Geospace Environment Modeling
System for Integrated Studies

GEMSIS-Sun: Modeling of Particle Acceleration and Transport in Solar Flares

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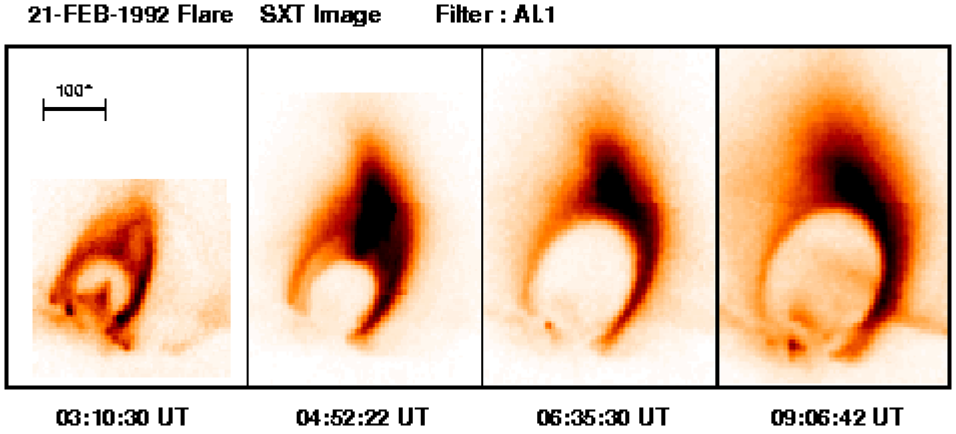
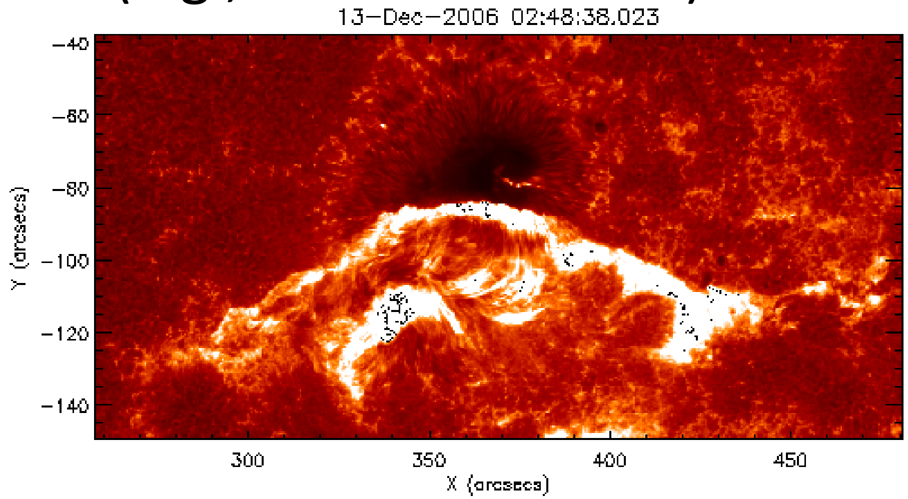
Flare = Successive Reconnection

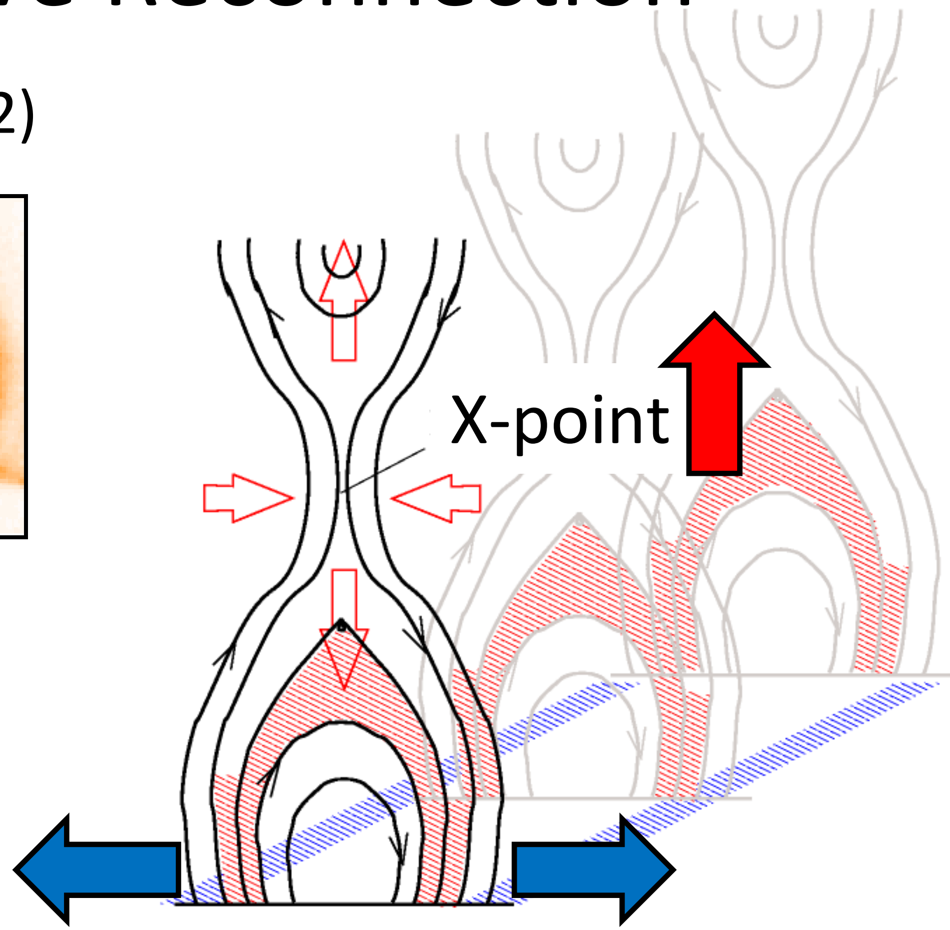
Cusp growth (Tsuneta et al. 1992)



Ribbon expansion

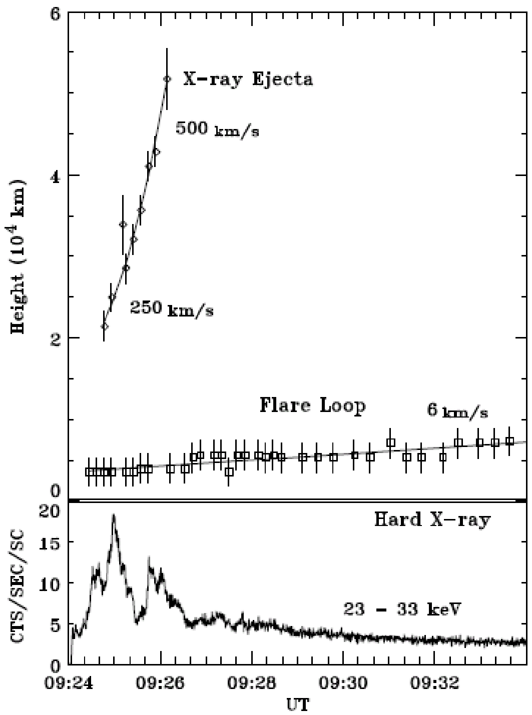
(e.g., Isobe et al. 2007)





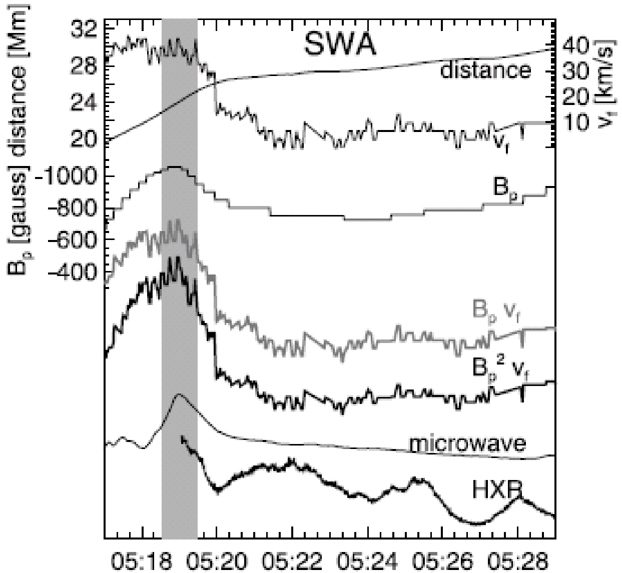
Non-stationary evolution

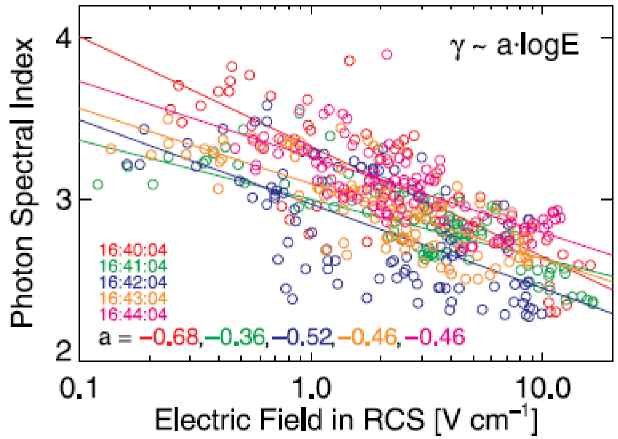
Observed Relationships between MHD Dynamics and Particle Acceleration



Ejecta velocity and non-thermal intensity (Ohyama & Shibata, 1998; Temmer et al. 2008)

Convection *E*-field and non-thermal intensity/spectra (Asai et al. 2004; Liu et al. 2008)





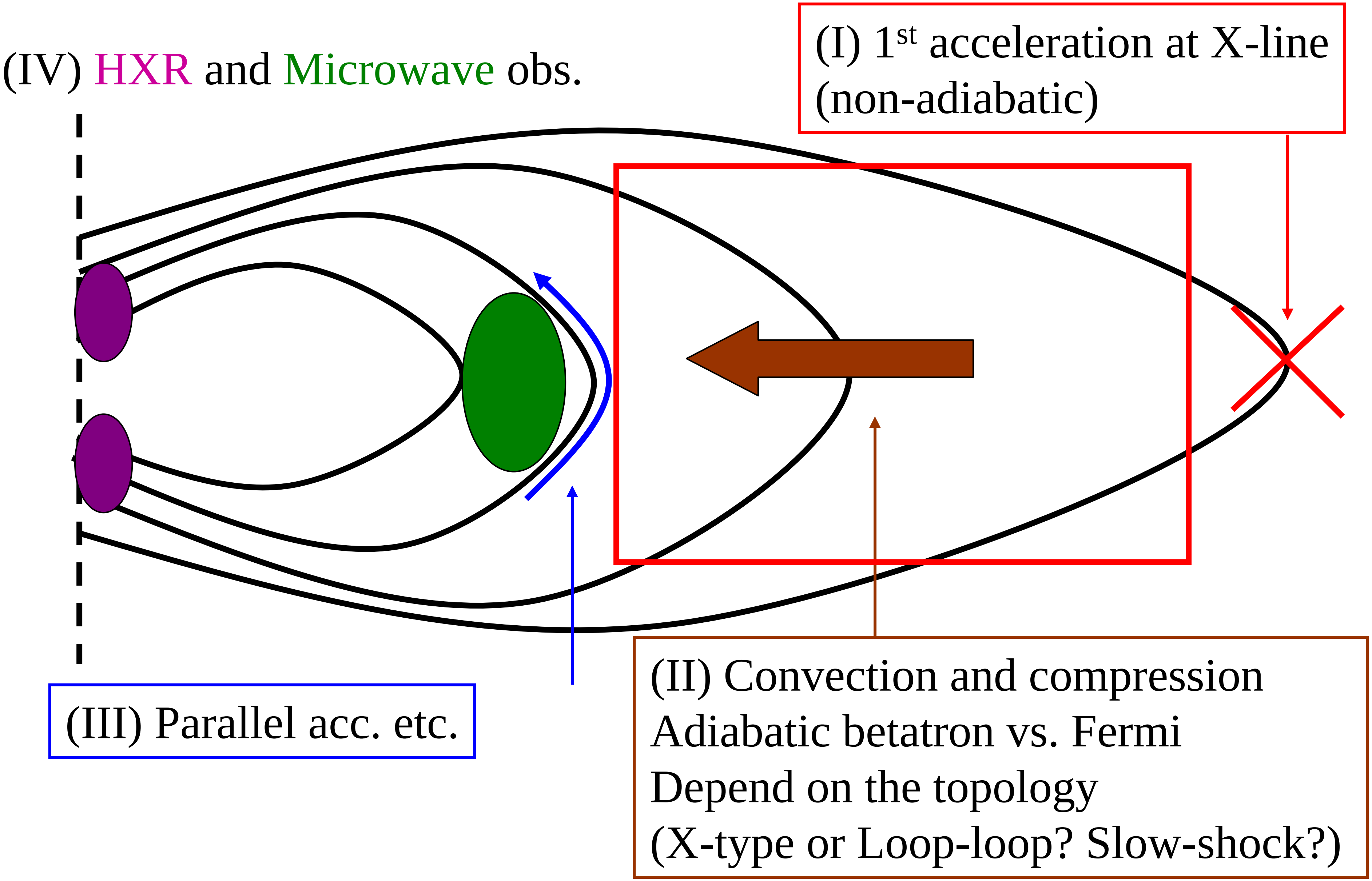
Aim

- Close relationship between **particle acceleration/transport** and the **configuration and evolution of the macroscopic electromagnetic field**

- Numerical calculation of the **time evolution of the particle phase-space distribution** in the flare electromagnetic field, performed with **coronal real parameters**

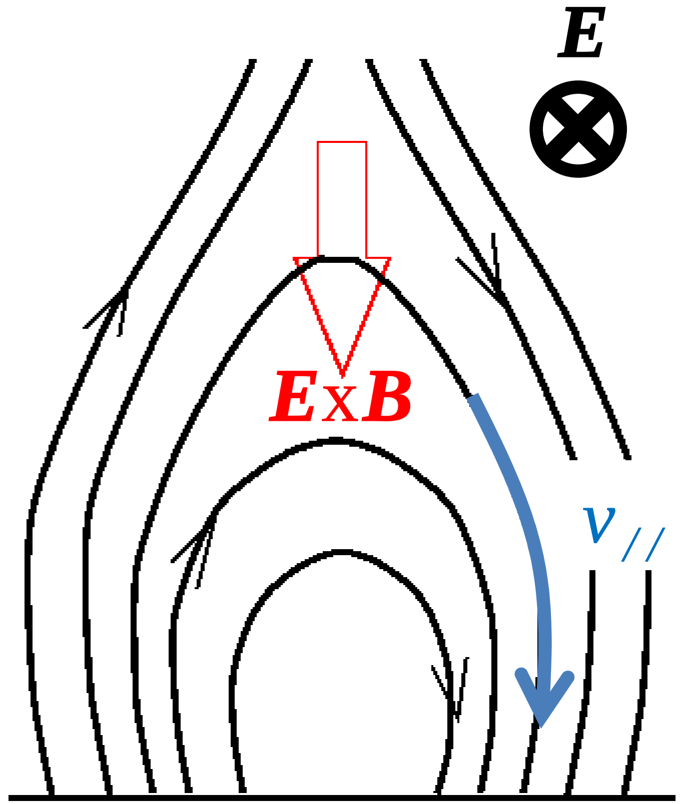
- Future: direct comparison between the hard X-ray and microwave observations

This study now focuses on acceleration during the transport.



Drift Approximation (Northrop, 1963)

- Macroscopic scale >> particle scale
- **<u>1st invariant is conserved</u>**
- Particle motion
  - $\boldsymbol{v}_{//}$ (along mag. field): fast
  - $\boldsymbol{E}\text{x}\boldsymbol{B}$ **drift**
  - Other drift: slow



Guiding-center drift kinetic equation

$$\frac{\partial f}{\partial t}+\nabla\cdot\left(\frac{d\mathbf{r}}{dt}f\right)+\frac{\partial}{\partial\gamma}\left(\frac{d\gamma}{dt}f\right)+\frac{\partial}{\partial\mu}\left(\frac{d\mu}{dt}f\right)=\left(\frac{\partial f}{\partial t}\right)_c$$

$$\frac{d\mathbf{r}}{dt}=\mathbf{v}_d+(\mathbf{v}\cdot\mathbf{B})\mathbf{B}/B^2$$

$$\frac{d\gamma}{dt}=\frac{u^2}{\gamma}\frac{1-\mu^2}{2}\frac{\partial\ln B}{\partial t}+\frac{\mathbf{v}_E}{c}\cdot\left[c\frac{u^2}{\gamma}\left\{\frac{1-\mu^2}{2}\nabla\ln B+\mu^2\left(\frac{\mathbf{B}}{B}\cdot\nabla\right)\frac{\mathbf{B}}{B}\right\}+\mu u\left(\frac{\partial}{\partial t}+\mathbf{v}_E\cdot\nabla\right)\frac{\mathbf{B}}{B}\right]$$

$$\frac{d\mu}{dt}=\left(1-\mu^2\right)\left[-\frac{1}{2}\left(\mu\frac{\partial}{\partial t}+\frac{cu}{\gamma}\frac{\mathbf{B}}{B}\cdot\nabla\right)\ln B+\frac{\mathbf{v}_E}{c}\cdot\left\{c\mu\left(-\frac{1}{2}\nabla\ln B+\left(\frac{\mathbf{B}}{B}\cdot\nabla\right)\frac{\mathbf{B}}{B}\right)+\frac{\gamma}{u}\left(\frac{\partial}{\partial t}+\mathbf{v}_E\cdot\nabla\right)\frac{\mathbf{B}}{B}\right\}\right]$$

$$u=\gamma v/c=\sqrt{\gamma^2-1}$$

$$\mathbf{v}_d\cong\mathbf{v}_E=\frac{\mathbf{E}\times\mathbf{B}}{B^2}c$$

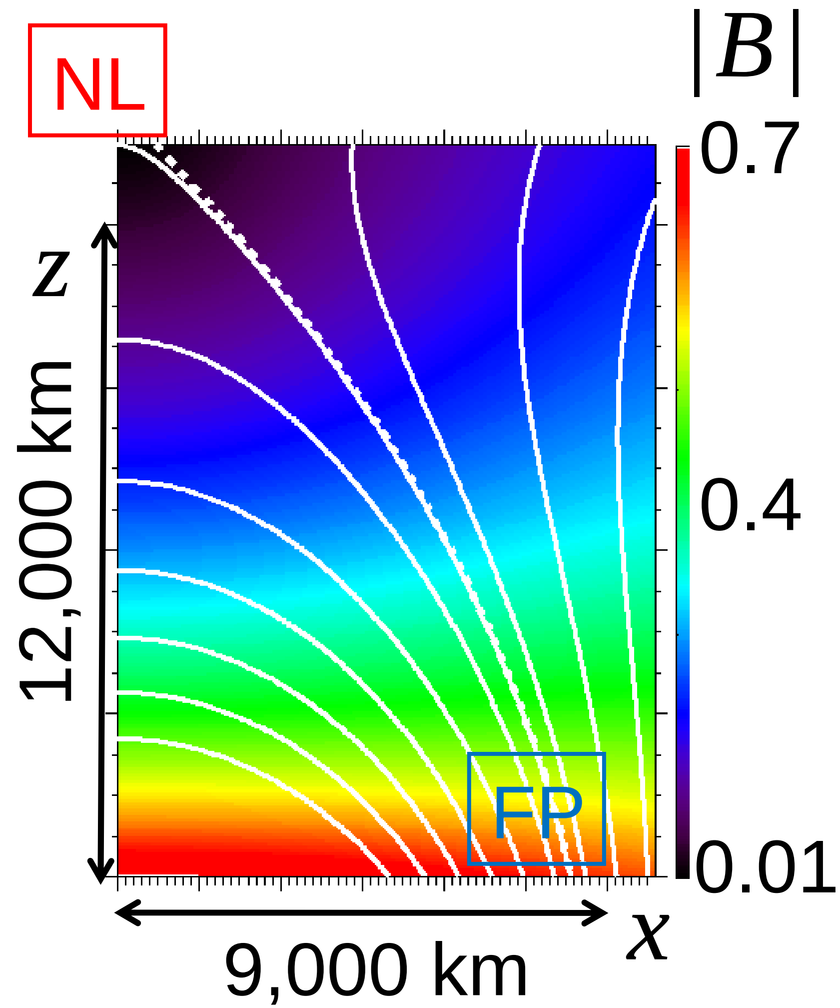
$$f=f(x,z,\mu,\gamma;t)$$

Acceleration due to gradient B drift

Acceleration due to Curvature drift

Centrifugal acceleration

Model description

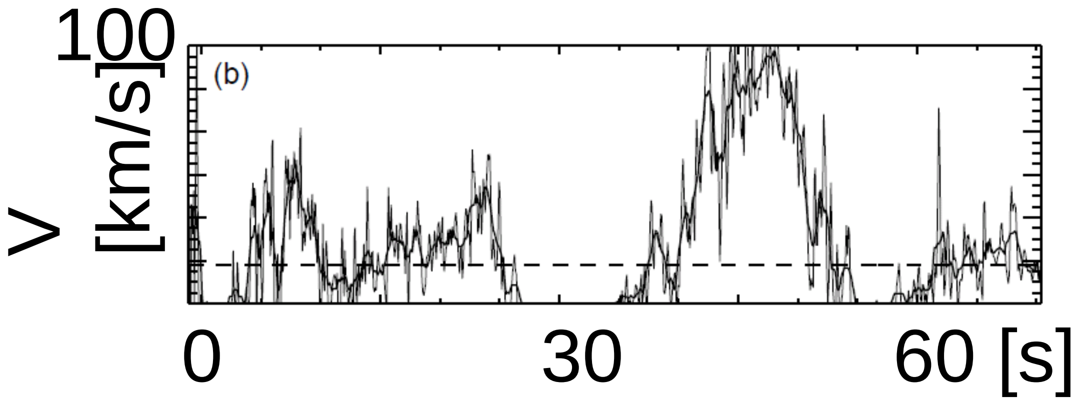


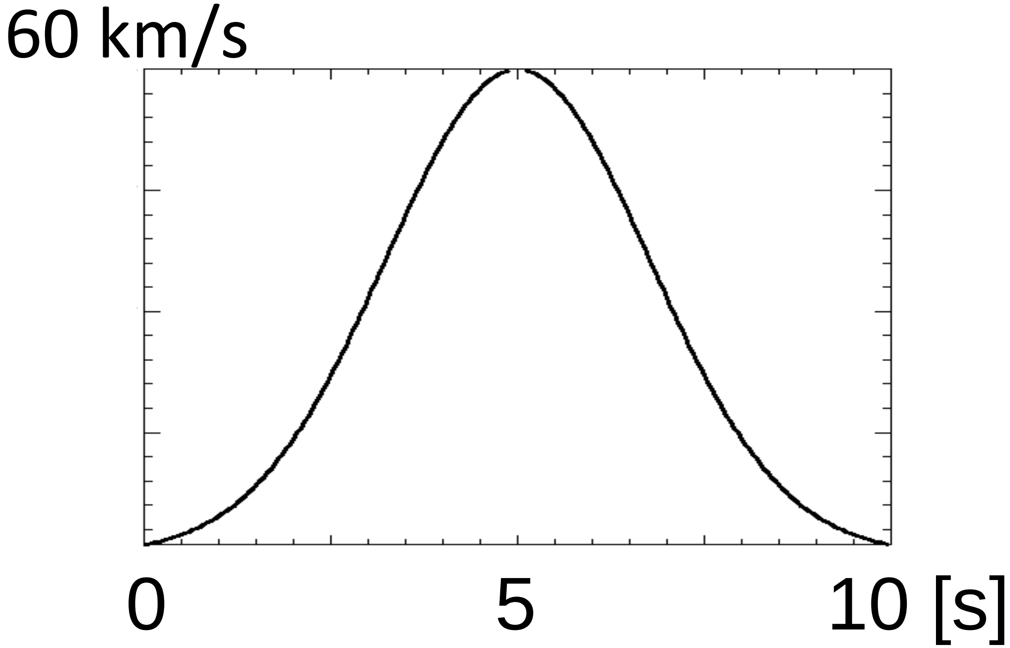
Thick: Magnetic field line
Dash: Mag. separatrix

- Magnetic field: Analytic model by Lin et al. (1995)
- 2-dimension
- **<u>Move the position of NL to upward</u>** => flare evolve
- Change the magnetic field configuration => **<u>induction electric field</u>**

Flare evolution

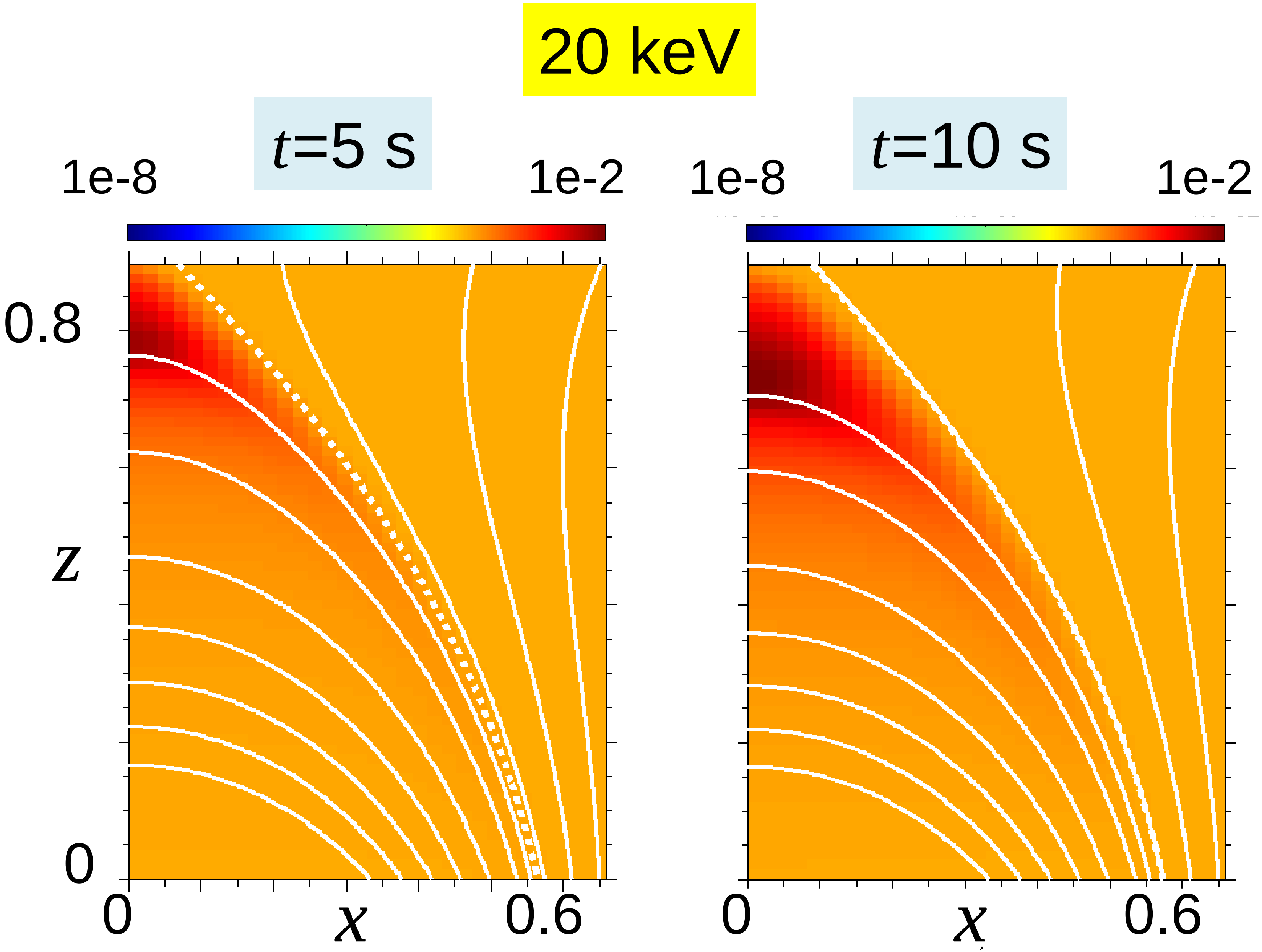
Observation (Qiu et al. 2002)

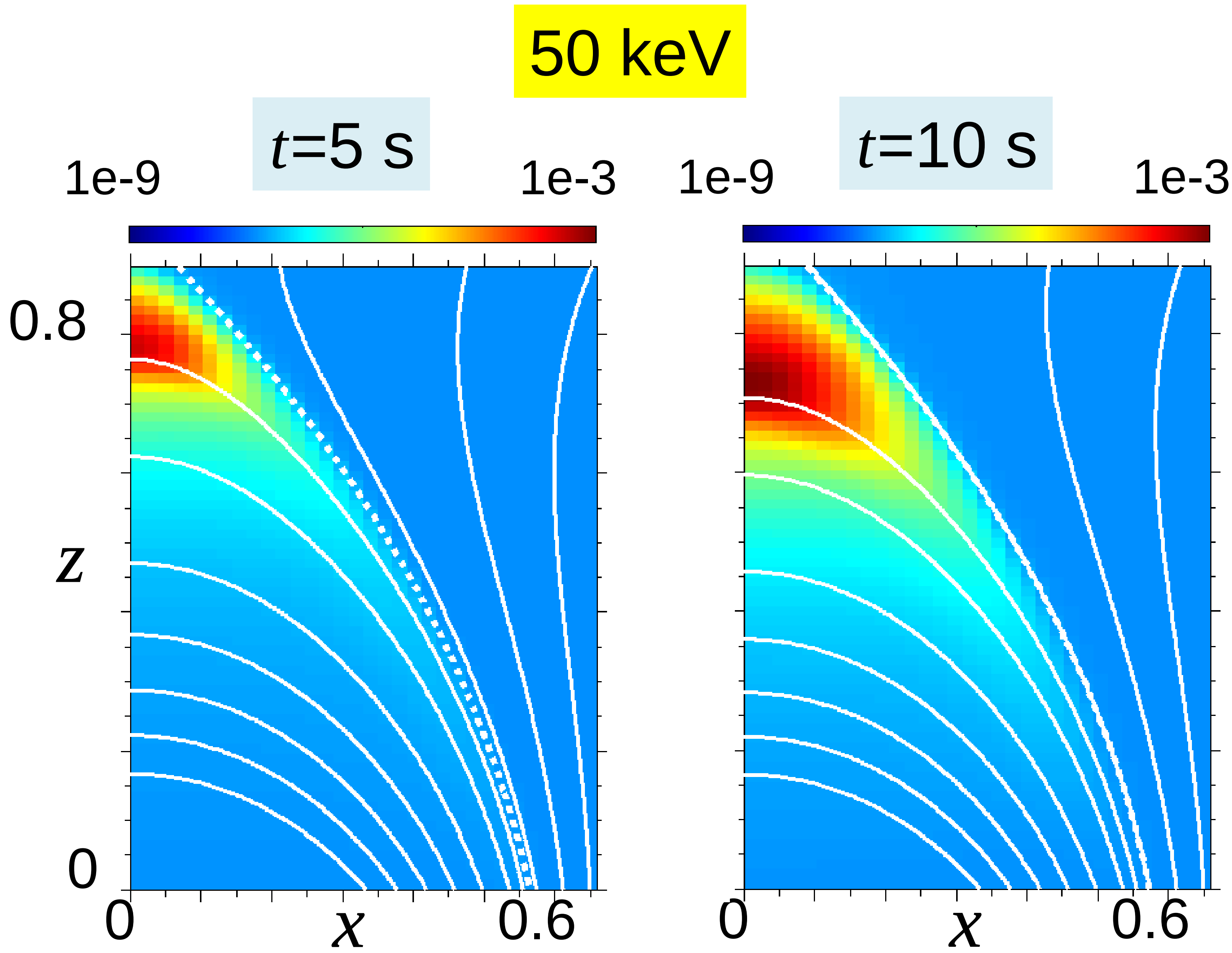




Model

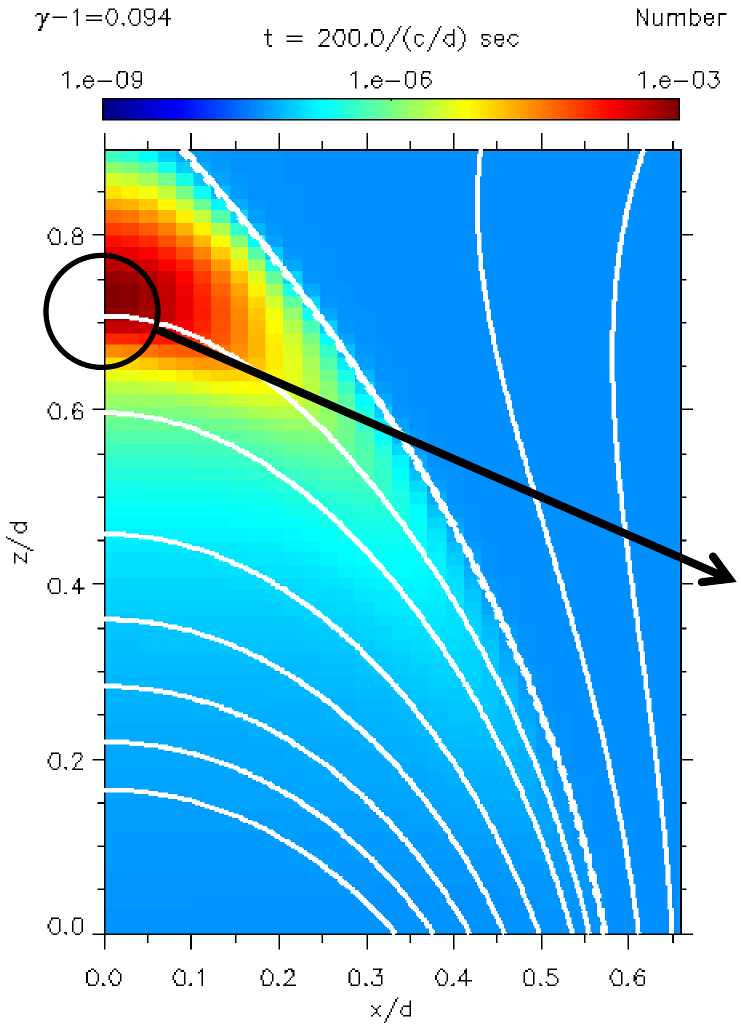
- Since the motion of NL is not directly observed
- **<u>Change the position of FP</u>**, which is connected with NL via separatrix
- The motion of FP is well observed as the flare ribbon (e.g., Qiu et al. 2002)


20 keV
t=5 s
t=10 s
1e-8
1e-2
1e-8
1e-2
0.8
z
0
0
x
0.6
0
x
0.6

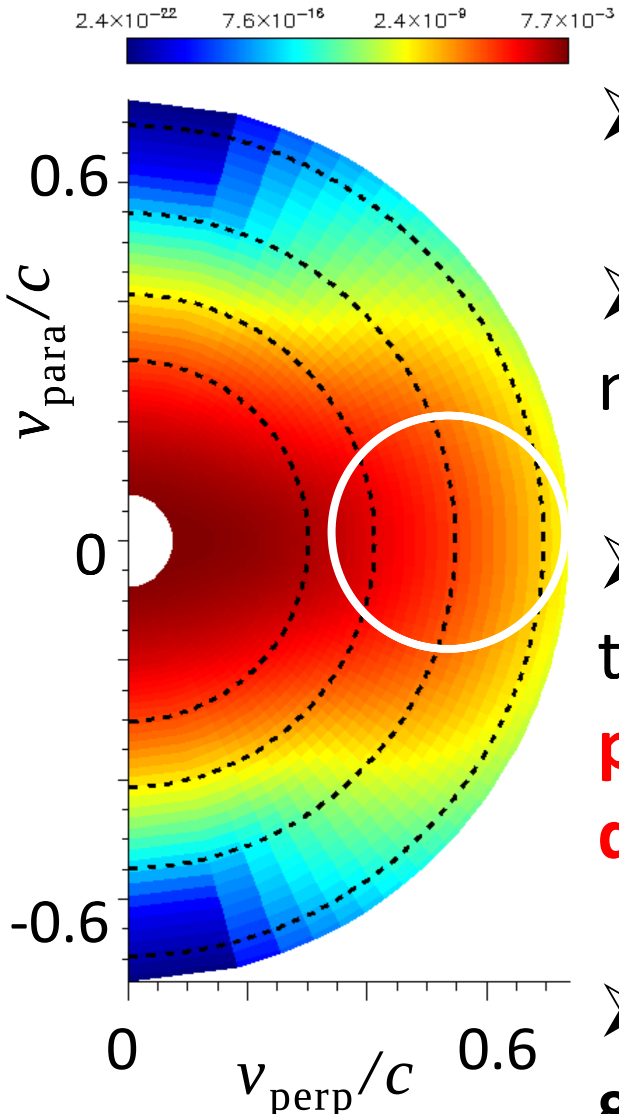


50 keV
t=5 s
t=10 s
1e-9
1e-3
1e-9
1e-3
0.8
z
0
0
x
0.6
0
x
0.6

50 keV



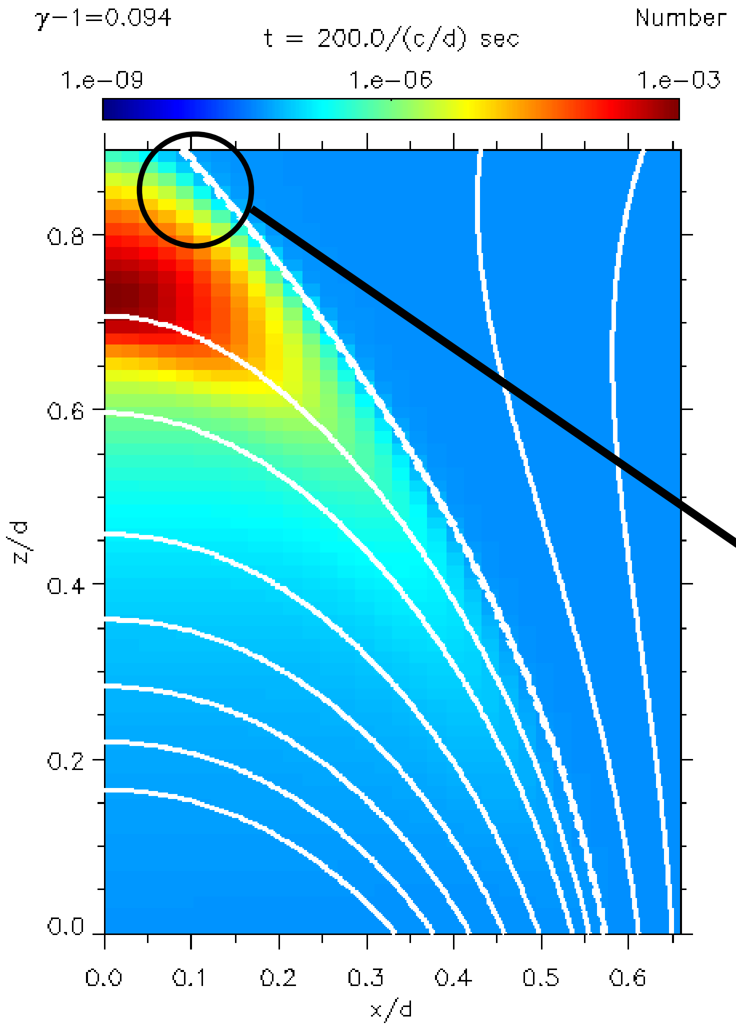
Phase space distribution

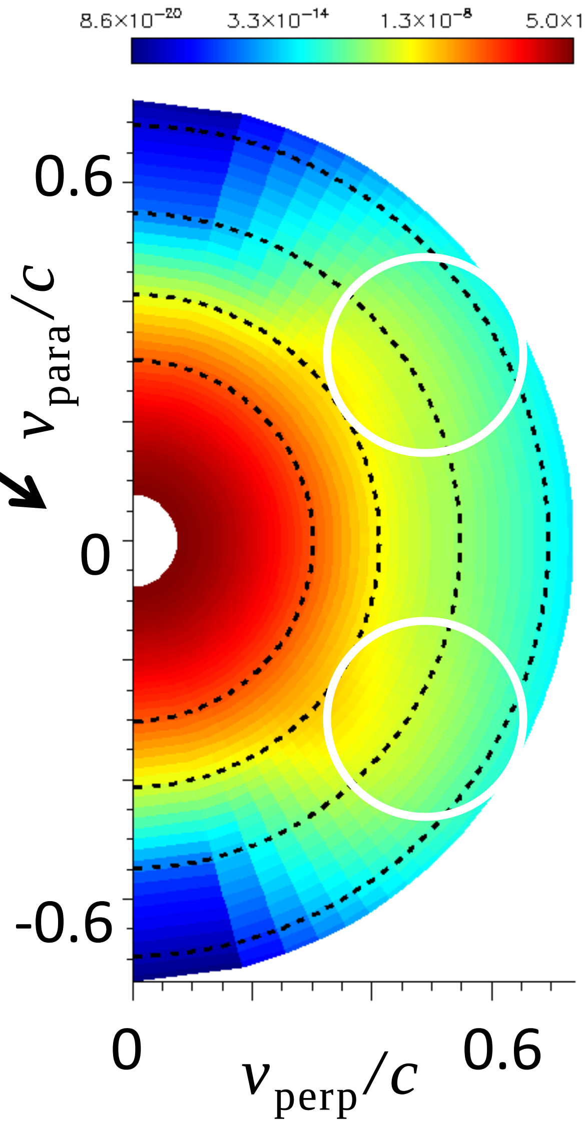


- ➢Loop-top
- ➢Largest particle number
- ➢Acceleration toward **perpendicular direction**
- ➢**Due to gradient B drift**

50 keV

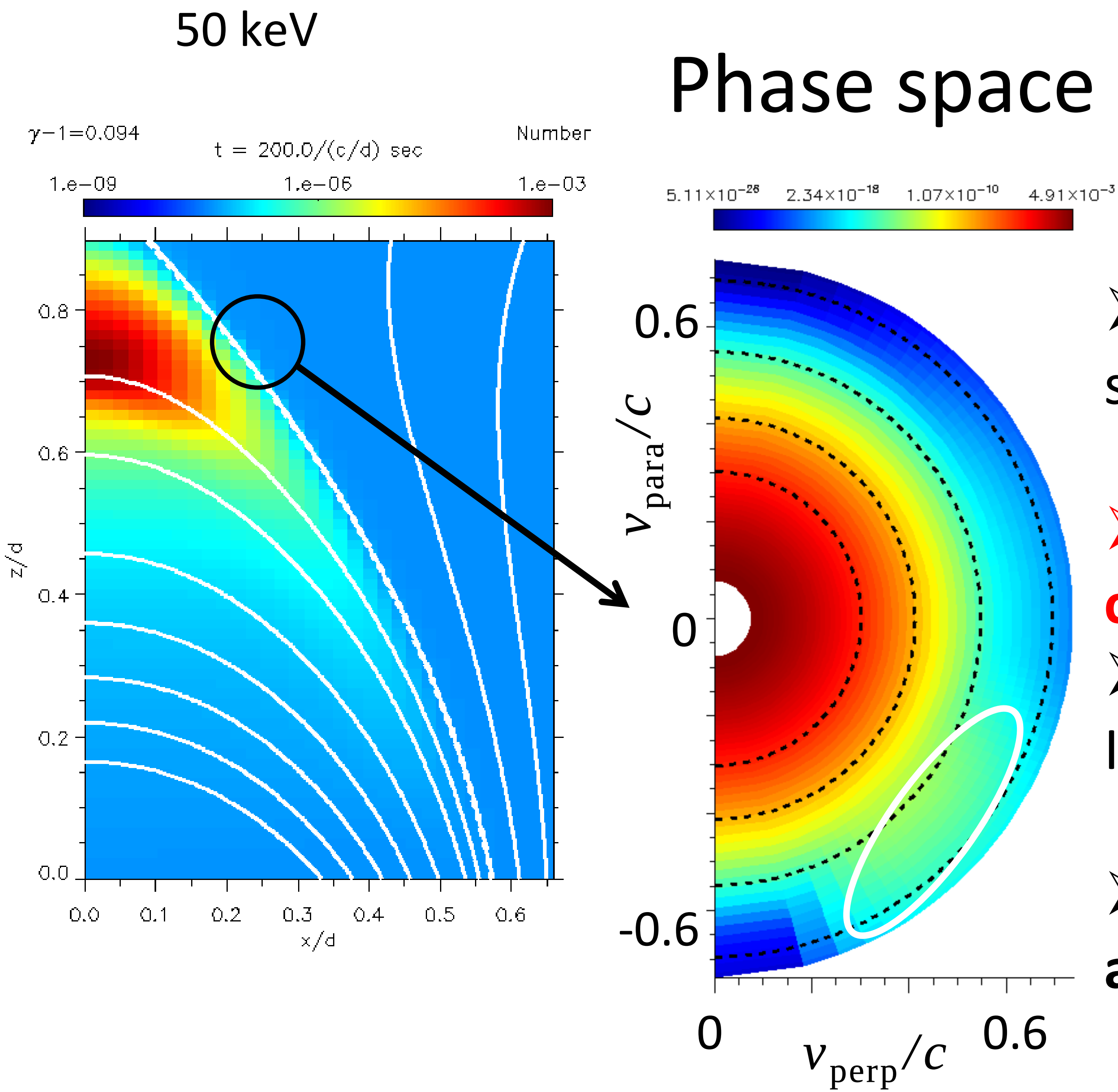
Phase space distribution





- Acceleration toward **parallel as well as perpendicular direction**
- **Due to curvature drift**

Phase space distribution



- Near the mag. separatrix
- **Upward beam component**
- Origin of type III radio burst
- **Centrifugal acceleration**

Summary

- Numerical modeling of particle acceleration and transport with the **drift-kinetic approach.**
- Three different types of acceleration mechanisms: **Gradient B and curvature drift acceleration, and centrifugal acceleration**.
- The resultant phase space distribution depends on which mechanism most efficiently works.
- Temporal evolution, spatial distribution, energy and pitch-angle distribution should be compared to the observations.

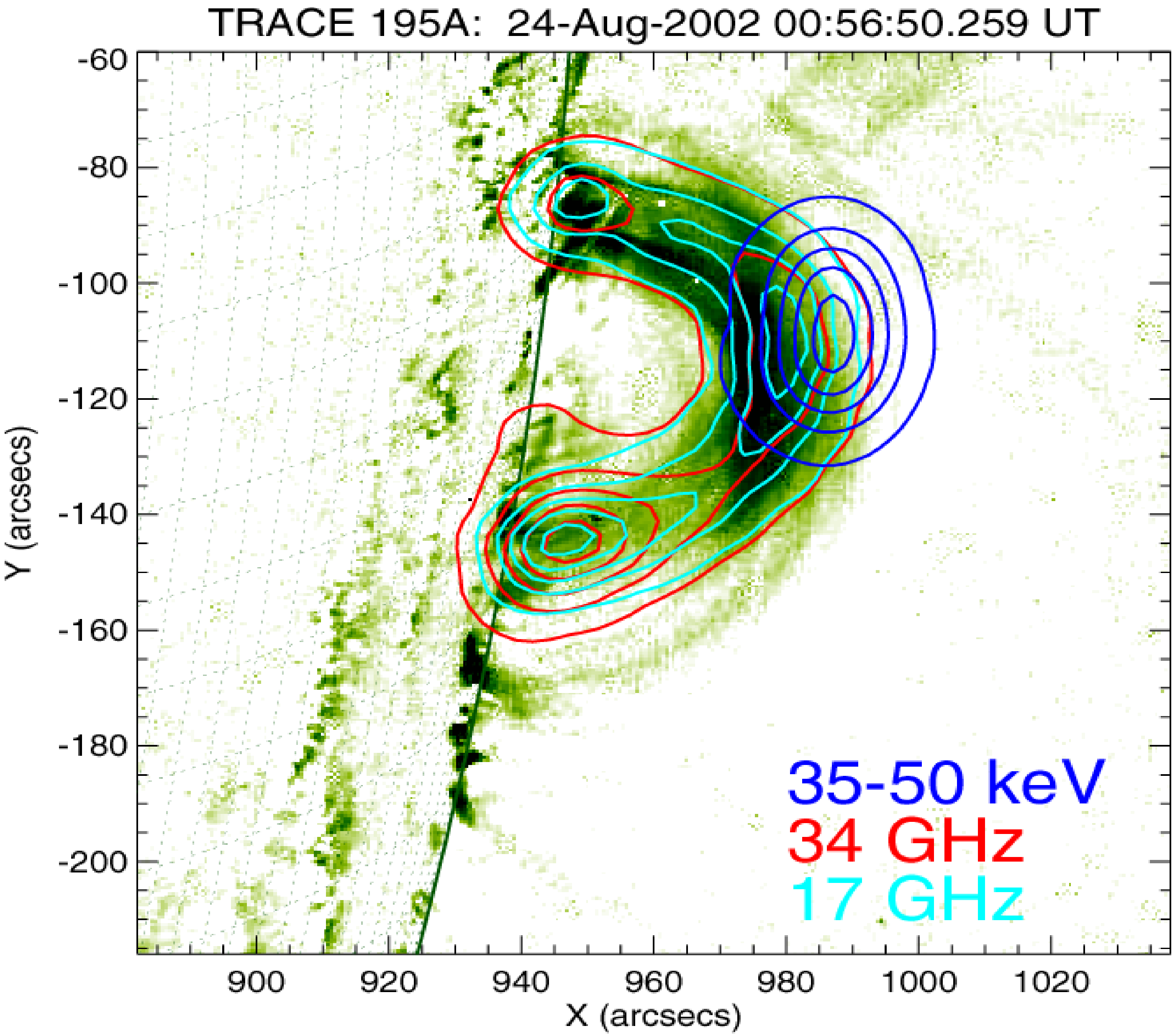
Future Plan

Diffusion processes (Coulomb collisions, wave-particle interactions) will be included.

Conversion to emissions is necessary for the direct comparison with the observations

A simulation using observational magnetic field data is possible through modeling of coronal magnetic field, e.g. Non-Linear Force Free Field model.

Comparison with multi-wavelength observations



Courtesy of Krucker