垂直衝撃波での加速時間とエネルギースペクトル

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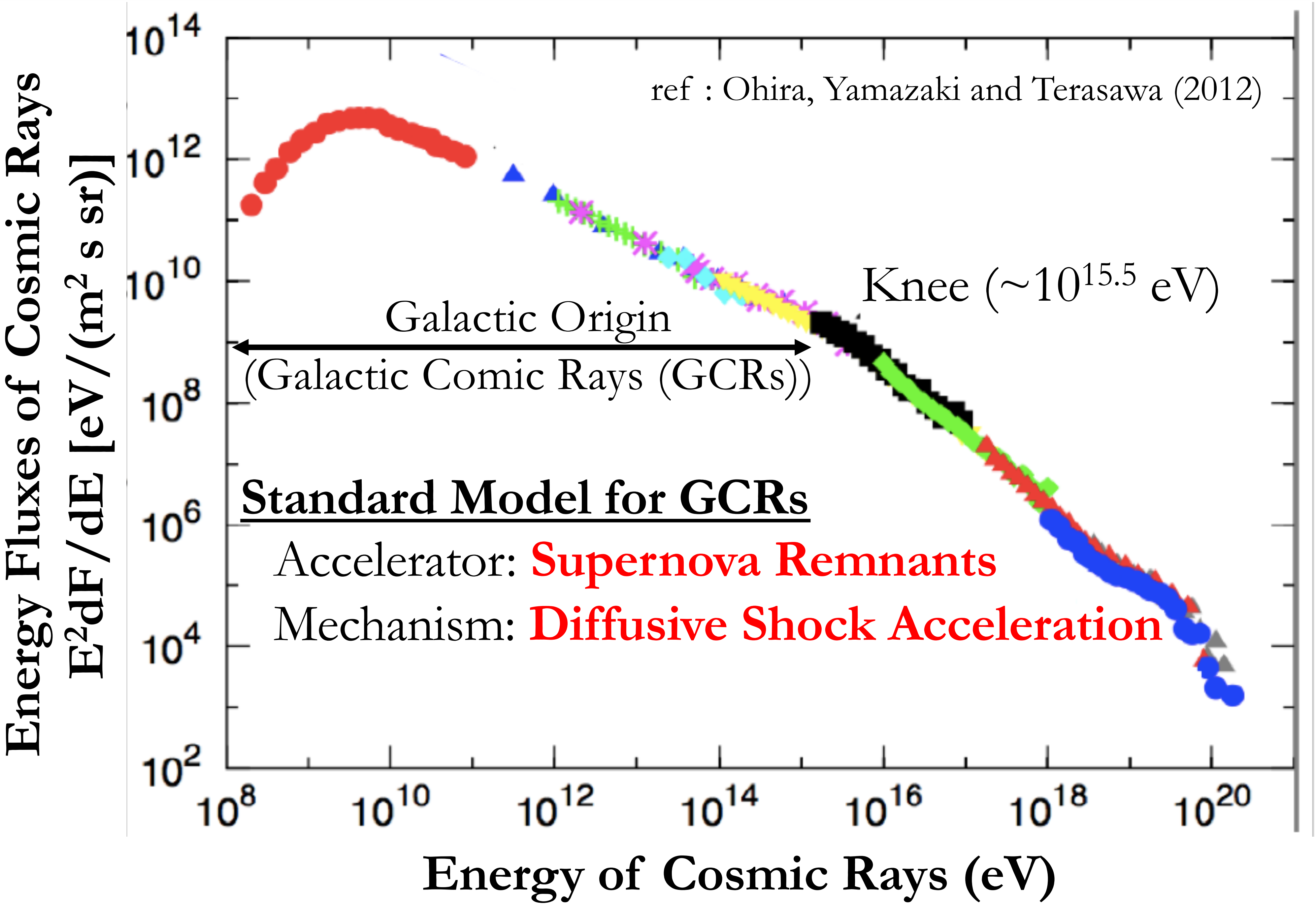
Cosmic Rays (CRs)

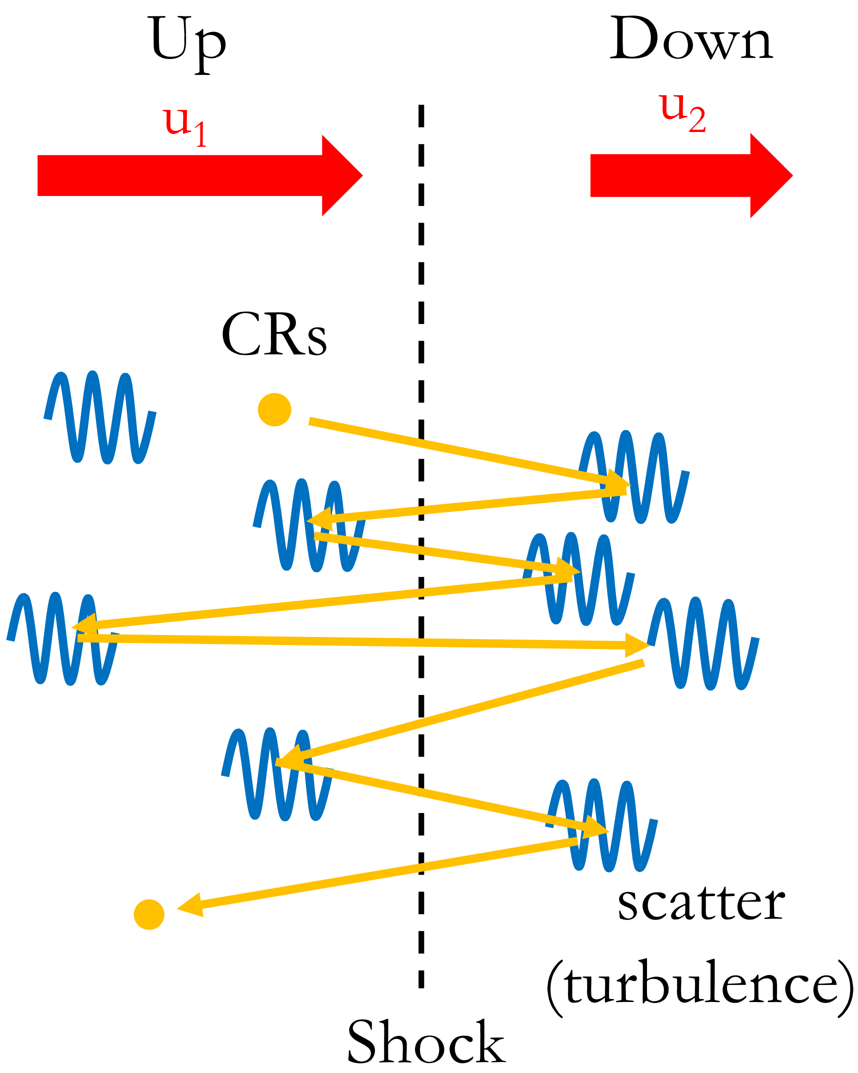


Standard Model for GCRs

Accelerator: **Supernova Remnants**

Mechanism: **Diffusive Shock Acceleration**

Diffusive Shock Acceleration (DSA)



@ shock rest frame

Assumption

- existence of shock
- existence of scatter

$$\frac{dN_{CR}}{dp} \propto p^{-s} \qquad s = \frac{r+2}{r-1} = 2$$

(compression ratio r = 4)

It does not depends on kinds of particles.

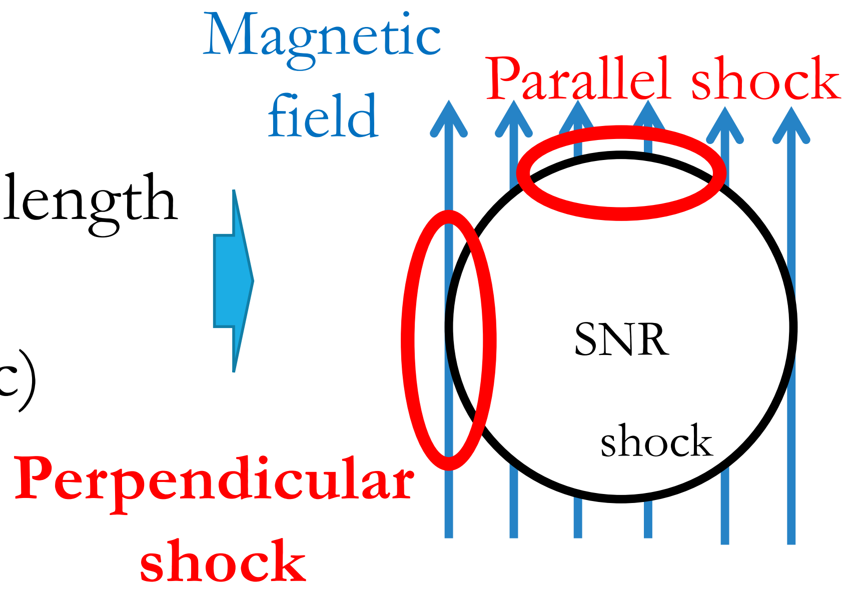
momentum gain (one cycle)

$$\frac{\Delta p}{p} = \frac{4(u_1 - u_2)}{3v}$$

Acceleration in Supernova Remnants

Supernova Remnants (type-Ia)

The size of supernova remnants (~ several pc) < The coherent length of ISM (< 100 pc)



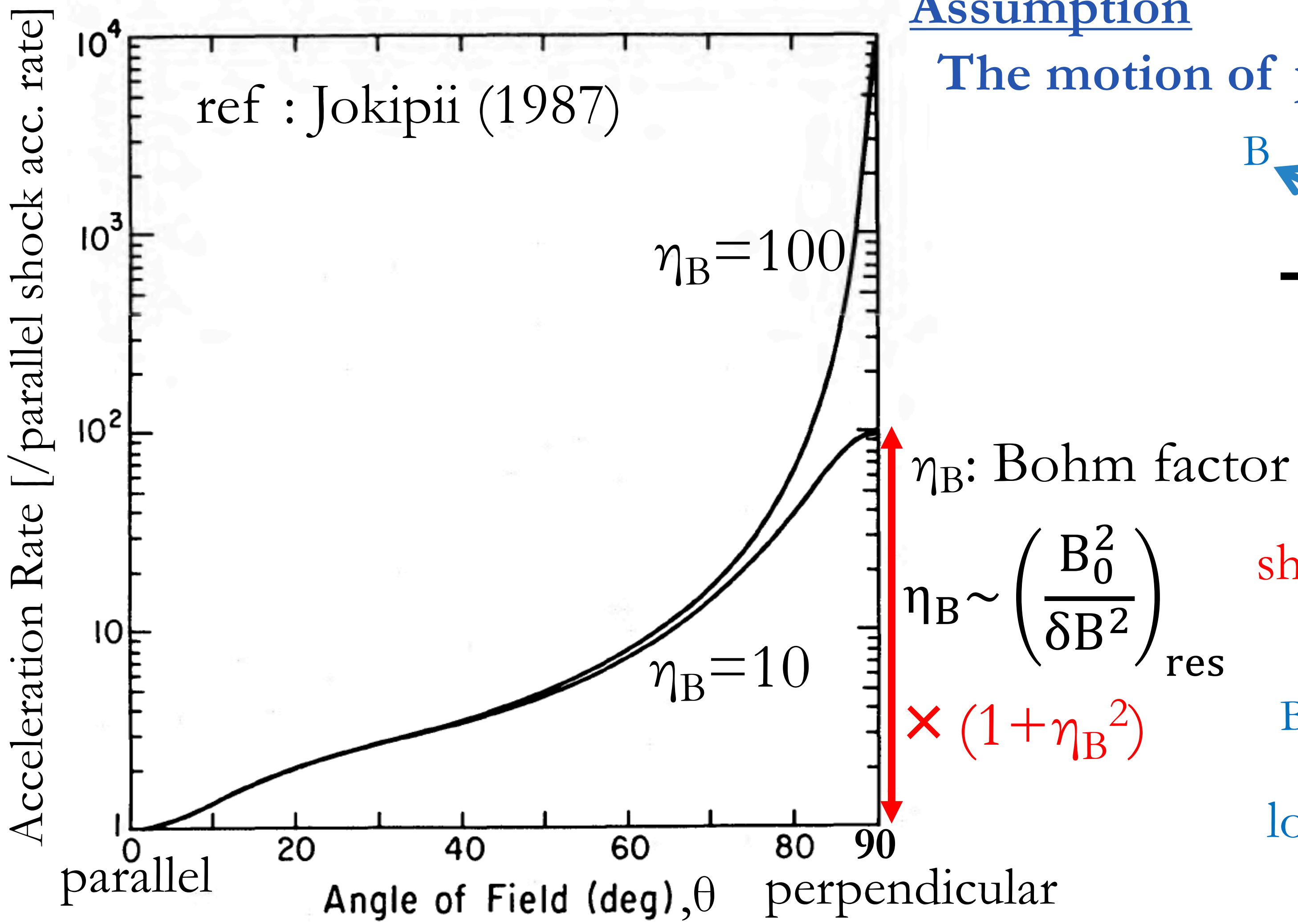
Main acceleration region

We focus on

Parallel shock	vs.	Perpendicular shock
High injection rate?		Low injection rate?
Slow acceleration?		Rapid acceleration!!!

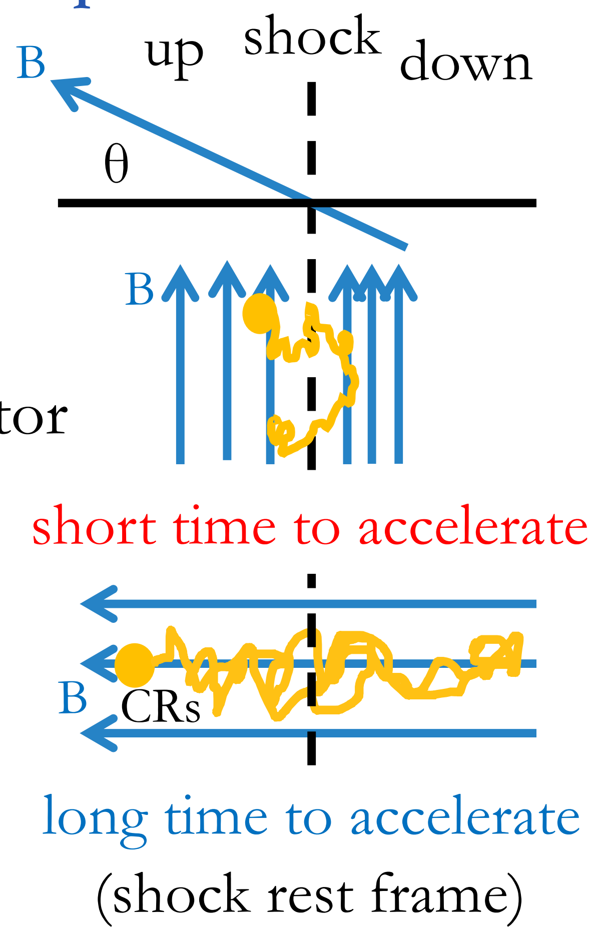
Acceleration Rate of a Perpendicular Shock

- The acceleration rate of a perp. shock is much larger than the acceleration rate of a parallel shock.
- Particles are efficiently accelerated in the case that the magnetic fluctuation is weak.



Assumption

The motion of particles is diffusive.



Energy Spectrum of a Perp. Shock Acceleration

The energy spectrum of a perpendicular shock acceleration becomes sorter than that of the standard DSA prediction in the case that the magnetic fluctuation is weak in downstream region.

ref: Takamoto & Kirk (2015)

Observations and simulations show that the magnetic field turbulence is amplified in the downstream region.

ref: observation : Bamba et al.(2003), Ohira and Yamazaki(2017)

simulation : Ohira (2016), Caprioli and Spitkovski(2013), Inoue et al.(2009) Giacalone and Jokipii(2007)

In this study, we assume the strong magnetic field amplification in the downstream region and the random walk in the downstream region.

Motivation

<u>Magnetic turbulence in this study</u>

- ❖ rapid acceleration → upstream : weak fluctuation ($\delta B/B_0<1$)
- ❖ observations and simulations in a downstream region

  → downstream : strong fluctuation ($\delta B/B_0 \geq 1$)

◆ Acceleration time at a perpendicular shock

◆ Energy spectrum of accelerated particles at a perp. shock

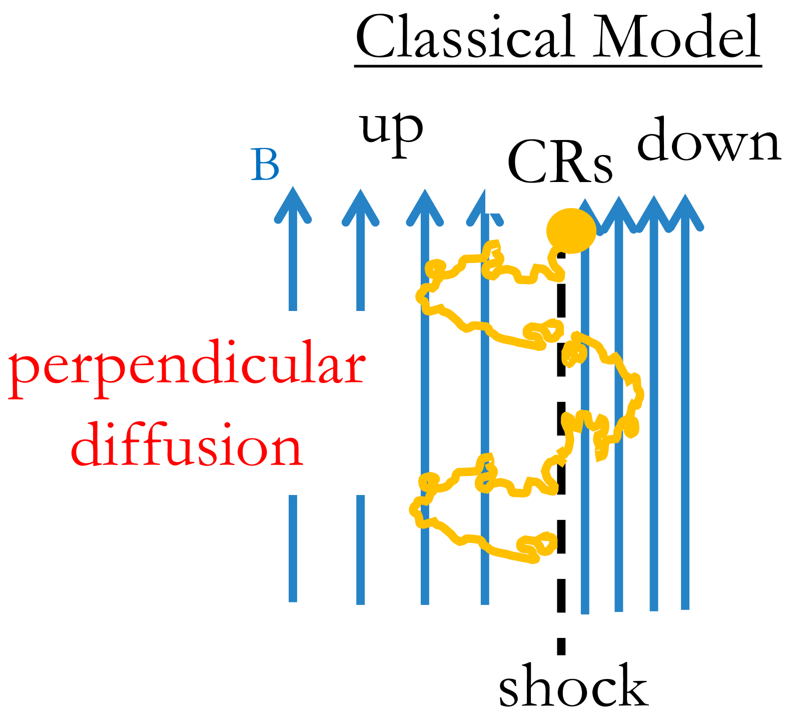
Classical Model and Our Model

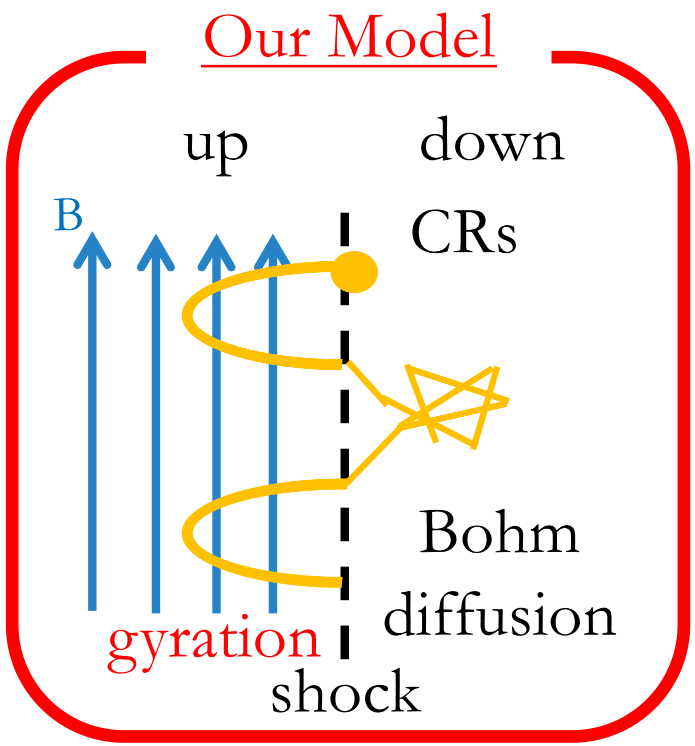
Magnetic turbulence in an upstream region

rapid acceleration → upstream : weak fluctuation ($\delta B/B_0<1$)

Under the condition that the upstream magnetic fluctuation is weak,

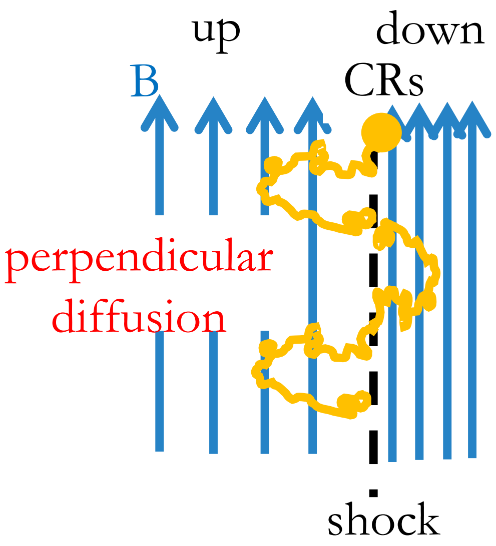
➡ The particle motion is **gyration**, **not diffusion.**



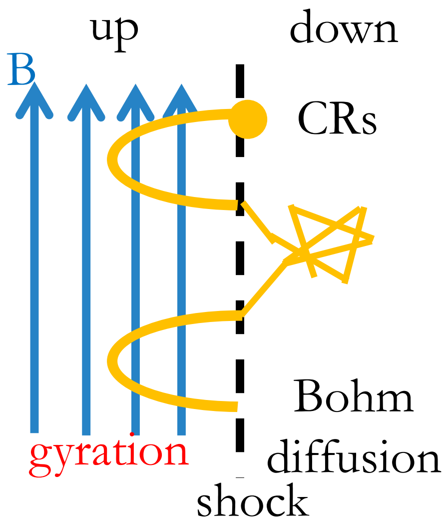


Acceleration Time

Classical Model



Our Model



Acceleration mechanism : DSA

$$\frac{\Delta p}{p} = \frac{u_{sh}}{c}$$

Assumption: downstream Bohm diffusion & B amplification

$$\lambda_{mfp,2} \sim r_{g,2}$$

the one cycle time

$$\Delta t = \begin{cases} \pi\Omega_{g,1}^{-1} + \dfrac{4D_{Bohm,2}}{u_2 c} & \text{gyration + Bohm} \\[2ex] \dfrac{4D_{\perp,1}}{u_1 c} + \dfrac{4D_{\perp,2}}{u_2 c} & \text{perpendicular diffusion} \end{cases}$$

Acceleration time

$$T_{acc} = \frac{p}{\Delta p/\Delta t} = \begin{cases} \pi\left(\dfrac{u_{sh}}{c}\right)^{-1} \Omega_{g,1}^{-1} + \dfrac{16}{3}\left(\dfrac{B_2}{B_1}\right)^{-1}\left(\dfrac{u_{sh}}{c}\right)^{-2} \Omega_{g,1}^{-1} & \text{gyration + Bohm} \\[2ex] \dfrac{4D_{\perp,1}}{u_{sh}^2} + \dfrac{16D_{\perp,2}}{u_{sh}^2} & \text{perpendicular diffusion} \end{cases}$$

Dependences

Acceleration Time of our model

$$T_{acc} = \frac{p}{\Delta p/\Delta t} = \pi \left(\frac{u_{sh}}{c}\right)^{-1} \Omega_{g,1}^{-1} + \frac{16}{3}\left(\frac{B_2}{B_1}\right)^{-1} \left(\frac{u_{sh}}{c}\right)^{-2} \Omega_{g,1}^{-1}$$

- dependence of the magnetic field amplification in downstream region
- dependence of the shock velocity

1st term (residence time in an upstream region) is dominant.

(large B_2/B_1 or fast shock velocity)

→ $T_{acc} \propto u_{sh}^{-1}$

2nd term (residence time in a downstream region) is dominant.

(small B_2/B_1 or slow shock velocity)

→ $T_{acc} \propto u_{sh}^{-2}$

c.f. If the particle motion in the upstream region is also **diffusion (classical model),**

→ $T_{acc} \propto u_{sh}^{-2}$ **for all cases** $\quad T_{acc} = \frac{4D_{\perp,1}}{u_{sh}^2} + \frac{16D_{\perp,2}}{u_{sh}^2}$

Setup : No Magnetic Fluctuation Case

- forward shock velocity (constant)
  $u_{sh}/c = 0.001, 0.00316, 0.01, 0.0316, 0.1, 0.316$

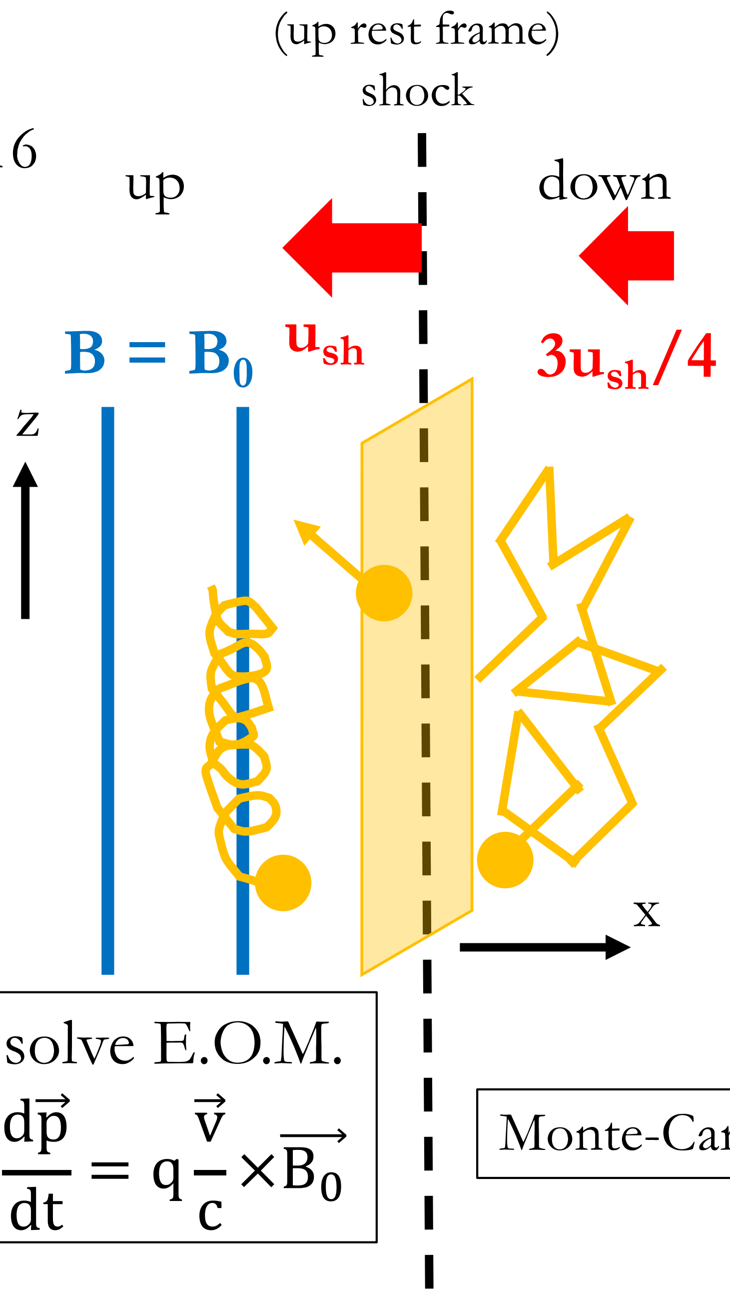
Assumption

Bohm diffusion in a downstream region
(isotropic scattering in downstream rest frame)
$B_2/B_1 = 1, 10, 100, 300, 1000$

- scattering time : $t_{scat} \propto p$
- impulsive injection @t=0 γ_0=15, isotropic
- The magnetic field in the upstream region consists of only uniform magnetic field.

→ **The weakest fluctuation limit**

$\overrightarrow{B_0} = (0, 0, B_0)$ B_0 : const.

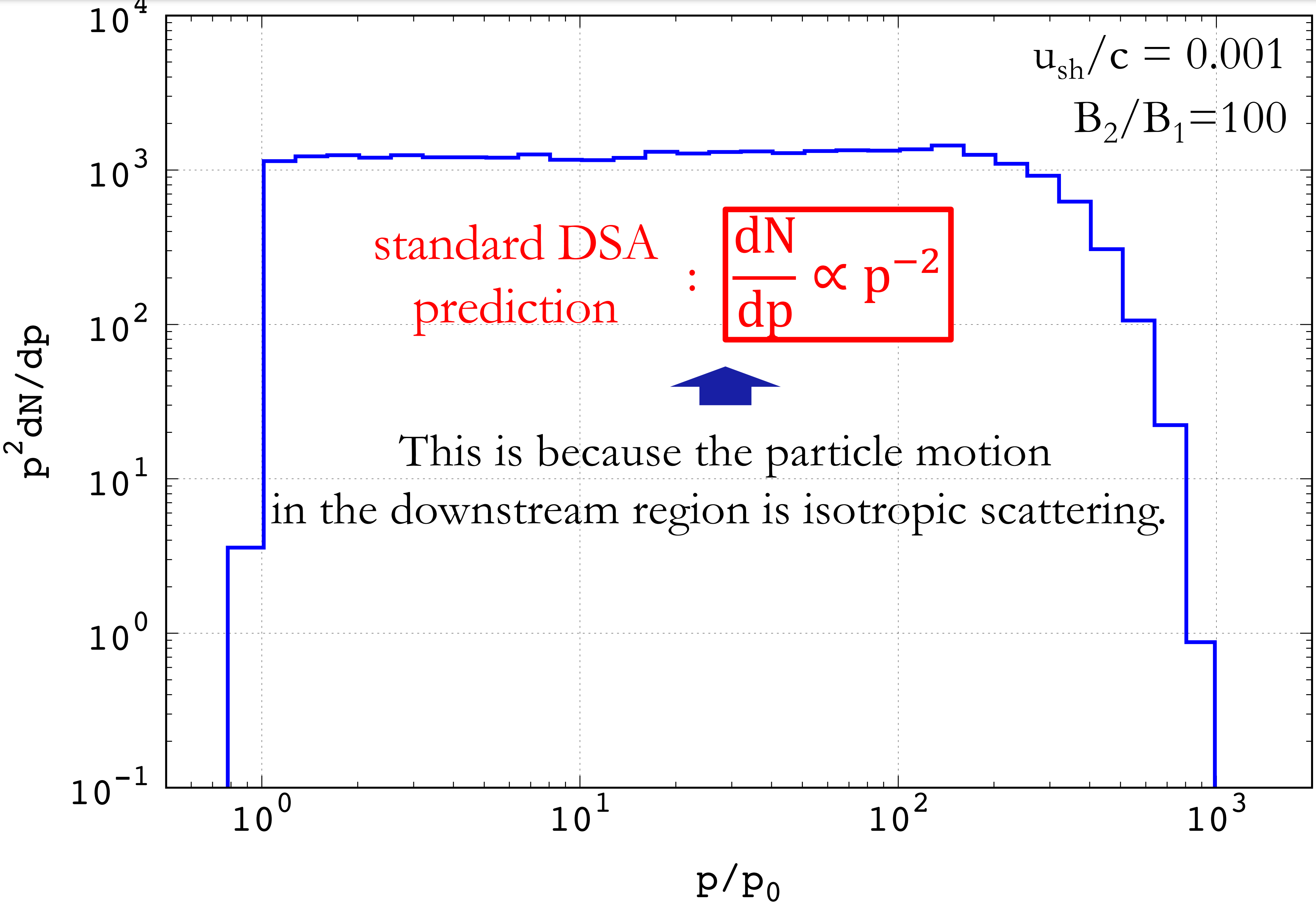


solve E.O.M.

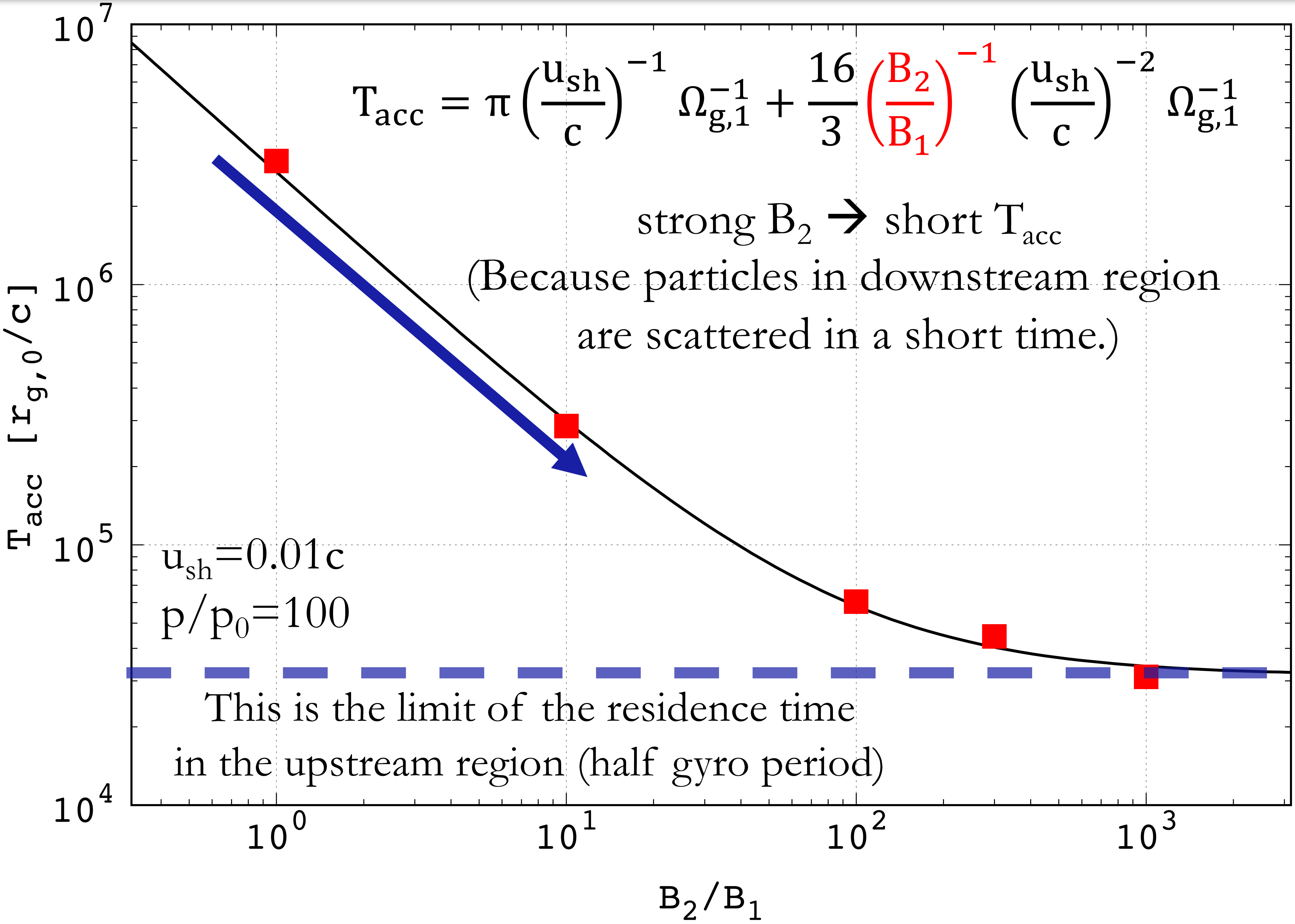
$$\frac{d\vec{p}}{dt} = q\frac{\vec{v}}{c} \times \overrightarrow{B_0}$$

Monte-Carlo

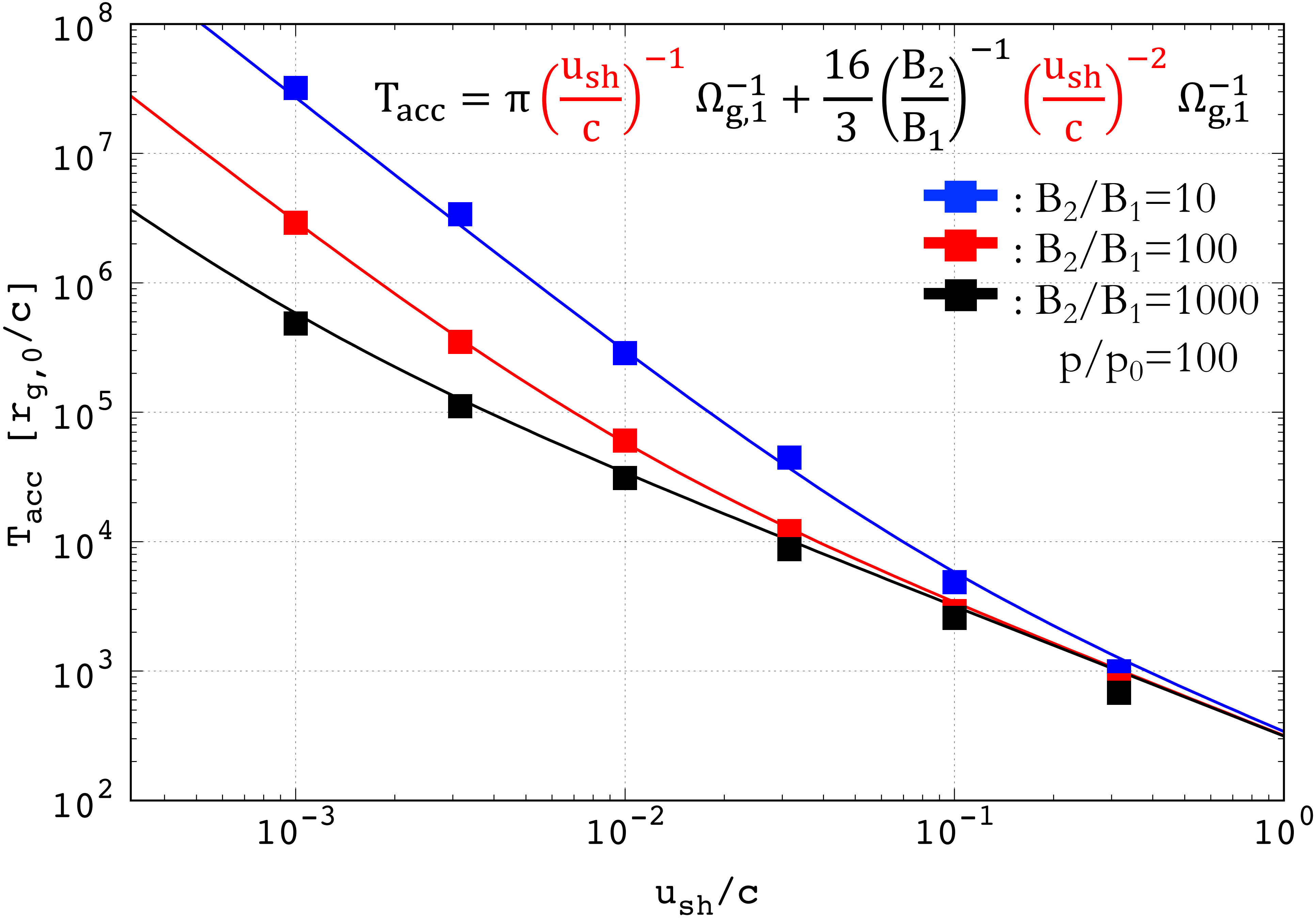
Spectrum of accelerated particles



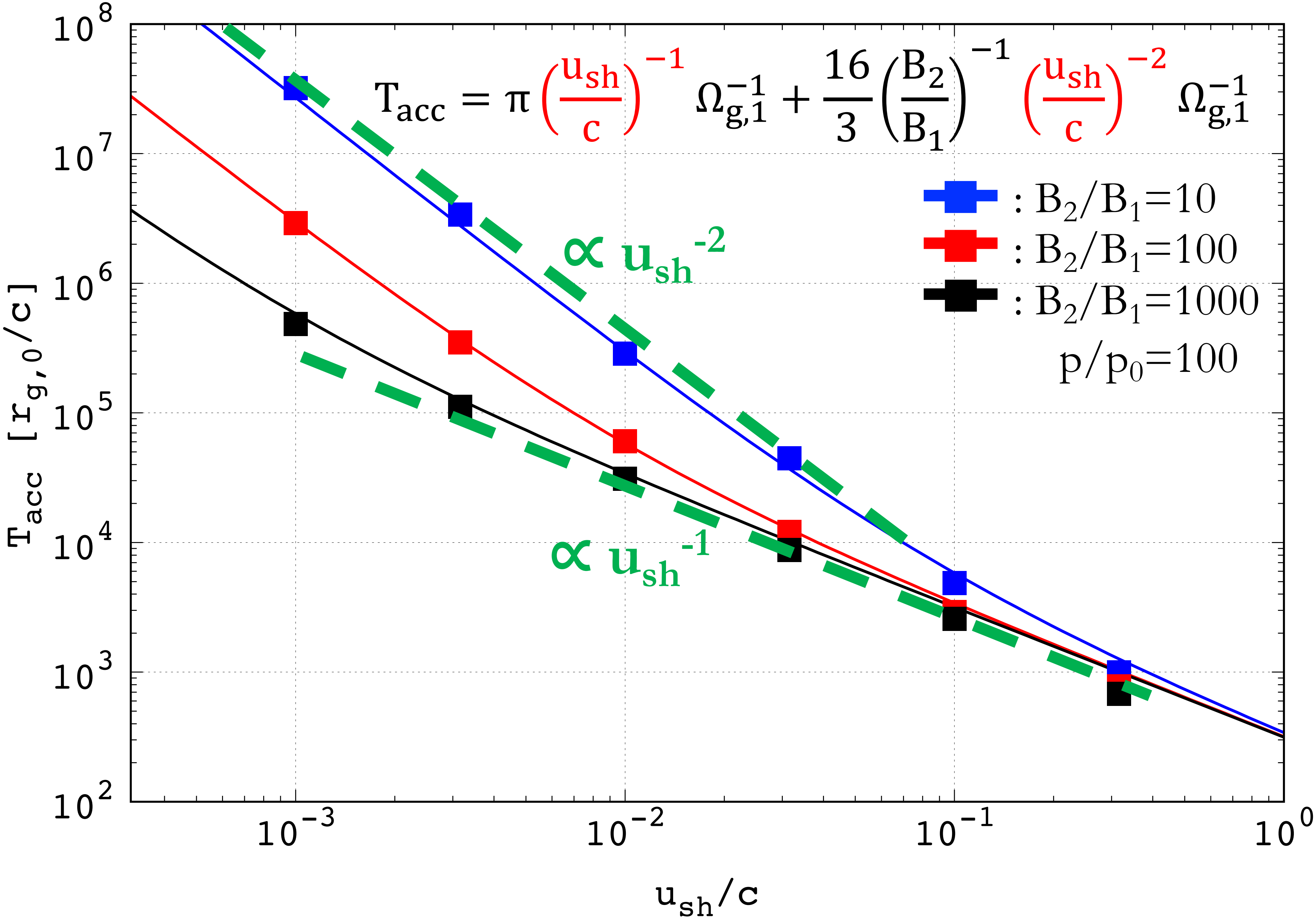
Acceleration Time T_{acc} vs. B field Amplification B_2/B_1



Acceleration Time T_{acc} vs. Shock Velocity u_{sh}/c



Acceleration Time T_{acc} vs. Shock Velocity u_{sh}/c



Summary

- We investigated a particle acceleration by a perpendicular shock.
- Weak and strong magnetic field turbulences are assumed in the upstream and downstream region, respectively.

Our Model

Gyration in the upstream region + Bohm diffusion in the downstream region

Energy spectrum of accelerated particles

- The energy spectrum at perp. shock become $\mathbf{E^{-2}}$ in the case that the magnetic fluctuation is sufficiently strong in downstream region.

Acceleration time

- The shock velocity dependence of the acceleration time changes.

When the upstream residence time is dominant, $\mathbf{T_{acc} \propto u_{sh}^{-1}}$

When the downstream residence time is dominant, $\mathbf{T_{acc} \propto u_{sh}^{-2}}$