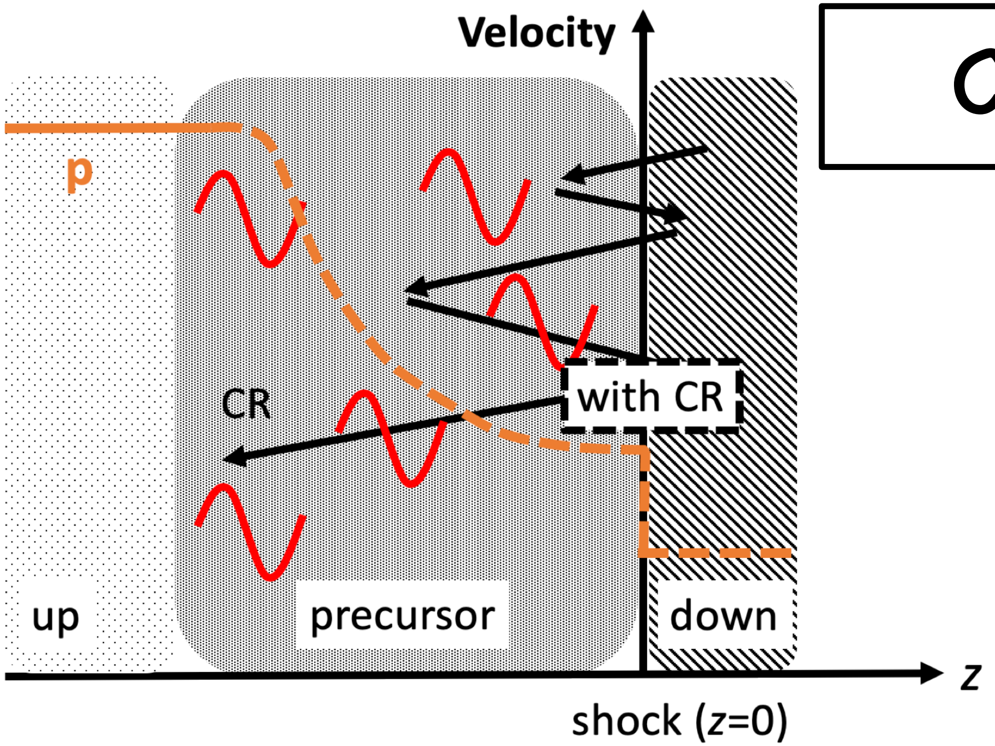
The effects of escaping cosmic-rays from Supernova Remnants in the interstellar medium

Jiro Shimoda[1]

1. The Univ. of Tokyo, ICRR

Cosmic Rays: Injection Problem



upstream → subscript “0”

downstream→ subscript “2”

Diffusive Shock Acceleration (DSA)
→The most accepted mechanism

Good Point

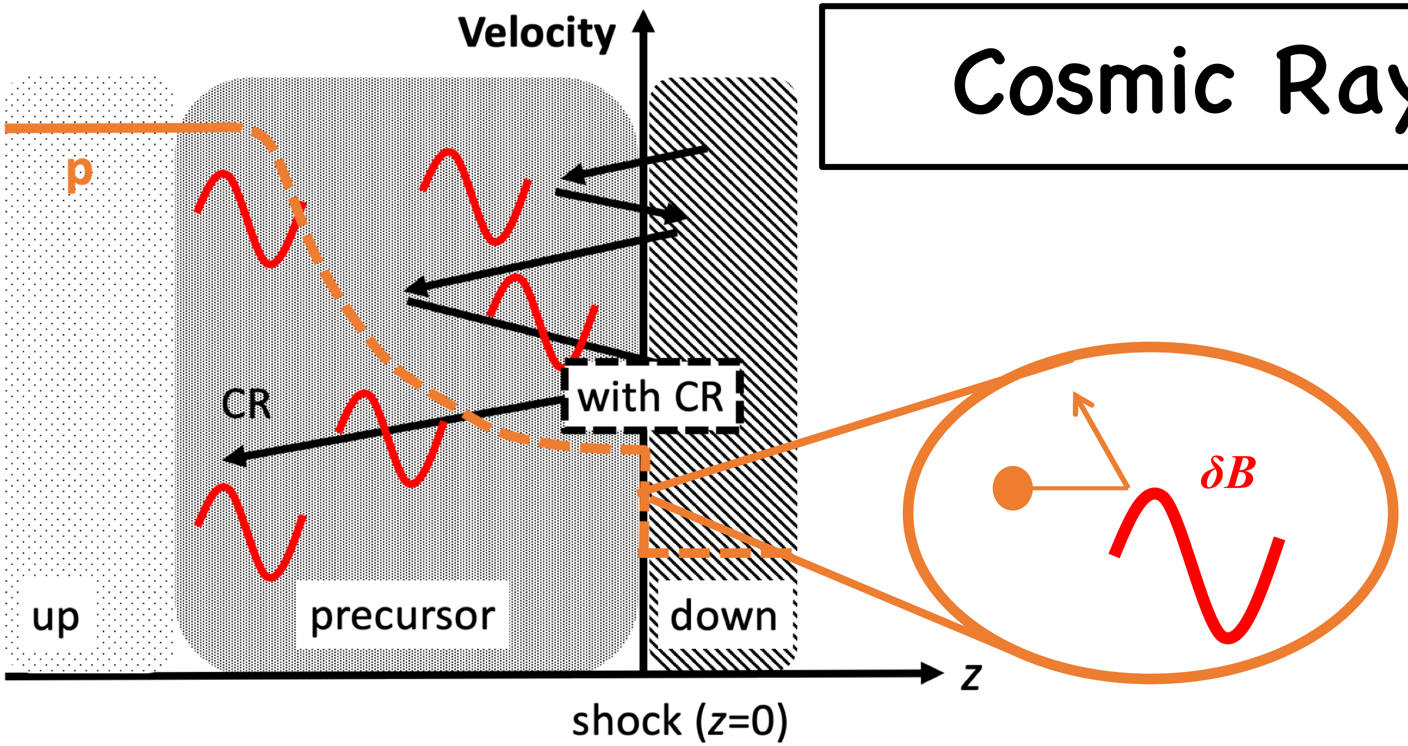
①The acceleration time can be short enough.
②**The power-law energy distribution** of CRs is robustly predicted.

Insufficient Point

NOT predicts the amount of CRs.

Other observational test or theory for the injection is required.

Cosmic Rays: Injection Problem



$$\Delta\tilde{Q} \sim \boldsymbol{J}\cdot\boldsymbol{E}\Delta t$$

$$\boldsymbol{J} \sim qN\langle v_0\rangle,\ |\boldsymbol{E}| \sim \frac{\langle v_0\rangle}{c}\delta B,\ \langle v_0\rangle \sim v_0 + \sqrt{\frac{2kT_0}{m}}$$

$$\Delta t \sim \frac{mc}{q\delta B}$$

$$dS = \frac{dQ}{kT} + \text{~~(p.p.collision)~~}$$

Negligible in Collisionless shocks

upstream → subscript "0"

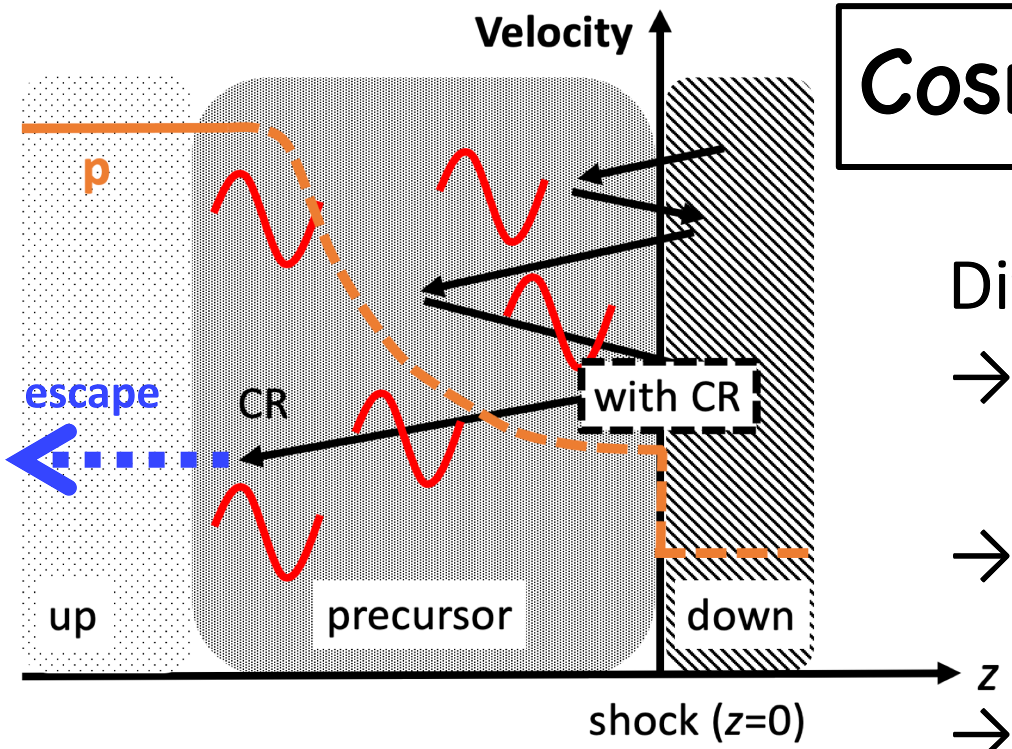
downstream→ subscript "2"

Shimoda et al. (2022)

- ➢ An example of **the injection model.**
- ➢ We also calculate **X-ray lines** from the downstream temperature as a prediction of this model.

→Future XRISM mission (after GVO4) can test the injection rate.

Cosmic Rays: Escape Problem



upstream → subscript "0"

downstream→ subscript "2"

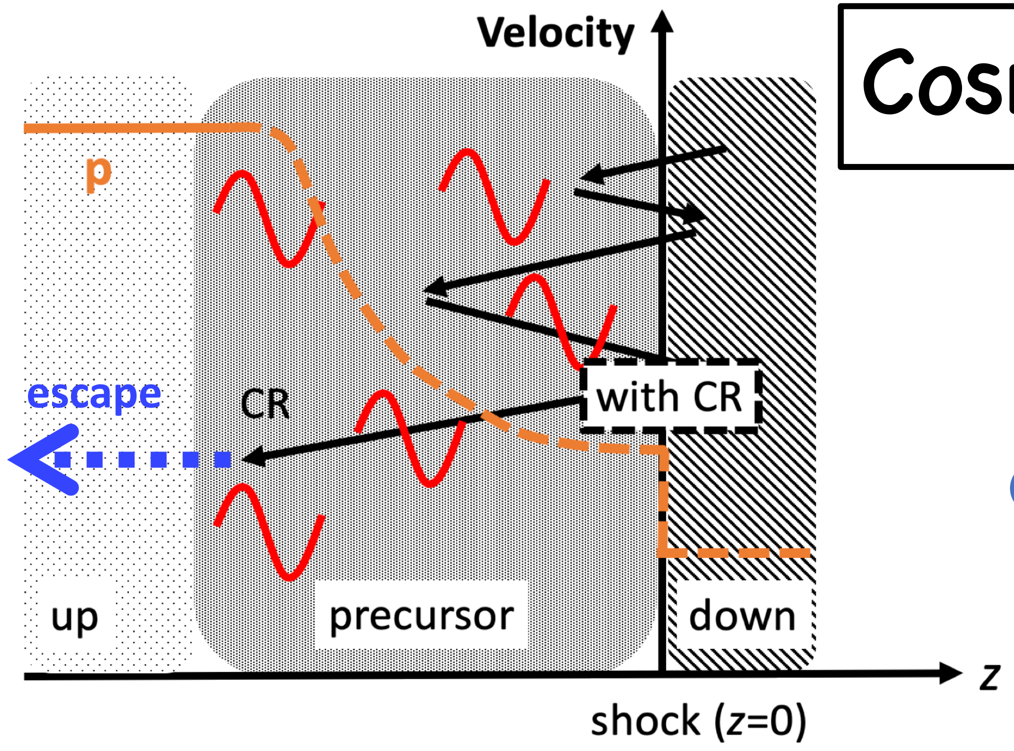
Diffusive Shock Acceleration (DSA)
→CRs are diffusing out from the shock

→The shock can catch up again the diffusing CRs

→**When the shock decelerates** or CR diffusion speed becomes large, **the CRs escape from the shock.**

The details of "escape" (i.e., the diffusion coefficient) over SNR time scale have not been established yet.

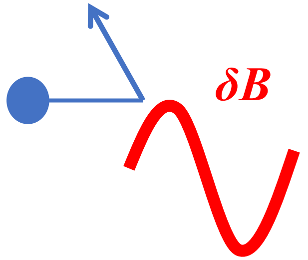
Cosmic Rays: Escape Problem



upstream → subscript “0”

downstream→ subscript “2”

What can be a probe for the Escape CRs?

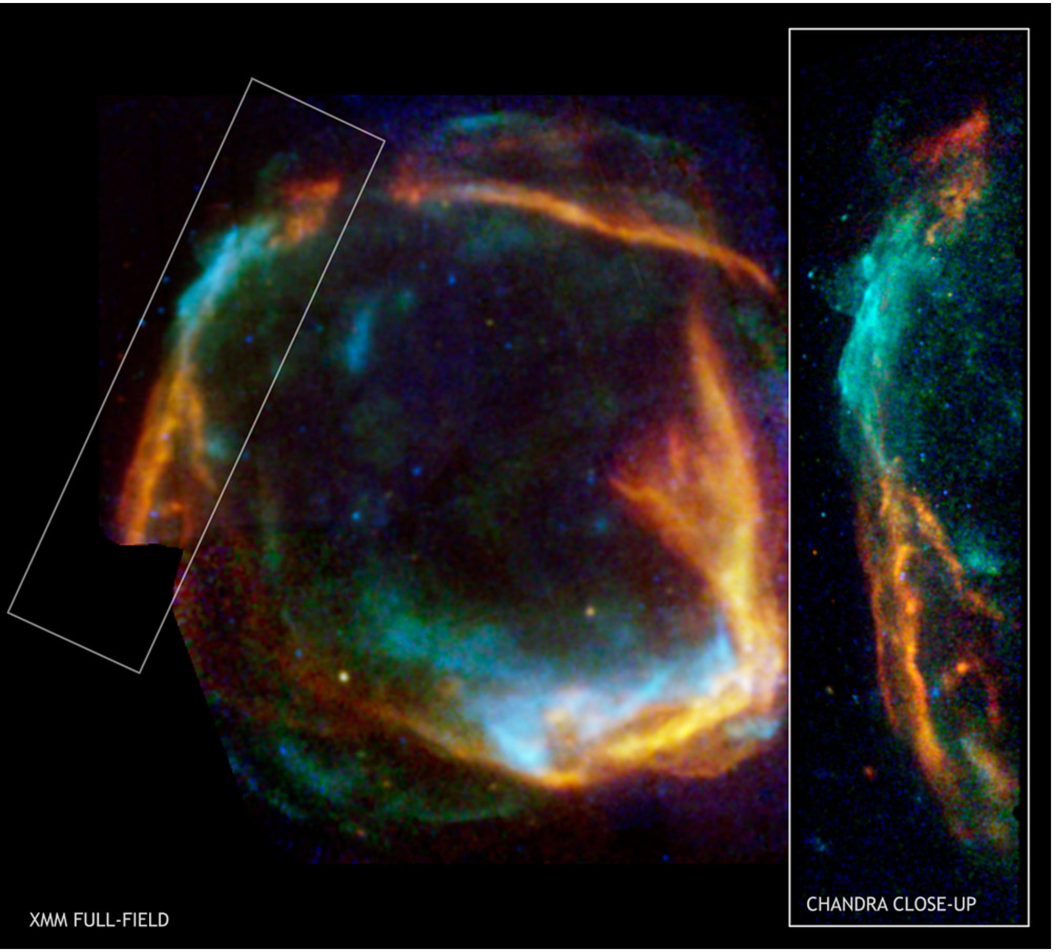


CRs scattered by δB
→Momentum transferred to δB
→δB grows
→dissipation of δB
→Thermal gas heated

$$\Gamma = |V_A \nabla P_{cr}| \ (\mathrm{erg/cc/s})$$ (e.g., Kulsrud 2005)

- **The ISM around the SNR can be heated by the Escaping CRs!**
- **We consider its possibility by constructing a simple model.**

Heating of the ISM by Escaping CRs



https://chandra.harvard.edu/photo/2006/rcw86/

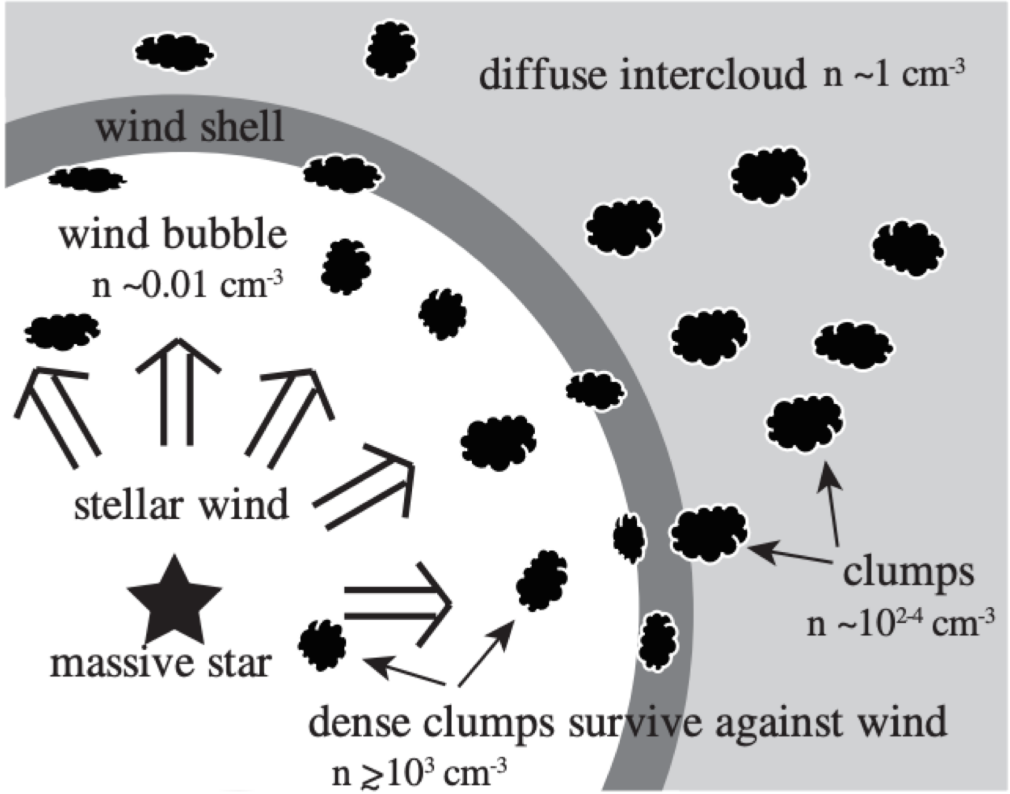
- Starting from a Mid. age（~Sedov）SNR
- 1D-spherical model for simplicity.
- But in reality…
  ISM is not uniform.

  Shock is stable for the upstream perturbations.

  If the number of "clumps" is small, the mean shock dynamics are not so affected (e.g., Inoue+13).

We take $\langle n_{ism} \rangle \sim 1$ /cc

Heating of the ISM by Escaping CRs



Inoue+12

- Starting from a Mid. age（~Sedov） SNR
- 1D-spherical model for simplicity.
- But in reality…

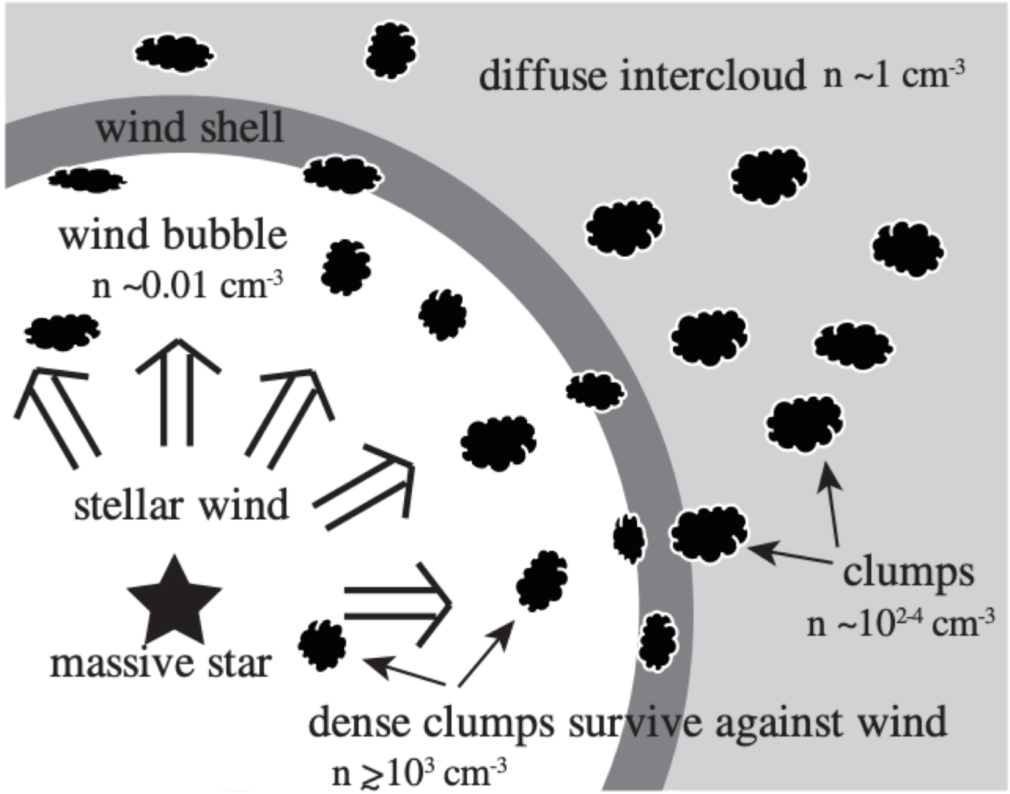
  ISM is not uniform.

  Shock is stable for the upstream perturbations.

  If the number of "clumps" is small, the mean shock dynamics are not so affected (e.g., Inoue+13).

We take $\langle n_{ism} \rangle \sim 1$ /cc

Model Setup



$$\frac{\partial f}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left\{ r^2 \left(v + D(\gamma)\frac{\partial}{\partial r} \right) f \right\} = f_{\rm inj}(t,\gamma)\delta(r - R_{\rm sh}(t))$$

$$f_{\rm inj} \propto \gamma^{-s} e^{-\gamma/\gamma_{\rm esc}(t)}$$

$$\gamma_{\rm esc}(t) = \gamma_{\rm max}\left(\frac{V_{\rm sh}(t)^2 t}{D_{\rm max}} \right)^{1/\alpha}$$

$$D(\gamma) = D_{\rm max}\left(\frac{\gamma}{\gamma_{\rm max}} \right)^{\alpha}$$

$$D_{\rm max} = \frac{{R_s}^2}{t_s}$$

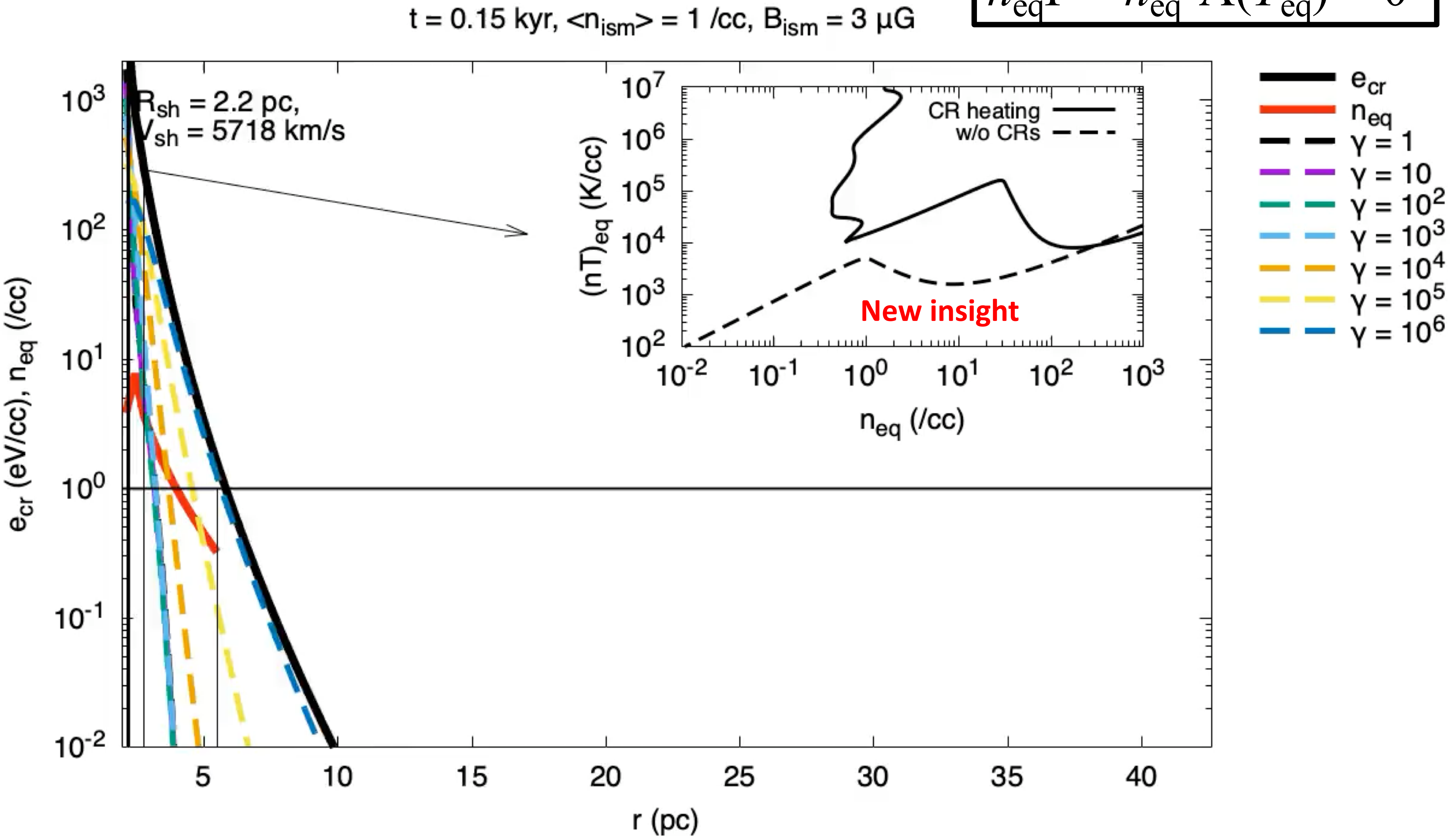
Sedov solution is adopted
CR Injection rate = 10% of Shock kinetic energy

Inoue+12 $\gamma_{max} = 10^{6.5}$ ： Maximum Energy＠Sedov time
$s = 2.1$ ：Spectral index＠shock front
$\alpha = 0.33$ ：Energy dependence of diffusion coefficient

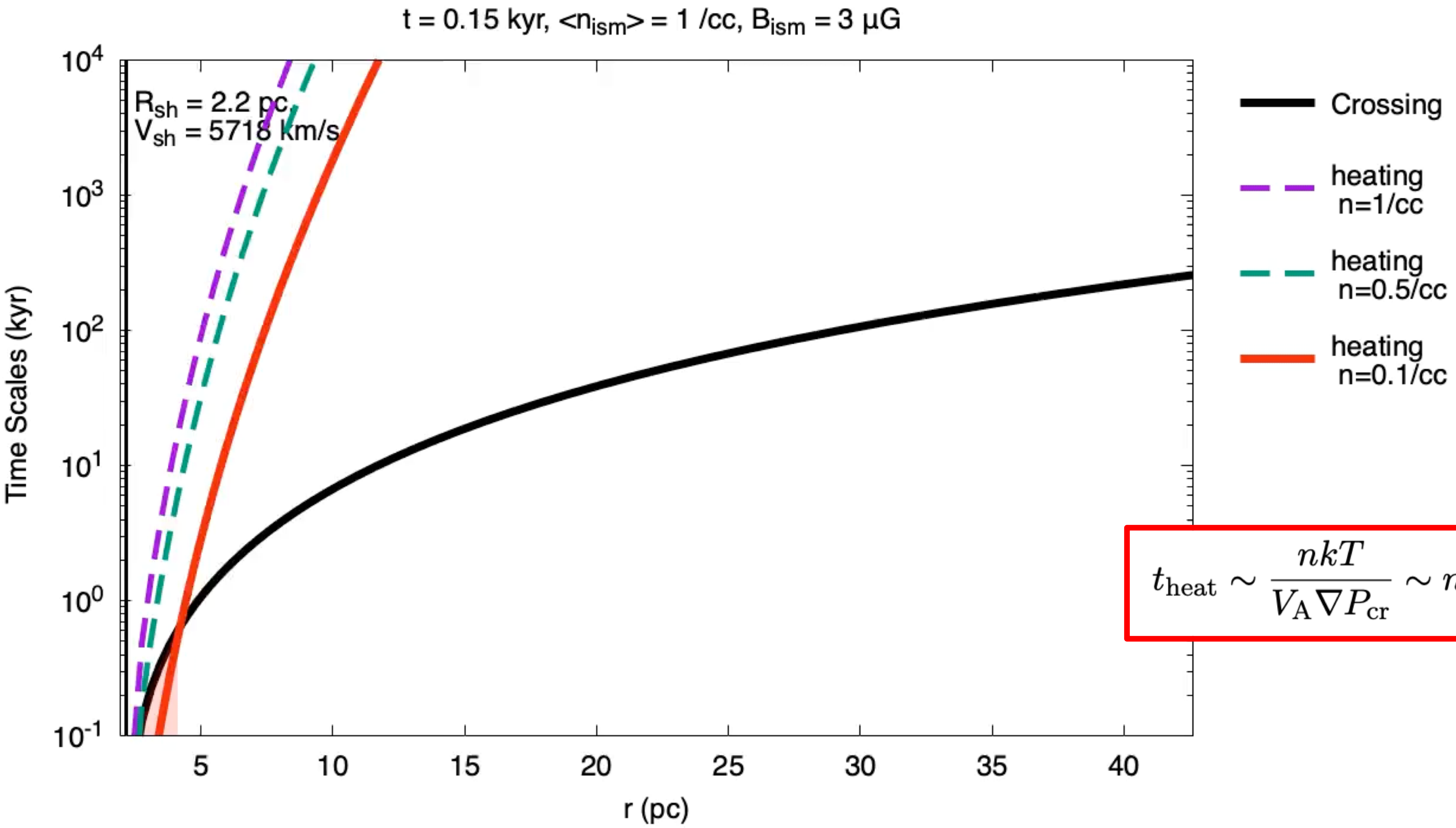
Profiles of Escaping CRs

Heating Cooling

$$n_{eq}\Gamma - n_{eq}^2\Lambda(T_{eq}) = 0$$

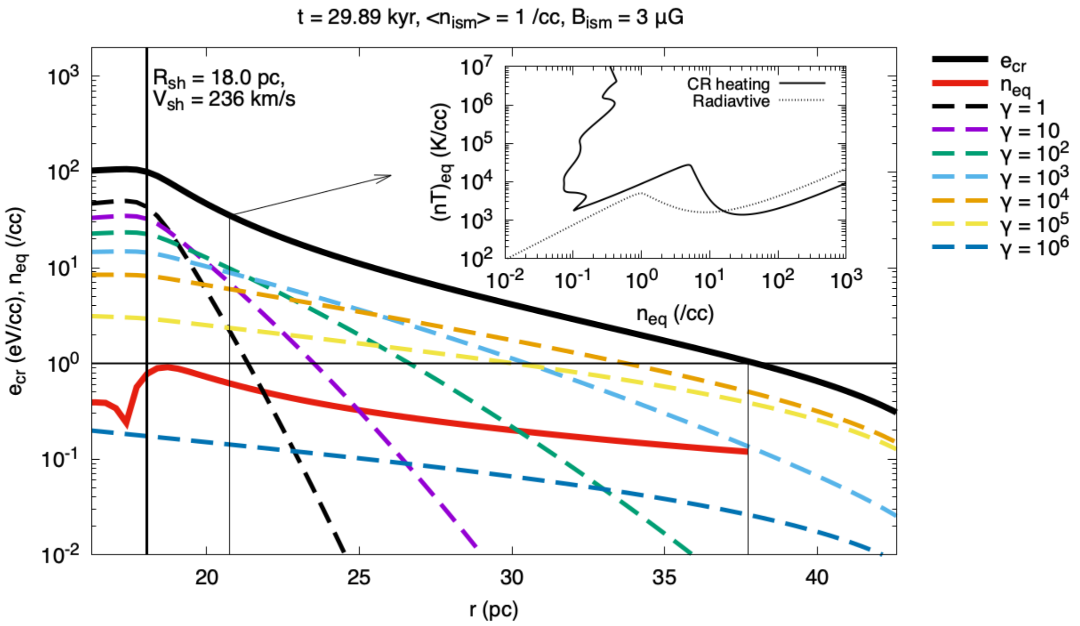


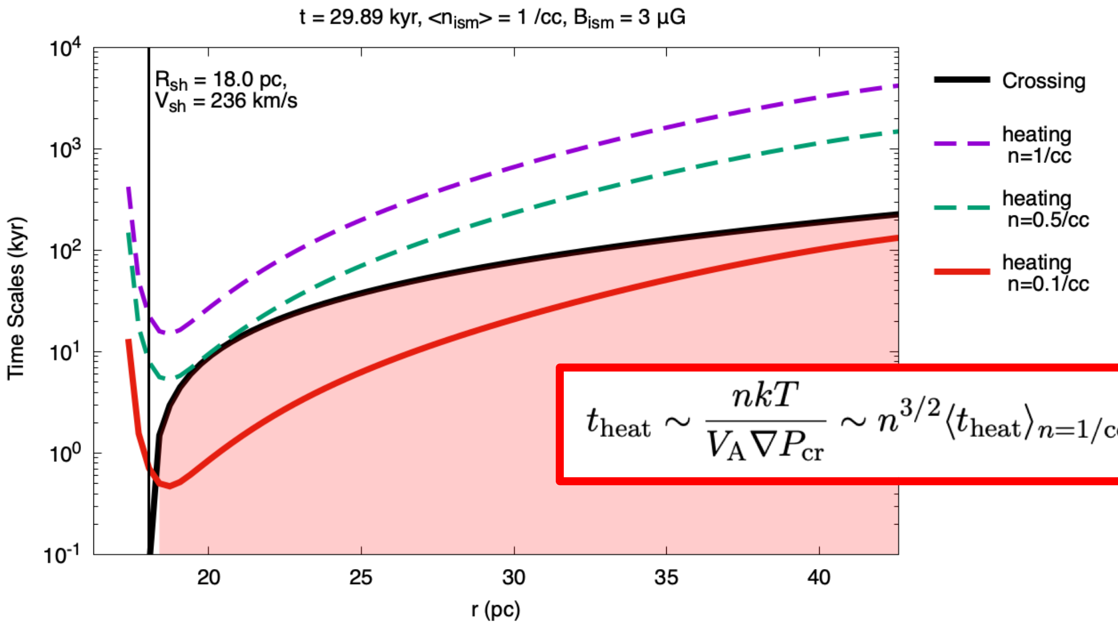
Heating time vs. Shock Crossing time



$$t_{\rm heat} \sim \frac{nkT}{V_{\rm A} \nabla P_{\rm cr}} \sim n^{3/2} \langle t_{\rm heat} \rangle_{n=1/{\rm cc}}$$

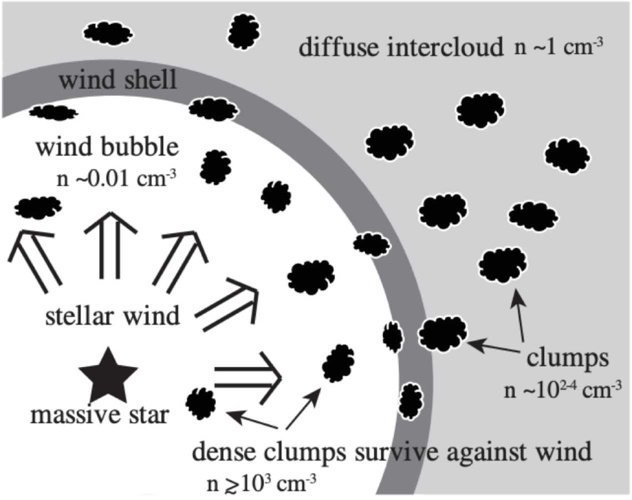
Heating time vs. Shock Crossing time





$$t_{\rm heat} \sim \frac{nkT}{V_{\rm A}\nabla P_{\rm cr}} \sim n^{3/2}\langle t_{\rm heat}\rangle_{n=1/{\rm cc}}$$

Inoue+12



- **n < 0.5 /cc gas components can be heated drastically.**
  There is many observational hints
  (Optical Atomic lines, IR dust emissions, Radio Molecular lines, etc)

- **It can also be important for the ISM thermal evolutions.**

Mysterious X-ray emissions

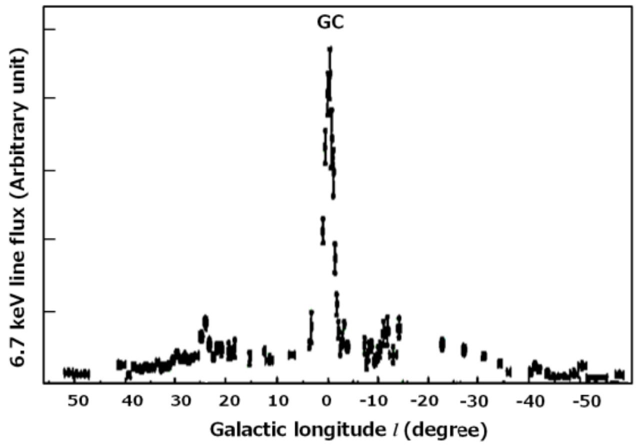
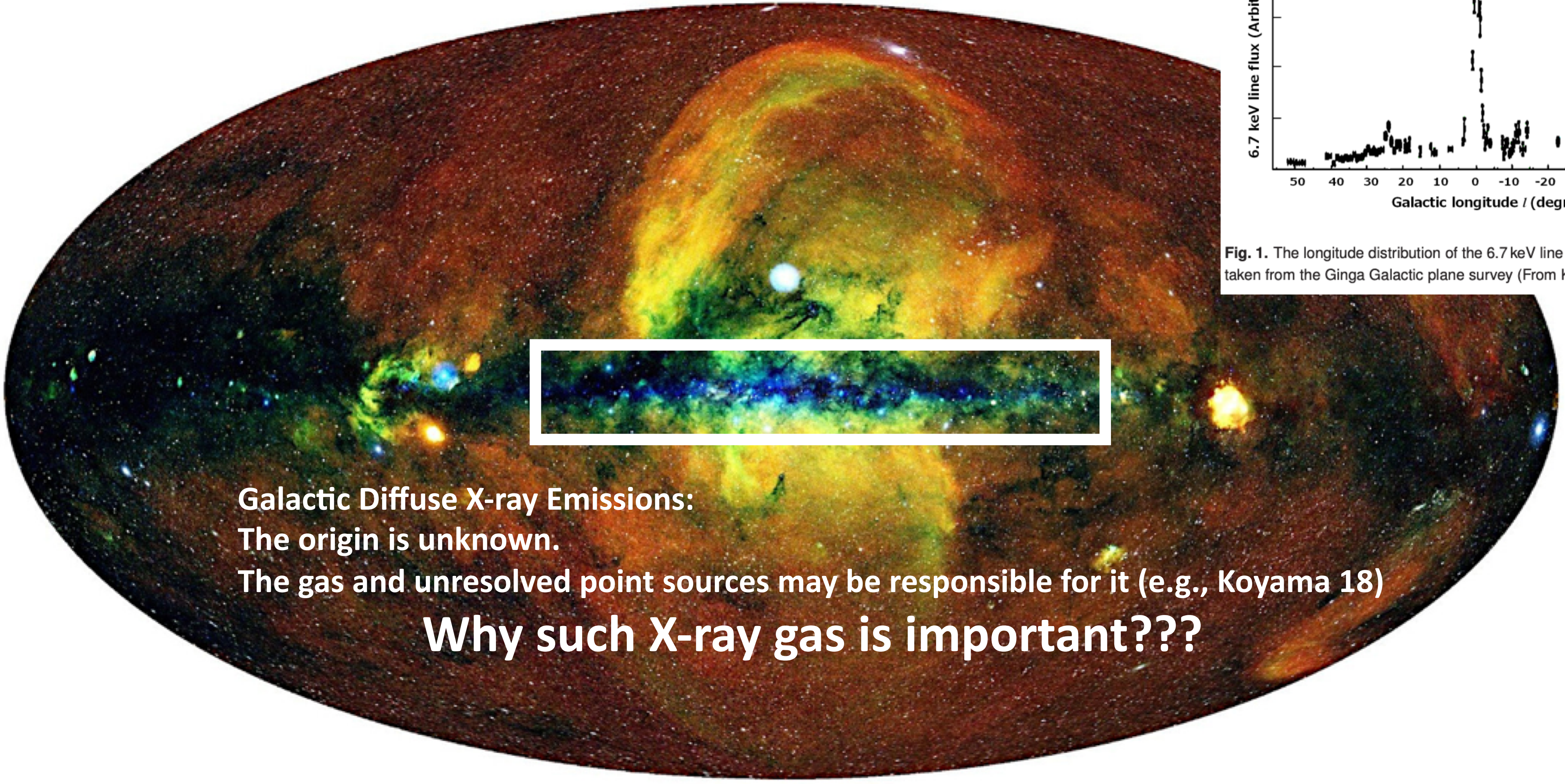


Fig. 1. The longitude distribution of the 6.7 keV line along the Galactic plane taken from the Ginga Galactic plane survey (From Koyama et al. 1989).

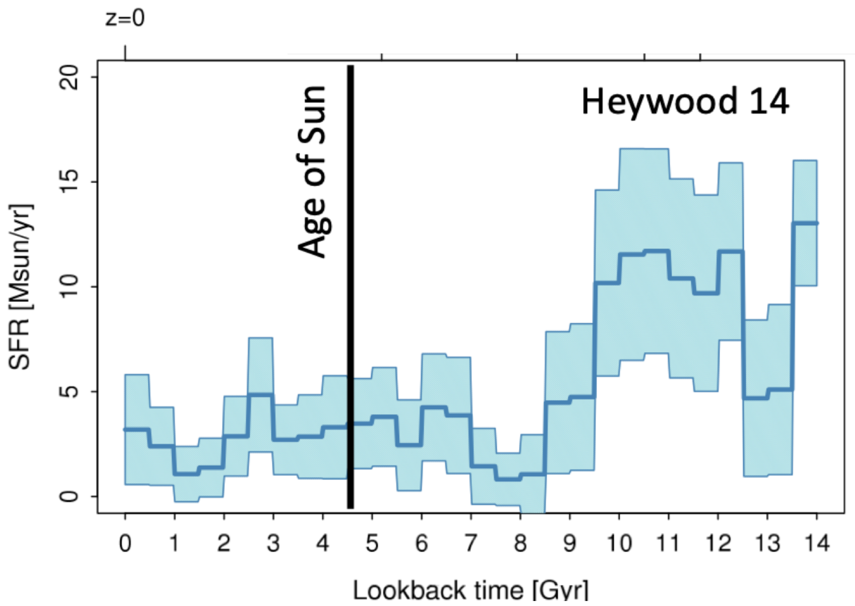


Galactic Diffuse X-ray Emissions:
The origin is unknown.
The gas and unresolved point sources may be responsible for it (e.g., Koyama 18)

Why such X-ray gas is important???

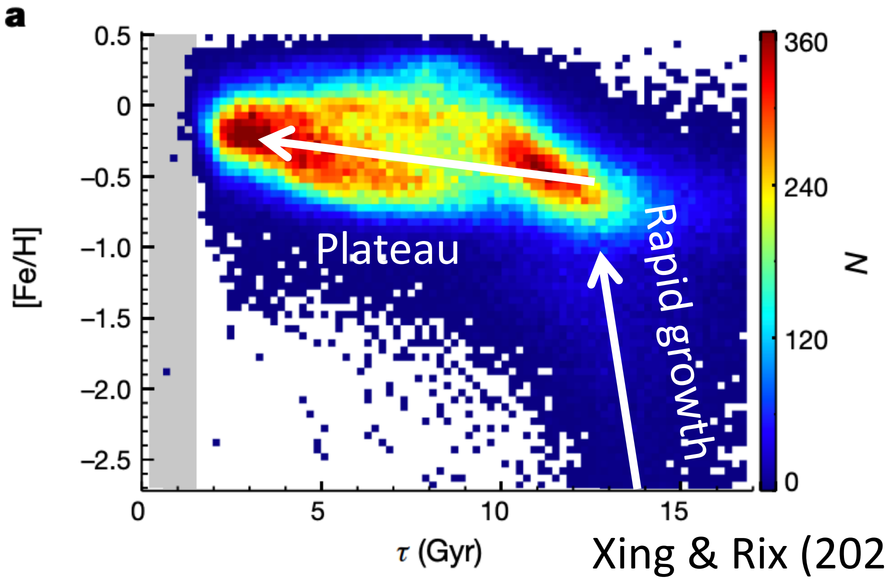
eROSITAによる全天画像。0.3〜0.6keVのエネルギーのX線を赤、0.6〜1keVを緑、1〜2.3keVを青に色付けして合成されています。
Credit: MPE/IKI

"Puzzling" Star Formation History
(the metal amount)



@ disk
SFR ~ 3 Mo/yr
Gas mass ~ 10^9 Mo (Metallicity Zo ~ 0.01 → Metal mass ~ 10^7 Mo)
Salpeter IMF → Massive Star FR ~ 0.1 Mo/yr

Total Metal Mass Ejected by SNe
→ ~ (SFR) x (Massive Star fraction) x (CO core mass fraction) x (14 Gyr)
~ (3 Mo/yr) x (0.1) x (3 Mo/8 Mo) x (14 Gyr)
~ 1.6 x 10^9 Mo



Xing & Rix (2022, by Gaia)

~99 % of metals should be removed from the disk!
→ Persistent Outflow is required!
X-ray emitting gas (~keV) can escape from the MW (Virial Temp. ~0.1 keV)

(SJ & Inutsuka 22, SJ, Inutsuka, & Nagashima 24, SJ & Asano 24)

Mysterious X-ray emissions

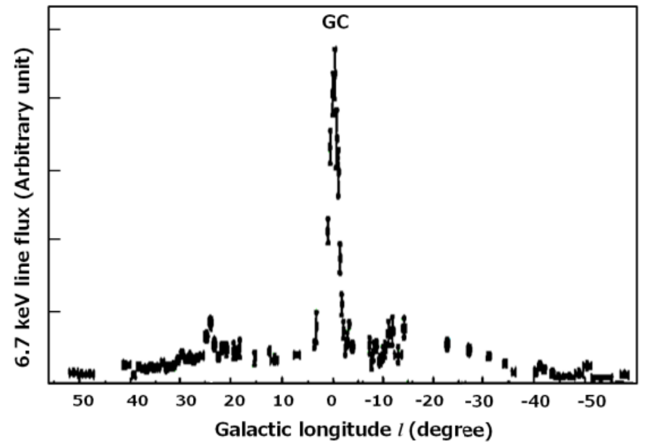
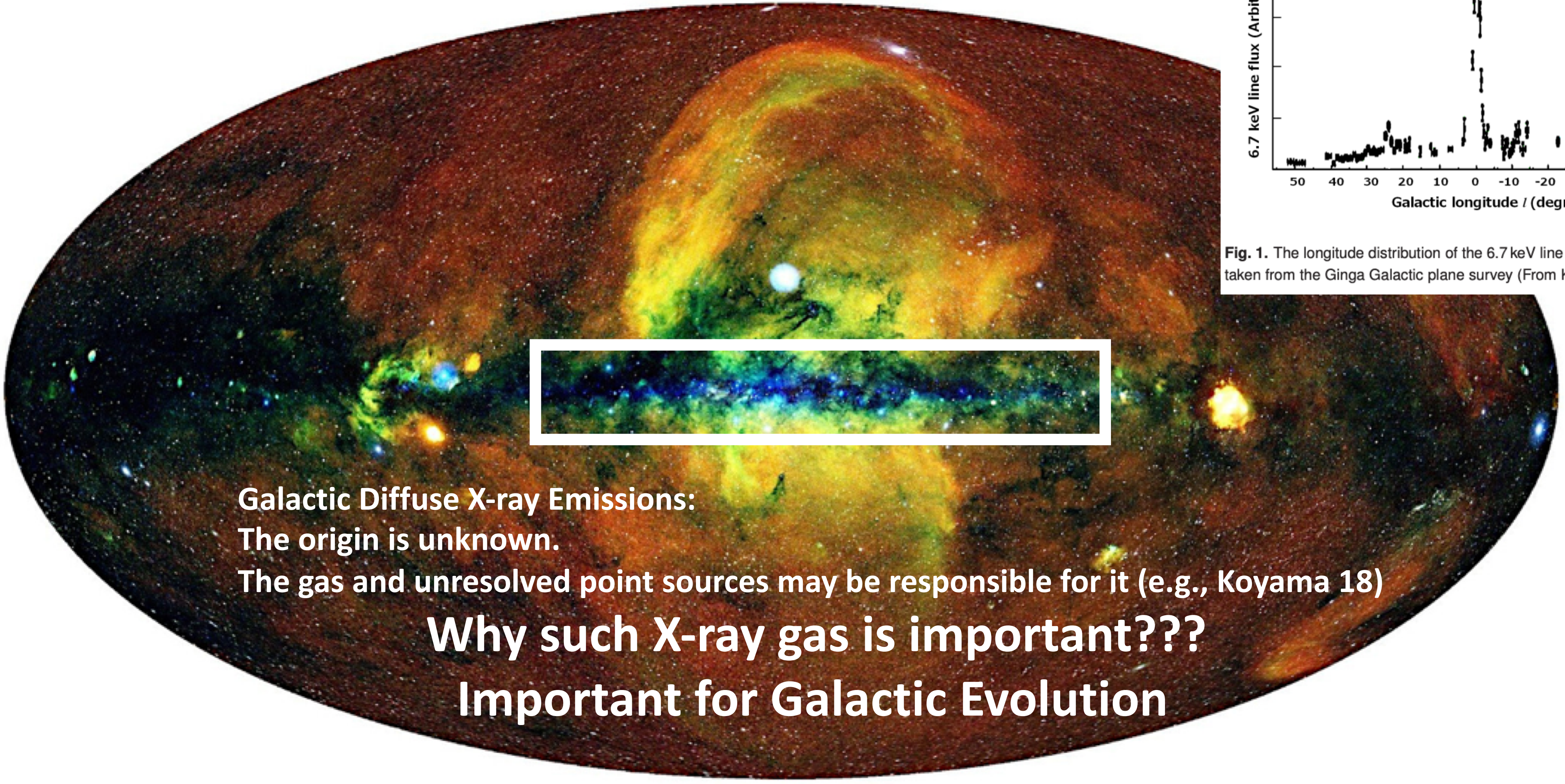


Fig. 1. The longitude distribution of the 6.7 keV line along the Galactic plane taken from the Ginga Galactic plane survey (From Koyama et al. 1989).



Galactic Diffuse X-ray Emissions:
The origin is unknown.
The gas and unresolved point sources may be responsible for it (e.g., Koyama 18)

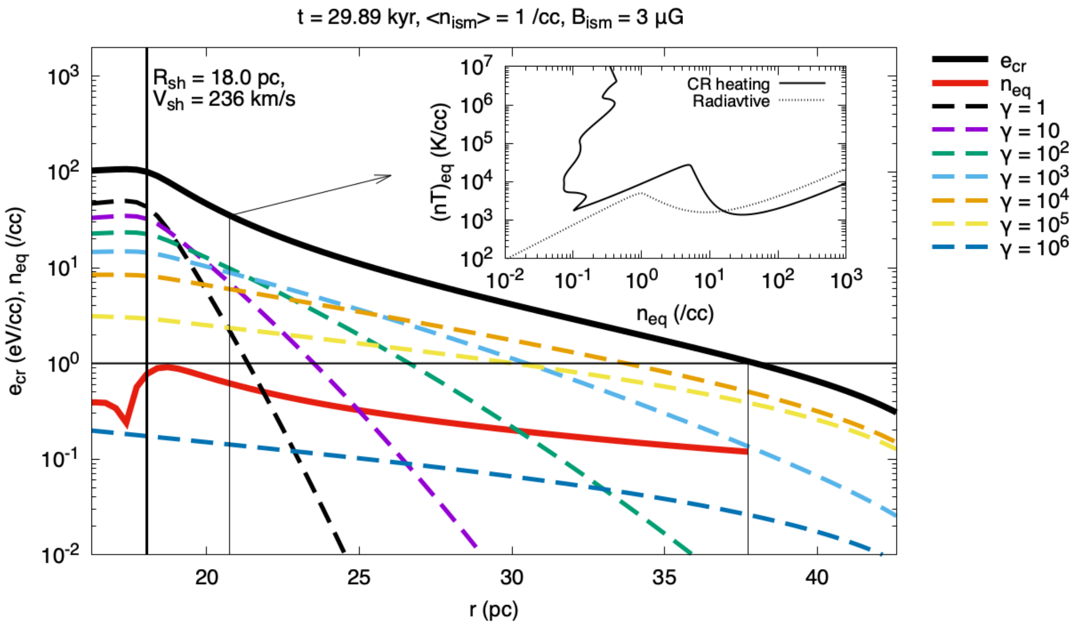
Why such X-ray gas is important???

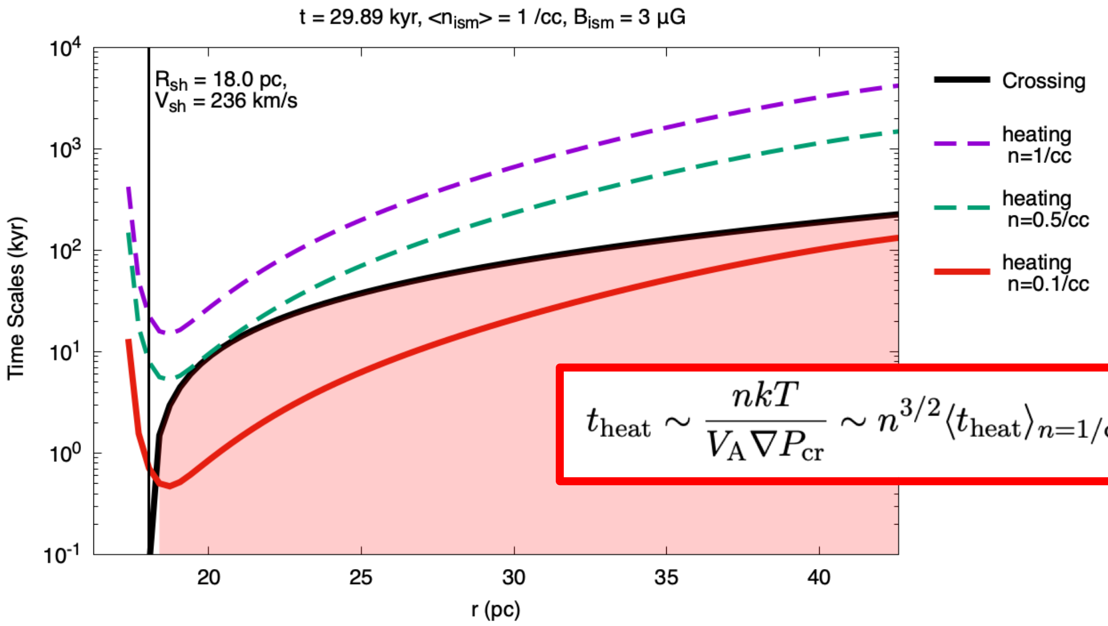
Important for Galactic Evolution

eROSITAによる全天画像。0.3〜0.6keVのエネルギーのX線を赤、0.6〜1keVを緑、1〜2.3keVを青に色付けして合成されています。

Credit: MPE/IKI

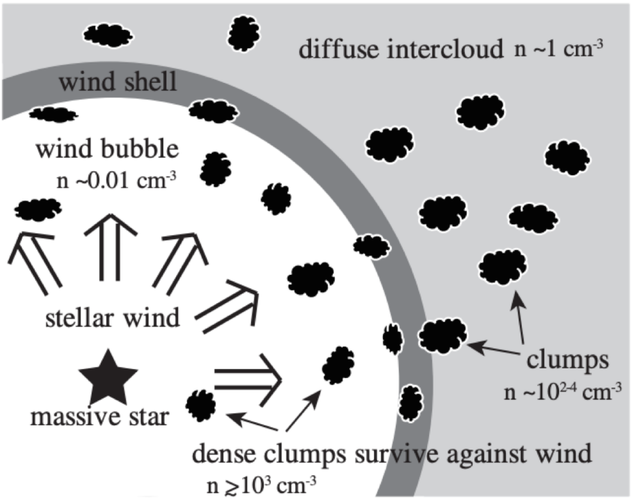
Heating time vs. Shock Crossing time





$$t_{\rm heat} \sim \frac{nkT}{V_{\rm A}\nabla P_{\rm cr}} \sim n^{3/2}\langle t_{\rm heat}\rangle_{n=1/{\rm cc}}$$

Inoue+12



- **n < 0.5 /cc gas components can be heated drastically.**
  There is many observational hints
  (Optical Atomic lines, IR dust emissions, Radio Molecular lines, etc)

- It can also be important for the ISM thermal evolutions.

We Investigate the CR-hydrodynamics!

The CR-hydrodynamics

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}(\rho \boldsymbol{v}) = 0$$

$$\rho \frac{d\boldsymbol{v}}{dt} = -\boldsymbol{\nabla}(P_{\rm g} + P_{\rm cr})$$

$P_{\rm g}$ is the pressure of thermal gas
$P_{\rm cr}$ is the CR pressure

The energy equation is not trivial

$$dQ = d(E_{\rm g} + E_{\rm cr}) + (P_{\rm g} + P_{\rm cr})dV$$

The 1st law of thermodynamics should include the CRs

The CR-hydrodynamics

$$\frac{\partial \rho}{\partial t} + \nabla (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla (P_{\rm g} + P_{\rm cr})$$

$P_{\rm g}$ is the pressure of thermal gas
$P_{\rm cr}$ is the CR pressure

The energy equation is not trivial

$$dQ = d(E_{\rm g} + E_{\rm cr}) + (P_{\rm g} + P_{\rm cr})dV$$

The 1st law of thermodynamics should include the CRs

$$\mathrm{d}Q_{\rm rad} + \mathrm{d}Q_{\rm conv} + \mathrm{d}Q_{\rm vis} + \mathrm{d}Q_{\rm cr} + \ldots$$

Radiation, (thermal) convection, viscosity, CRs energy interactions, ...

$$\frac{dP_{\rm g}}{dt} - {C_*}^2 \frac{d\rho}{dt} = \mathcal{L}_{\rm rad} + \nabla (K \nabla T) - \xi \left(\frac{dP_{\rm cr}}{dt} - D_{\rm cr} \nabla^2 P_{\rm cr} \right)$$

$${C_*}^2 = \frac{\gamma_{\rm g} P_{\rm g} + \gamma_{\rm e} P_{\rm cr}}{\rho}$$

$$\gamma_{\rm g} = 5/3, \quad \gamma_{\rm e} = \frac{\gamma_{\rm g} - 1}{\gamma_{\rm c} - 1} \gamma_{\rm c} = \frac{8}{3}, \quad \gamma_{\rm c} = 4/3$$

We model the CR effects by the parameter ξ

The CR-hydrodynamics

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{d\boldsymbol{v}}{dt} = -\boldsymbol{\nabla} (P_{\rm g} + P_{\rm cr})$$

$P_{\rm g}$ is the pressure of thermal gas

$P_{\rm cr}$ is the CR pressure

$$\frac{dP_{\rm g}}{dt} - {C_*}^2 \frac{d\rho}{dt} = \mathcal{L}_{\rm rad} + \boldsymbol{\nabla} (K \boldsymbol{\nabla} T) - \xi \left(\frac{dP_{\rm cr}}{dt} - D_{\rm cr} \nabla^2 P_{\rm cr} \right)$$

$${C_*}^2 = \frac{\gamma_{\rm g} P_{\rm g} + \gamma_{\rm e} P_{\rm cr}}{\rho}$$

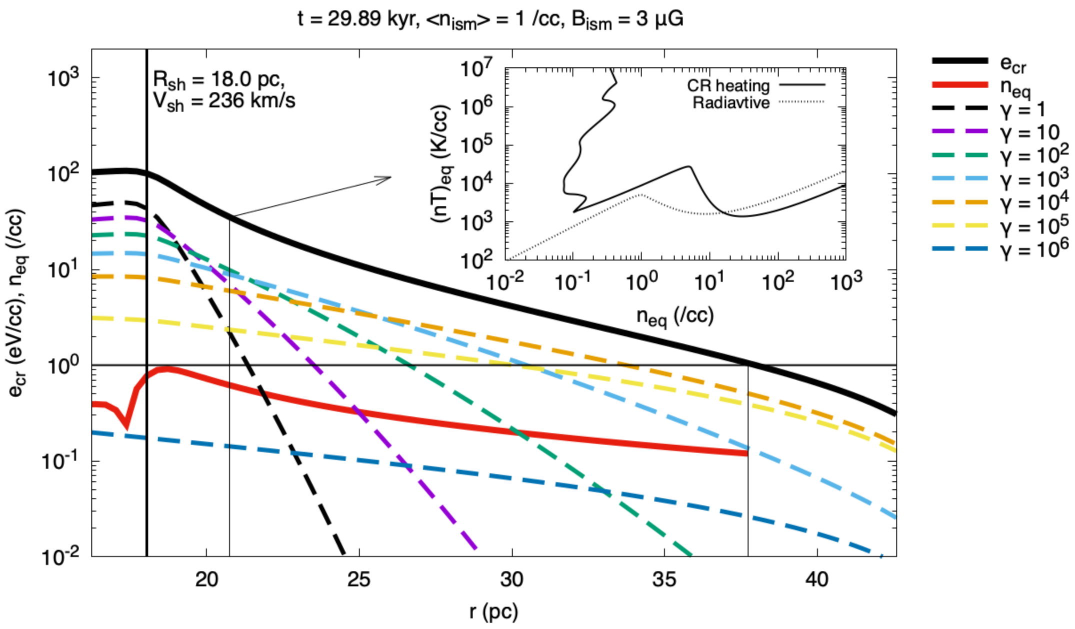
$$\gamma_{\rm g} = 5/3, \quad \gamma_{\rm e} = \frac{\gamma_{\rm g} - 1}{\gamma_{\rm c} - 1} \gamma_c = \frac{8}{3}, \quad \gamma_{\rm c} = 4/3 \qquad P_{\rm g} = \frac{\rho}{\bar{m}} kT$$

We model the CR effects by the parameter ξ

$\xi = 0$: Efficient heating by CRs

$\xi = 2$: No dissipation of CR generating waves

The CR-hydrodynamics: Linear Analysis in ideal situations



Unperturbed state: Total pressure equilibrium

$$\boldsymbol{\nabla}(P_{\mathrm{g}} + P_{\mathrm{cr}}) = 0$$

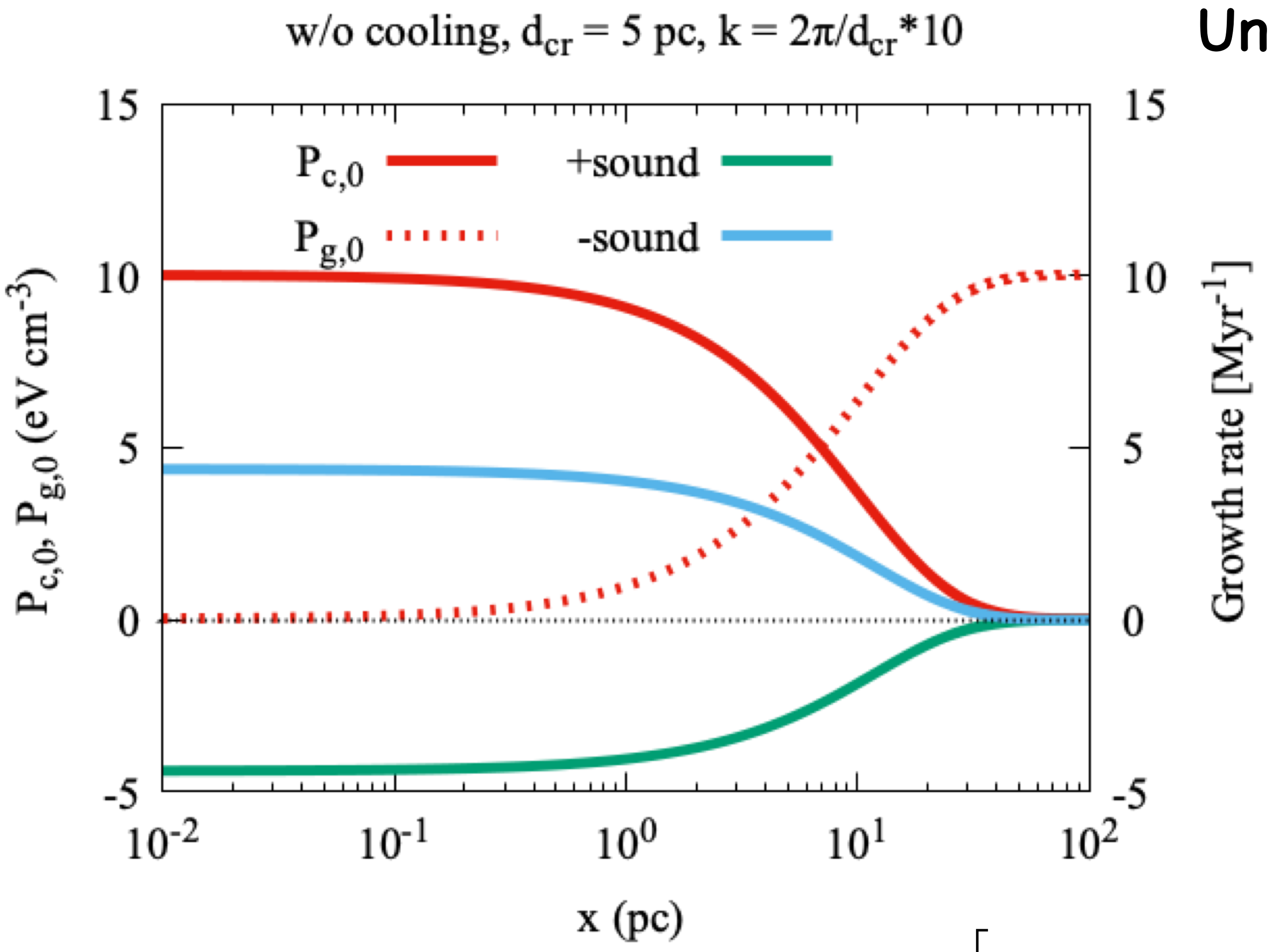
idealized

$$P_{\mathrm{cr}} = P_0 \mathrm{e}^{-x/d_{\mathrm{cr}}} + P_\infty$$

$$P_{\mathrm{g}} = P_0 (1 - \mathrm{e}^{-x/d_{\mathrm{cr}}}) + P_\infty$$

$$T(x) \propto P_{\mathrm{g}}(x)/\rho_0$$

The CR-hydrodynamics: Linear Analysis in ideal situations



Unperturbed state: Total pressure equilibrium

$$\nabla(P_{\rm g} + P_{\rm cr}) = 0$$

$$P_{\rm cr} = P_0 {\rm e}^{-x/d_{\rm cr}} + P_\infty$$

$$P_{\rm g} = P_0(1 - {\rm e}^{-x/d_{\rm cr}}) + P_\infty$$

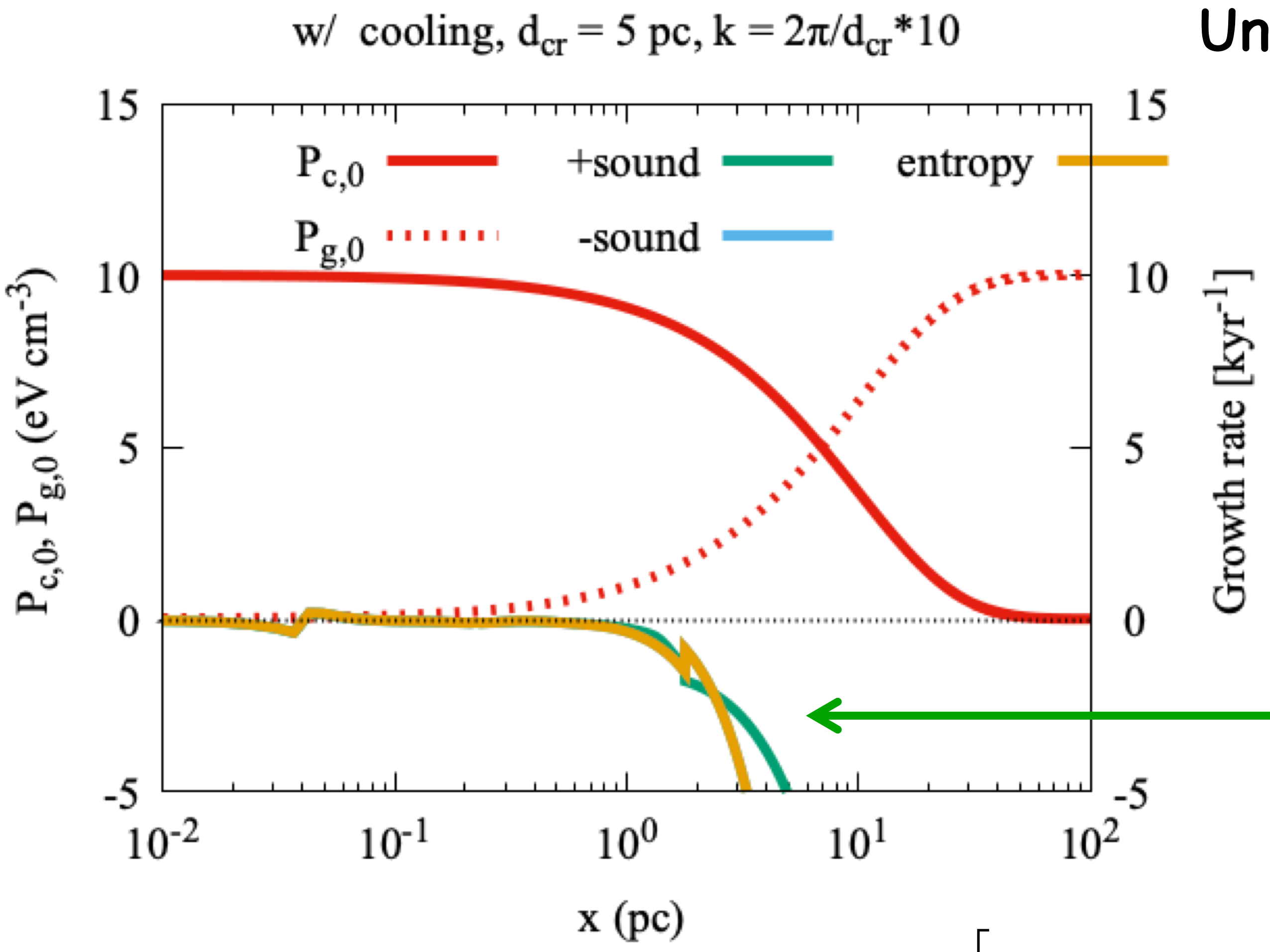
$$T(x) \propto P_{\rm g}(x)/\rho_0$$

The linearized equation is ...

$$\left[\partial_t \left\{\partial_{tt} - g(x)\partial_x - {C_*}^2(x)\nabla^2\right\} - \left\{\mathcal{L}_{\rm e}\partial_{tt} + \mathcal{L}_\rho\left(\nabla^2 - \frac{\rho'}{\rho}\partial_x\right)\right\}\right] P_{\rm g,1} = 0$$

$$g(x) = -(1-\xi)\frac{P'_{\rm cr}}{P_{\rm cr}} - \frac{\rho' {C_*}^2}{\rho}$$

The CR-hydrodynamics: Linear Analysis in ideal situations



Unperturbed state: Total pressure equilibrium

$$\nabla(P_{\rm g} + P_{\rm cr}) = 0$$

$$P_{\rm cr} = P_0 {\rm e}^{-x/d_{\rm cr}} + P_\infty$$

$$P_{\rm g} = P_0(1 - {\rm e}^{-x/d_{\rm cr}}) + P_\infty$$

$$T(x) \propto P_{\rm g}(x)/\rho_0$$

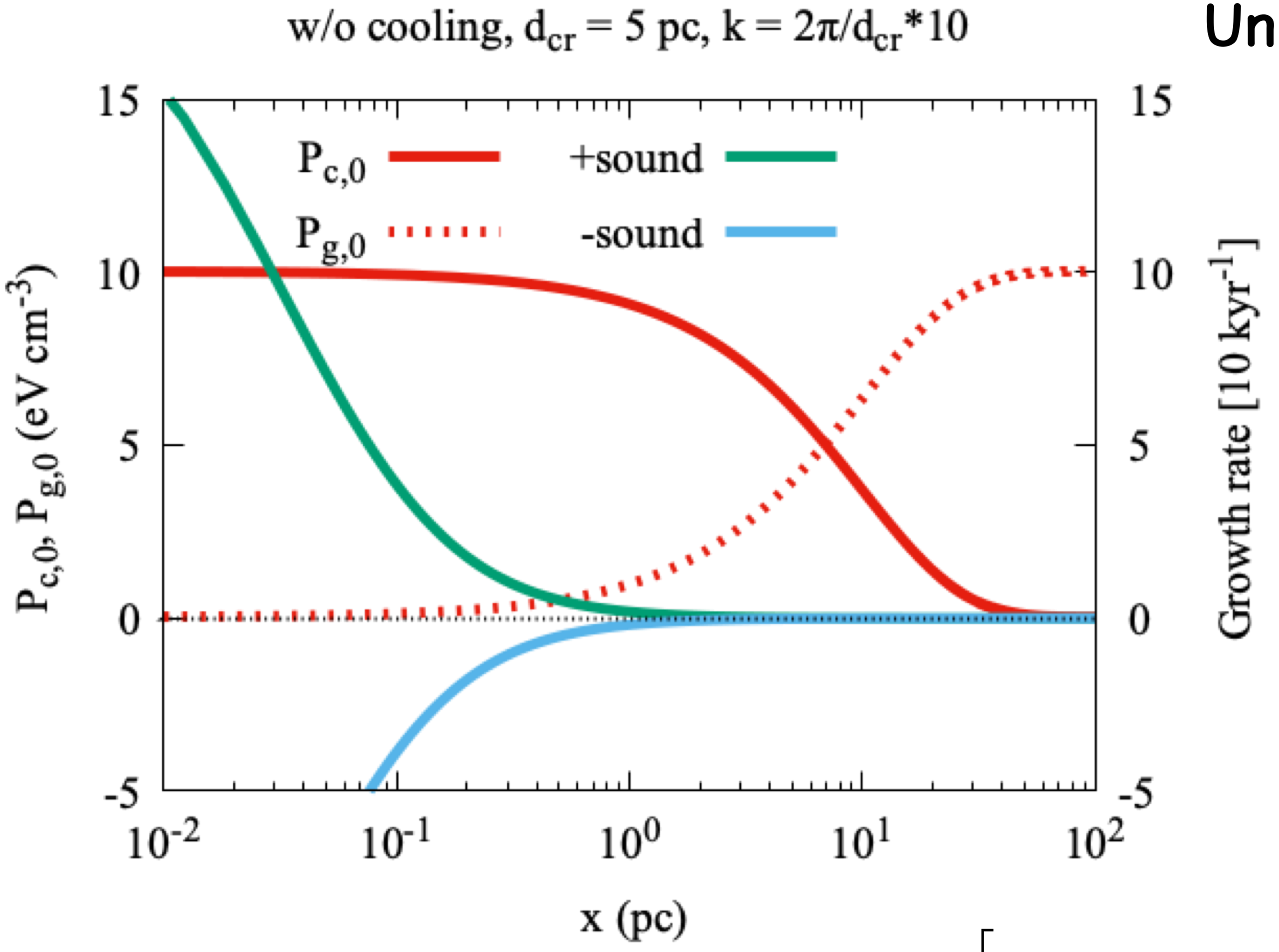
Stable due to the Thermal Conduction

The linearized equation is ...

$$\left[\partial_t \left\{\partial_{tt} - g(x)\partial_x - {C_*}^2(x)\nabla^2\right\} - \left\{\mathcal{L}_{\rm e}\partial_{tt} + \mathcal{L}_\rho\left(\nabla^2 - \frac{\rho'}{\rho}\partial_x\right)\right\}\right] P_{\rm g,1} = 0$$

$$g(x) = -(1-\xi)\frac{P'_{\rm cr}}{P_{\rm cr}} - \frac{\rho' {C_*}^2}{\rho}$$

The CR-hydrodynamics: Linear Analysis in ideal situations



Unperturbed state: Total pressure equilibrium

$$\nabla (P_{\rm g} + P_{\rm cr}) = 0$$

$$\Rightarrow \quad P_{\rm cr} = P_0 {\rm e}^{-x/d_{\rm cr}} + P_\infty$$

$$P_{\rm g} = P_0(1 - {\rm e}^{-x/d_{\rm cr}}) + P_\infty$$

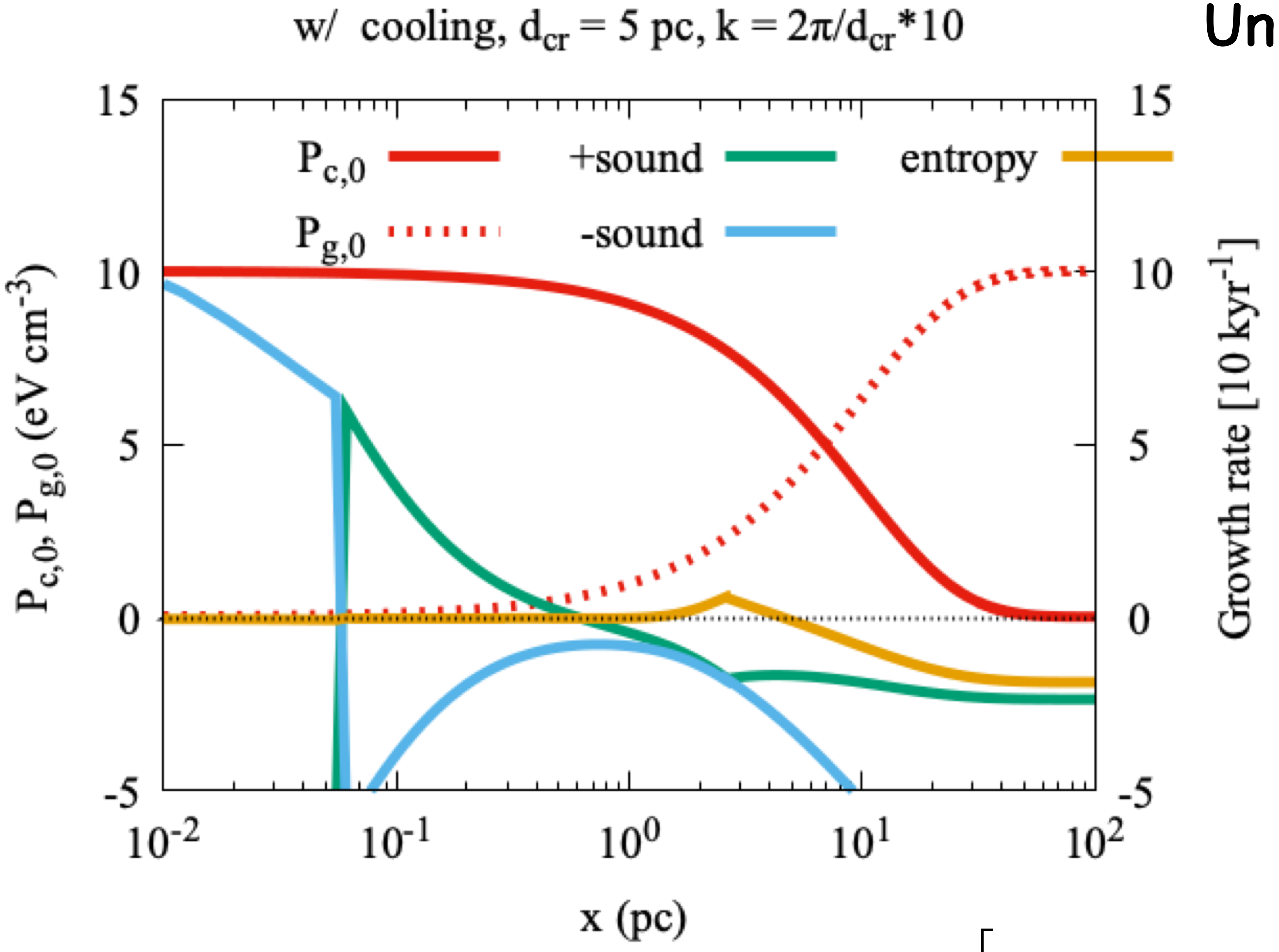
$$\rho(x) \propto P_{\rm g}(x)/T_0$$

The linearized equation is ...

$$\left[\partial_t \left\{\partial_{tt} - g(x)\partial_x - {C_*}^2(x)\nabla^2\right\} - \left\{\mathcal{L}_{\rm e}\partial_{tt} + \mathcal{L}_\rho \left(\nabla^2 - \frac{\rho'}{\rho}\partial_x\right)\right\}\right] P_{\rm g,1} = 0$$

$$g(x) = -(1-\xi)\frac{P'_{\rm cr}}{P_{\rm cr}} - \frac{\rho' {C_*}^2}{\rho}$$

The CR-hydrodynamics: Linear Analysis in ideal situations



Unperturbed state: Total pressure equilibrium

$$\nabla (P_{\rm g} + P_{\rm cr}) = 0$$

$$P_{\rm cr} = P_0 {\rm e}^{-x/d_{\rm cr}} + P_\infty$$
$$P_{\rm g} = P_0 (1 - {\rm e}^{-x/d_{\rm cr}}) + P_\infty$$

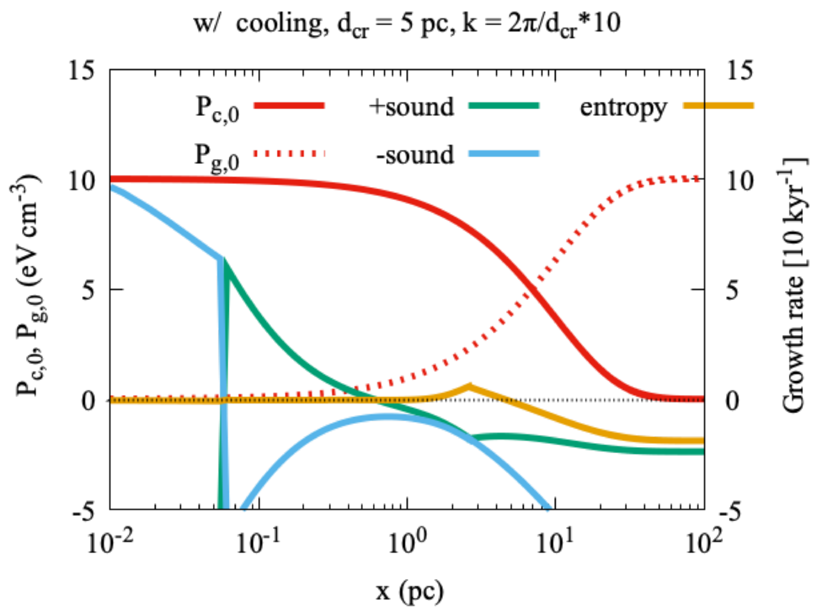
$$\rho(x) \propto P_{\rm g}(x)/T_0$$

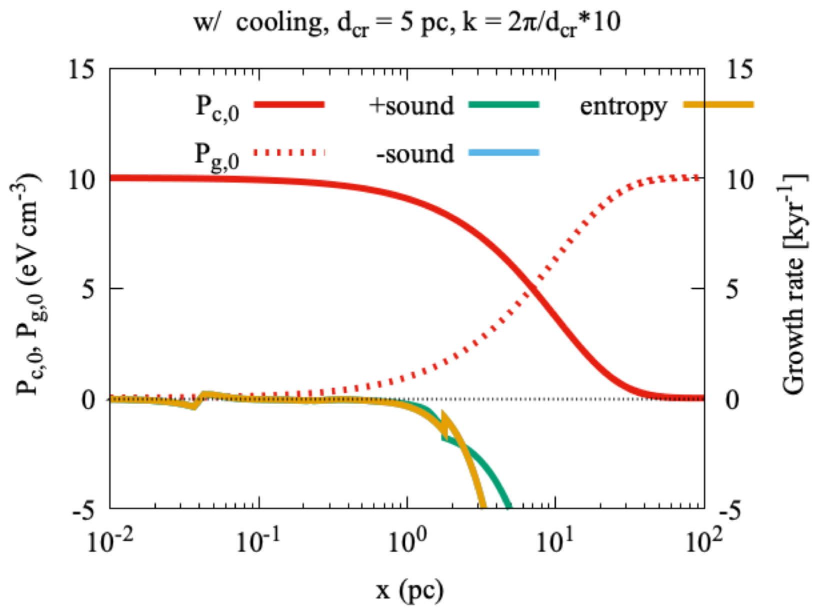
The linearized equation is ...

$$\left[\partial_t \left\{\partial_{tt} - g(x)\partial_x - {C_*}^2(x)\nabla^2\right\} - \left\{\mathcal{L}_{\rm e}\partial_{tt} + \mathcal{L}_\rho \left(\nabla^2 - \frac{\rho'}{\rho}\partial_x\right)\right\}\right] P_{\rm g,1} = 0$$

$$g(x) = -(1-\xi)\frac{P'_{\rm cr}}{P_{\rm cr}} - \frac{\rho' {C_*}^2}{\rho}$$

The CR-hydrodynamics: Linear Analysis in ideal situations



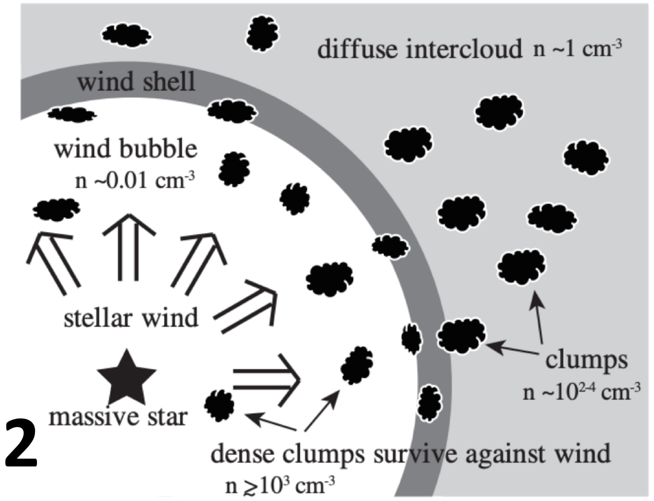


$$\rho(x) \propto P_{\rm g}(x)/T_0$$

- The non-uniform density may be important for the growth of the sound waves!

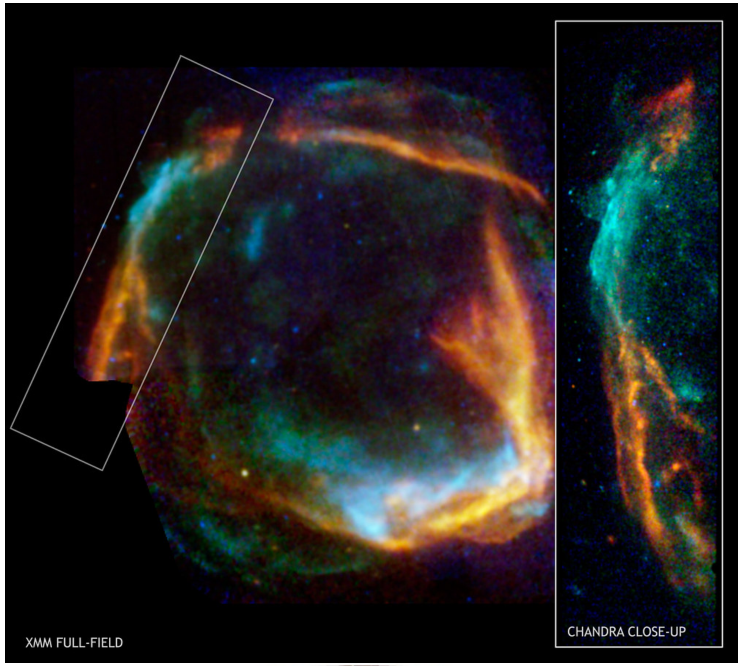
- The old SNRs "character" & its escaping "CR halo" may strongly depend on the environment.

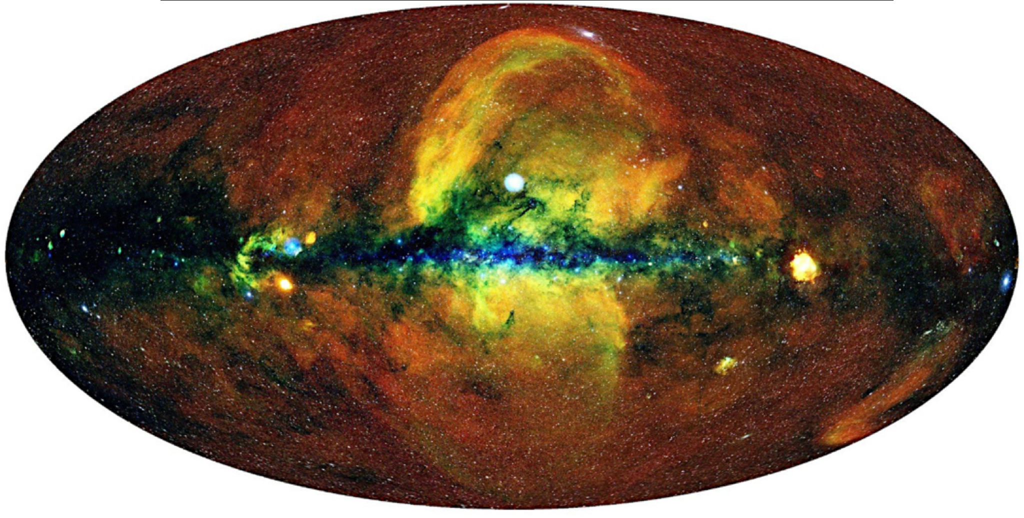
$$T(x) \propto P_{\rm g}(x)/\rho_0$$



Inoue+12

Summary





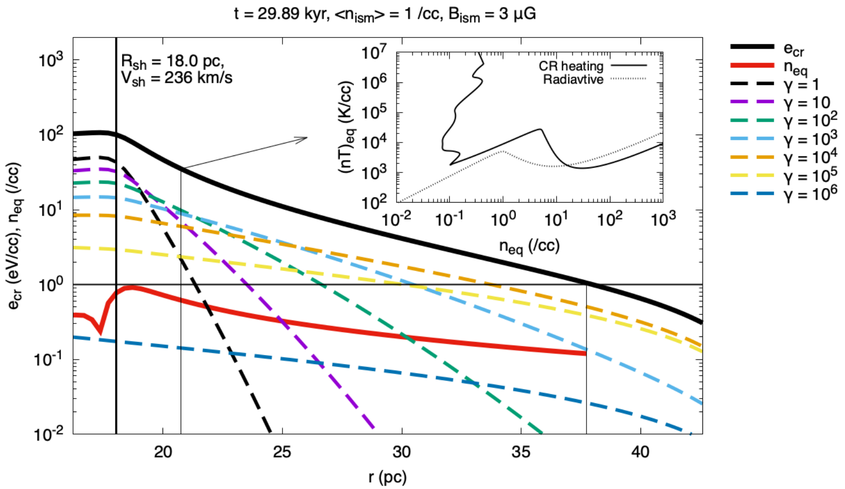
eROSITAによる全天画像。0.3〜0.6keVのエネルギーのX線を赤、0.6〜1keVを緑、1〜2.3keVを青に色付けして合成されています。
Credit: MPE/IKI

Escaping CRs can heat the ISM

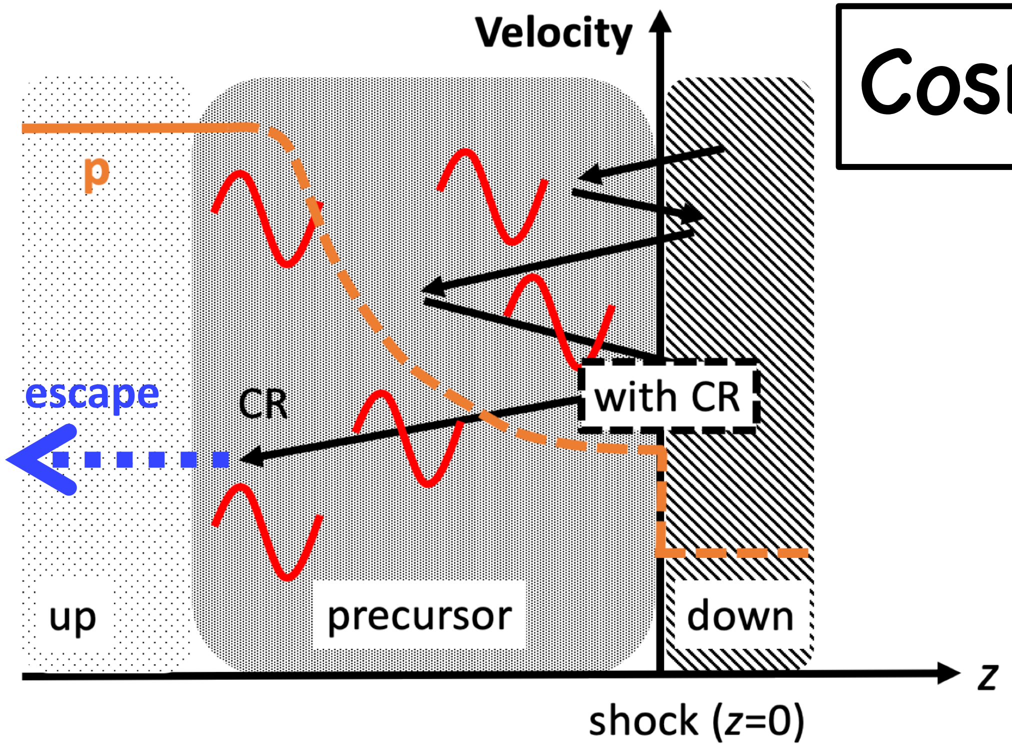
The CR physics & Galactic Evolution can be studied.

The sound waves can be unstable depending on its environment.
→ Systematic Survey & Analysis studies of SNRs like the 1st day of this conference are important.

We will develop our analysis (especially, the effects of B-filed).



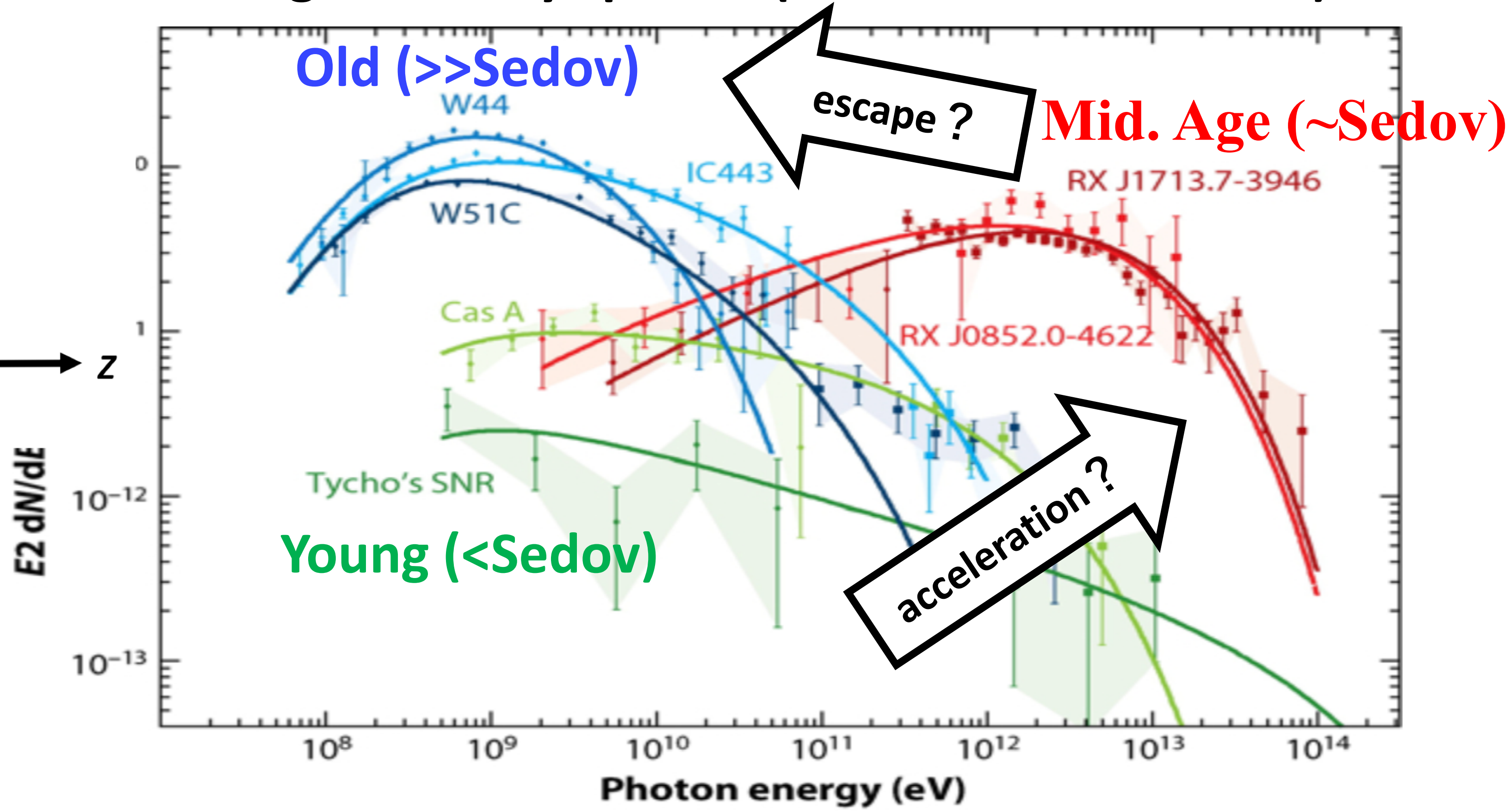
Cosmic Rays: Escape Problem



upstream → subscript "0"

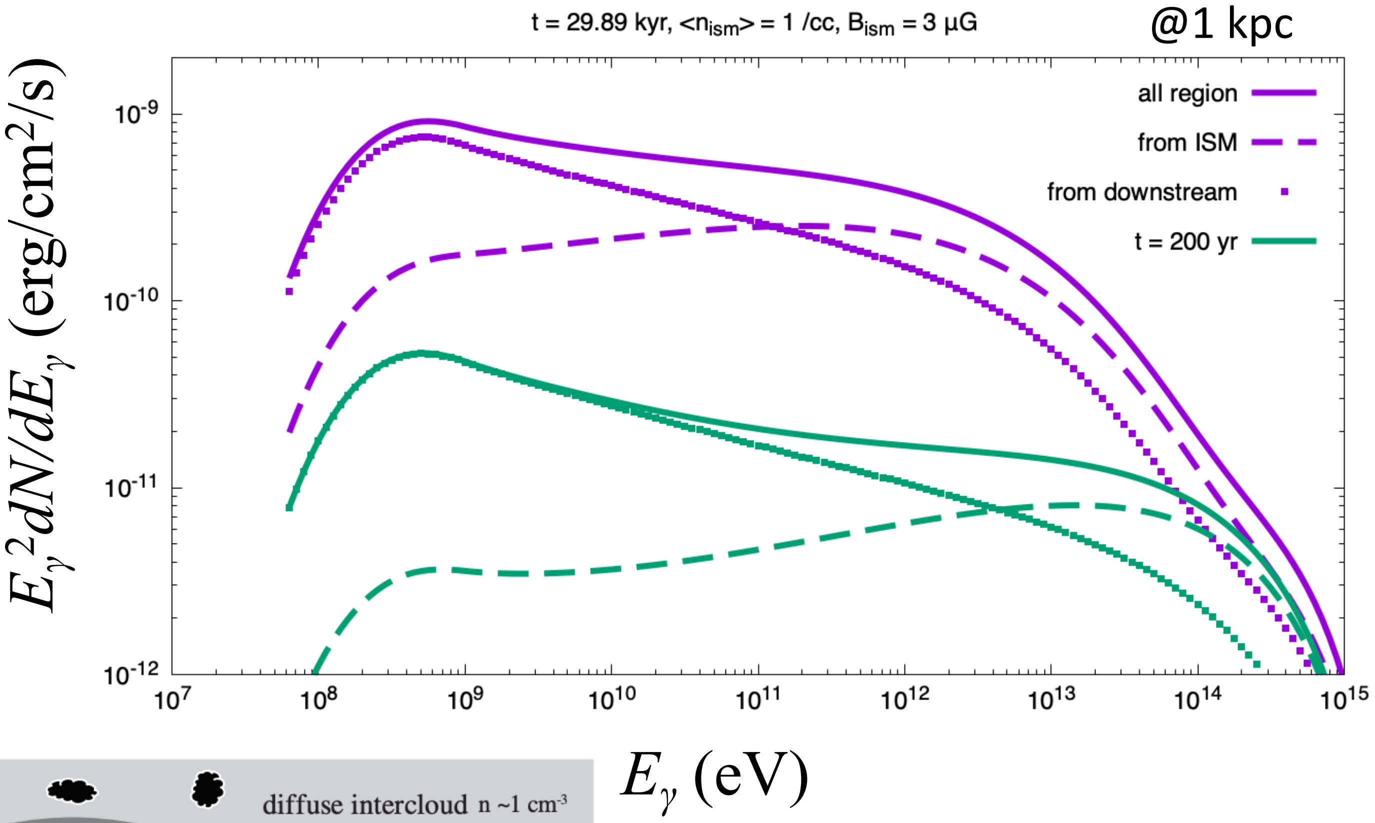
downstream → subscript "2"

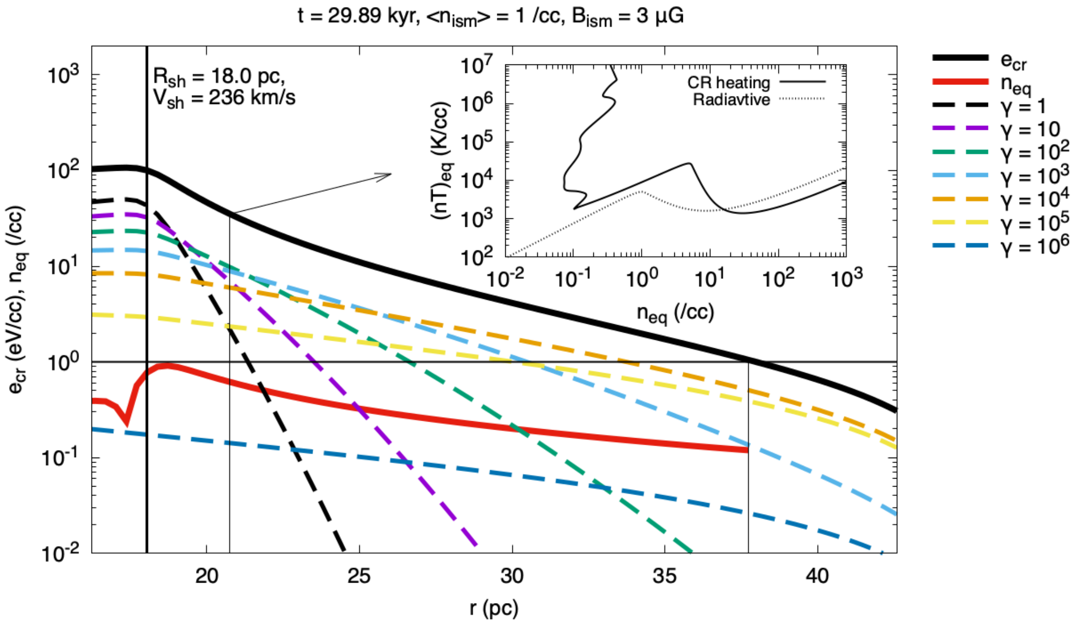
The gamma-ray spectra (see also H. Suzuki+22)

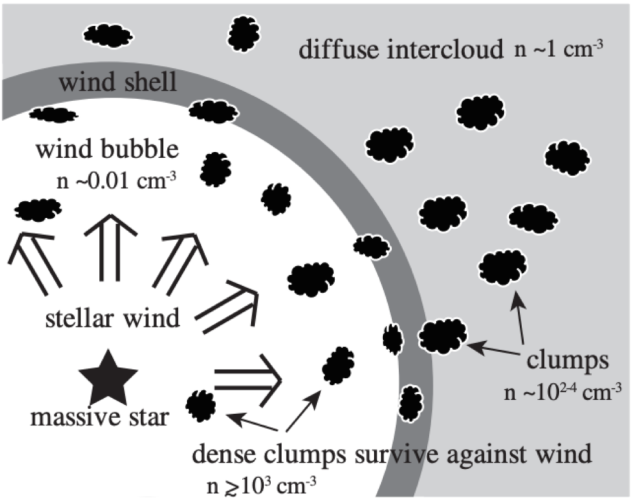


Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

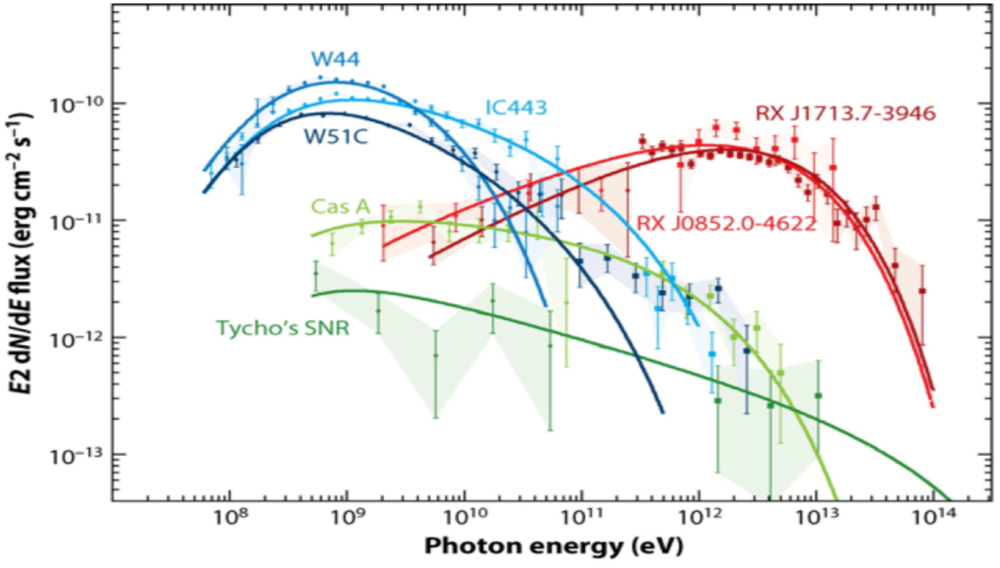
Gamma-ray spectra





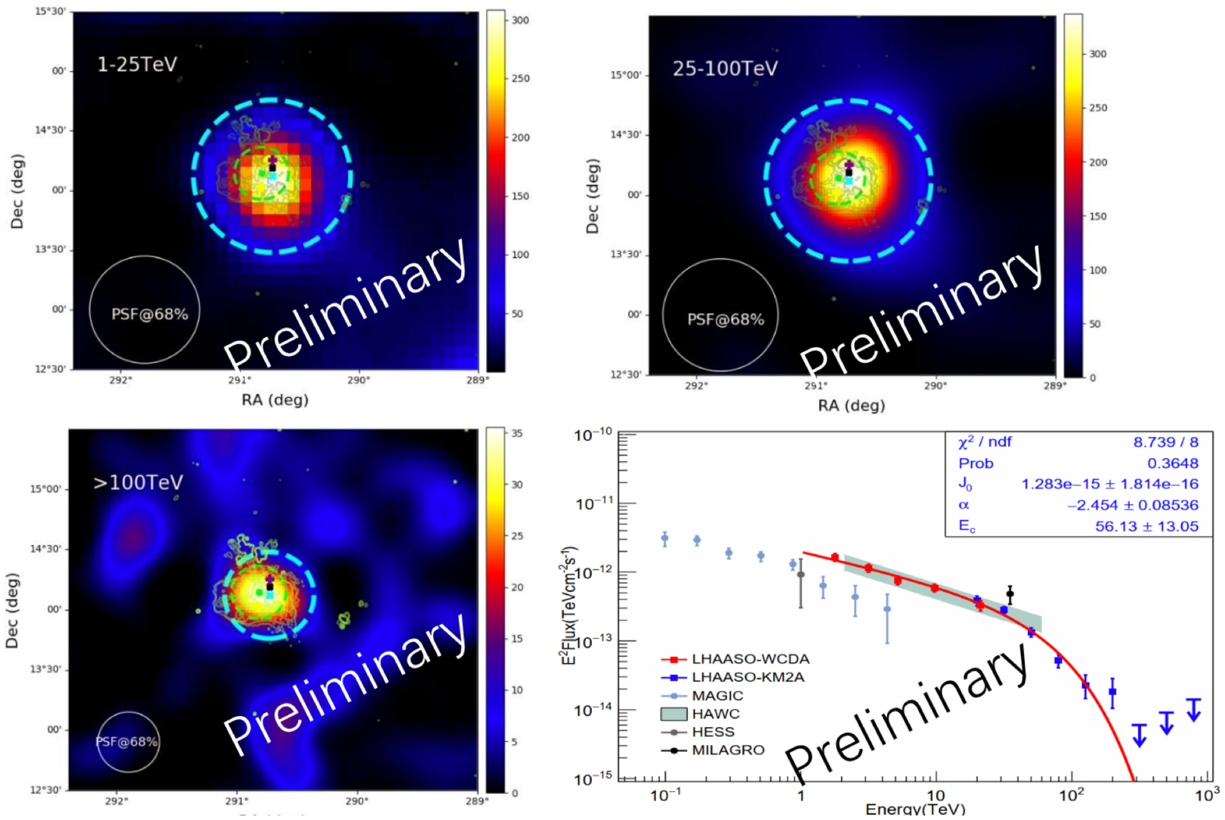


Inoue+12

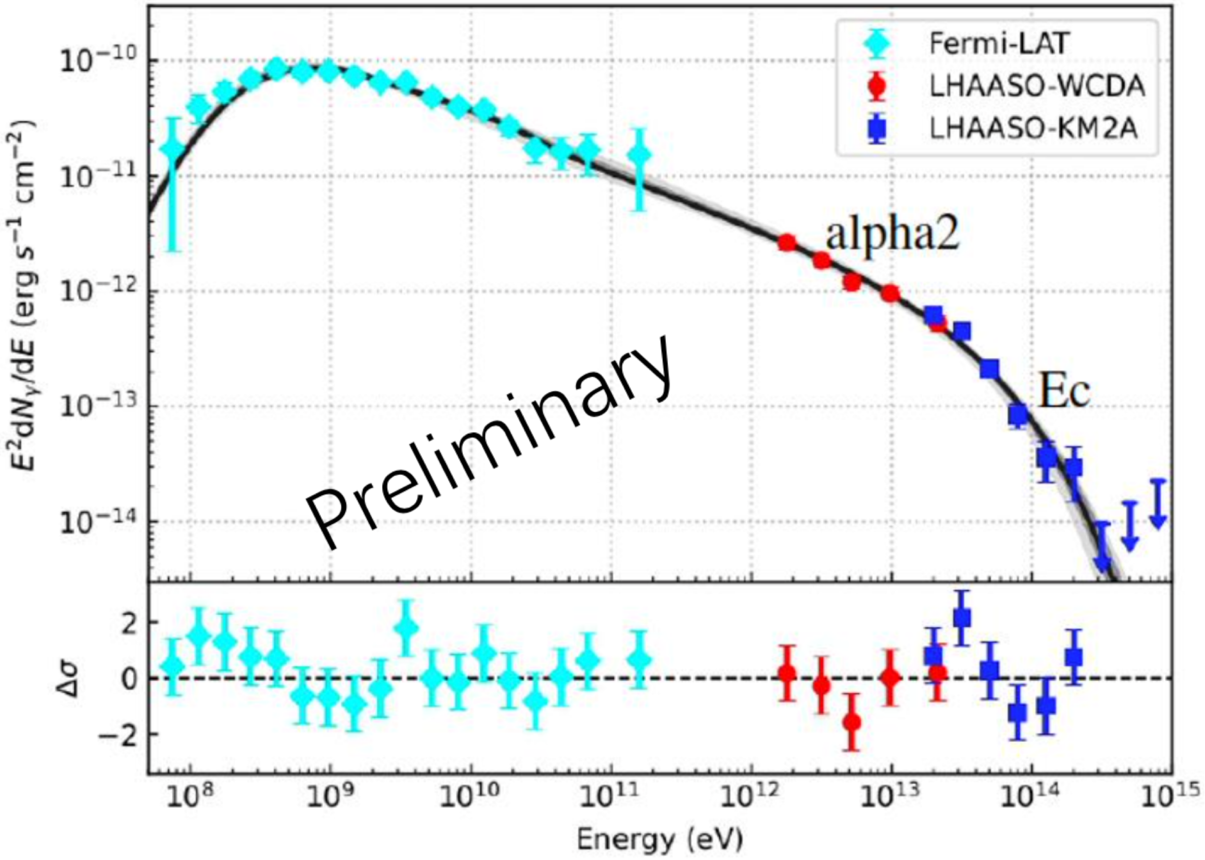


Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

LHAASO preliminary



W51C



XRISM mission

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

arXiv:1412.1169

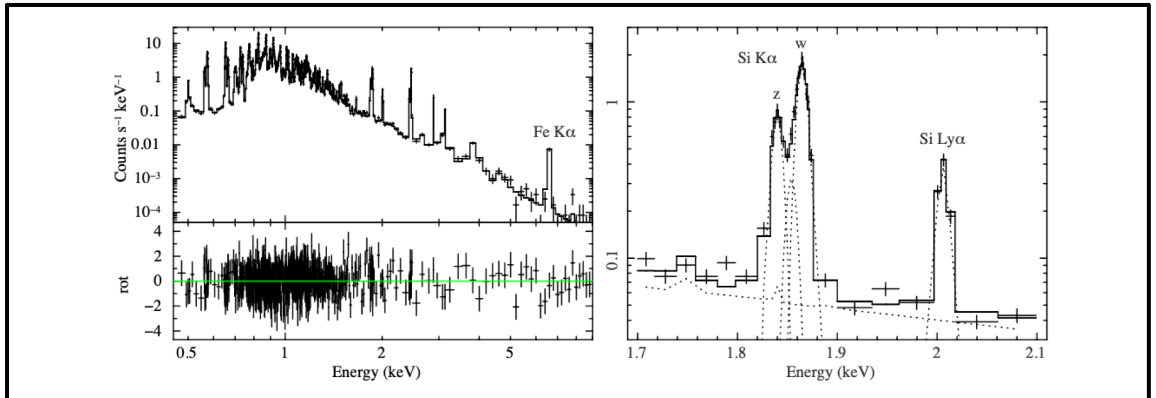
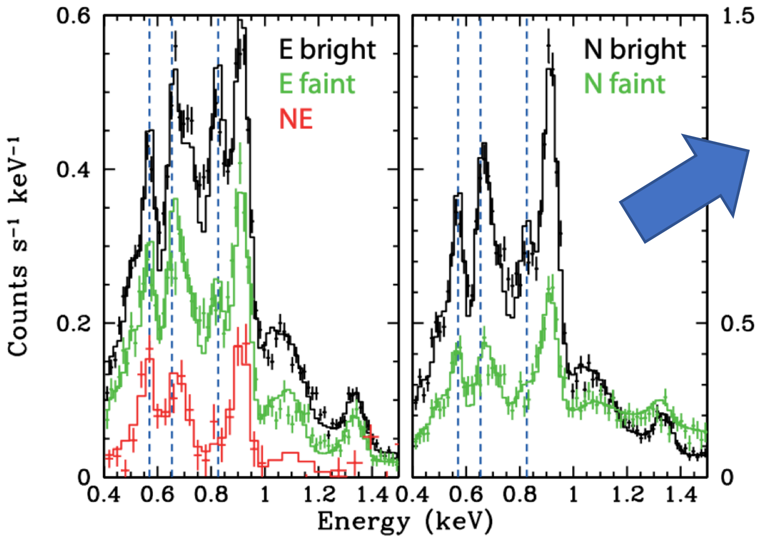


Figure 16: Simulated SXS spectrum of SNR 0519–69.0 with an exposure of 60 ksec. The widths of Si lines can be determined with an error of ~10%.



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***.

Shock energy budget

Without CRs

Kinetic energy of upstream ions

Thermal energy of downstream ions

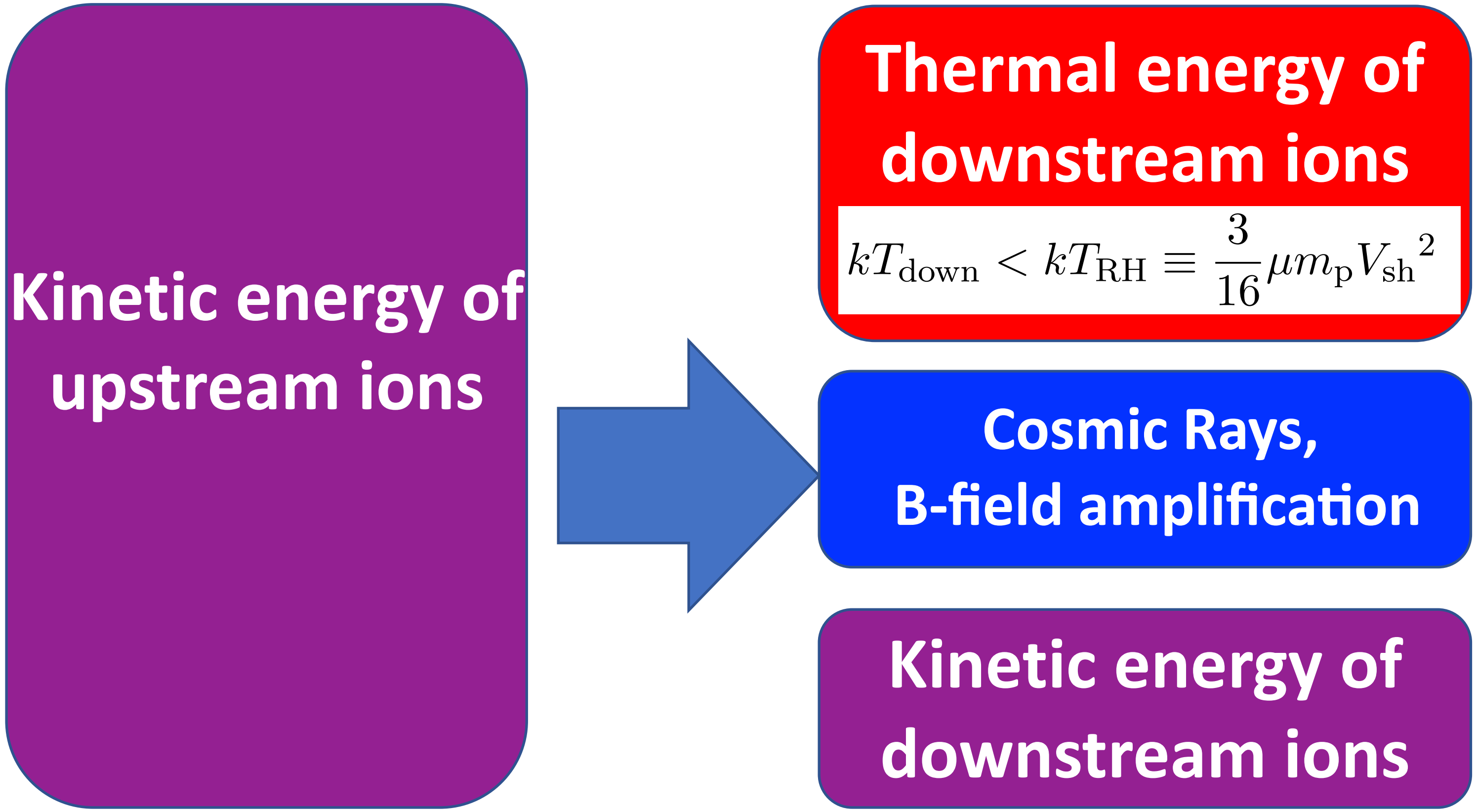
$$kT_{\rm down} = kT_{\rm RH} \equiv \frac{3}{16}\mu m_{\rm p} {V_{\rm sh}}^2$$

Kinetic energy of downstream ions

When CRs are accelerated…

Shock energy budget

With CRs



Energy loss rate (Shimoda+ 15)：

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