逃走宇宙線との闘争

霜田治朗

相対論的現象で探る宇宙の進化Ⅴ（2025/02/24-27）

部分的Collaborators: Y. Ohira, K. Asano, S. Inutsuka

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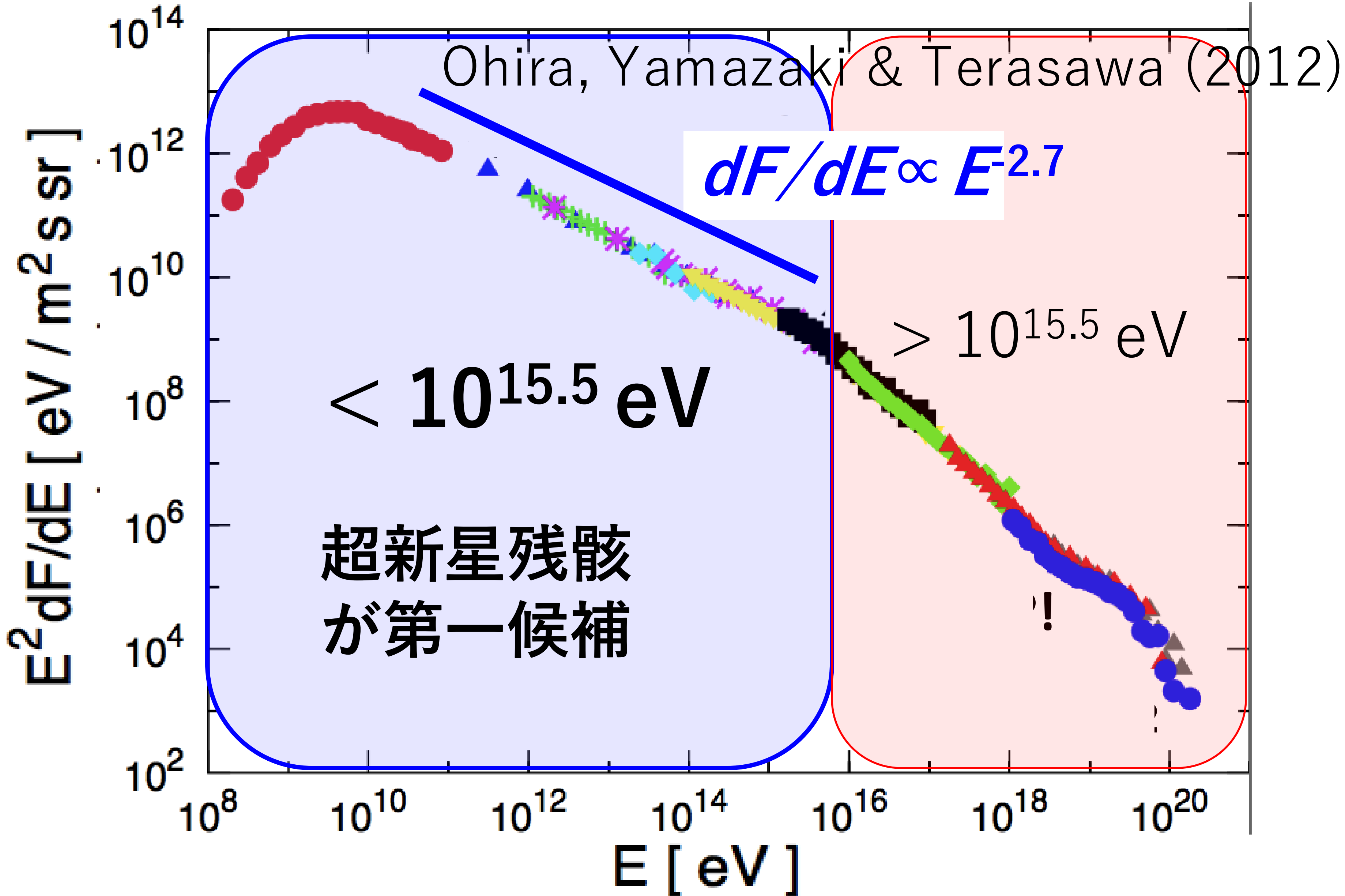

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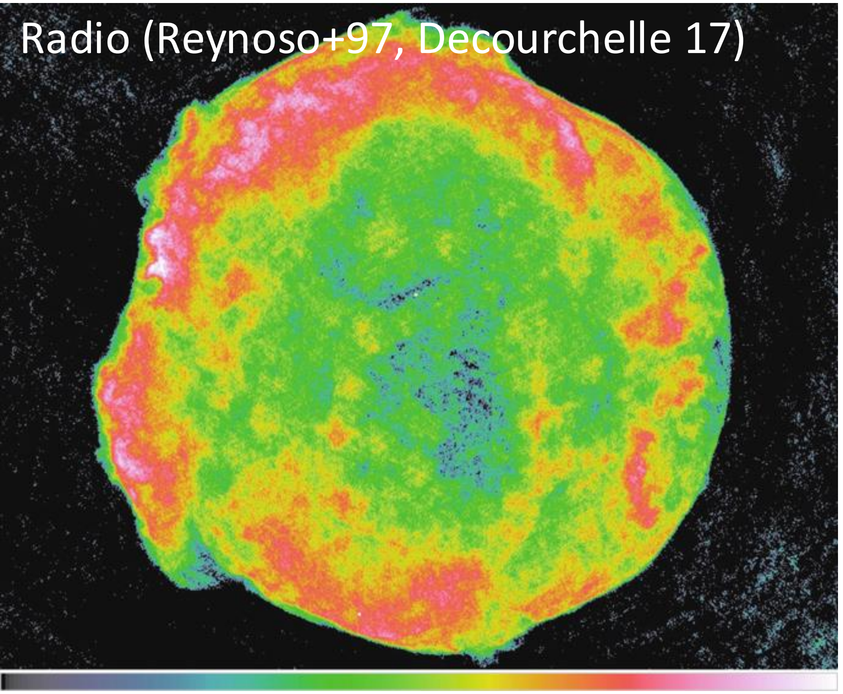
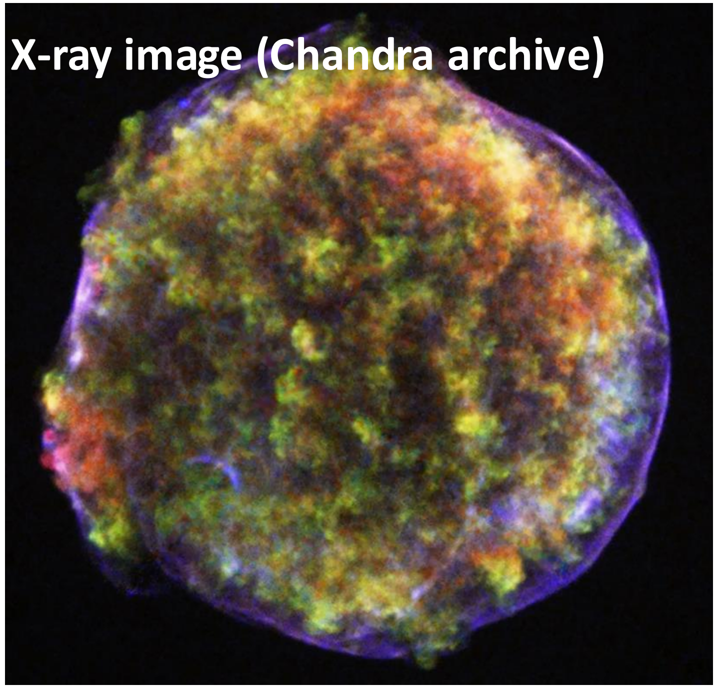
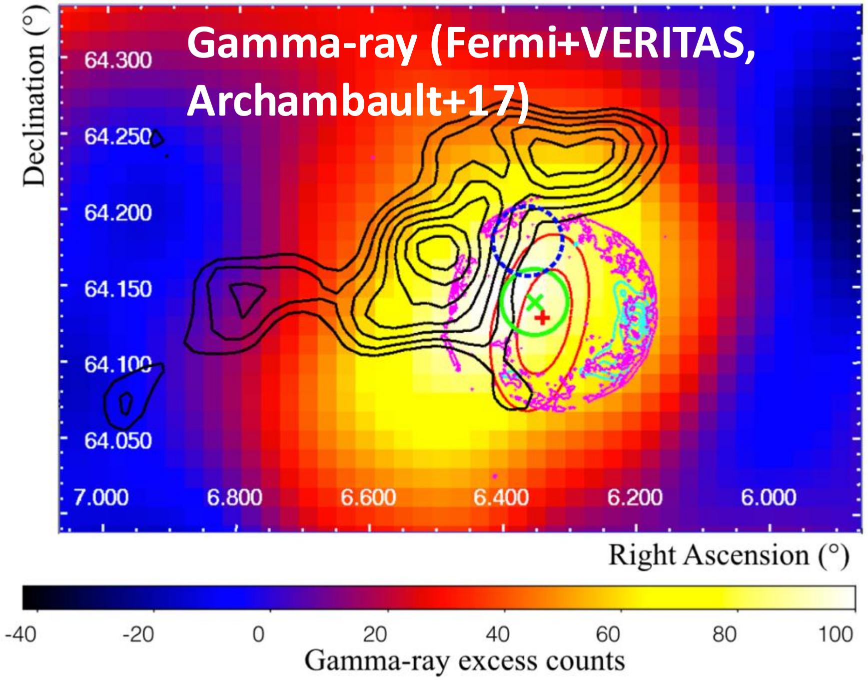
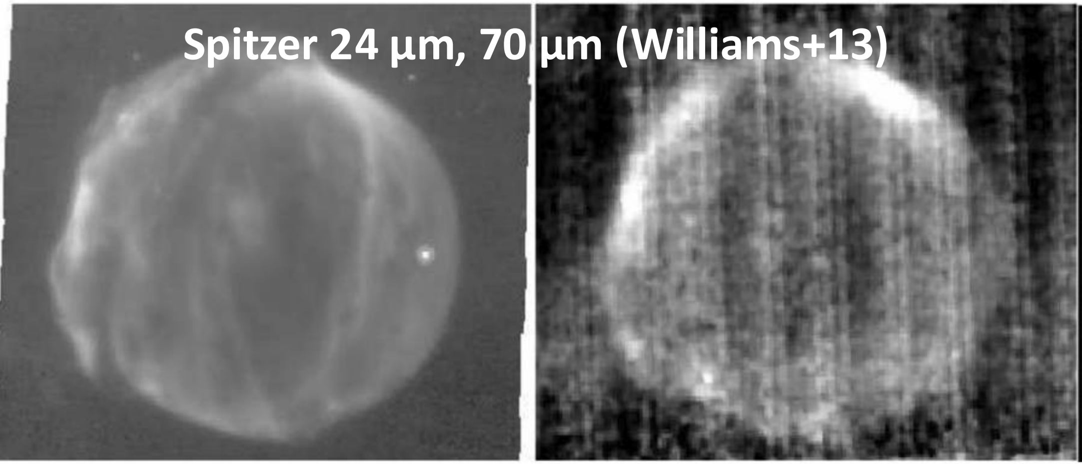
E2dF/dE [eV / m2 s sr]
E [eV]
1014
1012
1010
108
106
104
102
108
1010
1012
1014
1016
1018
1020

Supernova Remnants:e.g., Tycho's SNR (SN 1572, Ia)









Supernova Remnant (SNR)

・Supernovaの*残骸*

天文学的に、SNとSNRを区別する厳密な定義は無いとされる。発見者の気持ち次第。

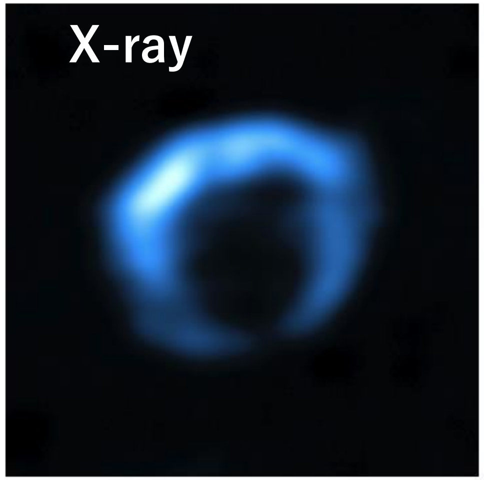
・粒子加速の現場

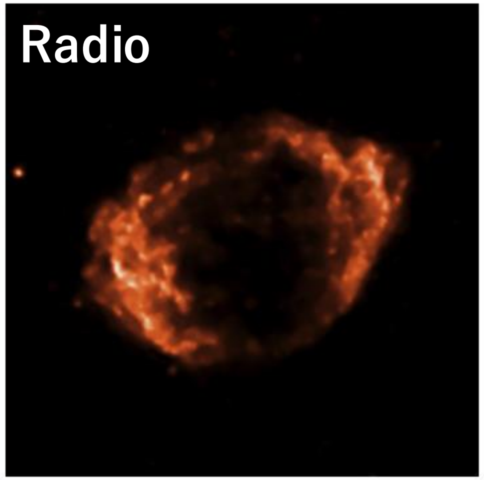
・ダスト=惑星・生命の材料の生成場所？

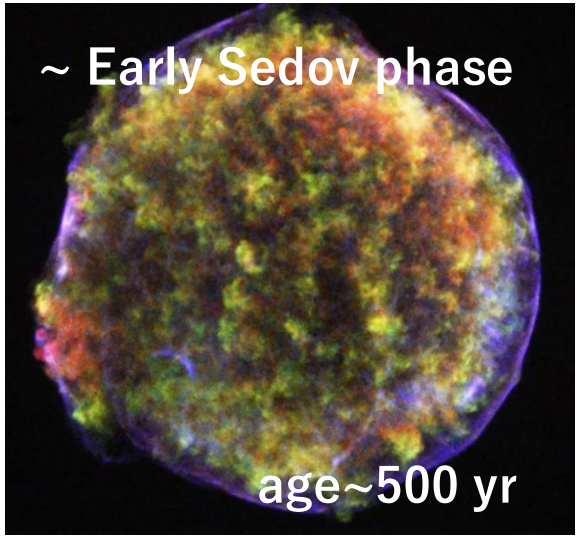
・ISMの相転移（分子雲形成）を促す、重要なエネルギー源（Mckee&Ostriker 77, Inutsuka+15）

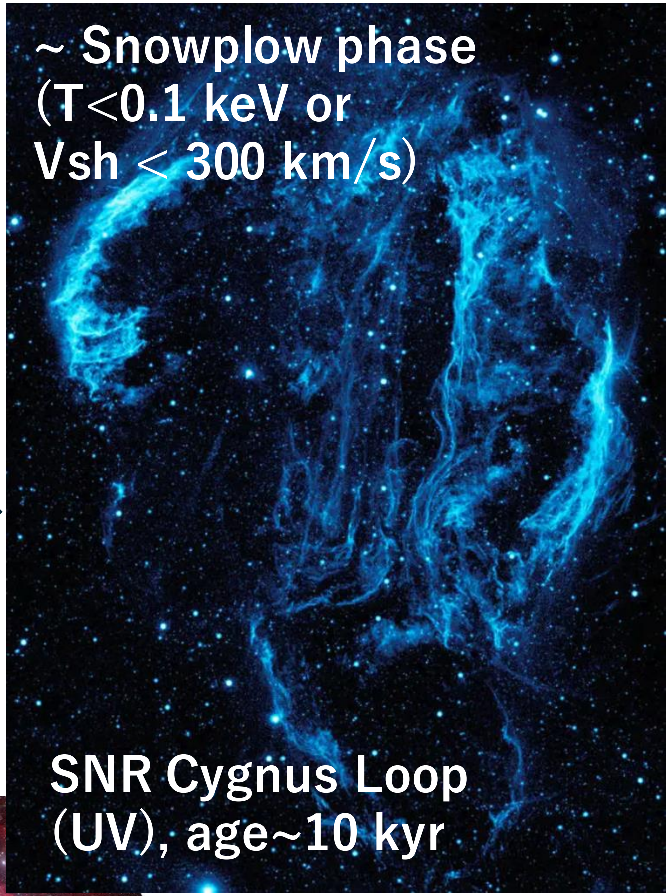
Supernova Remnants:Temporal Evolution

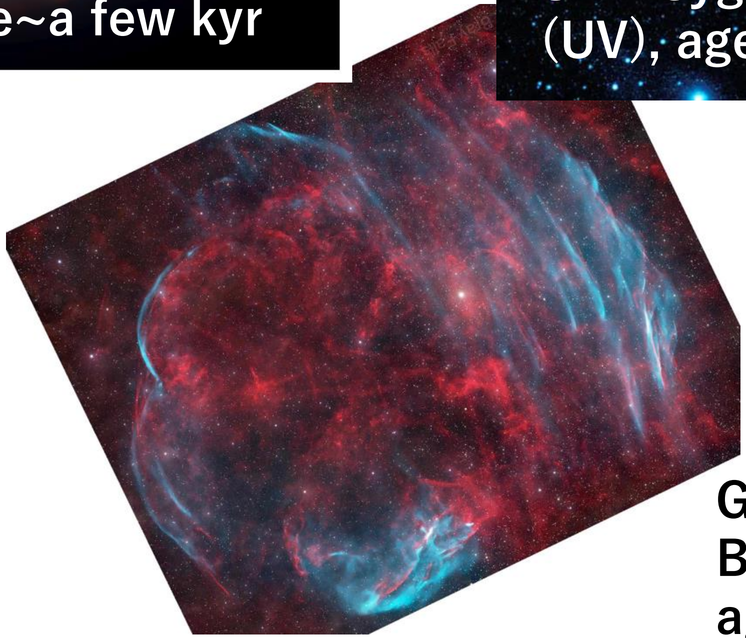
G1.9+0.3: Youngest SNR in our Galaxy
(age~140 yr, Bamba & Williams 22)
Free Expansion Phase





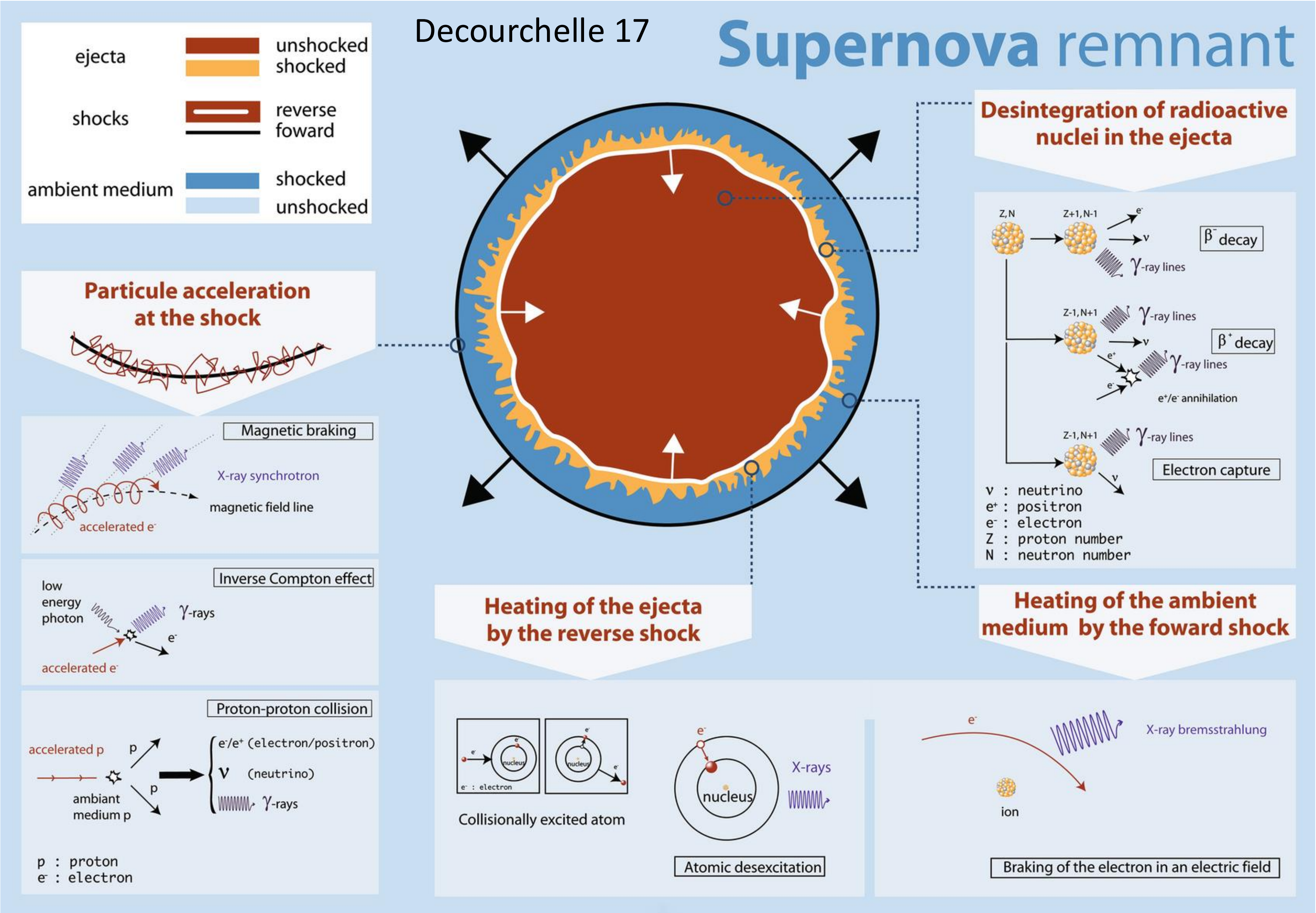






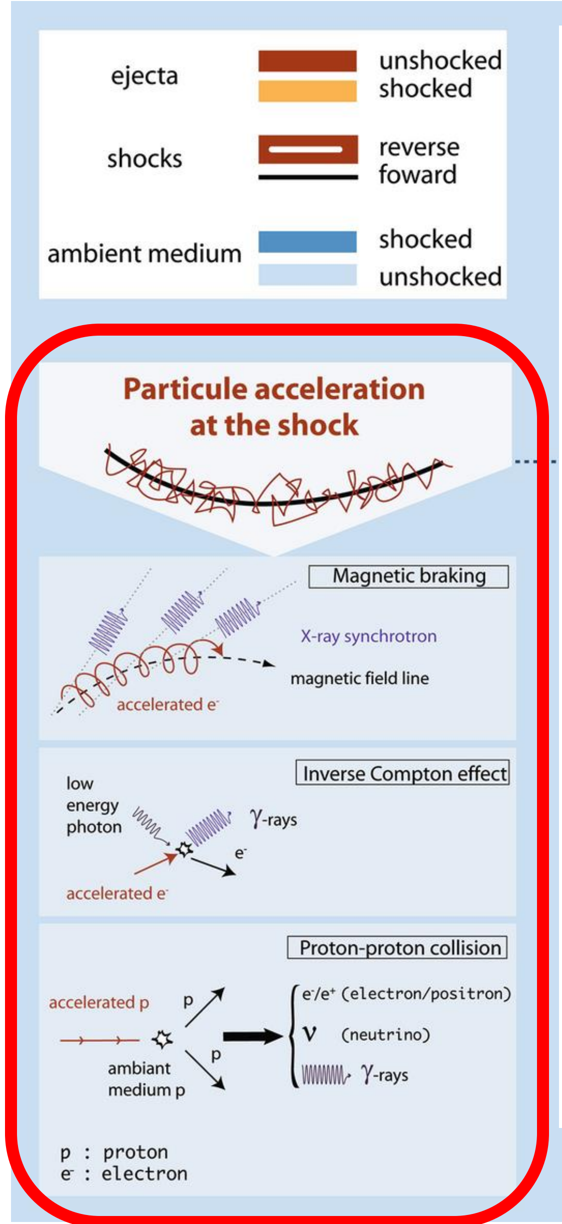
G70.0-21.5
Blue OIII, Red H α
age ~ 10-100 kyr?

Supernova Remnants:Emission Mechanism Examples



特に高エネルギー宇宙物学的なものが抜粋されている（X-ray ～ Gamma-ray）。

Supernova Remnants:Emission Mechanism Examples



Gamma-ray (Fermi+VERITAS, Archambault+17, @ Tycho's SNR)

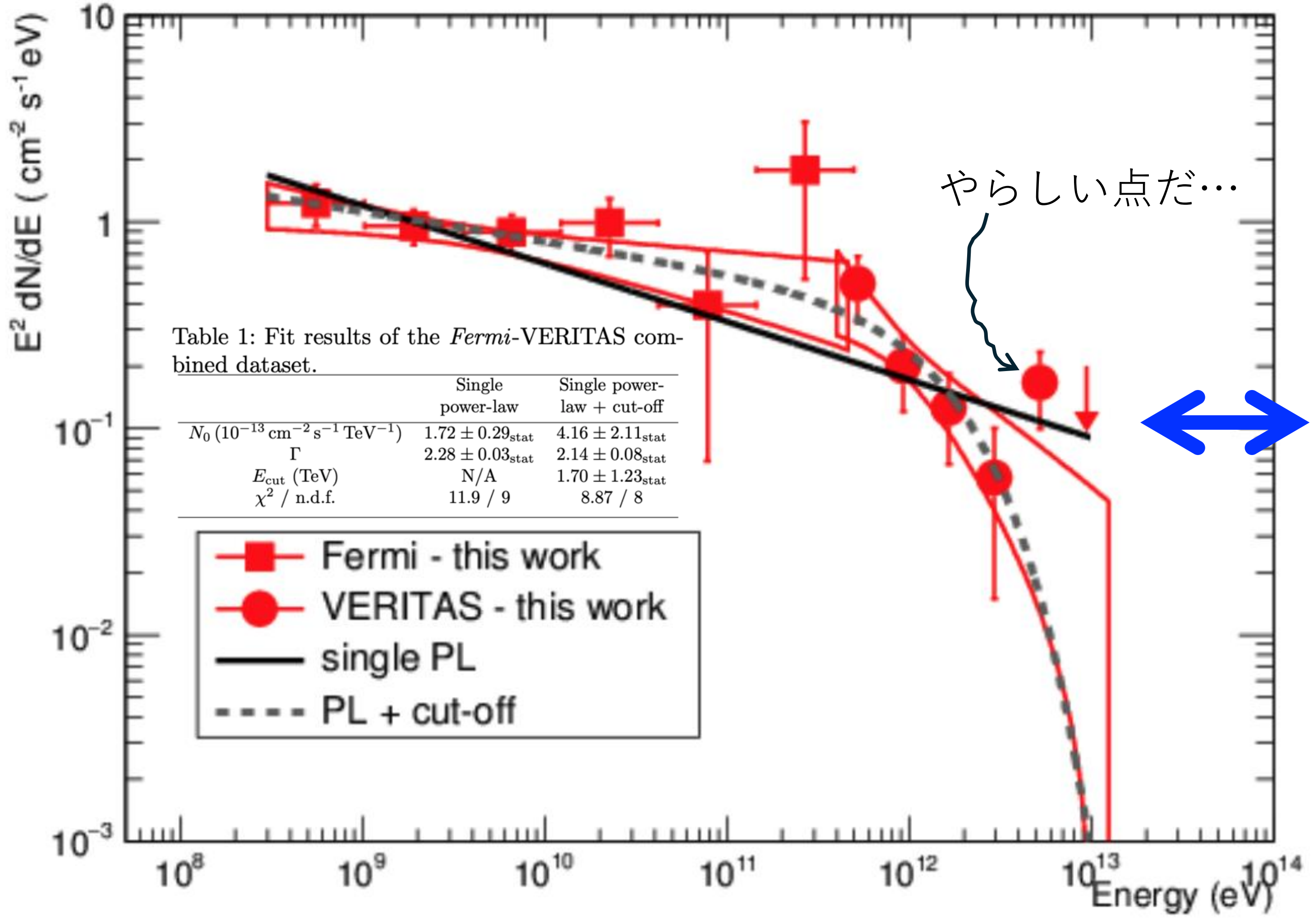


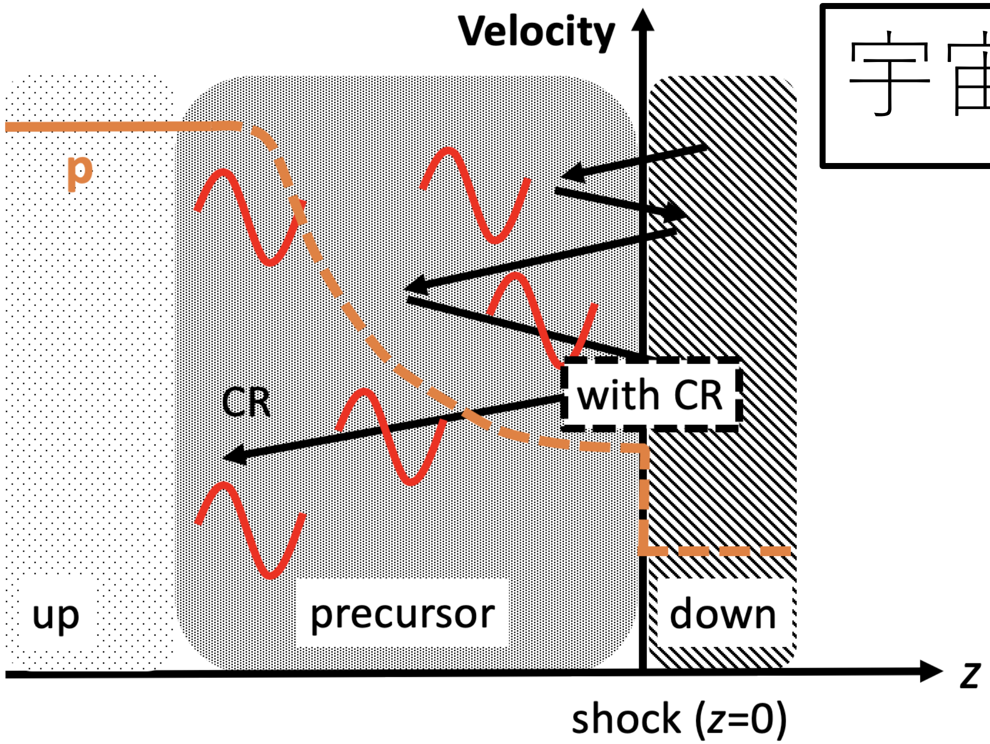
Table 1: Fit results of the *Fermi*-VERITAS combined dataset.

	Single power-law	Single power-law + cut-off
N_0 (10^{-13} cm^{-2} s^{-1} TeV^{-1})	$1.72 \pm 0.29_{\mathrm{stat}}$	$4.16 \pm 2.11_{\mathrm{stat}}$
Γ	$2.28 \pm 0.03_{\mathrm{stat}}$	$2.14 \pm 0.08_{\mathrm{stat}}$
E_{cut} (TeV)	N/A	$1.70 \pm 1.23_{\mathrm{stat}}$
χ^2 / n.d.f.	11.9 / 9	8.87 / 8

やらしい点だ…

ルギー宇宙物学的
枠されている
Gamma-ray）。

今日の話とは直接関係ないけど…
CR protonがKnee energyまで加速されているなら、~100 TeVガンマ線が受かって欲しい。



upstream　→ subscript “0”

downstream→ subscript “2”

宇宙線の加速効率問題（注入問題）

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

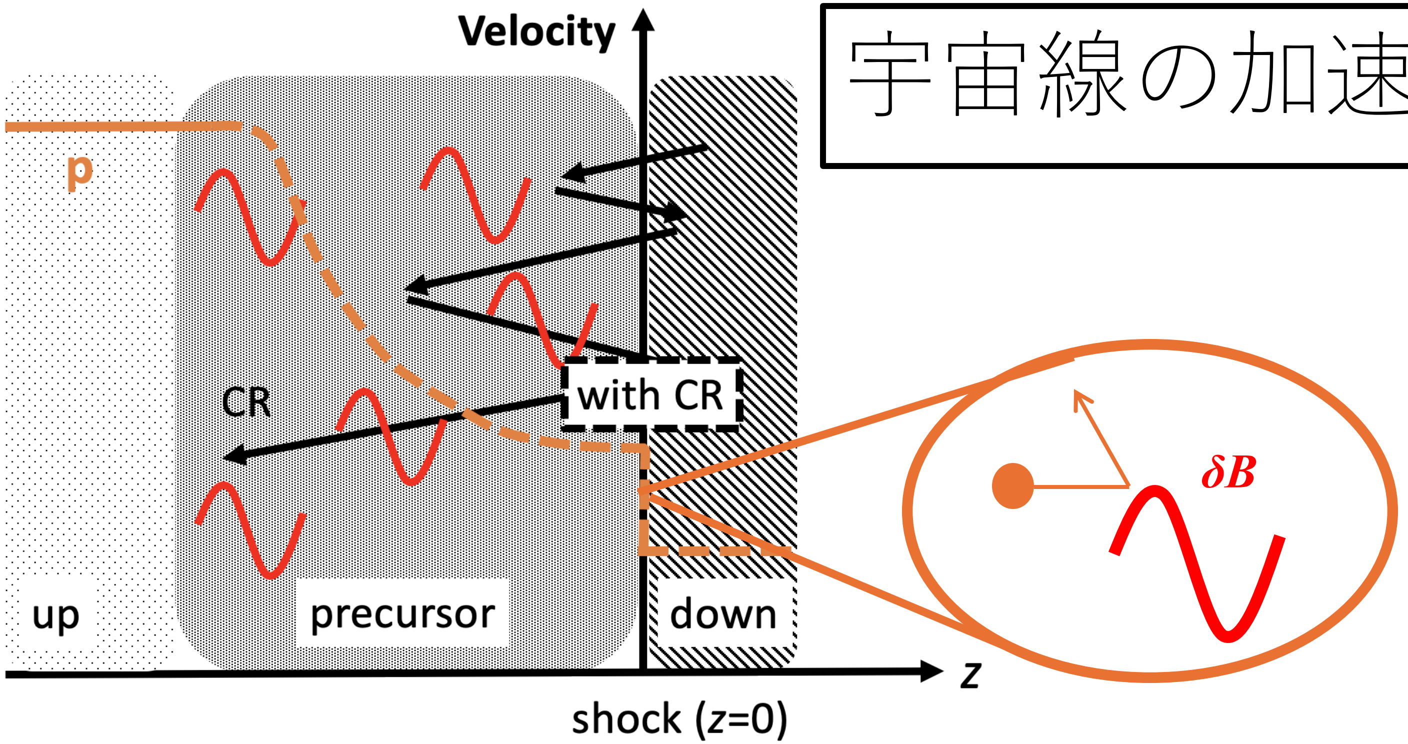
良いところ

①~PeV宇宙線を作りうるくらい，加速に時間がかからない．
②被加速粒子のエネルギースペクトルが，ベキ型になる．

ダメなところ

被加速粒子の量は予言しない．
→独立な検証が必要だが，特に理論的な理解はほとんど進んでいない．

宇宙線の加速効率問題（注入問題）



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

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

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

$$dS = \frac{dQ}{kT} + \cancel{(\mathrm{p.p.collision})}$$

無衝突衝撃波では効かない

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Shimoda et al. (2022)
衝撃波形成時のエントロピー生成の考察から，宇宙線生成量の理論的な制限に成功した.

→十分に時間が経過した衝撃波に対する宇宙線注入モデルとしては、ほぼ世界初（のはず）。

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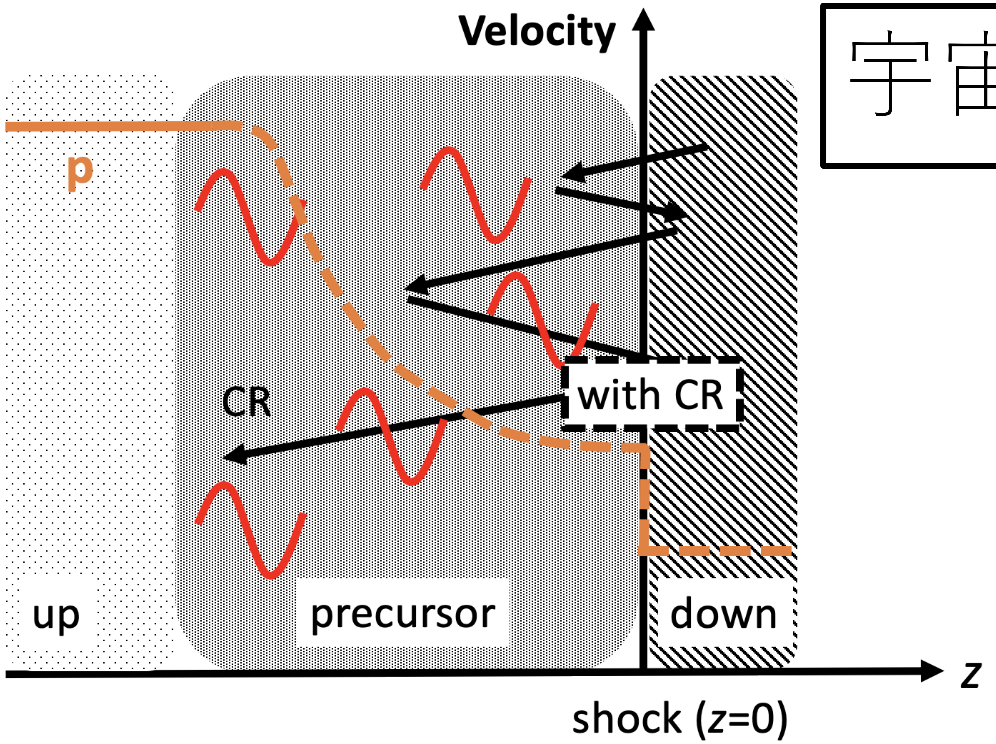

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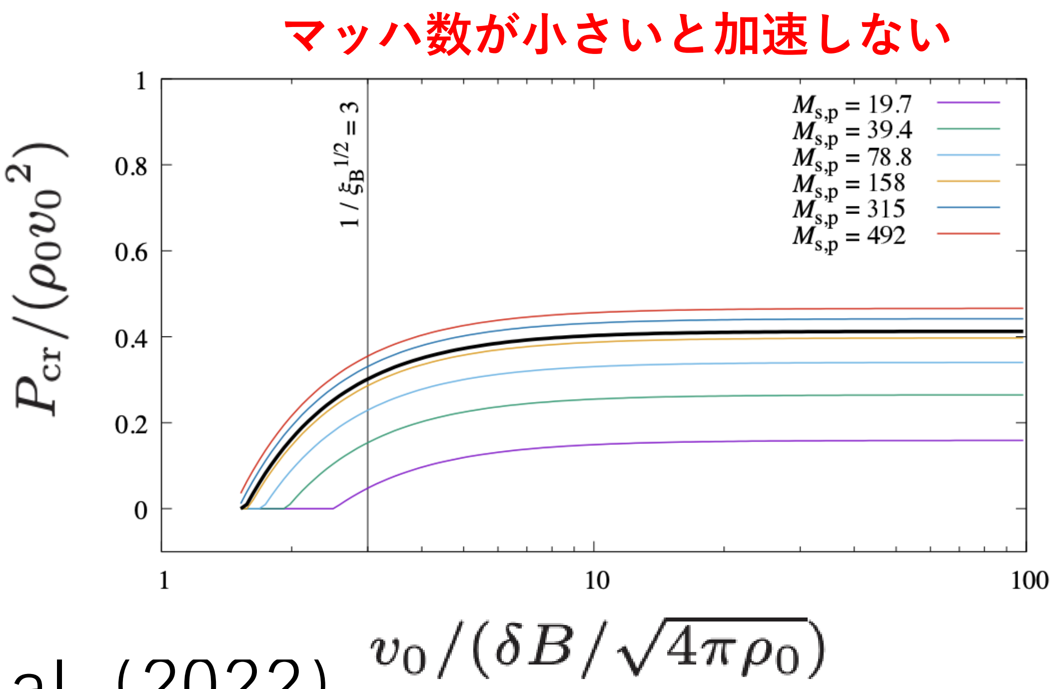

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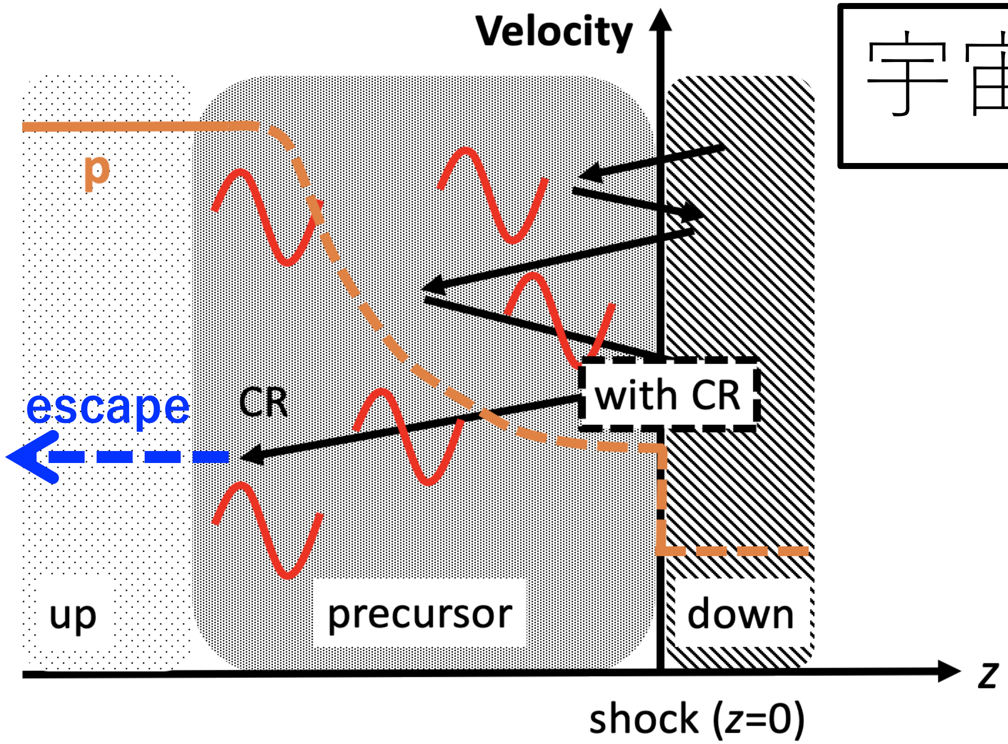
宇宙線の逃走問題（拡散係数問題）



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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**．**加速により到達可能な最高エネルギーを決める．**

「いつ，どれだけ逃走しているのか？」は分かっていない．

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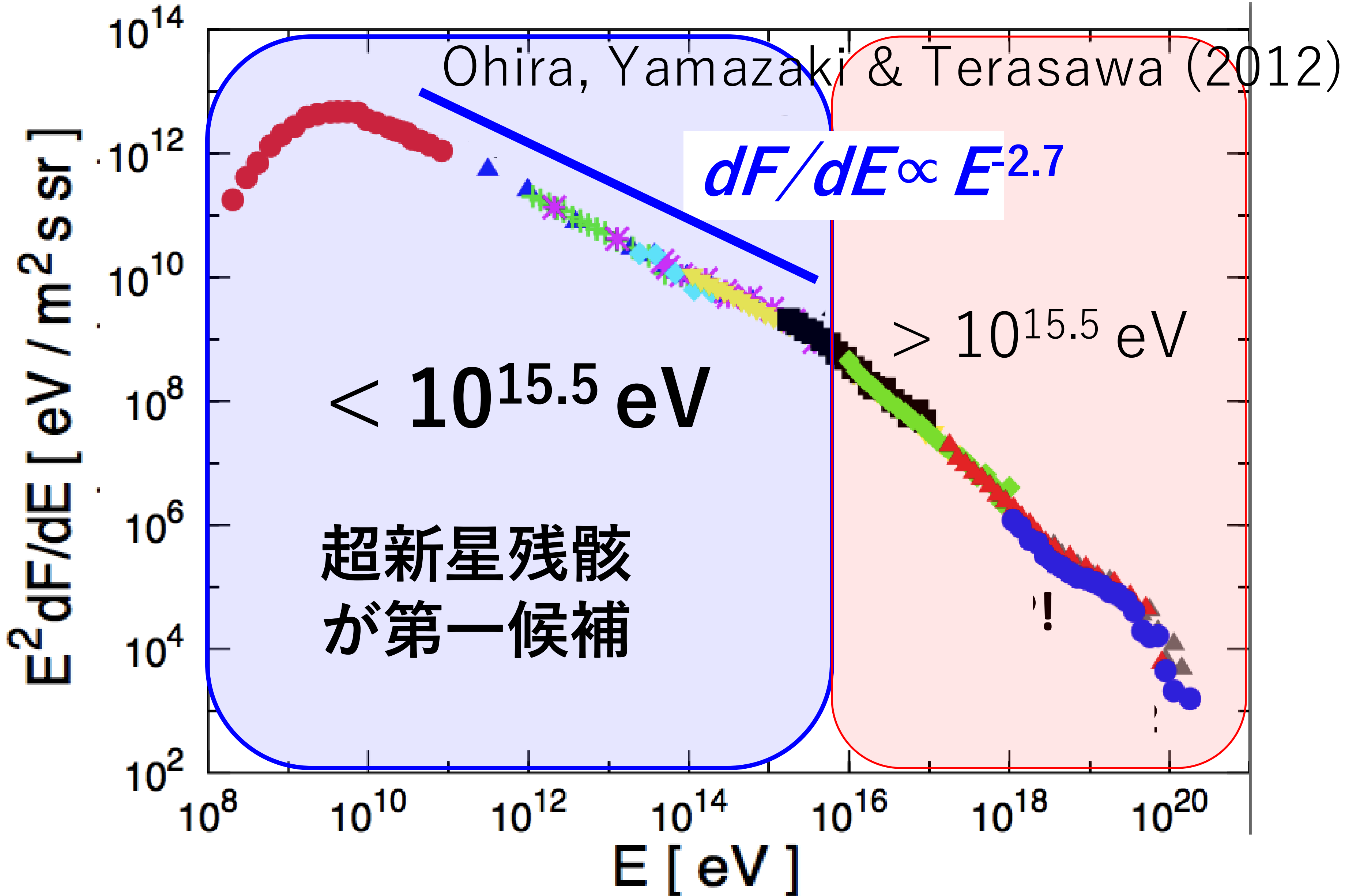

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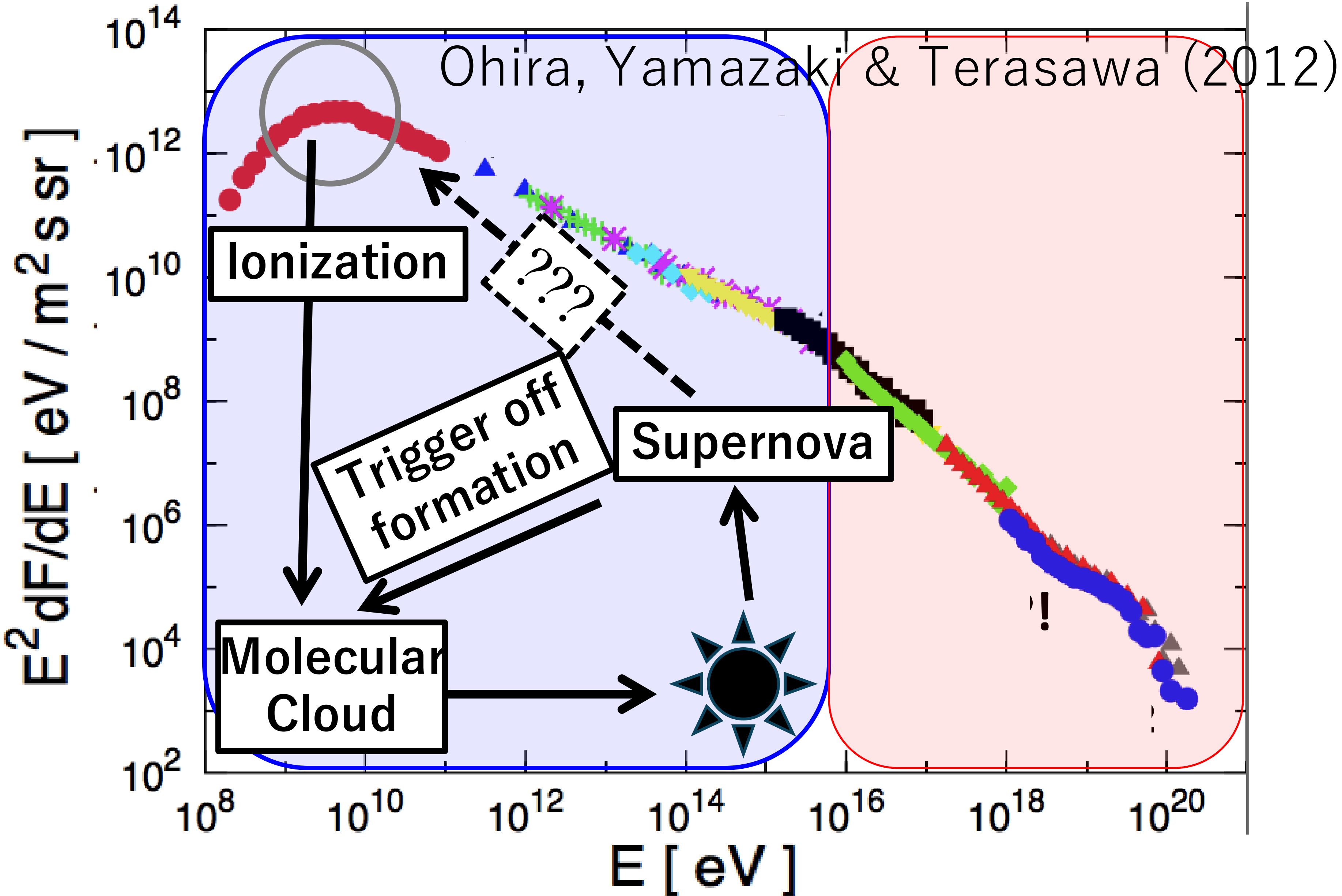
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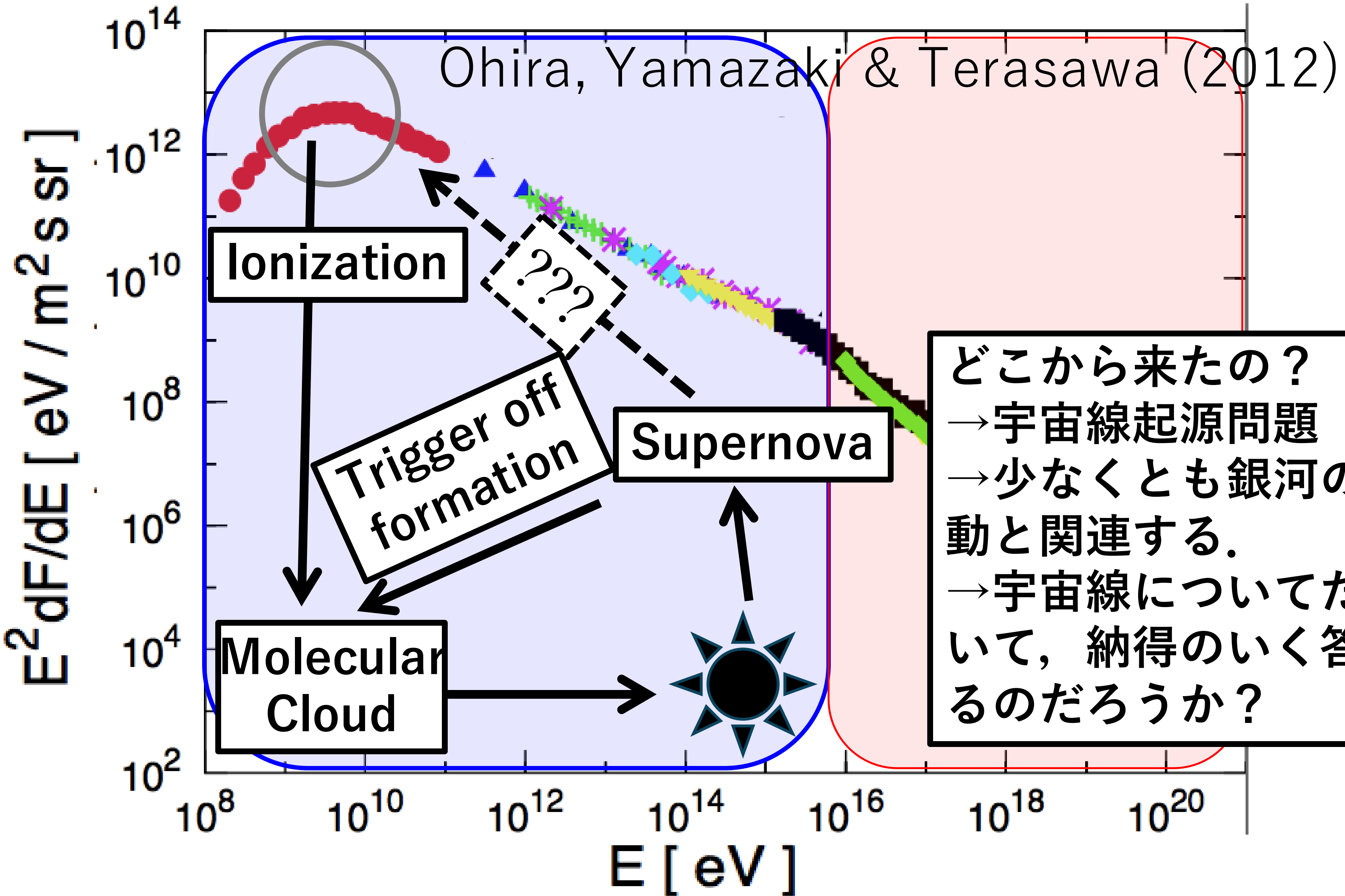
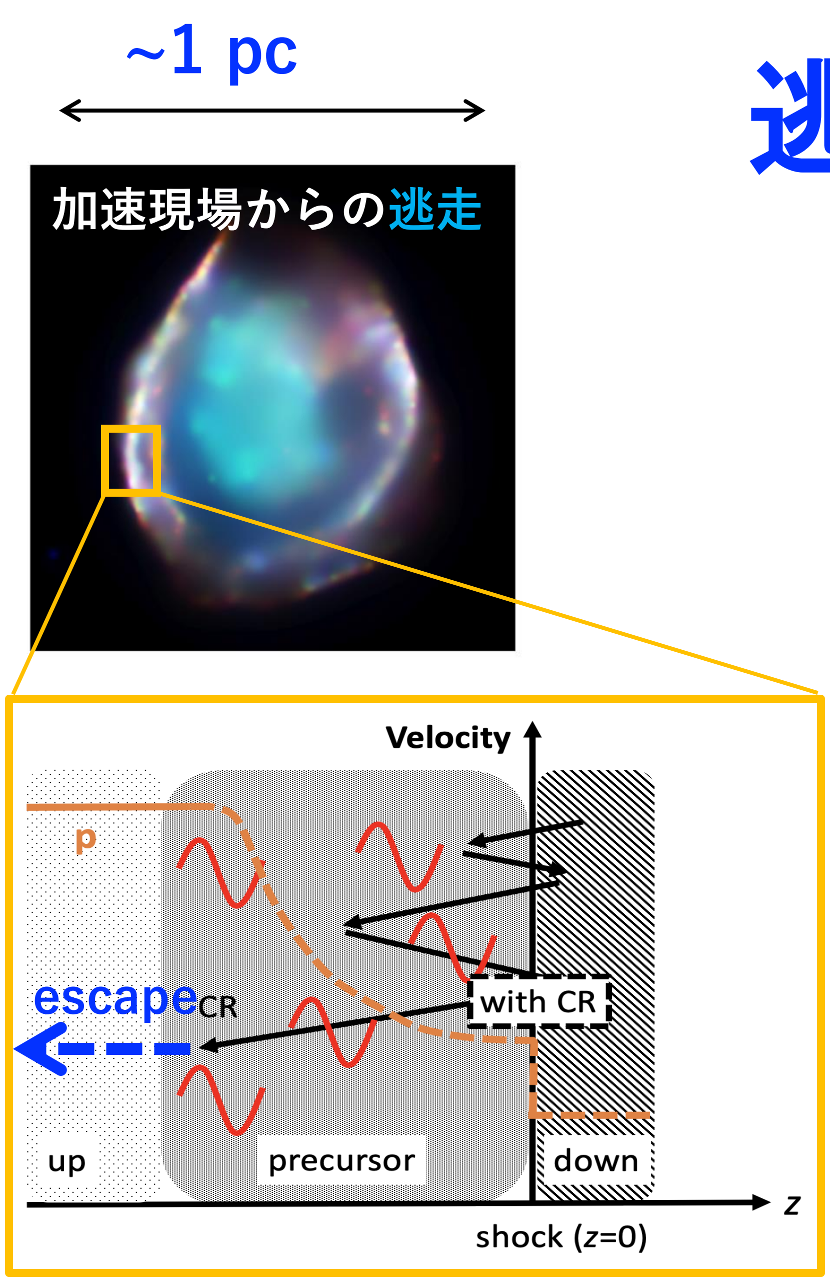
10^{14}
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
E^2dF/dE [eV / m^2 s sr]
Ionization
???
Trigger off formation
Supernova
Molecular Cloud
10^{8}
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
E [eV]

逃走宇宙線との闘争



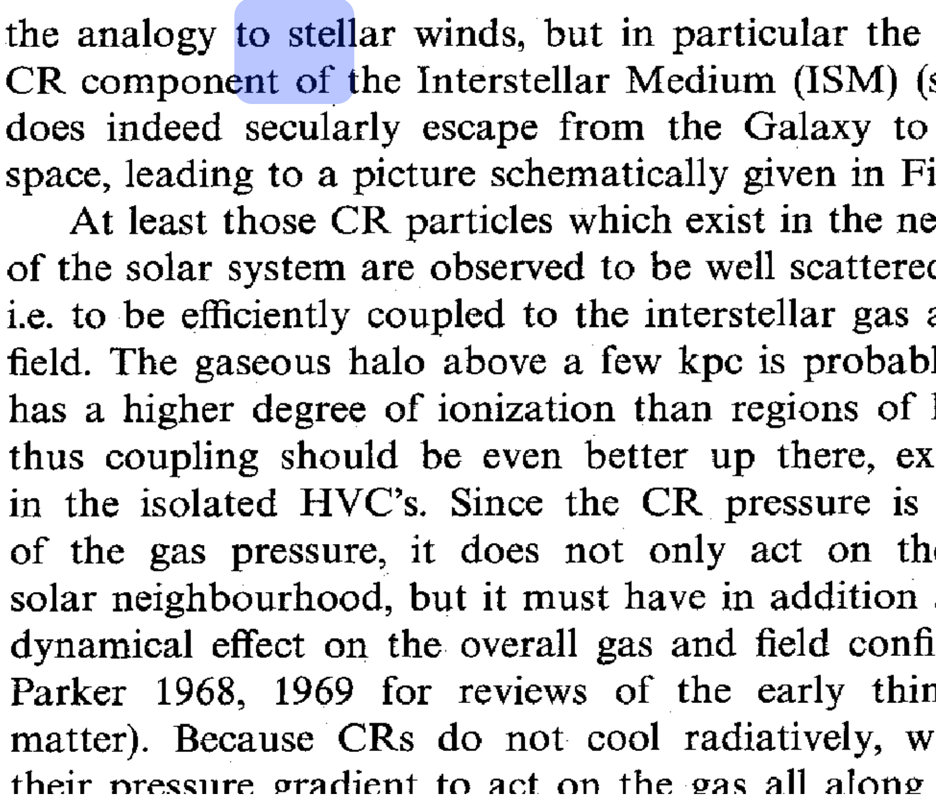
どこから来たの？
→宇宙線起源問題
→少なくとも銀河の星形成活動と関連する.
→宇宙線についてだけ考えていて，納得のいく答えが出せるのだろうか？

逃走宇宙線との闘争



~10 kpc

銀河系からの逃走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Parker 1968, 1969 for reviews of the early thin
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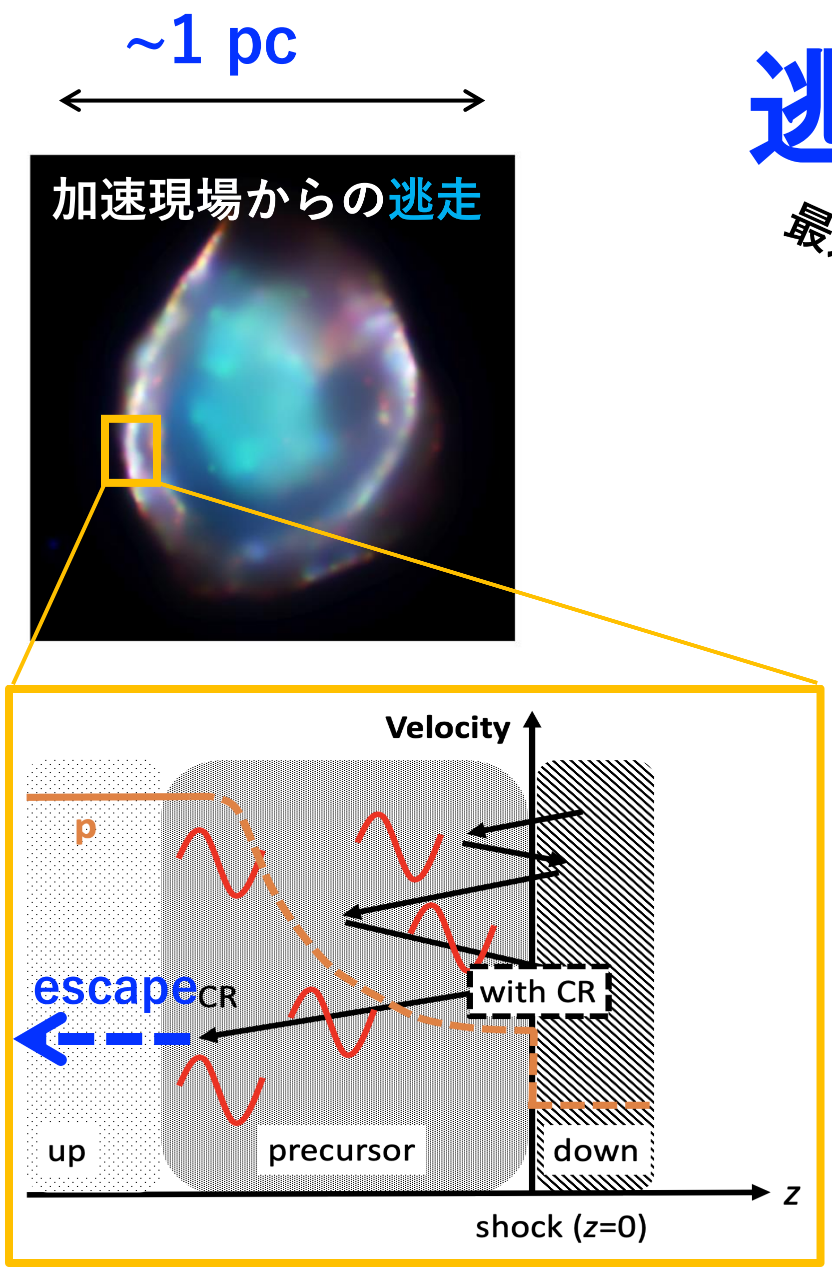
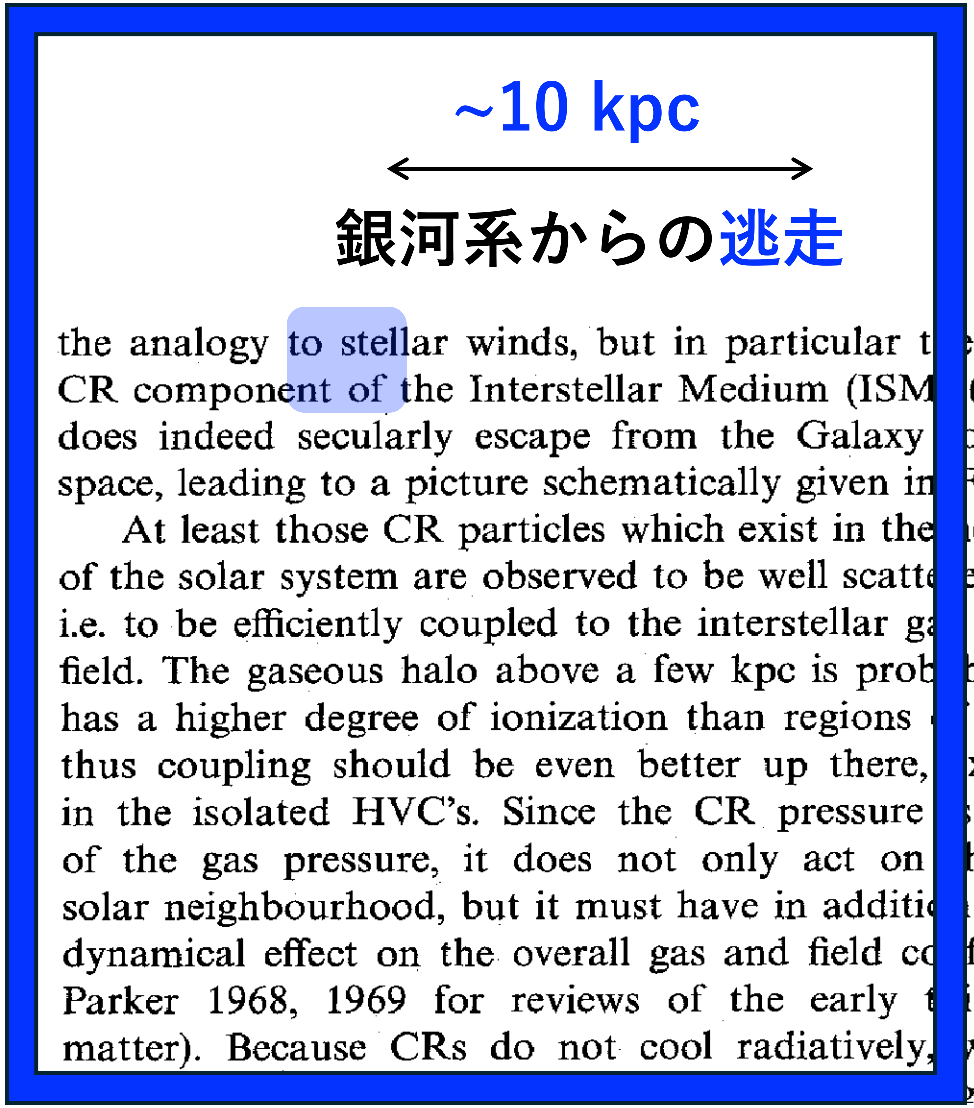
their pressure gradient to act on the gas all along

逃走宇宙線との闘争

最近の個人的な研究について．．．





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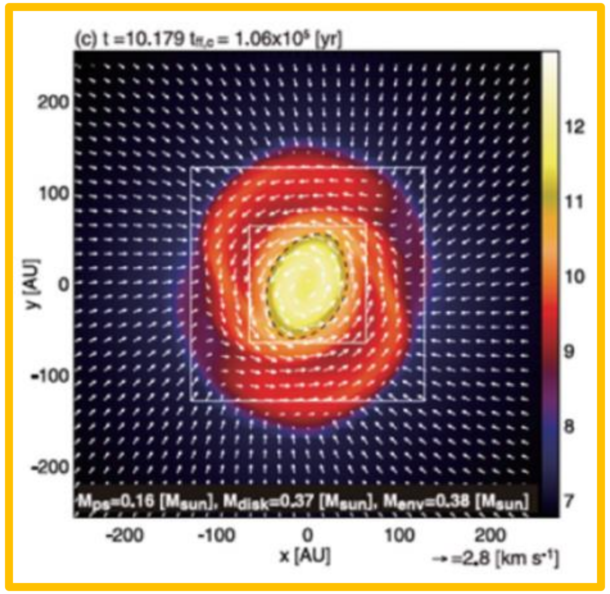
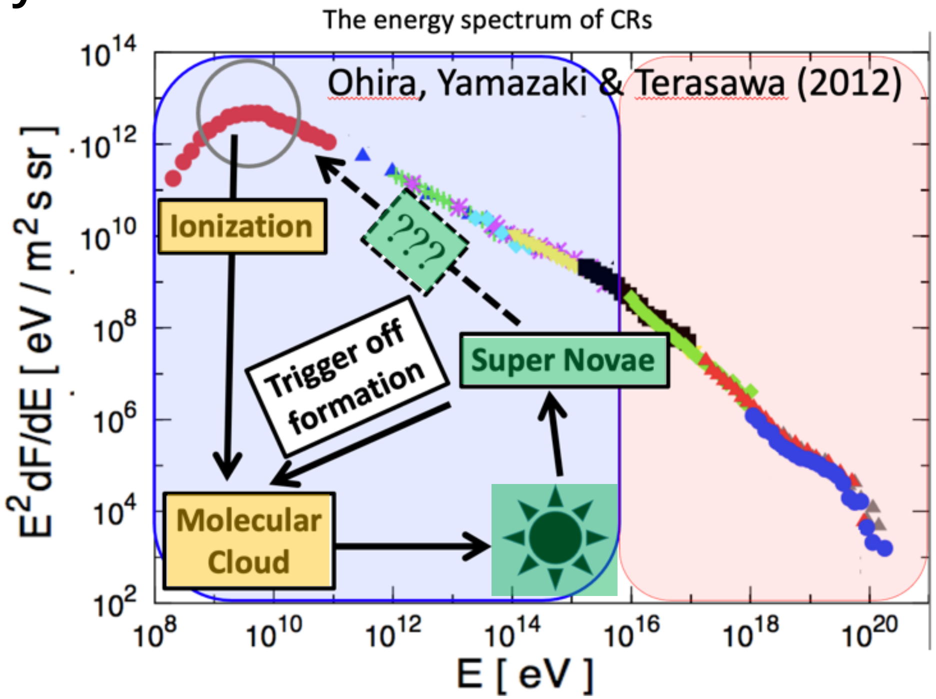
Roles of Galactic Cosmic Rays

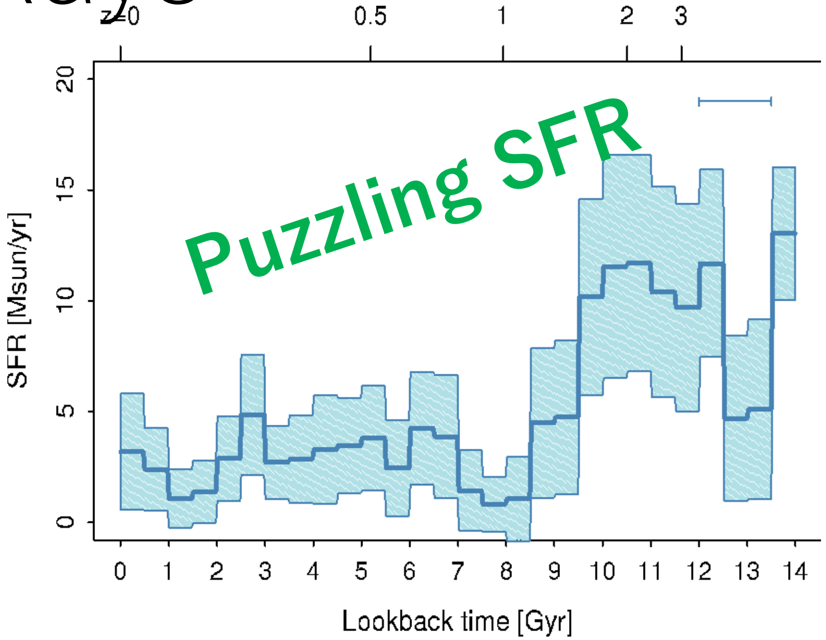
Evolution of the Protoplanetary disk



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

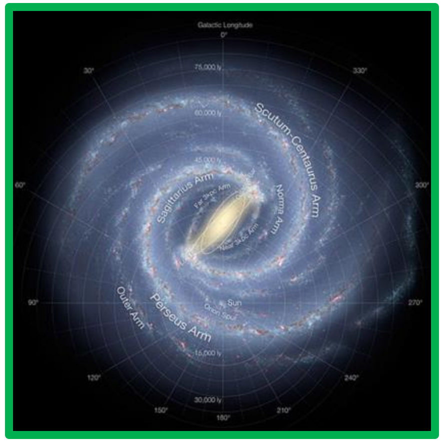
→ ***Planet formation***



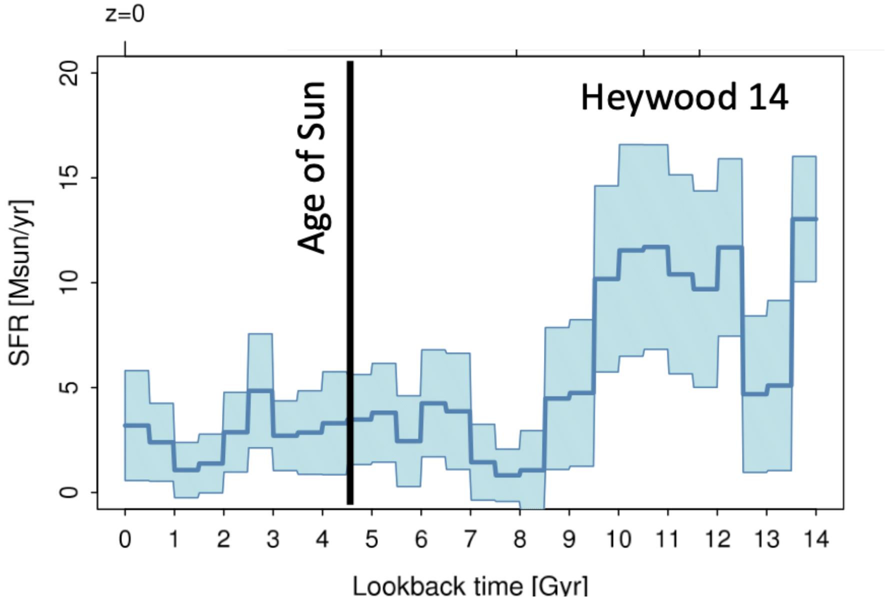


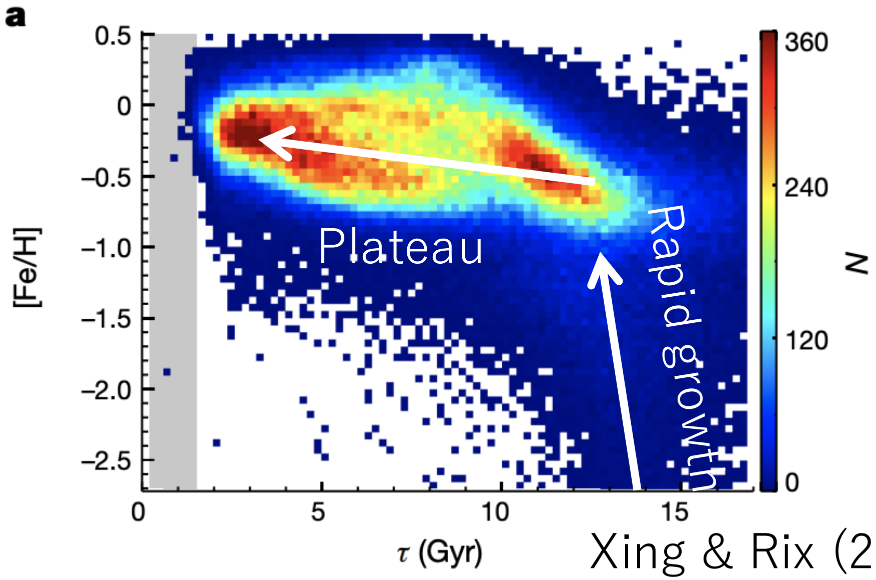
The long-term SFR is regulated by the galactic wind driven by CRs.

→ ***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)

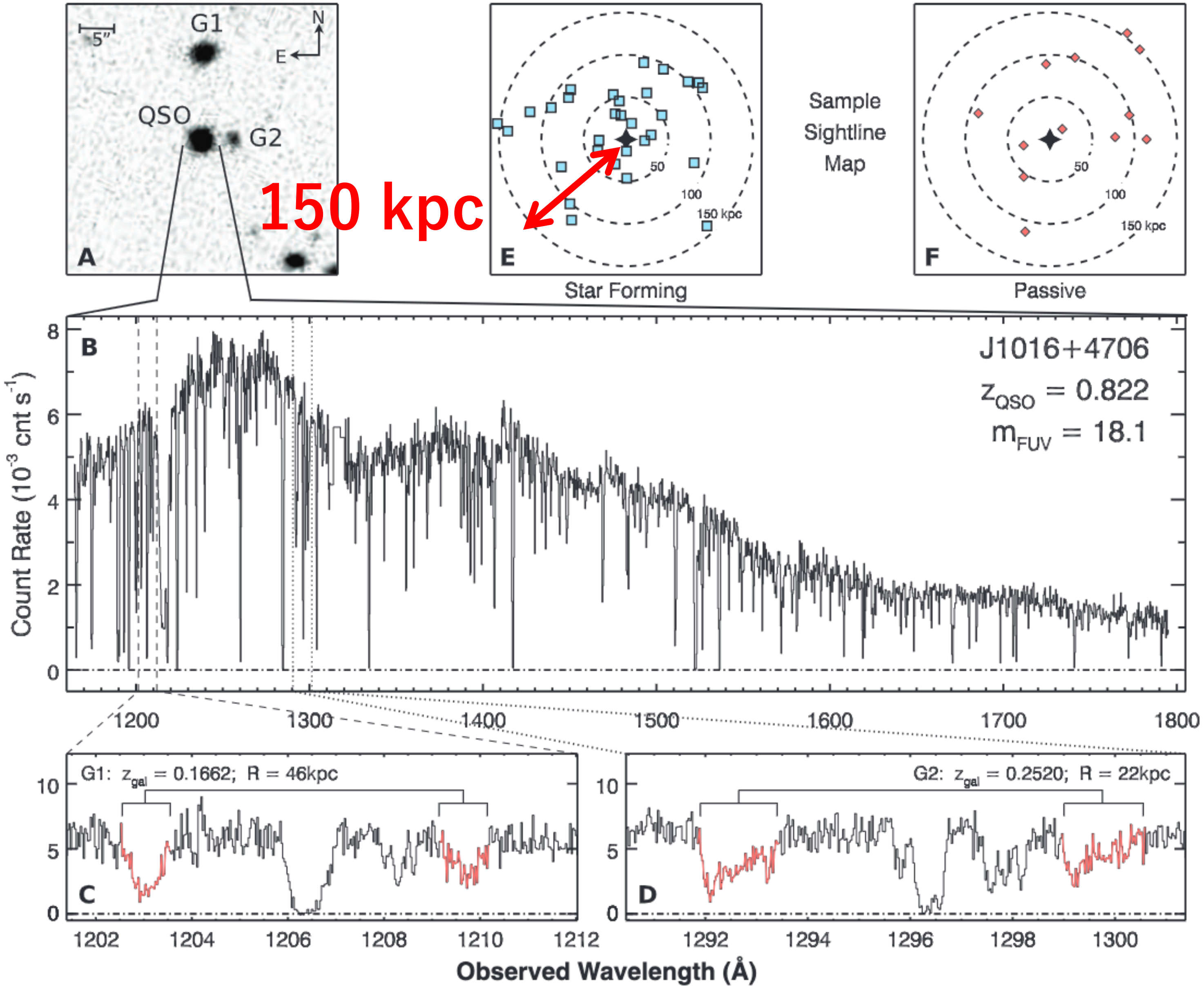
~ 1.6 x 10^9 Mo

~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)



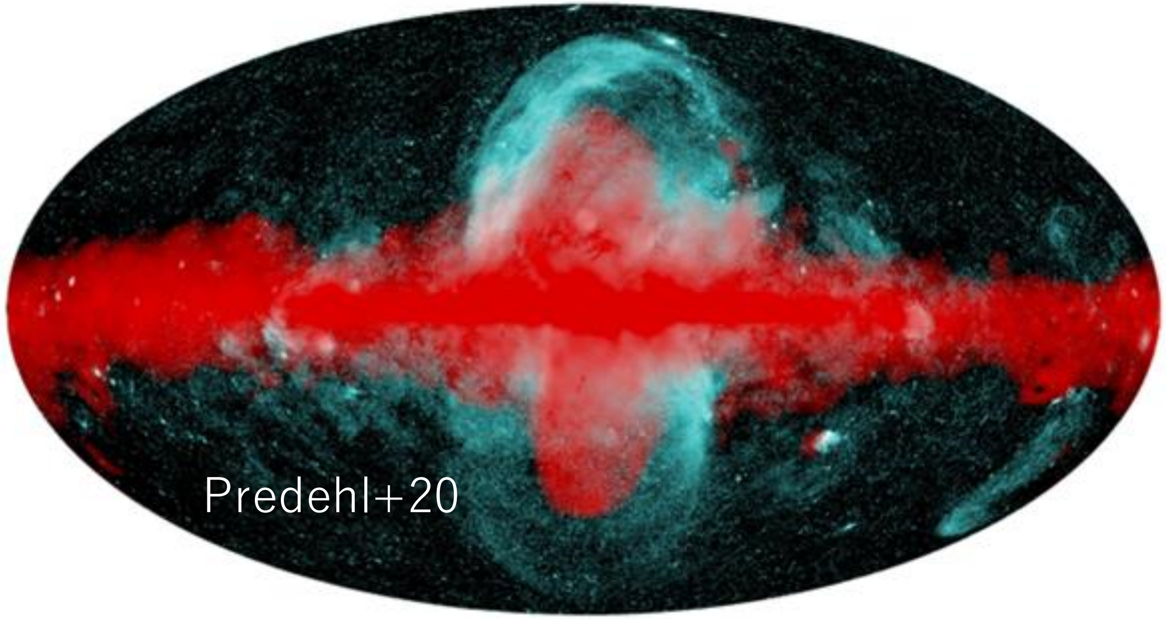
"Discovery" of hot, highly ionized medium around galaxies (Tumlinson+11, 17).

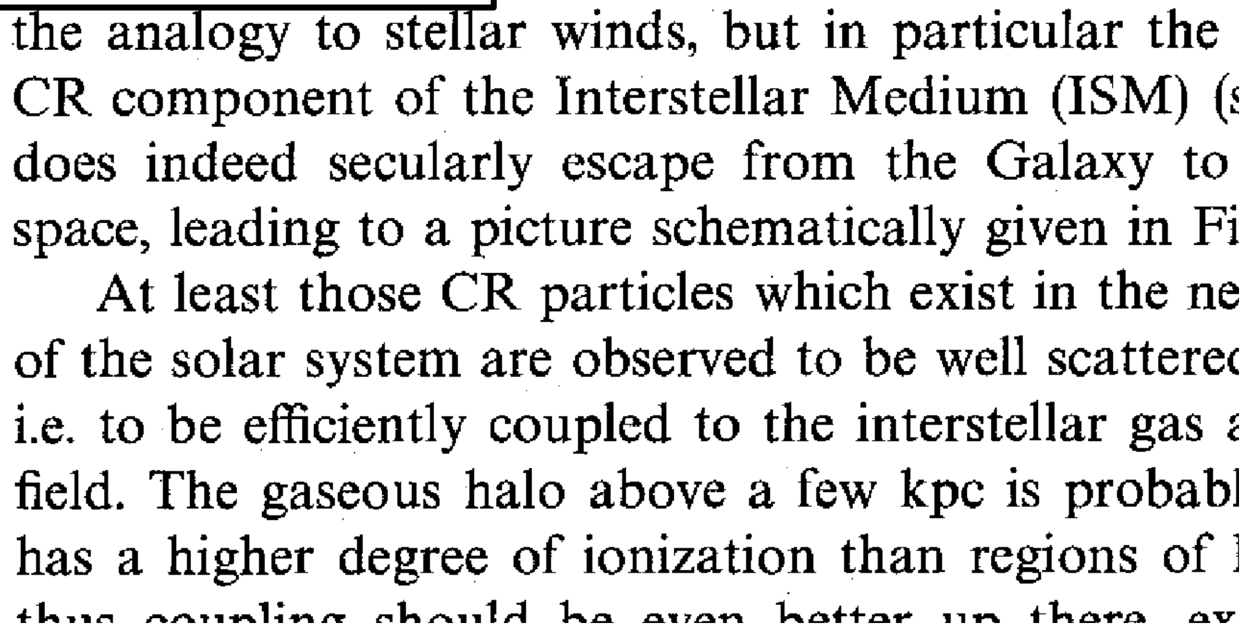
- O_{VI} absorption line
  - → $T_{ionized}$ ~ 3 x 10^5 K, N_{OVI} ~ 10^{14} cm^{-2}
  - → Estimated total gas mass ~ 10^{10}–10^{12} M_{sun}

Missing Metals may be in the Galactic halo.

→ The Outflow is required.

Fermi Bubble & eROSITA Bubble

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Breitschwerdt+91

Outflow:

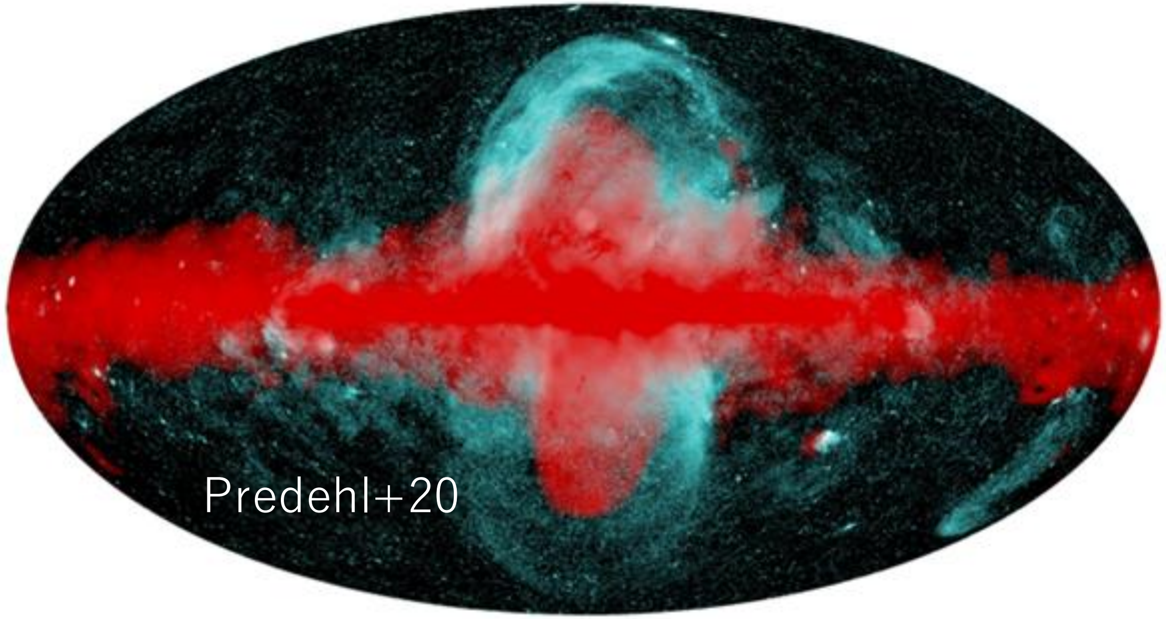
T ~ 0.1 keV (~virial temp. of the MW)

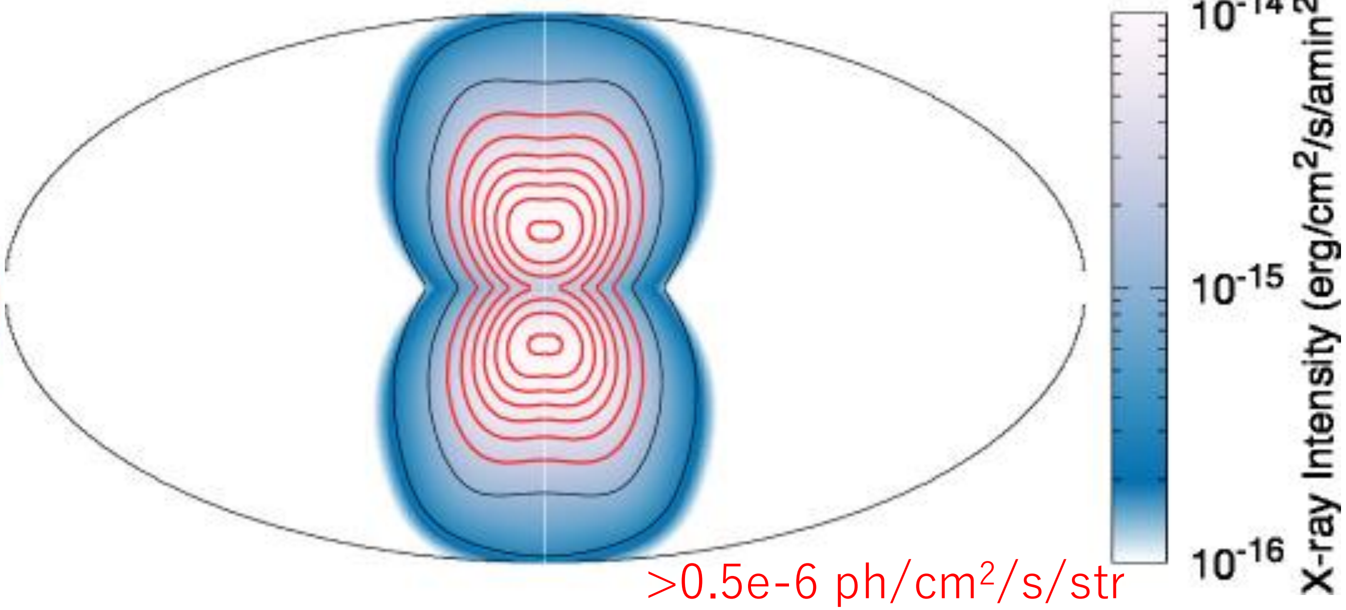
→eROSITA bubble is consistent with this expectation.

Should be launched at the disk (removing the metals)

→ Formation mechanism is unclear...

Galactic Wind Scenario (SJ&Asano 24)





Assumption:

~10 % of SNe energy is consumed for launching the wind.

This assumption should be tested.

We consider a possibility:

***ISM heated by CRs around the CR sources*.**

*Hadronic γ-ray scenario $p_{cr} + p_{gas} \rightarrow 2\gamma, \nu$

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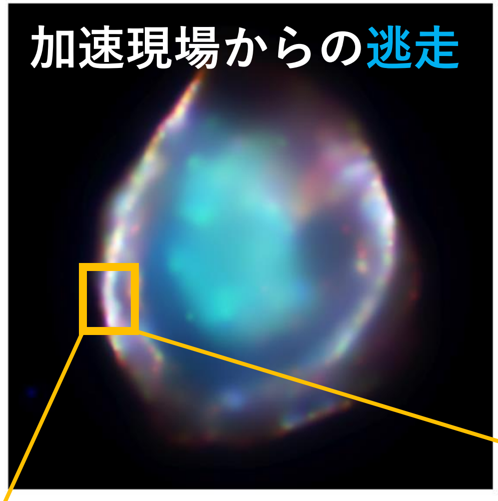
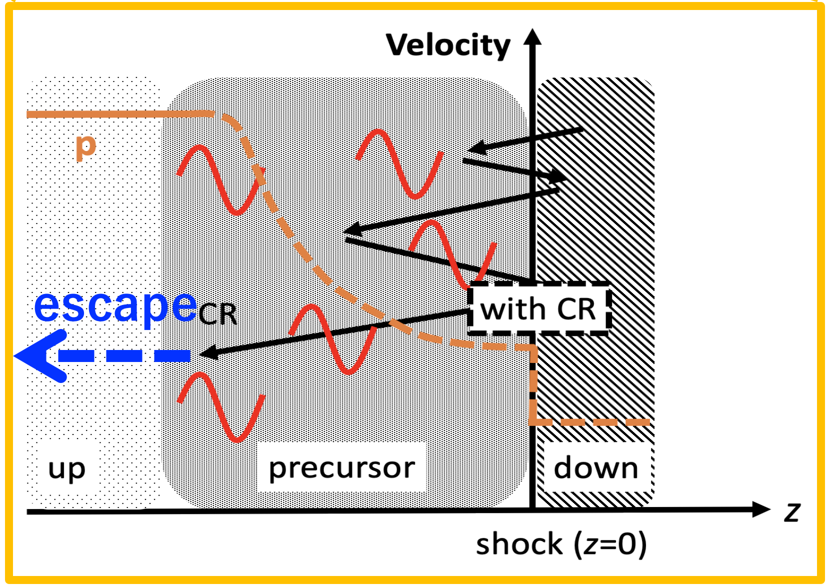
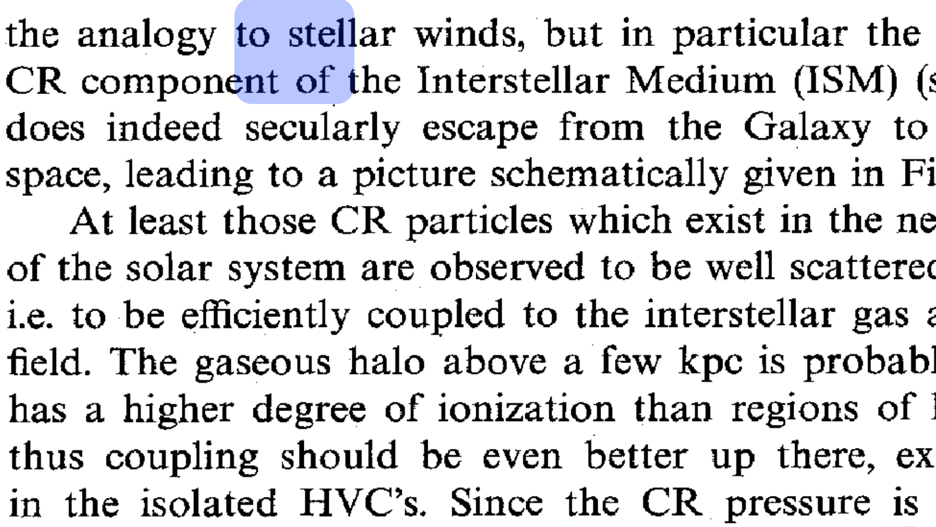
~1 pc





~10 kpc

銀河系からの逃走



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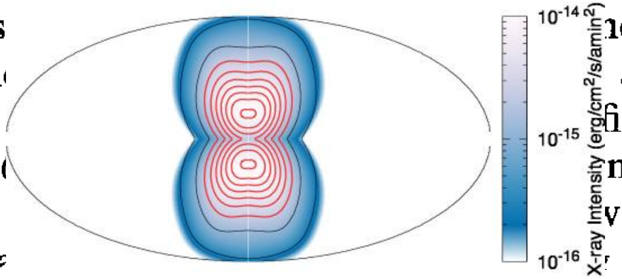

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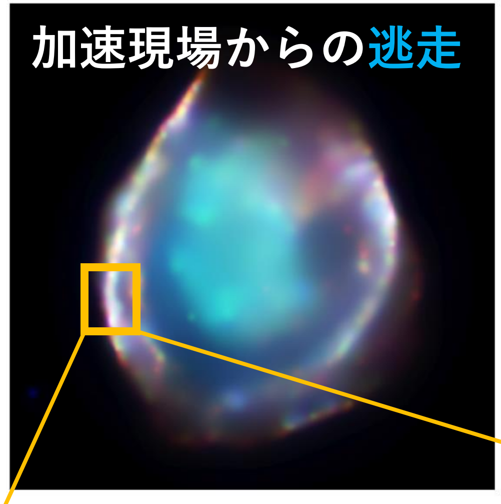
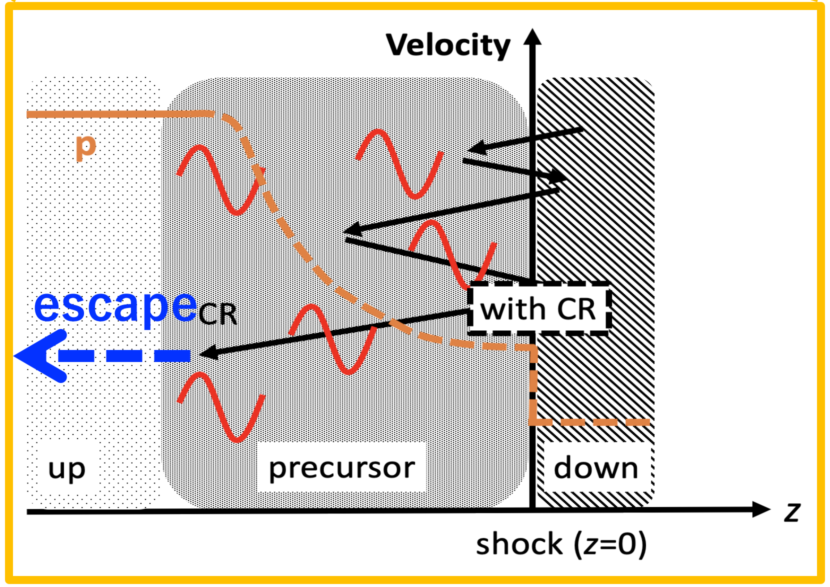




ISM中の輸送・伝搬

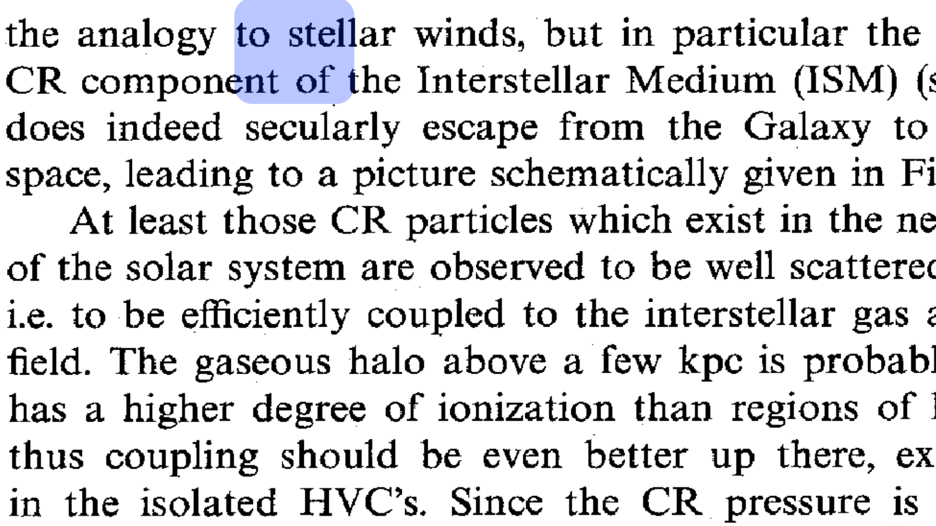
~10 pc-1 kpc

?

偉い先行研究
「拡散するん
ちゃう？知ら
んけど．」

~10 kpc

銀河系からの逃走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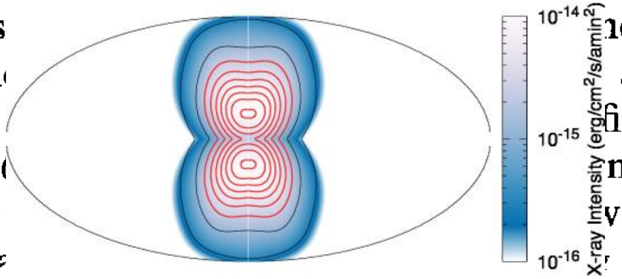
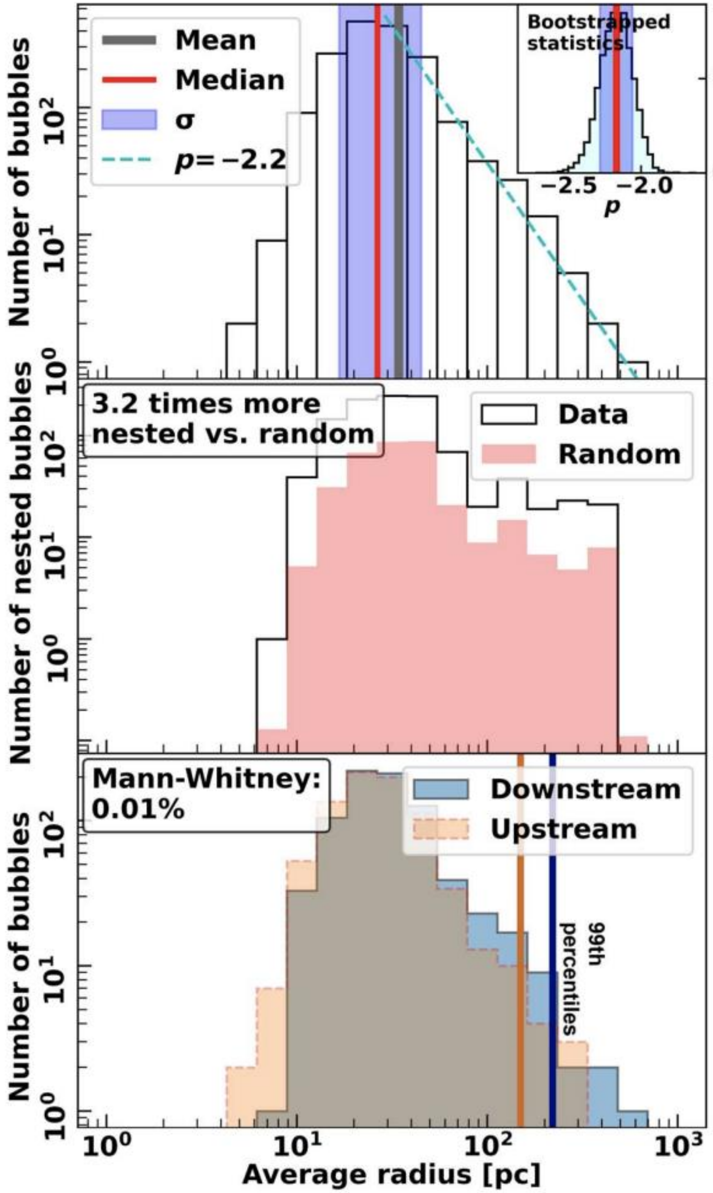
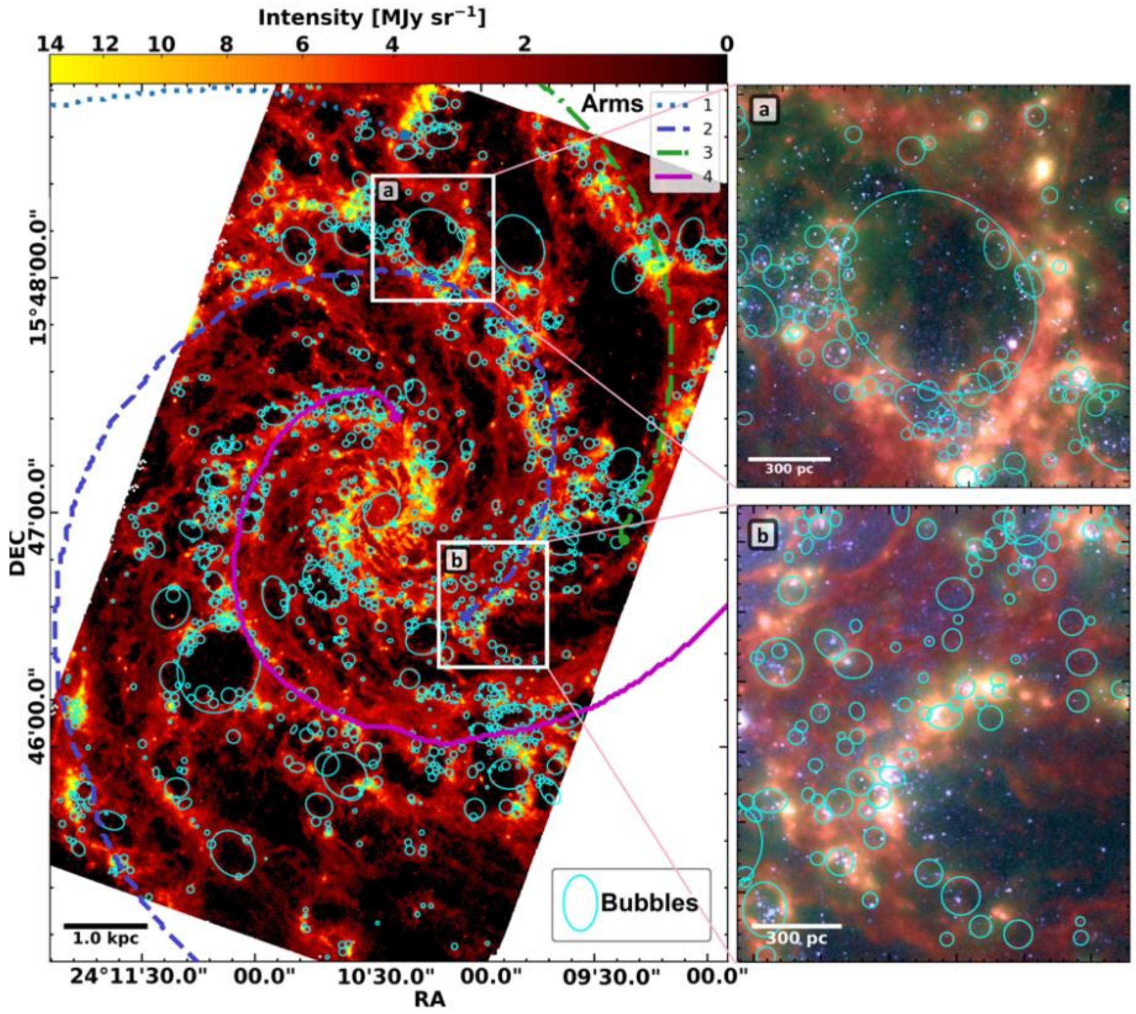


JWST bubbles: Hints for 10 pc-1 kpc physics/phenomena?

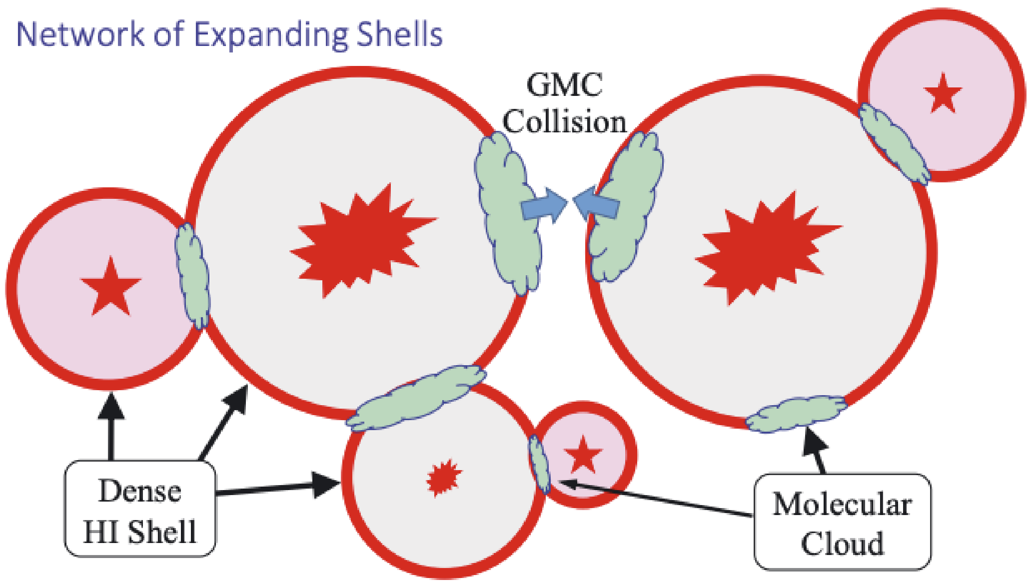




バブルを縁取るように**星形成領域**が分布している.

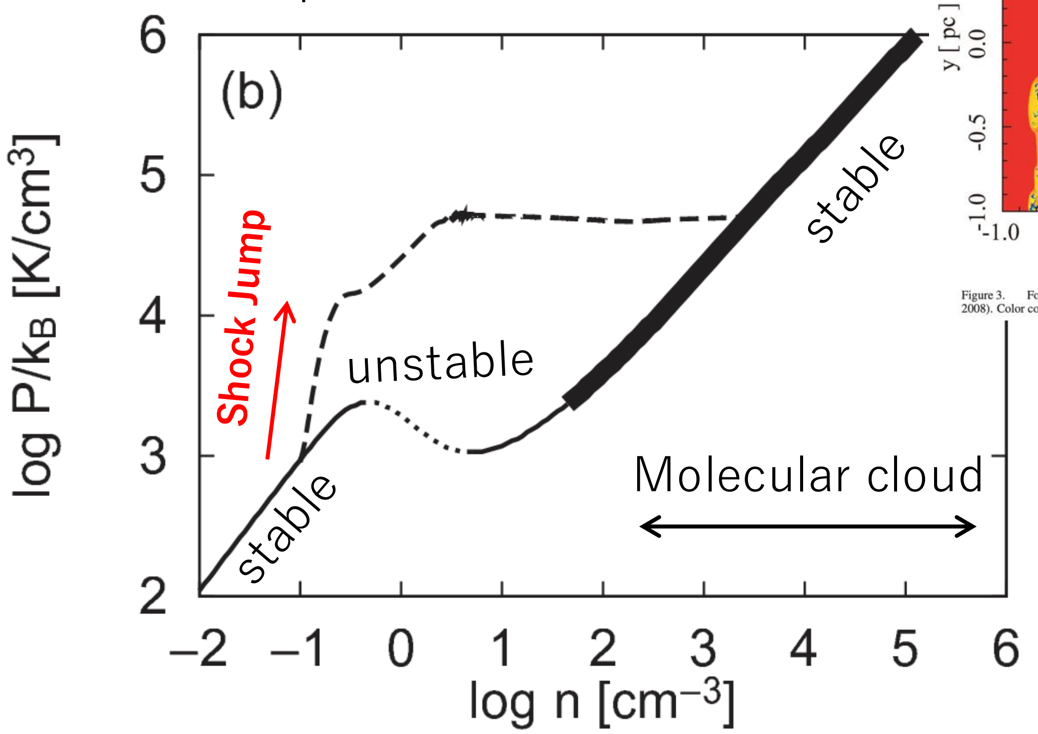
NGC 628: SFR~1.7 Mo/yr（MWとコンパラ）
＞3000個のバブルが見つかってはいる。これの
サイズ分布は説明されていない

Implications: Star Formation



Inutsuka+15

Thermal Equilibrium Curve for ISM



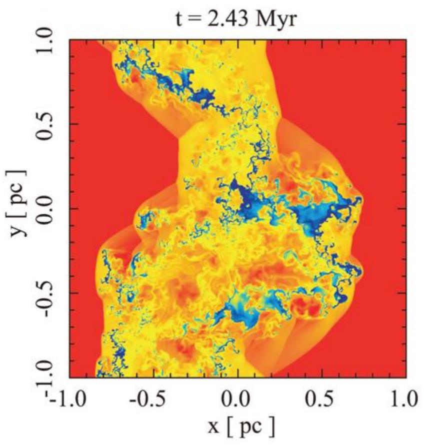


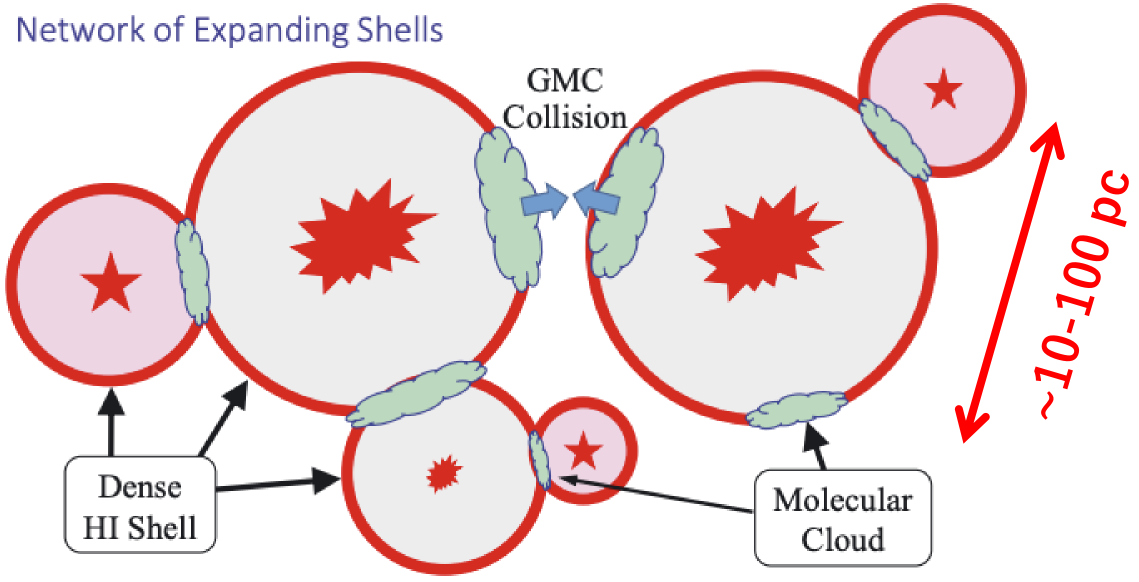
Figure 3. Formation of HI clouds in a shock-compressed layer (Inoue & Inutsuka 2008). Color corresponds to density from 1/cc (red) to 10^3/cc (blue).

Diffuse gas → Molecular gas → Star Formation

Massive stars

SN shocks, Expansion of Ionization Sphere, etc.

Implications: Star Formation



Inutsuka+15

- 天の川銀河の体積

  $V_g \sim (0.3\ \mathrm{kpc}) \times \pi (10\ \mathrm{kpc})^2 \sim 10^2\ \mathrm{kpc}^3$

- １つのシェルが占める体積

  $V_s \sim (0.1\ \mathrm{kpc})^3 \sim 10^{-3}\ \mathrm{kpc}^3$

- 天の川銀河全体を穴だらけにするのに必要なSNの個数

  $N_{sn} \sim V_g/V_s \sim 10^5$

- シェルが~0.1 kpc拡がるのにかかる時間

  $T_s \sim (0.1\ \mathrm{kpc})/(10\ \mathrm{km/s}) \sim 10\ \mathrm{Myr}$

- 必要なMSの形成率

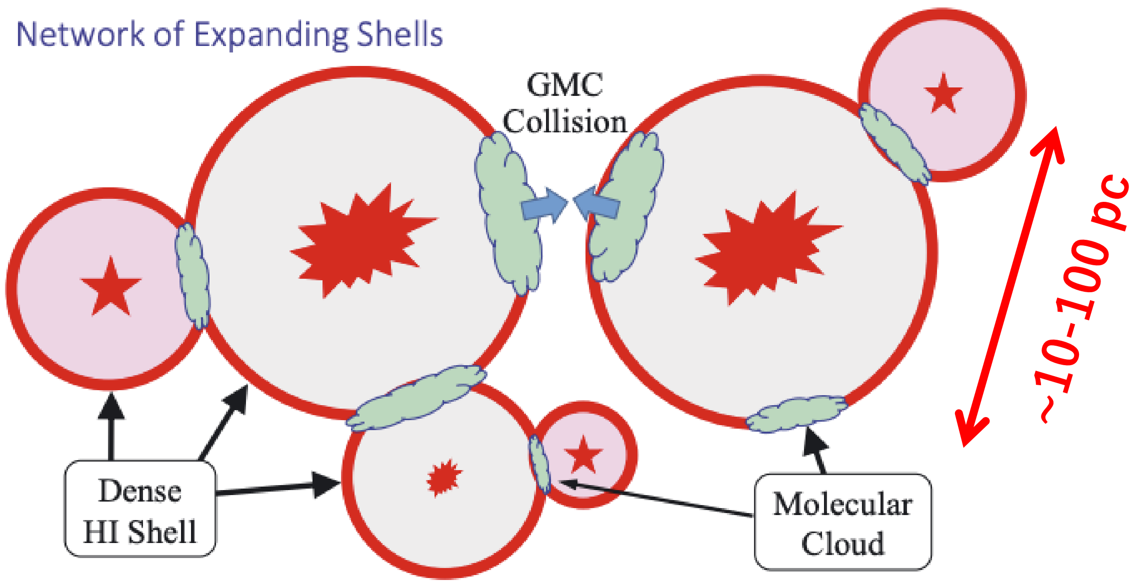
  $\mathrm{MSFR} \sim N_{sn}/T_s \times M_s$

  $\sim 0.1\ \mathrm{Mo/yr}(M_s/10\mathrm{Mo})$

- IMFからMSのmass fractionは~0.1

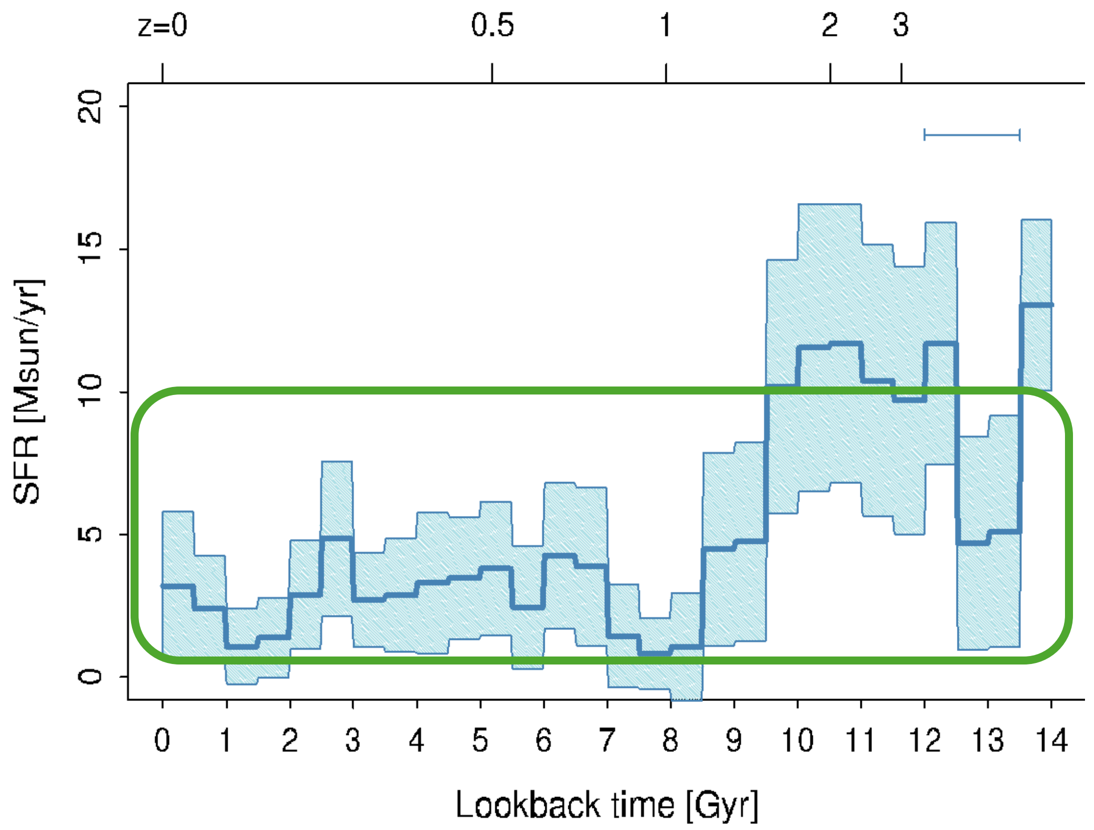
  SFR ~ MSFR/0.1 ~ 1 Mo/yr

Implications: Star Formation



Inutsuka+15

MWの星形成率（Haywood+14）

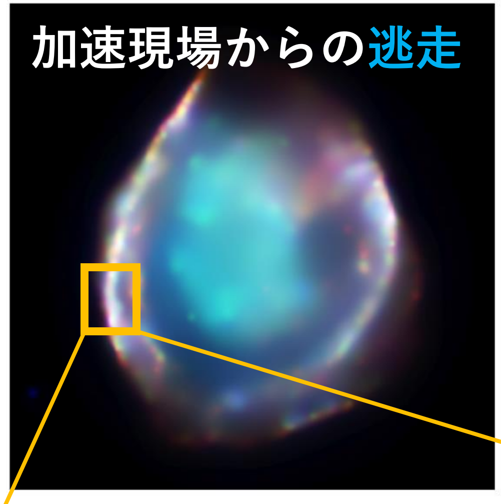


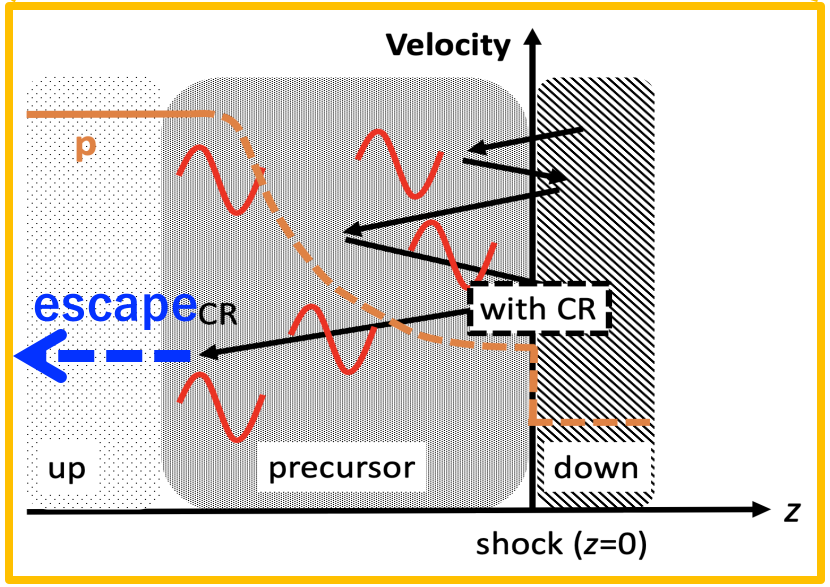
MWで提案されている星形成シナリオは，最近の観測と（1=10くらいの気持ちで）整合的.

***Bubble-Filament Paradigm* by Inutsuka**

逃走宇宙線との闘争

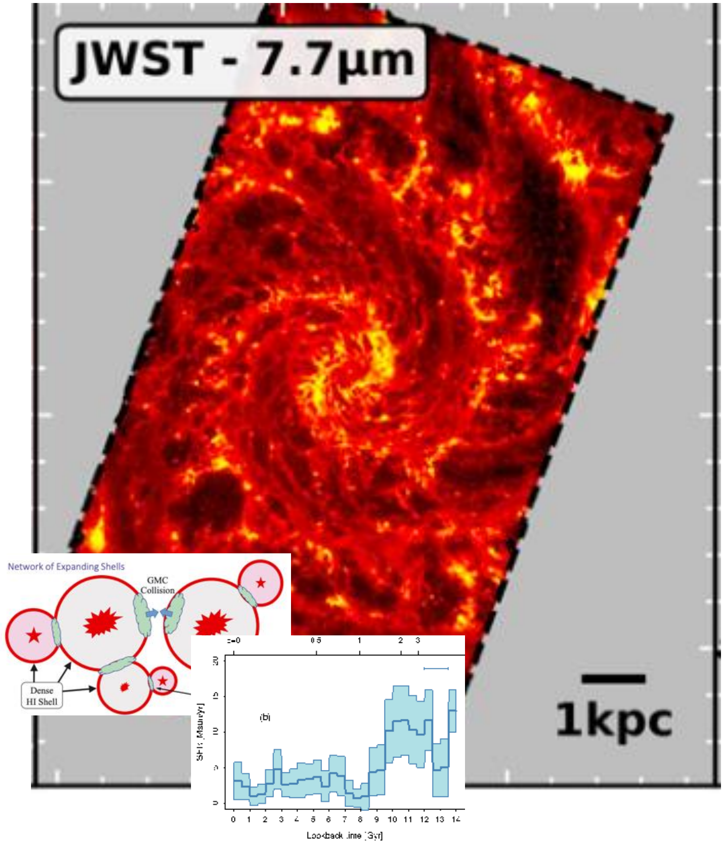
~1 pc





ISM中の輸送・伝搬

~10 pc-1 kpc



~10 kpc

銀河系からの逃走

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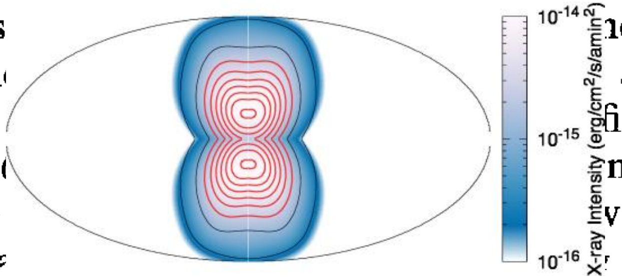
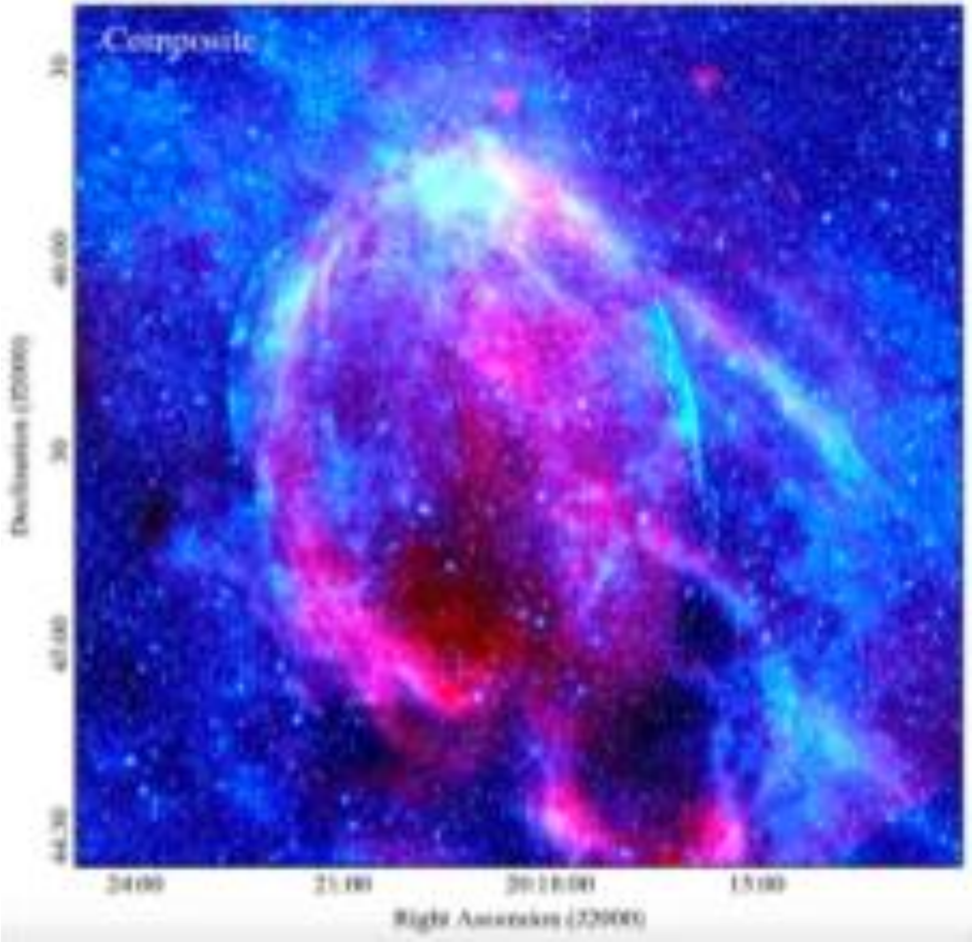


Old SNRs: Hints for 10 pc-1 kpc physics/phenomena?

Red: radio synchrotron
Blue: [OIII]λ5007



推定半径>10 pcの*Old SNR*で，最近見つかった**[OIII] λ 5007輝線.**

電波シンクロトロンのシェル（shock面）よりも***遠く***で明るい.
→なんで？？？
著者のFesen et al. 2024は，**CRの関与について言及**しているけれども，
具体的なシナリオ・物理過程は不明.
要するに，単純な説明がない.

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

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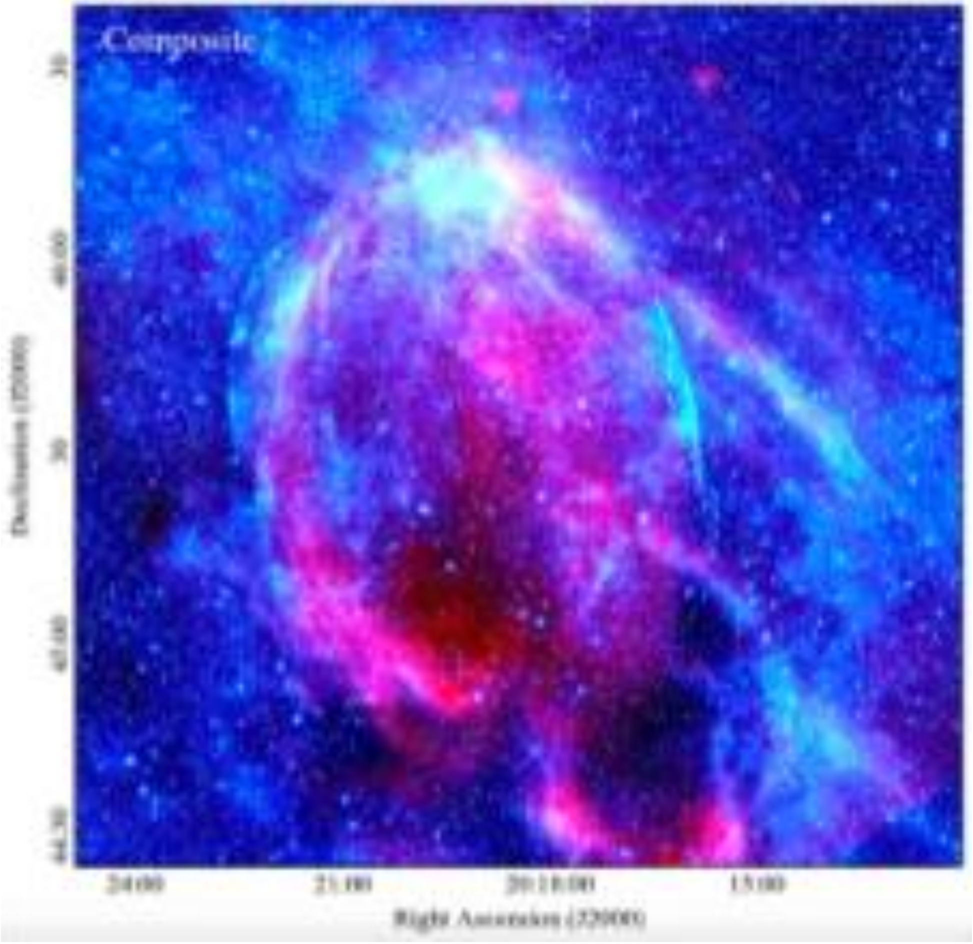

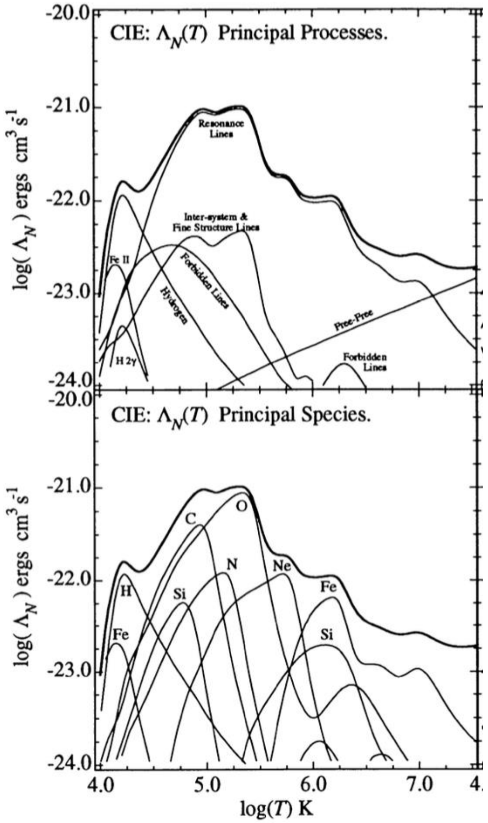

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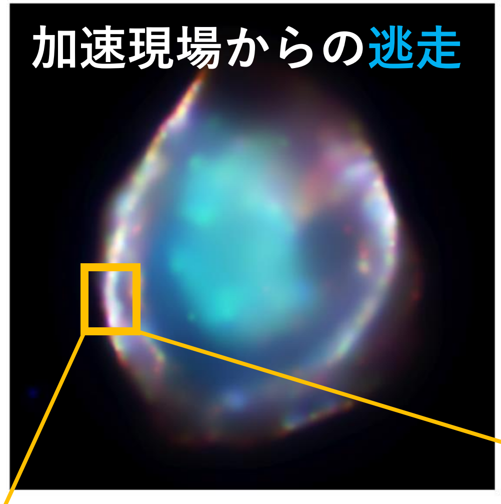
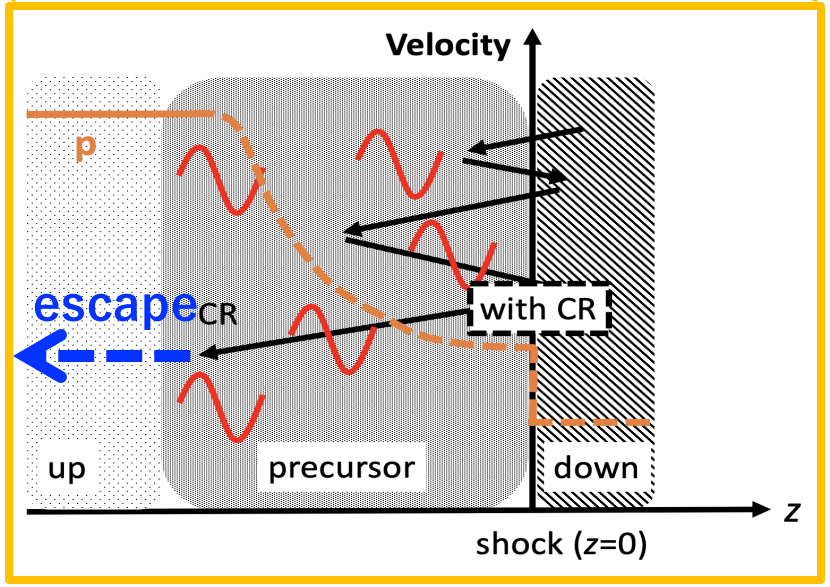
Sedov timeと同程度.
Old SNRだと思うと，あまりに短すぎる.
heating sourceが必要？

CRがガスを加熱する可能性自体は，昔から知られている.

逃走宇宙線との闘争

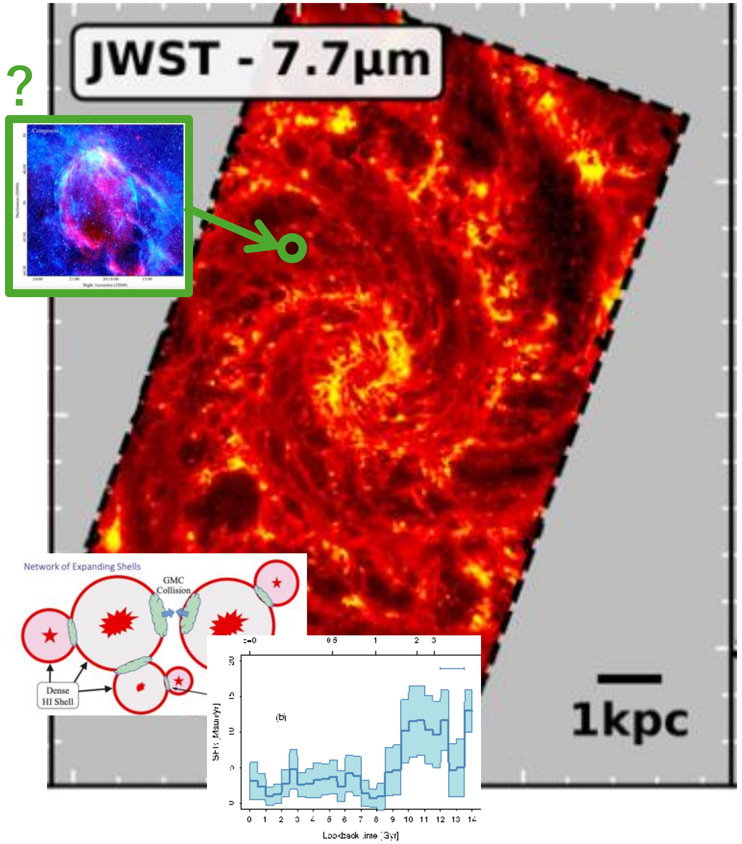
~1 pc





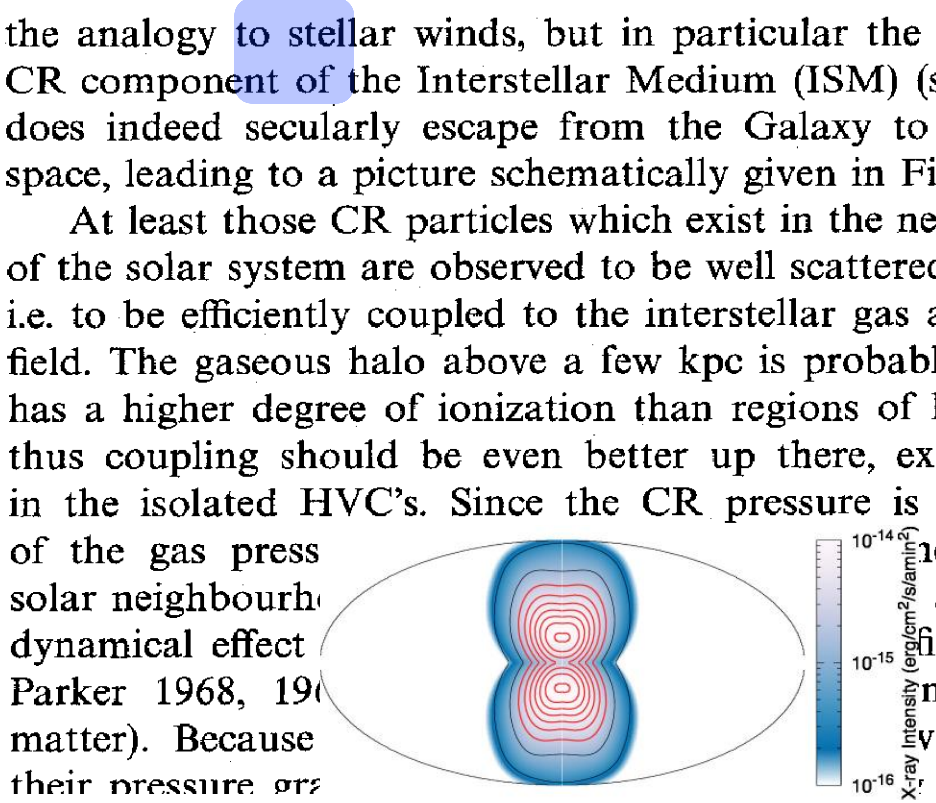
ISM中の輸送・伝搬

~10 pc-1 kpc



~10 kpc

銀河系からの逃走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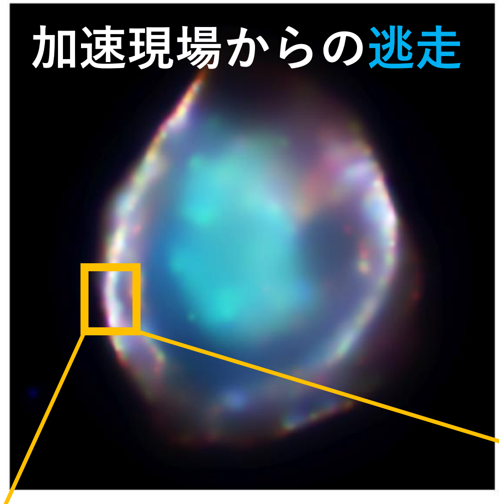
~1 pc



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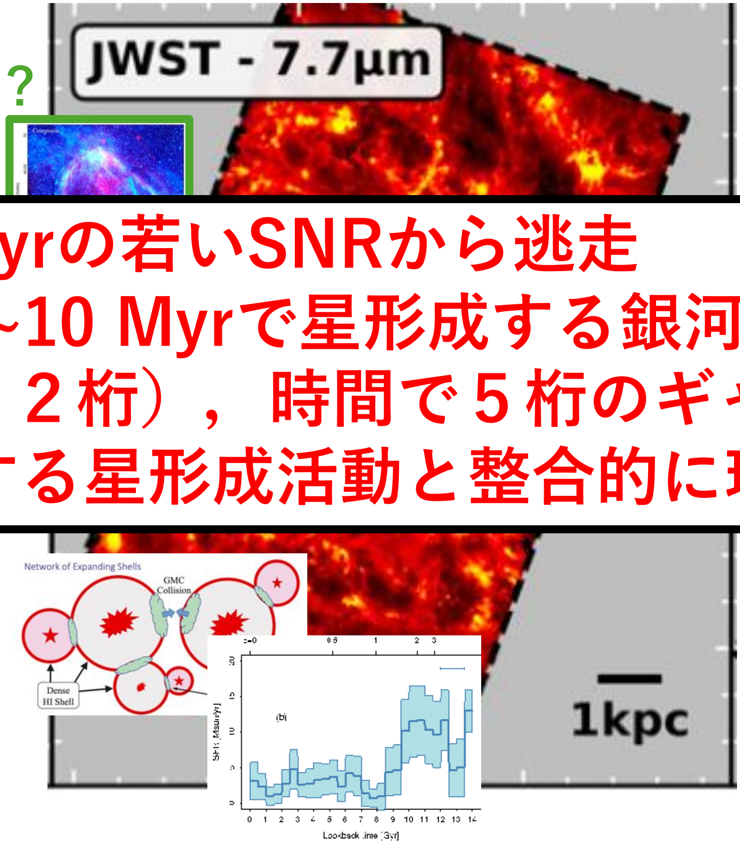
~10 pc-1 kpc



~10 kpc

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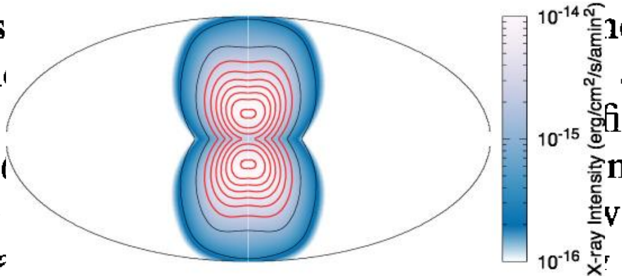
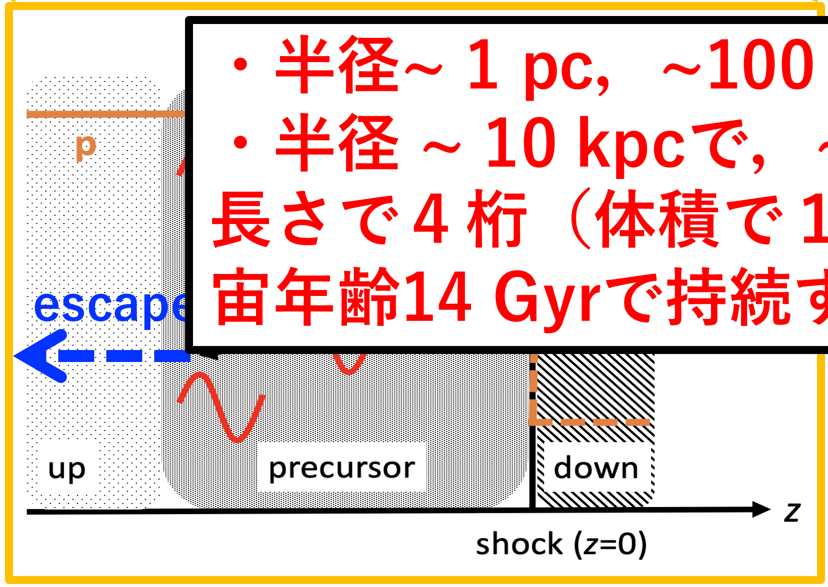
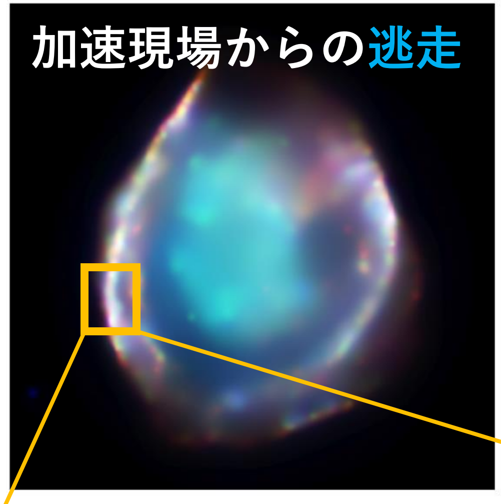




・半径~ 1 pc，~100 yrの若いSNRから逃走
・半径 ~ 10 kpcで，~10 Myrで星形成する銀河円盤からの逃走
長さで４桁（体積で１２桁），時間で５桁のギャップを埋めて，かつ宇宙年齢14 Gyrで持続する星形成活動と整合的に理解せよ．

逃走宇宙線との闘争

~1 pc

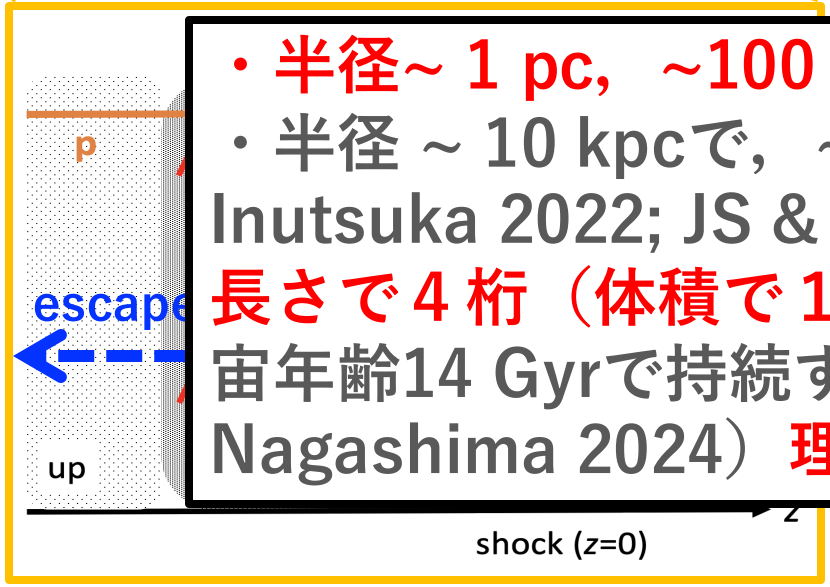


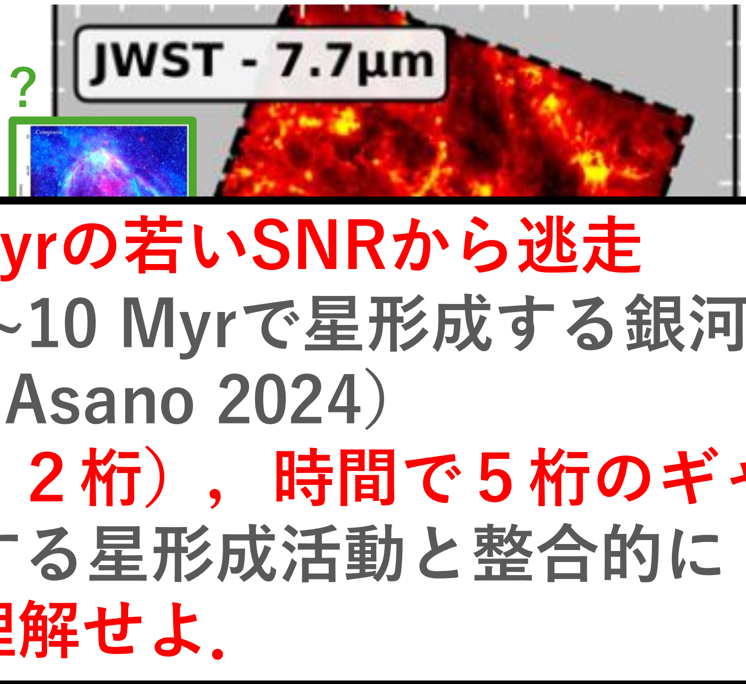
ISM中の輸送・伝搬

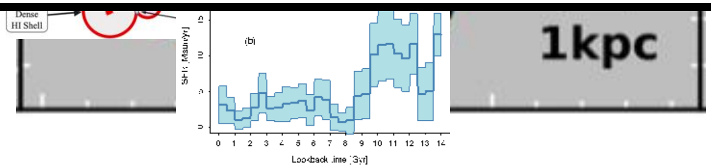
~10 pc-1 kpc

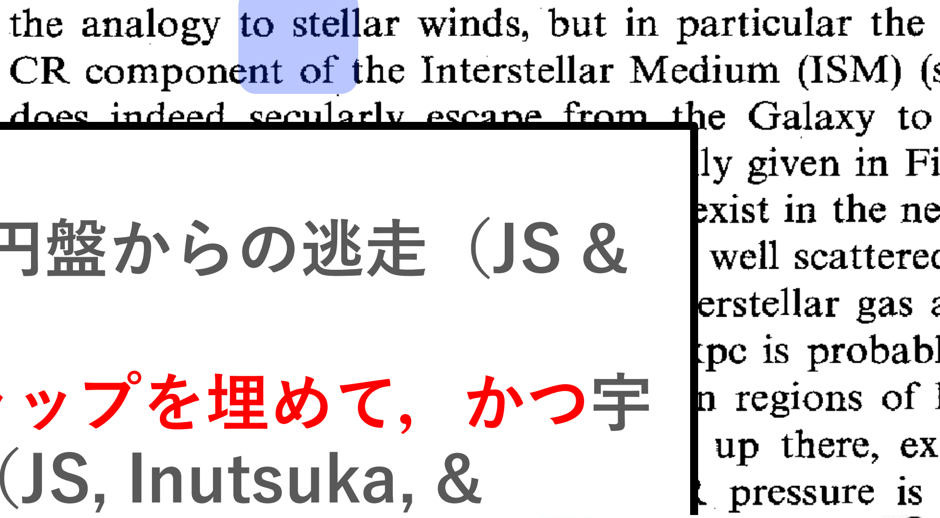
~10 kpc

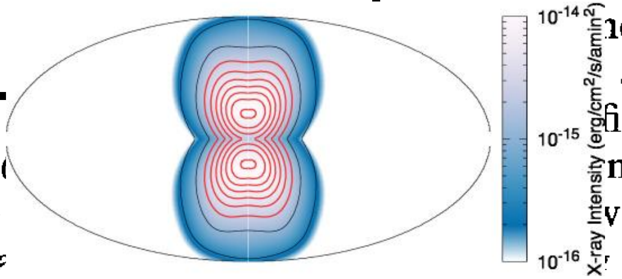
銀河系からの逃走







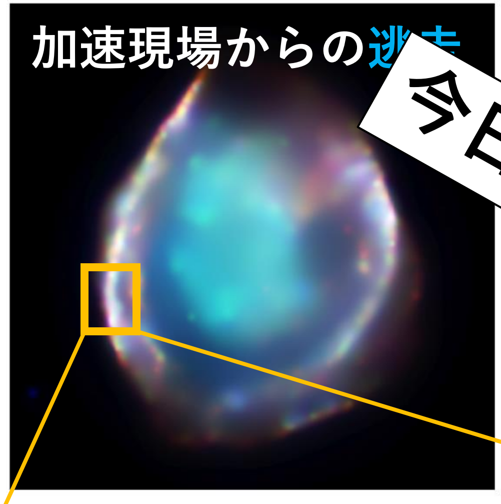




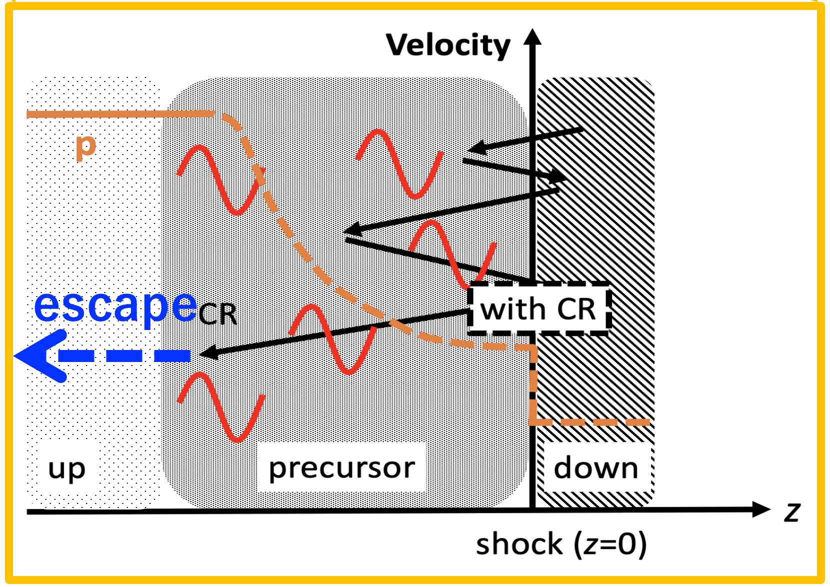
・半径~ 1 pc, ~100 yrの若いSNRから逃走
・半径 ~ 10 kpcで, ~10 Myrで星形成する銀河円盤からの逃走（JS & Inutsuka 2022; JS & Asano 2024）
長さで４桁（体積で１２桁），時間で５桁のギャップを埋めて，かつ宇宙年齢14 Gyrで持続する星形成活動と整合的に（JS, Inutsuka, & Nagashima 2024）理解せよ.

逃走宇宙線との**闘争**

~1 pc



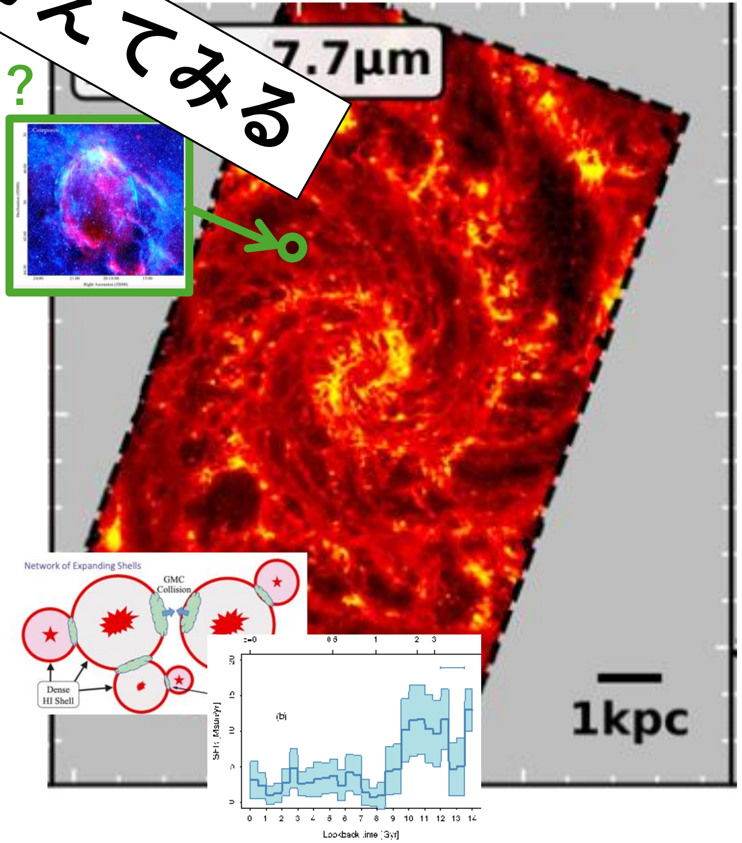
今日はここを考えてみる



ISM中の輸送・伝搬

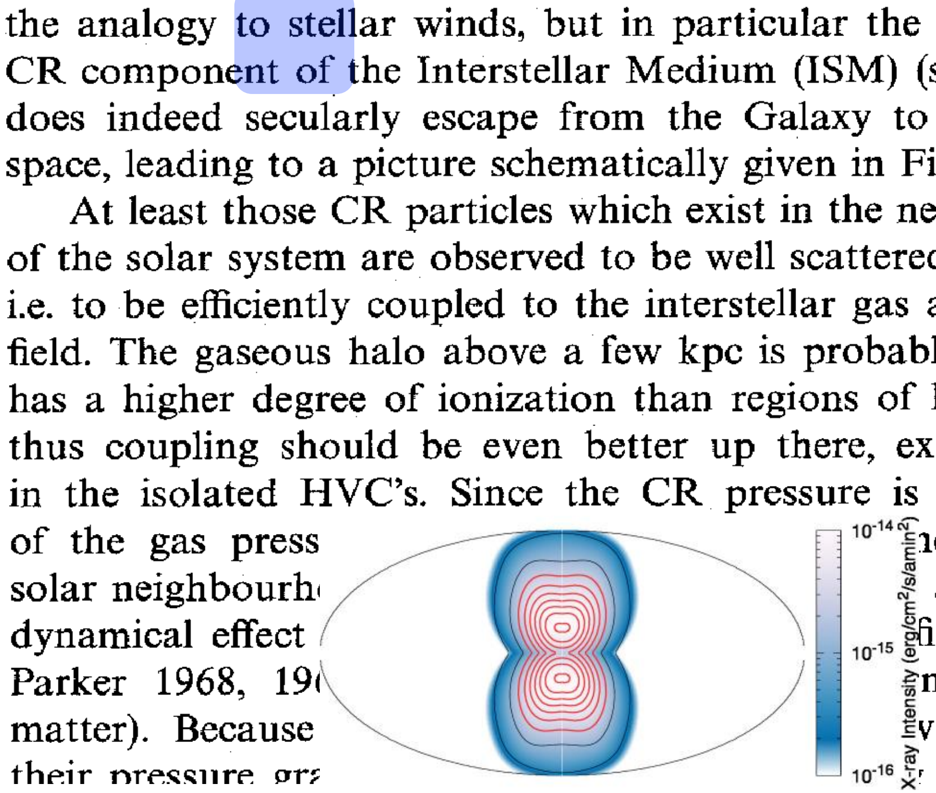
~10 pc-1 kpc

?



~10 kpc

銀河系からの逃走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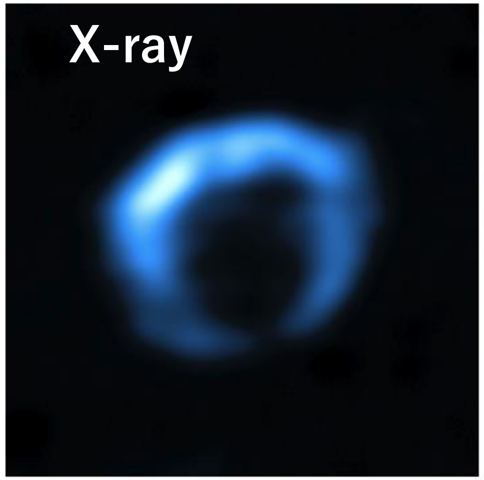
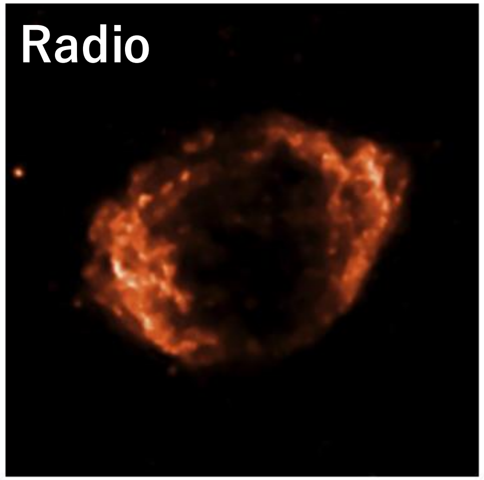
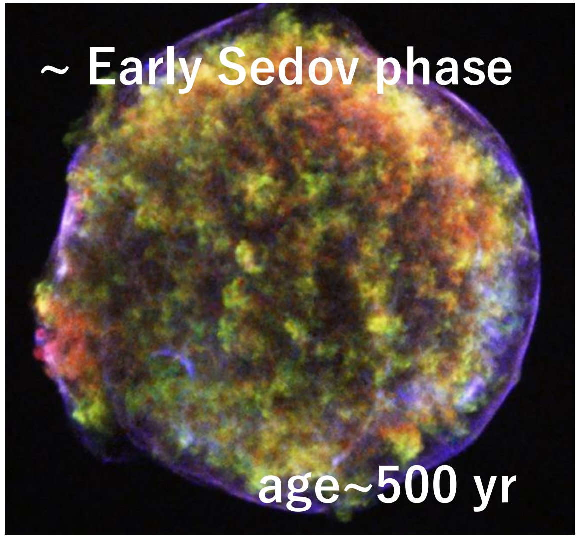
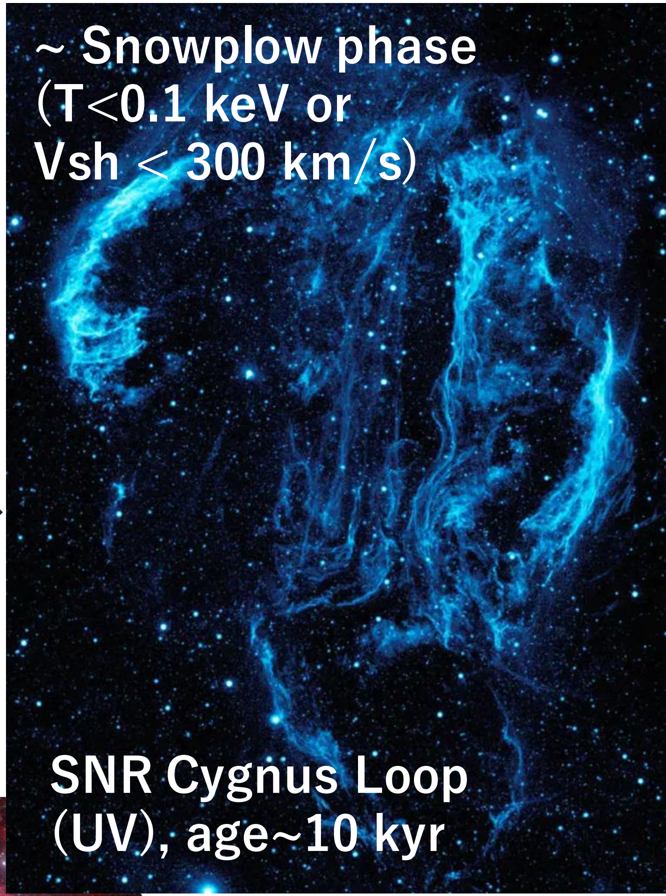
Supernova Remnants:Temporal Evolution

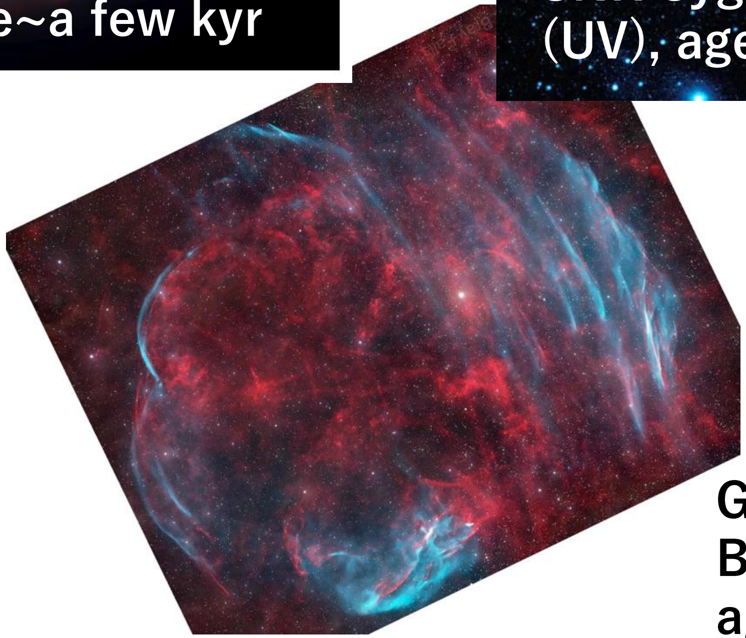
G1.9+0.3: Youngest SNR in our Galaxy
(age~140 yr, Bamba & Williams 22)
Free Expansion Phase







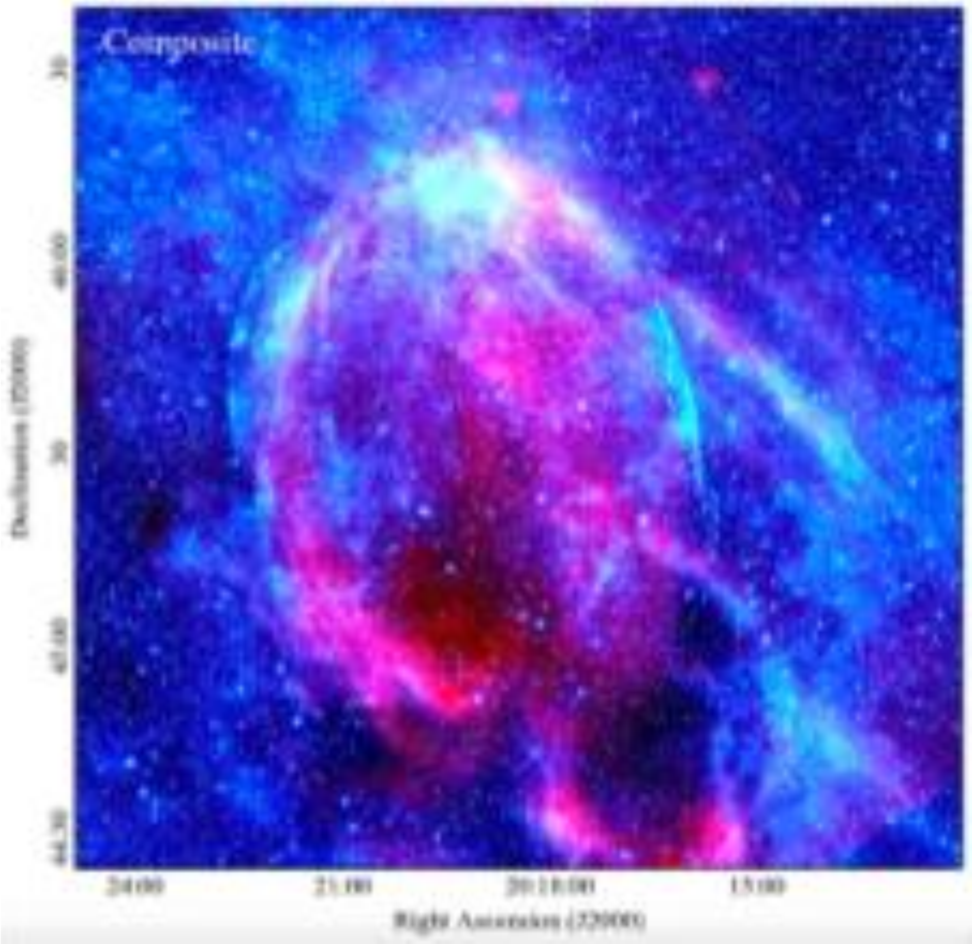


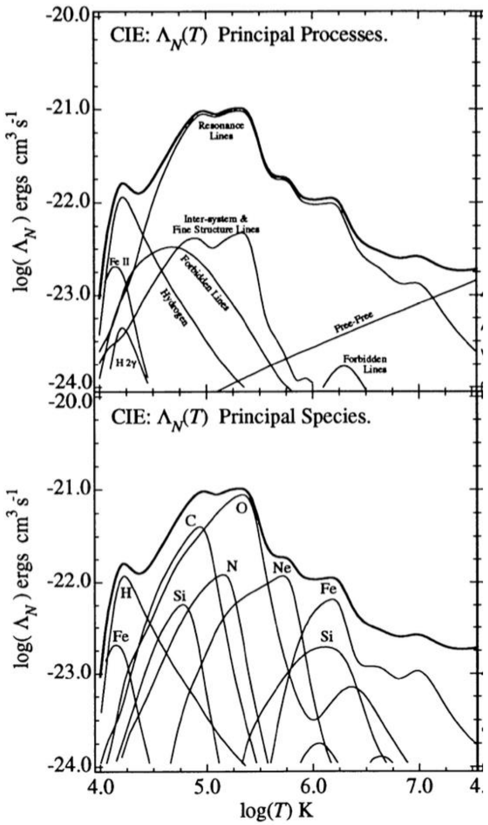


G70.0-21.5
Blue OIII, Red Hα
age ~ 10-100 kyr?

Old SNRs: Hints for 10 pc-1 kpc physics/phenomena?

Red: radio synchrotron
Blue: [OIII]λ5007





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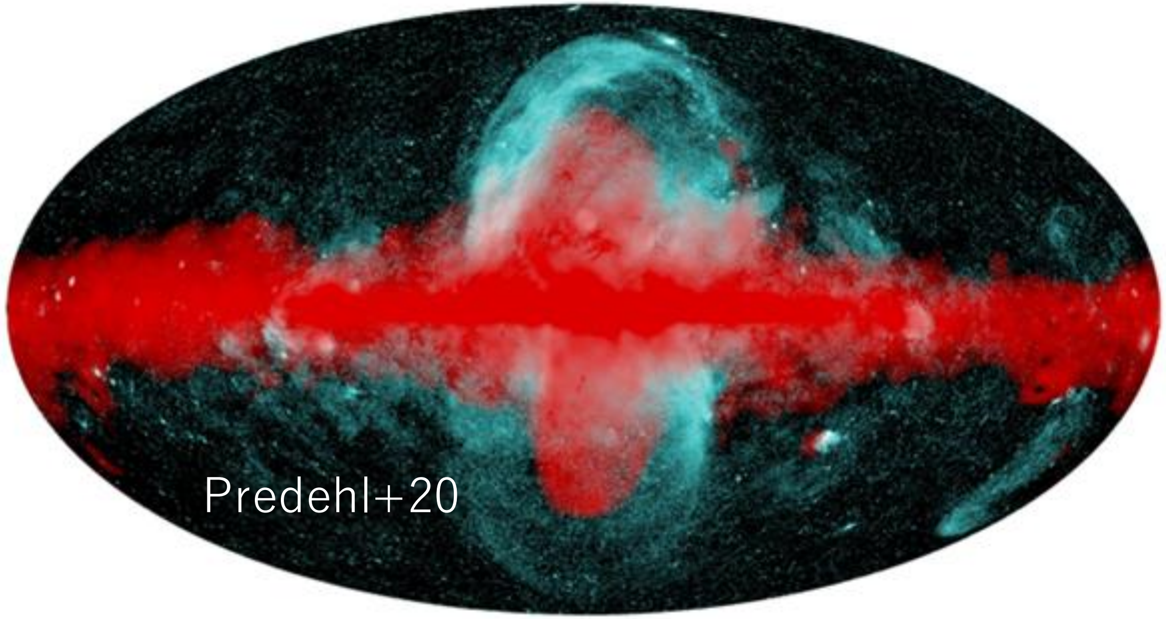
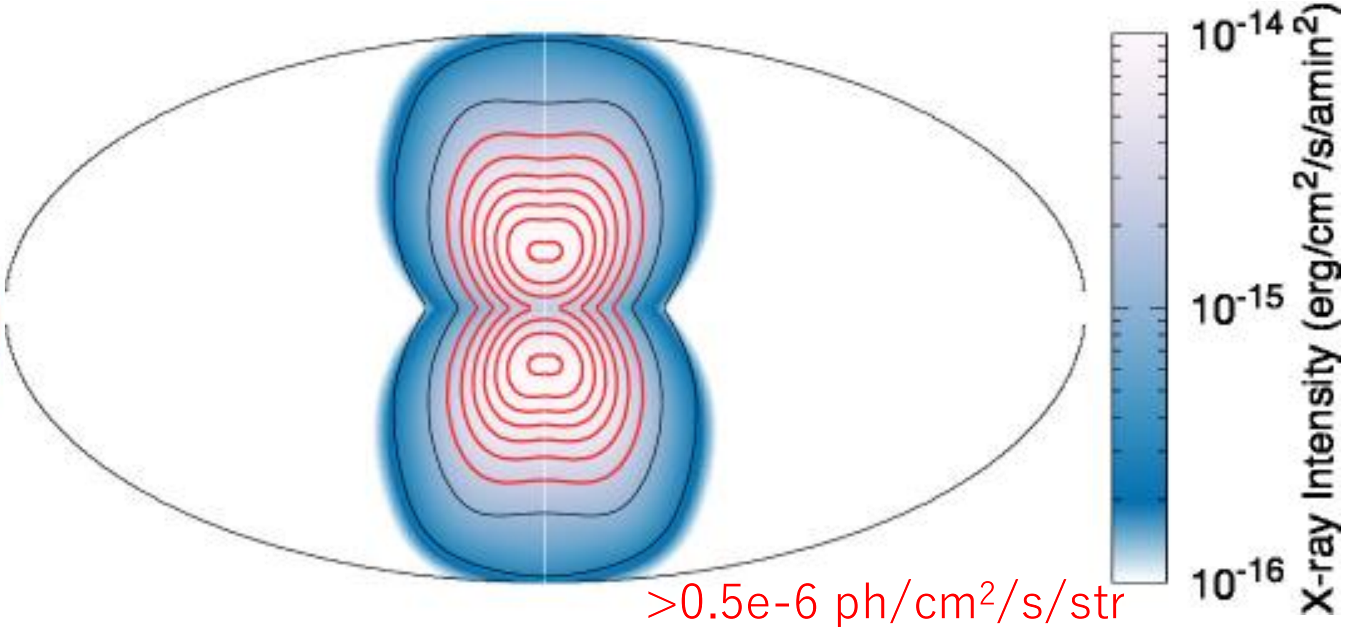
$$n_e k_B T/(n_e{}^2 \Lambda) \sim 500\ \mathrm{yr}\,(n_e/1\ \mathrm{cm}^{-3})^{-1}(T/10^5\ \mathrm{K})$$

Sedov timeと同程度.
Old SNRだと思うと，あまりに短すぎる.
heating sourceが必要？

CRがガスを加熱する可能性自体は，昔から知られている.
＊銀河風の種になる，高温希薄ガスをdiskの中に作れるとなお良し.

Galactic Wind Scenario (SJ&Asano 24)





Assumption:

~10 % of SNe energy is consumed for launching the wind.

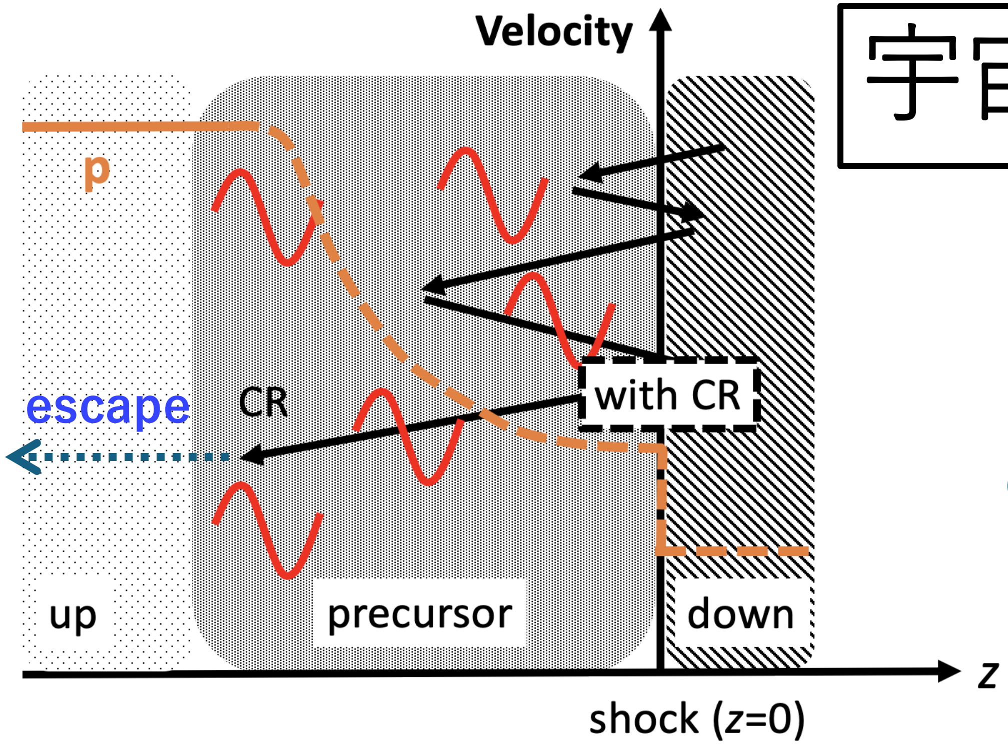
This assumption should be tested.

We consider a possibility:

***ISM heated by CRs around the CR sources*.**

*Hadronic γ-ray scenario $p_{cr} + p_{gas} \to 2\gamma, \nu$

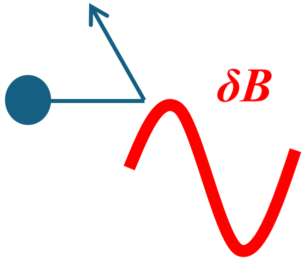
宇宙線加熱機構（one of them）



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（microphysicsがよく分からん）.**
- **CRの有無で，ガスの運動や熱力学的状態がどう変わるかも整備されていない（流体力学）.**

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 …

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

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

The 1st law of thermodynamics should include the CRs

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

The CR-hydrodynamics: the energy equation

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

Energy Exchange
(CRs heat the gas)

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

The CR-hydrodynamics: the energy equation

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

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

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

Energy Exchange effect

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

$$P_g = (\gamma_g - 1)e_g = 2e_g/3$$
$$P_{cr} = (\gamma_{cr} - 1)e_{cr} = e_{cr}/3$$

The CR heating produces additional total pressure!

The CR-hydrodynamics: the energy equation

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

The CR heating produces additional total pressure!

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

What happens???

→Test by Simple Numerical Model

The CR-hydrodynamics: Simple Numerical Model

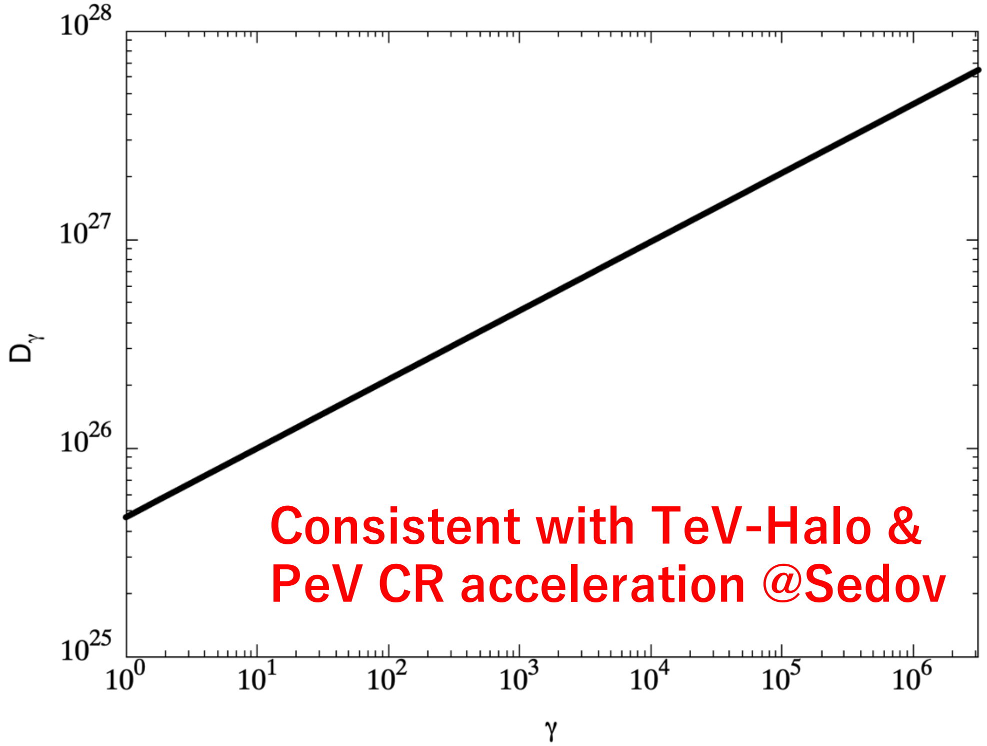
1D spherical
Uniform medium
Put *CR bomb*

CR transport equation

$$\boxed{\partial_t \mathcal{N} + \nabla\cdot(\boldsymbol{v}\mathcal{N} - \mathcal{D}_\gamma \nabla\mathcal{N}) - \partial_\gamma\left(\frac{\nabla\cdot\boldsymbol{v}}{3}\gamma\mathcal{N}\right) = -|V_A \partial_r \mathcal{N}|}$$

CR Heating

CR diffusion coefficient



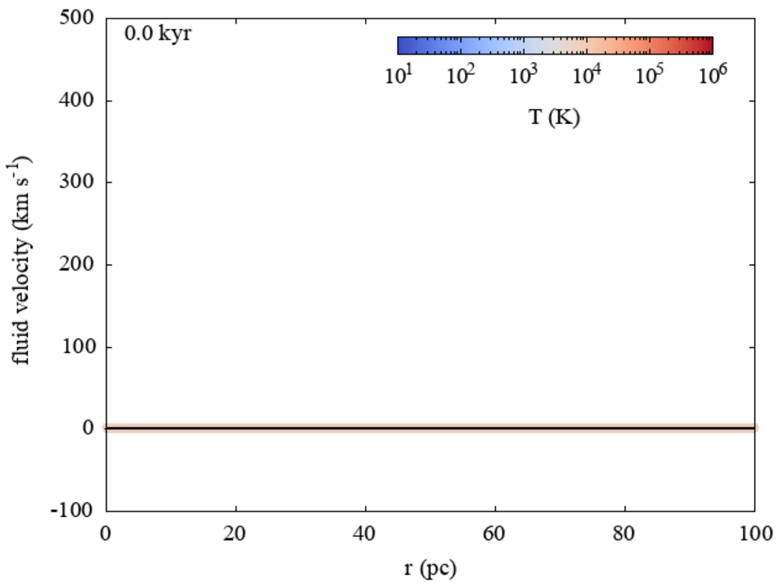
Consistent with TeV-Halo &
PeV CR acceleration @Sedov

CR initial condition

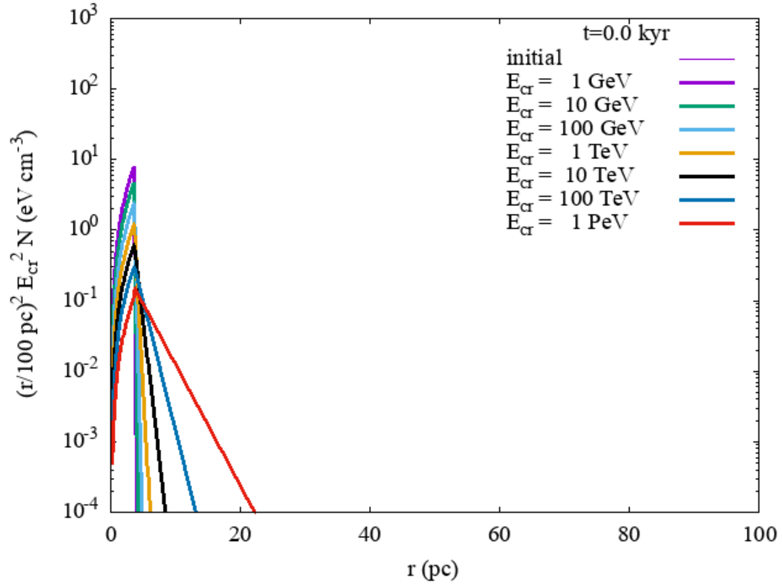
$$\mathcal{N} \propto \frac{\gamma^{-2.3}}{(r/R_s)^2}\exp\left[-\left(\frac{r}{R_s}-1\right)\left(\frac{\gamma}{\gamma_s}\right)^{-a}\right]$$

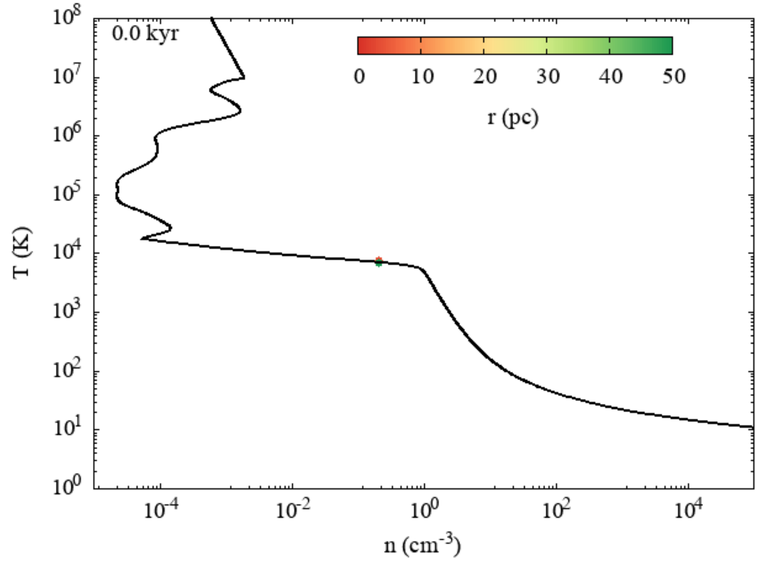
CR total energy = 10^{50} erg

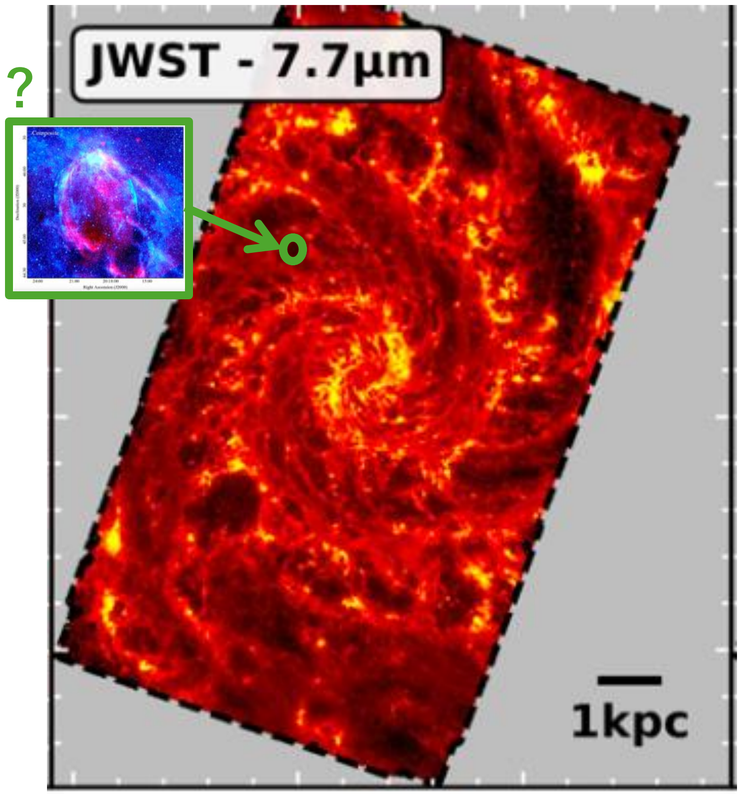
The CR-hydrodynamics: Simple Numerical Model

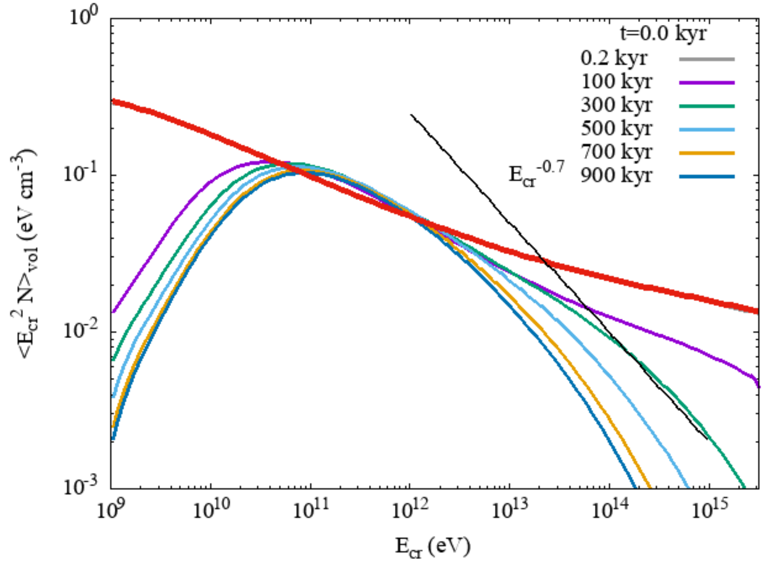


CRs w/ 10^{50} erg
can make hot gas and can keep it at 10^6 K during 1 Myr

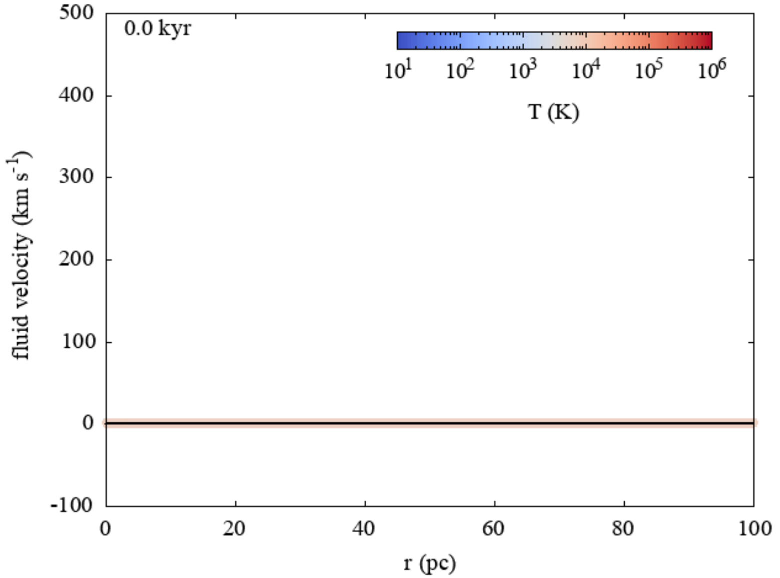


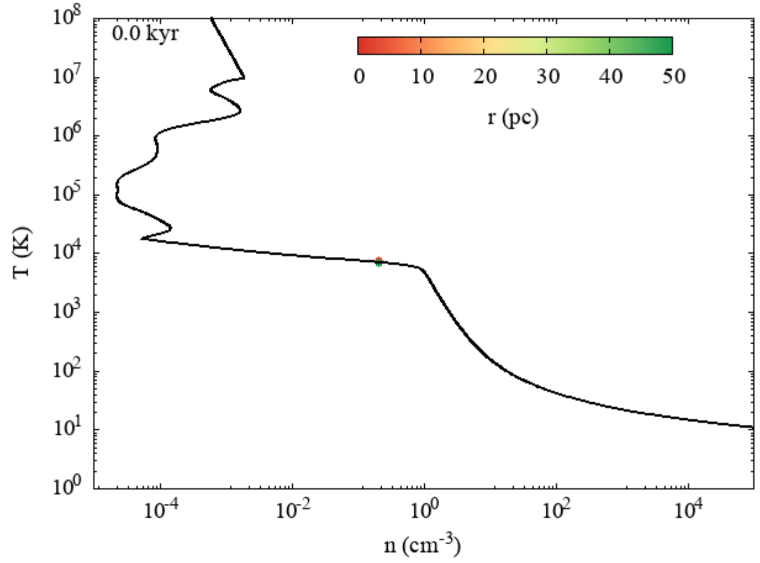




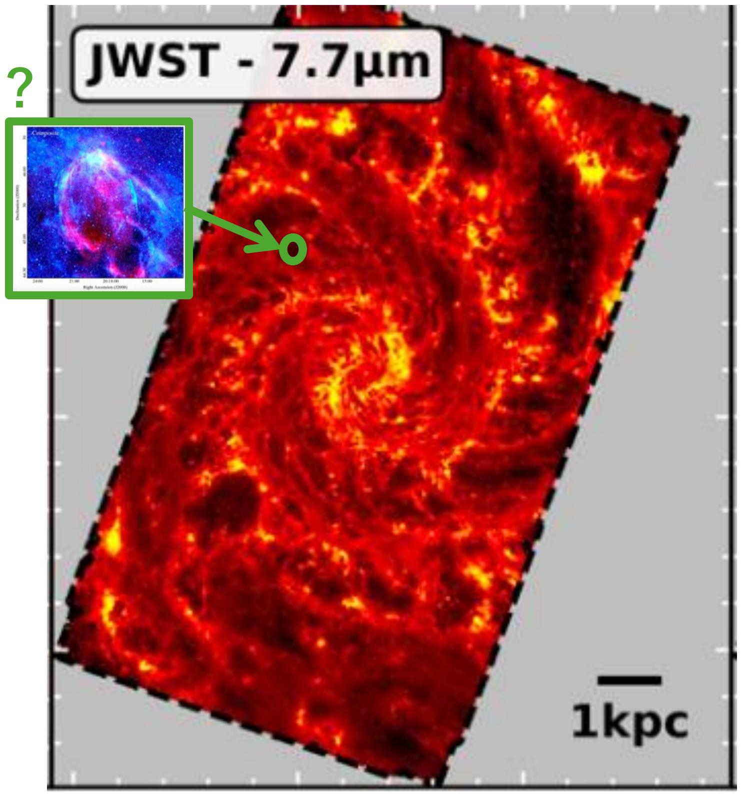


The CR-hydrodynamics: Simple Numerical Model

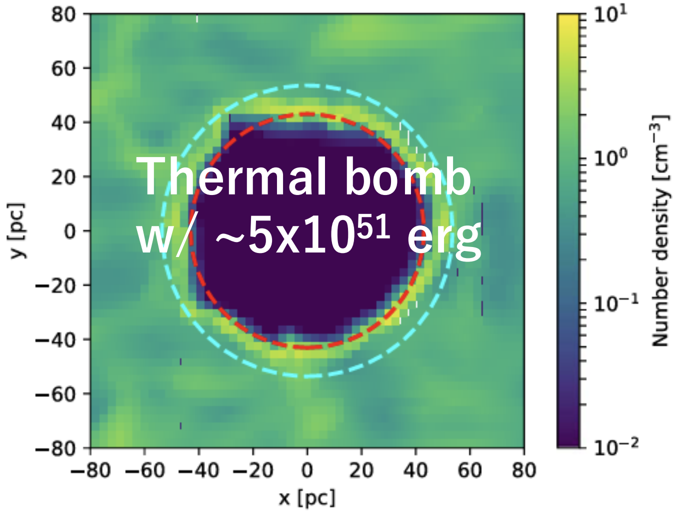




CRs w/ 10^{50} erg
can make hot gas and can keep it at 10^6 K during 1 Myr
More Efficient?



w/o CRs (Oku+22)



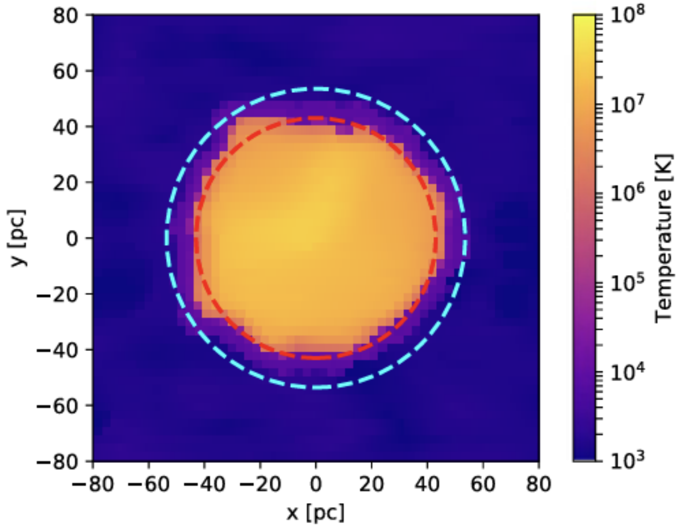


Figure 2. Slice plot of gas number density and temperature distribution at $t = 0.53$ Myr for the case of $n_H = 1$ cm^{-3}, $Z = Z_\odot$, $\Delta t_{SN} = 0.1$ Myr. The inner red circle shows R_{hot}, while the outer cyan circle shows R_{bub}.

The CR-hydrodynamics: the energy equation

$$\frac{de_g}{dt} - \frac{e_g + P_g}{\rho}\frac{d\rho}{dt} = \mathcal{L}_{\mathrm{rad,g}} + \boldsymbol{\nabla}\cdot(K\boldsymbol{\nabla}T) + \mathcal{L}_{\mathrm{em,cr}}$$

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

Energy Exchange
(CRs heat the gas)

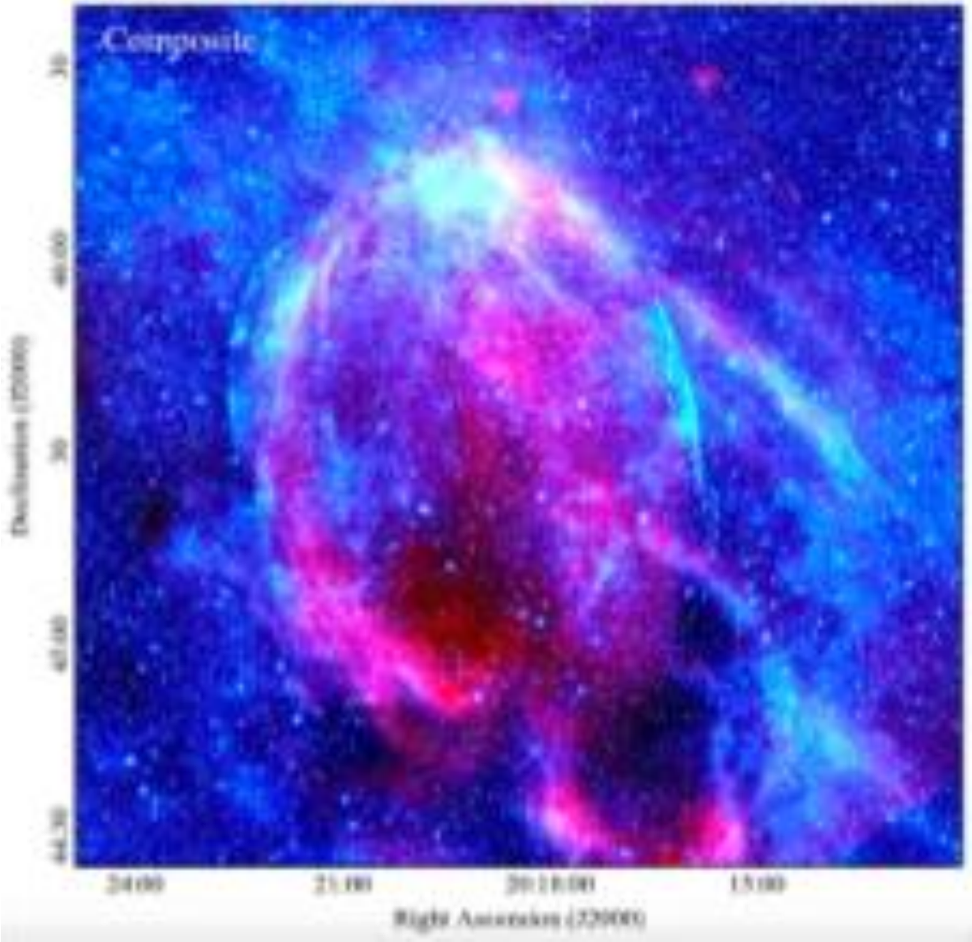
$$\mathcal{P} = P_g + P_{cr} = \mathcal{P}(e_g + |e_1|, e_{cr} - |e_1|) = \mathcal{P}(e_g, e_{cr}) + \frac{|e_1|}{3}$$

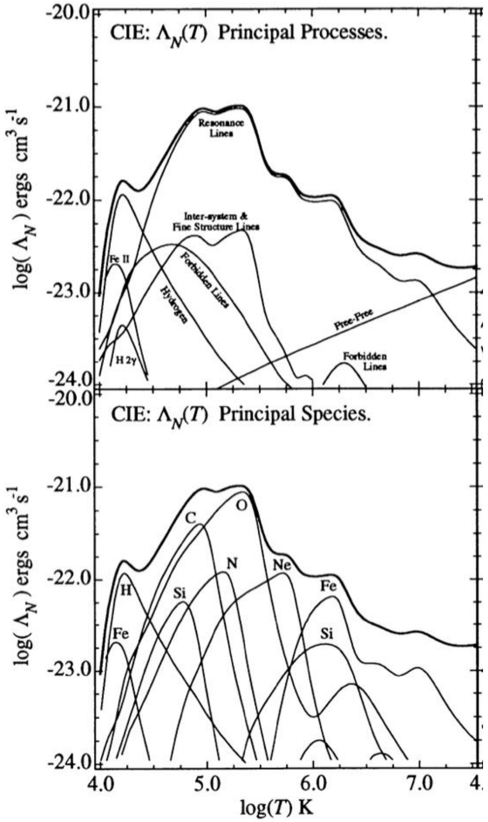
CR heating → Increasing total pressure → prefer to form hot & tenuous gas

Cooling rate decreases

Old SNRs: Hints for 10 pc-1 kpc physics/phenomena?

Red: radio synchrotron
Blue: [OIII]λ5007





Cooling time

$$n_e k_B T/(n_e{}^2 \Lambda) \sim 500\ \mathrm{yr}\,(n_e/1\ \mathrm{cm}^{-3})^{-1}(T/10^5\ \mathrm{K})$$

Sedov timeと同程度.
Old SNRだと思うと，あまりに短すぎる.
heating sourceが必要？

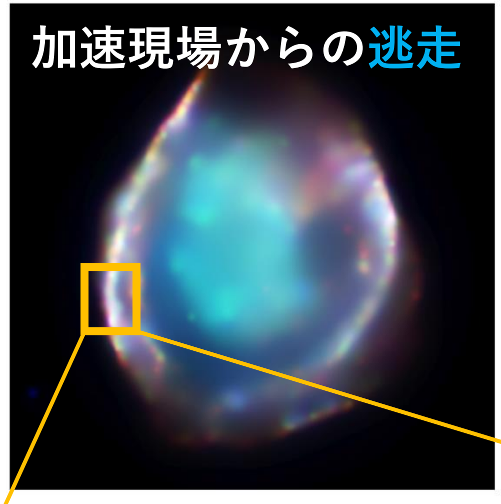
CRがガスを加熱する可能性自体は，昔から知られている.

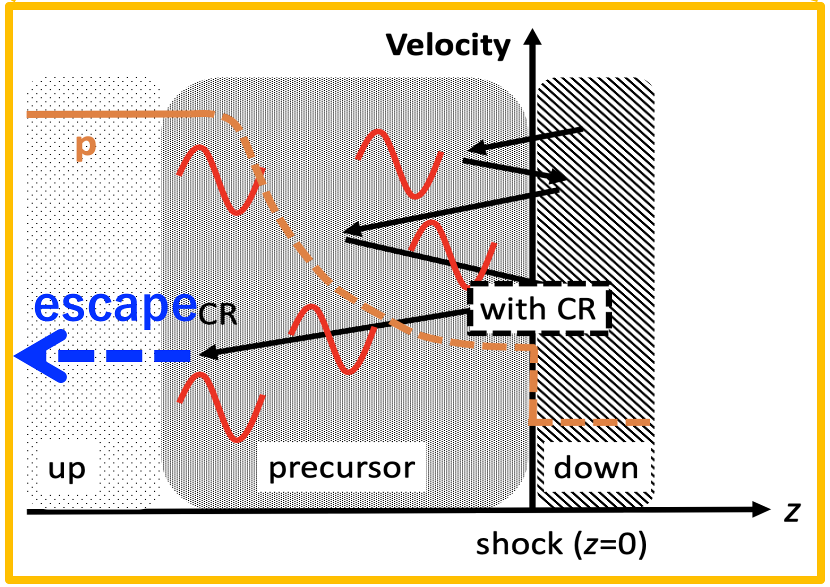
1st ionization potentials:
O^{+1}→35 eV
O^{+2}→55 eV
O^{+3}→77 eV

＊銀河風の種になる，高温希薄ガスをdiskの中に作れるとなお良し．→作れそうなので良し

逃走宇宙線との闘争

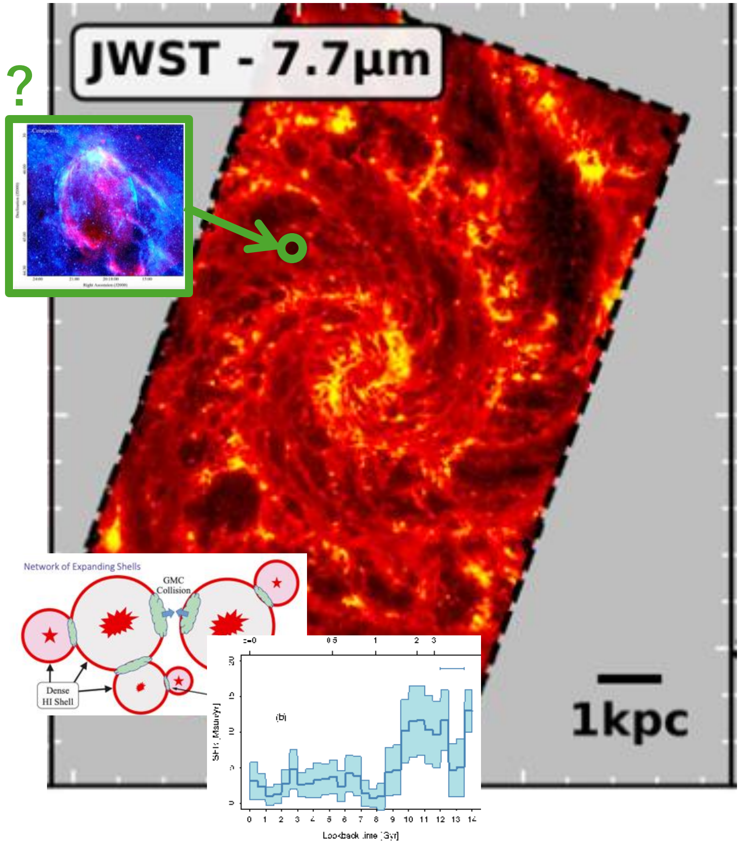
~1 pc





ISM中の輸送・伝搬

~10 pc-1 kpc



~10 kpc

銀河系からの逃走

the analogy to stellar winds, but in particular the
CR component of the Interstellar Medium (ISM) (s
does indeed secularly escape from the Galaxy to
space, leading to a picture schematically given in Fi
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Parker 1968, 19
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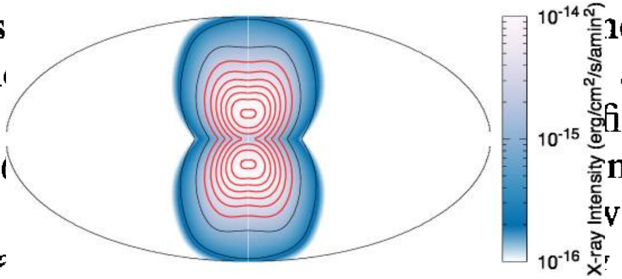
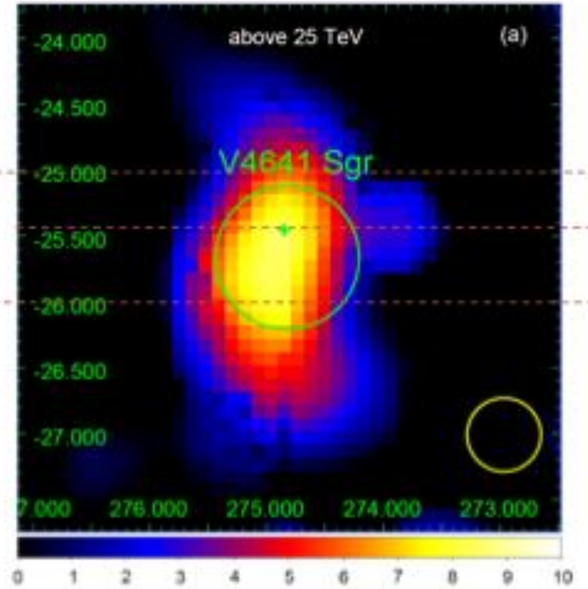
their pressure gra

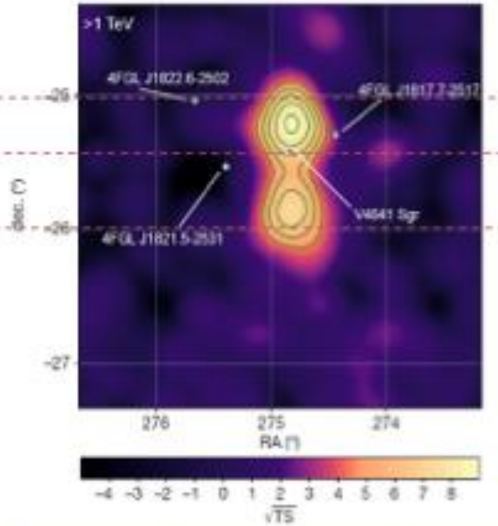


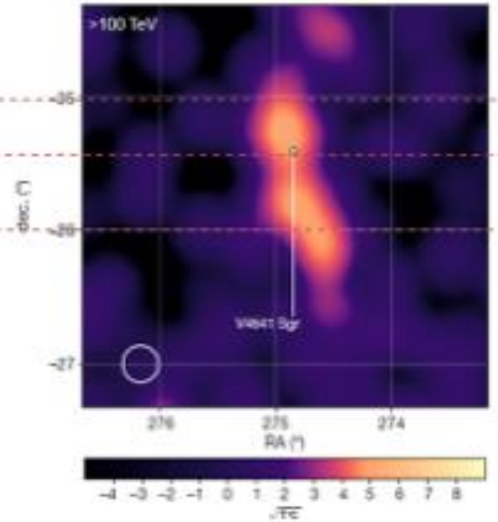
Microquasars

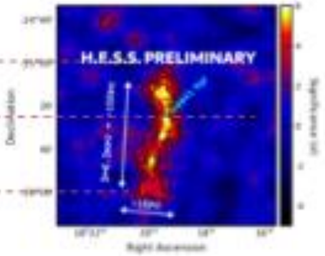
Ruoyu-Liu氏のスライドより

V4641 Sgr

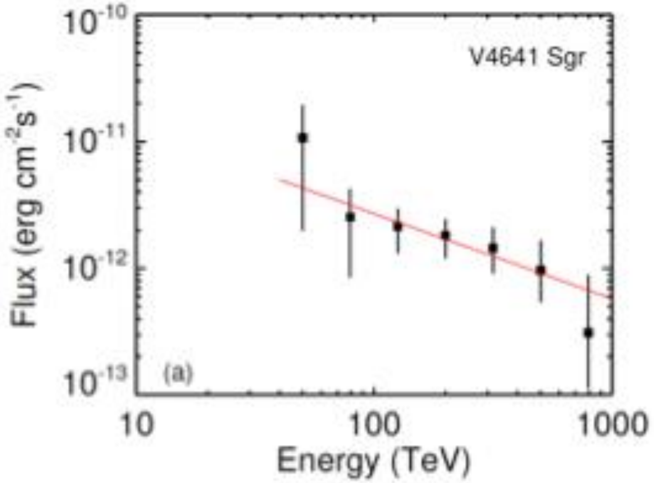








courtesy of L. Olivera-Nieto



Model	Ra	Dec	L./a	W./b	N of W angle	TS
2PS	274.94±0.08 274.94±0.08	-25.97±0.09 -25.11±0.12	N/A	N/A	N/A	130.1
Rect.	274.87±0.05	-25.72±0.09	1.78±0.24	0.18±0.30	84.8 ±6	133.7
eGauss	274.87±0.05	-25.72±0.09	0.52±0.10	0.1±0.2	86 ±6	132.9

HMXB & LMXB distribution (Yue+arxiv2412.13889)

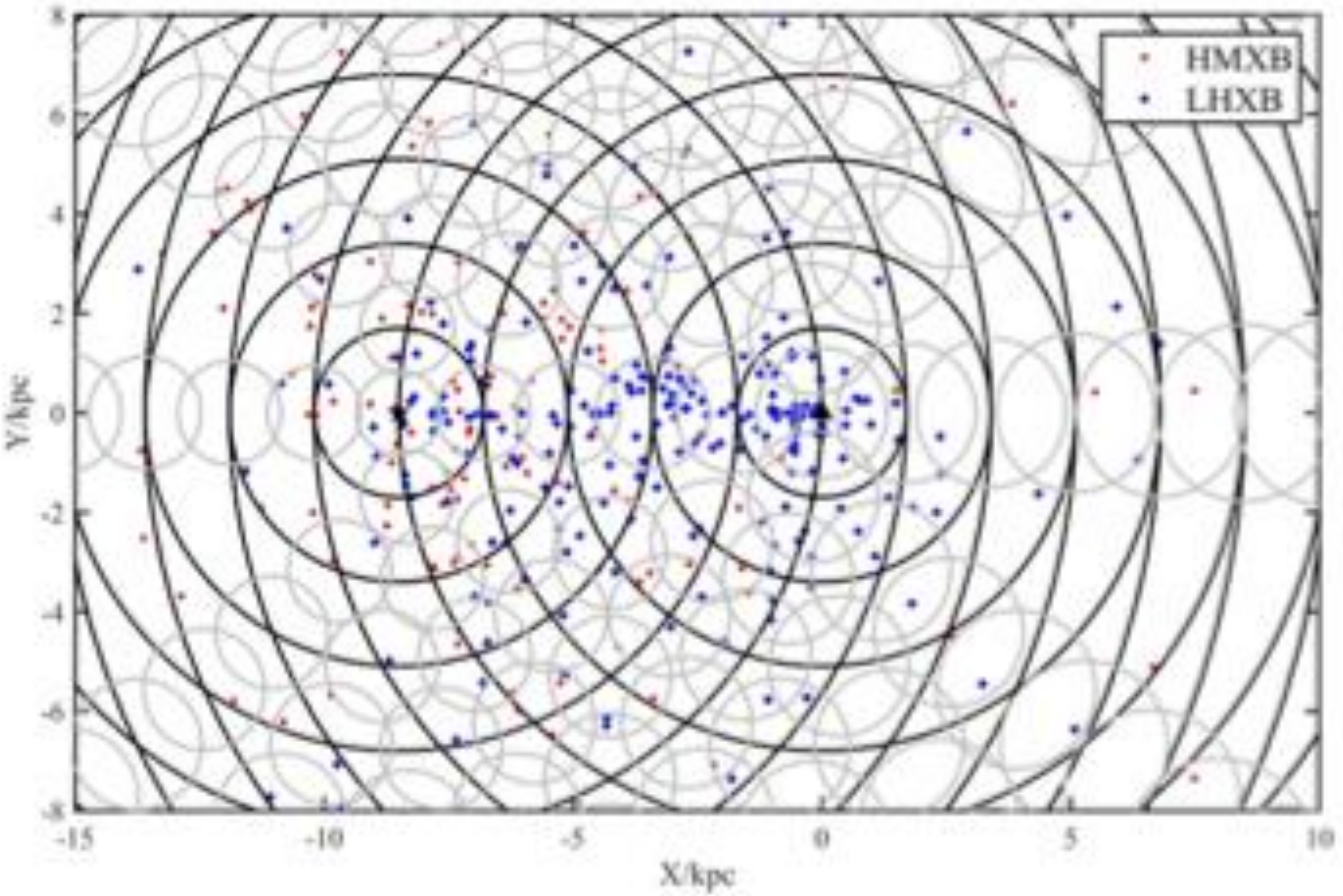
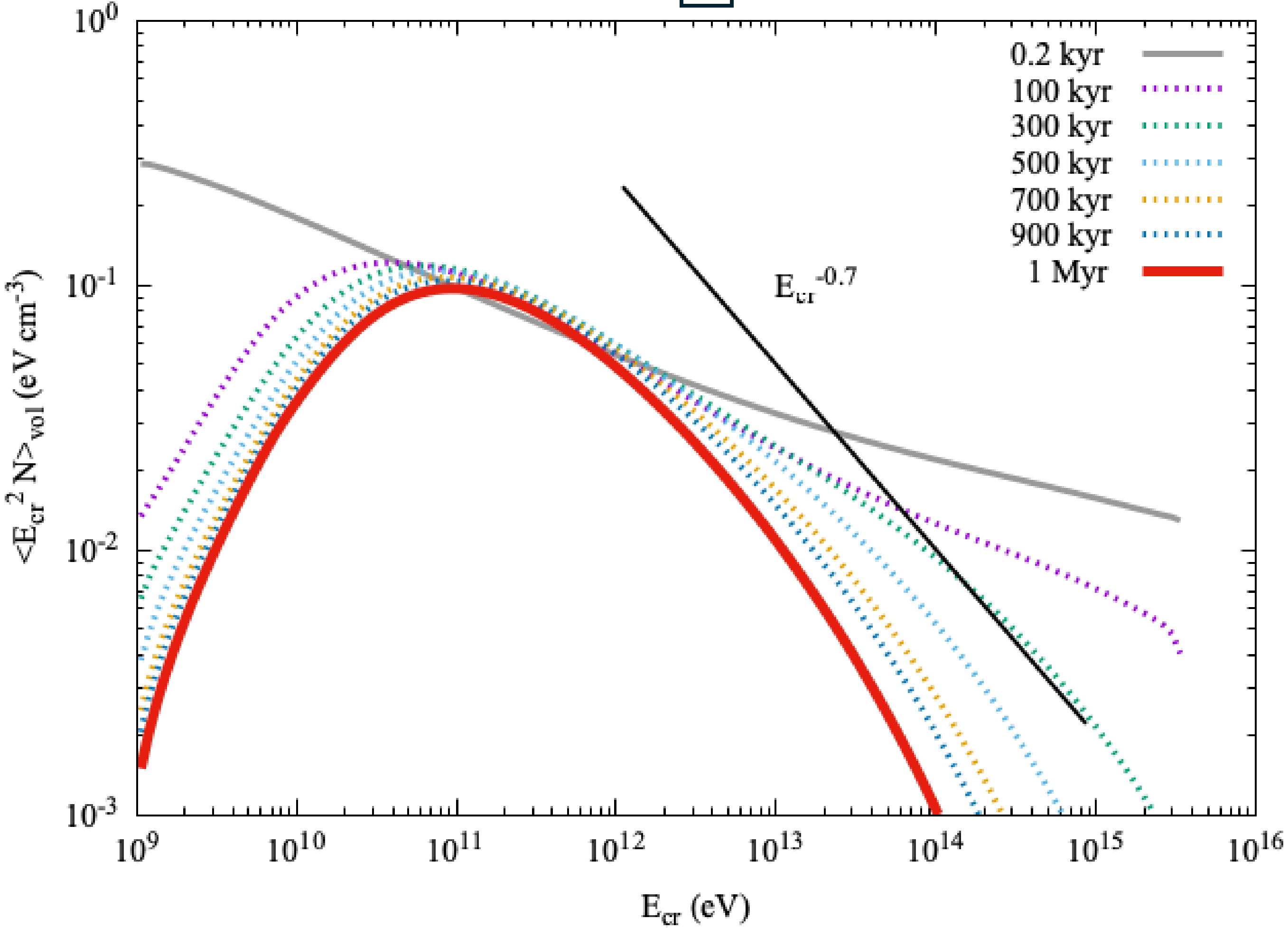


Figure 1. Projection of the sample pulsars on to the Galactic plane. High-mass X-ray binaries (HMXB) and low-mass X-ray binaries are marked as red dots and blue pluses, respectively. The GC is the origin of the coordinate system and the coordinates of the Sun are (-8.5, 0.0). Other lines and symbols are described in the text.

Substructureを説明する？



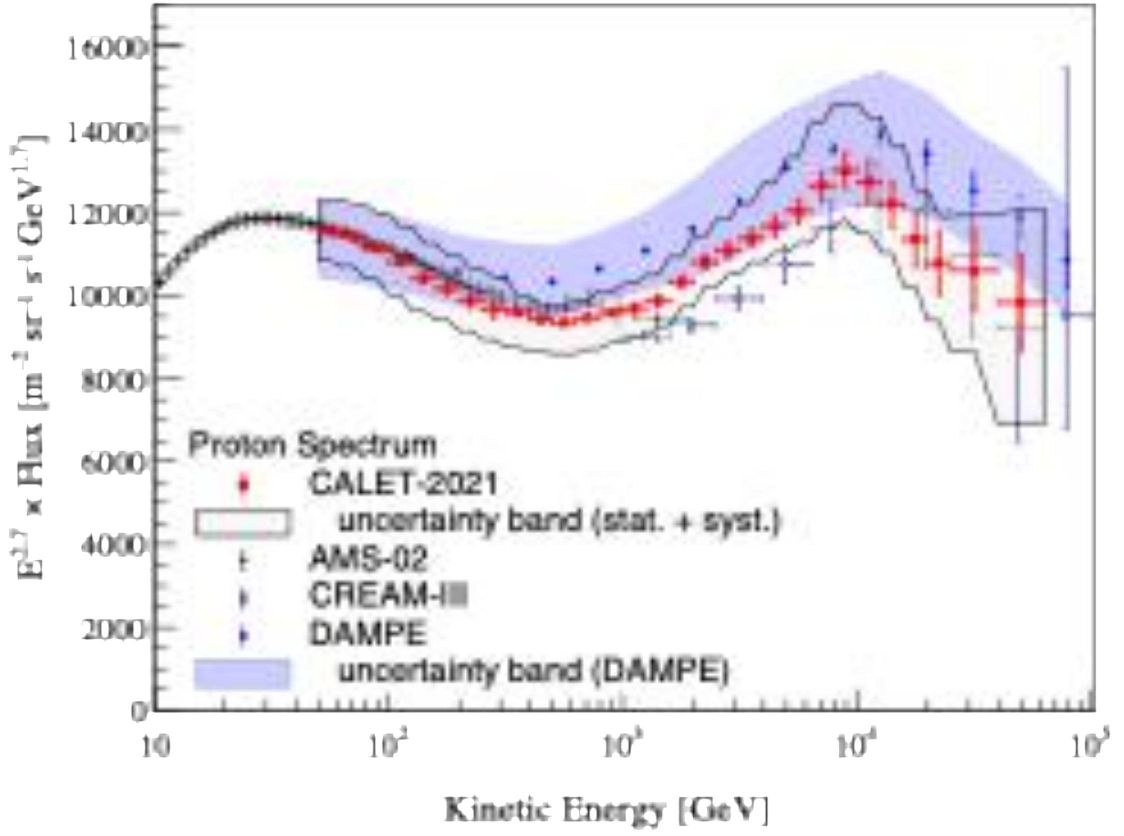
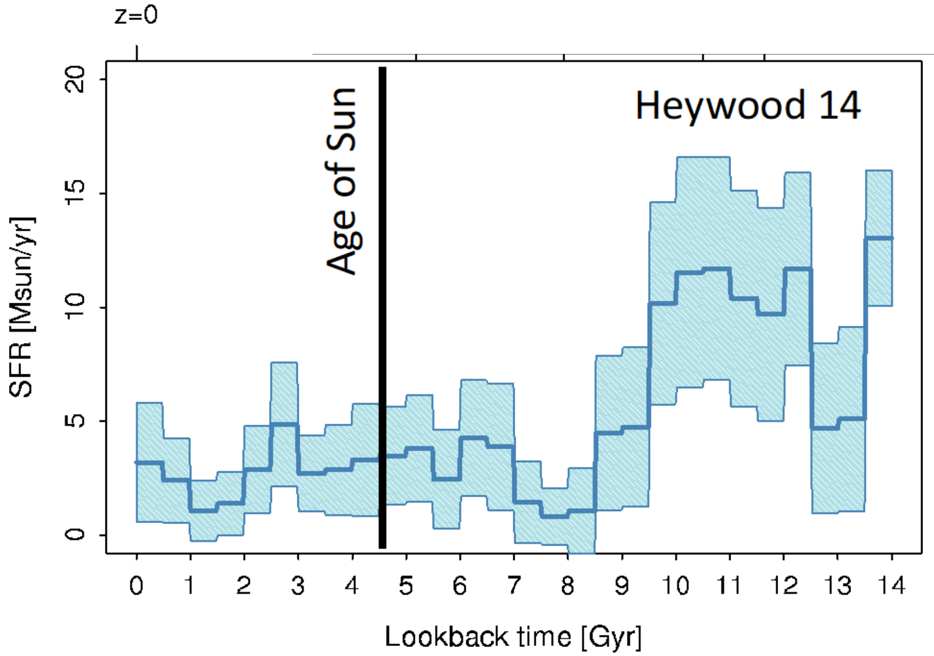


FIG. 3. Proton spectrum measured by CALET (red circles) compared with the experimental results of AMS-02 [6], CREAM-III [42], and DAMPE [39]. The hatched band shows the total uncertainty for CALET as the quadratic sum of the various uncertainties. The dark blue colored band shows the total uncertainty for DAMPE. The proton flux in tabular form can be found in the Supplemental Material [67].

Fermi & eROSITA Bubbles

The Galactic Evolution Scenario



Total mass of DM: ~ 10^{12} M_{sun}

Total mass of stars: ~ 4-6 x 10^{10} M_{sun}

Current SFR: ~ 1 M_{sun}/yr

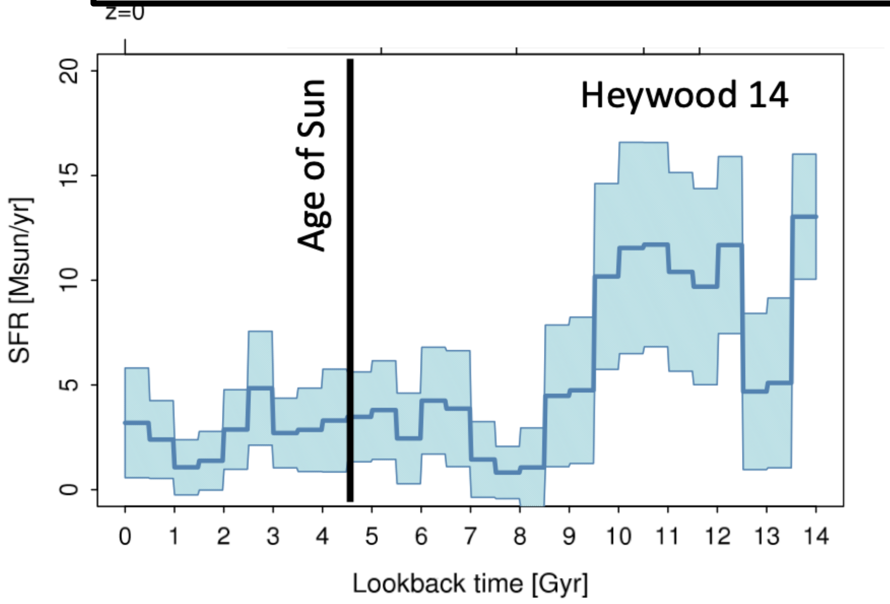
Total gas mass: ~ 10^{9} M_{sun}

Cf. Bland-Hawthorn & Gerhard 16, the Planck Collaboration 18

- **From the current MW …**

1. The gas should be depleted within ~ 1 Gyr !
2. Replenishment of gas is required.
3. Galactic halo (CGM) may be a dominant gas reservoir.

The Galactic Evolution Scenario

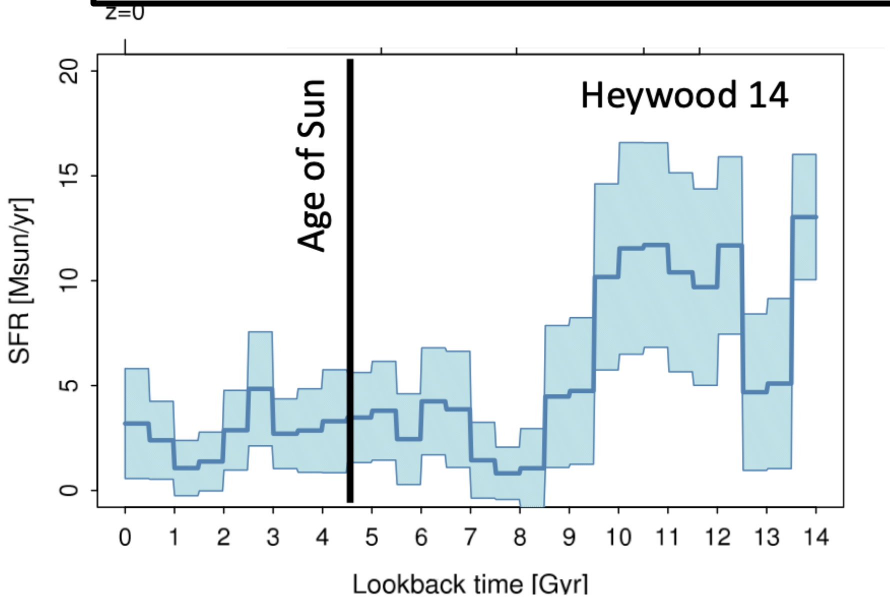


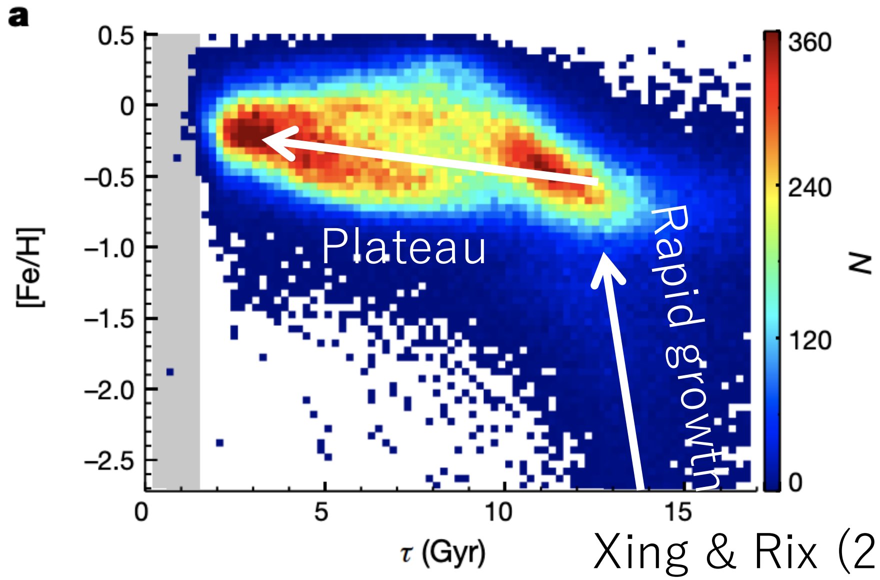
@ disk
SFR ~ 3 Mo/yr
Gas mass ~ 10^9 Mo (Metallicity Zo ~ 0.01 → Metal mass ~ 10^7 Mo)
Salpeter IMF → Massive Star Formation Rate ~ 0.1 Mo/yr

Total Metal Mass Ejected by SNe over Cosmic age
→ ~ (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!
(see, Shimoda, Inutsuka, & Nagashima 2024 for details)

The Galactic Evolution Scenario





Xing & Rix (2022, by Gaia)

@ disk

SFR ~ 3 Mo/yr

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~99 % of metals should be removed from the disk!

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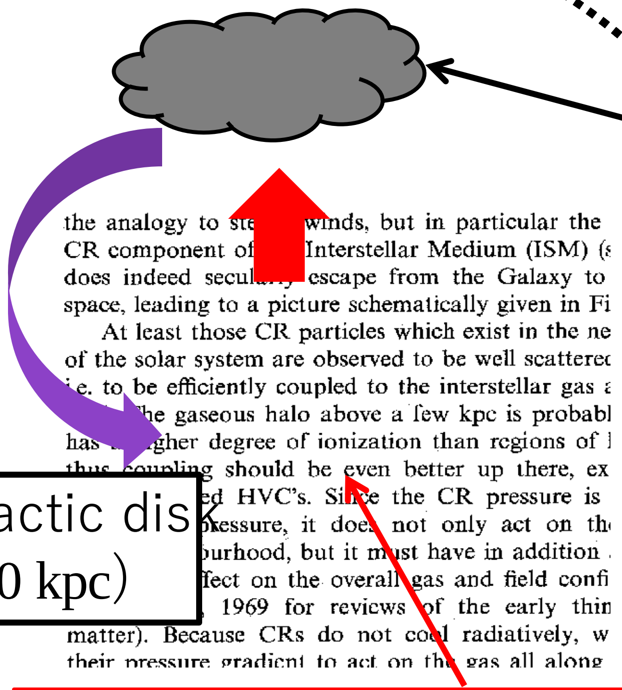
(SJ & Inutsuka 22, SJ, Inutsuka, & Nagashima 24, SJ & Asano 24)

Illustration of the Scenario

DM: ~ 10^{12} M_{sun}
Available gas: ~ 10^{11} M_{sun}
Stars: ~ 4-6 x 10^{10} M_{sun}
→ **Why half?**

Cosmological accretion flow (IGM)

How much gas finally accretes???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...urhood, but it must have in addition
...fect on the overall gas and field confi
... 1969 for reviews of the early thin
matter). Because CRs do not cool radiatively, w
their pressure gradient to act on the gas all along

CGM contains ~10^{10}–10^{12} M_{sun} gas!
From obs. of external galaxies.
→ **metal polluted**
→ **Wind is invoked (SJ & Inutsuk**
Number density: ~10^{-3} cm^{-3}
Mass loss rate : ~ several M_{sun}/yr

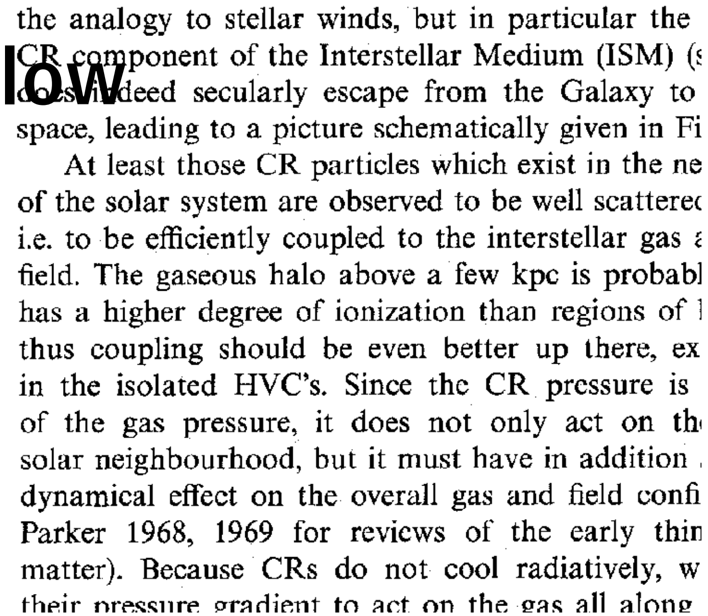
Galactic disk
(~ 10 kpc)

Virial radius
(~300 kpc)

M_{gas} ~ 10^9 M_{sun}
SFR ~ 3 M_{sun}/yr
→ The gas is depleted within ~ 1 Gyr < t_{univ}=13.8Gyr!

Outflow Model (SJ & Inutsuka 2022)
w/ Radiative cooling & CR diffusion

flow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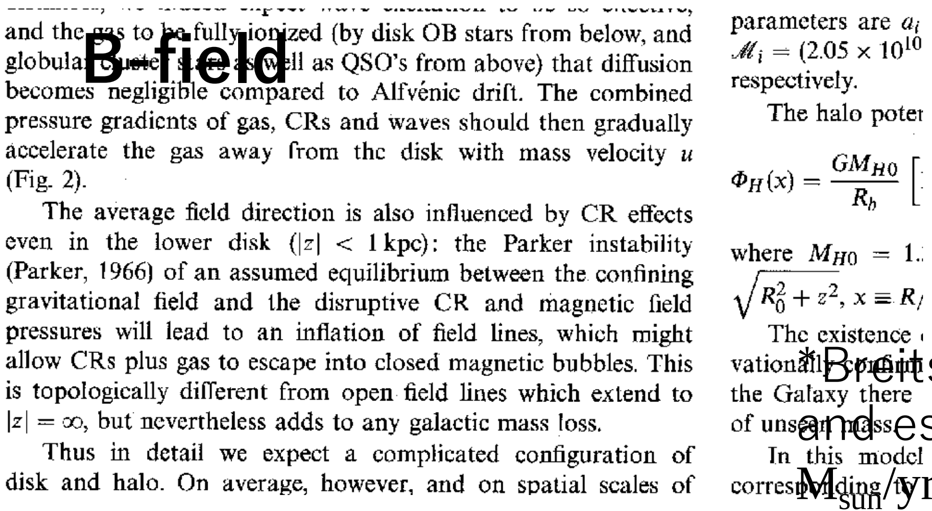
B field


and the gas to be fully ionized (by disk OB stars from below, and globular clusters as well as QSO's from above) that diffusion becomes negligible compared to Alfvénic drift. The combined pressure gradients of gas, CRs and waves should then gradually accelerate the gas away from the disk with mass velocity u (Fig. 2).

The average field direction is also influenced by CR effects even in the lower disk ($|z| < 1$ kpc): the Parker instability (Parker, 1966) of an assumed equilibrium between the confining gravitational field and the disruptive CR and magnetic field pressures will lead to an inflation of field lines, which might allow CRs plus gas to escape into closed magnetic bubbles. This is topologically different from open field lines which extend to $|z| = \infty$, but nevertheless adds to any galactic mass loss.

Thus in detail we expect a complicated configuration of disk and halo. On average, however, and on spatial scales of

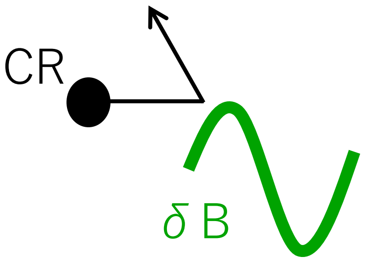
parameters are a_i
$\mathcal{M}_i = (2.05 \times 10^{10}$
respectively.
The halo poter
$\Phi_H(x) = \frac{GM_{H0}}{R_h}$ [
where $M_{H0} = 1.$
$\sqrt{R_0^2 + z^2}$, $x \equiv R/$
The existence
vational constr
the Galaxy there
of unseen mass
In this model
corresponding

Essence

(Shapiro & Field 76)

Radiative cooling → $T < T\_vir$ → wind never launchin

Heating by CRs→ Comparable with Radiative coolin



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

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

*Breitschwerdt+91 extended the pioneering work by Ipavich 75, and estimated that the mass loss rate due to the wind is ~ 1 $M_{\rm sun}$/yr.

Outflow Model (SJ & Inutsuka 2022)
w/ Radiative cooling & CR diffusion

flow

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B-field

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The average field direction is also influenced by CR effects even in the lower disk ($|z| < 1$ kpc): the Parker instability (Parker, 1966) of an assumed equilibrium between the confining gravitational field and the disruptive CR and magnetic field pressures will lead to an inflation of field lines, which might allow CRs plus gas to escape into closed magnetic bubbles. This is topologically different from open field lines which extend to $|z| = \infty$, but nevertheless adds to any galactic mass loss.

Thus in detail we expect a complicated configuration of disk and halo. On average, however, and on spatial scales of

parameters are a_i $\mathcal{M}_i = (2.05 \times 10^{10}$ respectively.

The halo poter

$\Phi_H(x) = \frac{GM_{H0}}{R_h}\left[\right.$

where $M_{H0} = 1.$ $\sqrt{R_0^2 + z^2}$, $x \equiv R/$

The existence vational constraint the Galaxy there of unseen mass

In this model corresponding

Essen
ce

(Shapiro & Field 76)

Radiative cooling → $T < T\_vir$ → wind never launchir

Heating by CRs→ Comparable with Radiative coolin

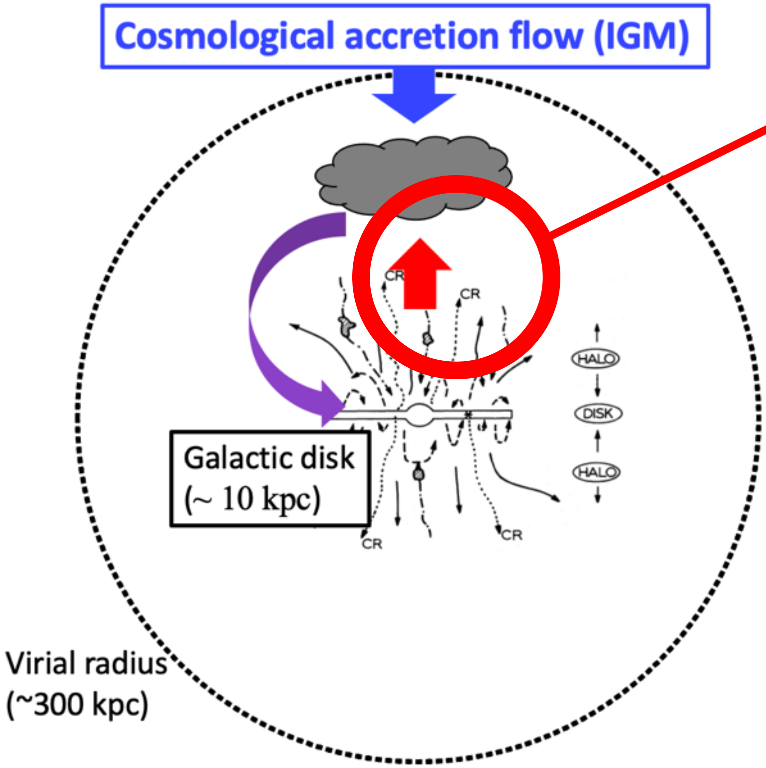
Shimoda & Inutsuka 2022

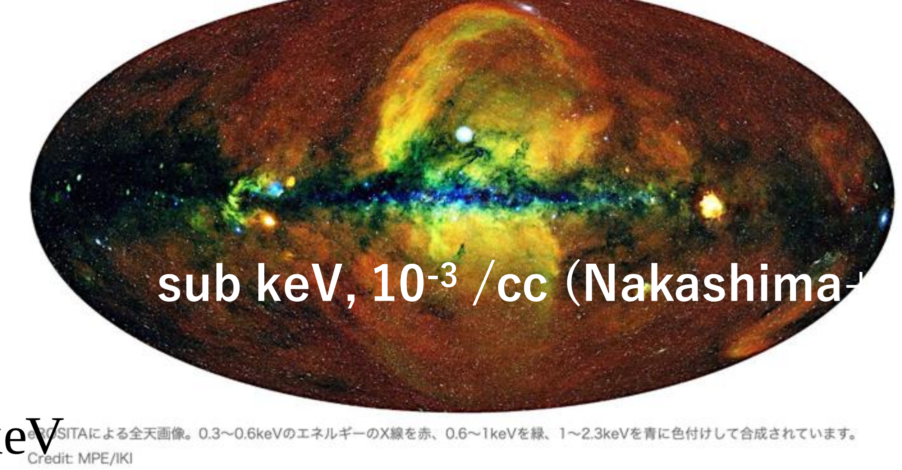
$$\frac{n^2\Lambda}{Q_{\mathrm{w}}} \simeq 0.91\left(\frac{n}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{5/2}\left(\frac{B}{1\ \mu\mathrm{G}}\right)^{-1}\left(\frac{P_{\mathrm{cr}}}{0.3\ \mathrm{eV\ cm}^{-3}}\right)^{-1} \times\left(\frac{H_{\mathrm{cr}}}{10\ \mathrm{kpc}}\right)\left(\frac{\Lambda}{10^{-22}\ \mathrm{erg\ cm}^{3}\ \mathrm{s}^{-1}}\right). \qquad (20)$$

The reasonable physical parameters result in the comparable heating rate!

*Breitschwerdt+91 extended the pioneering work by Ipavich 75, and estimated that the mass loss rate due to the wind is ~ 1 M_{sun}/yr.

What is essence?





Galactic wind

Temperature (<10 kpc): ~sub keV
Number density : $\sim 10^{-3}$ /cc
Mass loss rate : ~ several M_{sun}/yr

- **The X-ray emitting gas at the disk becomes the wind.**
- **The origin of the Galactic Diffuse X-ray Emission is an *open question*.**

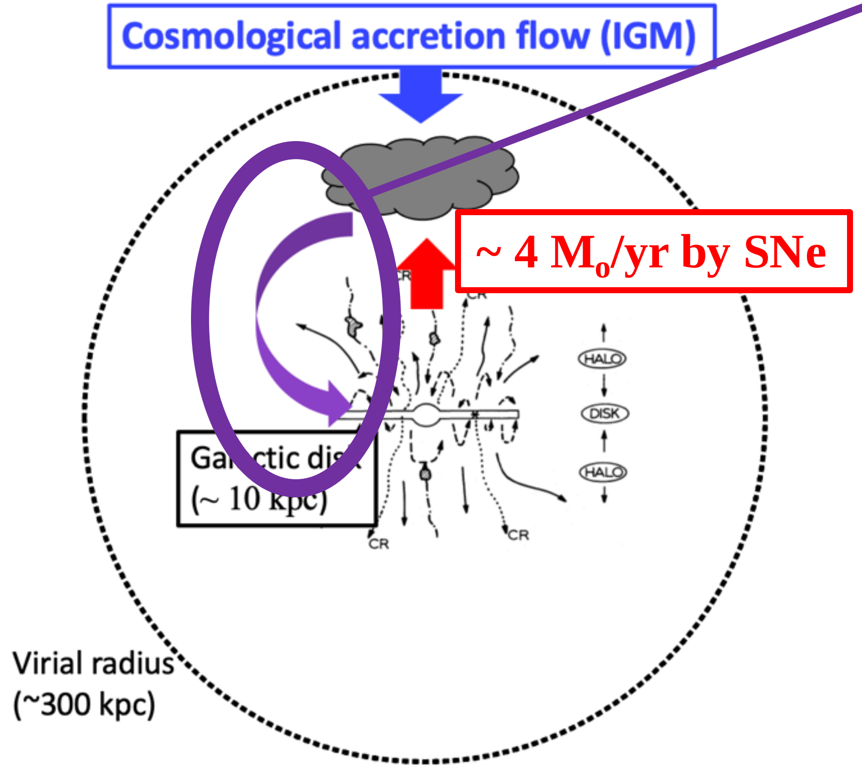
If ~10% of SNe energy is consumed for the X-ray gas…

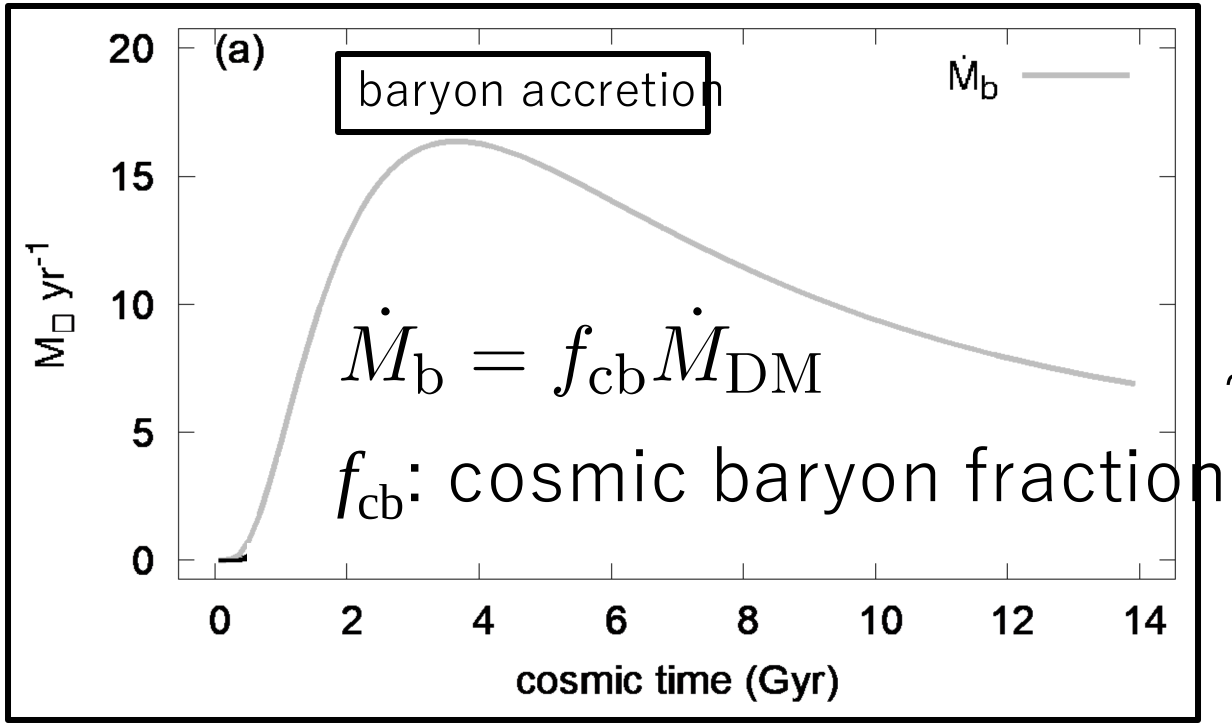
$$\frac{3}{2}\frac{kT_{\mathrm{w}}}{m_{\mathrm{p}}}\dot{M}_{\mathrm{w}} = \eta L_{\mathrm{SN}} \quad \Rightarrow \quad \dot{M}_{\mathrm{w}} \sim 4\, M_{\odot}/\mathrm{yr}\left(\frac{\eta}{0.1}\right)\left(\frac{L_{\mathrm{SN}}}{10^{42}\ \mathrm{erg/s}}\right)\left(\frac{kT_{\mathrm{w}}}{0.3\ \mathrm{keV}}\right)^{-1}$$

Consistent with both X-ray observations and theoretical model o
(SJ & Inutsuka 2022)

What is essence?

Accretion flow

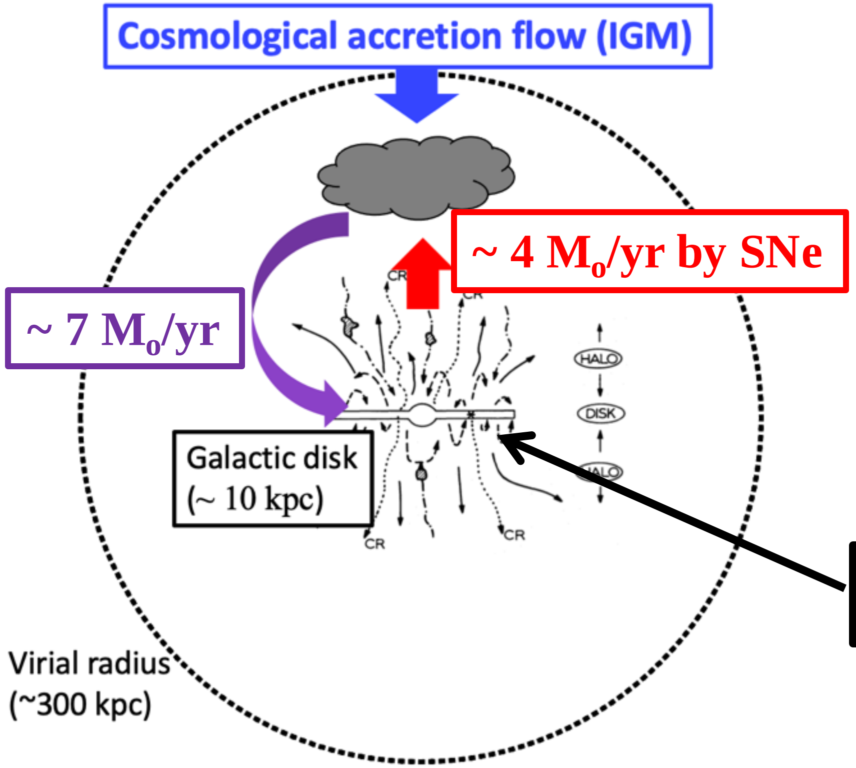


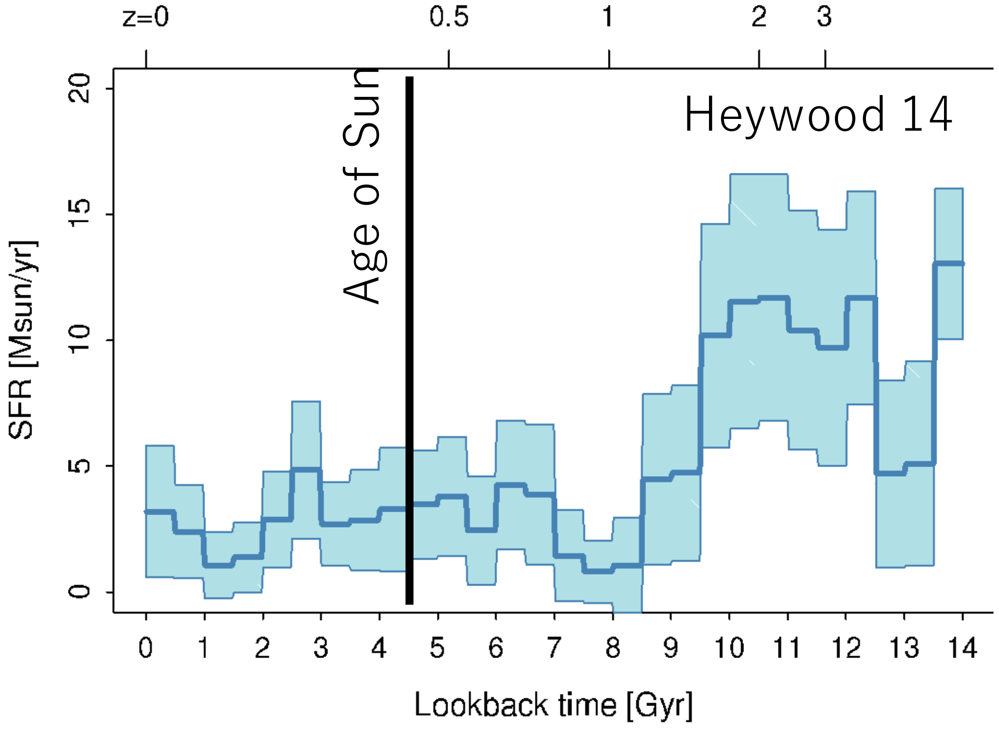


~ 7 M$_o$/yr

The baryon accretion rate
→ Use the results of the DM N-body simulation
(Rodriguez-Puebla+16)

What is essence?





Consequent star formation at the disk

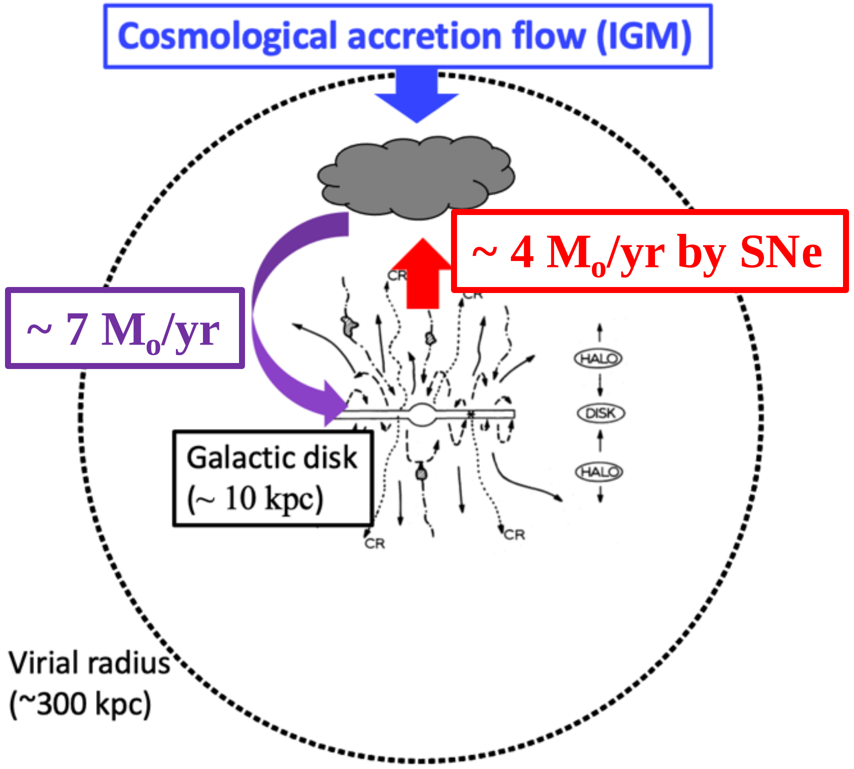
✓ Almost constant SFR

→ quasi steady-state

→ **SFR ~ 7 M_o/yr – 4 M_o/yr ~ 3 M_o/yr**

**Metals are removed from the disk*

What is essence?



Done (SJ+2024)

Problems

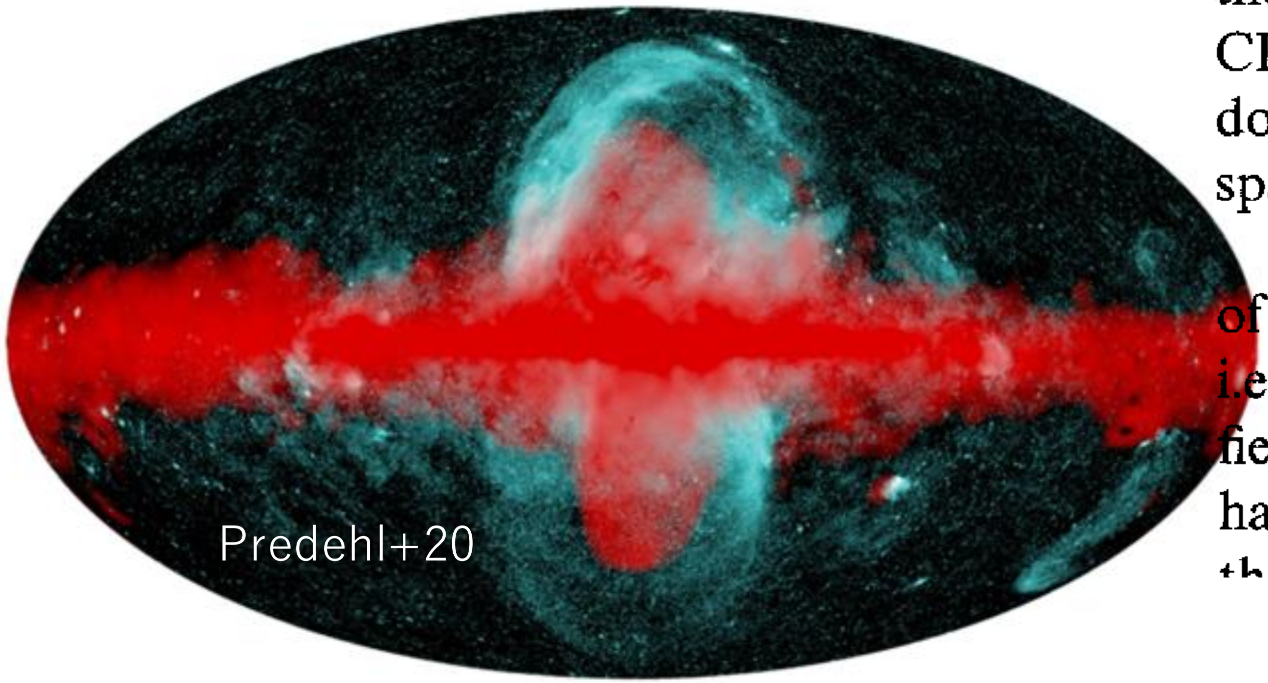
1. The origin of the X-ray emissions at/around the Galactic disk.
→Numerical simulations imply its existence, but actual physical processes are still under debated.

2. The existence of the Cosmological accretion gas onto the disk.
→If it has a virial temperature of ~ 10^6 K, the observations are difficult (FUV ~ soft X-rays are obscured).

3. The resultant disk & CGM conditions (including CRs, metal, etc.) are still unclear.

We introduce one of the consequences of the Galactic wind (SJ & Asano 2024)

Fermi Bubble & eROSITA Bubble



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Breitschwerdt+91

Using observational data of current MW, we will check whether our scenario is consistent with the observed bubbles.

***Hadronic γ-ray scenario** $p_{cr} + p_{gas} \to 2\gamma, \nu$

Gas distribution @the disk

Misiriotis+06

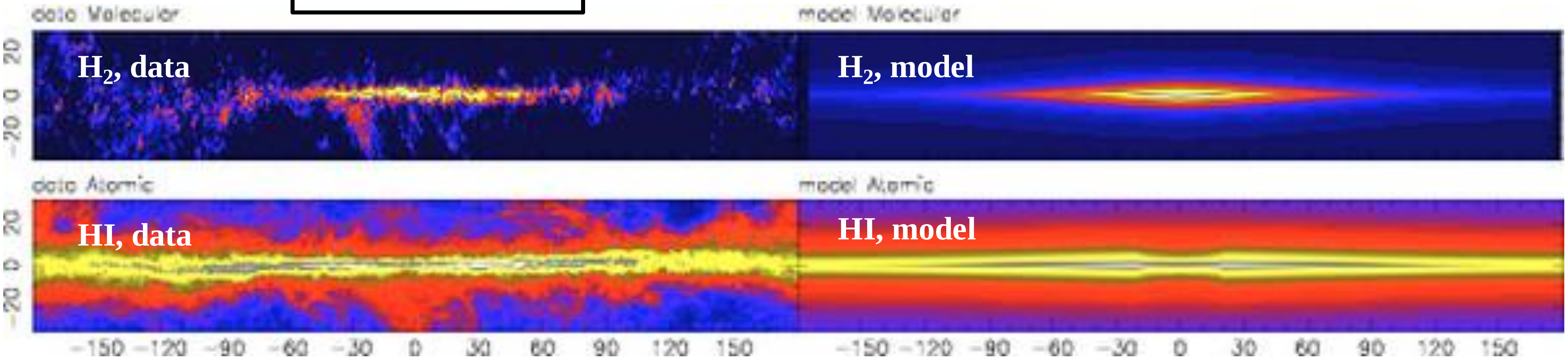


Fig. 3. The gas maps of the Galaxy (*left panels*) in direct comparison with the fitted model (*right panels*). The upper left panel shows the molecular hydrogen distribution (Dame et al. 2001), while the atomic hydrogen distribution (Kalberla et al. 2005) is presented in the bottom left panel. Both maps are given for the Galactic latitude range of −30 to 30 degrees.

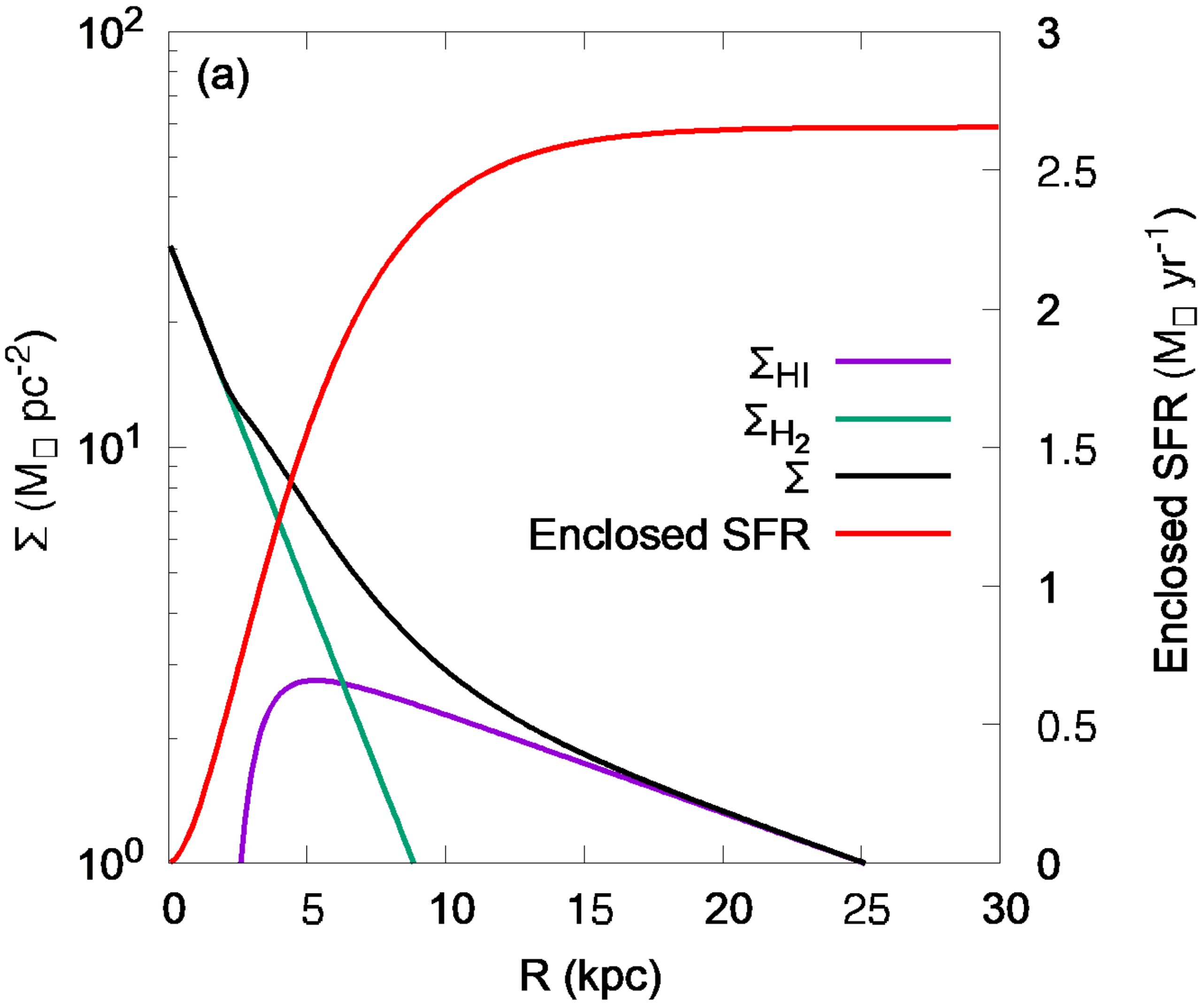
Parameter	Units	Value
$\rho_{H_2}(0,0)$	cm^{-3}	4.06
h_{H_2}	kpc	2.57
z_{H_2}	kpc	0.08
$\rho_{HI}(0,0)$	cm^{-3}	0.32
h_{HI}	kpc	18.24
z_{HI}	kpc	0.52
R_t	kpc	2.75

$$\rho_{H_2}(R,z) = \rho_{H_2}(0,0)\exp\left(-\frac{R}{h_{H_2}} - \frac{|z|}{z_{H_2}}\right),$$

$$\rho_{HI}(R,z) = \begin{cases} \rho_{HI}(0,0)\exp\left(-\frac{R}{h_{HI}} - \frac{|z|}{z_{HI}}\right) & , \rho > R_t \\ 0 & , \rho < R_t \end{cases}$$

Gas distribution @the disk

Misiriotis+06

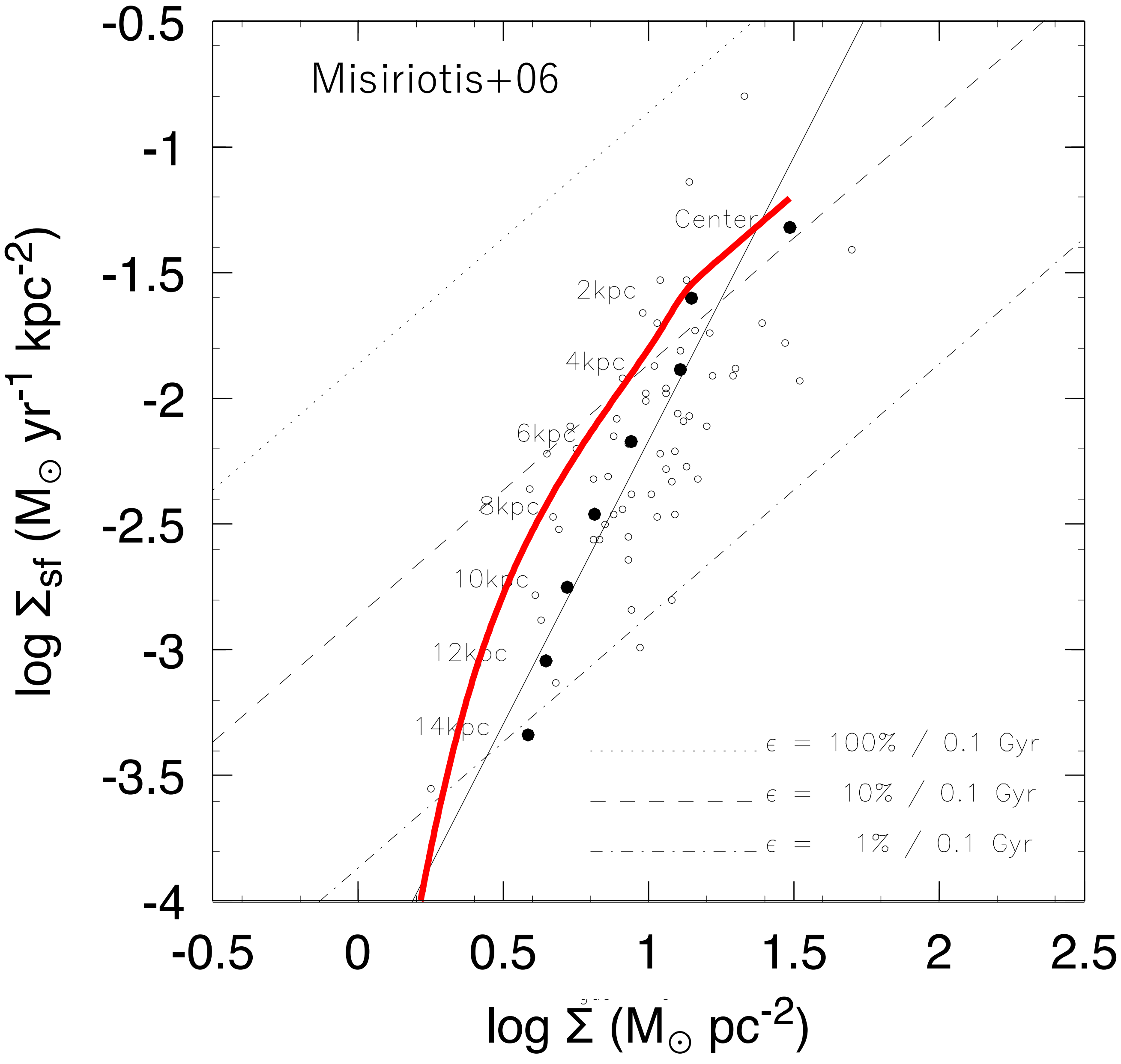


Total Mass at R < 30 kpc

$$M_{\rm HI} \simeq 3.9 \times 10^9 \, M_\odot$$

$$M_{\rm H_2} \simeq 1.3 \times 10^9 \, M_\odot$$

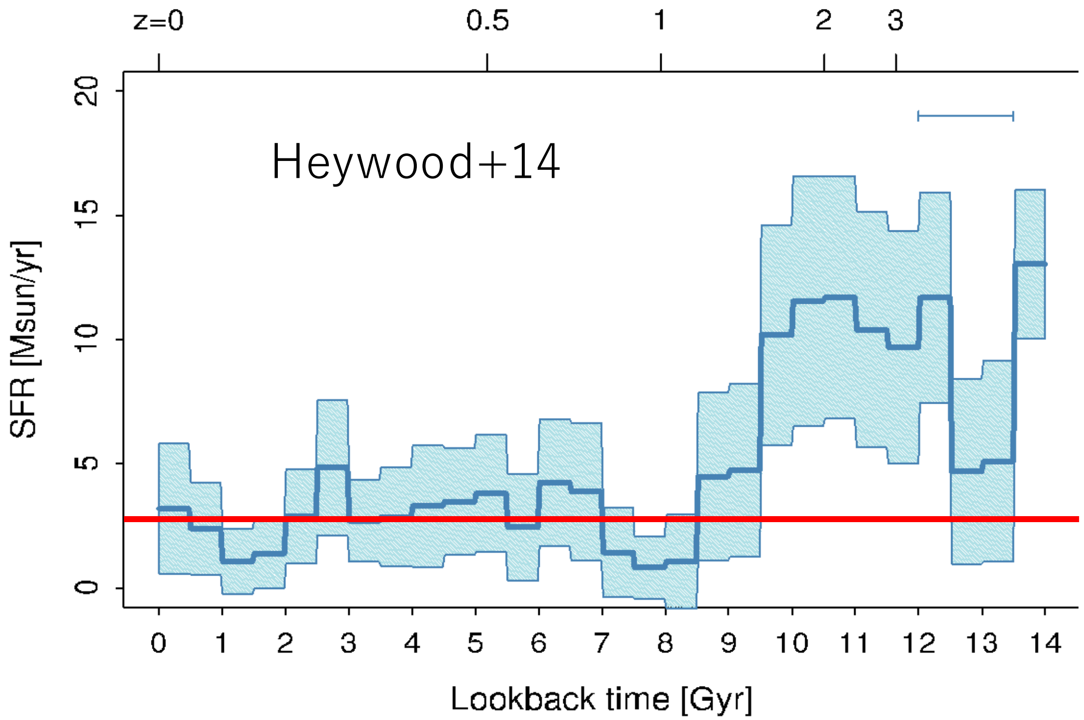
Star Formation Rate



$$\dot{\Sigma}_{\rm sf} = \frac{\epsilon_{\rm sf}}{\tau_{\rm sf}} \Sigma_{\rm H_2},$$

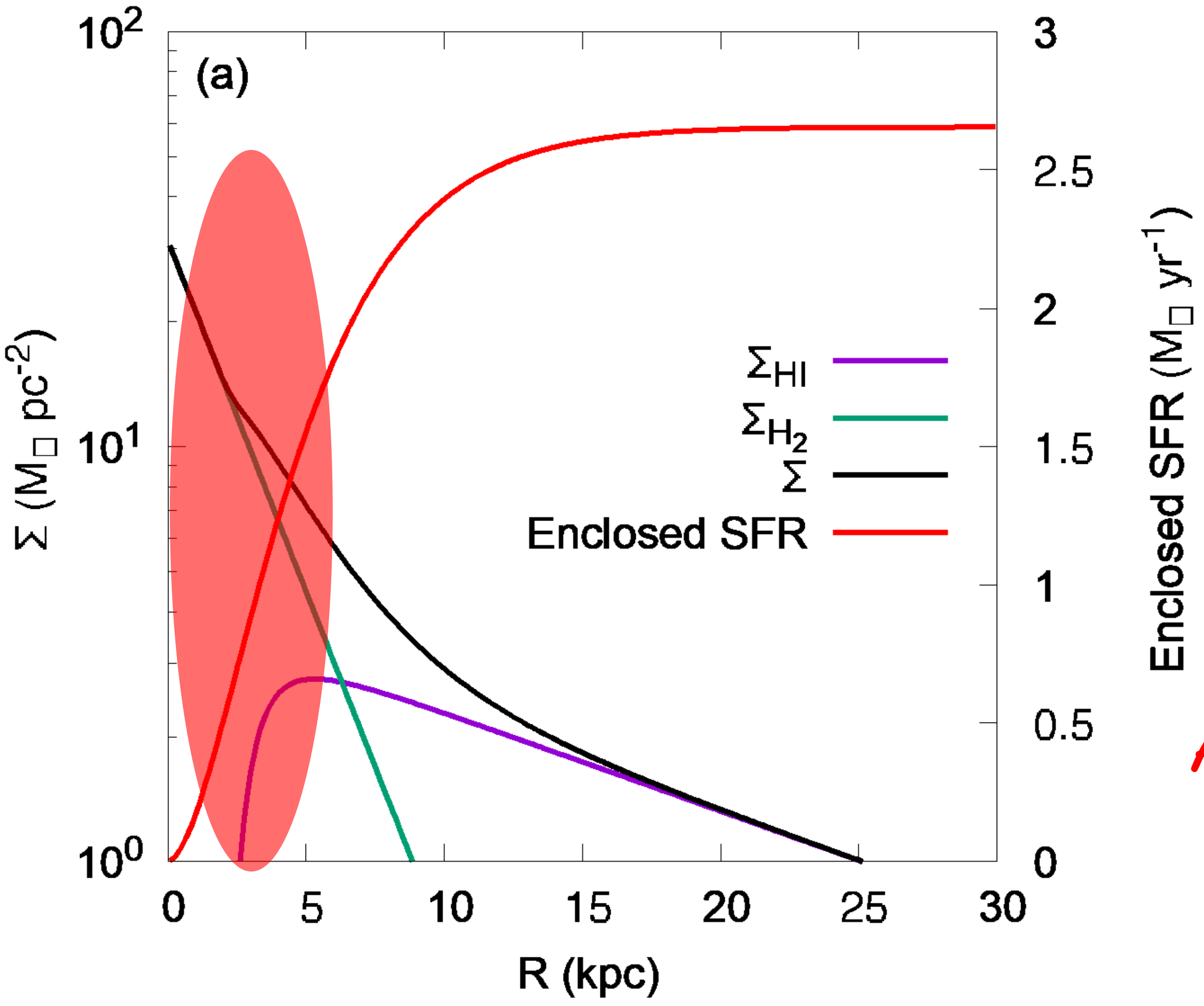
$$\tau_{\rm sf}/\epsilon_{\rm sf} = 0.5 \text{ Gyr}$$

Total Star Formation Rate: 2.7 Mo/yr



Gas distribution @the disk

Misiriotis+06



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$$\dot{\Sigma}_{\rm sf} = \frac{\epsilon_{\rm sf}}{\tau_{\rm sf}} \Sigma_{\rm H_2},$$

$$\tau_{\rm sf}/\epsilon_{\rm sf} = 0.5 \ {\rm Gyr}$$

Active Star Formation Region

$$R < 5 \ {\rm kpc} \equiv R_{\rm sf}$$

$$p_{cr} + p_{gas} \rightarrow 2\gamma,\ \nu$$

Out boundary = 30 kpc

$$\boxed{\frac{d\boldsymbol{v}_{\rm w}}{dt} = -\frac{\nabla P_{\rm cr}}{\rho_{\rm w}} - \boldsymbol{g}}$$

Wind parcels are prepared at each R and $z = z_h$.
Their trajectories are computed like test particles.

the analogy to stellar winds, but in particular the CR component of the Interstellar Medium (ISM) (s does indeed secularly escape from the Galaxy to space, leading to a picture schematically given in Fi

At least those CR particles which exist in the ne of the solar system are observed to be well scatterec i.e. to be efficiently coupled to the interstellar gas a field. The gaseous halo above a few kpc is probabl has a higher degree of ionization than regions of l coupling should be even better there

Hot gas layer

$z_h = 2$ kpc

midplane

Breitschwerdt+91

Model Computation

- CR transport

$$\frac{\partial N_{\rm cr}(r,\gamma)}{\partial t} = \dot N_{\rm cr,s}(r,\gamma) + D_{\rm cr}(\gamma)\nabla^2 N_{\rm cr}(r,\gamma)$$

- Steady-state

$$N_{\rm cr}(r,\gamma) \approx \frac{\tau_{\rm cr}(\gamma)}{4\pi H^2}\int \frac{\dot N_{\rm cr,s}(r',\gamma)}{|r-r'|}d^3r'$$

$$\tau_{\rm cr} = 1\ {\rm Myr}\left(\frac{\gamma}{2}\right)^{-0.6}$$

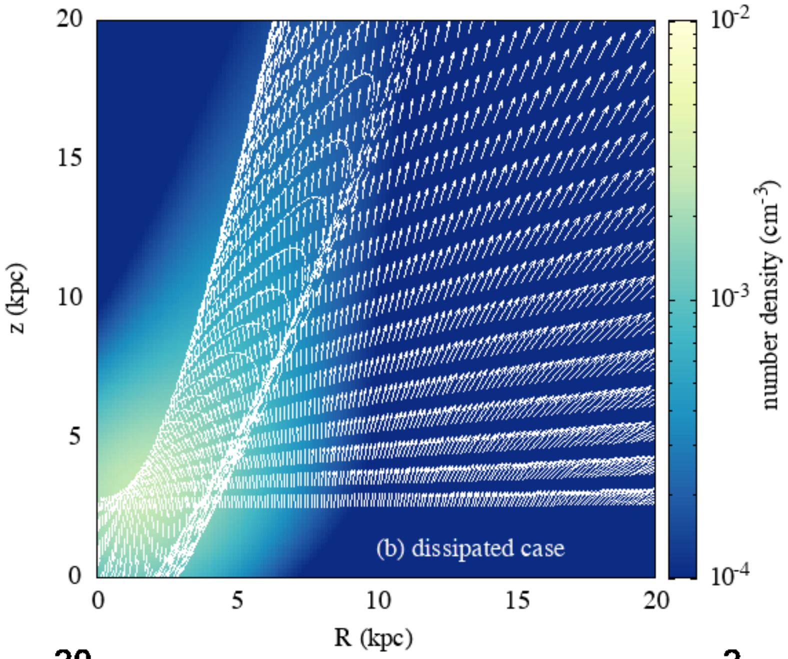
($D_{\rm cr} \approx 10^{28}$ cm^2 s$^{-1}(\gamma/2)^{0.6}$)

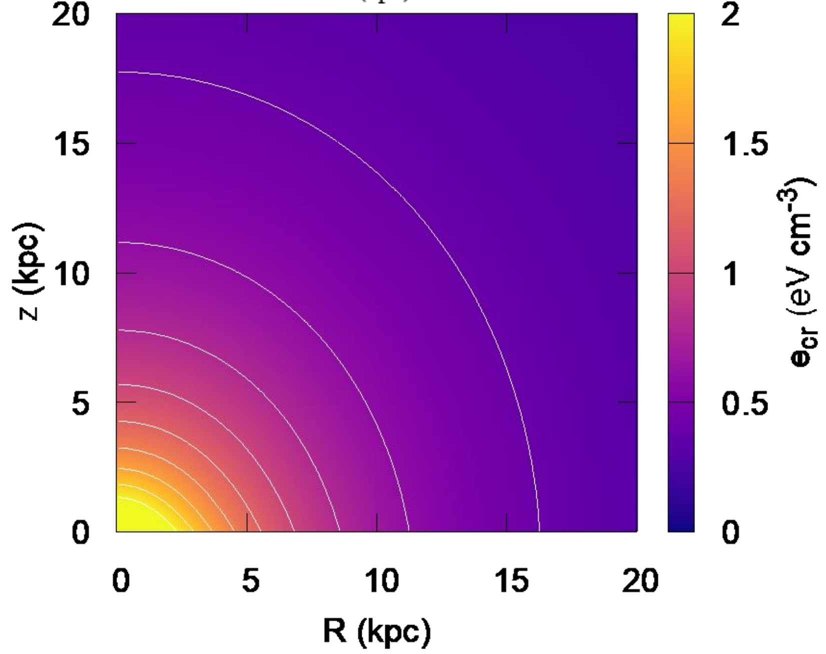
$$\dot N_{\rm cr,s} = \dot N_0\left(\frac{\gamma}{2}\right)^{-2.1}$$

＊10% of SN energy→CR acceleration

We estimate the wind dynamics assuming less efficient CR heating.

*density is smoothed by Gaussian with the width of ~z_h

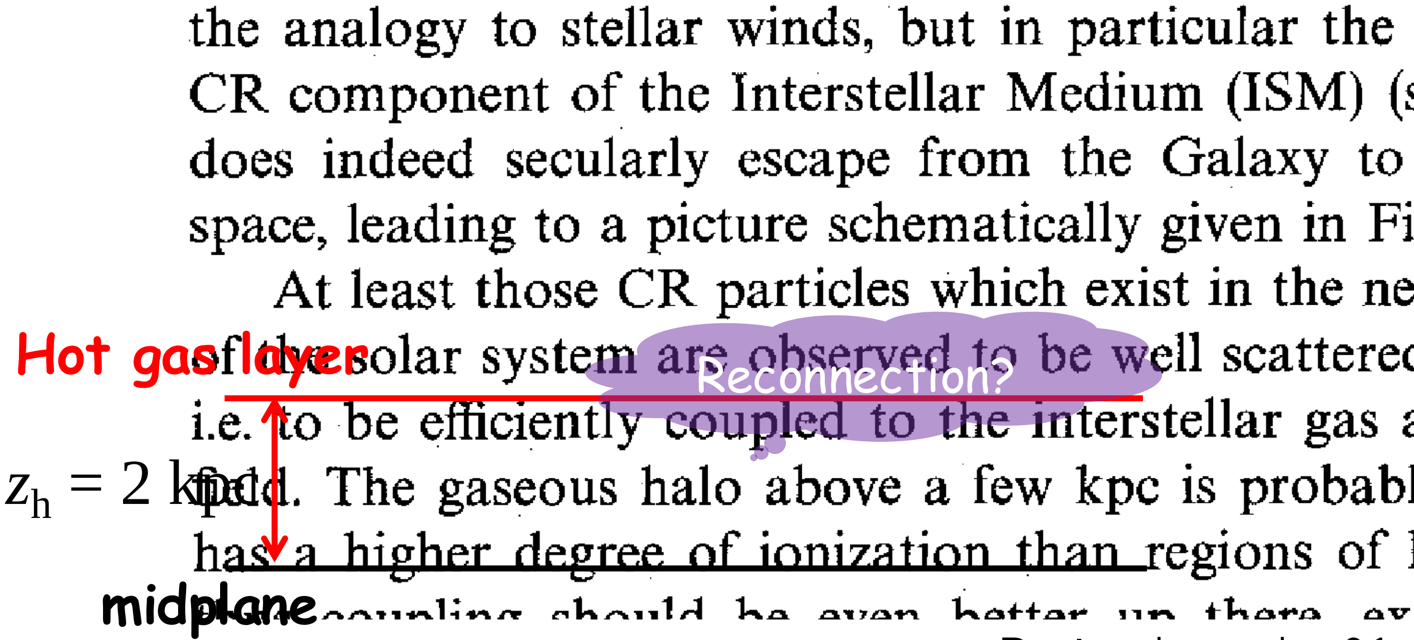




Results

Initial rotation velocity: $v_\varphi = 0.5\ v_{rot}(R,z_h)$

Dissipation of Angular Momentum happens at the disk-halo interface?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Breitschwerdt+91

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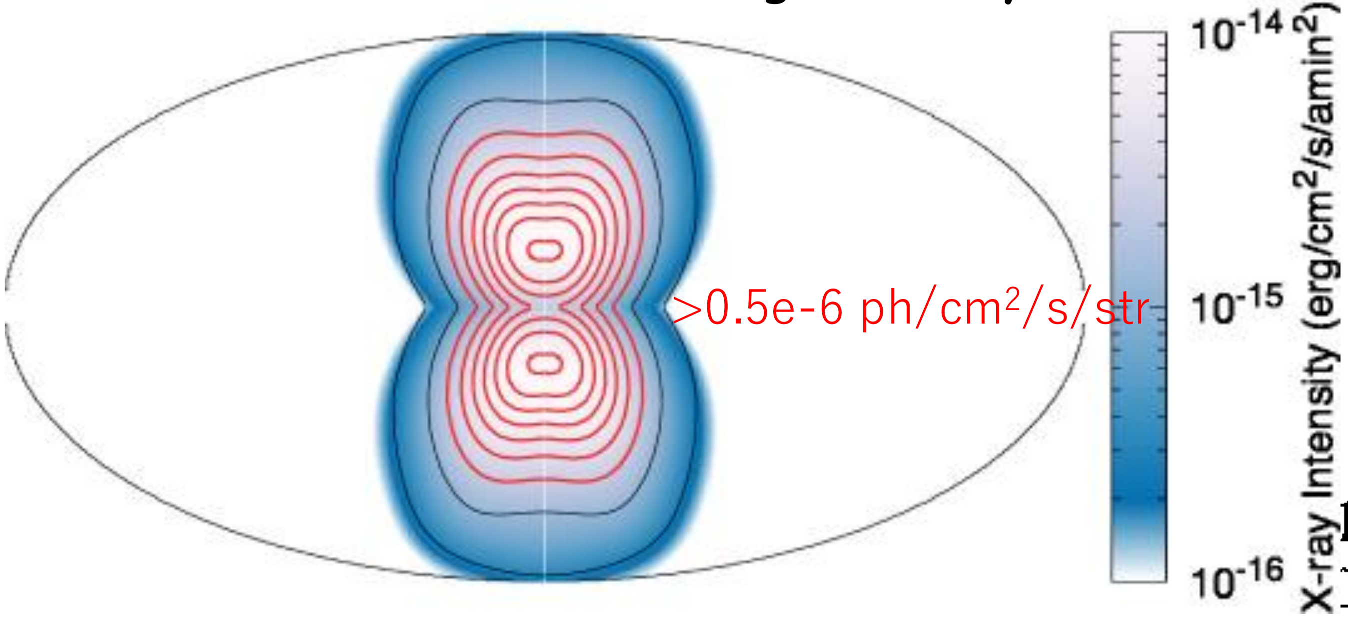
Results

Color: Thermal X-ray

Contour: 1 GeV hadronic gamma-ray



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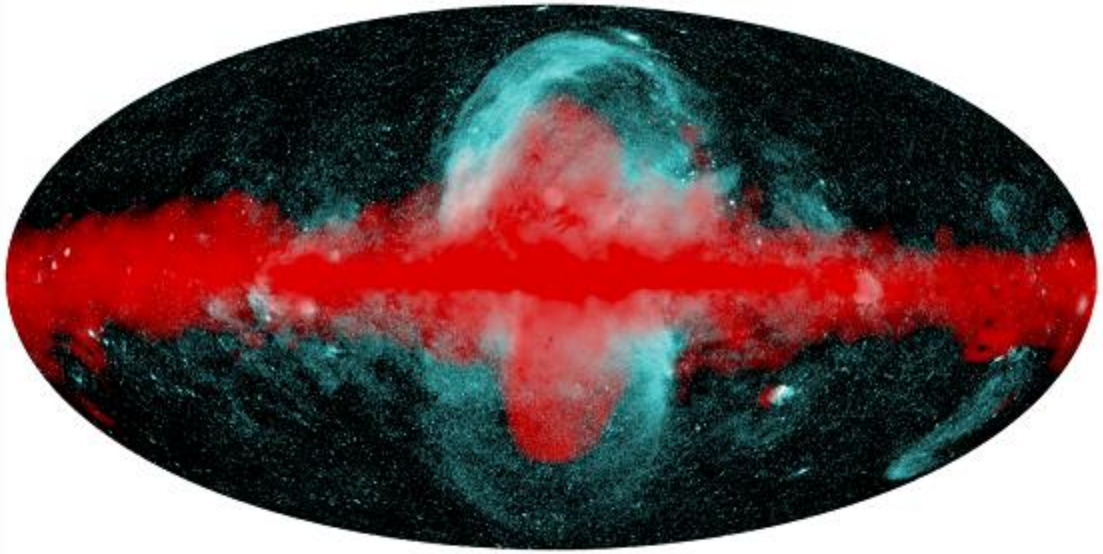
Dissipation of Angular Momentum happens at the disk-halo interface?



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Hot gas layer

Reconnection?

$z_{\rm h} = 2$ kpc

midplane

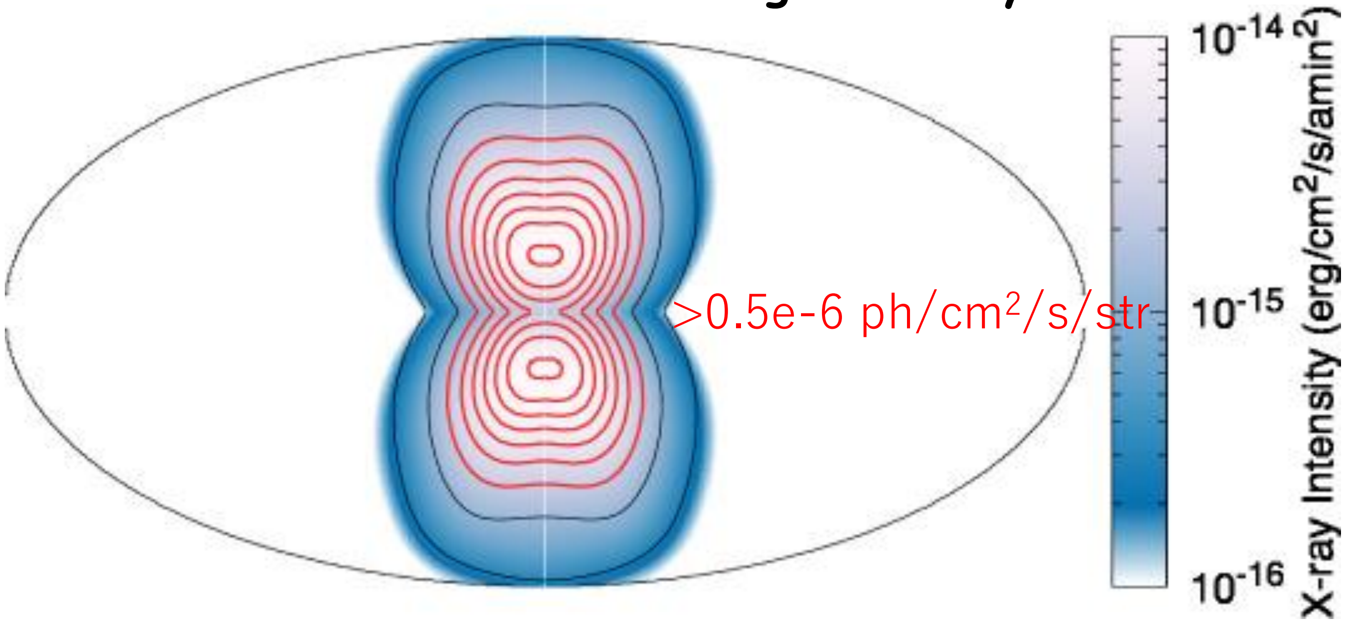
Breitschwerdt+91

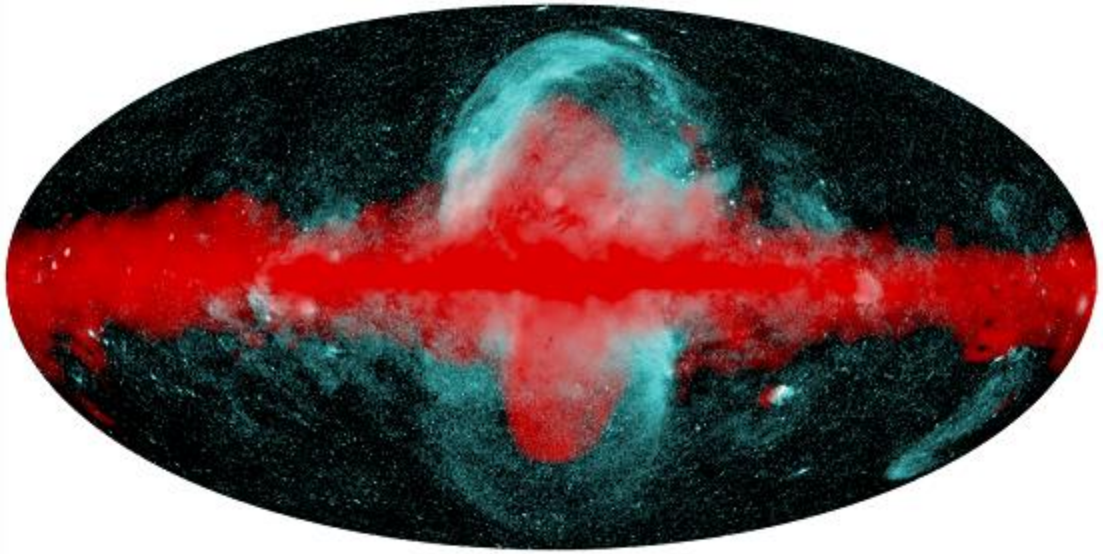
*density is smoothed by Gaussian with the width of ~z_h

Results

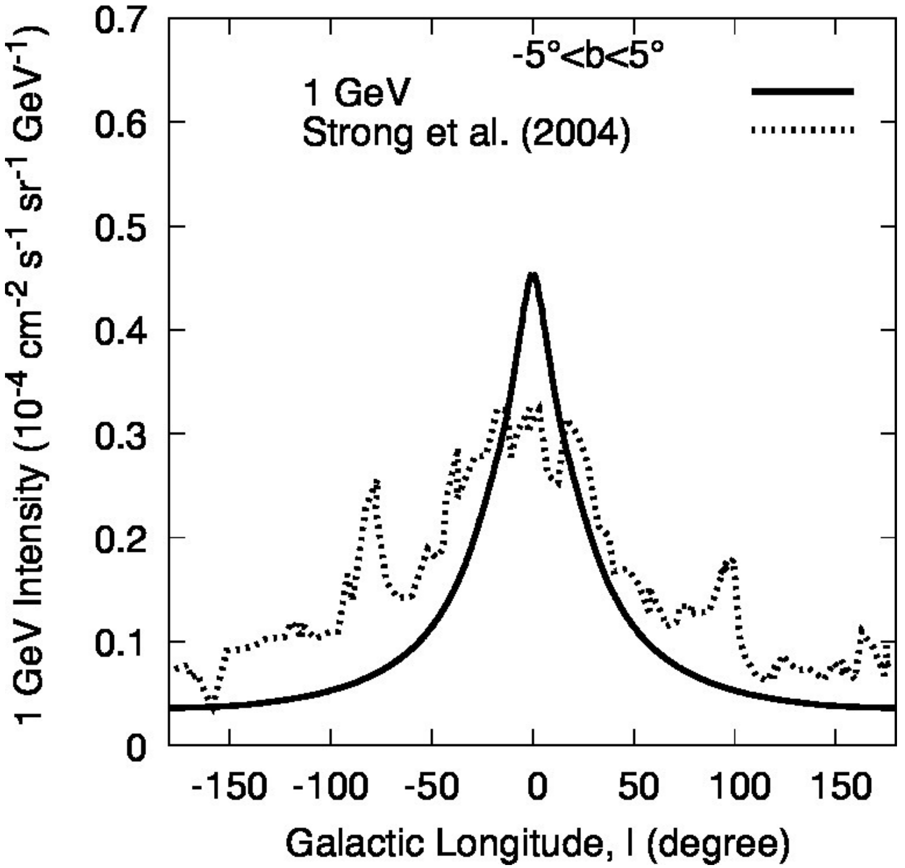
Color: Thermal X-ray

Contour: 1 GeV hadronic gamma-ray

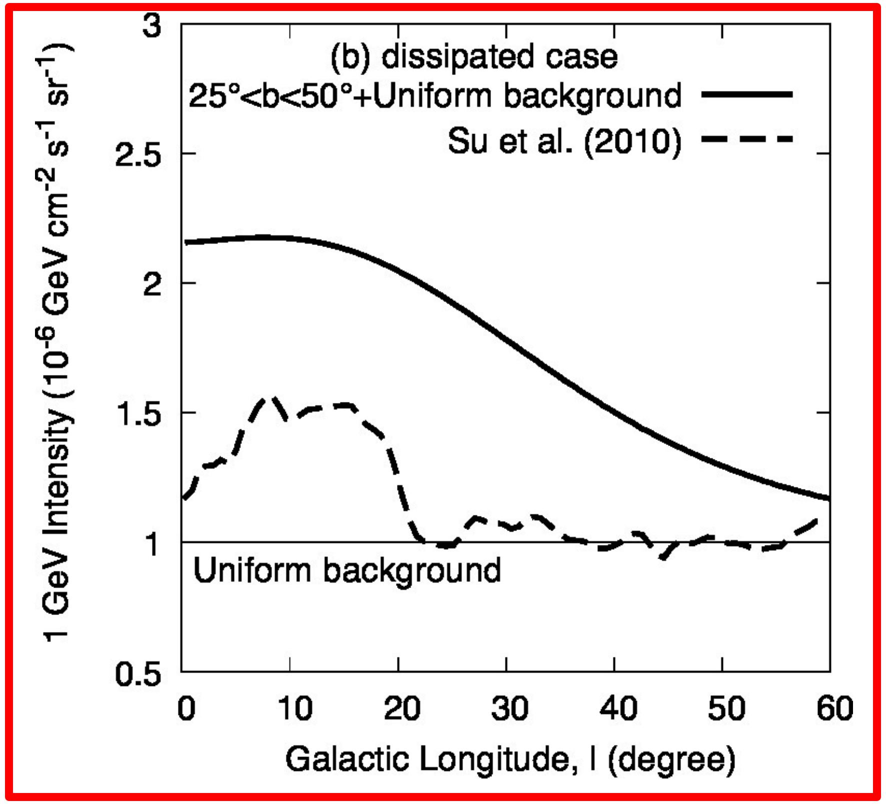




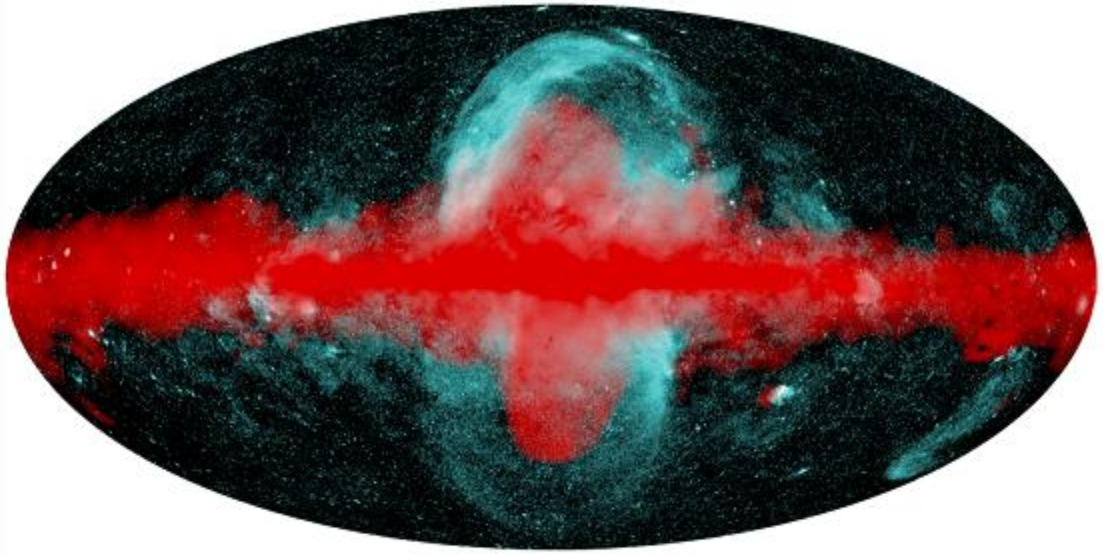
*Gamma-ray from the disk is consistent with the observation (Strong+04).



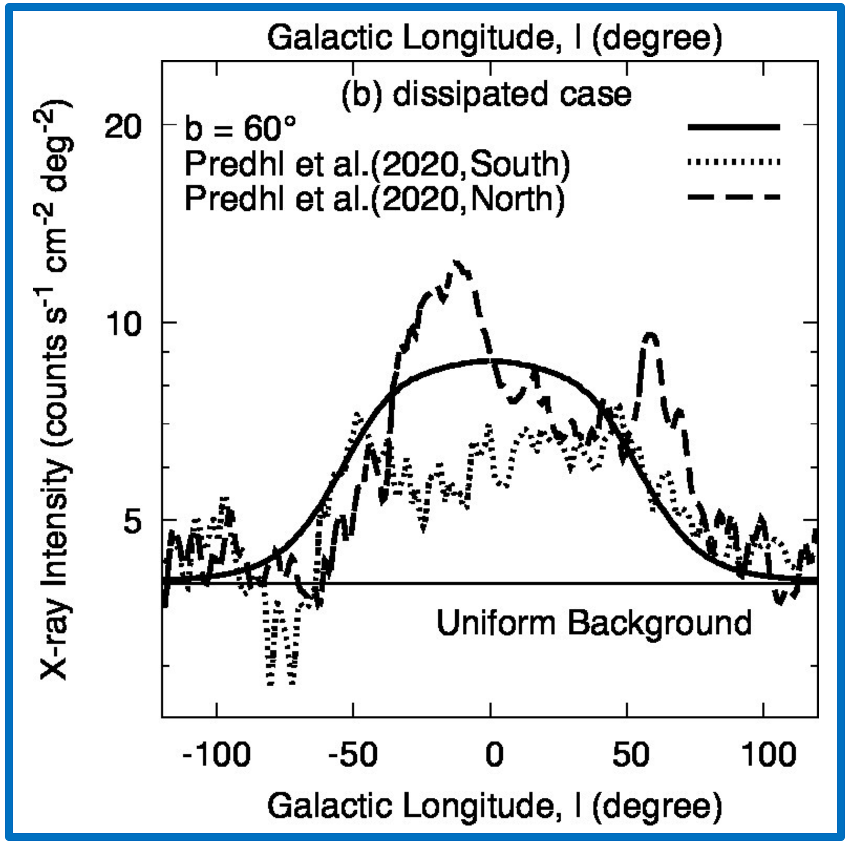
Results: vs. Fermi Bubble



*Hadronic γ-ray

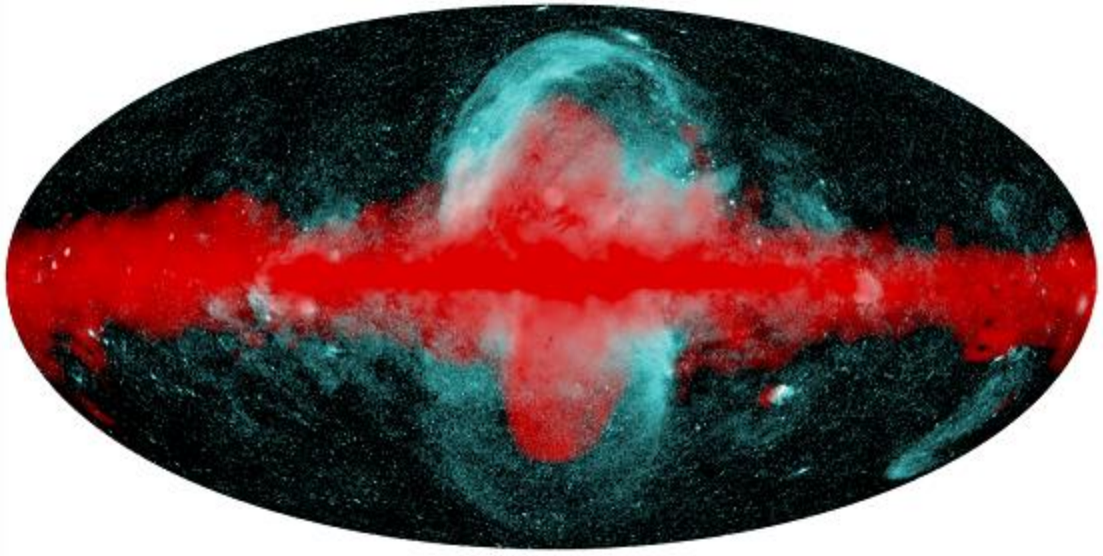


1. The intensity of 0.1-0.5e-6 is consistent.
2. The flat surface brightness profiles are well reproduced.



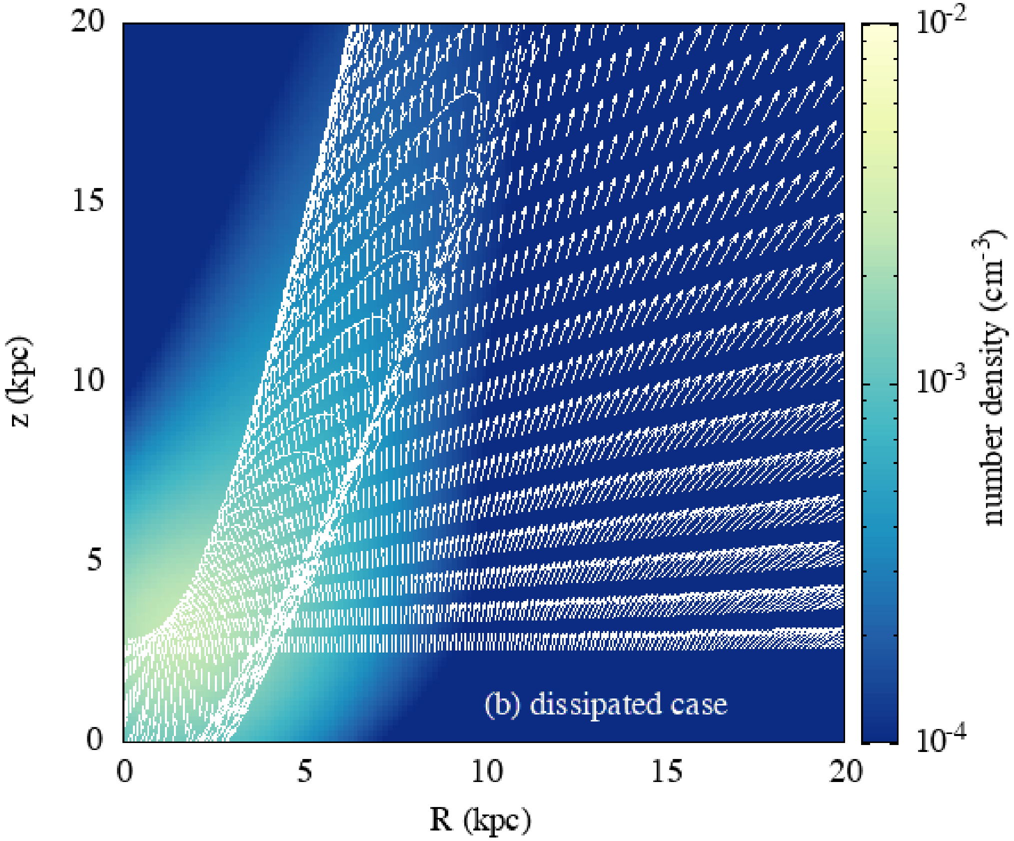
Results: vs. eROSITA Bubble

*Thermal X-ray emissivity = $n^2\Lambda/4\pi$
$\Lambda=10^{23}$ erg cm^3 s^{-1} is assumed
(Shimoda & Inutsuka 22)



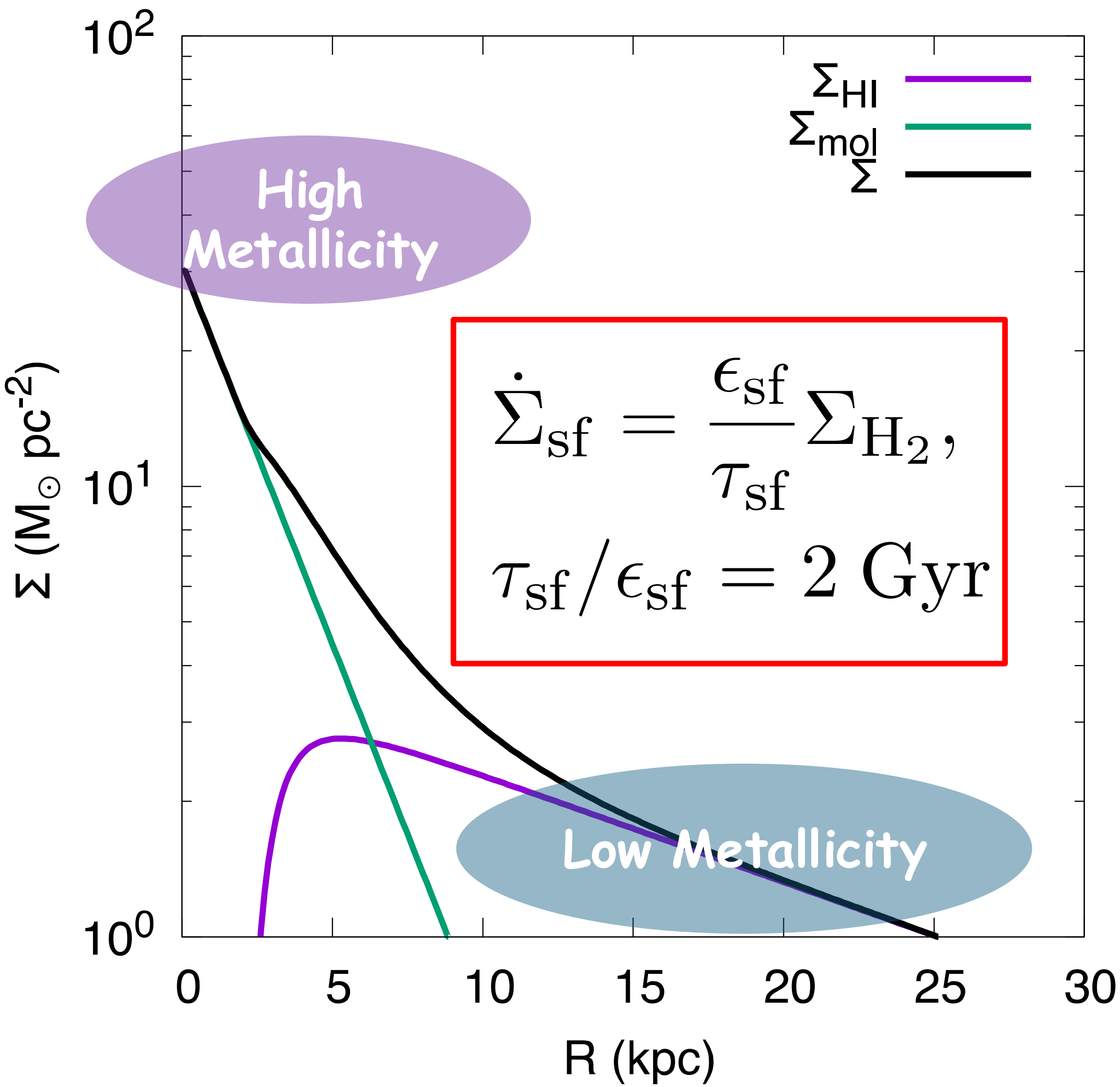
1. The flat surface brightness profiles are well reproduced.
2. The intensity depends on the assumed emissivity.

*density is smoothed by Gaussian with the width of ~z_h



Energetics (Lx ~ 10^{39} erg/s)?
Hardness (γ-ray)?

Summary



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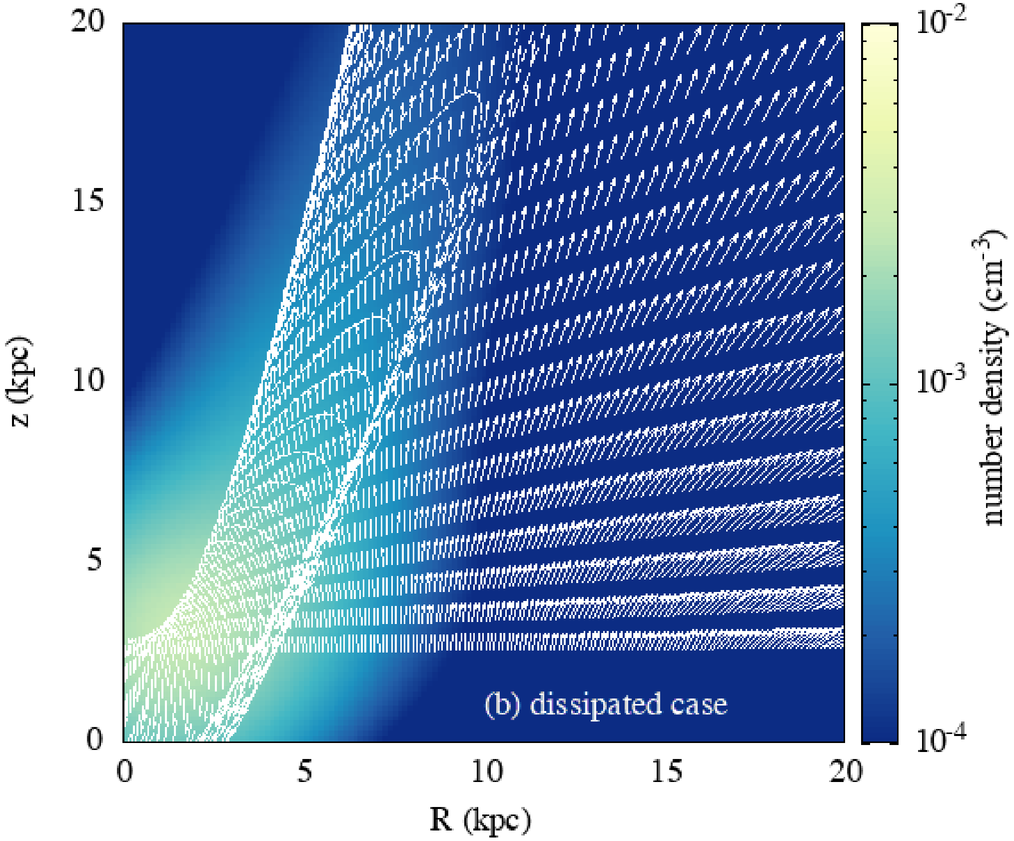

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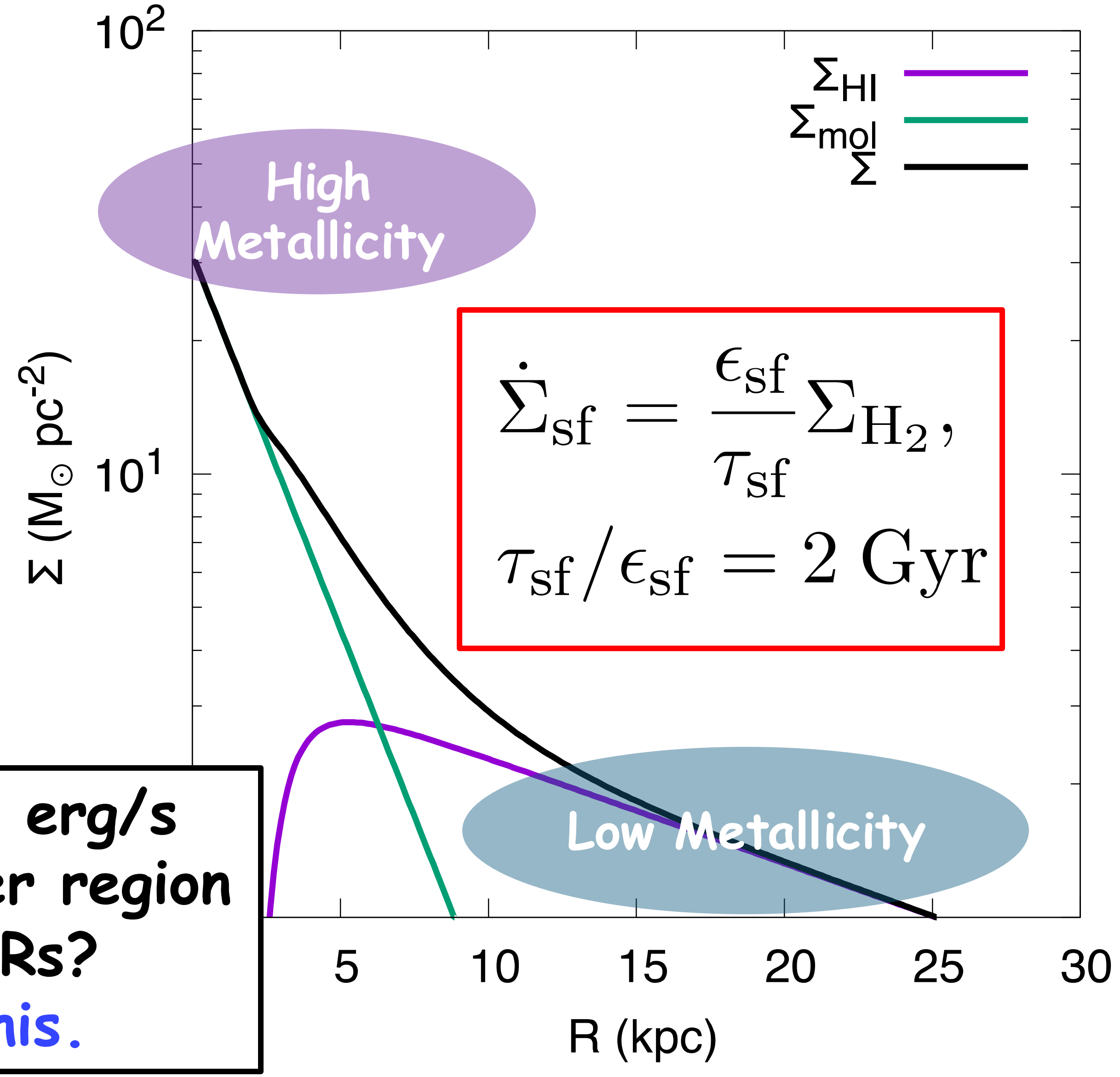

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$$\tau_{\rm sf}/\epsilon_{\rm sf} = 2\ {\rm Gyr}$$

Energetics (Lx ~ 10^{39} erg/s)?→ Lw~10^{41} erg/s
Hardness (γ-ray)?→Reacceleration@inner region
the Maximum energy of reaccelerated CRs?
→ Inamoto-kun(稲元くん) will examine this.

Prospects for New Motivations

➢ Reacceleration at the galactic halo

Can the turbulent halo re-accelerate CRs upto…?

High-energy Gamma-rays & Neutrinos can be emitted from *usual/starburst* galaxies?

→ I expect as a new candidate of the source of UHECRs .

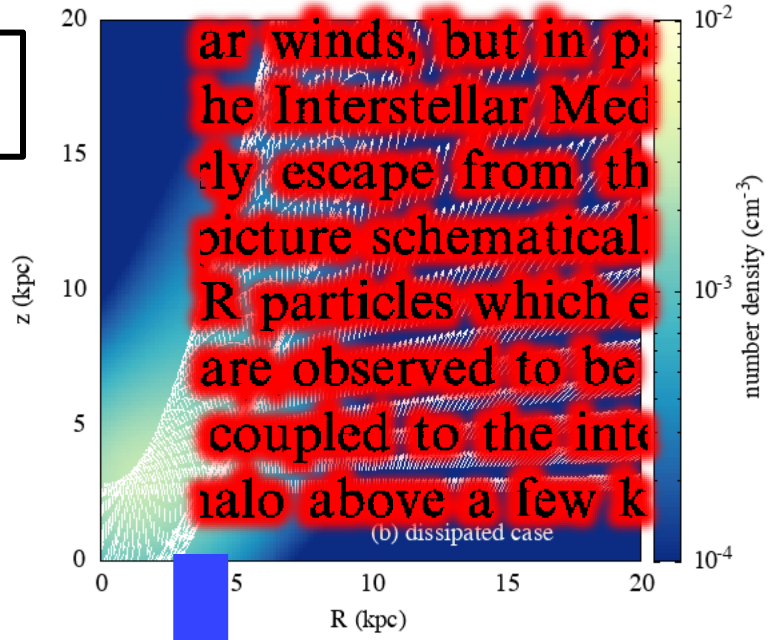
➢ The Angular Momentum should be redistributed.

The gas w/ smaller AM will return to the disk.

The resultant AM will be recorded into the formed stars.

The motions of stars in the disk will reflect the turbulent Halo.

Possible *Correlations* among the CRs, Gamma-rays, Neutrinos, and Stellar Dynamics!



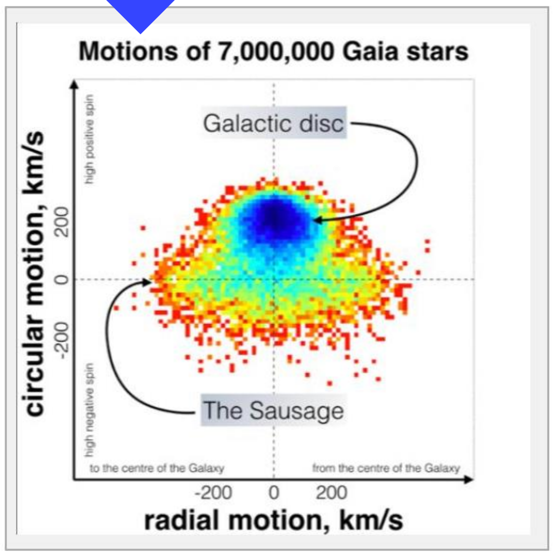
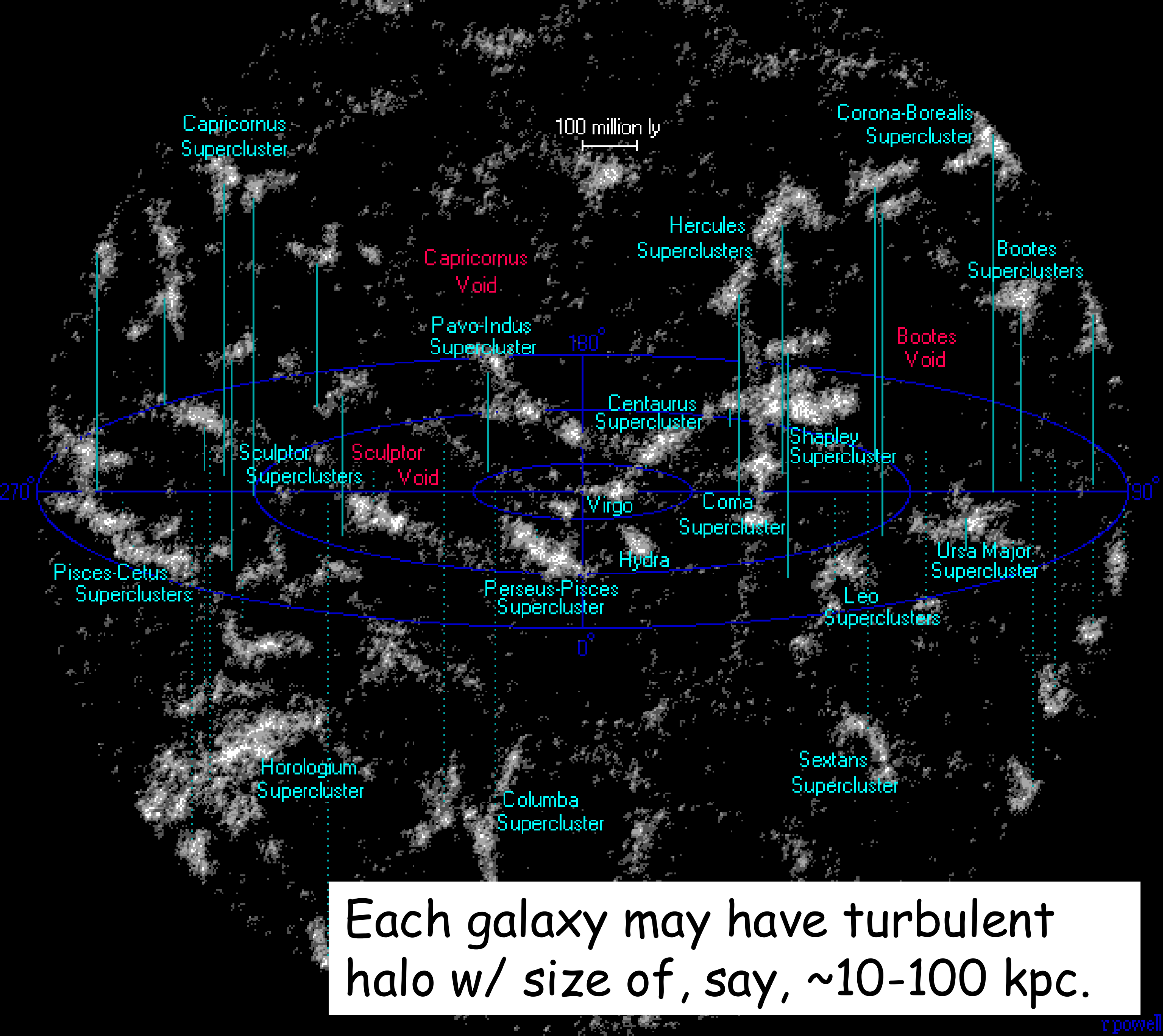


IMAGE: GAIA-SAUSAGE STRUCTURE DETECTED BY THE GAIA SATELLITE IN VELOCITY SPACE. (CREDIT: V. BELOKUROV ET AL. 2018, MNRAS, 478, 611).

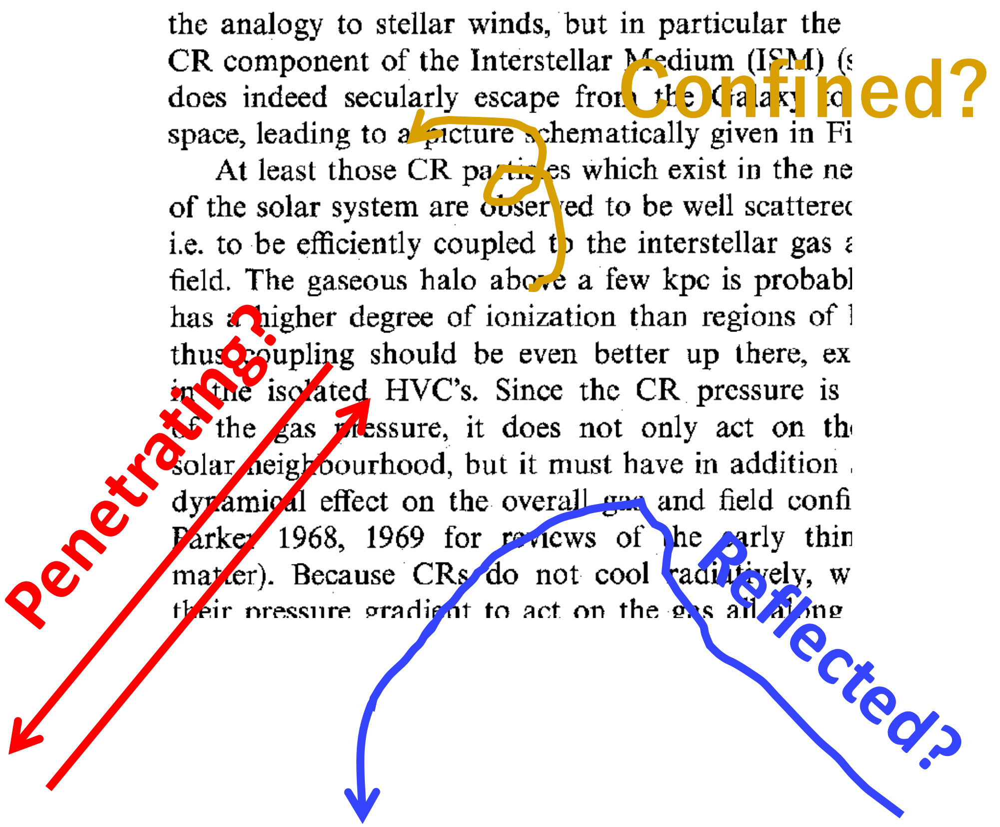
https://www.eurekalert.org/news-releases/6

Galaxy Walls within 307 Mpc (Wikipedia)



Each galaxy may have turbulent halo w/ size of, say, ~10-100 kpc.

Turbulent Halo affects the UHECRs?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has a higher degree of ionization than regions of l
thus coupling should be even better up there, ex
in the isolated HVC's. Since the CR pressure is
of the gas pressure, it does not only act on the
solar neighbourhood, but it must have in addition a
dynamical effect on the overall gas and field confi
Parker 1968, 1969 for reviews of the early thin
matter). Because CRs do not cool radiatively, w
their pressure gradient to act on the gas all along

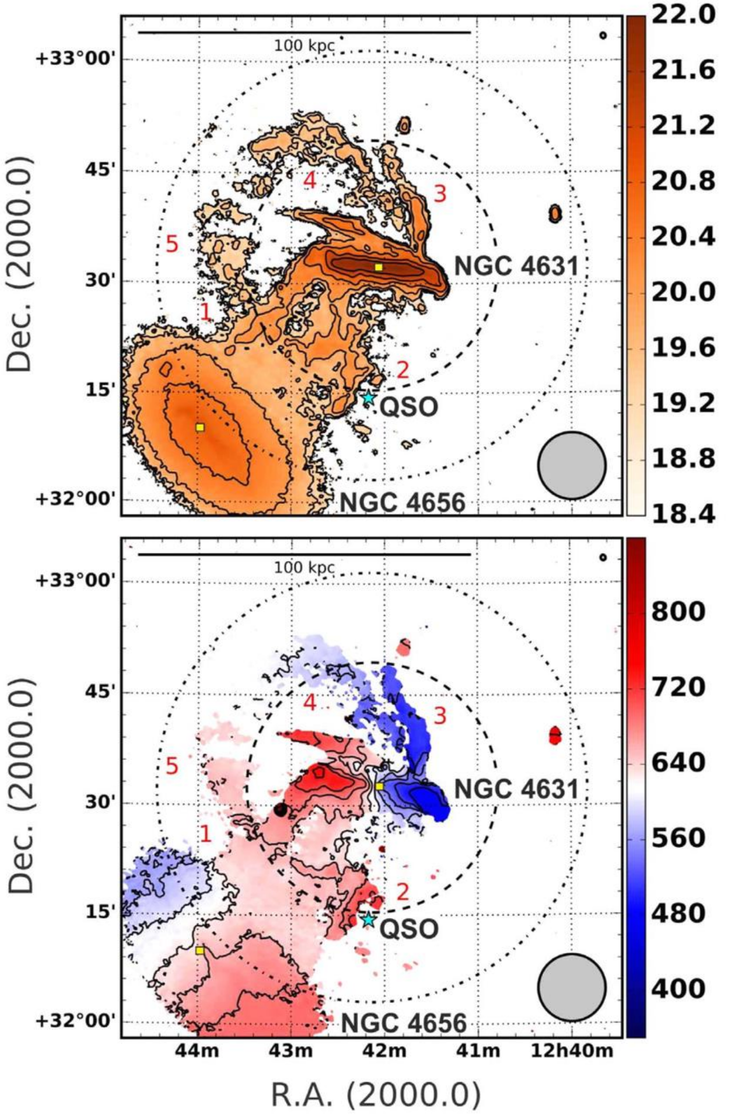
$R \sim 1\ \mathrm{kpc}\ (B/1\ \mu\mathrm{G})^{-1}(E_{cr}/1\ \mathrm{EeV})$

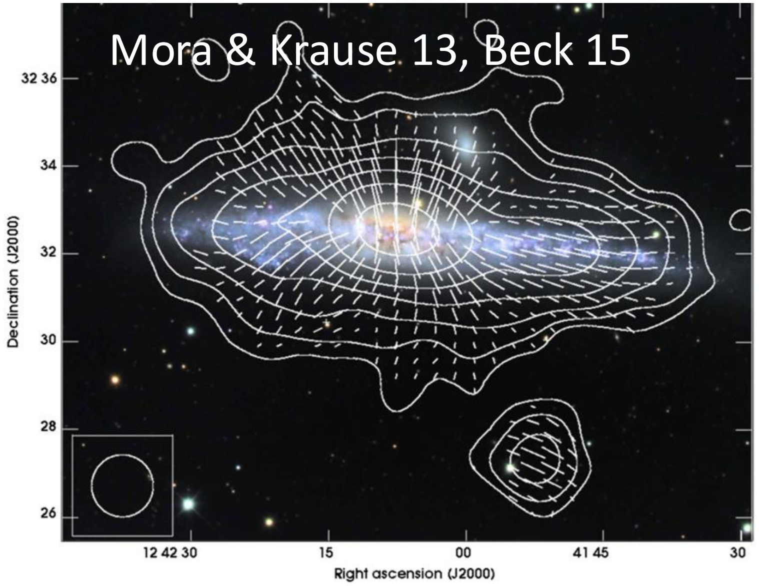
Examine B-filed @ Halo!

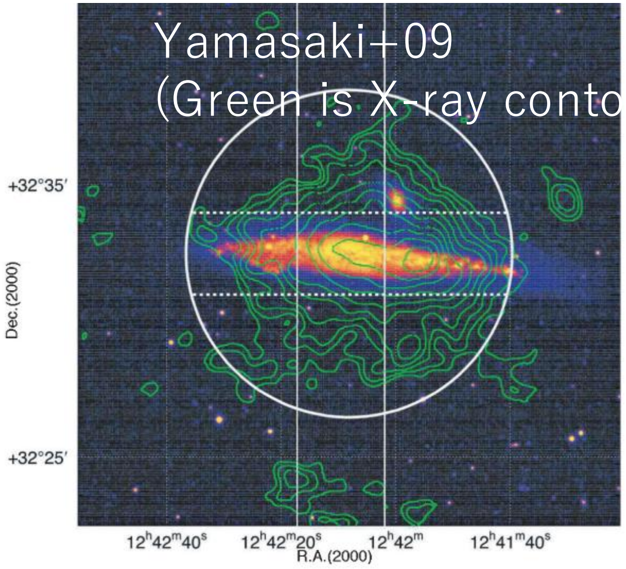
Hints: Case of NGC 4631 (starburst?, D~7 Mpc)

SFR ~ 1 - 5 Mo/yr (Rand+92, Hunter+86, Kennicutt+83)

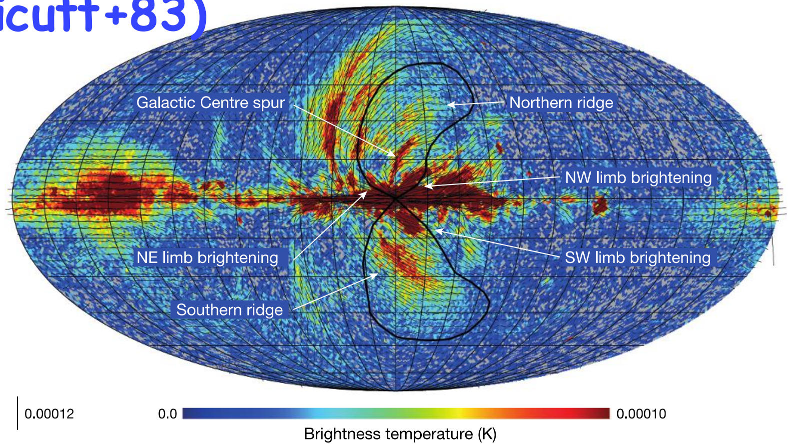
Richter+18

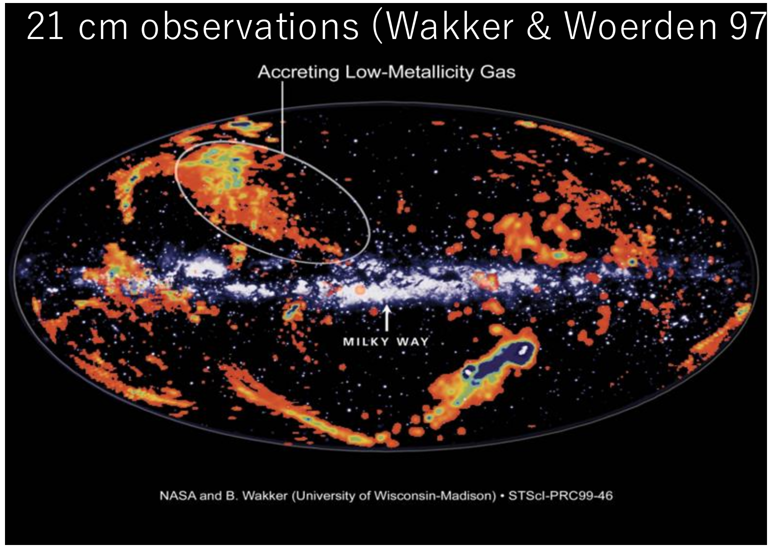






Carretti+13





The external galaxies exhibit many information of the Halo.

I still don't know the diversity...