爆発前の星風中を伝播する超新星残骸における宇宙線の加速と逃走

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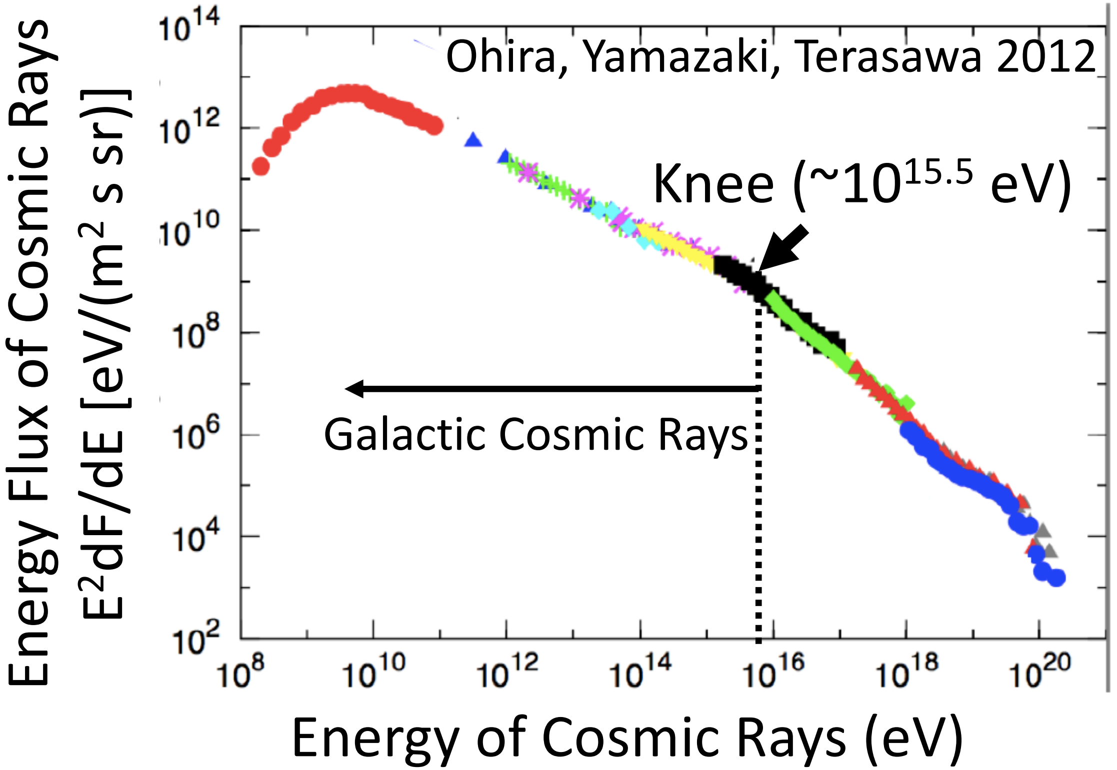
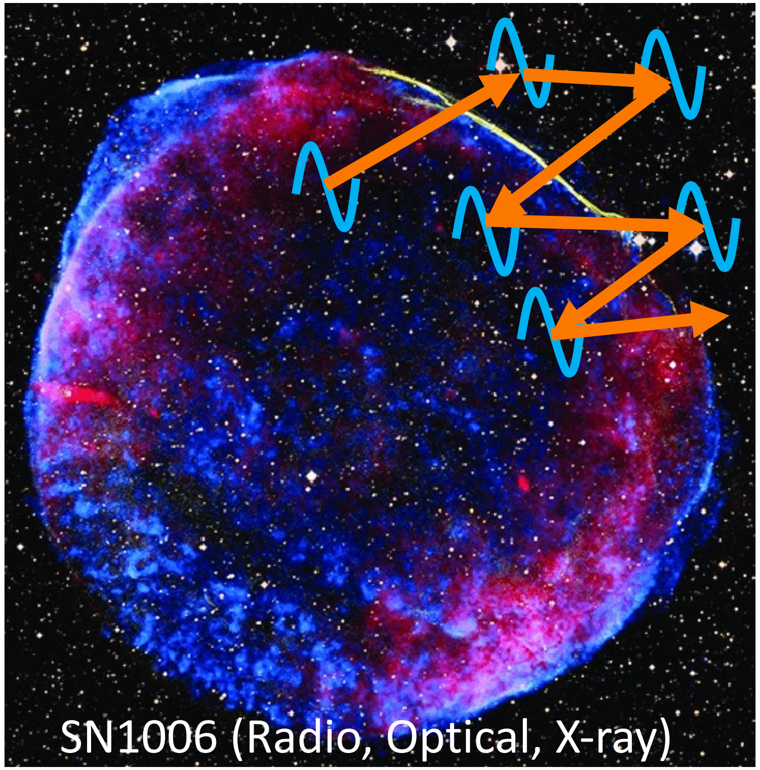
Origin of Galactic Cosmic Rays (GCRs)





Diffusive Shock Acceleration (DSA)

$$\frac{dN}{dE} \propto E^{-s} \qquad s = \frac{u_1/u_2+2}{u_1/u_2-1} = 2 \quad \text{(for strong shock)}$$

Axford 1977, Krymsky 1977, Blandford & Ostriker 1978, Bell 1978

Which shock accelerates GCRs, parallel shock or perpendicular shock ?

rapid acceleration

What types of supernovae accelerate GCRs up to PeV ?

Escape & Environment around SNRs

Cosmic-ray escape can determine the maximum energy of cosmic rays and the spectral index of escaped cosmic rays.

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

The **gyration** makes crucial role to realize **rapid acceleration in a perpendicular shock.**

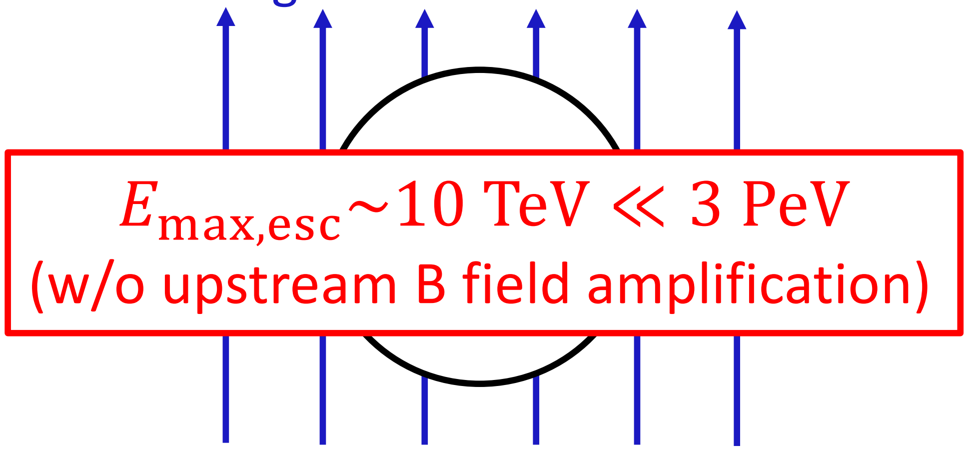
→ We cannot use **the diffusion approximation** that is assumed in previous work.

(Takamoto & Kirk 2015, Kamijima, Ohira, Yamazaki 2020)

The **environment around SNRs** and the **shock geometry** are important.

<u>Type Ia</u>

Environment: Interstellar medium (ISM)



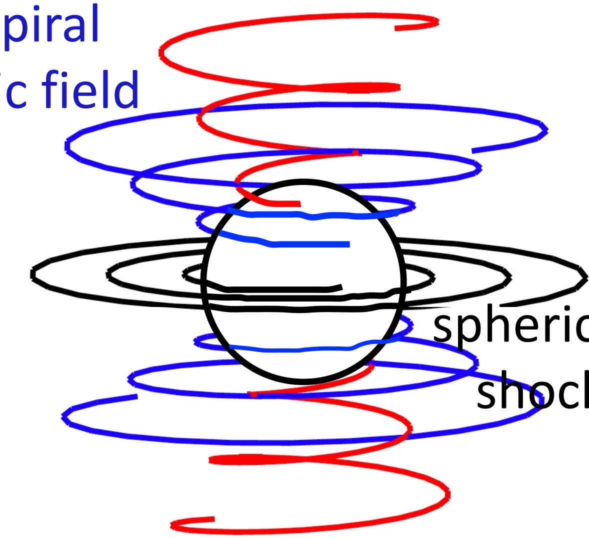
$E_{\rm max,esc} \sim 10\ {\rm TeV} \ll 3\ {\rm PeV}$

(w/o upstream B field amplification)

Kamijima & Ohira 2021

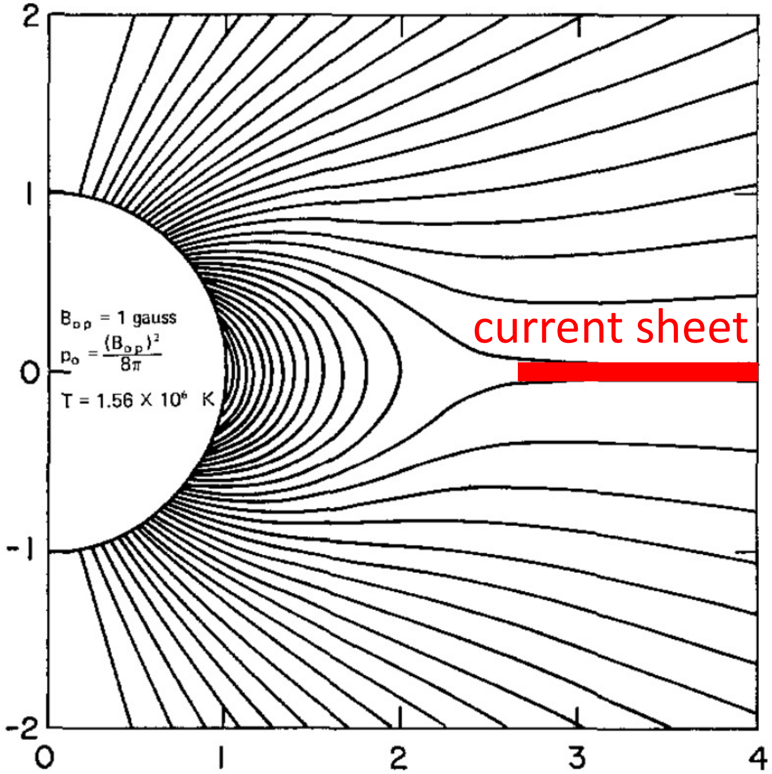
<u>core collapse</u>

Environment: ISM, **stellar wind**



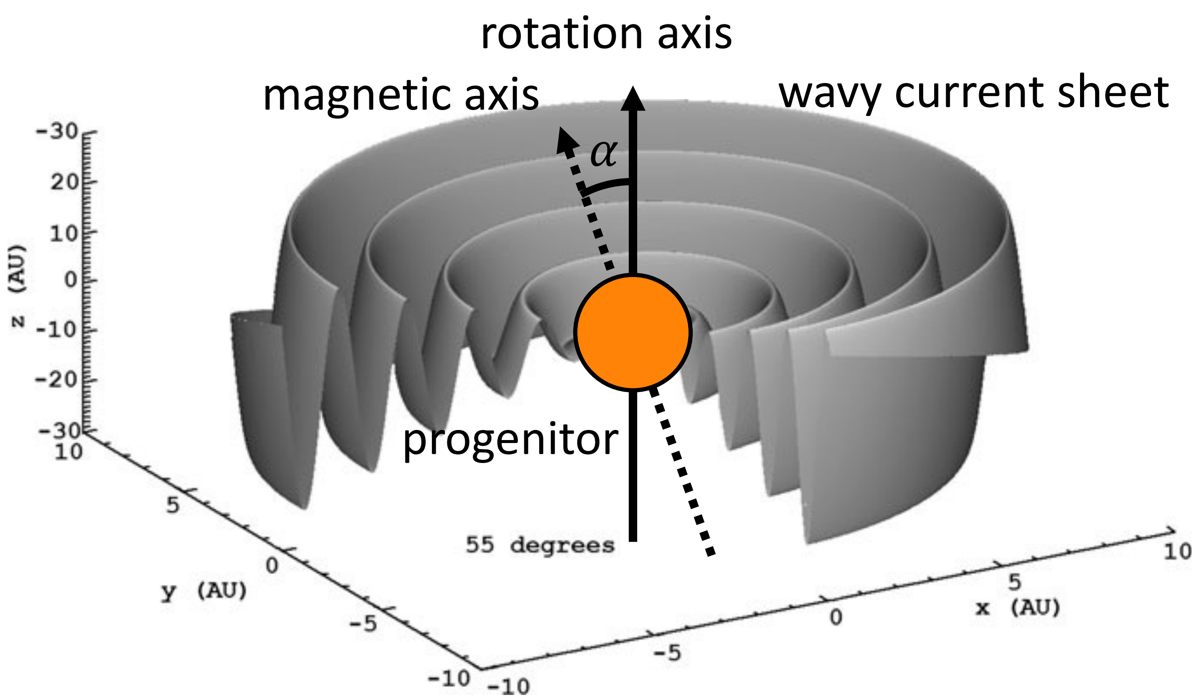
Aligned Rotator & Oblique Rotator

Aligned Rotator ($\alpha = 0$)



Neuman & Kopp 1970

Oblique Rotator ($\alpha \neq 0$)



Straus et al. 2012

The current sheet becomes the wavy structure if the rotation axis and the magnetic axis are misaligned.

Motivation

Previous work about cosmic-ray escape assumed **the diffusion approximation**.
(The rapid acceleration in perpendicular shocks is induced by a gyration.)

We found that typical type Ia SNRs cannot accelerate CRs to PeV without the upstream magnetic amplification(Kamijima & Ohira 2021).
→ How about SNRs in the circumstellar medium?

We investigate the escape process and the maximum energy limited by escape from a SNR in the circumstellar medium.

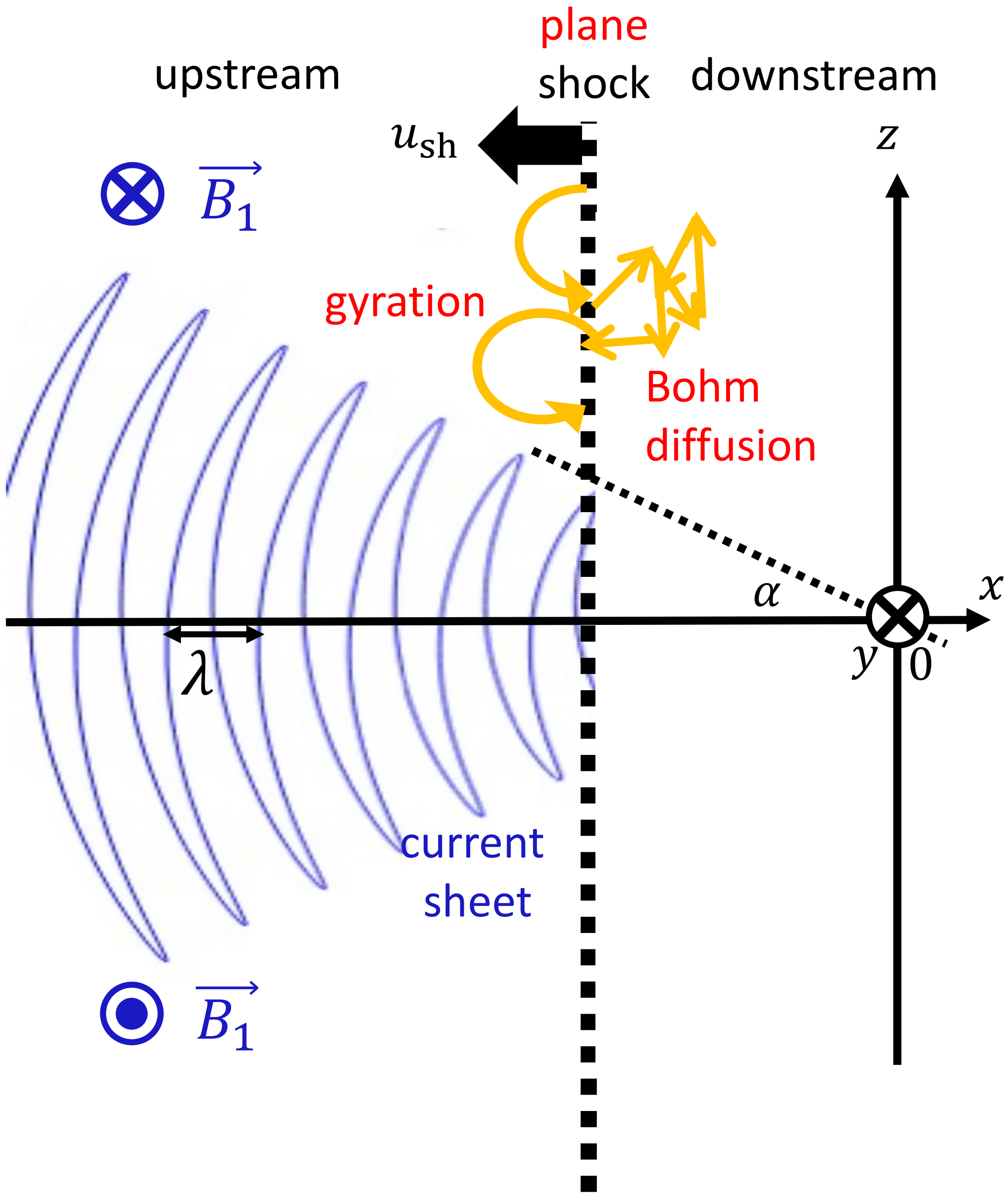
In this study,

- We exactly solve the gyration in the upstream region.
- We consider the shock geometry, the upstream magnetic field configuration, and the current sheet structure.

Our Simplified Model

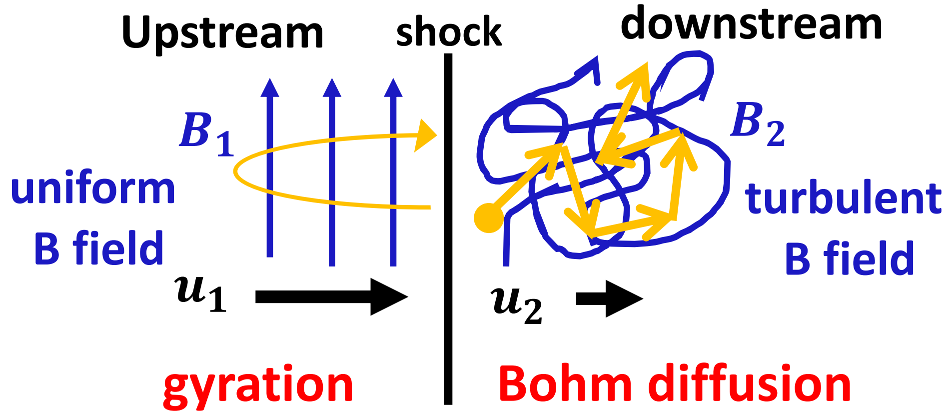
- plane shock approximation
- stationary wavy structure
- The same wavy structure infinitely continue in y direction.
- turbulent magnetic field in the downstream region
- magnetic field in the wind (only uniform component)

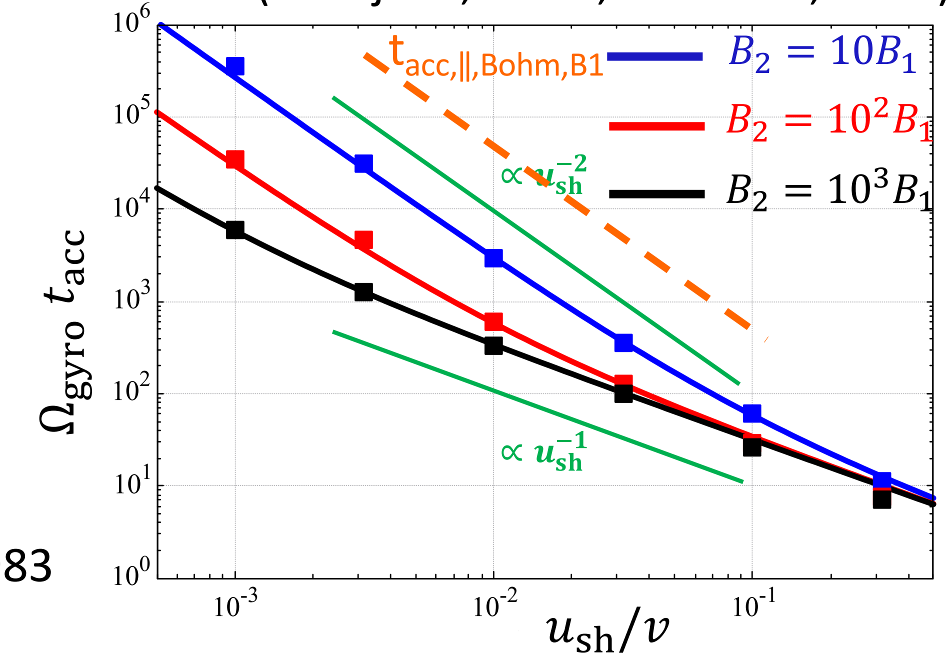
$$B_r = B_\theta = 0 \qquad B_\phi = \text{const.}$$



Perpendicular Shock Acceleration Model

(Kamijima, Ohira, Yamazaki, 2020)





residence time

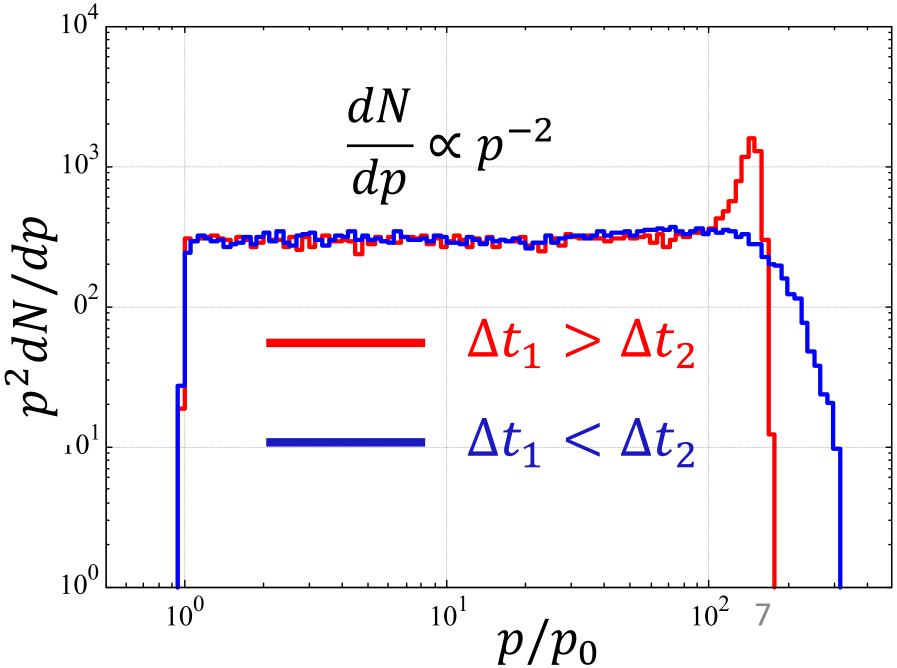
$$\Delta t_1 = \pi \Omega_{g,1}^{-1} \qquad \Delta t_2 = \frac{4\kappa_2}{u_2 v} \qquad \text{Drury 1983}$$

aceleration time

$$t_{acc} = (\Delta t_1 + \Delta t_2) p/\Delta p \qquad \frac{\Delta p}{p} = \frac{u_1}{v}$$

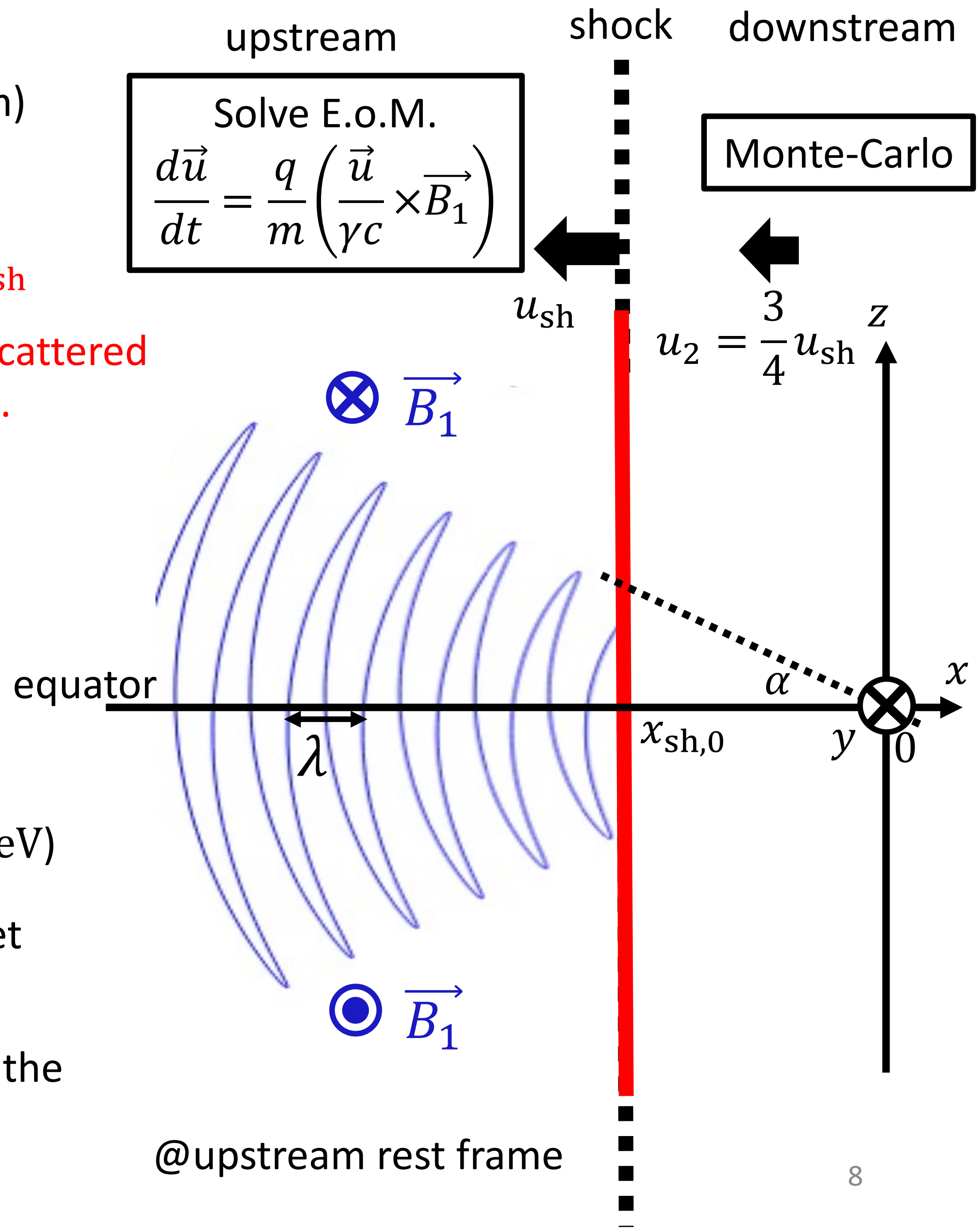
$$t_{acc} = \pi \left(\frac{u_{sh}}{v}\right)^{-1} \Omega_{g,1}^{-1} + \frac{16}{3}\left(\frac{B_2}{B_1}\right)^{-1} \left(\frac{u_{sh}}{v}\right)^{-2} \Omega_{g,1}^{-1}$$

Our model can realize the rapid acceleration and the canonical spectrum, $dN/dp \propto p^{-2}$, simultaneously.



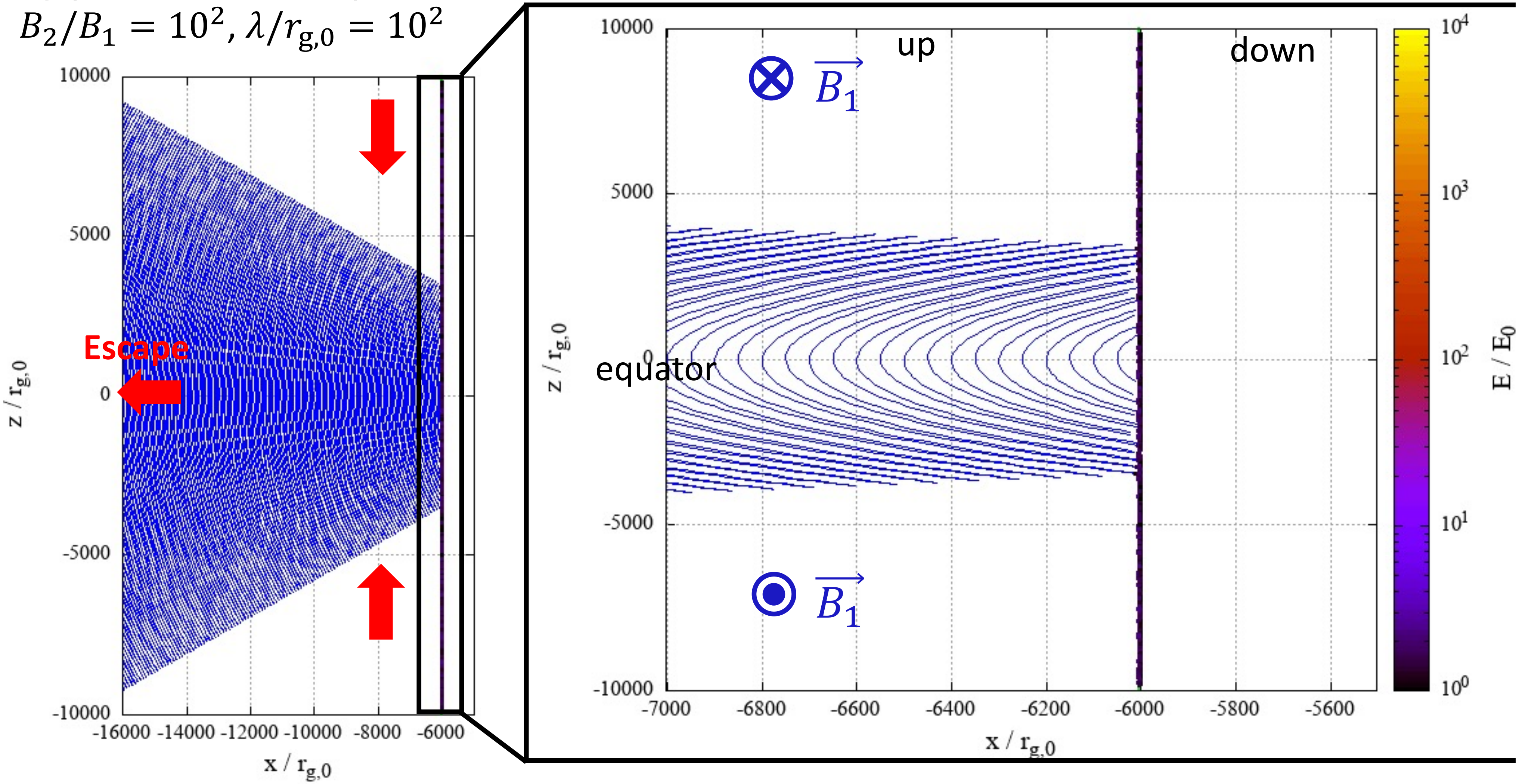
Simulation Setup: Oblique Rotator

- test particle simulation (upstream) + Monte-Carlo (downstream)
- shock velocity $u_{\rm sh} = 0.1c$ (const.)
- downstream flow velocity $u_2 = (3/4)u_{\rm sh}$
- Downstream particles are isotropically scattered in the local downstream fluid rest frame.
- upstream B field $B_1 = 1\mu{\rm G}$ (only uniform component)
- polarity: pole → equator
- downstream B field $B_2 = 100B_1$
- impulsive injection at the initial time (isotropic velocity distribution, $E_0 = 1$ TeV)
- the wavelength of the wavy current sheet structure: $\lambda = 100\ r_{\rm g,0}$
- the angle between the rotation axis and the magnetic axis: $\alpha = \pi/6$
- particle splitting method



Oblique Rotator (Pole → Equator)

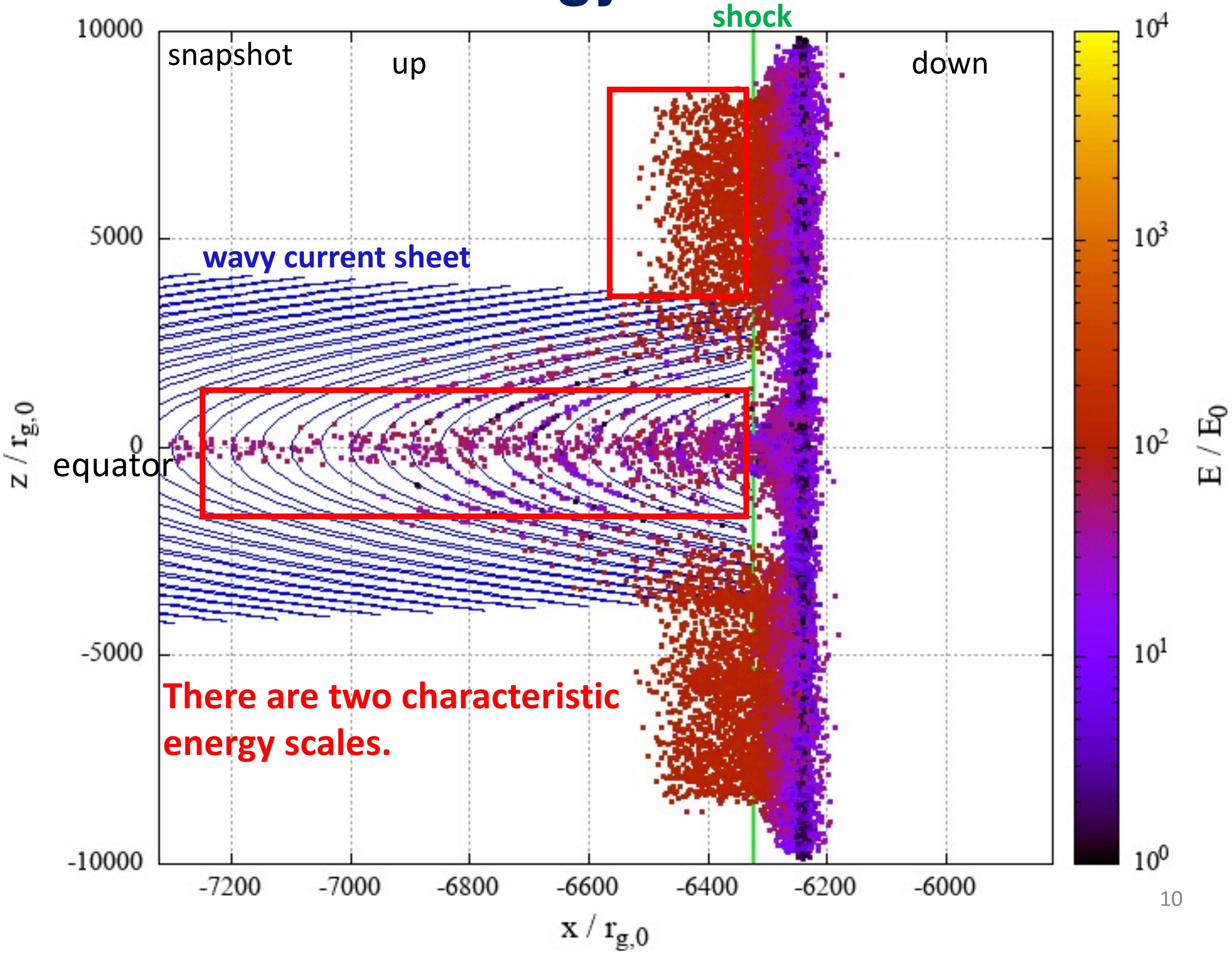
$u_{sh}/c = 10^{-1}, \alpha = \pi/6,$
$B_2/B_1 = 10^2, \lambda/r_{g,0} = 10^2$



Particles in the wavy structure **move along the current sheet**.

Particles escape to the far upstream region **along the equatorial plane.**

Energy Scale



There are two characteristic energy scales.

Maximum Energy

① Particles injected far from the equator:

The maximum energy is given by **the potential drop.**

→ $E_{\mathrm{max,PD}} = e\frac{u_{\mathrm{sh}}}{c}B_1\left(z_{\mathrm{inj}} - \left|x_{\mathrm{sh,0}}\right|\tan\alpha\right)$

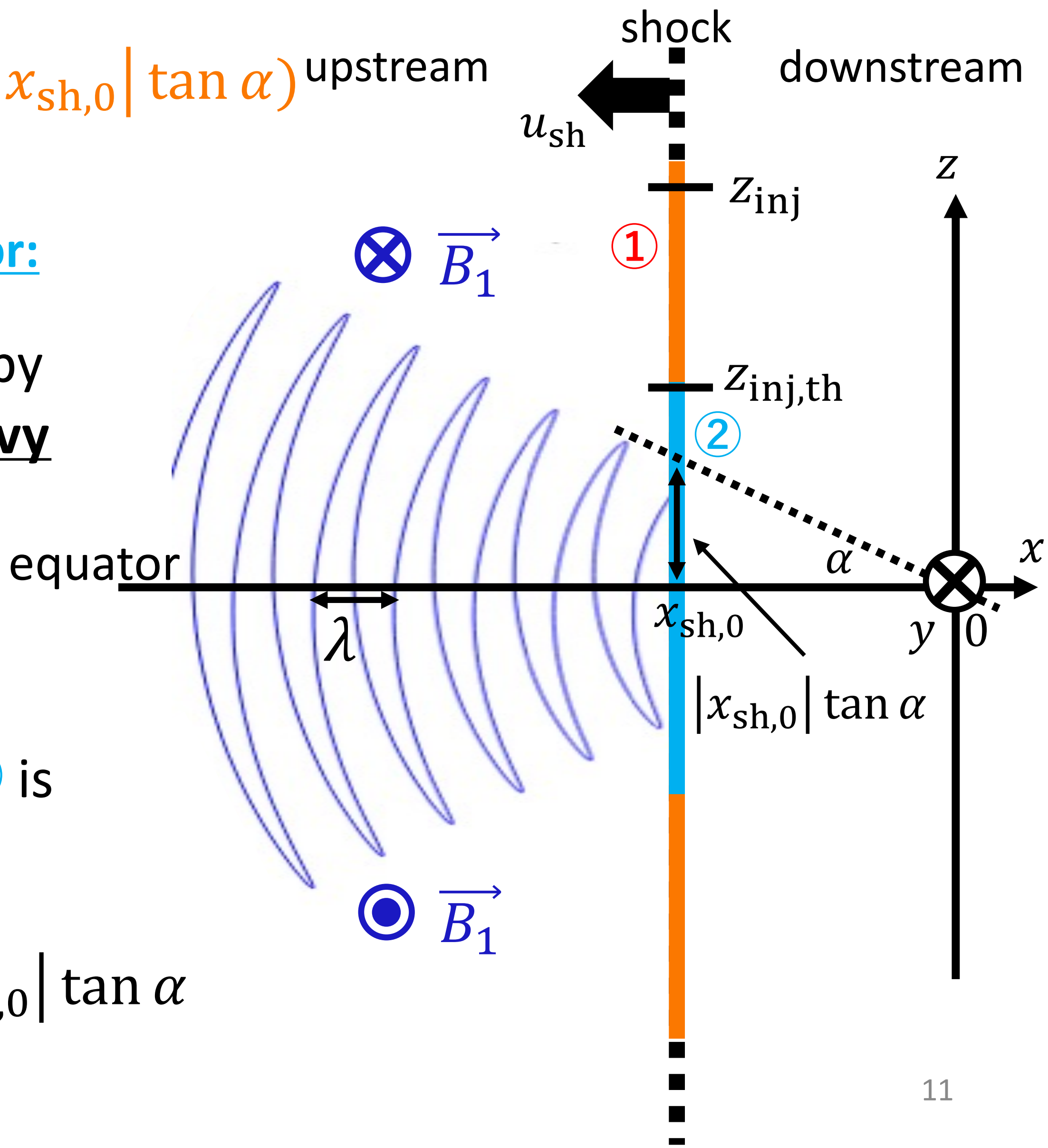
② Particles injected near the equator:

The maximum energy is given by **the half wavelength of the wavy structure ($r_g = \lambda/2$).**

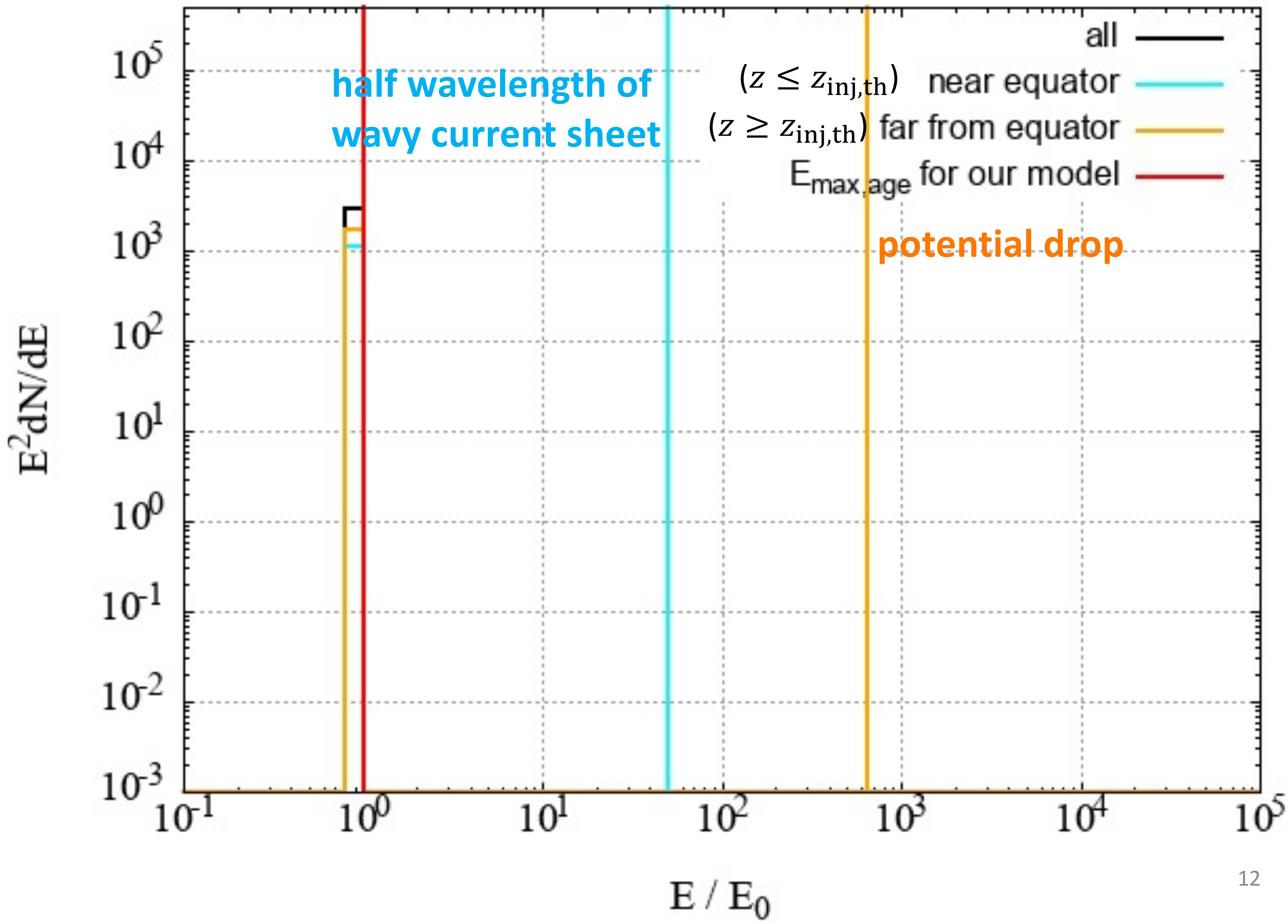
→ $E_{\mathrm{max},\lambda/2} = eB_1\frac{\lambda}{2}$

The transition between ① and ② is given by $\boldsymbol{E_{\mathrm{max,PD}} = E_{\mathrm{max},\lambda/2}}$.

→ $z_{\mathrm{inj,th}} = \frac{\lambda}{2}\left(\frac{u_{\mathrm{sh}}}{c}\right)^{-1} + \left|x_{\mathrm{sh,0}}\right|\tan\alpha$



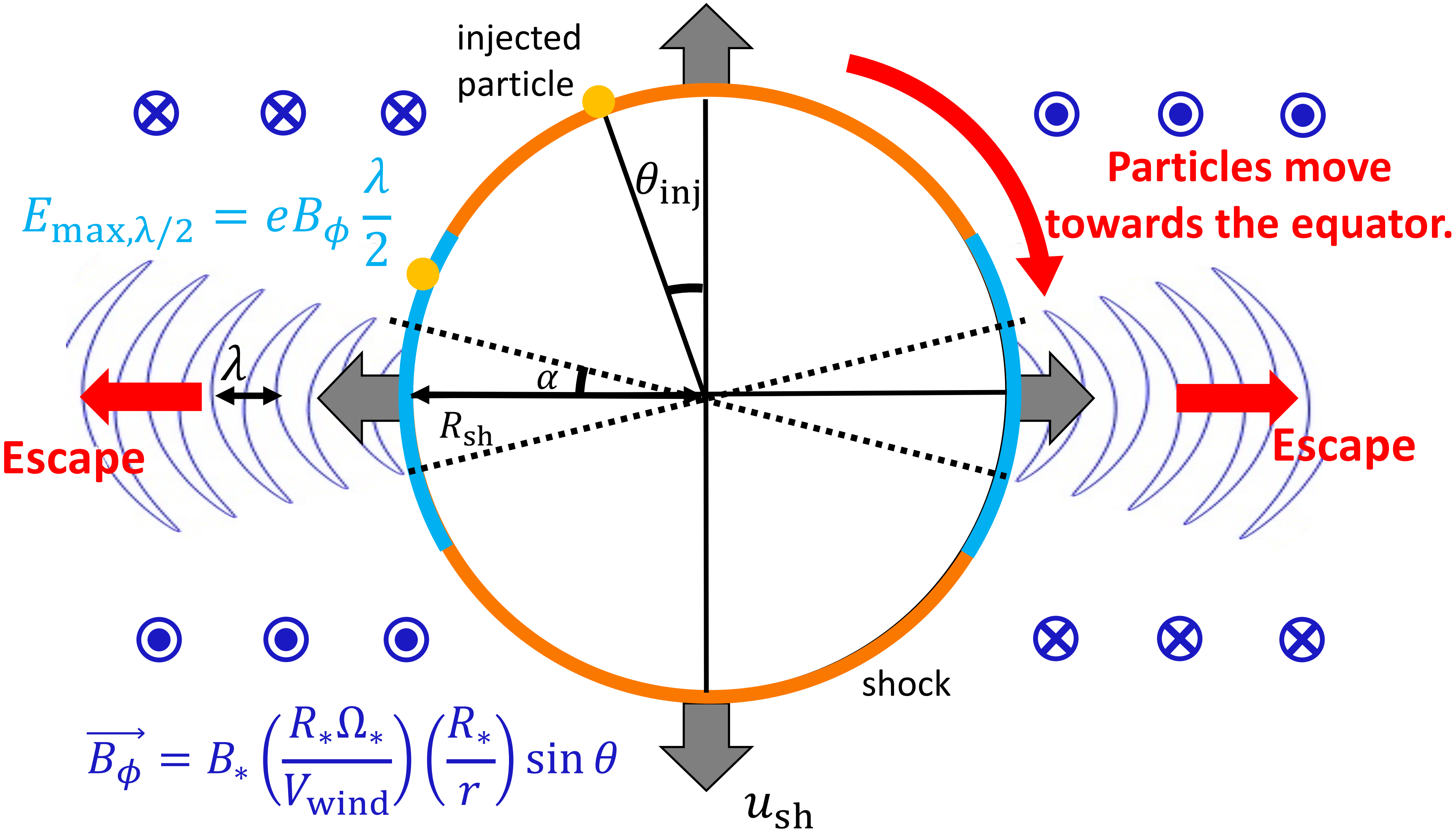
Oblique Rotator (Pole → Equator)



Oblique Rotator (Pole → Equator)

$$E_{\mathrm{max,PD}} = e\frac{u_{\mathrm{sh}}}{c}B_\phi\left(\frac{\pi}{2} - \alpha - \theta_{\mathrm{inj}}\right)R_{\mathrm{sh}}$$

$$E_{\mathrm{max},\lambda/2} = eB_\phi\frac{\lambda}{2}$$



$$\overrightarrow{B_\phi} = B_*\left(\frac{R_*\Omega_*}{V_{\mathrm{wind}}}\right)\left(\frac{R_*}{r}\right)\sin\theta$$

Estimation of Maximum Energy

・ E_{max} given by potential drop

$$B_\phi \sim B_* \left(\frac{R_*\Omega_*}{V_{\rm wind}}\right)\left(\frac{R_*}{R_{\rm sh}}\right)$$

$$E_{\rm max,PD} = e\frac{u_{\rm sh}}{c}B_\phi\left(\frac{\pi}{2}-\alpha\right)R_{\rm sh} = \left(\frac{\pi}{2}-\alpha\right)\frac{u_{\rm sh}}{c}\frac{R_*\Omega_*}{V_{\rm wind}}eB_*R_*$$

E_{max} does not depend on the shock radius.
If the shock velocity is constant (e.g. free expansion phase), E_{max} becomes constant during this phase.

Red Supergiant

$$E_{\rm max,PD} \sim 7.5\times10^{12}\ {\rm eV}\left(\frac{u_{\rm sh}}{0.01c}\right)\left(\frac{V_{\rm wind}}{10\ {\rm km/s}}\right)^{-1}\left(\frac{\Omega_*}{5\times10^{-9}{\rm s}^{-1}}\right)\left(\frac{B_*}{10{\rm G}}\right)\left(\frac{R_*}{100R_\odot}\right)^2$$

$T_{\rm rot} = 2\pi/\Omega_* \sim 36 \pm 8\ {\rm yr} \rightarrow \Omega_* \sim 5\times10^{-9}\ {\rm s}^{-1}$ for Betelgeuse (Kervella et al. 2018)

WR star

$$E_{\rm max,PD} \sim 3.2\times10^{13}\ {\rm eV}\left(\frac{u_{\rm sh}}{0.01c}\right)\left(\frac{V_{\rm wind}}{1000\ {\rm km/s}}\right)^{-1}\left(\frac{\Omega_*}{2\times10^{-4}{\rm s}^{-1}}\right)\left(\frac{B_*}{1{\rm kG}}\right)\left(\frac{R_*}{R_\odot}\right)^2$$

$T_{\rm rot} = 2\pi/\Omega_* \sim 10\ {\rm hours} \rightarrow \Omega_* \sim 2\times10^{-4}\ {\rm s}^{-1}$ for WR46 (Hubrig et al. 2020)

Estimation of Maximum Energy

・ E_{max} given by $r_g = \lambda/2$

$$E_{\max,\lambda/2} = eB_\phi \frac{\lambda}{2} = \frac{1}{2} e \left(B_* \frac{R_* \Omega_*}{V_{\rm wind}} \frac{R_*}{R_{\rm sh}} \right) V_{\rm wind} T_{\rm rot} = \pi e B_* \left(\frac{R_*}{R_{\rm sh}} \right) R_*$$

$$B_\phi \sim B_* \left(\frac{V_{\rm rot}}{V_{\rm wind}} \right) \left(\frac{R_*}{R_{\rm sh}} \right) \qquad V_{\rm rot} = R_* \Omega_* \qquad \lambda = V_{\rm wind} T_{\rm rot} = V_{\rm wind} \frac{2\pi}{\Omega_*}$$

E_{max} depend on the shock radius.
Even if the shock velocity is constant, E_{max} decreases as the shock expands.

Red Supergiant $$E_{\max,\lambda/2} \sim 10^{15}\ {\rm eV} \left(\frac{B_*}{10{\rm G}} \right) \left(\frac{R_*}{100 R_\odot} \right)^2 \left(\frac{R_{\rm sh}}{6000 R_\odot} \right)^{-1}$$

WR star $$E_{\max,\lambda/2} \sim 10^{15}\ {\rm eV} \left(\frac{B_*}{1{\rm kG}} \right) \left(\frac{R_*}{R_\odot} \right)^2 \left(\frac{R_{\rm sh}}{20 R_\odot} \right)^{-1}$$

We confirmed that $E_{\max,\lambda/2}$ can be larger than $E_{\rm max,PD}$ in more realistic simulation.

Summary & Future Work

Summary

Pole → Equator

- Particles injected inside the wavy current sheet structure move along the current sheet (meandering motion).
- Particles move towards the equator while being accelerated.
- Particles escape to the far upstream region while moving along the equator.

two types of maximum energy

① **potential drop:** $E_{\mathrm{max}} = \left(\frac{\pi}{2} - \alpha\right) e \frac{u_{\mathrm{sh}}}{c} B_\phi R_{\mathrm{sh}}$

② **the half wavelength of the wavy structure:** $E_{\mathrm{max}} = e B_\phi \frac{\lambda}{2}$

Future Work

We investigate escape from a spherical shock in the Parker-spiral magnetic field.