Comparing Kinetic Methods for Phase Space Dynamics of Weibel-type Instabilities

James Juno

Acknowledgements:
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Marc Swisdak and William Dorland

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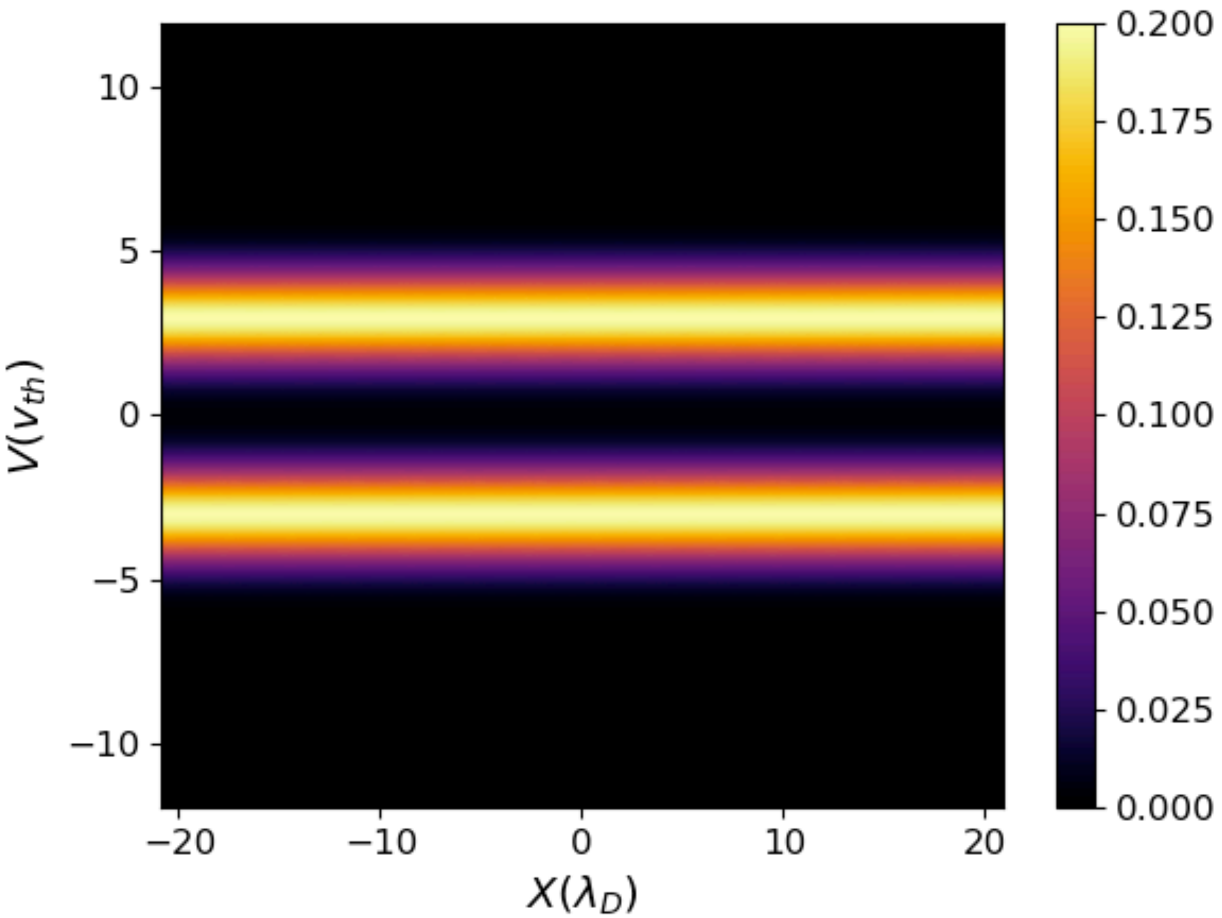
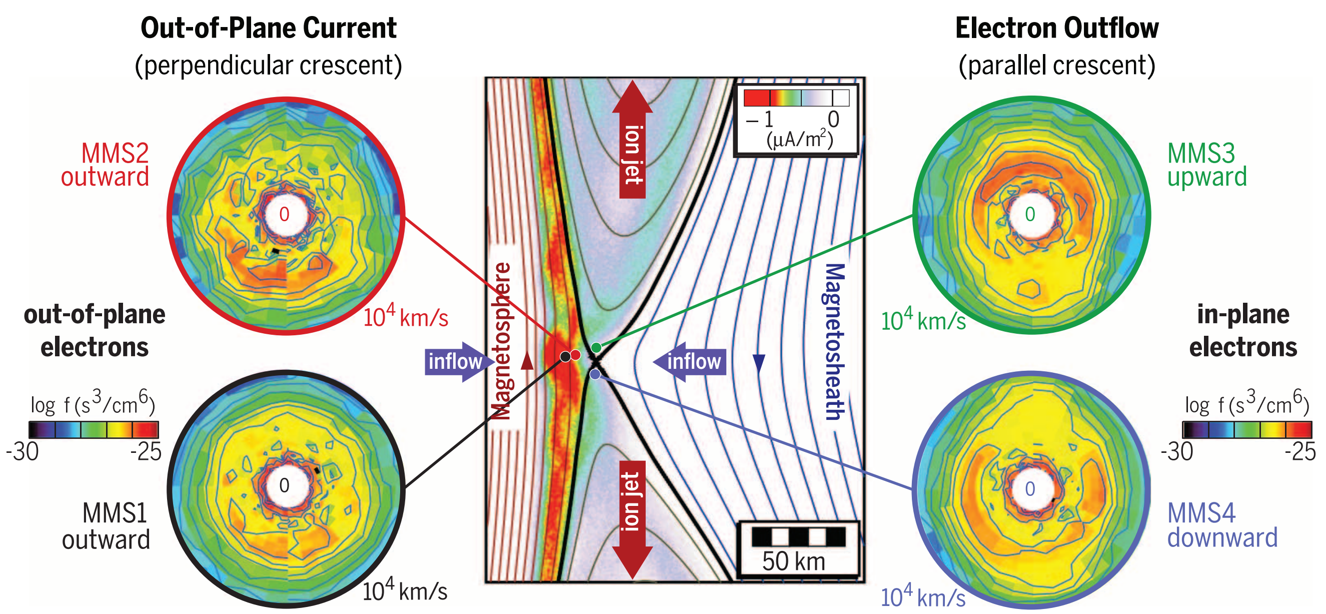
A deep dive into phase space

- We know the distribution function contains a wealth of data
- Obtaining a clean enough representation of the distribution function, and accessing this data is hard
- But well worth the effort since, for example, many energization mechanisms are most easily identified by the phase space structure they create





MMS electron data from Burch et al (2016).

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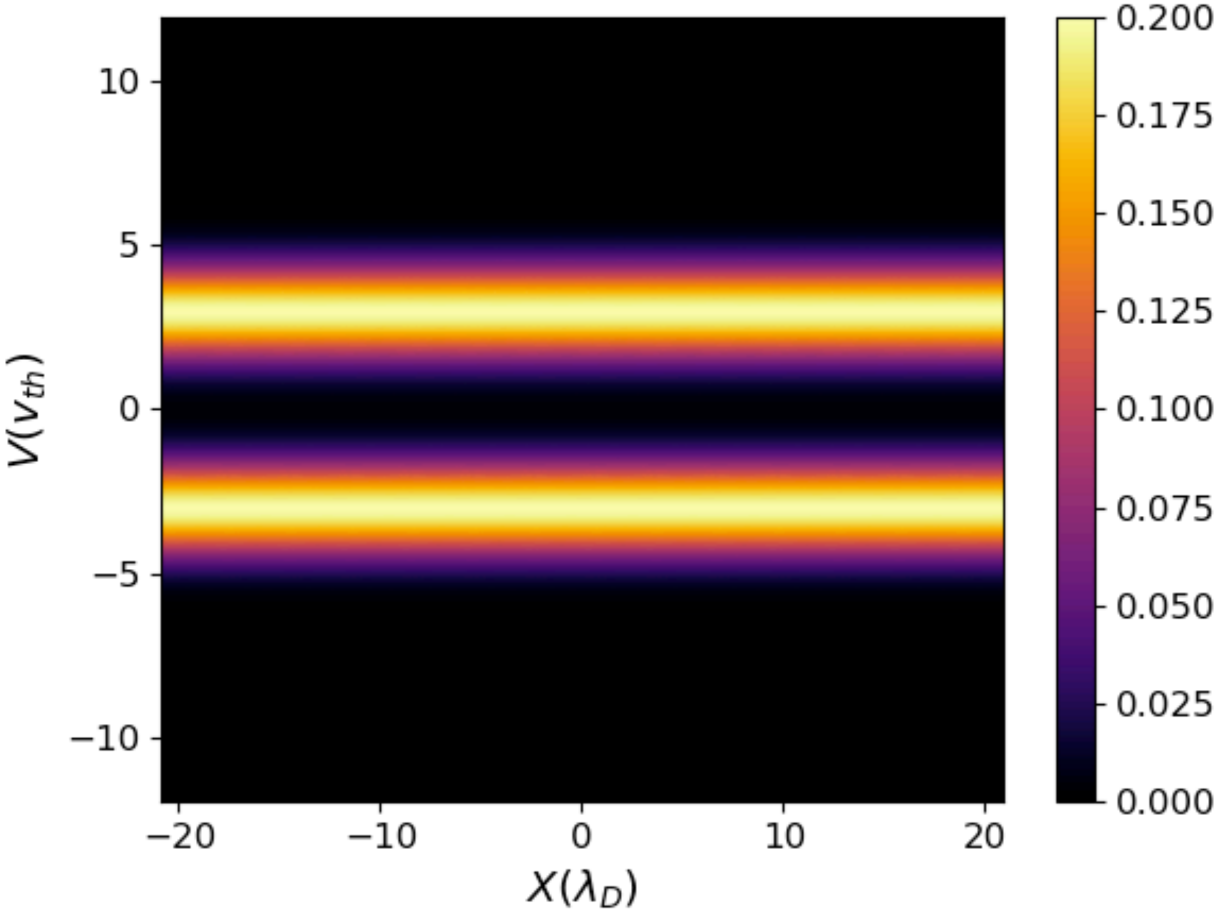

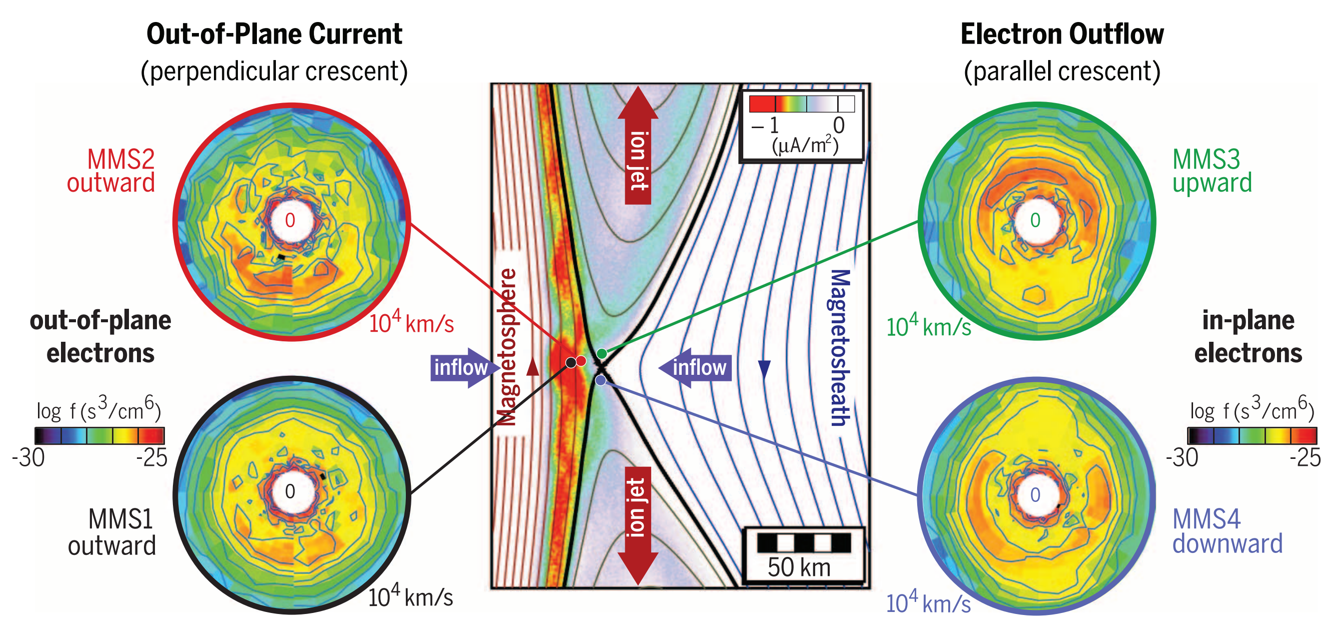

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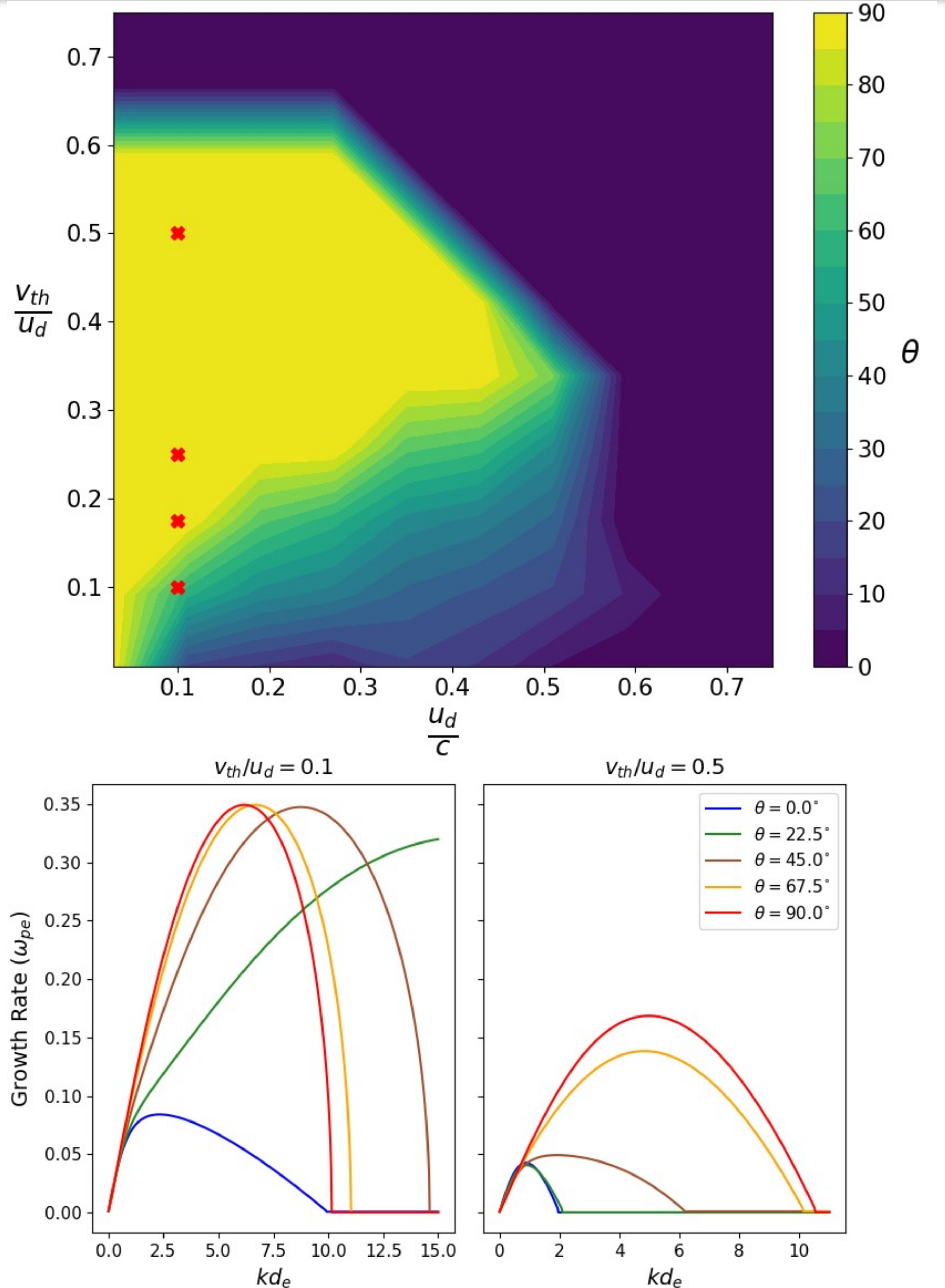
Two-Stream & Filamentation Instability

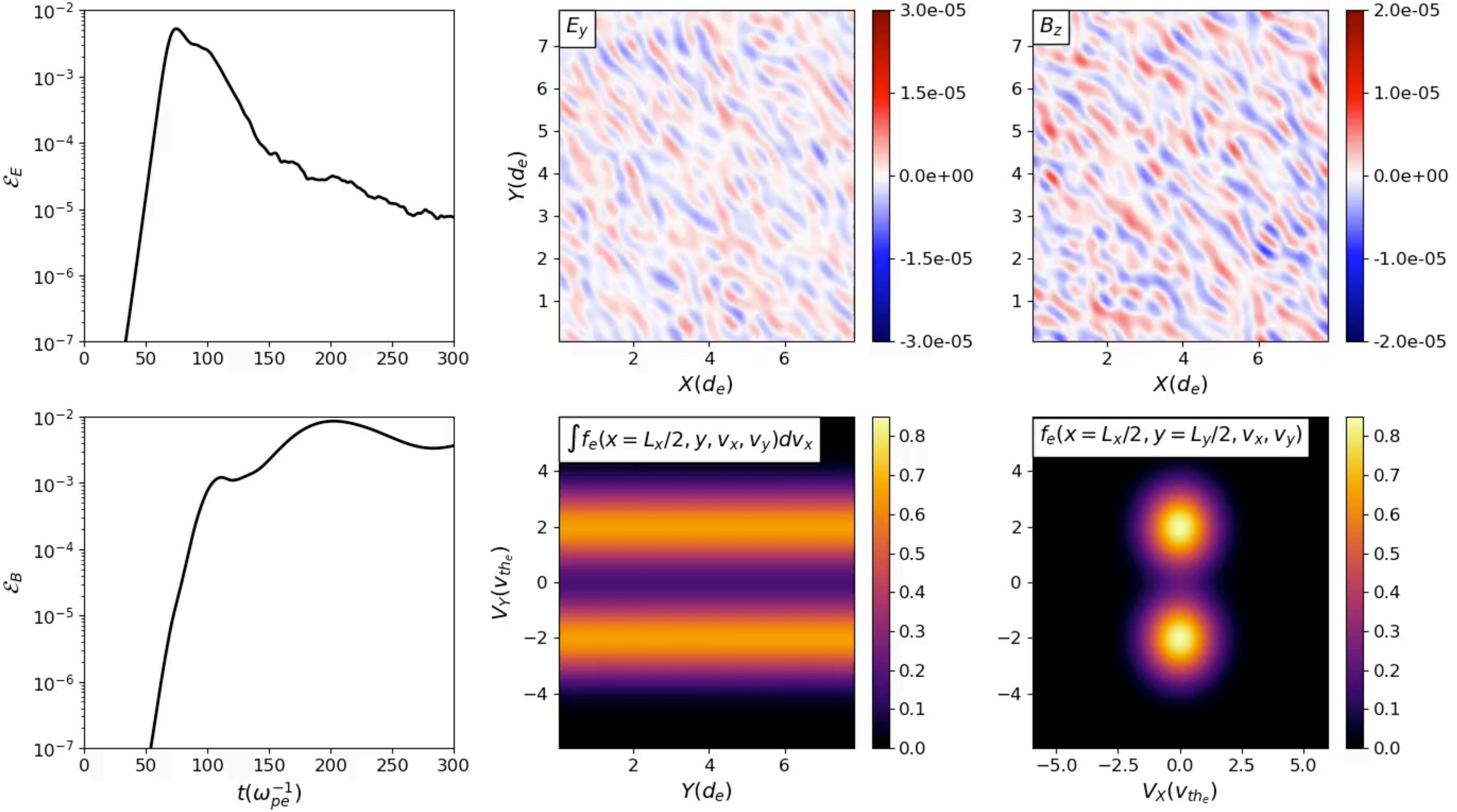
- The two-stream instability and filamentation instability are two oft-studied 1D kinetic instabilities
- Two-stream from perturbations aligned with counter-streaming drifts
- Filamentation from perturbations orthogonal
- In 2D, two-stream and filamentation can compete with each other
- In addition, oblique modes can be present
- When drifts non-relativistic, many of these modes all have similar growth rates, the ultimate nonlinear evolution will involve a competition between these instabilities
- Non-relativistic system relevant for reionization epoch



The “hot” case

$$v_{th_e}/u_d = 0.5$$

$$\Delta x \sim \pi\lambda_D, \quad \Delta v \sim v_{th_e}/4, \quad p = 2$$



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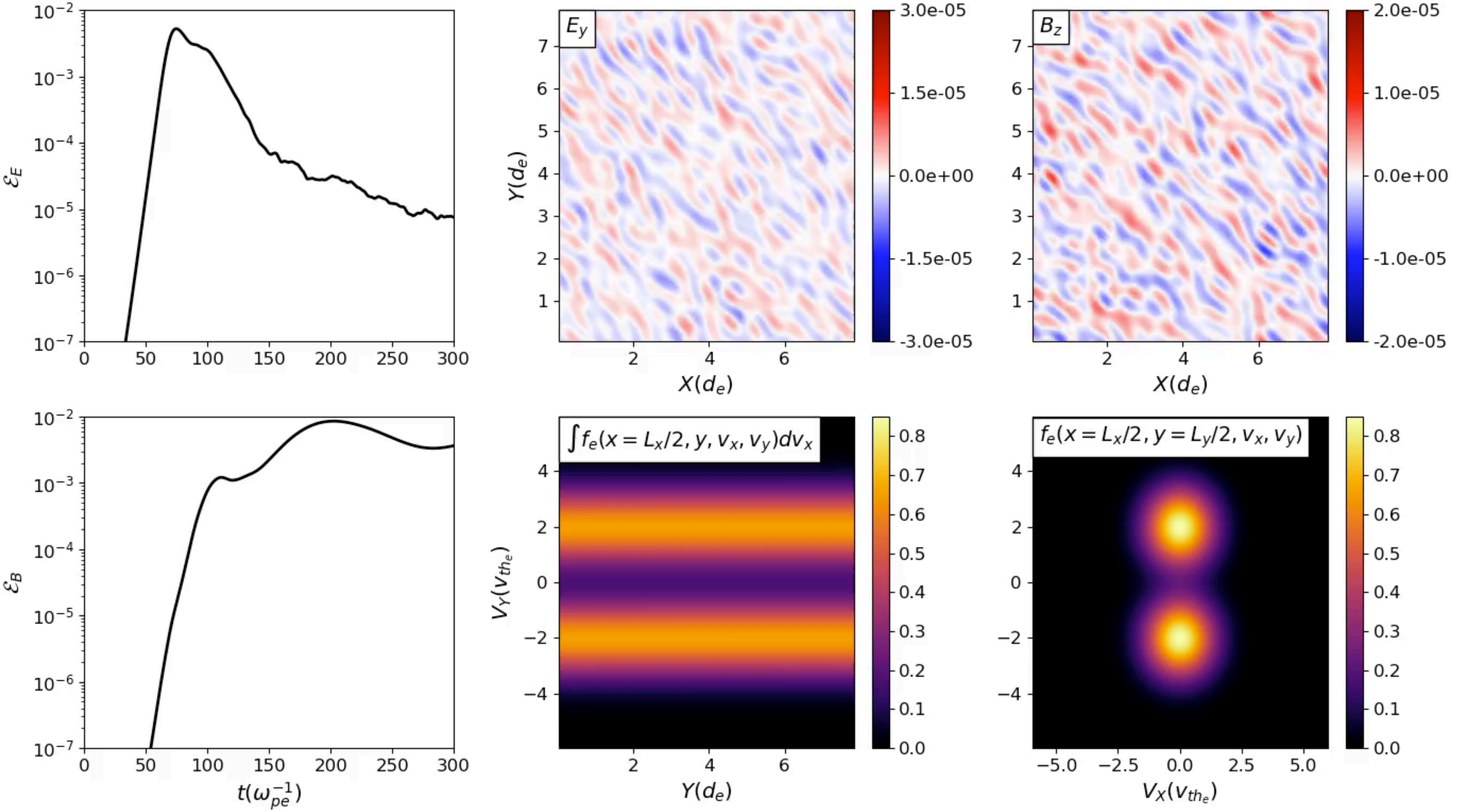

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$$v_{th_e}/u_d = 0.1$$

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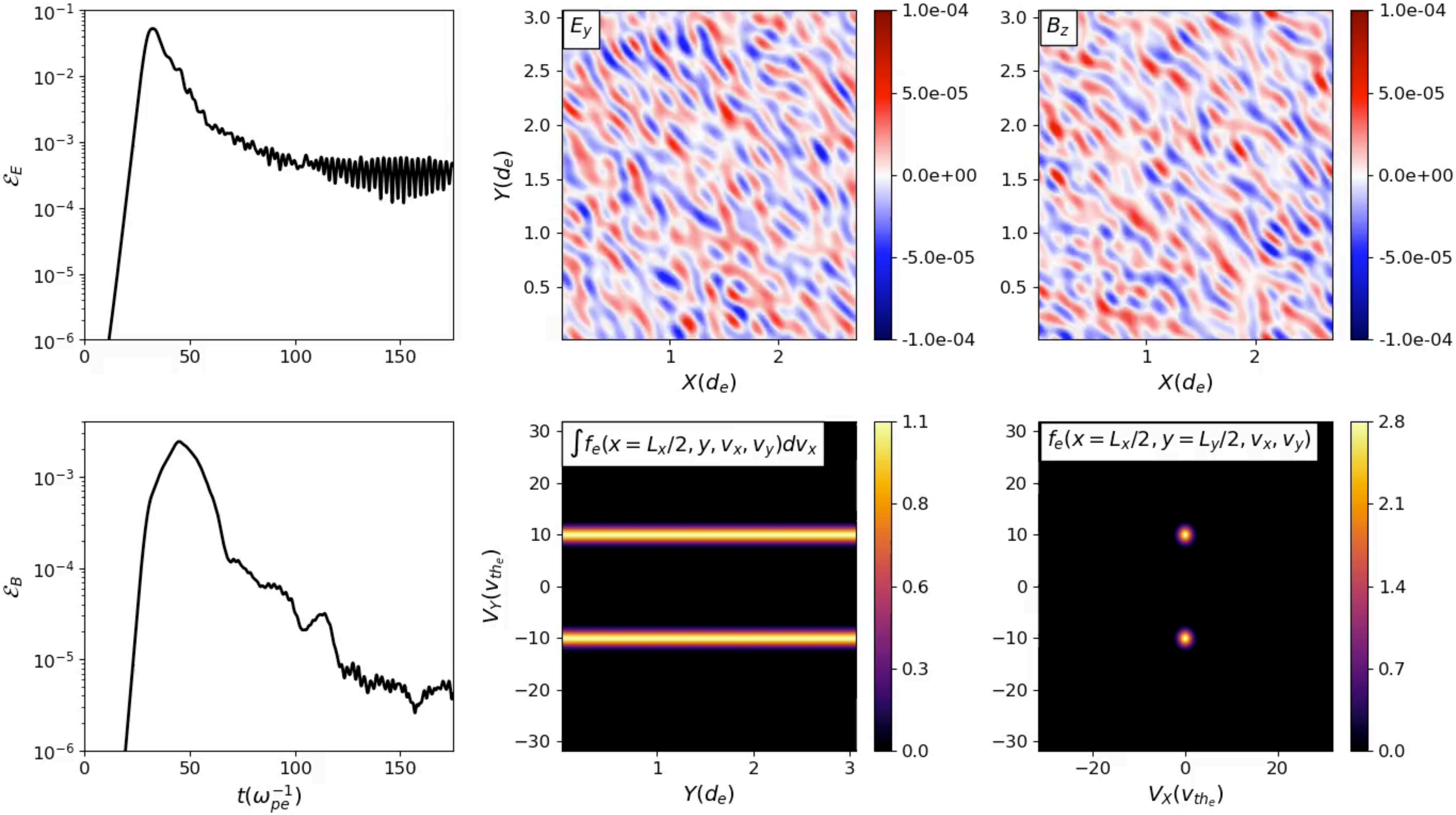

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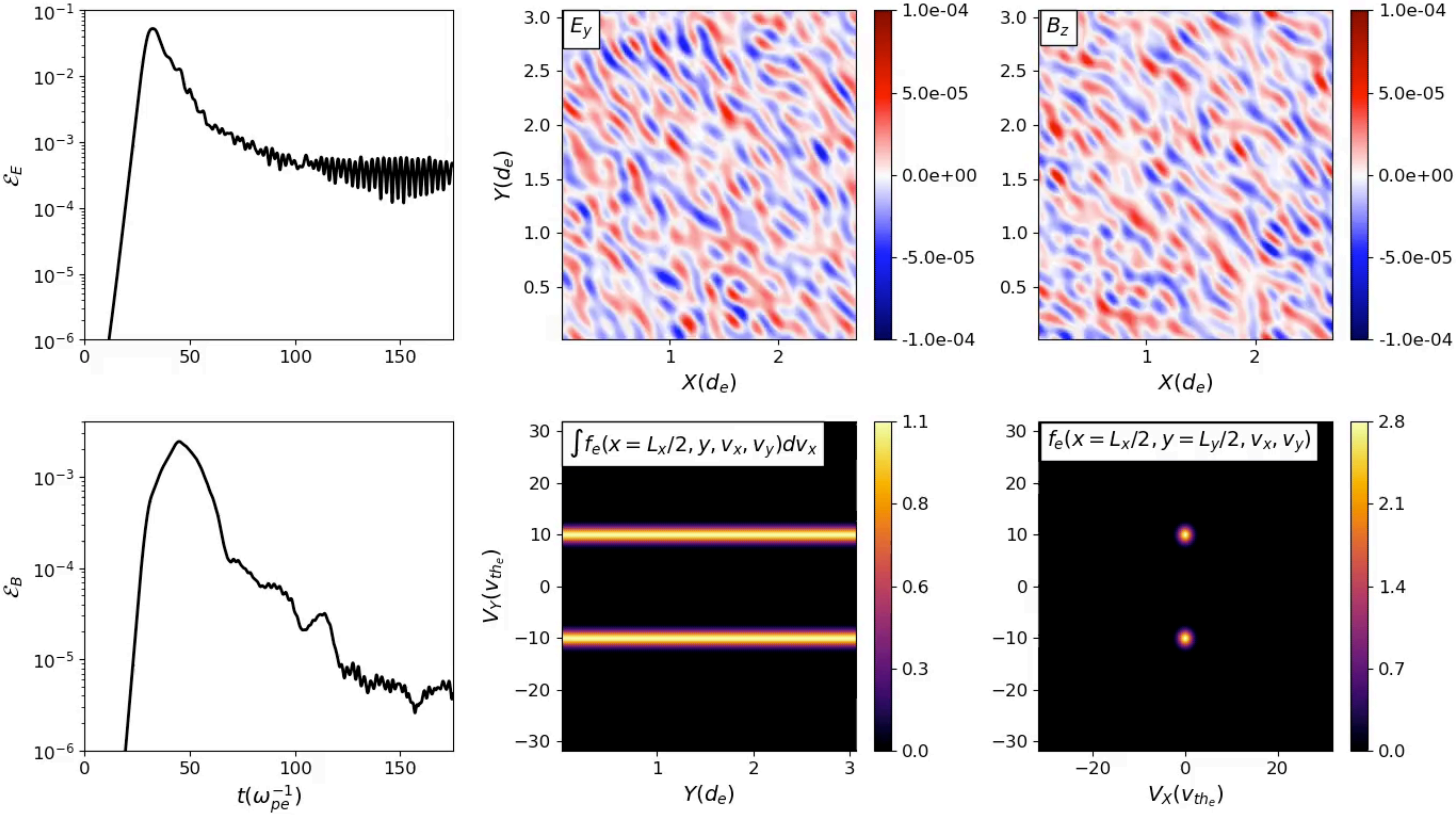
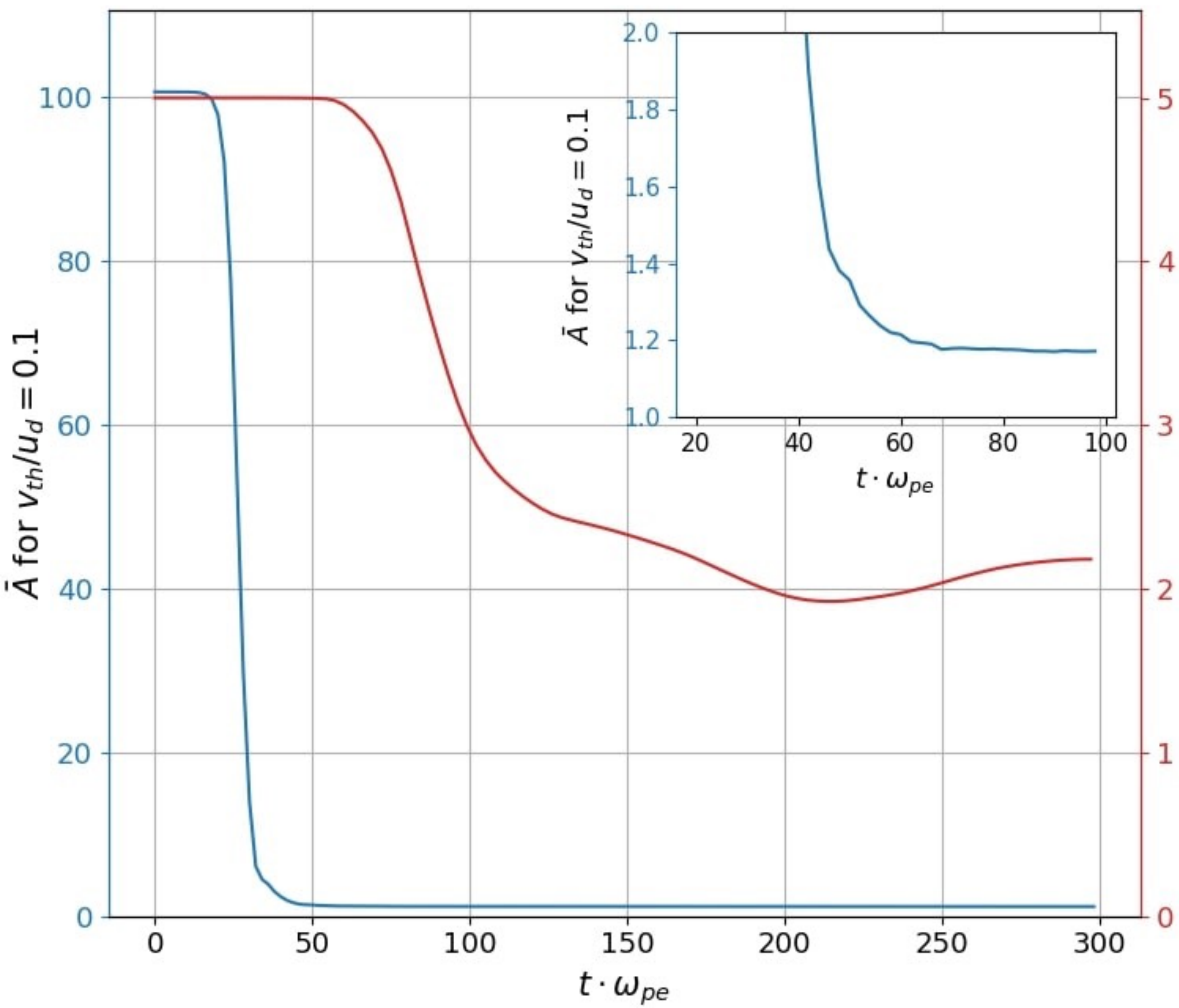
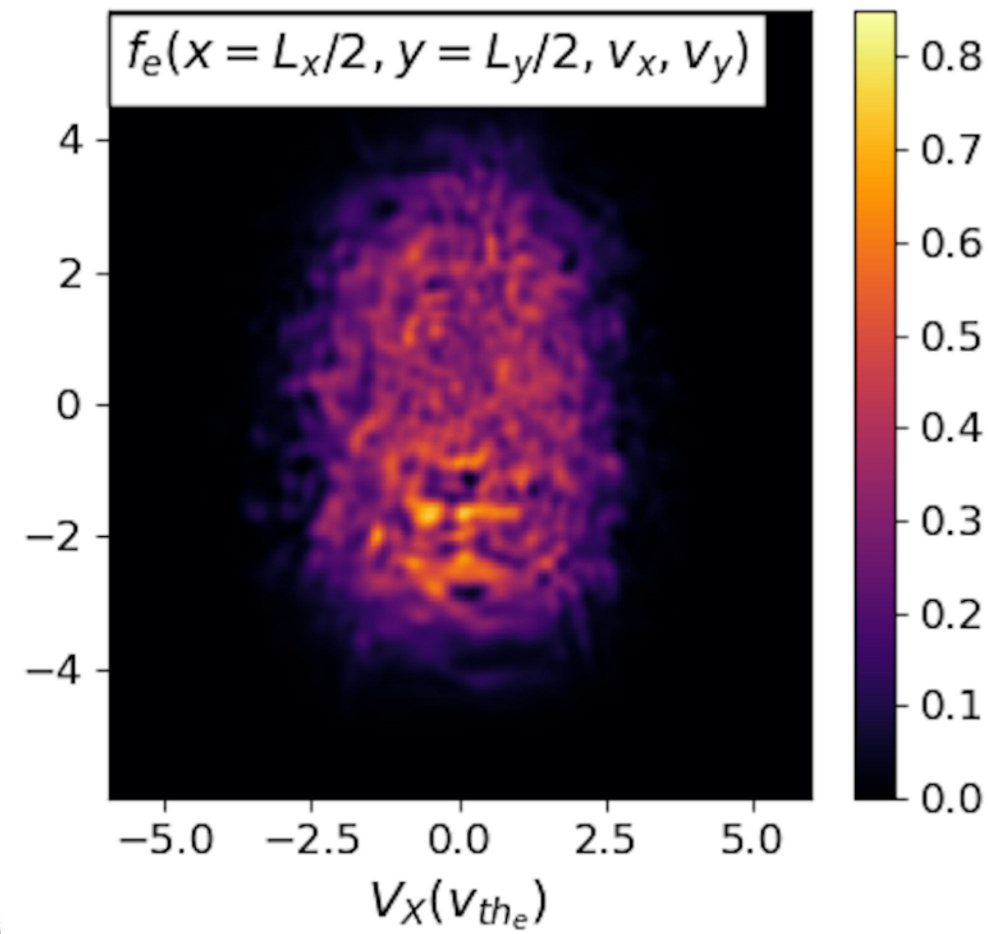
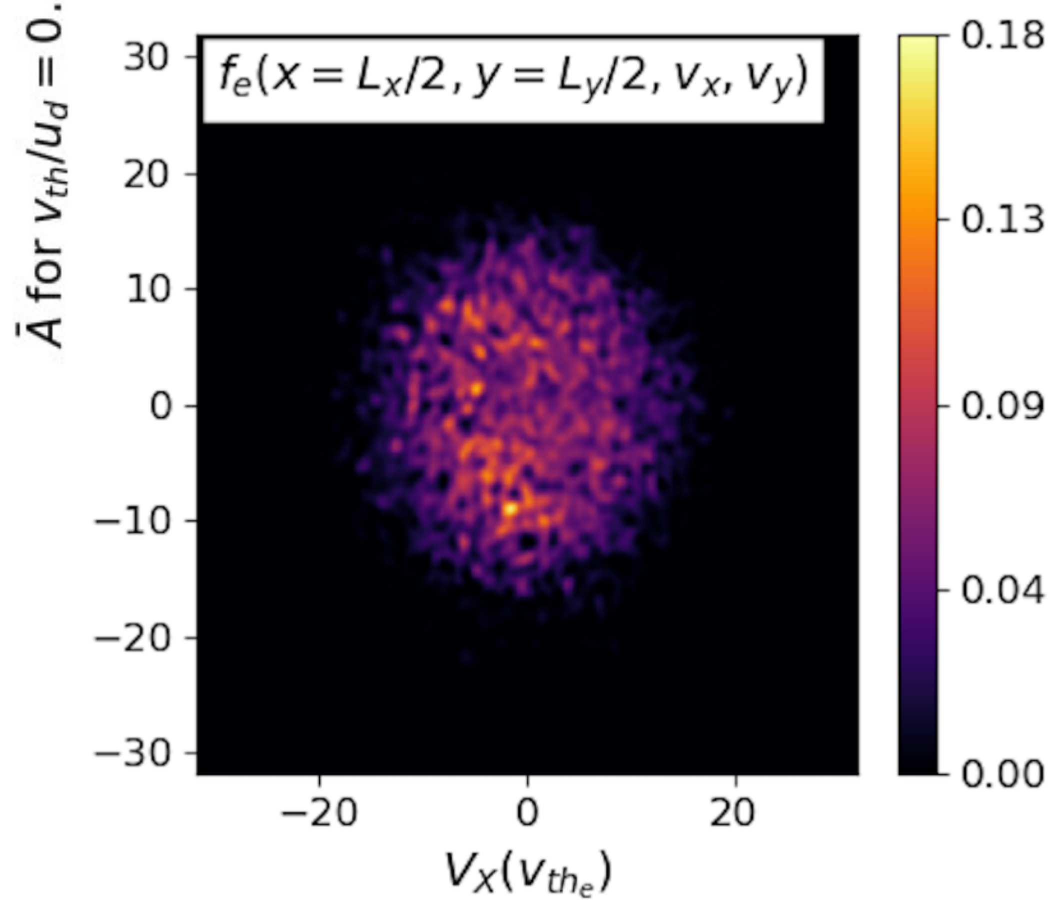


The energy exchange

- In the “hot” case, the energy exchange is dominantly in one velocity dimension, resulting in a net temperature anisotropy
- In the “cold” case, the energy exchange is more isotropic, leading to the collapse of the magnetic field







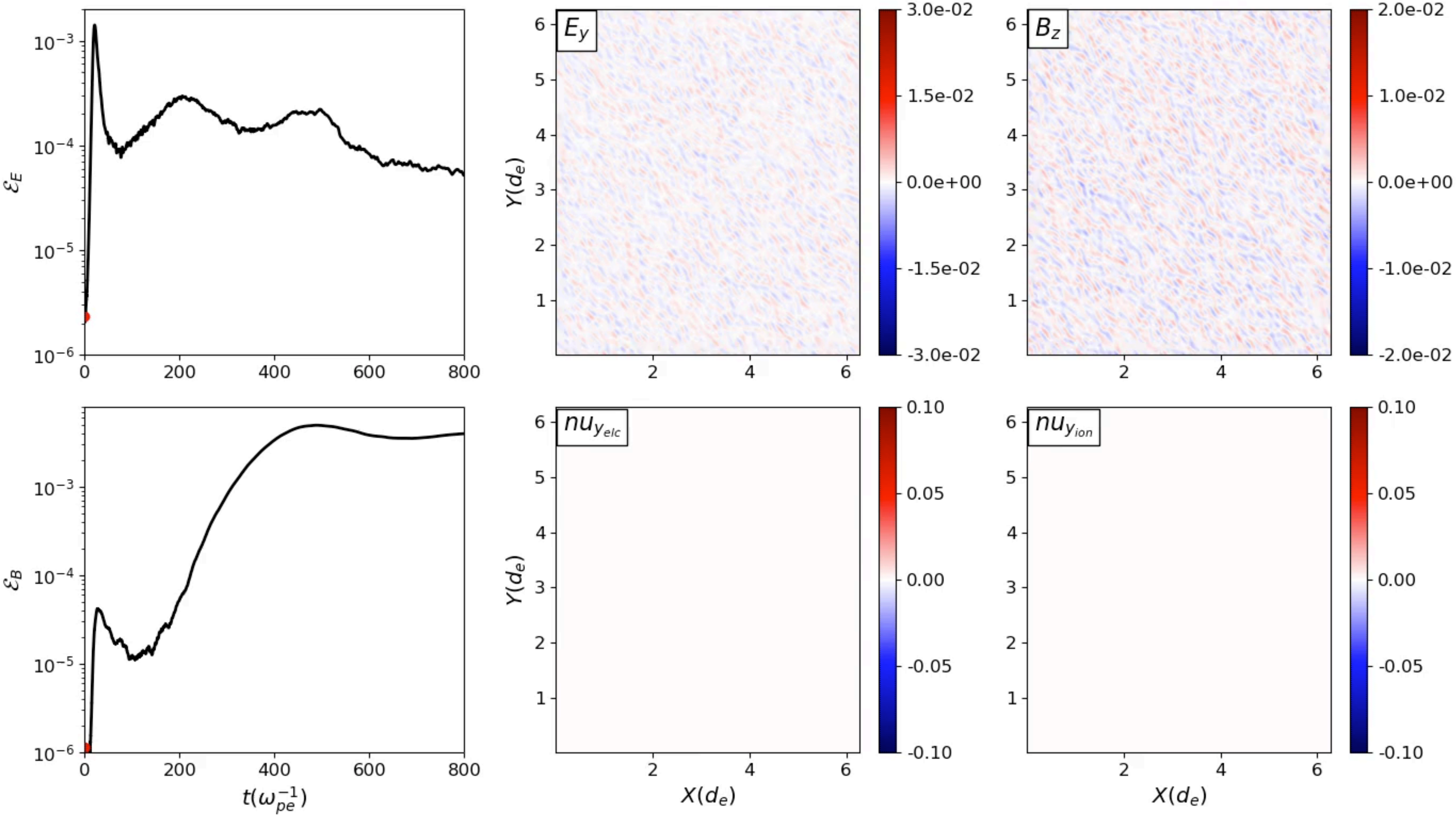
What about protons?

Proton dynamics

$$v_{th_e}/u_d = 0.1, \quad m_p/m_e = 64,$$

$$T_p = T_e, \quad u_{d_e} = u_{d_p} \quad \rightarrow \quad \mathcal{E}_p \gg \mathcal{E}_e$$

$$\Delta x \sim \pi\lambda_D, \quad \Delta v_e \sim v_{th_e}, \quad \Delta v_i \sim 2v_{th_i}, \quad p = 2$$



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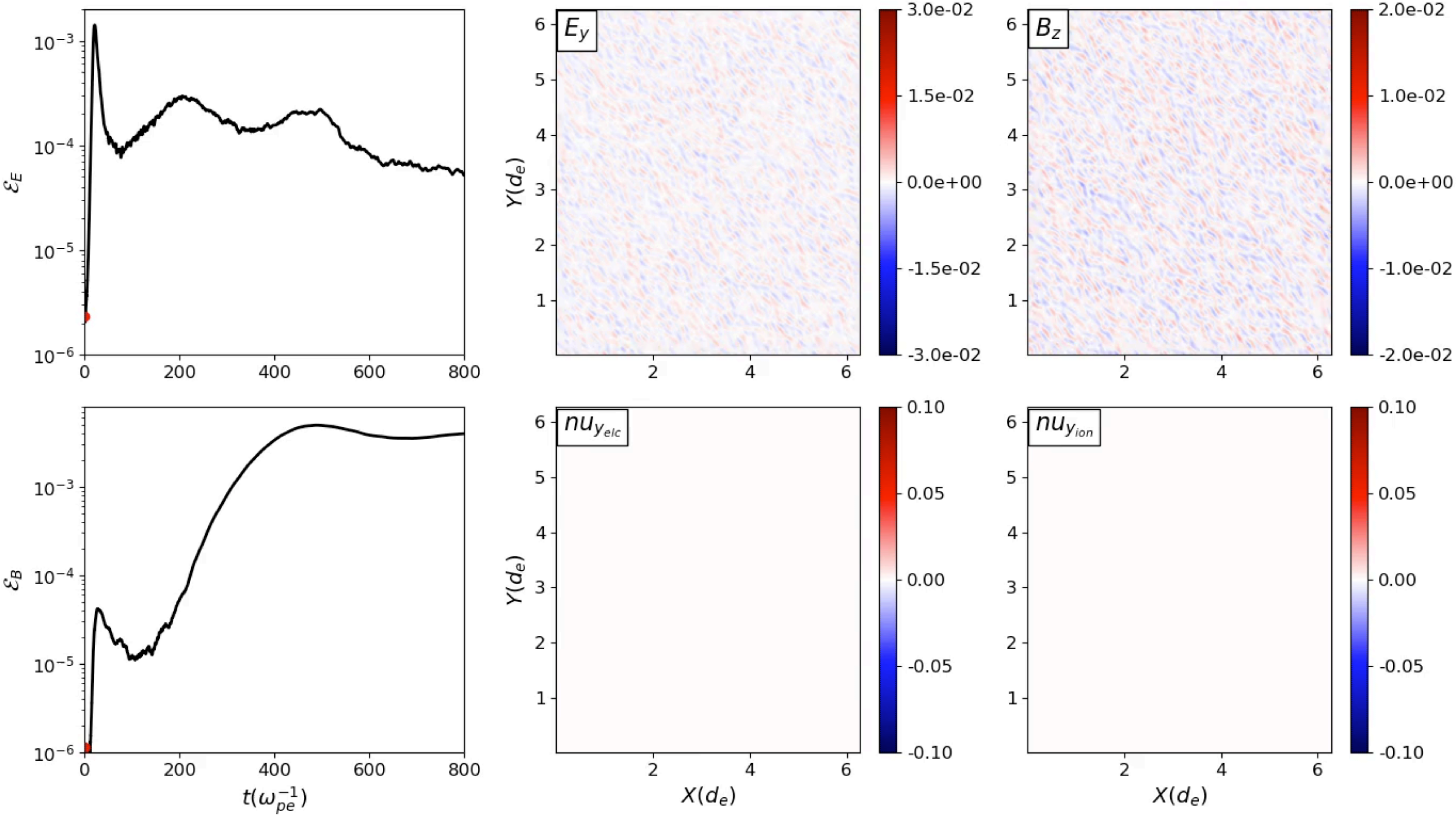

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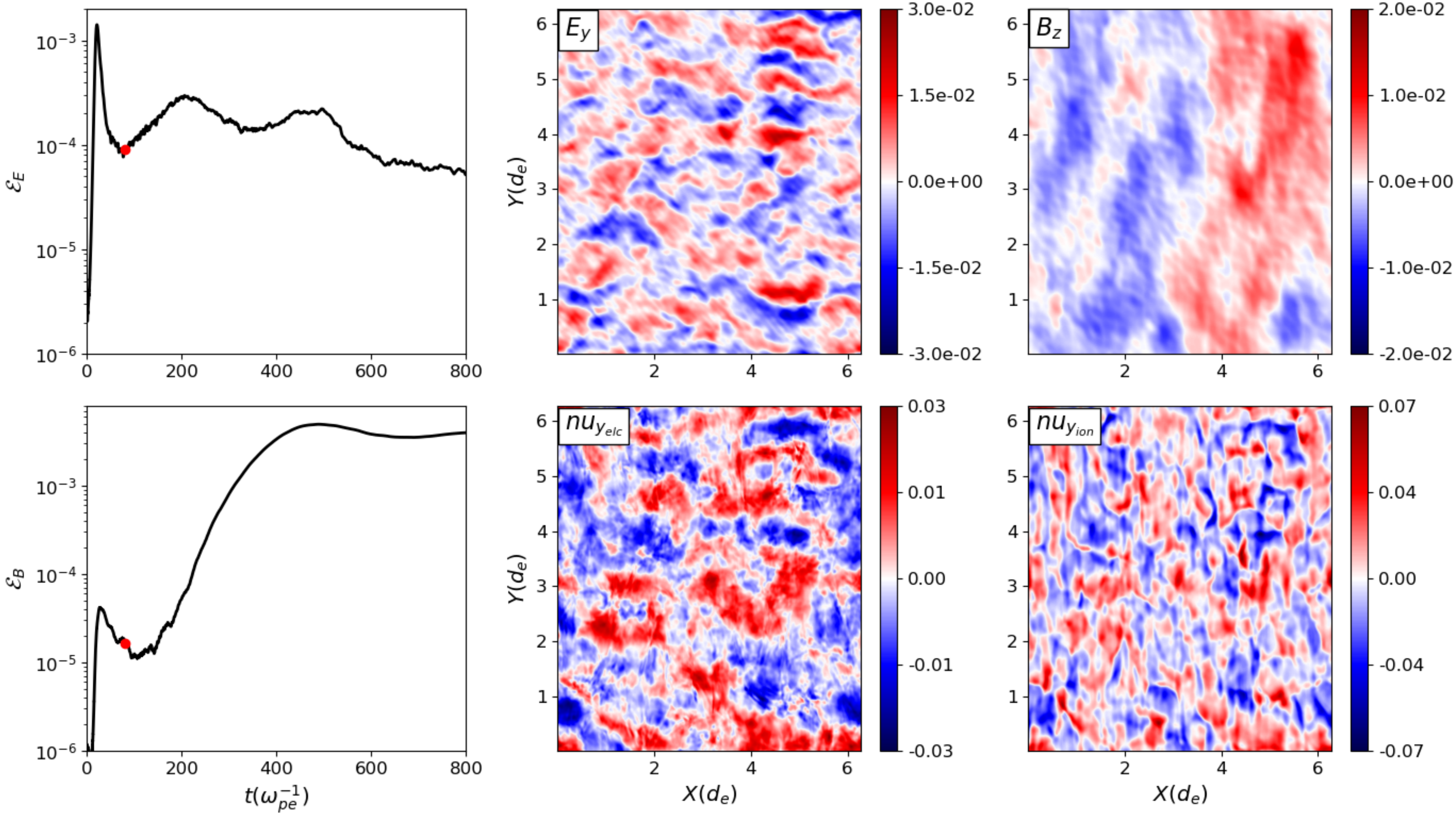

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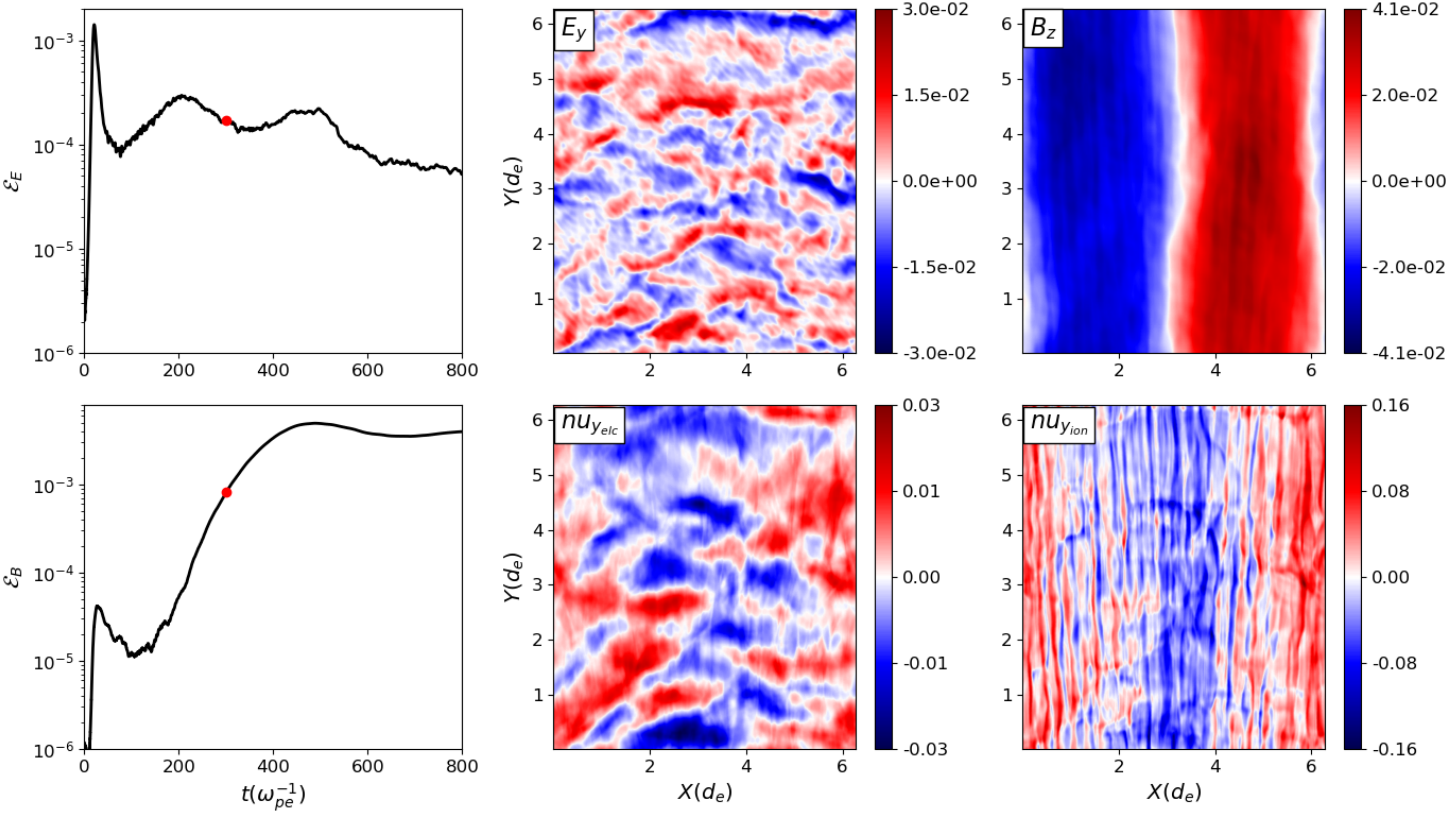

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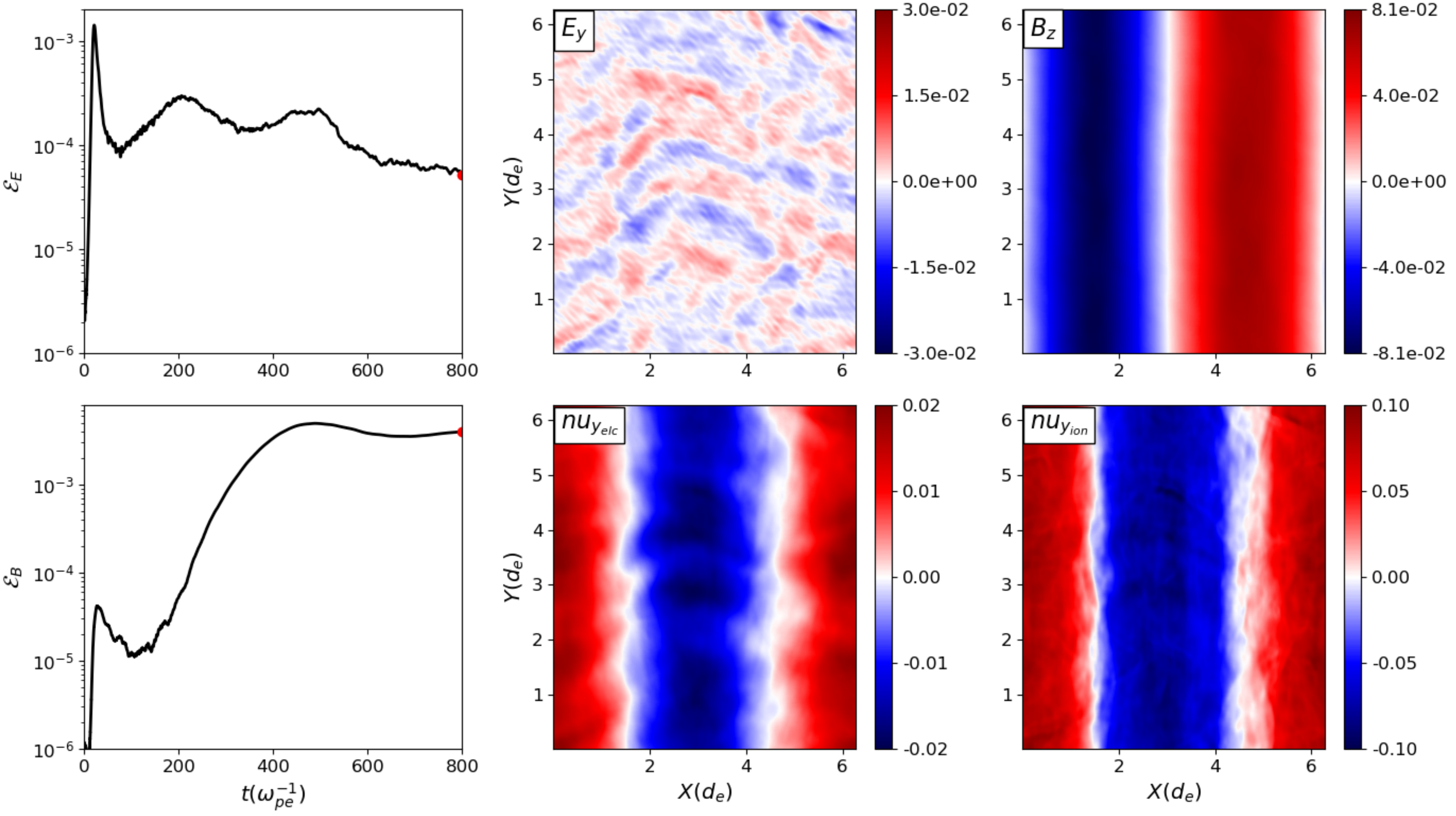
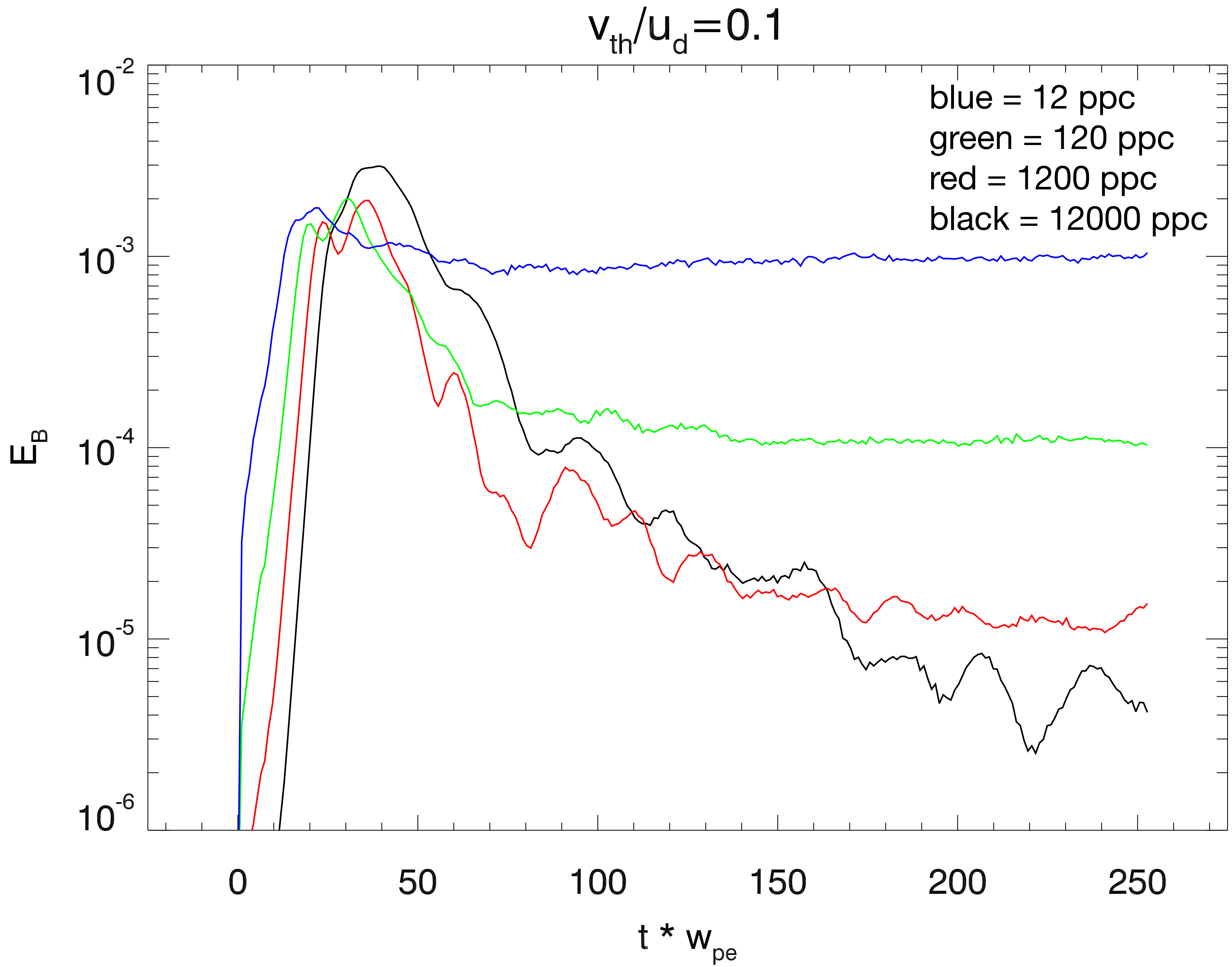


Comparing to the Particle in Cell Method

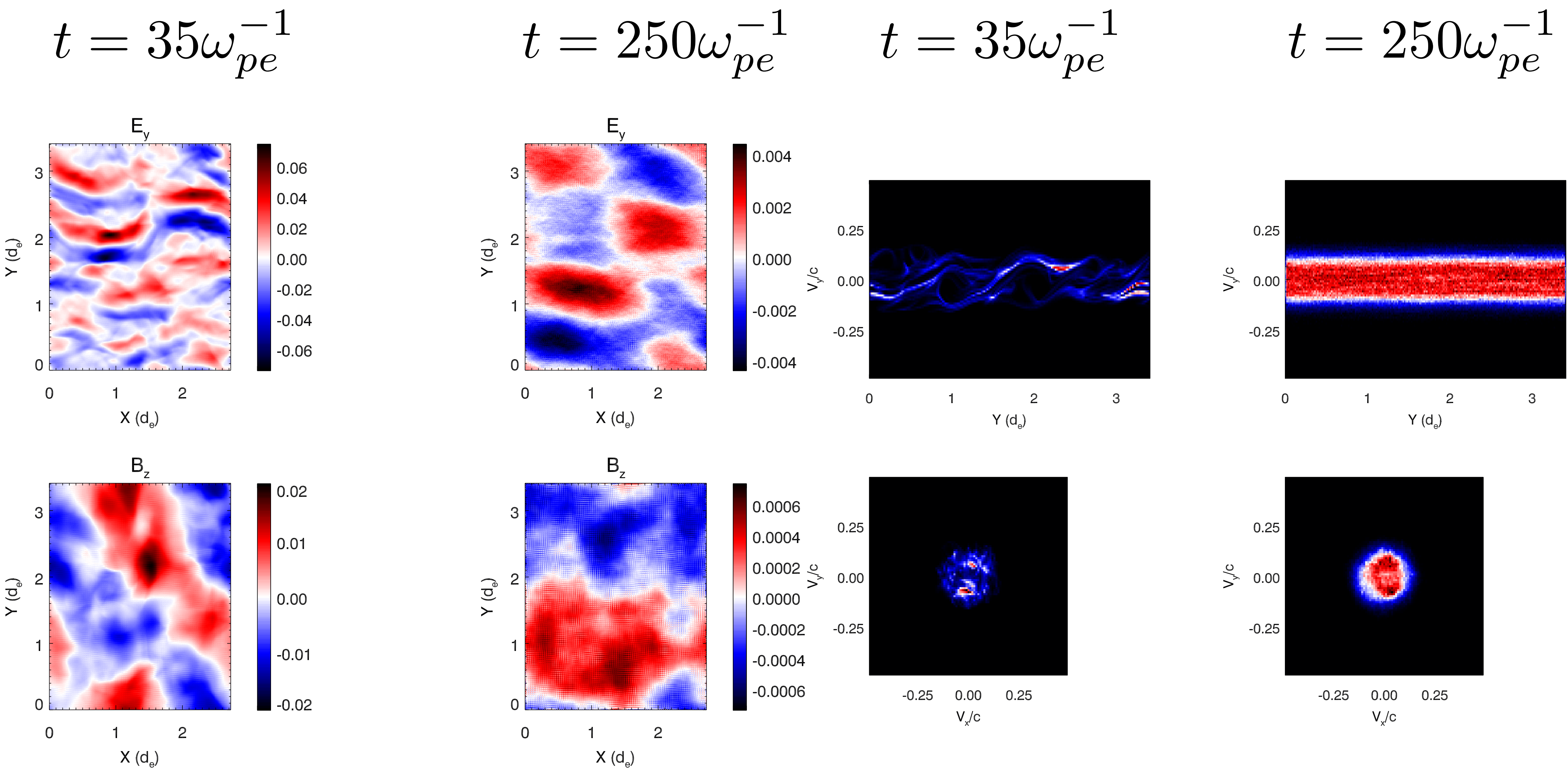
Looking for the collapse of the magnetic field

- When the counter-streaming beams are “cold” we have two extremes in the simulations presented
    - Stationary protons -> collapse of the magnetic field
    - Protons moving at the same speed as the electrons, but also cold -> growth of the magnetic field, with the current carried by the protons
- Let’s return to the stationary proton case, but with a PIC method, for comparison

Thermal Fluctuations in the magnetic field

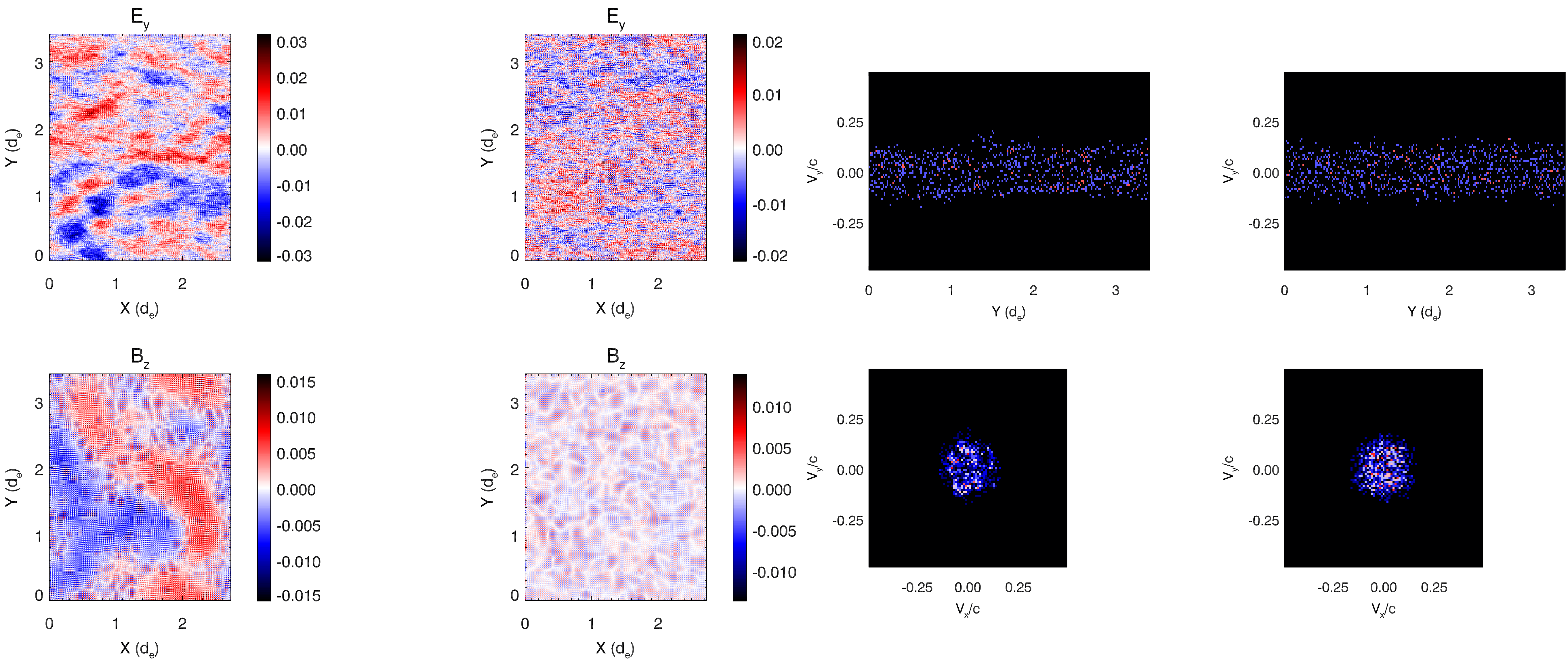


PIC “cold” data, 12000 particles per cell



PIC “cold” data, 12 particles per cell

$t = 35\omega_{pe}^{-1}$ $t = 250\omega_{pe}^{-1}$ $t = 35\omega_{pe}^{-1}$ $t = 250\omega_{pe}^{-1}$



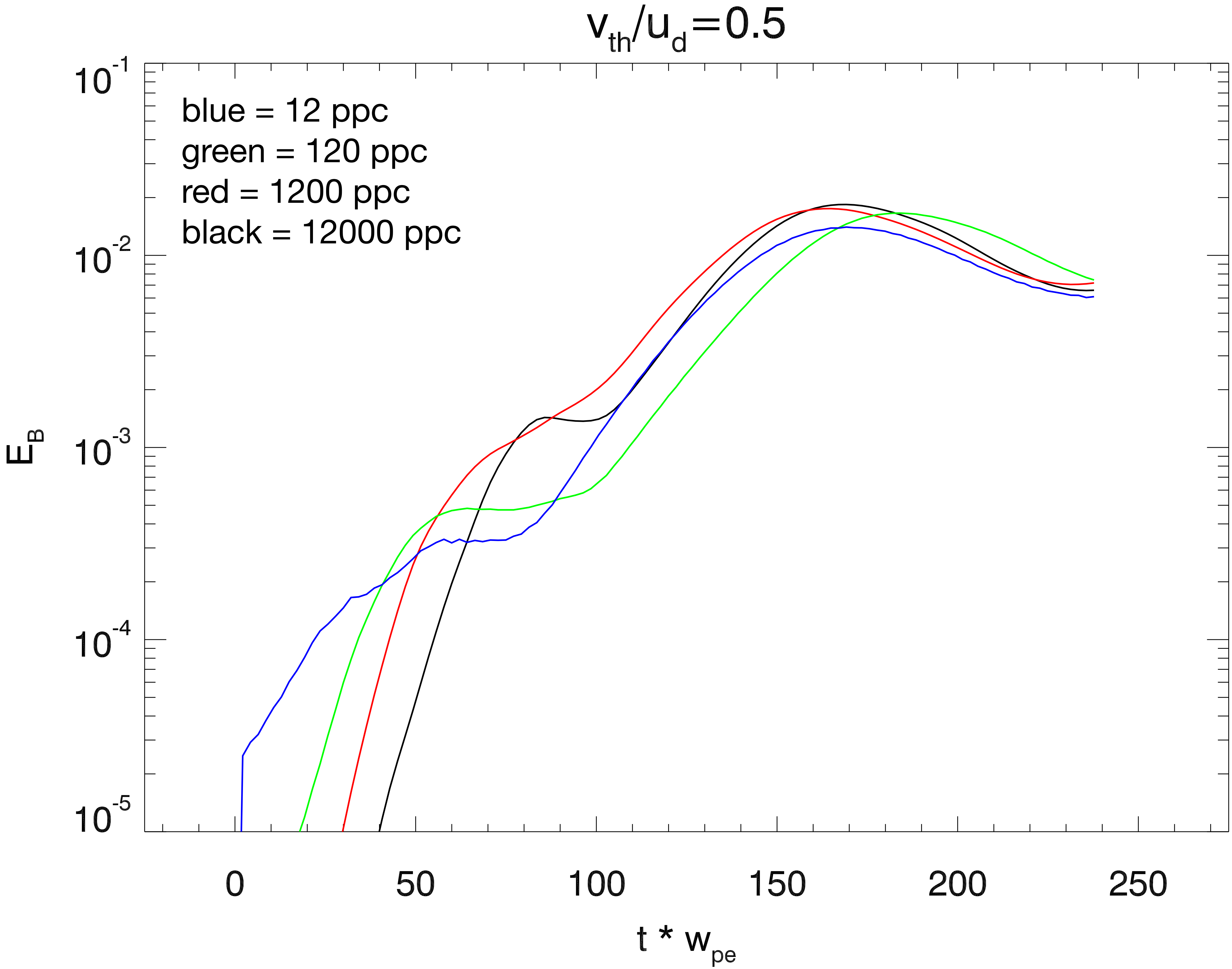
Summary and Future Outlook

- Parameter space for the competition between these instabilities is large
  - If the proton species is initially stationary, magnetic field collapses
  - If the proton species is moving at the same flow speed as the electrons, magnetic field grows and currents which support this field are driven by the protons (the proton energy density is very large)
- Because the system is "cold" have to worry more about quasi-thermal noise, but in the magnetic field, in equivalent particle-in-cell simulations
- "Cold" system most relevant to reionization epoch
  - Want to understand what role plasma instabilities played in creation of a seed magnetic field for the turbulent dynamo
  - Parameter space for reionization epoch also very large
- ***V. Skoutnev, A. Hakim, J. Juno, J. TenBarge. Temperature Dependent Saturation of Weibel-Type Instabilities in Counter-Streaming Plasmas, ApJ Letters, 2019***

$$n \sim 10^4 - 10^8 \, \frac{1}{m^3}, \quad T \sim 10^4 - 10^6 \, K, \quad v_{shock} \sim 10^2 - 10^4 \, \frac{km}{s}$$

Supplemental slides

What about the “hot” case?



PIC “hot” data, 12000 particles per cell

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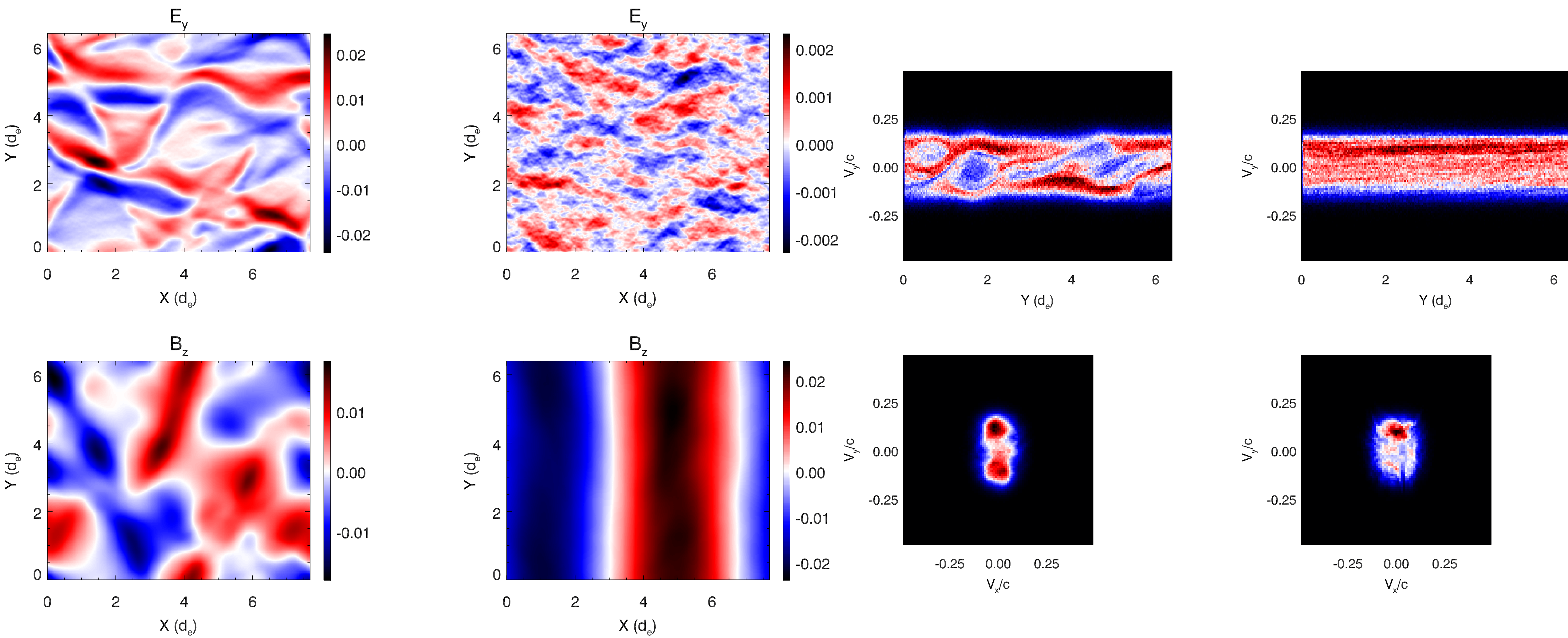

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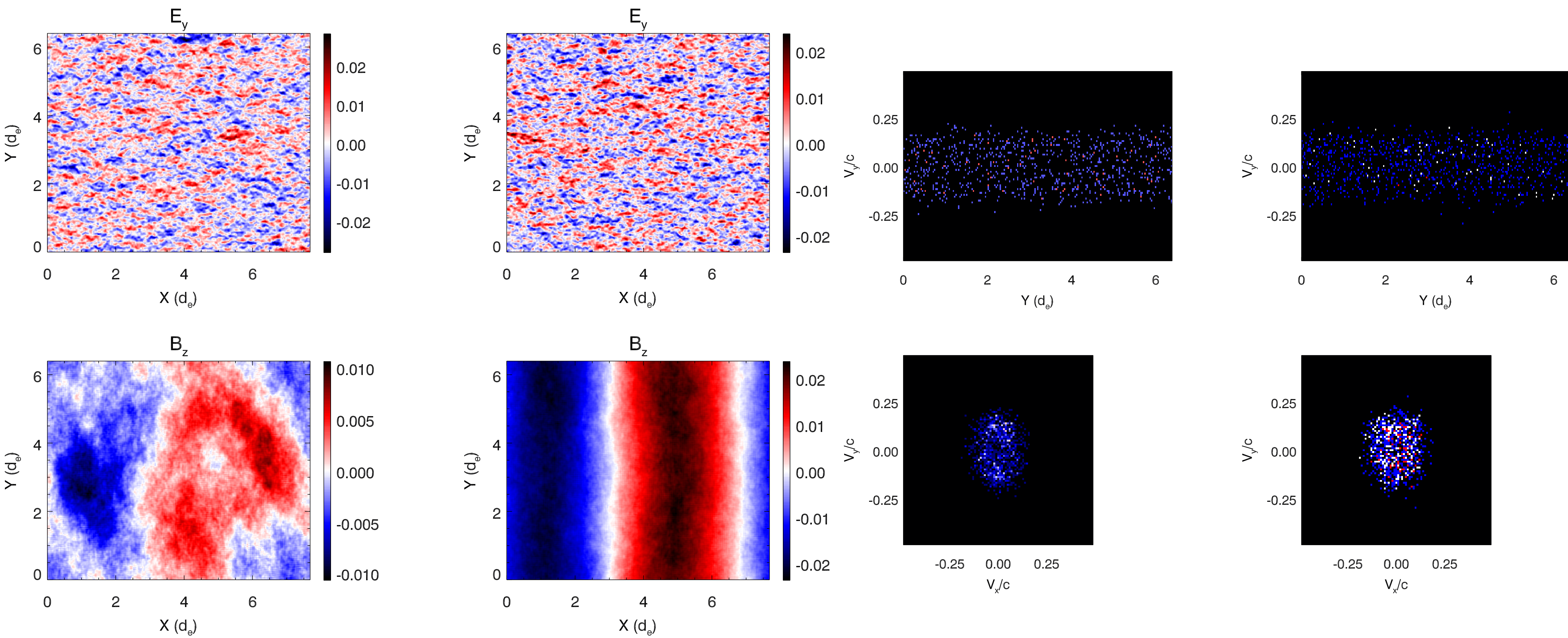
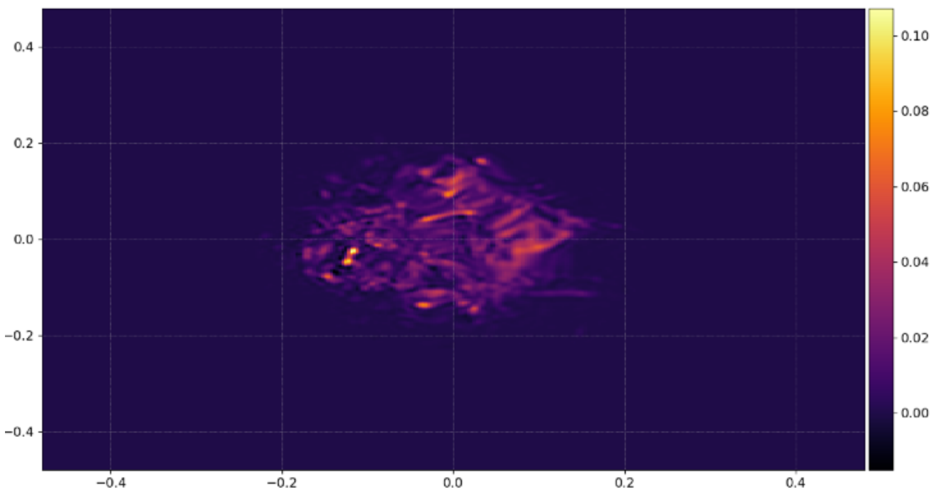
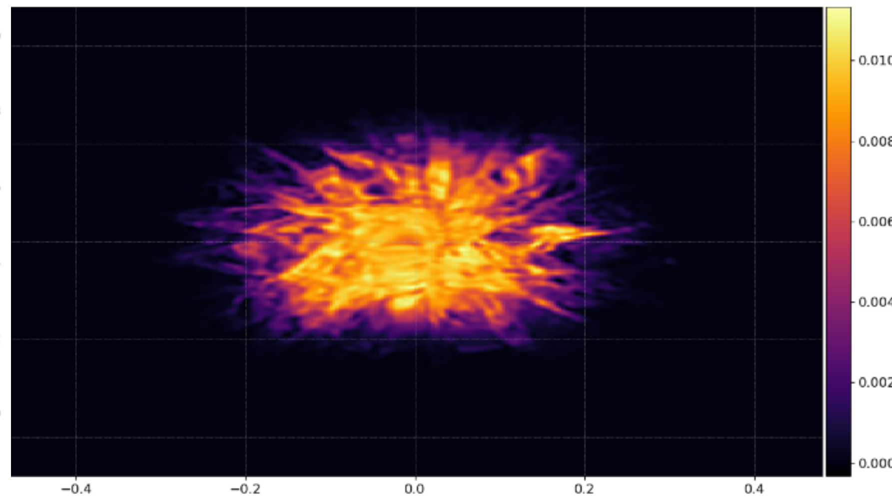
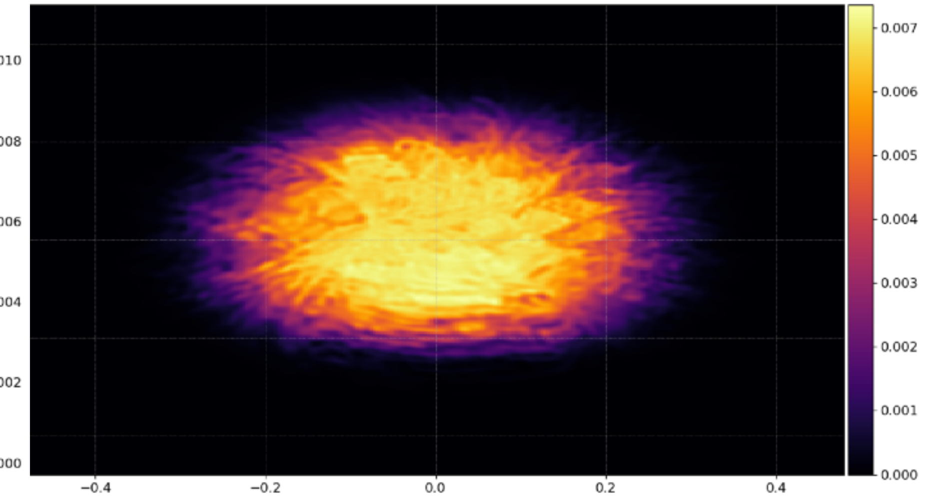
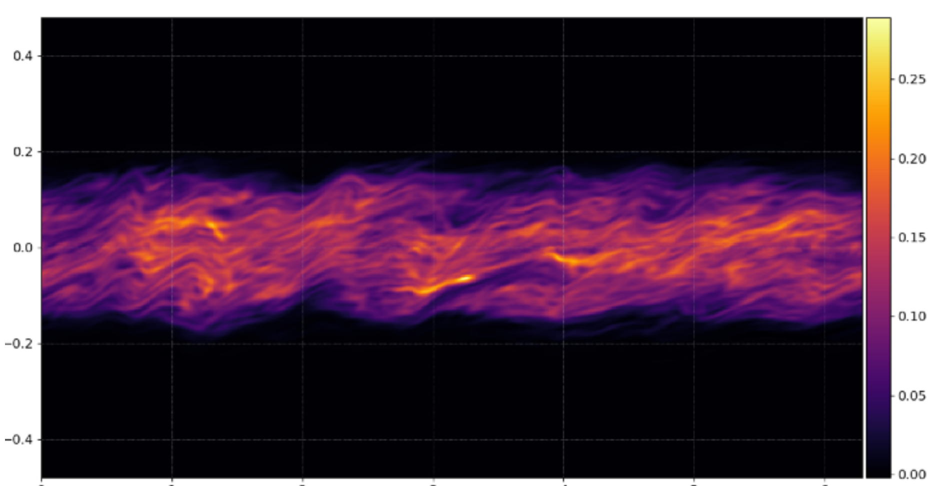


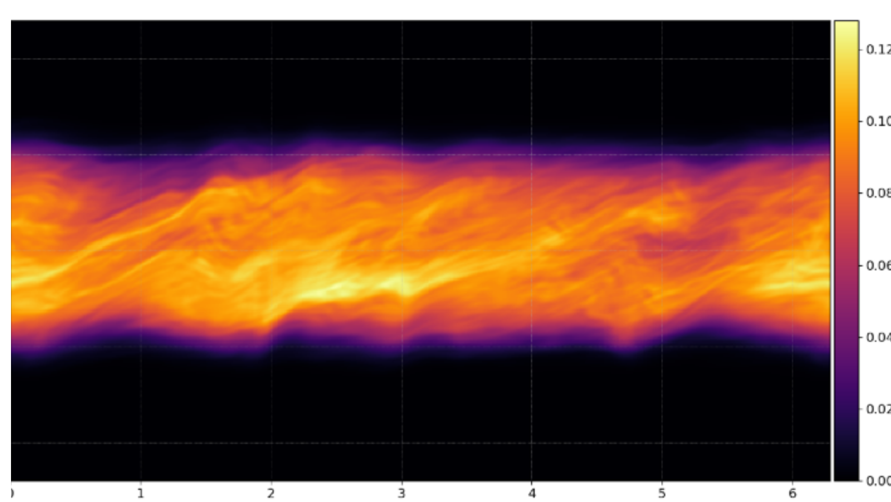
Proton simulation, electron distributions

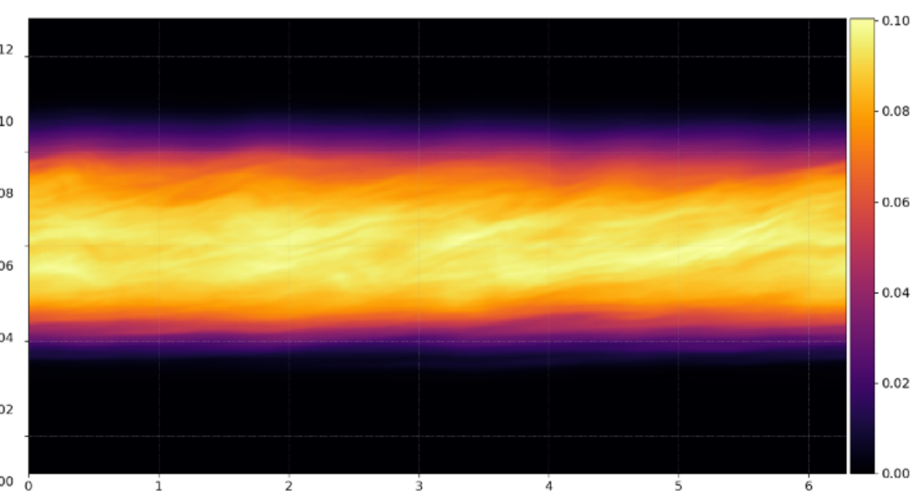












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