Cosmic-ray origin via unstable isotope ^{60}Fe produced in supernovae clusters

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1. Introduction

The supernovae remnants (SNR)
promising sites for accelerating particles
persistent, observed across wavebands and messengers

The unstable isotope of iron-60 (**^{60}Fe**)
- a half-life of 2.6 million years
- only produced in SN explosions

The observed presence of ^{60}Fe
- in cosmic rays
- in deep-sea crusts and sediments

indicating cosmic ray production in SN

Two possible acceleration sites
- inside the SN ejecta
- in the enrichment of the circumstellar material around the SN progenitors ➡ **our focus in this poster!**

interstellar ^{60}Fe inflow from past supernova activities in the Local Bubble

3D HD simulations:
[-400 pc, 400 pc]
Resolution: 0.781 pc

Including the effects of:
- identified 14 SN explosions, using *Gaia* EDR3, subgroups of the Scorpius-Centaurus OB association
- Monte Carlo-type approach for the trajectories
- initial mass-dependent age & stellar winds loss
- the radioisotopes ejected during the past explosions (^{60}Fe, ^{26}Al, ^{53}Mn, and ^{244}Pu)

Snapshot:
taken before the next SN explosion
at (X, Y, Z) = (99.32, -18.04, 55.57) pc,
with initial mass 13.28 $M_\odot$

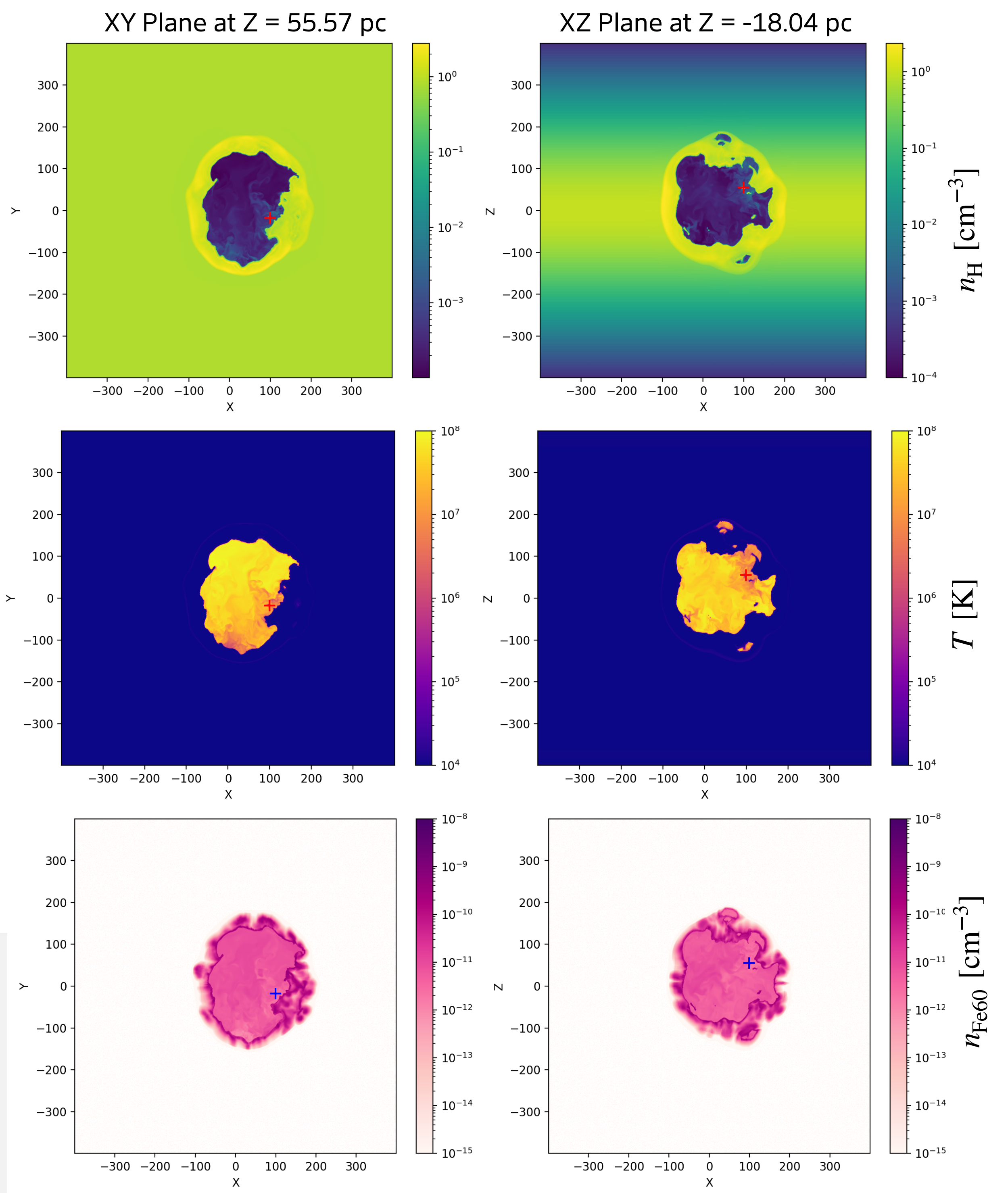


Fig. 2D axis-aligned slices at the position of the next SN.

2. Numerical Setup

Hydrodynamic

Input data:
CCSN Ejecta: Chevalier 1982
Ambient environment: Snapshot of the Local Bubble, convert from 3D to 1D from different directions

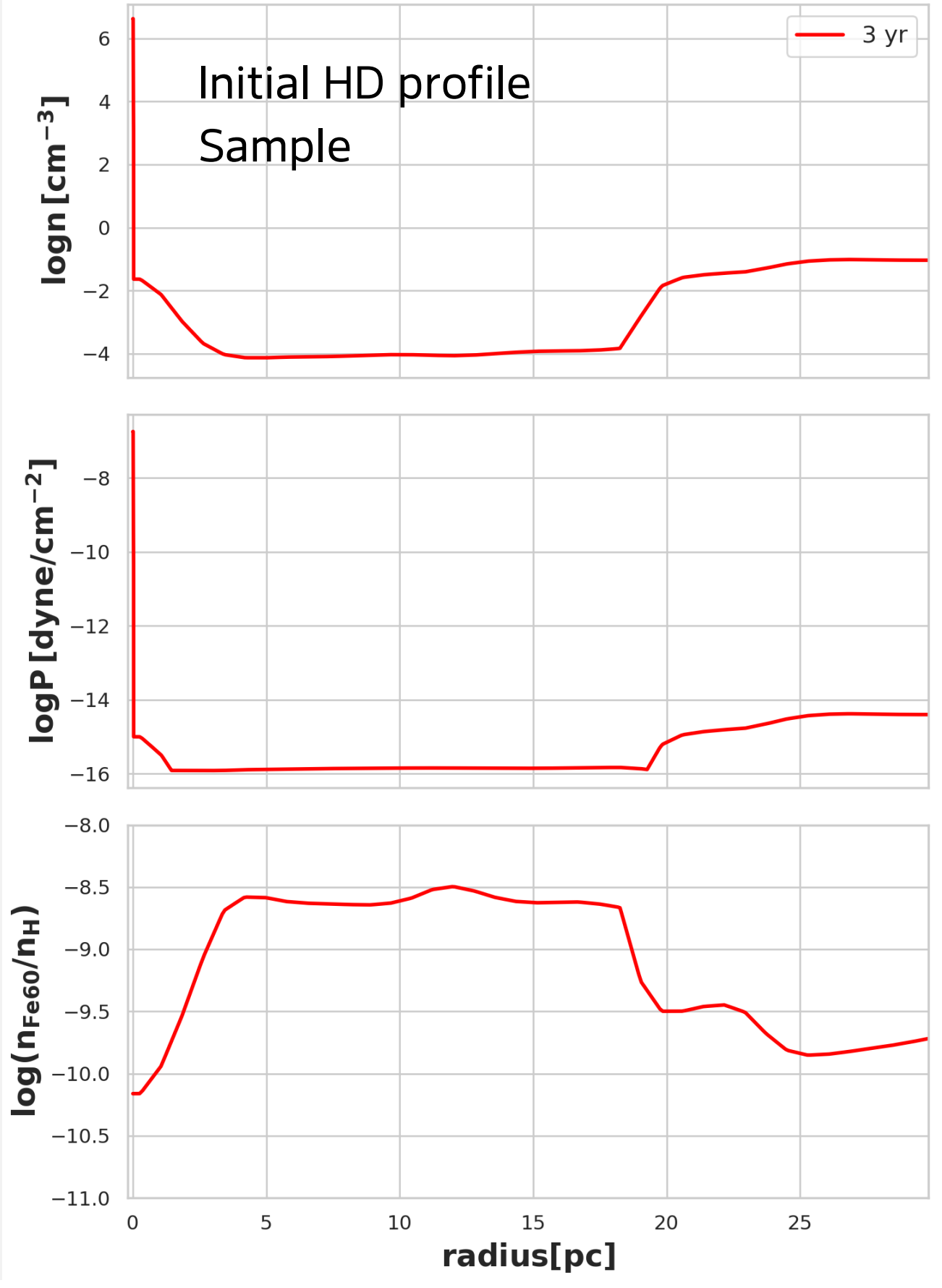
$E_{ej} = 10^{51}$ erg
$M_{ej} = 8.32 M_\odot$

PLUTO
pure HD

Geometry:
1D, Spherical

Resolution:
3×10^{-4} pc

^{60}Fe ratio:
passive tracer



Particle acceleration

RATPaC (Radiation Acceleration Transport Parallel Code)
The cosmic ray (CR) transport equation

$$\frac{\partial N(p,r,t)}{\partial t} = \nabla(D\nabla N - vN) - \frac{\partial}{\partial p}[(\dot{p}N) - \frac{\nabla v}{3}Np] + Q(p,r,t)$$

- **Large-scale magnetic field:**

$r < R_{sh}$ (downstream) $B(r) \propto n_H^{2/3}$
$r > R_{sh}$ (upstream) $B = 5\ \mu$G or $\propto n_H^{2/3}$

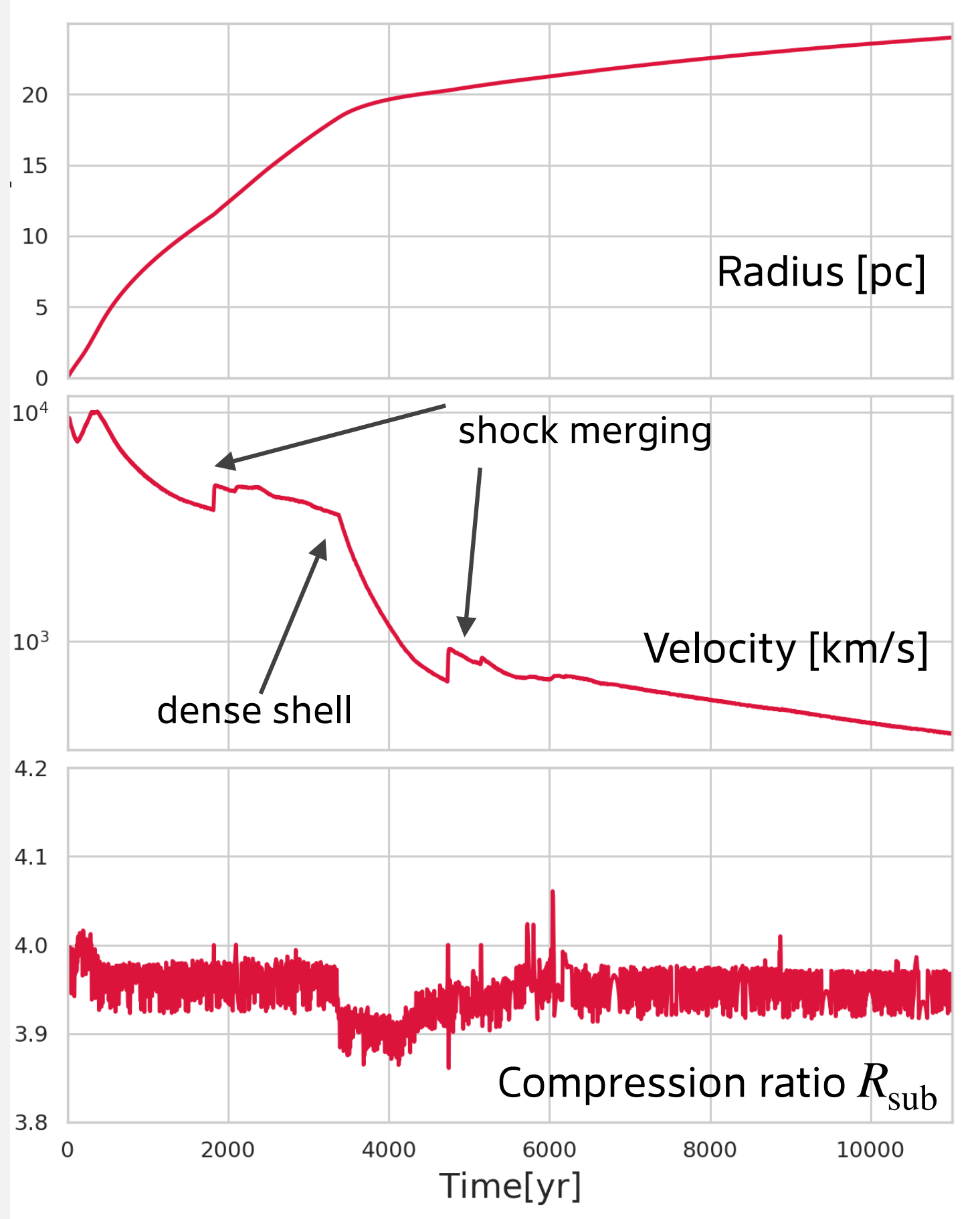
- **Spatial diffusion**

$$D = D_0(\frac{pc}{10\mathrm{GeV}})^{\alpha}(\frac{B}{3\mu\mathrm{G}})^{-\alpha}$$

$r < R_{sh}$, Bohm diffusion $\alpha = 1$, $D_0 \propto cr_g/3 = pc/qB$,
⇕ an exponential transition in between
$r > 2R_{sh}$, Kolmogorov diffusion $\alpha = 1/3$, $D_0 = 10^{29}\ \mathrm{cm^2 s^{-1}}$

- **The source term: Q**

Particle injection with thermal leakage injection model: particles with sufficiently high energies can cross a shock front.



Time evolution of the forward shock (FS)

- Free expansion stage
v$_{sh}$ from ~10000 km/s to ~3600 km/s, R_{sub}~4
- Deceleration
due to the interaction with the dense shell, v$_{sh}$ < 1000 km/s, R_{sub} ~3.9
- Shock merging
weak reflected shocks catch up with the FS, accelerate the FS for several times

3. Results

Particle Momentum Spectrum of proton and ^{60}Fe

- a power law, with index -2

N$_{Fe60}$ is multiplied by a factor of 10^{10}

- Two peaks/a bump in higher energy range:

higher-energy peak: acceleration in the early stage, v$_{sh}$ is fast
lower-energy peak: in the later stage, slow v$_{sh}$ but in a denser area, more particle injections

Differences:
- Diffusion coefficient $D \propto r_g$
- Injection momentum per nucleon $p_{inj} \propto m^{-1/2}$
- Maximum achievable momentum $p_{max} \propto r_g^{-1} v_{sh}^2$
- Variation of ^{60}Fe injection fractions in different "radius/stages"

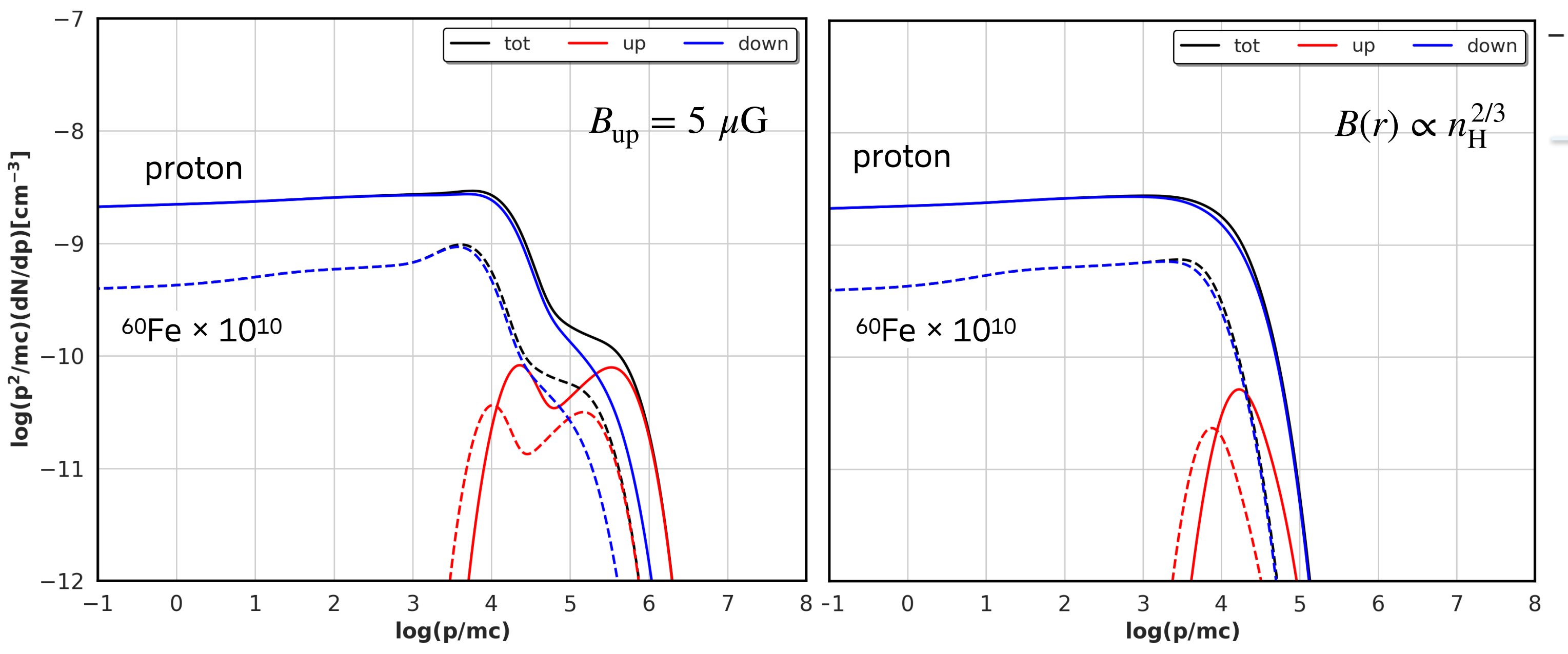
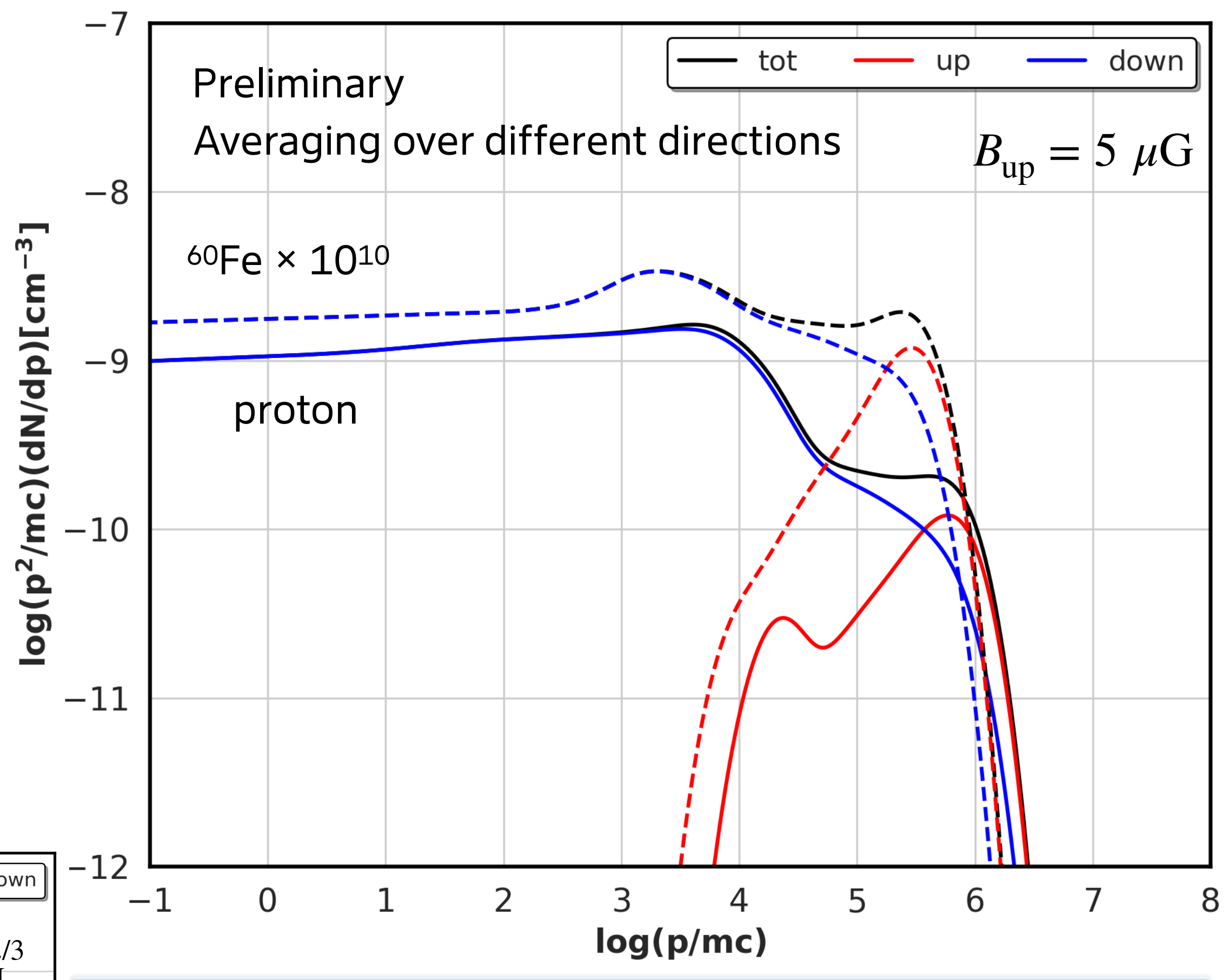


Fig. Proton (solid) and iron-60 (dashed) momentum spectra as function of momentum per nucleon at 10 kyr after the SN explosion.



Different assumptions for *B* in the upstream
Magnetic field in the bubble becomes significantly diminished to ~0.01 μG, limiting the maximum achievable energy

Future works:
- More directions, more data
- Further investigations: small spectra differences near the high energy cut-off
- Acceleration inside the supernova ejecta: Reverse shock

4. Conclusions

- We investigate the accelerations of protons and ^{60}Fe, within the ambient environment of several past SN-generated Local Bubble.
- Using RATPaC, the CR transport equation and the HD utilising PLUTO were solved simultaneously in 1-D spherical symmetry.
- The time evolution of ^{60}Fe mass ratio is tracked independently using passive scalars.

We calculate and compare the momentum spectra of the proton and ^{60}Fe as function of momentum per nucleon at 10 kyr after the SN explosion in the Local Bubble.
- Inside the bubble, higher ^{60}Fe fraction with faster shock speed, results in greater ^{60}Fe injection fraction at higher energies
- Different assumptions for large-scale magnetic fields can have significantly effects on the spectra