20mins

PIC simulation services at the CCMC in support of MMS mission and GEM Magnetic Reconnection Focus Group

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Outline:

- Previous successful comparisons between Particle-in-Cell (PIC) simulations & in-situ observations

- The era of MMS
  -- why needs PIC Now?

- Currently Planned Services
  -- Help find the electron diffusion region
  -- Help optimize the LMN coordinate

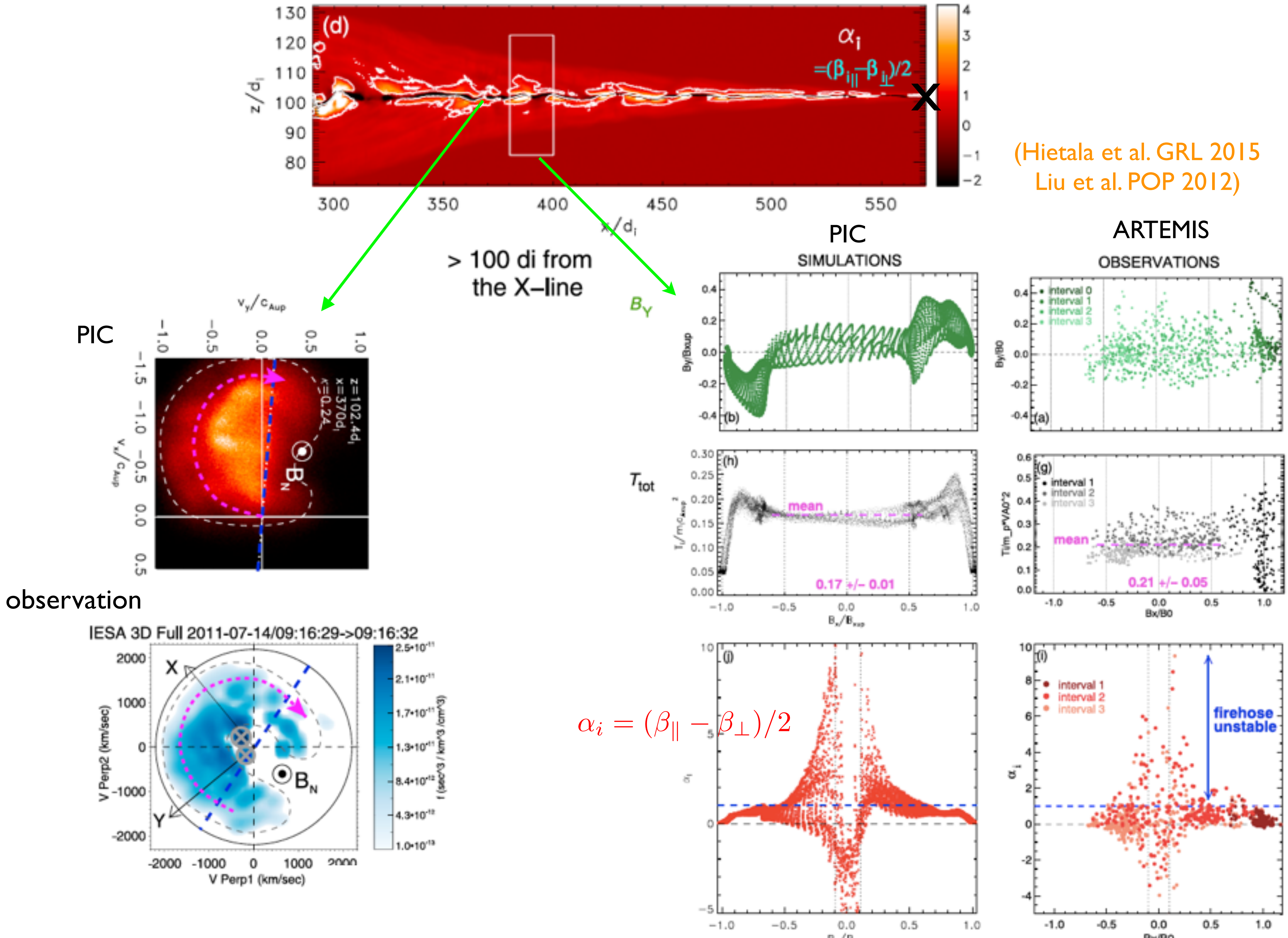
- Potential Science Project

- Summary

Comparisons between in-situ observations & PIC

-- kinetic-scale

Example 1: Ions temperature anisotropy

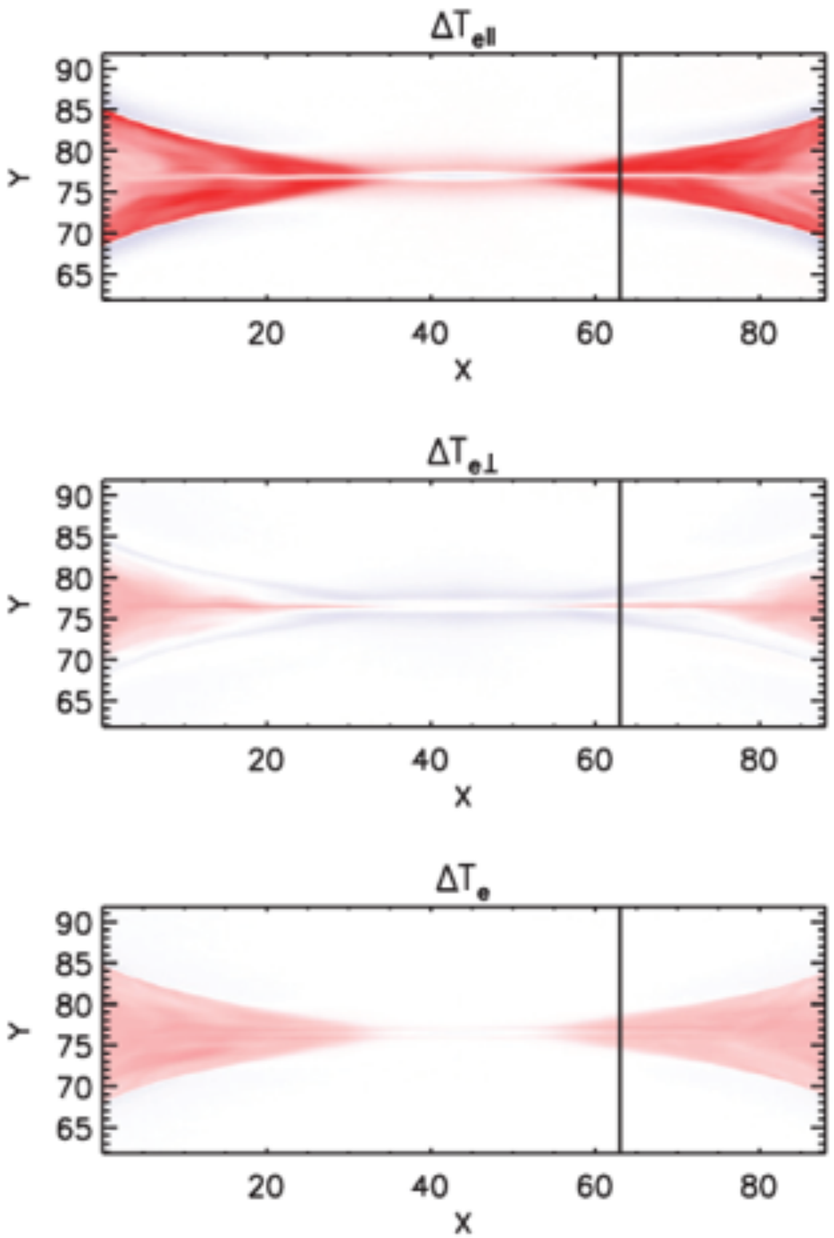


(Hietala et al. GRL 2015
Liu et al. POP 2012)

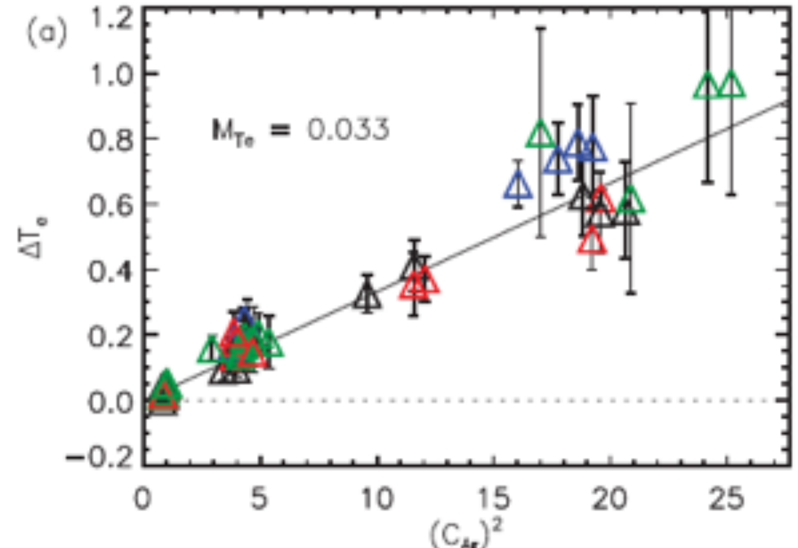
- A self-consistent moment closure.

(Hietala et al. GRL 2015)

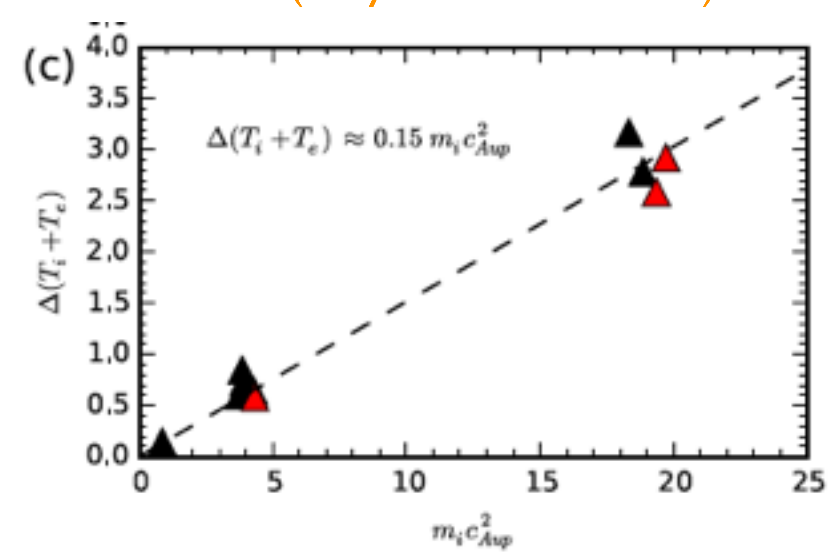
Example 2: Energy conversion



PIC



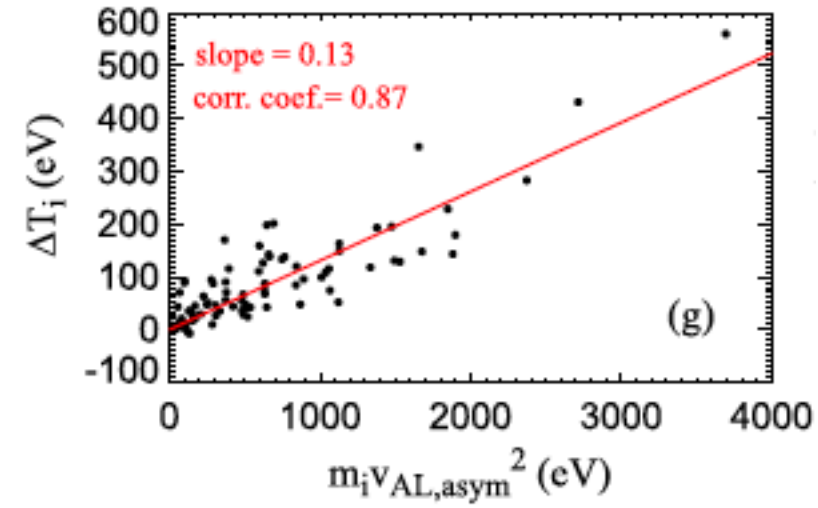
(Shay et al. POP 2014)

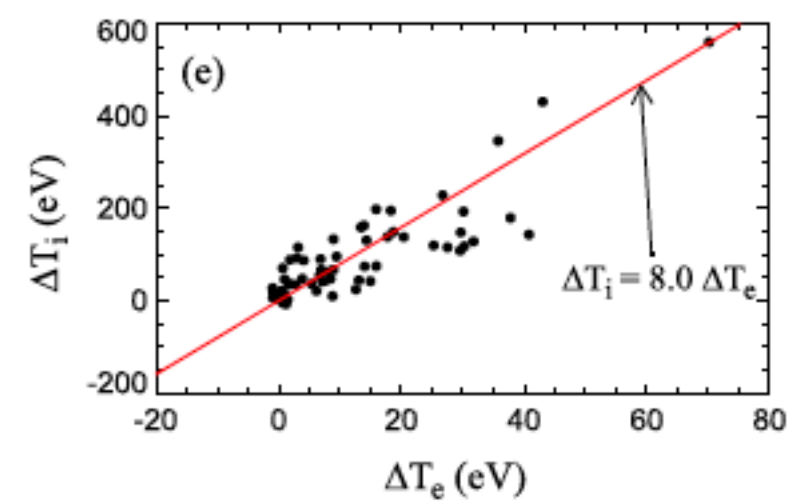


(Haggerty et al. GRL 2015)

THEMIS Observation

(Phan et al. GRL 2014)





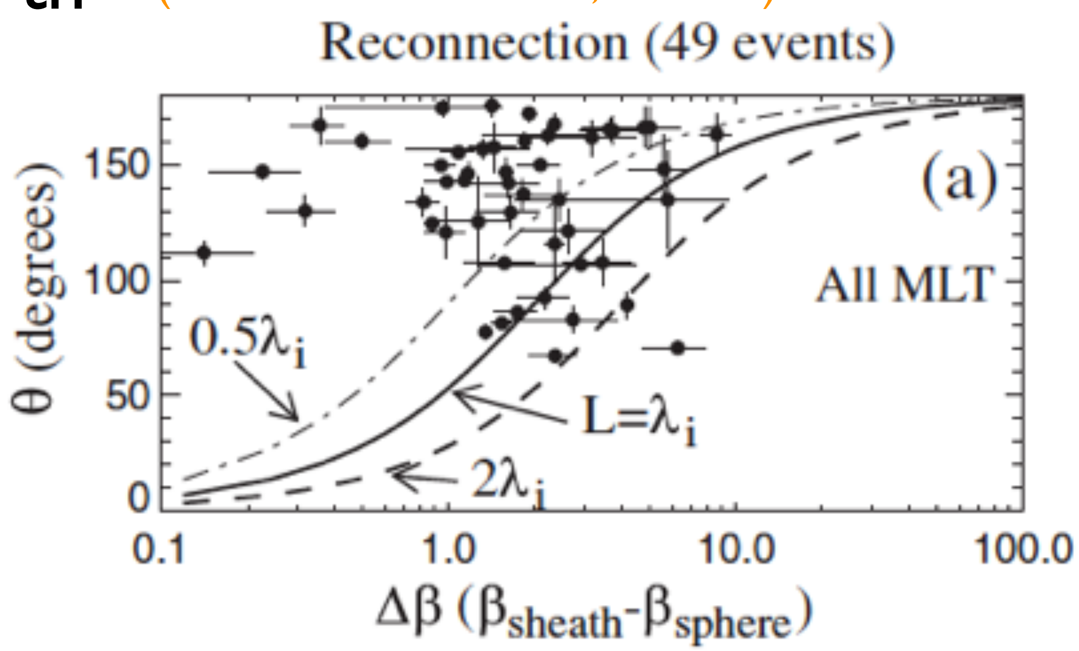
$$\Delta T_i \sim 0.13 m_i C_A^2$$
$$\Delta T_e \sim 0.016 m_i C_A^2$$

- Energy partition between electrons and ions.
- Non-thermal acceleration. (Drake et al. Science 2006; Egedal et al. Nature Physics 2012)

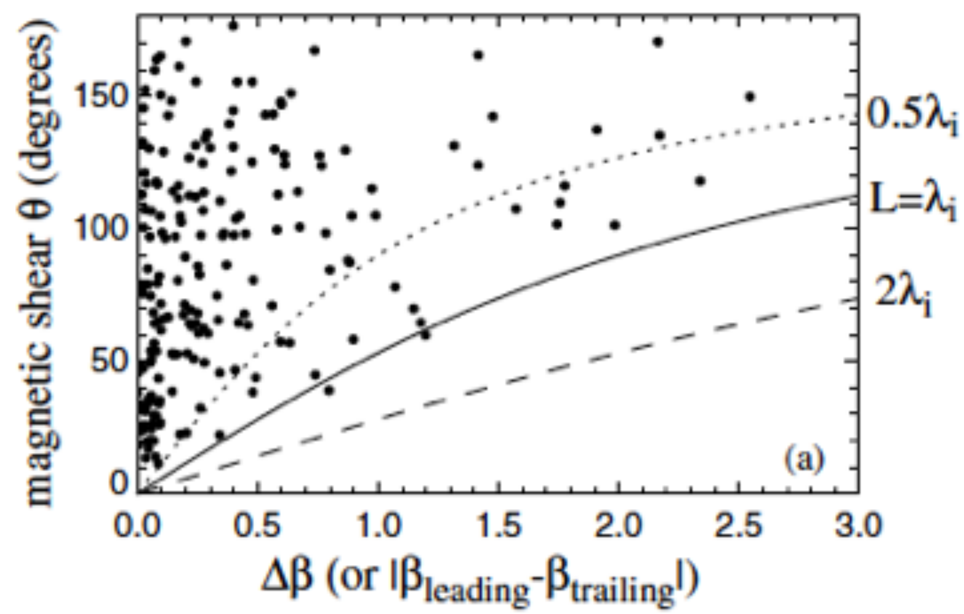
Example 3: Occurrence distribution of MR

MR is suppressed by diamagnetic drifts $\Delta\beta \gg 2(L/\lambda_i)\tan(\theta/2)$ ← From PIC (Swisdak et al. JGR 2003)

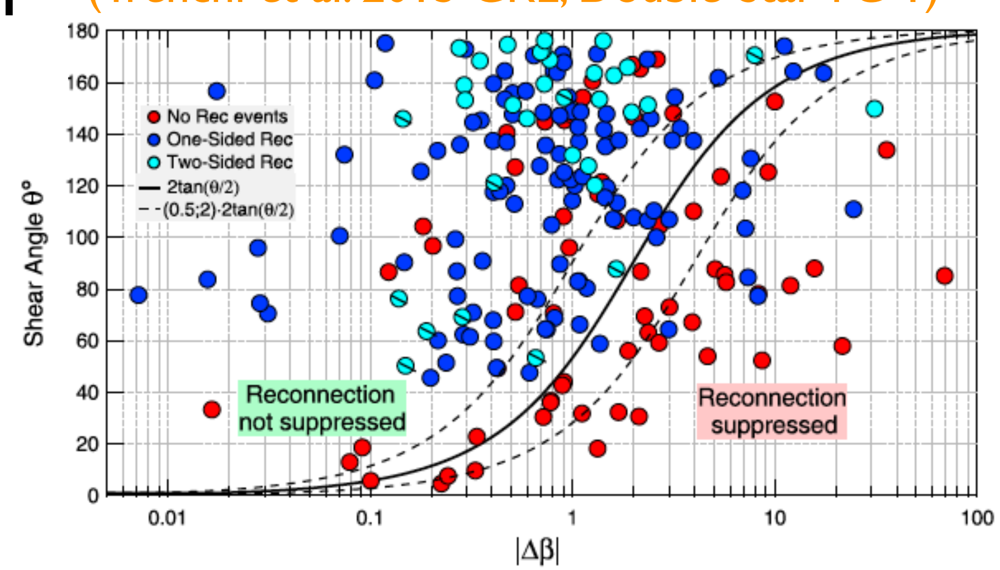
Earth (Phan et al. 2013 GRL, THEMIS)



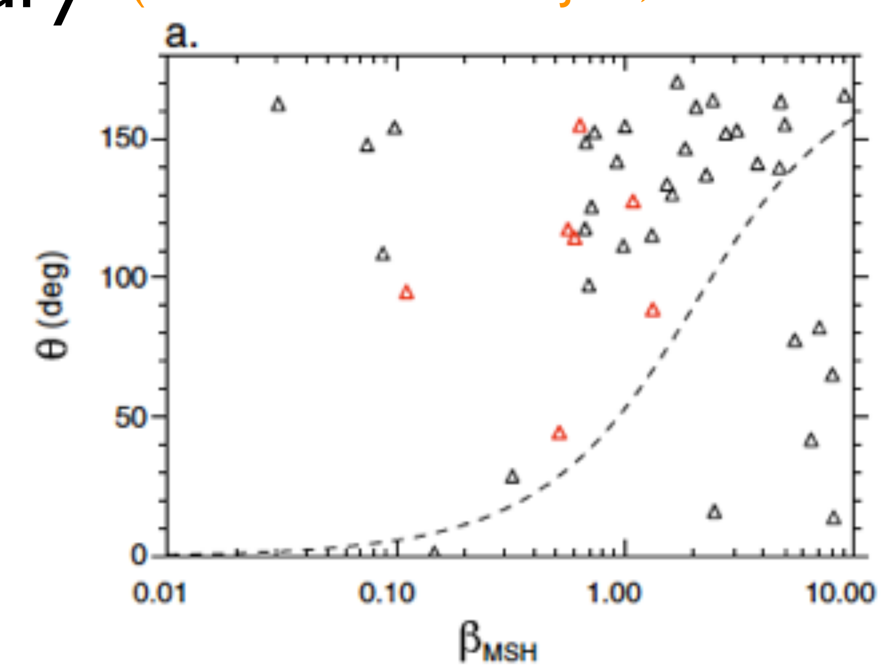
Solar Wind (Phan et al. 2010 APJ, Wind)



Earth (Trenchi et al. 2015 GRL, Double-Star TC-1)



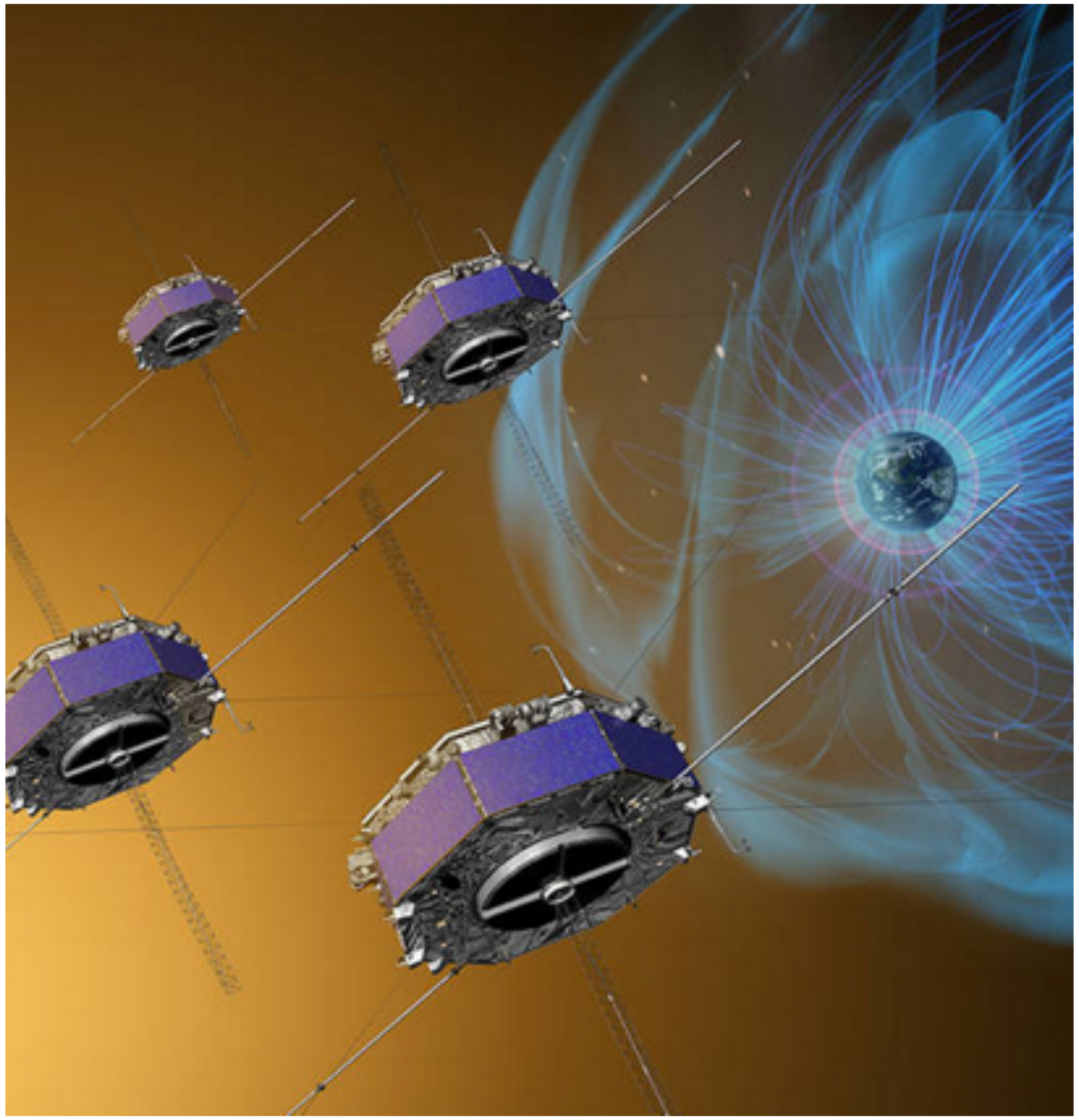
Mercury (DiBraccio et al. 2013 JGR, MESSENGER)



- Kinetic physics that affect the dynamics of reconnection.

The era of MMS

Magnetospheric Multiscale Mission (MMS)



http://mms.gsfc.nasa.gov

100x faster for electrons (30 ms)
30x faster for ions (150 ms)
separation down to 10 km

~ one year ago

- MMS leads us into a stage where the kinetic physics in the electron-scale can be closely compared with PIC in an unprecedented manner!!

For instance,

What breaks the frozen-in condition?

In electron-scale...

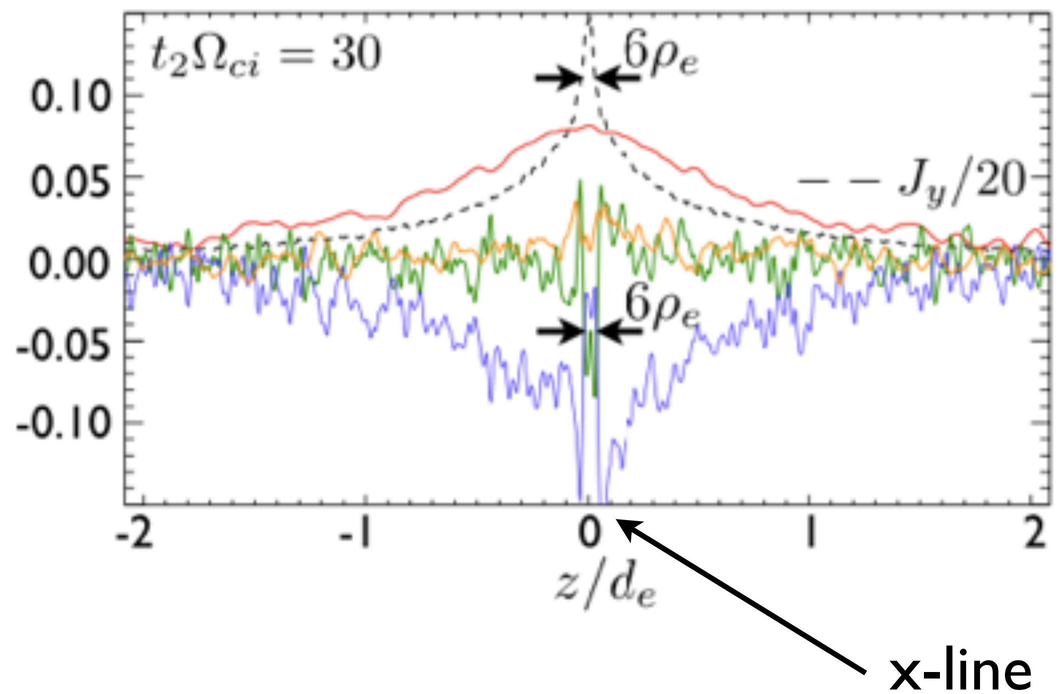
$$en_e(\mathbf{E} + \mathbf{V}_e \times \mathbf{B})_y$$

$$= -m_e n_e \mathbf{V}_e \cdot \nabla \mathbf{U}_{ey}$$

$$-(\nabla \cdot \mathbf{P}_e)_y \quad ✔$$

$$-m_e n_e \partial_t \mathbf{U}_{ey}$$

PIC simulation



(Hesse et al. 2004; Horiuchi et al. 2002; Ricci et al. 2002; Liu et al. 2014)

- The close deployment of the 4 MMS spacecrafts will allow human kind to measure this, for the first time, in nature!!
  --p.s. No laboratory plasma experiment can measure this, so far, and in the short future.

Service I:

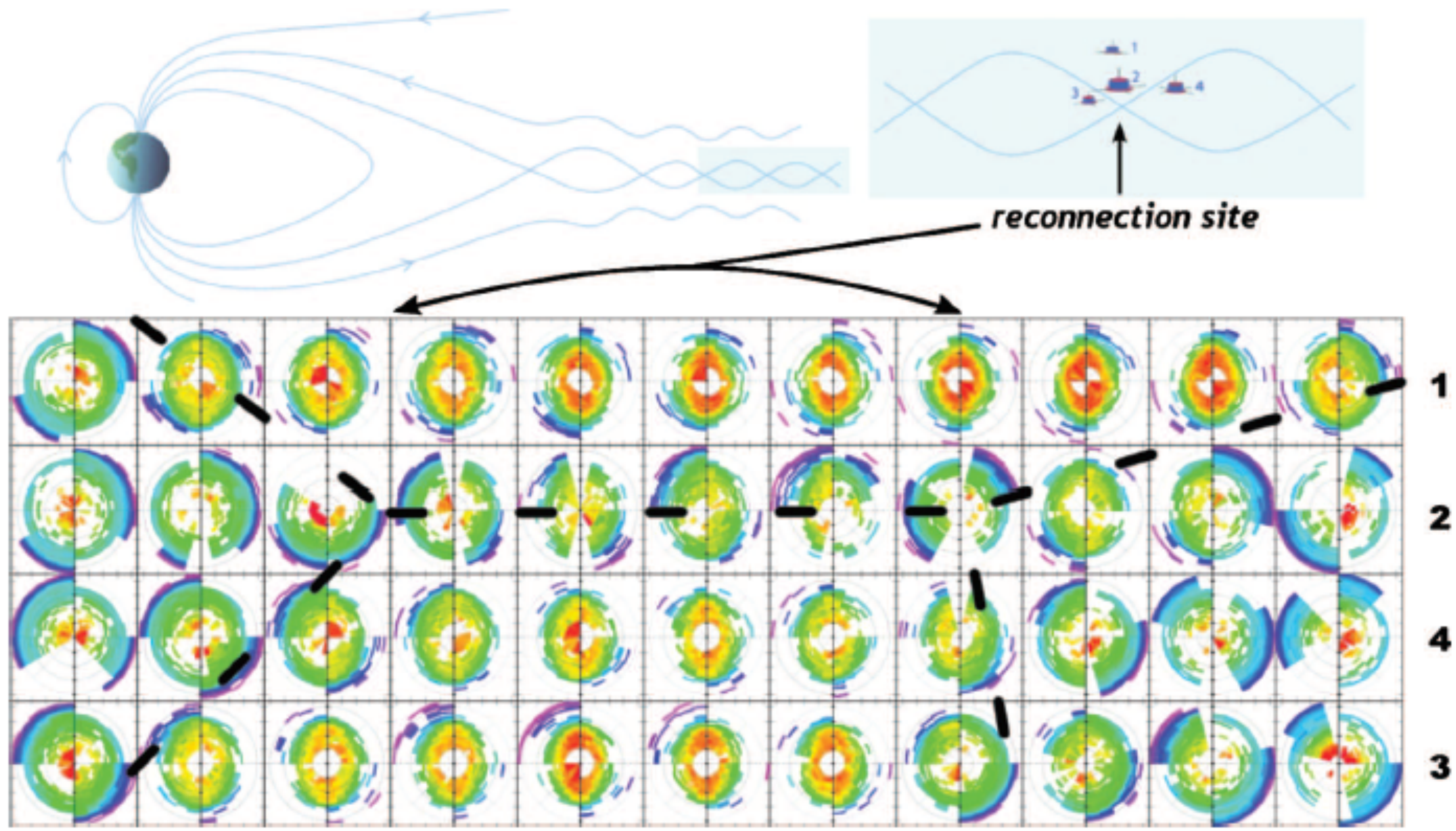
Find the electron diffusion region!

-- using particle distributions

Signature of diffusion region crossing:

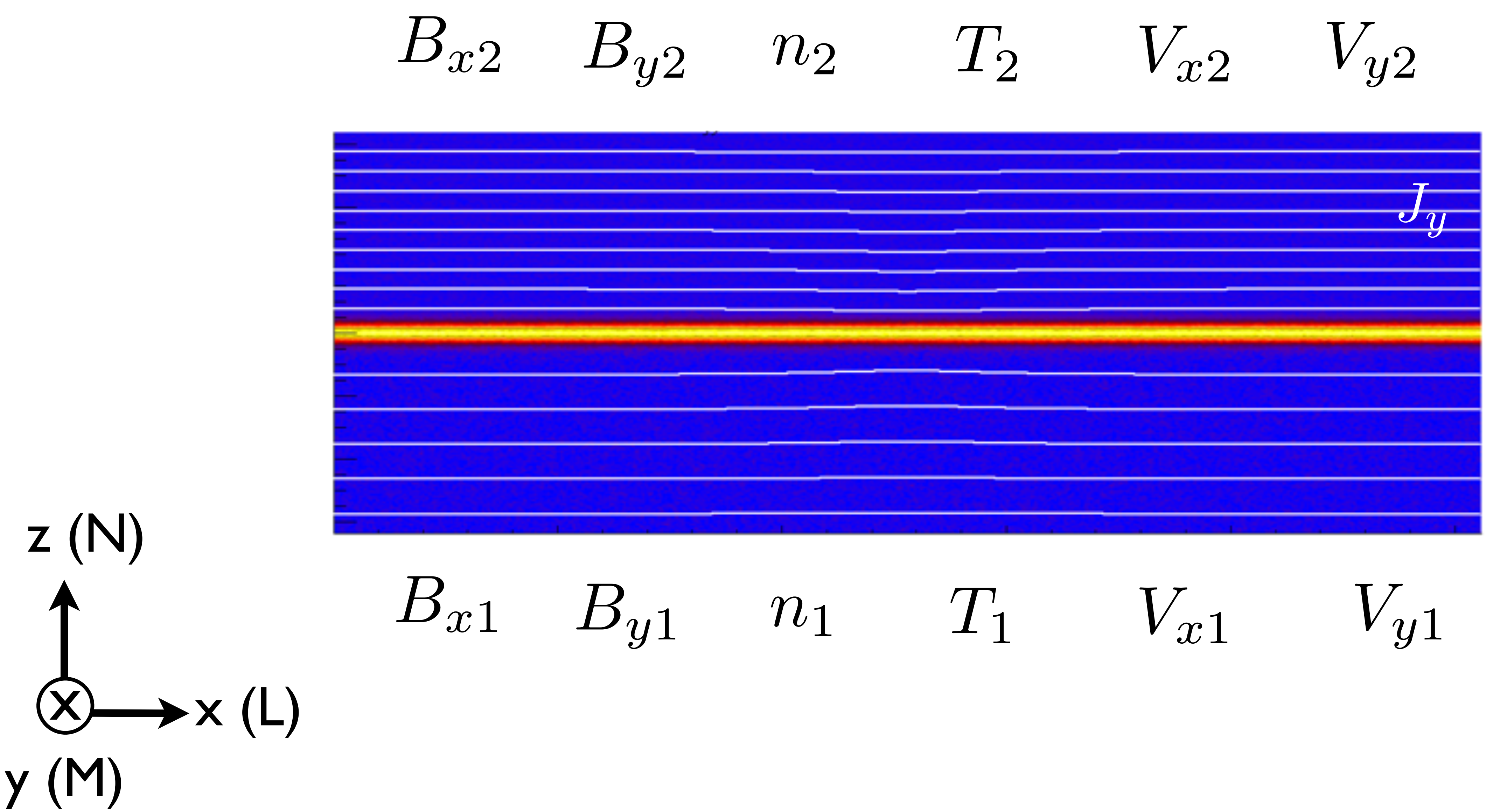
- Jet reversal
  + Walén test.
- B_n sign change
- finite $E + V_e \times B$
  (Doable now with MMS!!!)
- finite J.E'
  (Zenatani et al. PRL 2011)
- Non-gyrotropy
  (Swisdak GRL 2015;
  Auni et al. POP 2013;
  Scudder et al. JGR 2008)
- ...

(Li-Jen Chen et al. 2009 using CLUSTER)



Observations

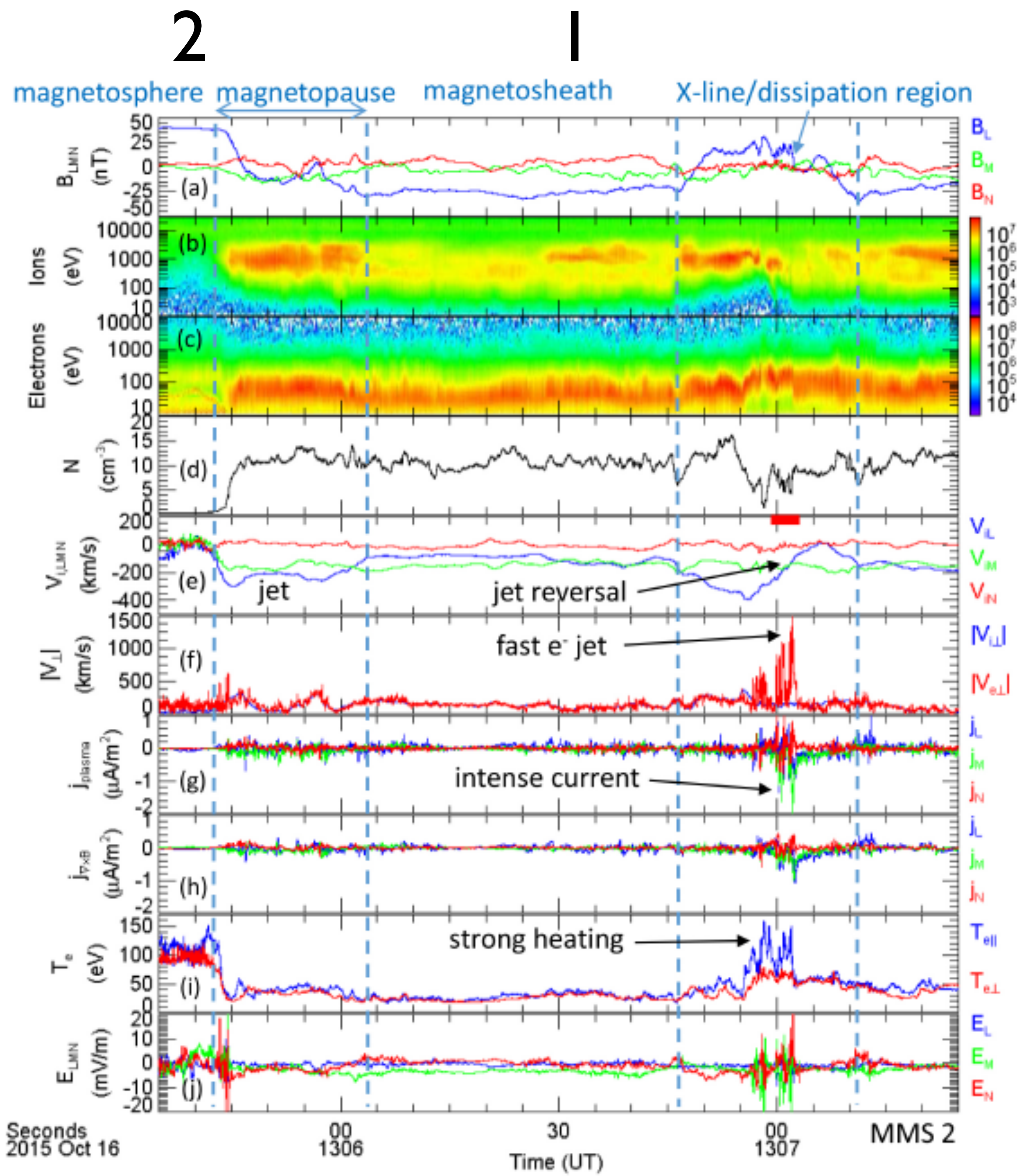
We have generalized the initial condition



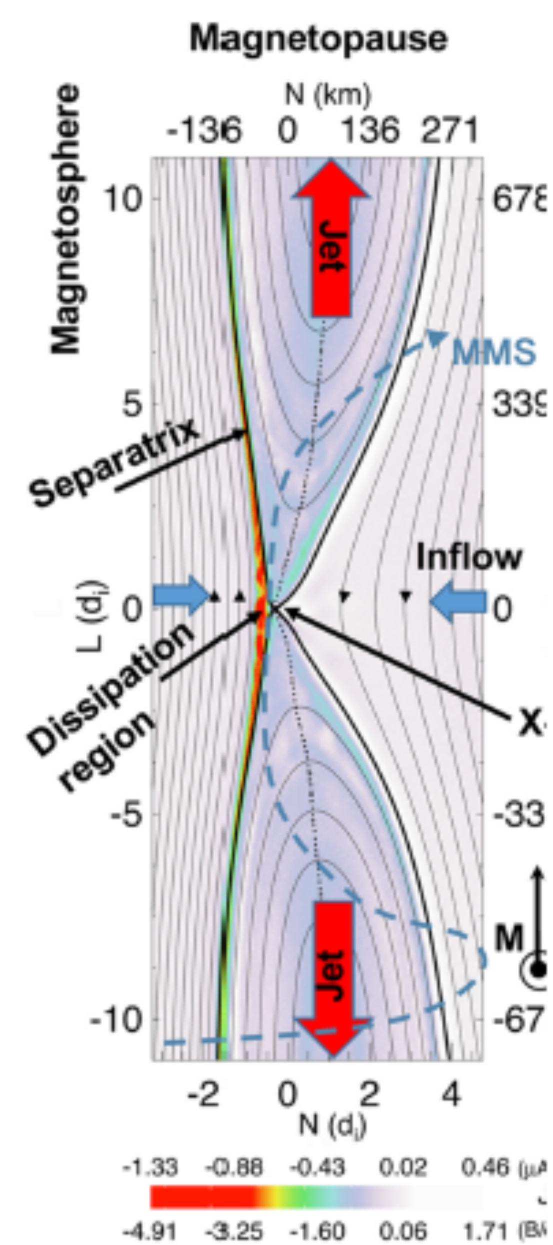
- It turns out that 2D approximation seems to be reasonably good!
  -- as shown in the comparison between MMS data & 2D PIC

(Burch et al. SCIENCE 2016)

Step1: Give us the upstream condition

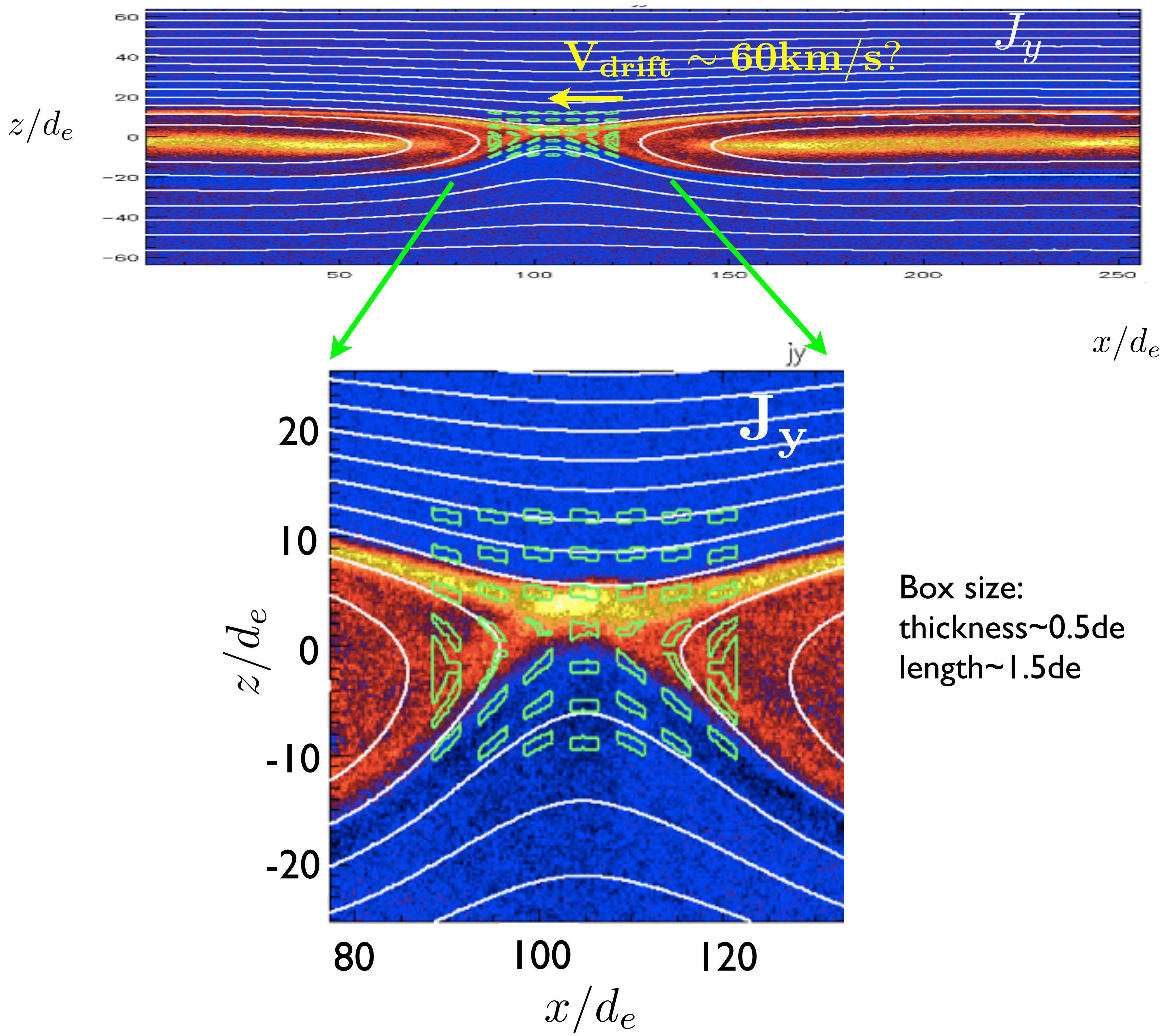


PIC simulation



(Burch et al. SCIENCE 2016)

Step 2: We can generate a map of distributions

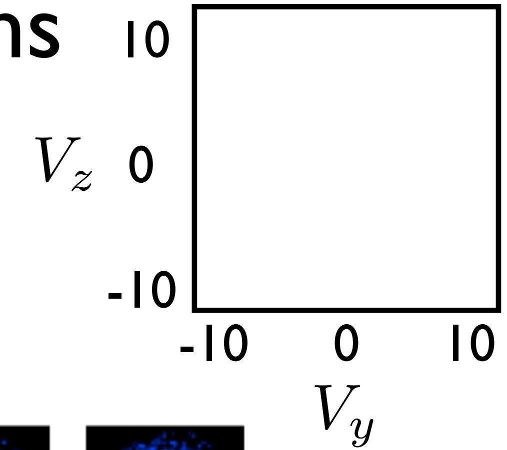


Box size:
thickness~0.5de
length~1.5de

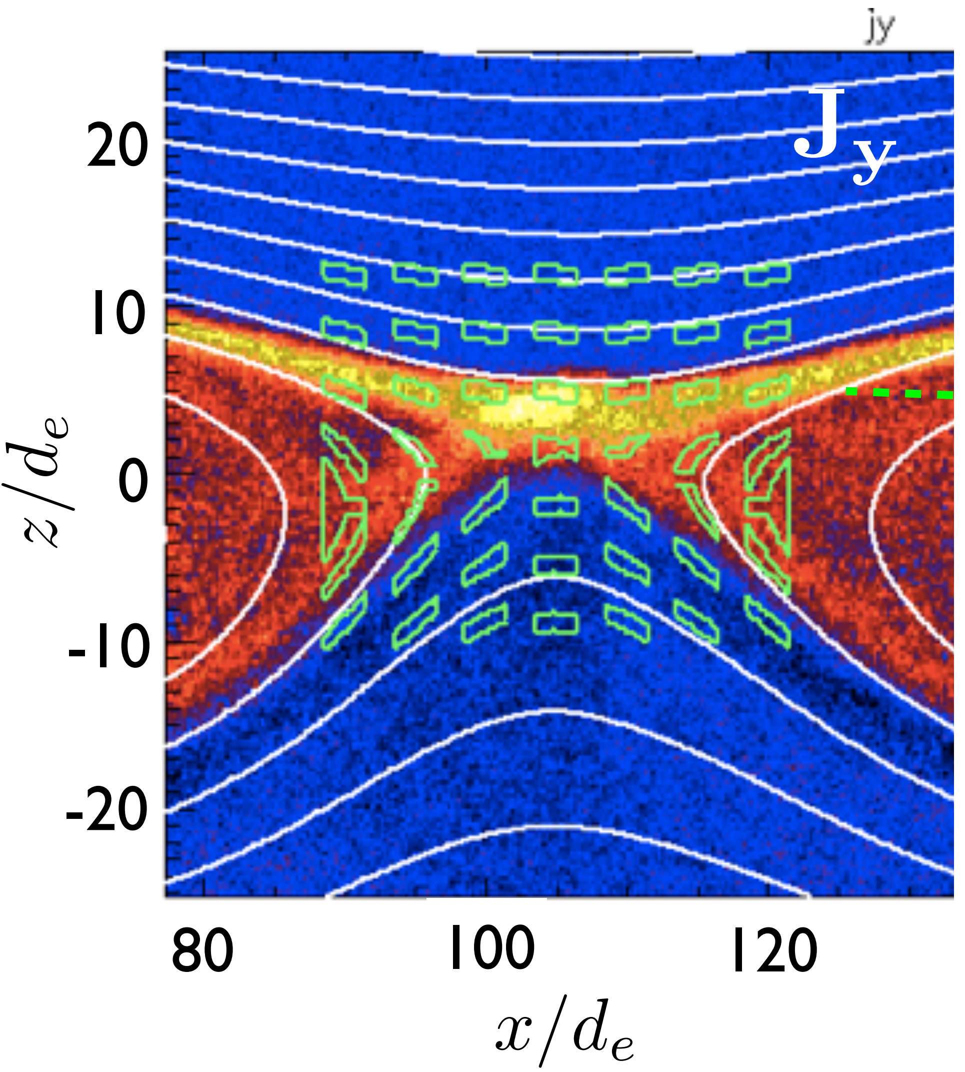
- We can also predict the drift speed of the x-line under shear flows & diamagnetic drifts!

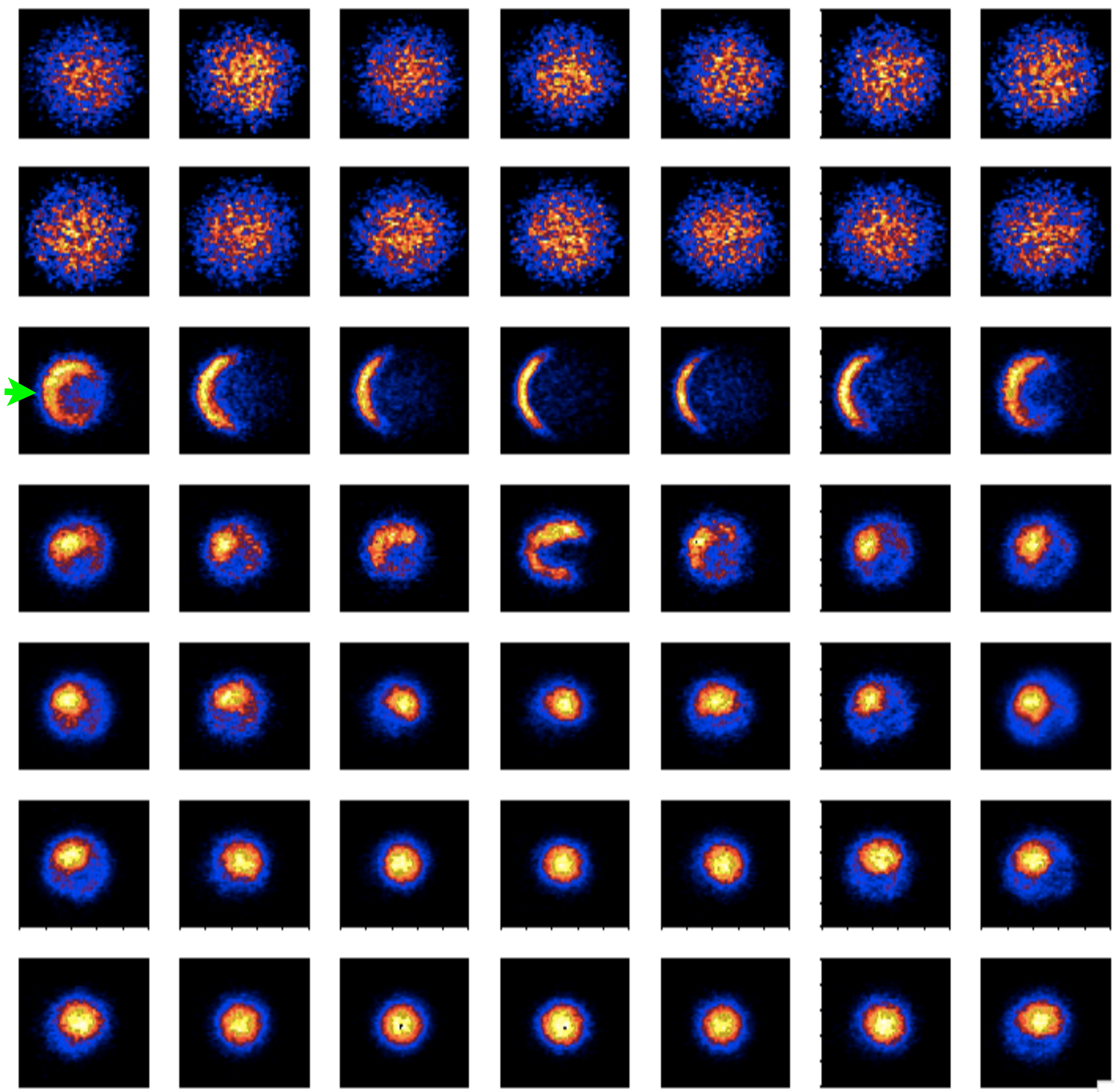
Step 2: We can generate a map of distributions

(e.g., Shuster et al. 2015)



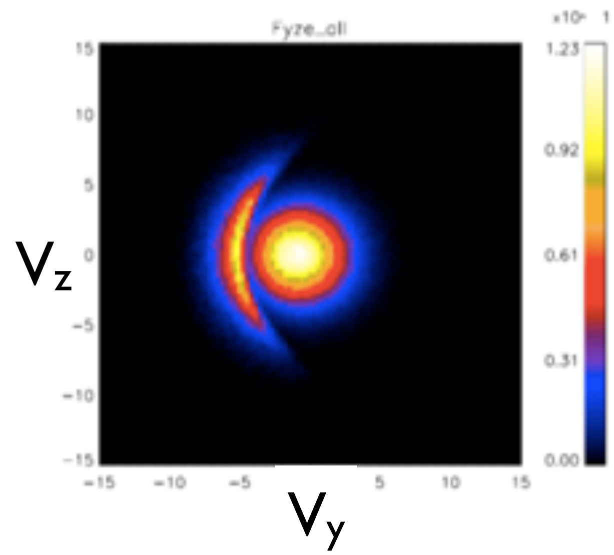
PIC simulation



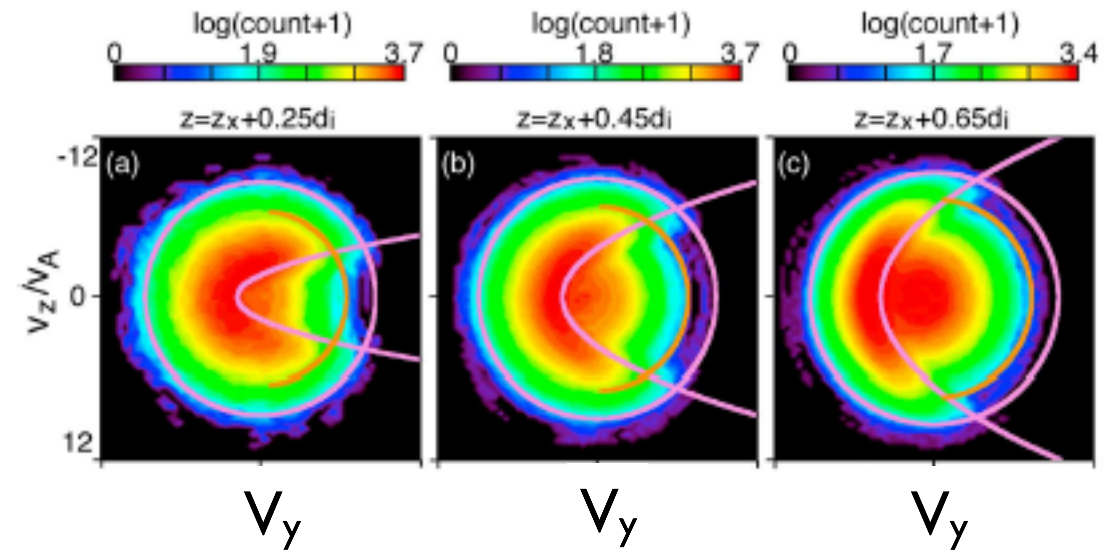


One of the popular distributions: Crescent

Reduced

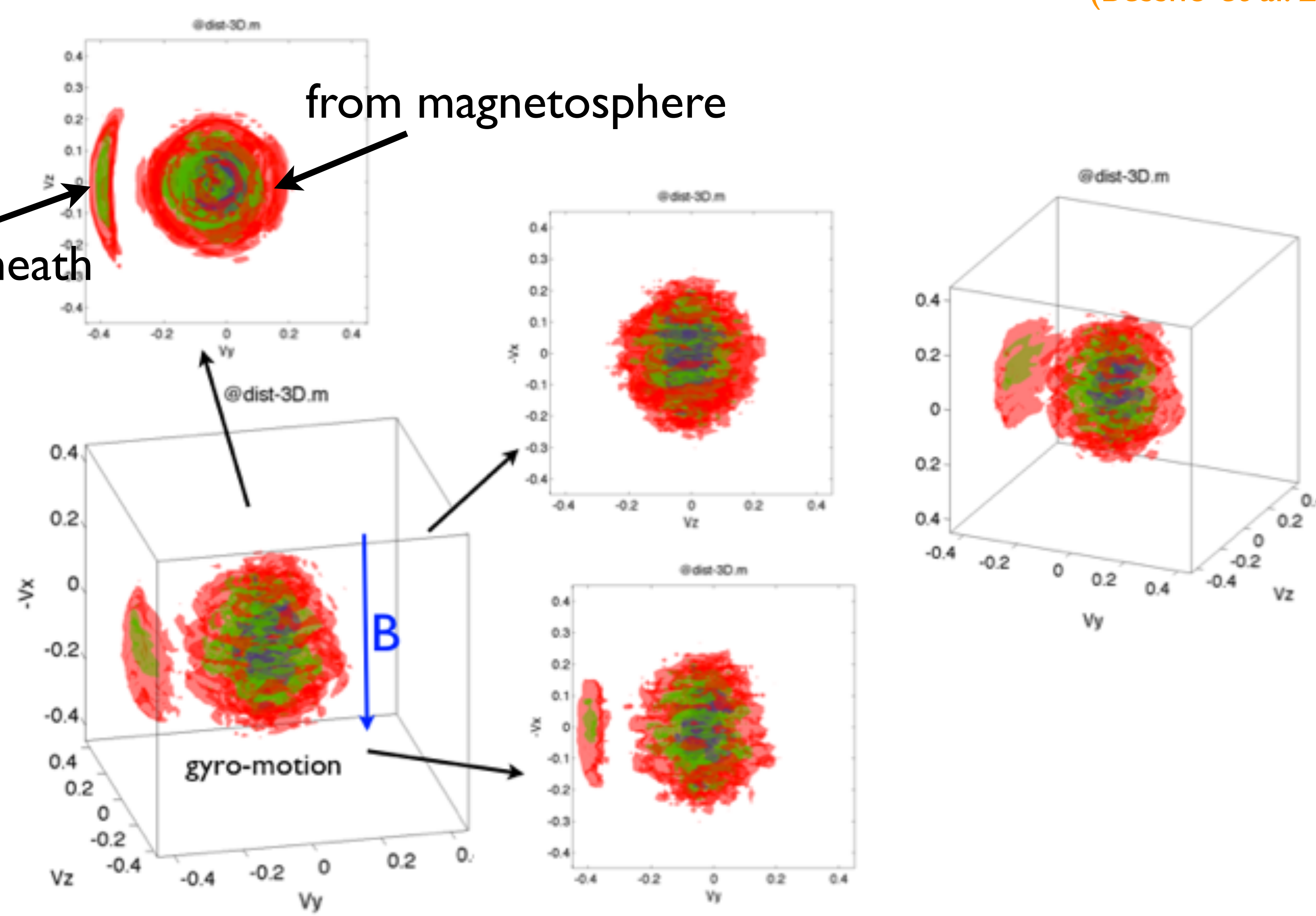


(Hesse et al. 2013; Hesse et al. 2016; Bessho et al. 2016 Chen et al. 2016 Shay et al. 2016)

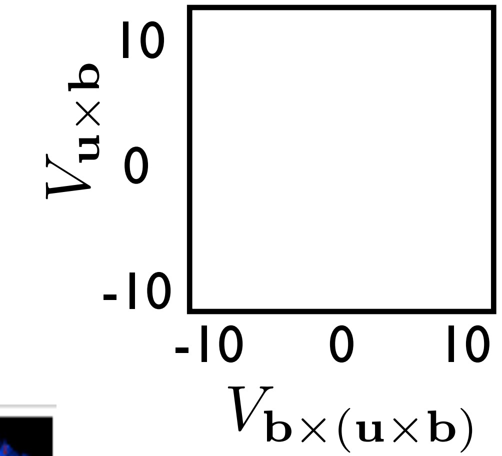


(Bessho et al. 2016)

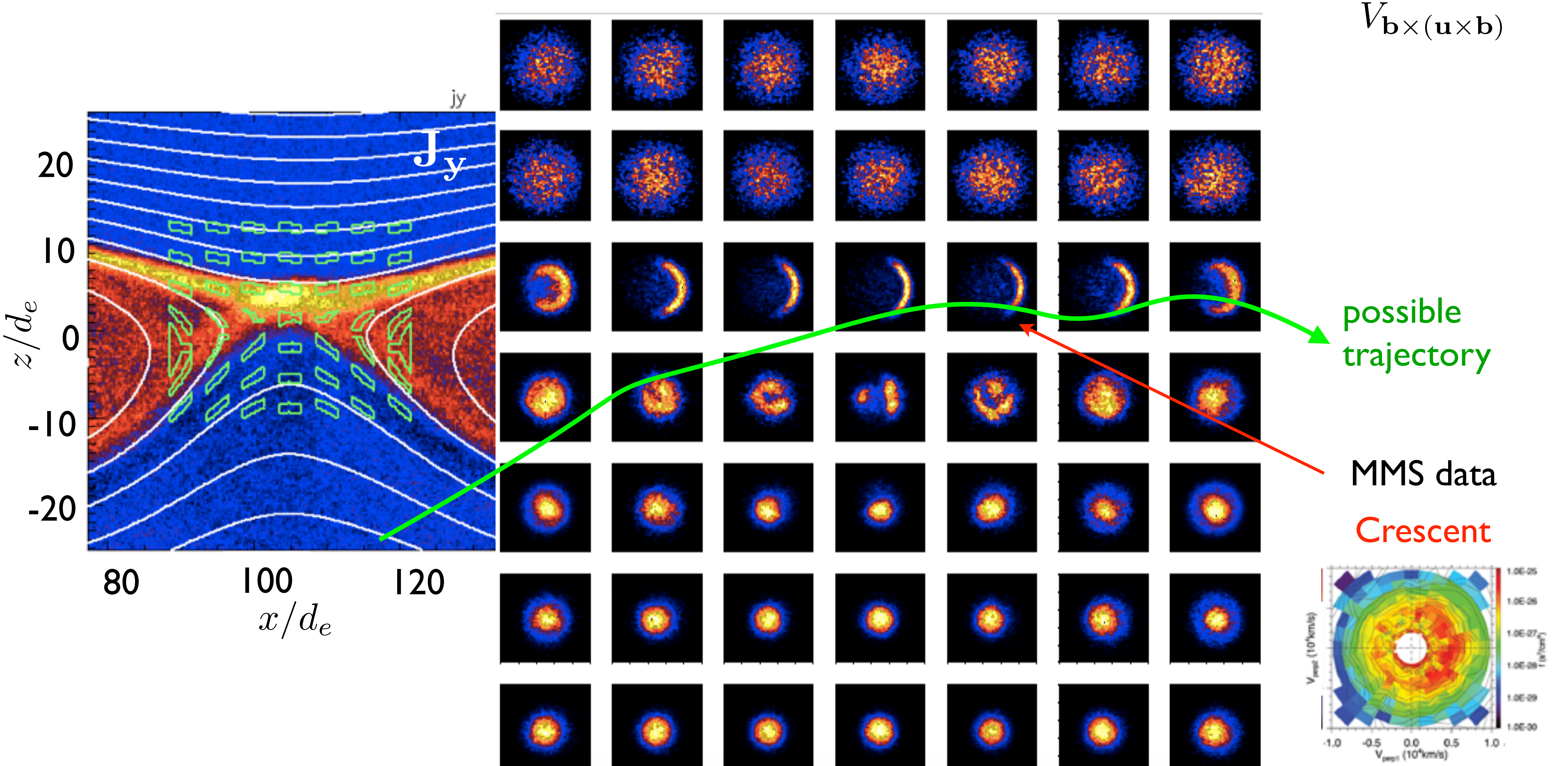
Full 3D



Field line coordinate



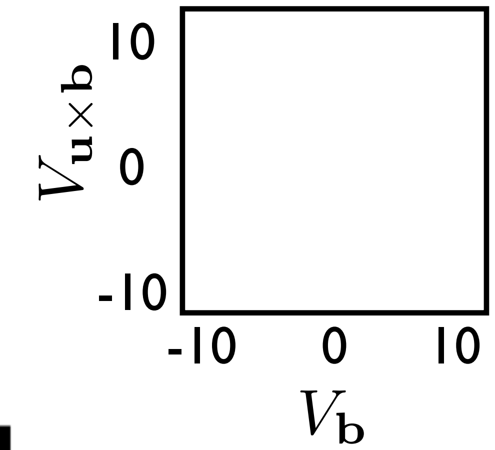
PIC simulation



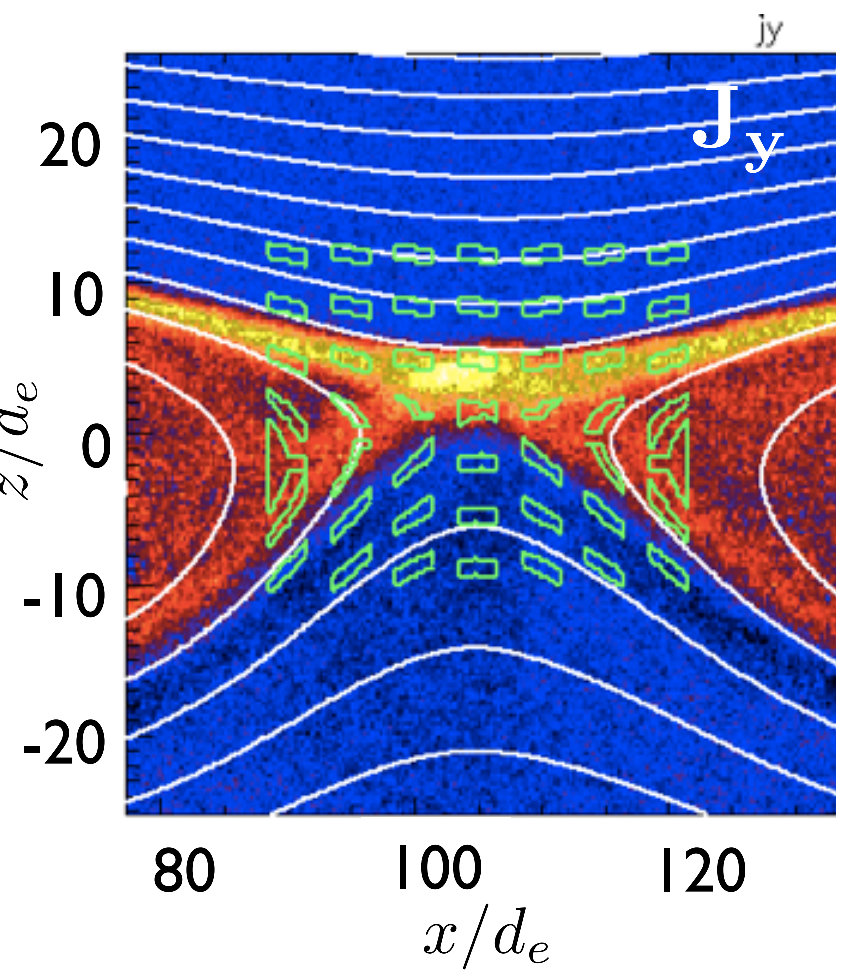
(Burch et al. SCIENCE 2016)

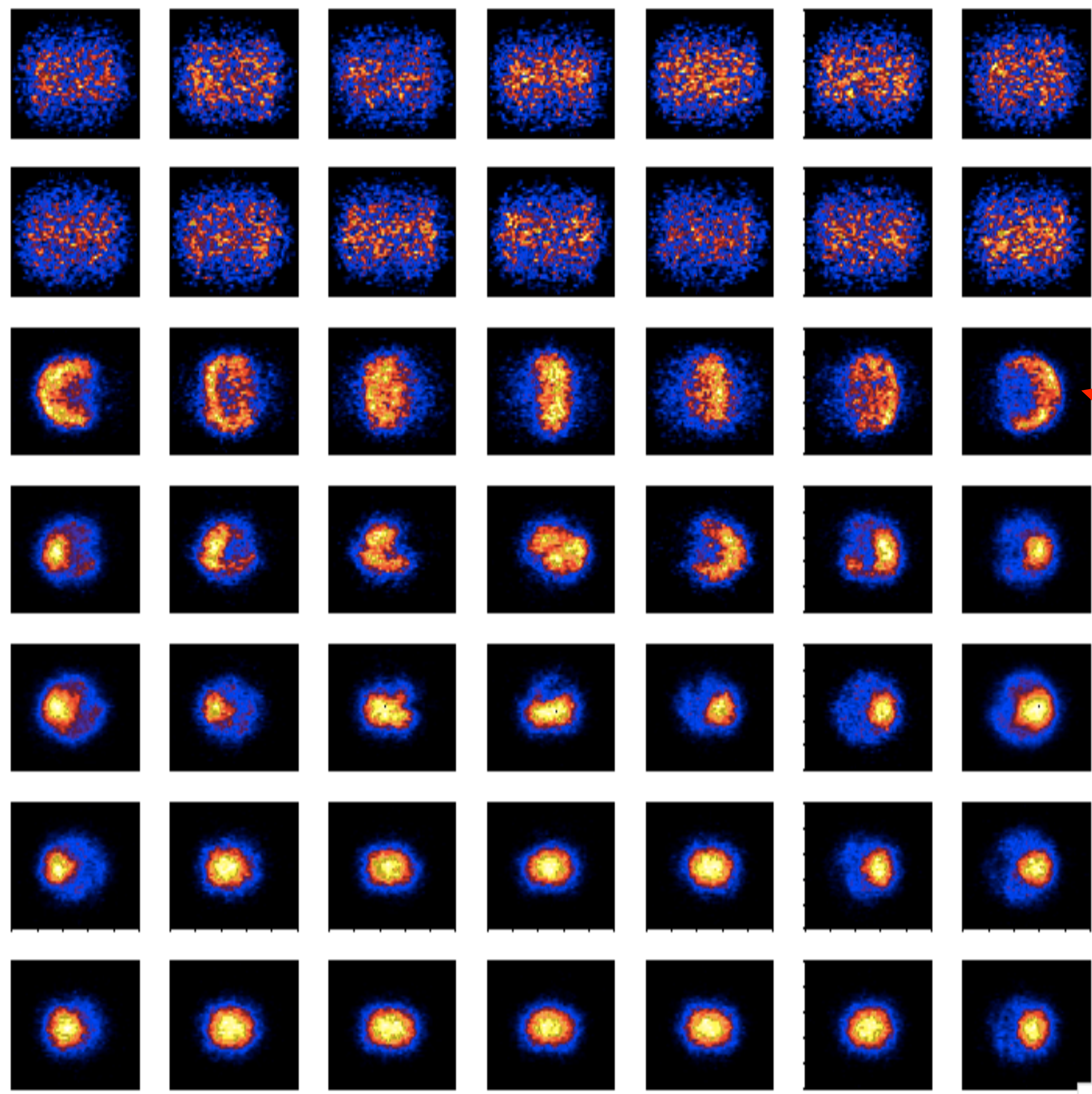
- Help figure out the trajectory of spacecrafts.

Field line coordinate



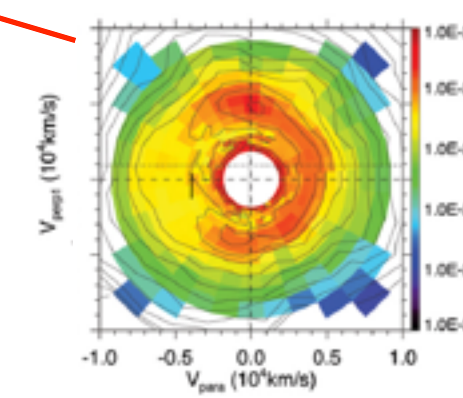
PIC simulation





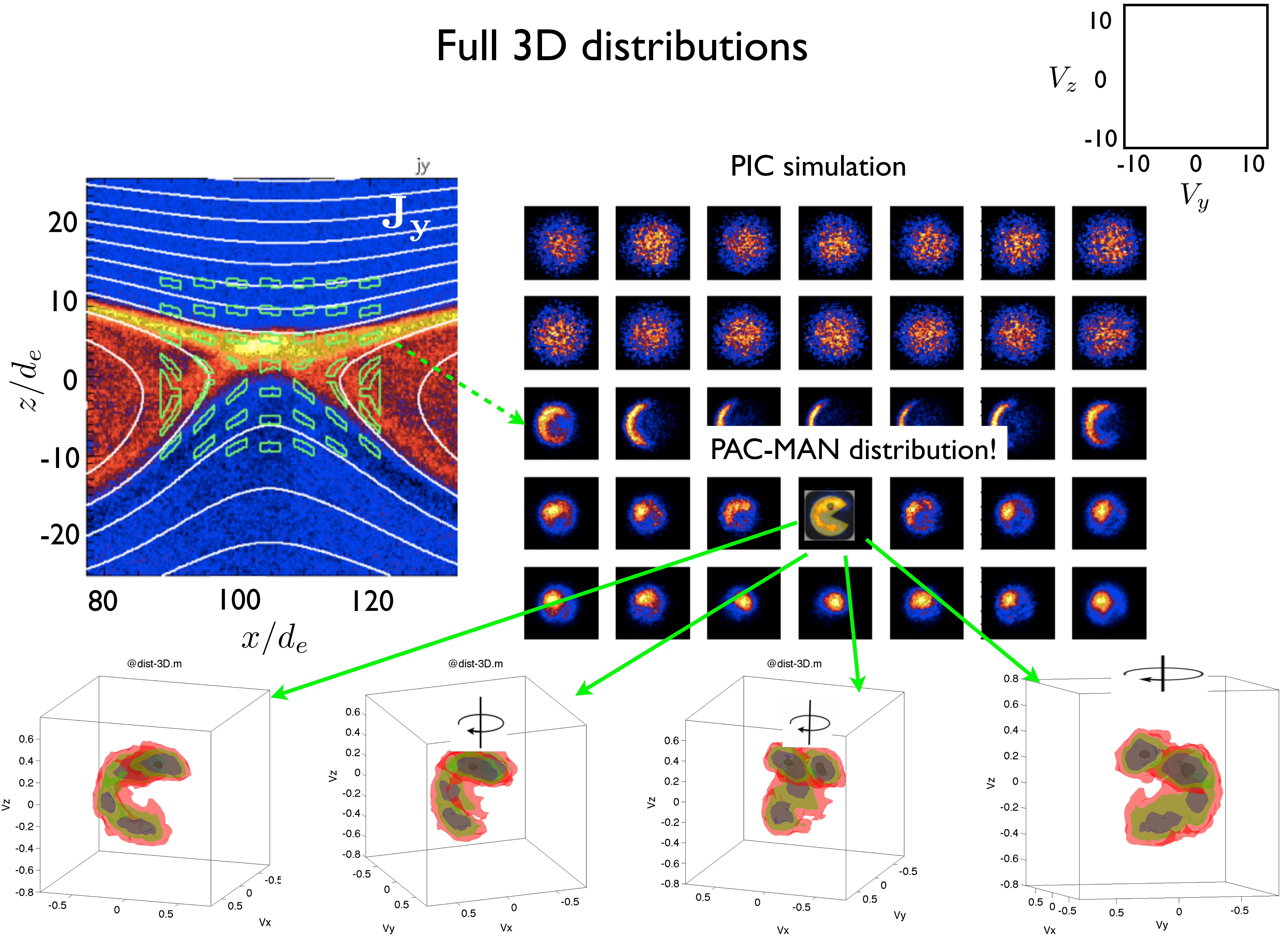
MMS data

Parallel Crescent



(Burch et al. SCIENCE 2016)

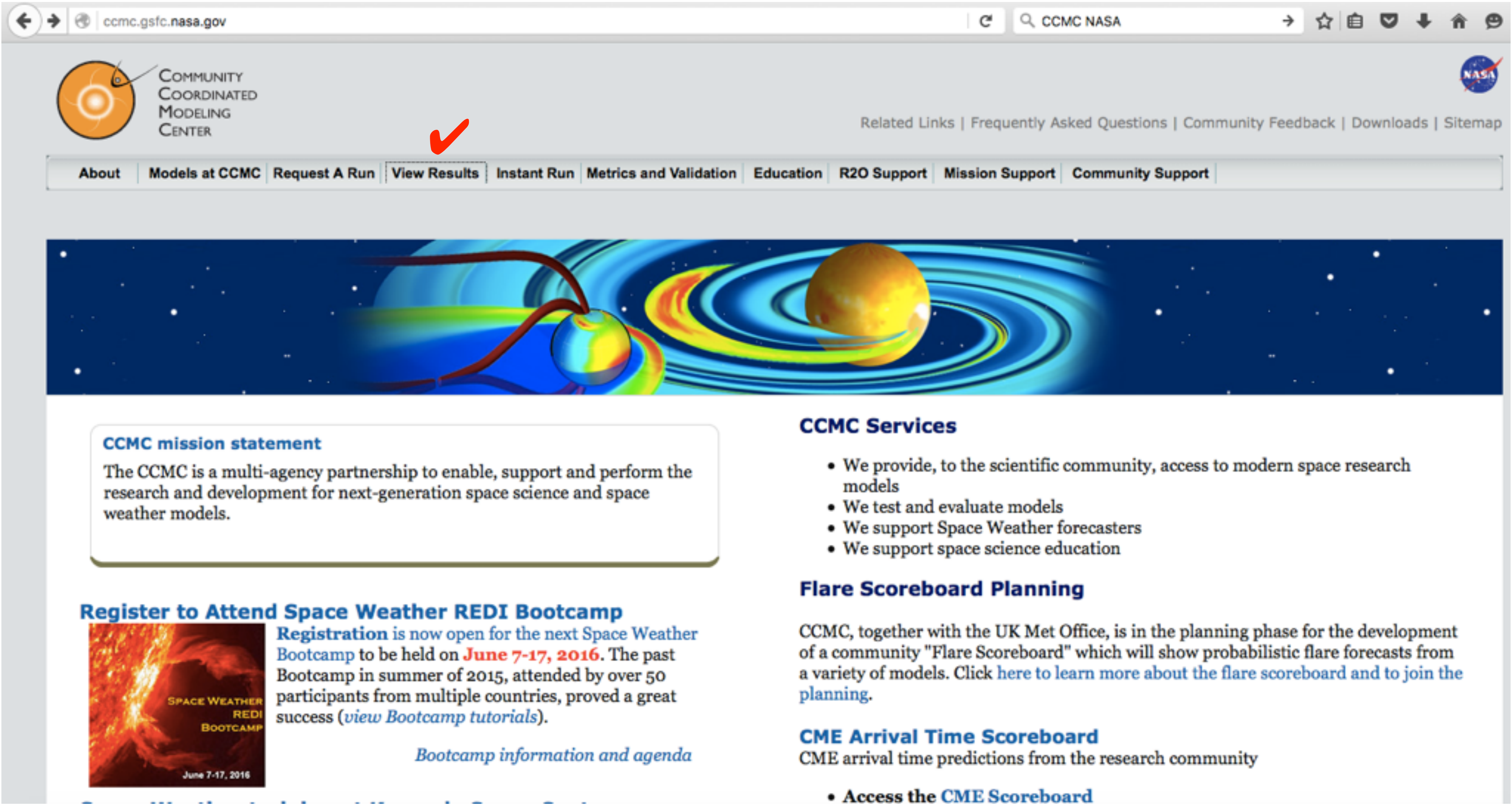
Full 3D distributions



How can we use these distributions?

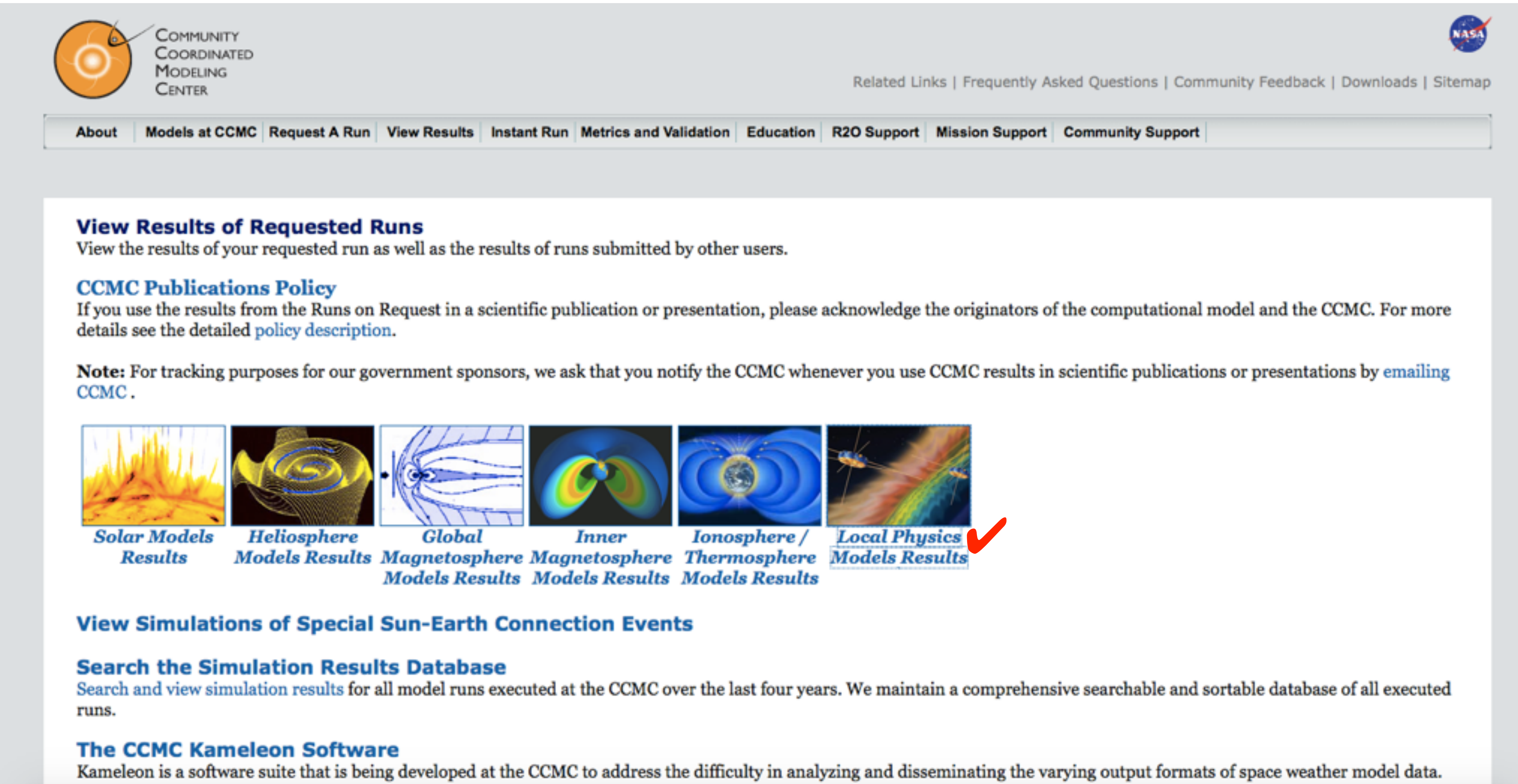
- Explaining the particle distribution in MMS.
- A 2D-map helps determine the trajectory of spacecrafts.
  -- Help find the electron diffusion region.
- Identify the mechanism that breaks frozen-in.
  -- non-gyrotropic feature
- Study the particle energization, particle mixing.
- Study the partition between electrons and ions.
- Study the temperature anisotropy, and its potential effect.
- ....

CCMC online interface
/show me the crescent!



CCMC online interface

/show me the crescent!



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View Simulations of Special Sun-Earth Connection Events

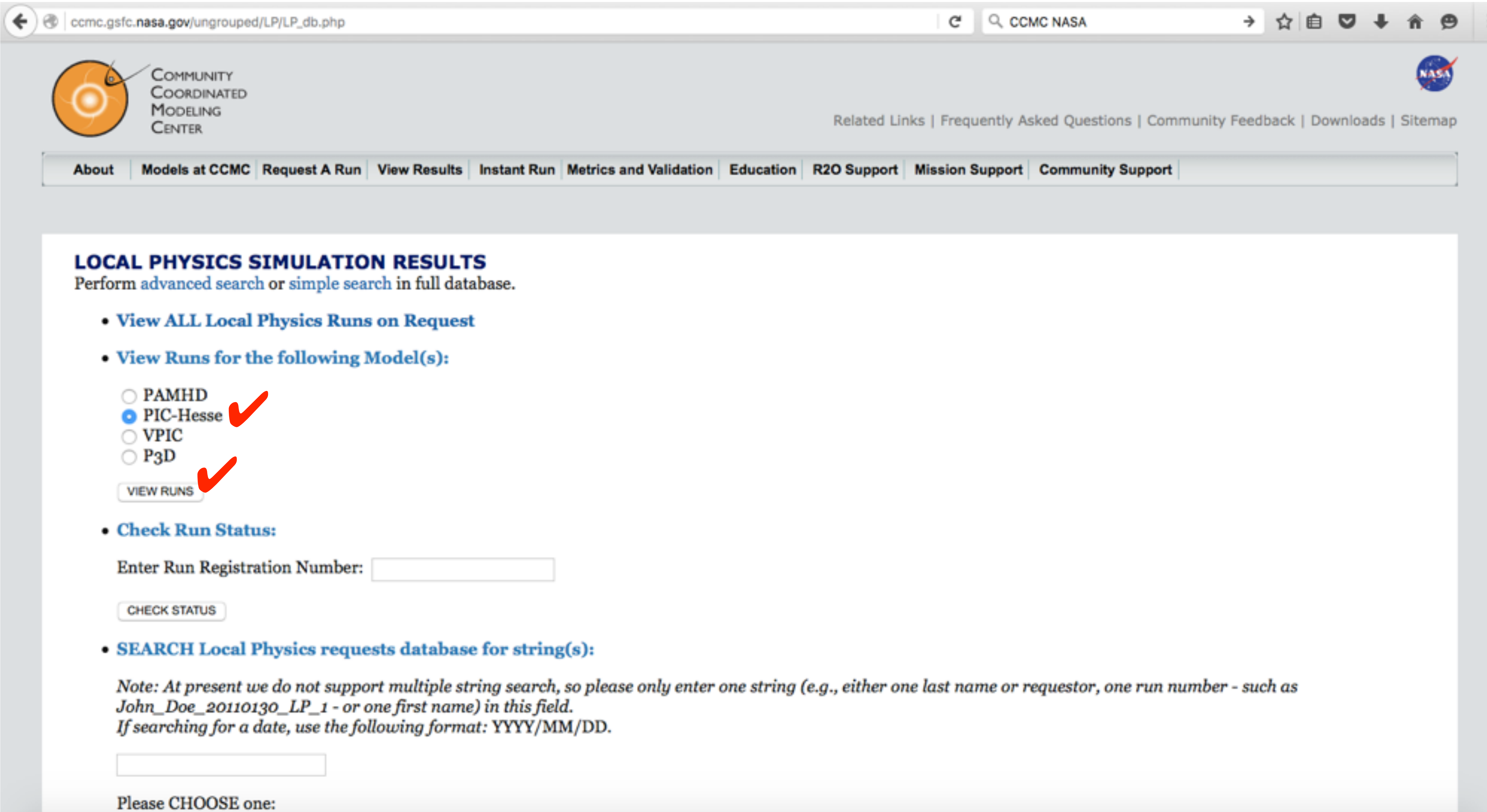
Search the Simulation Results Database

Search and view simulation results for all model runs executed at the CCMC over the last four years. We maintain a comprehensive searchable and sortable database of all executed runs.

The CCMC Kameleon Software

Kameleon is a software suite that is being developed at the CCMC to address the difficulty in analyzing and disseminating the varying output formats of space weather model data.

CCMC online interface
/show me the crescent!



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▸Runs on Request: Simulations Results

Total Number of Runs in the Database: 94
Total Number of Search Results in this Database: 1

Status	Run Number	Title	Key Words	Model	Model Version	Grid	Validation Level	Simulation Type	Coordinate System	Dim.	X_0	X_1	Y_0
published	Michael_Hesse_20150219_LP_2	2D Asymmetric reconnection	MMS Support, 2D Asymmetric reconnection, SSW16	PIC-Hesse	20150219	(1000)x(1)x(800)	0	Harris Sheet along X with added Bx	uniform Cartesian	2D	0.00000	64.00000	0.0000

Curator: Anna Chulaki | NASA Official: Dr. Masha Kuznetsova | Privacy, Security Notices

CCMC logo designed by artist Nana Bagdavadze

CCMC online interface
/show me the crescent!

Model Type: LP/PIC/
Model: PIC-Hesse version 20150219

Initial Configuration: Harris Sheet along X with added Bx

Run parameters:

- proton/electron mass ratio: 25.00000
- electron/proton temperature ratio: 0.2
- electron cyclotron/electron plasma time ratio (ω_{pe}/ω_{ce}): 2.00000

Boundary parameters (N and P averaged for each particle species):

Quantity	bottom (Z=-12.80000)	top (Z=12.80000)
B_x	-0.50000	1.50000
B_y	0.00000	0.00000
B_z	0.00000	0.00000
N_e	0.99700	0.33000
P_e	0.24900	0.08300
N_i	0.99700	0.33000
P_i	1.24500	0.41300

Select 3D distribution function (in velocity space) by Region-of-Interest (ROI) from one of these ROI maps:

- Select ROI map 1 ✔
- Select ROI map 2
- Select ROI map 3
- Select ROI map 4
- Select ROI map 5

} particle distributions

- View 2D fields output

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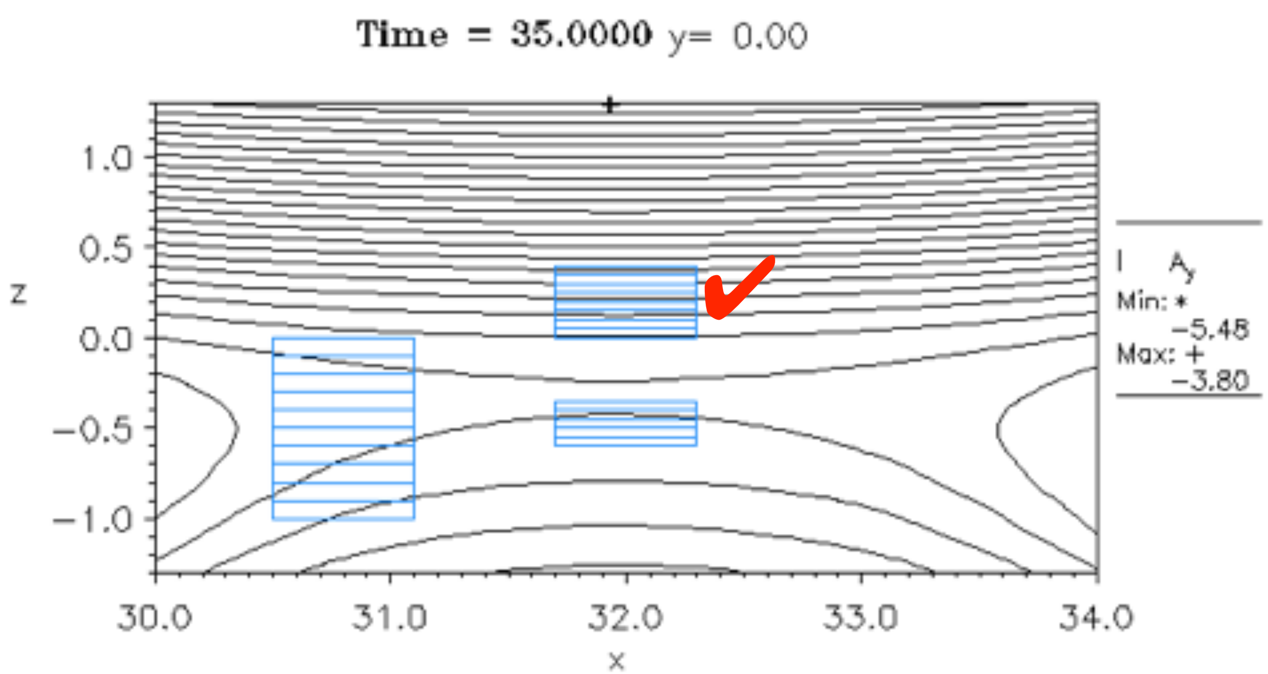
Run: Michael_Hesse_20150219_2



Model at CCMC: PIC−Hesse

Move through adjacent ROIs:

- Along Z:
  - between X= 30.5 and 31.1
  - between X= 31.7 and 32.3

CCMC online interface

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3D-Surface, 3D-Flowlines, Color Contour on Sphere:

View angles:

AX [-90..90]: 30 (viewer's elevation angle)

AZ [-180 ... 180]: 30 (viewer's azimuth angle; 0: along negative Y)

Color Contour, (Vertical) Line:

Color table: Rainbow

Reverse Colortable

Number of levels: 32

Lock color range:

Min.: -1 Max.: 1

Log scale (use all data>0 in non-negative fields)

Contour:

show values with contour levels

32 **Number of Levels**

Lock range:

Min.: 0 Max.: 1

Log scale (use all data>0 in non-negative fields)

Choose Plot Area:

All **Plot Modes** except **Line Plot** and **Vertical Plot**: Select lower left corner of plot area on the left, and the upper right corner on the right.

Line Plot: Select start point of line on the left, the end point on the right.

Vertical Plot: Select Vx and Vy position on the left.

Choose Cut Plane:

Vx_1	-11	Vx_2	11	Range: -11 ... 11	Vx=constant	0
Vy_1	-11	Vy_2	11	Range: -11 ... 11	Vy=constant	0
Vz_1	-11	Vz_2	11	Range: -11 ... 11	Vz=constant	0

Reset Form *Reset Form* will reset changes to the defaults specified by the previous run of this script.

Update Plot *Update Plot* will update (generate) the plot with the chosen time and plot parameters above.

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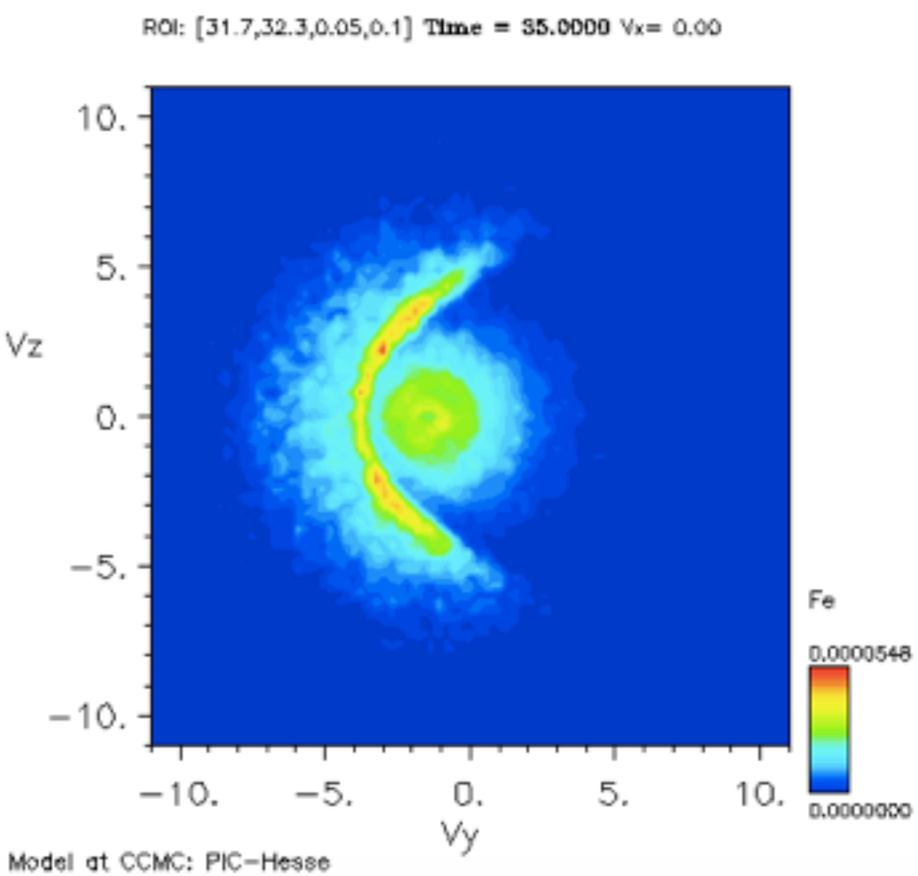
Please wait - computation is estimated to take 0 minutes and 5 seconds.
A "." will appear for each 5 seconds elapsed.

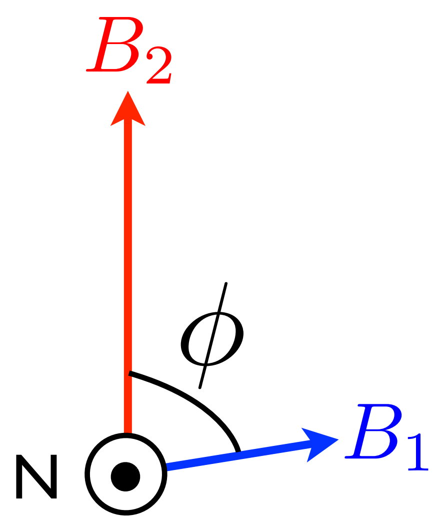


Bingo!

Figure: Particle-in-cell distribution function of local region.

Service II:
Help determine the reconnection plane
i.e., Help optimize the LMN coordinate

- Minimum Variance Analysis (MVA) determines N, while L is the direction of the maximum eigenvalue, but B_L is not necessary the reconnecting component!



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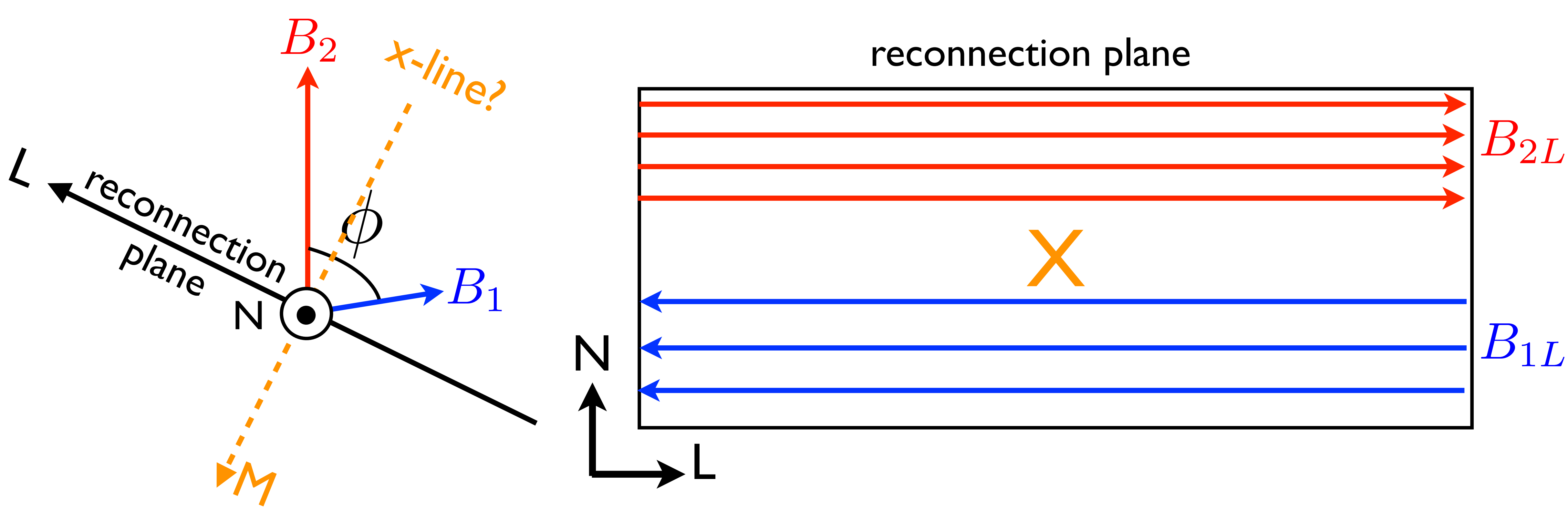

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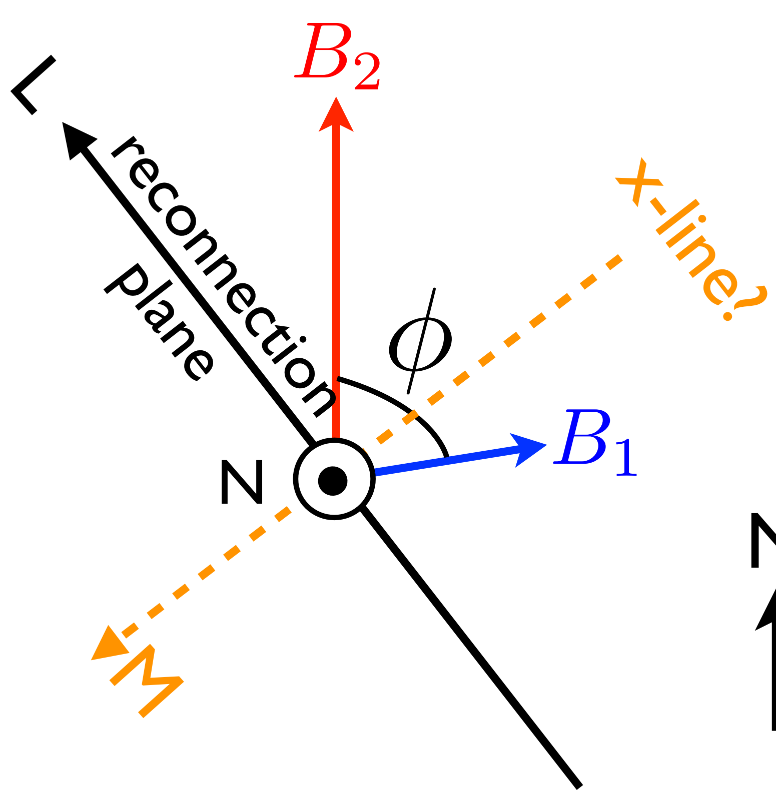
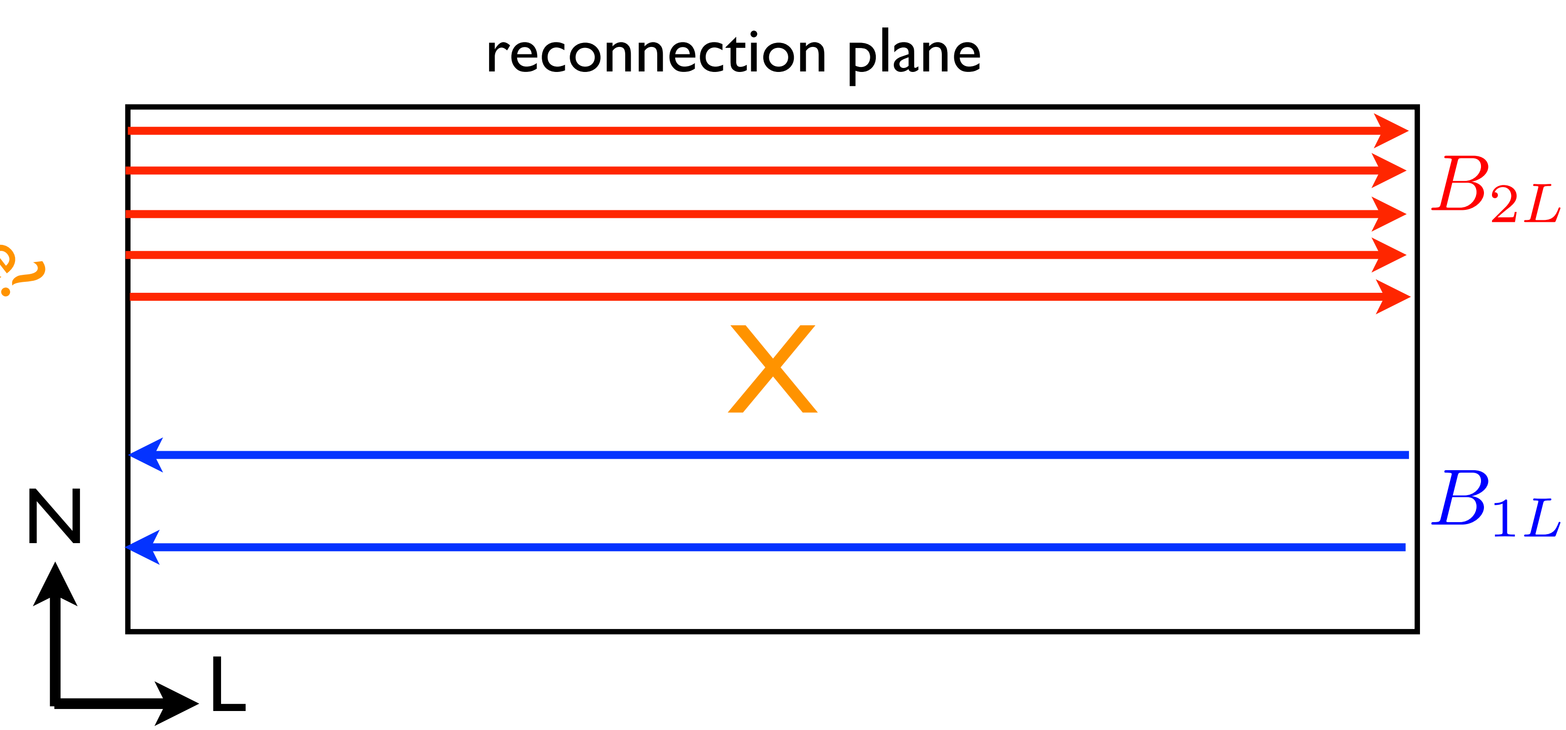


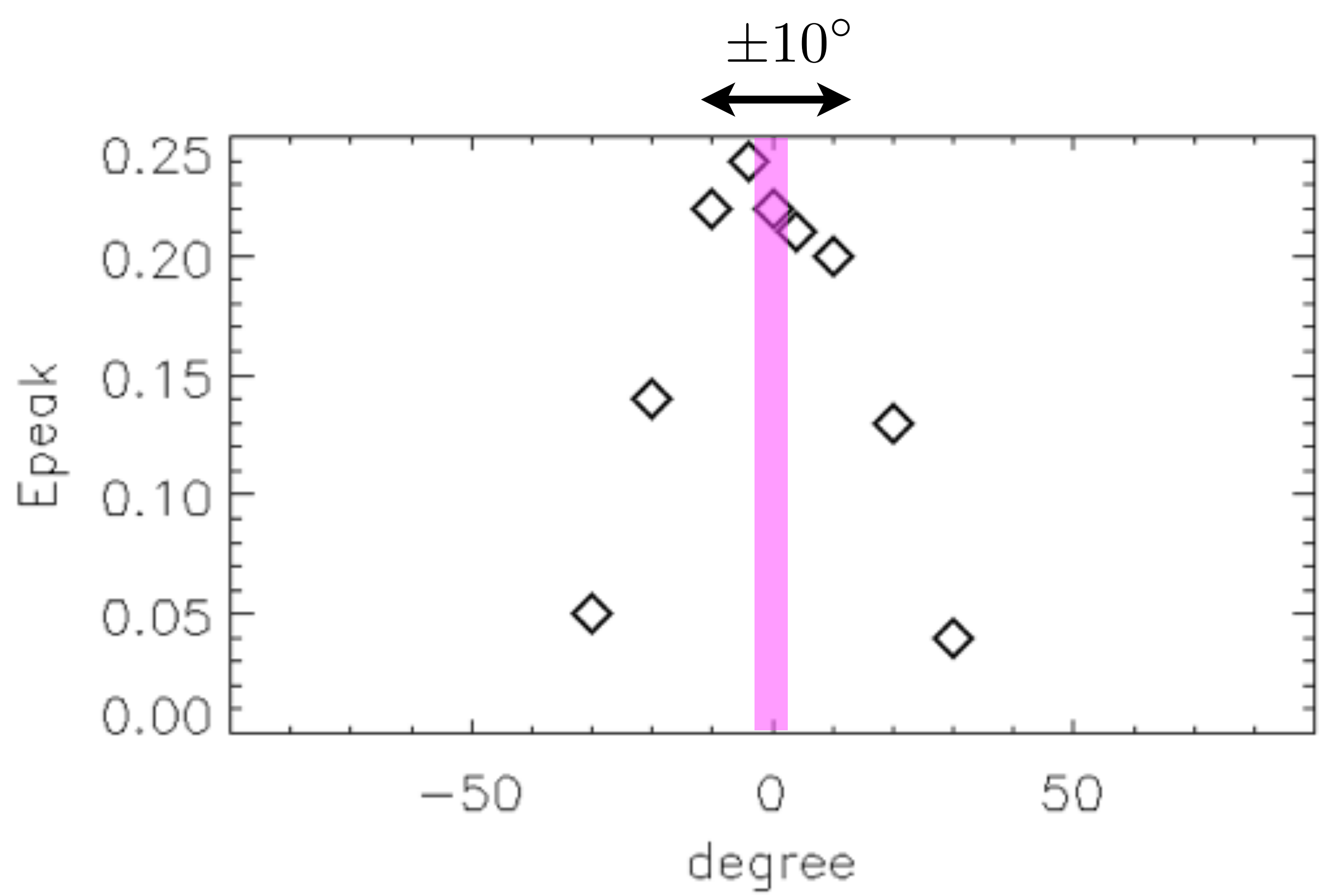


Step1: Give us the upstream condition & N

Step2: We can perform a scan of 2D simulations at different clock angles

Step3: We determine the plane of maximum rate, outflow speed,....etc

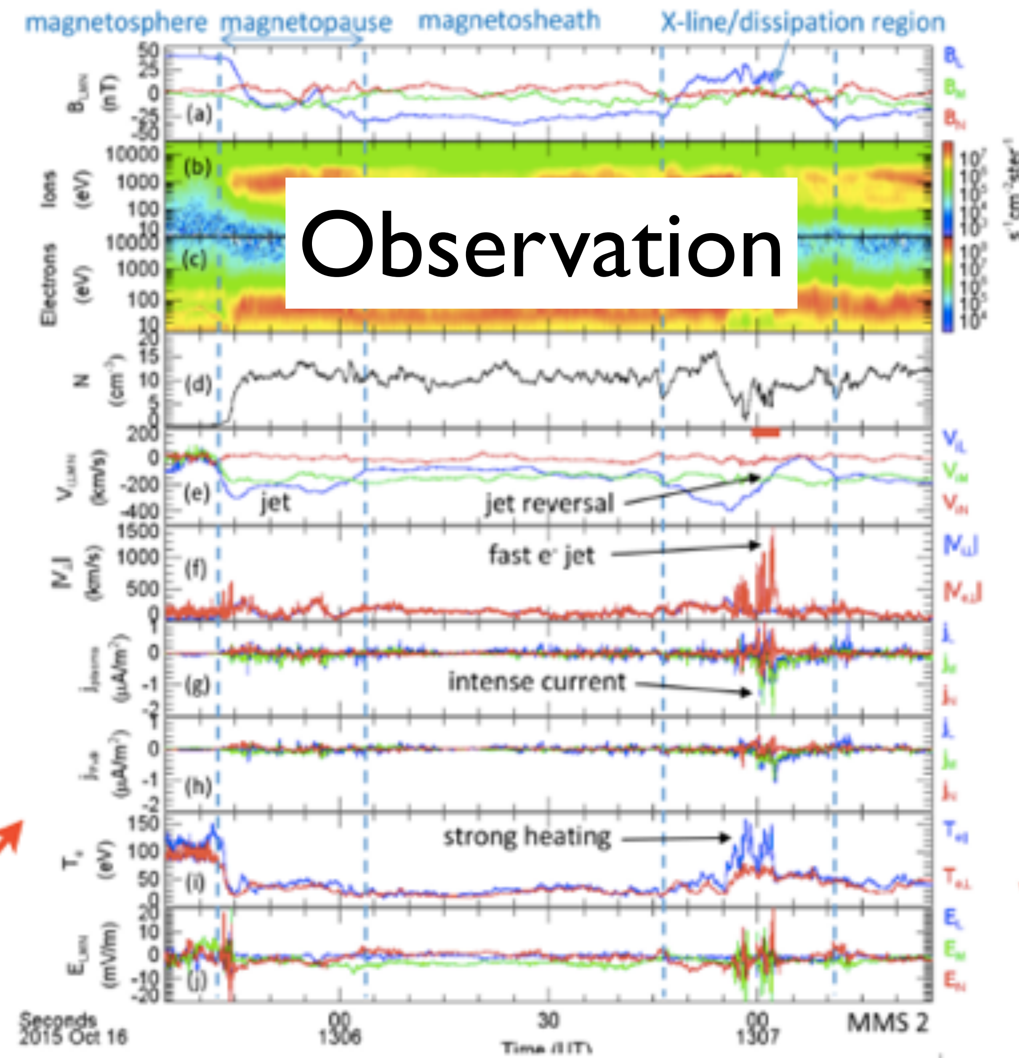
(Sonnerup 1974; Gonzalez & Mozer 1974; Swisdak & Drake 2007; Cassak & Shay 2007; Schreier et al. 2010; Hesse et. al. 2013; Liu et al. 2015....etc)



LMN used in Burch et al. SCIENCE 2016

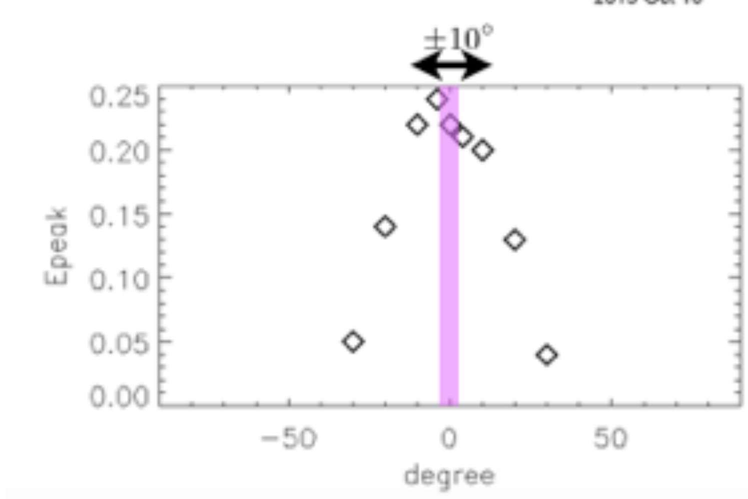
- The derived LMN for this event seems to agree with the maximum $E_{reconn.}$!
- Now, we can handle arbitrary asymmetric guide fields, shear flows and diamagnetic drifts.
- User feedback?

Potential Science Project
-- Local vs. Global

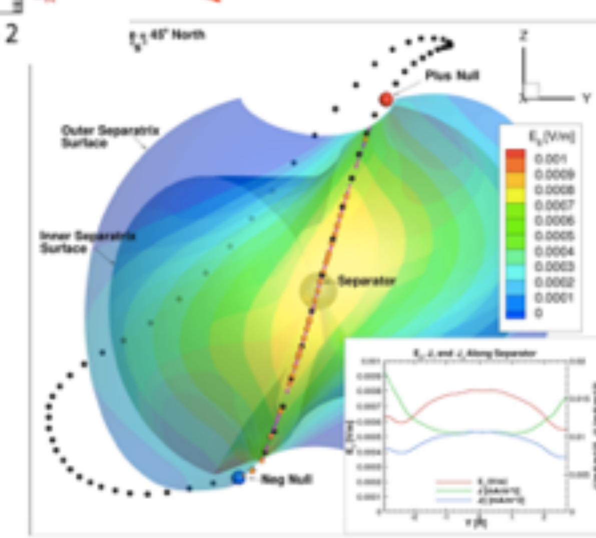


Maybe, reconstructing the local magnetic geometry.
(Shi et al. 2005,
Denton et al. 2012
Guo & Pu et al. 2013)

Local x-line



Global magnetic separator



(Glocer et al. 2015; Komar et al. 2015)

- A project that may connect observation, global and local simulations!
- If possible, comparison with embedded-PIC simulations will also be interesting. (e.g., Daldorff et al. 2014, Toth et al. 2016)

Summary
-- Why do we need PIC in CCMC?

- rich kinetic physics.
- full particle distributions.
- self-consistent particle energizations.
- self-consistent moment closure.
- capture the physics that breaks the frozen-in condition.
- correctly describe the local physics that controls x-lines.
- correctly capture the kinetic physics of explosive events.
  -- such as tail reconnection Onset.
- MMS needs comparison from PIC!

There were successful comparisons between observation and PIC, there will be more in the future!

Computational requirement

mi/me=25
particle/cell=200
Lx x Lz = 51.2di x 25.6di
nx x nz = 1024 x 512
wpe/wce=4.0

resource required:
256 CPUs x 1 hour ~ 256 CPU-hours
Particle data/frame ~ 3 GB
Total fields & moments data ~ 3 GB

Particle-in-cell Simulations

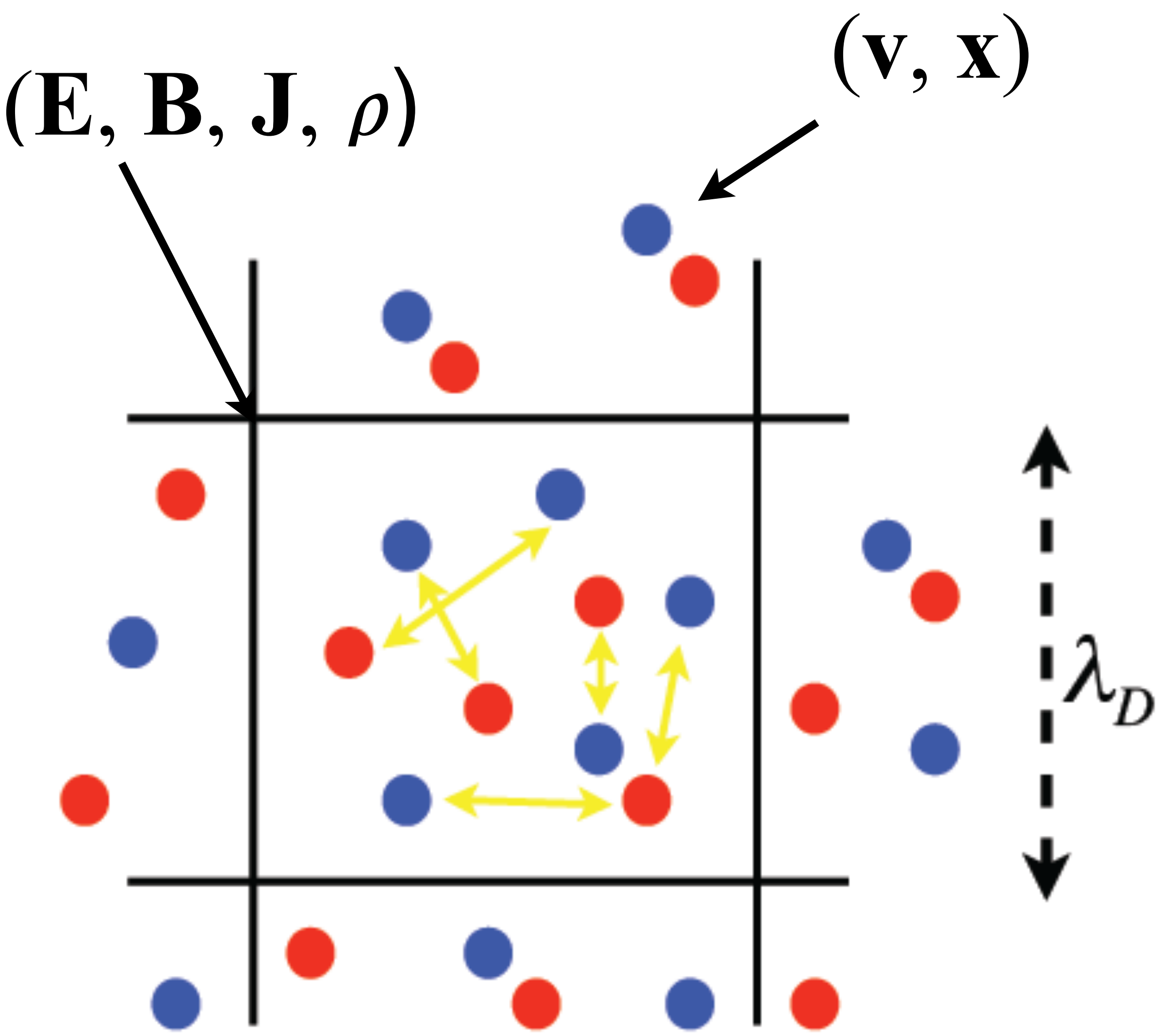
Lorentz Force

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Maxwell Equation

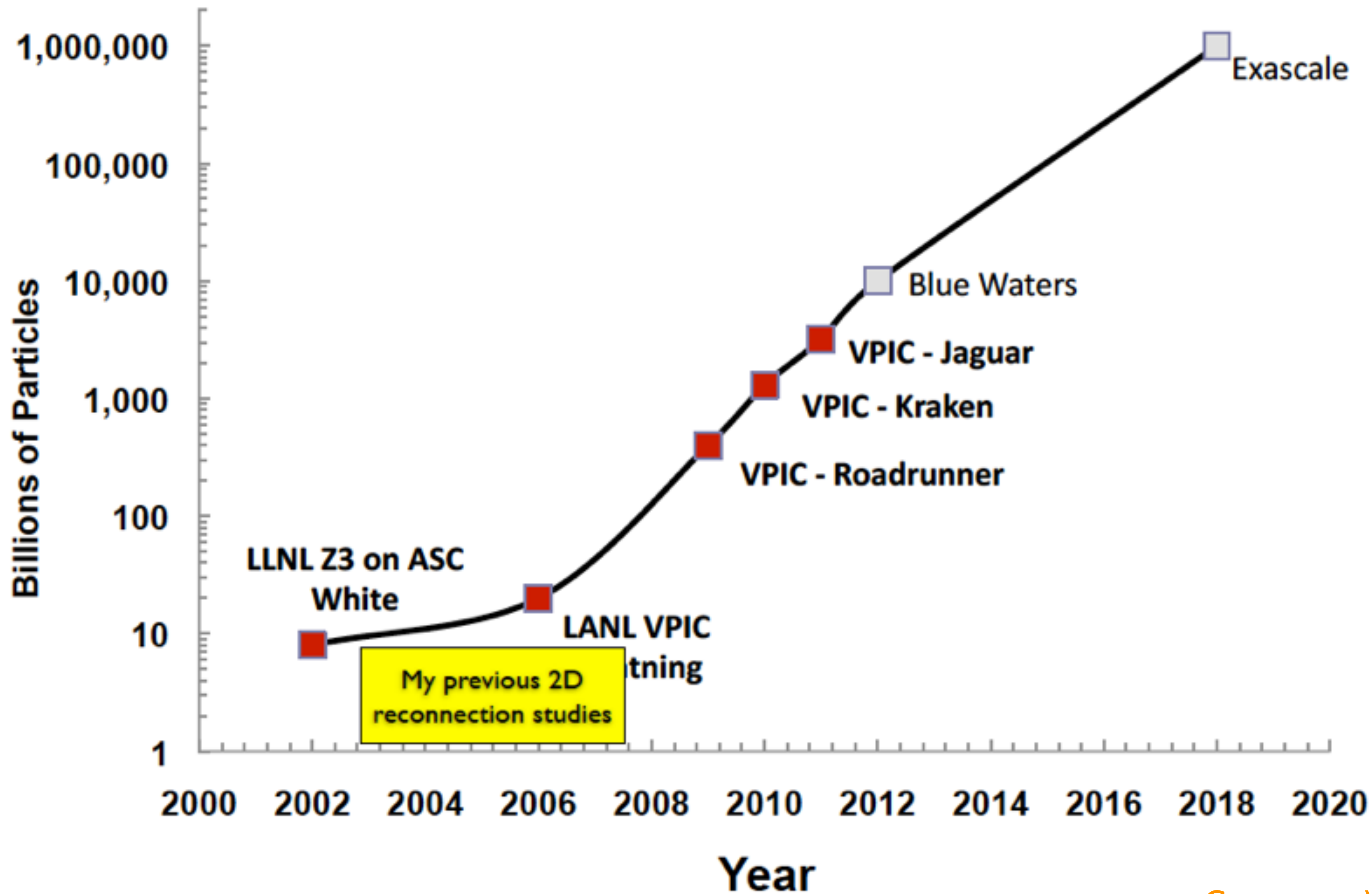
$$\nabla \cdot \mathbf{B} = 0 \qquad \nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho \qquad \nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$



✔ First-principle kinetic description

Feature of VPIC?

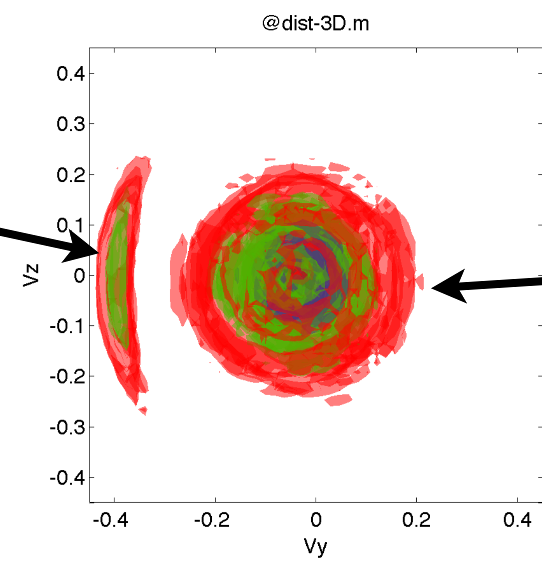


Courtesy to W. Daughton

Test particle simulations

Since we have saved: $\mathbf{B}$ $\mathbf{E}$

from magnetosheath



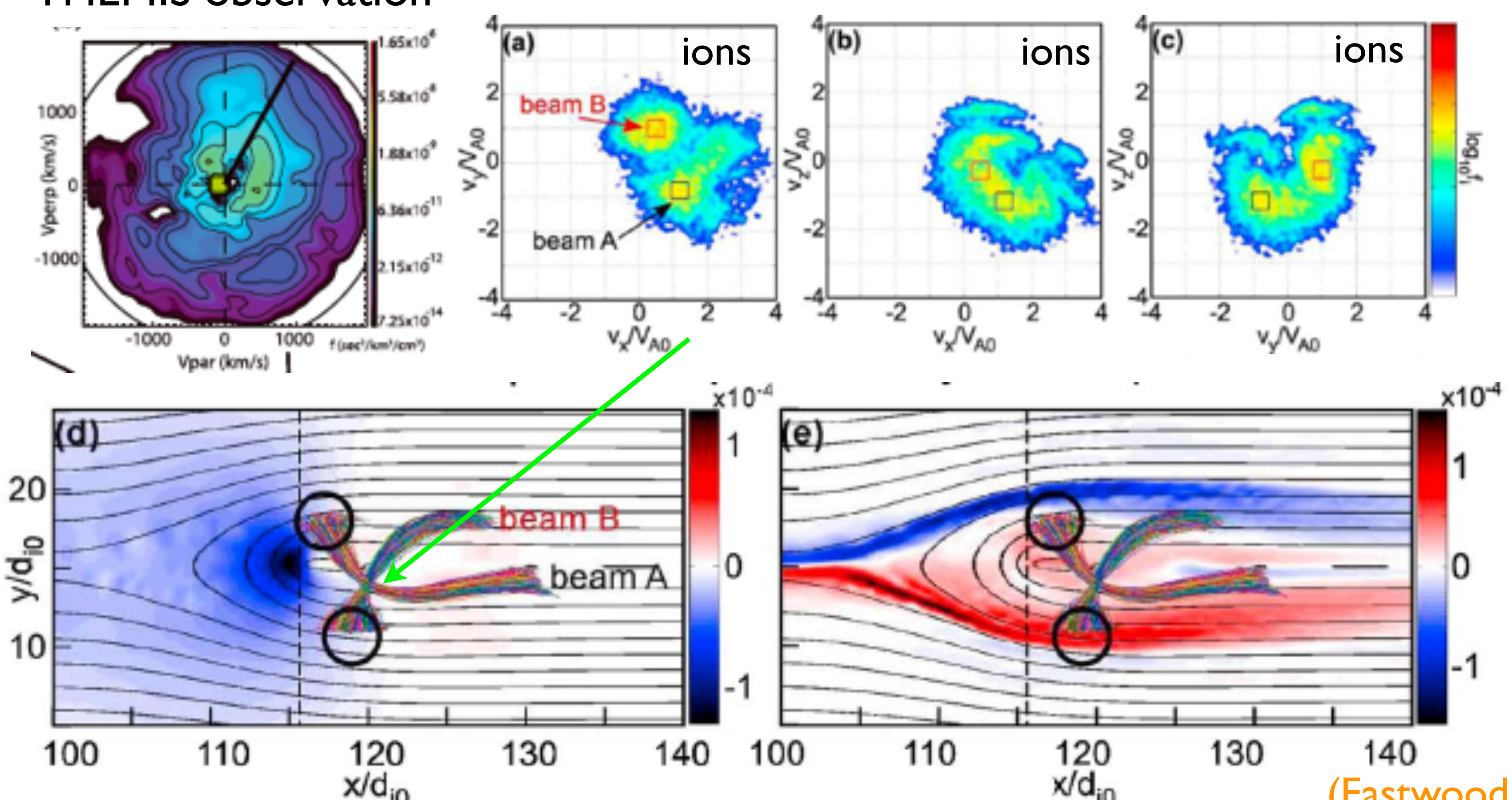
from magnetosphere

- Track particles backward in time will tell you their origins.

One example that studied DF at tail:

THEMIS observation

PIC simulation

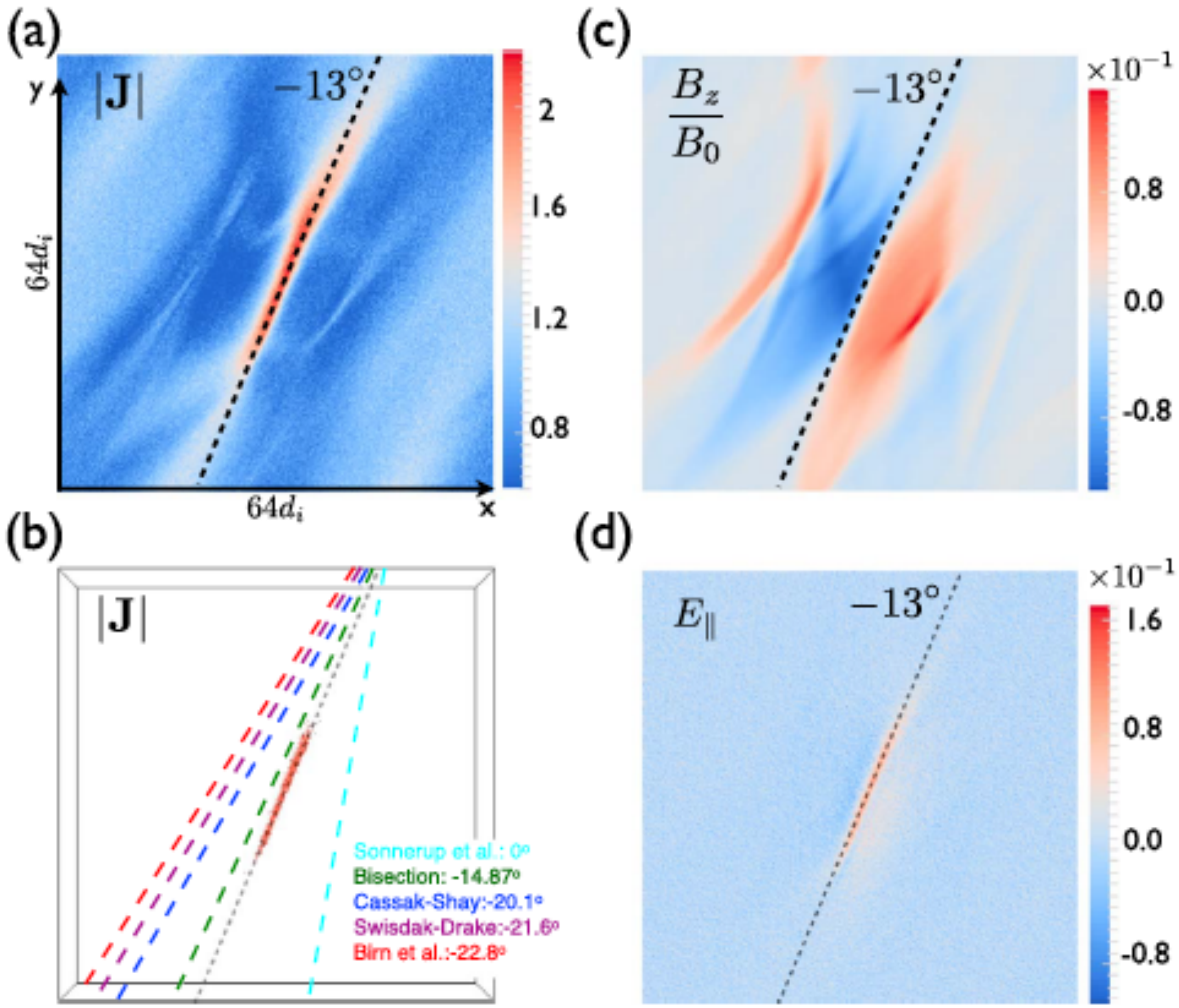


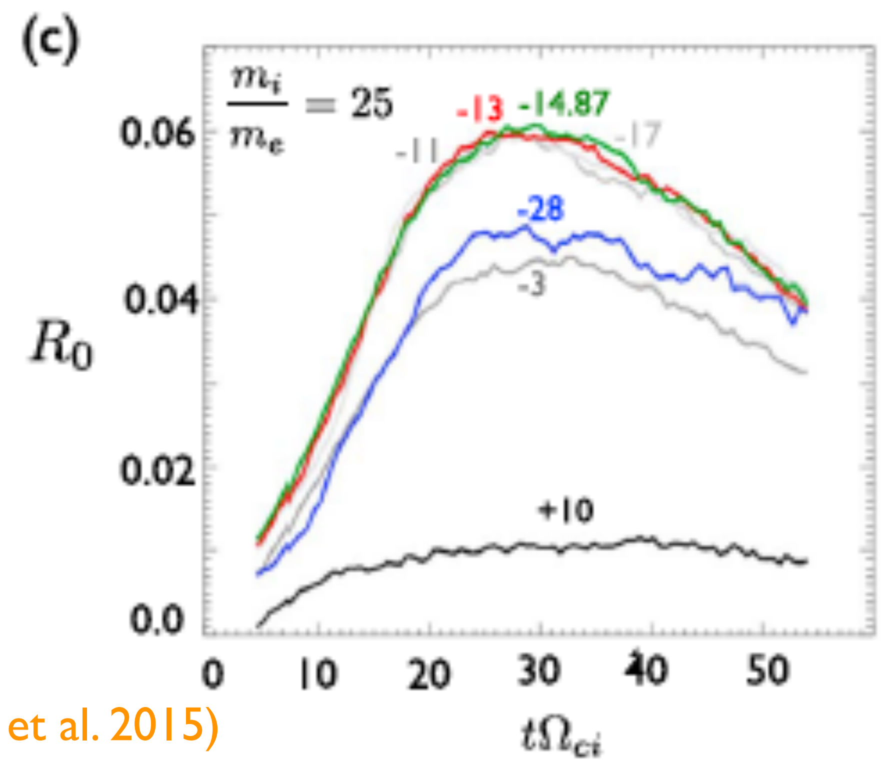
(Eastwood et al. JGR, 2015)

The era of MMS

"MMS reveals, for the first time, the small-scale three-dimensional structure and dynamics of the elusively thin and fast-moving electron diffusion region. It does this in both of the key reconnection regions near Earth, where the most energetic events originate."

Find the plane of reconnection in 3D





(Liu et al. 2015)

*may tell us the optimized coordinate for analyzing the data

- The optimized reconnection plane is the plane that maximize reconnection rate .

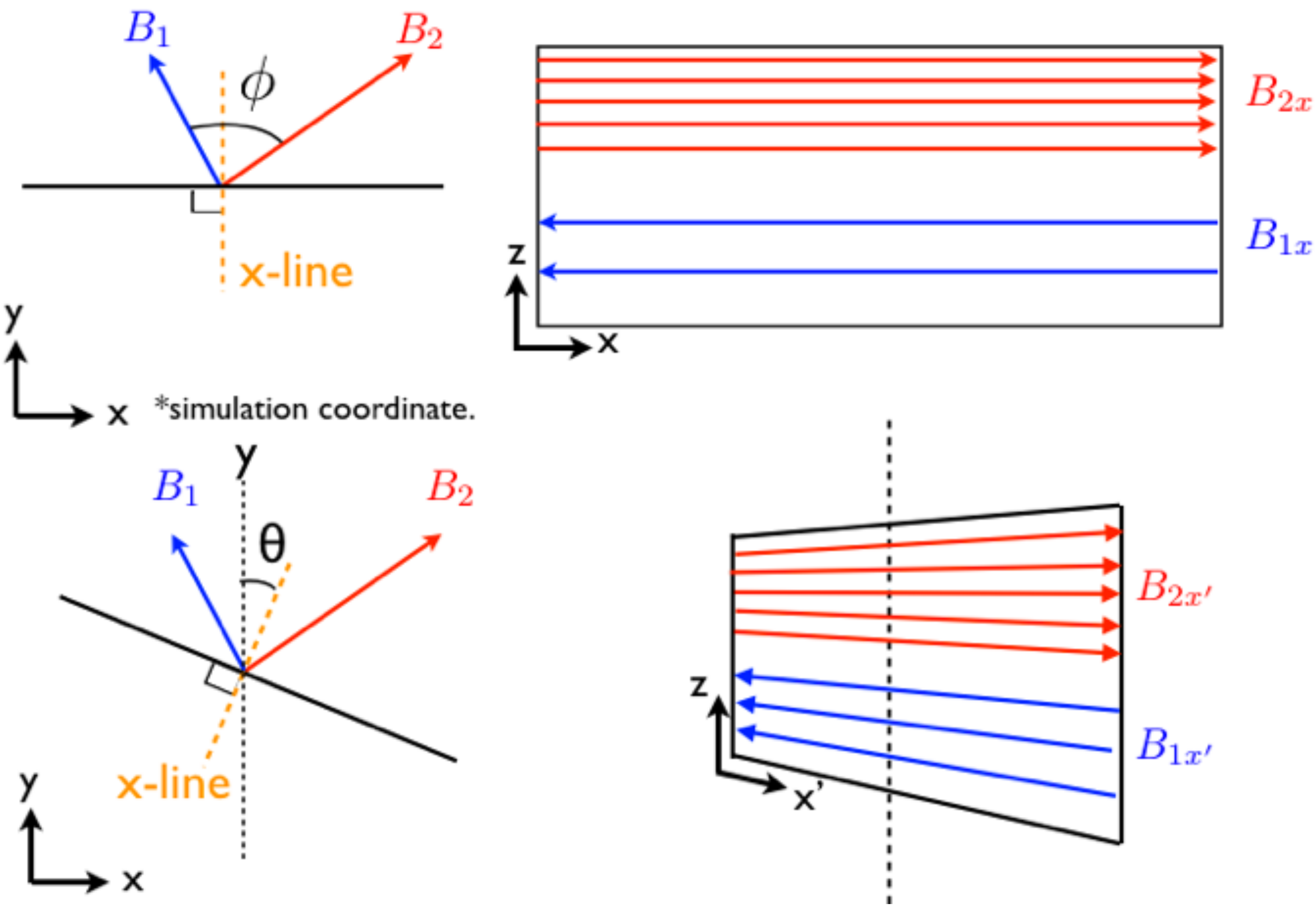
  -- outflow speed (Swisdak & Drake et al. 2007)

  (Cassak & Shay 2007; Hesse et. al. 2013 = bisection solution)

  -- tearing growth rate (Liu et al. 2015)

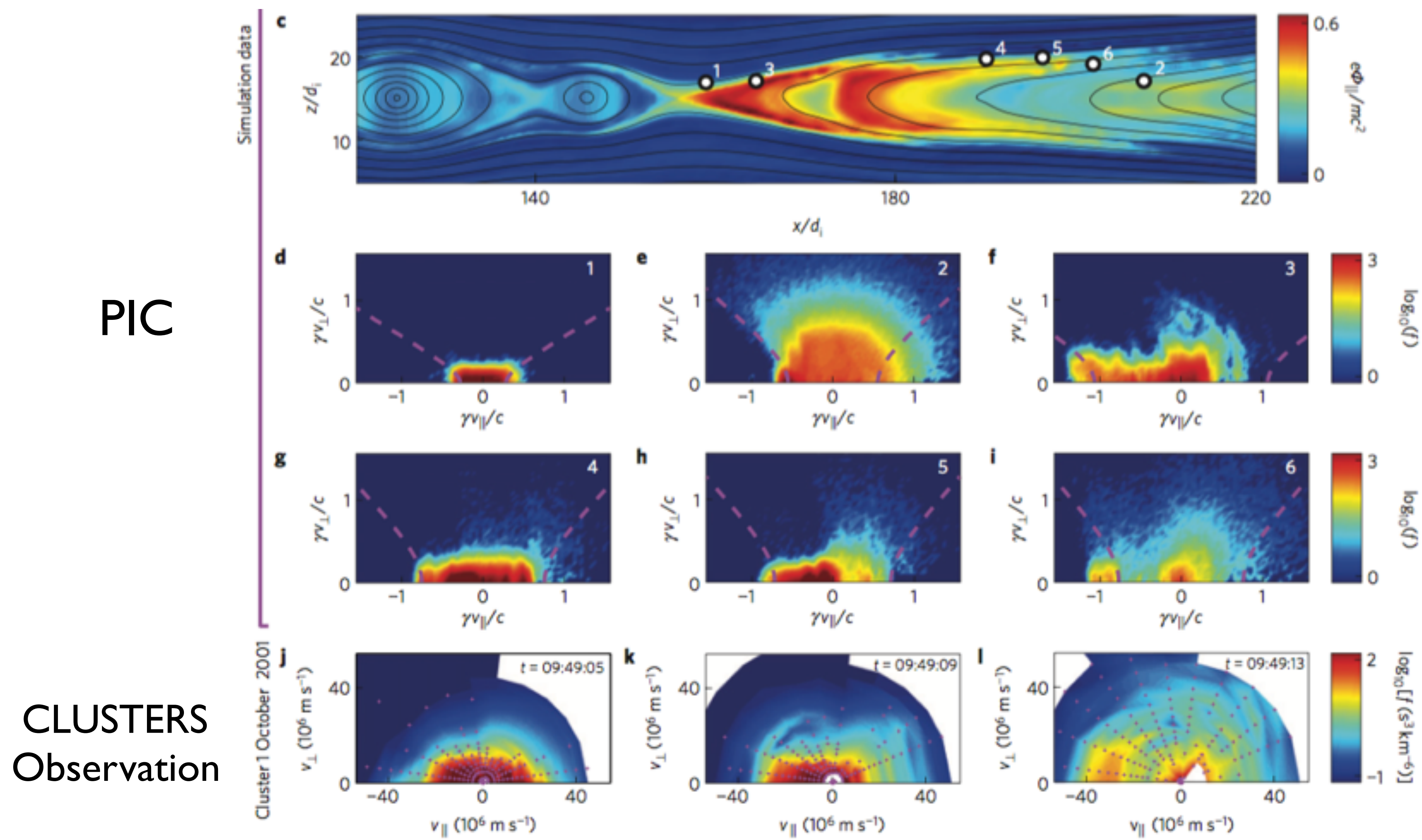
  -- ....

Q: Which plane does reconnection prefer?



- In principle, reconnection is possible in all planes where the in-plane component reverses sign!

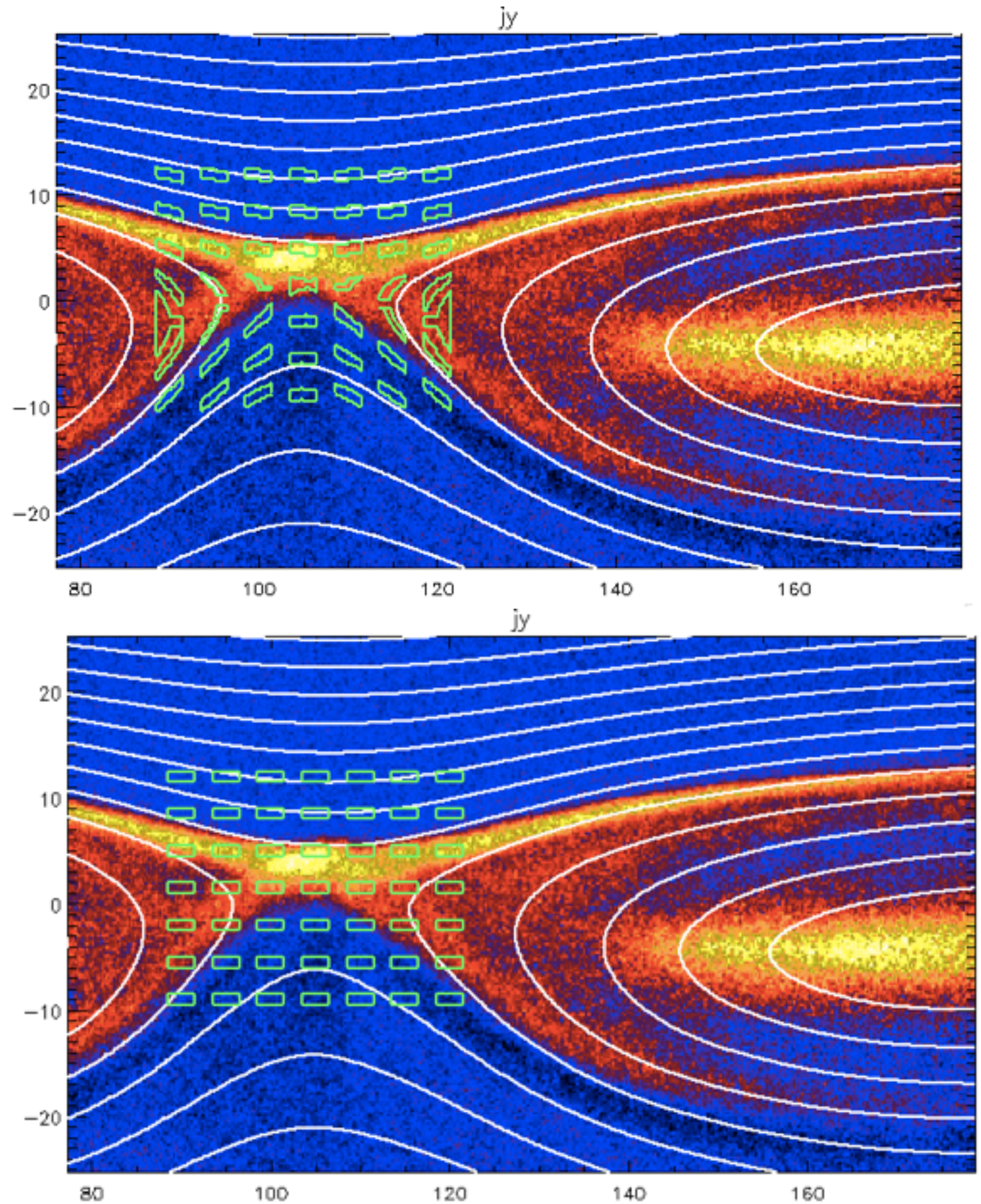
Example 2: Electrons heating



(Egedal et al. NATURE Physics 2012)

- Electrostatic potential.
- Acceleration of non-thermal particles.

Step2: We can generate a bunch of particle distributions

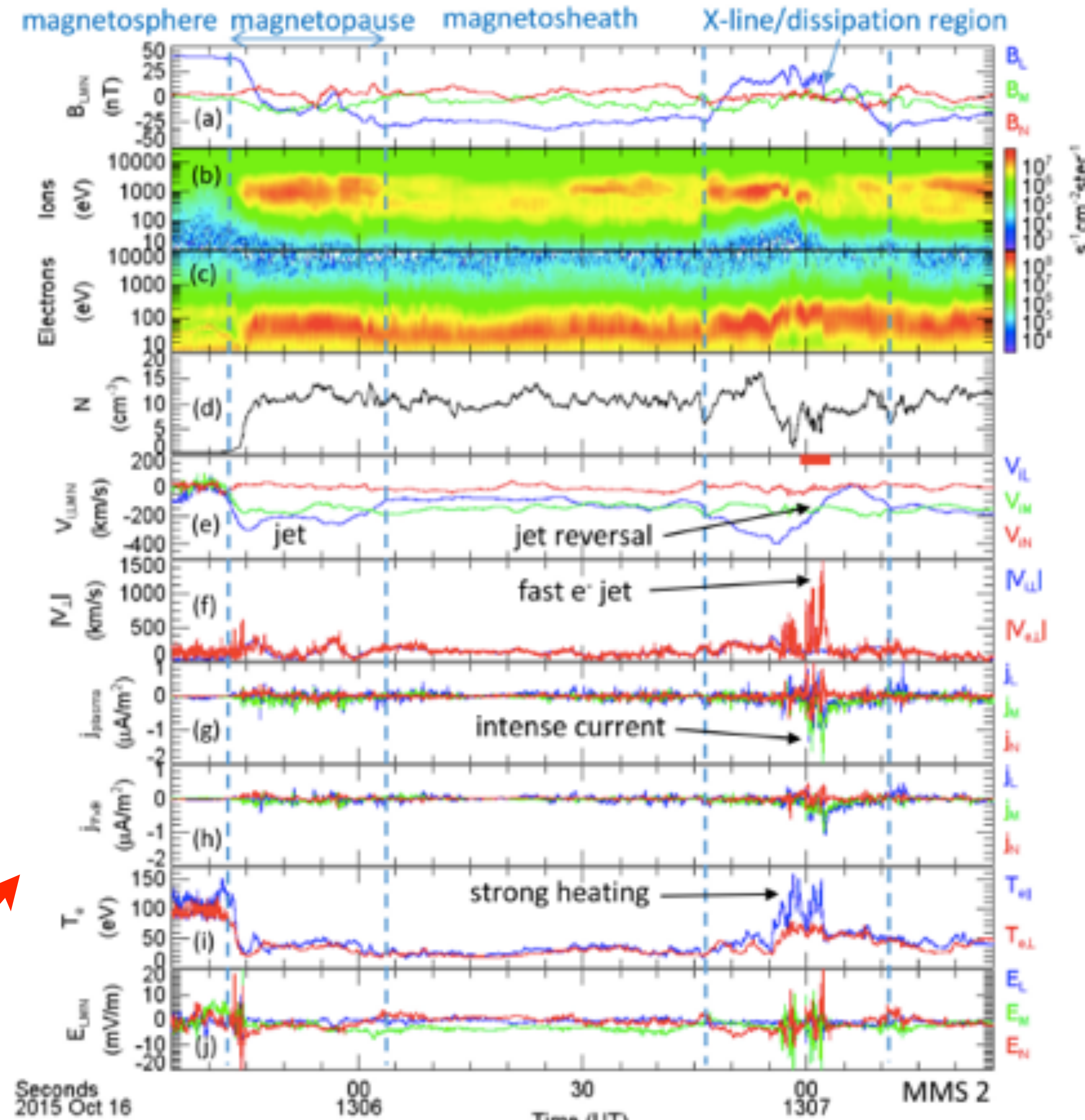


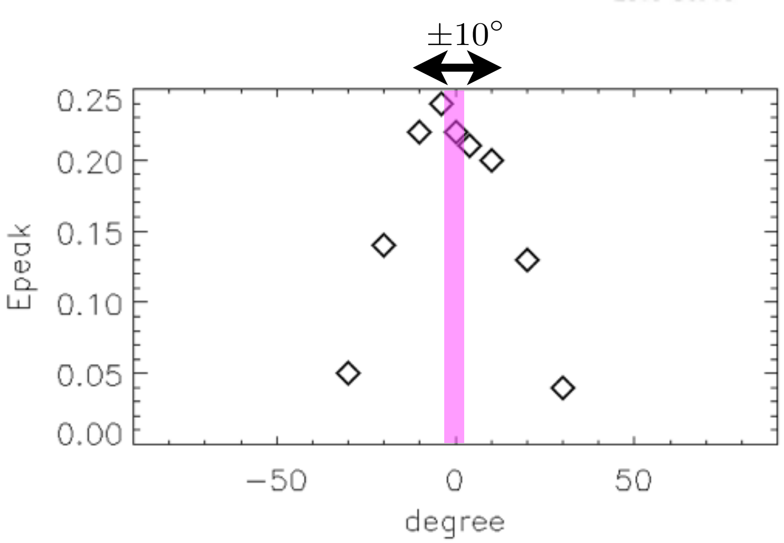
Why do we need to find the reconnection plane???

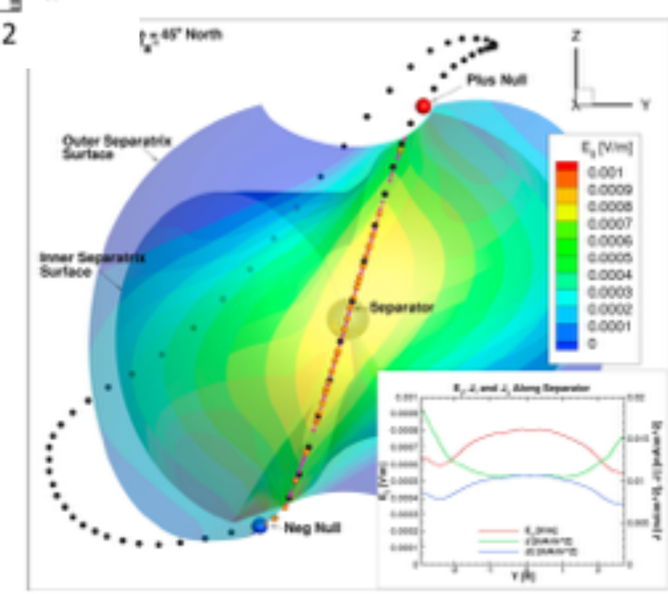
Tools of observers. It is easy to test if reconnection occurs,
-- Generation of normal B
-- Walen test, Alfvenic jet reversal
-- Distributions.
However, to learn more about reconnection, we better know the plane of reconnection.

- Better estimate the energy conversion (Shay, Phan, Yamada ....etc), particle energization.
- If you want to know the reconnection rate-Ey- quasi-2D approximation!
  - -- impossible to integrate along E||.
  - -- but measures Ey at one point.
- Better compare with PIC simulations.
  - -- distribution differs at different plane.
  - -- you want to compare with those in a right plane.
- Local geometry near the diffusion region.
  - -- local reconstruction.
- One of the topic brought up in GEM workshop, "global vs. local".
  - -- Local or global physics (global separator) that controls the x-line orientation?
  - -- local reconstruction of the event + global simulation+ local simulation
- Better understand the effect of shear flows & diamagnetic drift on reconnection.
  - -- shear flows & diamagnetic drift along the L direction could suppress
  - -- shear flows & diamagnetic drift along the M direction does not suppress.

- More reasons?


magnetosphere
magnetopause
magnetosheath
X-line/dissipation region
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
jet
jet reversal
fast e⁻ jet
intense current
strong heating
Seconds
2015 Oct 16
00
1306
30
00
1307
MMS 2


±10°
Epeak
0.25
0.20
0.15
0.10
0.05
0.00
−50
0
50
degree


Plus Null
Outer Separatrix Surface
Inner Separatrix Surface
Separator
Neg Null