Numerical study of orbital and statistical behaviors of galactic cosmic rays invading into the heliosphere

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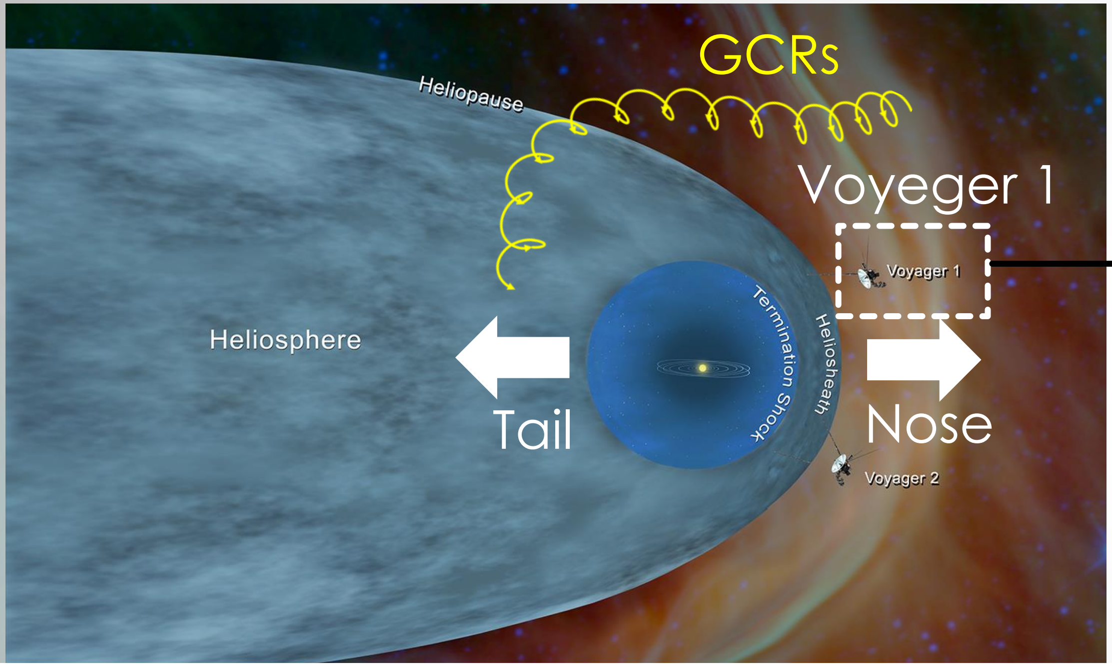
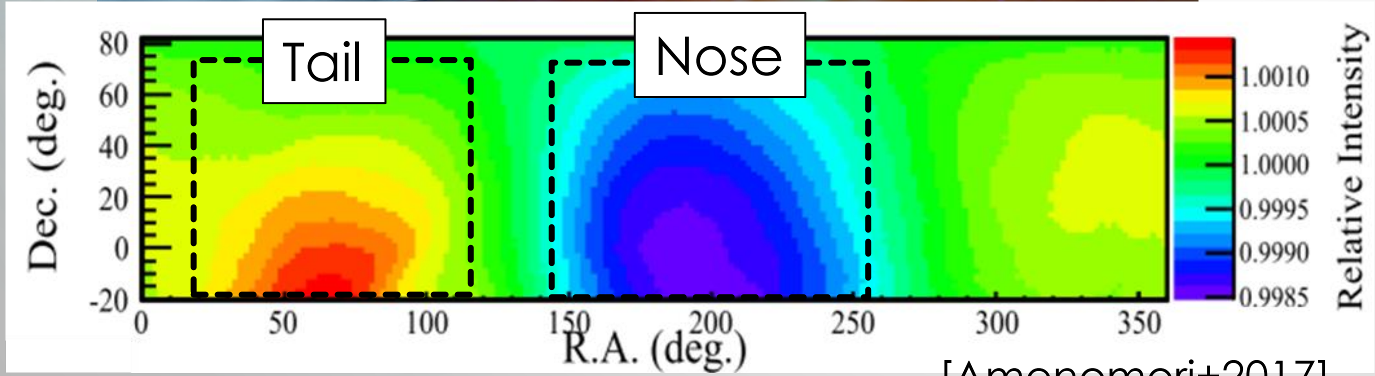
Introduction (Objective)

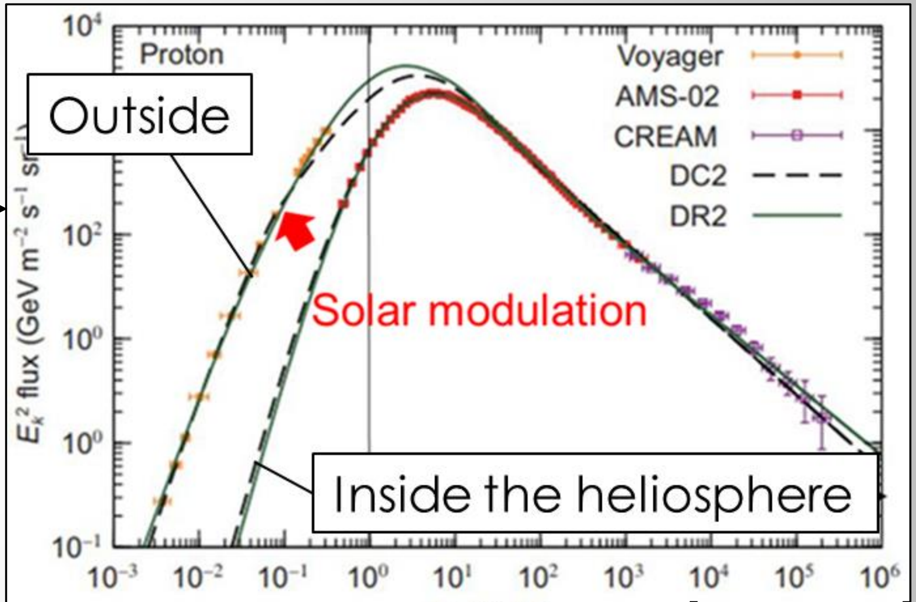
Galactic cosmic rays (GCRs) : $10^{9} \sim 10^{15.5}$ eV





[Amenomori+2017]

- Solar modulation
  (< several tens of GeV)



[Yuan2019]

- Arrival direction anisotropies observed on the Earth
  (≤ several hundred TeV)

Introduction (Objective)

Conventional study on CRs transport : convection-diffusion equation

➡ Some assumptions have been made to derive the equation

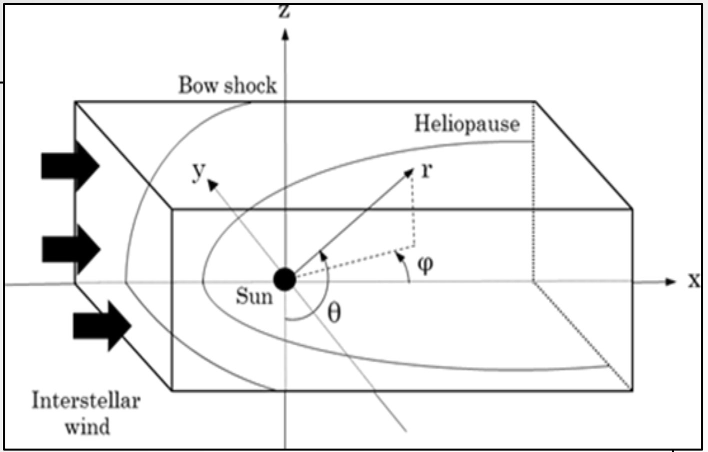
Objective of our study

- **To understand the invading process of GCRs in the level of particle trajectory**
- **To understand the origin of statistical behaviors of solar modulation of GCRs**

This research : Global MHD simulation + Test particle simulation

Methods (MHD simulation)

Simulation system



- Coordinate system

-- Sun rest frame

- Boundary

-- Inner boundary - 50 AU

-- Outer boundary - 900 AU

- Assumption

-- Steady solar wind (400km/s)

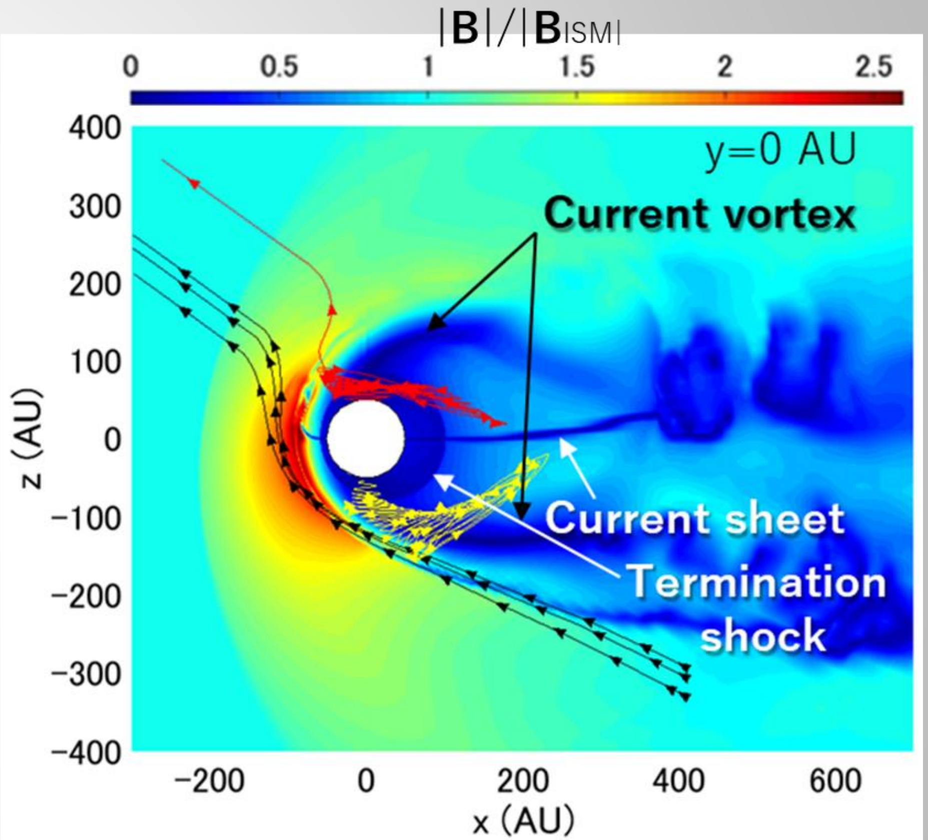
-- Northward polarity

-- Tilt angle 0°

-- Charge exchange caused only between the solar wind and the hydrogen of interstellar origin

-- No pitch angle scattering

Investigating the roles of **the heliospheric boundaries** in the behavior of GCRs in this study.



Global structure of the magnetic field reproduced on the plane at y = 0. The background color denotes the field strength normalized by B_{ISM} (3μG).

Methods (Test particle simulation)

$$\frac{d\boldsymbol{p}}{dt} = q\left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B}\right), \boldsymbol{p} = m\gamma\boldsymbol{v}, \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-1/2}$$

Using electromagnetic fields $\boldsymbol{E}$, $\boldsymbol{B}$ of the heliosphere reproduced by MHD simulation

Simulation parameters

- Number of particles (protons) -- 3×10^6
- Velocity distribution

-- Mono-energetic shell distribution

- Initial position

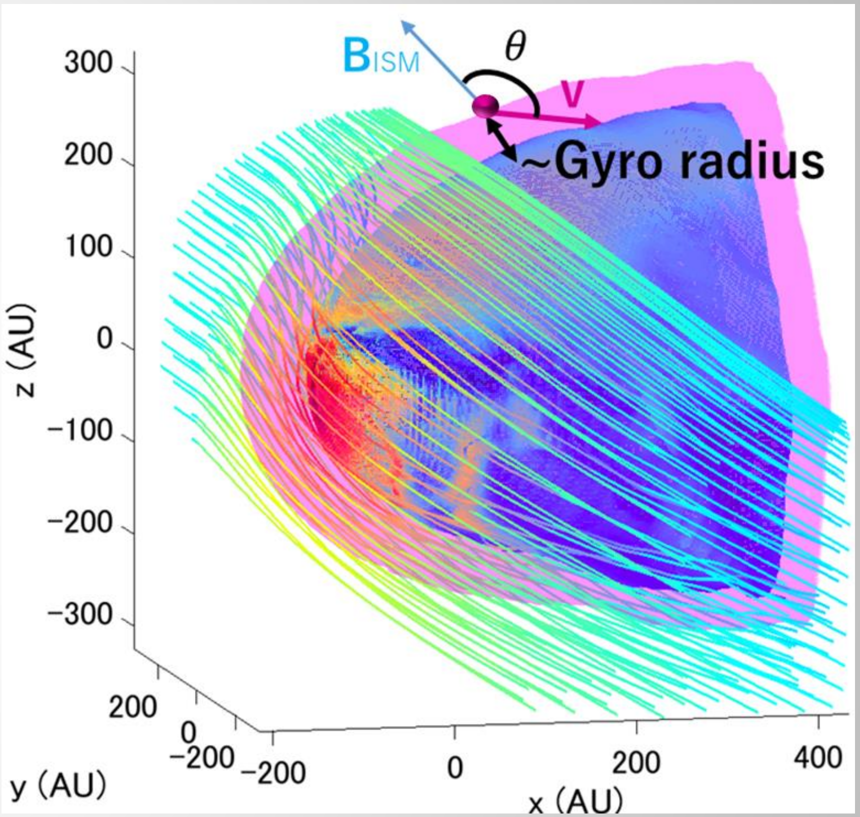
-- Outside the heliosphere by gyro radius away from the heliopause

- Initial Lorentz factor

-- γ =10, 1000 (~ 10 GeV, 1 TeV)

- Pitch angle to the B_{ISM}

-- θ = 0°~180°



Initial positions of particles with γ = 1000 (magenta sheet). The inside-colored sheet denotes an iso-temperature surface of 57,500K, which is defined as the heliopause.

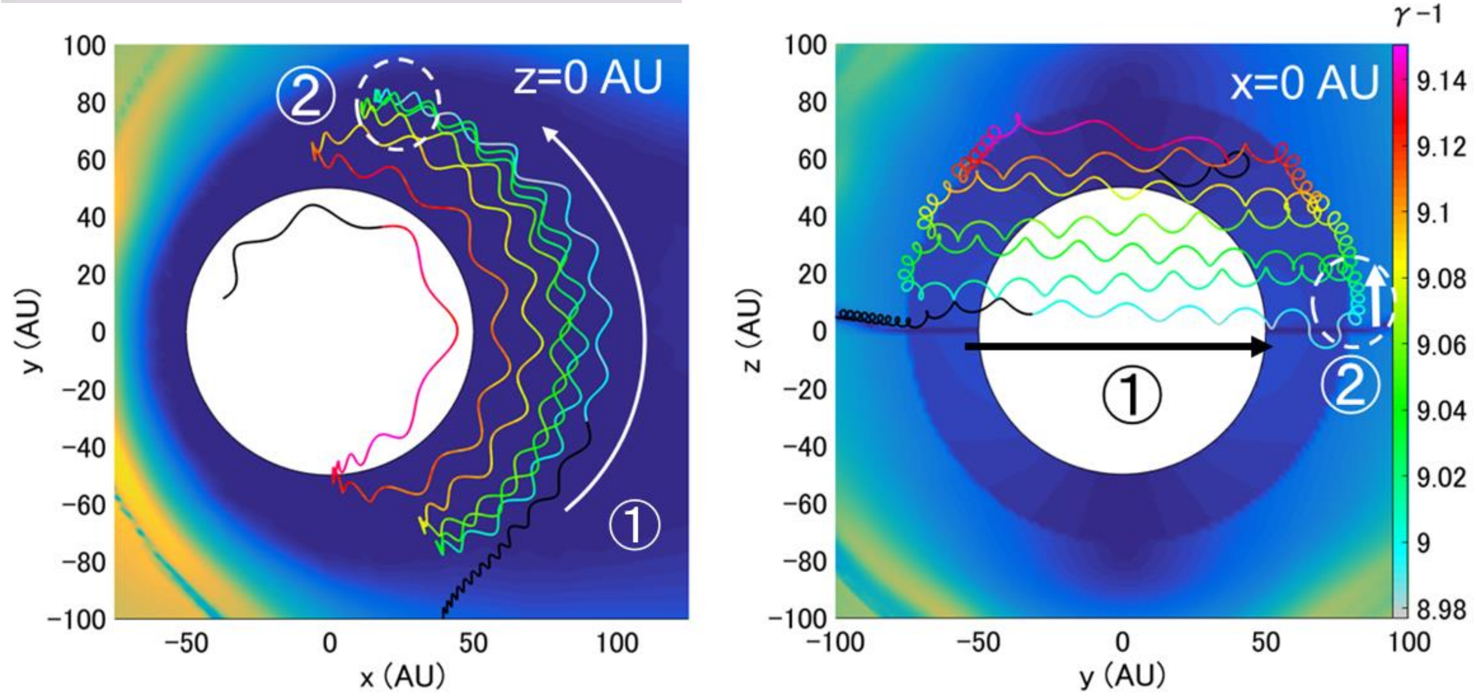
Particle orbits: γ = 10 (~10 GeV)

r_g: Maximum gyro radius in the interstellar space

L : Spatial scale of the heliosphere

γ = 10 (~10 GeV), r_g ~ 0.7 AU << L ▶ Particles in heliosphere are strongly affected by small-scale heliospheric structures.

- **Fermi acceleration**



① Propagating along the spiral magnetic field in upstream of the termination shock.

② Being reflected at termination shock and accelerated.

Yoshida + 2021, ApJ 916 29

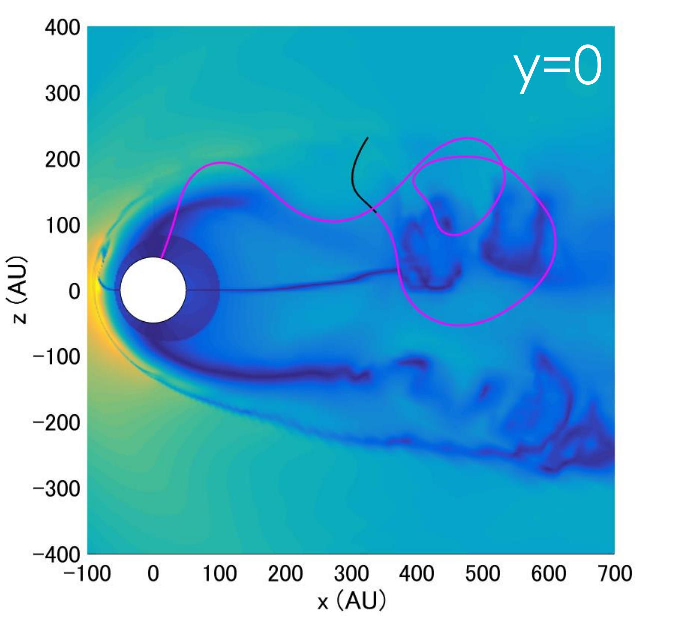
Particle orbits: γ = 1000 (~1 TeV)

r_g: Maximum gyro radius in the interstellar space

L : Spatial scale of the heliosphere

γ = 1000 (~1 TeV), r_g ~ 70 AU ~ L ▶ Particles are almost insensitive to the small-scale structures of the heliosphere.

- **Resonantly scattered by the turbulent eddy**



Local gyro radius > 100 AU.

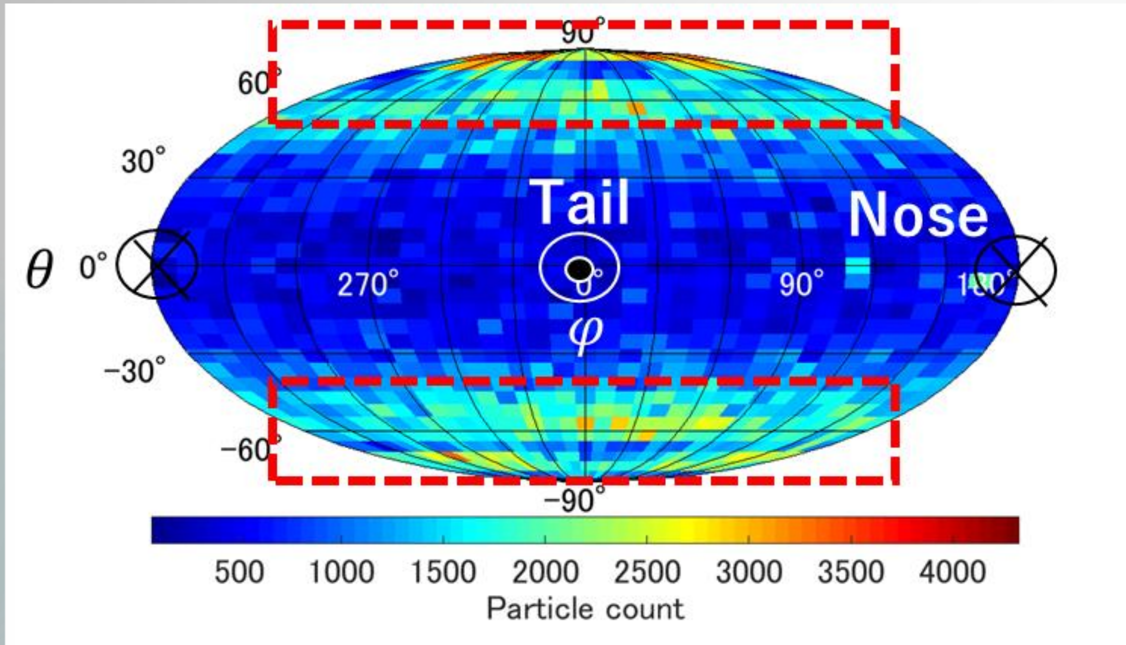
~ The spatial scale of the local turbulent eddy.

▶ The particle can be resonantly scattered by the turbulent eddy.

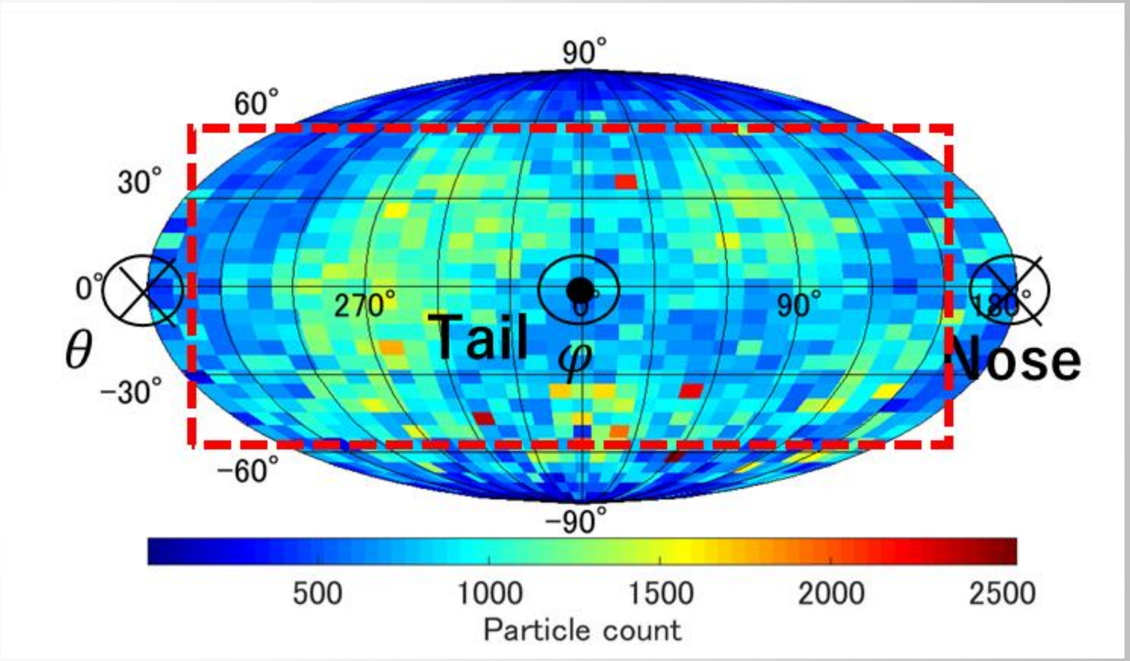
Yoshida + 2021, ApJ 916 29

Arrival directional map

γ = 10



γ = 1000



- Many particles reach high latitudes. Because of the polarity of the solar magnetic field, the particles approaching the Sun tend to drift poleward.

- There is a tendency that more particles to reach the lower latitudes.
- Particles accumulate in the tail side.

Summary

We investigated trajectory patterns of the GCRs in the simplest heliosphere model.
(North polarity/ Steady solar wind/ Tilt angle 0°/ No magnetic wave)

We found that characteristics of particle orbits and statistics change depending on the relative scales between particle gyro-radii and spatial scale of heliospheric structures.

- **γ = 10 (~10 GeV), r_g ~ 0.7 AU << L**
  - Particles in heliosphere are strongly affected by small-scale heliospheric structures.
  - Many particles reach the high latitude of inner boundary
- **γ = 1000 (~1 TeV), r_g ~ 70 AU ~ L**
  - Particles are almost insensitive to the small-scale structures of the heliosphere.
  - Many particles reach the low latitude of the heliotail of the inner boundary