Invading process of GCRs into the heliosphere

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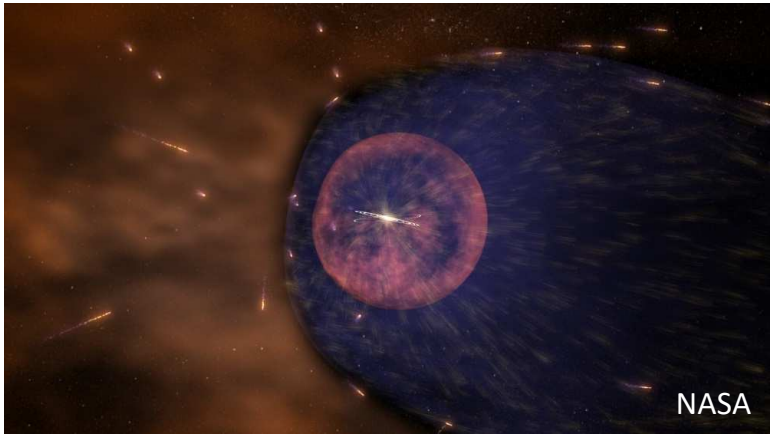
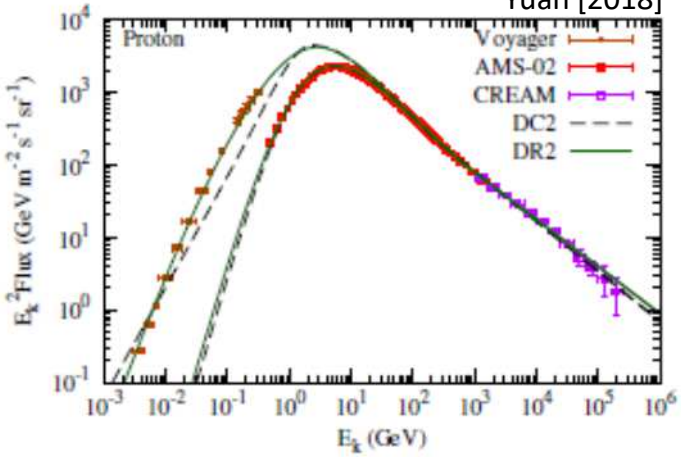
Background

Solar modulation of CR spectrum

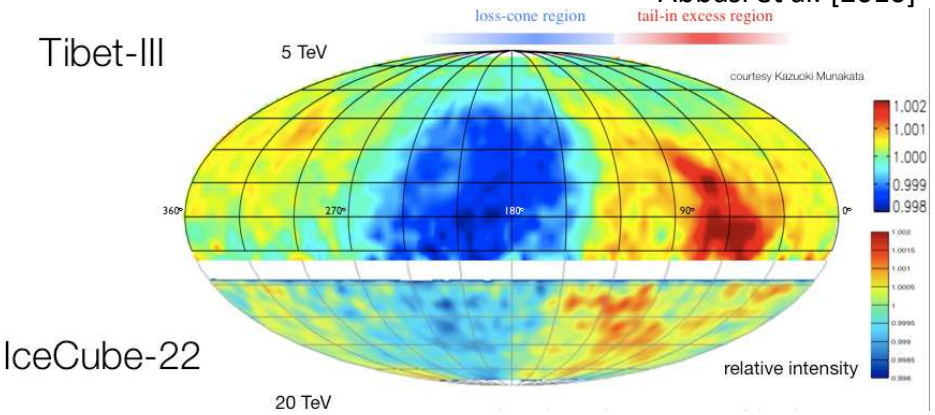
- Remarkable for E < a few 10 GeV
- Anisotropy for TeV CRs
- Effect of convected spiral SW B field
- Effect of large scale structures (TS, HP)
- Effect of wave-particle interactions
- Effect of non-stationarity of SW
- …



Yuan [2018]



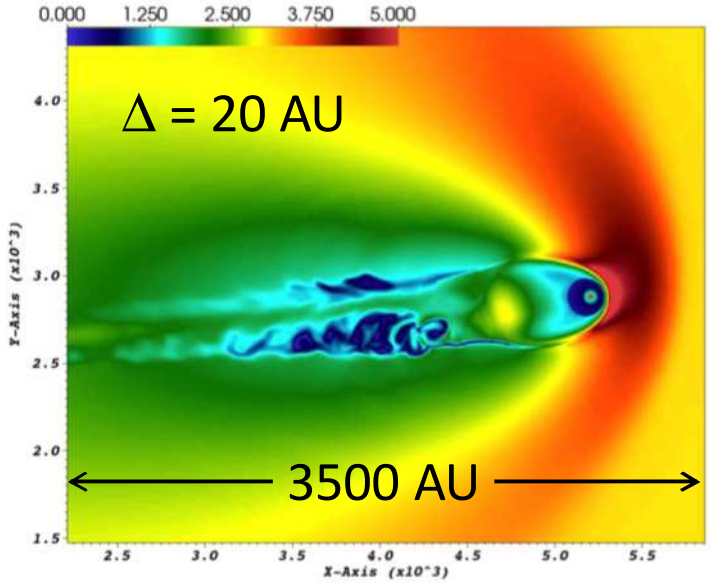
Abbasi et al. [2010]

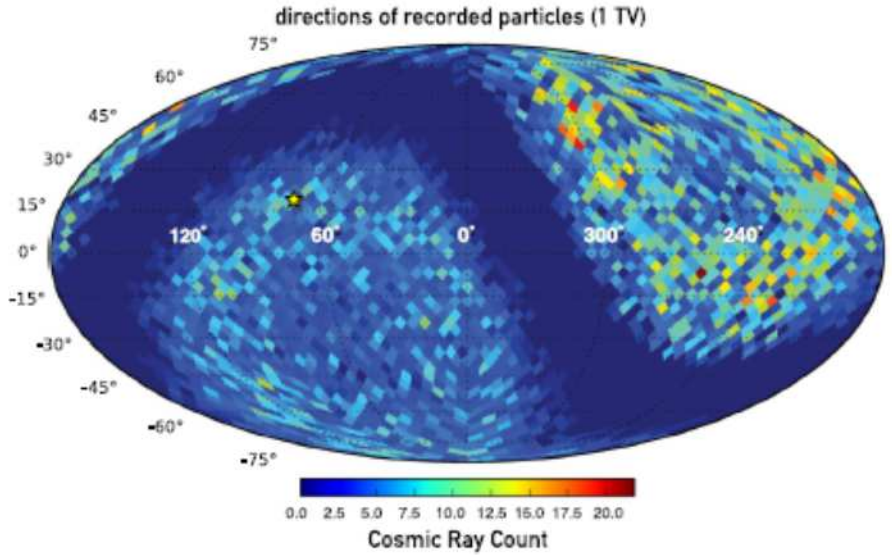


Background

Past approach

- Diffusion-convection eq. based
  Yuan (2018), Aloisio et al. (2015), Yamazaki et al. (2015),
  …
- Test particle simulation + global MHD simulation
  Lopez-Barquero et al. (2016, 2017), …

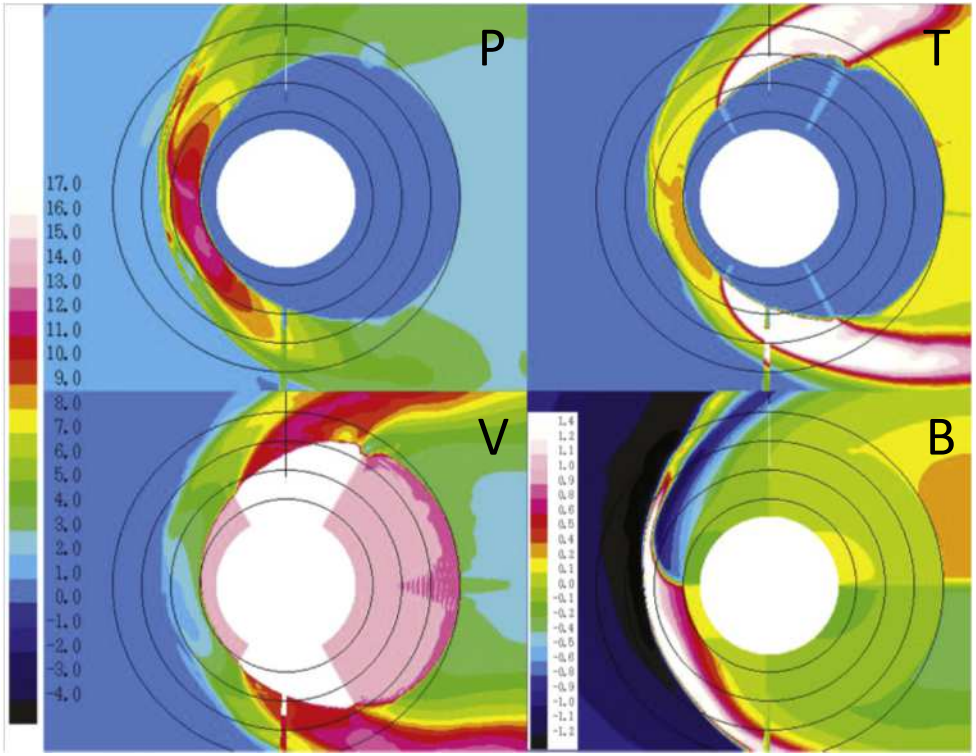




Purpose

- To understand detailed process of GCR invasion into the heliosphere and further into the Earth
- To reveal energy dependence of the invasion process

Approach:
Test particle simulation + high resolution global MHD simulation (Δ = 0.2 AU)



Washimi et al. [2015]

Test particle simulation + MHD simulation

Test particle simulation using $\boldsymbol{E}$, $\boldsymbol{B}$ fields reproduced by MHD simulation

$$\frac{d\boldsymbol{p}_i}{dt} = e\left(\boldsymbol{E} + \frac{\boldsymbol{v}_i}{c} \times \boldsymbol{B}\right), \qquad \frac{d\boldsymbol{r}_i}{dt} = \boldsymbol{v}_i$$

$\#\ \text{particles} = 10^6$

No waves/turbulence

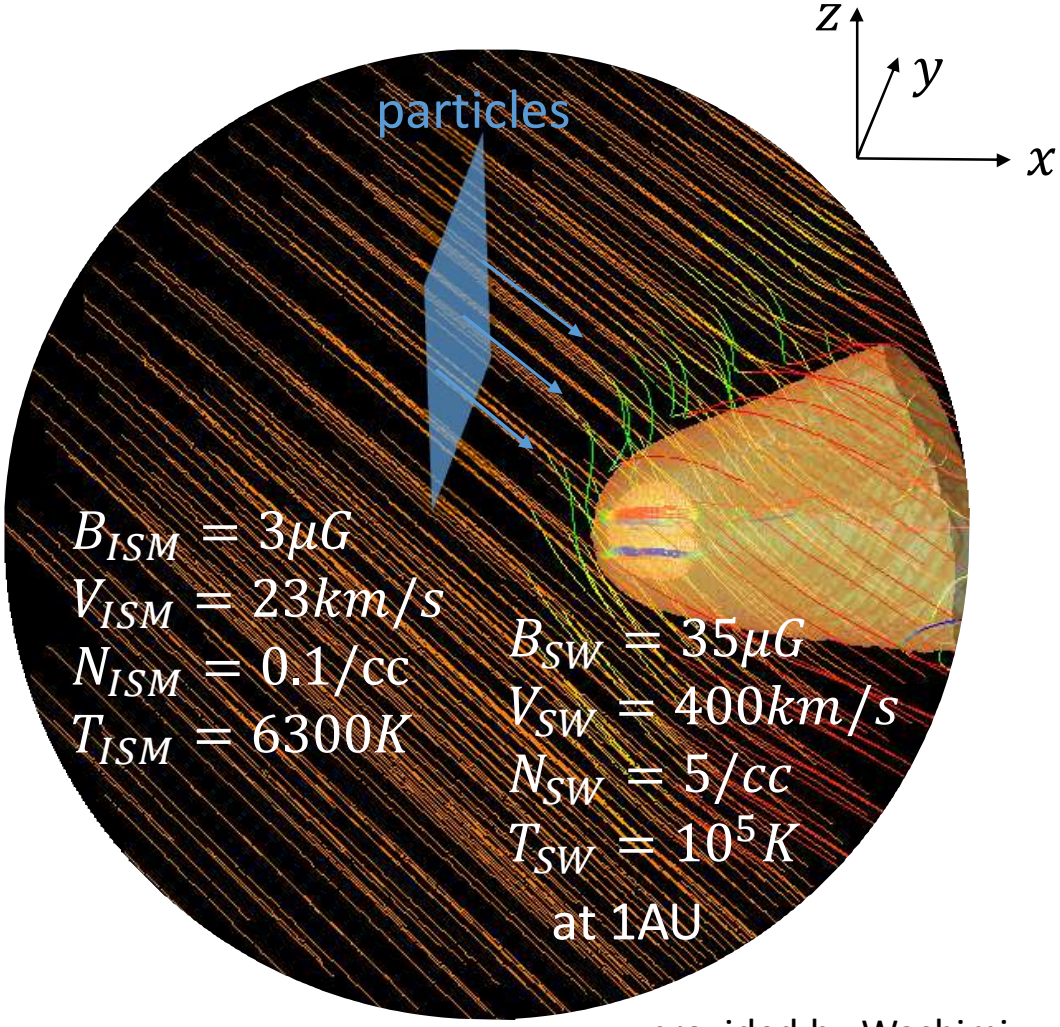
Initial distribution function

-- uniform on a sheet at a certain X in interstellar space

-- monoenergetic jet along local $\boldsymbol{B}$ field

$\gamma = 10, \quad (100) \quad 1000$

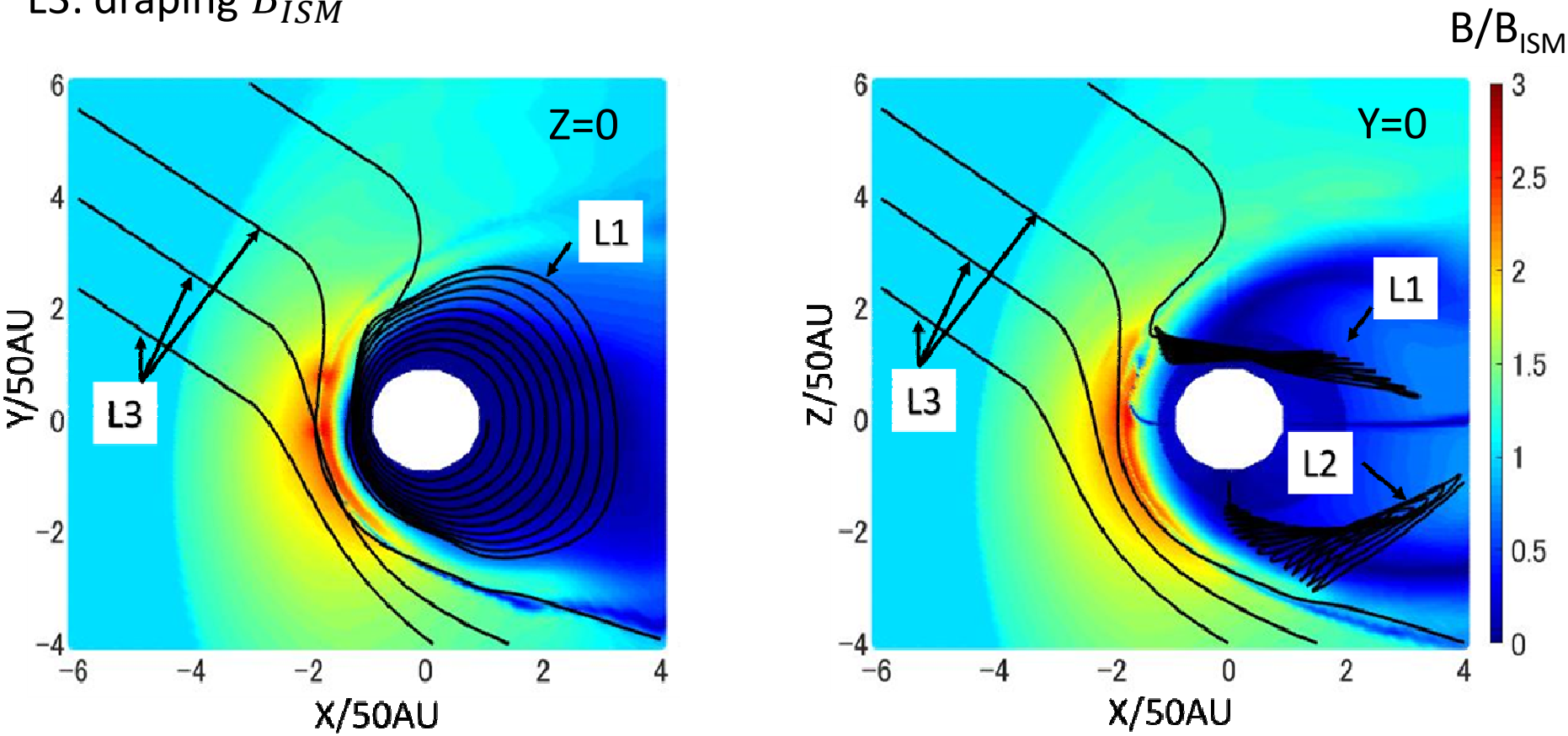
$(\sim 10GeV, (100\ GeV)\ 1000GeV)$



provided by Washimi

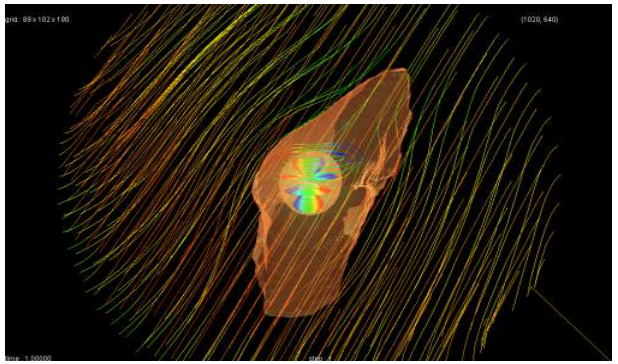
Field lines

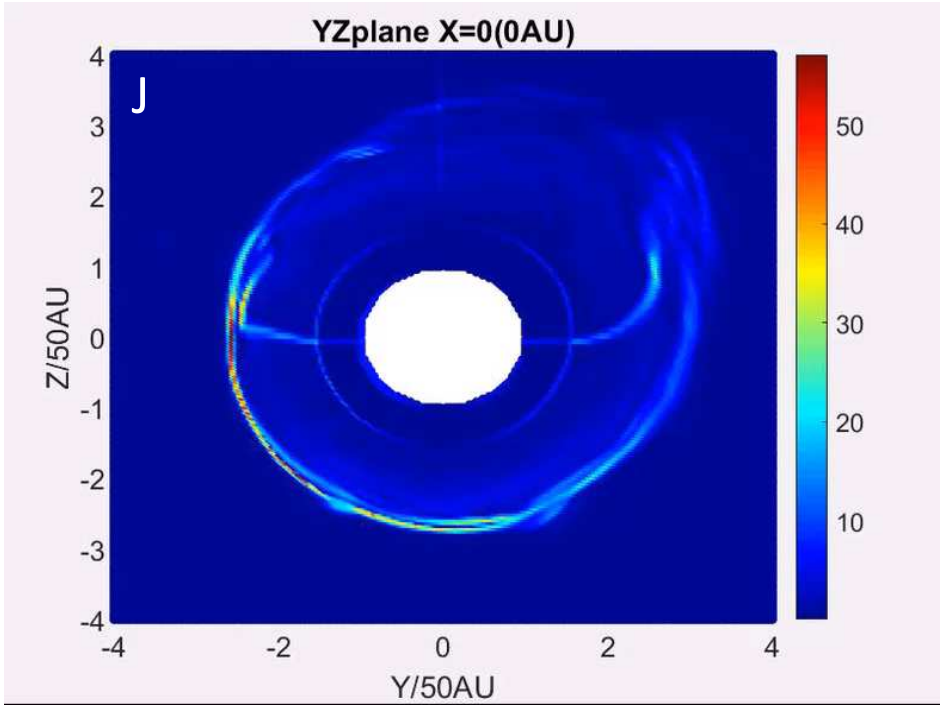
L1: draping B_{ISM} connected to spiral B_{SW}
L2: spiral B_{SW}
L3: draping B_{ISM}

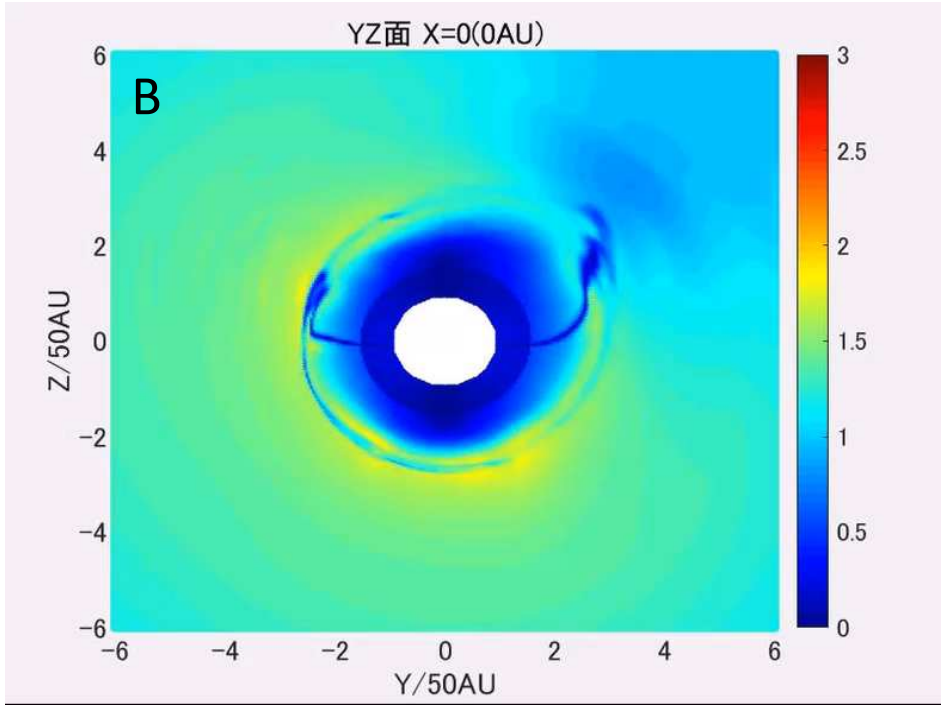


Field structure

- Bow shock, heliopause, termination shock are reproduced.
- The above discontinuities and SW current sheet form current layers.

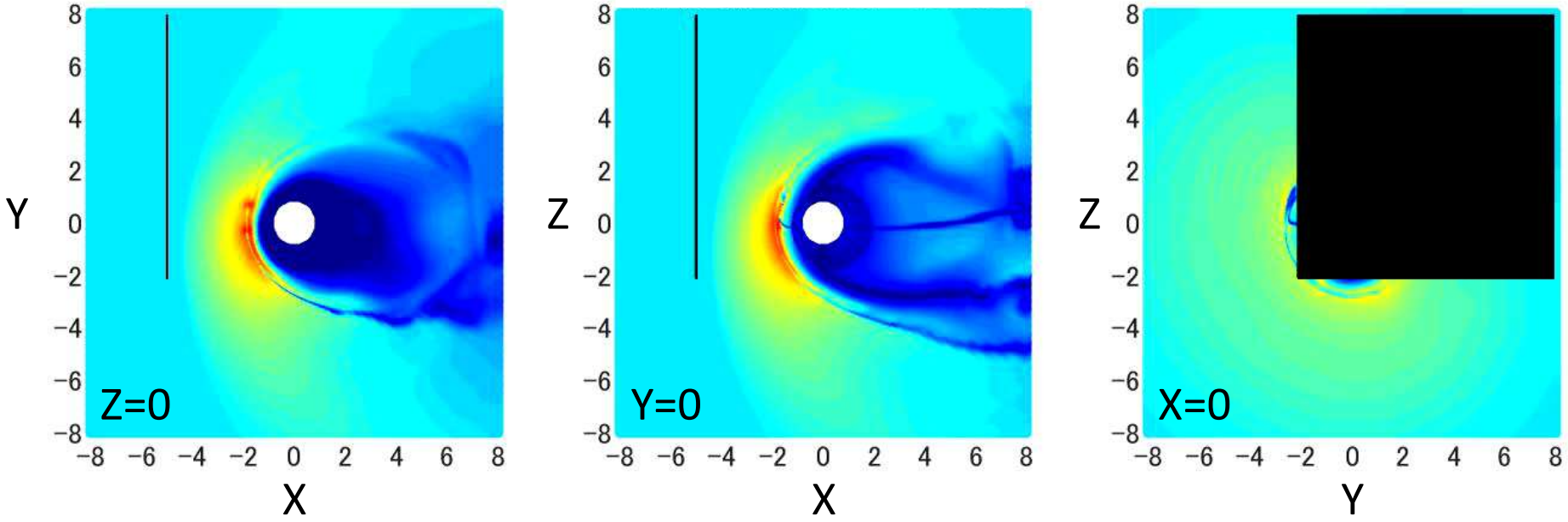






Particle behaviors ($\gamma = 10$)

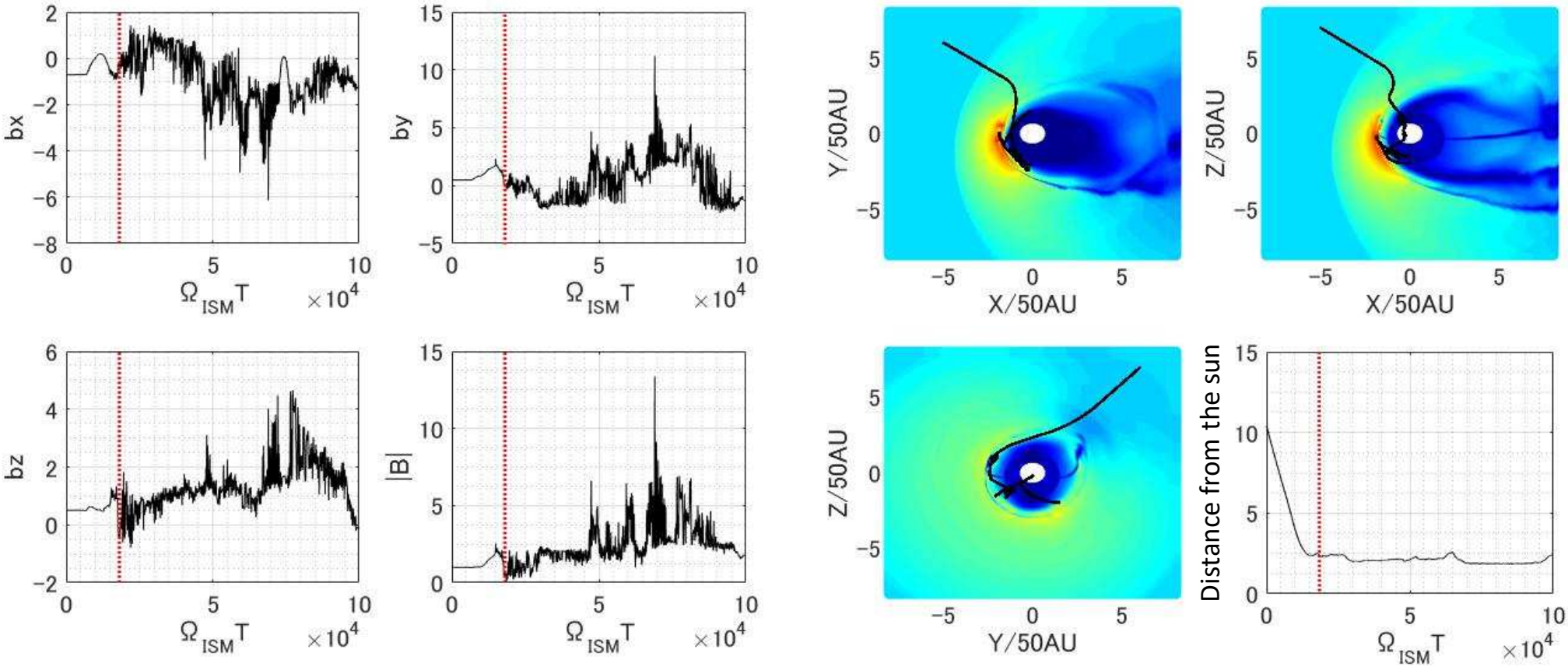
- Most of particles follow L3 field lines and pass outside the HP or are mirror reflected at the HP
- Some particles come in and out of the heliosphere when they come close enough to the heliopause along the draping IS B field lines
- A part of them reach the inner boundary (r = 50AU) of the polar region
- Very few particles reach the inner boundary after a short time (weeks)



Particle behaviors ($\gamma = 10$)

- Direction of field felt by a particle changes when it crosses the HP.
- The particle stays near current sheet for a long time.

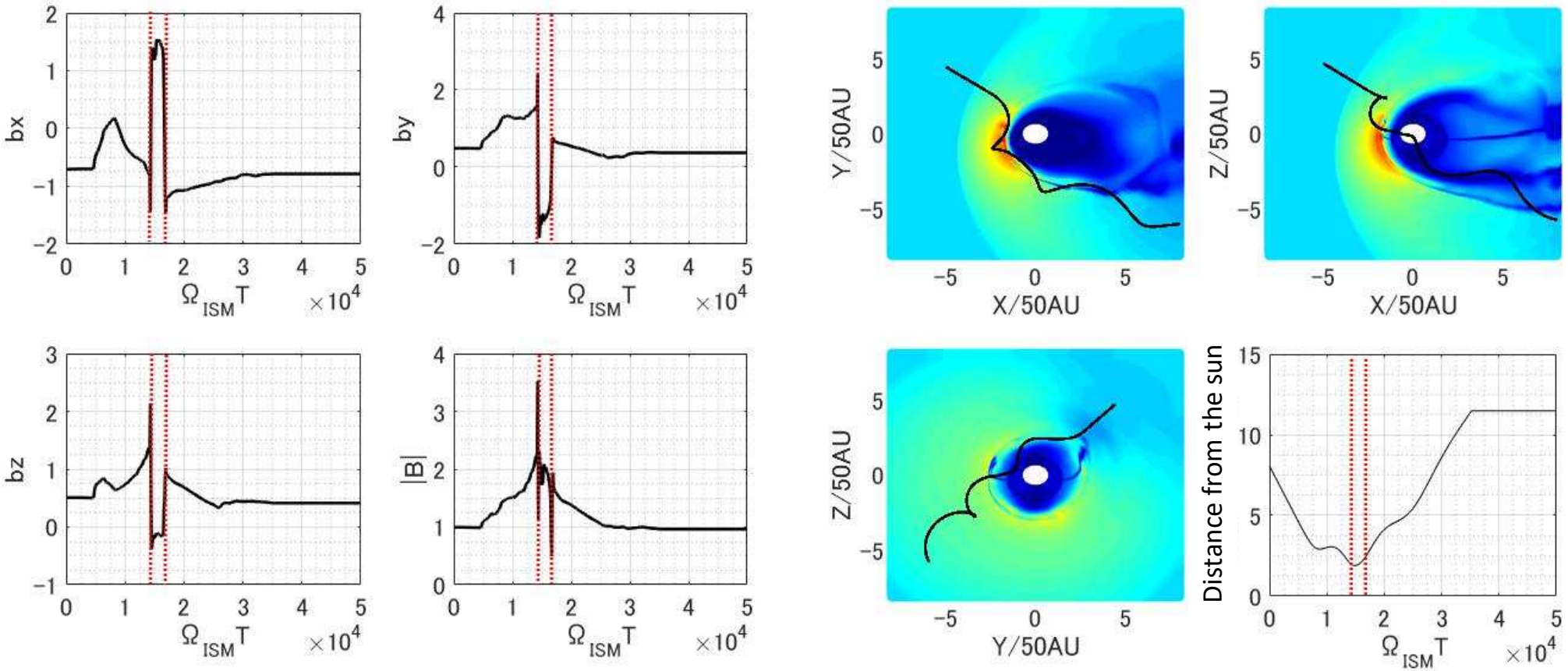
$\rho_i = 0.013$



Particle behaviors ($\gamma = 1000$)

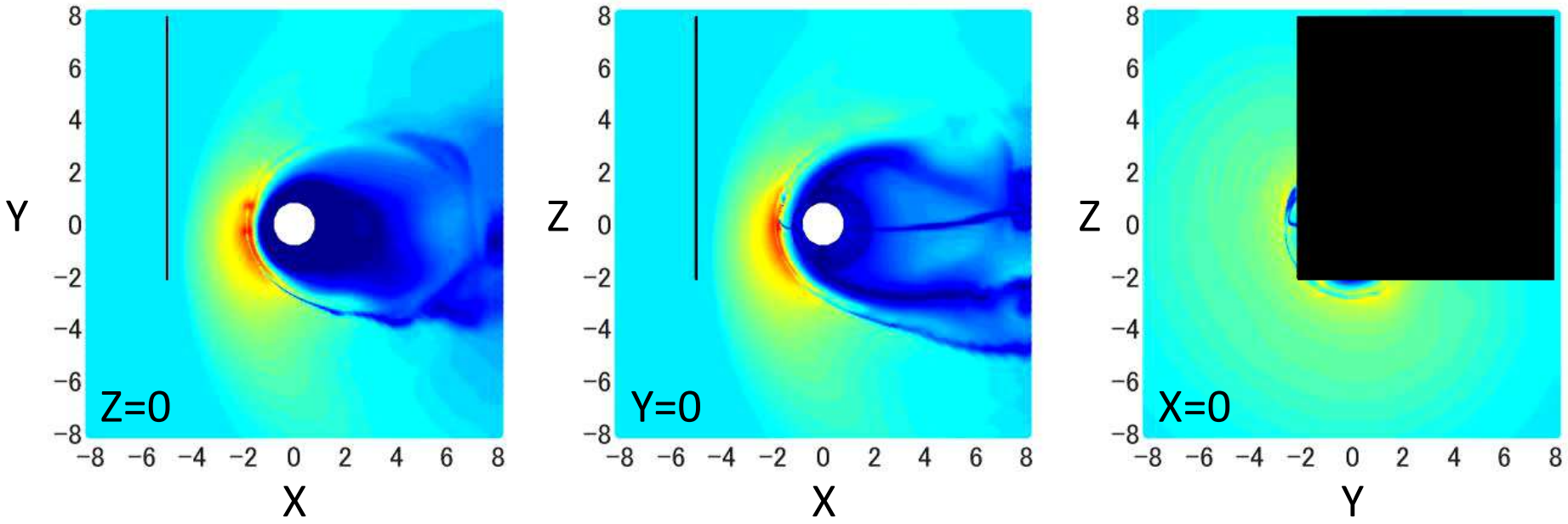
- Direction of field felt by a particle changes when it crosses the HP.
- They do not stay in the current sheet due to large gyro radii.

$\rho_i = 1.3$



Particle behaviors ($\gamma = 1000$)

- Easy to come in and out of the heliosphere due to large gyro radius
- No mirror reflection for the particular case
- Particles can reach the inner boundary (r = 50AU) with a short time
- Some particles coil about the heliosphere even after that most of the other particles flow away.

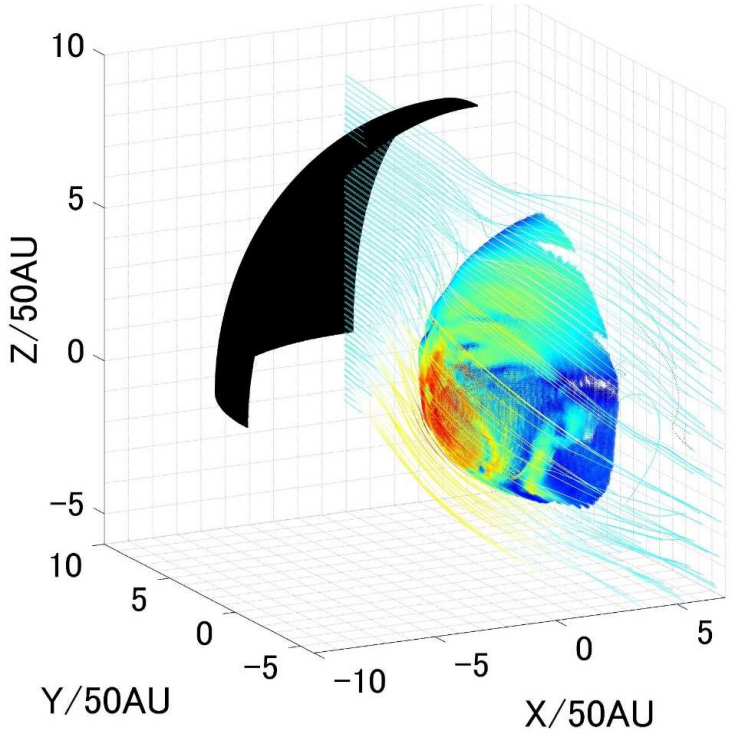


Statistics

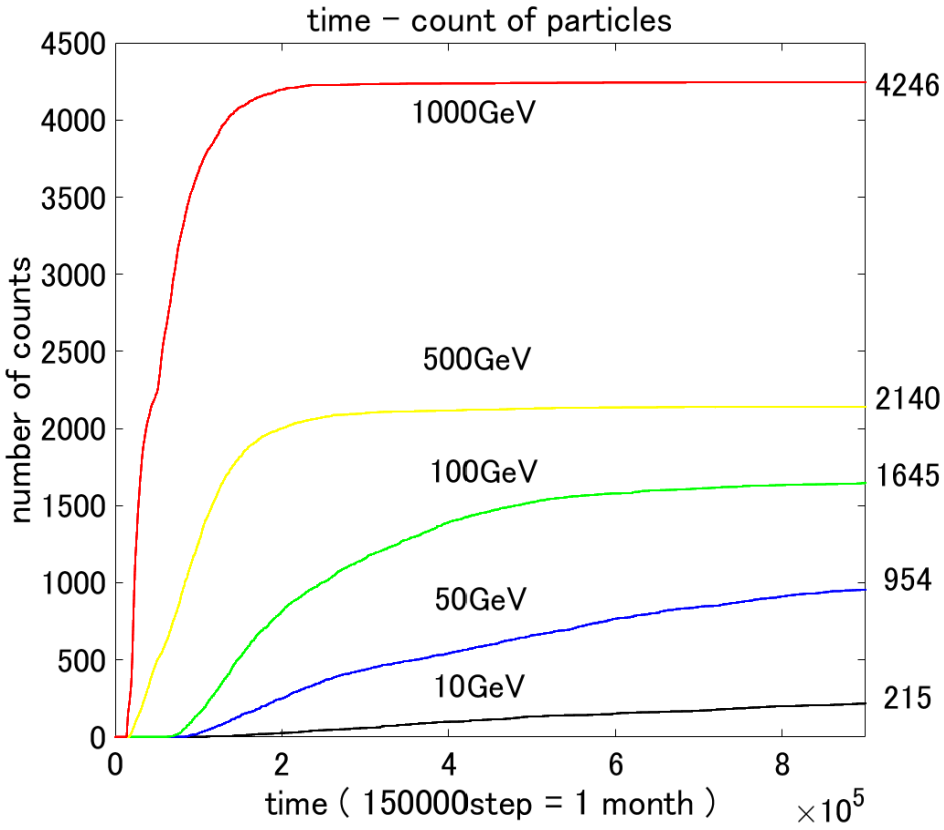
Initial particle distribution:

uniform on a 1/8 sphere

velocity shell (uniform pitch angle)

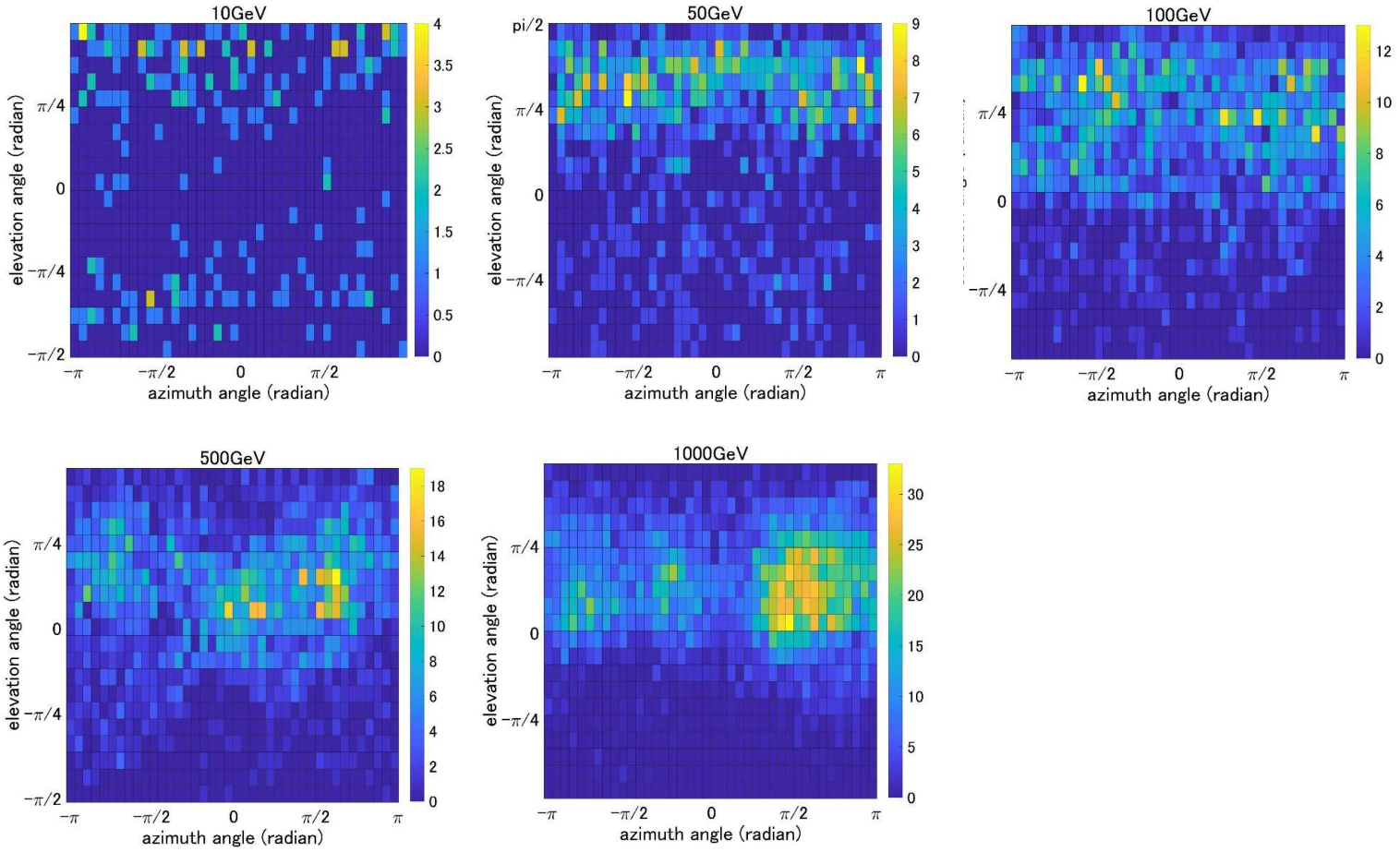


particles reached at inner boundary



Statistics

Energy dependence of anisotropy



Summary

- Test particle simulation of CR invasion process using EB field obtained by global MHD simulation has been started.

Future Issues

- Detailed analysis of particle behavior will be focused
- Effect of wave-particle interaction will be incorporated
- Statistics of particles will be discussed
- …