Lecture18:

Plasma Physics 1: PIC

APPH E6101x
Columbia University

This Lecture

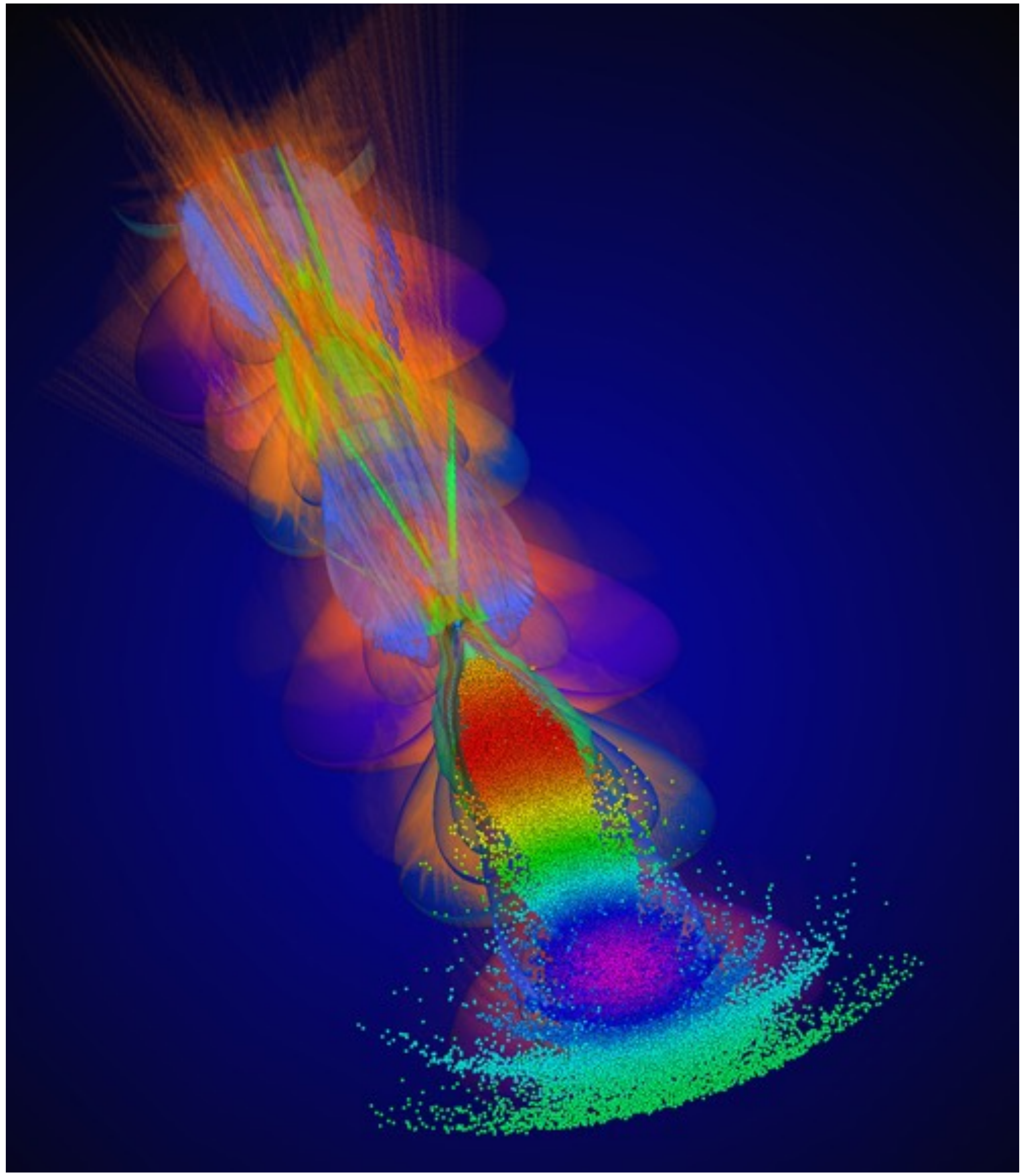
- PIC simulation of kinetic instabilities

  Chapter 9, Section 9.4

https://picksc.physics.ucla.edu/

The UCLA Particle-in-Cell (PIC) and Kinetic Simulation Software Center (PICKSC) uses and develops simulation and data science tools to make fundamental discoveries in plasma based acceleration, plasma based light sources, plasma astrophysics, intense laser and plasma interactions, the nonlinear optics of plasmas, and high fidelity simulation. The Center is also committed to making its software available to others to accelerate the rate of scientific discovery and to provide unique educational tools. We are users and developers of OSIRIS, UPIC, QuickPIC, and QPAD and a set of Jupyter notebooks aimed at education. If you would like more information on this software please look at the software page.

PICKSC is housed within the UCLA Departments of Physics and Astronomy and of Electrical and Computer Engineering. It is co-led by Professors W.B. Mori and E. Paulo Alves. We are closely connected with thc UCLA Laser-Plasma Group led by Professor C. Joshi.



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Series in Plasma Physics

Plasma Physics via Computer Simulation

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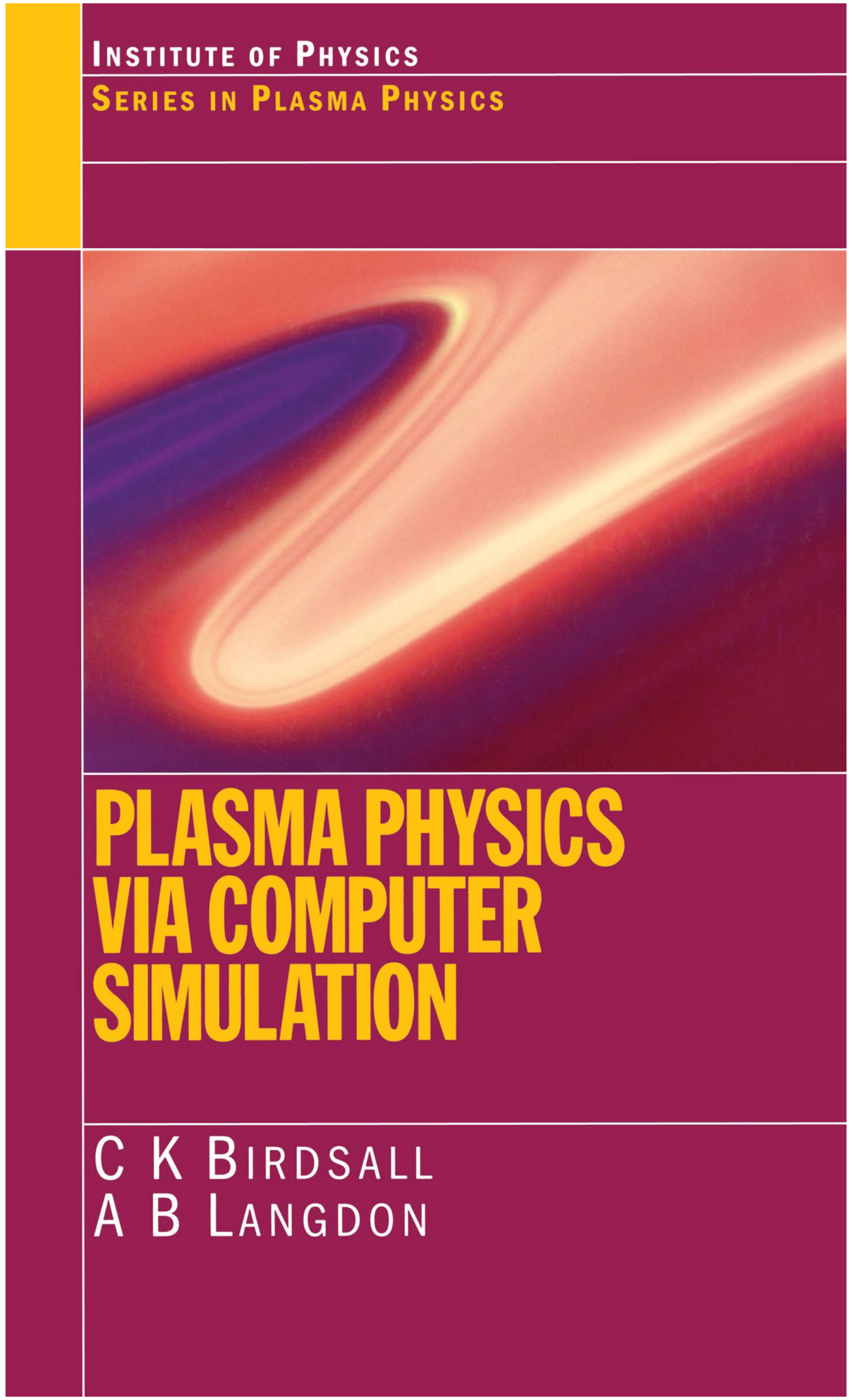

Anomalous Relativistic Emission from Self-Modulated Plasma Mirrors

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The interaction of intense laser pulses with plasma mirrors has demonstrated the ability to generate high-order harmonics, producing a bright source of extreme ultraviolet (XUV) radiation and attosecond pulses. Here, we report an unexpected transition in this process. We show that the loss of spatiotemporal coherence in the reflected high harmonics can lead to a new regime of highly efficient coherent XUV generation, with an extraordinary property where the radiation is directionally anomalous, propagating parallel to the mirror surface. With analytical calculations and numerical particle-in-cell simulations, we discover that the radiation emission is due to laser-driven oscillations of relativistic electron nanobunches that originate from a plasma surface instability.

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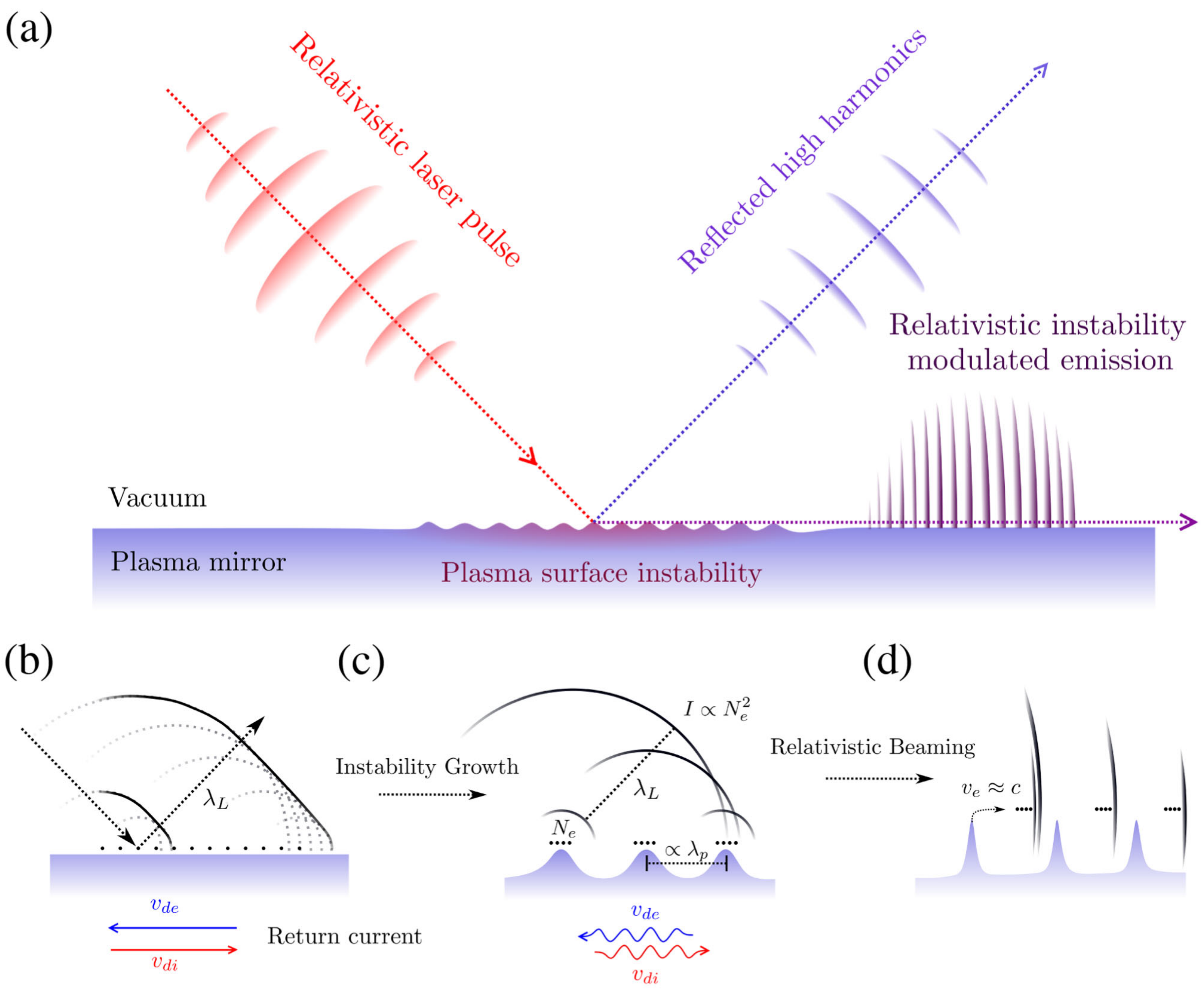


FIG. 1. Principle of relativistic instability-modulated emission (RIME).

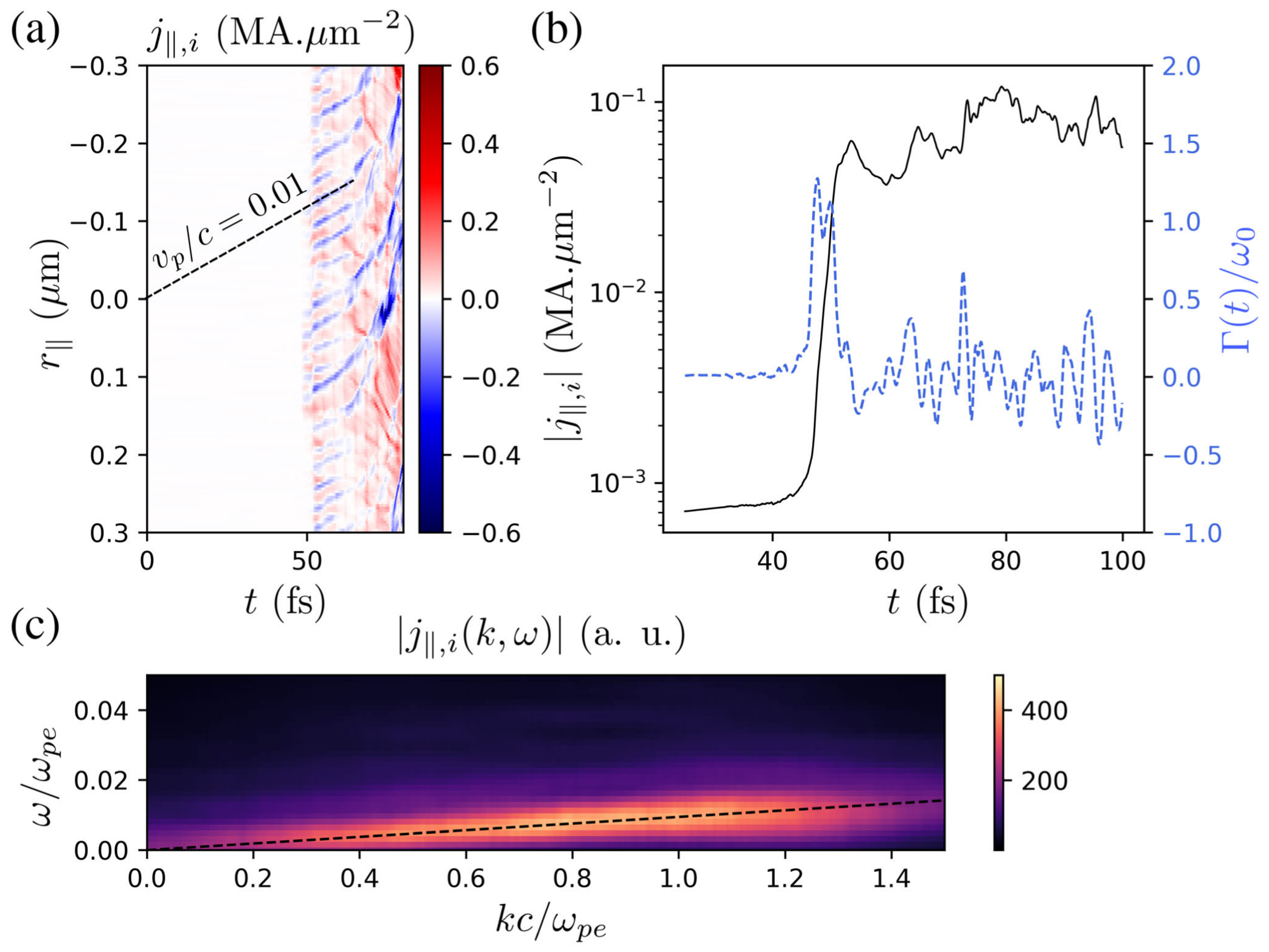


FIG. 2. PIC simulation of the surface instability.

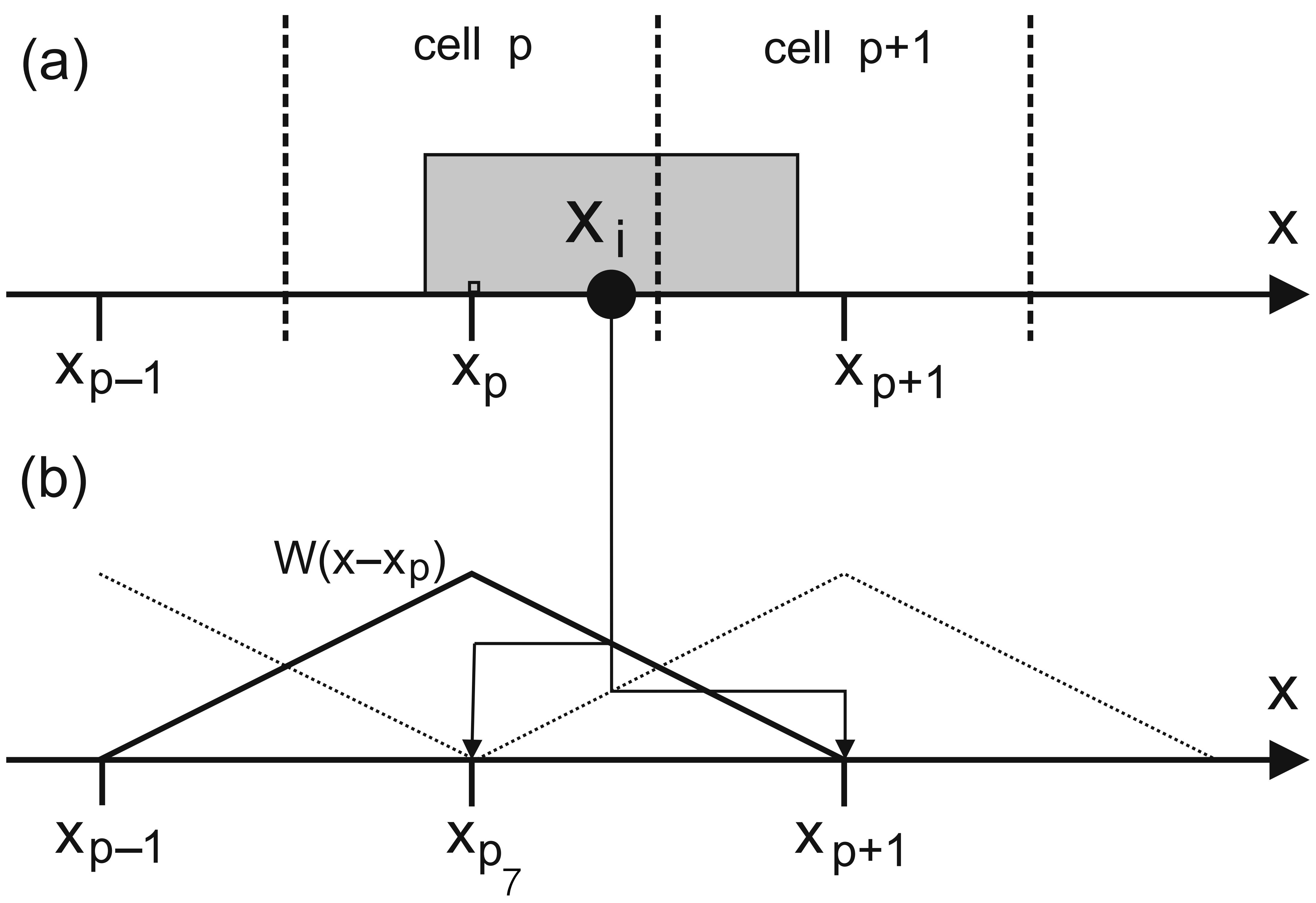
PIC Algorithm (Charge Assignment)

The charge assignment to grid point x_p is made by

$$\rho_p = \frac{q N_s}{\Delta x} \sum_{i=1}^{N_p} W(x_i - x_p)$$

with the linear weighting function

$$W(x) = \begin{cases} 1 - |x| & : \quad |x| < 1 \\ 0 & : \quad |x| \geq 1\,. \end{cases}$$



Poisson's Equation and Electric Force

$$\frac{\Phi_{p-1} - 2\Phi_p + \Phi_{p+1}}{(\Delta x)^2} = -\frac{\rho_p}{\varepsilon_0}$$

$$E_p = \frac{\phi_{p-1} - \phi_{p+1}}{2\Delta x}$$

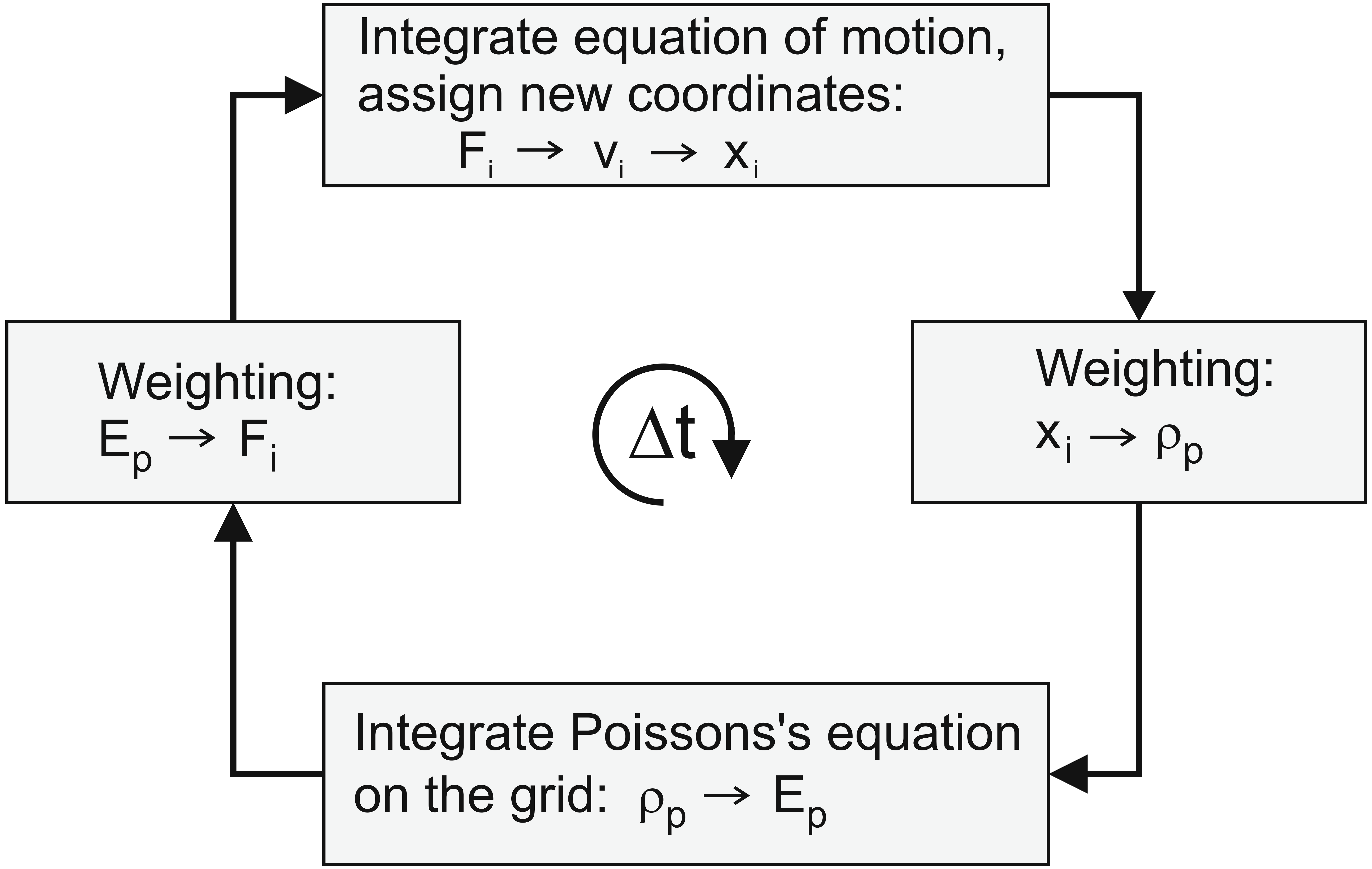
$$F_i = q N_s \sum_{p=0}^{N_\mathrm{g}-1} W(x_i - x_p) E_p$$

"Leap Frog" Time-Stepping

$$\frac{x_i^{n+1} - x_i^n}{\Delta t} = v_i^{n+1/2}$$

$$\frac{v_i^{n+1/2} - v_i^{n-1/2}}{\Delta t} = \frac{F(x_i)\Delta t}{m_i}$$

Calculate and Repeat



Dimensionless Parameters

- $\Delta x = 1$ and $\Delta t = 1$
- $\Delta x/L << 1$ (so L must be large, with $\Delta x \approx 1$)
- $(q_e/m_e) = -1$
- $(q_i/m_i) = +1/25$
- $\Delta t\ \omega_{pe} << 1$, so $\omega^2_{pe} = n\ (q_e/m_e)(q_e/\varepsilon_0)$. Therefore, $(q_e/\varepsilon_0) << 1$ if $n \approx 1$

Dimensionless Parameters

```
Average Density = 4

Electron Thermal Velocity = 0.5

Ion Thermal Velocity = 0.0632456

Plasma Frequency = 0.04

Debye Length = 12.5

Number of particles per cell = 4

Number of Debye lengths in box = 40.

Number of time steps per plasma oscillation = 25.
```

Dynamics (Leap-Frog)

$$x_{n+1} = x_n + v_{n+1}$$
$$v_{n+1} = v_n - E_n$$

$$x_{n+1} = x_n + v_{n+1}$$
$$v_{n+1} = v_n + E_n/M_i$$

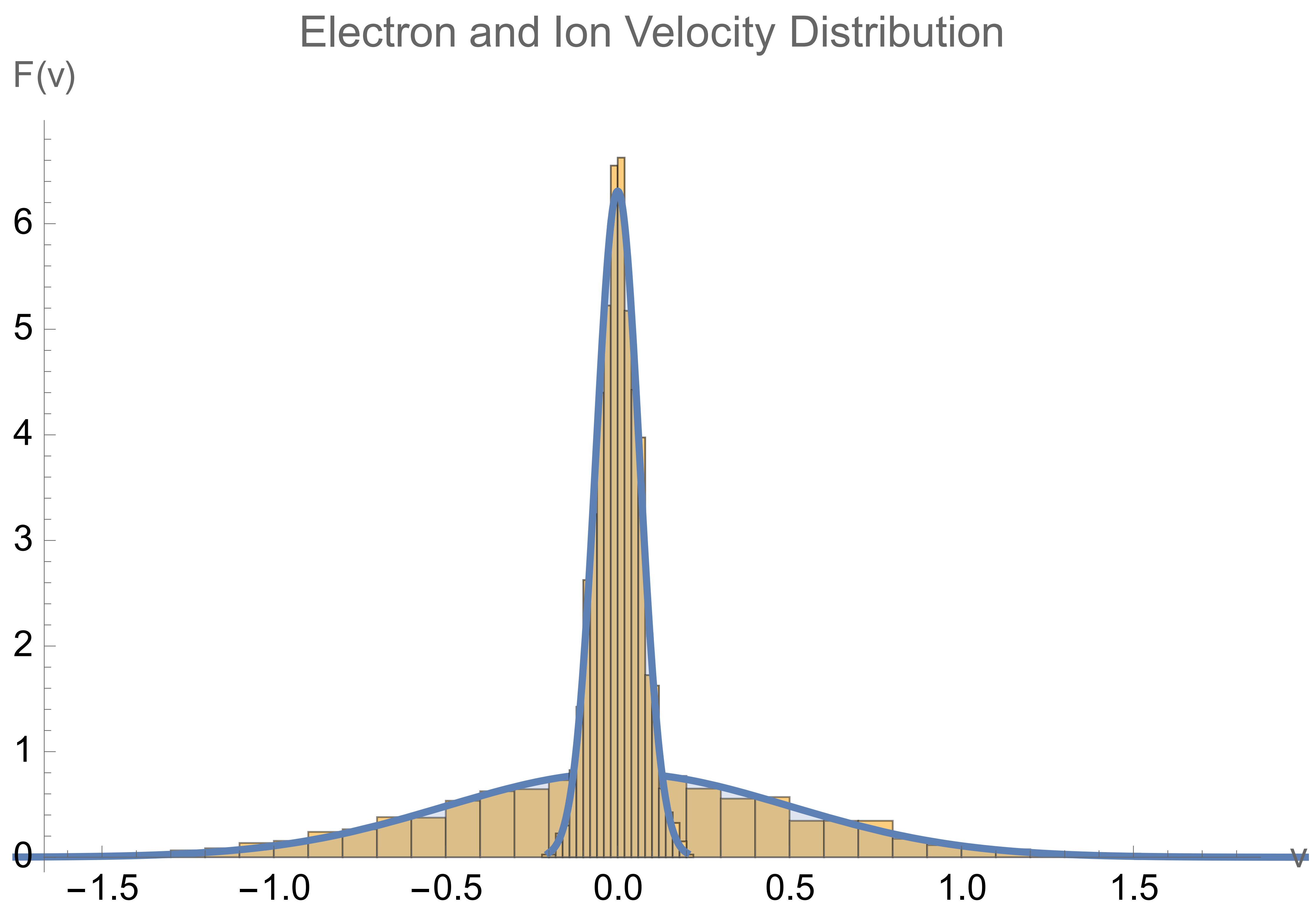
Poisson's Eq

$$\frac{d^2\Phi}{dx^2} = -\frac{q}{\epsilon_0}\,\left(\rho_i(x) - \rho_e(x)\right)$$

$$\Phi_k = \frac{1}{k^2}\frac{q}{\epsilon_0} FFT[\rho_i(x) - \rho_e(x)]$$

Mathematica Notebooks

- **Plasma_PIC-Simulation-Clump.nb**
    - Expanding plasma cloud
    - Ambipolar diffusion
- **Plasma_PIC-Simulation-electron.nb**
    - Heavy stationary ions
    - Two-stream and e-beam instabilities
    - Nonlinear saturation



Electrostatic Plasma Simulation: Ion Clump

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Electrostatic Plasma Simulation: Electrons

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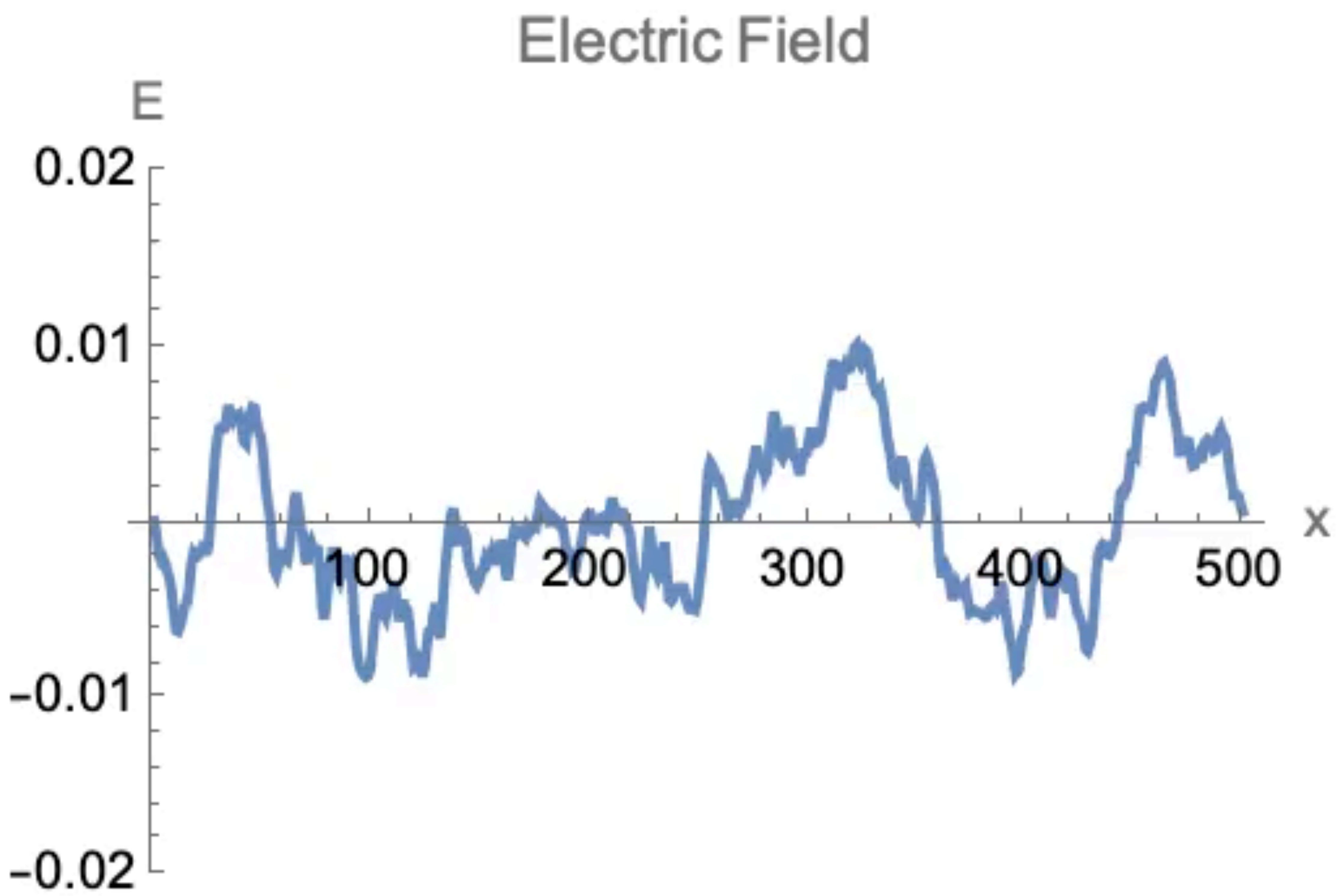
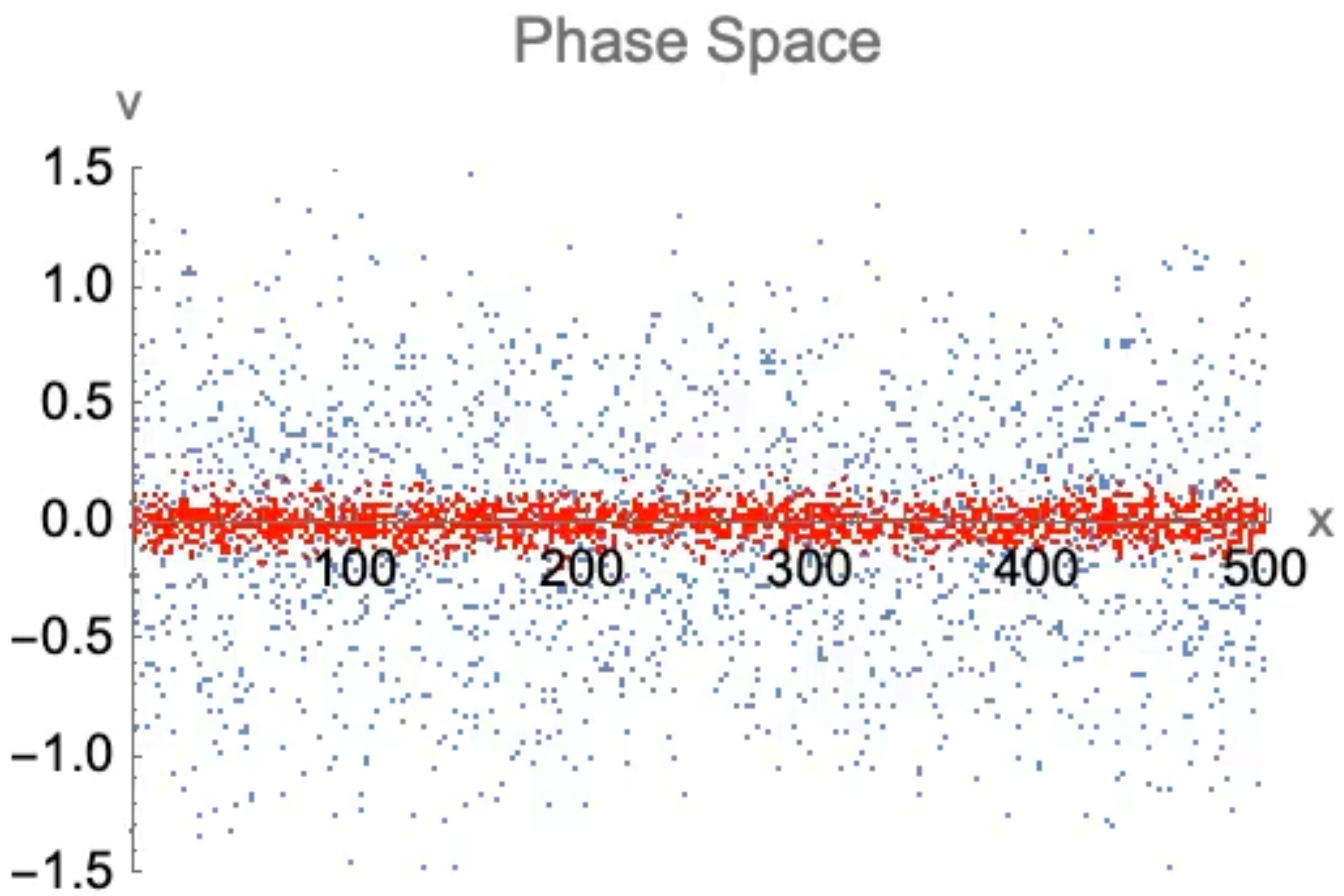
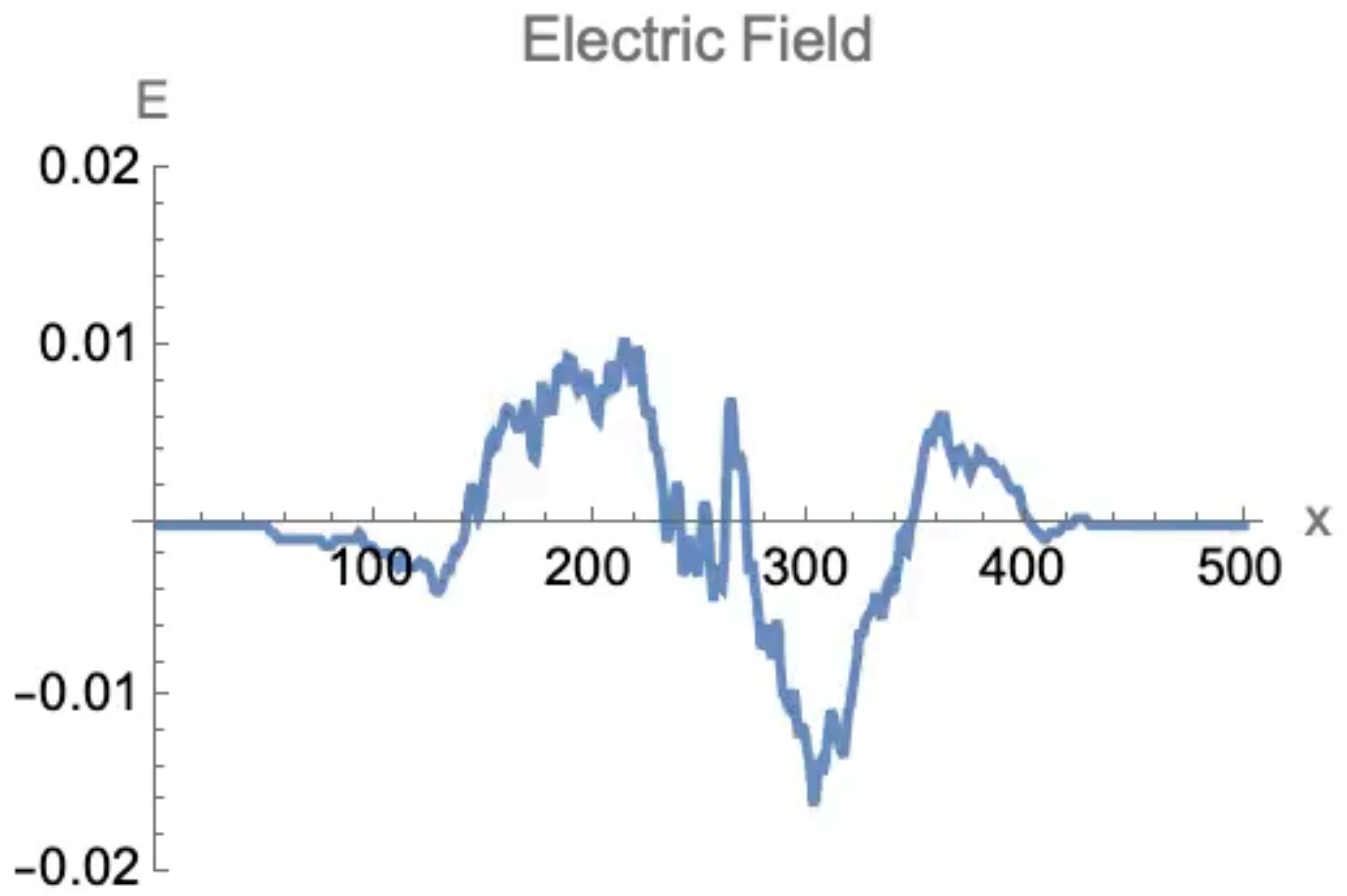
Simple Example: Uniform Plasma

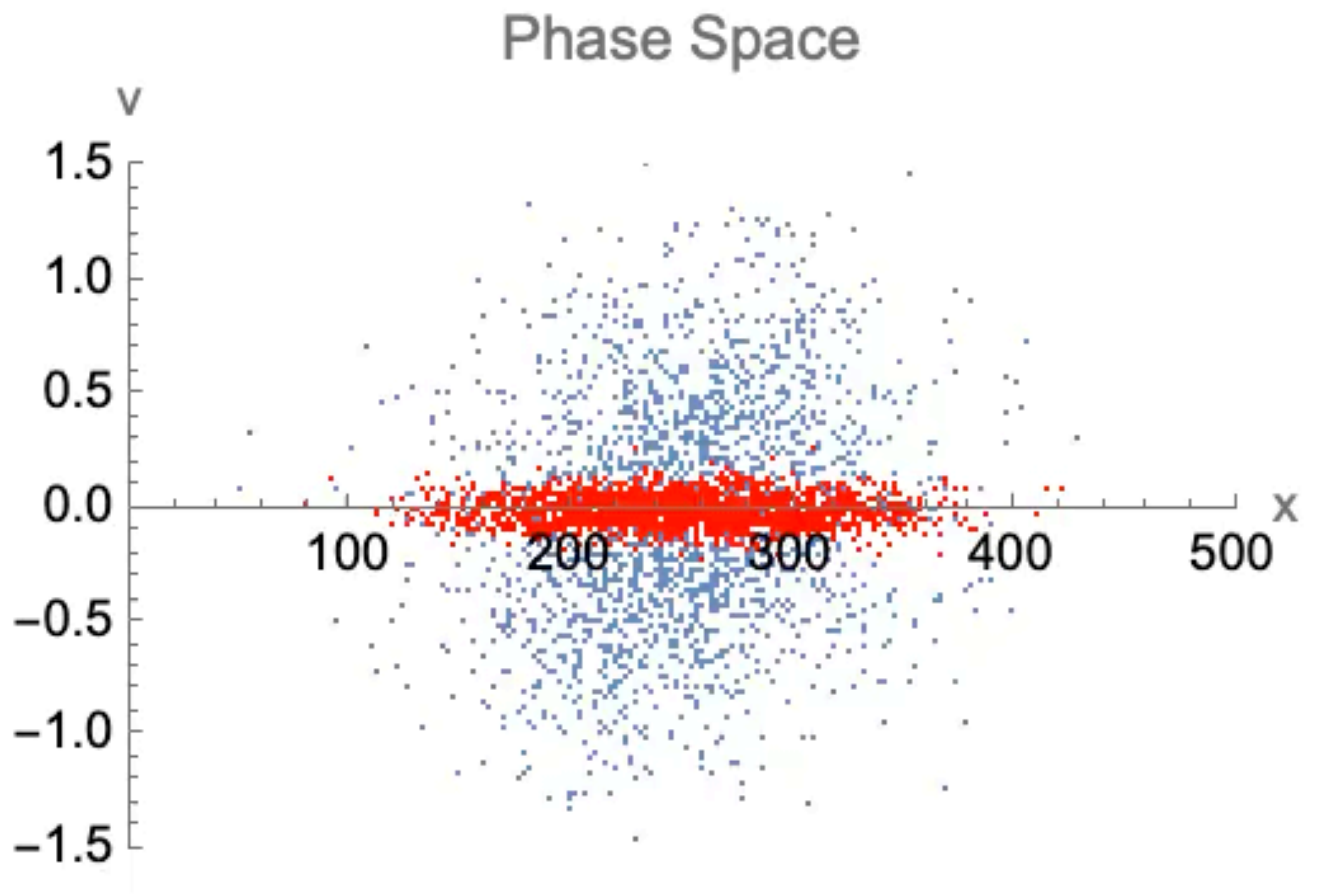




Plasma_PIC-Simulation-Clump.nb

Plasma Clump: Ambipolar Diffusion





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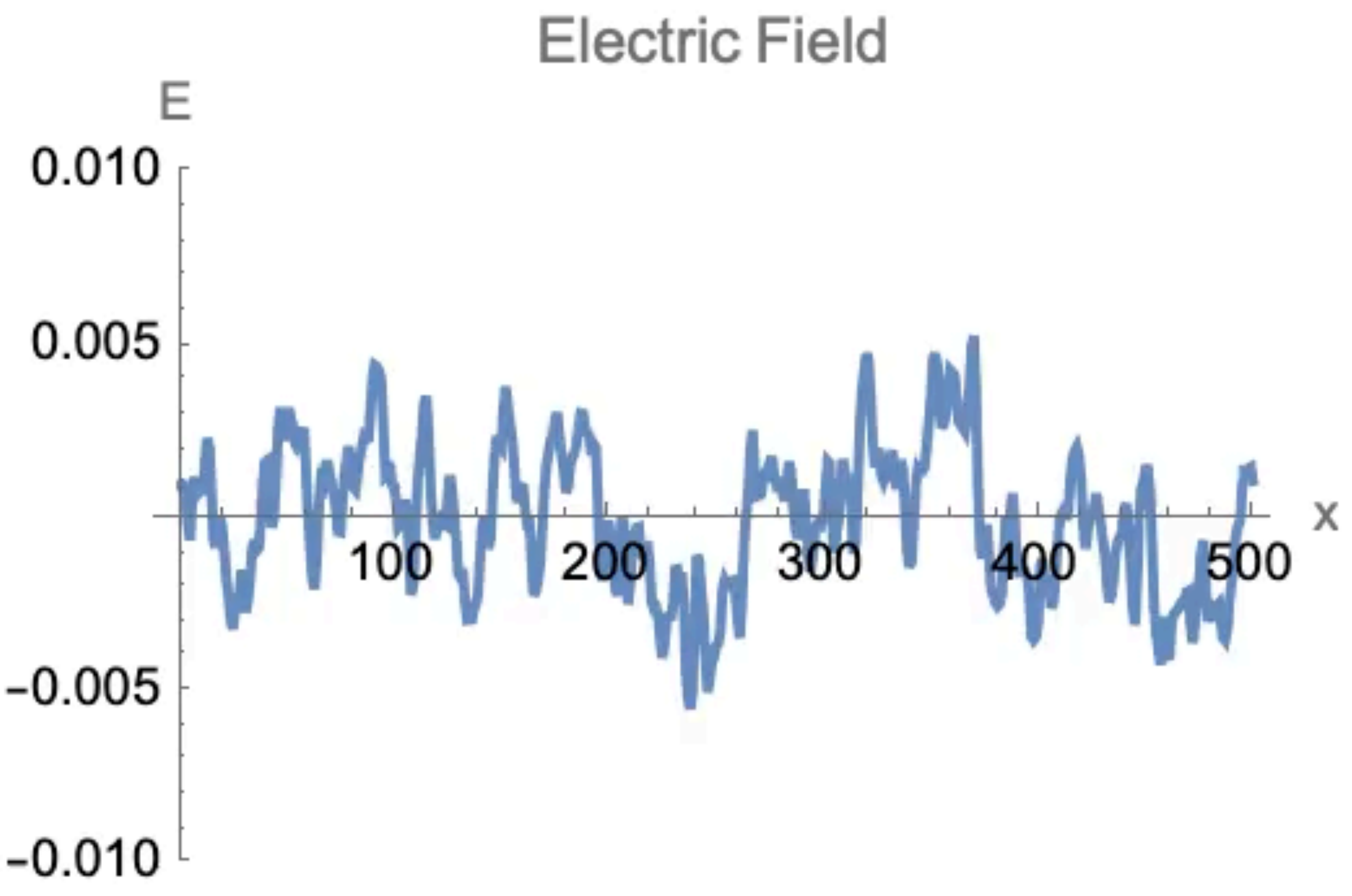
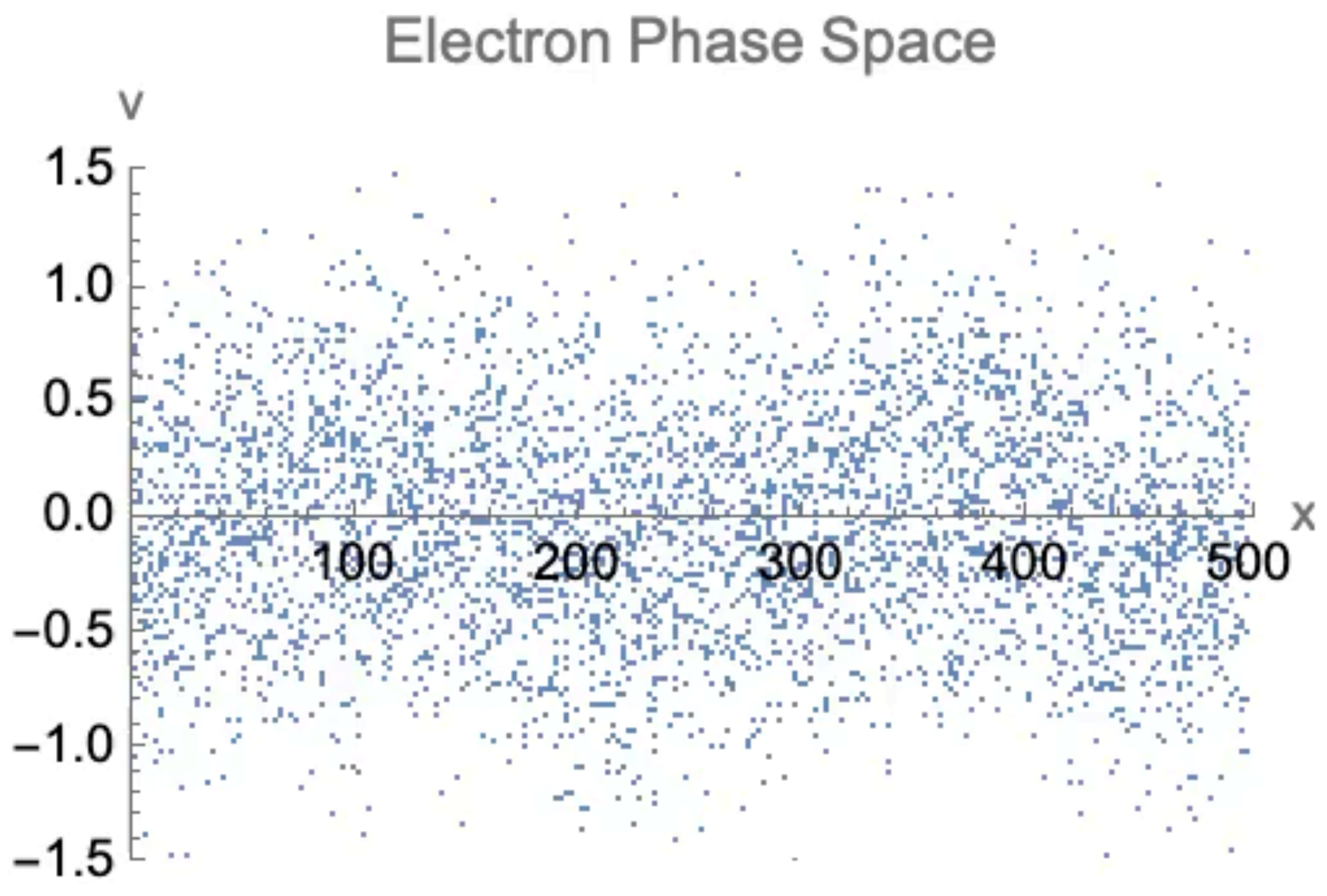
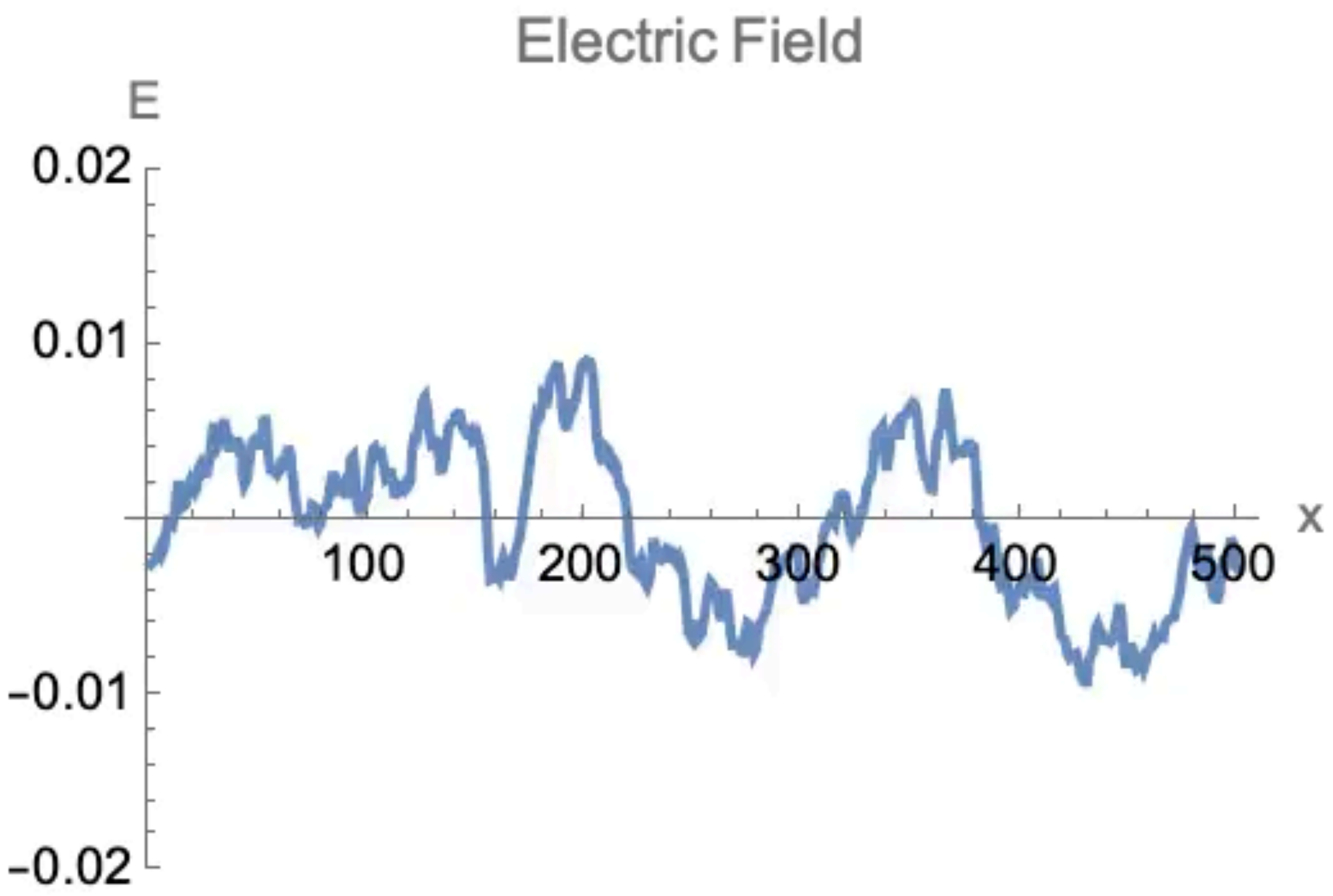
Plasma Electrons (stationary ions)

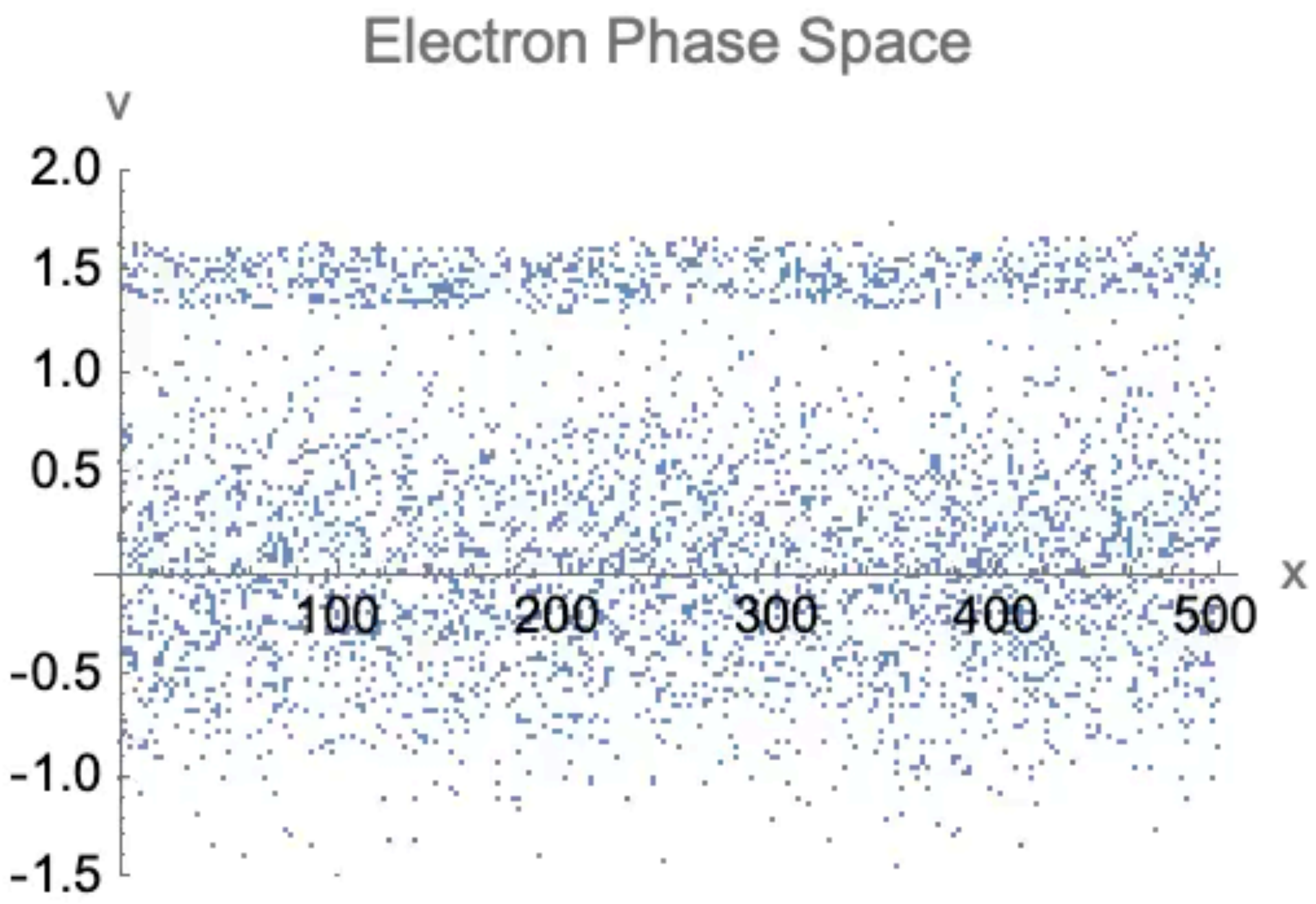




Plasma_PIC-Simulation-electron.nb

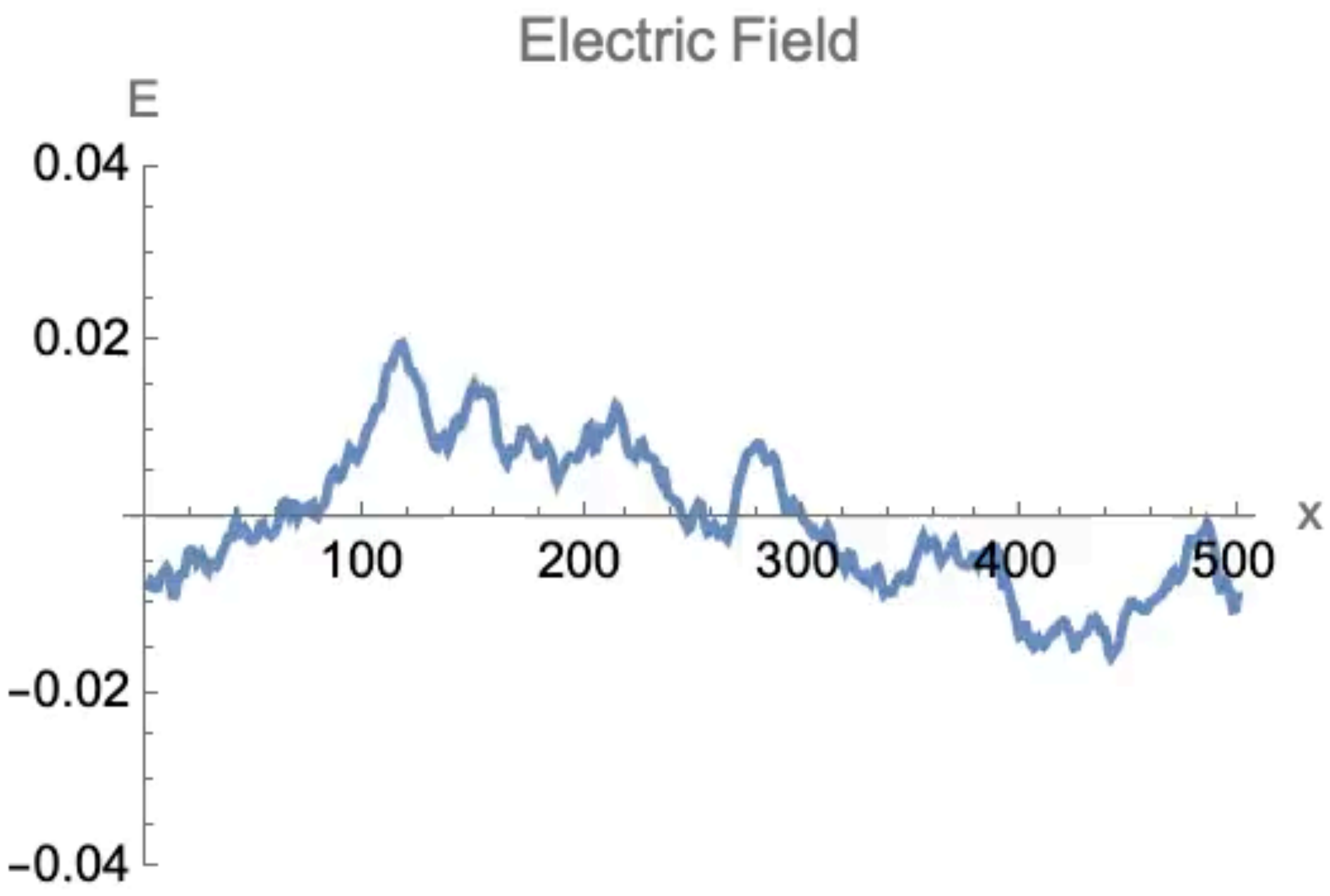
Plasma & E-Beam

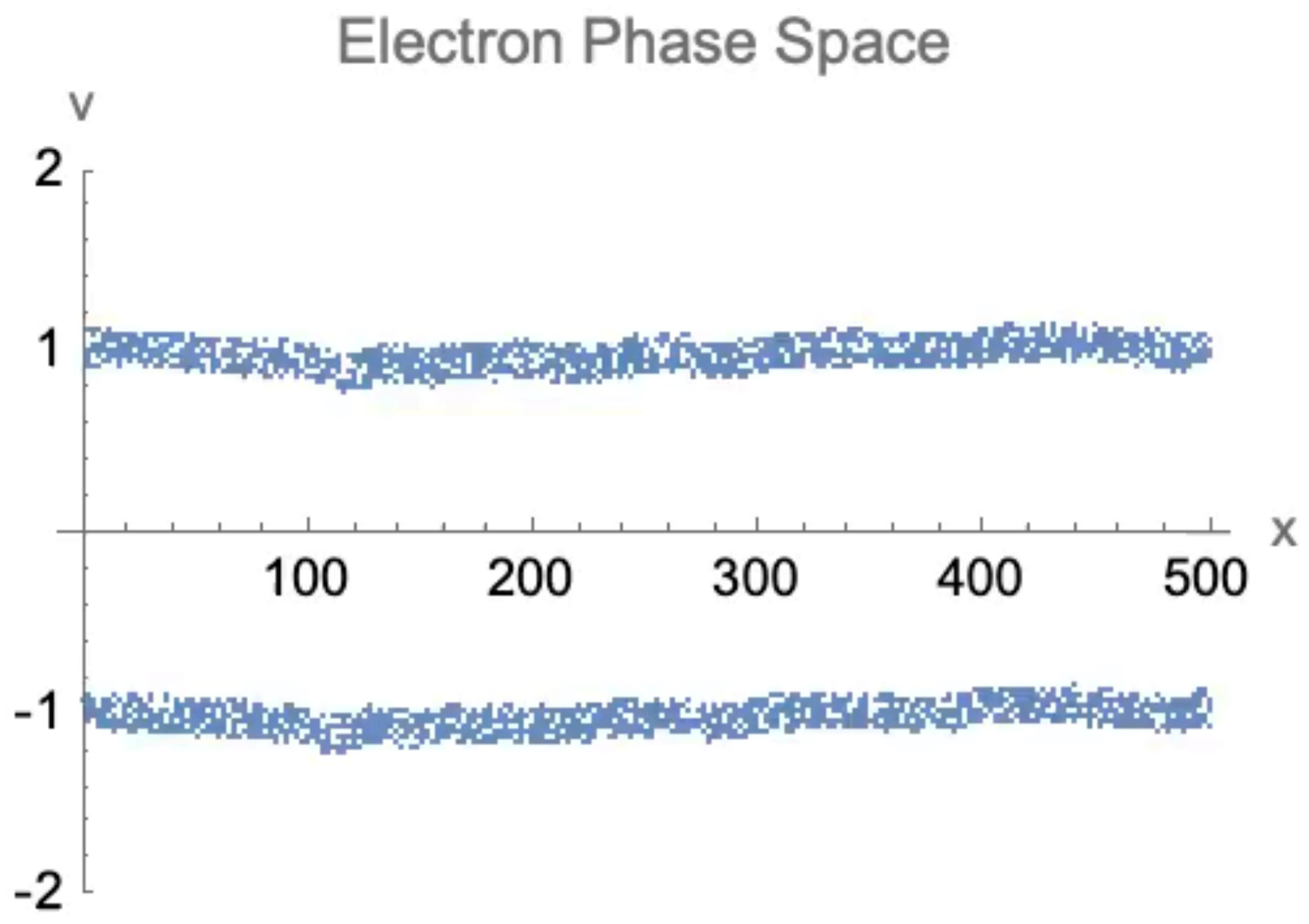




Plasma_PIC-Simulation-electron.nb

Two Electron Beams





Plasma_PIC-Simulation-electron.nb

Next Week

- Ch 8 (Piel): Sec. 8.4 Macroscopic Instabilities
- Ch 7 (Gurnett and Bhattacharjee): MHD Equilibria and Stability (esp Sec. 7.3)