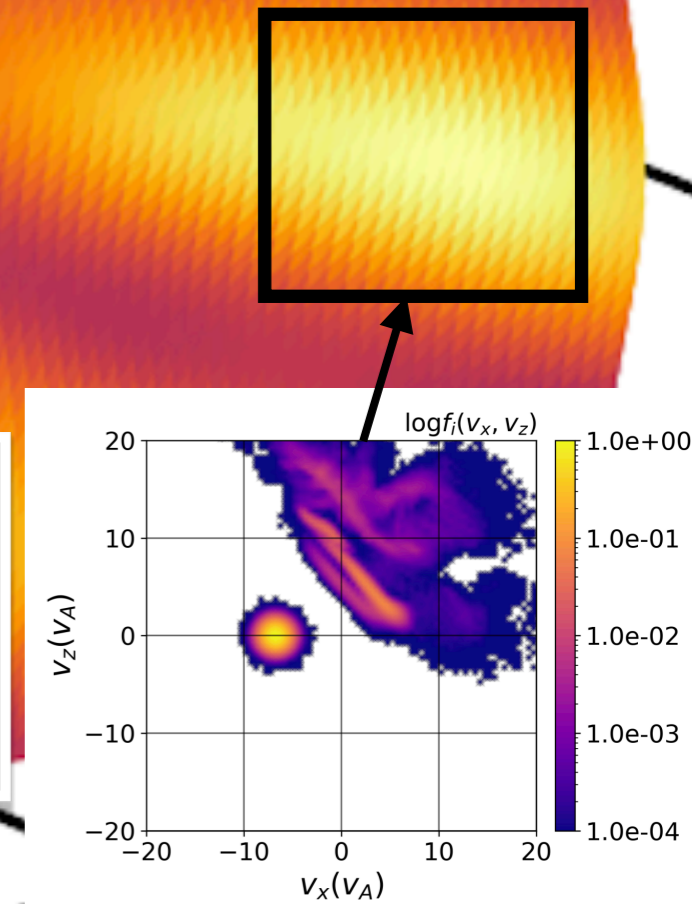


# Leveraging Phase Space to Understand Energization in Collisionless Shocks

James Juno

With many thanks to the **Gkeyll** team: Ammar Hakim, Noah Mandell, Manaure Francisquez, Liang Wang, Jason TenBarge, Gregory Hammett, Tess Bernard, Petr Cagas, Kolter Bradshaw, John Rodman, Bhuvana Srinivasan  
**And other collaborators:** Bill Dorland, Greg Howes, Collin Brown, Colby Haggerty, Kris Klein, Lynn Wilson III, Anatoly Spitkovsky, Damiano Caprioli



# So what is this session all about?

Shocks are a key mechanism responsible for transforming super-sonic flow energy into particle energization. However, most plasma in the heliosphere is sufficiently weakly collisional that the shocks are collisionless and must irreversibly process flow energy into thermal energy through means other than particle-particle collisions. These other processes are inherently kinetic, whether the shocks are driven by coronal mass ejections, the solar wind impinging on the Earth's magnetosphere, or at the heliospheric termination shock. Understanding these processes and how they connect the different systems separated by a collisionless shock requires a coordinated community effort combining kinetic modeling, in situ spacecraft data, and remote observations.

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How do these kinetic mechanisms depend on the local plasma environment throughout the heliosphere?

How well can we address these questions with current and upcoming missions?

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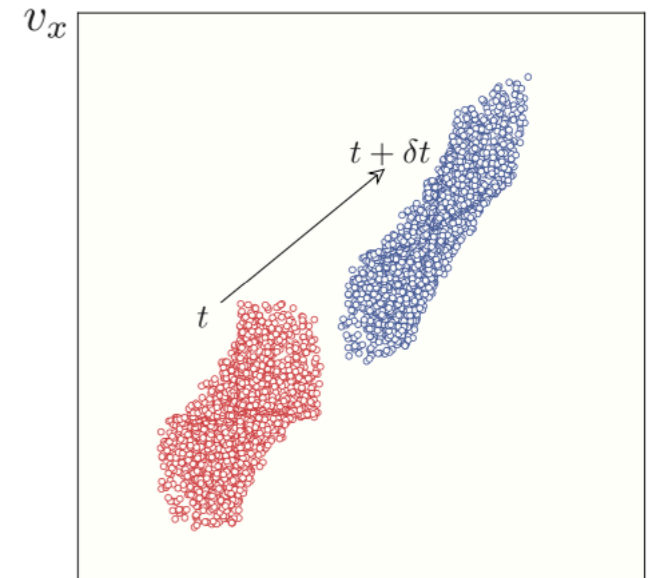
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Adapted from  
Colonna & D'Angola  
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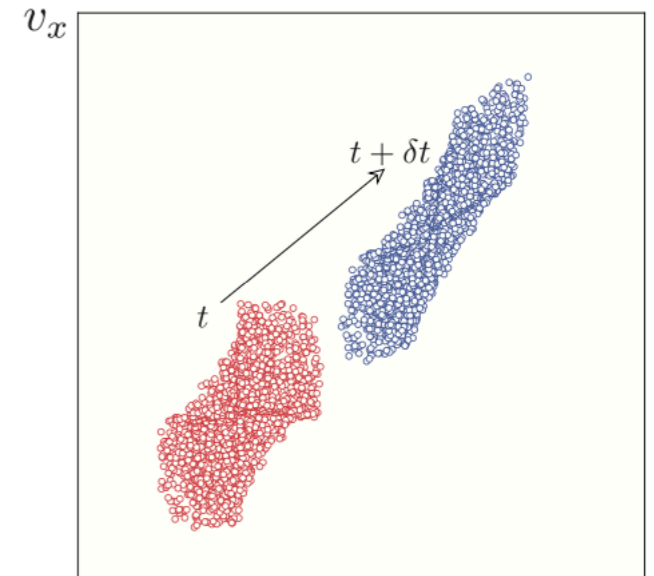
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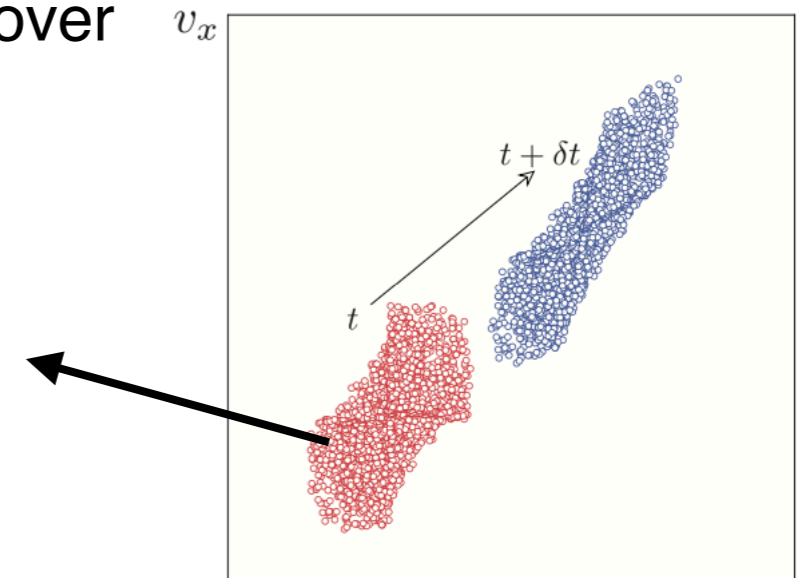
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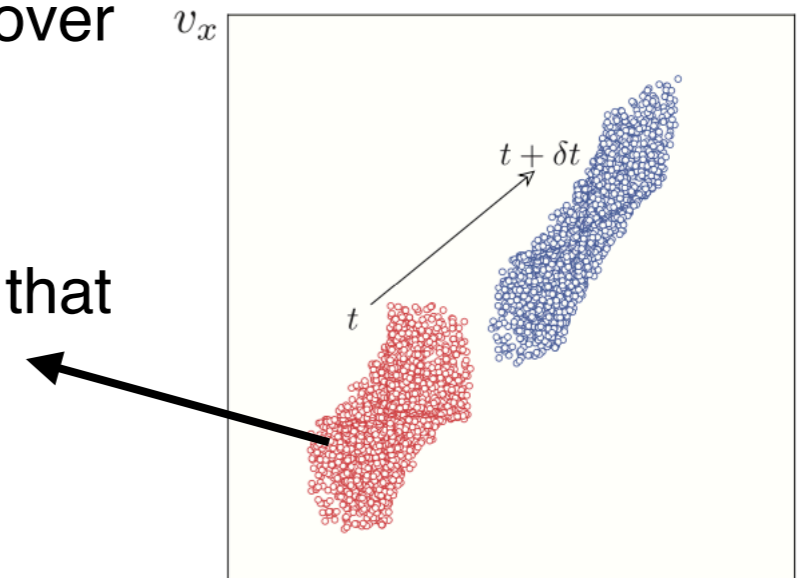
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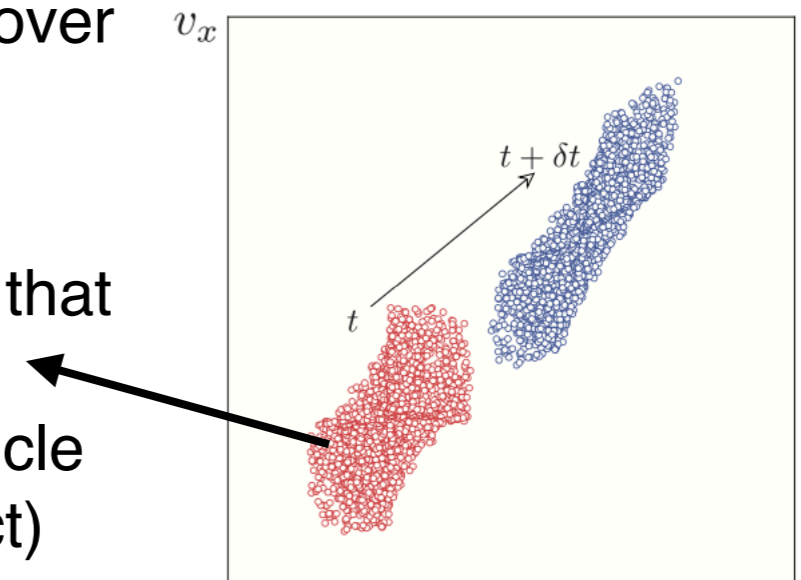
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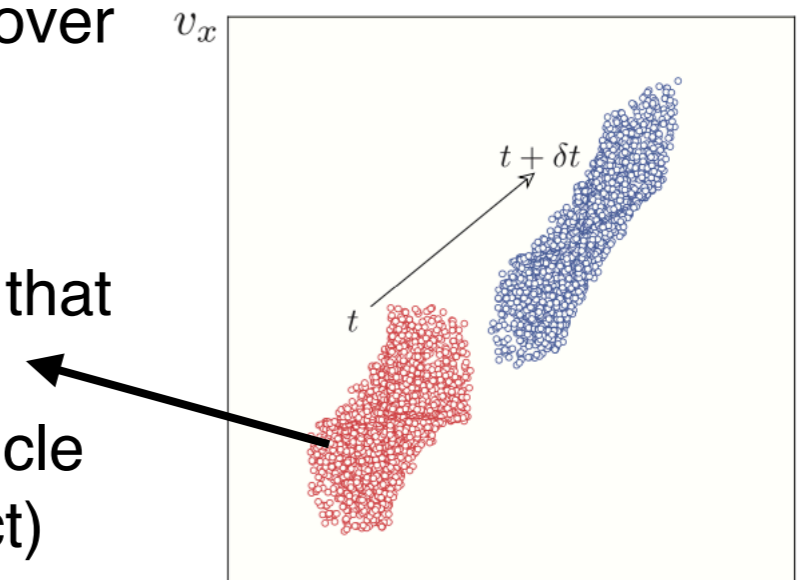
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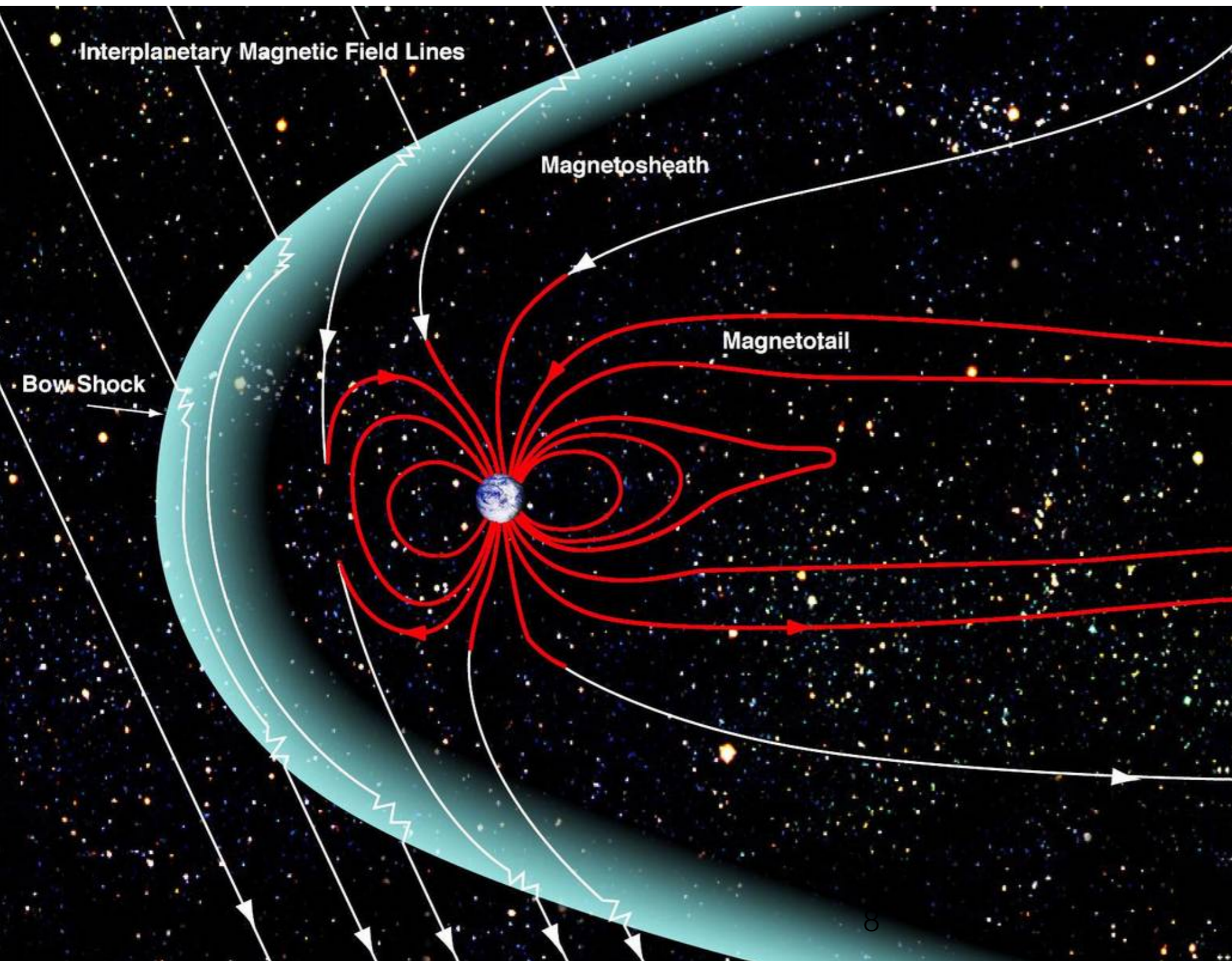
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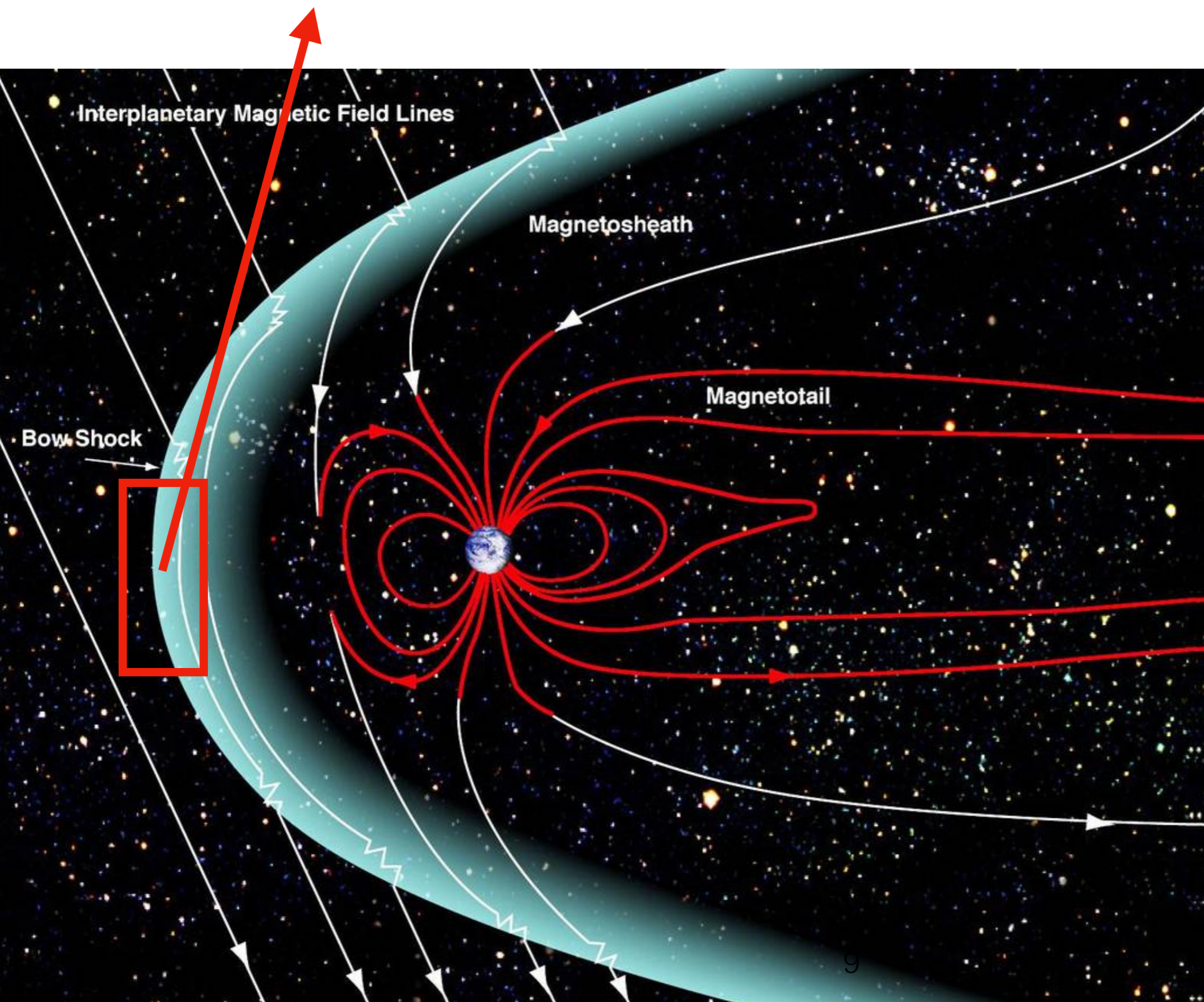
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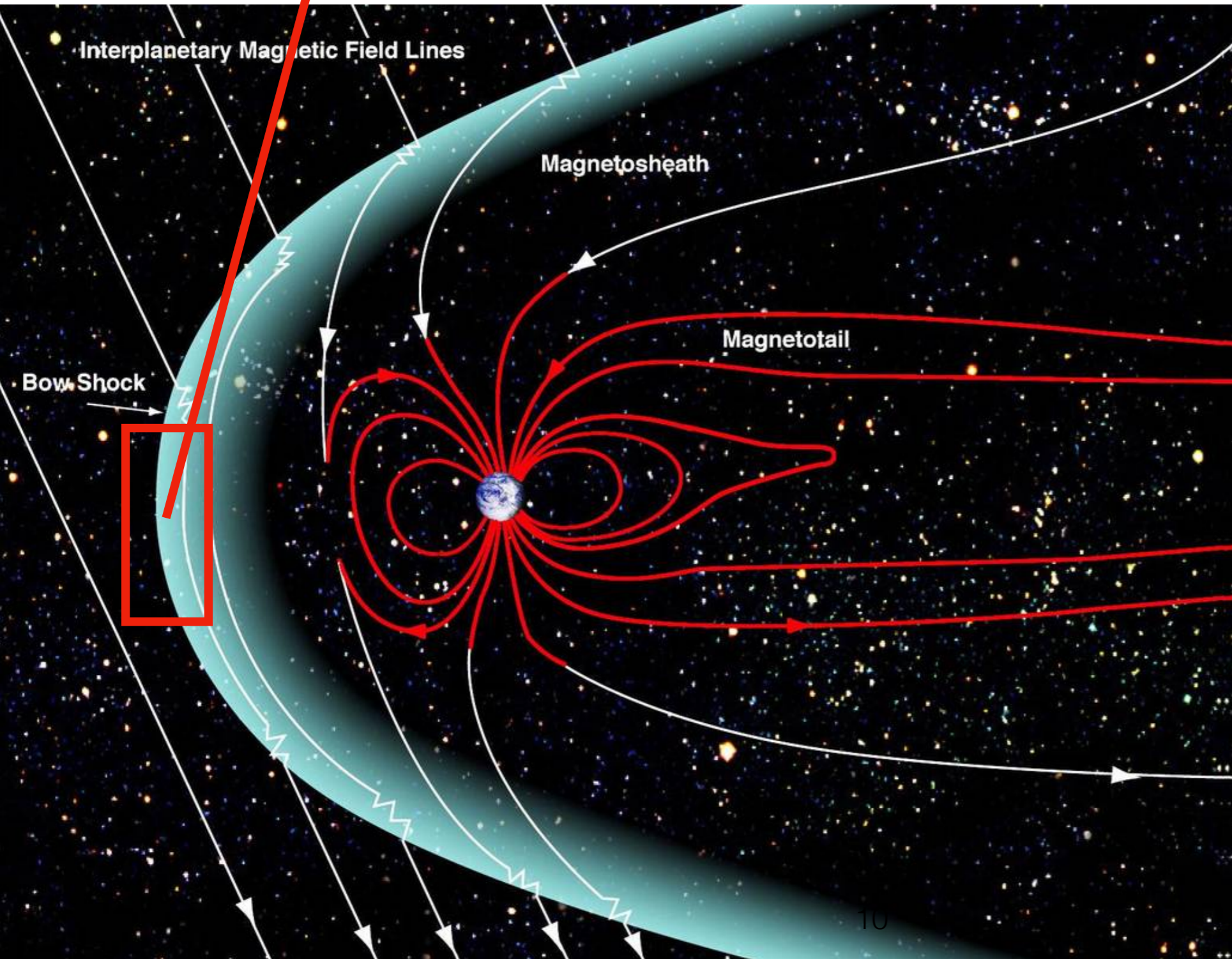
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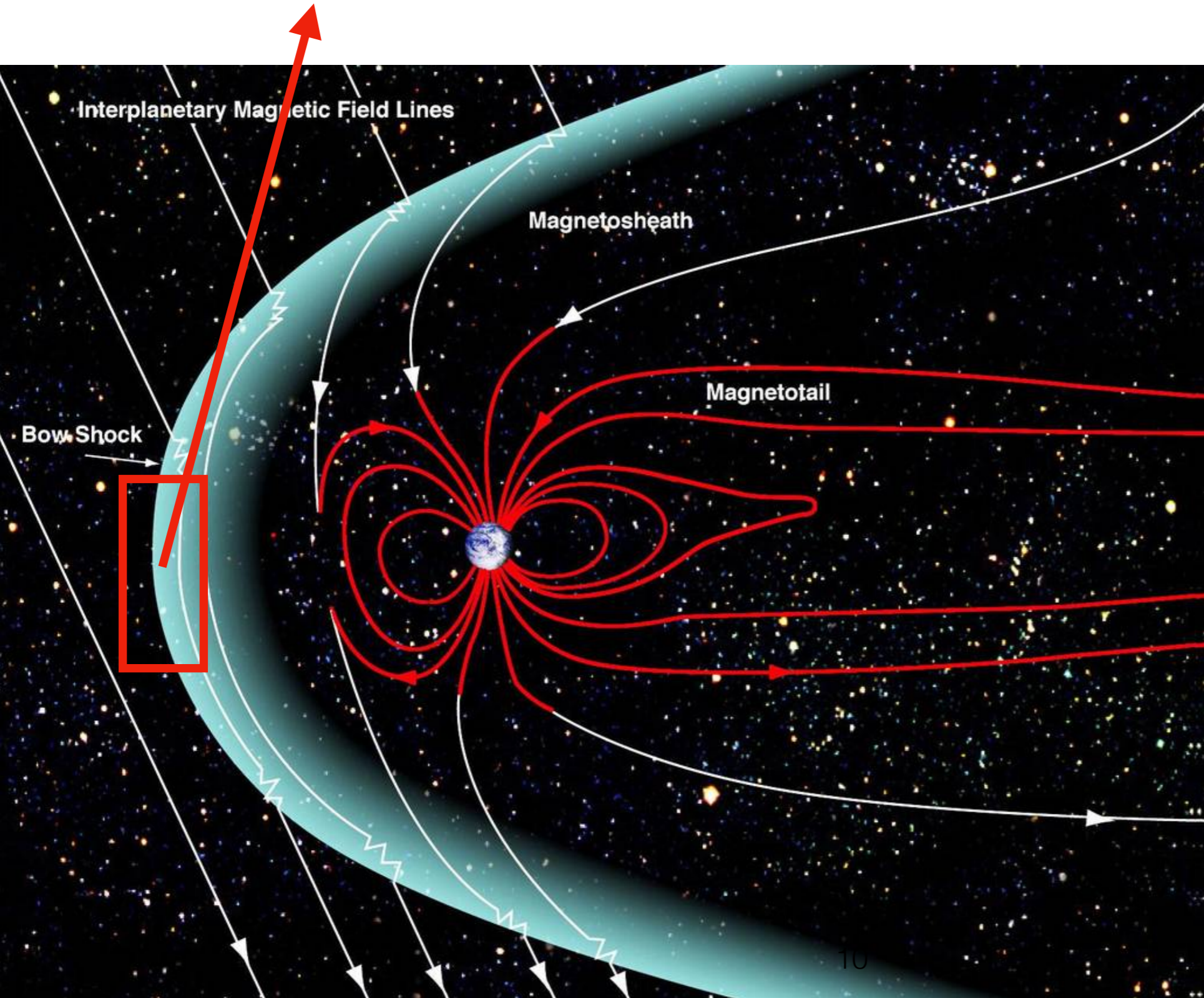
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Artist's rendering MMS Bow shock crossing  
 image credit: NASA, SwRI

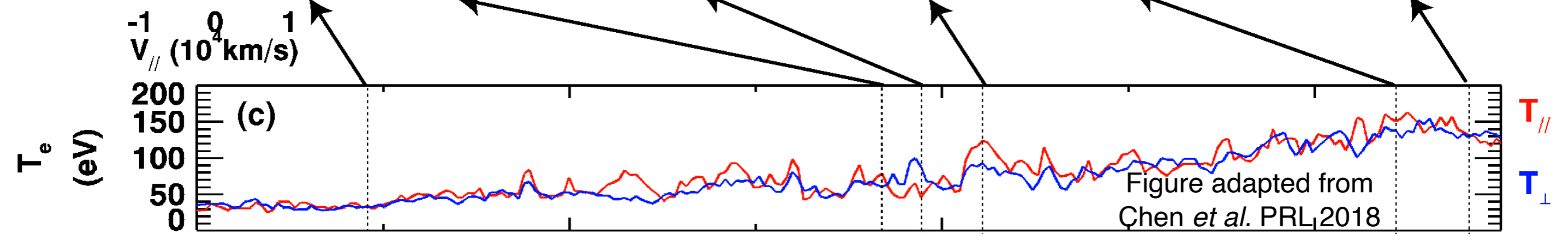
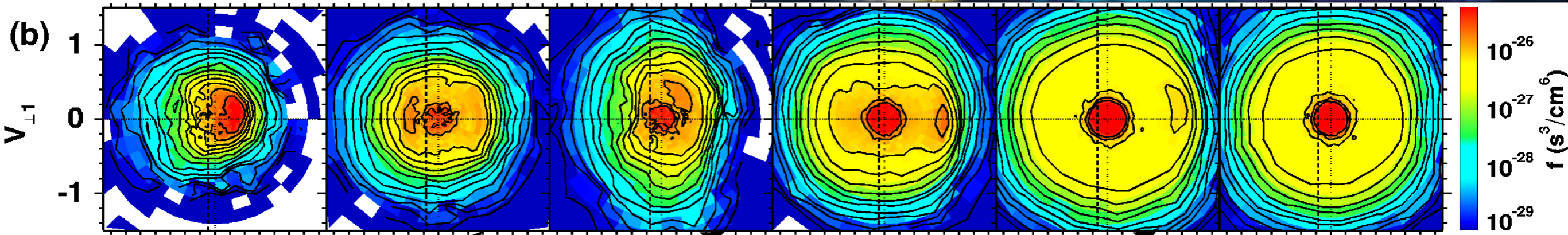
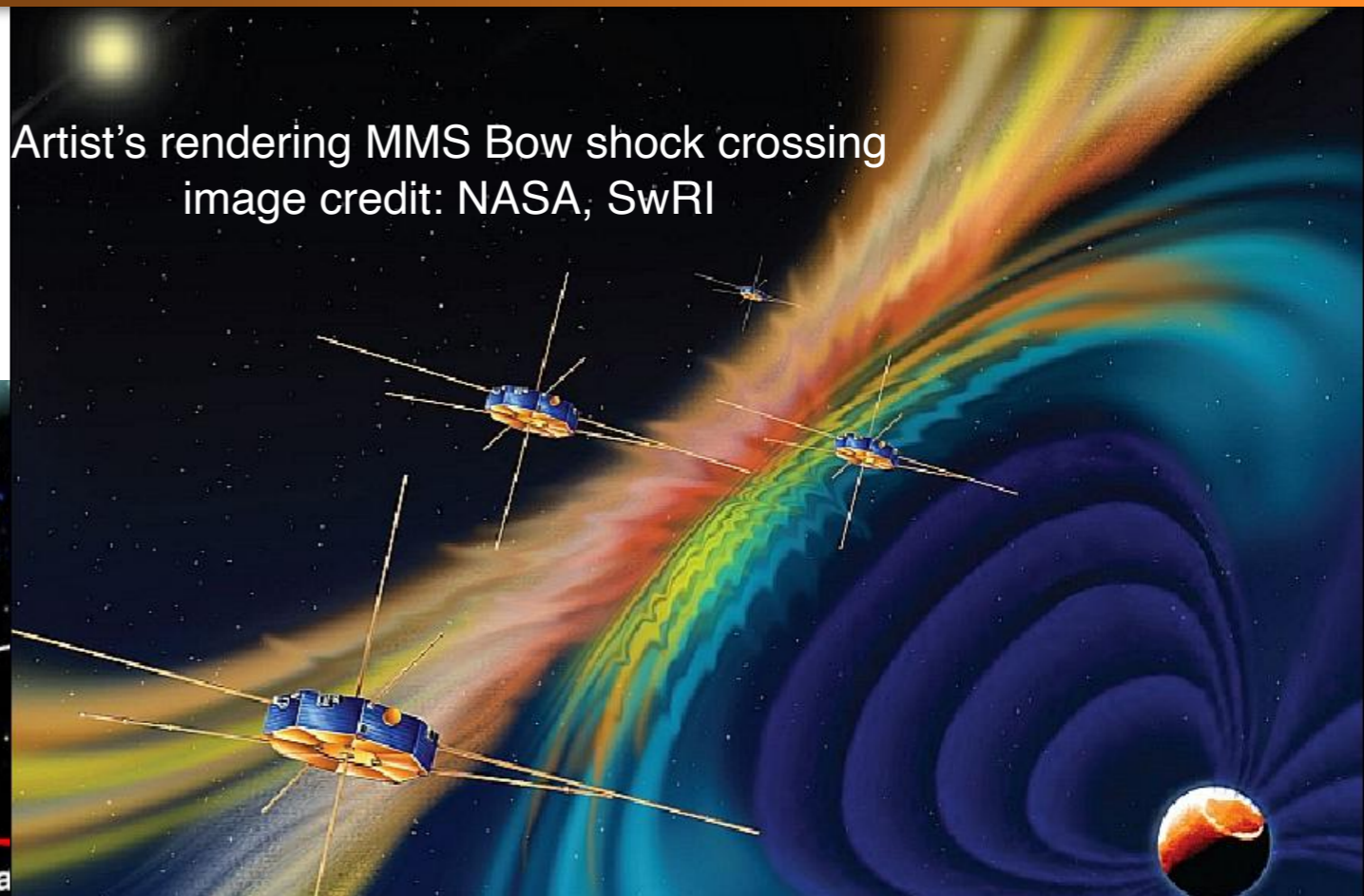
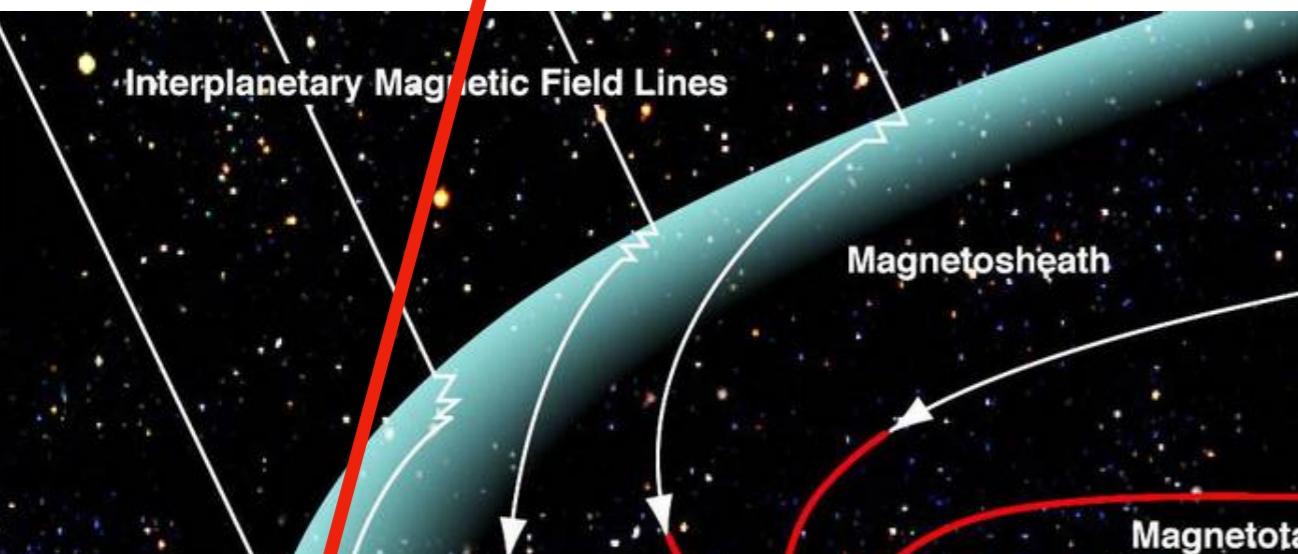


Figure adapted from  
 Chen *et al.* PRL, 2018

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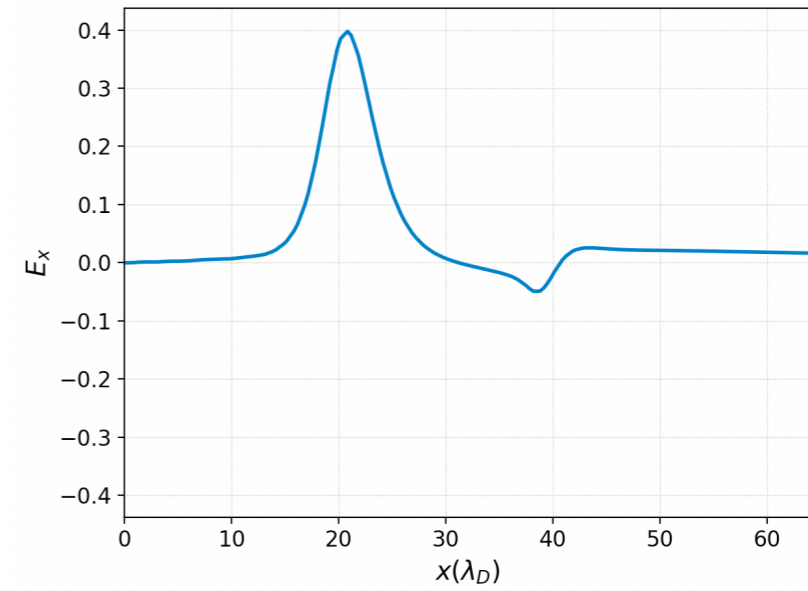
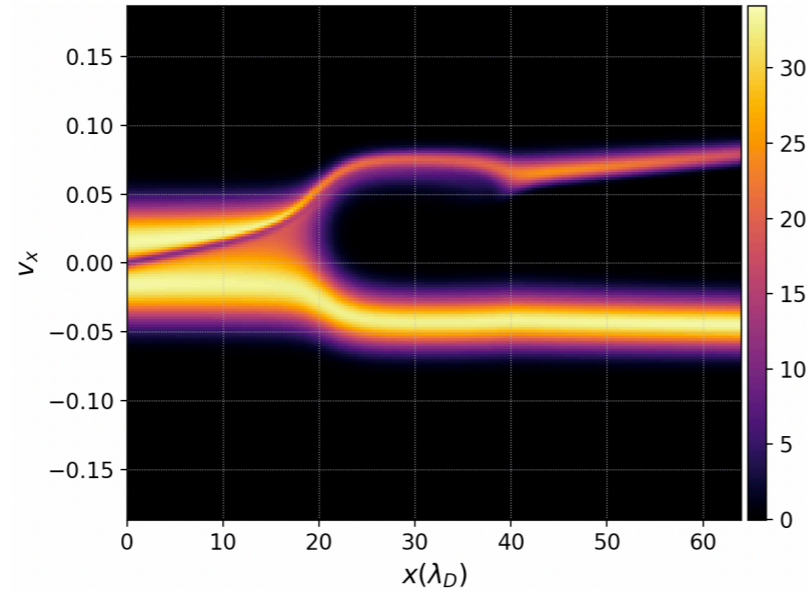
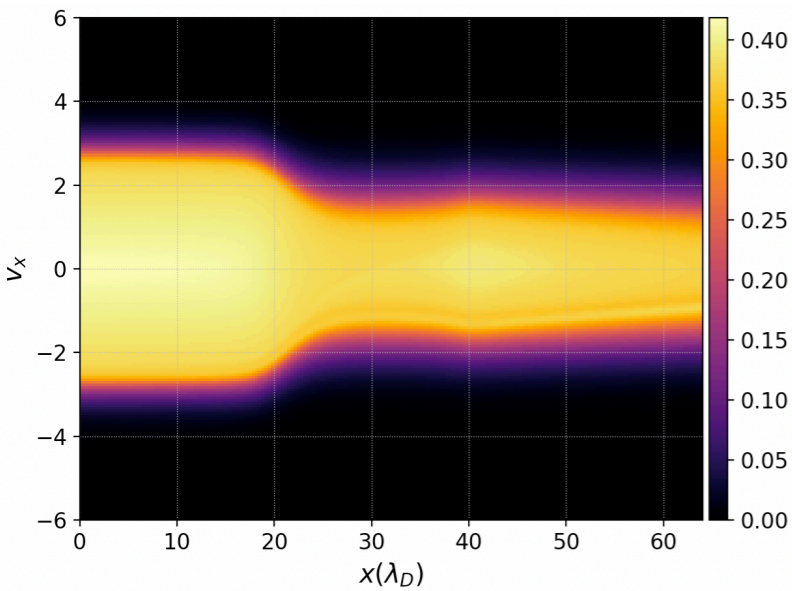
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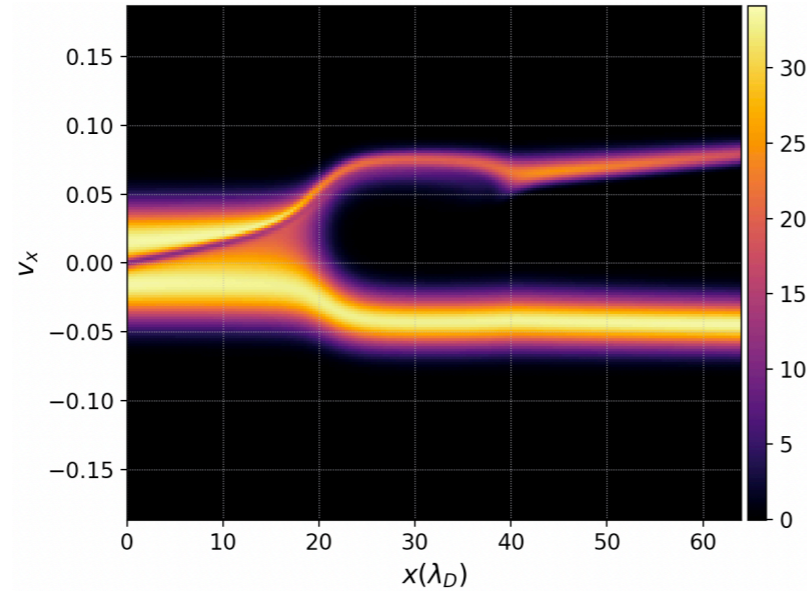
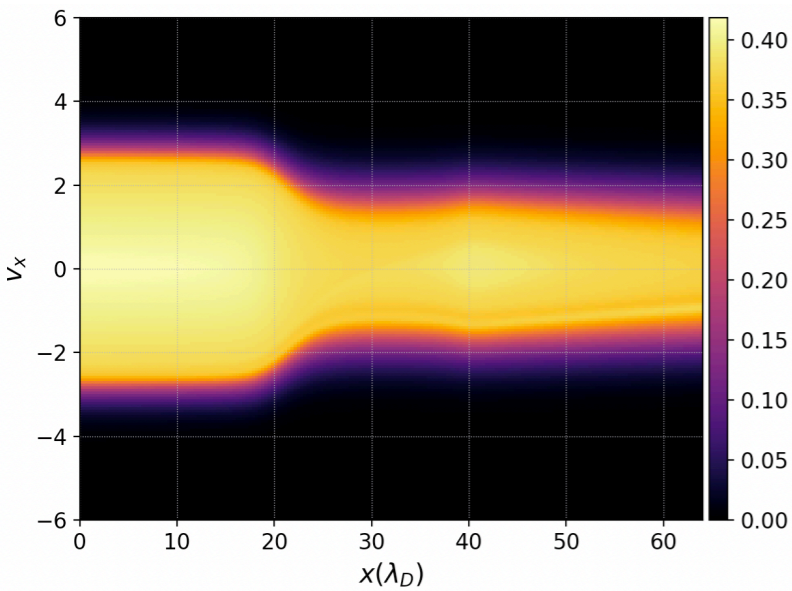
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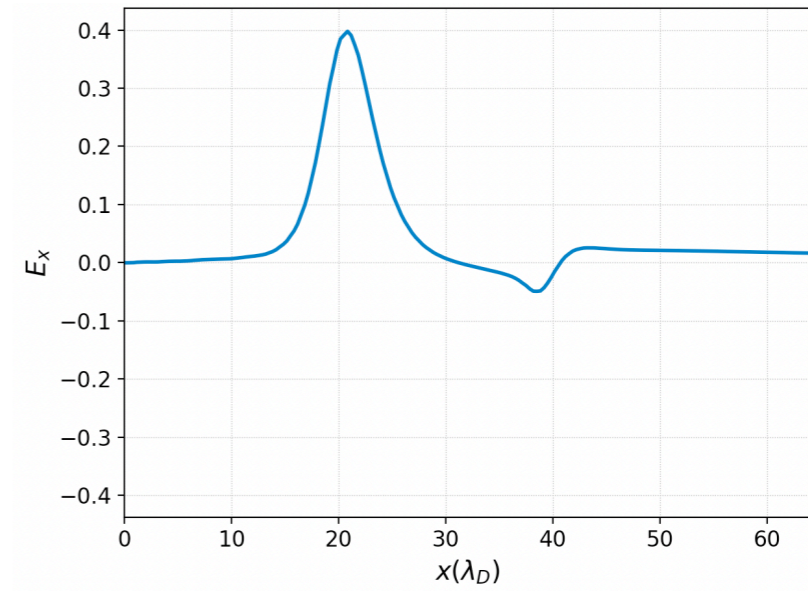
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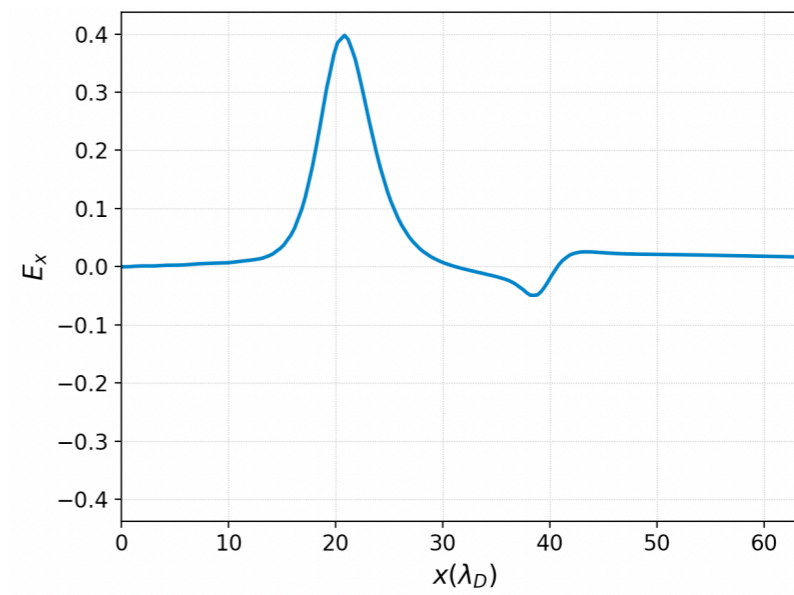
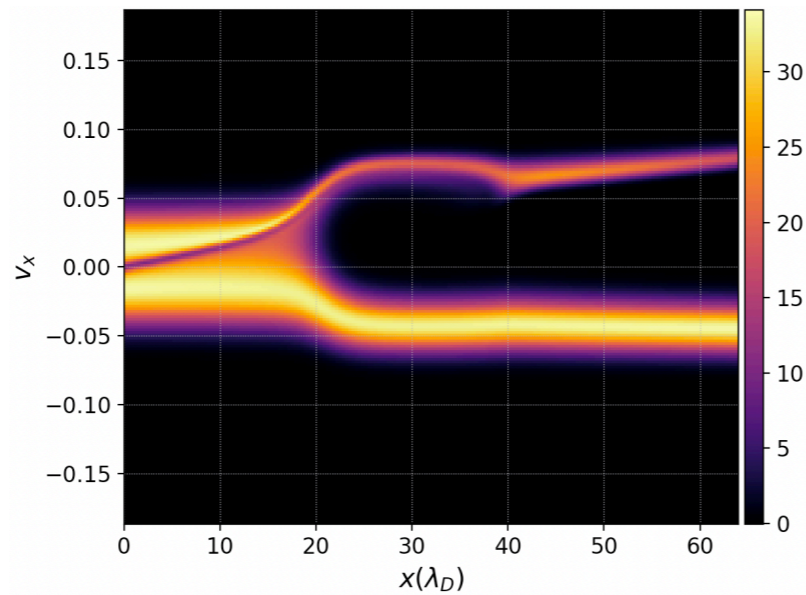
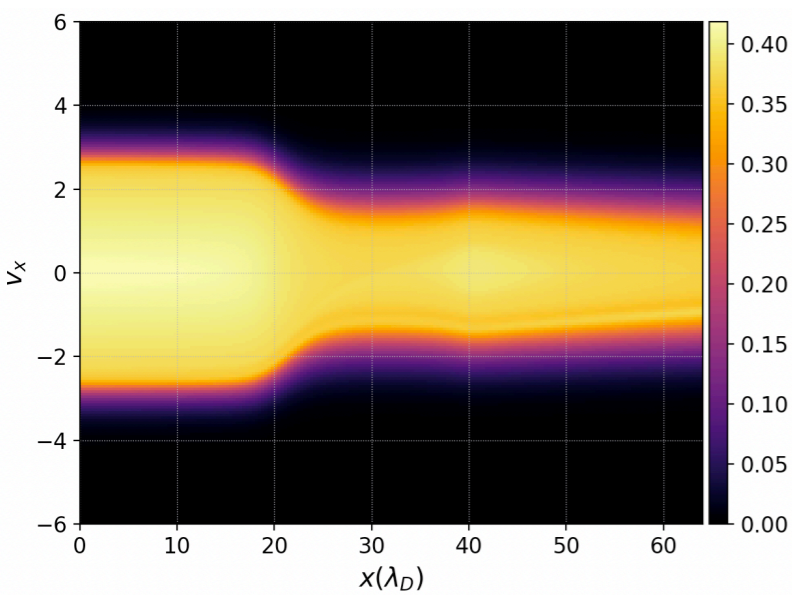
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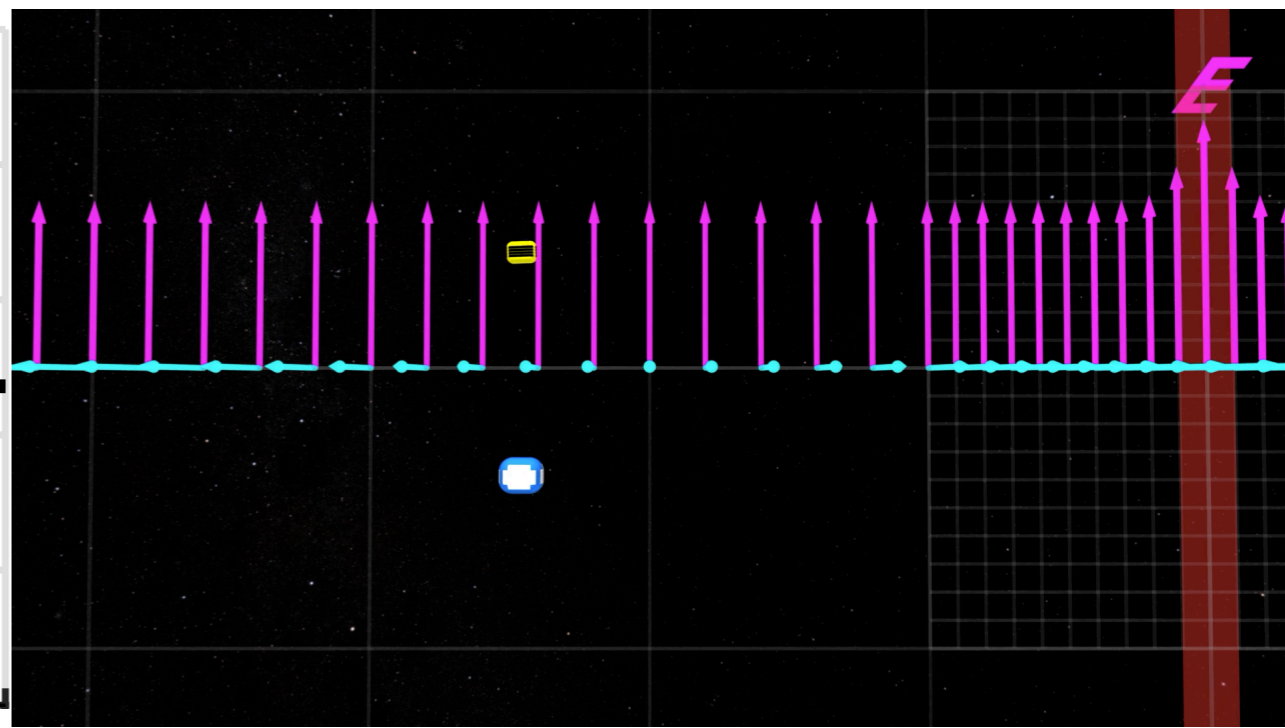
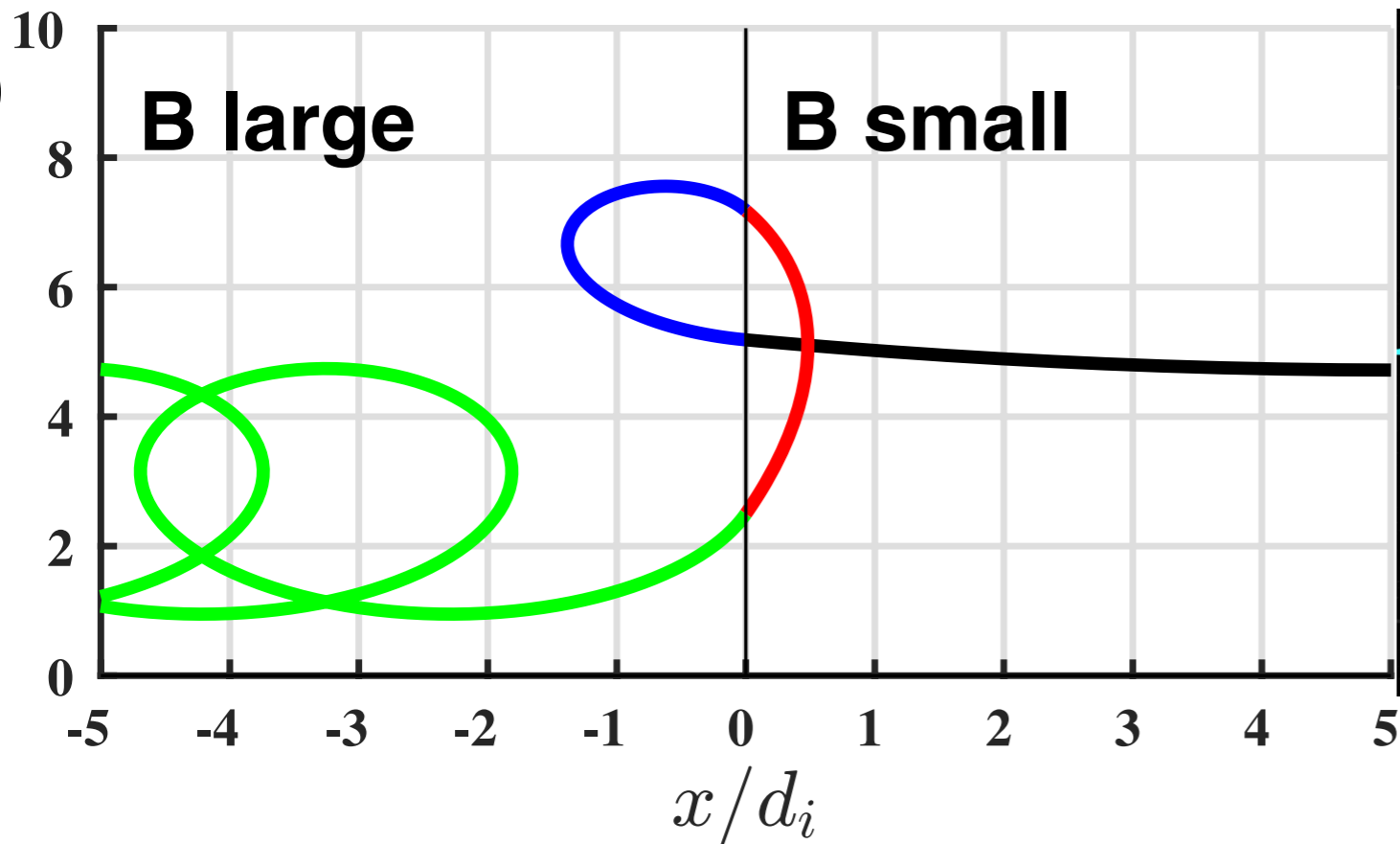
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Video courtesy of NASA Scientific Visualization (Tom Bergman) and Lynn Wilson III: <https://svs.gsfc.nasa.gov/4513>

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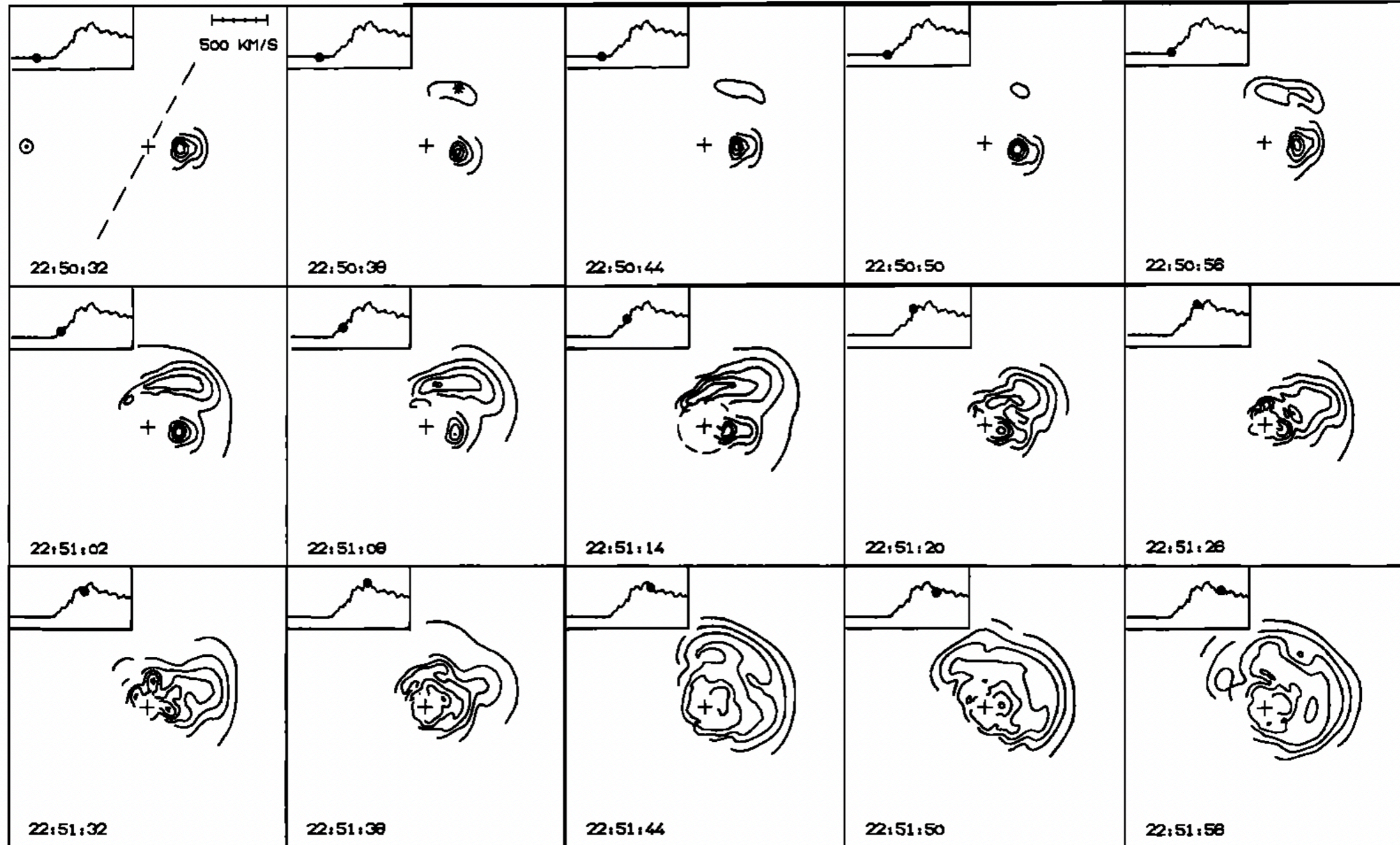
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Figure adapted from Paschmann *et al.* GRL 1982

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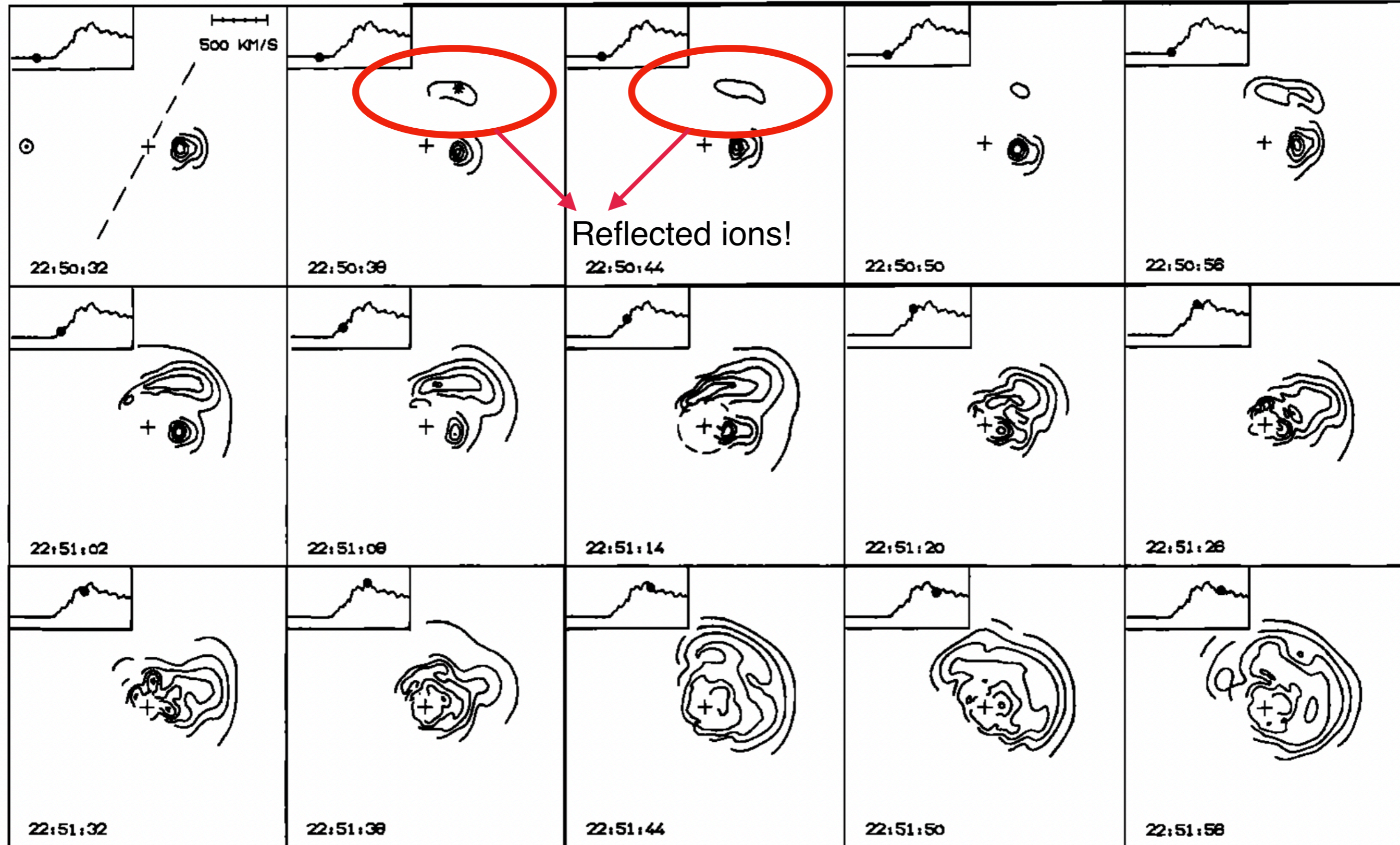


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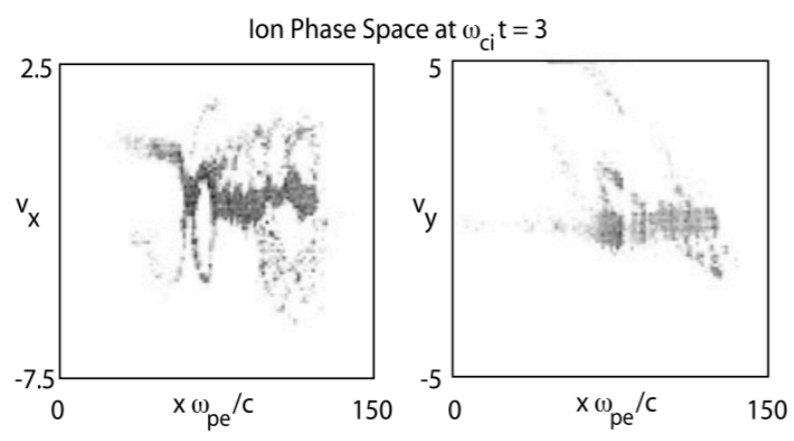
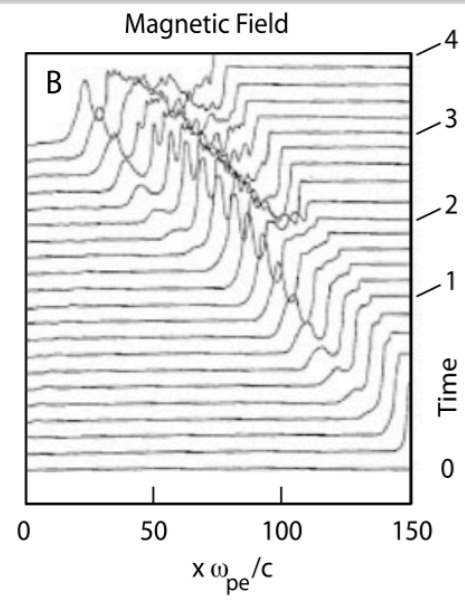
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# Requires kinetic simulations and these are only getting better

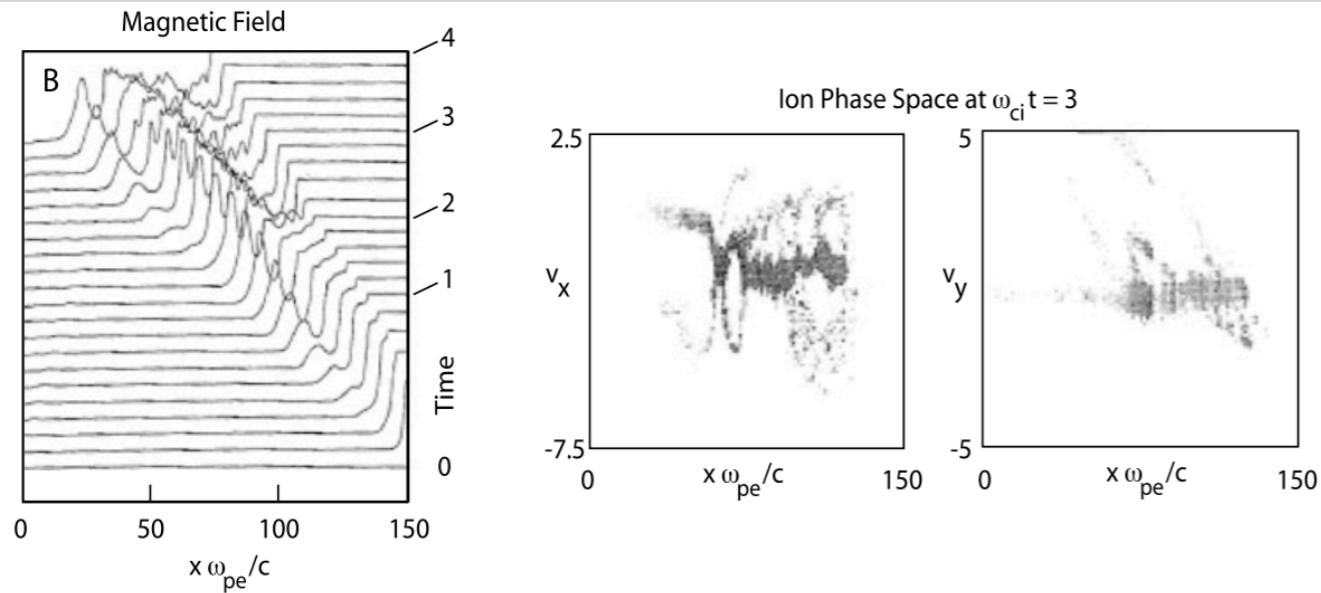


Biskamp & Welter JGR 1972  
(Adapted from Balogh & Treumann 2013)

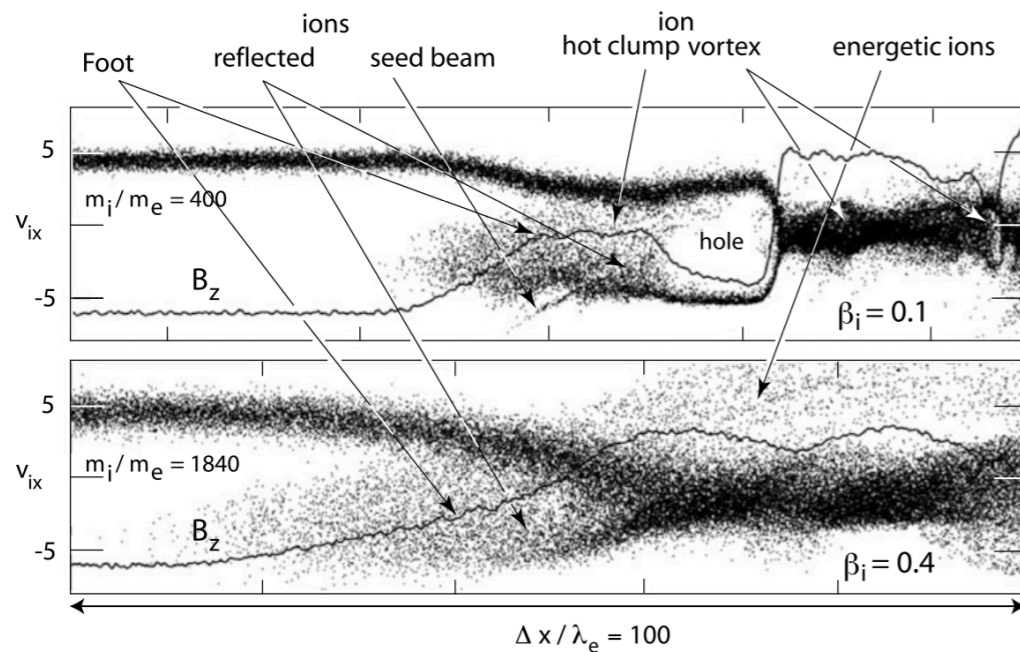
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New algorithms



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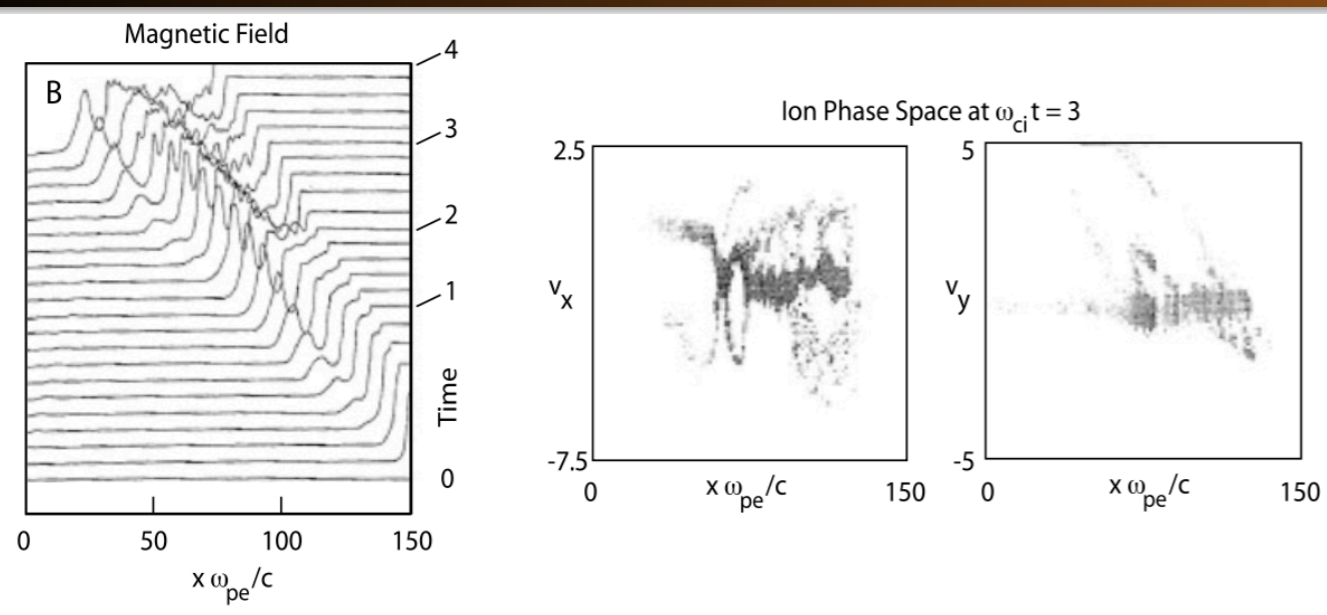
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more particles = more structure  
can even do realistic mass ratios!

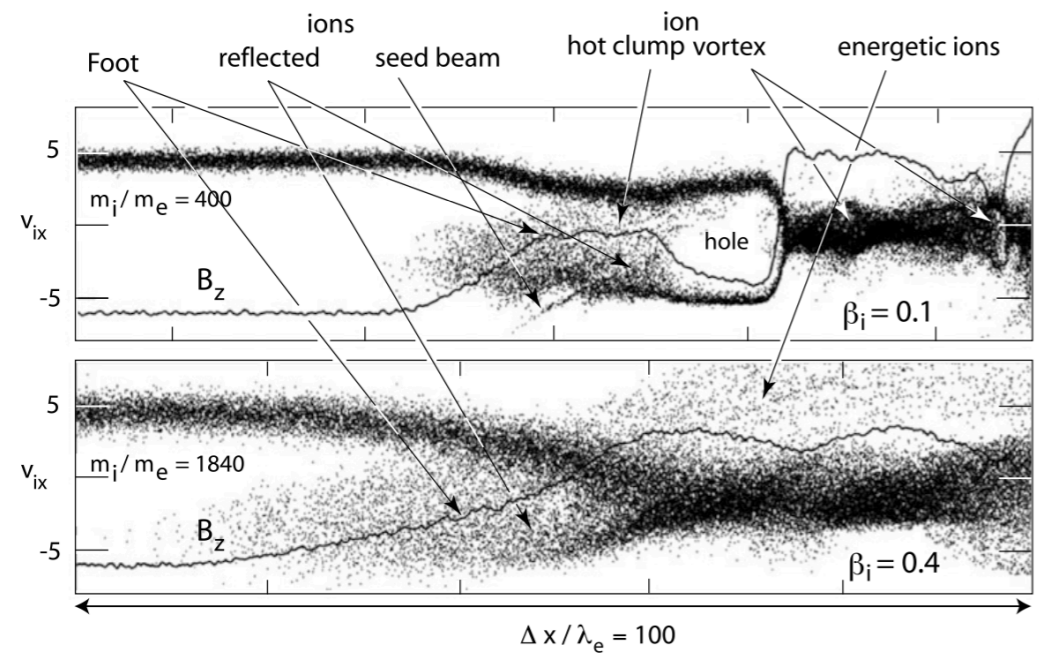
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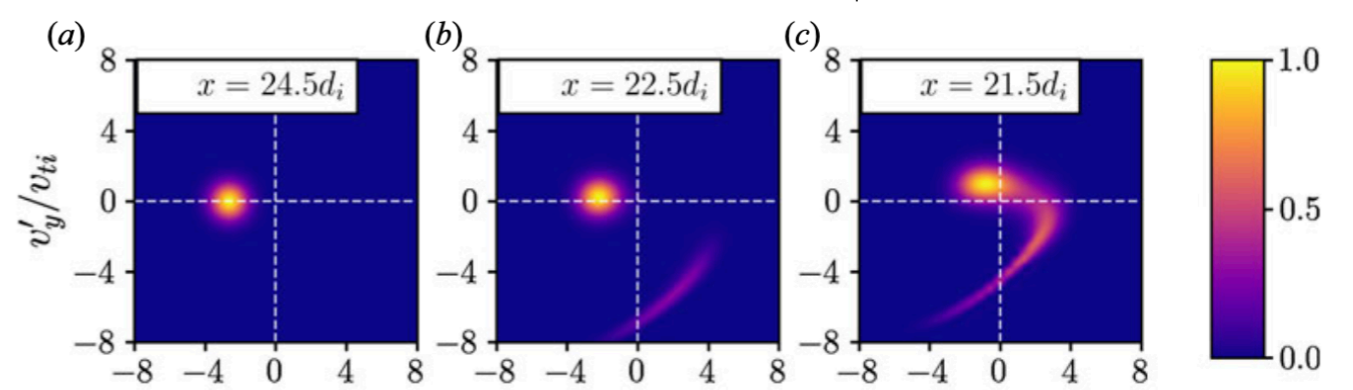
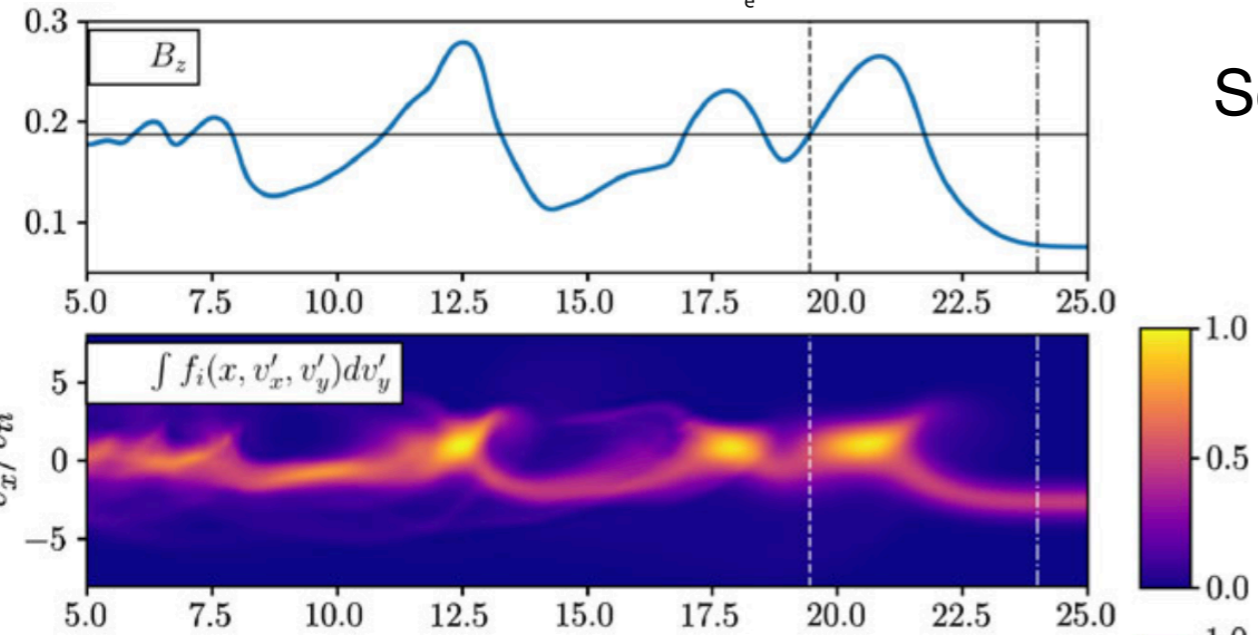
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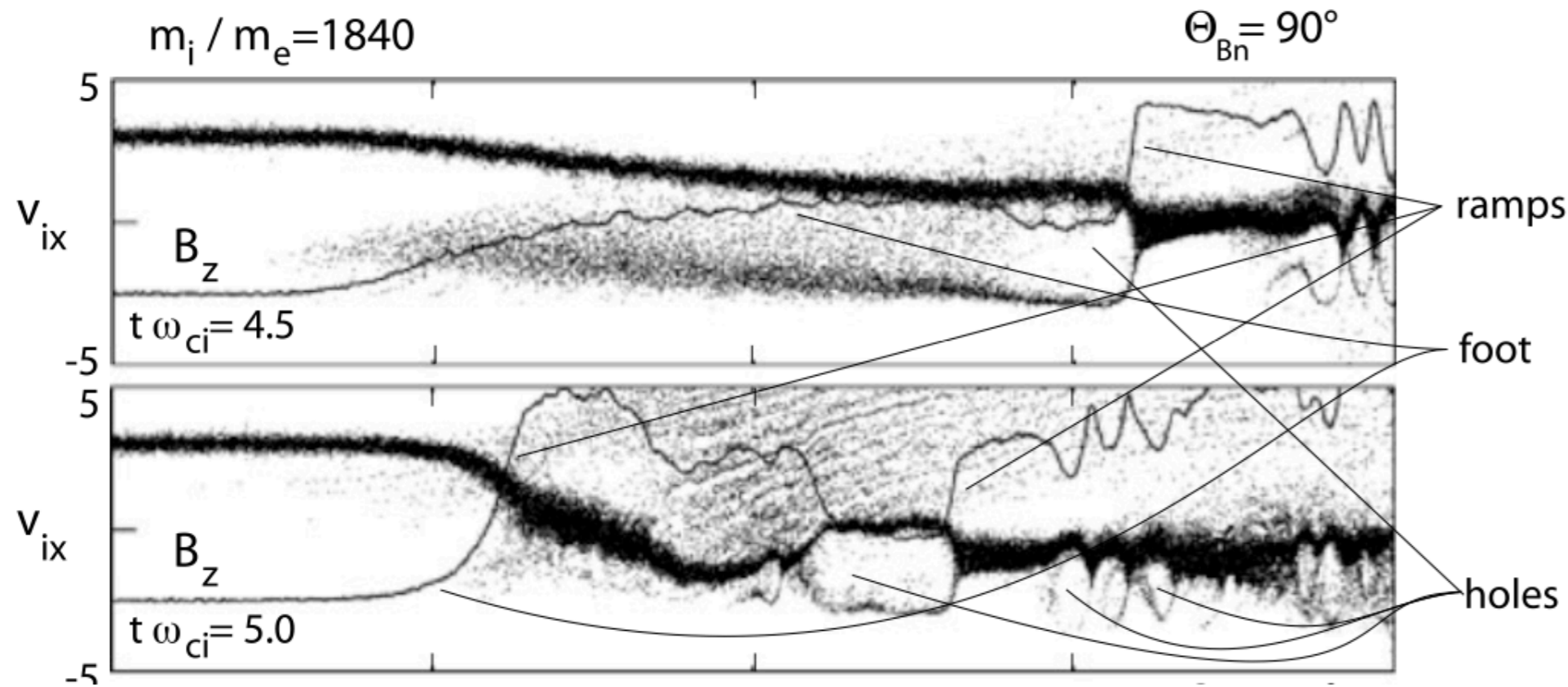
Juno *et al.* JPP 2020  
Noise-free distribution functions  
with grid-based methods!  
See Juno *et al.* JCP 2018, Hakim & Juno Supercomputing 2020

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# And then things go unstable... and then they mix...

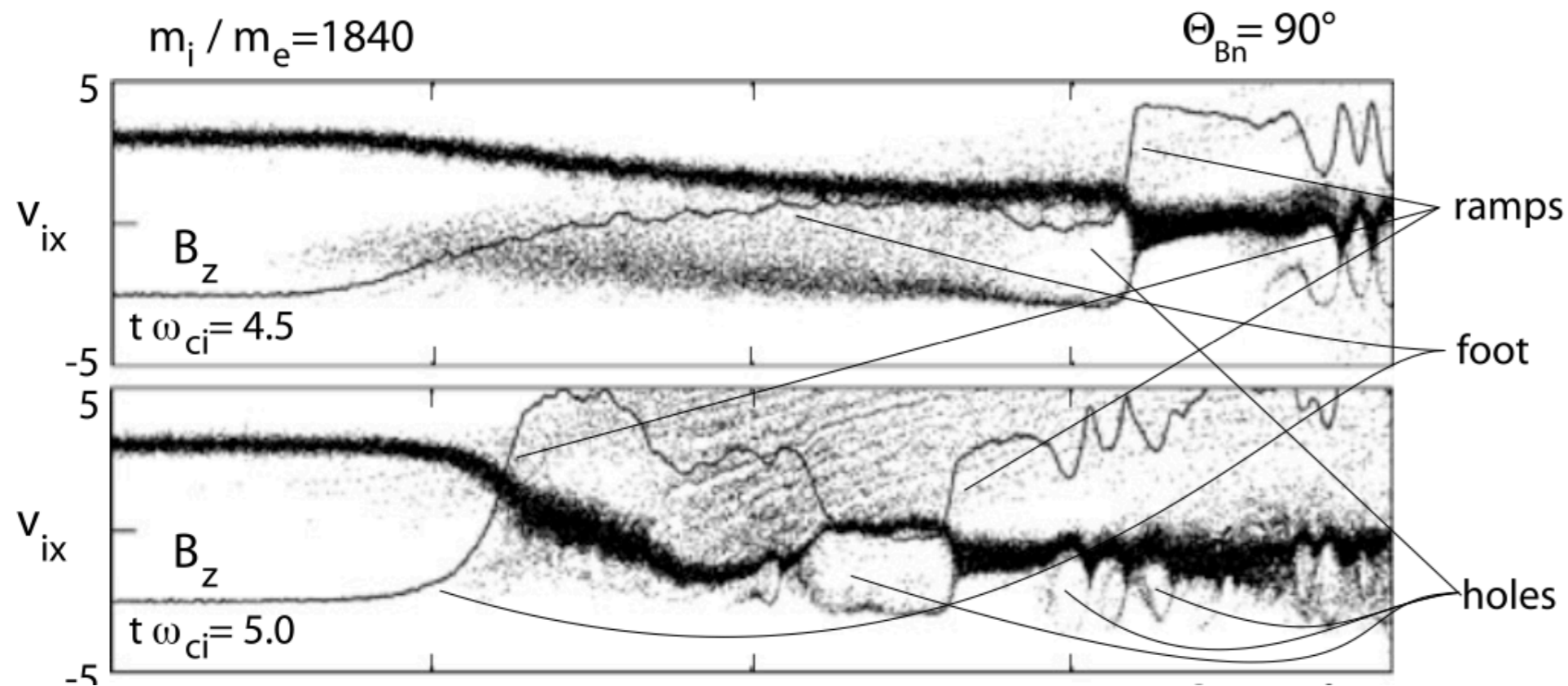
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Matsukiyo & Scholer 2006  
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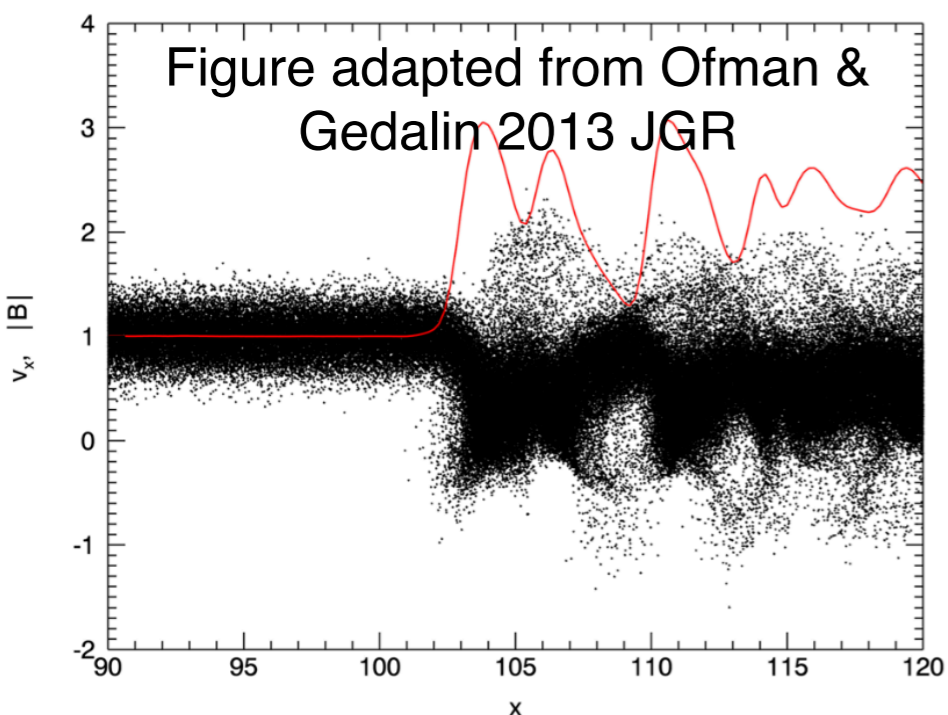
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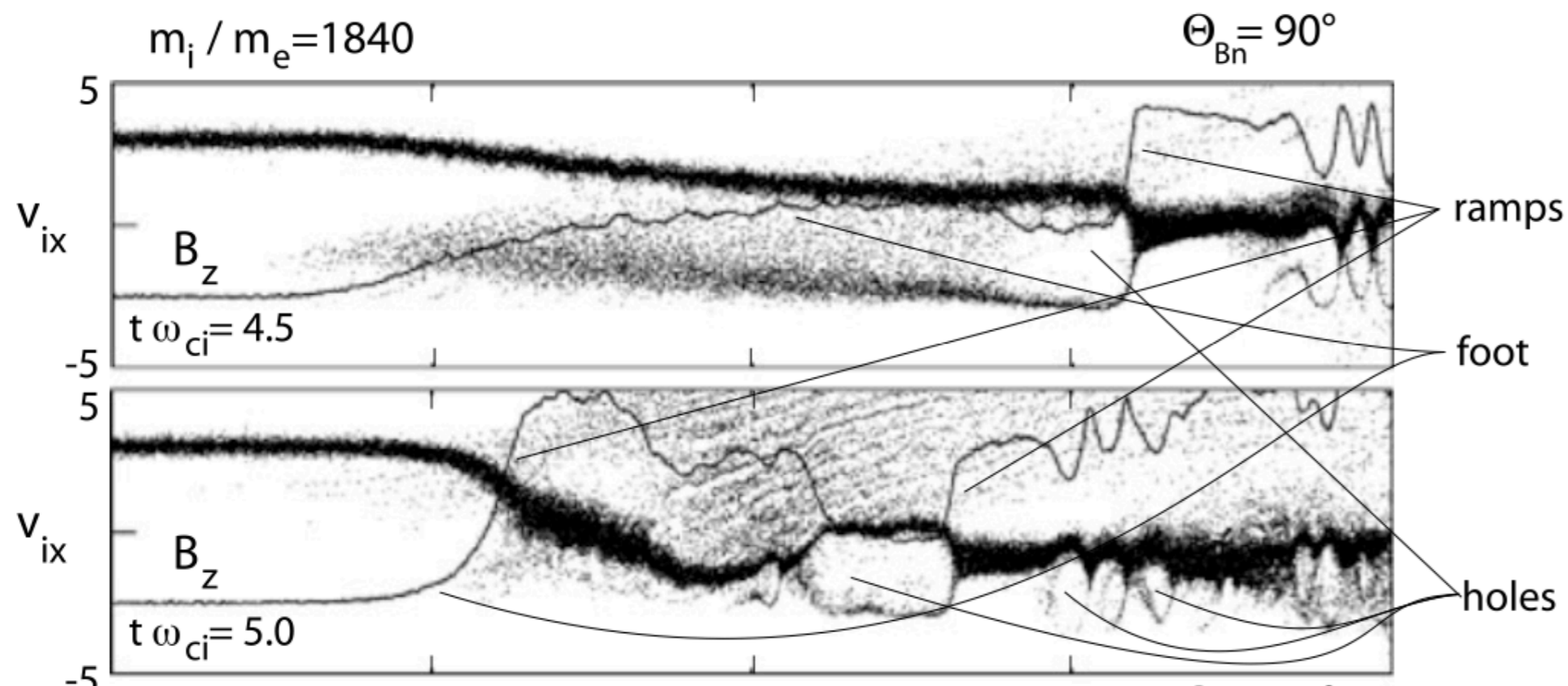
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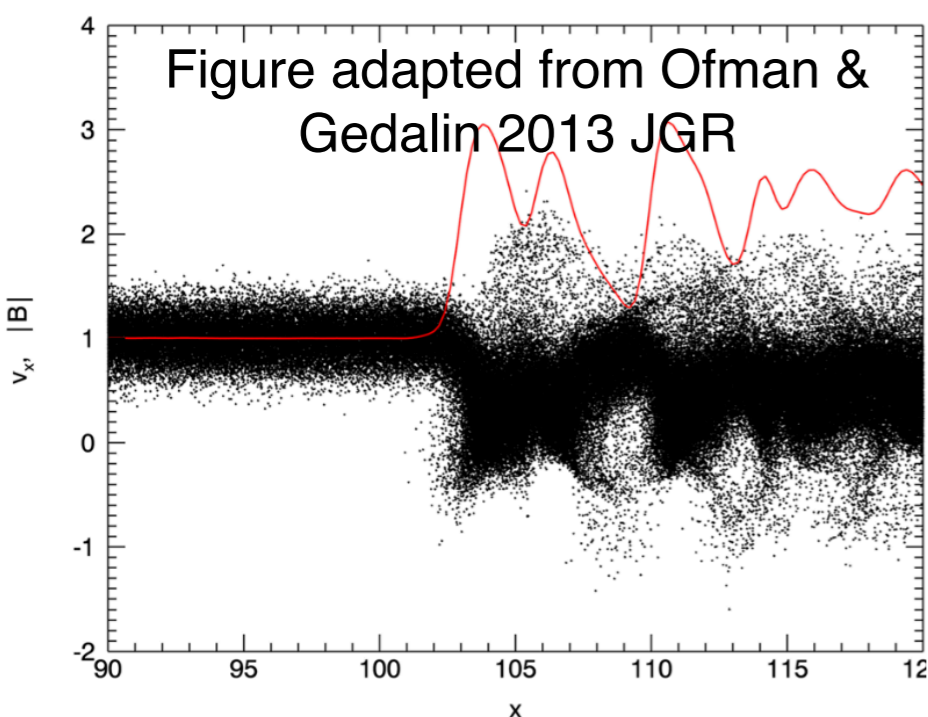
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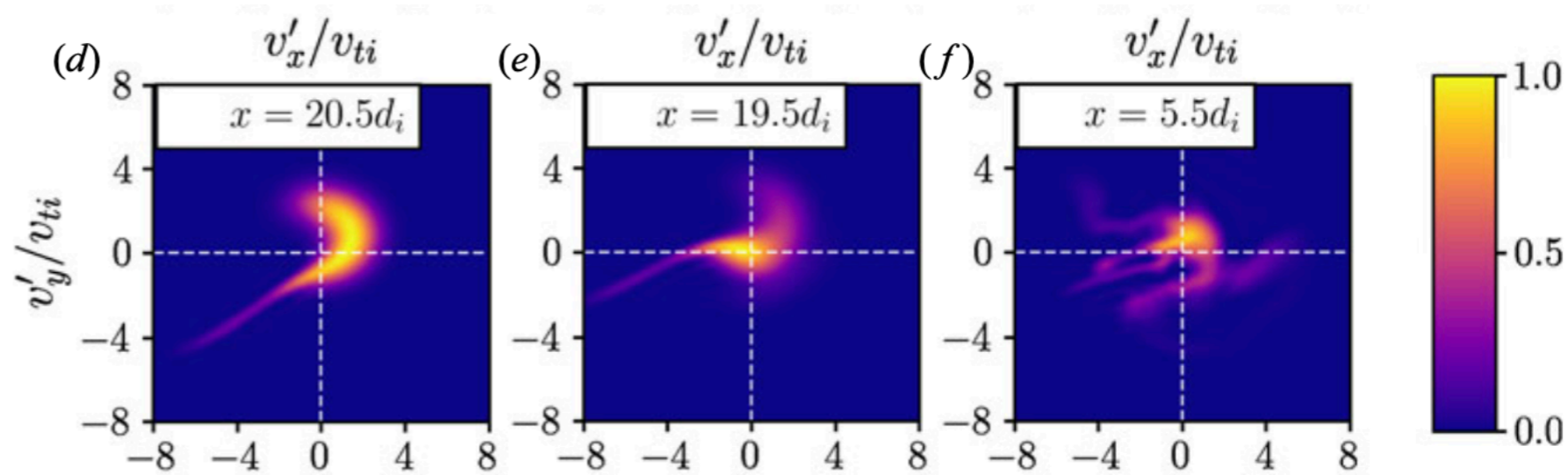


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Mixing driving strong gradients in velocity space  $C[f] \propto \nabla_v^2 f$



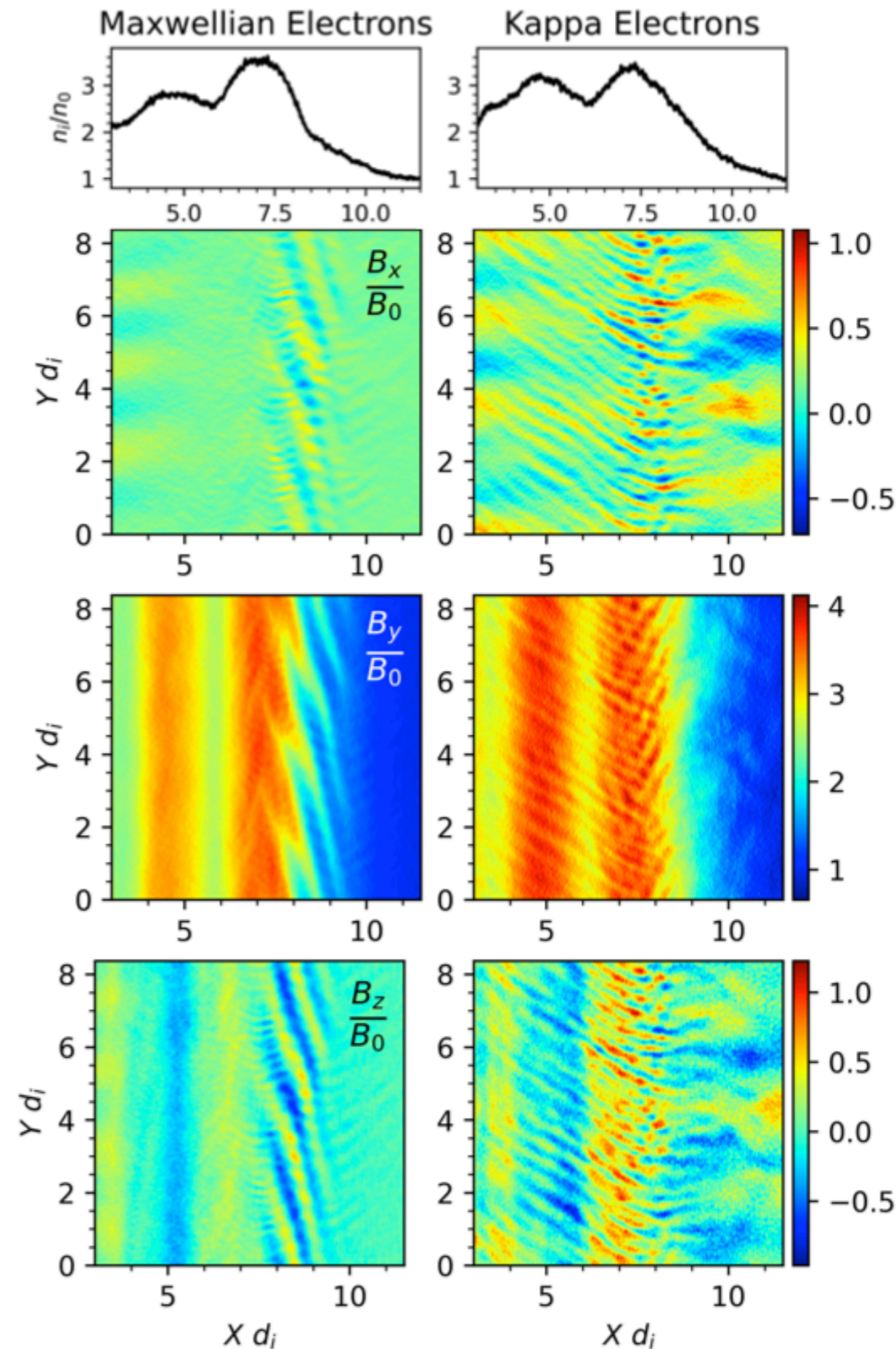
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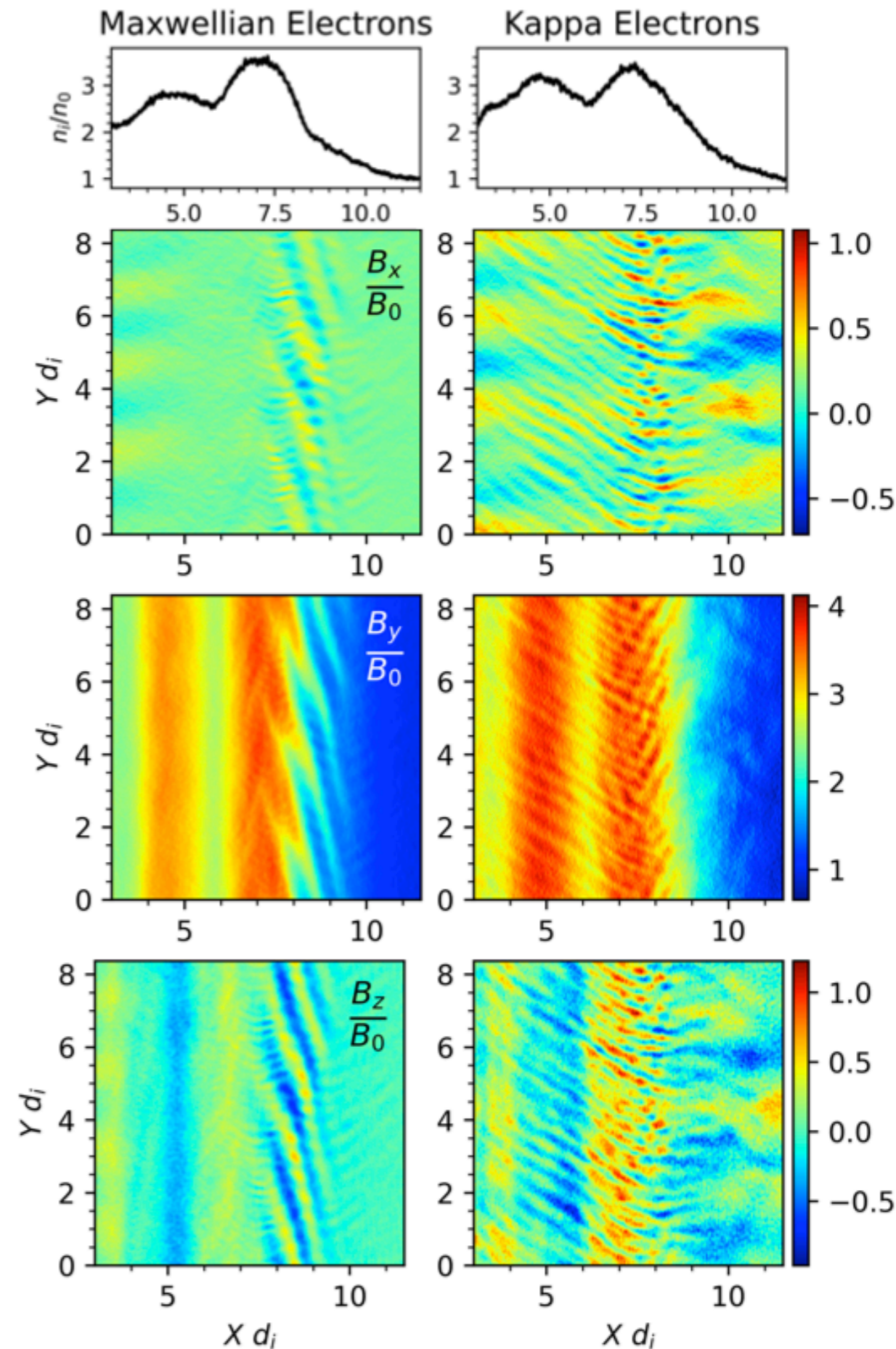
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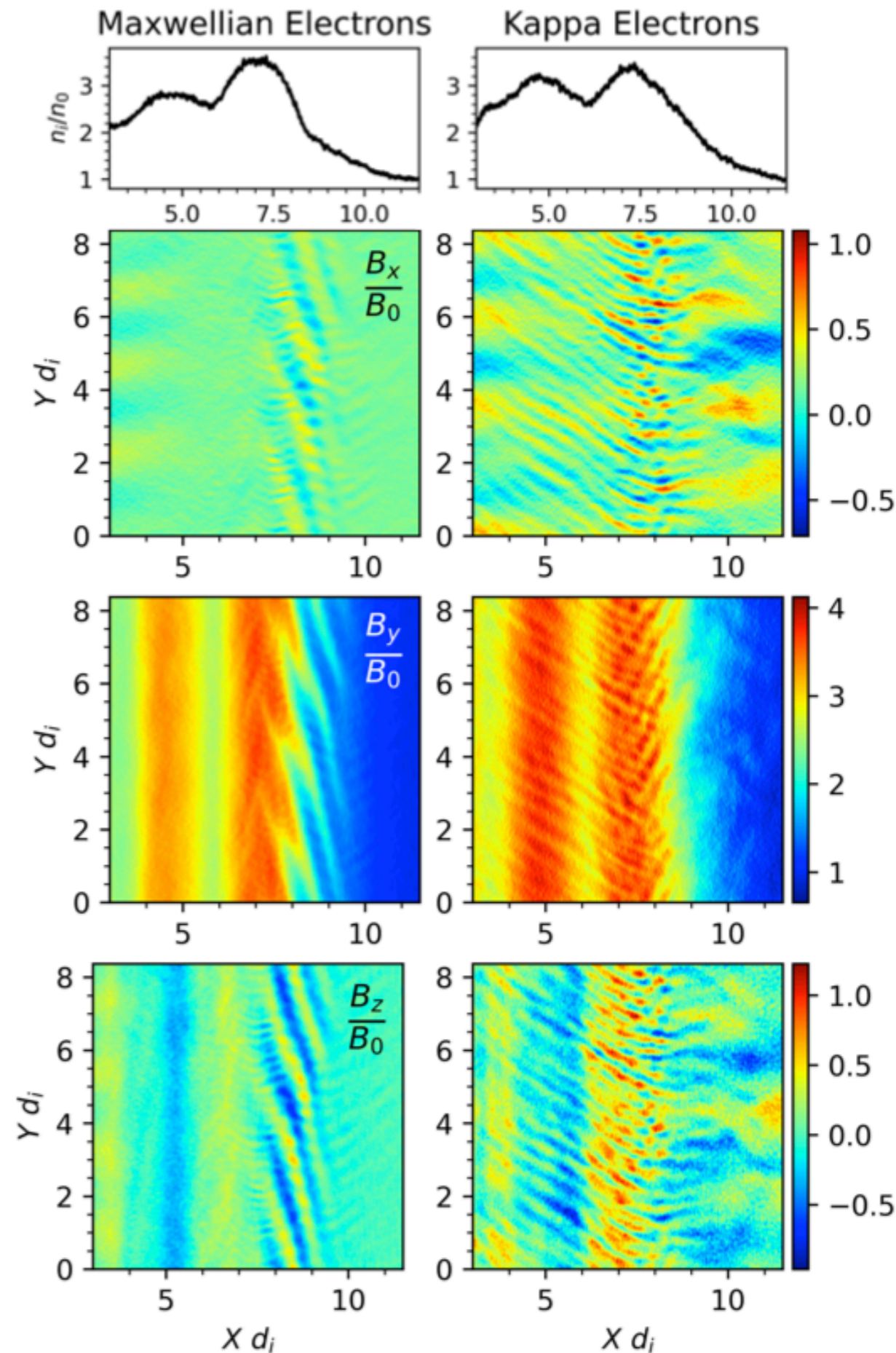
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- Details of phase space may explain why electric fields in simulations (typically Maxwellian initial conditions) **do not** match observations! Too low of amplitude! (See Wilson III, Chen, & Roytershteyn 2020 *Frontiers in Astronomy and Astrophysics*)



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- All this phase space structure has real practical consequences
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- Details of phase space may explain why electric fields in simulations (typically Maxwellian initial conditions) **do not** match observations! Too low of amplitude! (See Wilson III, Chen, & Roytershteyn 2020 *Frontiers in Astronomy and Astrophysics*)



195 Jada Walters

199 Emily Lichko

216 Jason TenBarge

# So what is this session all about?

Shocks are a key mechanism responsible for transforming super-sonic flow energy into particle energization. However, most plasma in the heliosphere is sufficiently **weakly collisional that the shocks are collisionless** and must irreversibly process flow energy into thermal energy through **means other than particle-particle collisions**. These other processes are **inherently kinetic**, whether the shocks are driven by coronal mass ejections, the solar wind impinging on the Earth's magnetosphere, or at the heliospheric termination shock. Understanding these processes and how they connect the different systems separated by a collisionless shock requires a coordinated community effort combining kinetic modeling, in situ spacecraft data, and remote observations.

**How is energy dissipated/transferred at collisionless shocks through self-generated kinetic plasma mechanisms?**

How do these kinetic mechanisms depend on the local plasma environment throughout the heliosphere?

How well can we address these questions with current and upcoming missions?

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**How is energy dissipated/transferred at collisionless shocks through self-generated kinetic plasma mechanisms? *Phase space is a good way to answer this question!***

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$$\frac{\partial f_s}{\partial t} + \nabla_{\mathbf{z}} \cdot (\boldsymbol{\alpha}_s f_s) = \sum_{s'} C[f_s, f_{s'}]$$

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# Leveraging phase space with the field-particle correlation technique

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**Field-particle correlation (FPC):** see, e.g., Klein & Howes ApJ 2016, Howes, Klein, Li JPP 2017, and Klein, Howes, and TenBarge JPP 2017

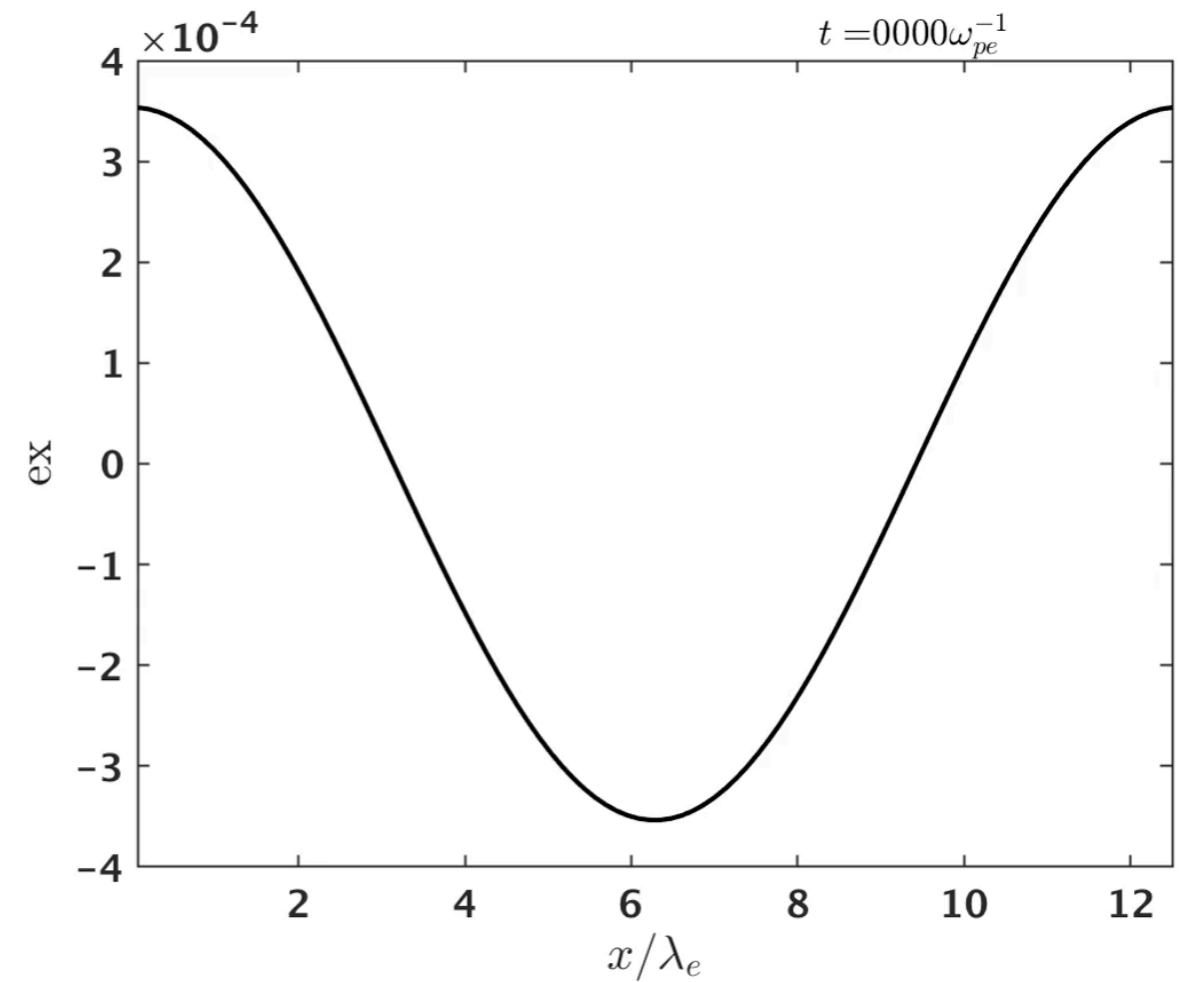
# Phase space energy transfer, a simple example

$$\delta n/n_0 = 0.005$$

$$(n_x, n_v) = (32, 64), p = 2$$

$$L_x = 4\pi\lambda_D$$

$$-10v_{te} \leq v \leq 10v_{te}$$



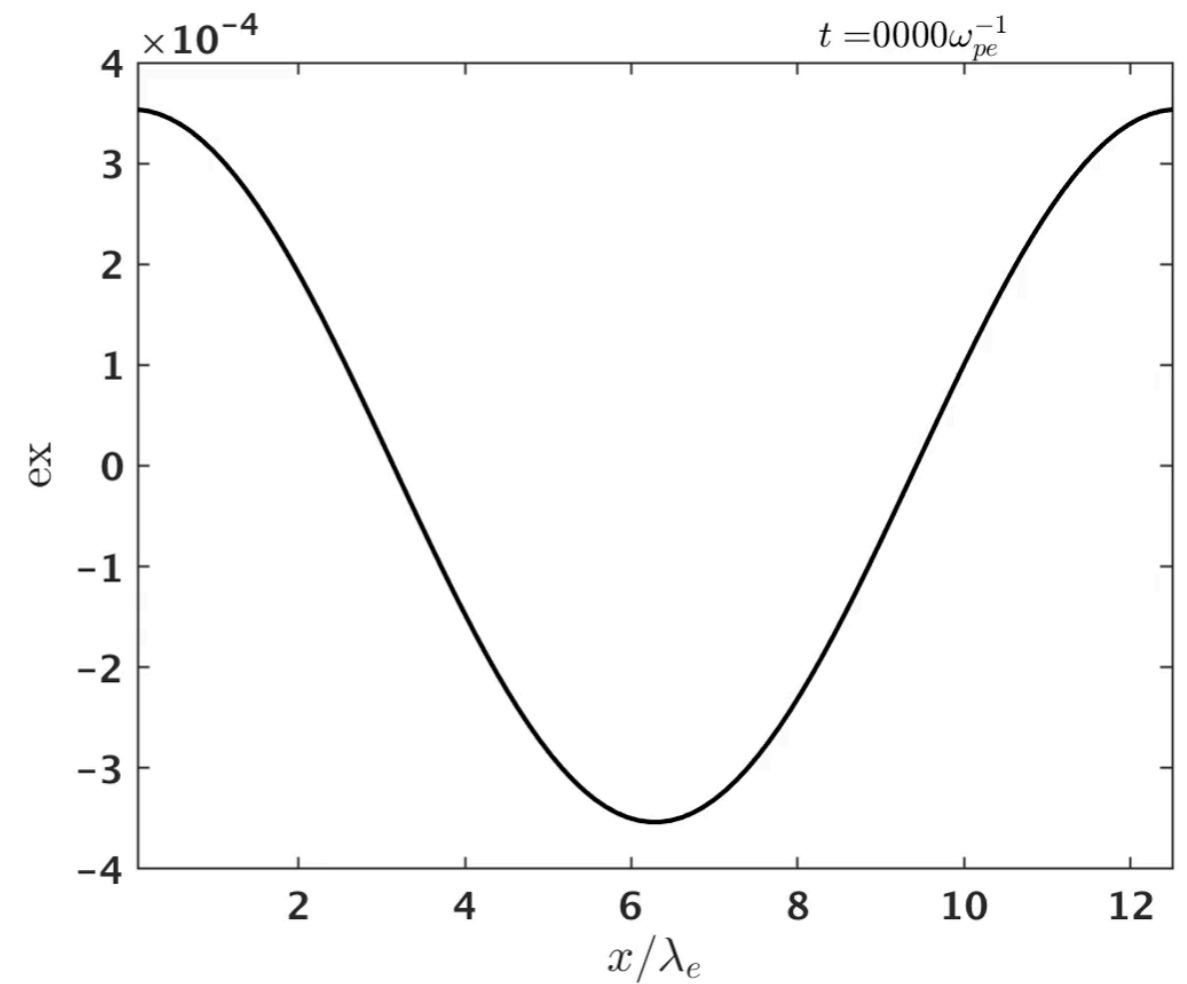
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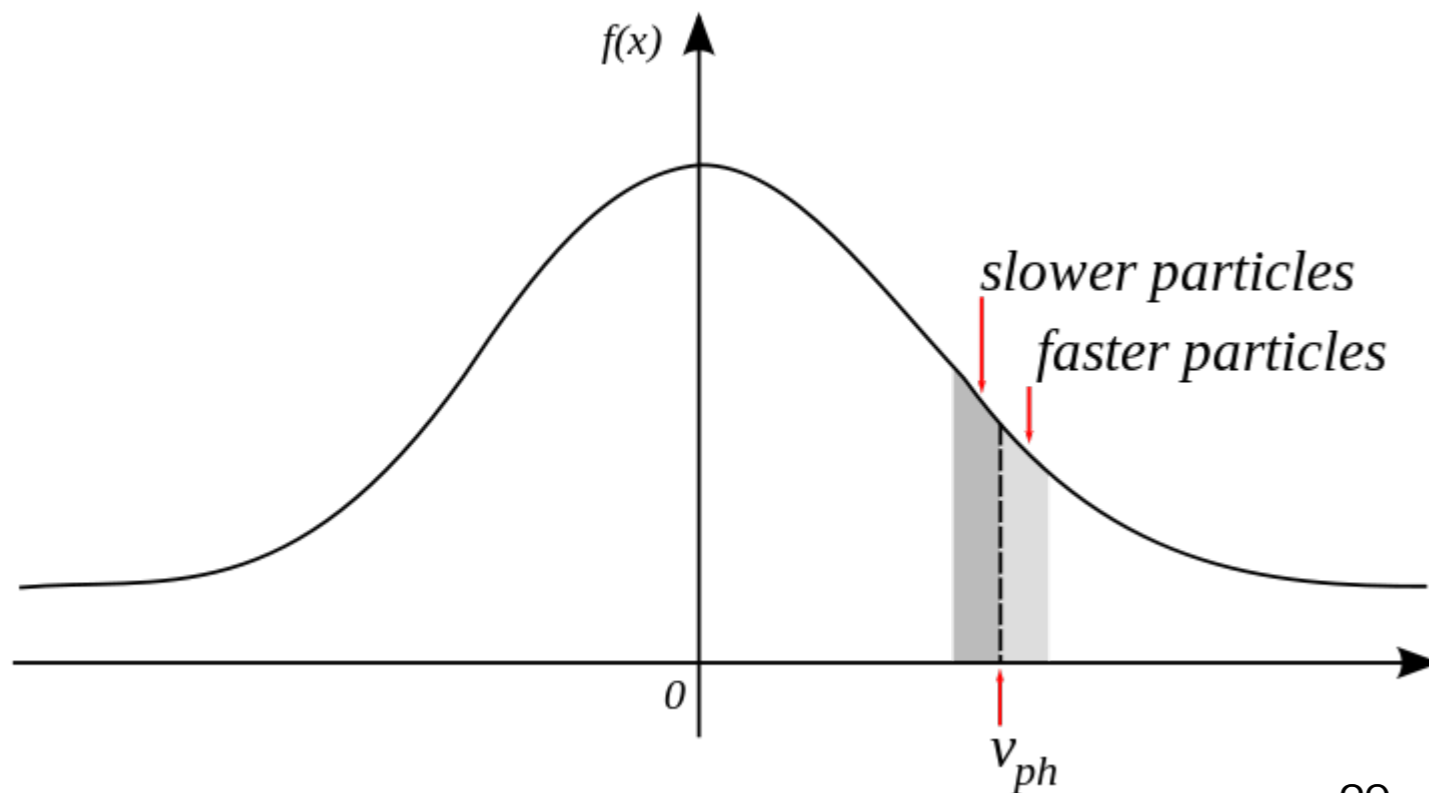
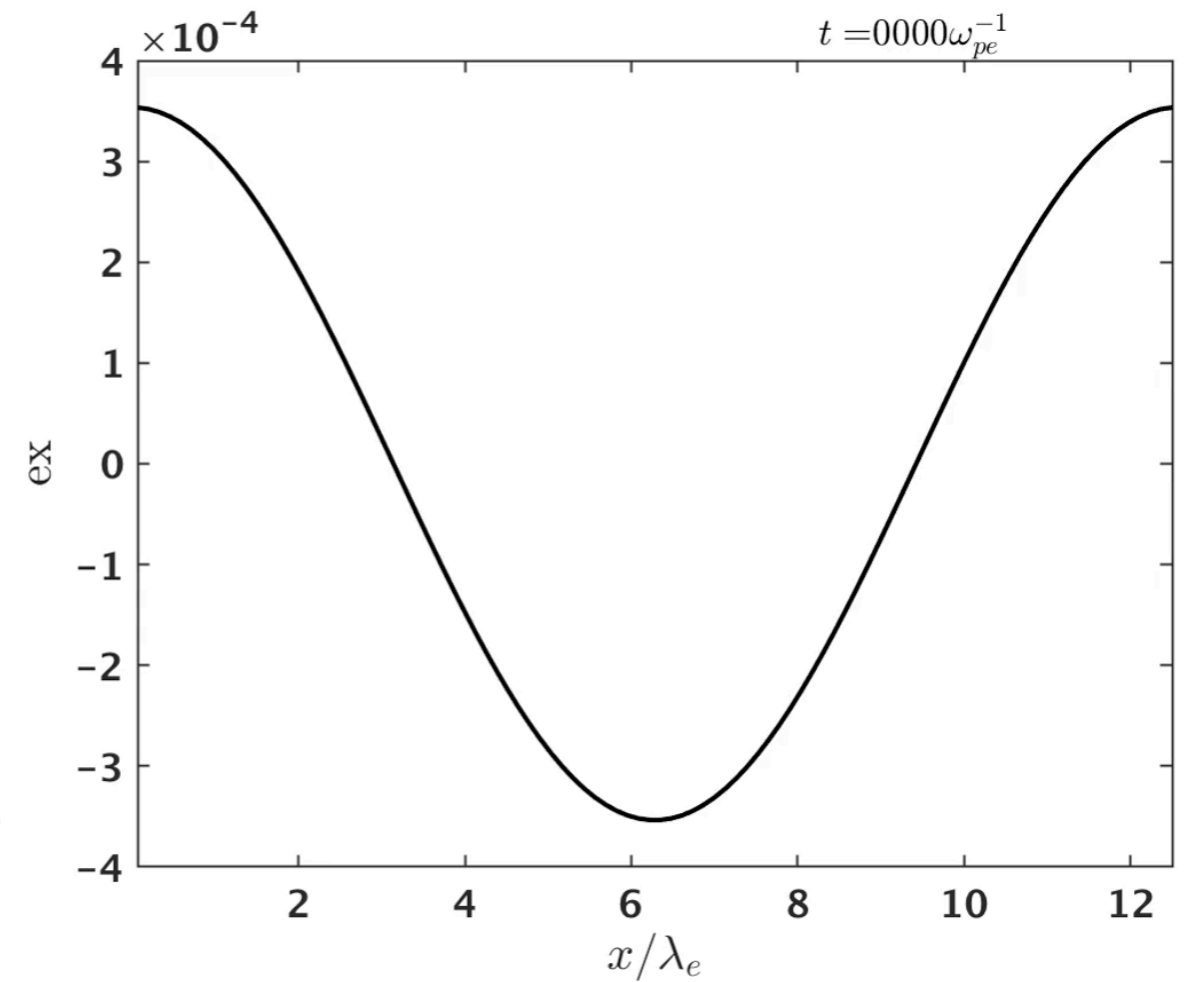
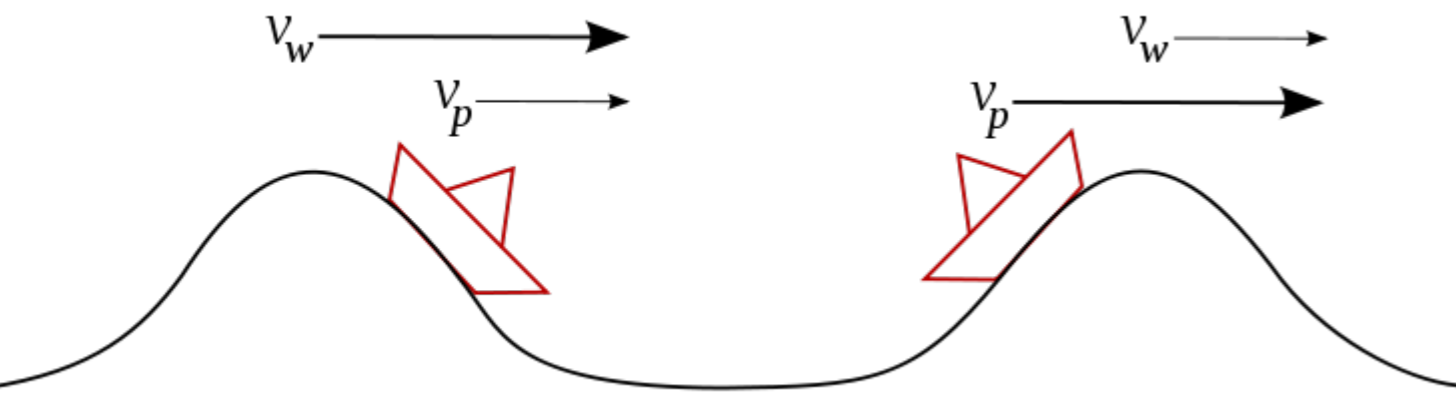
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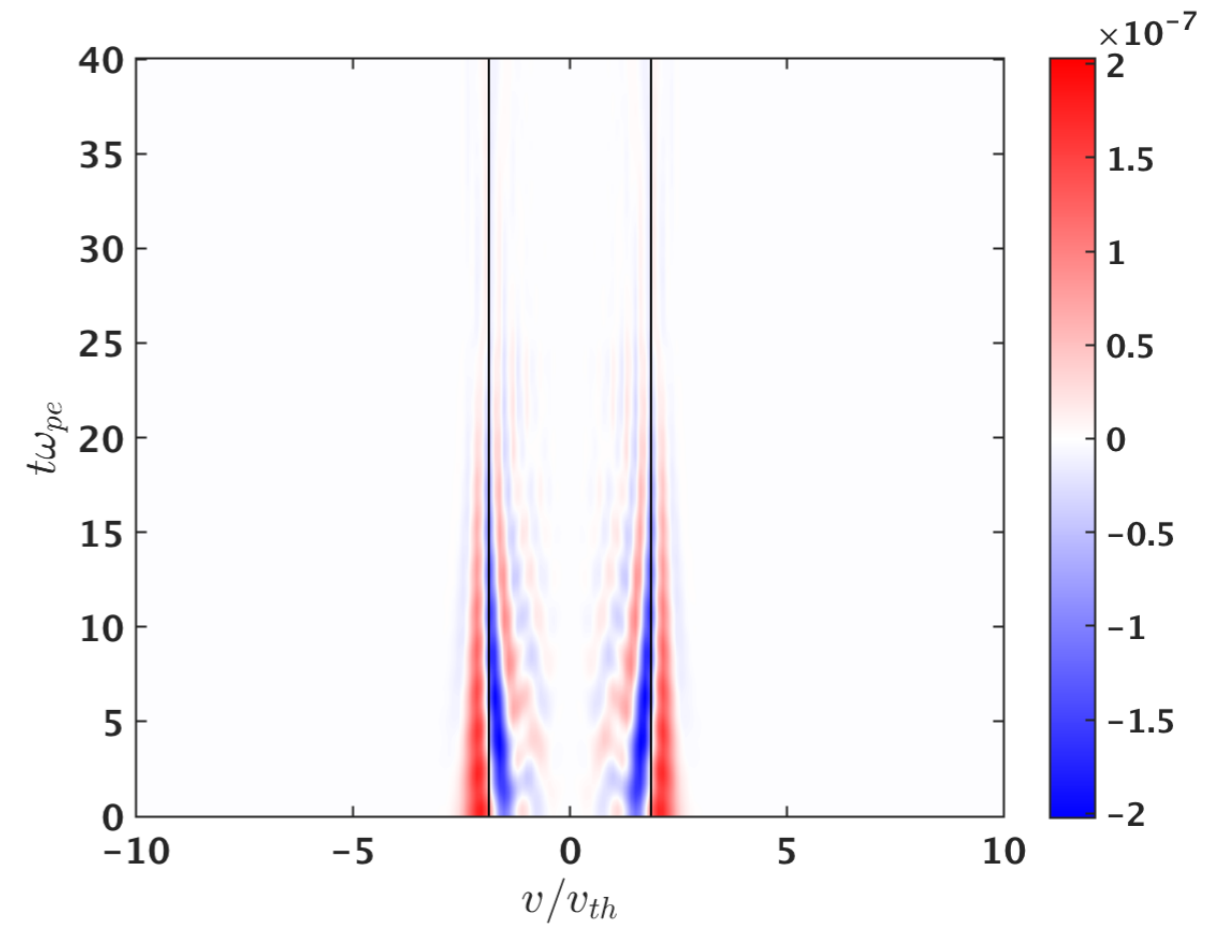
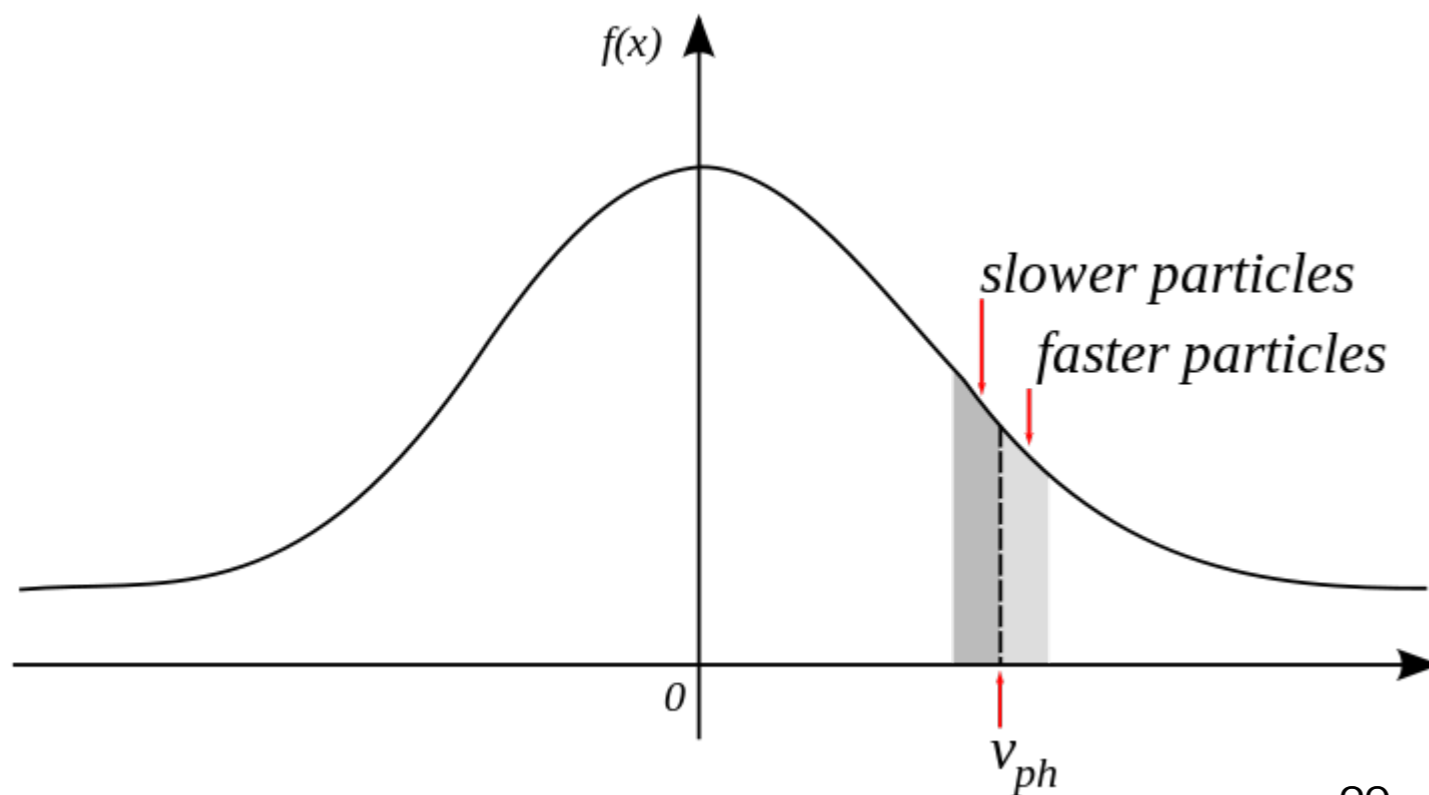
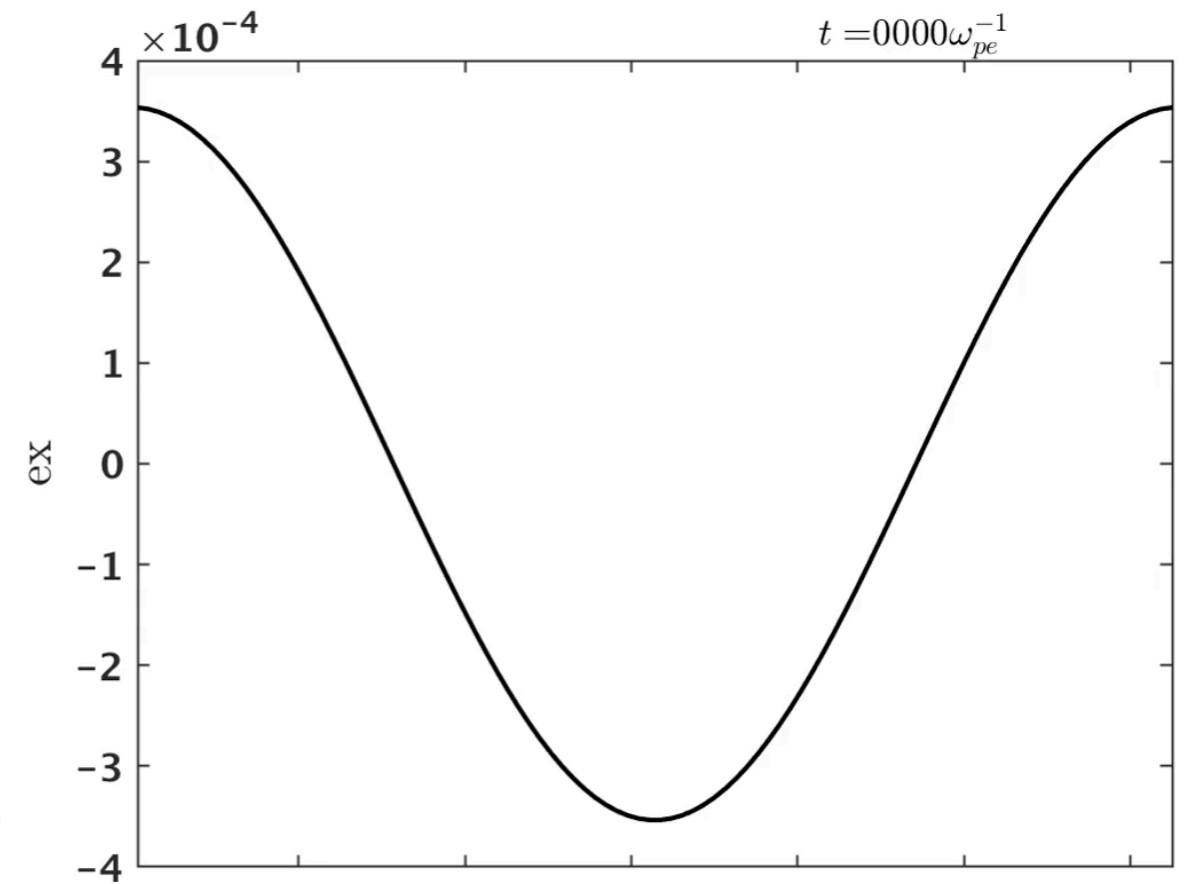
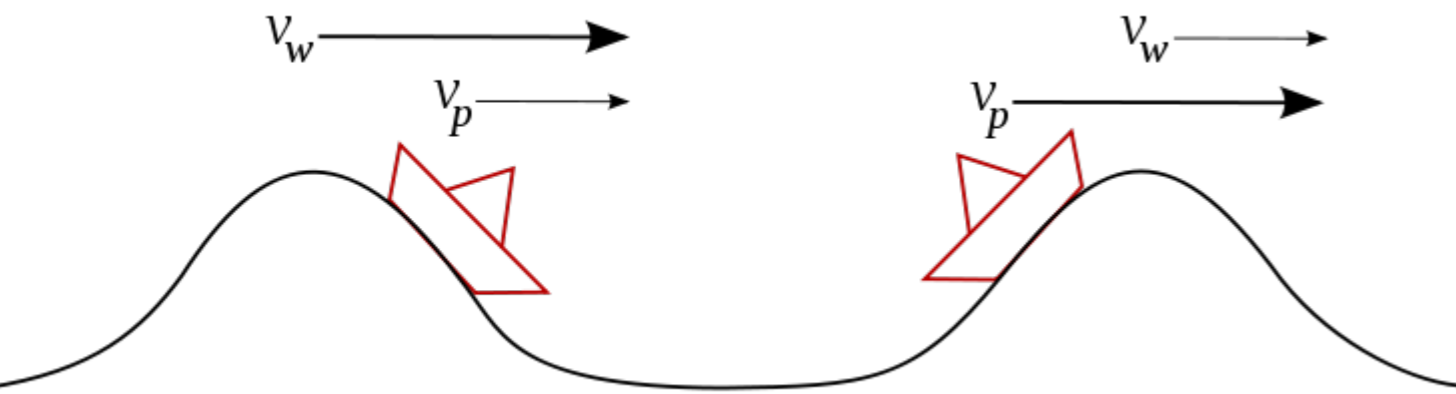
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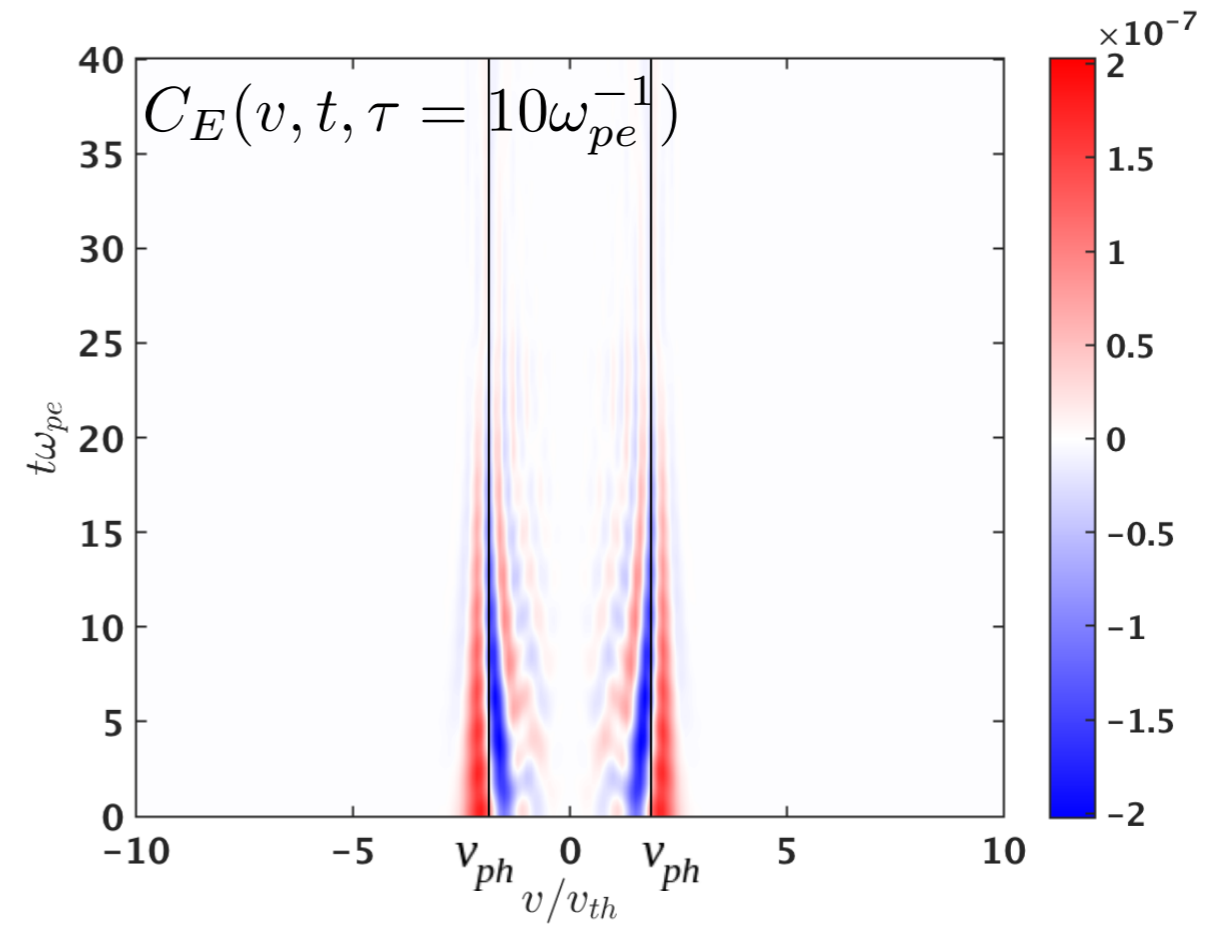
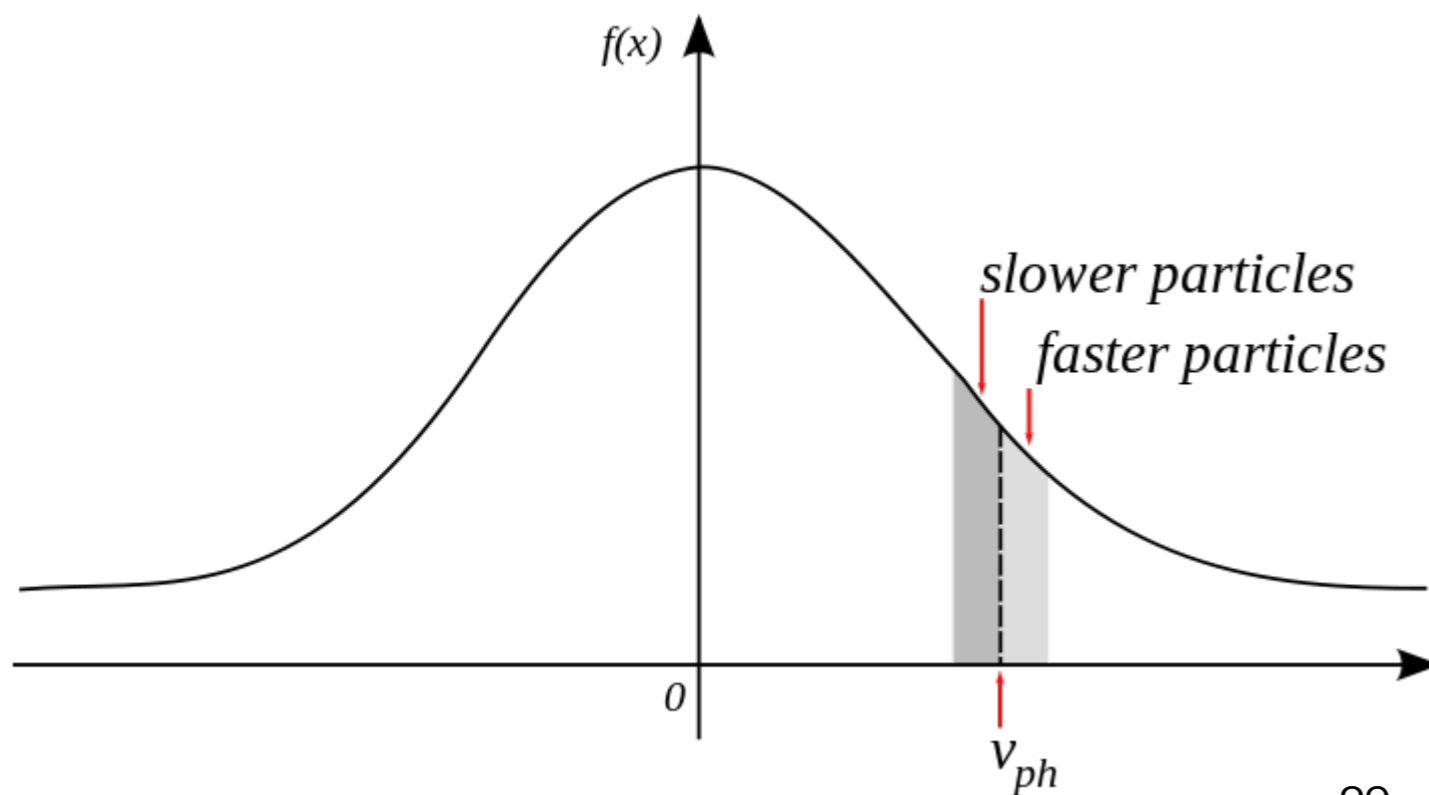
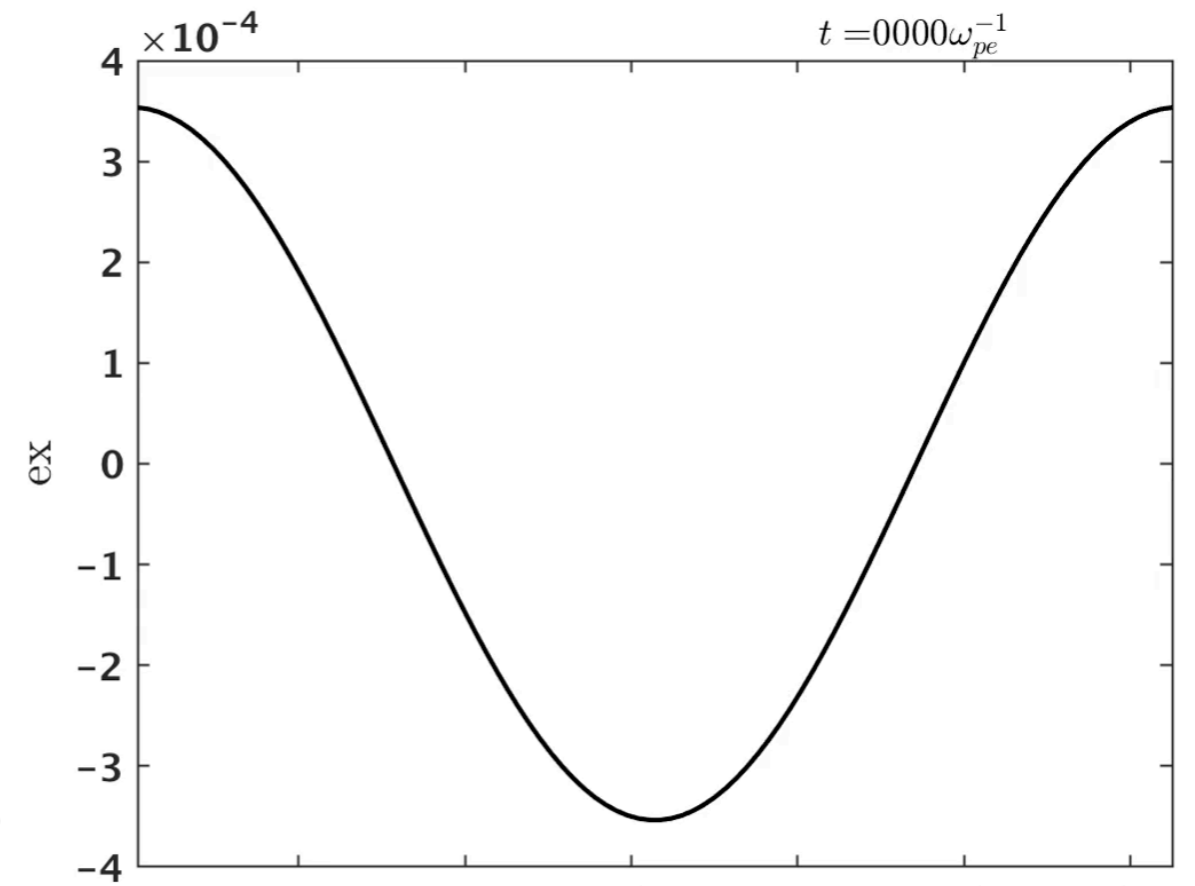
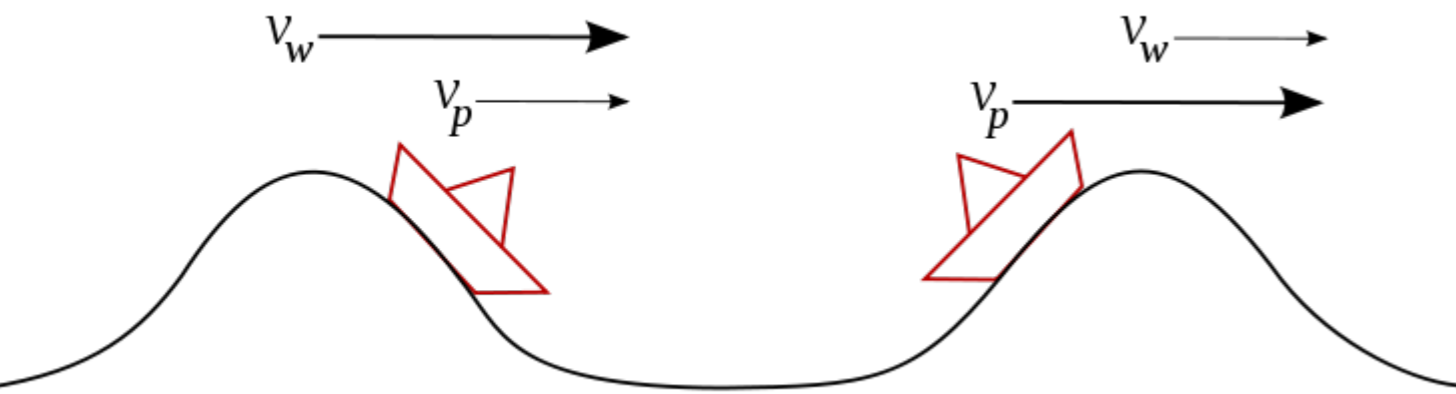
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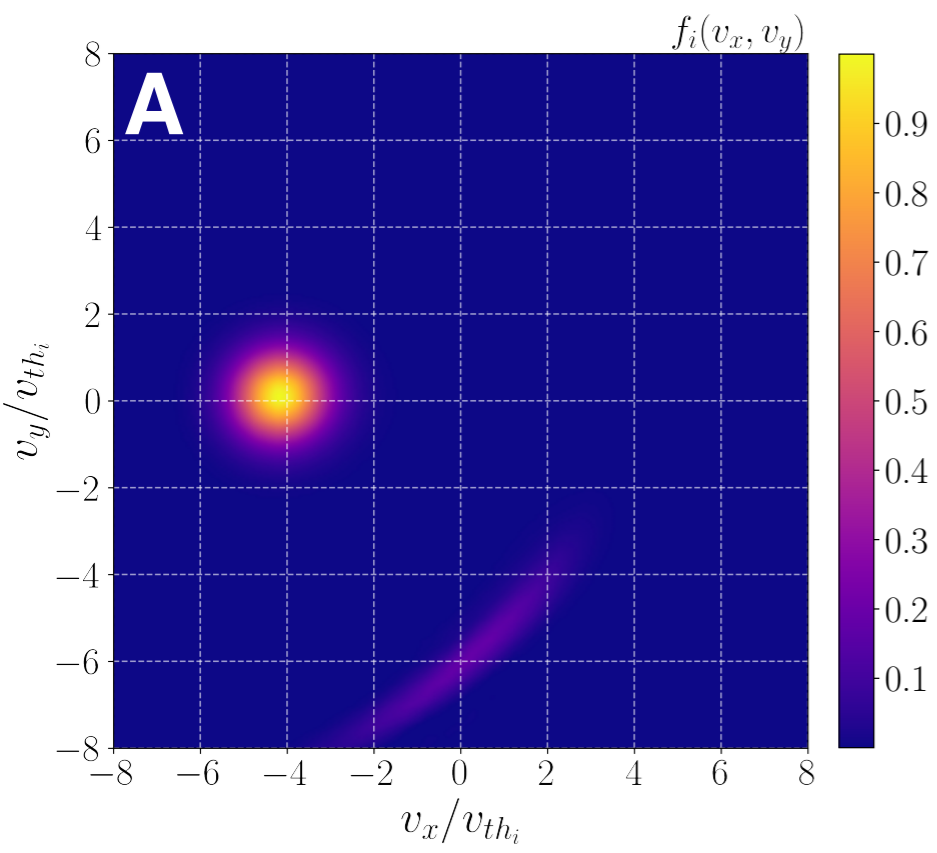
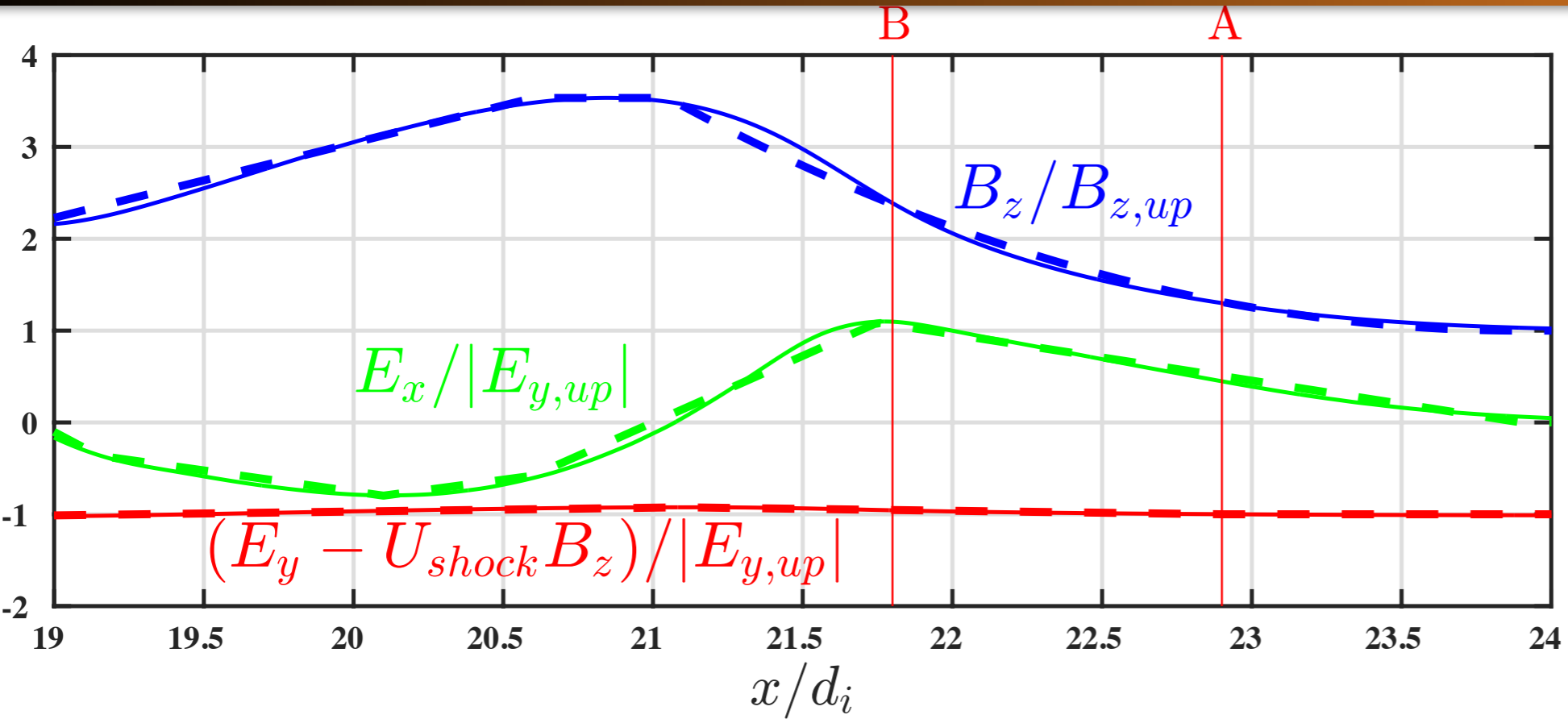
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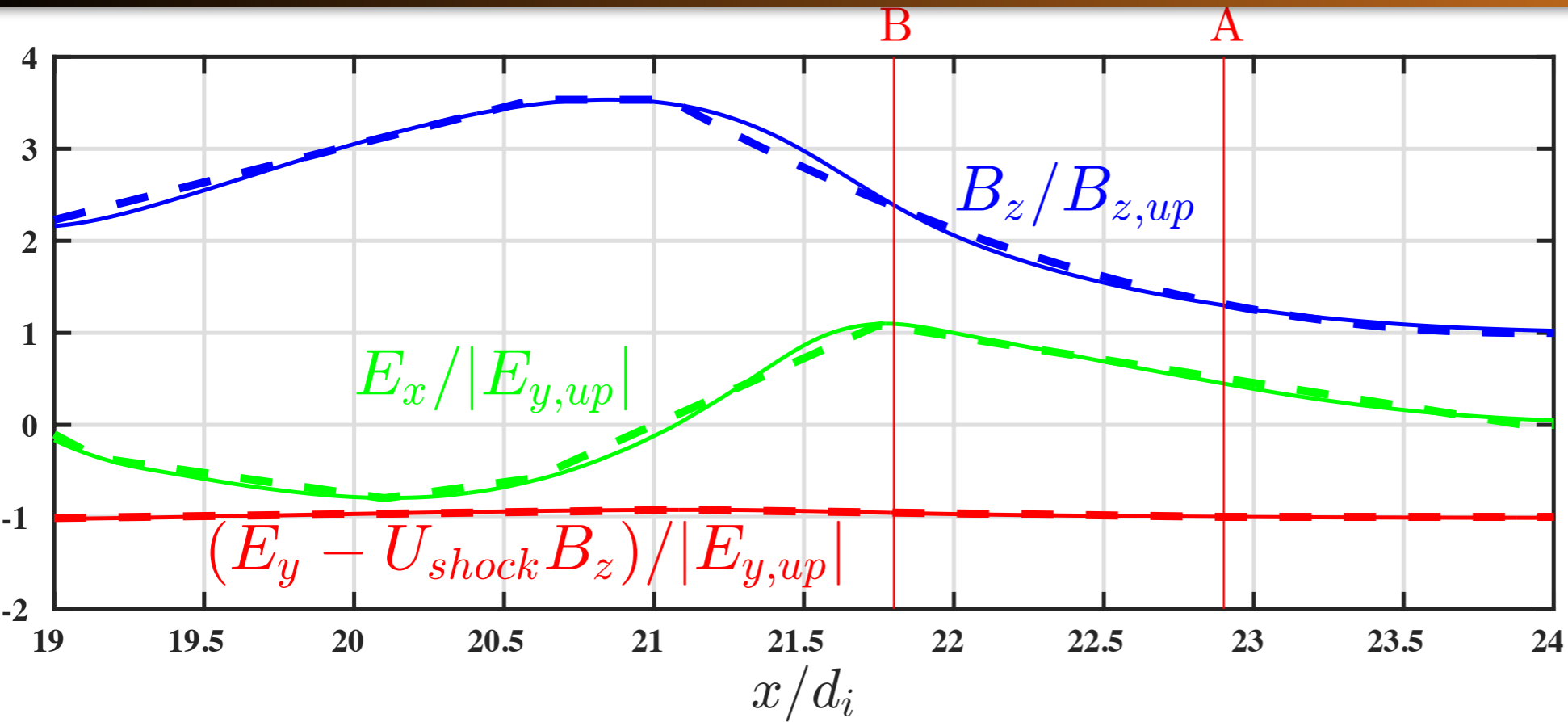
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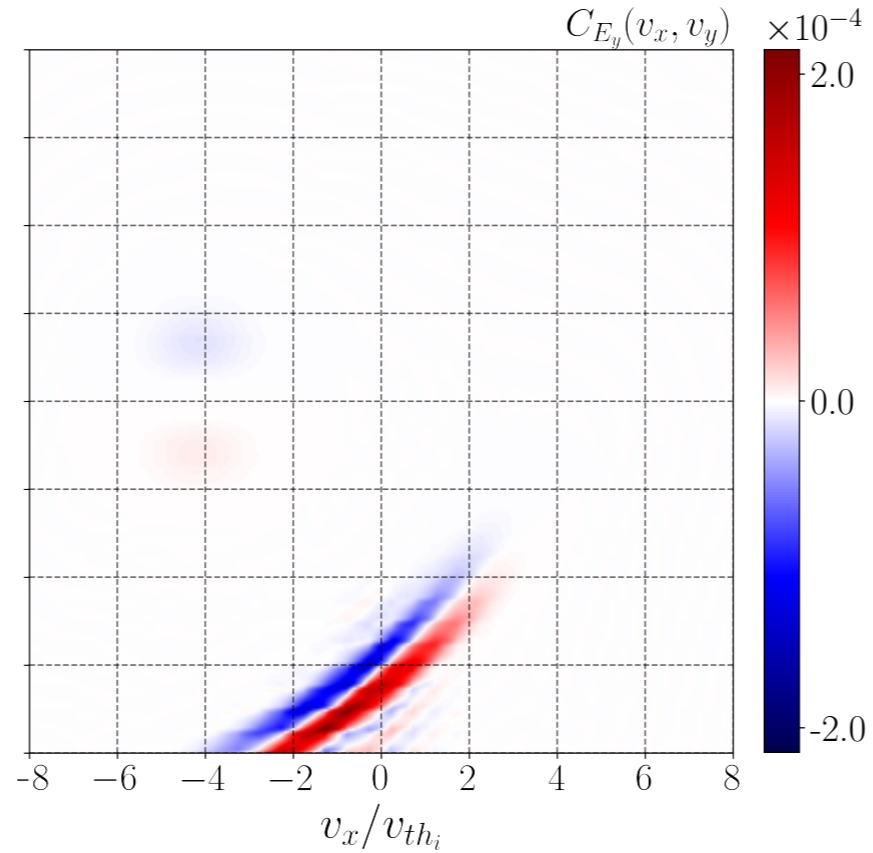
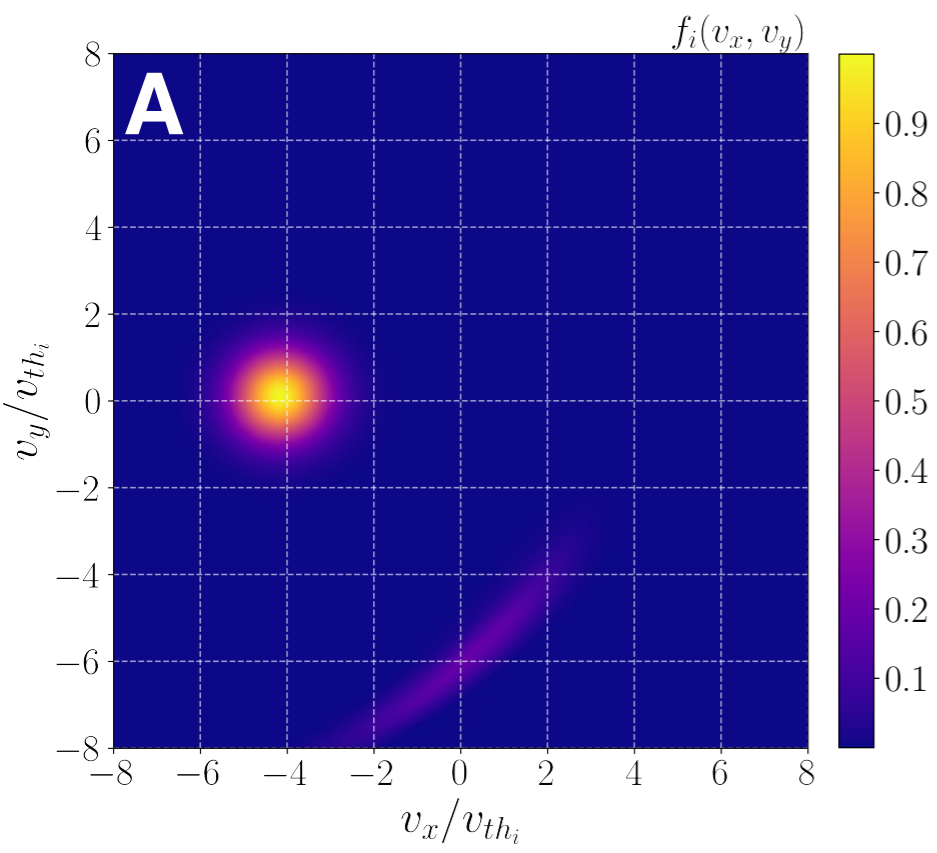
# Applying the FPC to the reflected proton population



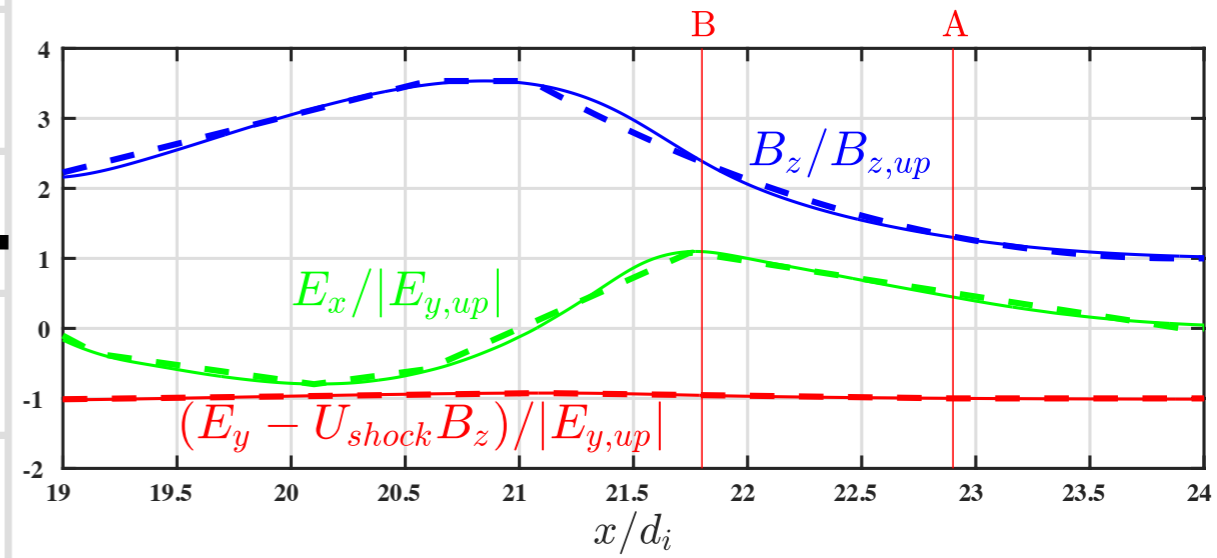
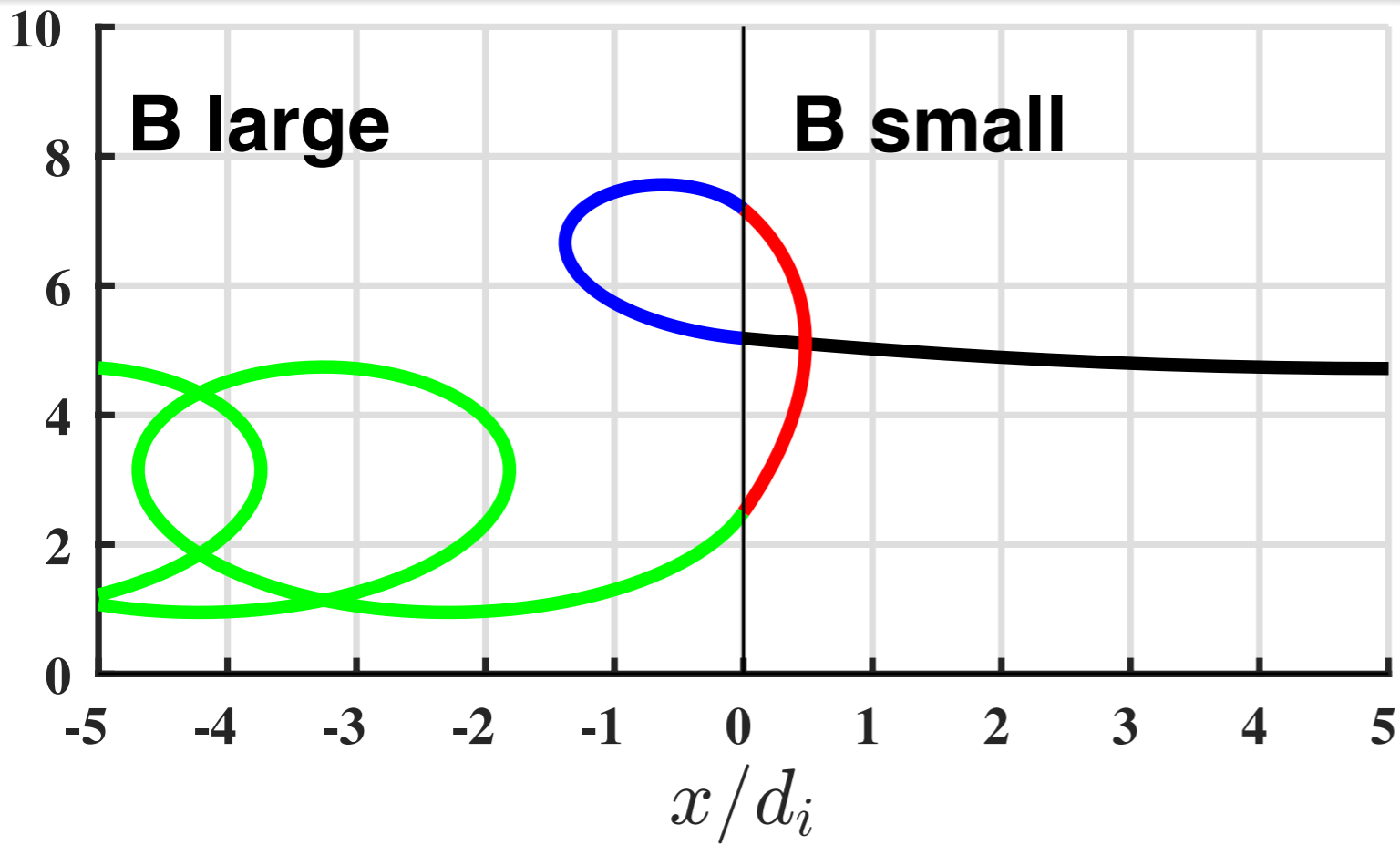
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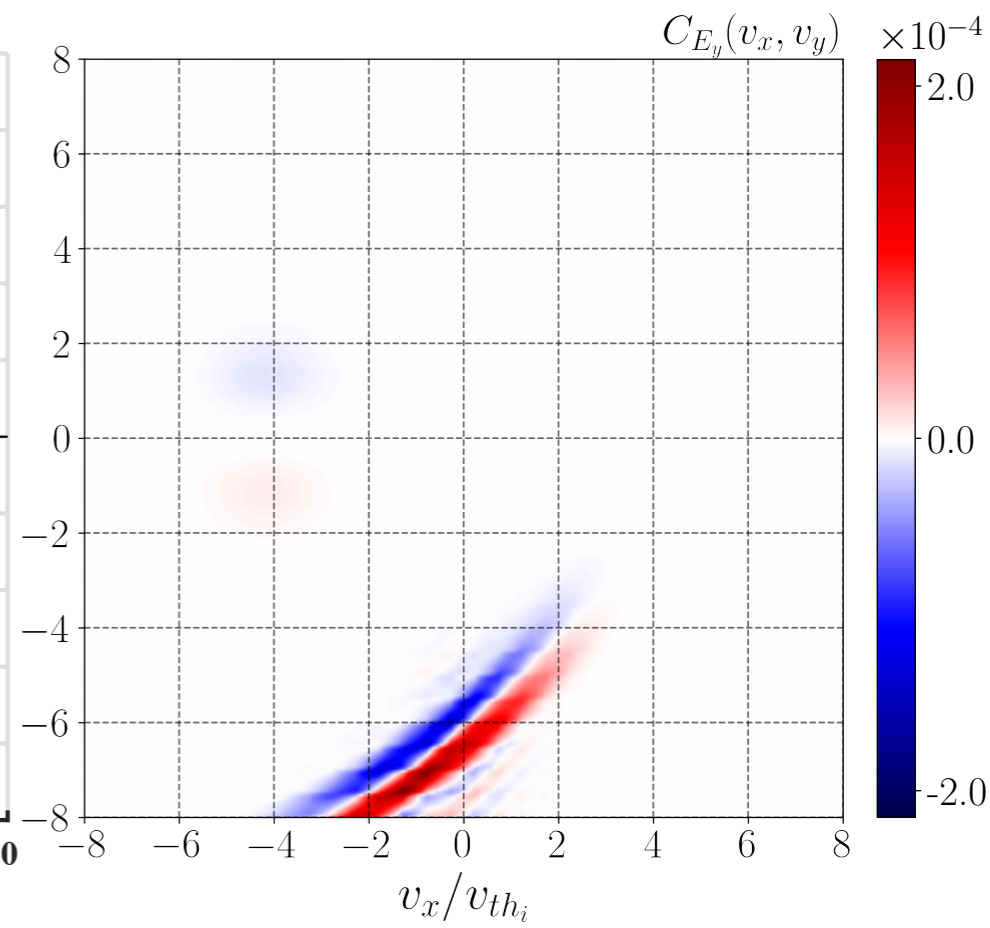
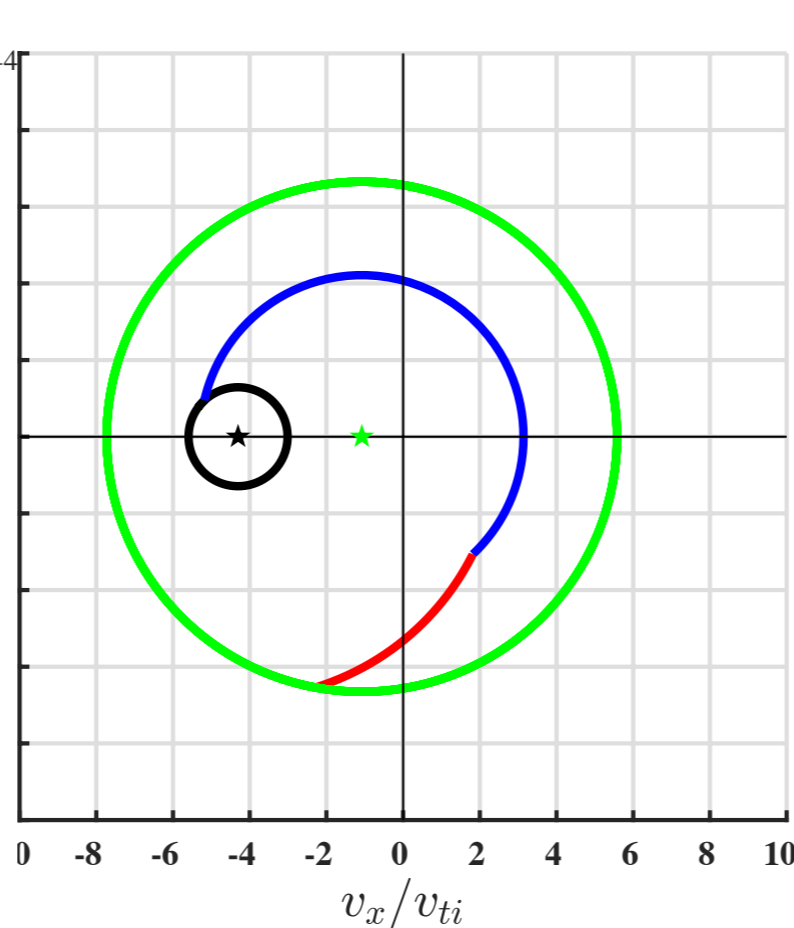
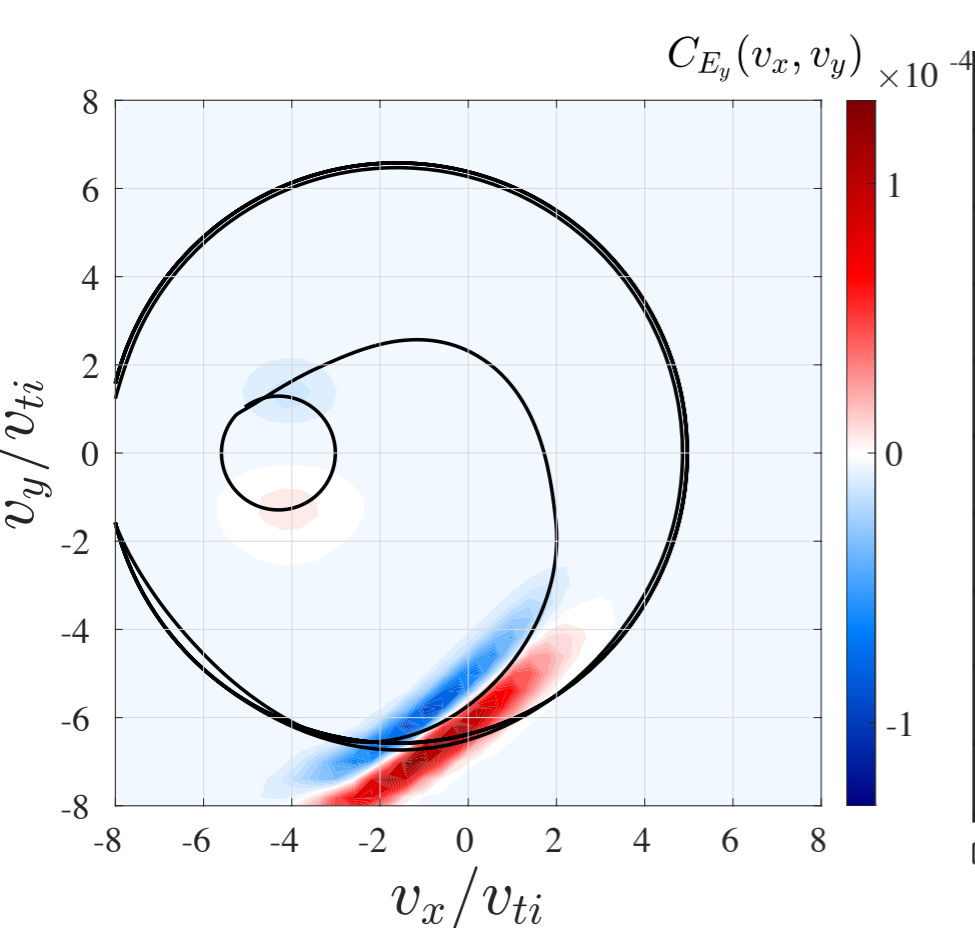
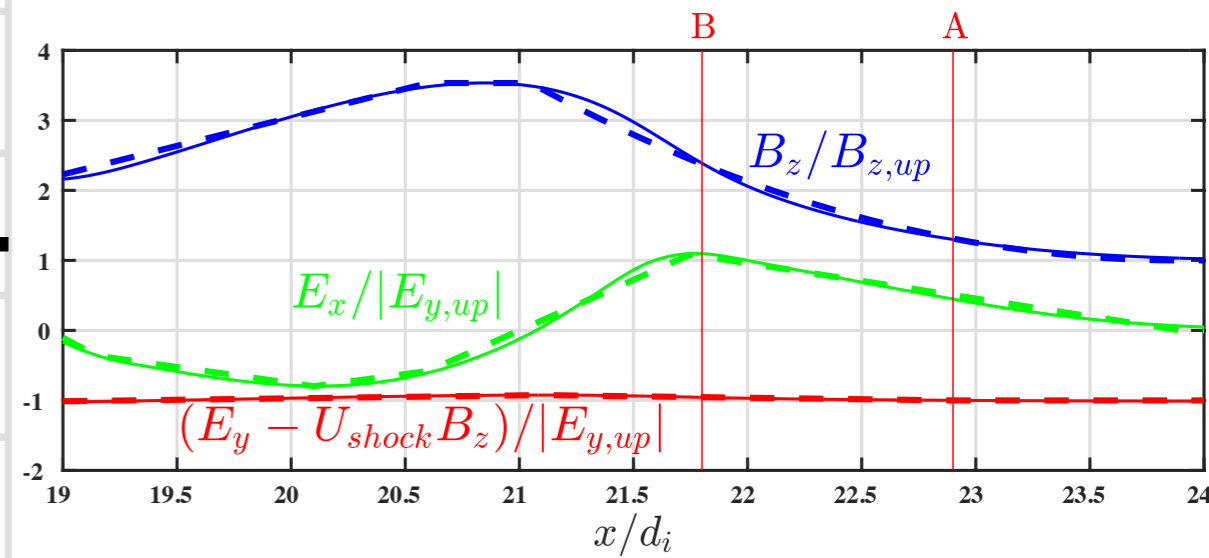
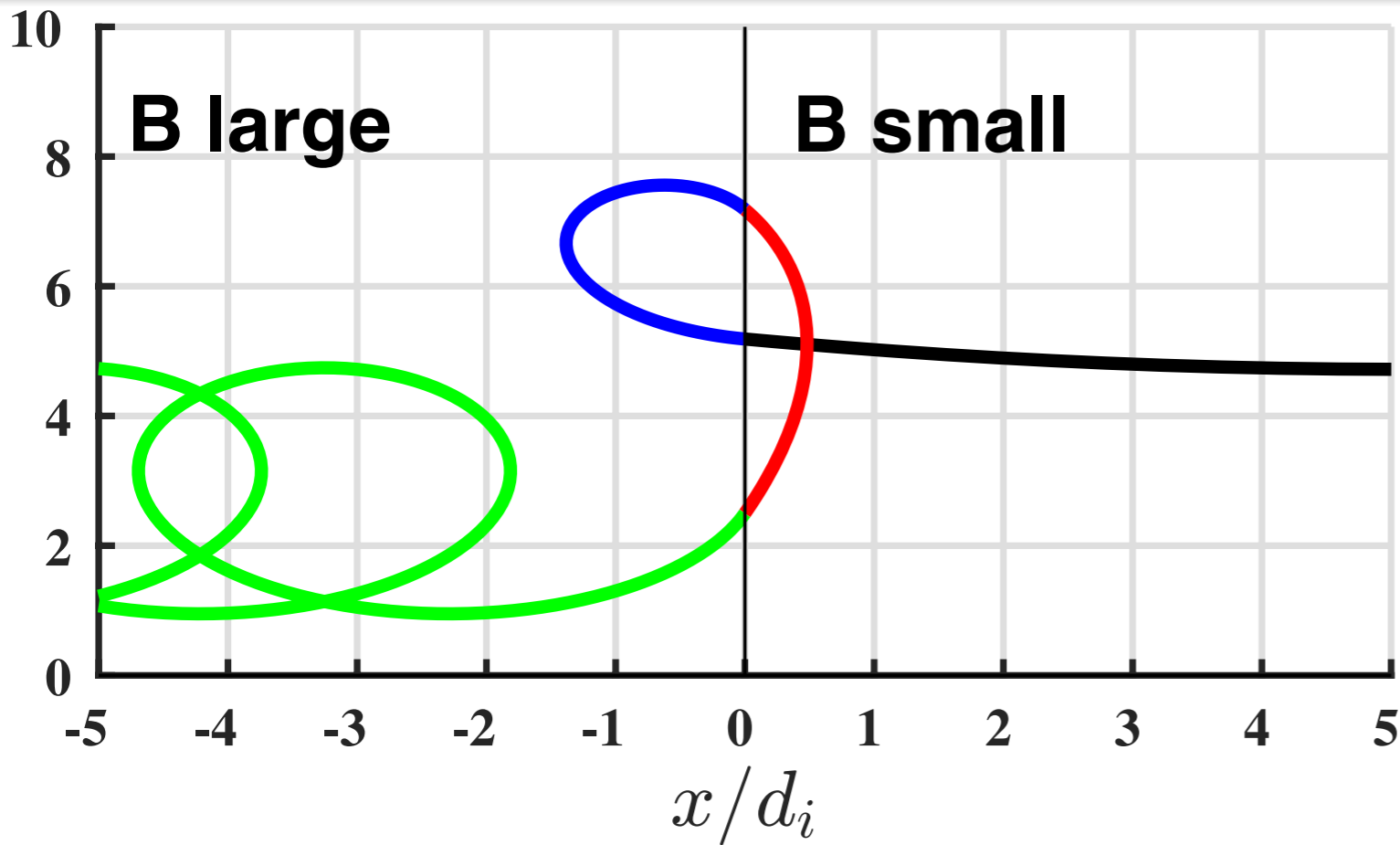
$$C_{E_y}(x, v'_x, v'_y, t) = -q_s \frac{v_y'^2}{2} [E_y'(x, t) - U_{shock} B_z(x, t)] \frac{\partial f_s(x, v'_x - U_{shock}, v'_y, t)}{\partial v'_y}$$



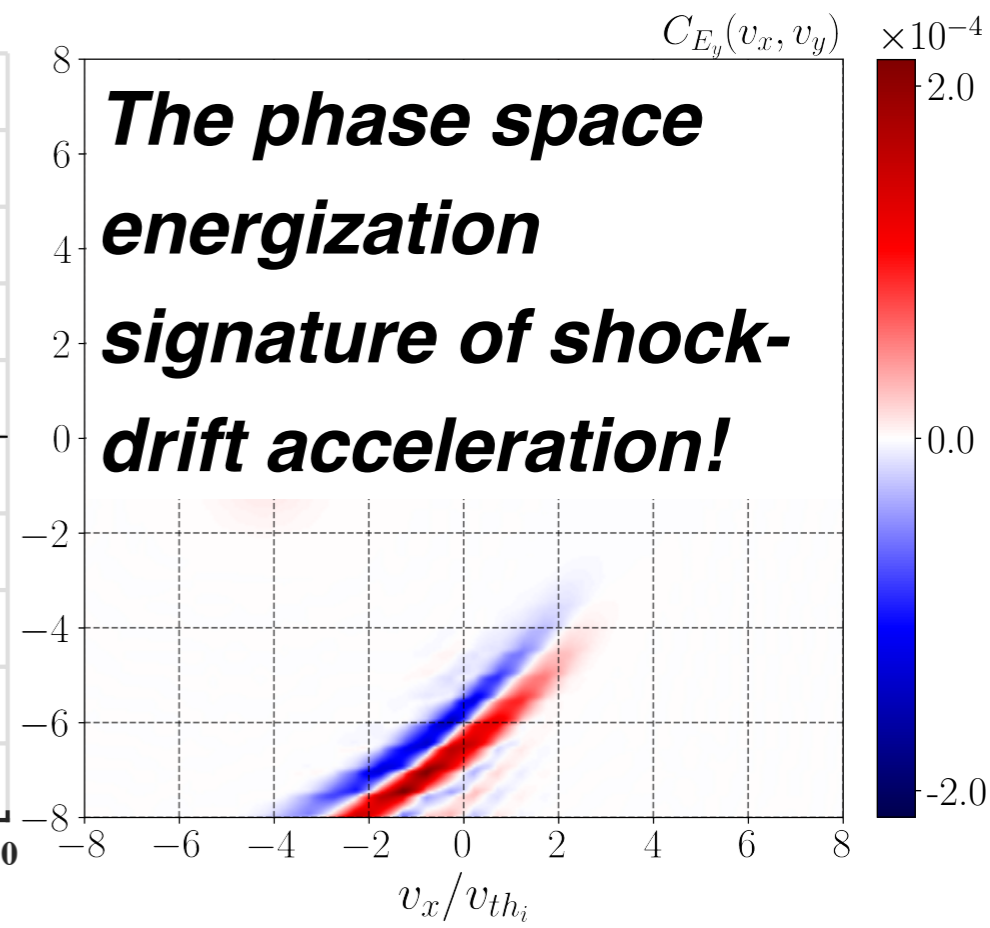
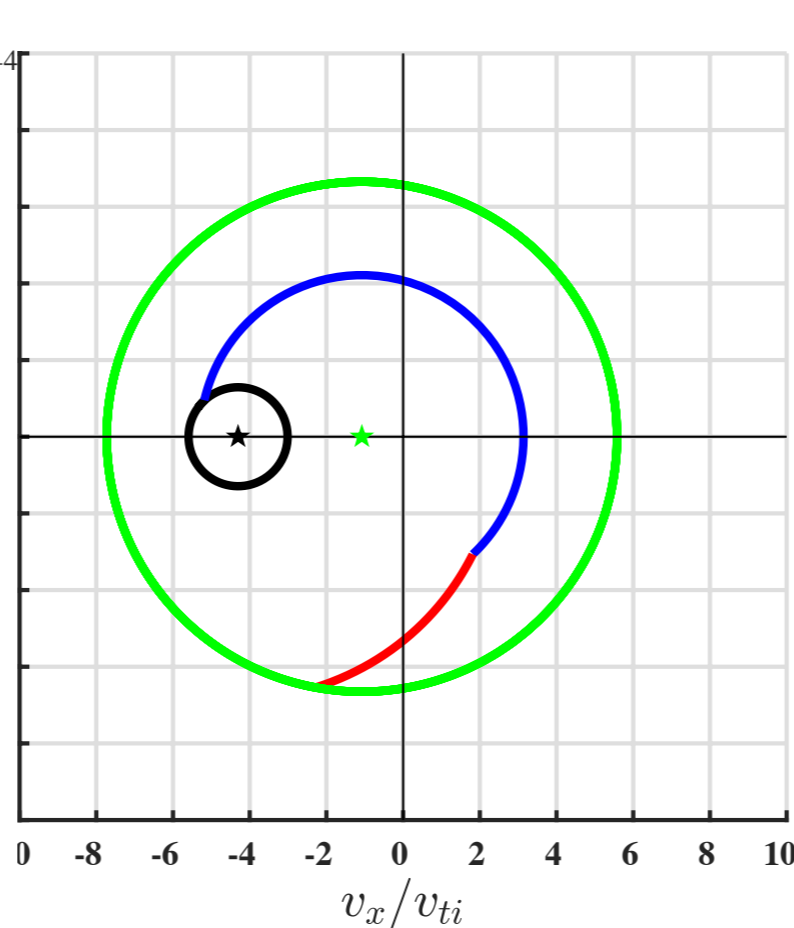
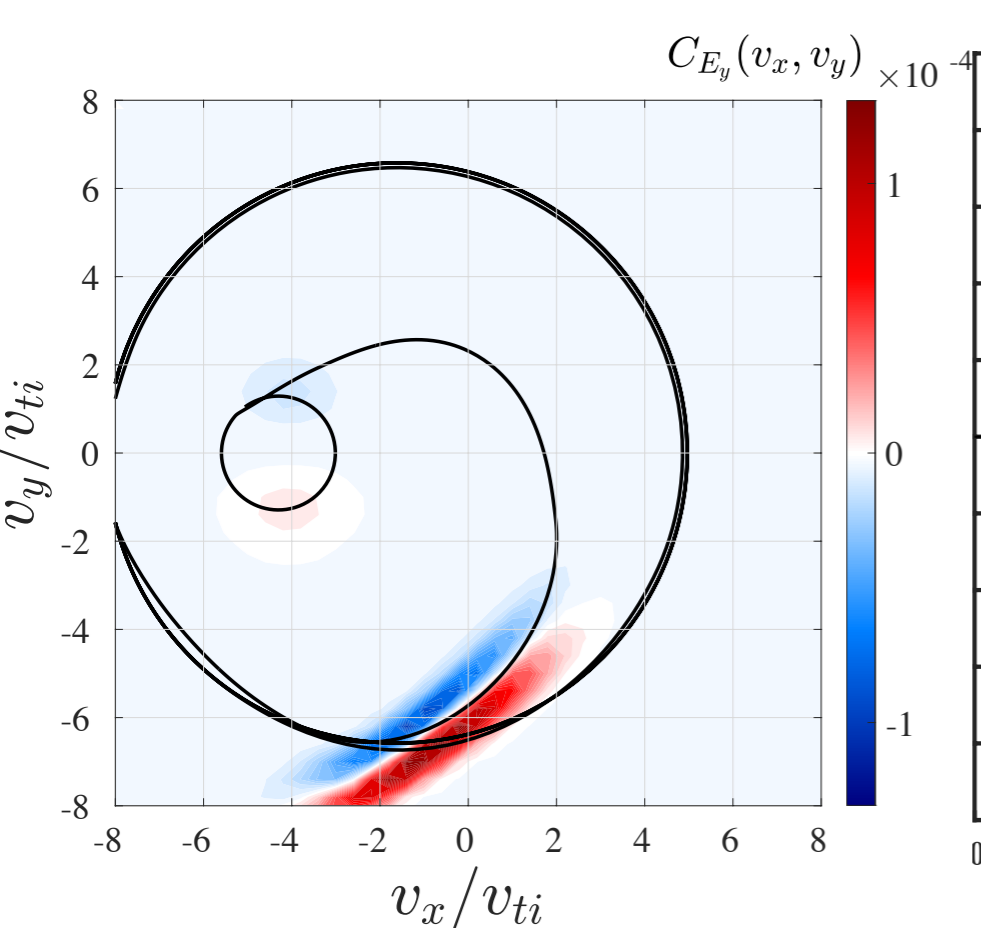
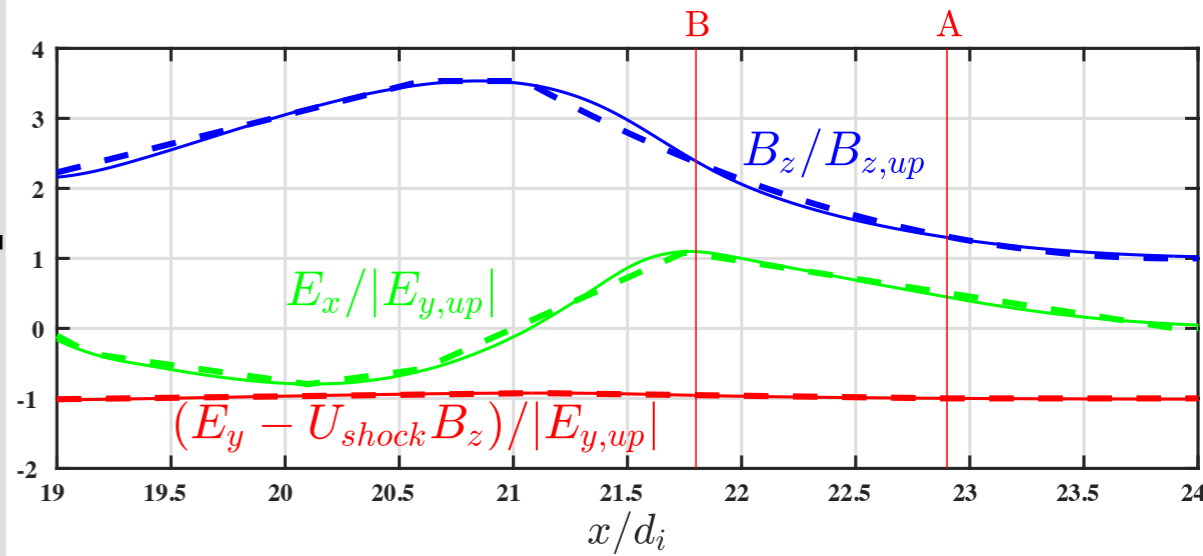
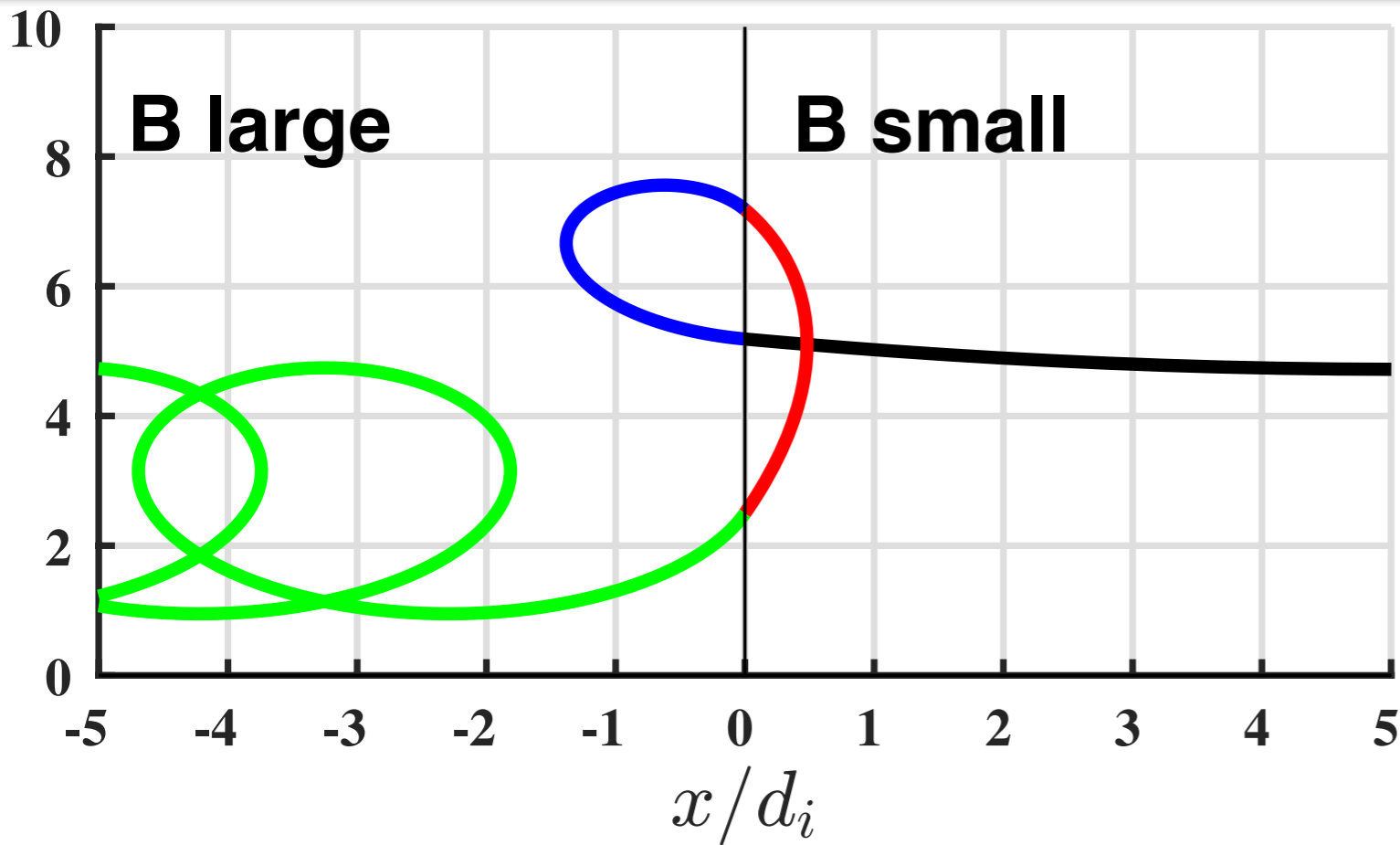
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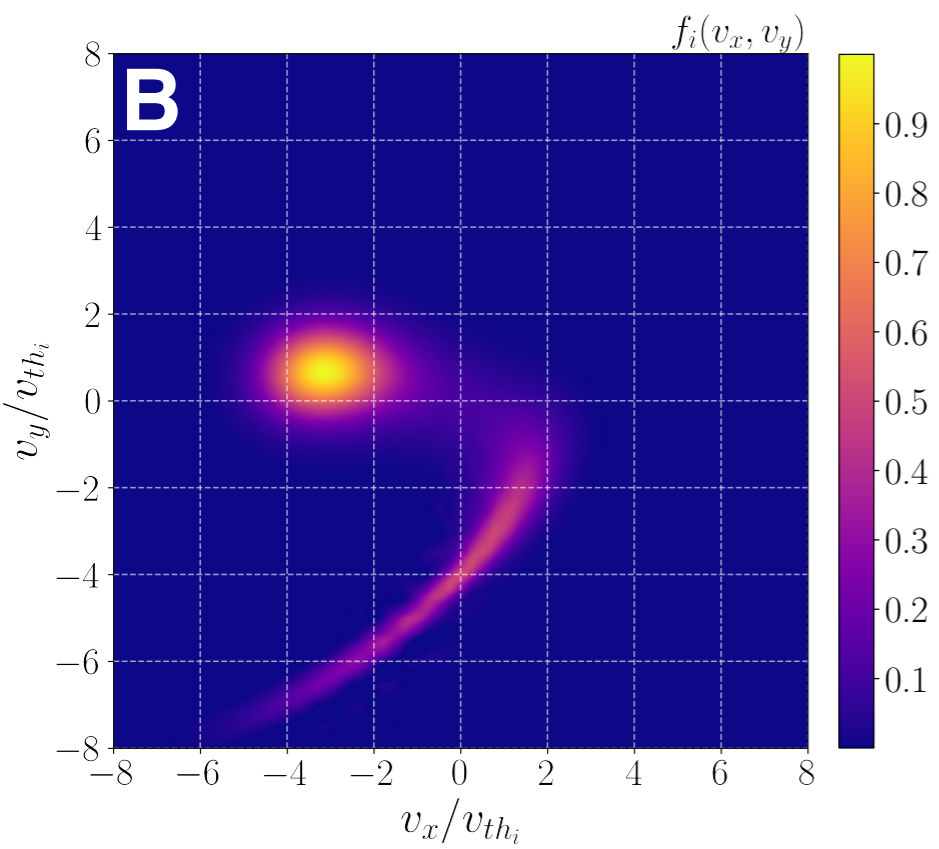
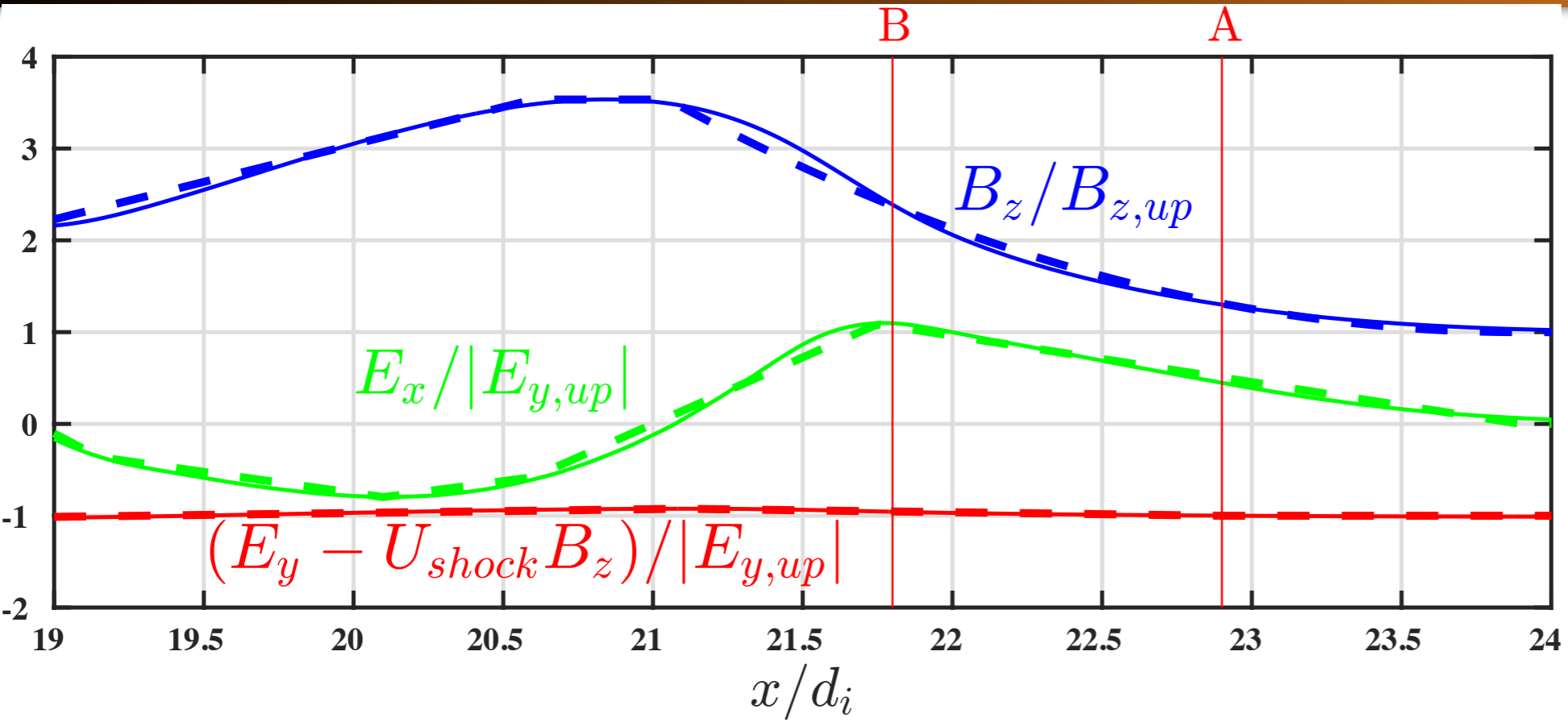
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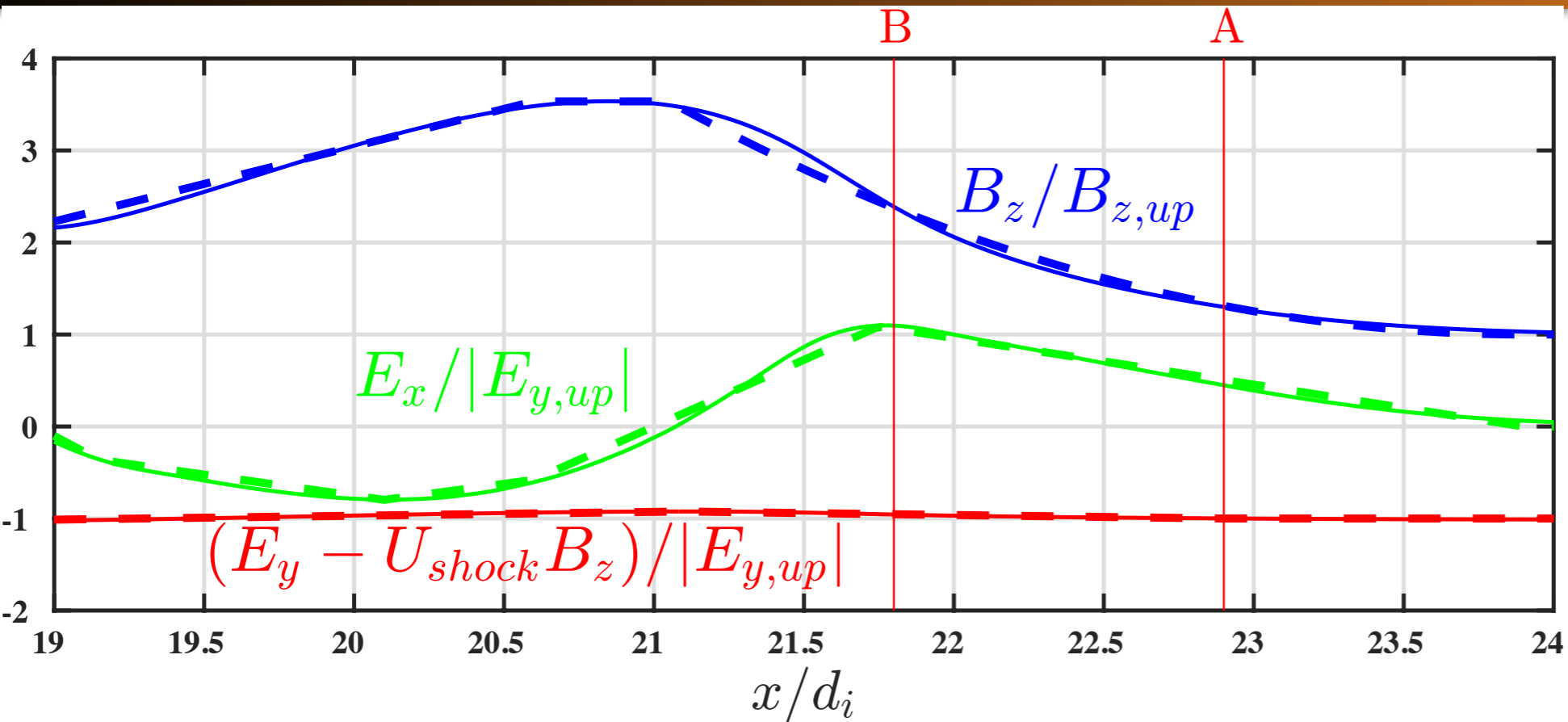
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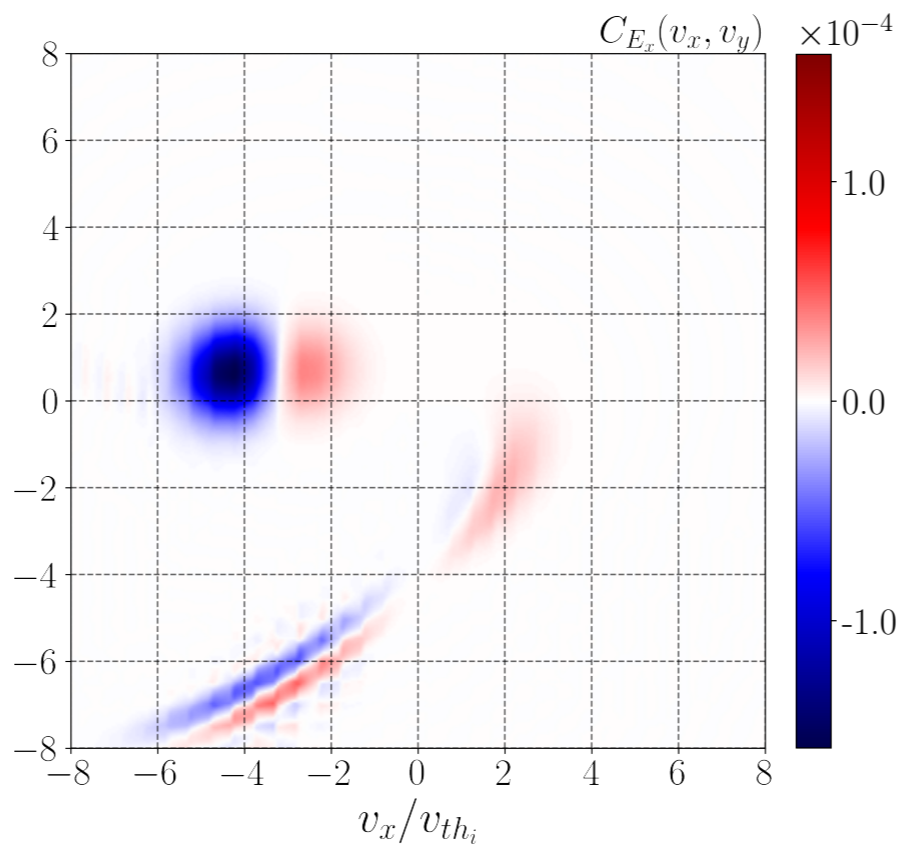
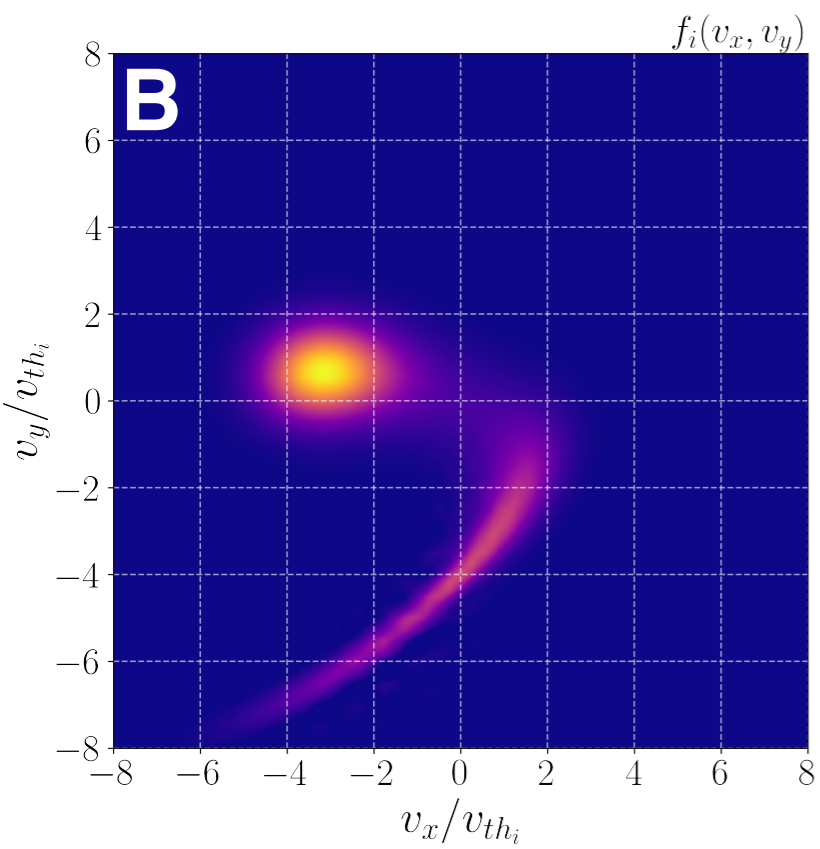
# Phase space allows for holistic view of energization



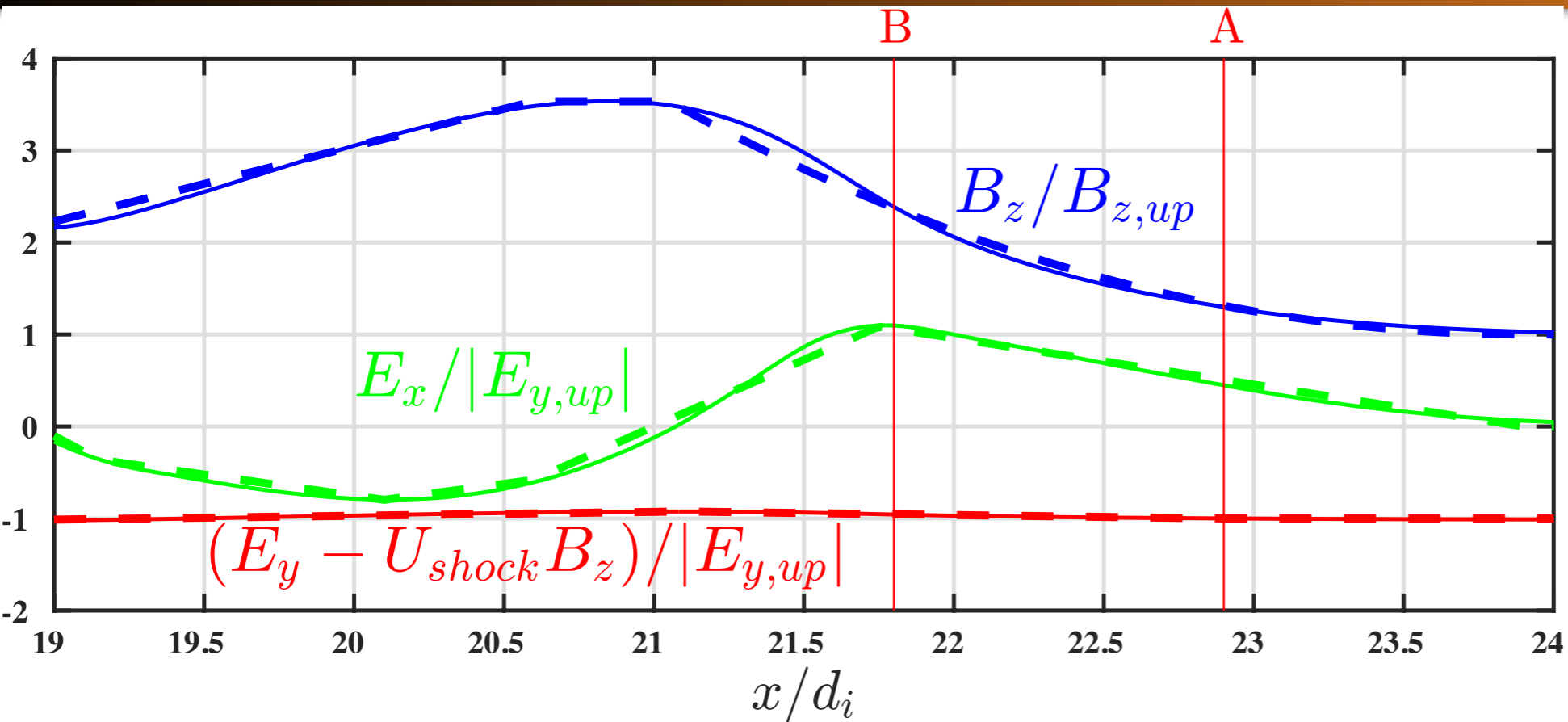
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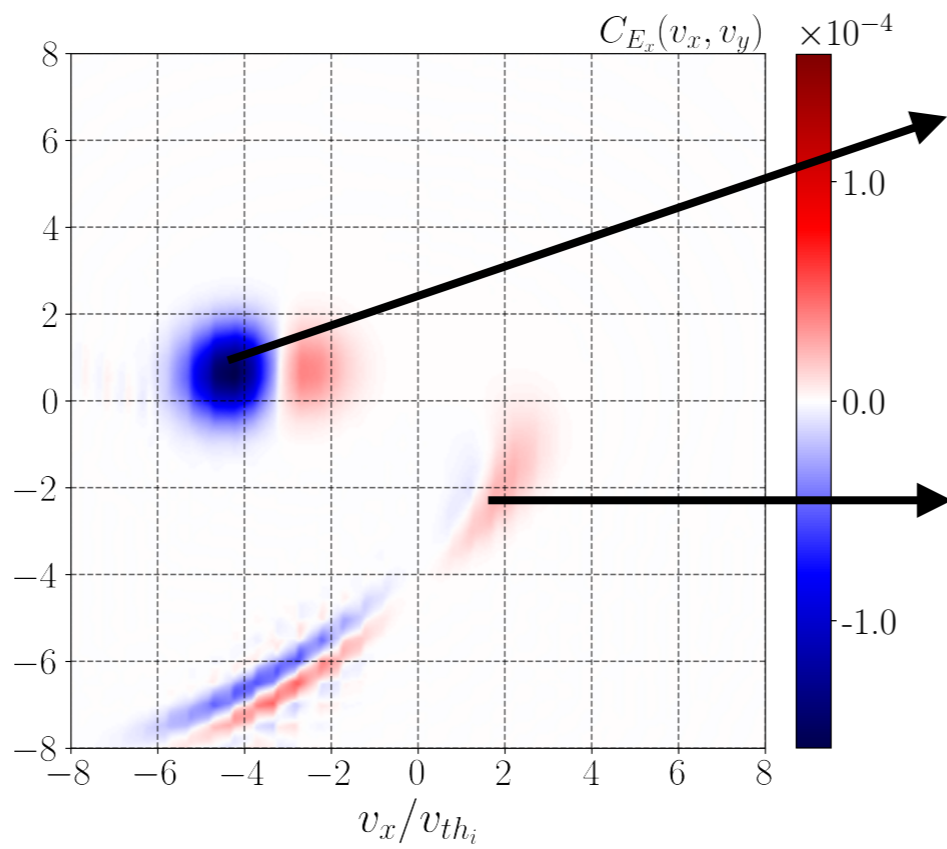
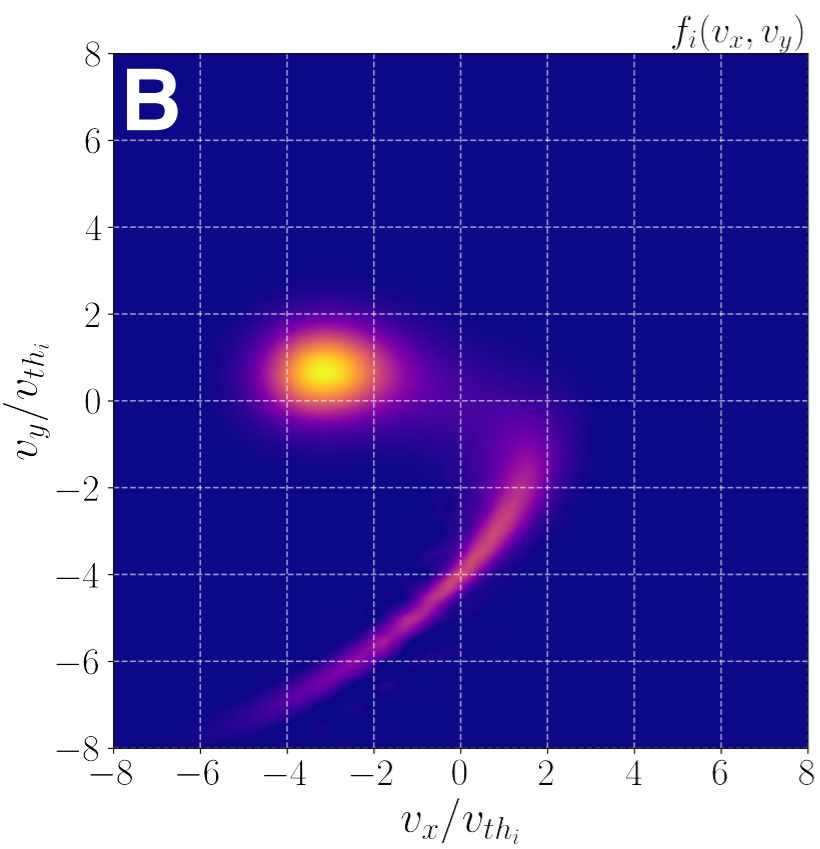
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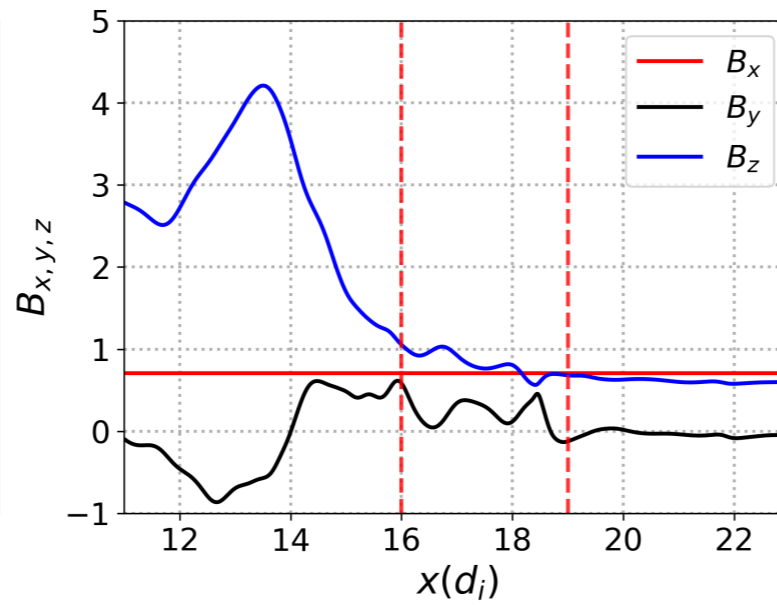
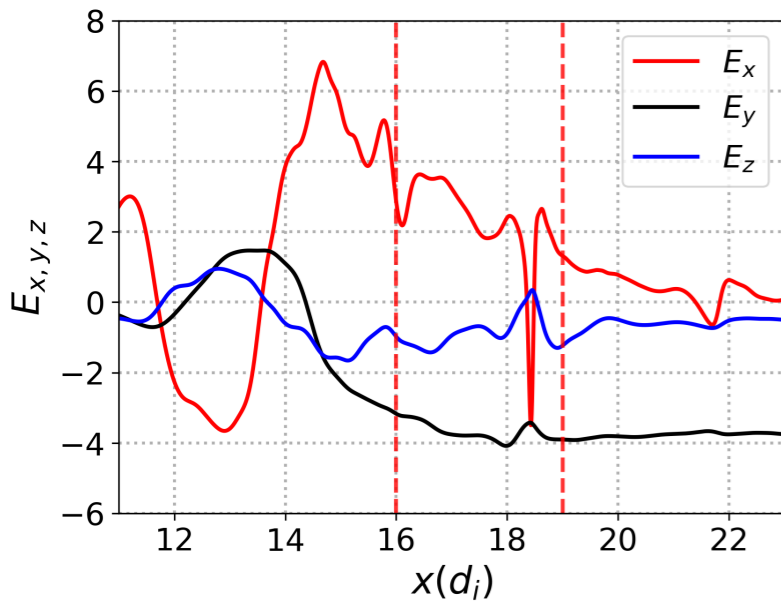
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- Bulk incoming protons being slowed down
- Portion of proton distribution being accelerated by cross-shock electric field **back** upstream!

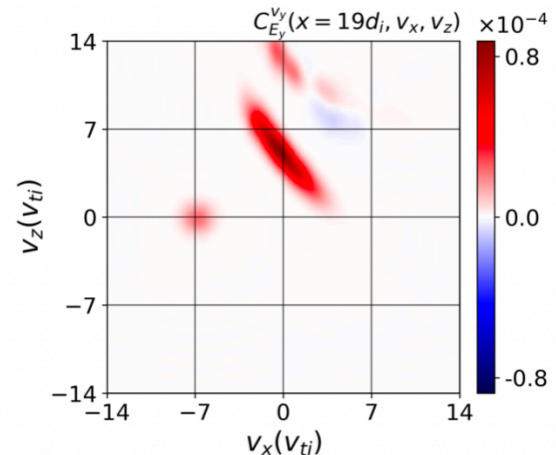
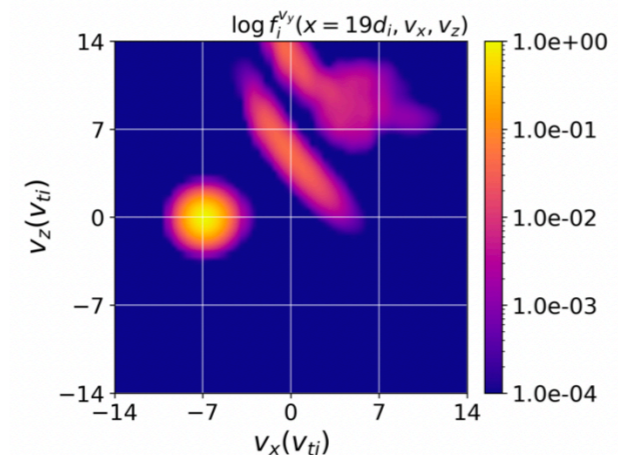
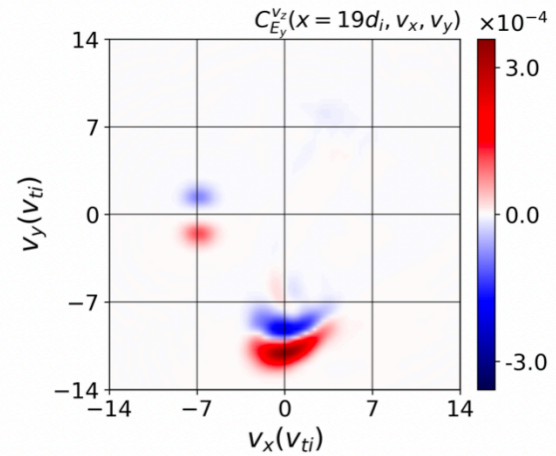
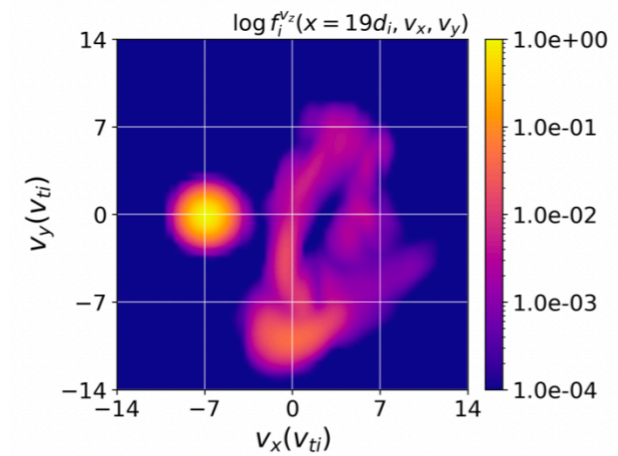
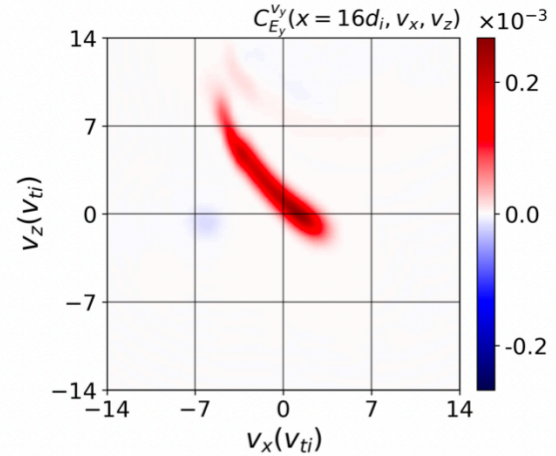
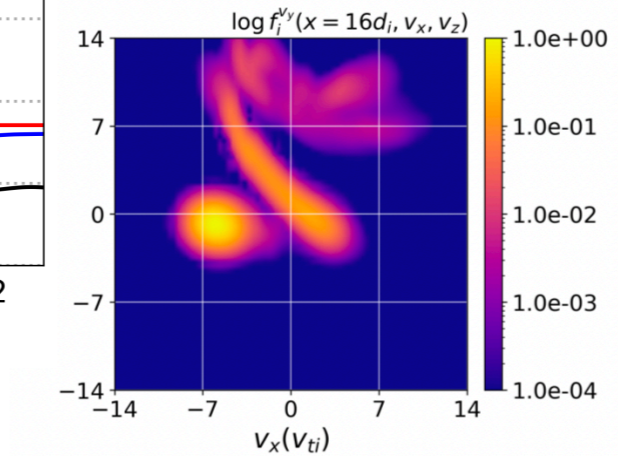
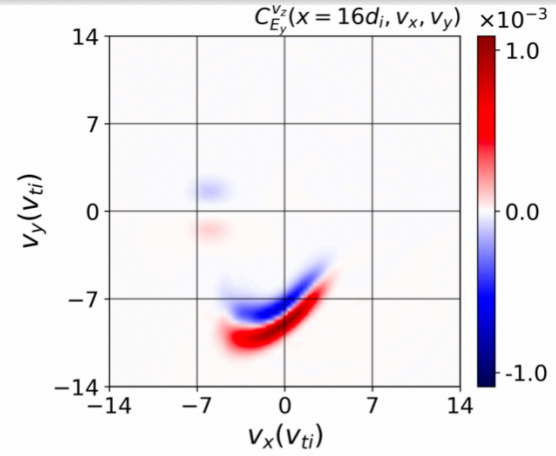
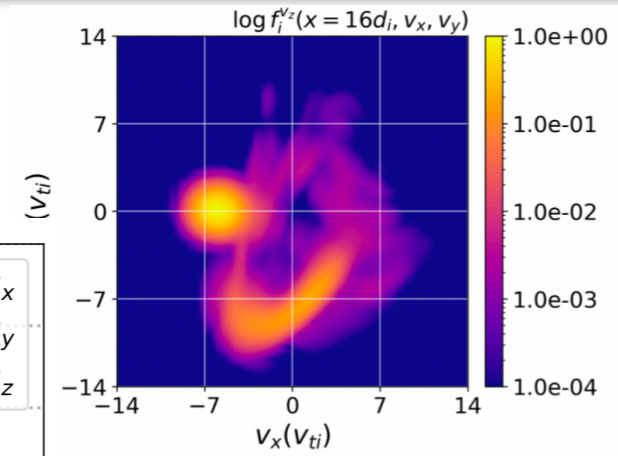
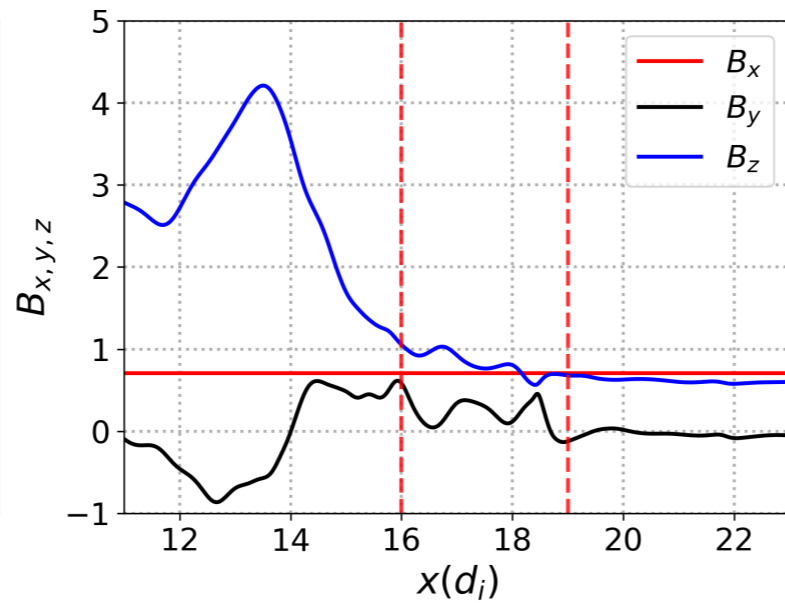
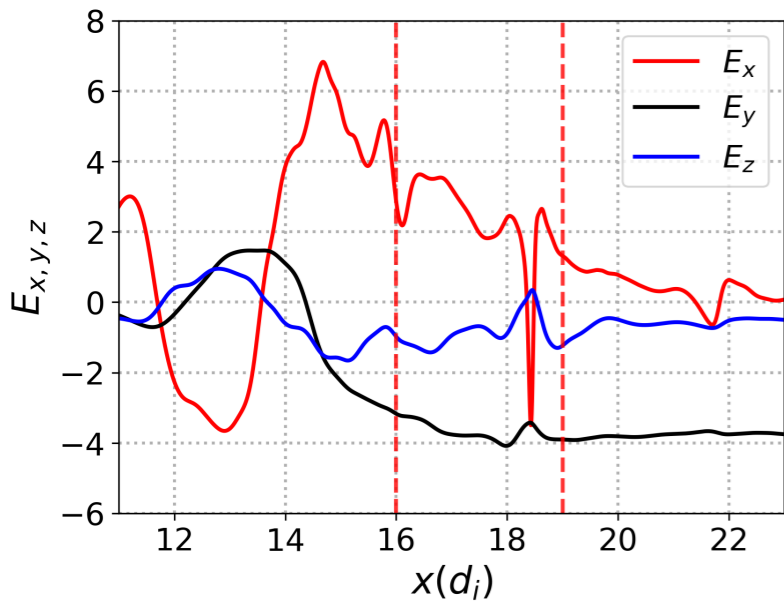
# Phase space allows for holistic view of energization

- Alfvén Mach 6 injection; 45 degrees;  
1X3V kinetic simulation



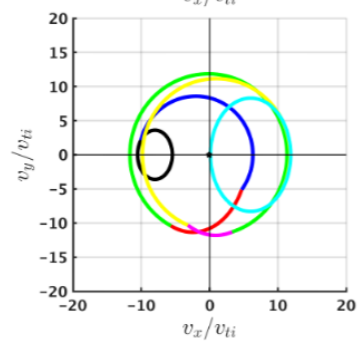
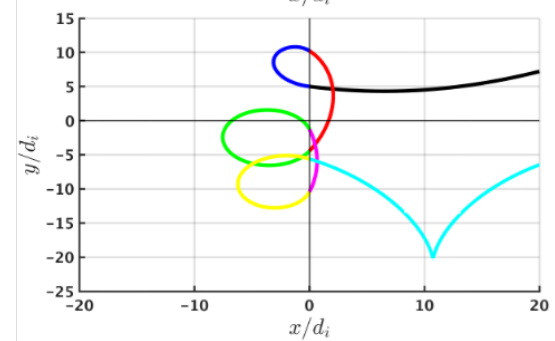
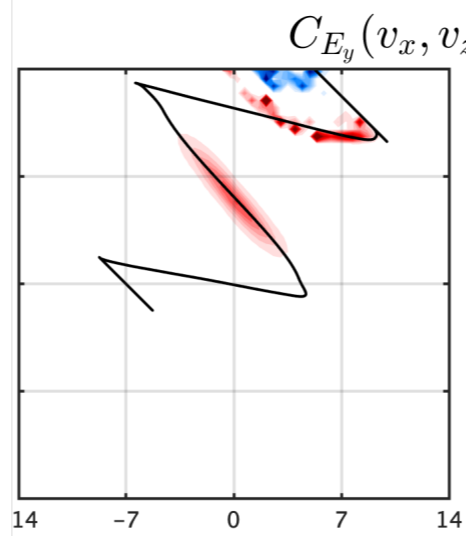
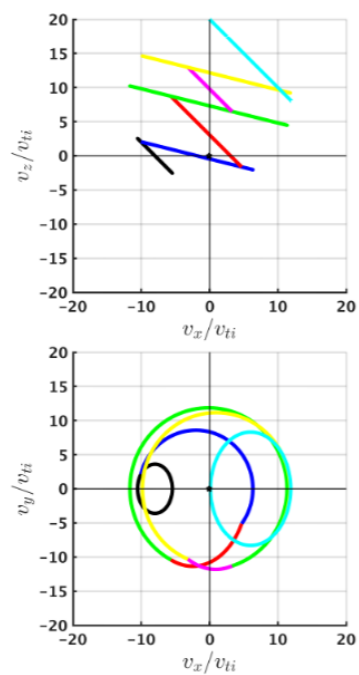
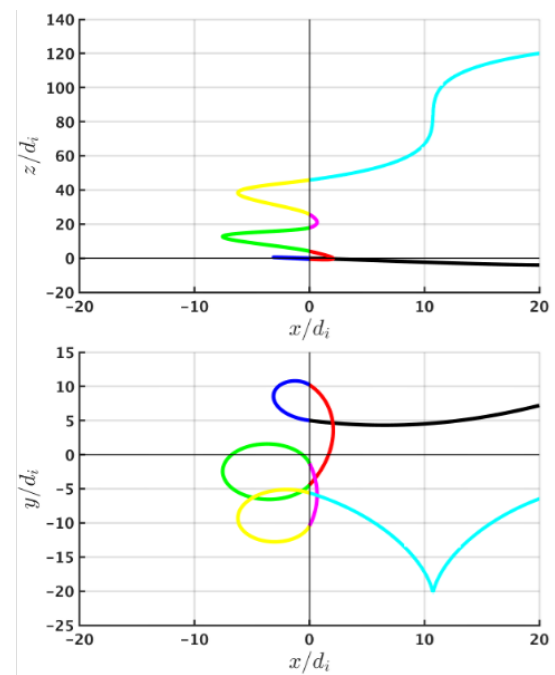
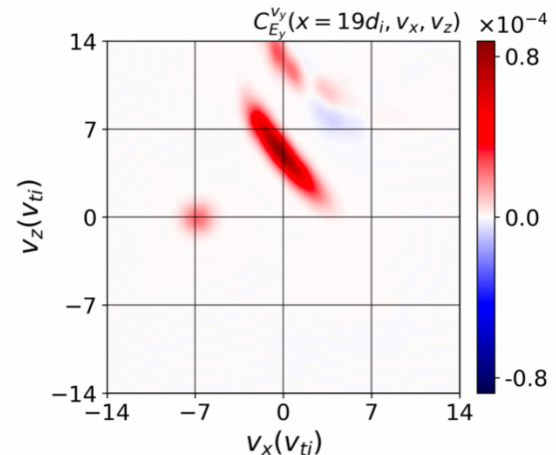
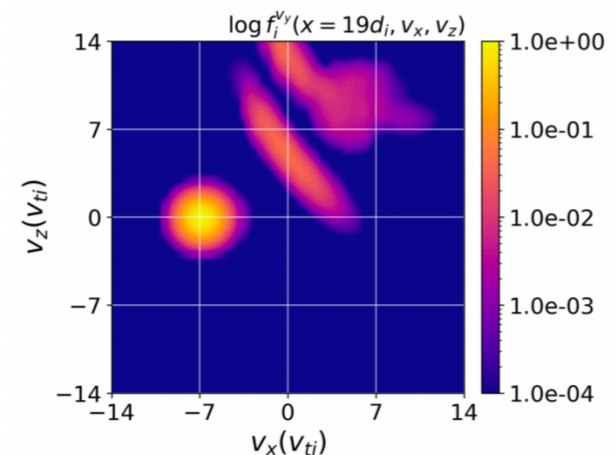
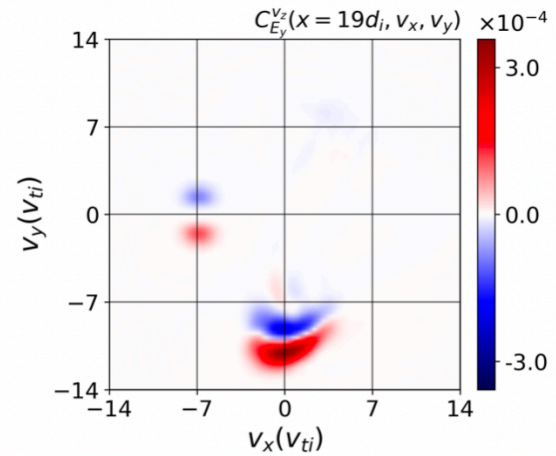
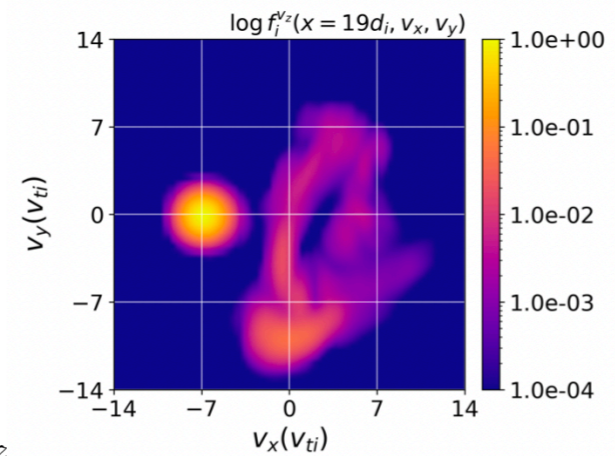
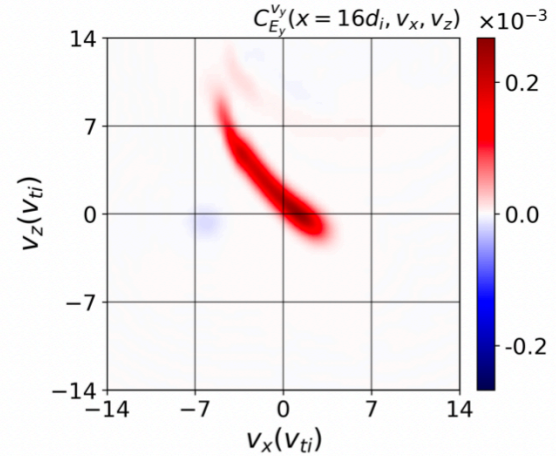
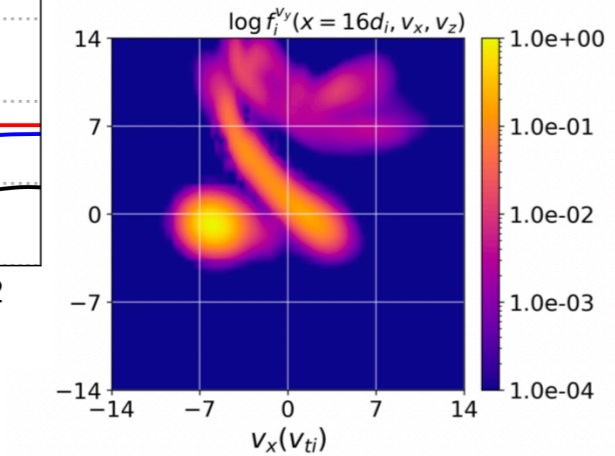
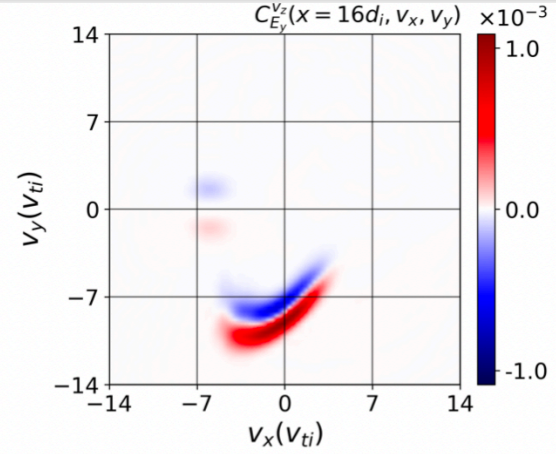
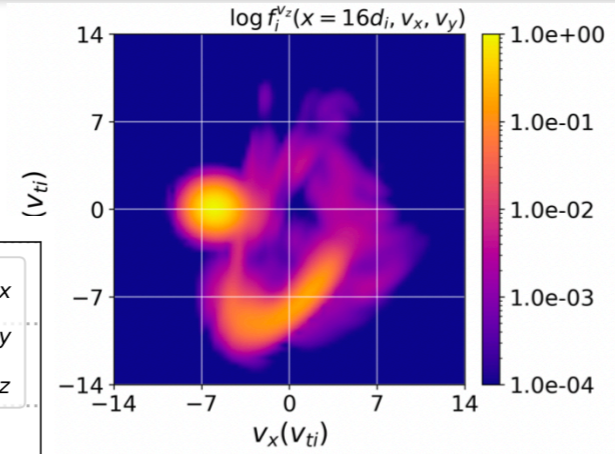
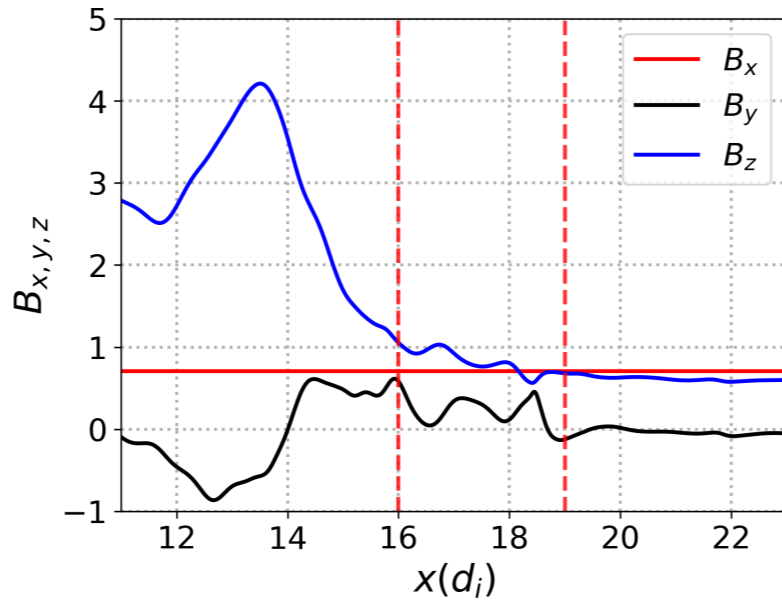
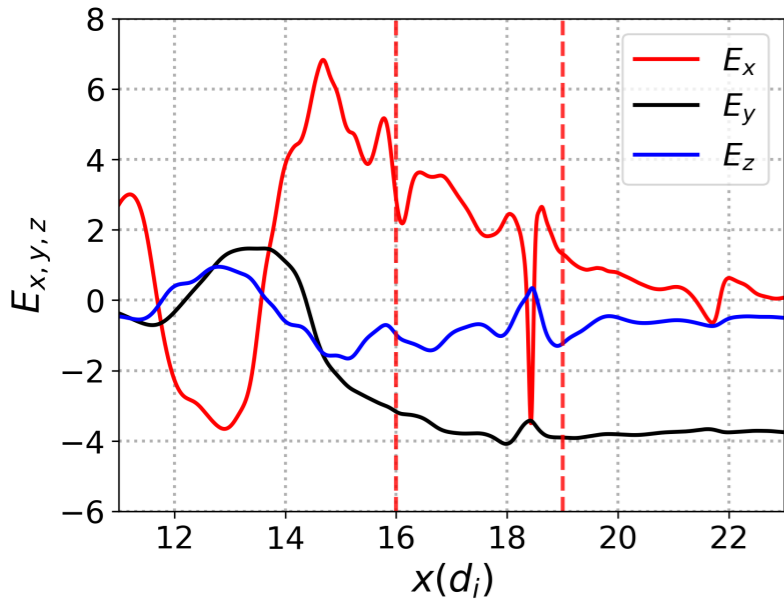
# Phase space allows for holistic view of energization

- Alfvén Mach 6 injection; 45 degrees;  
1X3V kinetic simulation



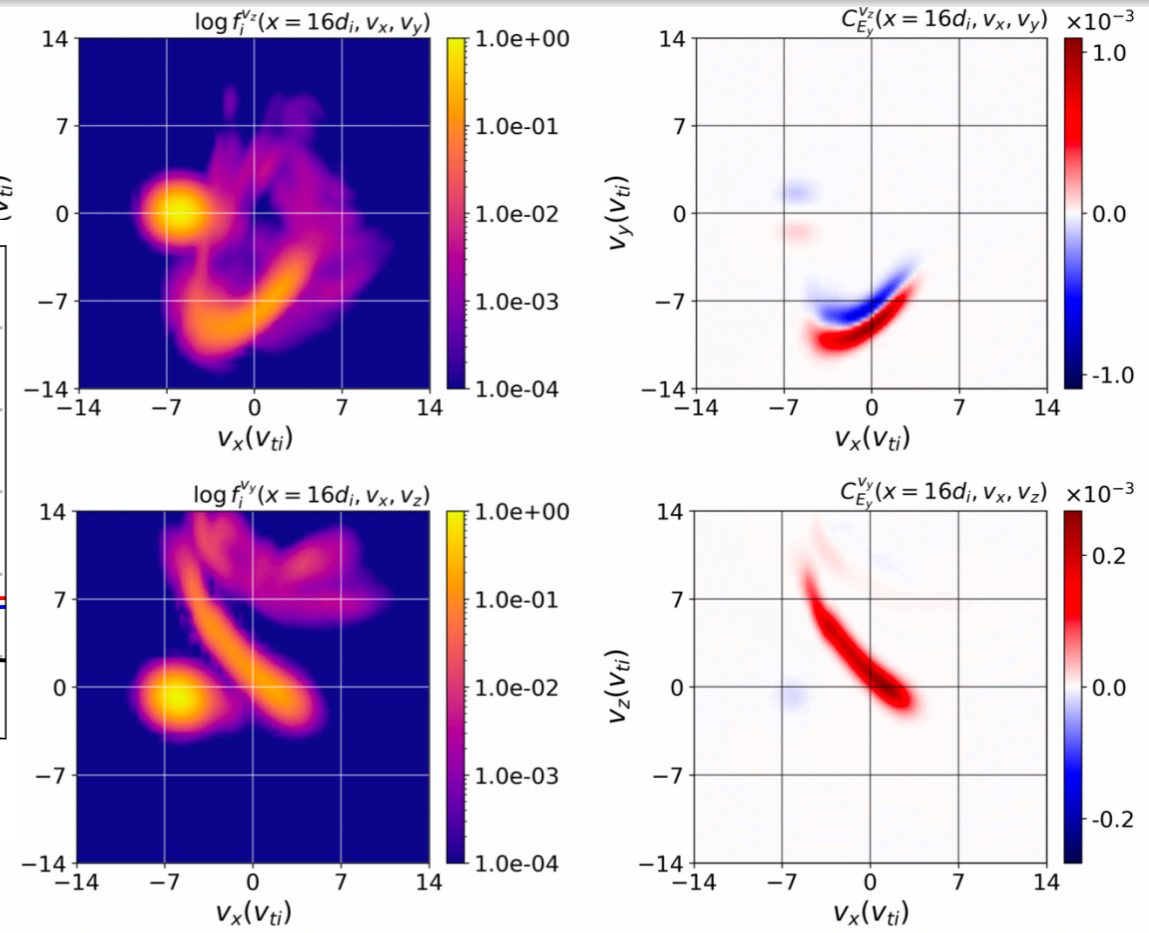
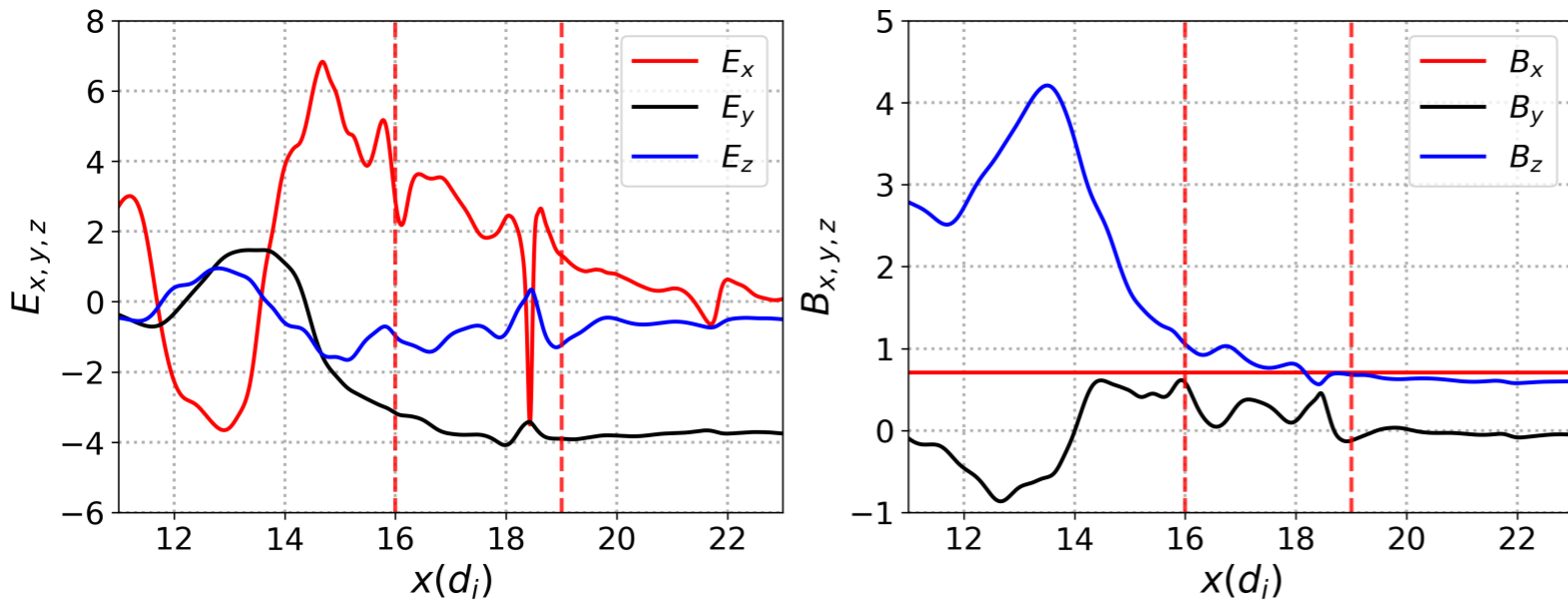
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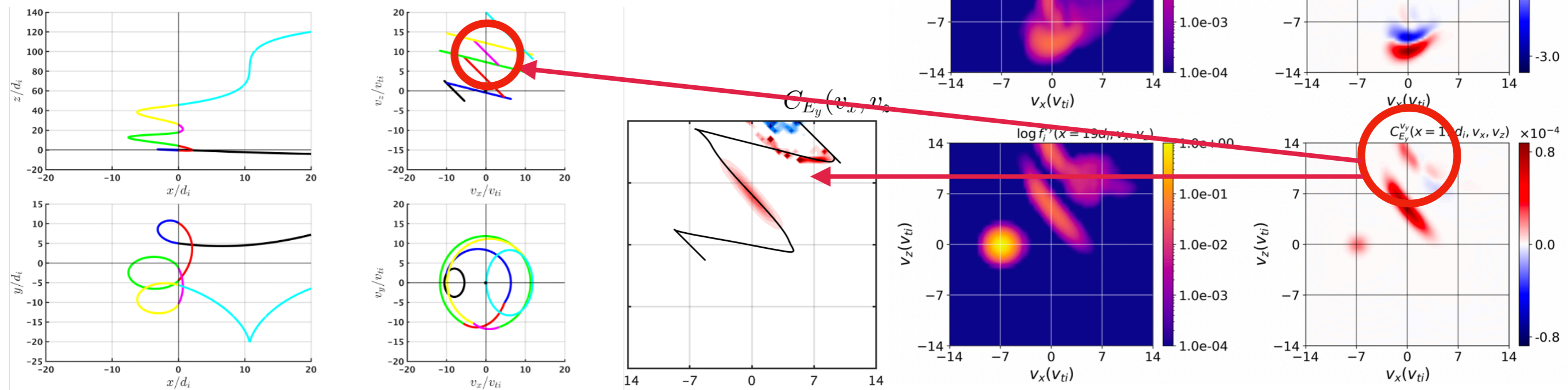


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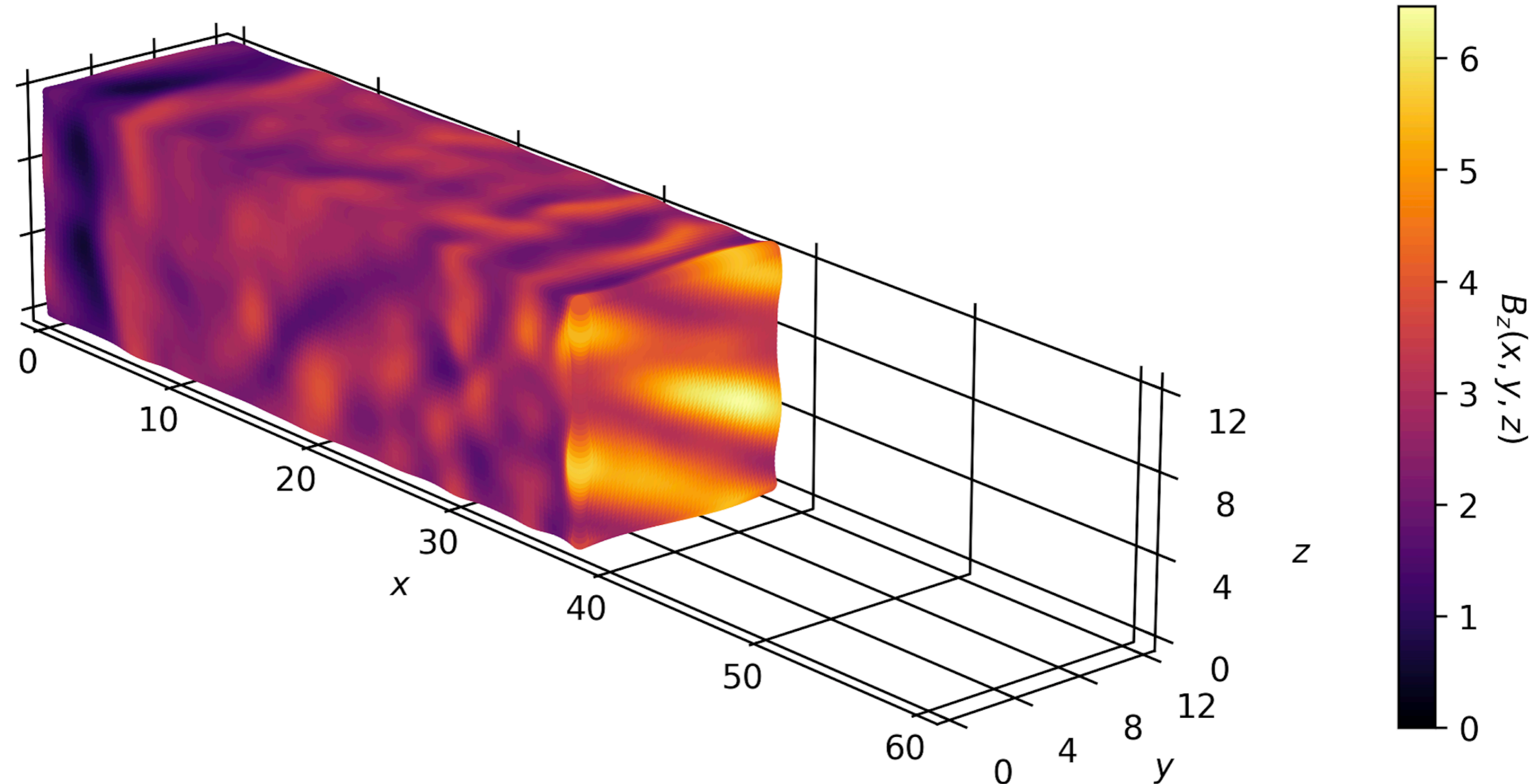


- Energization at higher velocities corresponds to particles which bounced multiple times
- Diagnostic tells us how **regions** of phase space are being energized



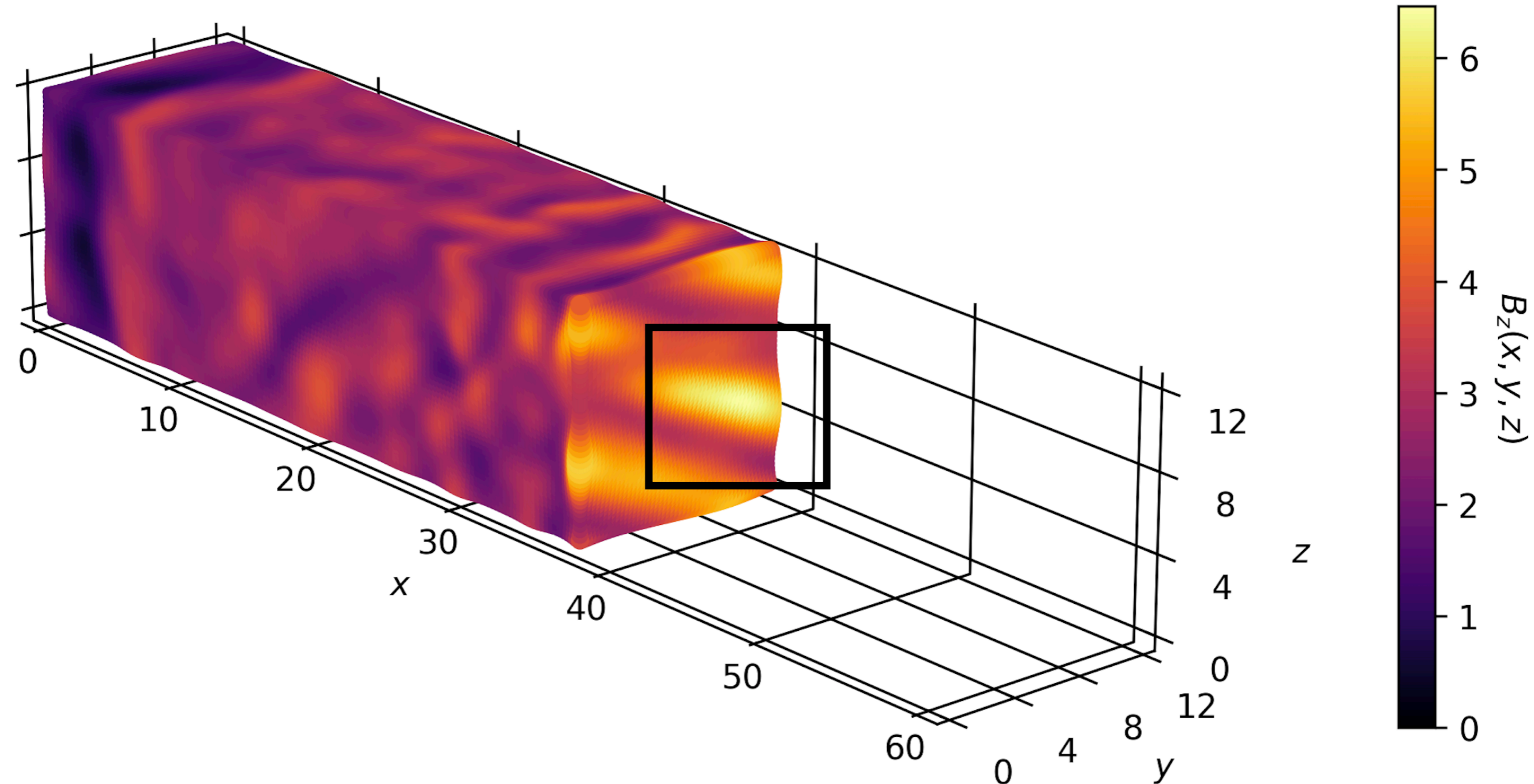
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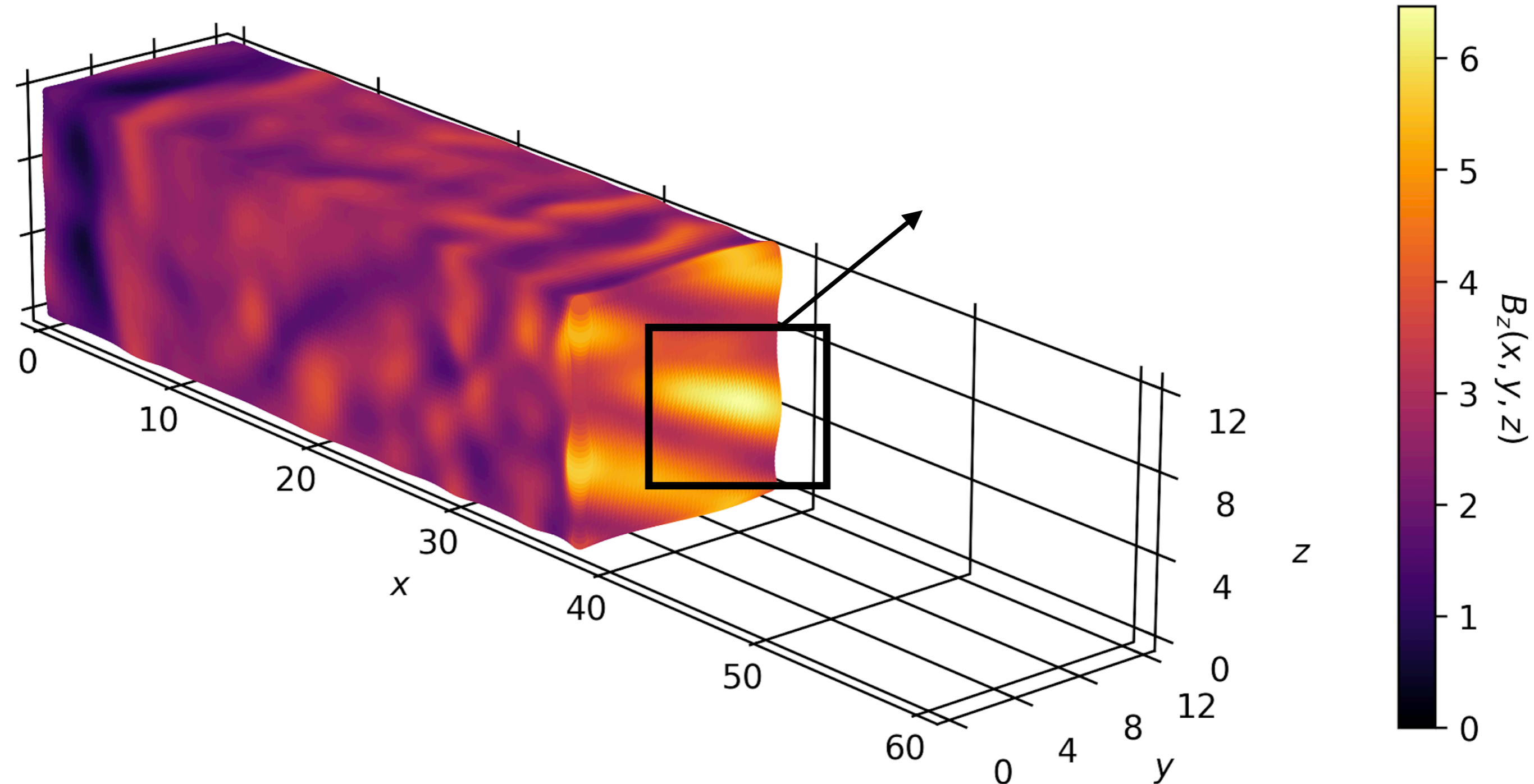
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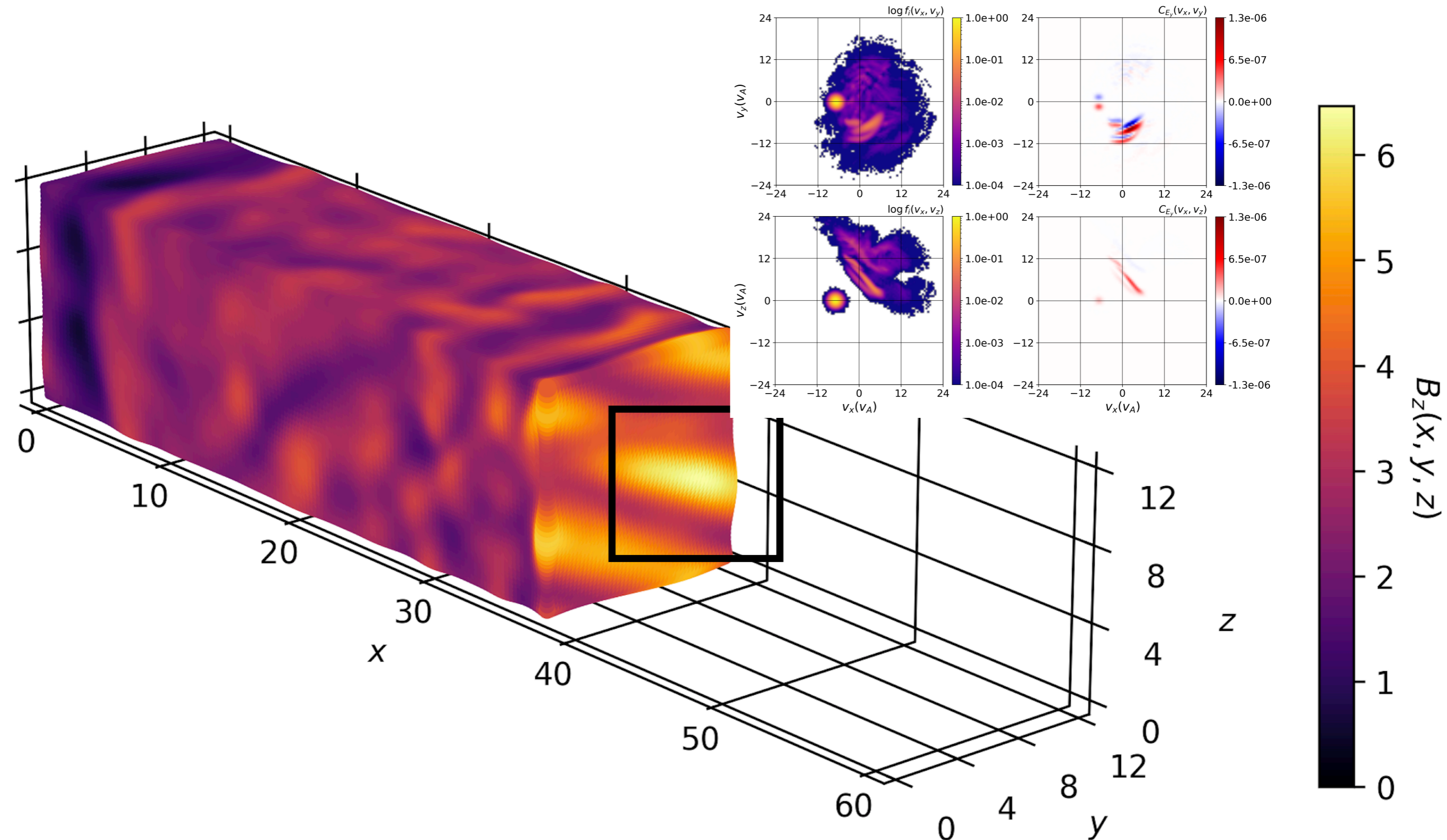
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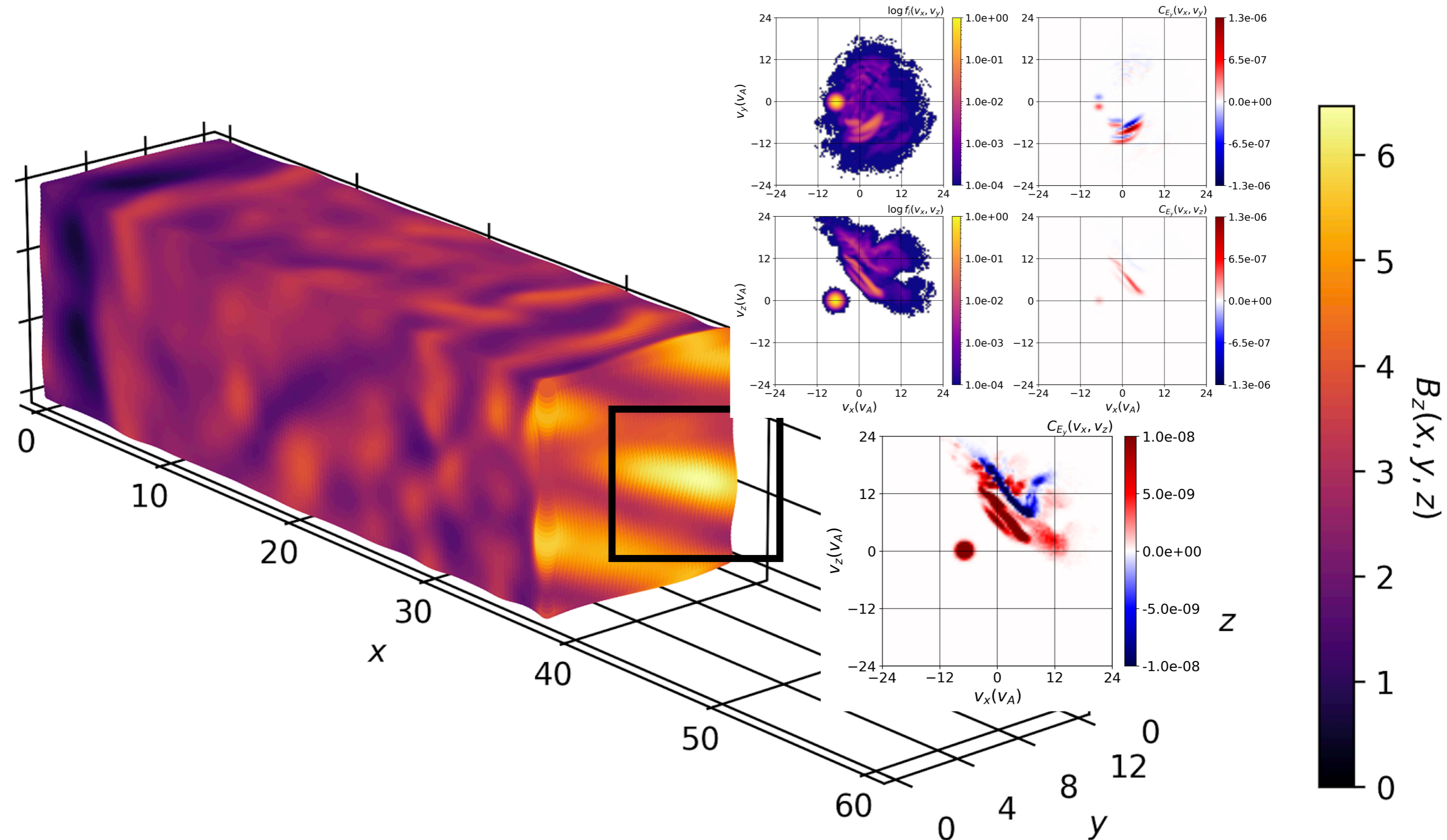
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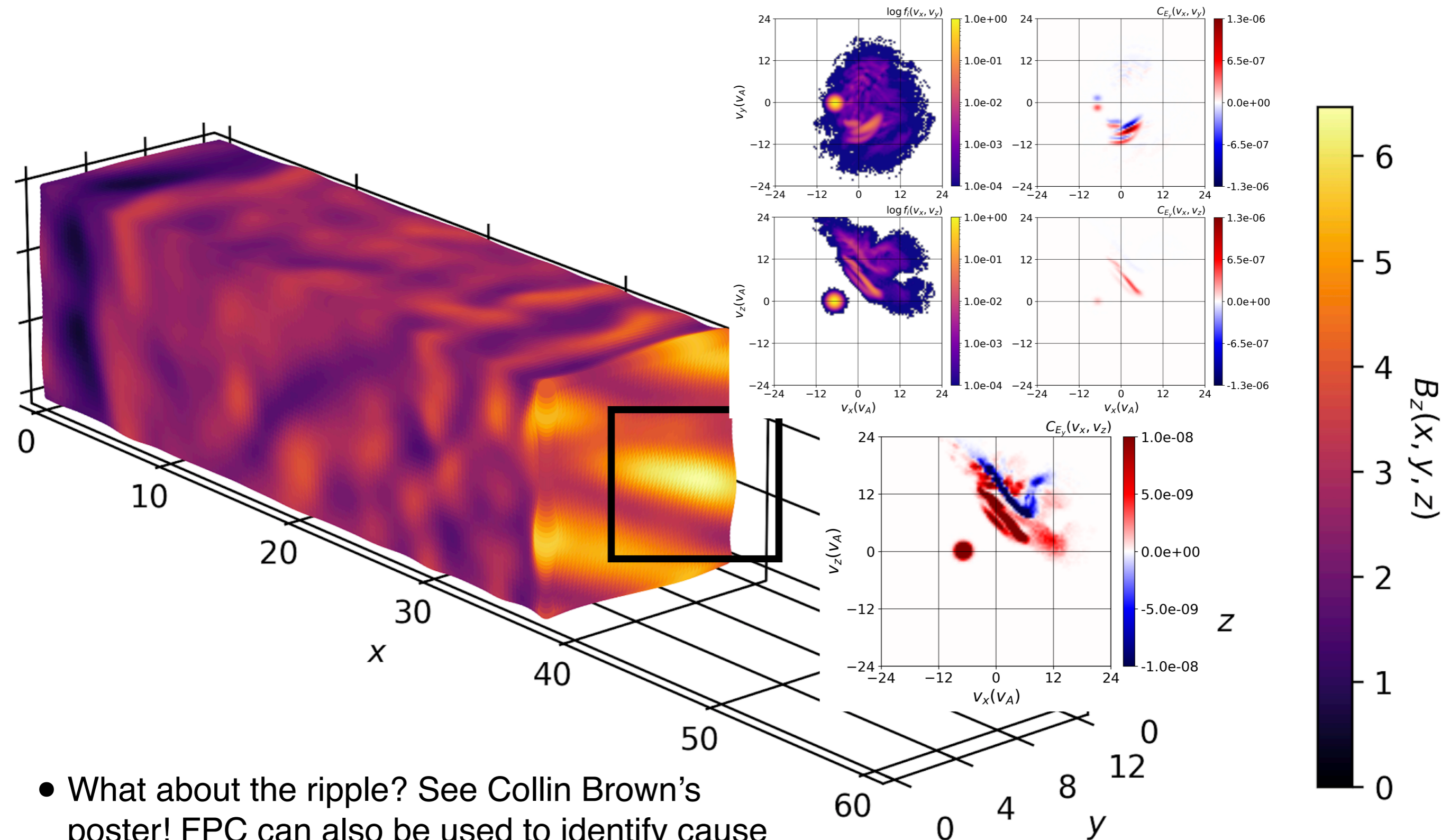
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- What about the ripple? See Collin Brown's poster! FPC can also be used to identify cause of ripple and contribution to energetics!

# Looking ahead to new phase-space frontiers

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- 50+ years of looking at the details of the distribution function and still *a lot* more to do on this front; new algorithmic approaches, higher resolution computations, and novel diagnostics all exciting!

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  - Phase space diagnostics applied to *both* simulation and spacecraft data will be necessary to understand the impact of this structure

**Thank you for your attention!**