垂直衝撃波領域からの宇宙線の逃走過程と最高エネルギー

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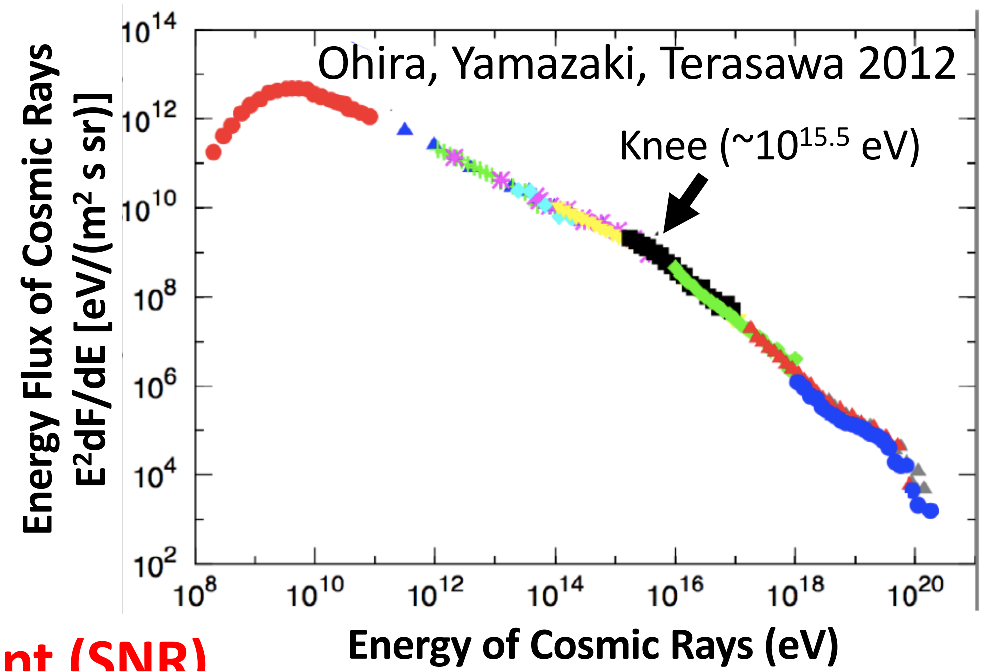
Galactic Cosmic Rays

✓ Energy spectrum of cosmic rays (CR)

$$\frac{dN}{dE} \propto E^{-2.8} \; (E \leq 10^{15.5} \text{ eV })$$

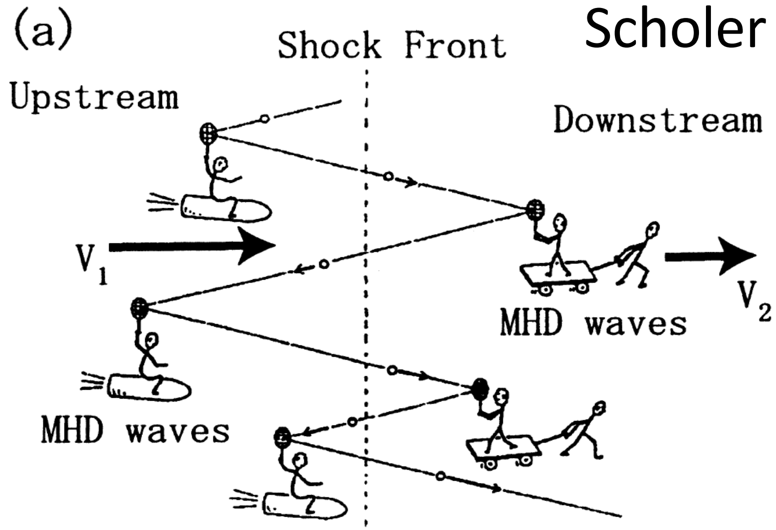
(Lipari & Vernetto 2020)



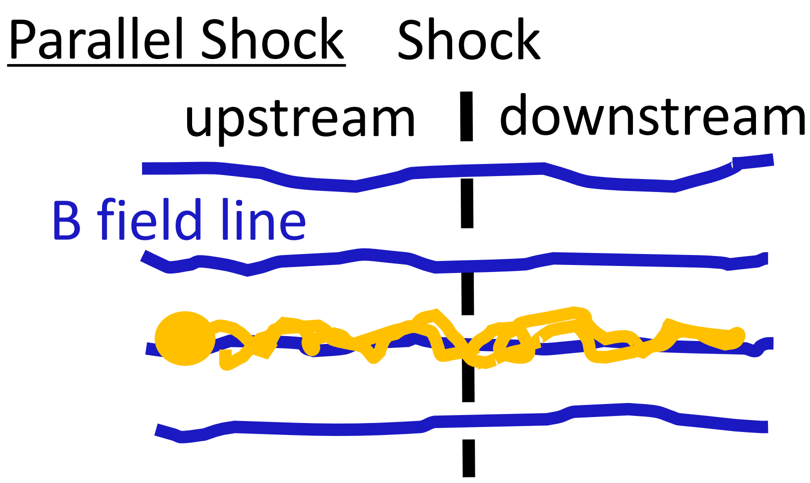
✓ Acceleration Site: **Supernova Remnant (SNR)**

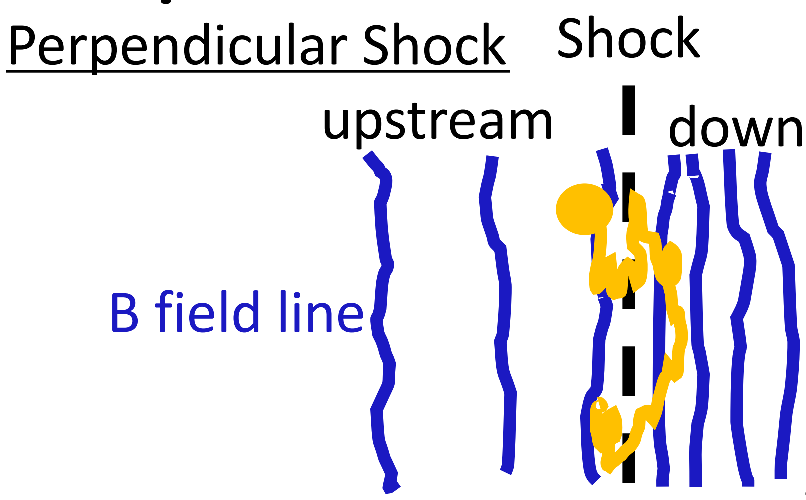
✓ Acceleration Mechanism: **Diffusive Shock Acceleration (DSA)**
(Axford 1977, Krymsky 1977, Blandford & Ostriker 1978, Bell 1978)

$$\frac{dN}{dE} \propto E^{-s} \quad s = \frac{u_1/u_2+2}{u_1/u_2-1} = 2$$



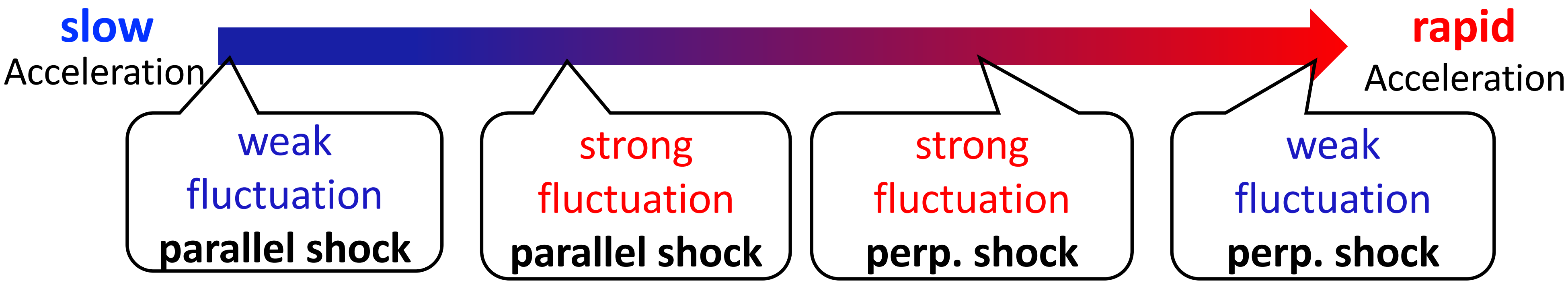
Parallel Shock vs. Perpendicular Shock





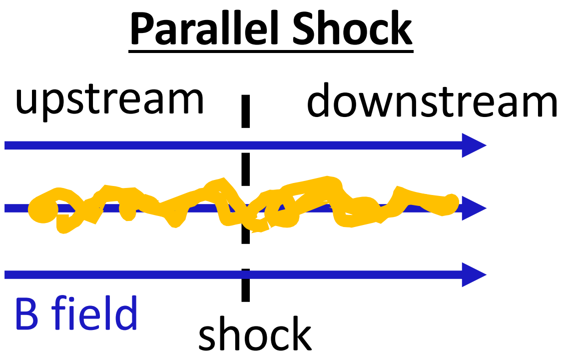
Jokipii 1987

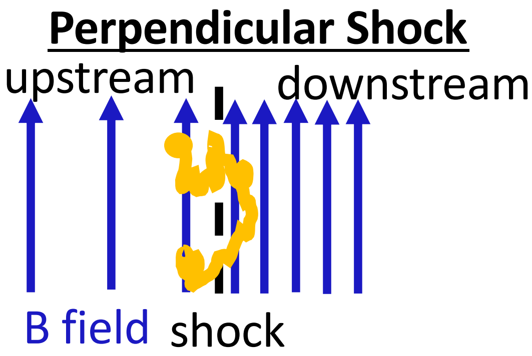
※The strength of the fluctuation is smaller than that of the uniform magnetic field.



- ✓ Particles are accelerated in shorter time in a perp. shock region than a parallel shock region.
- ✓ Particles are accelerated in shorter time in a weaker fluctuation case.

Perpendicular Shock Acceleration

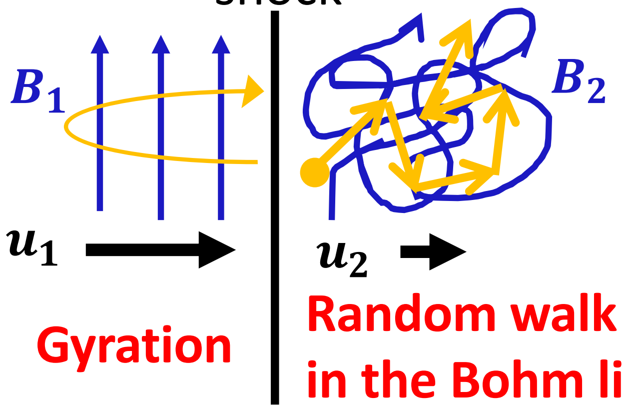


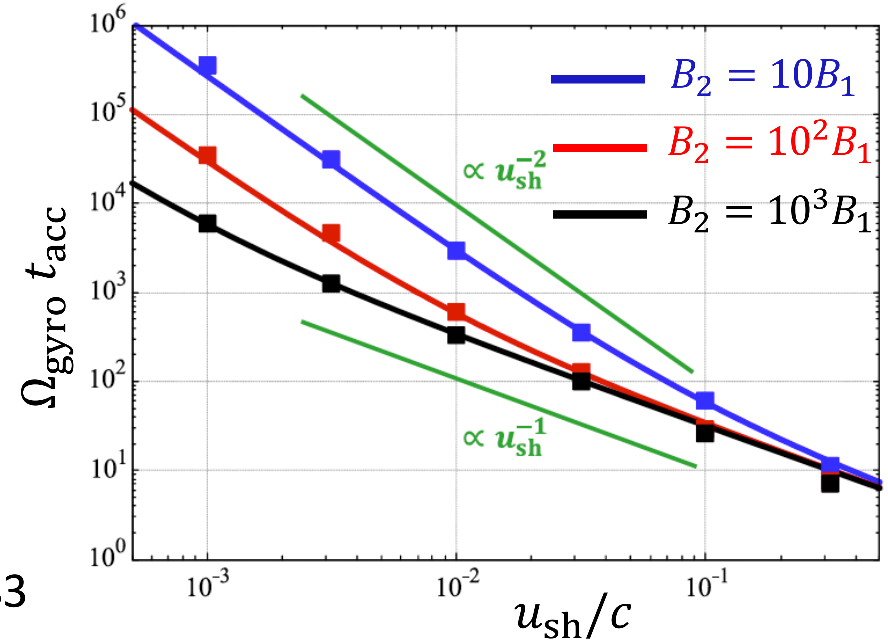


The perpendicular shock can be more efficient accelerator than the parallel shock.

- **Perpendicular Shock Acceleration** (Jokipii 1987, Takamoto & Kirk 2015, Kamijima et al. 2020)
  - ✓ Jokipii 1987 assumes the diffusion approximation.
  - ✓ $\delta B_{\rm up} \ll B_0$ & $\delta B_{\rm down} \ll B_0$
    → Rapid Acceleration & **the softer spectrum than the canonical spectrum**
    (Takamoto & Kirk 2015)
  - ✓ $\delta B_{\rm up} \ll B_0$ & $\delta B_{\rm down} \gg B_0$
    → Rapid Acceleration & **the canonical spectrum, $dN/dp \propto p^{-2}$**
    It realizes even if there is no upstream magnetic field amplification.
    (Kamijima, Ohira, Yamazaki 2020)

Our Acceleration Model





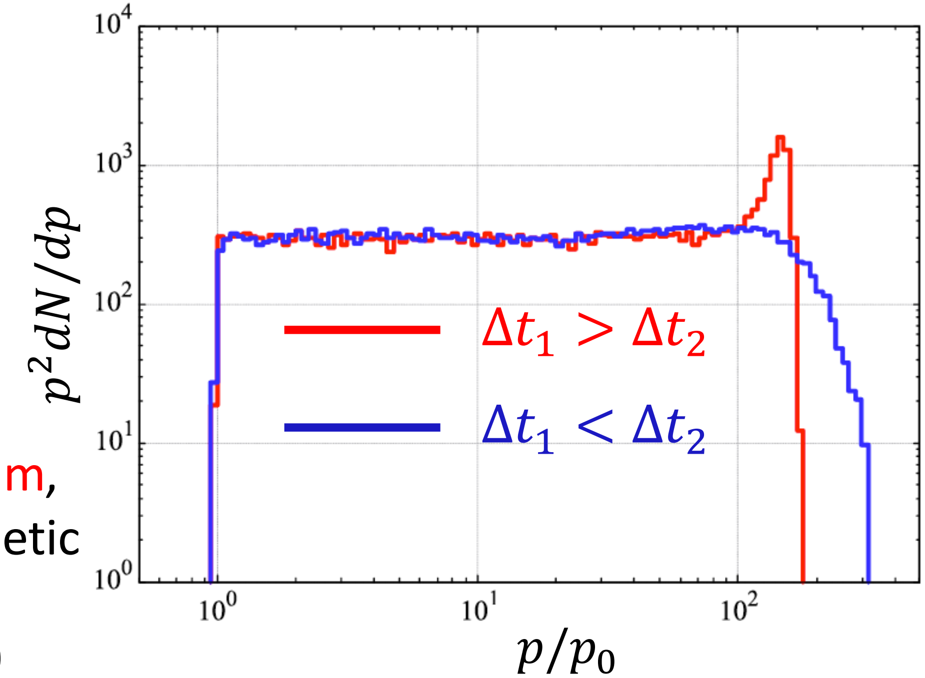
<u>Residence time</u>

$$\Delta t_1 = \pi \Omega_{g,1}^{-1} \qquad \Delta t_2 = \frac{4\kappa_2}{u_2 v}$$ Drury 1983

<u>Acceleration time</u>

$$t_{acc} = (\Delta t_1 + \Delta t_2)p/\Delta p$$

$$t_{acc} = \pi \left(\frac{u_{sh}}{v}\right)^{-1} \Omega_{g,1}^{-1} + \frac{16}{3}\left(\frac{B_2}{B_1}\right)^{-1} \left(\frac{u_{sh}}{v}\right)^{-2} \Omega_{g,1}^{-1}$$



Our model simultaneously realizes the rapid acceleration and the canonical spectrum, $dN/dp \propto p^{-2}$, even if there is no upstream magnetic field amplification.

Kamijima, Ohira, Yamazaki 2020

Effects of Cosmic Ray Escape

Escape process can determine the maximum energy of cosmic rays and the spectral index of escaped particles.

Ptuskin & Zirakashvili 2003, 2005, Ohira et al. 2010, Ohira & Ioka 2011

diffusion length $L_{\rm diff}$ vs. SNR radius $R_{\rm SNR}$

$$L_{\rm diff} \propto t^{1/2} \qquad R_{\rm SNR} \propto \begin{cases} t^{1} & (t \le t_{\rm Sedov}) \\ t^{2/5} & (t \ge t_{\rm Sedov}) \end{cases}$$

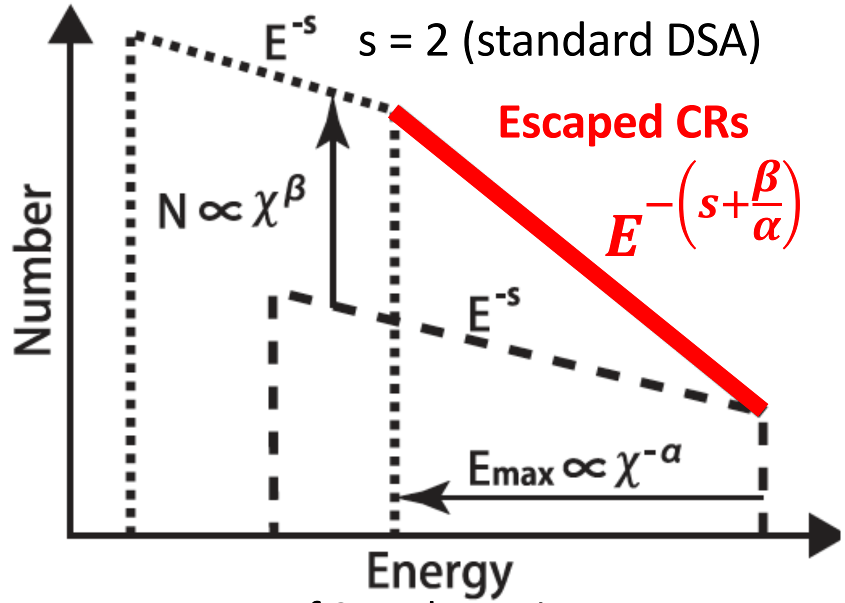
In $t<t_{\rm Sedov}$, the shock surface catches up with diffusing particles.

→ Particle cannot escape from SNRs.

In $t>t_{\rm Sedov}$, particles can escape from SNRs and higher energy particles escape from an acceleration region in earlier period.

Escape: $L_{\rm diff} (= D/u_{\rm sh}) \sim R_{\rm SNR}$

→ $E_{\rm max} \propto u_{\rm sh} R_{\rm SNR} \propto t^{-1/5} \; (t \ge t_{\rm Sedov})$



χ : parameter of SNR dynamics (e.g. time, radius of SNR)

α, β : const.

Previous studies assume the diffusion approximation.
The diffusion approximation can violate in a perpendicular shock.
→ We do not know the escape process from the perp. shock region.

We investigate the escape process from the perpendicular shock region.

- the escape process from the perpendicular shock region
- the maximum energy limited by the escape

In this poster

1) **Maximum Energy limited by the SNR age (Age limit)**

- ✓ Plane shock
- ✓ Shock velocity u_{sh} : evolution (Mckee & Truelove 1995)
- ✓ B_2/B_1 : evolution (ε_B model)

In previous work (Kamijima, Ohira, Yamazaki 2020)

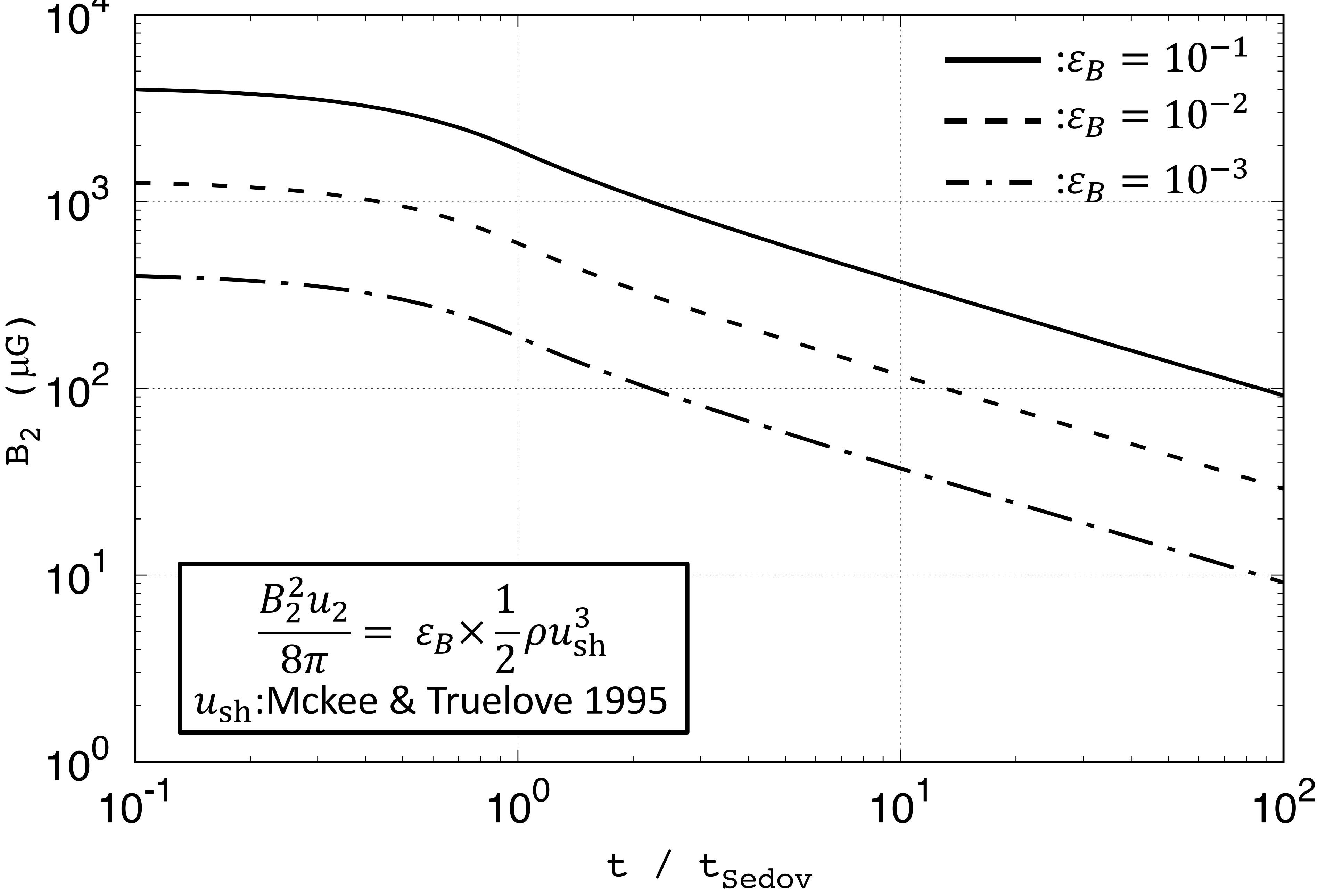
- ✓ Plane shock
- ✓ Shock velocity u_{sh} : constant
- ✓ B_2/B_1 : constant

2) **Maximum Energy limited by the Escape (Escape limit)**

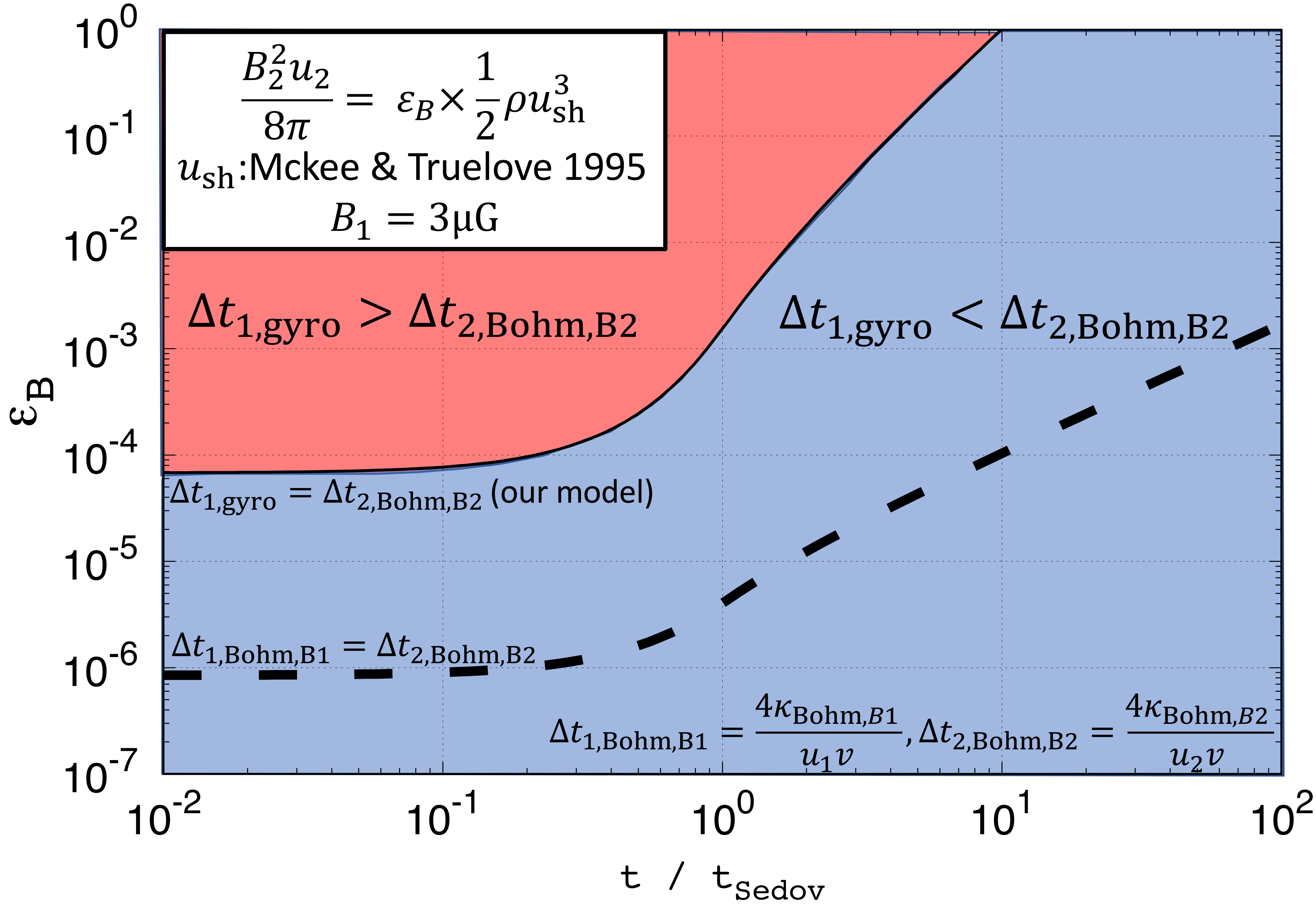
- ✓ Spherical shock
- ✓ Shock velocity u_{sh} : evolution
- ✓ B_2/B_1 : evolution

3) If cosmic ray streaming instability driven by High energy escaped particles is efficient in the subluminal shock region, Particles can be confined by CR driven turbulence in subluminal shock region.

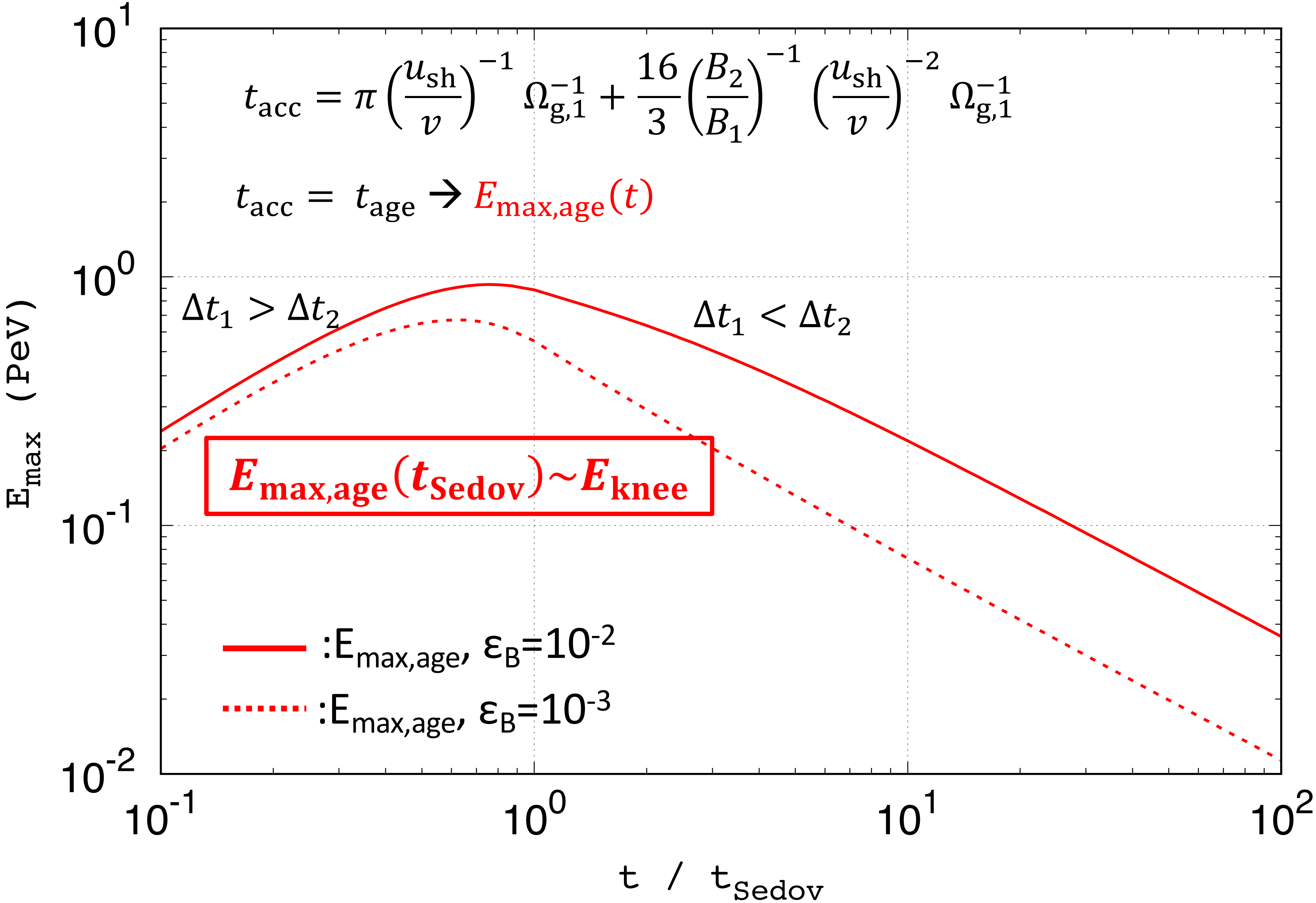
ε_B Model: Evolution of B_2



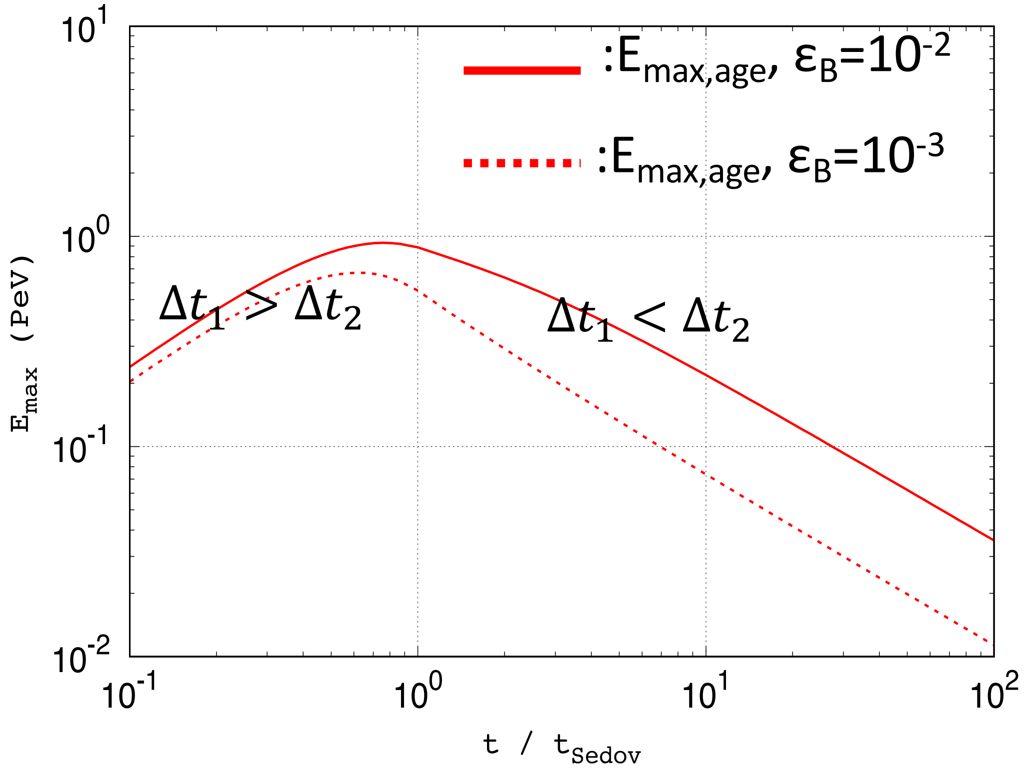
Dominant Residence Time of Our Model

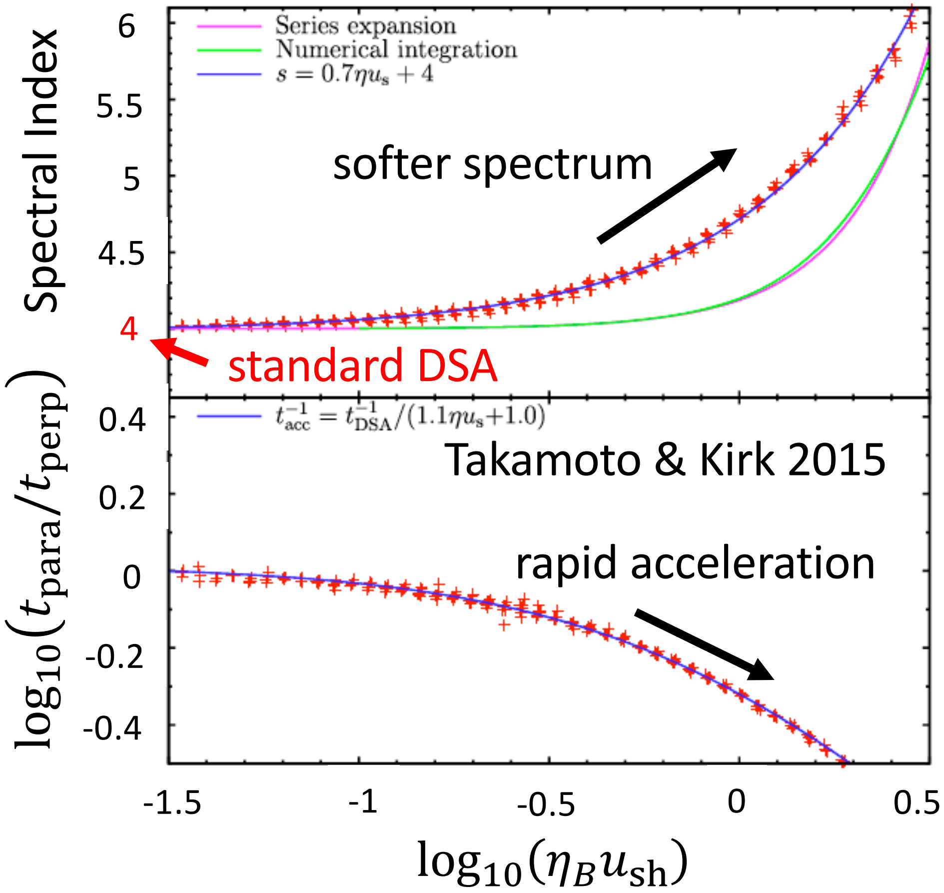


E_{max} Limited by the SNR Age (Age Limit)



E_{max} Limited by the SNR Age (Age Limit)

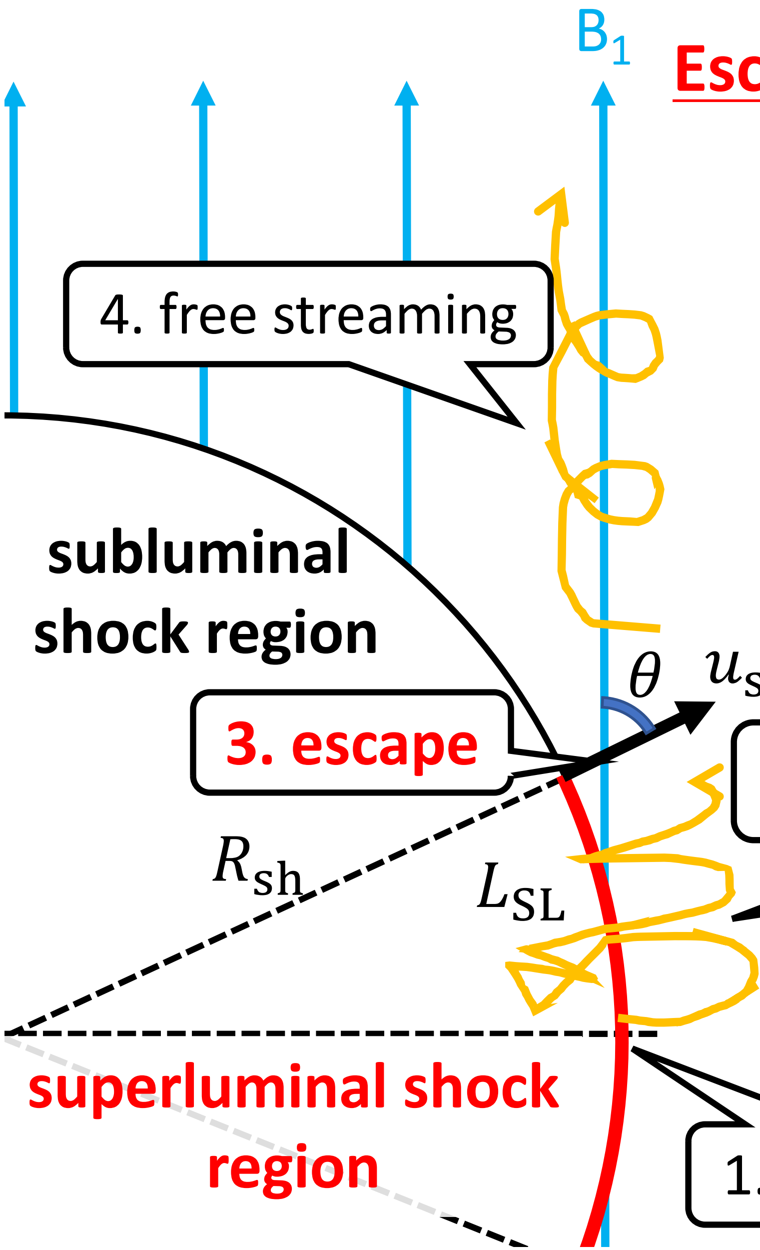




In $t > t_{Sedov}$, the downstream residence time is longer than the upstream residence time. → The acceleration becomes slow.

Both upstream and downstream fluctuation are weak. → **rapid acceleration**
However, **the momentum spectrum becomes softer than the canonical spectrum.**

Rapid Acceleration in Superluminal Shock & Escape



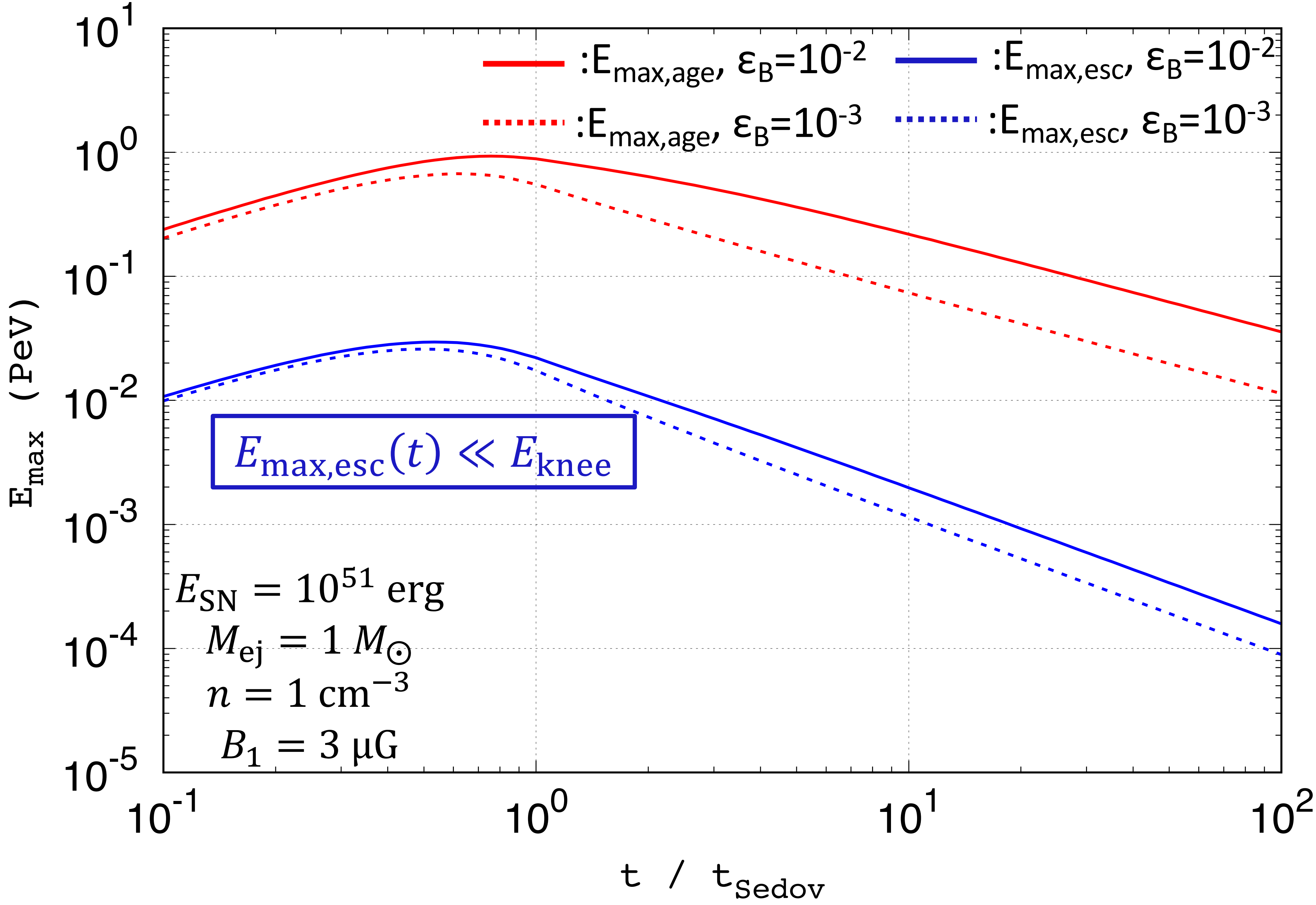
Escape Process : Diffusion along B field line

$$t_{\rm acc} = t_{\rm esc} \rightarrow E_{\rm max,esc}(t)$$

$$t_{\rm esc} = \frac{L_{\rm SL}^2}{D_{{\rm Bohm},B_1}} \qquad L_{\rm SL} \sim \frac{u_{\rm sh}}{c} R_{\rm sh}$$

superluminal shock: $\dfrac{u_{\rm sh}}{\cos\theta} > c$

E_{max} Limited by the Escape (Escape Limit)



Simulation Setup

- ✓ upstream region → test particle simulation
- ✓ downstream region → Monte-Carlo

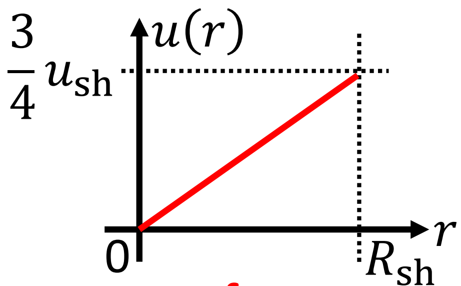
✓ SNR shock is spherically symmetric.

✓ SNR shock evolution : Mckee & Truelove 1995

✓ flow velocity profile

Assumption: only radial velocity

Ohira, Kisaka, Yamazaki (2018)



✓ Assumption

isotropic scattering in the downstream rest frame.

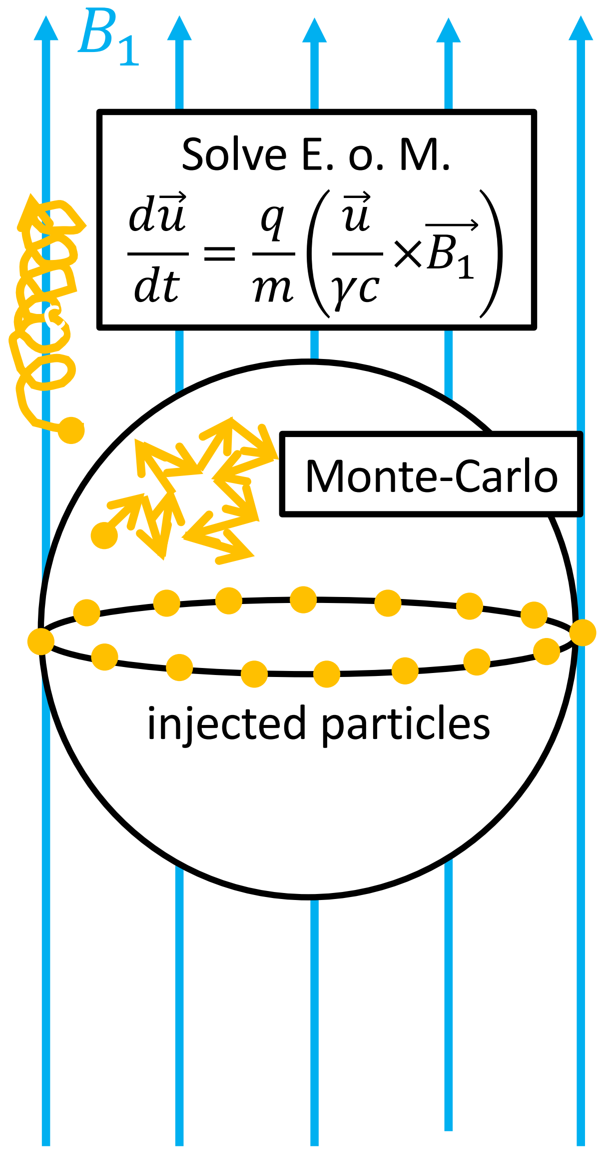
$$\frac{B_2^2 u_2}{8\pi} = \varepsilon_B \times \frac{1}{2}\rho u_{\rm sh}^3 \qquad \varepsilon_B = 0.01$$

✓ impulsive injection at an initial time on the equator

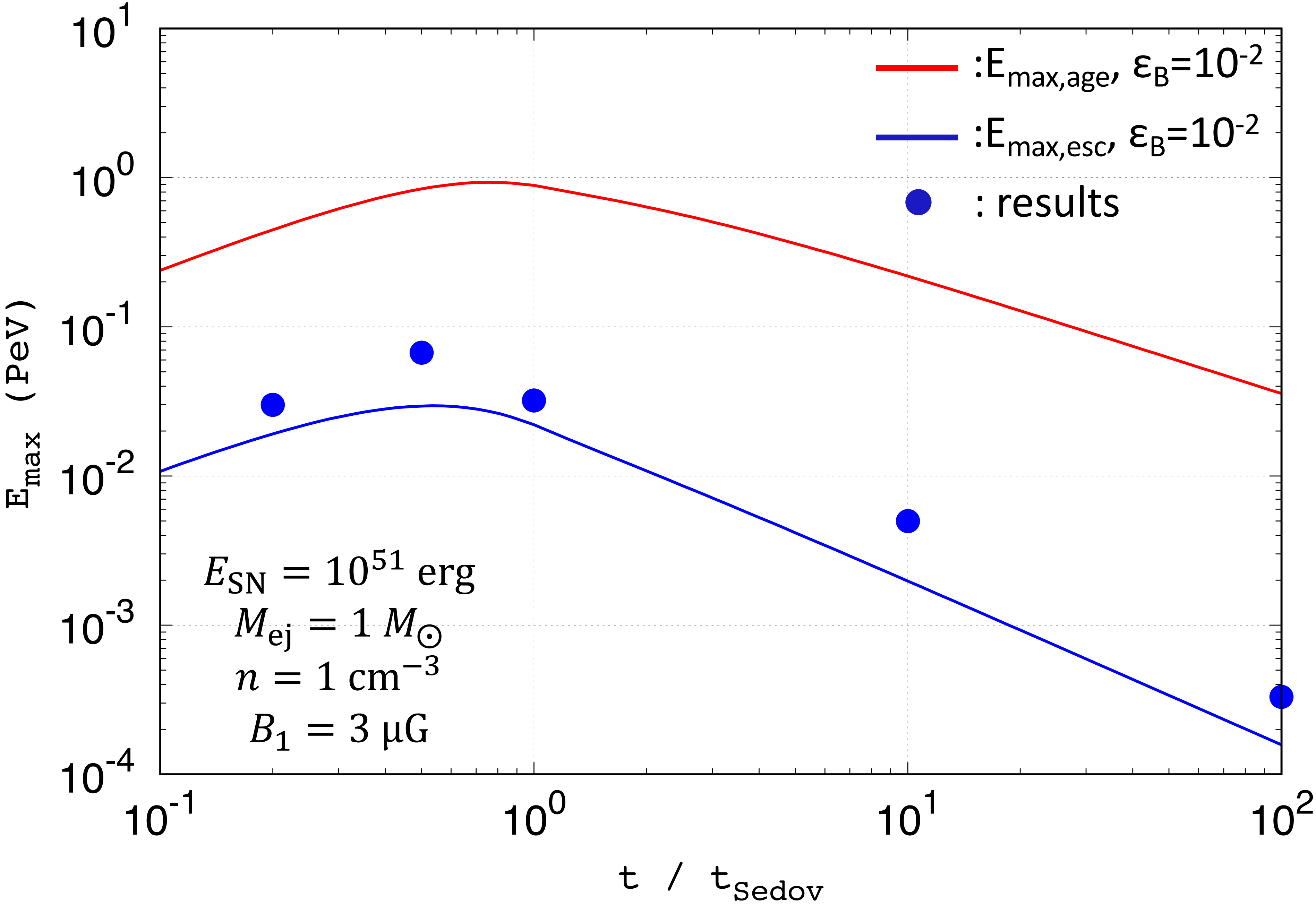
(isotropic distribution in a velocity space)

✓ upstream magnetic field (Only uniform magnetic field)

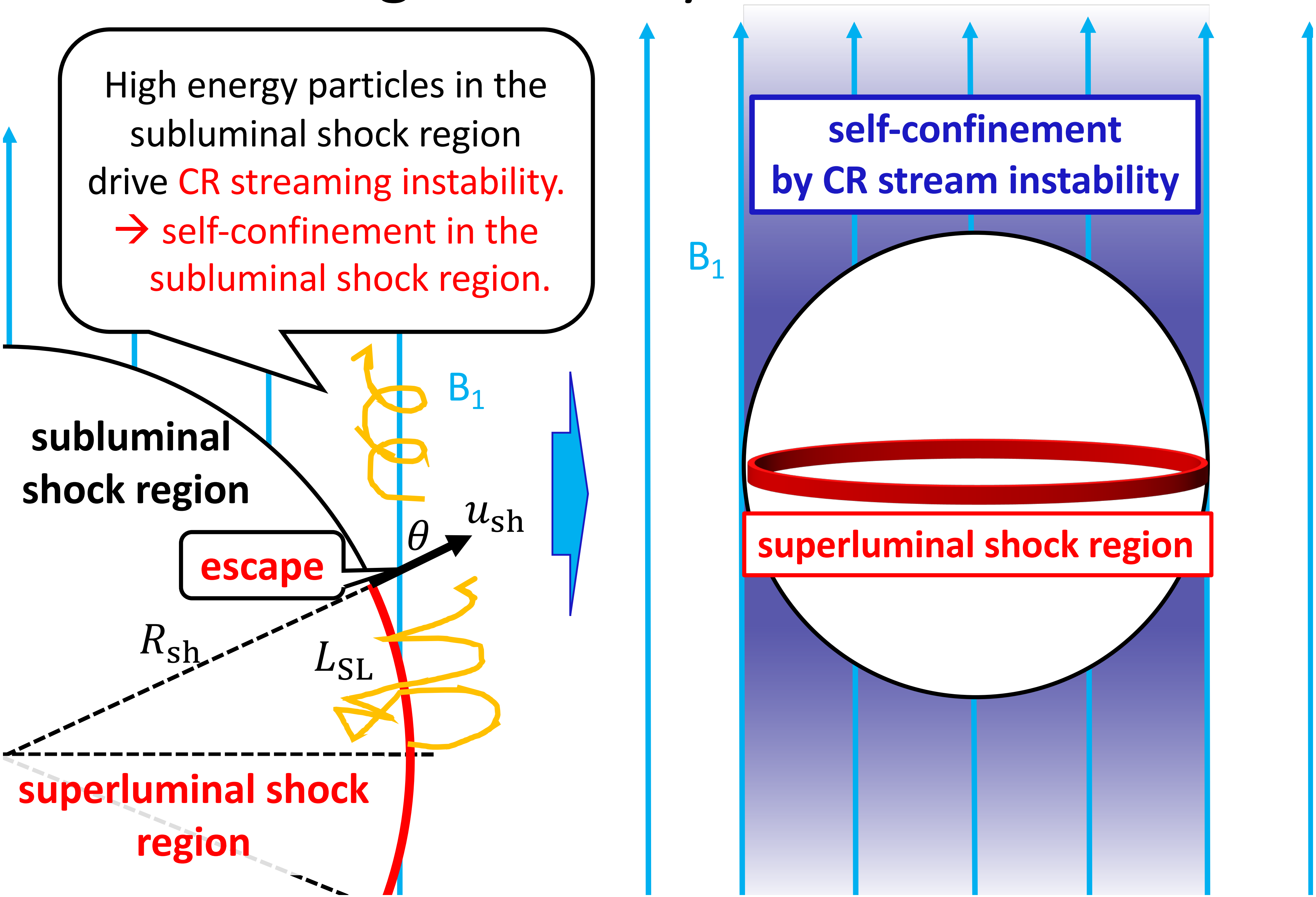
$$\overrightarrow{B_1} = (0, 0, B_1) \quad B_1 = 3\ \mu\mathrm{G}$$



Simulation Results



CR streaming instability & Self-confinement



Simulation Setup with Self-confinement

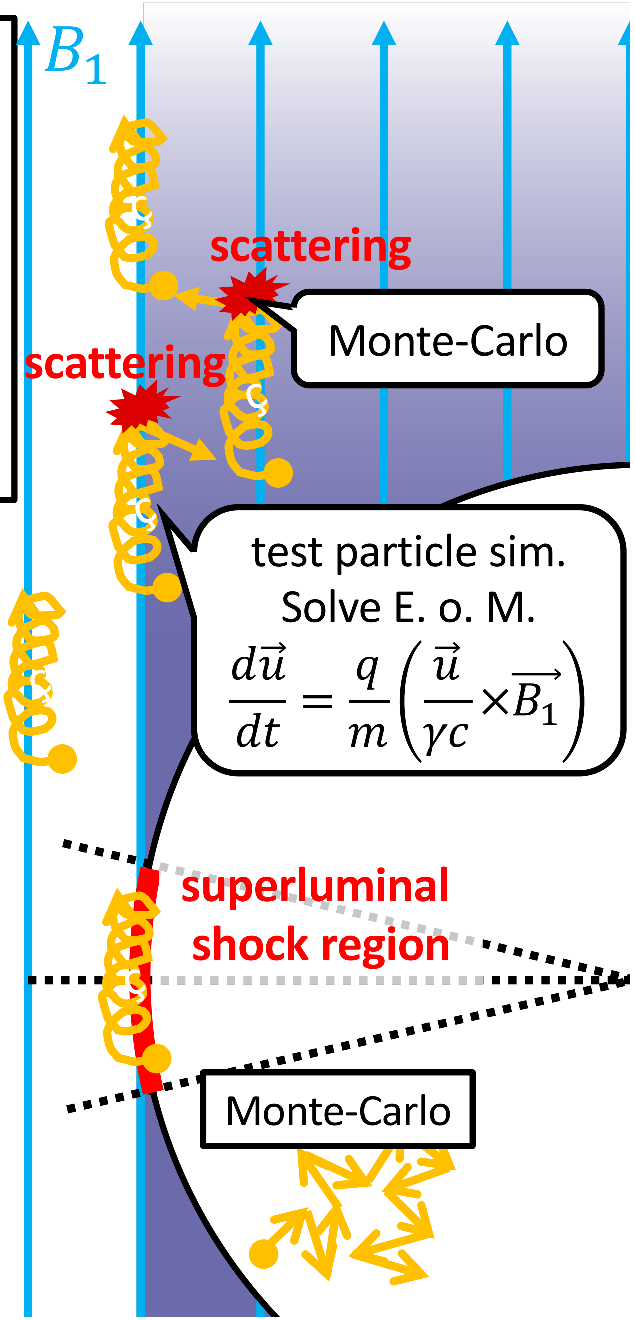
- ✓ downstream region → Monte-Carlo
- ✓ upstream region
  - ・subluminal shock region(= CRSI active region)
    → test particle simulation + Monte-Carlo
  - (Scattering rate is characterized by Bohm factor $\eta_{\mathrm{B}} = 0.3, 1.$)
  - ・superluminal shock region & another region
    → test particle simulation

- ✓ SNR shock is spherically symmetric.
- ✓ SNR shock evolution : Mckee & Truelove 1995
- ✓ flow velocity profile: Ohira, Kisaka, Yamazaki (2018)
- ✓ isotropic scattering in the downstream rest frame.

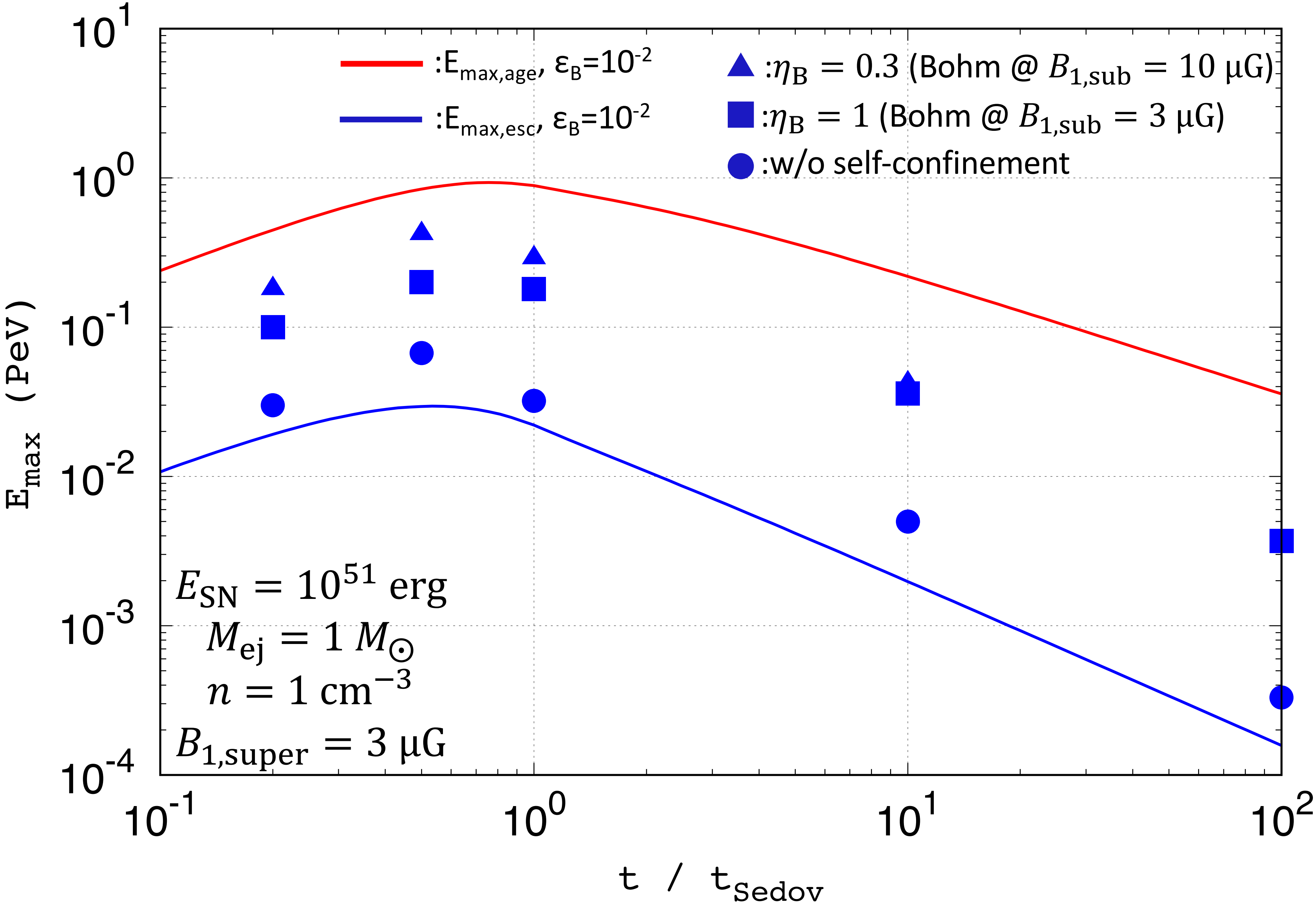
$$\frac{B_2^2 u_2}{8\pi} = \varepsilon_B \times \frac{1}{2}\rho u_{\mathrm{sh}}^3 \qquad \varepsilon_B = 0.01$$

- ✓ impulsive injection at an initial time on the equator
  (isotropic distribution in a velocity space)
- ✓ upstream magnetic field (Only uniform magnetic field)

$$\overrightarrow{B_1} = (0, 0, B_1) \qquad B_1 = 3\ \mu\mathrm{G}$$



Simulation Results



Summary

- We investigated the escape process from the perpendicular shock region of type Ia SNRs.
- The age limited maximum energy becomes comparable to PeV at $t = t_{Sedov}$.
- Particles injected to the equatorial plane are rapidly accelerated in the superluminal shock region and escape from the superluminal shock region while diffusing along the magnetic field line.
- The escape limited maximum energy is much smaller than PeV.
- If cosmic ray streaming instability driven by high energy escaped particles is active, particles are confined and accelerated in the subluminal shock region and the maximum energy reaches sub-PeV.