宇宙線による星間媒質の不安定的加熱機構の可能性について

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高エネルギー現象で探る宇宙の多様性（2024/11/12）

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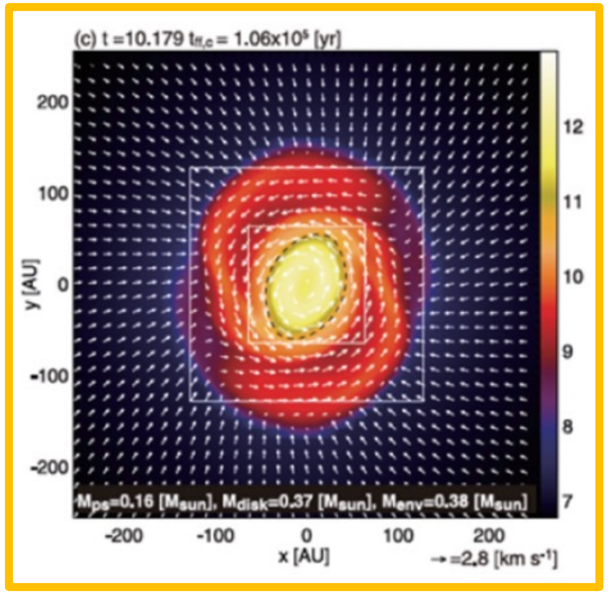
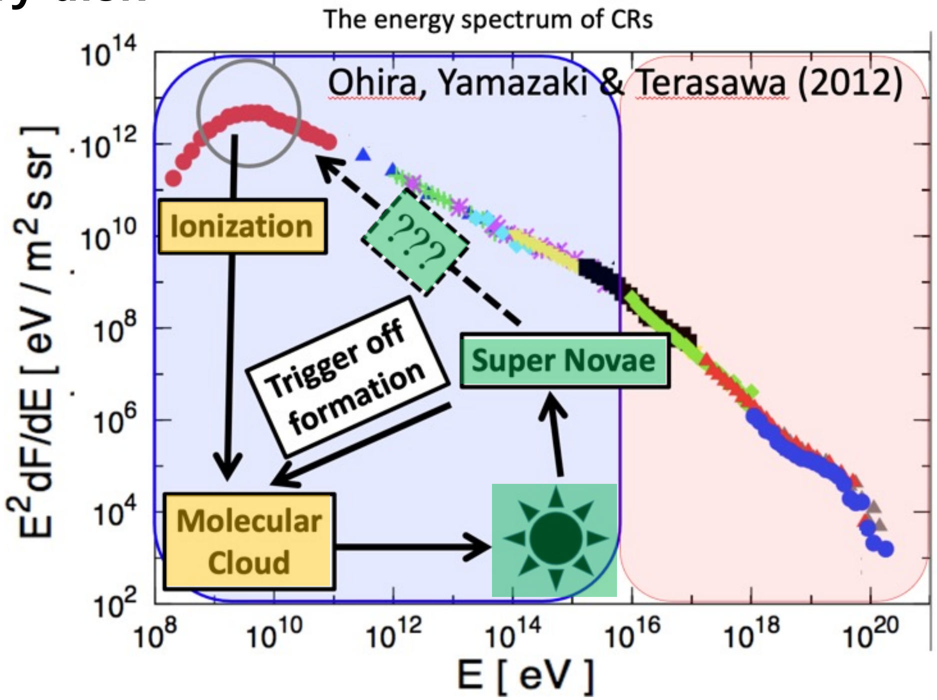
Roles of Galactic Cosmic Rays

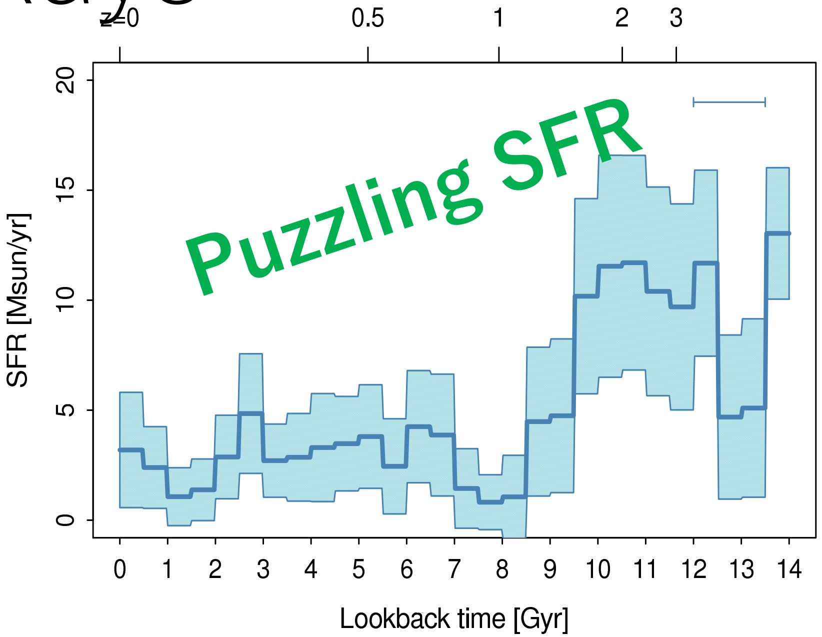
Evolution of the Protoplanetary disk

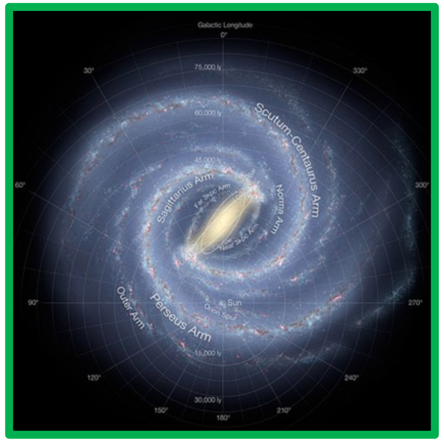


CR ionization rate controls the size/life-time of protoplanetary disk via the angular momentum transportation by B-field.

→ ***Planet formation***



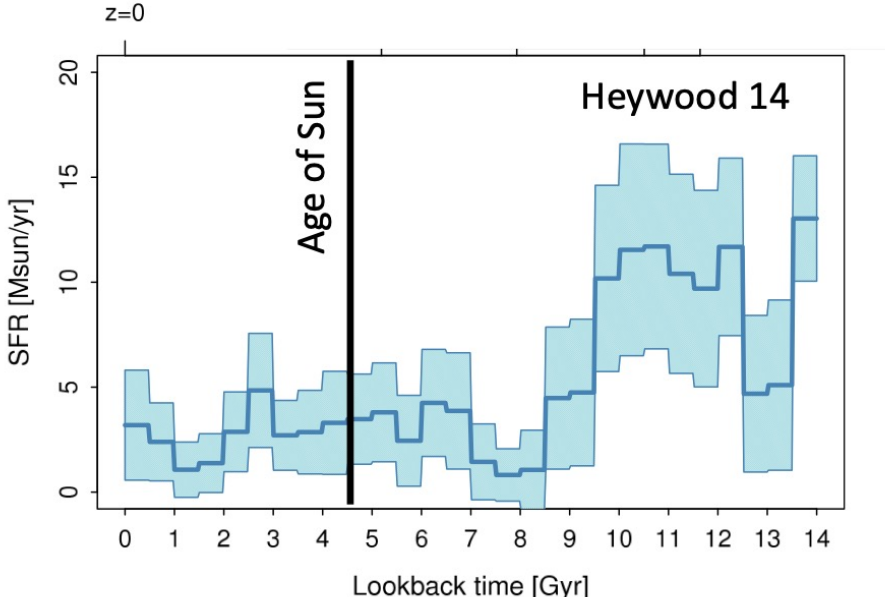


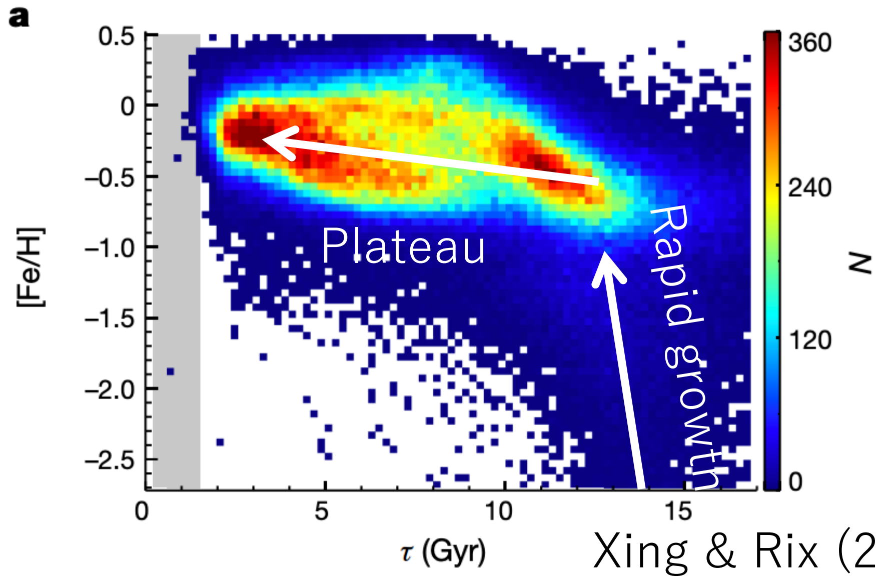


The long-term SFR is regulated by the galactic wind driven by CRs.

→ ***Galaxy formation***

"Puzzling" Star Formation History
(the metal amount)





Xing & Rix (2022, by Gaia)

@ 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

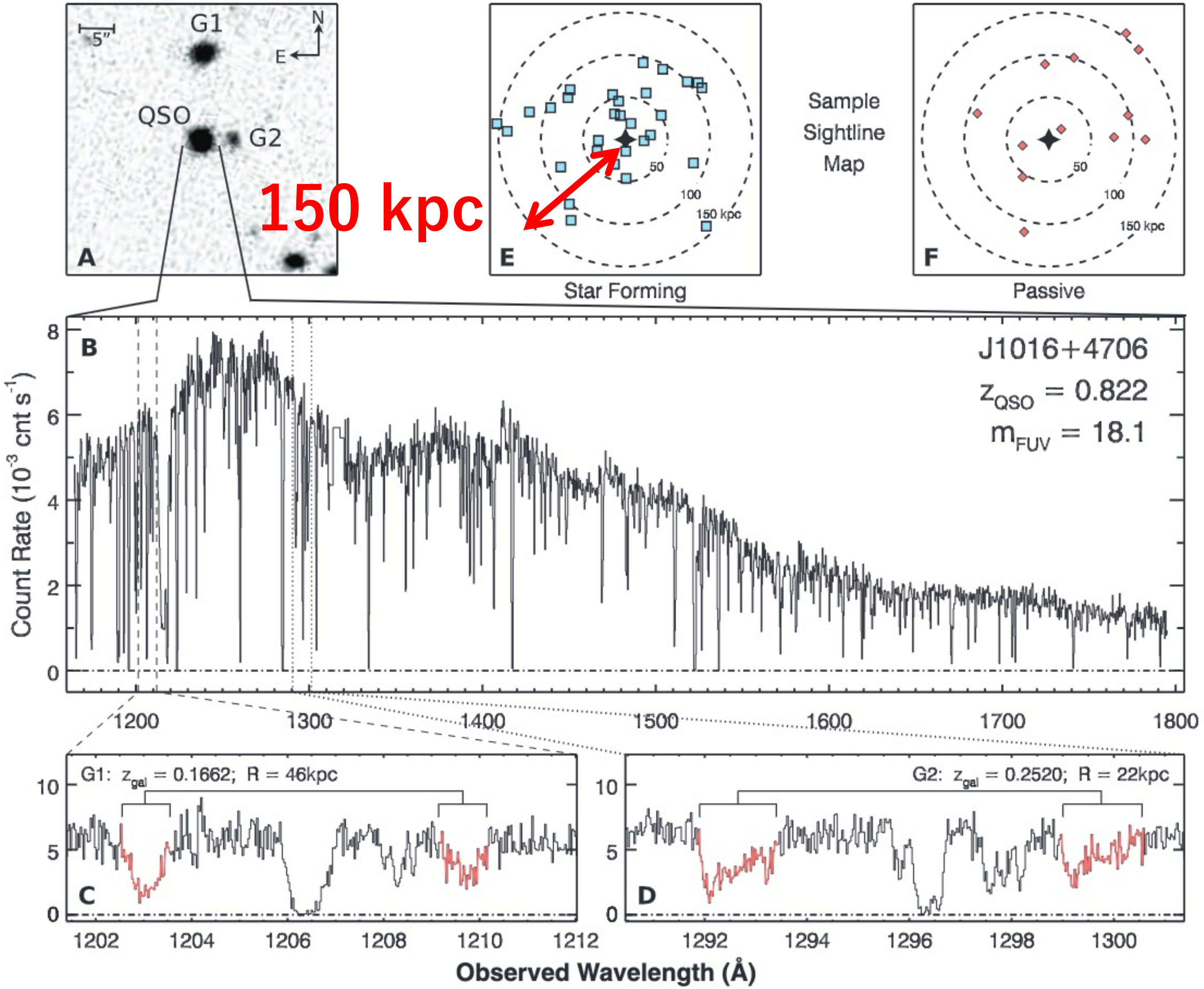
→ ~ (SFR) x (Massive Star fraction) x (CO core mass fraction) x (14 Gyr)

~ (3 Mo/yr) x (0.1) x (3 Mo/8 Mo) x (14 Gyr)

~ 1.6 x 10^9 Mo

~99 % of metals should be removed from the disk!
→ Persistent Outflow is required!
(SJ & Inutsuka 22, SJ, Inutsuka, & Nagashima 24, SJ & Asano 24)

Circum-Galactic Medium (CGM)



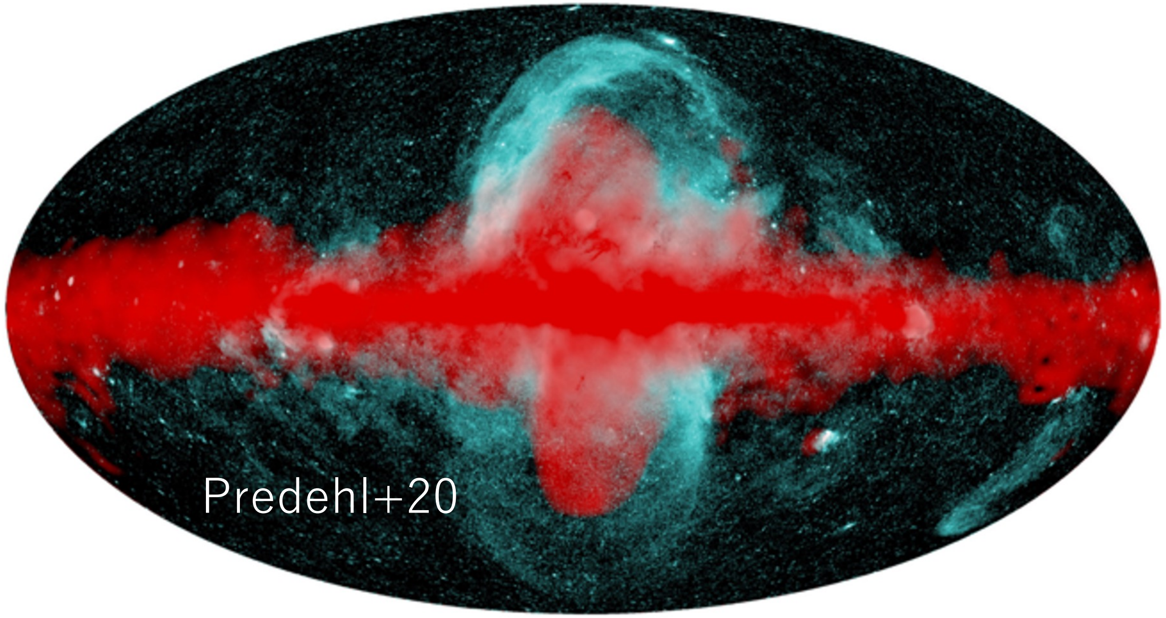
"Discovery" of hot, highly ionized medium around galaxies (Tumlinson+11, 17).

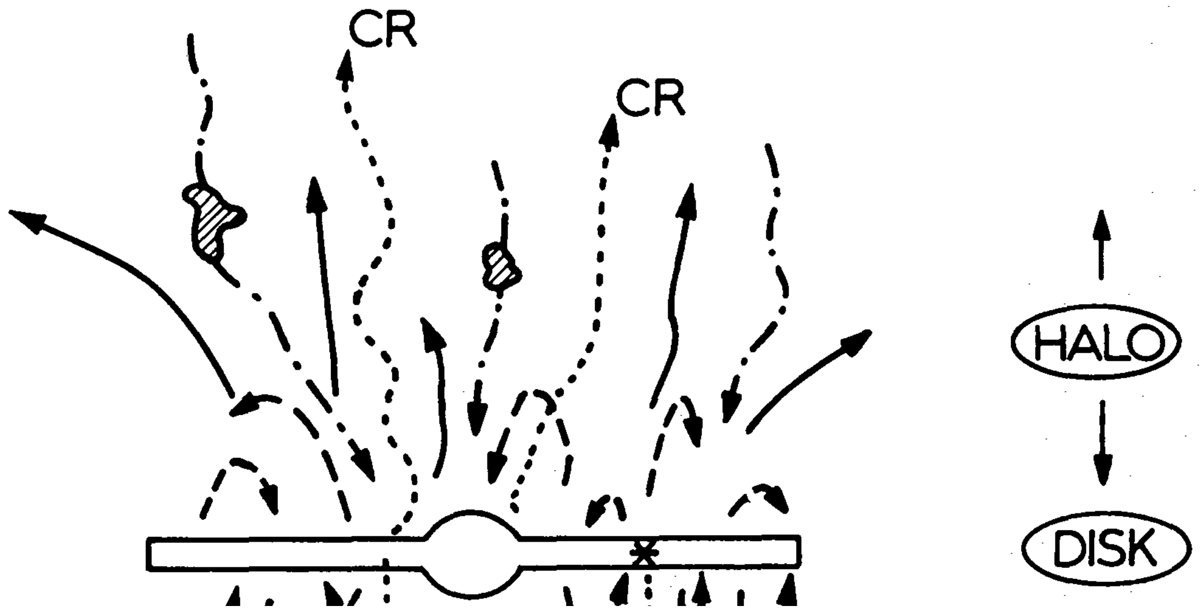
- O_{VI} absorption line
  → $T_{ionized} \sim 3 \times 10^5$ K, $N_{OVI} \sim 10^{14}$ cm^{-2}
  → Estimated total gas mass
  $\sim 10^{10}$–10^{12} M_{sun}

Missing Metals may be in the Galactic halo.

→ The Outflow is required.

Fermi Bubble & eROSITA Bubble





Breitschwerdt+91

Outflow:

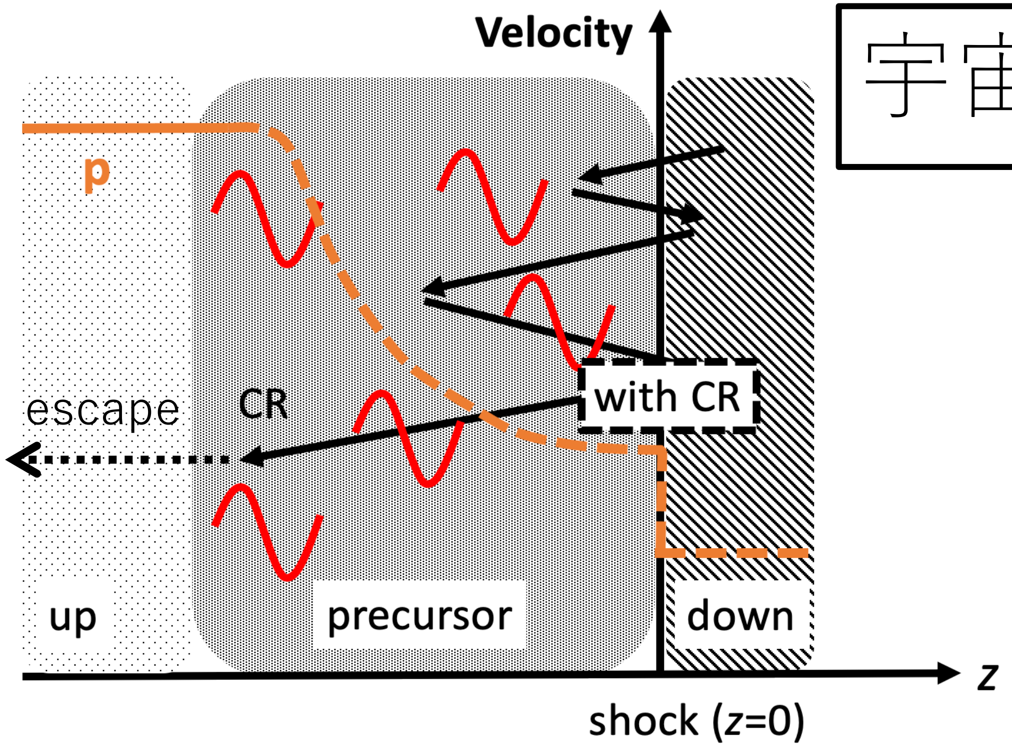
T ~ 0.1 keV (~virial temp. of the MW)

→eROSITA bubble is consistent with this expectation.

Should be launched at the disk (removing the metals)

→ Formation mechanism is unclear…

宇宙線の逃走問題（拡散係数問題）



upstream　→ subscript “0”

downstream→ subscript “2”

Diffusive Shock Acceleration (DSA)
→衝撃波を往復して粒子が加速していく

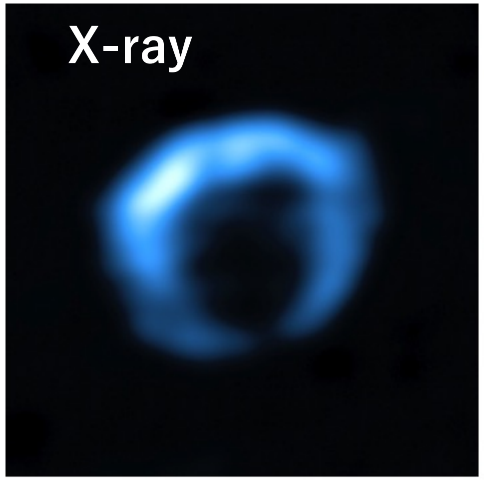
→**Vshが小さくなると**，衝撃波が拡散する
宇宙線に追いつけない.

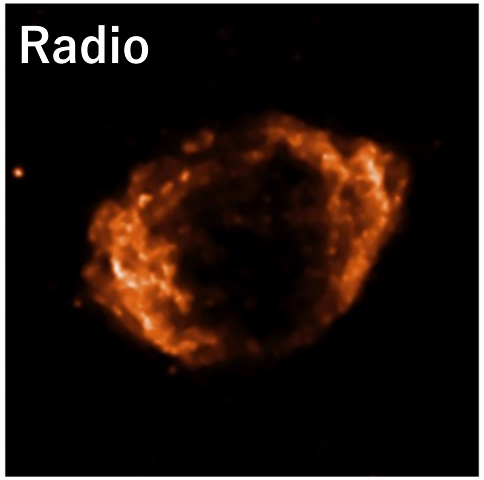
→宇宙線が上流に**逃走して加速終了**.

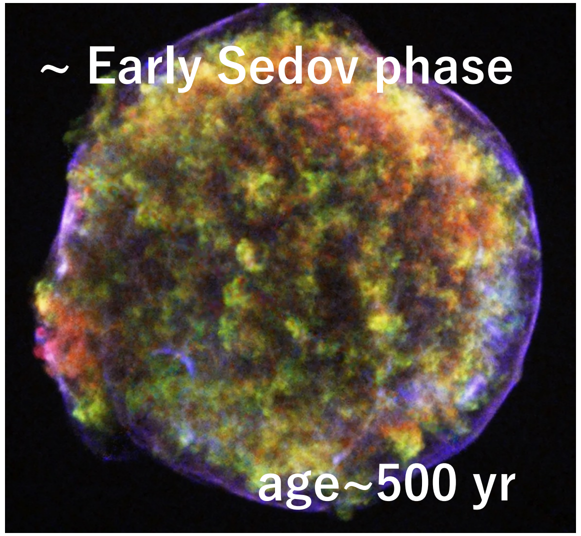
「いつ，どれだけ逃走しているのか？」は分かっていない.

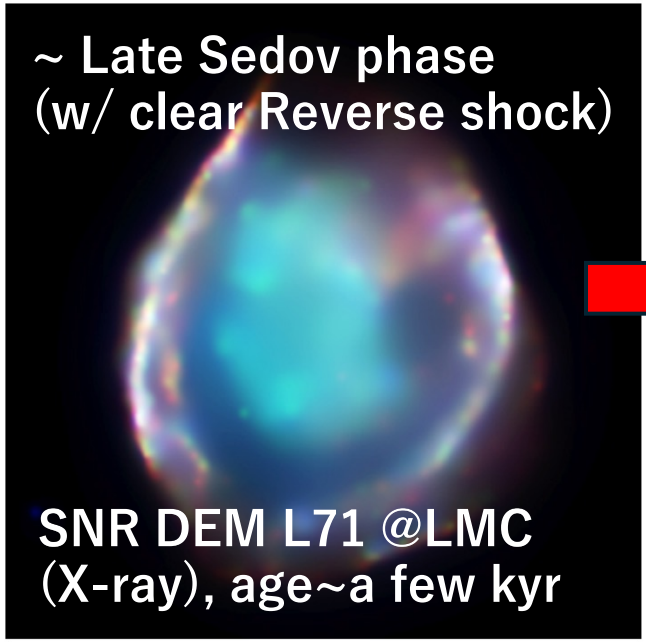
Supernova Remnants:Temporal Evolution

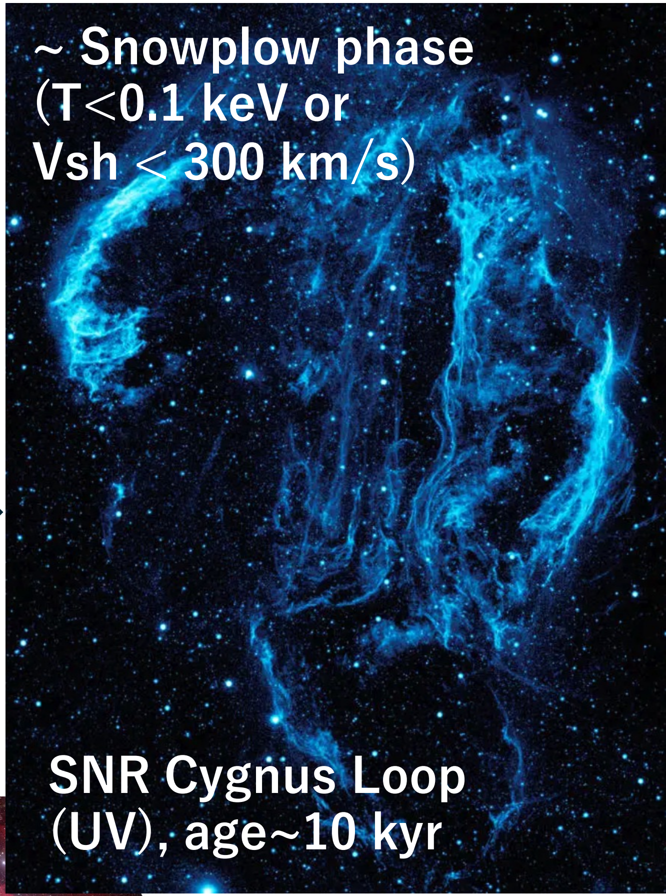
G1.9+0.3: Youngest SNR in our Galaxy
(age~140 yr, Bamba & Williams 22)
Free Expansion Phase

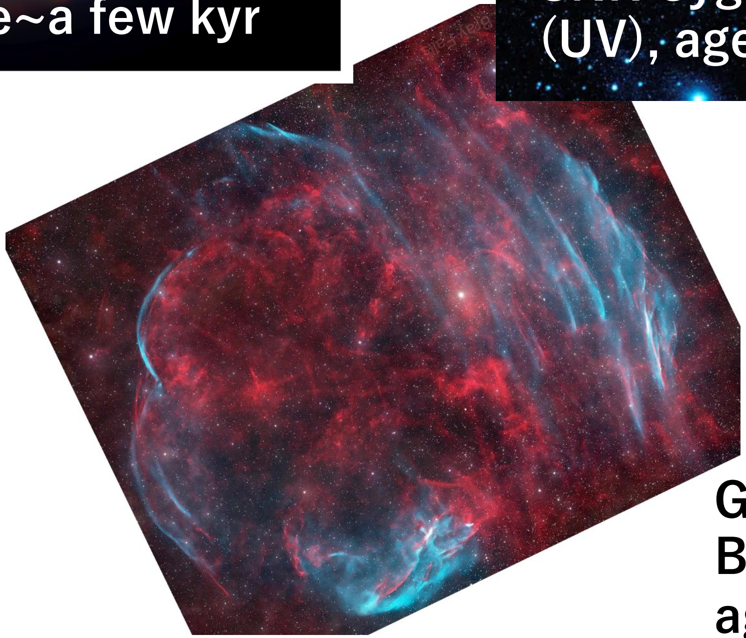






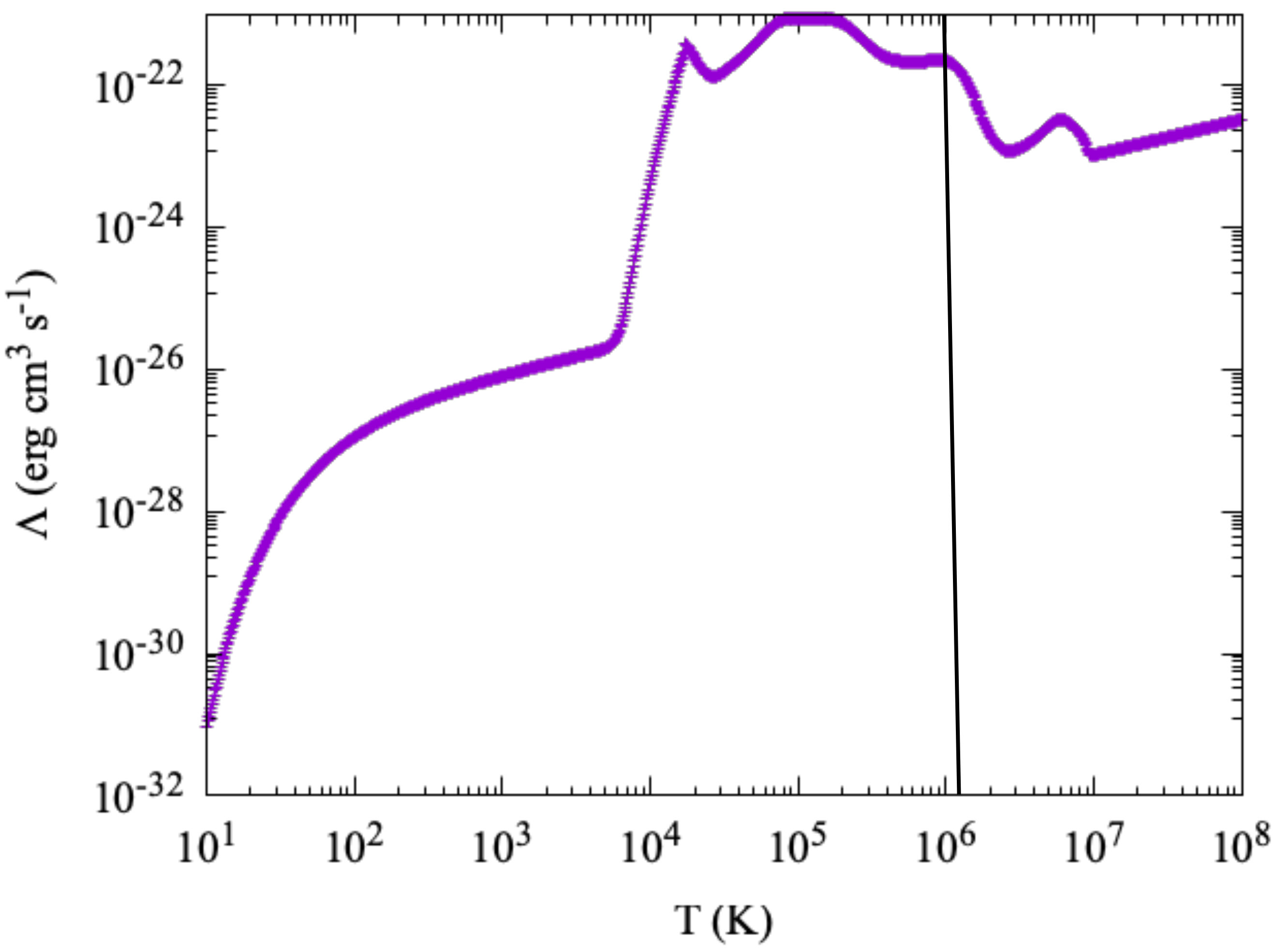


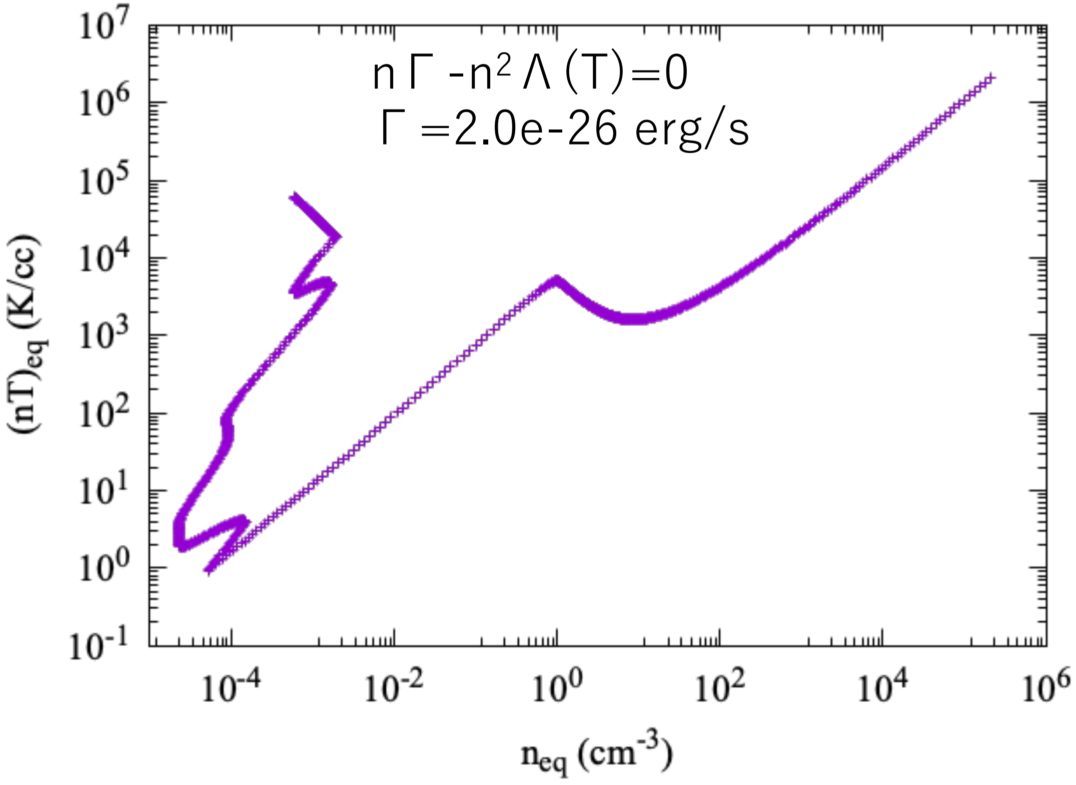




G70.0-21.5
Blue OIII, Red Hα
age ~ 10-100 kyr?

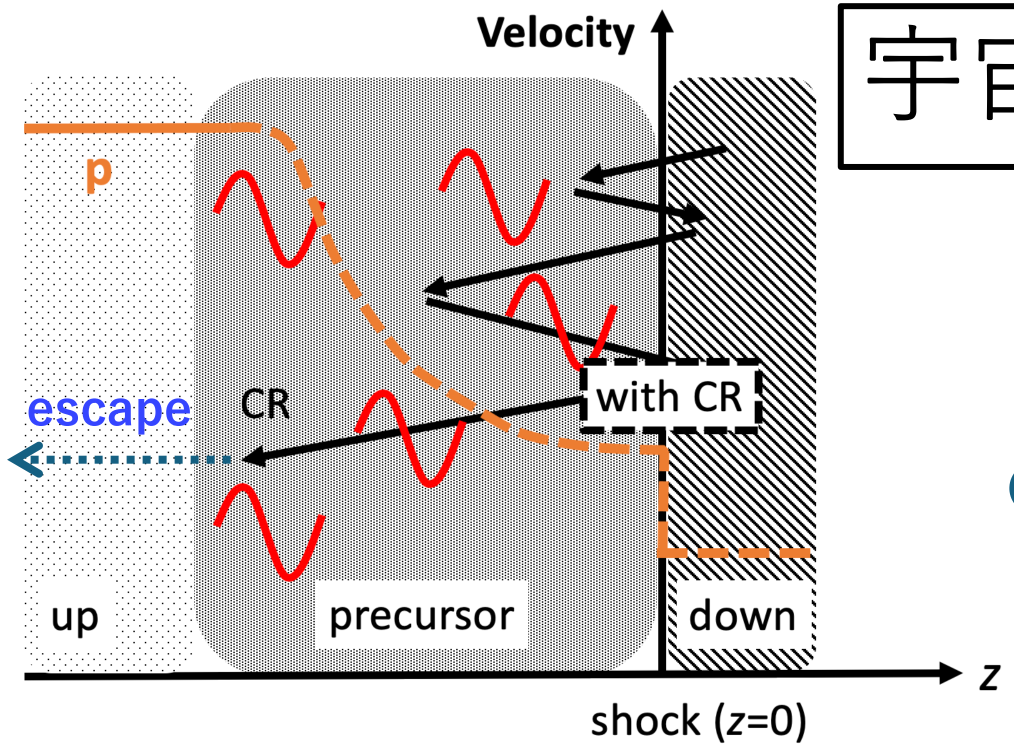
Cooling function by SJ et al. 22 (high-Temp. side) + Koyama & Inutsuka 02 (low-Temp. side)





$t\_cool \sim nkT/(n^2\Lambda) \sim 46\ \mathrm{kyr}(T/10^6\ \mathrm{K})(n\Lambda/10^{-22})$

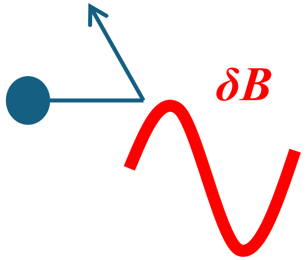
宇宙線加熱機構（one of them）



upstream → subscript “0”

downstream→ subscript “2”

逃走宇宙線が存在すると？



宇宙線が**電磁場**に散乱される
→運動量がδBに輸送される
→**δBが成長する**
（ここで止まれば、磁場増幅）
→成長したδBが散逸する
→ガスが加熱される

(e.g., Kulsrud 2005)

・SNRから離れたところでISMが加熱されるなどが起こりうる。

・CR加熱率($\mathcal{H}$)は色々提案されている（e.g., Acterberg+81, Zweibel 20, Yokoyama & Ohira 23）が、実際のところよく分かっていない。

$$
\begin{aligned}
\mathcal{H} &< \mathcal{H}_0, \\
\mathcal{H}_0 &= e_{\rm cr}/\tau_{\rm res} = 1.8\times10^{-26}\,{\rm erg\,cm^{-3}\,s^{-1}}(e_{\rm cr}/1\,{\rm eV/cc})(\tau_{\rm res}/1\,{\rm Myr})^{-1}.
\end{aligned}
$$

The CR-hydrodynamics

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

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

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

The energy equation is …

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

The 1st law of thermodynamics should include the CRs

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

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

The CR-hydrodynamics: the energy equation

$$\frac{de_{\rm g}}{dt} - \frac{e_{\rm g} + P_{\rm g}}{\rho}\frac{d\rho}{dt} = \mathcal{L}_{\rm rad,g} + \boldsymbol{\nabla}\cdot(\mathcal{K}\boldsymbol{\nabla}T) + \mathcal{L}_{\rm em,cr},$$

$$\frac{de_{\rm cr}}{dt} - \frac{e_{\rm cr} + P_{\rm cr}}{\rho}\frac{d\rho}{dt} = \boldsymbol{\nabla}\cdot(\mathcal{D}\boldsymbol{\nabla}e_{\rm cr}) - \mathcal{L}_{\rm em,cr}$$

Energy Exchange
(CRs heat the gas)

$$P_{\rm g} = (\gamma_{\rm g} - 1)e_{\rm g} = 2e_{\rm g}/3$$

$$P_{\rm cr} = (\gamma_{\rm cr} - 1)e_{\rm cr} = e_{\rm cr}/3$$

The CR-hydrodynamics: the energy equation

$$\frac{dP_{\rm g}}{dt} - {C_{\rm g}}^2\frac{d\rho}{dt} = G(\rho,T,P_{\rm cr})$$
$$\frac{dP_{\rm cr}}{dt} - {C_{\rm cr}}^2\frac{d\rho}{dt} = R(\rho,T,P_{\rm cr})$$

$$\begin{aligned} C_{\rm g} &= \sqrt{\frac{\gamma_g P_{\rm g}}{\rho}}, \\ G(\rho,T,P_{\rm cr}) &= \mathcal{L}^*(\rho,T) + \boldsymbol{\nabla}\cdot(\mathcal{K}^*\boldsymbol{\nabla}T) + \mathcal{H}, \\ \mathcal{L}^*(\rho,T) &= (\gamma_{\rm g}-1)\,\mathcal{L}_{\rm rad,g}(\rho,T), \\ \mathcal{H}(\rho,T,P_{\rm cr}) &= (\gamma_{\rm g}-1)\,\mathcal{L}_{\rm em,cr}(\rho,T,P_{\rm cr}), \end{aligned}$$

Energy Exchange effect

$$\begin{aligned} C_{\rm cr} &= \sqrt{\frac{\gamma_{\rm cr} P_{\rm cr}}{\rho}} \\ R(\rho,T,P_{\rm cr}) &= \boldsymbol{\nabla}\cdot(\mathcal{D}\boldsymbol{\nabla}P_{\rm cr}) - \gamma_*\mathcal{H}, \\ \gamma_* &= \frac{\gamma_{\rm cr}-1}{\gamma_{\rm g}-1} = \frac{1}{2}, \end{aligned}$$

$$\frac{d(P_{\rm g}+P_{\rm cr})}{dt} - ({C_{\rm g}}^2+{C_{\rm cr}}^2)\frac{d\rho}{dt} \sim (1-\gamma_*)\mathcal{H}$$

$$P_{\rm g} = (\gamma_{\rm g}-1)e_{\rm g} = 2e_{\rm g}/3$$
$$P_{\rm cr} = (\gamma_{\rm cr}-1)e_{\rm cr} = e_{\rm cr}/3$$

The CR heating produces additional total pressure!

The CR-hydrodynamics: the energy equation

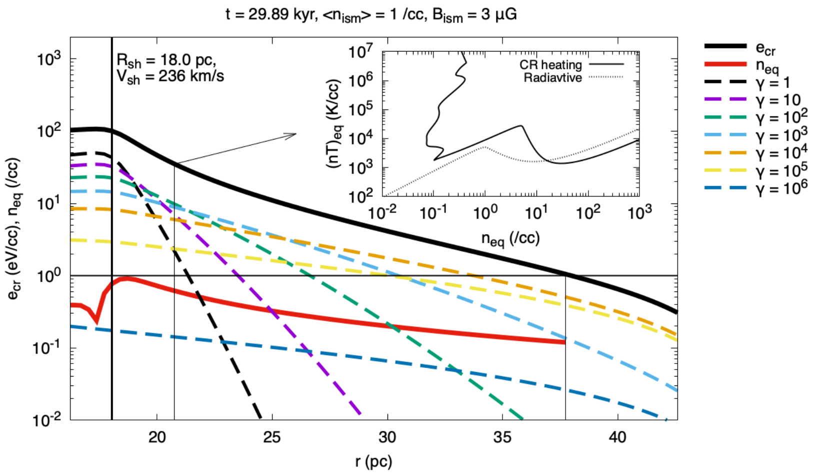
$$P_{\rm g} = (\gamma_{\rm g} - 1) e_{\rm g} = 2 e_{\rm g}/3$$
$$P_{\rm cr} = (\gamma_{\rm cr} - 1) e_{\rm cr} = e_{\rm cr}/3$$

The CR heating produces additional total pressure!

$$\begin{aligned} \mathcal{P} = P_{\rm g} + P_{\rm cr} &= \mathcal{P}(e_{\rm g} + |e_1|, e_{\rm cr} - |e_1|) \\ &= \mathcal{P}(e_{\rm g}, e_{\rm cr}) \boxed{+ \frac{|e_1|}{3}} \end{aligned}$$

What happens???→ Linear analysis

The CR-hydrodynamics: Linear Analysis in uniform medium



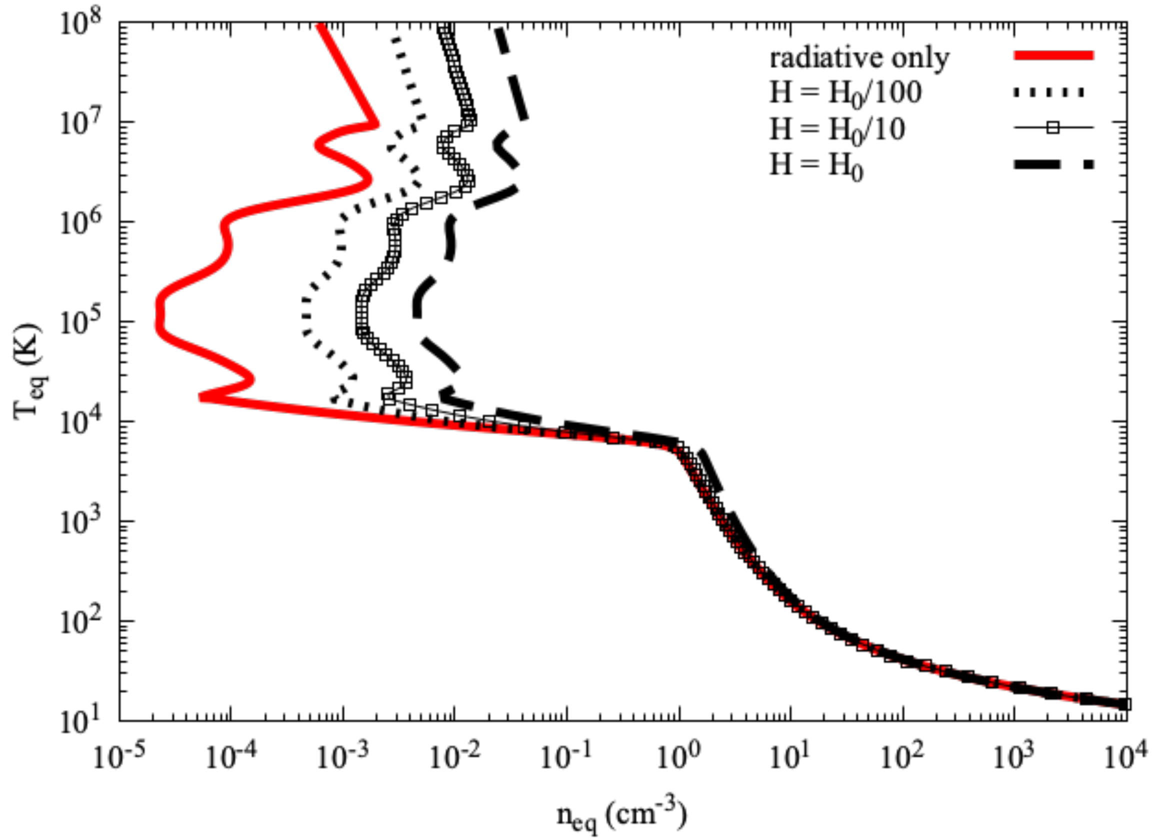
CRs supplied by the source (SNR)

$$\mathcal{Q}_{\rm ex} = \mathcal{H} = \frac{\mathcal{H}_0}{10}$$

$$\mathcal{H}_0 = \frac{e_{\rm cr}}{\tau_{\rm res}} = 1.8 \times 10^{-26}\ {\rm erg\ cm^{-3}\ s^{-1}} \left(\frac{e_{\rm cr}}{1\ {\rm eV/cc}}\right) \left(\frac{\tau_{\rm res}}{1\ {\rm Myr}}\right)^{-1}$$

Equilibrium condition

$$n\Gamma - n^2\Lambda(T) + \mathcal{H} = 0$$



The CR-hydrodynamics: Linear Analysis in uniform medium

* $\rho_{\rm rad} = \Gamma / \Lambda$: the case w/o CR

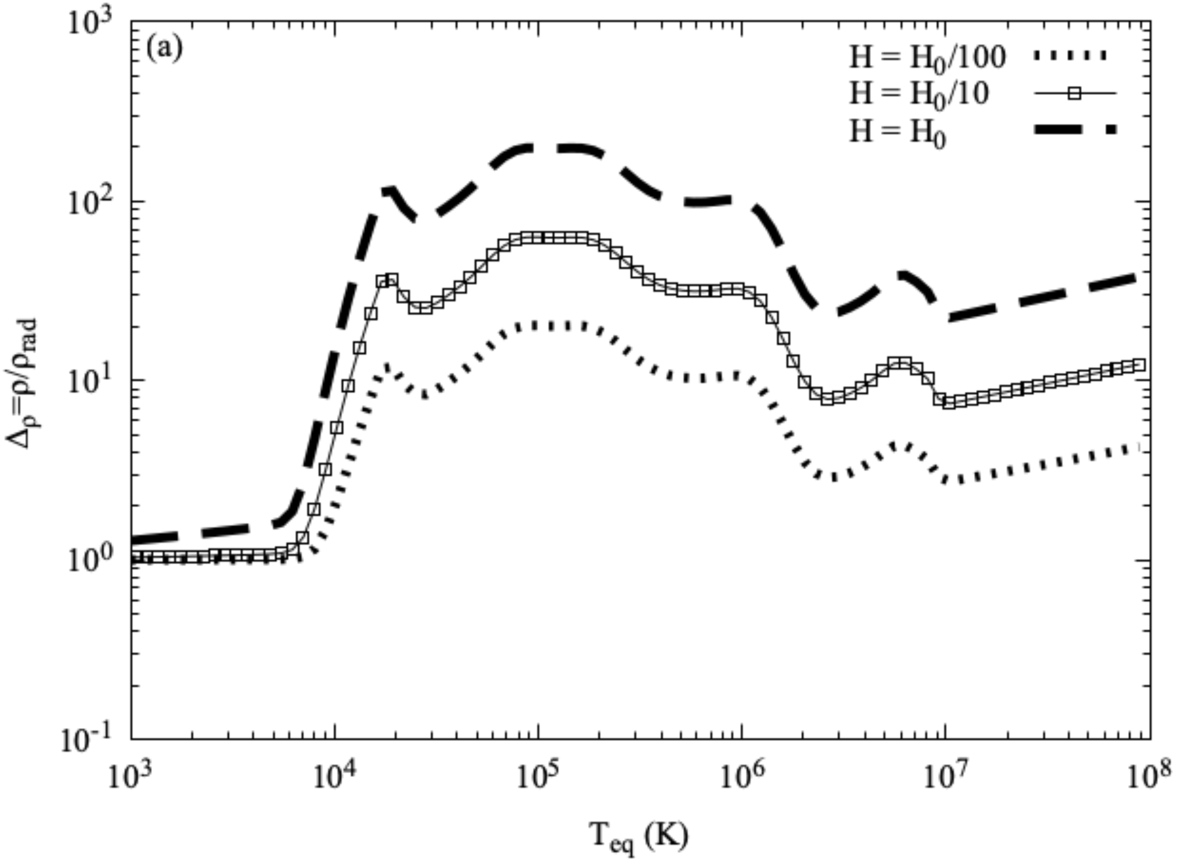
$$P_{\rm g} = \rho \mathcal{T} \text{ where } \mathcal{T} = k_{\rm B} T / \bar{m} \ [\text{cm}^2 \ \text{s}^{-2}]$$

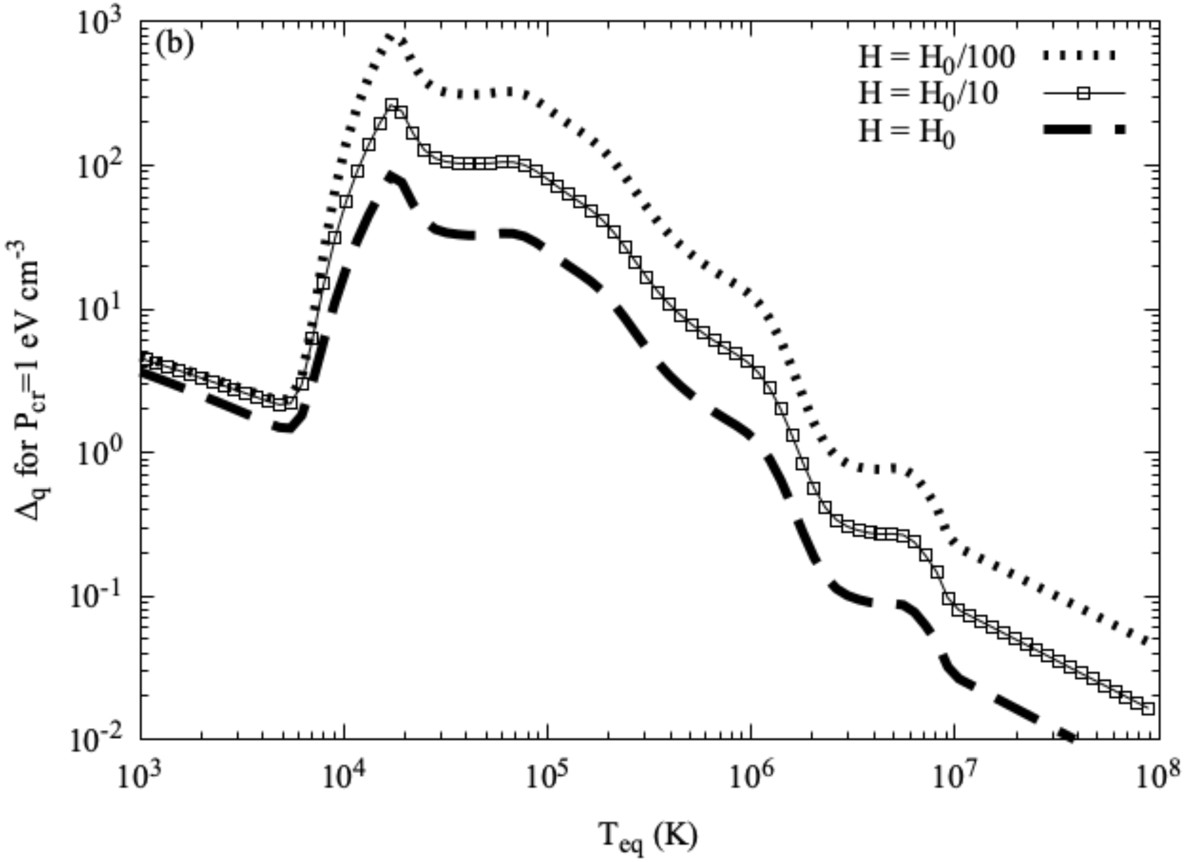
Equilibrium condition

$$n\Gamma - n^2 \Lambda(T) + \mathcal{H} = 0$$

$$\Delta_\rho \equiv \rho / \rho_{\rm rad}$$

$$\Delta_q \equiv P_{\rm cr} / \rho_{\rm rad} \mathcal{T}$$





The CR-hydrodynamics: Linearized Equations

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

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

$$\begin{aligned} \frac{dP_{\rm g}}{dt} - {C_{\rm g}}^2 \frac{d\rho}{dt} &= G(\rho, T, P_{\rm cr}) \\ \frac{dP_{\rm cr}}{dt} - {C_{\rm cr}}^2 \frac{d\rho}{dt} &= R(\rho, T, P_{\rm cr}) \end{aligned}$$

The CR-hydrodynamics: Linearized Equations

$$\partial_t \rho_1 + \rho\partial_x v_1 + \rho\partial_y u_1 = 0,$$
$$\rho\partial_t v_1 + \partial_x P_{\mathrm{g},1} = 0,$$
$$\rho\partial_t u_1 + \partial_y P_{\mathrm{g},1} = 0,$$
$$(\partial_t - G_p)\,P_{\mathrm{g},1} - \left({C_{\mathrm{g}}}^2\partial_t + G_\rho\right)\rho_1 - G_q P_{\mathrm{cr},1} = 0,$$
$$(\partial_t - R_q)\,P_{\mathrm{cr},1} - \left({C_{\mathrm{cr}}}^2\partial_t + R_\rho\right)\rho_1 - R_p P_{\mathrm{g},1} = 0,$$

$$\begin{aligned}
G_r &= \partial_\rho G - \frac{\mathcal{T}}{\rho}\partial_{\mathcal{T}} G \\
&= \Gamma^* - \rho\Lambda^*\,(2-\chi) + \frac{\mathcal{H}}{\rho}\,(\eta_r - \eta_{\mathcal{T}}) - \frac{\mathcal{K}^*\mathcal{T}}{\rho}\boldsymbol{\nabla}^2, \\
G_p &= \frac{\partial_{\mathcal{T}} G}{\rho} = -\frac{\rho\Lambda^*}{\mathcal{T}}\chi + \frac{\mathcal{H}}{\rho\mathcal{T}}\eta_{\mathcal{T}} + \frac{\mathcal{K}^*}{\rho}\boldsymbol{\nabla}^2, \\
G_q &= \frac{\mathcal{H}}{P_{\mathrm{cr}}}\eta_q, \\
R_r &= -\frac{\gamma_*\mathcal{H}}{\rho}\,(\eta_r - \eta_{\mathcal{T}}), \\
R_p &= -\frac{\gamma_*\mathcal{H}}{\rho\mathcal{T}}\eta_{\mathcal{T}}, \\
R_q &= -\frac{\gamma_*\mathcal{H}}{P_{\mathrm{cr}}}\eta_q + \mathcal{D}\boldsymbol{\nabla}^2, \\
\chi &= \frac{\Lambda}{\mathcal{T}}\frac{\partial\Lambda}{\partial\mathcal{T}} = \frac{\partial\ln\Lambda}{\partial\ln\mathcal{T}}, \\
\eta_r &= \frac{\partial\ln\mathcal{H}}{\partial\ln\rho},\ \eta_{\mathcal{T}} = \frac{\partial\ln\mathcal{H}}{\partial\ln\mathcal{T}},\ \eta_q = \frac{\partial\ln\mathcal{H}}{\partial\ln P_{\mathrm{cr}}},
\end{aligned}$$

The CR-hydrodynamics: Linearized Equations

$$\nu = G_p + R_q$$
$$\dot{\epsilon} = G_r + R_r + (R_p - R_q)\, {C_{\rm g}}^2 + (G_q - G_p)\, {C_{\rm cr}}^2$$

$$\dot{\nu} = G_q R_p - G_p R_q$$
$$\ddot{\epsilon} = (R_q - R_p) G_r + (G_p - G_q) R_r$$

$$\boxed{\begin{aligned}\Big[\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right) \quad &- \quad \partial_t \left(\nu \partial_t^2 + \dot{\epsilon} \boldsymbol{\nabla}^2\right) \\ &- \quad \left(\dot{\nu}\partial_t^2 - \ddot{\epsilon}\boldsymbol{\nabla}^2\right)\Big]\, P_{{\rm g},1} = 0,\end{aligned}}$$

$$C_* = \sqrt{{C_{\rm g}}^2 + {C_{\rm cr}}^2}$$

$$\frac{dP_{\rm g}}{dt} - {C_{\rm g}}^2 \frac{d\rho}{dt} = G(\rho, T, P_{\rm cr})$$
$$\frac{dP_{\rm cr}}{dt} - {C_{\rm cr}}^2 \frac{d\rho}{dt} = R(\rho, T, P_{\rm cr})$$

The CR-hydrodynamics: Linearized Equations

Know as Thermal Instability (Field 65)

$$\left[\partial_t^2\left(\partial_t^2 - C_*{}^2\boldsymbol{\nabla}^2\right) \quad - \quad \partial_t\left(\nu\partial_t^2 + \dot{\epsilon}\boldsymbol{\nabla}^2\right) \\ - \quad \left(\dot{\nu}\partial_t^2 - \ddot{\epsilon}\boldsymbol{\nabla}^2\right)\right] P_{\mathrm{g},1} = 0,$$

Sound Waves

$$C_* = \sqrt{C_{\mathrm{g}}{}^2 + C_{\mathrm{cr}}{}^2}$$

The CR heating effect (disappear when R=0)

$$\begin{aligned} \nu &= G_p + R_q \\ \dot{\epsilon} &= G_r + R_r + (R_p - R_q)\, C_{\mathrm{g}}{}^2 + (G_q - G_p)\, C_{\mathrm{cr}}{}^2 \end{aligned}$$

$$\begin{aligned} \dot{\nu} &= G_q R_p - G_p R_q \\ \ddot{\epsilon} &= (R_q - R_p) G_r + (G_p - G_q) R_r \end{aligned}$$

$$\begin{aligned} \frac{dP_{\mathrm{g}}}{dt} - C_{\mathrm{g}}{}^2\frac{d\rho}{dt} &= G(\rho, T, P_{\mathrm{cr}}) \\ \frac{dP_{\mathrm{cr}}}{dt} - C_{\mathrm{cr}}{}^2\frac{d\rho}{dt} &= R(\rho, T, P_{\mathrm{cr}}) \end{aligned}$$

The CR-hydrodynamics: Linearized Equations

Know as Thermal Instability (Field 65)

$$
\begin{aligned}
\left[\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right)\right. & - \partial_t \left(\nu \partial_t^2 + \dot{\epsilon} \boldsymbol{\nabla}^2\right) \\
& - \left.\left(\dot{\nu} \partial_t^2 - \ddot{\epsilon} \boldsymbol{\nabla}^2\right)\right] P_{\mathrm{g},1} = 0,
\end{aligned}
$$

Sound Waves

$$C_* = \sqrt{{C_\mathrm{g}}^2 + {C_\mathrm{cr}}^2}$$

The CR heating effect (disappear when R=0)

extract

$$\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right) P_{\mathrm{g},1} = \dot{\nu} \left(\partial_t^2 - \frac{\ddot{\epsilon}}{\dot{\nu}} \boldsymbol{\nabla}^2\right) P_{\mathrm{g},1}$$

$$
\begin{aligned}
\nu &= G_p + R_q \\
\dot{\epsilon} &= G_r + R_r + (R_p - R_q)\, {C_\mathrm{g}}^2 + (G_q - G_p)\, {C_\mathrm{cr}}^2
\end{aligned}
$$

$$
\begin{aligned}
\dot{\nu} &= G_q R_p - G_p R_q \\
\ddot{\epsilon} &= (R_q - R_p) G_r + (G_p - G_q) R_r
\end{aligned}
$$

$$
\begin{aligned}
\frac{dP_\mathrm{g}}{dt} - {C_\mathrm{g}}^2 \frac{d\rho}{dt} &= G(\rho, T, P_\mathrm{cr}) \\
\frac{dP_\mathrm{cr}}{dt} - {C_\mathrm{cr}}^2 \frac{d\rho}{dt} &= R(\rho, T, P_\mathrm{cr})
\end{aligned}
$$

The CR-hydrodynamics: Linearized Equations

Know as Thermal Instability (Field 65)

$$\left[\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right) \quad - \quad \partial_t \left(\nu \partial_t^2 + \dot{\epsilon} \boldsymbol{\nabla}^2\right) \right.$$
$$\left. \quad - \quad \left(\dot{\nu} \partial_t^2 - \ddot{\epsilon} \boldsymbol{\nabla}^2\right)\right] P_{\mathrm{g},1} = 0,$$

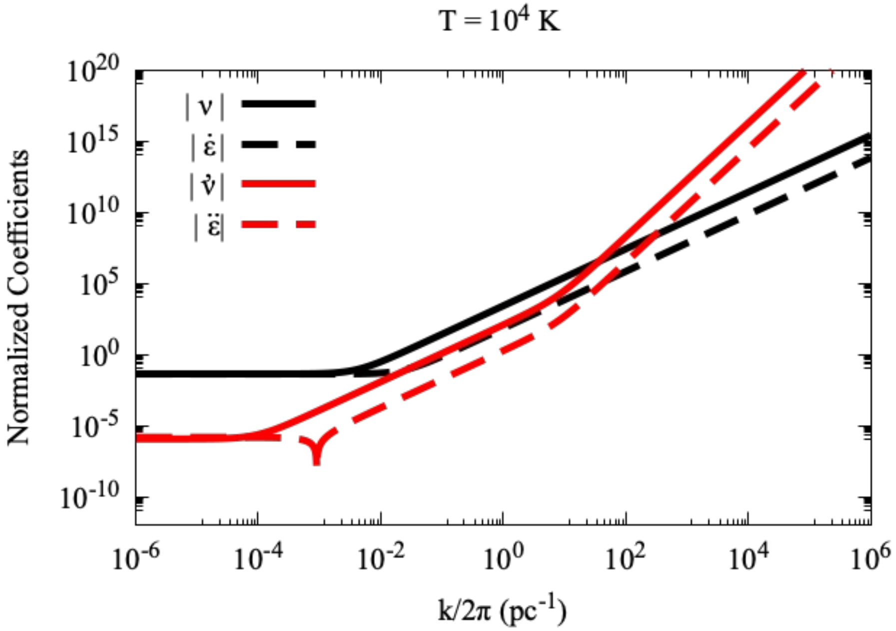
Sound Waves

$$C_* = \sqrt{{C_\mathrm{g}}^2 + {C_\mathrm{cr}}^2}$$

The CR heating effect (disappear when R=0)

extract

$$\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right) P_{\mathrm{g},1} = \dot{\nu} \left(\partial_t^2 - \frac{\ddot{\epsilon}}{\dot{\nu}} \boldsymbol{\nabla}^2\right) P_{\mathrm{g},1}$$



Examples (Pcr=1 eV/cc)

The CR-hydrodynamics: Linearized Equations

Sound Waves

Oscillating Force

$$\partial_t^2 \left(\partial_t^2 - {C_*}^2 \boldsymbol{\nabla}^2\right) P_{\mathrm{g},1} = \dot{\nu}\left(\partial_t^2 - \frac{\ddot{\epsilon}}{\dot{\nu}}\boldsymbol{\nabla}^2\right) P_{\mathrm{g},1}$$

$$\begin{aligned} \ddot{x} &= -\omega^2 x + f_0 \cos(\omega_0 t) \\ x(t) &= A\cos(\omega t) + f_0 \frac{\cos(\omega_0 t) - \cos(\omega t)}{\omega^2 - {\omega_0}^2} \end{aligned}$$

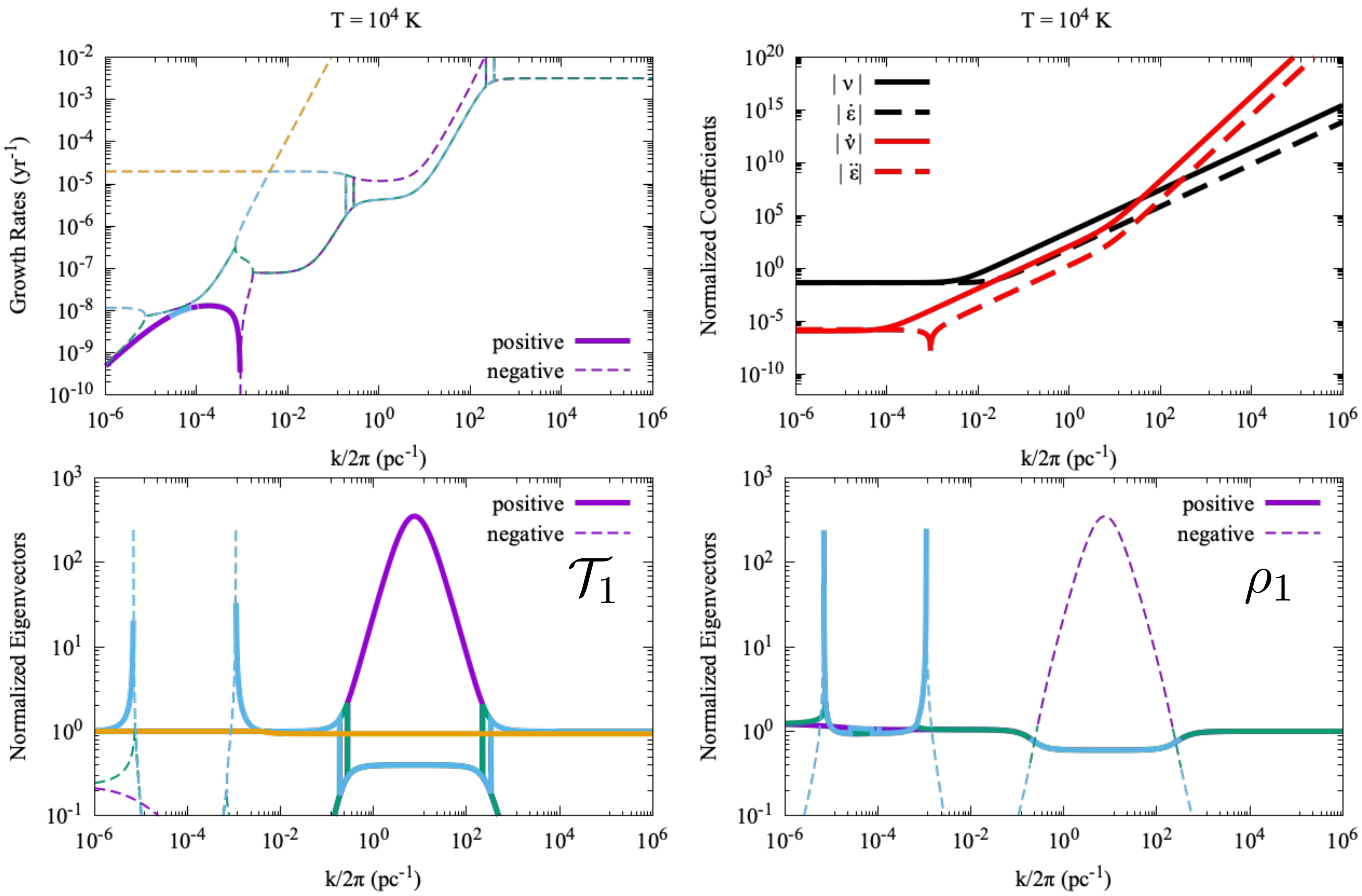
Making Oscillation

Like Forced Oscillation

$\rightarrow$ Eigenvectors may show kind of resonance

$$\begin{aligned}
\xi_q &\equiv \frac{P_{\mathrm{cr},1}/P_{\mathrm{cr}}}{P_{\mathrm{g},1}/P_{\mathrm{g}}} \\
&= \frac{(\mathrm{i}\omega + G_p)(\mathrm{i}\omega {C_{\mathrm{cr}}}^2 - R_r) - R_p(\mathrm{i}\omega {C_{\mathrm{g}}}^2 - G_r)}{(\mathrm{i}\omega + R_q)(\mathrm{i}\omega {C_{\mathrm{g}}}^2 - G_r) - G_q(\mathrm{i}\omega {C_{\mathrm{cr}}}^2 - R_r)} \frac{P_{\mathrm{g}}}{P_{\mathrm{cr}}}, \\
\xi_\rho &\equiv \frac{\rho_1/\rho}{P_{\mathrm{g},1}/P_{\mathrm{g}}} = \frac{\rho_1 \mathcal{T}}{P_{\mathrm{g},1}}\left(1 + \frac{P_{\mathrm{cr},1}}{P_{\mathrm{g},1}}\right), \\
\xi_{\mathcal{T}} &\equiv \frac{\mathcal{T}_1/\mathcal{T}}{P_{\mathrm{g},1}/P_{\mathrm{g}}} = 1 - \frac{\rho_1 \mathcal{T}}{P_{\mathrm{g},1}}, \\
\xi_v &\equiv \frac{\rho C_{\mathrm{g}} v_1}{P_{\mathrm{g},1}} = \frac{k_c C_{\mathrm{g}}}{\omega}\left(1 + \frac{P_{\mathrm{cr},1}}{P_{\mathrm{g},1}}\right).
\end{aligned}$$

The CR-hydrodynamics: Growth rates & Eigenvectors



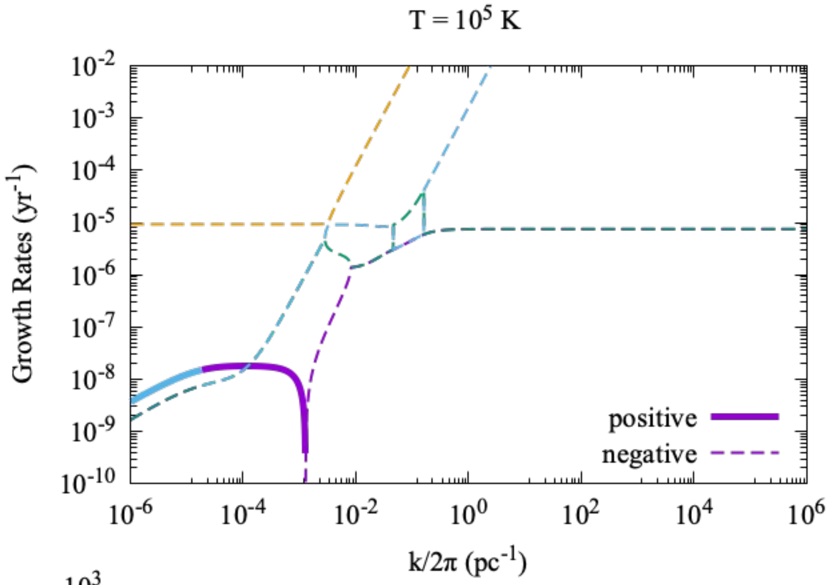
The resonance appears in T_1 and ρ_1

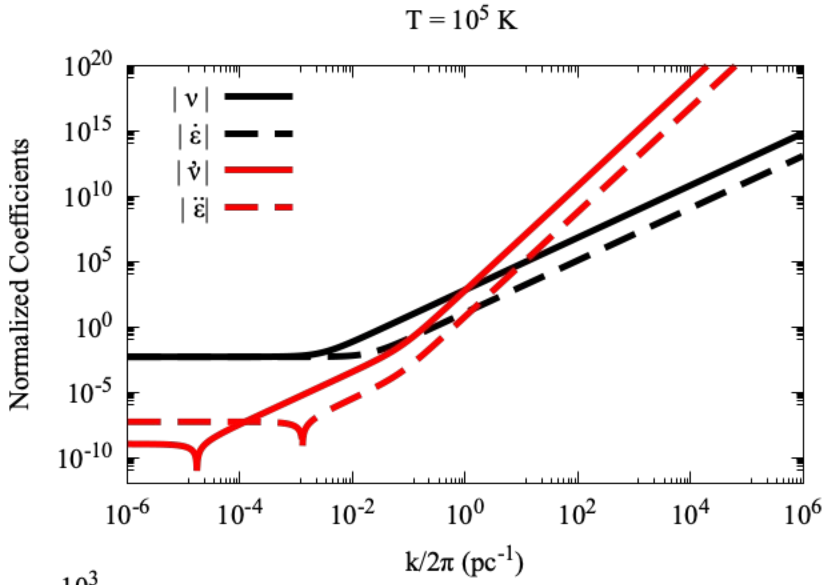
Damping time ~0.1 Myr is longer than the SNR lifetime.

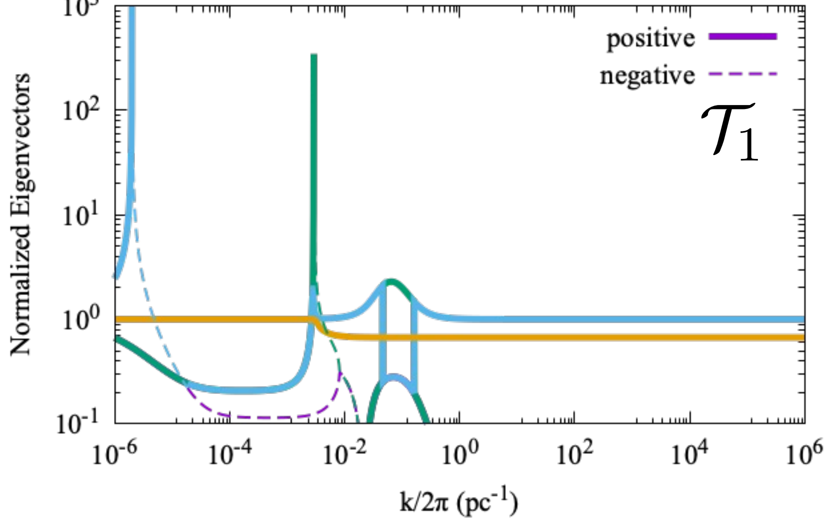
The CR heating possibly works around SNR/PWN.

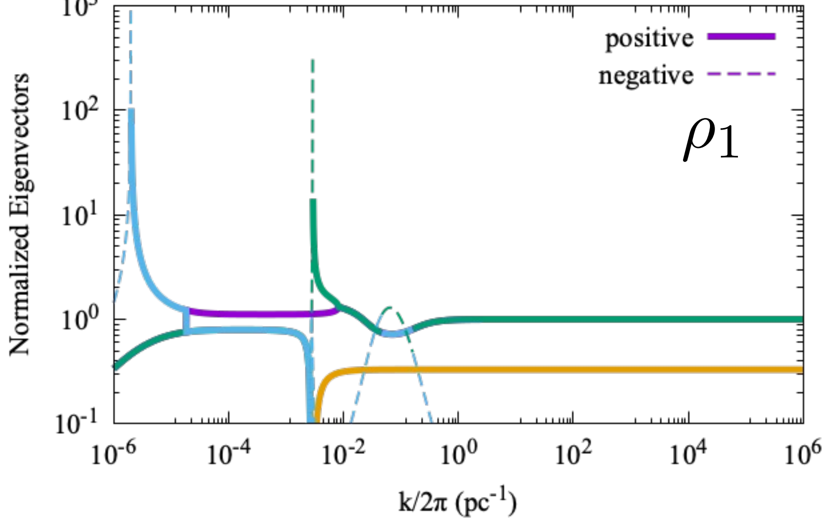
Affected scale: ~0.01 pc - 10 pc

The CR-hydrodynamics: Growth rates & Eigenvectors









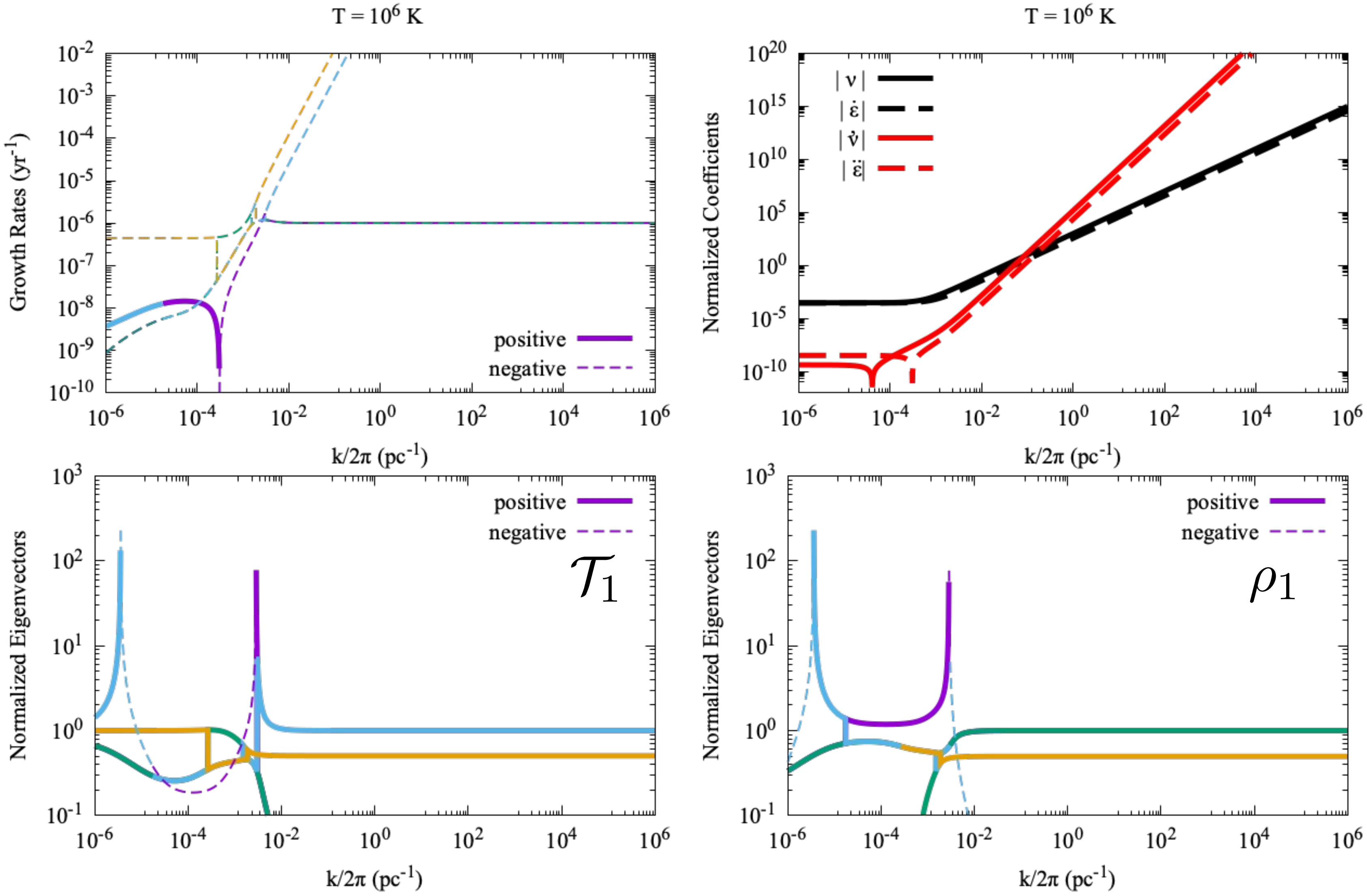
The resonance appears in T_1 and ρ_1

Damping time ~0.1 Myr is longer than the SNR lifetime.

The CR heating possibly works around SNR/PWN.

Affected scale: ~10 pc

The CR-hydrodynamics: Growth rates & Eigenvectors



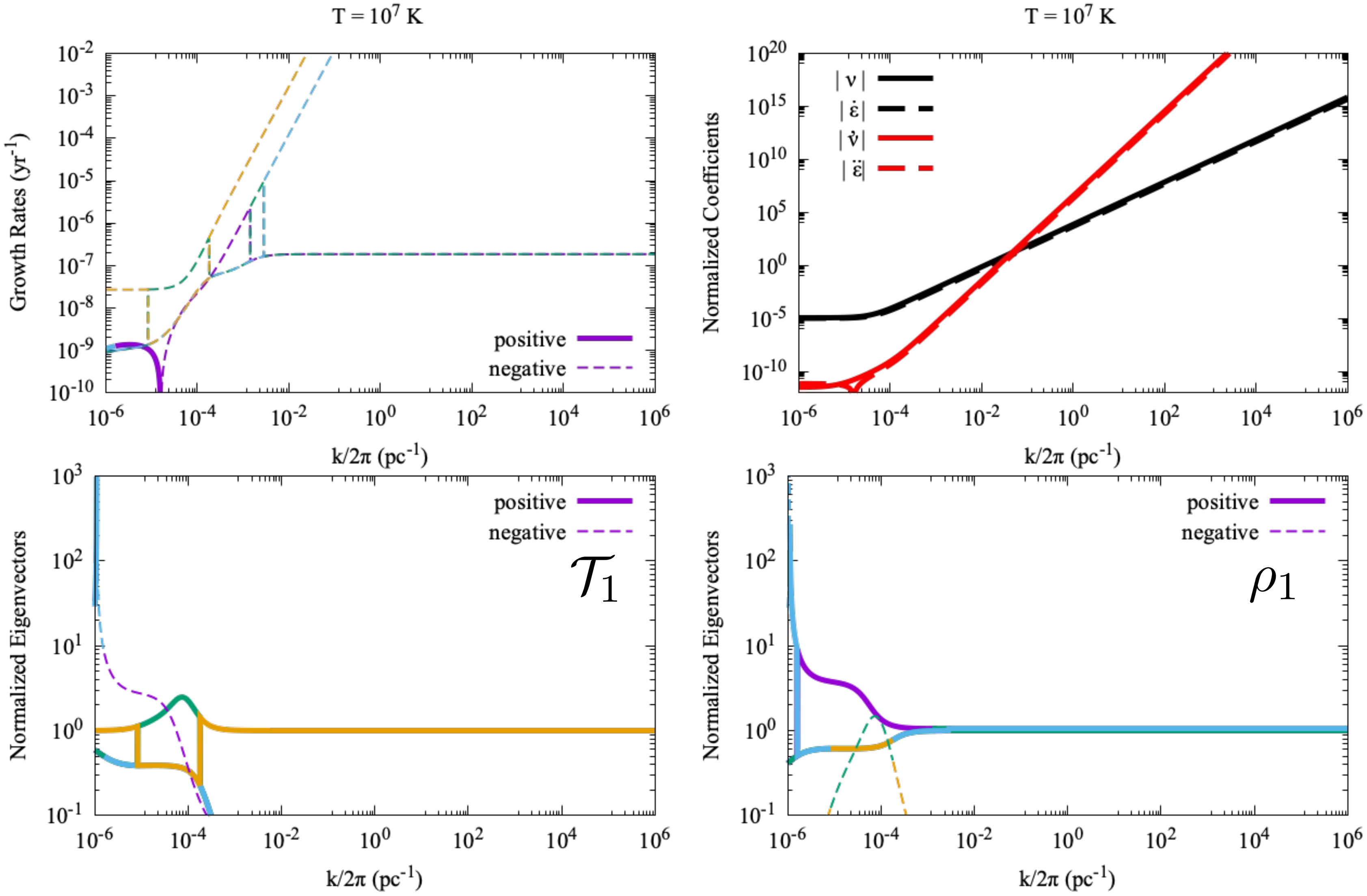
The resonance appears in T_1 and ρ_1

Damping time ~0.1 Myr is longer than the SNR lifetime.

The CR heating possibly works around SNR/PWN.

Affected scale: ~100 pc?

The CR-hydrodynamics: Growth rates & Eigenvectors



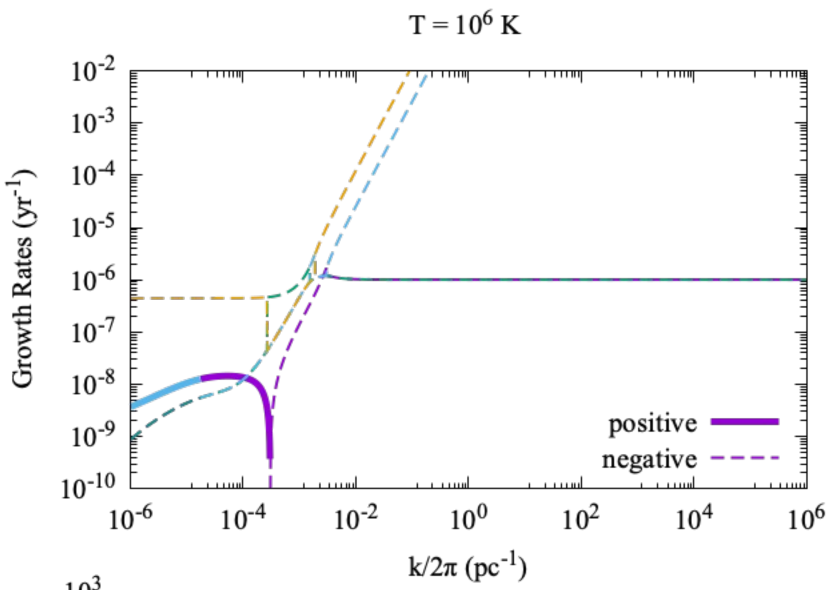
The resonance appears in T_1 and ρ_1

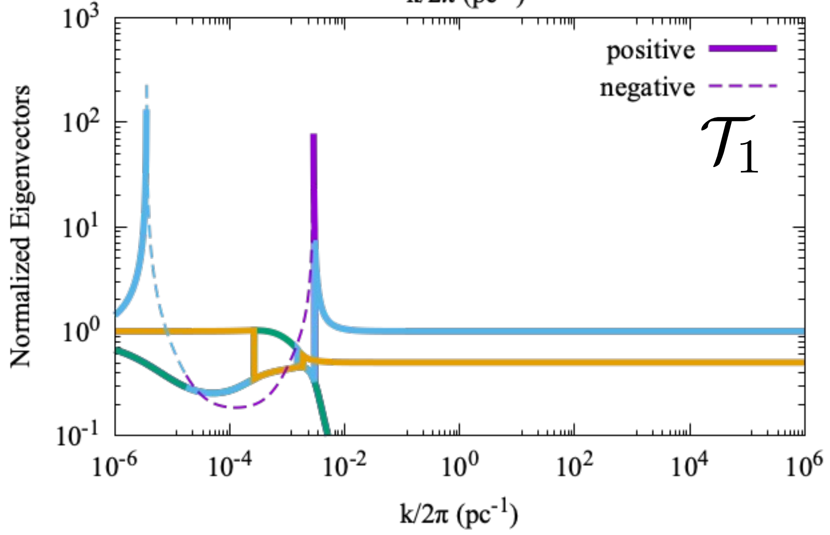
Damping time ~0.1 Myr is longer than the SNR lifetime.

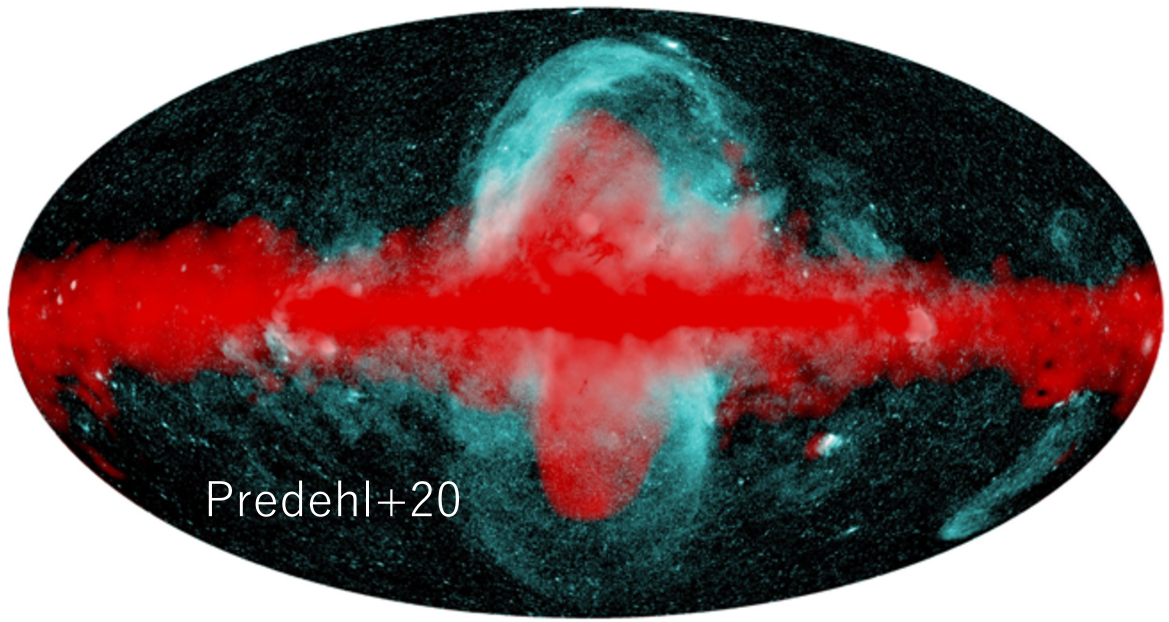
The CR heating possibly works around SNR/PWN.

Affected scale: ~100 kpc

Outflow Launching?

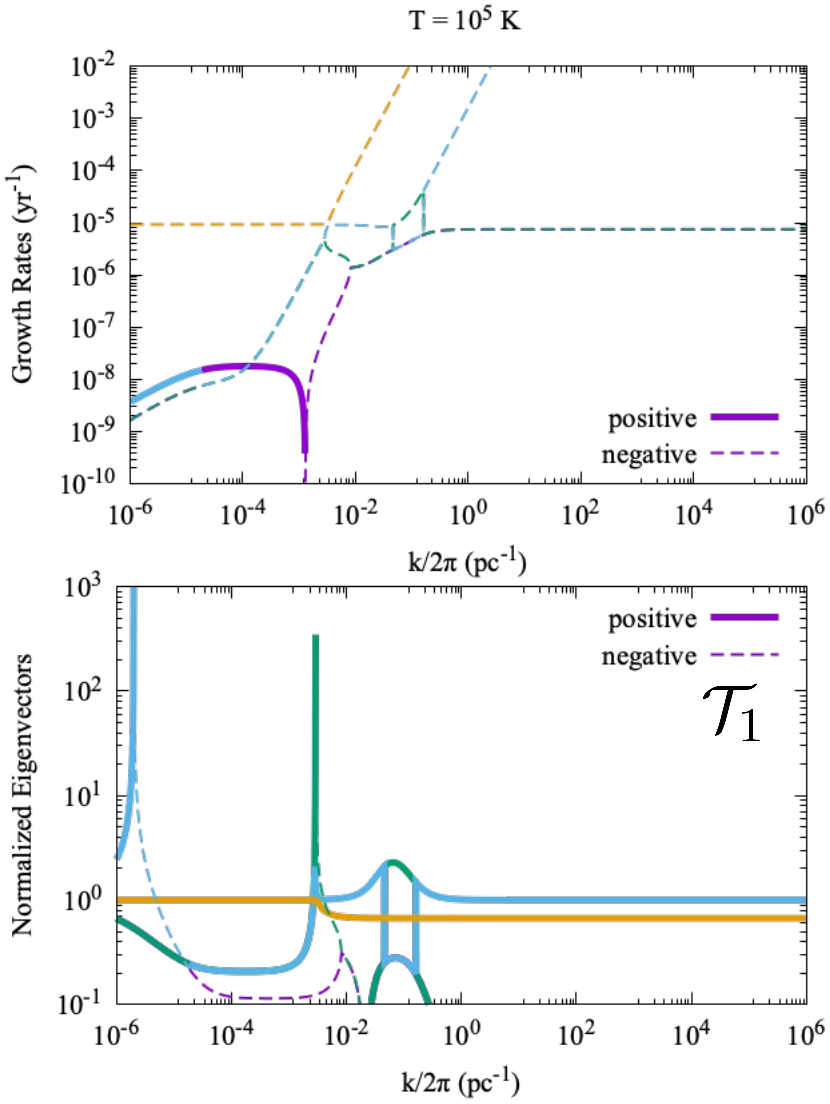




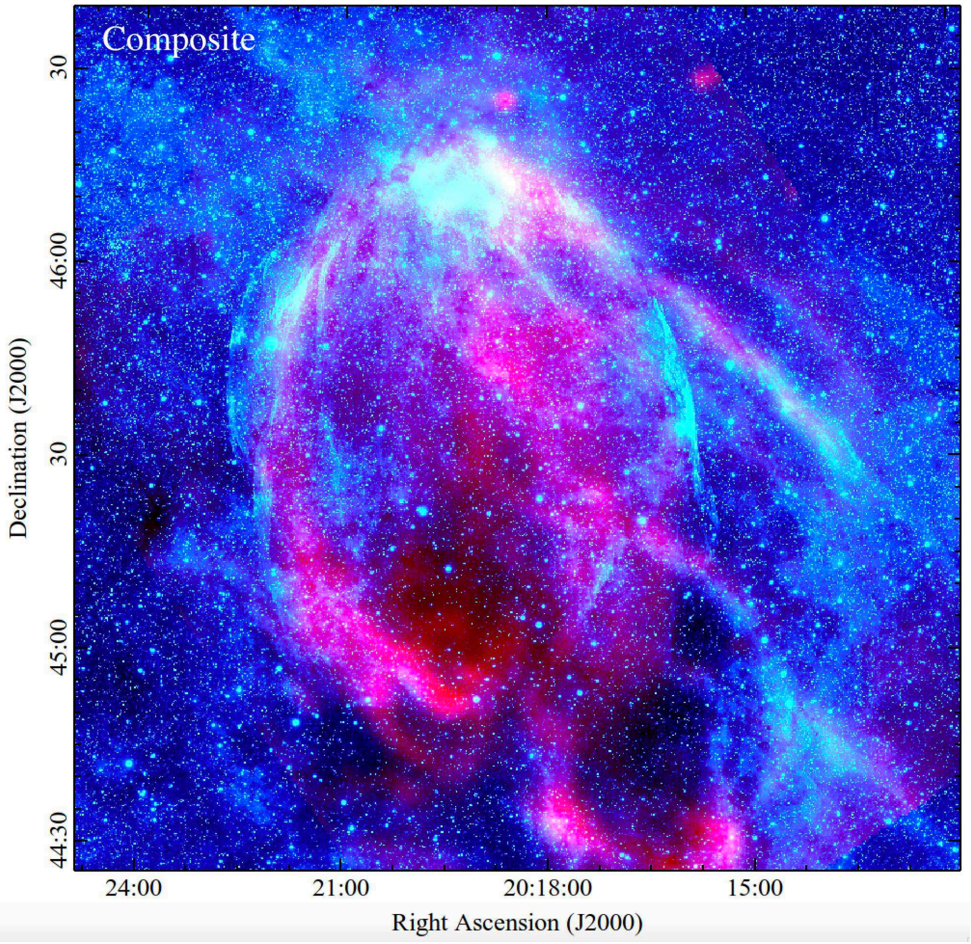


NOT SIMPLE @ T ~ 0.1 keV scale…

Fesen et al. 2024 report [OIII]λ5007 (in old SNRs)



Red: radio synchrotron
Blue: [OIII]λ5007



The CR heating effect explains such emission?

Hadronic γ-ray observed?

Future work

1st ionization potentials:
O^{+1}→35 eV
O^{+2}→55 eV
O^{+3}→77 eV

Summary

The Galactic Wind

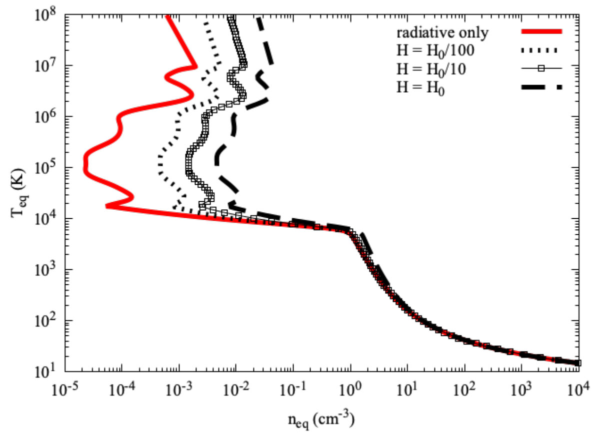
- Invoked to explain metals in/around galaxies.
- Possibly explain eROSITA bubble & Fermi bubble simultaneously.
- We must find the formation mechanism of the “seed gas” in the disk.

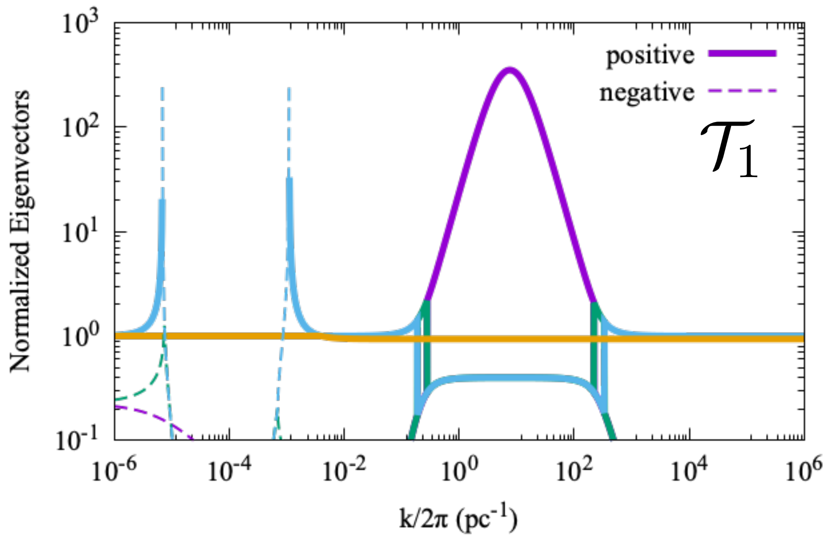
The effects of CR heating

- The heating can be seen like forced oscillation (damped within ~0.1 Myr).
- Possibly work around CR sources like SNRs/PWNe.
- Details are still not derived.

$$\begin{aligned} \mathcal{P} = P_{\rm g} + P_{\rm cr} &= \mathcal{P}(e_{\rm g} + |e_1|, e_{\rm cr} - |e_1|) \\ &= \mathcal{P}(e_{\rm g}, e_{\rm cr}) + \frac{|e_1|}{3} \end{aligned}$$

Reason is Simple





Diverse Phenomena