Two-Dimensional Vlasov Simulation of Driven, Nonlinear Electron Plasma Waves

17 June 2010

Jeffrey Hittinger
Center for Applied Scientific Computing

Jeffrey Banks
Center for Applied Scientific Computing

Bruce Cohen
Fusion Energy Program

Richard Berger
AX Division

Stephan Brunner
Centre de recherches en physique des plasmas

40th Anomalous Absorption Conference
Snowmass Village, CO

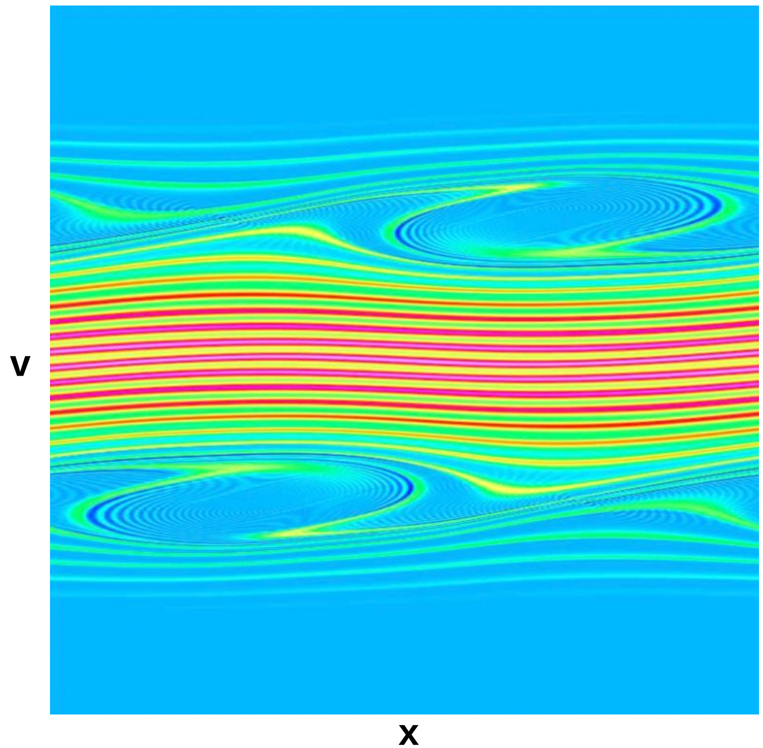
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and funded by the Laboratory Research and Development Program at LLNL under project tracking code 08-ERD-031

UCRL-XXXX-12345

Why two-dimensional Vlasov simulation?

- Wave-particle interaction and particle trapping are important physical effects that influence:
  - Laser-plasma interactions
  - RF heating and current drive
  - Micro-instability and associated turbulence
- Simulation of wave-particle interactions requires a kinetic description
  - *Challenging for accurate and efficient representation*

1D Landau Damping (2048x2048)

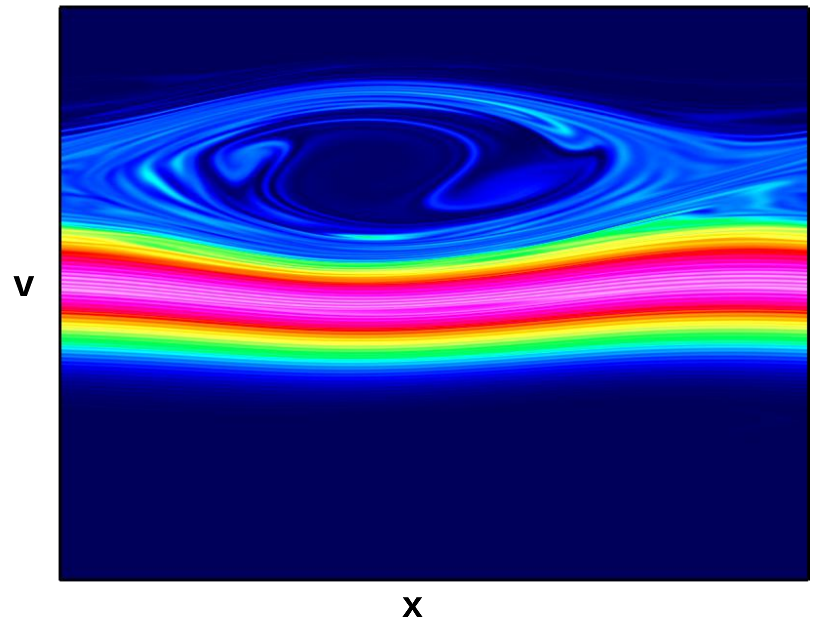


- Two-dimensional Vlasov Simulation is **expensive**, but still valuable
  - Regimes where PIC fluctuations can mask or alter physical effects
  - Benchmark comparison for PIC results

To make 2D Vlasov simulation more practical, we have developed new algorithms

- Traditional Vlasov simulation typically semi-Lagrangian
- We have been developing new, high-order finite volume discretizations†
  - Conservative
  - Oscillation suppression
  - Inherently local (scalable)
  - Well suited for mesh adaptivity
- Our current (2+2)D Vlasov code:
  - Parallel
  - Single grid
  - Single species
  - Electrostatic and electromagnetic*

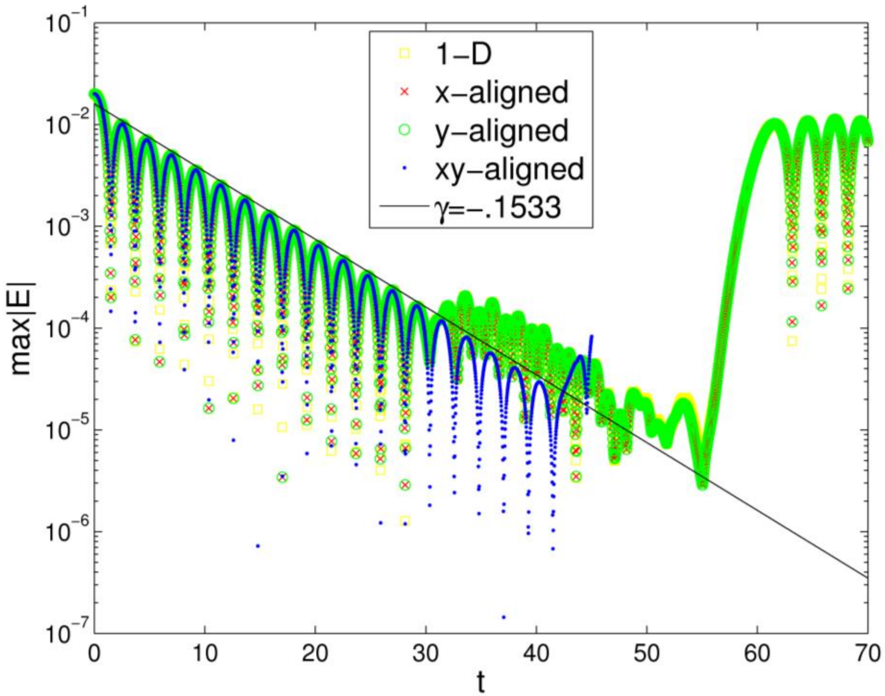
1D Bump-On-Tail Instability (512x2048)



† Banks and Hittinger, IEEE Trans. Plasma Sci., to appear

*general boundary conditions not yet implemented for electromagnetics

We have verified our code using a variety of physically-motivated test problems



Example: Weak Landau Damping

$$f = f_0\left[1 + 0.01\cos(k_x x + k_y y)\right]$$
$$(x, y) \in [-L_x, L_x] \times [-L_y, L_y]$$
$$(v_x, v_y) \in [-2\pi, 2\pi] \times [-2\pi, 2\pi]$$
$$N_{v_x} = N_{v_y} = 64$$

(k_x, k_y)	(L_x, L_y)	$N_x \times N_y$
$(1/2, 0)$	$(2\pi, 2\pi)$	64×64
$(1/2, 0)$	$(2\pi, 2\pi)$	64×64
$(1/2, 1/2)$	$(2\sqrt{2}\pi, 2\sqrt{2}\pi)$	128×128

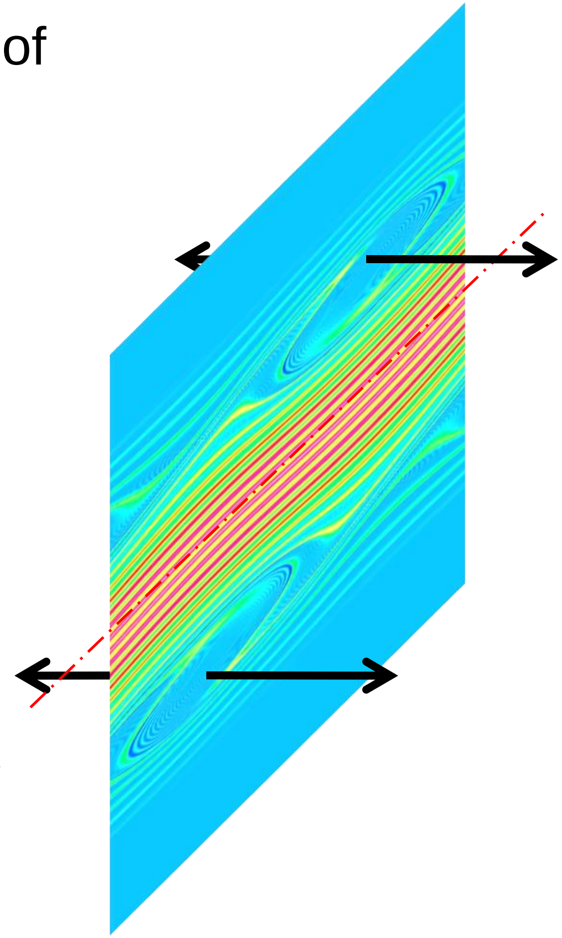
- In 2D, we performed simulations of 1D Landau damping in directions aligned with and diagonal to the grid
- We recovered the correct linear damping rate and frequency

Consider trapping effects in a finite-amplitude Electron Plasma Wave (EPW)

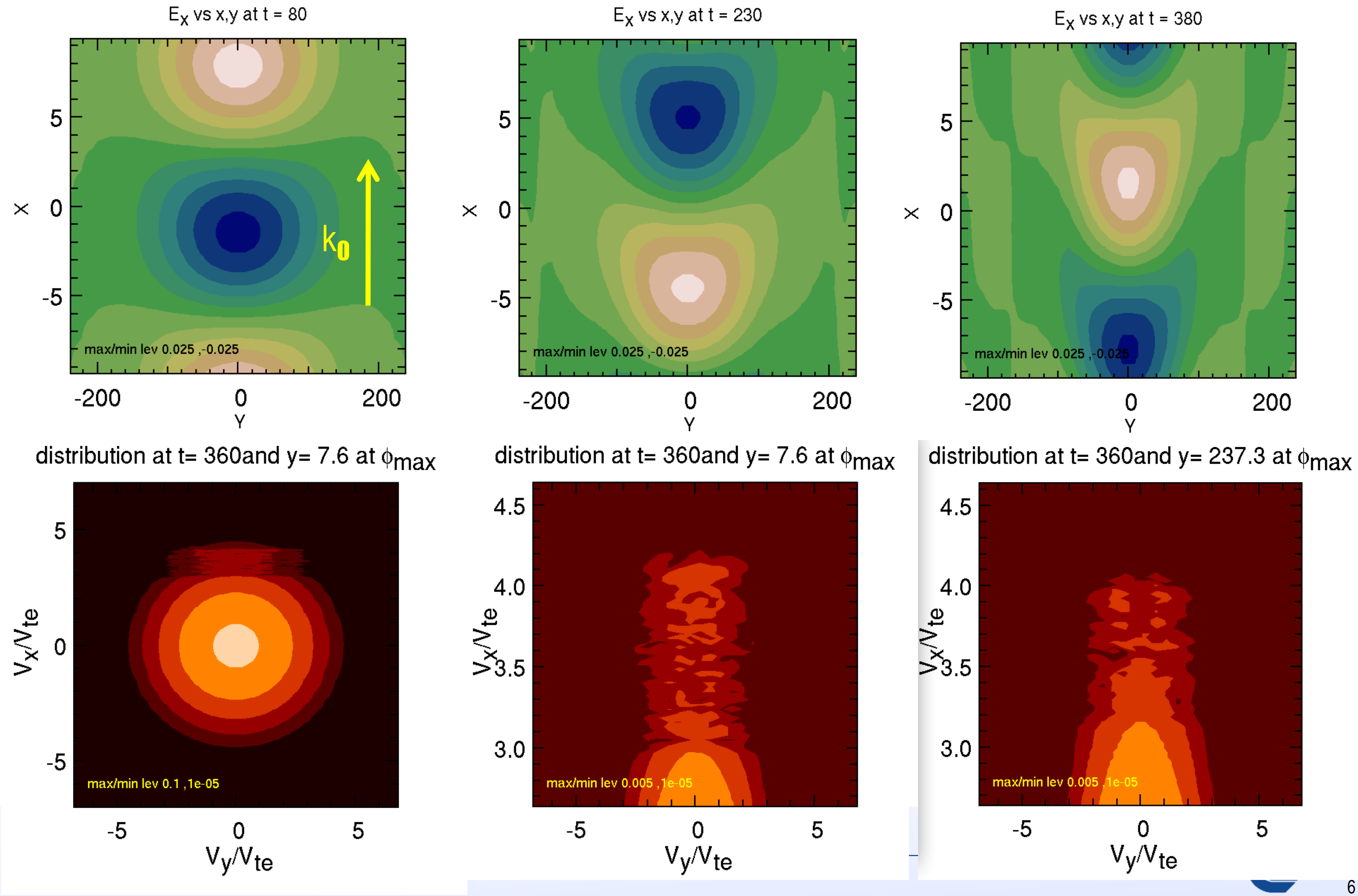
- SRS-driven waves are localized in laser speckles of transverse size $f\lambda_0 \sim 3 \times 10^{-4}$ cm
  - Electrons trapped are lost in a time:

    $$t_r \sim f\lambda_0/v_{th} = 10^{-13}\ \mathrm{s}$$

  - *Commensurate with the SRS growth time*
- Large-amplitude EPWs are more nonlinear in 2D
  - Self-focusing dependent on the transverse variation of the nonlinear frequency shift
- Two-dimensional Vlasov simulation can:
  - Test carefully theoretical models of the dependence of the trapped electron frequency shift and the damping rate on t_r
  - Eliminate doubts about the influence of non-physically large fluctuation levels



The field appears to focus and maintain its amplitude on axis even as electrons de-trap



Simulation of a driven nonlinear traveling EPW of finite width in one-wavelength-long system ($L_x = \lambda$)

- The wave is driven by a traveling wave potential:

$$E_{ext} = A(Y)\ E_0 \cos(kx - \omega t)\ P(t)$$

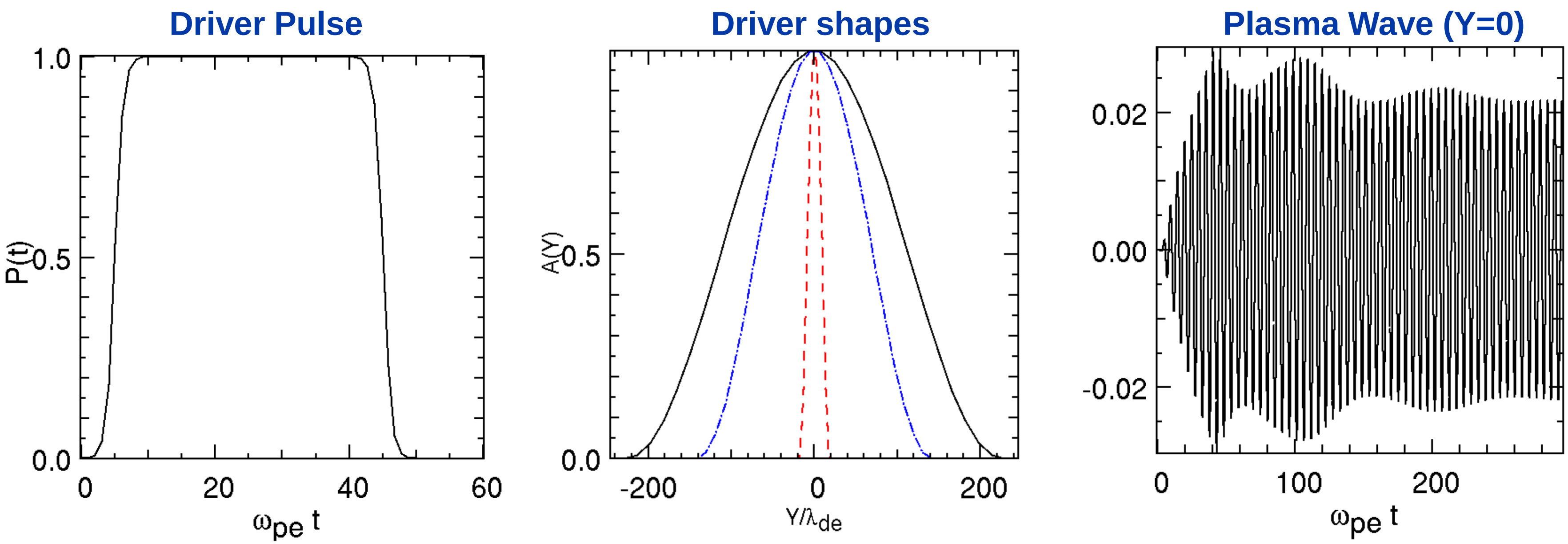
with ω and *k* chosen to satisfy the linear dispersion:

$$k\lambda_{de} = 1/3 \Rightarrow \omega/\omega_{pe} = 1.201$$

- Varied the driver width as shown: FWHM = 20,144, 220 λ_{de}

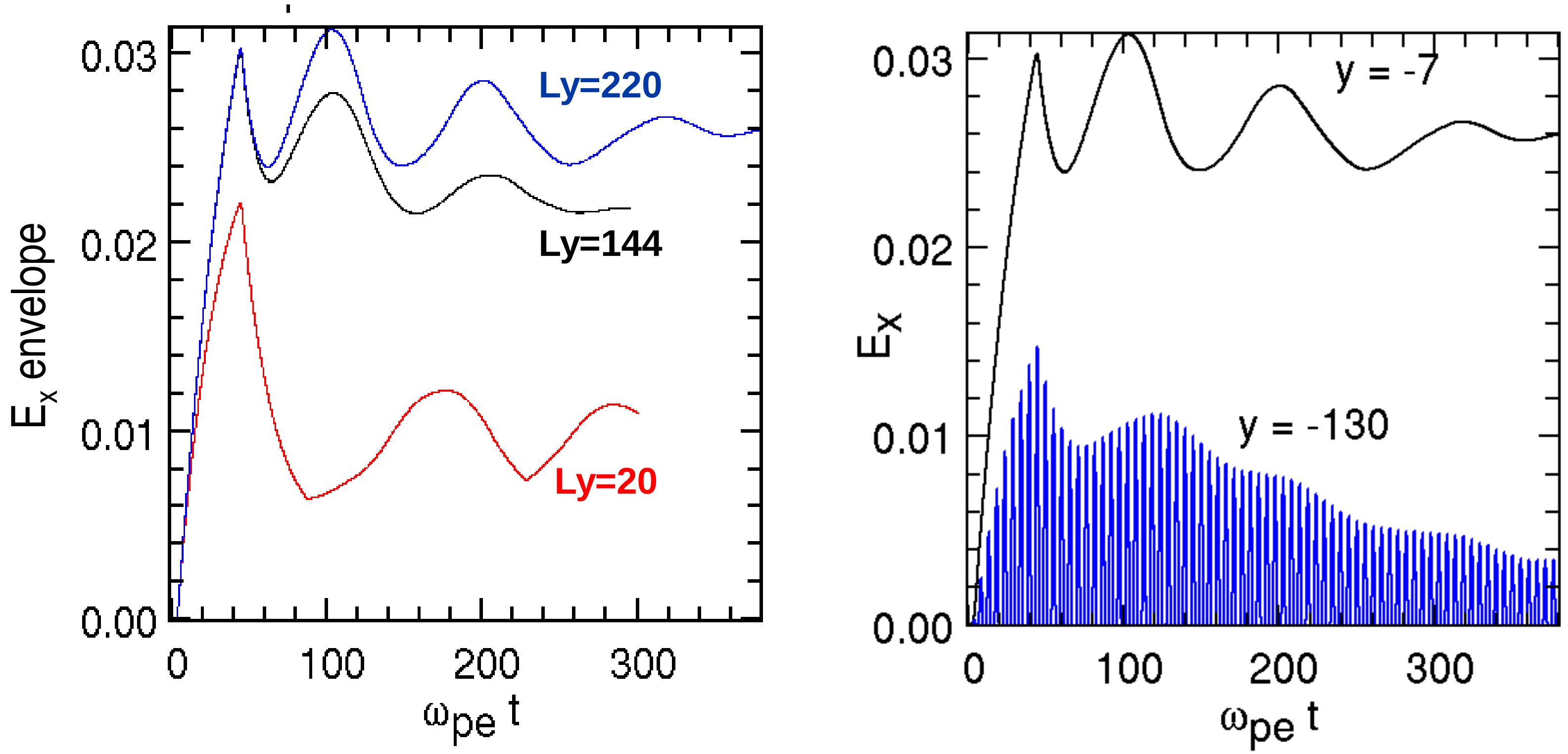
$$L_x = \lambda = 2\pi/k$$
$$L_y \gg L_x$$

Periodic in x
In/Outflow in y



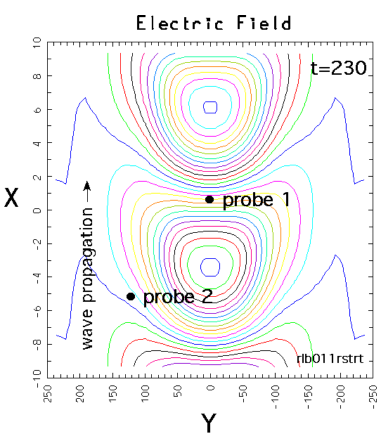
The final amplitude of the plasma wave depends on the width of the driving potential

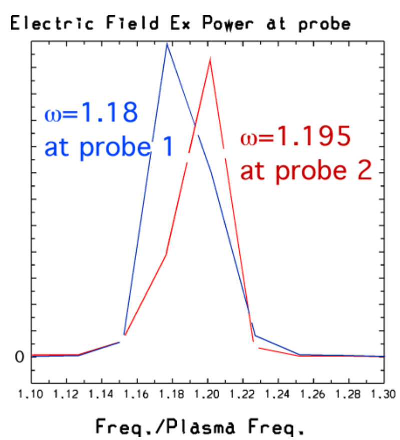
- Narrow drivers produce lower amplitude EPWs
  - For laser speckle: $f\lambda_0/\lambda_{de}$ = 225 [f/8, λ_0=351nm, Te=2.5, N_e/N_c=0.1]
- EPW amplitude in wings of driver decay after driver is off

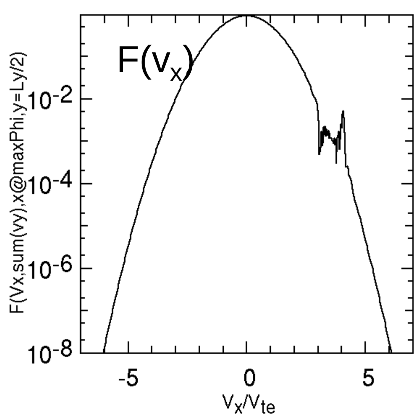


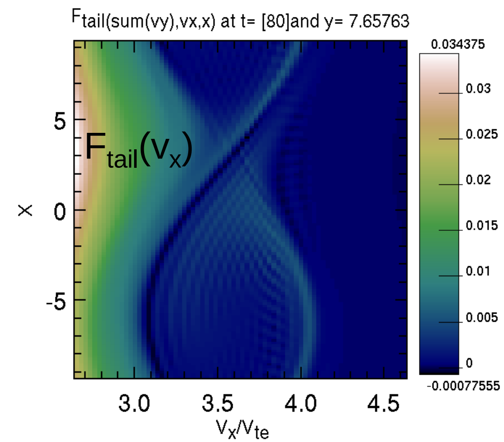
Trapping effects in a 2D finite-amplitude EPW induce wave-front bending

- Electrons are trapped in the wave
  - more are trapped ***along the axis*** of the wave where ***amplitude is stronger***
- After the driver is off, a nonlinear shift (<0) of the normal mode frequency occurs
  - ***Shift is smaller*** at a finite *y* displacement ***away from the axis***
  - Thus, the ***phase velocity is larger*** away from the axis
- This phase velocity variation causes the wave front to bow
  - Consistent with the Raman studies of Yin, *et al.,* PRL **99**, 265004 (2007)





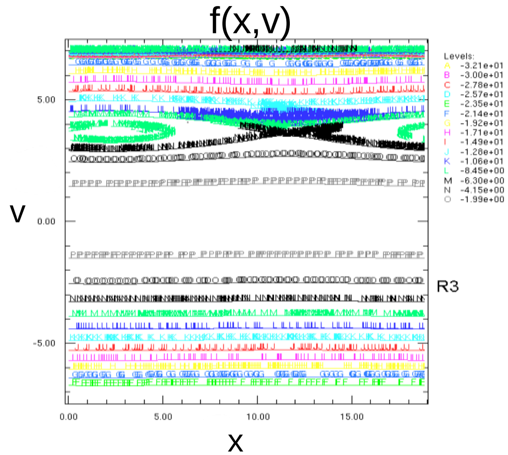


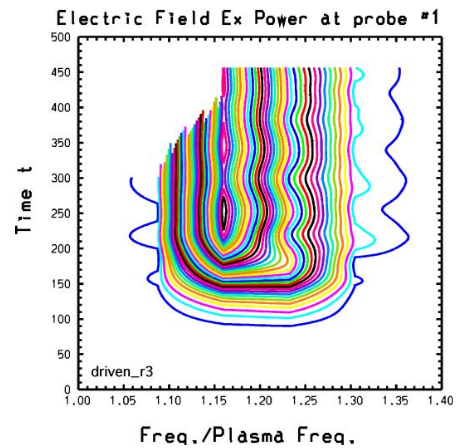


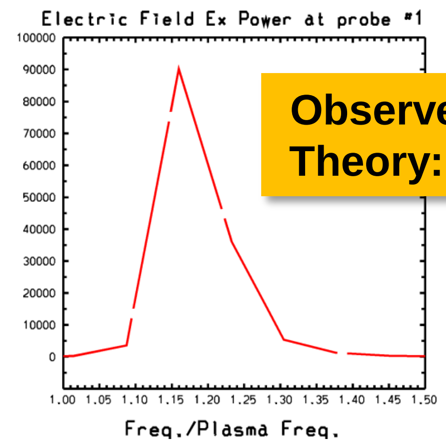
$(N_x, N_y, N_{vx}, N_{vy}) = (128, 32, 512, 32)$

For sufficient resolution, frequency shift dependence on wave amplitude agrees with adiabatic theory

- Results of example 1D simulation with (Nx,Nv)=(512,1024):

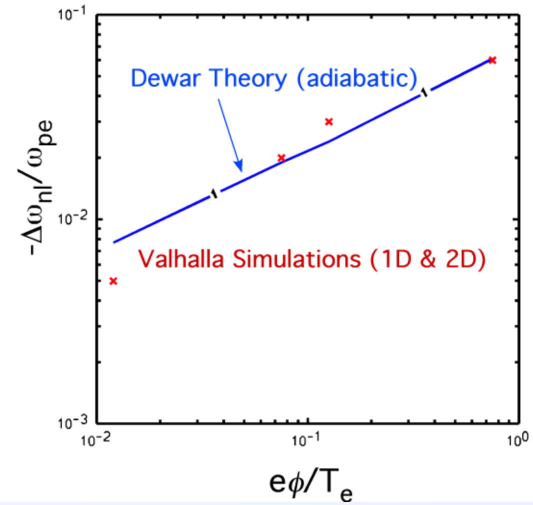




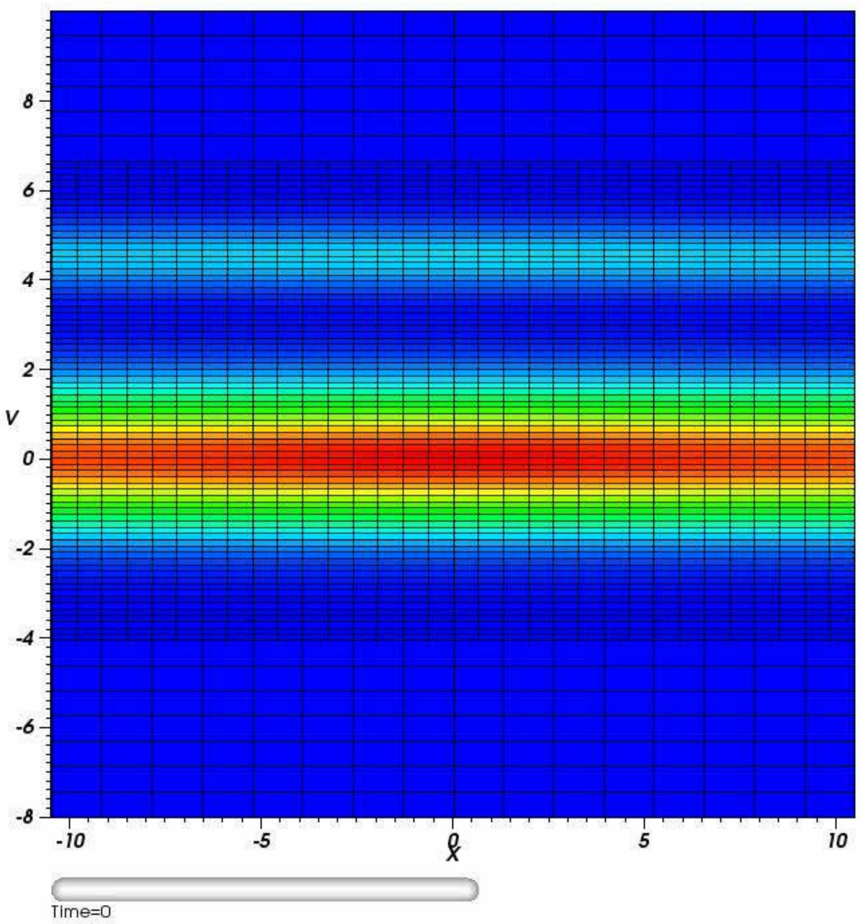


Observed: ω=1.17
Theory: ω_{ad}=1.175

- Scan in wave amplitude in 1D and 2D
  - With adequate (x,v) resolution, compares well with Dewar's theory (adiabatic drive)
- Less resolution in (x,v) space degrades the results
  - Trapped particles must be resolved
  - Particle motion links x and v resolution needs
  - Resolution scan done with uniform mesh



Adaptive Mesh Refinement (AMR) will further reduce the cost of 2D Vlasov simulation



- Our runs required 385 - 768 processors for ~24 hours
- AMR could further reduce the expense
  - Fewer cell
  - Larger time steps
  - Savings increase geometrically with dimension
- Current AMR code:
  - 1D Vlasov-Poisson
  - Multi-species
  - Same discretizations
  - Based on SAMRAI library

Conclusions and Future Work

- We have demonstrated two-dimensional detrapping effects on driven, nonlinear EPWs using Vlasov simulation
- We will continue to investigate Raman-relevant problems:
  - Parametric studies of driven EPWs
  - Vlasov-Maxwell simulation of SRS
- We will continue to improve our simulation capability:
  - Extend AMR implementation to 2D
  - Extend AMR implementation to electromagnetics
  - Investigate improved refinement criteria
  - Investigate improved time integration techniques
  - Investigate improved non-reflective boundary conditions