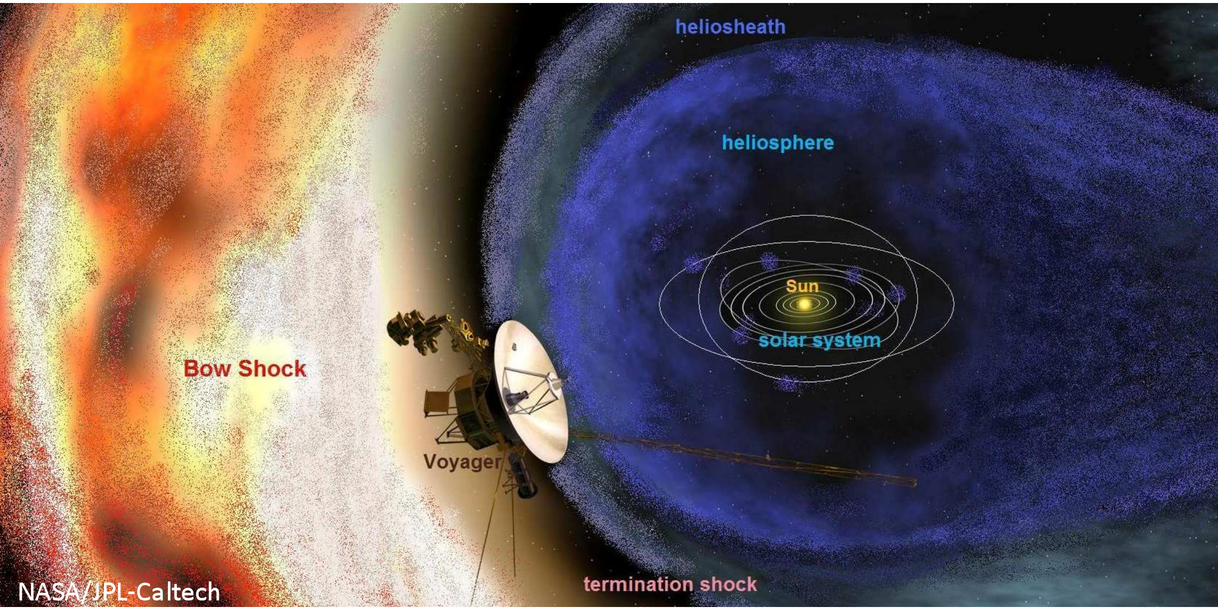
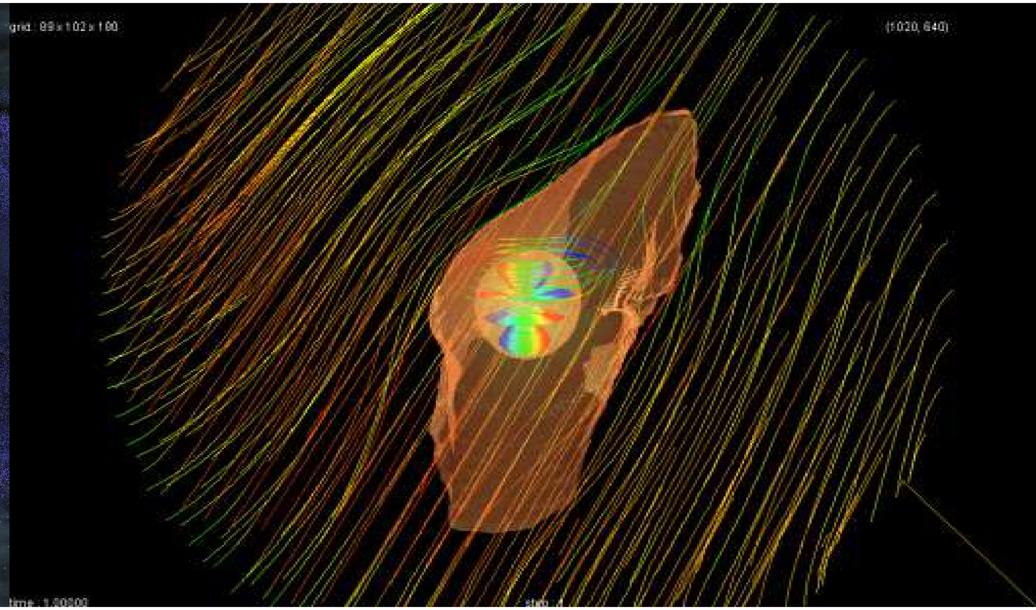


# Properties of cosmic ray test particles in global MHD simulation of the heliosphere

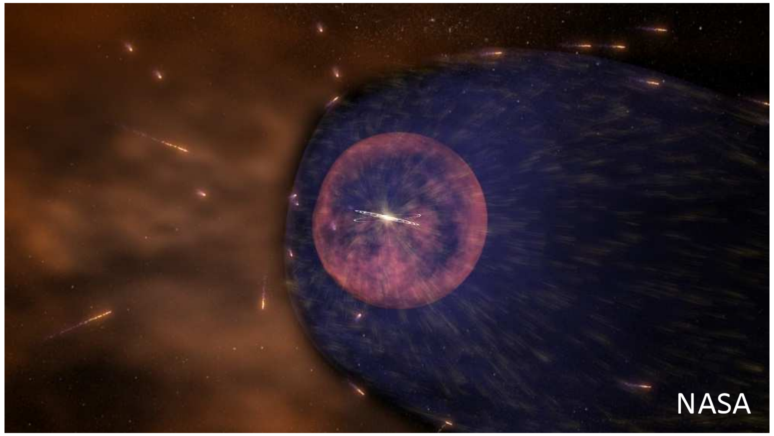
S. Matsukiyo, K. Yoshida, H. Washimi, T. Hada

Kyushu Univ.

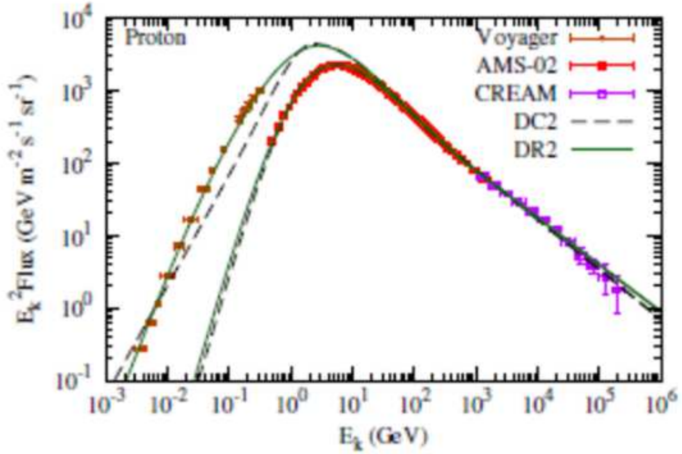
# Kinetic properties of invading galactic cosmic rays

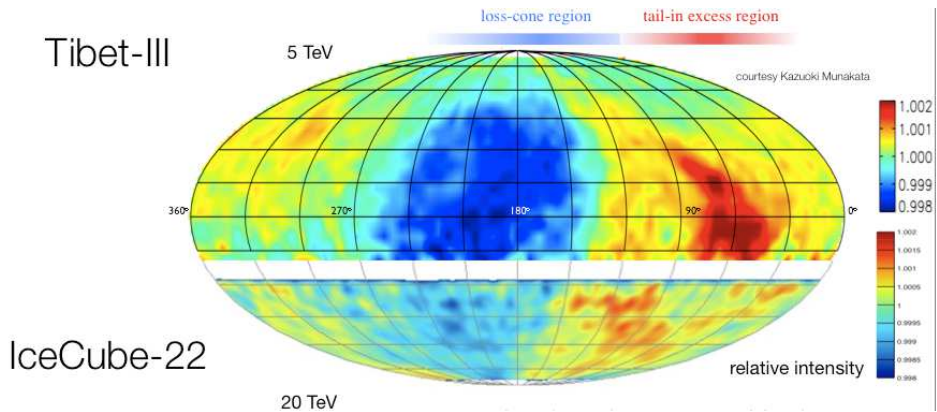
Solar wind modulation of GCRs

- Flux decline for E < a few 10 GeV
- Anisotropy for TeV CRs
- Possible causes:
  -- convected spiral SW B field
  -- large scale heliospheric structures
  -- wave-particle interactions
  -- non-stationarity of SW
  -- ...




Yuan [2018]




Abbasi et al. [2010]

# Approaches

Standard approach

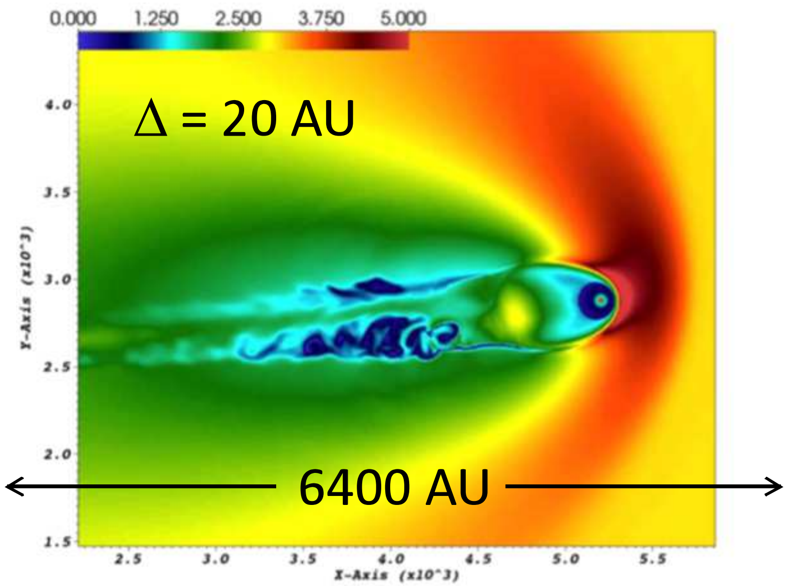
- Diffusion-convection eq. based

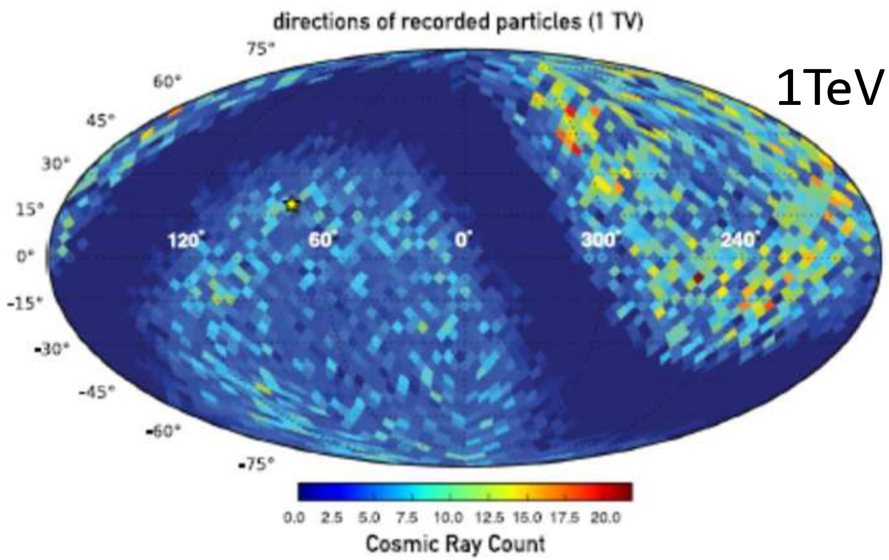
  Parker (1965), Moraal (2013), Potgieter (2013), …

Recent approach

- Test particle simulation + global MHD simulation

  Lopez-Barquero et al. (2016, 2017), …



# Test particle simulation + HR MHD simulation

MHD simulation ($\Delta$ = 0.2 AU)

Inner/outer boundary at r = 50/900 AU

Steady SW and IS plasmas

Test particle simulation

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

$\#$ particles $= 3 \times 10^6$

Initial distribution function

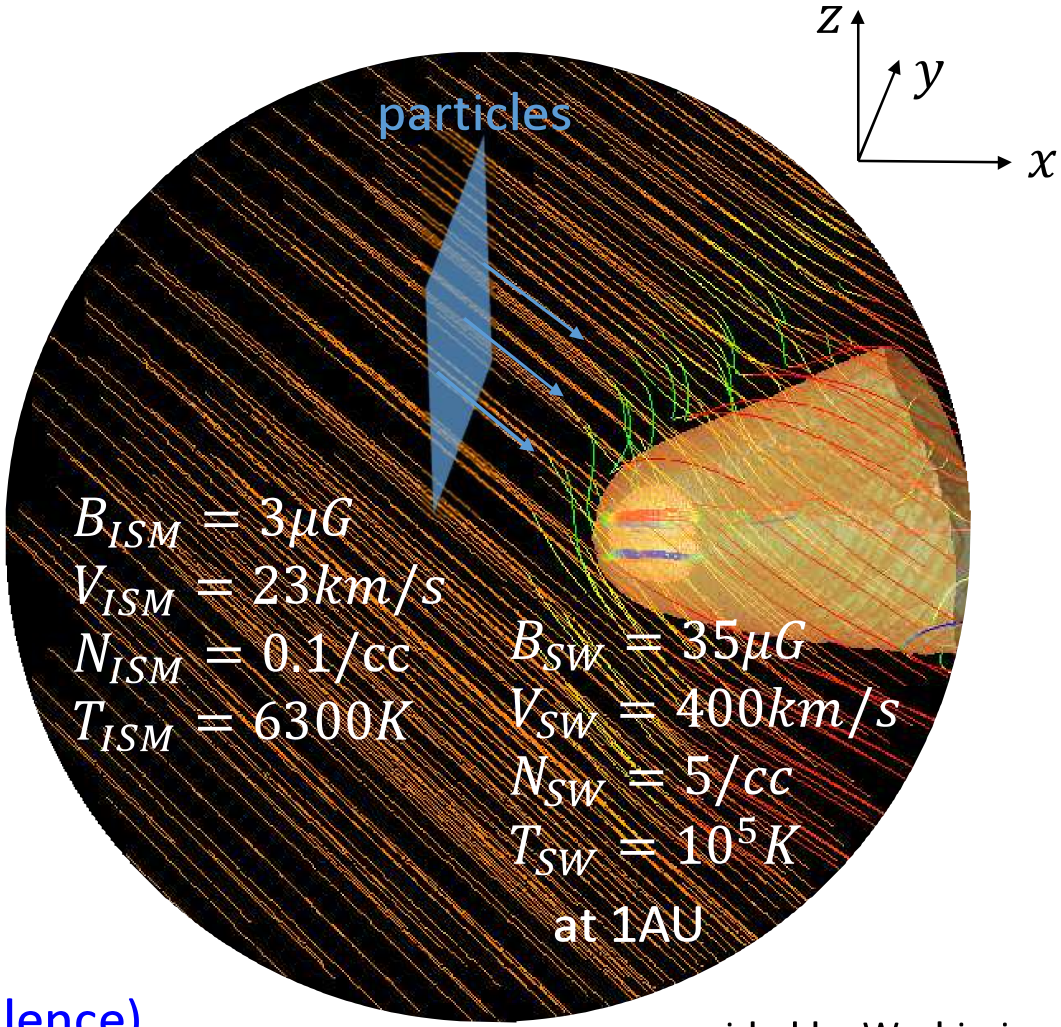
-- uniform on a sheet at a certain $X$ in interstellar space

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

$\gamma = 10\sim1000$

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

No pitch ang. scattering (no waves/turbulence)

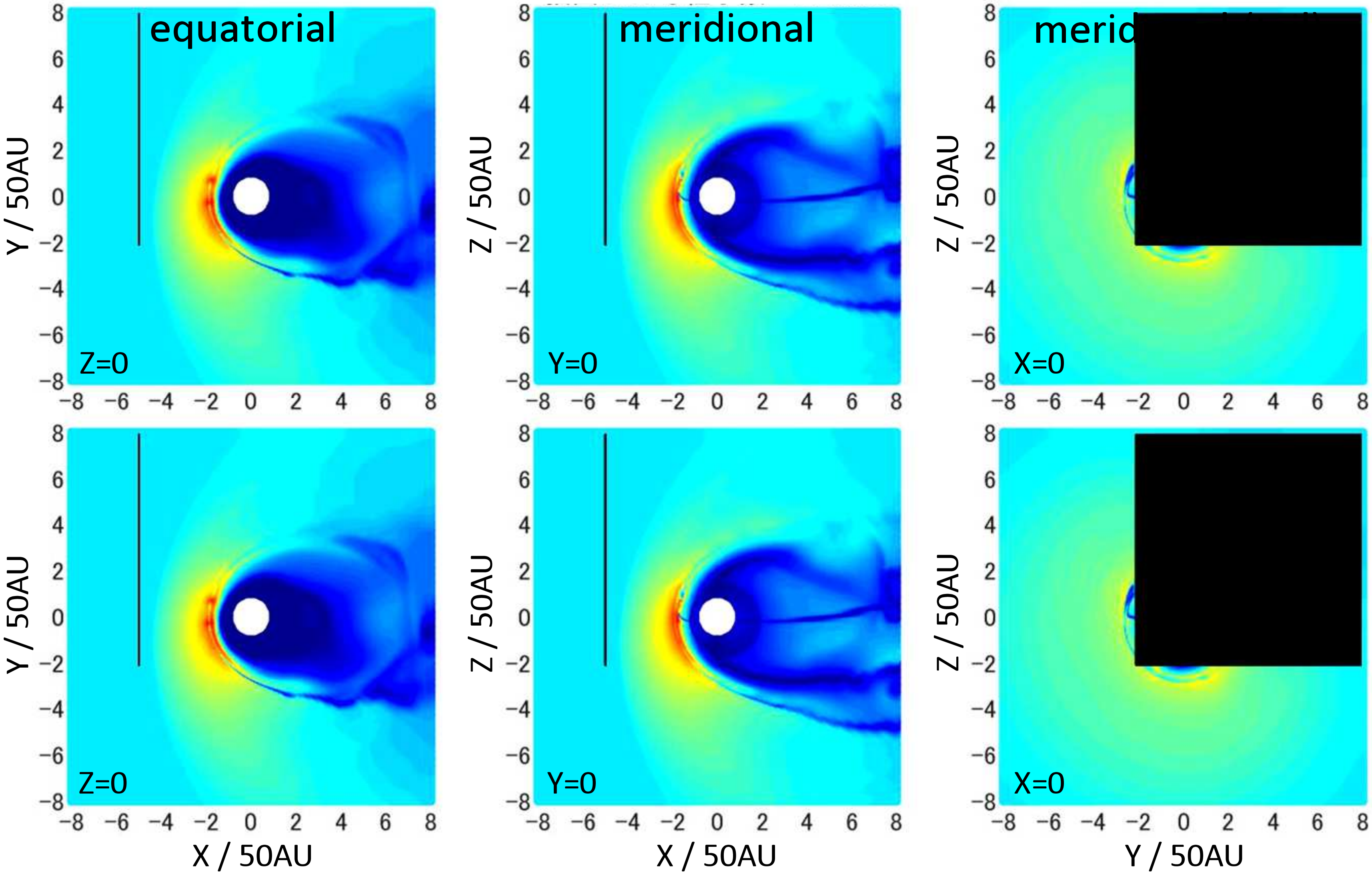



provided by Washimi

# Particle behaviors

$\gamma = 10$
$(\sim 10GeV)$
$\rho_{10} \sim 0.6AU$

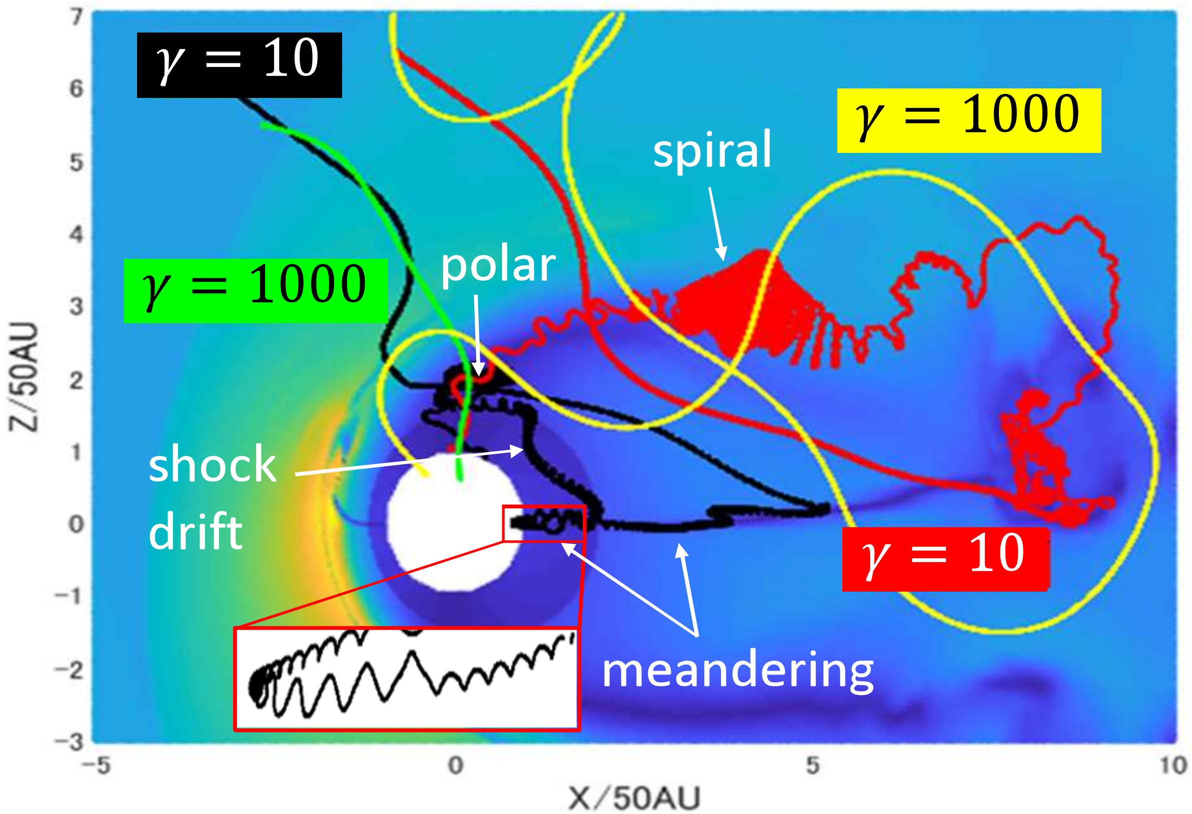
$\gamma = 1000$
$(\sim 1TeV)$
$\rho_{10} \sim 70AU$



# Invading GCRs (test particle sim. + MHD sim.)

Yoshida, SM, et al., ApJ, 2021

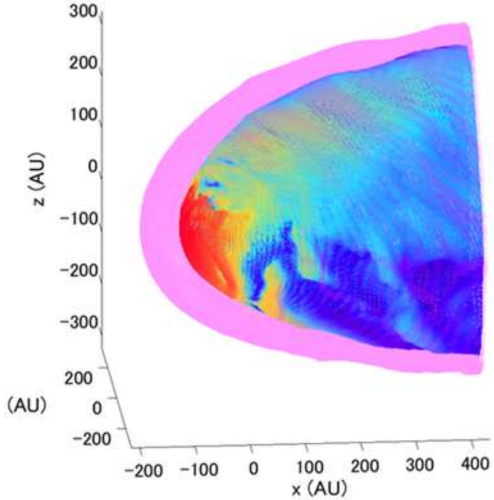
- **Meandering motion**
  -- traveling in the equatorial current sheet
- **Bounce motion**
  -- bouncing due to multiple reflection at TS
- **Spiral motion**
  -- following the spiral magnetic field
- **Polar**
  -- following the polar magnetic field



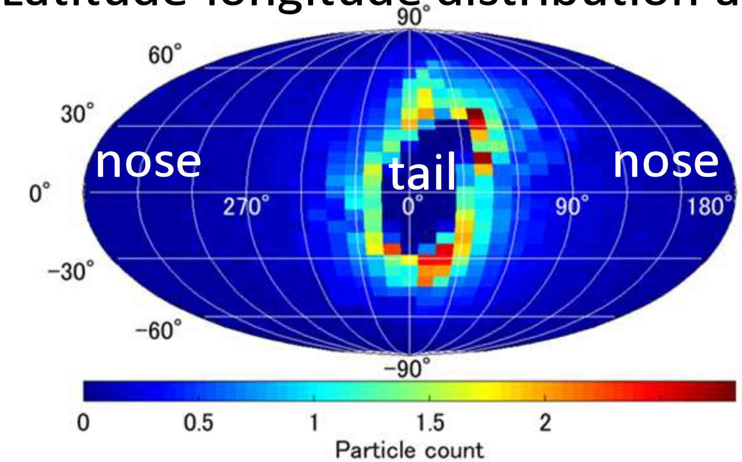

- **Almost linear motion**
  -- reach the inner boundary with almost linear orbit within very short time
- **Resonant motion**
  -- resonantly kicked back by the heliotail then reach the inner boundary

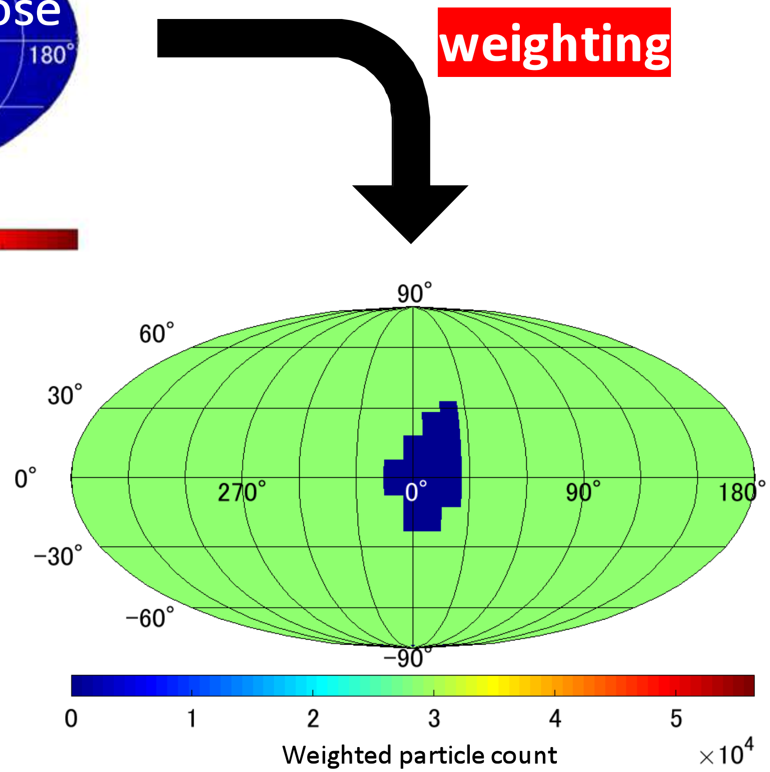
# Particle statistics

Initial particle distribution is non-uniform in direction




Latitude-longitude distribution at t=0

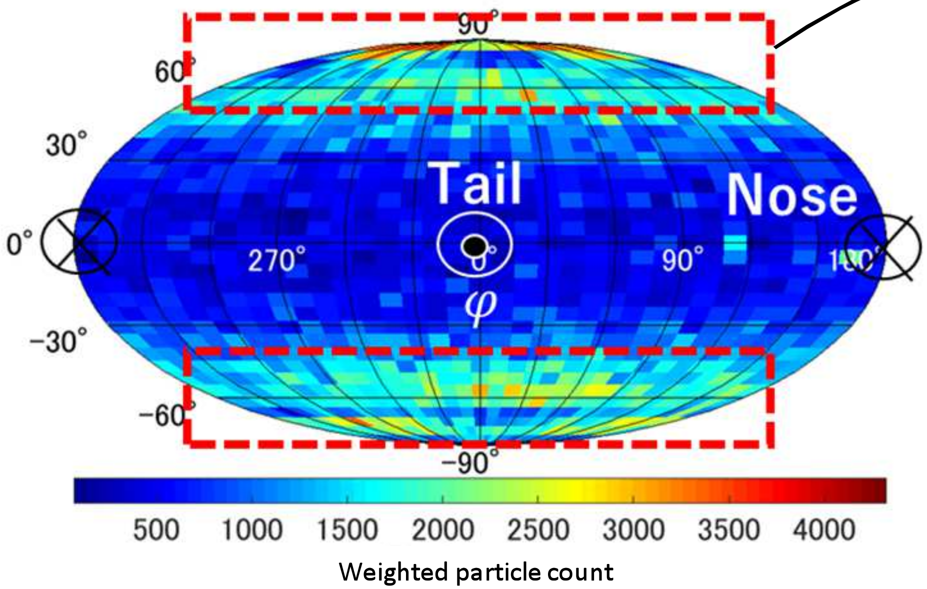


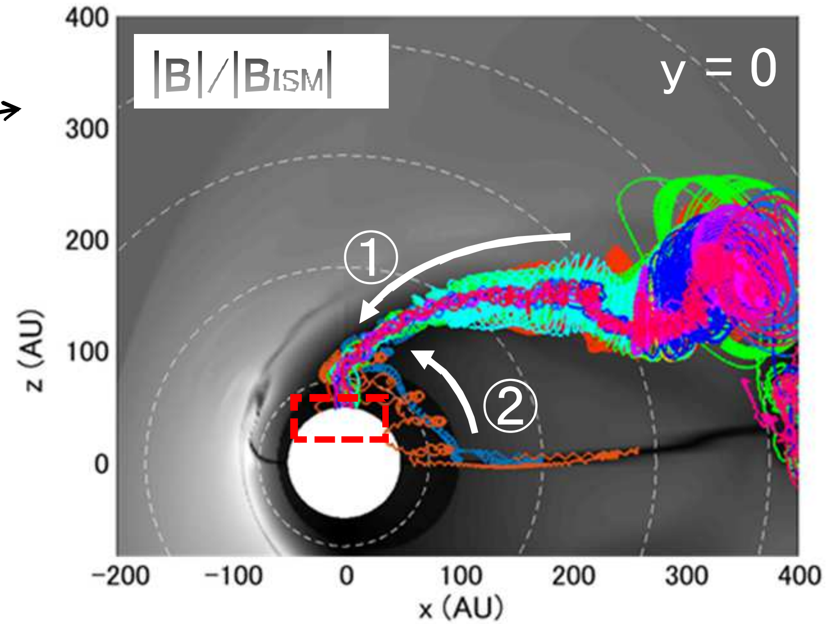




Weighting function was applied so that initial latitude-longitude distribution becomes uniform.

# γ=10: Arrival positions

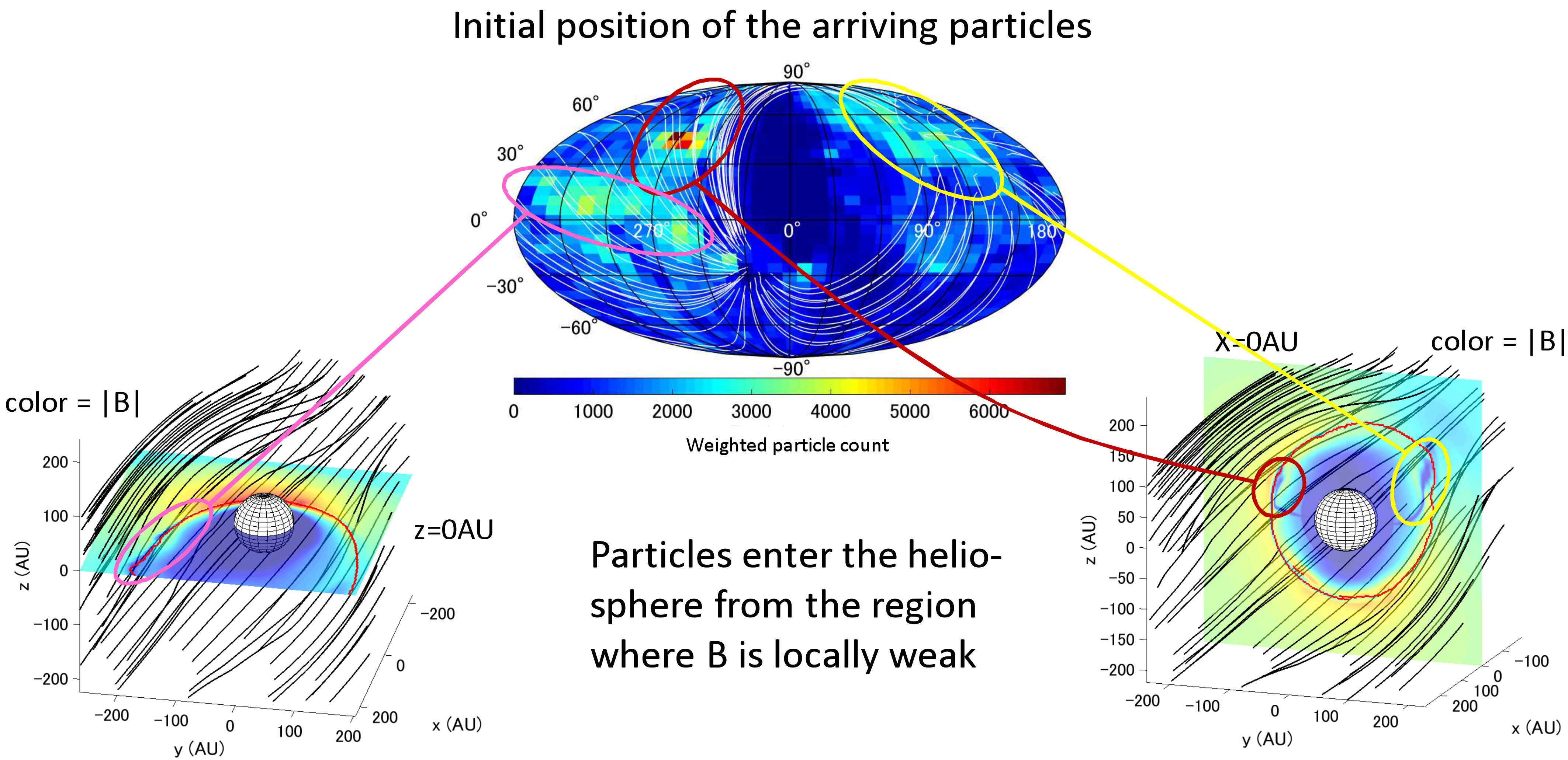
More particles arrive in high latitude region




- Along the spiral field (finally along the polar current vortex)
- Poleward drift along the termination shock

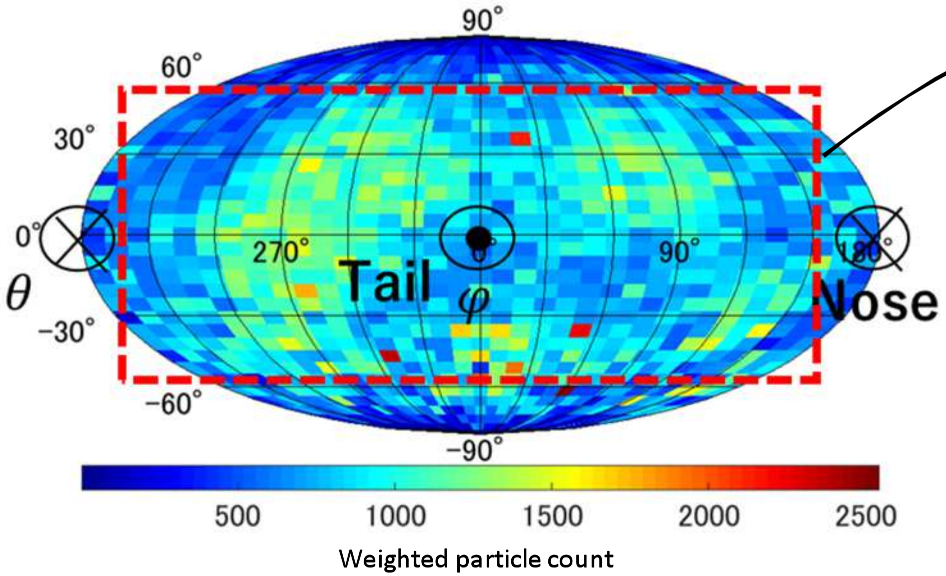
# γ=10: Where are they from?

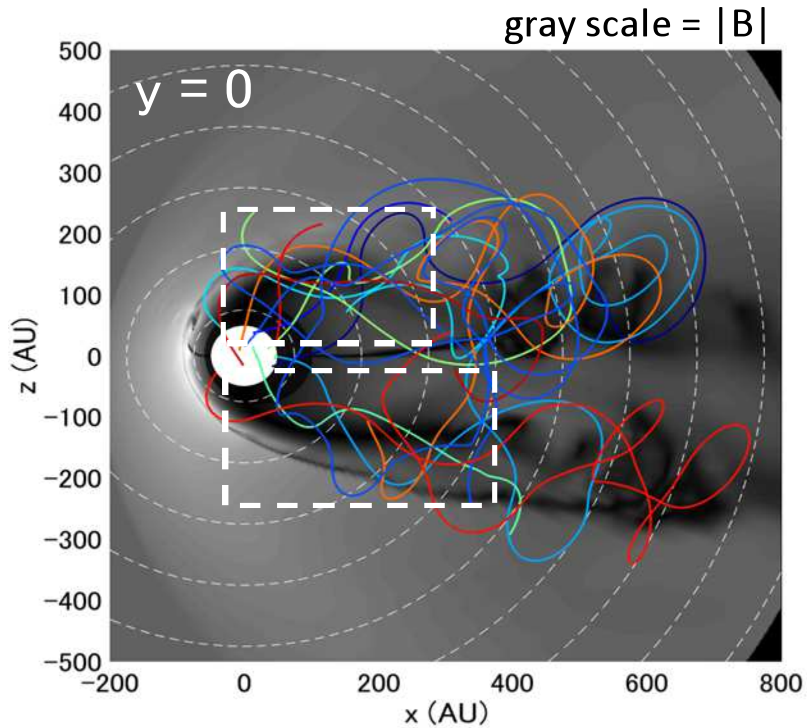



Particles enter the helio-
sphere from the region
where B is locally weak

# γ=1000: Arrival positions

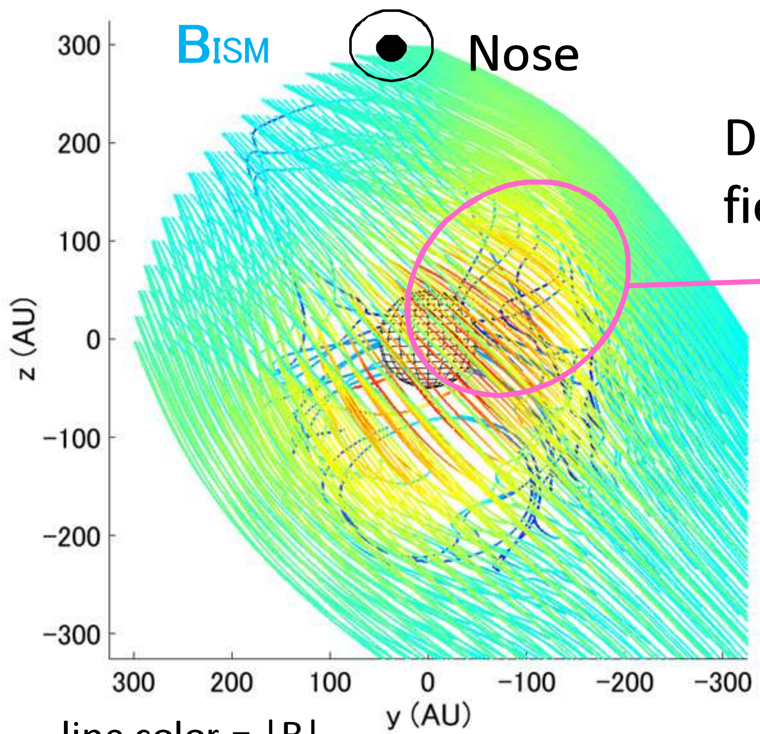
More particles arrive from the tail region




- Along with the trailing SW carrying weak B field

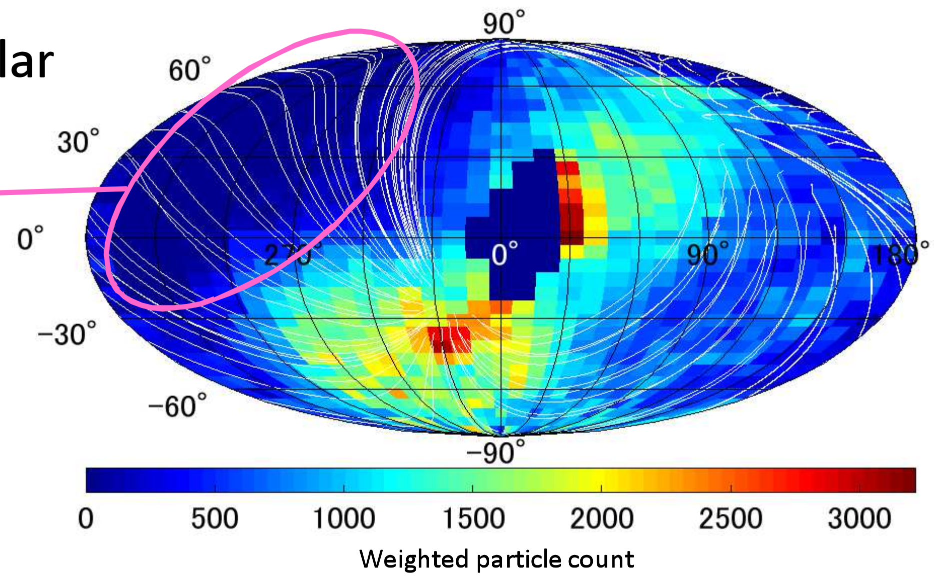
# γ=1000: Where are they from?




line color = |B|

Draped interstellar field is strong

Initial position of the arriving particles




More particles enter the heliosphere from its tail region

# Summary and Future Issues

- GCR invading process into the heliosphere was investigated by conducting a test particle simulation combined with a global MHD simulation of the heliosphere
- We found a variety of patterns of invading particle trajectory
  -- current sheet drift/ polar drift/ spiral motion/ shock drift/ Fermi-like/ linear motion/ resonantly scattered/ mirrored by draped field/ …
- Low energy particles enter the heliosphere from the region where local B field on the heliopause is weak and they reach high latitude regions of the inner boundary
- High energy particles easily enter the heliosphere from the tail region and they reach the tail side of the inner boundary

- Improving accuracy of MHD simulation
  -- solar activity (long term, short term) / tilt angle/ …
- Including wave-particle interactions