Cosmic-ray transport in the multiphase galactic halo

: Local spectral hardening in Fermi bubbles

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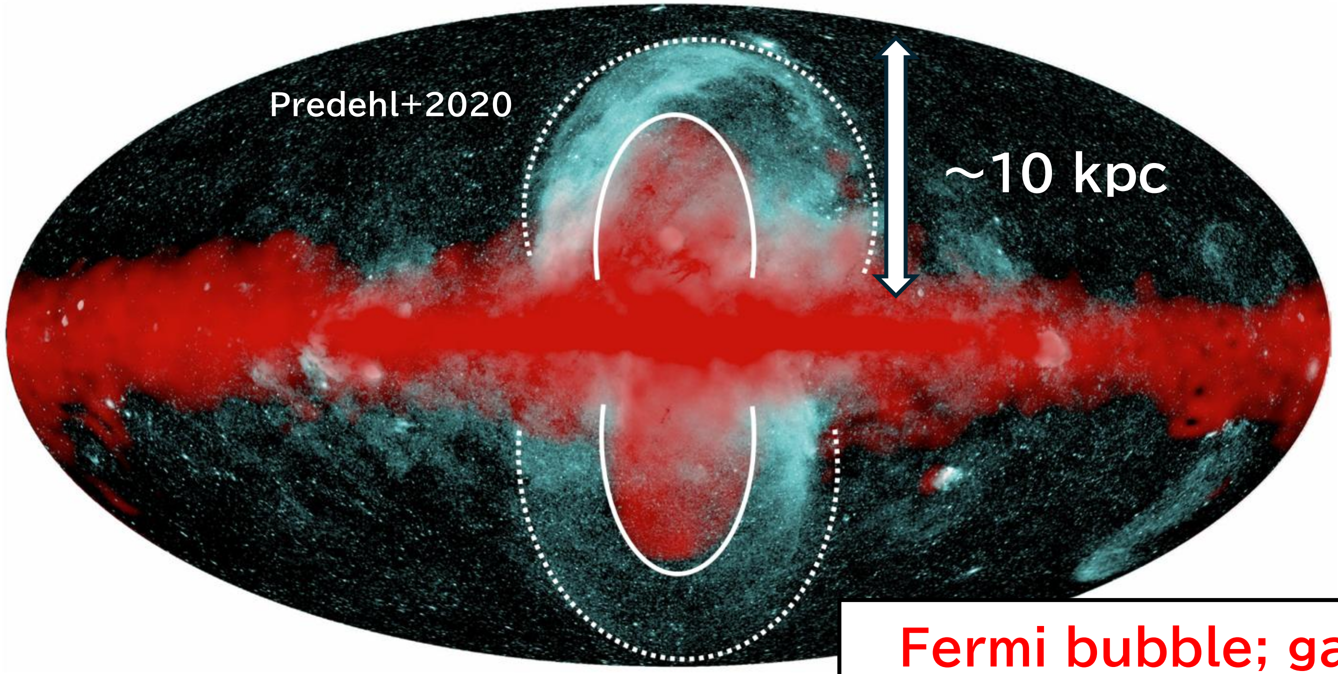
Fermi bubbles

- Large gamma-ray bipolar structures in the Milky Way halo
- **Origin & emission mechanism:** still under debate
- The spatial structure is well resolved



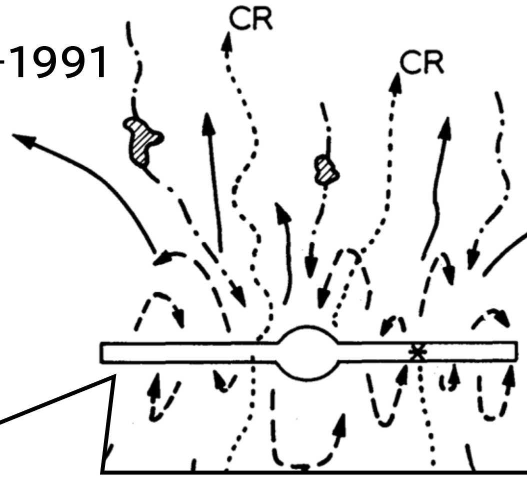
Fermi bubble; gamma ray
eROSITA bubble; X-ray

Fermi bubbles are a unique laboratory for studying where and how CRs are accelerated and transported!

The origin of FBs

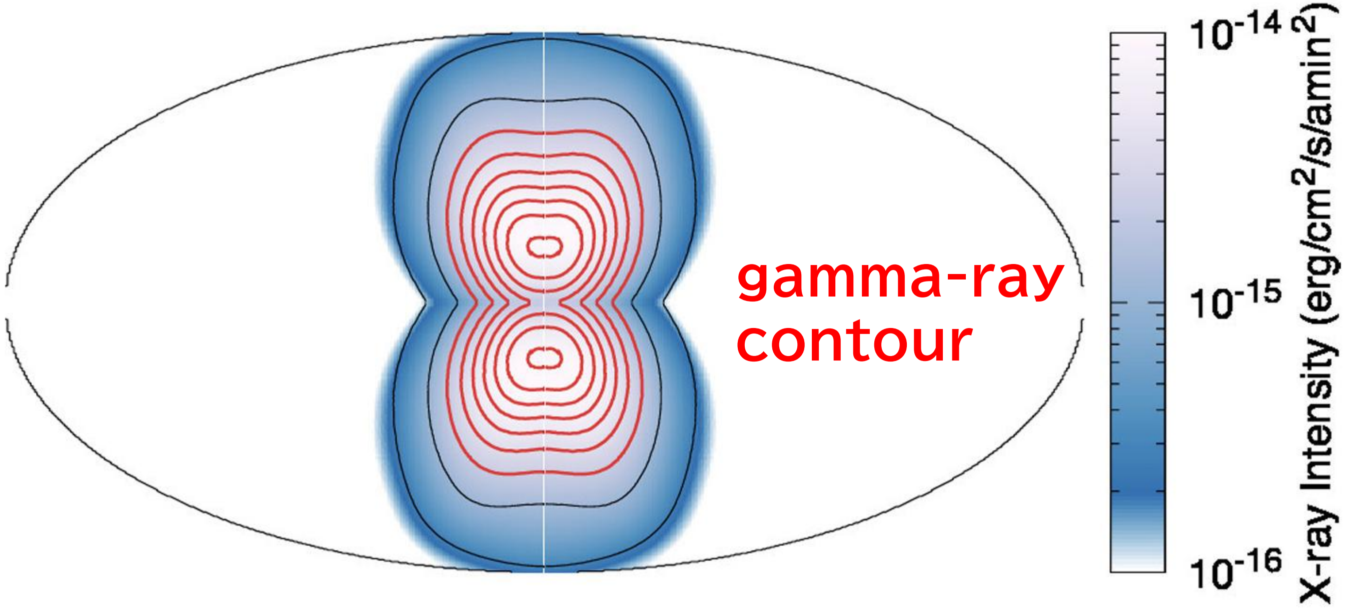
Hadronic scenario:
We focus on persistent <u>CR-driven galactic winds</u>

Breitschwerdt+1991



SNRs continuously supply CRs
&
CRs launch the winds

Analytical model Shimoda & Asano 2024

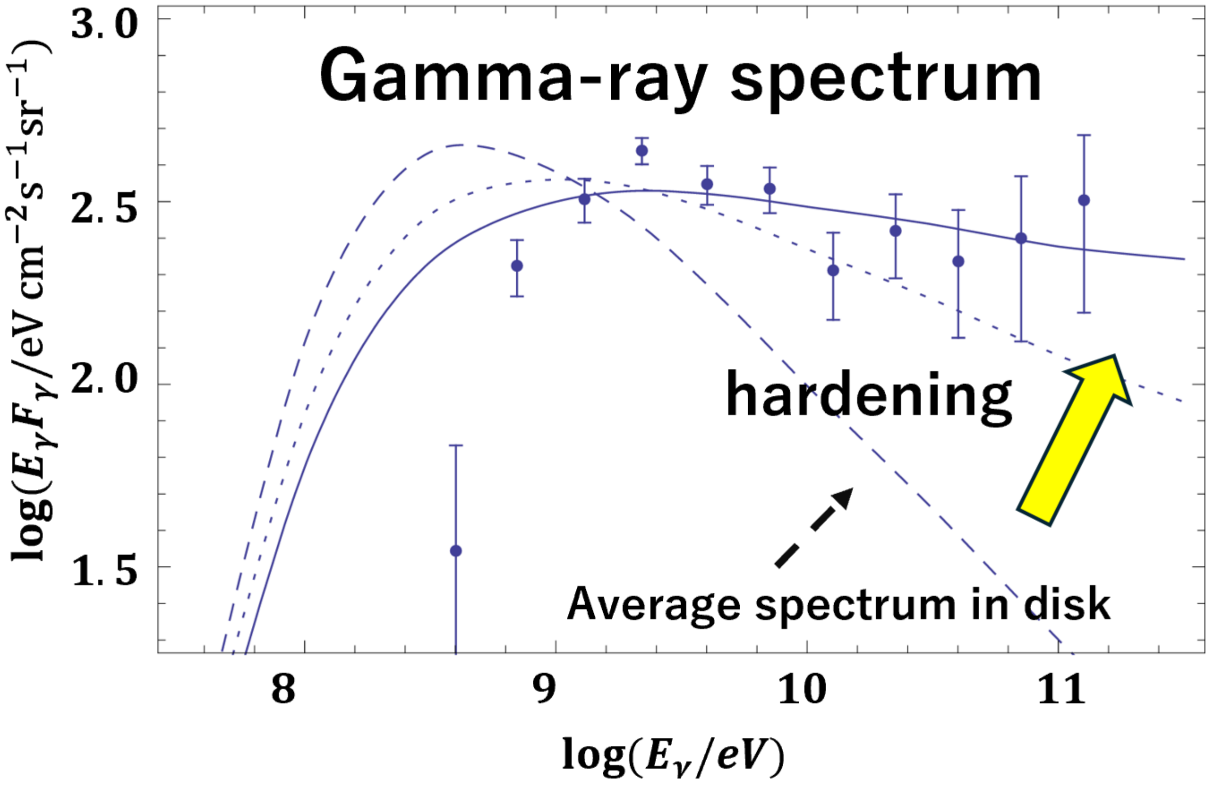


But their hard gamma-ray spectrum remains unexplained.

Challenge for hadronic scenarios

<u>Core problem in hadronic scenarios:</u>
how to **re**accelerate CR protons
enough to explain the **hard gamma-ray spectrum.**

Crocker & Aharonian+2011



CRs escape from the galactic disk...

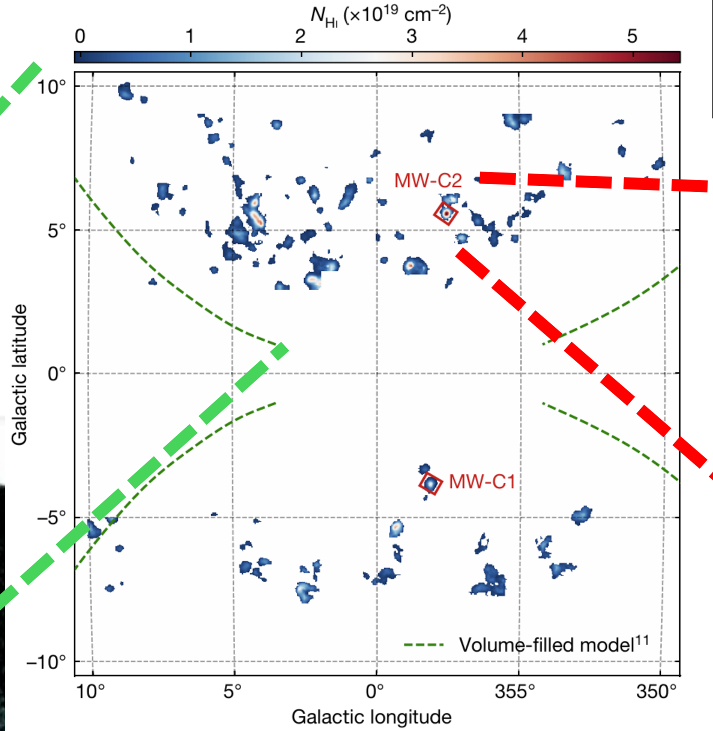
We need to follow CR reacceleration together with the gas dynamics.

Molecular clouds in the MW halo

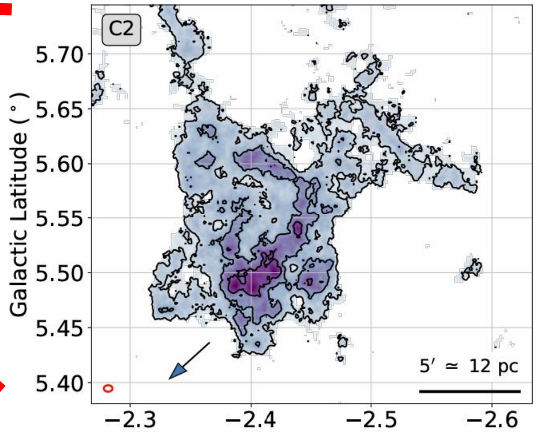
MCs are observed in **outflows** from the galactic disk
(Di Teodoro+2020)

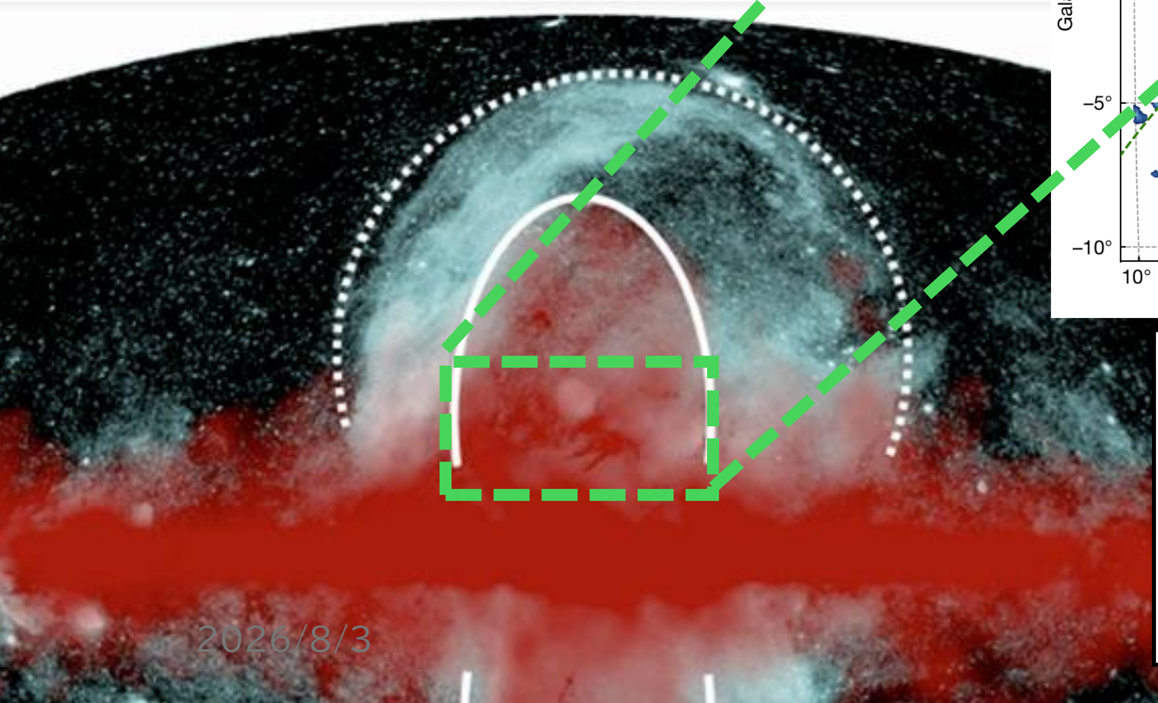
But is the cloud only a passive target?

HI gas density map



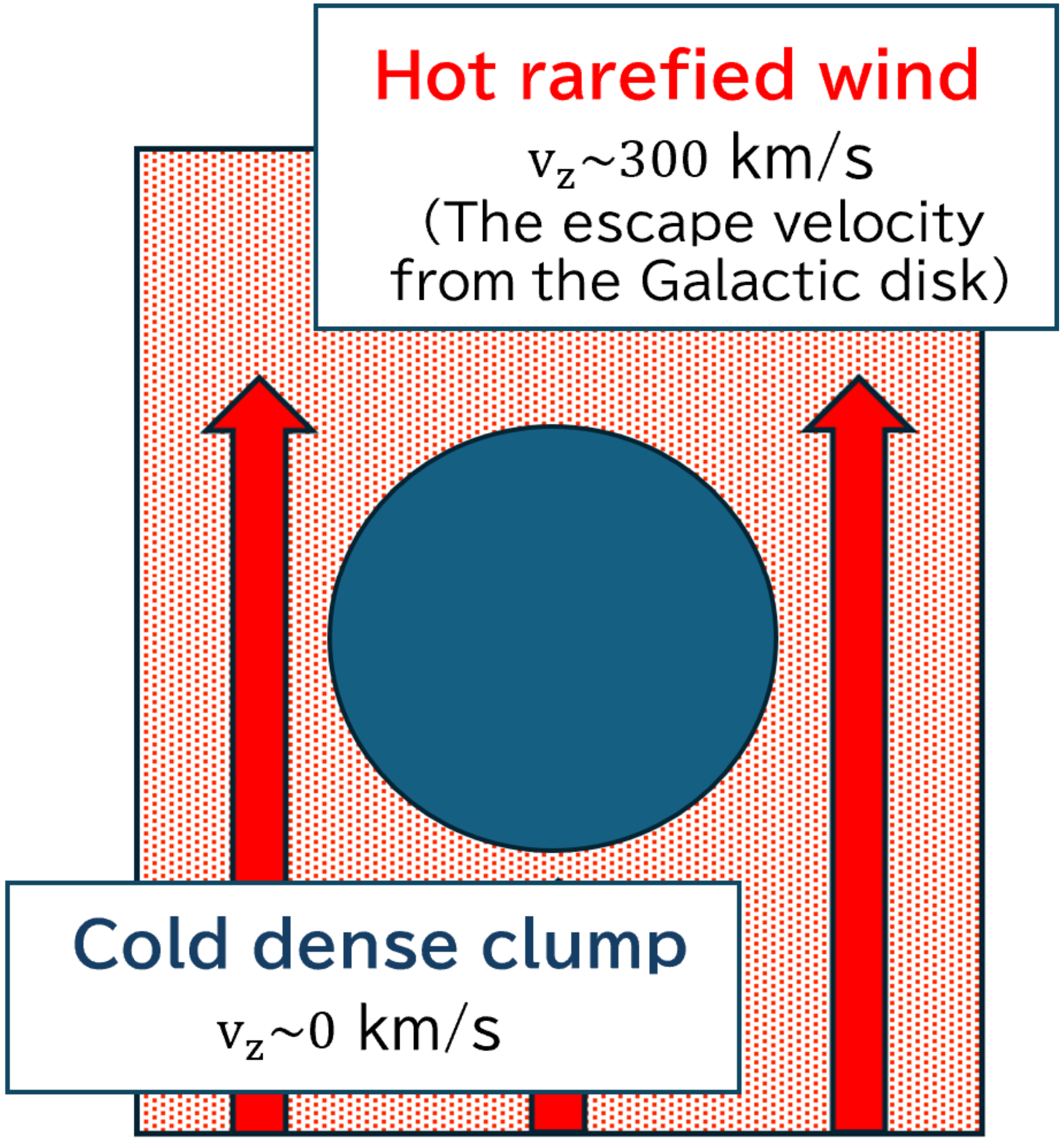
Wind-clump interaction may reaccelerate CRs





If such a cloud is located in the FBs, reaccelerated CRs can penetrate the cloud and produce enhanced, harder gamma-ray emission.

Set up



2D axisymmetric CR-hydrodynamic simulation with momentum-dependent CR transport

Two initial CR conditions

- Low-CR-density case

$$P_{CR} \sim 0.01 P_{gas}$$

- High-CR-density case

$$P_{CR} \sim P_{gas}$$

Equation

CR: Advection-diffusion equation

CR acceleration by gas compression

$$\frac{\partial \psi_{\rm CR}(r,z,p)}{\partial t} = \nabla \cdot (D(p)\nabla\psi_{\rm CR} - \boldsymbol{v}\psi_{\rm CR}) + \frac{\partial}{\partial p}\left[\frac{p}{3}(\nabla\cdot\boldsymbol{v})\psi_{\rm CR}\right]$$

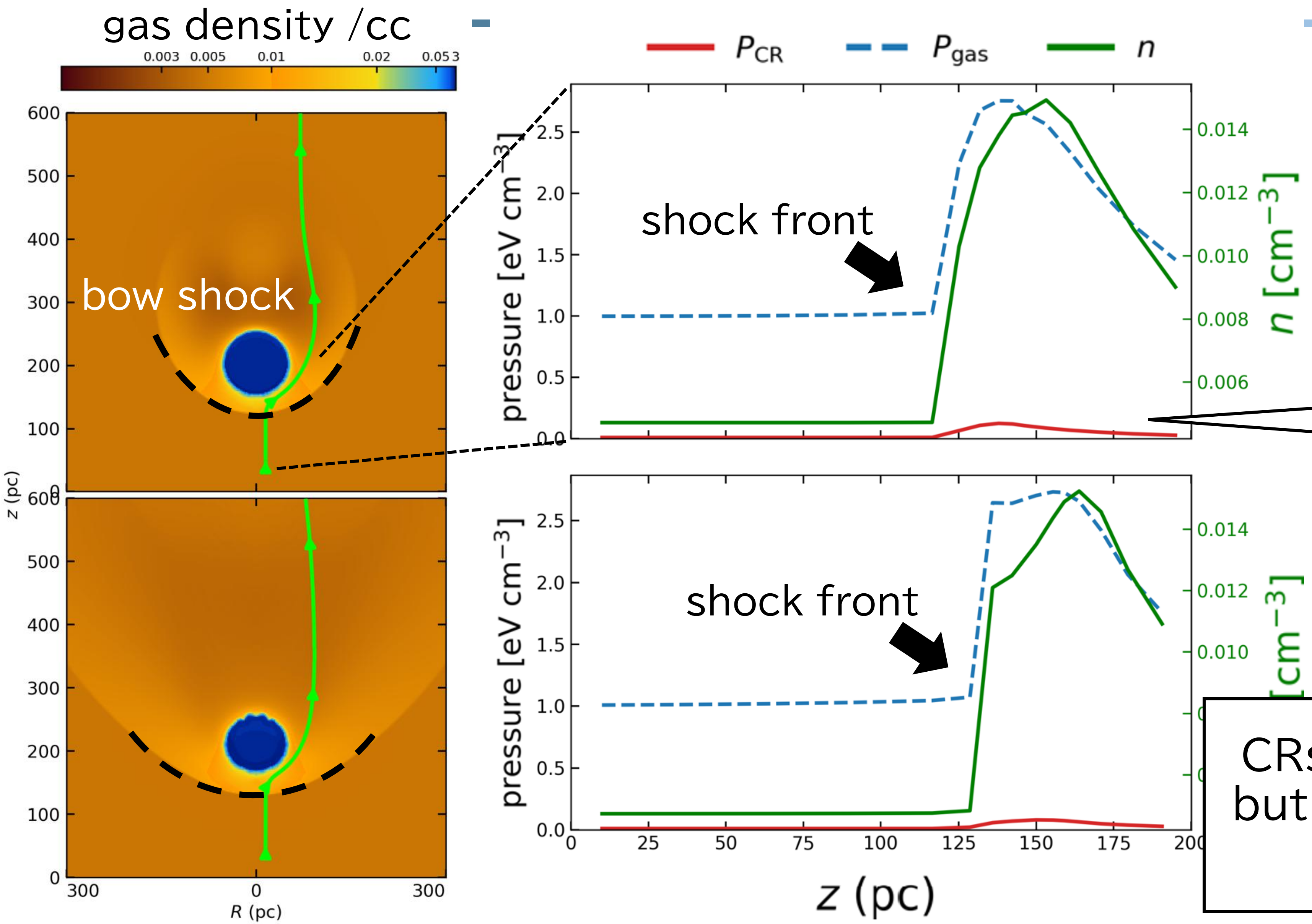
$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho\boldsymbol{v}\\ e\end{pmatrix} + \nabla\cdot\begin{pmatrix}\rho\boldsymbol{v}\\ \rho\boldsymbol{v}\boldsymbol{v}+P\mathbf{I}\\ (e+P)\boldsymbol{v}\end{pmatrix} = \begin{pmatrix}0\\ -\nabla P_{\rm CR}\\ -\boldsymbol{v}\cdot\nabla P_{\rm CR} - n\mathcal{L}(n,T) - \nabla\cdot\boldsymbol{q}_{\rm cond}\end{pmatrix}$$

Radiative cooling

Cosmic-ray pressure

$$P_{\rm CR} = \frac{1}{3}\int p\, v(p)\, \psi_{\rm CR}(p)\, dp$$

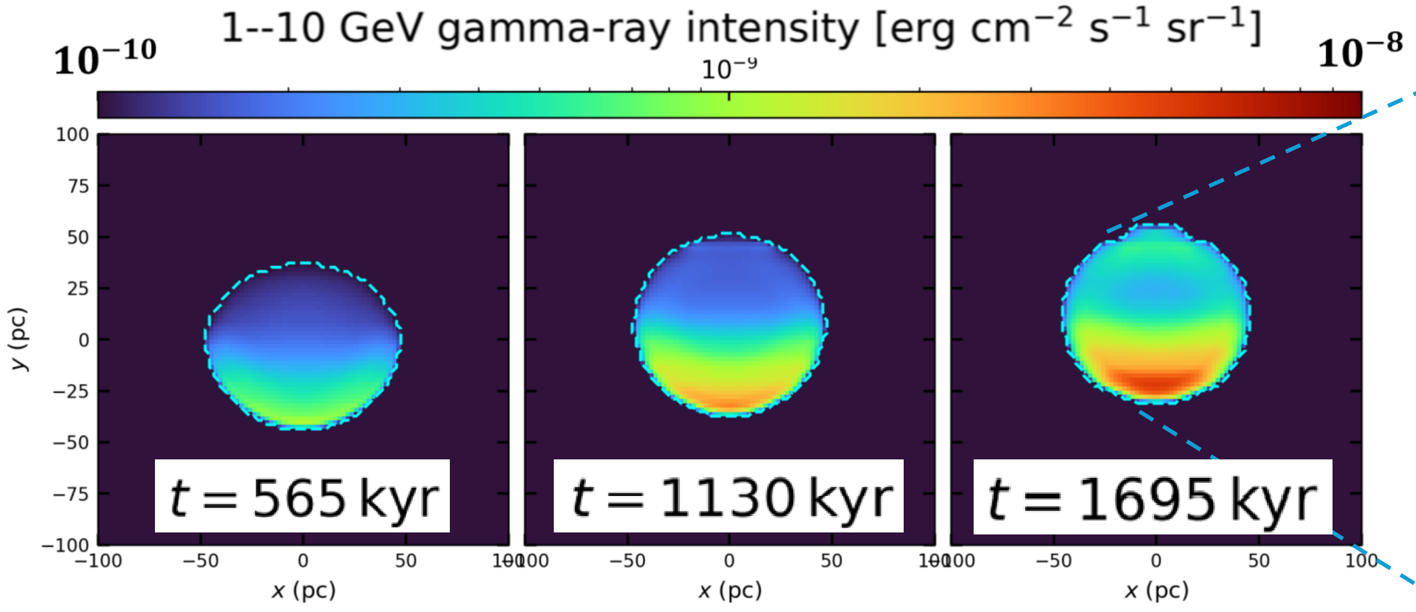
Result: Low-CR-density case



still $P_{CR} \ll P_{gas}$

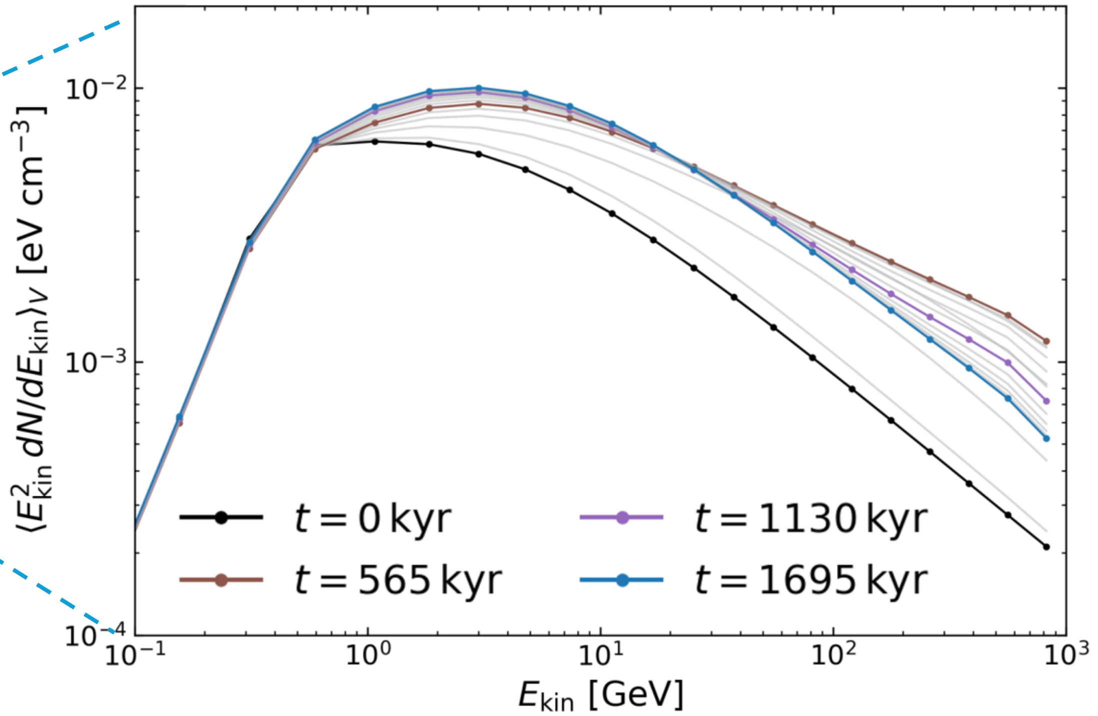
CRs are reaccelerated but remain dynamically subdominant.

Low case: gamma-ray intensity



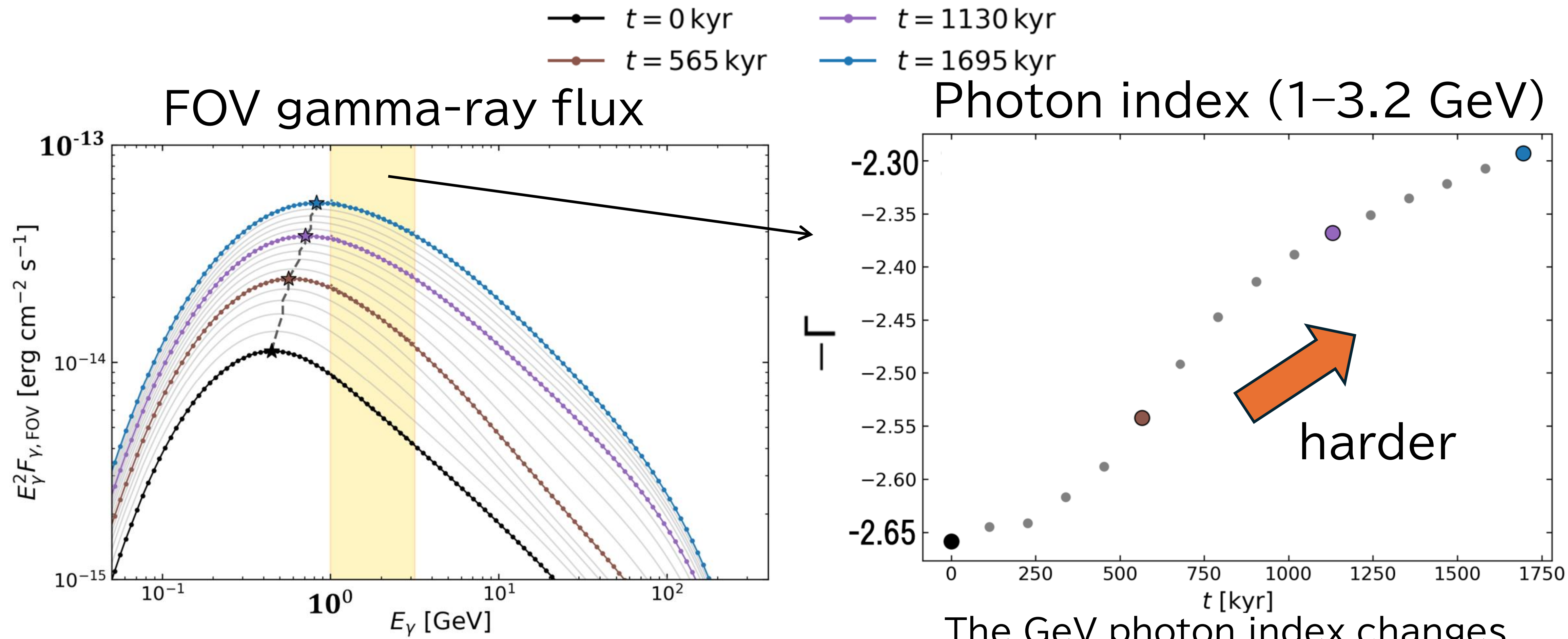
Gamma-ray emission increases by ~50×

CR energy spectrum



CRs reaccelerated upstream of the clump diffuse into it.

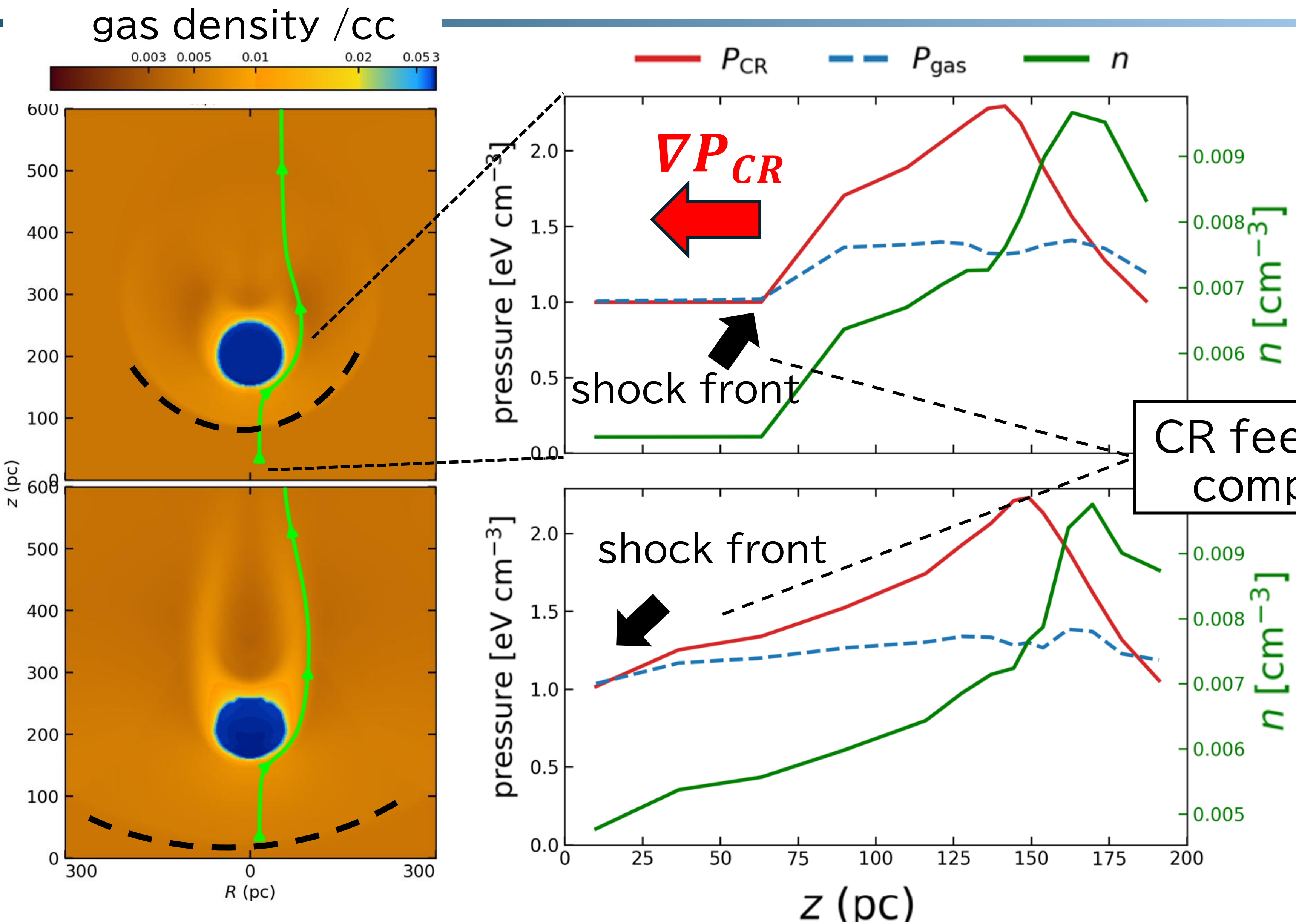
Low case: gamma-ray spectrum



The GeV photon index changes from about 2.65 to below 2.3

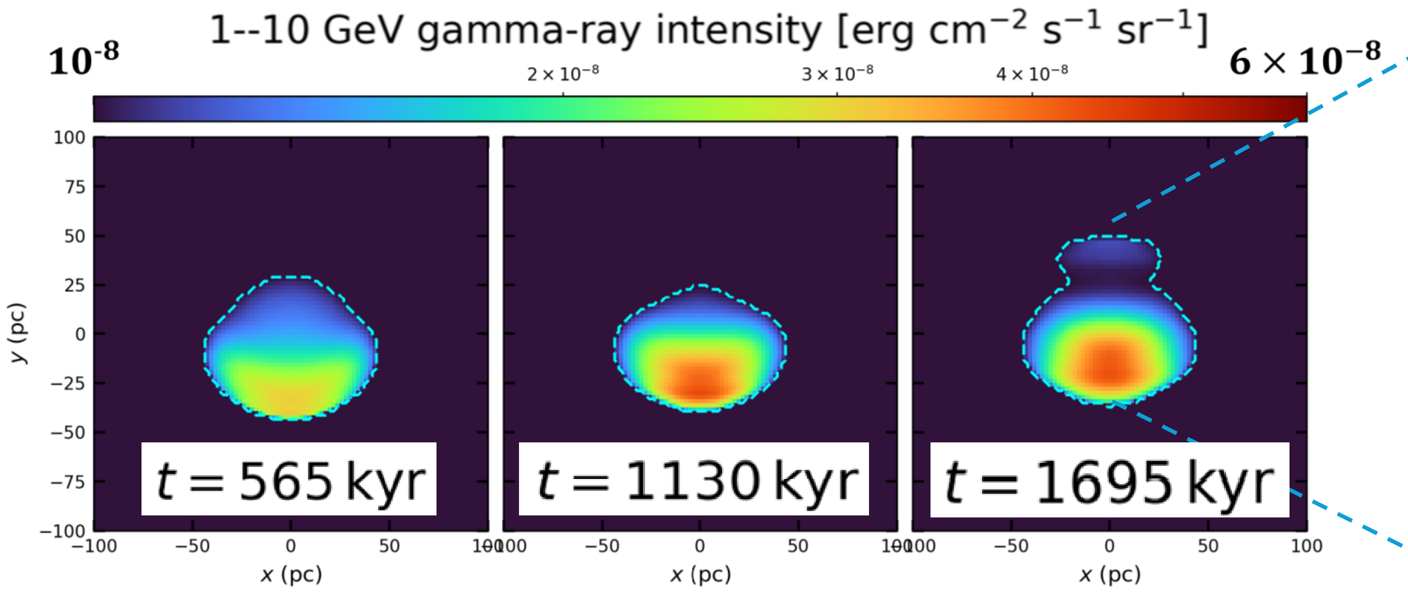
Compressive reacceleration produces spectral hardening.

Result: High-CR-density case

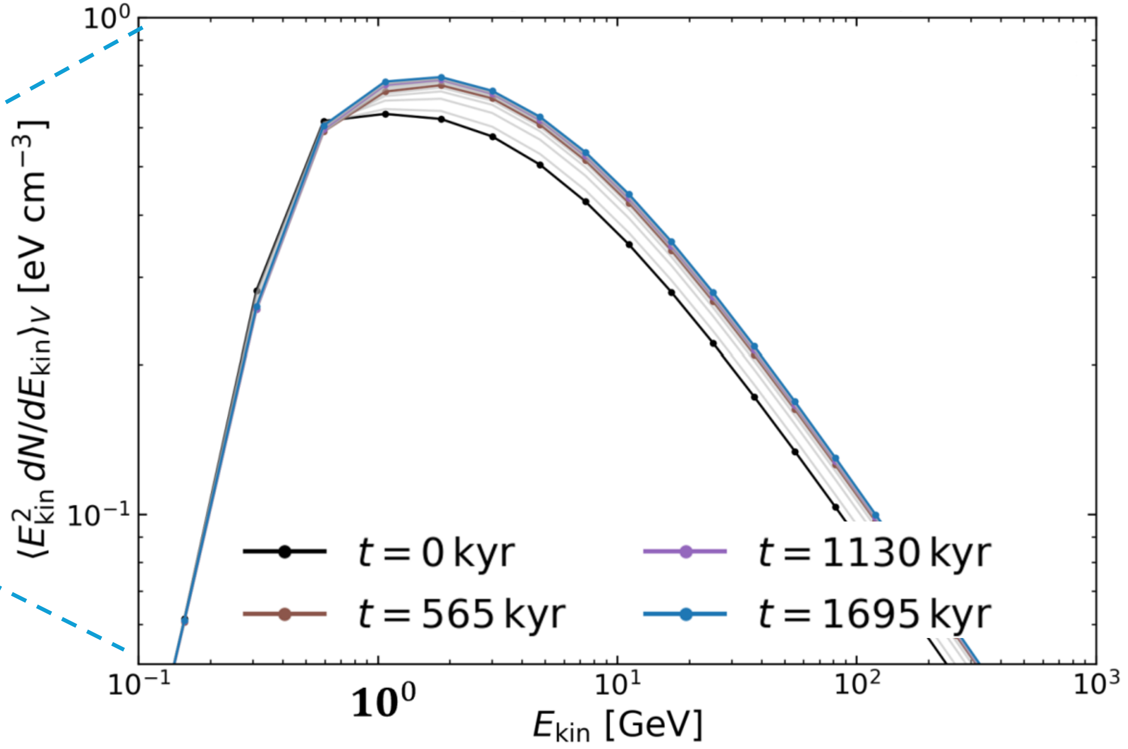


CR feedback modifies the compression structure

High case: gamma-ray intensity



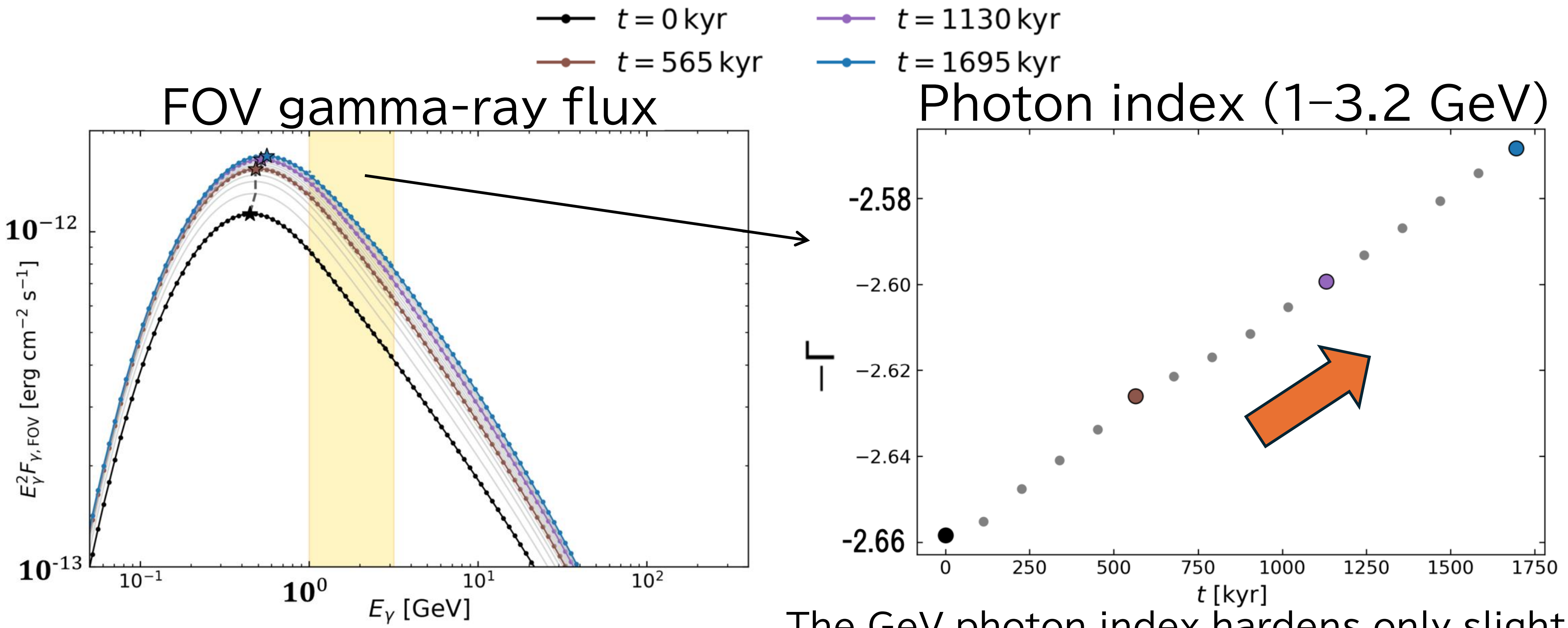
CR energy spectrum



Gamma-ray enhancement is limited to ~5×

CR feedback limits reacceleration

High case: gamma-ray spectrum



The GeV photon index hardens only slightly, from about 2.66 to 2.56

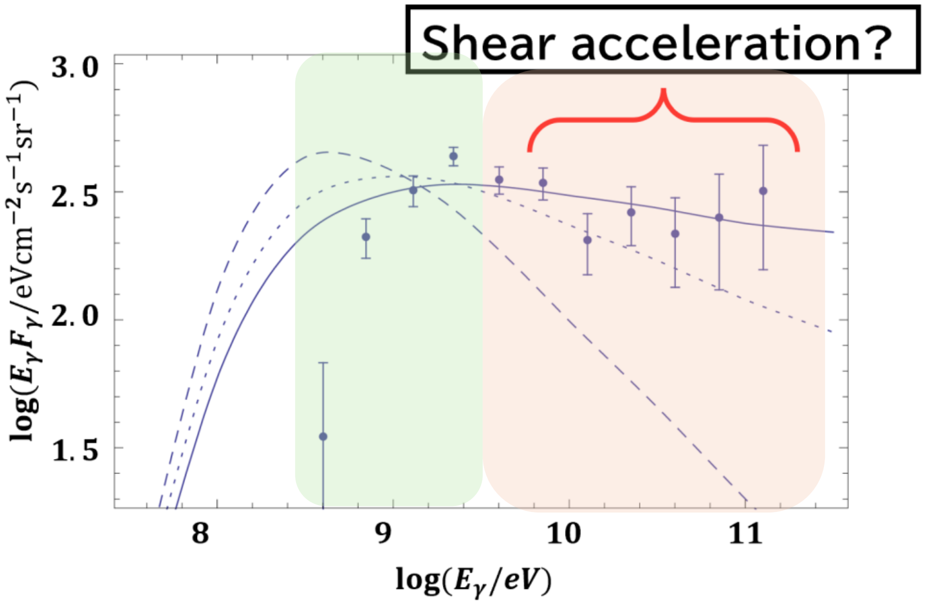
CR feedback suppresses spectral hardening

Summary & Prospect

1. Wind-clump interaction can locally reaccelerate CRs.
2. In the low-CR-density case, reaccelerated CRs penetrate the dense clump, producing strongly enhanced(~50 times) and harder (Γ<2.3) hadronic gamma rays.
3. In the high-CR-density case, CR feedback modifies the flow and suppresses further reacceleration.

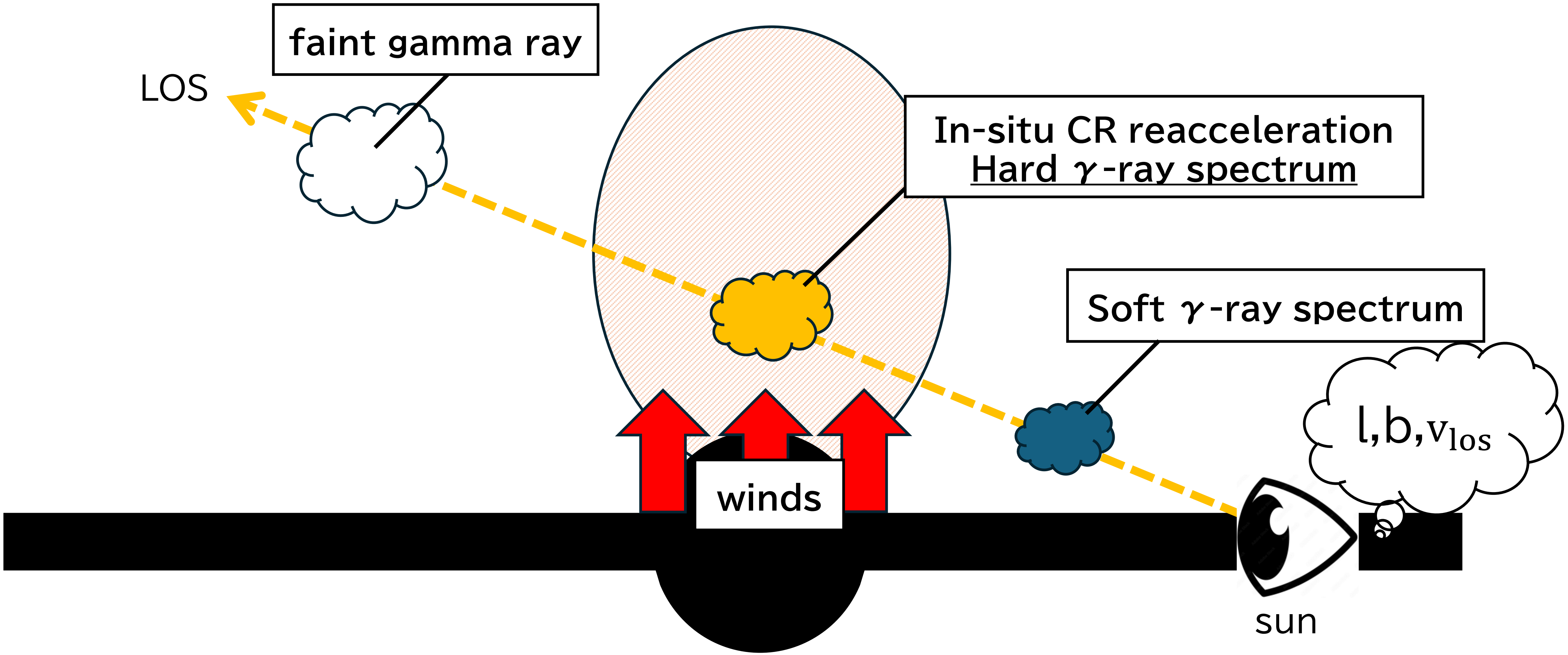
GeV spectral hardening can be explained by gas compression

Higher-energy acceleration may require additional mechanisms, e.g., turbulence/shear.

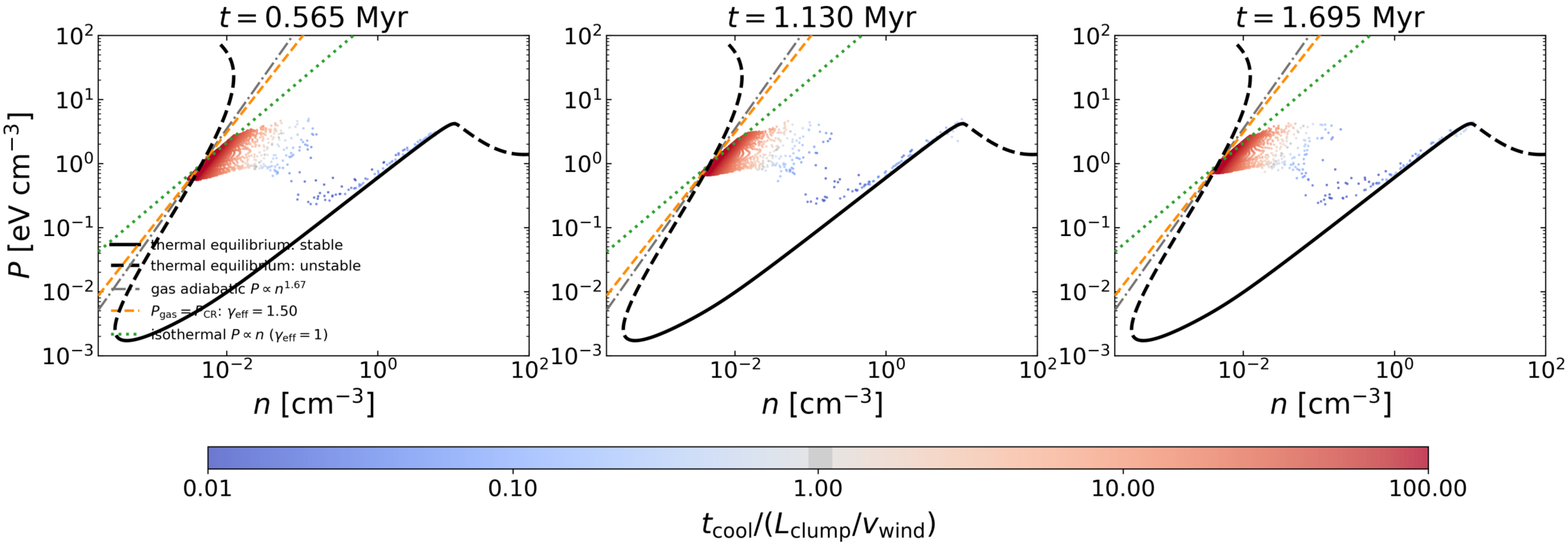


Potential New Diagnostic of 3D Position of MCs

Gamma-ray spectra may reveal where molecular clouds lie along the line of sight.



Appendix



$t = 0.565$ Myr
$t = 1.130$ Myr
$t = 1.695$ Myr
P [eV cm^{-3}]
n [cm^{-3}]
thermal equilibrium: stable
thermal equilibrium: unstable
gas adiabatic $P \propto n^{1.67}$
$P_{gas} = P_{CR}$: $\gamma_{eff} = 1.50$
isothermal $P \propto n$ ($\gamma_{eff} = 1$)
0.01
0.10
1.00
10.00
100.00
$t_{cool}/(L_{clump}/v_{wind})$