Energetic electron acceleration by unsteady magnetic reconnection

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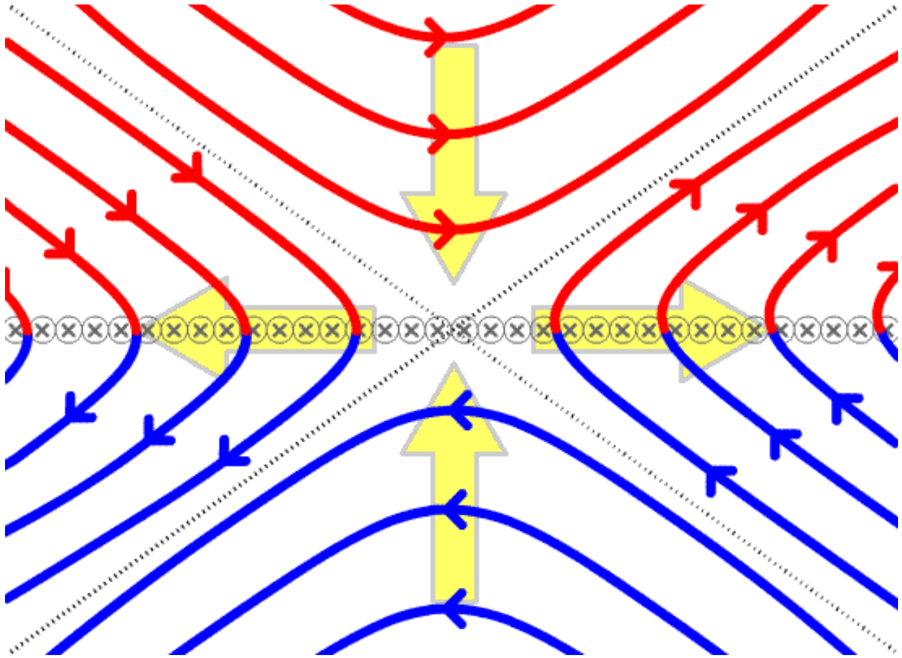
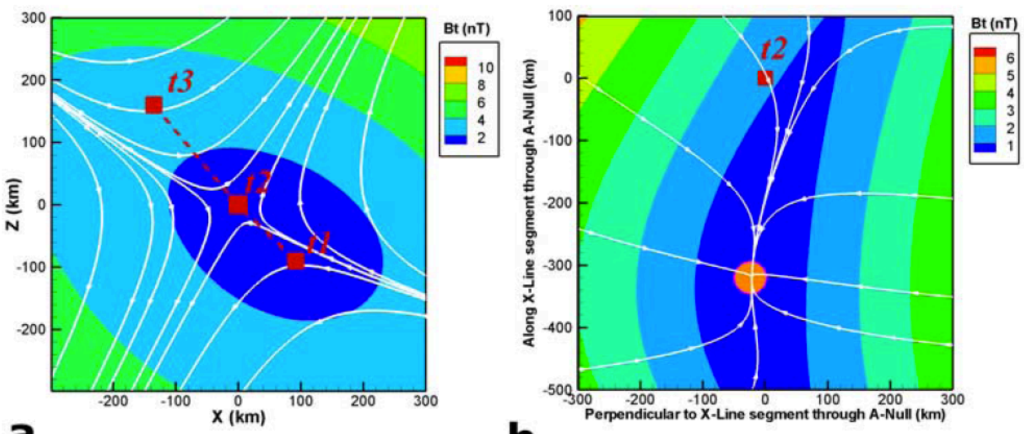
Steady magnetic reconnection

- Magnetic energy => kinetic energy
- Magnetic topology changes
- Two fluid picture:
    - Ion diffusion region (Cluster)
    - Electron diffusion region (MMS)
- Solar flare & substorm & fusion
- Magnetopause & magnetotail
- Guide-field reconnection
- Non-guide-filed reconnection (null)
- Reconnection rate (Alfven velocity)

- Steady reconnection
- Unsteady reconnection

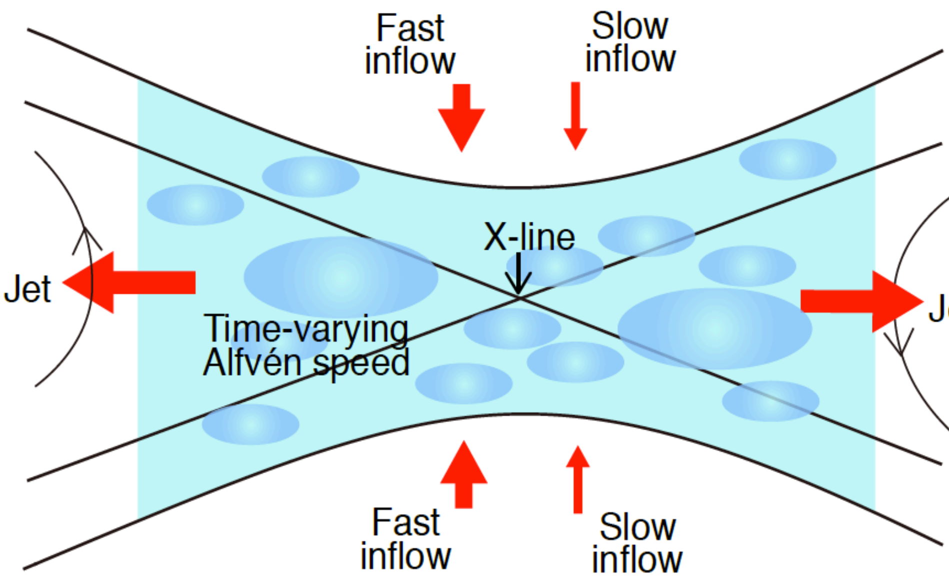




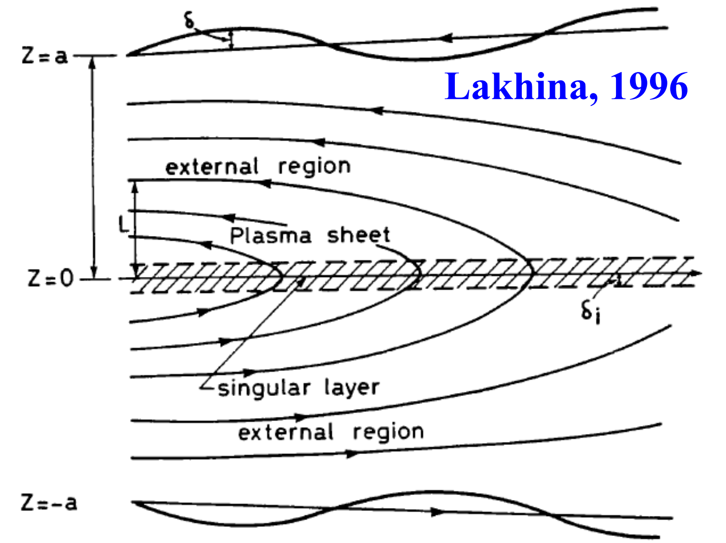
He+, 2008GRL

Unsteady magnetic reconnection (1)

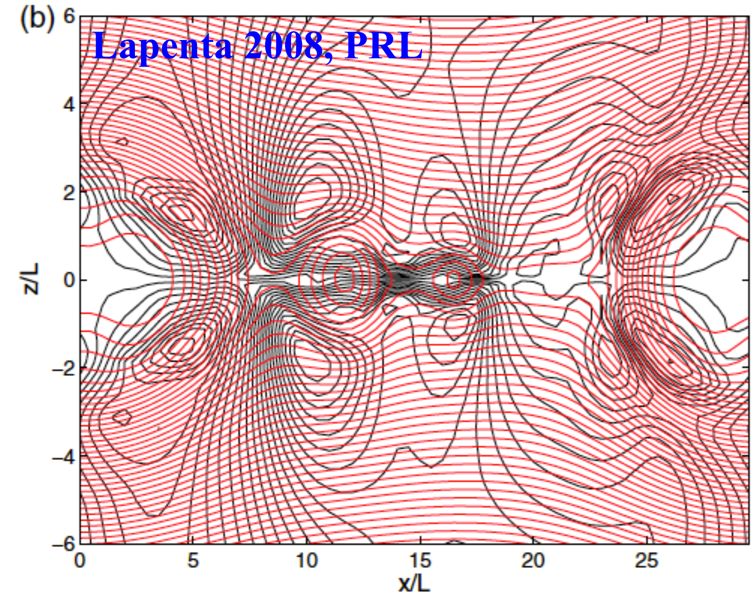
- Time-varying inflow speed lead to the change of reconnection rate (unsteady)



Fu+ 2013, Nature Physics



Lakhina, 1996

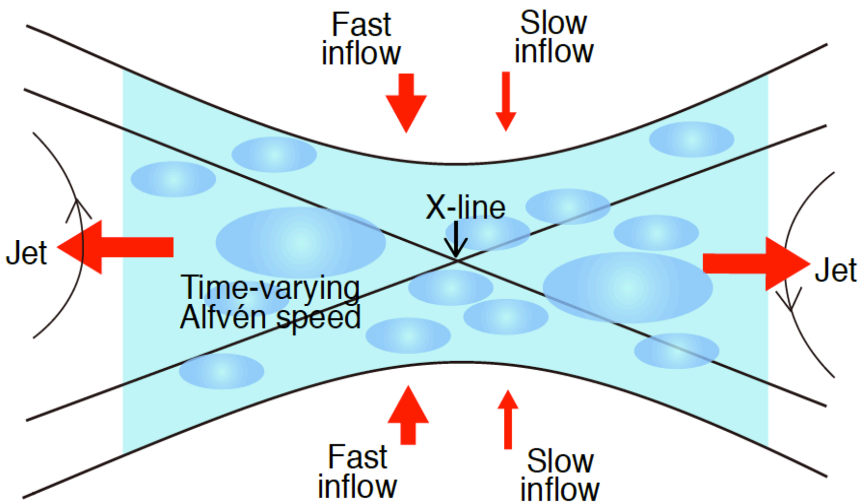


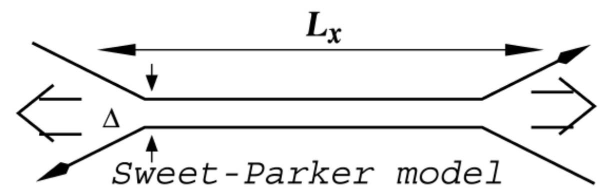
Lapenta 2008, PRL

- Variable boundary => inflow speed change
- Outflow speed => inflow speed change

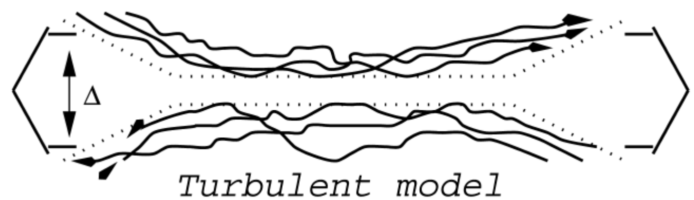
Unsteady magnetic reconnection (2)

- Turbulence & secondary island lead to unsteady reconnection

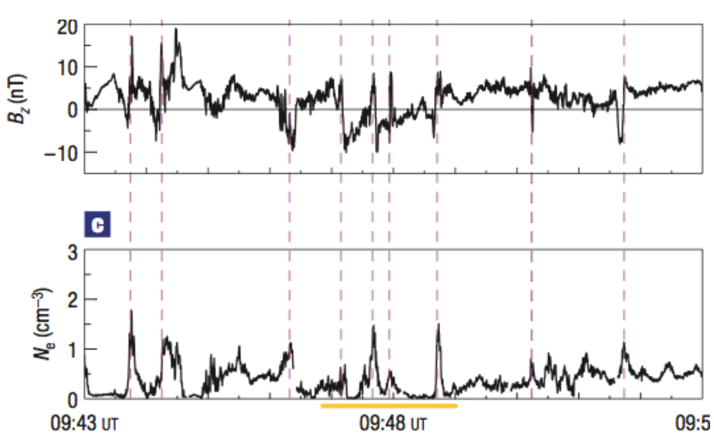




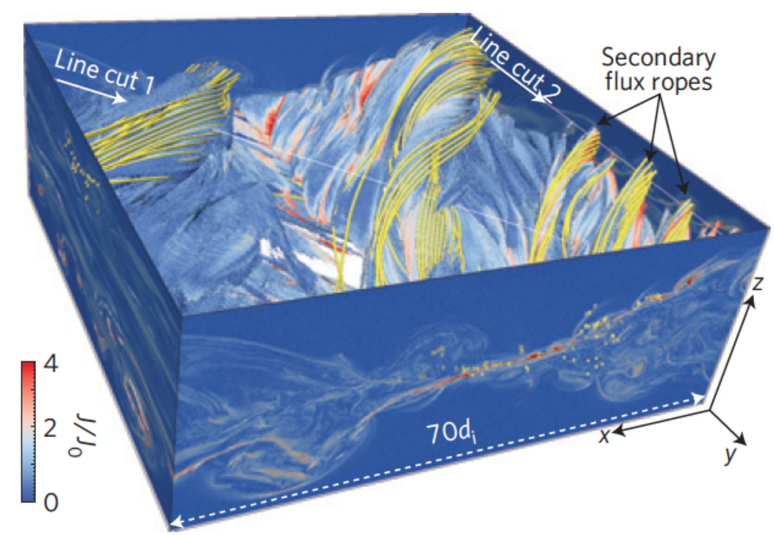
Lazarian + Vishniac, 1999, APJ



Chen+ 2008, Nature Phys. **Fu+ 2013, Nature Phys.**

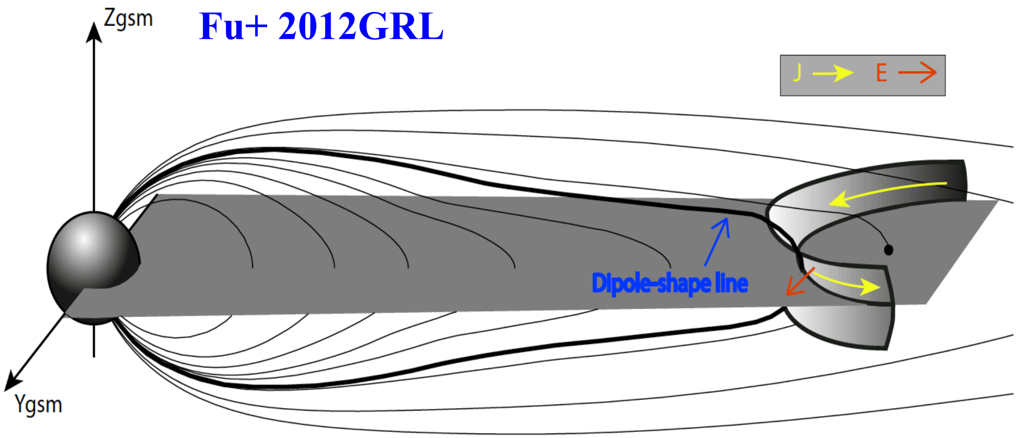


Daughton+, 2011, Nature Phys.



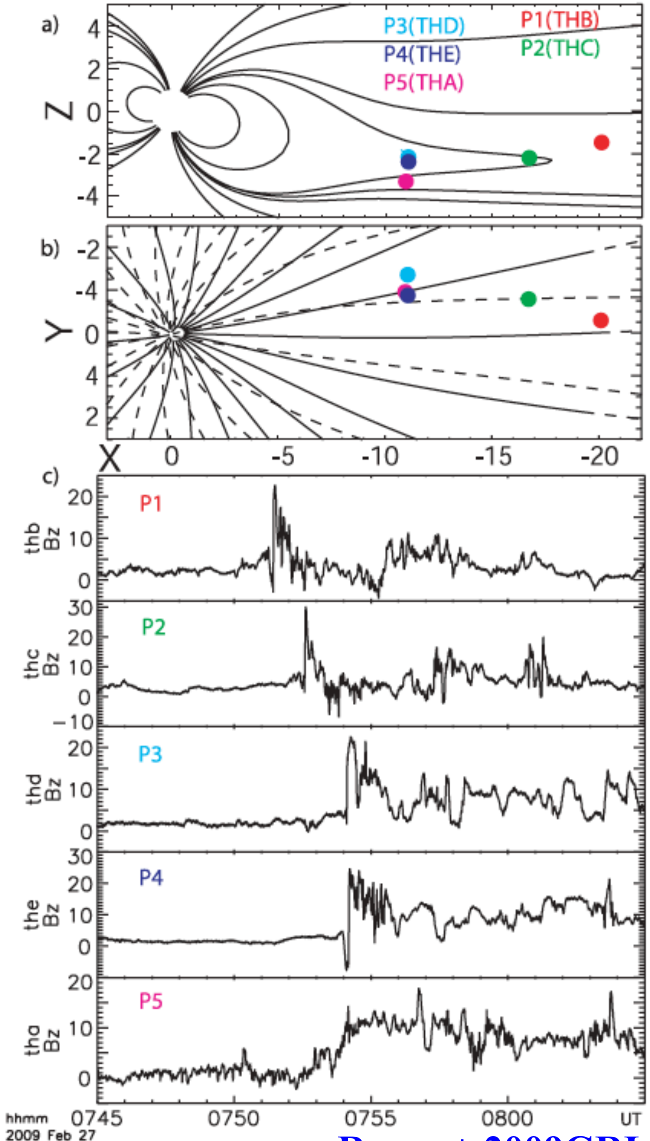
Signature of unsteady reconnection(1)

Fu+ 2012GRL



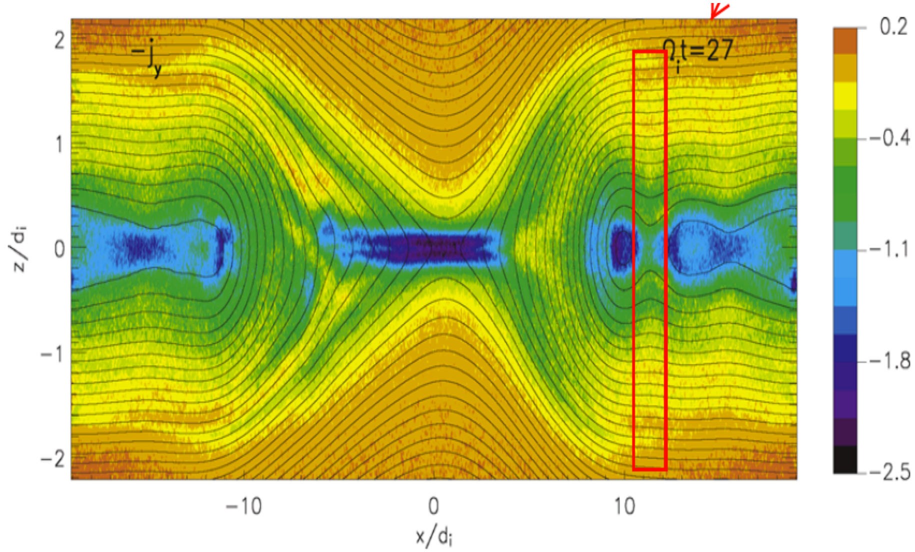
Dipolarization front

- Significant increase of Bz
- Separate dense & tenuous plasma
- Typical scale: ion inertial length
- Typical duration: 1 - 4 s
- Earthward & tailward

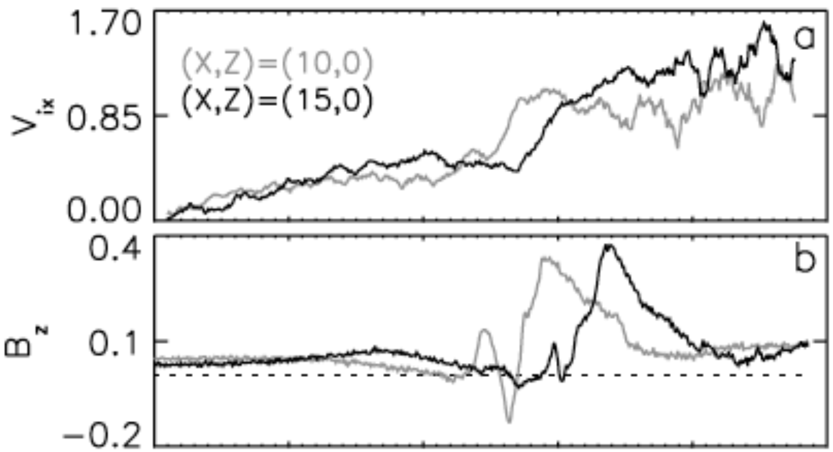


Runov+ 2009GRL

Signature of unsteady reconnection(2)

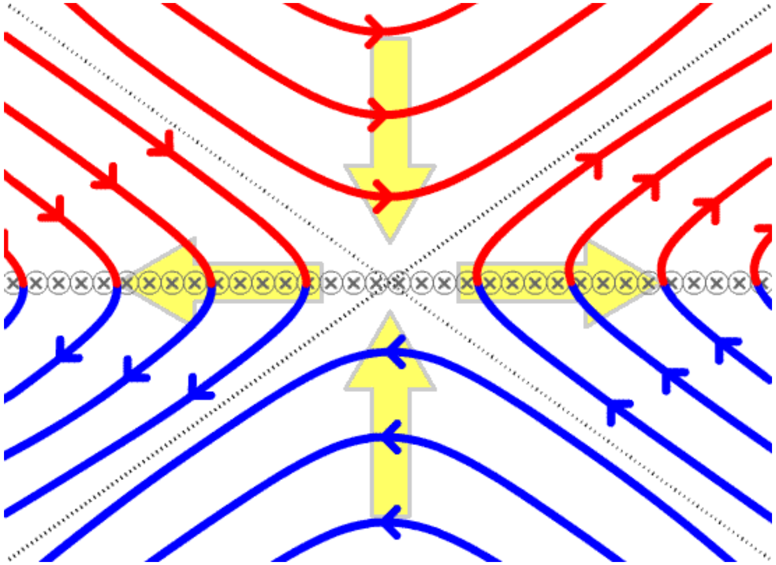


Sitnov+ 2009JGR



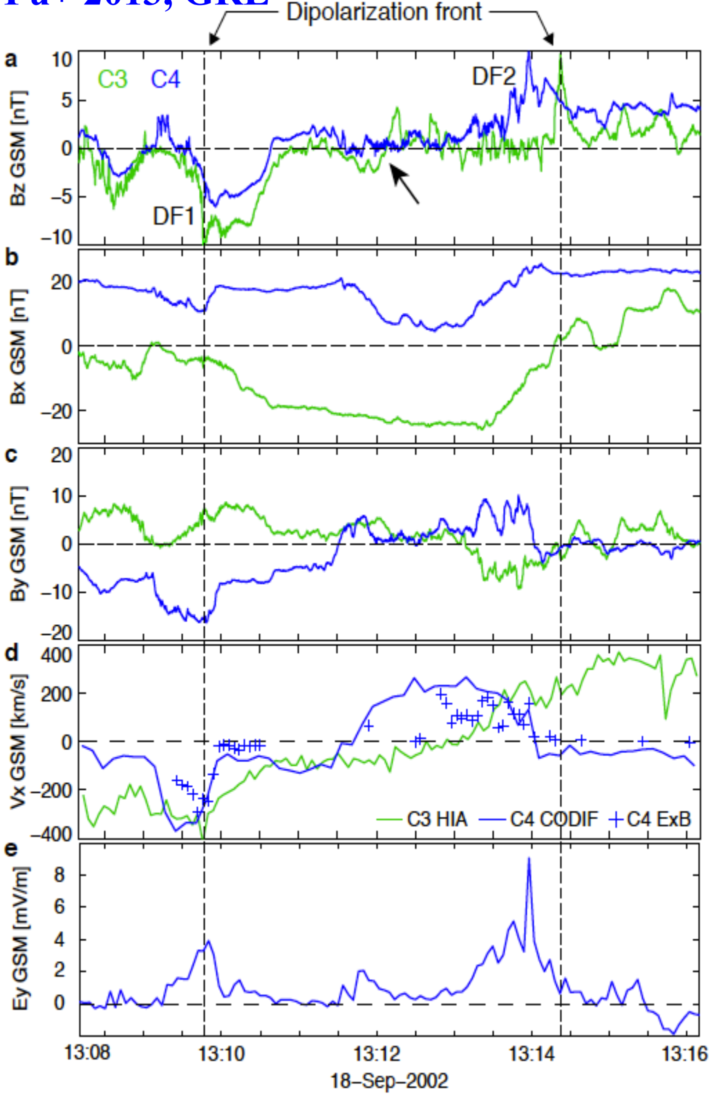
Open boundary simulation:

- Dipolarization front is a signature of unsteady magnetic reconnection.



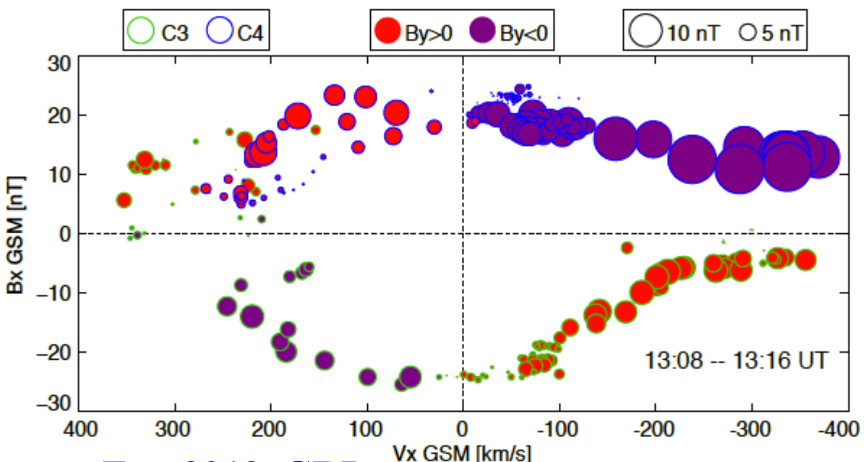
Signature of unsteady reconnection(3)

Fu+ 2013, GRL



Observational evidence:

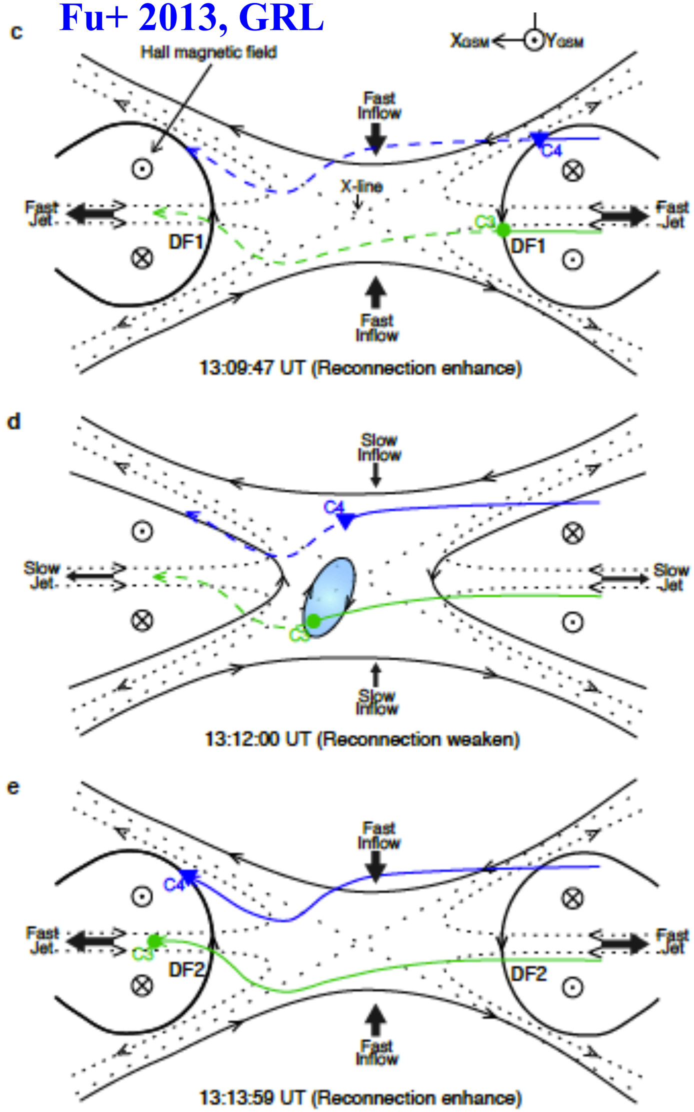
- Two satellites: south + north of CS
- Reversal of high-speed flow
- Quadrupole structure– hall fields
- Crossing of **ion diffusion region**
- Dipolarization front



Fu+ 2013, GRL

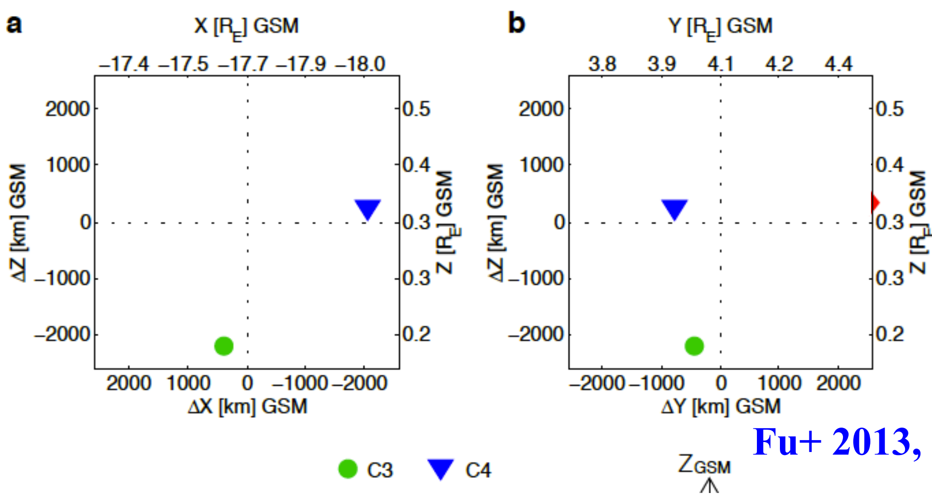
Signature of unsteady reconnection(3)

Fu+ 2013, GRL



Interpretation of observation:

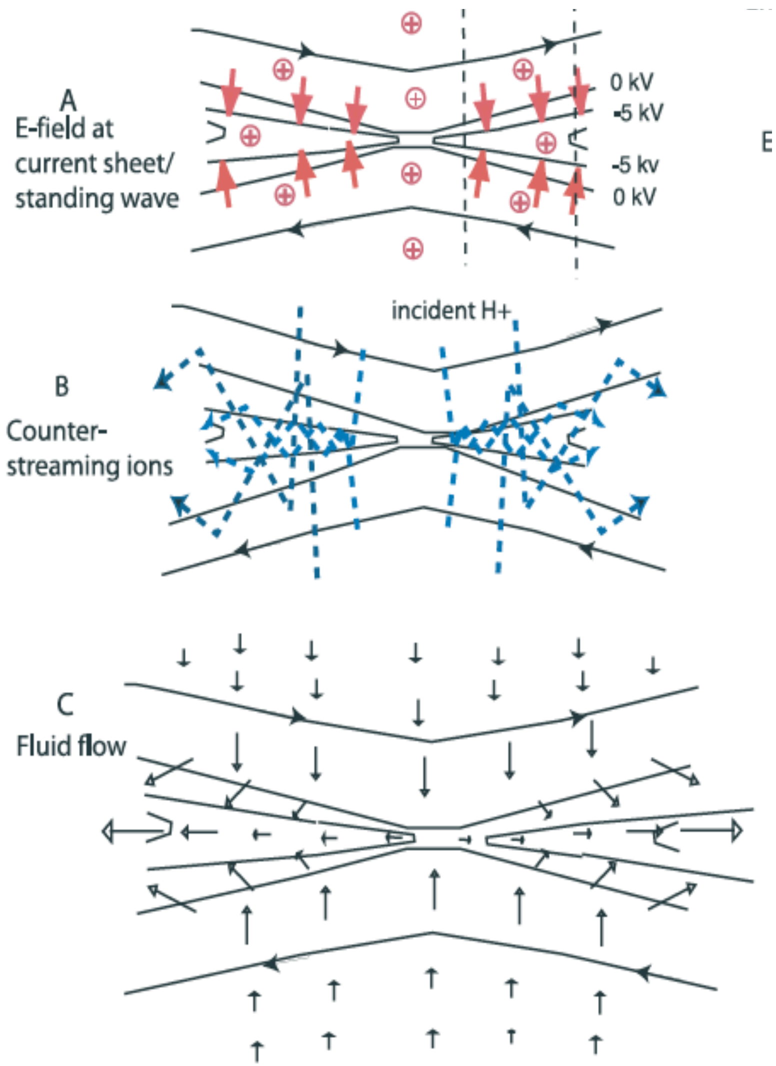
- First reconnection (large Ey): C3C4 observed tailward flow & negative DF
- Reconnection weaken (small Ey): C3C4 close to X-line (C3 observed island)
- Second reconnection (large Ey): C3C4 observed earthward flow & positive DF



Fu+ 2013, GRL

Signature of unsteady reconnection(3)

Wygant+, 2005JGR



Conclusion:

- Flow is produced by unsteady reconn.
- DF is produced by unsteady reconn.
- <u>No causality between flow and DF</u>

- In ion diffusion region:
  - frozen-in condition is violated
  - flow doe not break

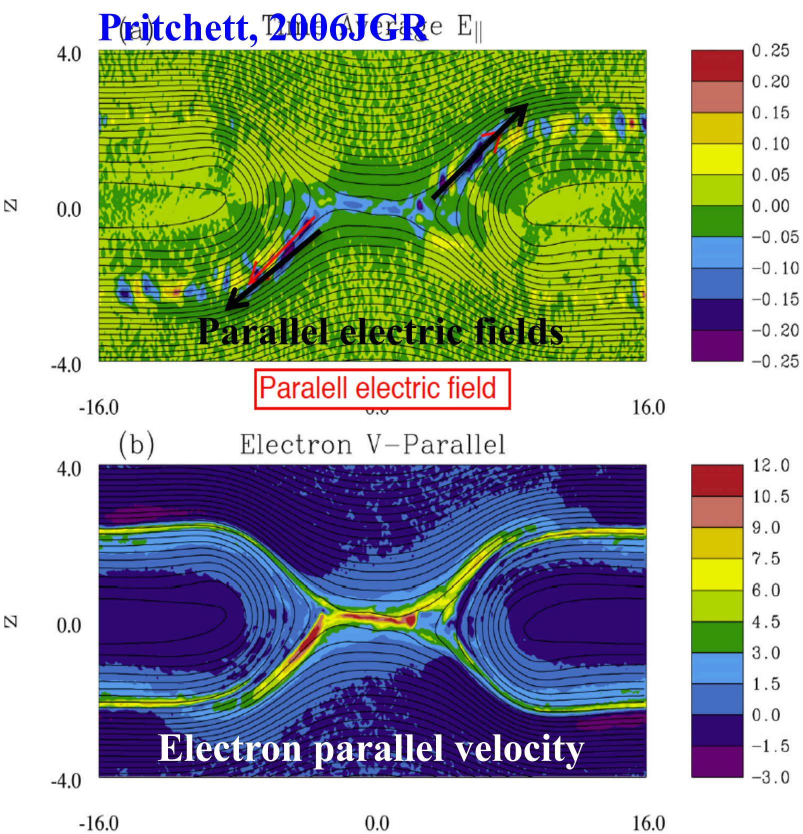
<u>DF is a signature of unsteady reconnection</u>

Acceleration by steady reconnection - theory

Primary mechanism: Acceleration by parallel electric fields

PIC simulation

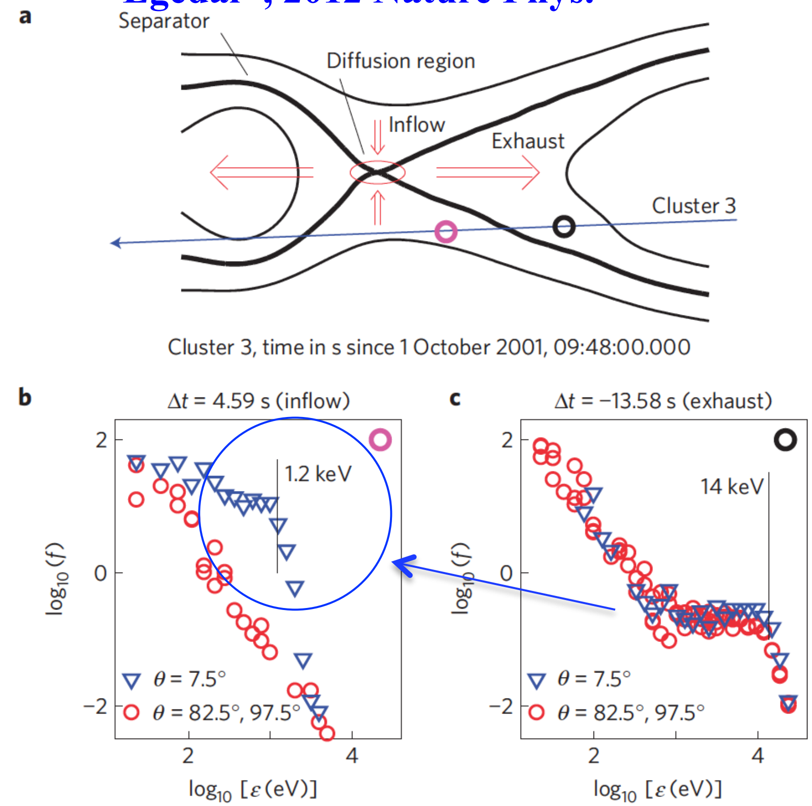
Pritchett, 2006JGR



- large V// related to large E//
- Effective in guide-field reconn.

Observation

Egedal+, 2012 Nature Phys.



- PSD in parallel direction is enhanced significantly

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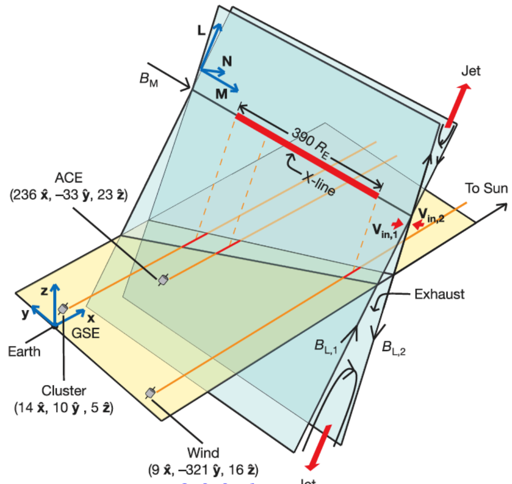
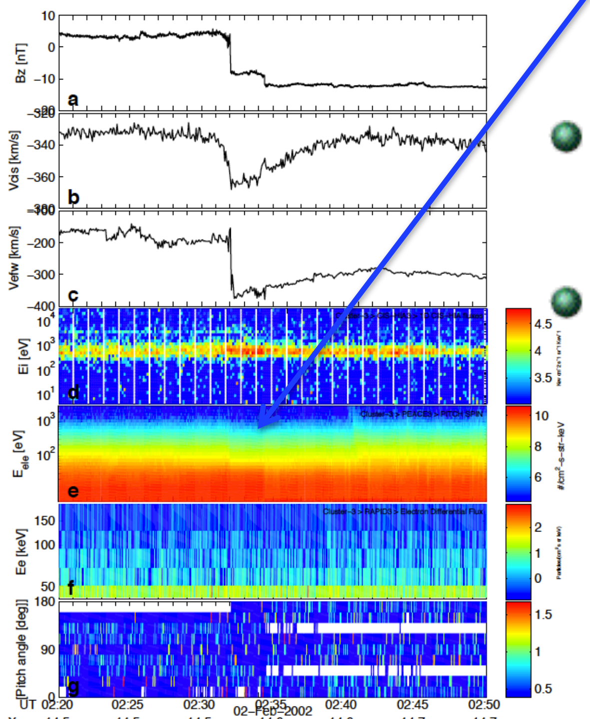
Acceleration by steady reconnect–debatable

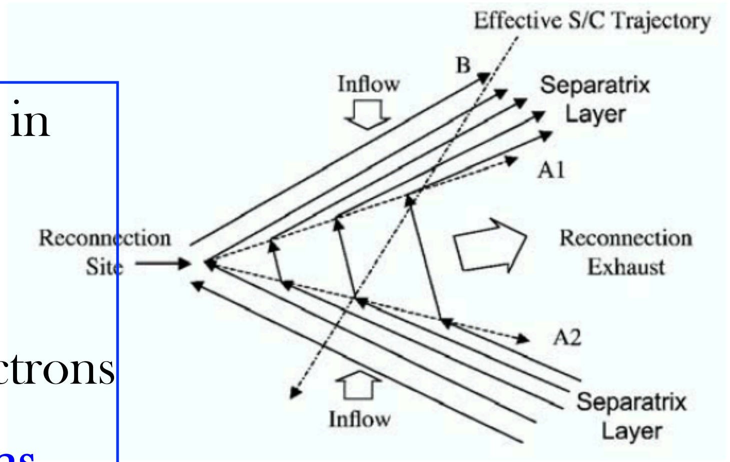


Phan+ 2006Nature



- Steady reconnection in solar wind
- Large scale (390 Re)
- 100 eV– 25 keV electrons

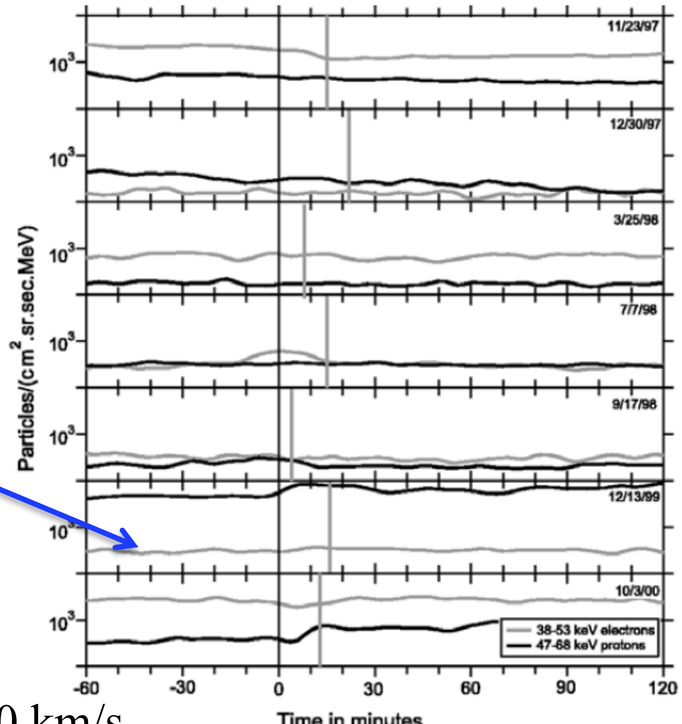
No energetic electrons



Gosling+ 2005GRL

- Six events of diffusion region
- 38 – 53 keV electrons

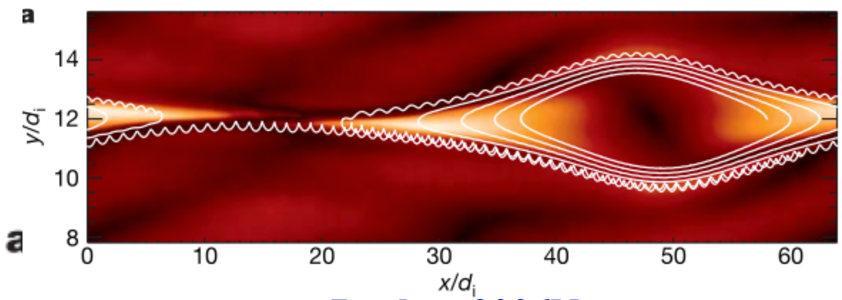
No energetic electrons



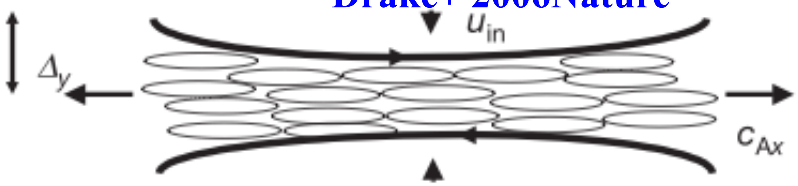
Va ~ 80 km/s

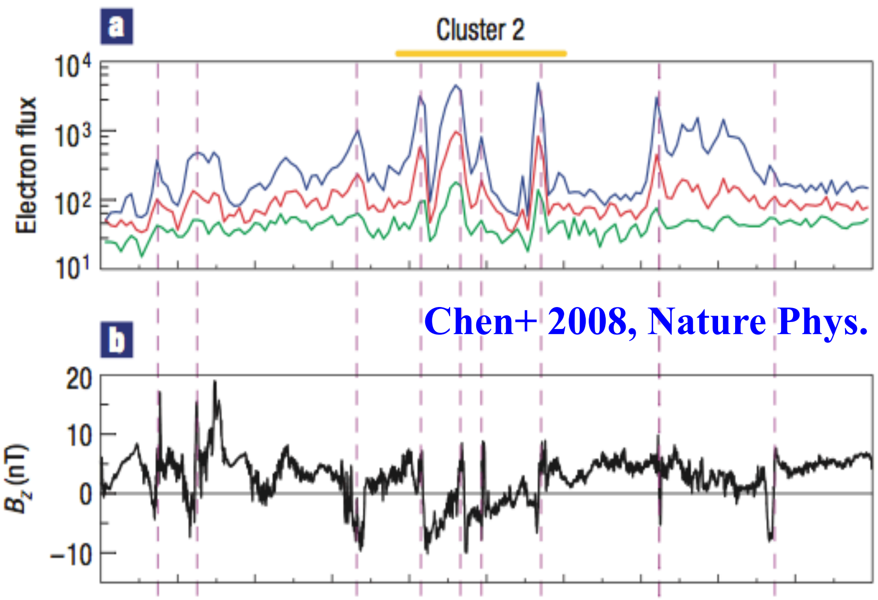
Acceleration at multiple sites - theory

Contracting islands

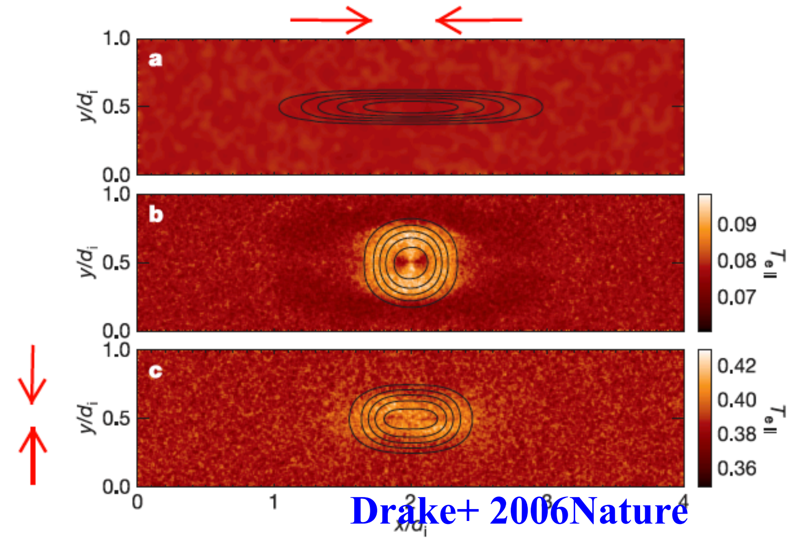


Drake+ 2006Nature





Chen+ 2008, Nature Phys.

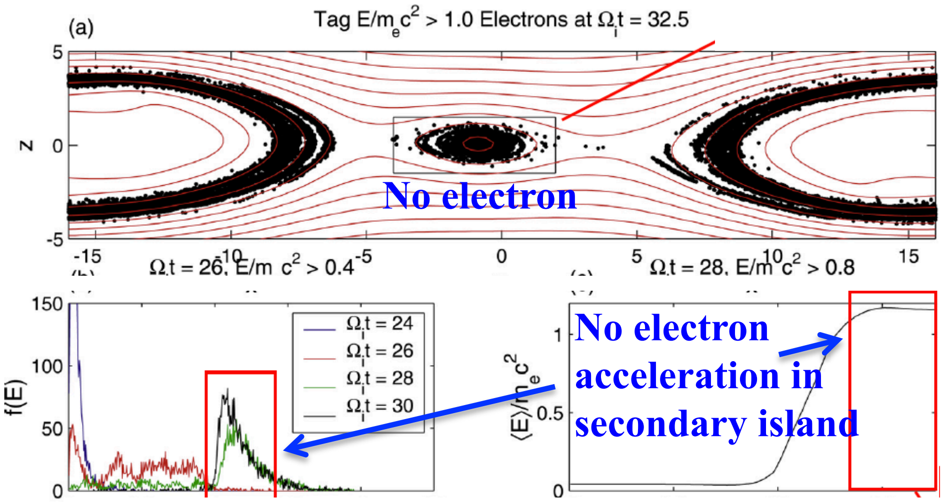


Drake+ 2006Nature

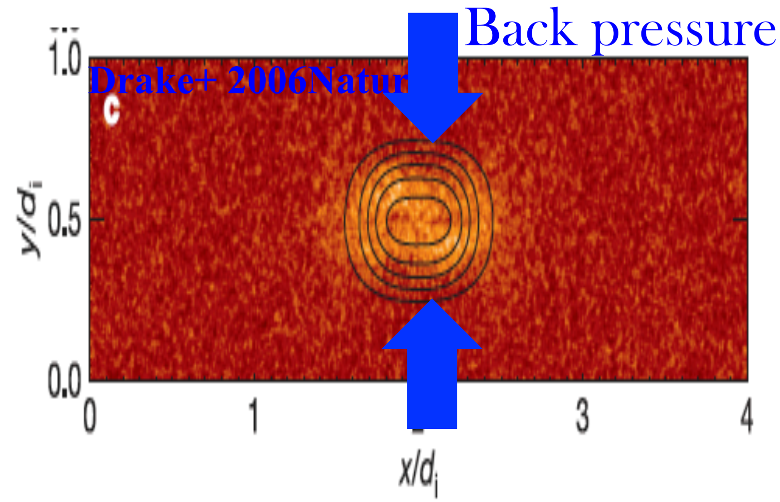
- Magnetic island is contracting, leading to shrink of magnetic field line, and then first-order Fermi acceleration
- Multiple-island assumption
- Observation evidence: energetic electrons associated with islands

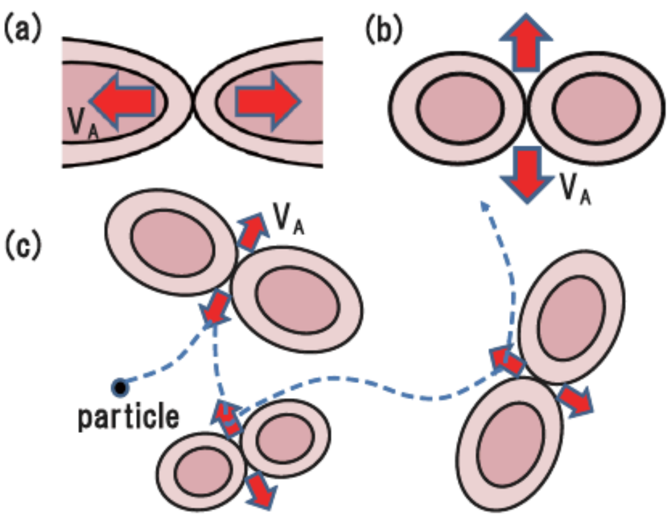
Acceleration at multiple sites – debatable

Contradictory simulation?

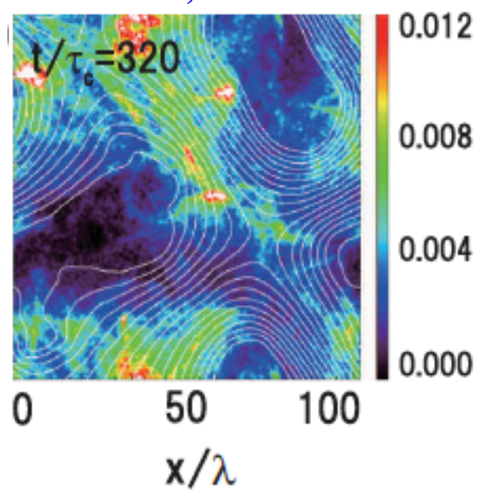


Pritchett, 2006JGR





Hoshino+, 2012PRL



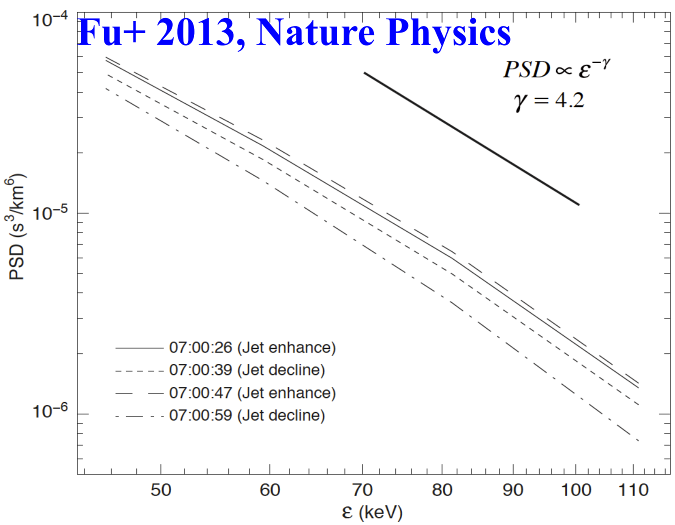
- No acceleration inside island
- electron acceleration outside island (second-order Fermi)
- Island contraction is limited by back pressure, so electron acceleration is not so efficient

Acceleration by unsteady reconnection

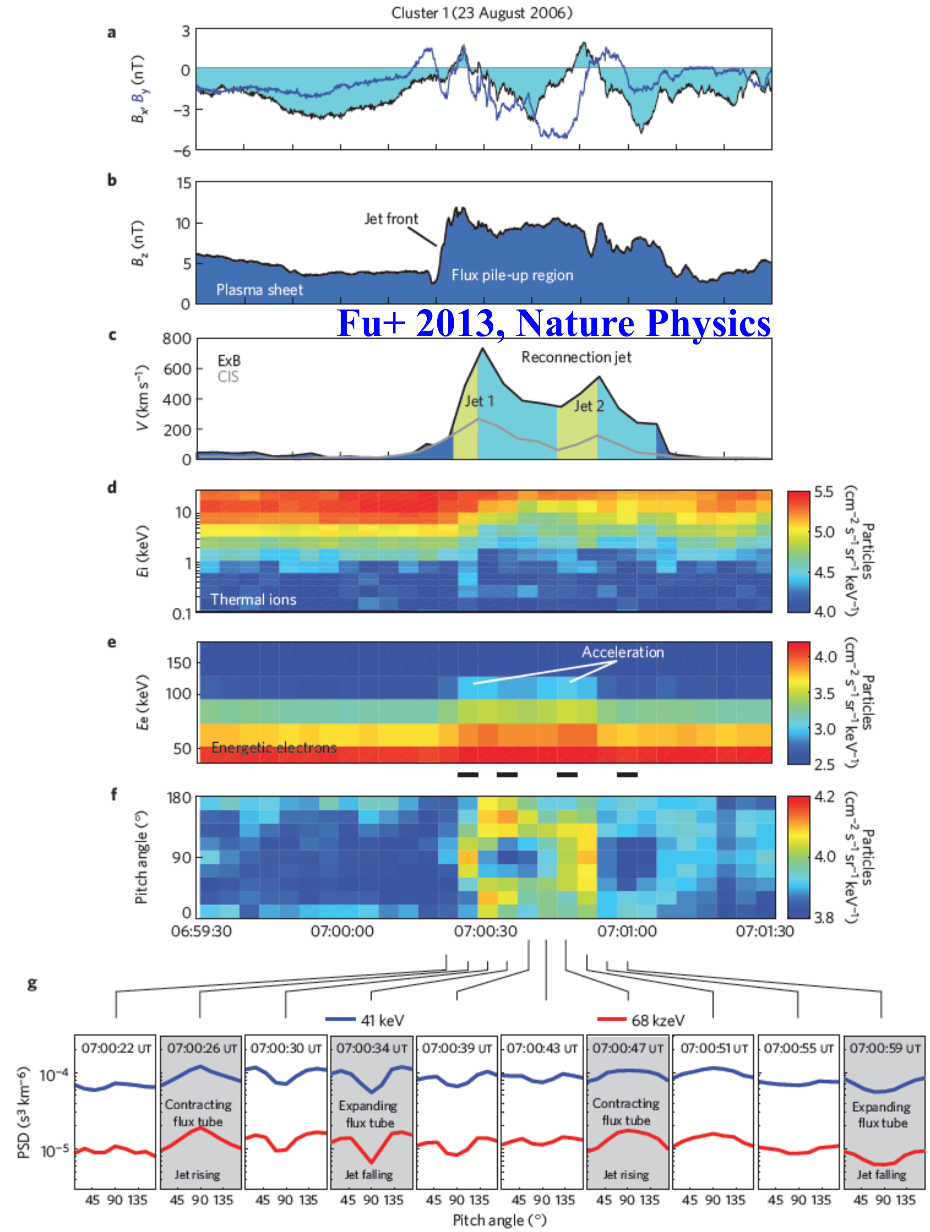
Observation:

- Dipolarization front
- Two reconnection jets
- Unsteady reconnection
- Growing & decaying phase
- Betatron & Fermi acceleration
- Adiabatic process

Fu+ 2013, Nature Physics



Fu+ 2013, Nature Physics



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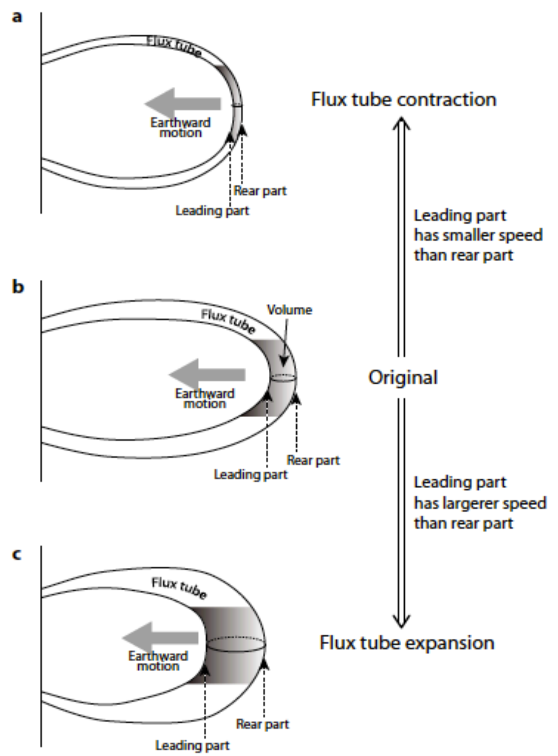
Acceleration by unsteady reconnection

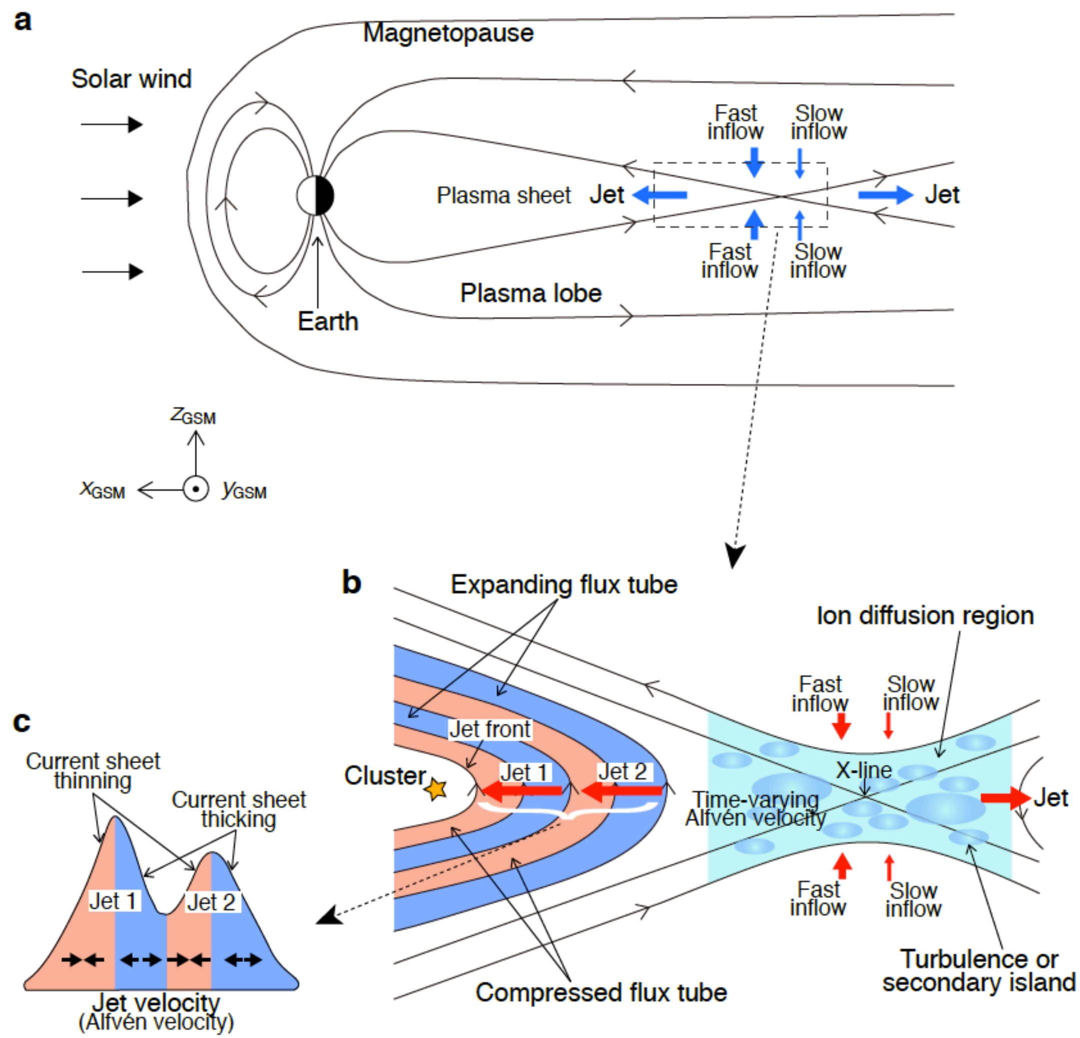
Interpretation:

Fu+ 2013, Nature Physics

Acceleration mechanisms:

- Betatron acceleration
- Global Fermi acceleration



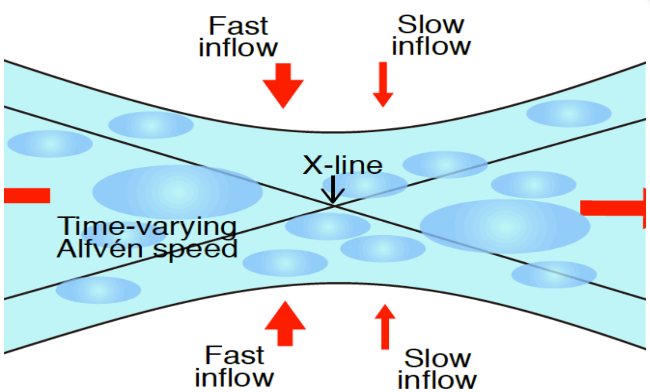


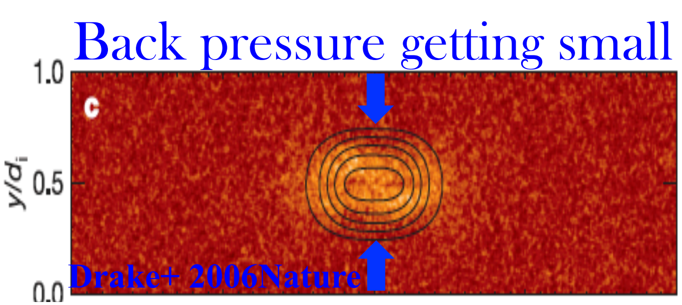
- Growing phase:
  strong inflow => current sheet thinning => increasing Alfven velocity => betatron acceleration

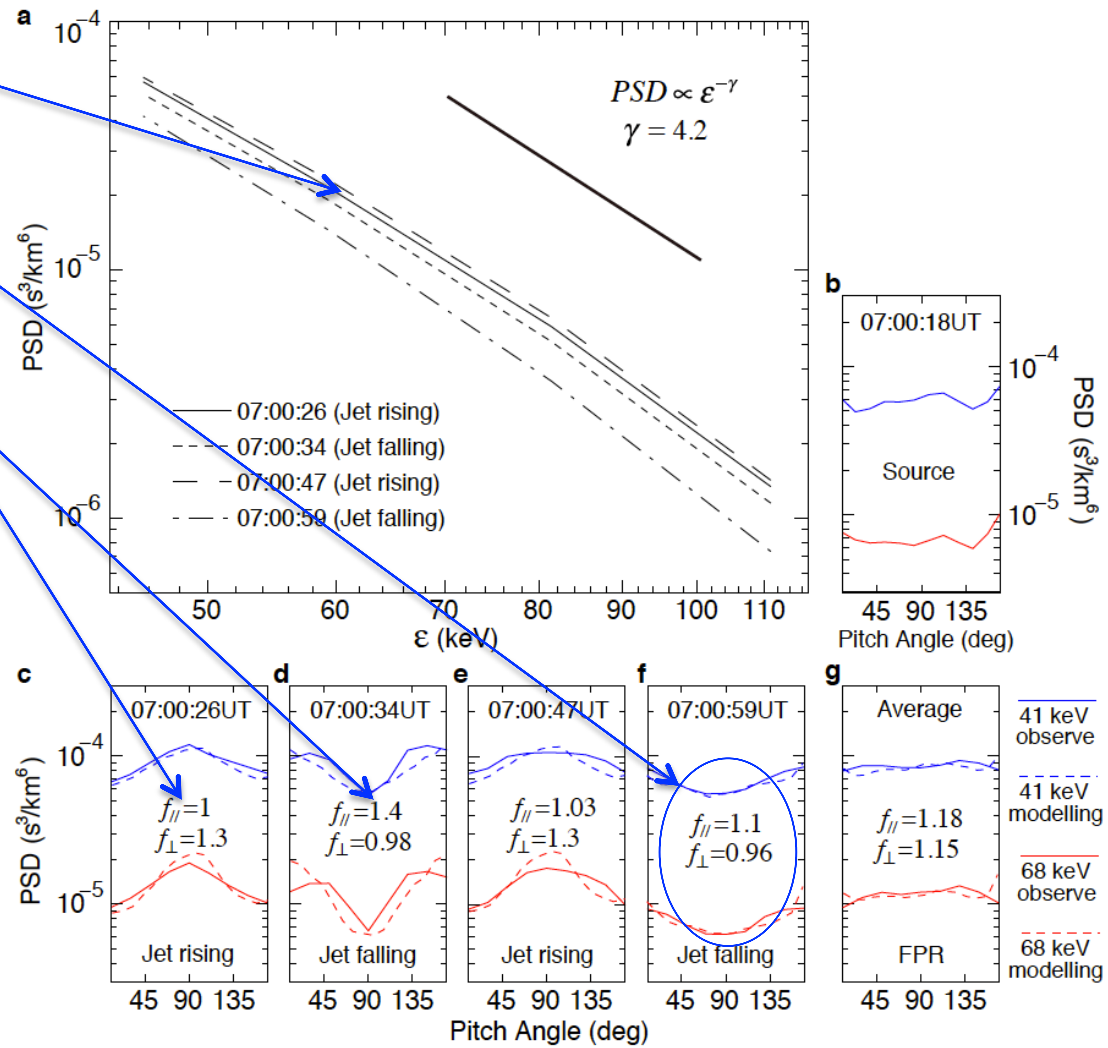
Acceleration by unsteady reconnection

Modelling:

- Betatron acceleration is very efficient
- Fermi acceleration is partial balanced by betatron cooling
- Fermi acceleration not uniform, suggest local Fermi process.



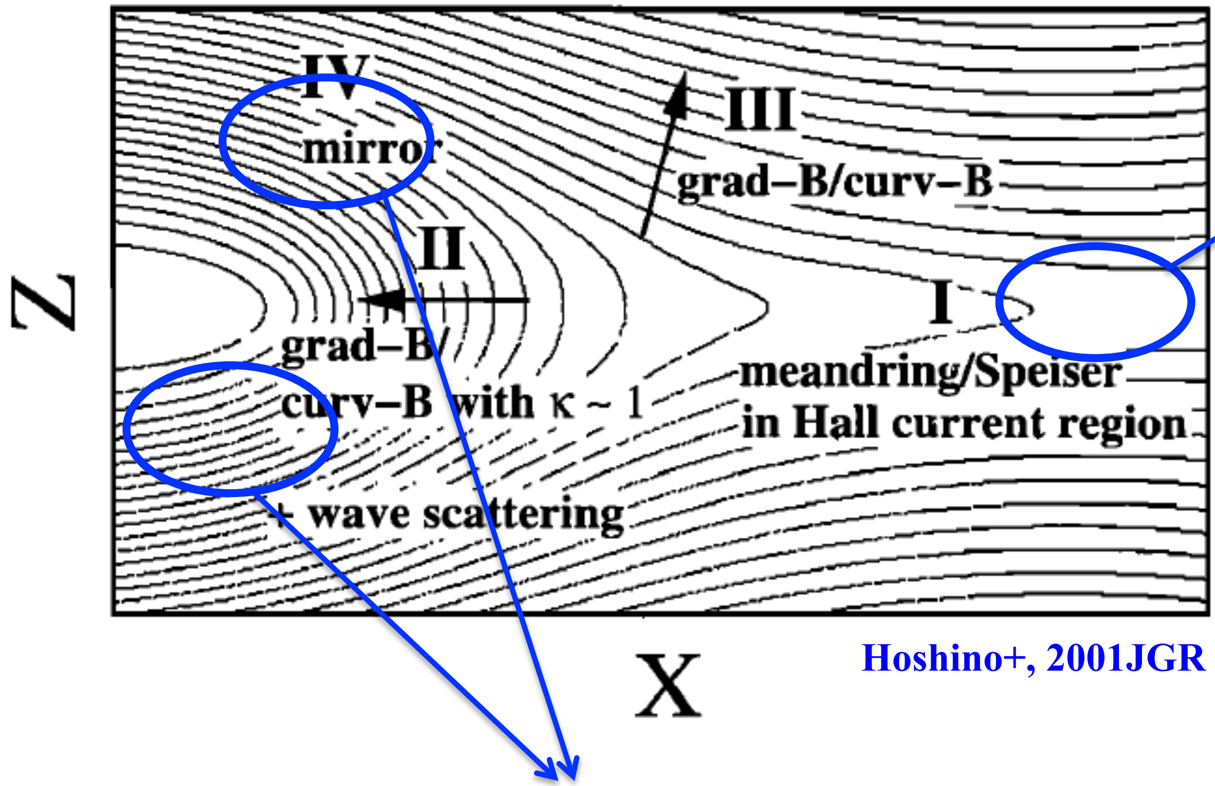




Fu+ 2013, Nature Physics

Compare to previous studies

Two different point:

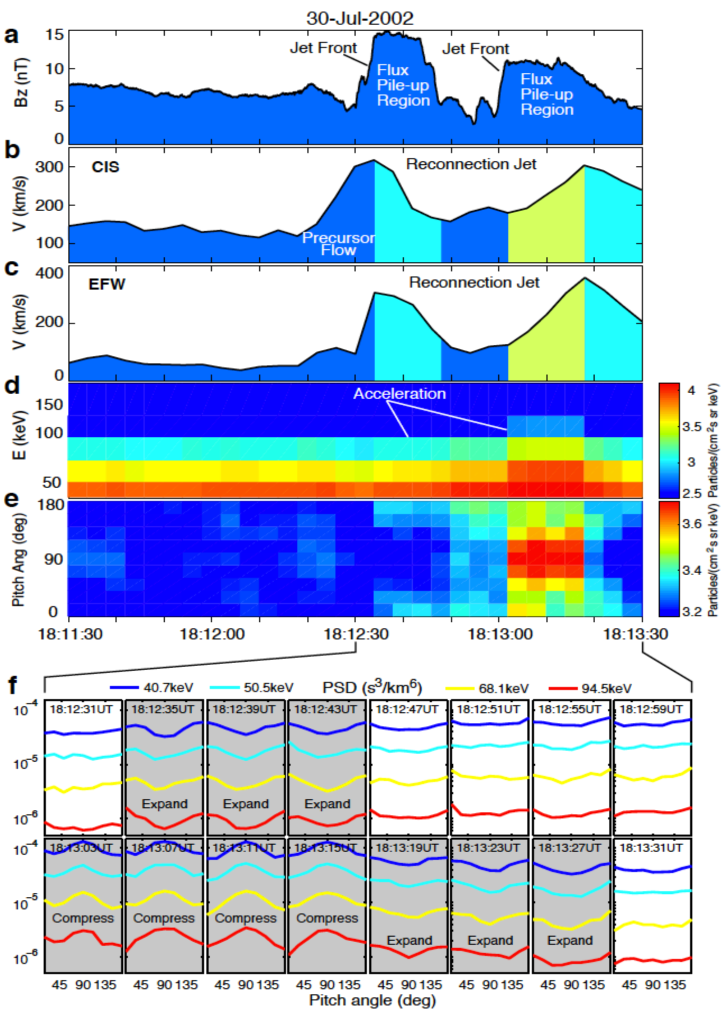


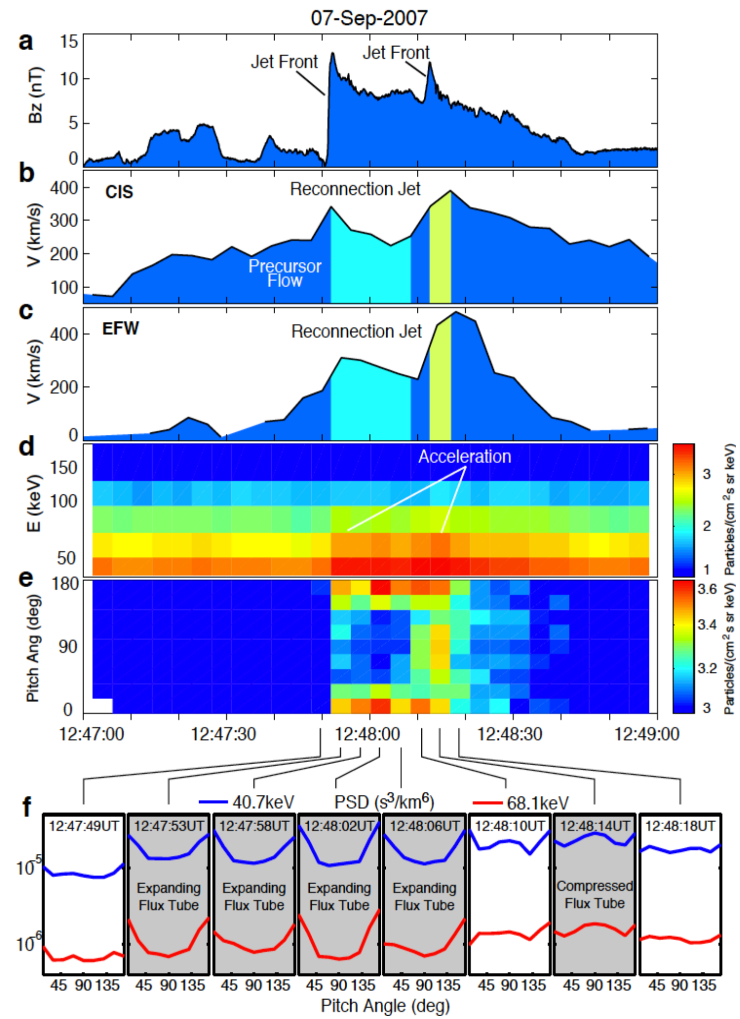
Hoshino+, 2001JGR

- Local Fermi acceleration may be limited by the back pressure, because the magnetic reconnection is steady.

- Mirror point is more clear in our case, because there is dipolarization front. As a result, accelerated electrons are easily trapped and detected by the spacecraft

Another two similar events





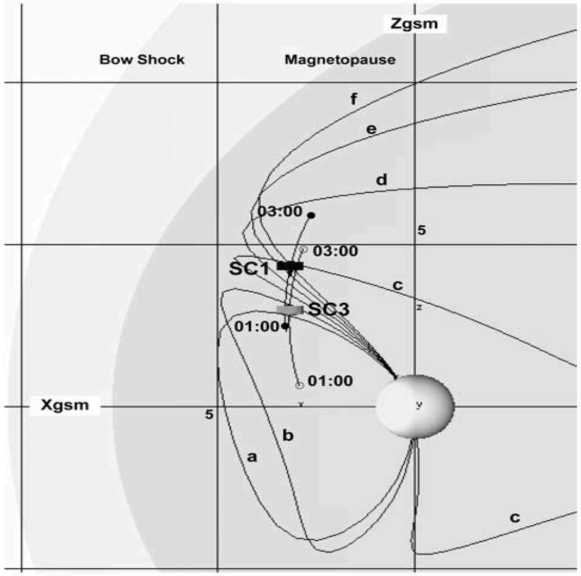
- Growing phase:

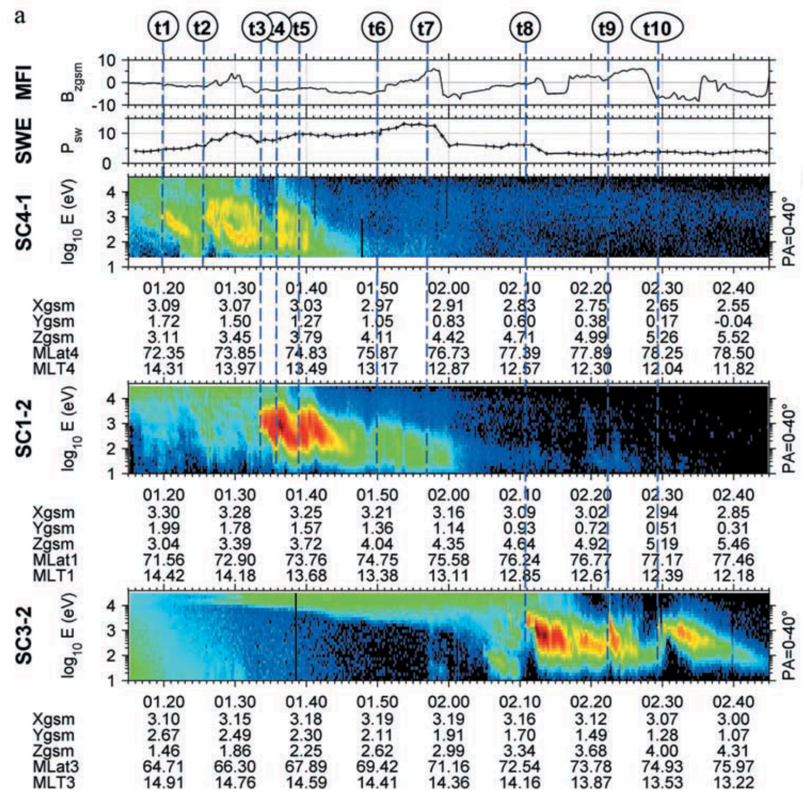
  strong inflow => current sheet thinning => increasing Alfven velocity => betatron acceleration

- Decaying phase:

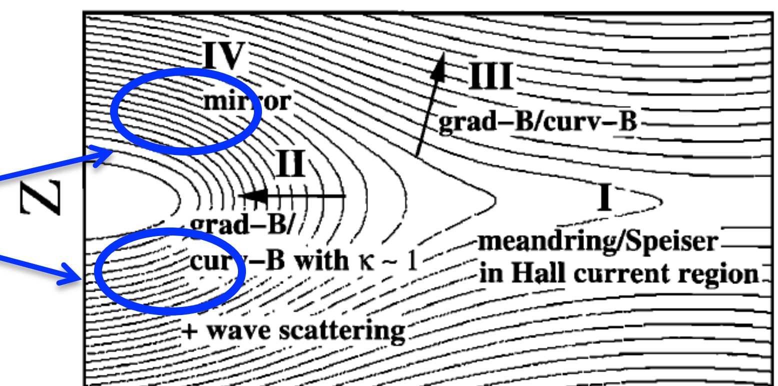
  weak inflow => CS thicking => decreasing Alfven velocity => weak back pressure => Fermi acceleration

Why no acceleration at magnetopause?





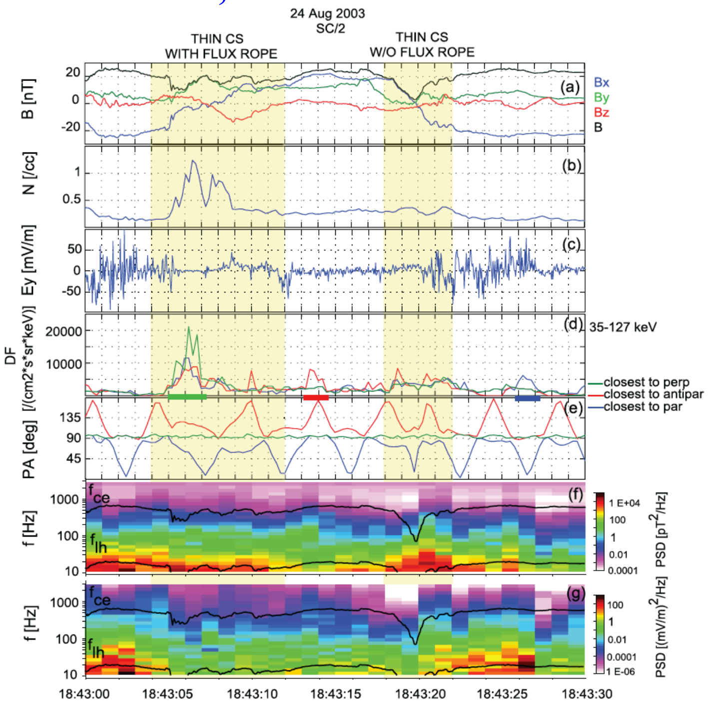
- Usually, reconnection at magnetopause is unsteady.
- Example: multiple, impulsive downward ion injections
- Signature of unsteady magnetic reconnection at magnetopause
- Did not capture DF => Did not capture mirror point => Did not capture energetic electrons

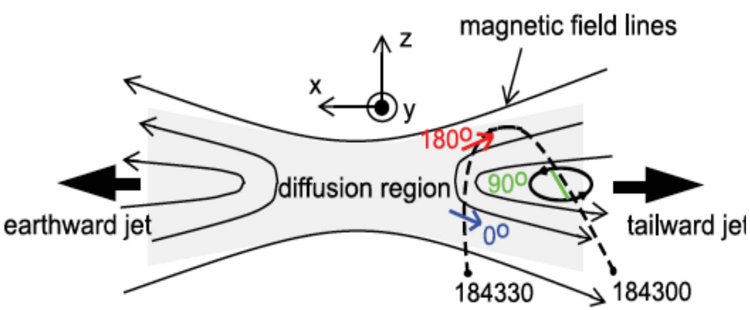


Energetic electrons must be trapped by mirror points

Other acceleration mechanism: nonadiabatic

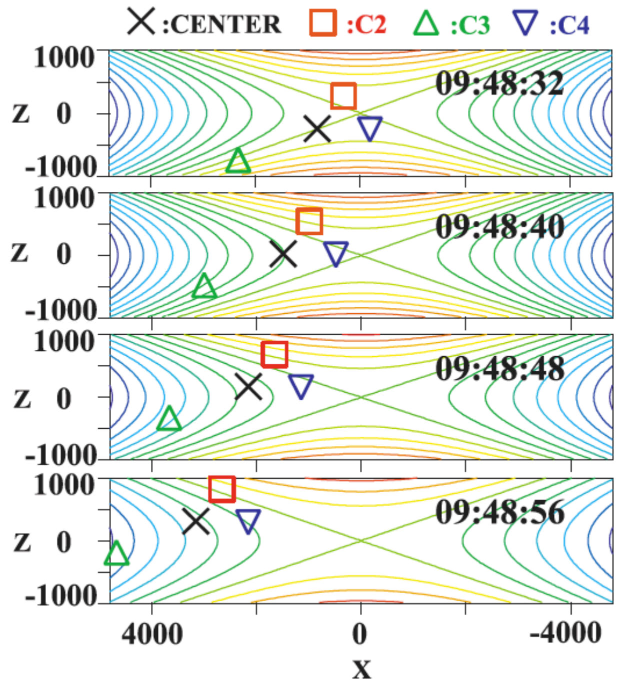
Retino+, 2008JGR

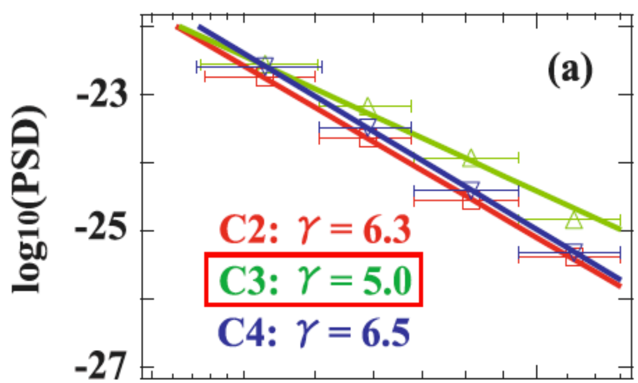




nonadiabatic acceleration inside island

Imada+, 2007JGR



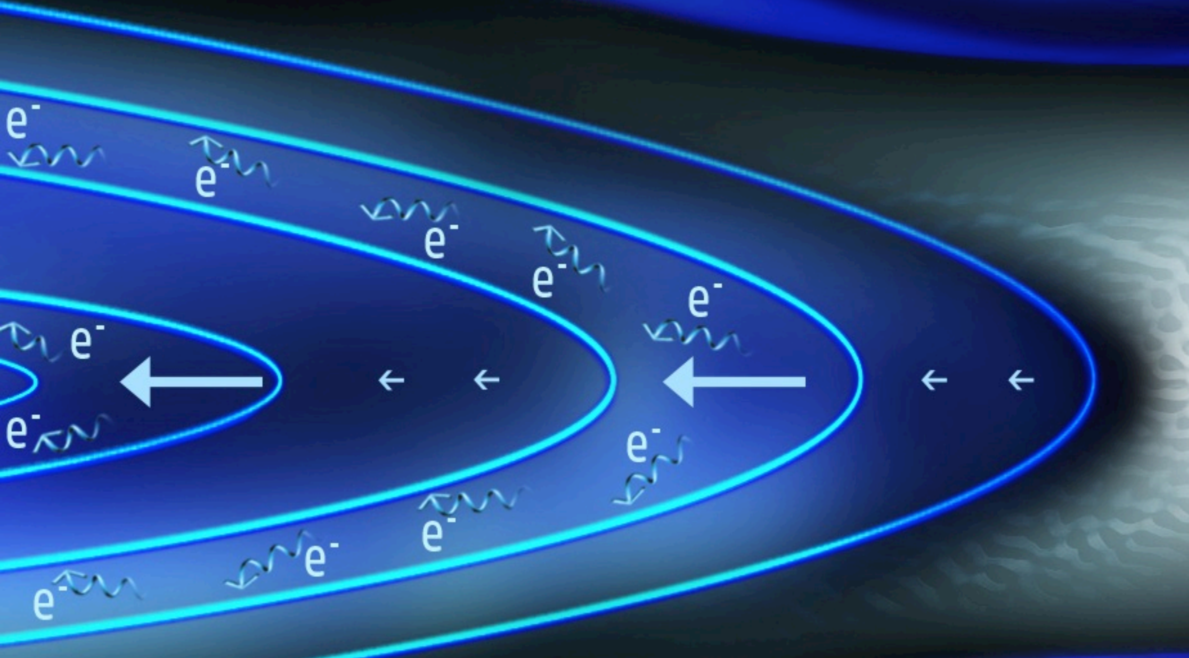


nonadiabatic acceleration in outflow region

- In our case, power-law index does not change => adiabatic acceleration
- In other cases, nonadiabatic acceleration could be involved.

Conclusion

1. In situ evidence: unsteady reconnection => DF



Credit: ESA

2. Unsteady reconnection can significantly accelerate electrons

3. Betatron acceleration effective, Fermi acceleration may be partially balanced by the betatron cooling