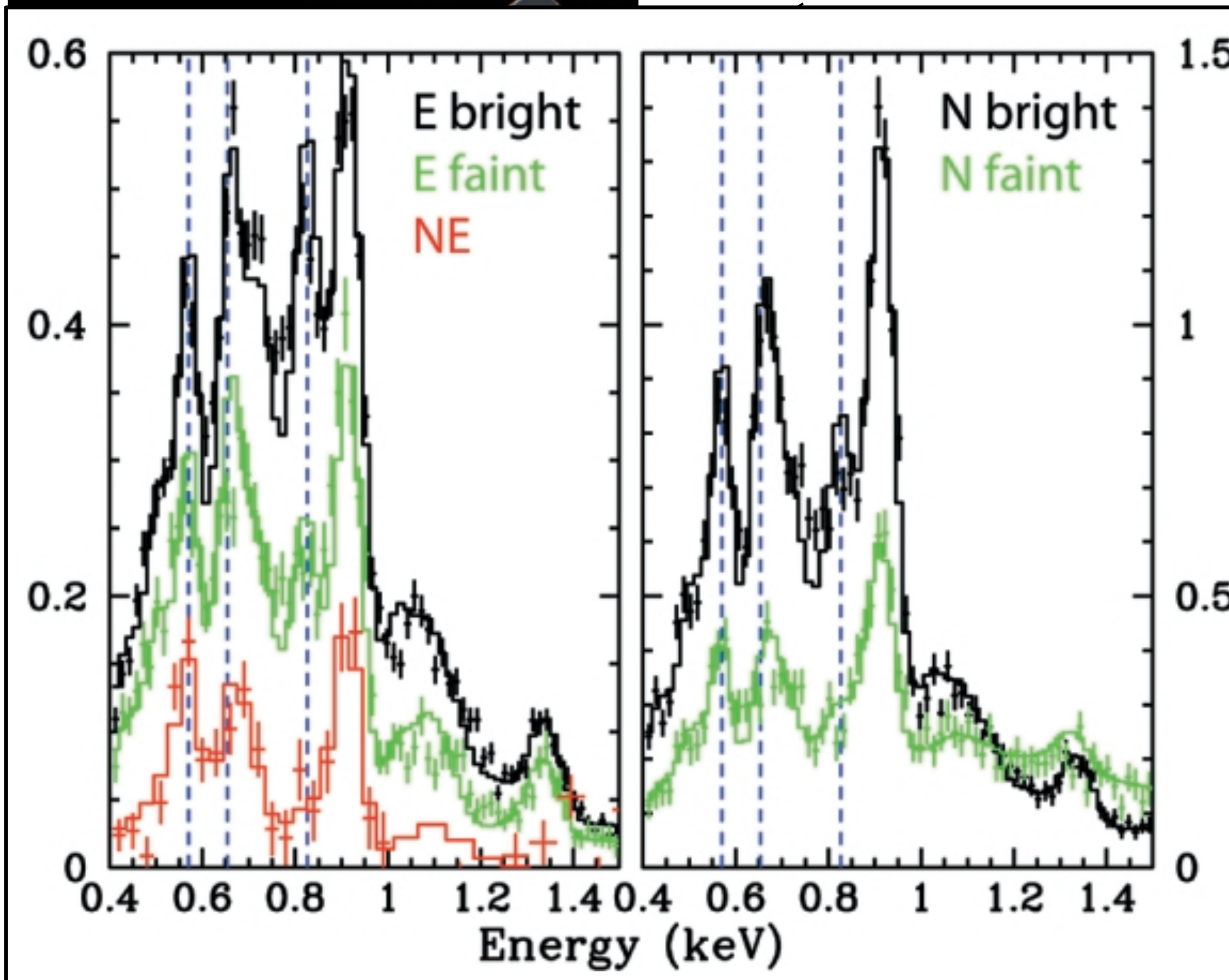

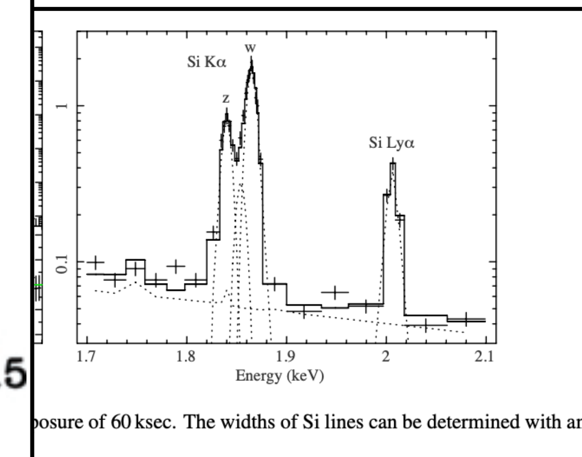

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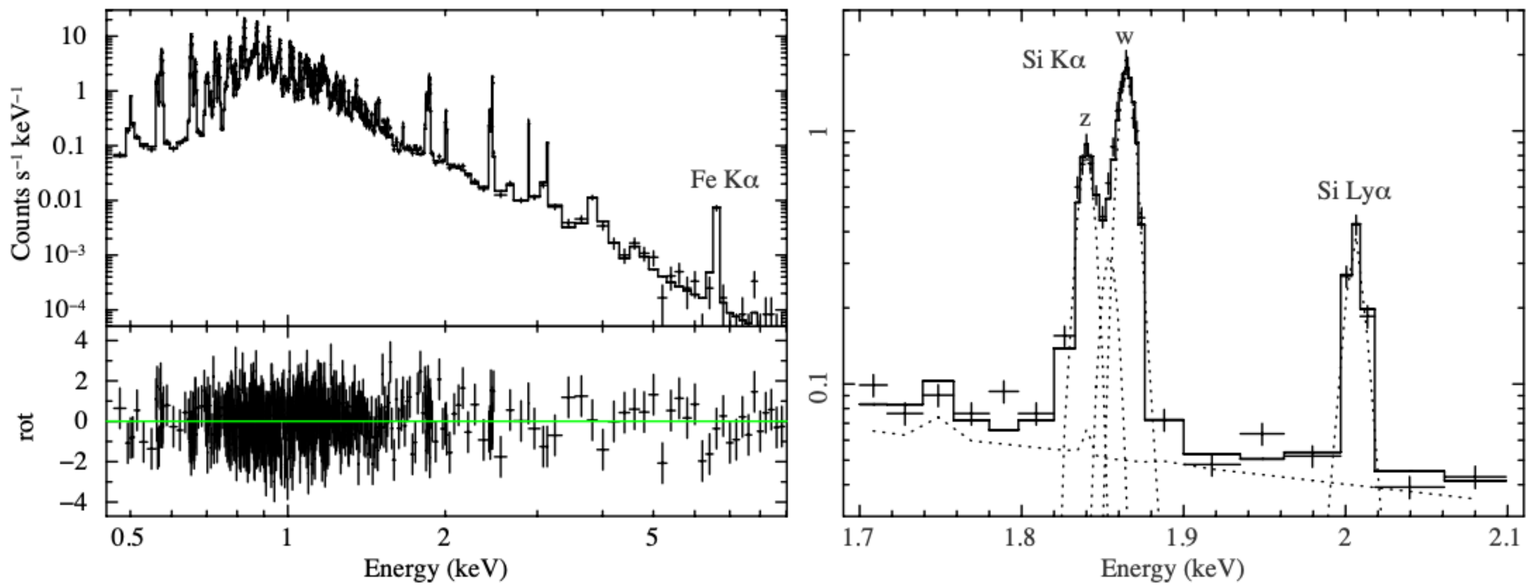

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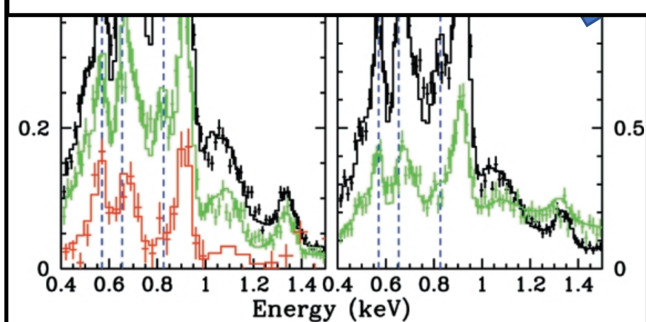

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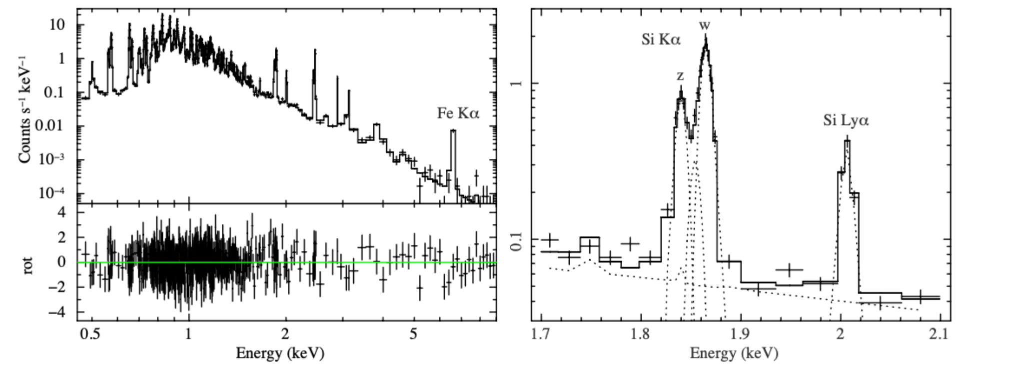

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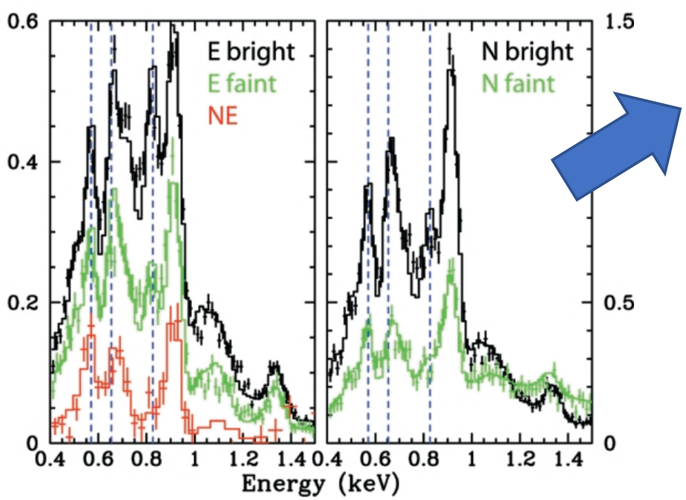

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Supernova Remnant (SNR)

γ-ray: CRs

X-ray: ~TeV CR electrons
Shocked ISM & ejecta

Hα: useful tracer of shock condition & physics

Radio: ~ GeV CR electrons (synchrotron emission)

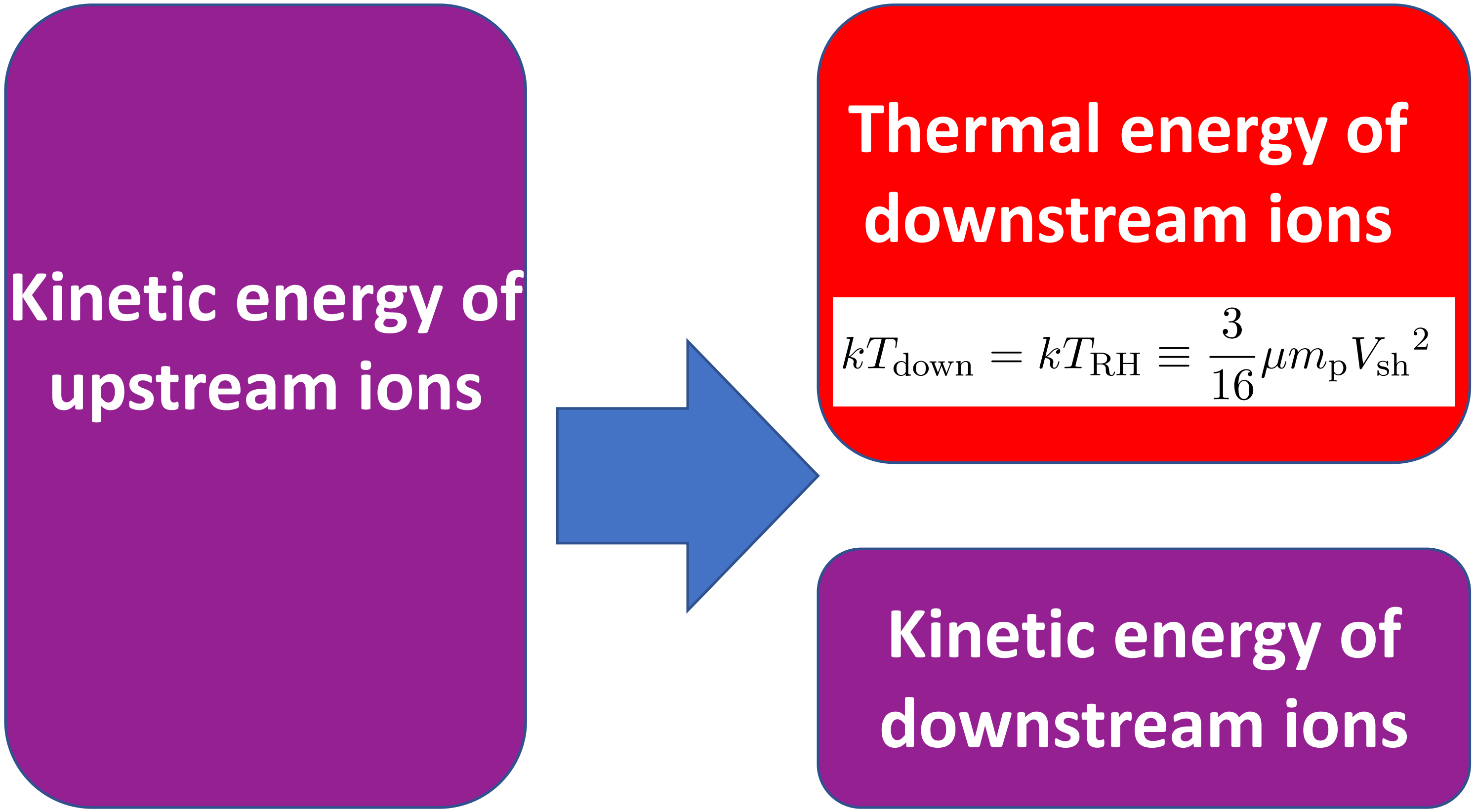
SNR 0509-67.5 (Chandra & HST)

Blue: 1.5 – 7.0 keV
Green: 0.2 – 1.5 keV
Red: Hα

Why is the XRISM mission important for the CR problem?

Shock energy budget

Without CRs



When CRs are accelerated…

Shock energy budget

With CRs

Kinetic energy of upstream ions

Thermal energy of downstream ions

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

Cosmic Rays, B-field amplification

Kinetic energy of downstream ions

Energy loss rate (Shimoda+ 15)：

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

Shock energy budget

With CRs

Thermal energy of downstream ions

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

Kinetic energy of

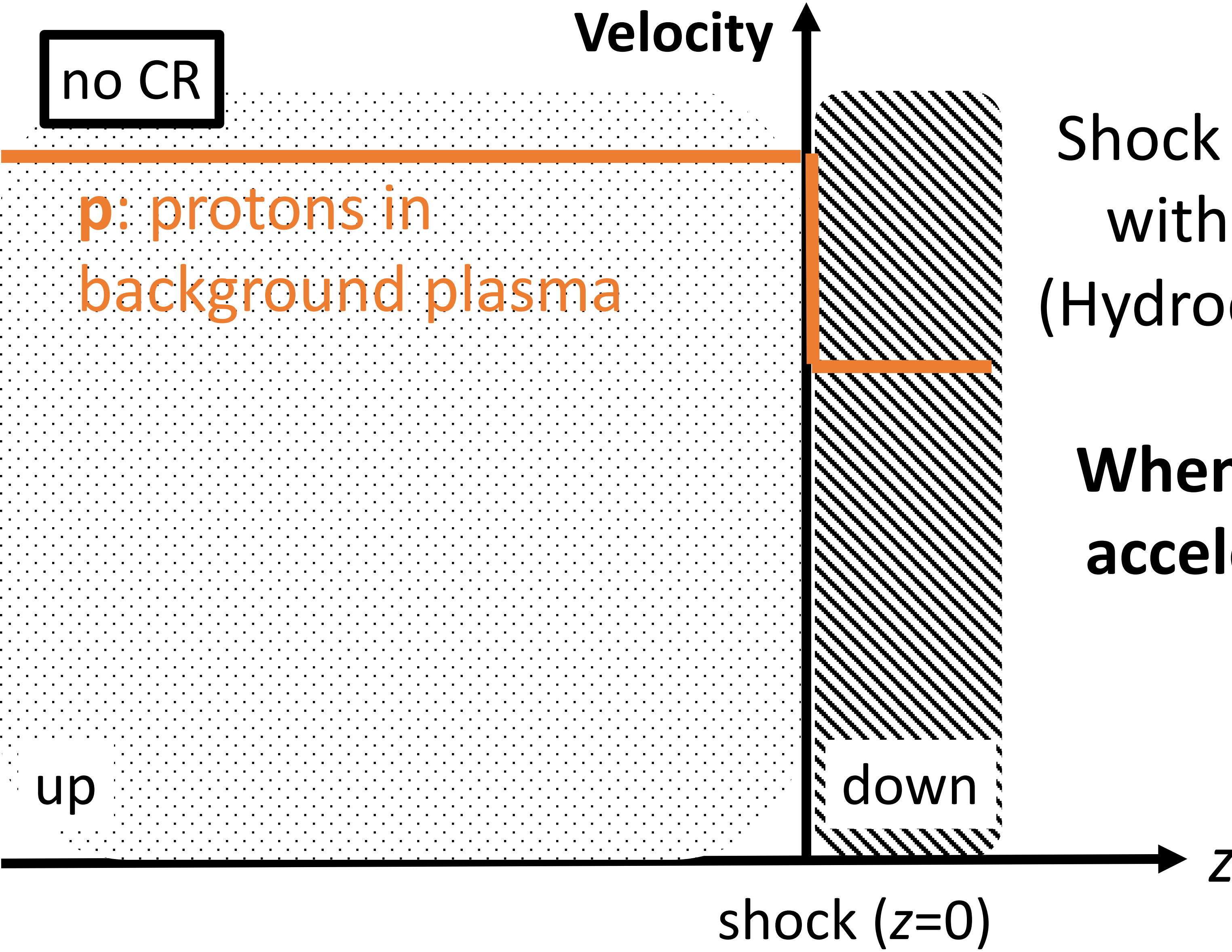
If we measure the downstream ion temperature $T_{\rm down}$ （XRISM mission） and the shock velocity $V_{\rm sh}$ independently, the loss rate η can be estimated.
In the CR acceleration models, the η is ***assumed*** to be large.

downstream ions

Energy loss rate (Shimoda+ 15)：

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

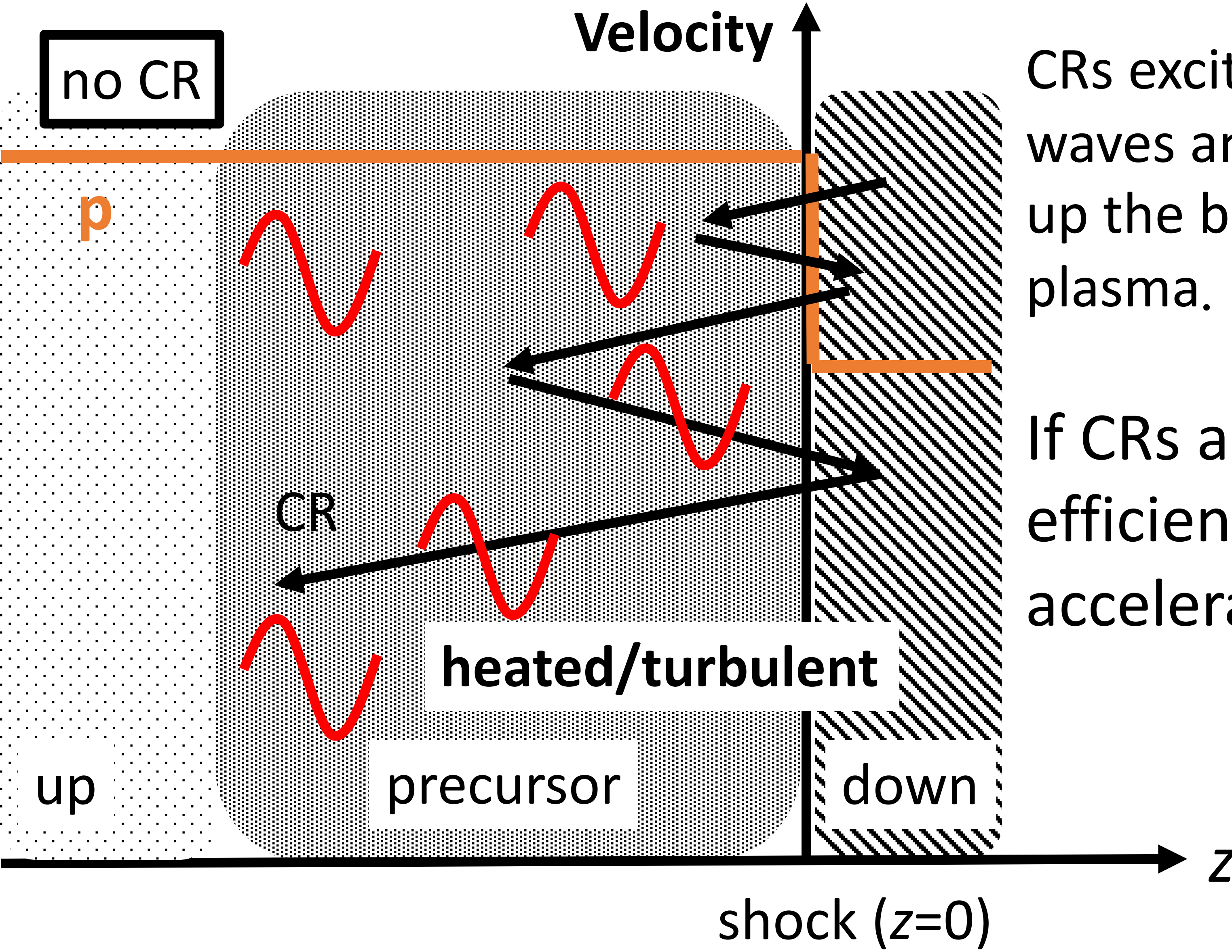
Cosmic-Ray Modified Shock (CRMS)



Shock structure without CRs (Hydrodynamics)

When CRs are accelerated…

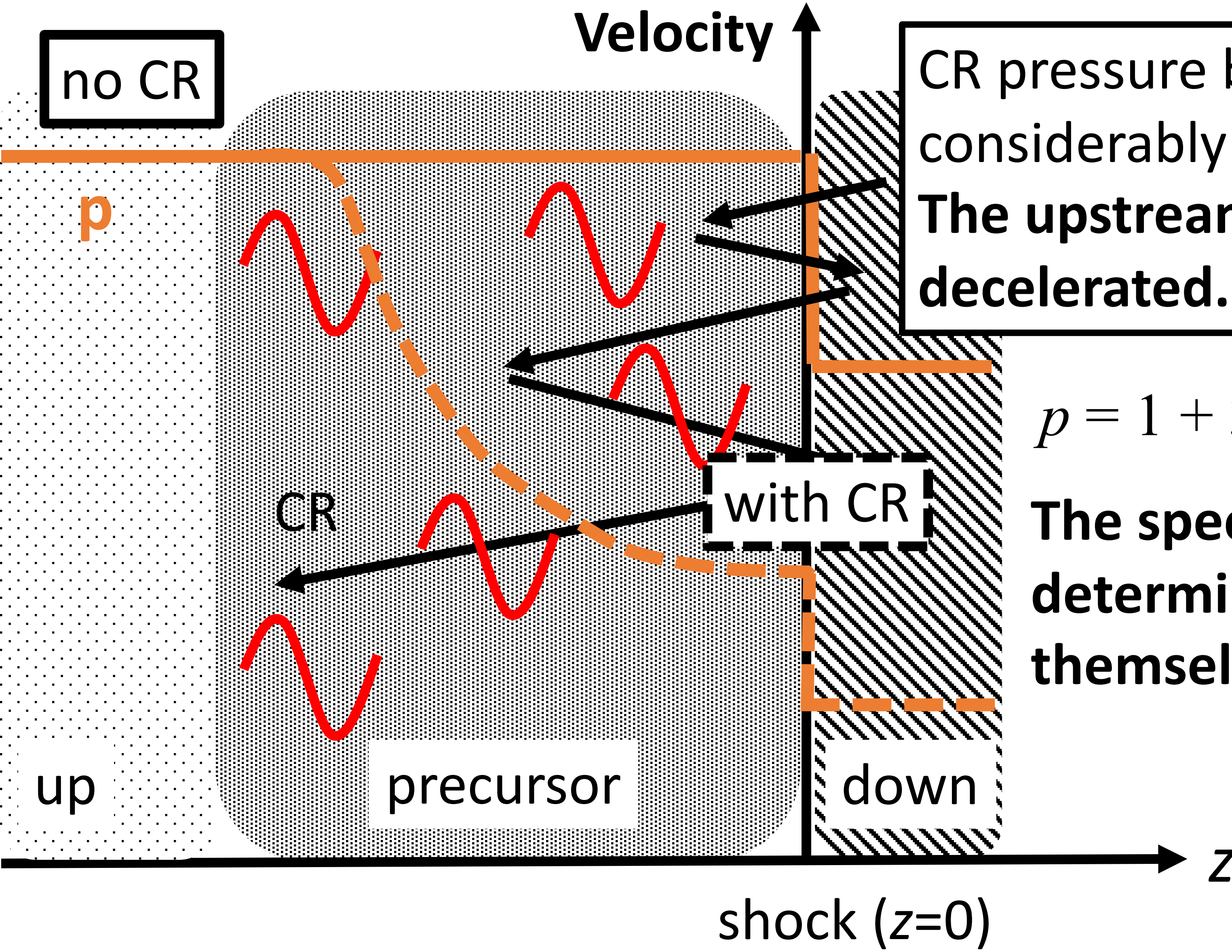
Cosmic-Ray Modified Shock (CRMS)



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.

$$p = 1 + 3u_2 / (u_0 - u_2)$$

The spectrum is determined by CRs themselves!

Shock energy budget

With CRs

Kinetic energy of upstream ions

Thermal energy of downstream ions

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

Cosmic Rays, B-field amplification

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

Shock energy budget

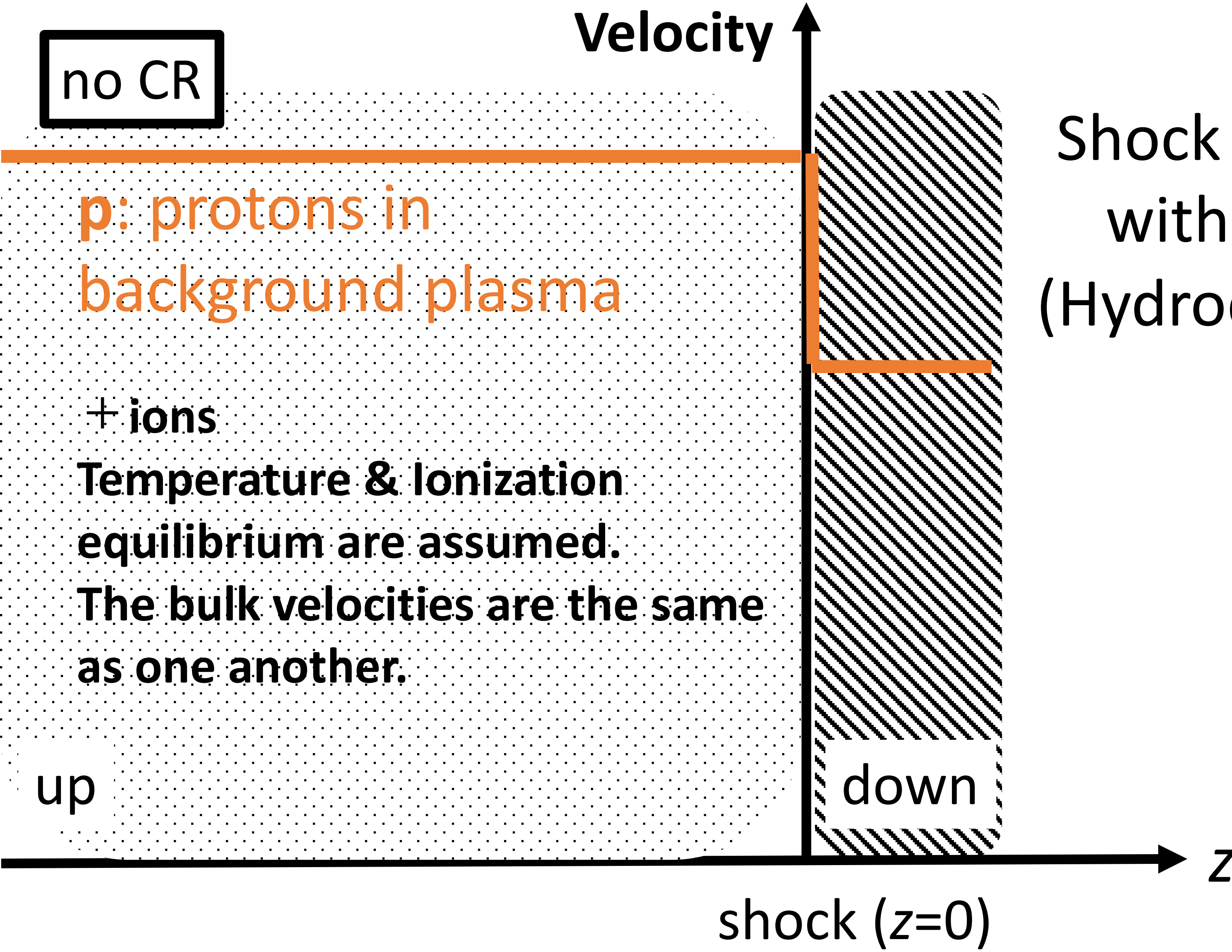
With CRs

- The shock jump w/o CRs is given by the flux conservation laws in hydrodynamics.
- To describe the CR accelerating shock, an additional relation giving η needs!
- We reconsider ***ion heating mechanisms*** in the collisionless shock to determine $T_{\rm down}$.

Energy loss rate (Shimoda+ 15)：

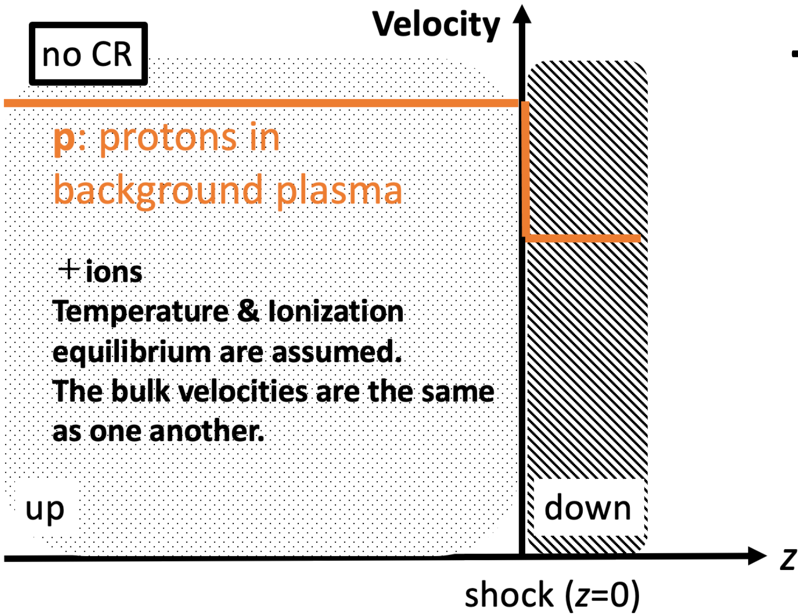
$$\eta \equiv \frac{T_{\rm RH} - T_{\rm down}}{T_{\rm RH}}$$

Step 1: Shock Jump condition w/o CRs



Shock structure without CRs (Hydrodynamics)

Step 1: Shock Jump Condition w/o CRs



upstream → subscript "0"

downstream→ subscript "2"

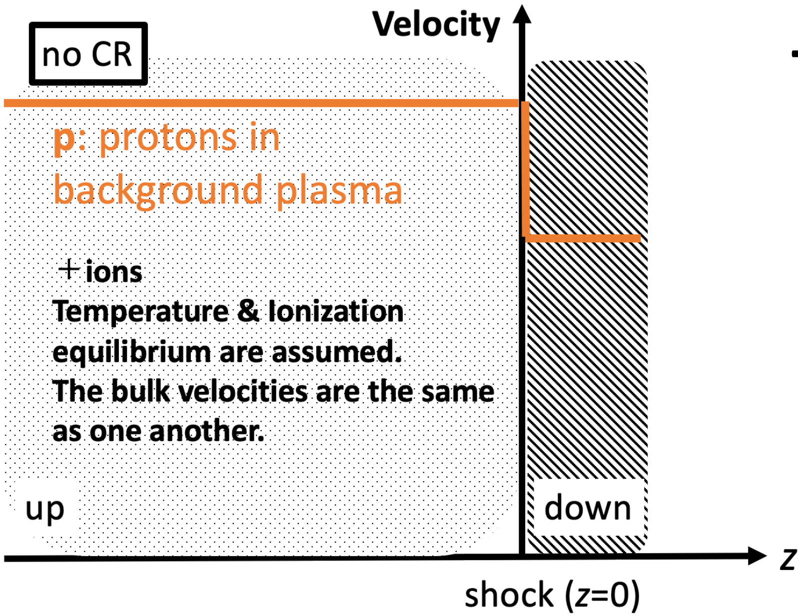
The subscript "j" denotes ion species.

$$\rho_{j,0} v_0 = \rho_j v_{j,2},$$
$$\rho_{j,0} {v_0}^2 + P_{j,0} = \rho_{j,2} {v_{j,2}}^2 + P_{j,2},$$
$$\frac{{v_0}^2}{2} + \frac{\varepsilon_{j,0} + P_{j,0}}{\rho_{j,0}} = \frac{{v_{j,2}}^2}{2} + \frac{\varepsilon_{j,2} + P_{j,2}}{\rho_{j,2}},$$

$$P_j = n_j k T_j$$
$$\varepsilon_j = \frac{3}{2} n_j k T_j = \frac{n_j k T_j}{\gamma - 1}$$

We regard each ion as independent fluid. From the flux conservation laws…

Step 1: Shock Jump Condition w/o CRs



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$$kT_{j,2} = \frac{m_j {v_0}^2}{r_c}\left(1 - \frac{1}{r_c} + \frac{1}{\gamma {\mathcal{M}_s}^2}\right)$$

$$= \frac{(\gamma - 1)\, m_j {v_0'}^2}{2} \frac{\left({\mathcal{M}_s}^2 + \frac{2}{\gamma - 1}\right)\left({\mathcal{M}_s}^2 - \frac{\gamma - 1}{2\gamma}\right)}{\left({\mathcal{M}_s}^2 - 1\right)^2}$$

Strong shock limit

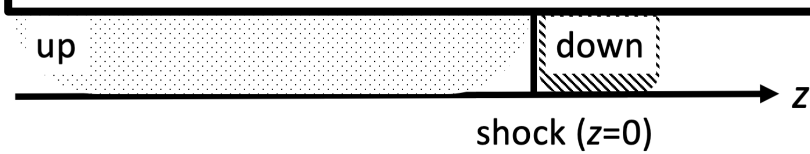
$$kT_{j,2} = \frac{3}{16} m_j {v_0}^2$$

downstream rest →

$$\boxed{\frac{3}{2} kT_{j,2} = \frac{1}{2} m_j {v_0'}^2}$$

Step 1: Shock Jump Condition w/o CRs

- Strong shock limit is good approximation in (young) SNRs.
- The upstream coherent flow is converted to the downstream random motion of particles. → ***randomization***
- The kinetic energy of the downstream random motion ($3kT_{j,2} / 2$) is equal to that of the upstream coherent motion ($m_j v'_0{}^2 / 2$).



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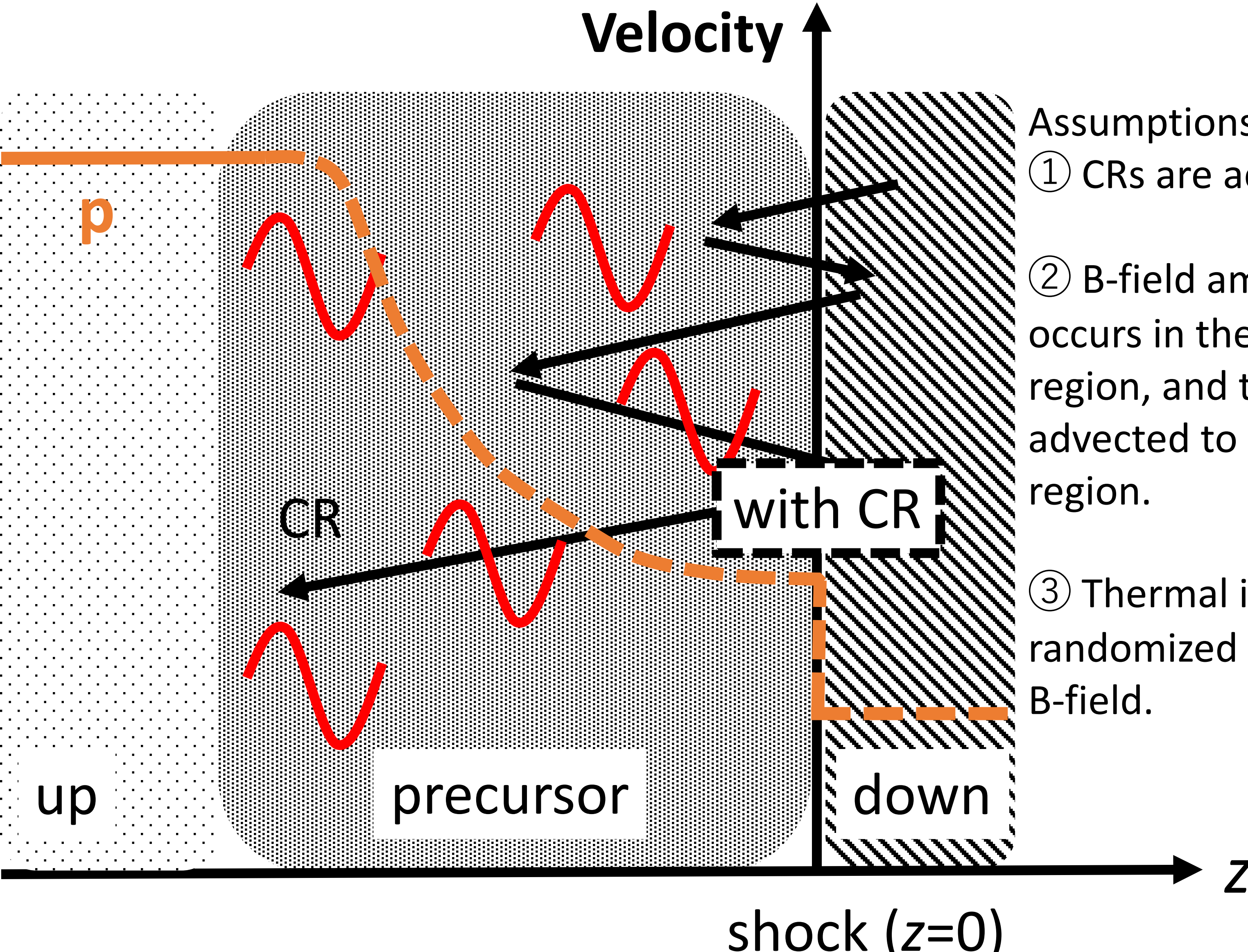
However,

- In hydrodynamics, **the particle-particle interaction** is implicitly assumed as the randomization mechanism.
  → The Maxwell distribution & no CRs

- The SNR shock is formed by **the wave-particle interaction** (collisionless shock).
  → We should reconsider the randomization mechanism.

Step 2: Shock Jump Condition w CRs



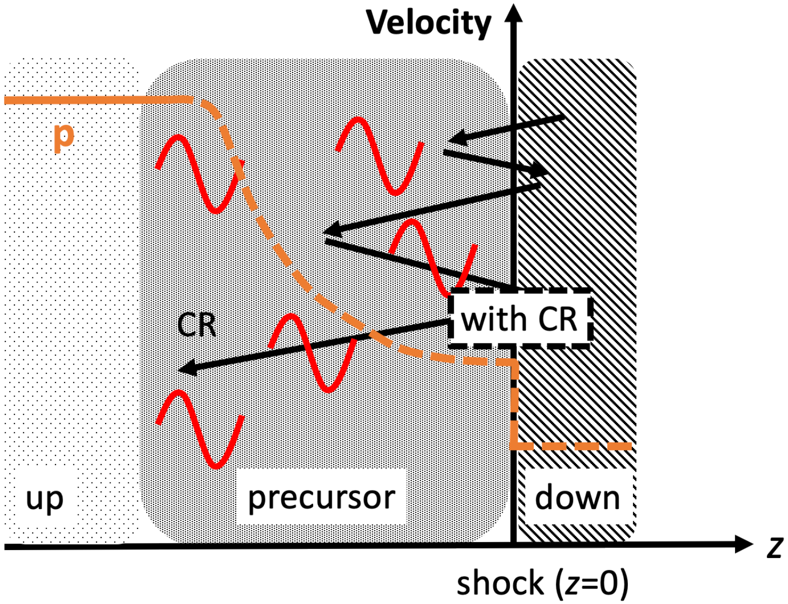
Assumptions：

① CRs are accelerated

② B-field amplification occurs in the precursor region, and the fields are advected to the downstream region.

③ Thermal ions are randomized by the amplified B-field.

Step 2: Shock Jump Condition w CRs



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randomization of **thermal particles**

→ We should consider the entropy.

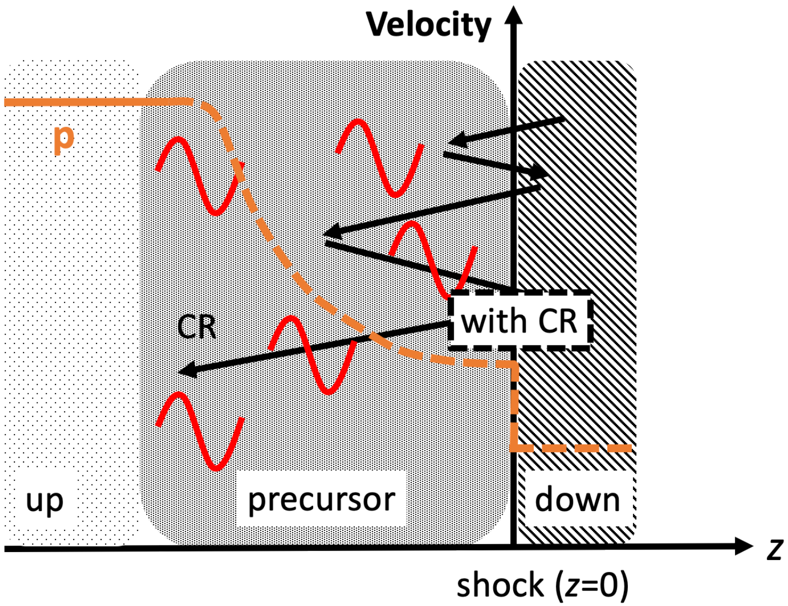
$$ds_j = \frac{1}{M_j}\frac{d\tilde{Q}_j}{kT_j}, \qquad \text{(per unit mass)}$$

$$M_j \equiv N_j m_j \qquad \text{Total mass of species j}$$

$d\tilde{Q}_j$ [erg]

- **The energy is transferred from the electromagnetic fields.**

Step 2: Shock Jump Condition w CRs



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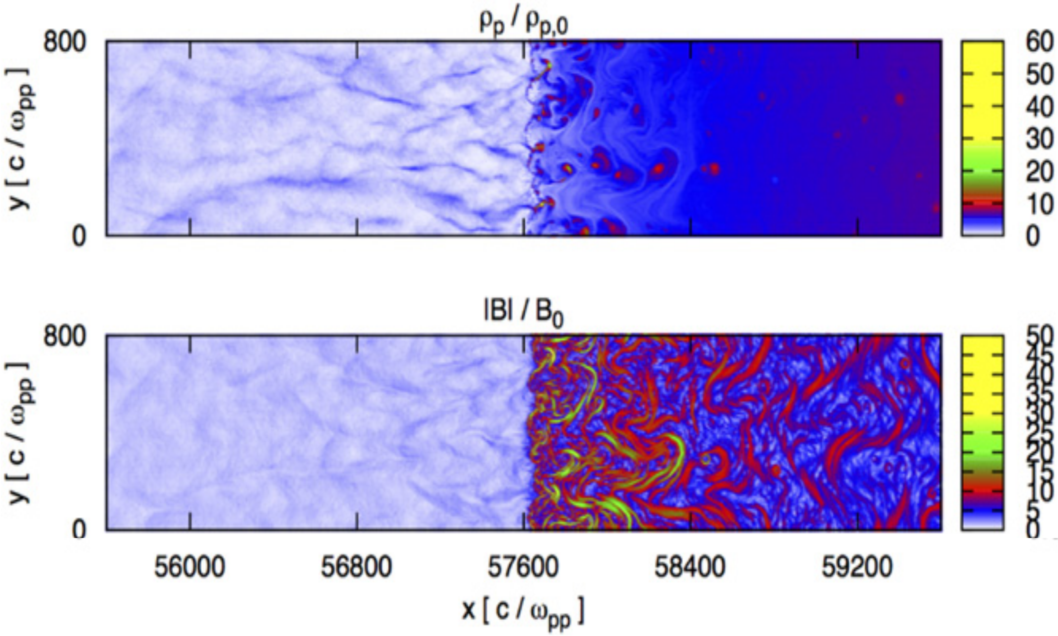
$$M_j \equiv N_j m_j$$ Total mass of species j

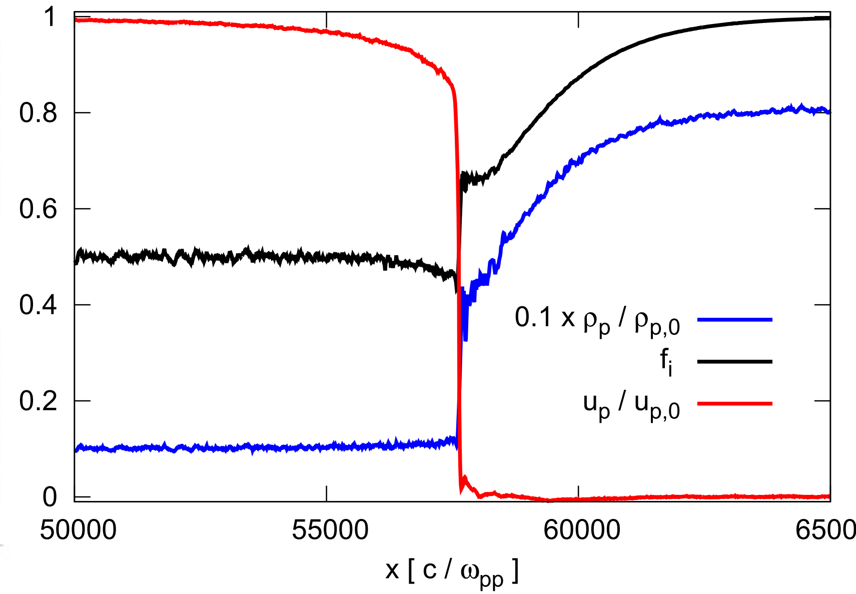
$$d\tilde{Q}_j \sim \boldsymbol{J}_j \cdot \boldsymbol{E}\Delta t_j$$

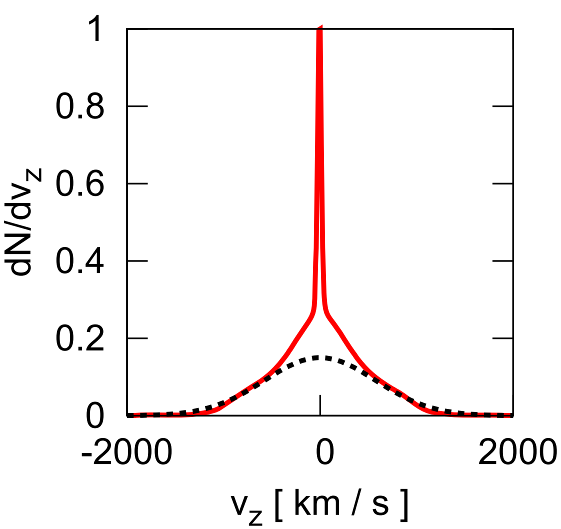
$$J_j \sim q_j N_j \langle \tilde{v}_j \rangle,\ E \sim \frac{\langle \tilde{v}_j \rangle}{c}\delta B,\ \langle \tilde{v}_j \rangle \sim v_0 + \sqrt{\frac{2kT_0}{m_j}}$$

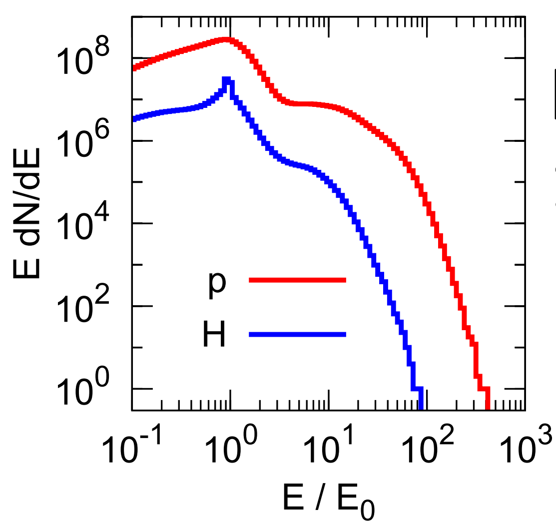
- Δt_j shock transition time

Step 2: Shock Jump Condition w CRs



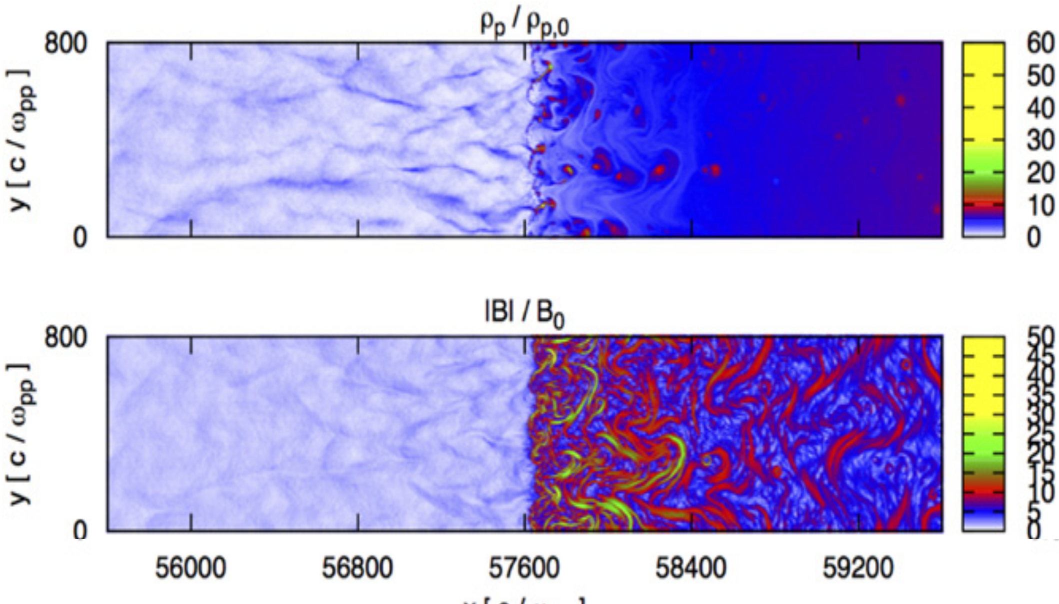


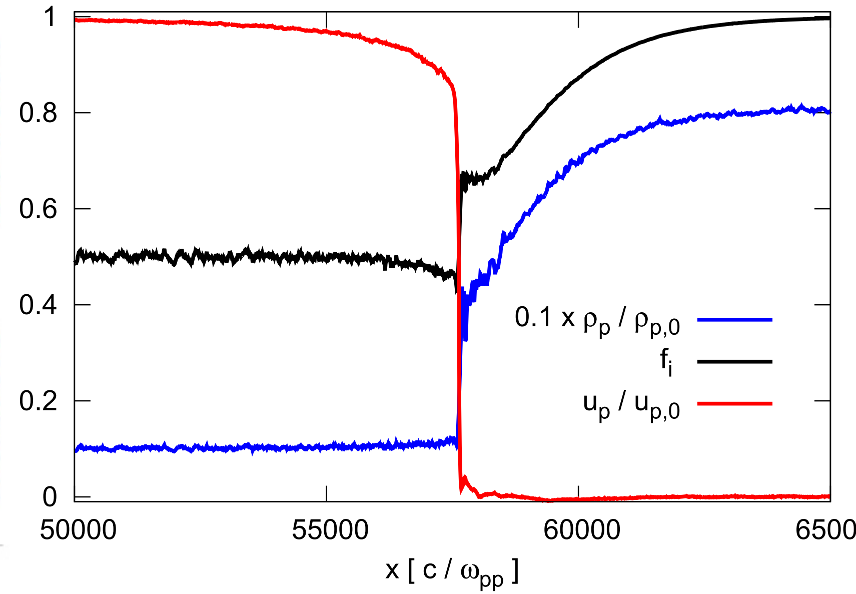




hybrid simulation (Ohira 16).

Step 2: Shock Jump Condition w CRs





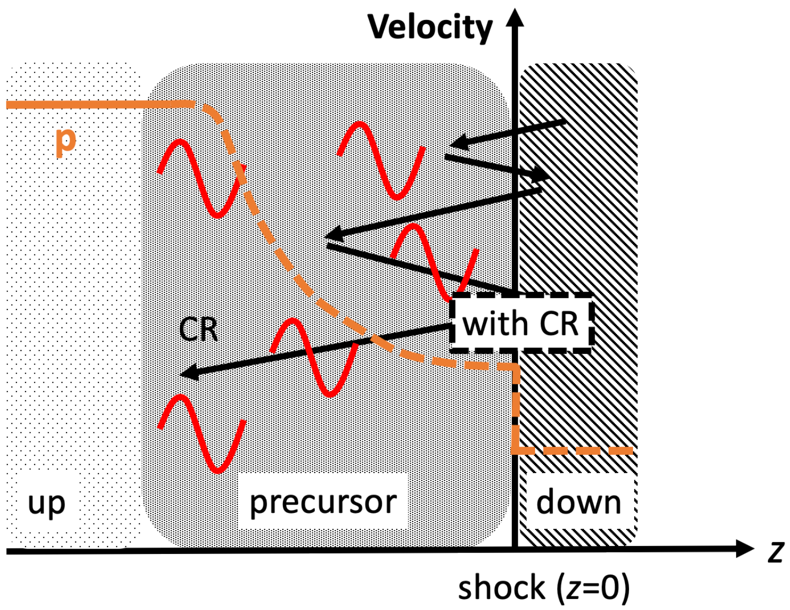
➢ Δt_j shock transition time.

Numerical simulations show the shock transition at very small length-scale.

→ We assume the transition occurs at the gyro period.

$$\Delta t_j \sim \frac{m_j c}{q_j \delta B}$$

Step 2: Shock Jump Condition w CRs



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randomization of **thermal particles**

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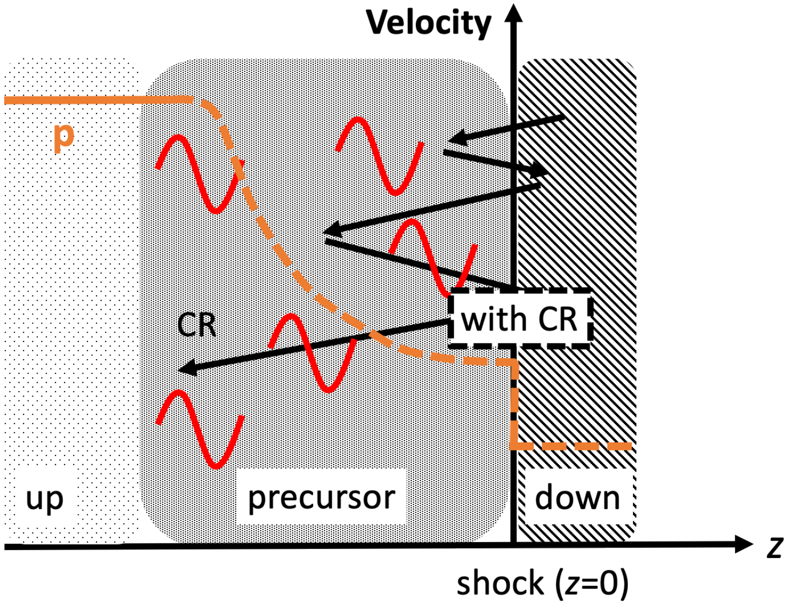
$$d\tilde{Q}_j \sim \boldsymbol{J}_j \cdot \boldsymbol{E}\Delta t_j$$

$$J_j \sim q_j N_j \langle \tilde{v}_j \rangle,\ E \sim \frac{\langle \tilde{v}_j \rangle}{c}\delta B,\ \langle \tilde{v}_j \rangle \sim v_0 + \sqrt{\frac{2kT_0}{m_j}}$$

$$\Delta t_j \sim \frac{m_j c}{q_j \delta B}$$

From the relations in thermodynamics, …

Step 2: Shock Jump Condition w CRs



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randomization of thermal particles

The first law per unit mass

$$de_j = kT_j ds_j + (P_j/\rho_j) d\rho_j$$

$$d\varepsilon_j = d(\rho_j e_j)$$

$$\rightarrow \frac{d\varepsilon_j}{\varepsilon_j} = \gamma \frac{d\rho_j}{\rho_j} + (\gamma - 1) m_j ds_j$$

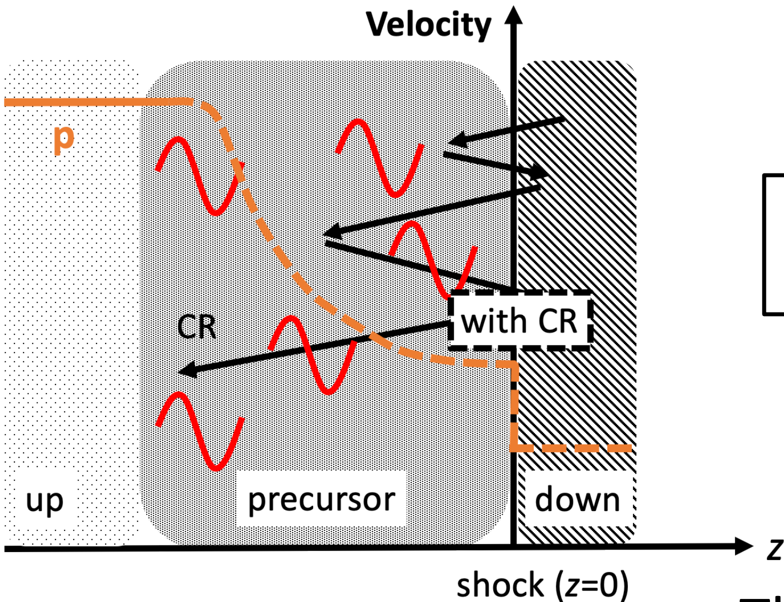
$$\rightarrow \boxed{(\gamma - 1)\, m_j \Delta s_j = \ln\left(\frac{\varepsilon_{j,2}}{\varepsilon_{j,0}}\right) - \gamma \ln\left(\frac{\rho_{j,2}}{\rho_{j,0}}\right)}$$

substituting

$$\Delta s_j = \frac{1}{M_j} \frac{J_j E \Delta t_j}{kT_j} = \frac{\langle \tilde{v}_j \rangle^2}{kT_0} \frac{x_j}{r_j}$$

$$r_j \equiv \frac{n_{j,2}}{n_{j,0}} \quad x_j \equiv \frac{\varepsilon_{j,2}}{\varepsilon_{j,0}}$$

Step 2: Shock Jump Condition w CRs



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randomization of **thermal particles**

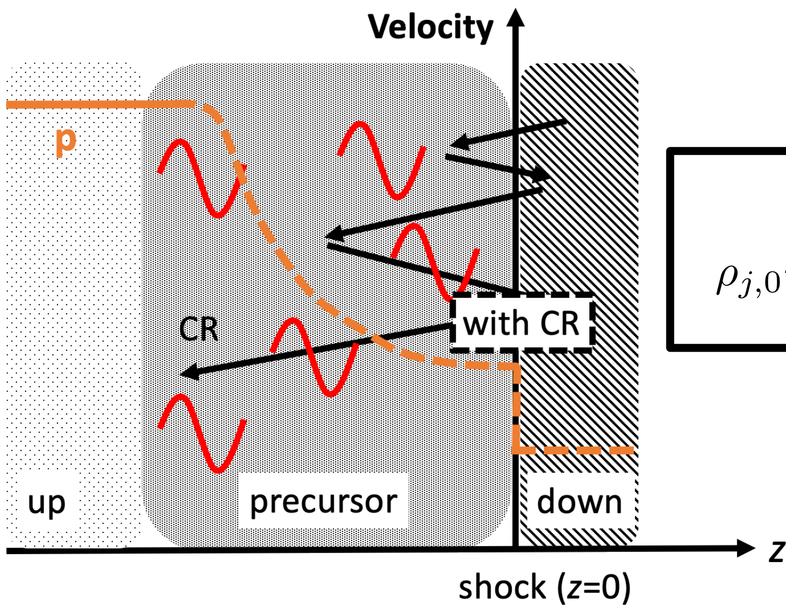
$$f \equiv \frac{x_j}{r_j}\left[\ln x_j - \gamma \ln r_j\right] - \gamma\left(\gamma - 1\right)\left(\frac{\langle \tilde{v}_j \rangle}{v_0}\right)^2 {\mathcal{M}_{\mathrm{s},j}}^2 = 0$$

$$r_j \equiv \frac{n_{j,2}}{n_{j,0}} \quad x_j \equiv \frac{\varepsilon_{j,2}}{\varepsilon_{j,0}}$$

This corresponds to the equation of state.

The shock jump is given by $f = 0$ with the mass & momentum flux conservation laws.

Step 2: Shock Jump Condition w CRs



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Mass & Momentum flux

$$\rho_{j,0}v_0 = \rho_{j,2}v_2,$$
$$\rho_{j,0}{v_0}^2 + P_{j,0} + F_{\mathrm{esc},j} = \rho_{j,2}{v_2}^2 + P_{j,2} + \left(\frac{\delta B^2}{4\pi} + P_{\mathrm{cr}}\right)\frac{\rho_{j,0}}{\rho_0}$$

- The compression ratio

$$r_j = \rho_{j,2}/\rho_{j,0} = r \quad (v_{j,2} = v_2)$$

- The contribution of the species j for the P_{cr} & δB is proportional to the kinetic energy.

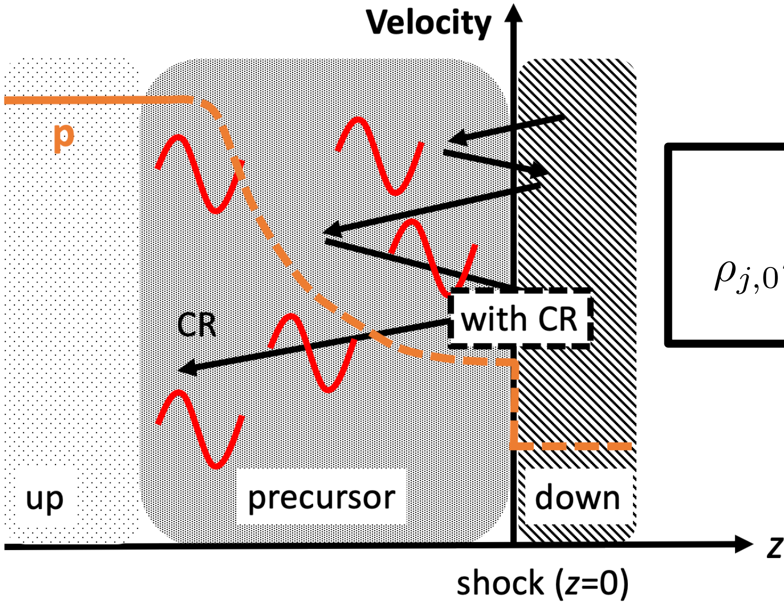
$$\rho_{j,0}{v_0}^2/2.$$

- $F_{\mathrm{esc},j}$ is the momentum flux of the espcaping CRs

$$F_{\mathrm{esc}} \lesssim \rho_0 {v_0}^3/3c.$$

→negligibly small

Step 2: Shock Jump Condition w CRs



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Mass & Momentum flux

$$\rho_{j,0} v_0 = \rho_{j,2} v_2,$$

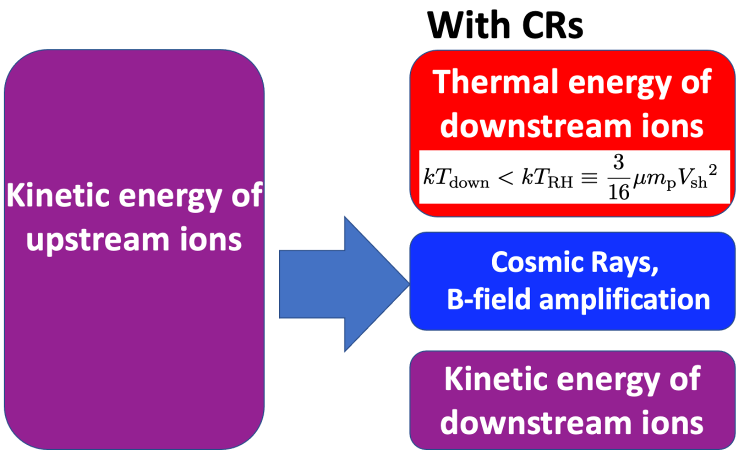
$$\rho_{j,0} {v_0}^2 + P_{j,0} + F_{\mathrm{esc},j} = \rho_{j,2} {v_2}^2 + P_{j,2} + \left(\frac{\delta B^2}{4\pi} + P_{\mathrm{cr}} \right) \frac{\rho_{j,0}}{\rho_0}$$

$$r = \left[1 + \frac{1 - x_j}{\gamma {\mathcal{M}_{\mathrm{s},j}}^2} - (\xi_{\mathrm{B}} + \xi_{\mathrm{cr}}) \right]$$

$$x_j = 1 + \gamma {\mathcal{M}_{\mathrm{s},j}}^2 \left(1 - \frac{1}{r} - \xi_{\mathrm{B}} - \xi_{\mathrm{cr}} \right)$$

$$\xi_{\mathrm{B}} = \frac{\delta B^2}{4\pi \rho_0 {v_0}^2}, \quad \xi_{\mathrm{cr}} = \frac{P_{\mathrm{cr}}}{\rho_0 {v_0}^2}$$

Step 2: Shock Jump Condition w CRs



$$f \equiv \frac{x_j}{r_j}\left[\ln x_j - \gamma \ln r_j\right] - \gamma\left(\gamma - 1\right)\left(\frac{\langle \tilde{v}_j \rangle}{v_0}\right)^2 {\mathcal{M}_{{\rm s},j}}^2 = 0$$

$$r = \left[1 + \frac{1 - x_j}{\gamma {\mathcal{M}_{{\rm s},j}}^2} - (\xi_{\rm B} + \xi_{\rm cr})\right]$$

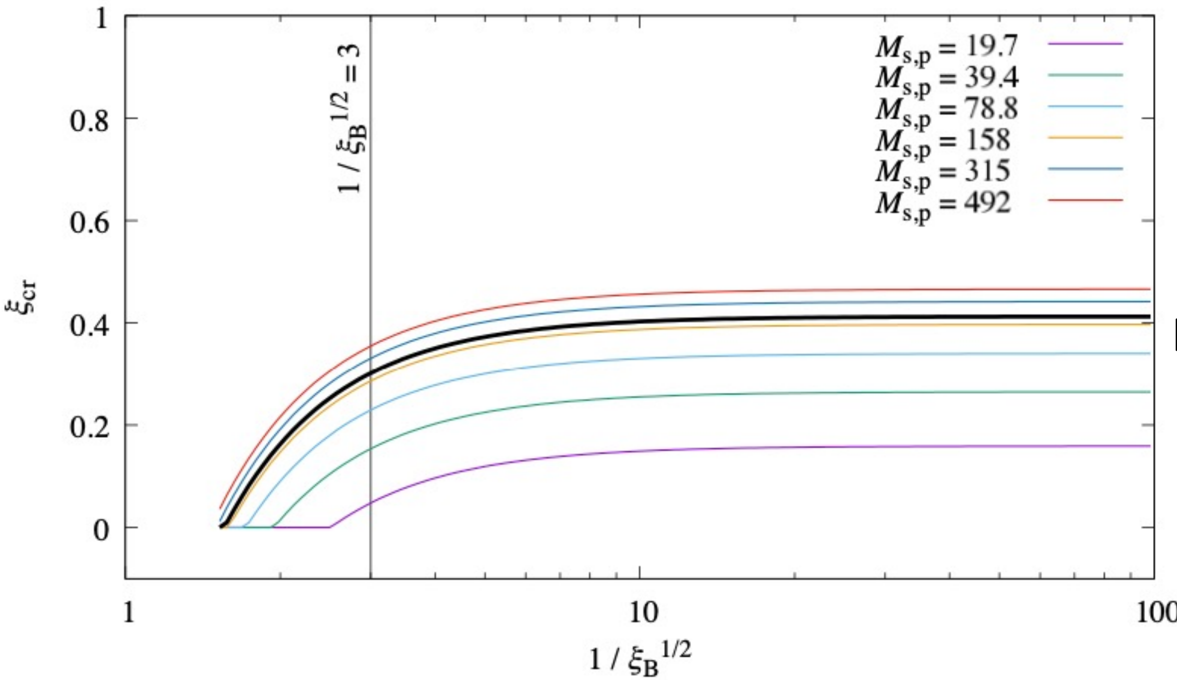
$$x_j = 1 + \gamma {\mathcal{M}_{{\rm s},j}}^2 \left(1 - \frac{1}{r} - \xi_{\rm B} - \xi_{\rm cr}\right)$$

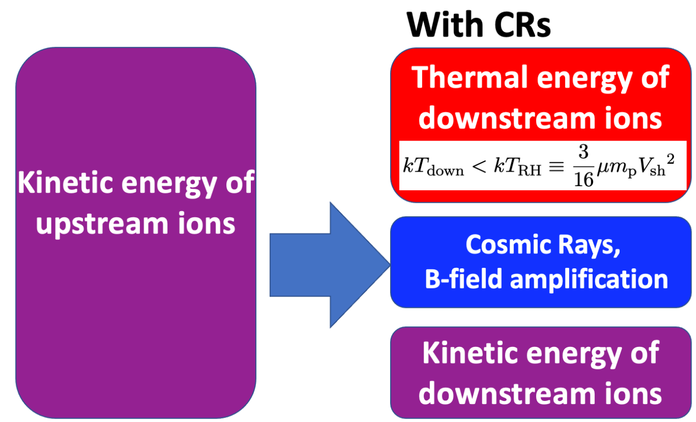
$$\xi_{\rm B} = \frac{\delta B^2}{4\pi \rho_0 {v_0}^2}, \quad \xi_{\rm cr} = \frac{P_{\rm cr}}{\rho_0 {v_0}^2}$$

We solve $f = 0$ with given $\xi_{\rm B}$ & $\xi_{\rm cr}$.

Step 2: Shock Jump Condition w CRs

➢ ***Maximum P_{cr}* is function of δB (from the energy budget).**





black $\mathcal{M}_{\mathrm{s},j} = 197$

The large δB is expected in young SNRs (e.g., Bamba+05; Uchiyama+07).

$$\rightarrow \; 1/\sqrt{\xi_{\mathrm{B}}} \sim 3$$

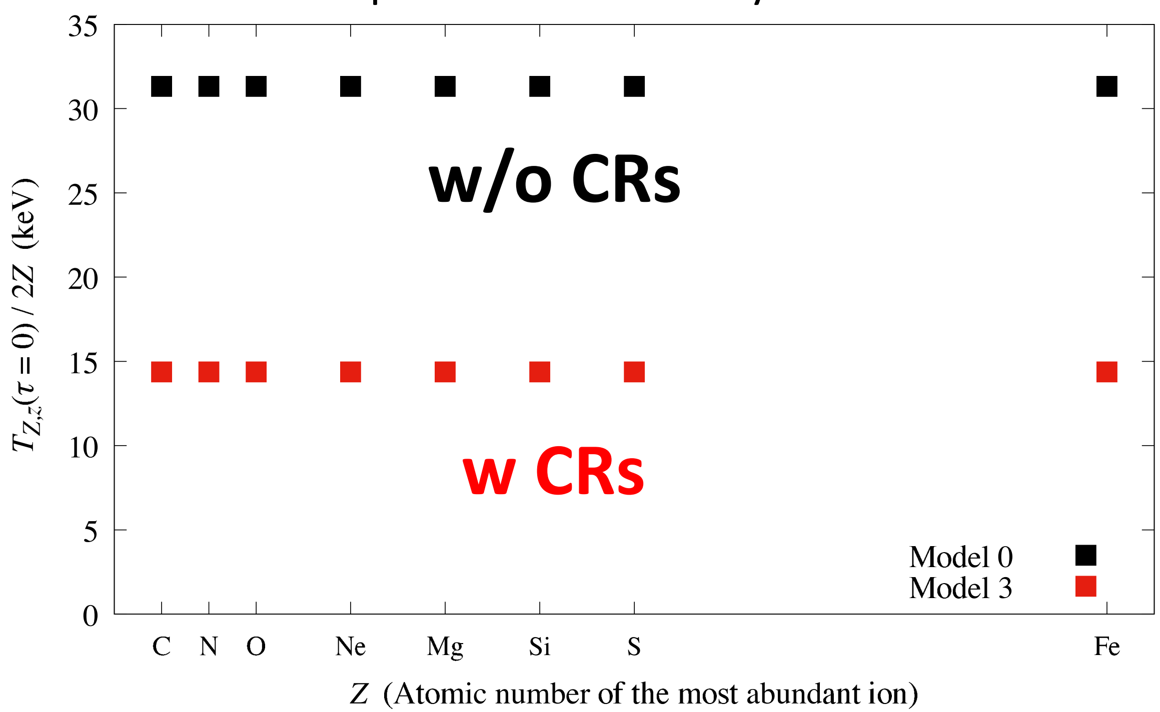
Step 2: Shock Jump Condition w CRs

$$v_0 = 4000\ \mathrm{km\ s^{-1}} \qquad \mathcal{M}_{\mathrm{s},j} = 197$$

$$\delta B \simeq 611\ \mu\mathrm{G} \left(\frac{v_0}{4000\ \mathrm{km\ s^{-1}}}\right) \left(\frac{n}{1\ \mathrm{cm^{-3}}}\right)^{1/2} \left(\frac{1/\sqrt{\xi_\mathrm{B}}}{3}\right)^{-1}$$

Consistent with Synchrotron X-ray (Bamba+05, Uchiyama+07)

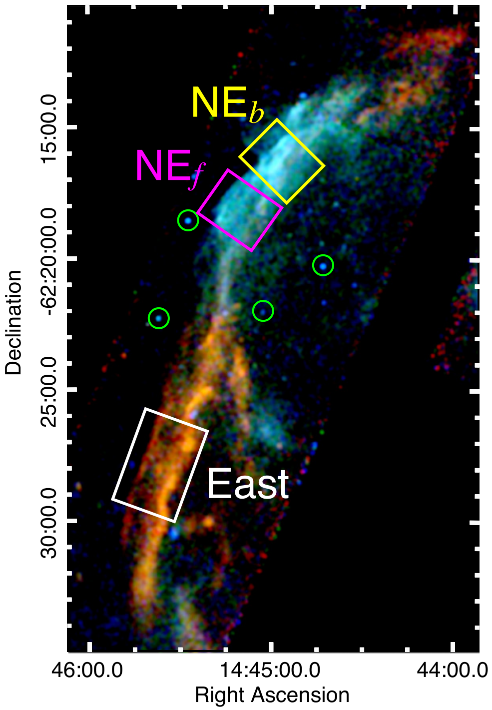
Ion temperatures divided by the ion mass

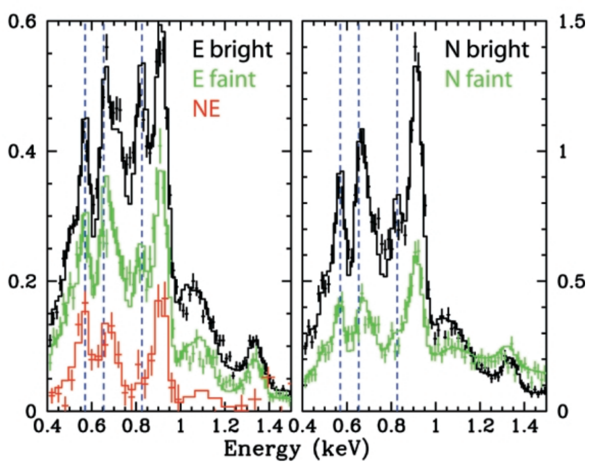


The mass-proportional ion temperatures are obtained which are consistent with observations of SN 1987A (Miceli+19).

Apply to RCW 86

Yamaguchi+16





Yamaguchi+16 | Vink+06

NE$_f$: $v_0 = 3000 \pm 340$ km/s, $nt \sim 10^9$ cm^{-3} s

NE$_b$: $v_0 = 1780 \pm 240$ km/s, $nt \sim 10^9$ cm^{-3} s

East : $v_0 = 720 \pm 360$ km/s, $nt \sim 10^{10}$ cm^{-3} s

$B \sim 24 \pm 5$ μG

$t \sim 2$ kyr & $1/\sqrt{\xi_{\rm B}} \sim 3$

$\xi_{\rm cr,3000} \simeq 0.28$

$P_{\rm cr,3000} \sim 0.438$ keV cm^{-3}

$\delta B_{3000} \sim 59.2\ \mu$G

$\xi_{\rm cr,1780} \simeq 0.24$

$P_{\rm cr,1780} \sim 0.132$ keV cm^{-3}

$\delta B_{1780} \sim 35.1\ \mu$G

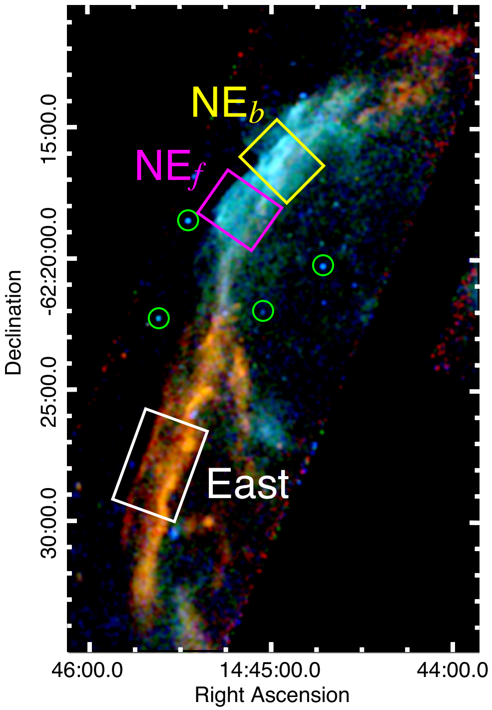
$\xi_{\rm cr,720} \simeq 0.14$

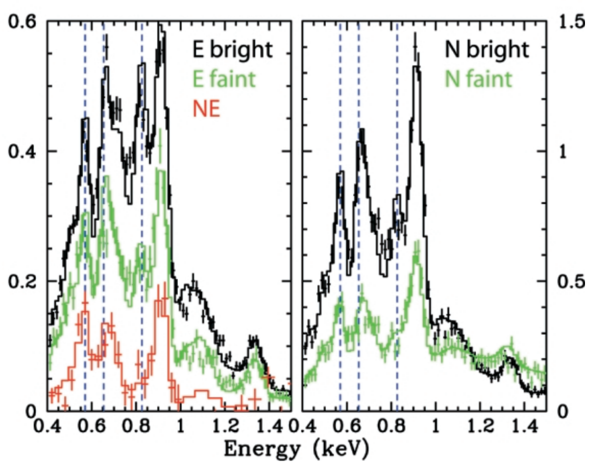
$P_{\rm cr,720} \sim 0.126$ keV cm^{-3}

$\delta B_{720} \sim 44.9\ \mu$G

Apply to RCW 86

Yamaguchi+16





Yamaguchi+16 Vink+06

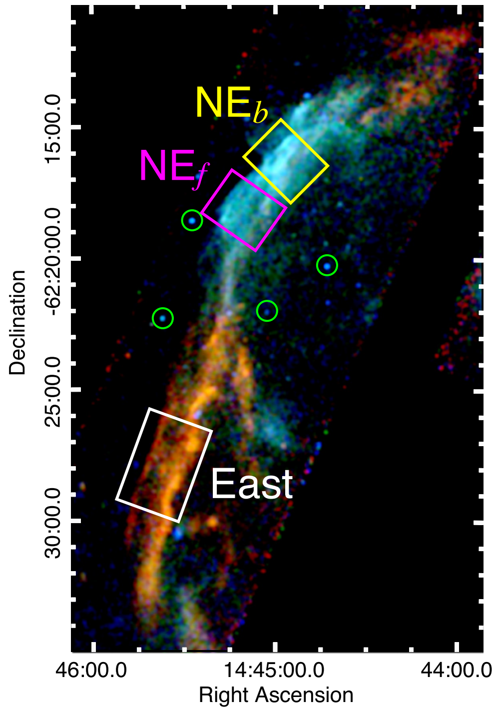
$$\mathrm{NE}_f\ : v_0 = 3000 \pm 340\ \mathrm{km/s},\ nt \sim 10^9\ \mathrm{cm^{-3}\ s}$$

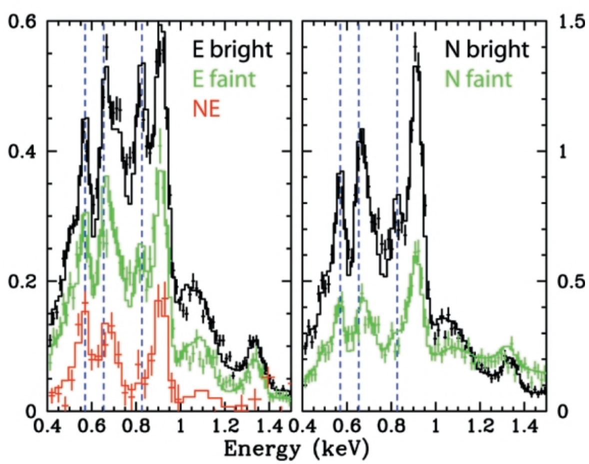
We perform synthetic observation of X-ray line at $\mathrm{NE_f}$ region with assuming…

- Recent expansion of RCW 86 is approximated by the Sedov-Taylor solution (1-D model).
- The downstream temperature relaxation is dominated by the Coulomb interaction.

Apply to RCW 86

Yamaguchi+16





Yamaguchi+16 Vink+06

$$\mathrm{NE}_f \;:\; v_0 = 3000 \pm 340\ \mathrm{km/s},\ nt \sim 10^9\ \mathrm{cm^{-3}\ s}$$

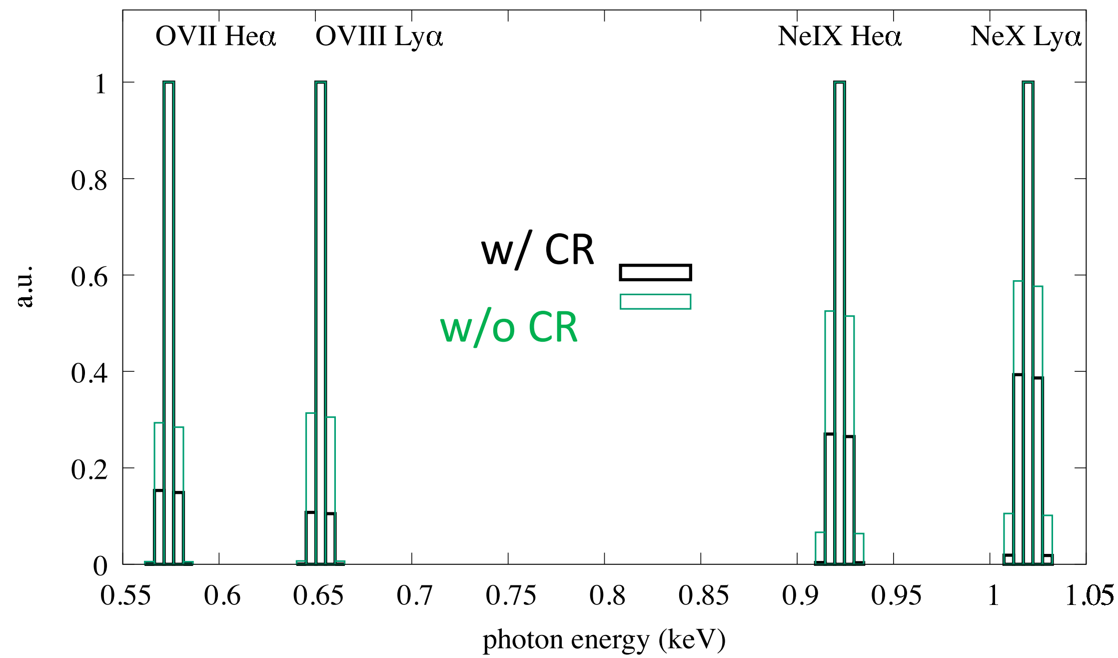


Fig. 14. The line profiles with 5 eV resolution for $\delta = 0.5$. We display O VII Heα, O VIII Lyα, Ne IX Heα, and Ne X Lyα for Model 5 (black solid line) and Model 2 (green solid line).

Summary

- XRISM era: The ion temperature is measured by ***the line width***.
- **We construct the theoretical model of ion heating at the shock transition.**
- Future XRISM/Athena observation will distinguish whether the SNR shock accelerates the CRs or not.