Nonlinear Nonstationary Self-Organized Asymptotic States in High Energy Density Plasmas (ex: KEEN Waves)

Bedros Afeyan

Polymath Research Inc.

Pleasanton, CA

M. Mehrenberger, A. Dodhy, E. Sonnendrücker

IPP, Garching, DE

Michigan Institute for Plasma Science and Engineering, 1200 EECS Noon, 6-20-2014

Special thanks to long term collaborators:

M. Charbonneau-Lefort, M. Shoucri

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Work Supported by a DOE NNSA-OFES Joint Program in HEDLP and an OFES SBIR Grant

The Big Picture

- What are the Plasma Kinetic Theory Equations we need to solve? **VP, VM, VLFP, LGBT, …, all the way to MD**.

- What are the physical states we wish to simulate? **Nonlinear, Non-Stationary, Self-Organized, Asymptotic States** of plasma and their interactions with each other and with classical, small-amplitude-excited, resonant waves such as EPW and IAW.

- How about their interactions? We also wish to study their **stimulated scattering states,** when, for example, crossing laser beams drive them and are amplified off these structures at the same time. Parametric Instabilities such as SRS, SBS, SKEENS, … Rich physics, multiscale, cool!

What is (Classical) Kinetic Theory?

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- **Klimontovich equation:** Conservation of Densities in Phase Space of a finite number of classical point particles belonging to a set of species (q_s, m_s) meets self-consistent microscopic electric and magnetic fields via Maxwell's equations. $\Sigma_i\ \delta(\mathbf{x}-\mathbf{x}_i)\ \delta(\mathbf{v}-\mathbf{v}_i)$.

$$\frac{DN_s}{Dt} = \left[\frac{\partial}{\partial t} + \mathbf{v} \bullet \nabla_{\mathbf{x}} + \frac{q_s}{m_s} \left(\mathbf{E}^m + \frac{\mathbf{v}}{c} \times \mathbf{B}^m \right) \bullet \nabla_{\mathbf{v}} \right] N_s = 0$$

$$\nabla_{\mathbf{x}} \bullet \mathbf{E}^m = 4\pi \rho^m \qquad \rho^m = \sum_s q_s \int d\mathbf{v}\, N_s$$

$$\nabla_{\mathbf{x}} \bullet \mathbf{B}^m = 0$$

$$\nabla_{\mathbf{x}} \times \mathbf{E}^m = -\frac{1}{c} \frac{\partial \mathbf{B}^m}{\partial t}$$

$$\nabla_{\mathbf{x}} \times \mathbf{B}^m = \frac{1}{c} \frac{\partial \mathbf{E}^m}{\partial t} + \frac{4\pi}{c} \mathbf{J}^m \qquad \mathbf{J}^m = \sum_s q_s \int d\mathbf{v}\, \mathbf{v}\, N_s$$

Can We Separate Out the Smooth Part of the Distribution Function from the Fluctuating? This Is How You Get Plasma Kinetic Equations

$$N_s = f_s + \delta N_s$$

$$\mathbf{E}^m = \mathbf{E} + \delta\mathbf{E}$$

$$\mathbf{B}^m = \mathbf{B} + \delta\mathbf{B}$$

$$\left[\frac{\partial}{\partial t} + \mathbf{v}\bullet\nabla_{\mathbf{x}} + \frac{q_s}{m_s}\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\bullet\nabla_{\mathbf{v}}\right] f_s = -\frac{q_s}{m_s}\left(\delta\mathbf{E} + \frac{\mathbf{v}}{c}\times\delta\mathbf{B}\right)\bullet\nabla_{\mathbf{v}}\delta N_s$$

The right hand side is less and less significant the more particles you have in a Debye sphere. Collective effects dominate when the plasma parameter is large: $\Lambda = n\lambda_D^3 >> 1$, where $\lambda_D = \sqrt{\frac{T}{4\pi n q^2}}$

In the limit of RHS = 0 we have the **Vlasov** or **collisionless Boltzmann equation** description of the collective effects in a plasma.

How much of the fluctuating density and fields on the RHS do we want to keep? **BBGKY**

Lenard-Guernsey-Balescu theory (LGBT) or **Fokker-Planck (Fo-Pla)?**
Or you can get tangled up in knots over the Boltzmann collisional operator: **Knots in Boltz.**

Lenard-Guernsey-Balescu Theory: Two-Point Correlation Functions Are In (correlations assumed small), Three Particle Collisions Are Completely Out.

$$f_2\left(\mathbf{x}_1,\mathbf{v}_1,\mathbf{x}_2,\mathbf{v}_2,t\right)=f_1\left({}_1,\mathbf{v}_1,t\right)f_1\left({}_1,\mathbf{v}_1,t\right)+g\left(\mathbf{x}_1,\mathbf{v}_1,\mathbf{x}_2,\mathbf{v}_2,t\right)$$

Ignoring spatial inhomogeneity, working in Fourier space, LGBT reads:

$$\frac{Df}{Dt}=-\frac{8\pi^4 n}{m^2}\nabla_{\mathbf{v}}\bullet\int d\mathbf{k}\,d\mathbf{v}'\mathbf{k}\,\mathbf{k}\bullet\frac{\varphi^2(k)}{\left|\varepsilon\left(\mathbf{k},\mathbf{k}\bullet\mathbf{v}\right)\right|^2}\delta\left[\mathbf{k}\bullet\left(\mathbf{v}-\mathbf{v}'\right)\right]\left[f\left(\mathbf{v}\right)\nabla_{\mathbf{v}'}f\left(\mathbf{v}'\right)-f\left(\mathbf{v}'\right)\nabla_{\mathbf{v}}f\left(\mathbf{v}\right)\right]$$

Plasma Dielectric Function: $$\varepsilon\left(\mathbf{k},\omega\right)=1+\frac{\omega_p^2}{k^2}\int d\mathbf{v}\frac{\mathbf{k}\bullet\nabla_{\mathbf{v}}f\left(\mathbf{v}\right)}{\left(\omega-\mathbf{k}\bullet\mathbf{v}\right)}$$

Coulomb Potential Fourier Transformed: $$\varphi\left(\mathbf{k}\right)=\frac{e^2}{2\pi^2k^2}$$

See Dwight Nicholson’s Introduction to Plasma Theory for a derivation in Appendix A

See Ichimaru’s Statistical Plasma Physics, Vol. I, Chapter 2. It is more comprehensive

Vlasov-Landau-Fokker-Planck: Small Angle Scattering Takes Over the RHS

$$\left[\frac{\partial}{\partial t} + \mathbf{v}\bullet\nabla_{\mathbf{x}} + \frac{q_s}{m_s}\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\bullet\nabla_{\mathbf{v}}\right] f_s = -\nabla_{\mathbf{v}}\bullet\left[\mathbf{C}_{DF} f_s\right] + \frac{1}{2}\nabla_{\mathbf{v}}\bullet\nabla_{\mathbf{v}} : \left[\overleftrightarrow{\mathbf{D}}_{DC}\, f_s\right]$$

$$\mathbf{C}_{DF} = \frac{8\pi n e^4 \ln\Lambda}{m^2}\nabla_{\mathbf{v}}\int d\mathbf{v}'\,\frac{f}{\left|\mathbf{v}-\mathbf{v}'\right|}$$

$$\overleftrightarrow{\mathbf{D}}_{DC} = \frac{8\pi n e^4 \ln\Lambda}{m^2}\nabla_{\mathbf{v}}\nabla_{\mathbf{v}}\int d\mathbf{v}'\left|\mathbf{v}-\mathbf{v}'\right| f$$

$\mathbf{C}_{DF}$ **Coefficient of dynamical friction: Slow down a particle by numerous small angle scattering events.**

$\overleftrightarrow{\mathbf{D}}_{DC}$ **Diffusion Coefficient: for diffusion or spread sideways.**

We Aim To Understand the Behavior of Kinetic Electrostatic Oscillations Excited and Sustained in a Plasma: Nonlinear, Nonstationary, Self-Organized, Asymptotic States. Ex. KEEN Waves

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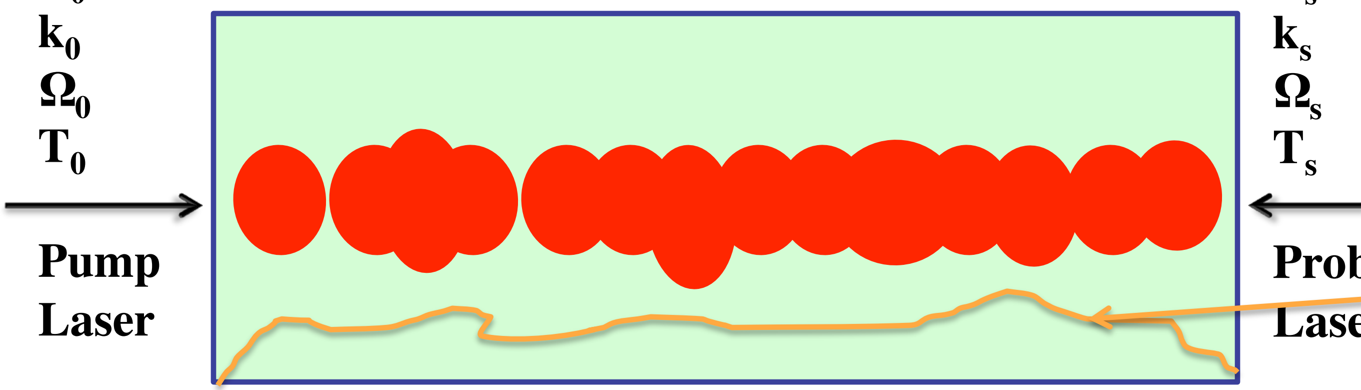
E_0
k_0
Ω_0
T_0

Pump Laser



E_s
k_s
Ω_s
T_s

Probe Laser

Background Ion density Profile $n_I(x)$

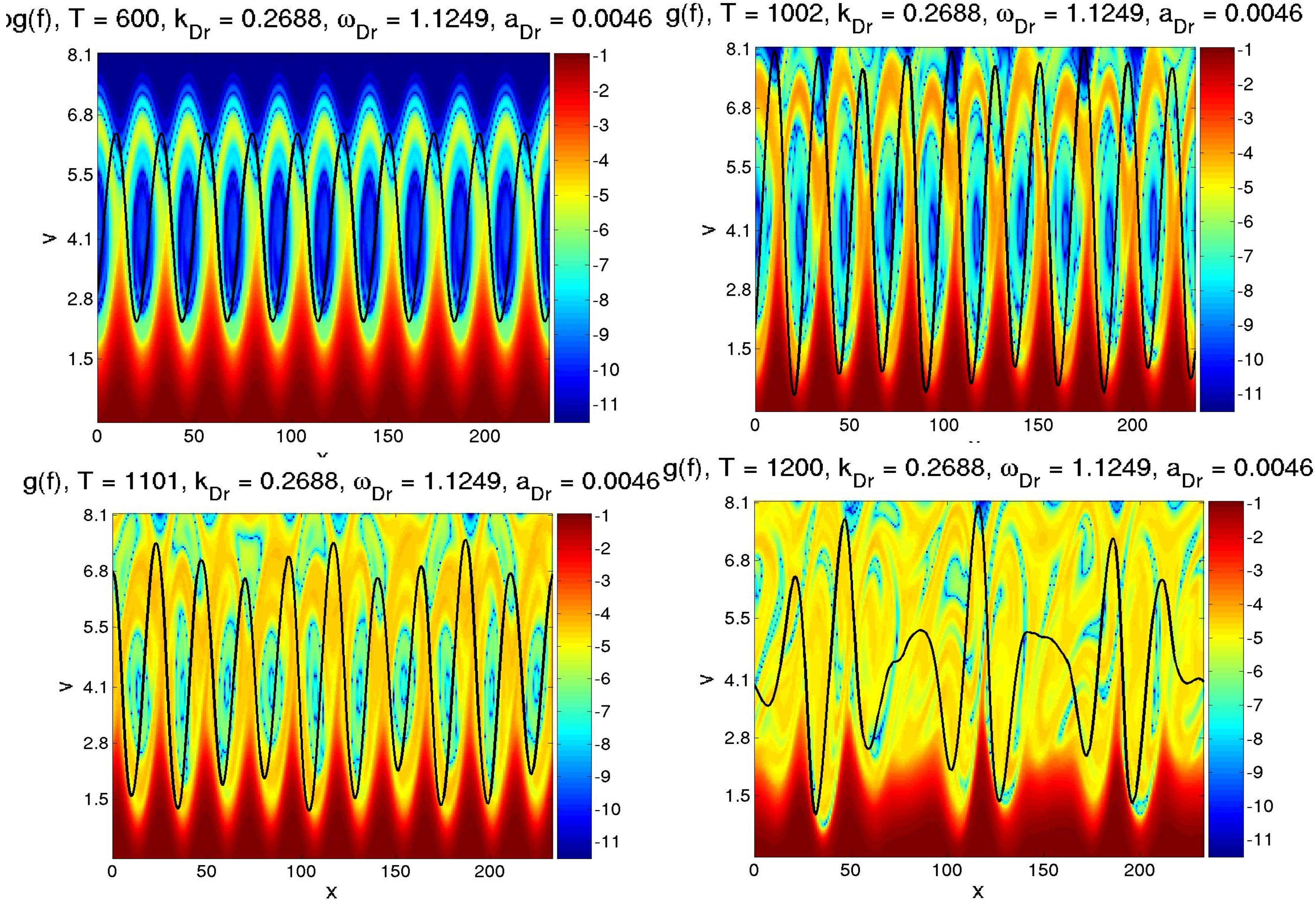
Make simulation box length between 30 and 100 vortices

This depends on the amplitude and duration of the drive

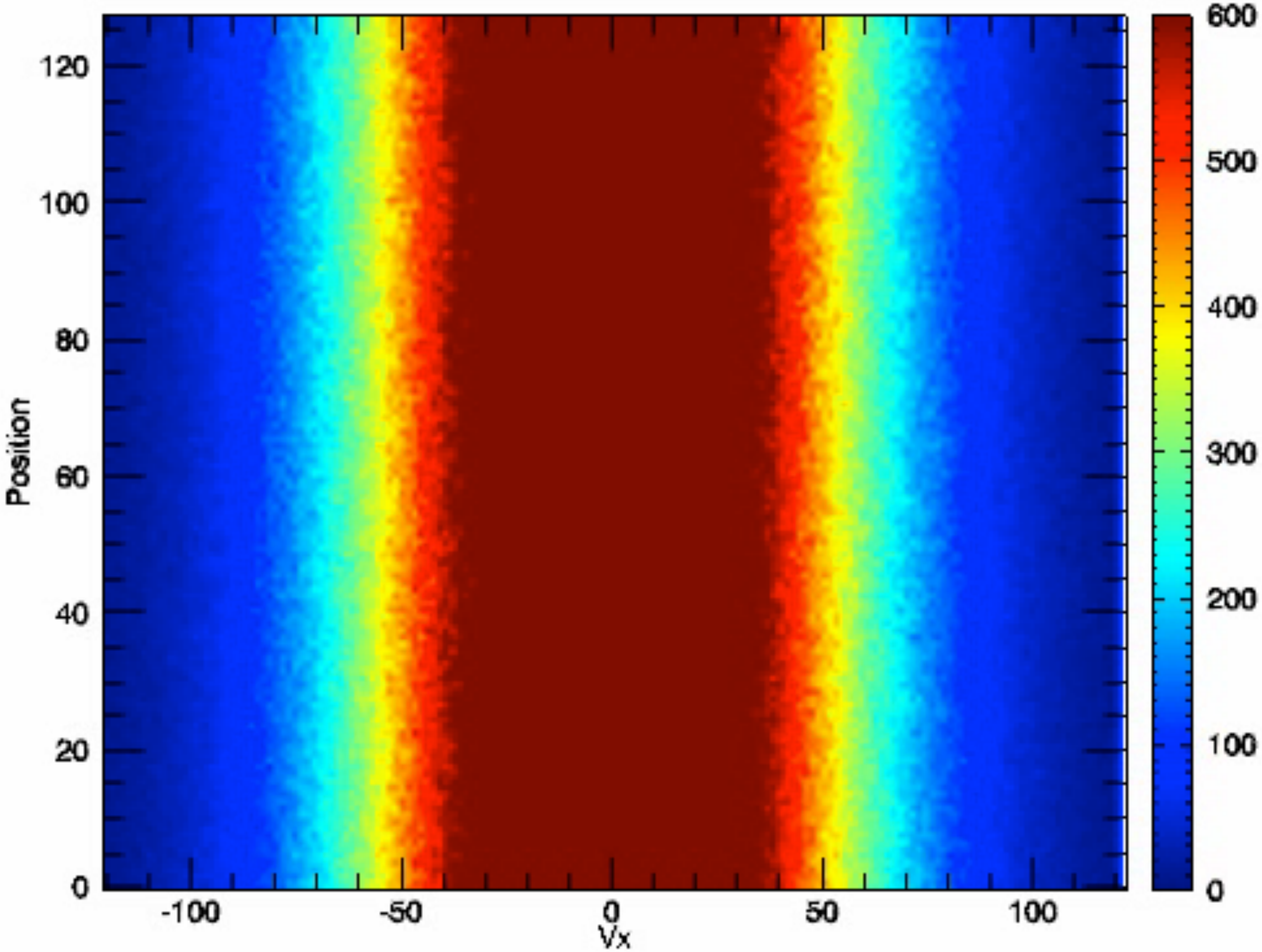
The ponderomotive force drives waves as long as the pump and probe are both 'on' at the same time: (@ EPW frequency drive SRS)

The plasma excitation will have a driver whose amplitude scales as $\sqrt{(E_0 \bullet E_S)}$
Whose duration is the overlap between the Pump and Probe pulses
Whose wavevector and frequency will be at the difference between the pump and the probe wavevectors and frequencies, respectively.

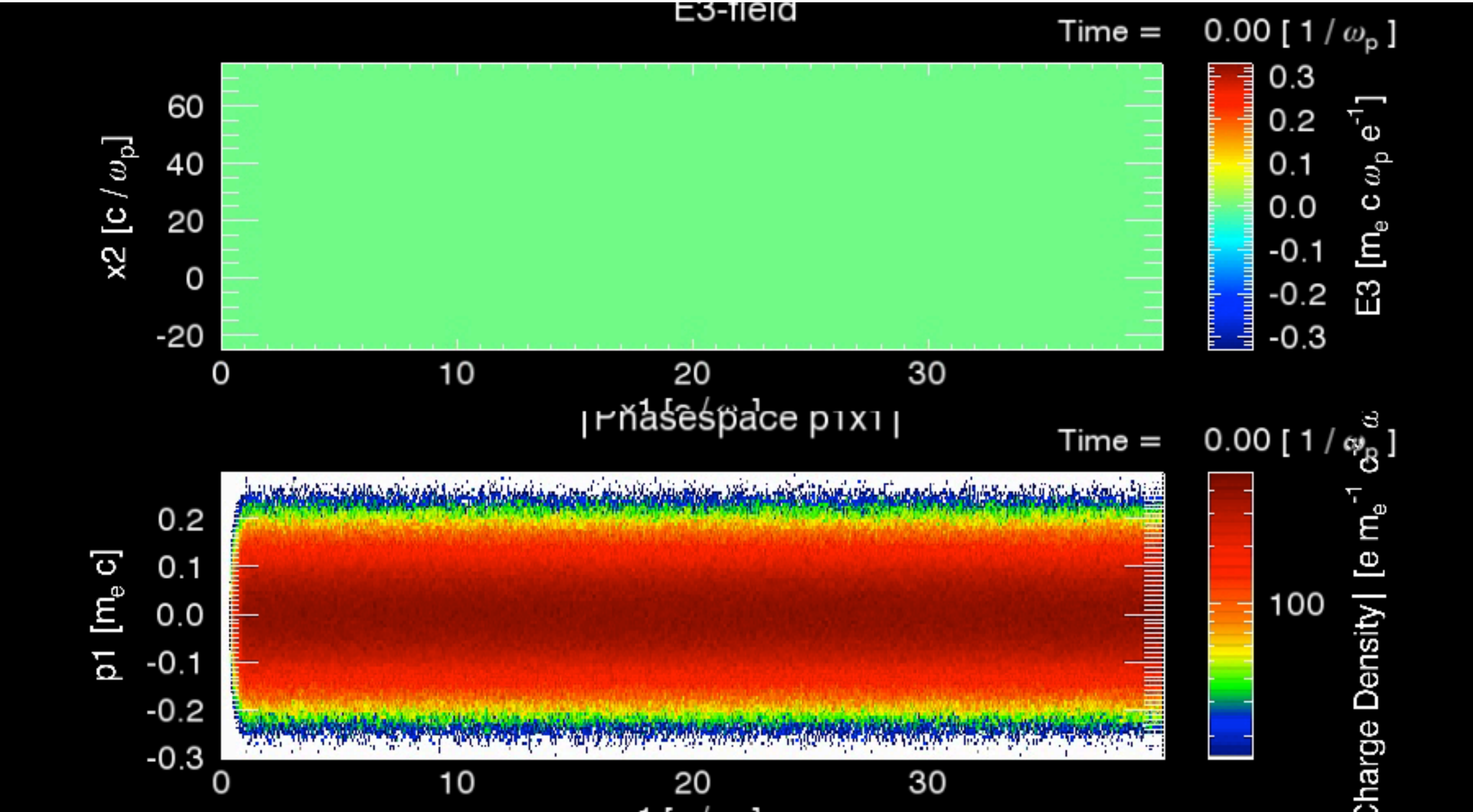
Vortex Merging Is Commonly Observed in V-P & V-M Simulations of SRS, For Instance



BEPS an ES PIC Codes Has Observed Ponderomotively Driven KEEN Waves as Well (F. Tsung, UCLA)



Optical Mixing Driven KEEN Waves Are Also Detected with EM PIC Code (OSIRIS, F. Tsung)



The Origin of the Bias towards EPW, EMW, IAW & EAW-Centrism and Its Shortcomings

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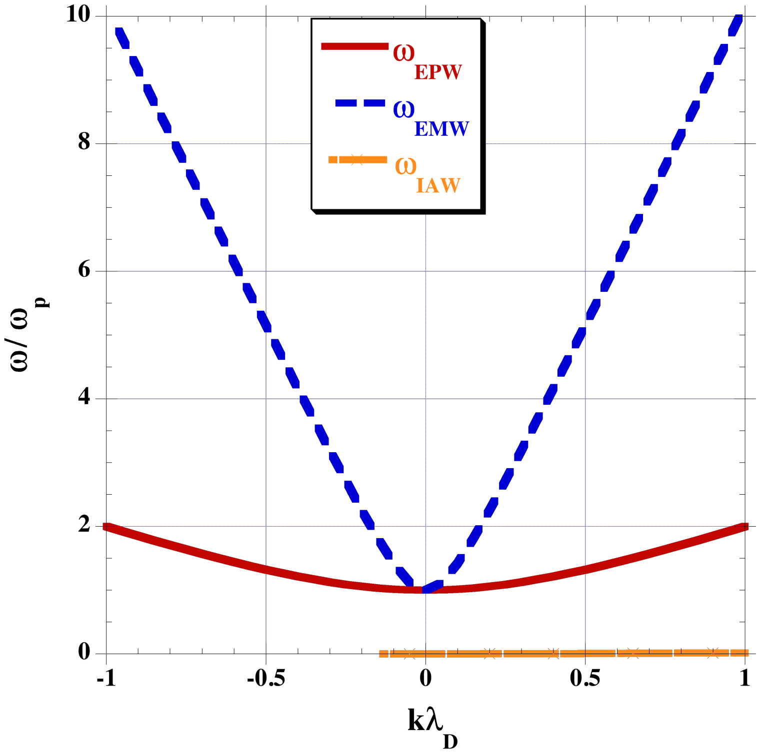
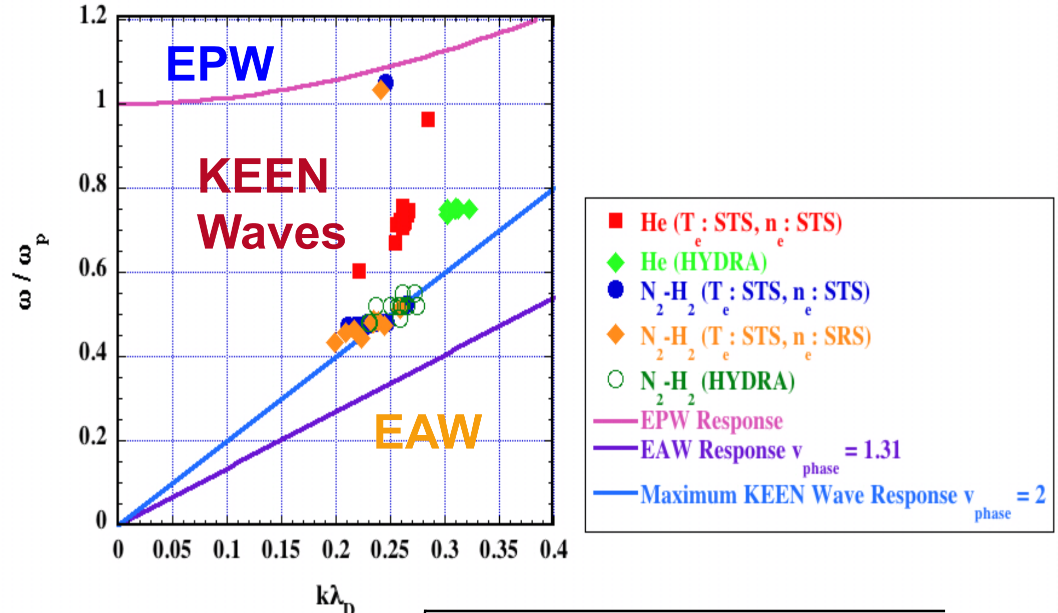
Dispersion Relations of EPWs, EMWs and IAWs in Uniform Plasmas



Ponderomotive Drive Parameters (ω-k) Used to Excite KEEN Waves on Trident



$$\omega_{\mathrm{EMW}} = \sqrt{1 + \left(511 / T_{e,keV}\right) k_{\mathrm{EMW}}^2}$$

$$\omega_{\mathrm{EMW}}^2 = \omega_p^2 + c^2 k_{\mathrm{EMW}}^2$$

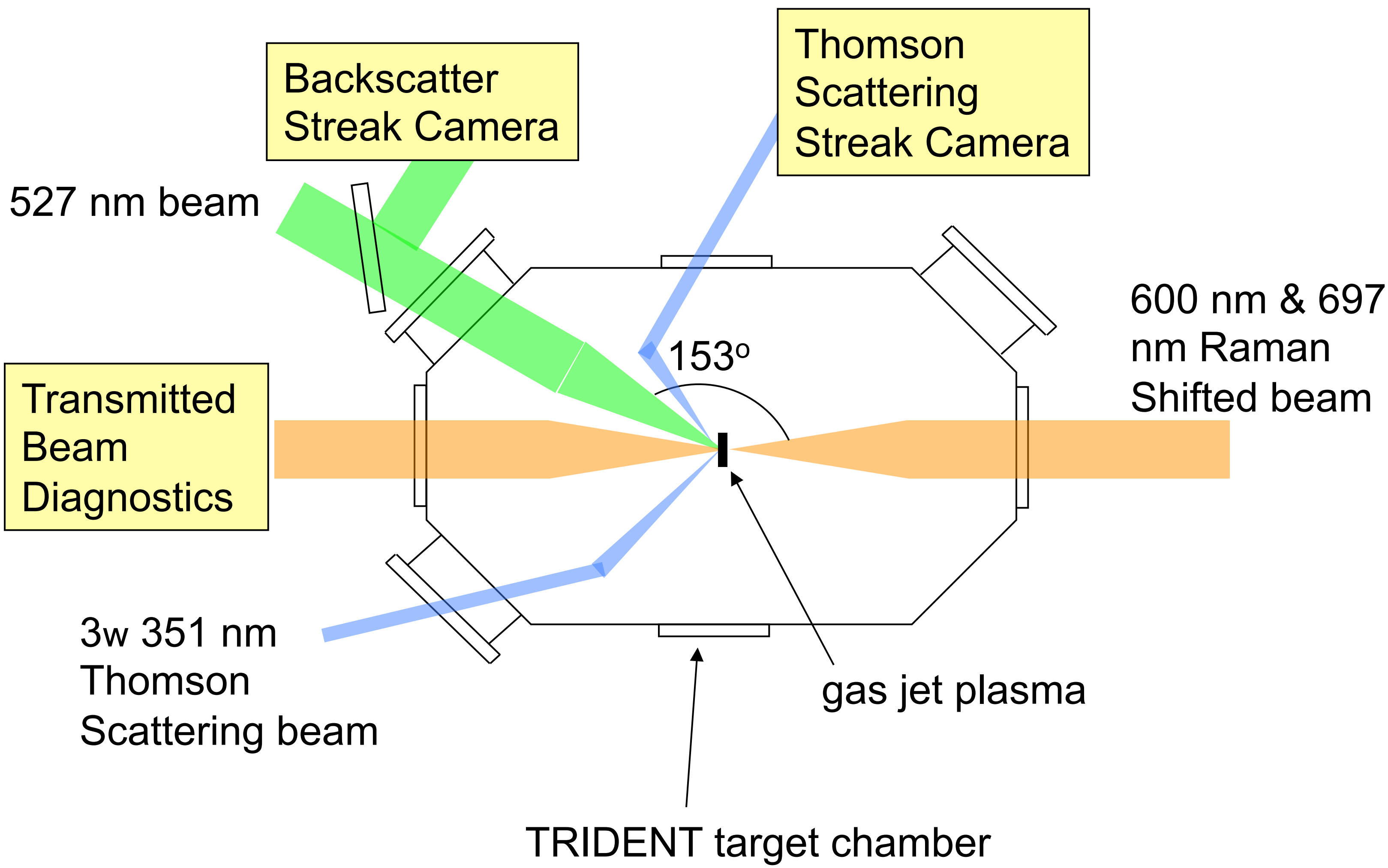
$$\omega_{\mathrm{EPW}} = \sqrt{1 + 3\, k_{\mathrm{EPW}}^2}$$

$$\omega_{\mathrm{EPW}}^2 = \omega_p^2 + 3\,\mathrm{v}_{th}^2\, k_{\mathrm{EPW}}^2$$

$$\omega_{\mathrm{IAW}} = \mathbf{u} \bullet \mathbf{k}_{\mathrm{IAW}} + c_s k_{\mathrm{IAW}}$$

$$\omega_{\mathrm{IAW}} = \sqrt{\frac{Z\, m_e}{M_I}}\; k_{\mathrm{IAW}}$$

KEEN Wave Experimental Layout of the Beams and Diagnostics on Trident



We Have Excited and Detected via Thomson Scattering KEEN Waves on Trident at LANL in the Spectral Gap of Traditional Plasma Physics Lore

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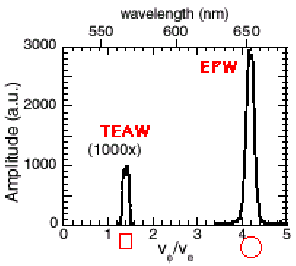
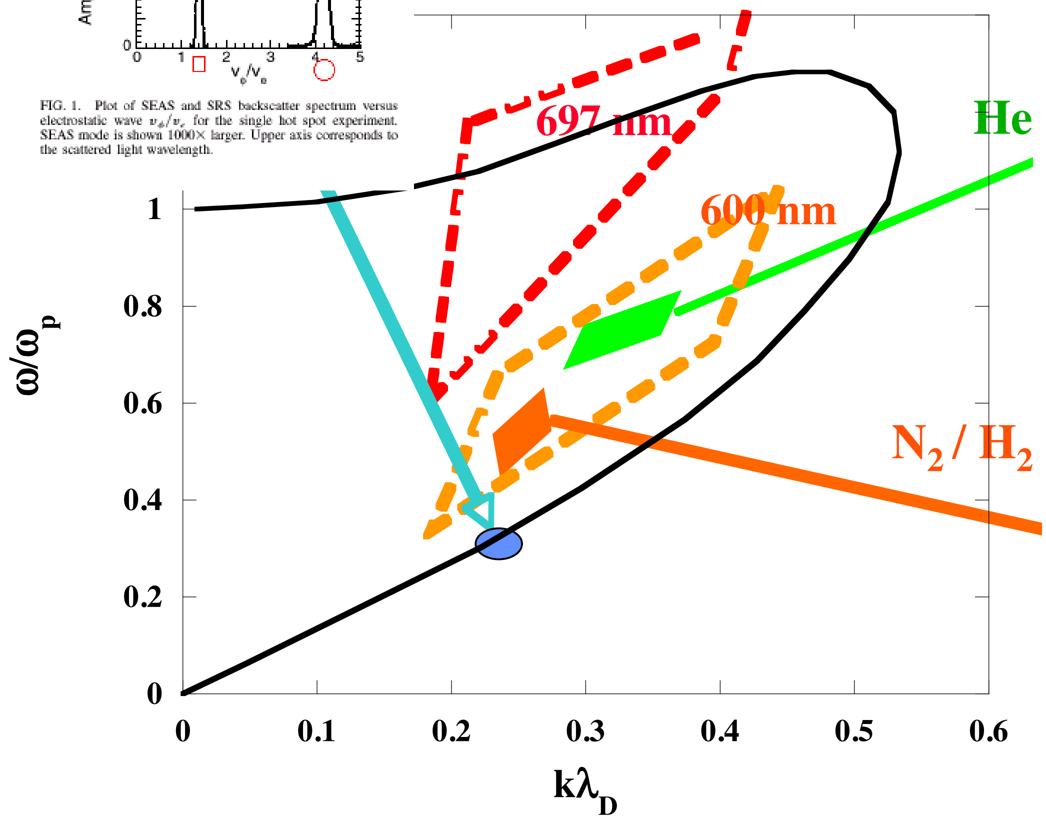
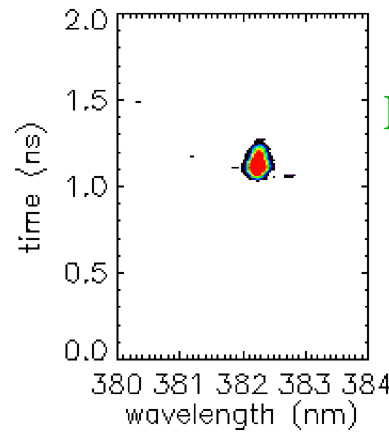
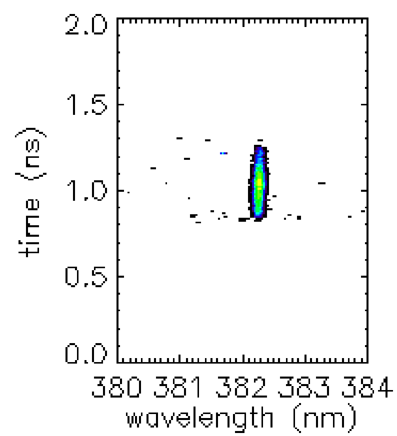


FIG. 1. Plot of SEAS and SRS backscatter spectrum versus electrostatic wave v_ϕ/v_e for the single hot spot experiment. SEAS mode is shown 1000× larger. Upper axis corresponds to the scattered light wavelength.





PRI-LANL KEEN Team



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Paradigms of Kinetic Behavior of Vlasov Plasmas: 4 Old, 1 New

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Quasilinear Theory Flatten the e-VDF by Phase Space Diffusion balancing growing modes (RPA) dynamic Equilibrium '62

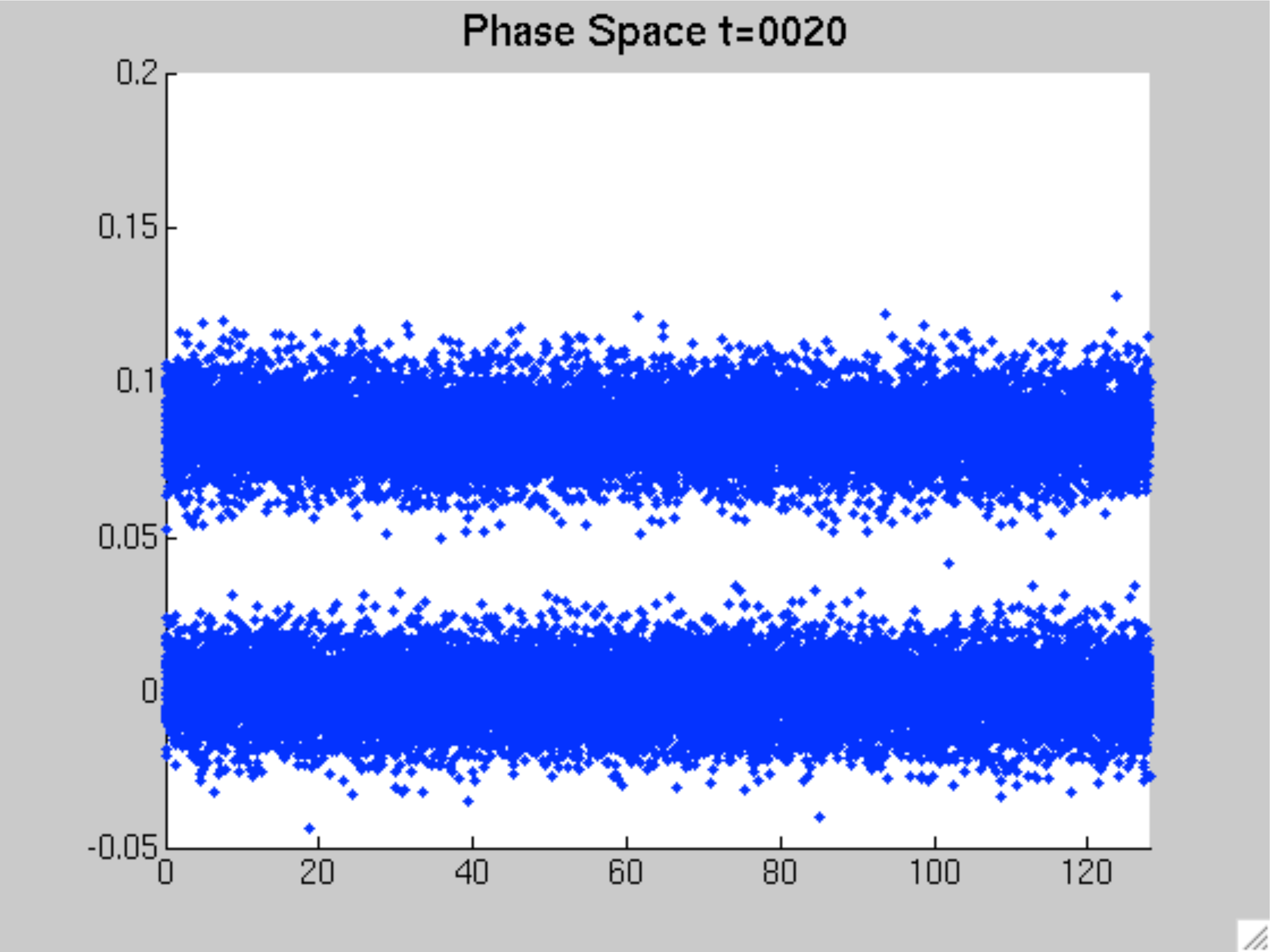
Landau Damping
Linear Collisionless Dissipation! '46

KEEN Waves
'02-'03, Self Consistent NL non-stationary self-organized states

BGK Modes
Static Equilibria Nonlinear '57

Stochasticity found almost always when particles are injected into nonstationary electric or EM fields '80's and '90's Stochasticity, Diffusion, Loss of Coherence **NOT** Self-Consistent

Archetypal Kinetic Instability Leading to Stochasticity in Plasma Physics is the Beam-Plasma Instability



Our Relativistic V-M Code Solves Maxwell's Equations on a Staggered Mesh

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Step 1

$$\mathbf{J}_\perp = -\mathbf{a}_\perp m \int \frac{f}{\gamma}\, dp$$
$$\left(\frac{\partial}{\partial t} \pm \frac{\partial}{\partial x}\right) E^{\pm} = -J_y$$
$$\left(\frac{\partial}{\partial t} \mp \frac{\partial}{\partial x}\right) F^{\pm} = -J_z$$

Leapfrog scheme with advection on a Courant grid:

$$E^{\pm}(x \pm \Delta t, t_{n+1/2}) = E^{\pm}(x, t_{n-1/2}) - \Delta t J_z(x \pm \Delta t/2, t_n)$$
$$F^{\pm}(x \pm \Delta t, t_{n+1/2}) = F^{\pm}(x, t_{n-1/2}) - \Delta t J_z(x \mp \Delta t/2, t_n)$$

Step 2

$$\mathbf{a}_\perp = -\int \mathbf{E}_\perp\, dt$$

Leapfrog scheme:

$$\mathbf{a}_\perp(x, t_{n+1}) = \mathbf{a}_\perp(x, t_n) - \Delta t\, \mathbf{E}_\perp(x, t_{n+1/2})$$

Step 3

$$J_x = m \int \frac{p}{\gamma} f\, dp$$
$$E_x = -\int J_x\, dt$$

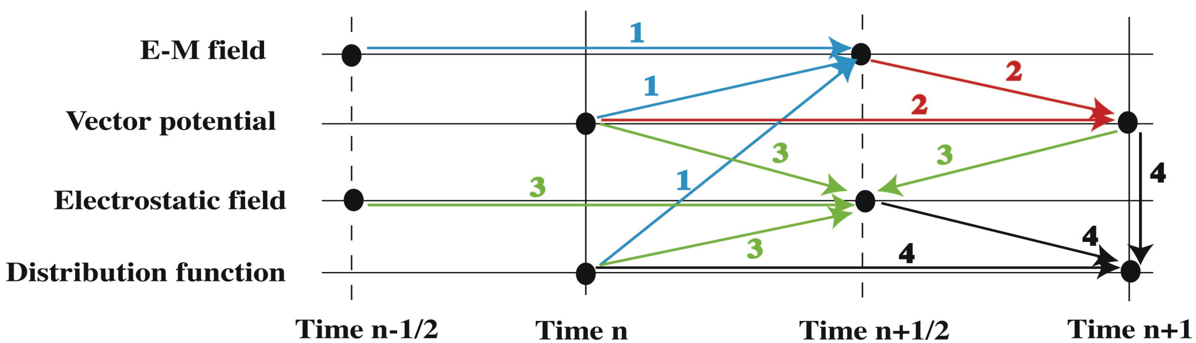
Leapfrog scheme:

$$E_x(x, t_{n+1/2}) = E_x(x, t_{n-1/2}) - \Delta t J_x(x, t_n)$$

Step 4

$$\frac{\partial f}{\partial t} + m\frac{p}{\gamma}\frac{\partial f}{\partial x} - \left(E_x + \frac{m}{2\gamma}\frac{\partial a_\perp^2}{\partial x}\right)\frac{\partial f}{\partial p} = 0$$

2-D interpolation using splines



The Vlasov Equation is Solved Using 2-D Interpolation with a Tensor Product of Splines

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$$\frac{\partial f_e}{\partial t} + m_e \frac{p_{xe}}{\gamma_e}\frac{\partial f_e}{\partial x} - \left(E_x - \frac{m_e}{2\gamma_e}\frac{\partial a_\perp^2}{\partial x} \right)\frac{\partial f}{\partial p_{xe}} = 0$$

The characteristics are solutions of the equations:

$$\frac{dx}{dt} = m\frac{p_{xe}}{m_e} \equiv V_{xe}(x, p_{xe}) \qquad \frac{dp_{xe}}{dt} = -E_x - \frac{m_e}{2\gamma_e}\frac{\partial a_\perp^2}{\partial x} \equiv V_{pe}(x, p_{xe})$$

Let $x(t_n)$ and $p_{xe}(t_n)$ be the point from whence the characteristic originates at time t_n. Then

$$\Delta_{xe} = \frac{\Delta t}{2} V_{xe}(x_{j_x} - \Delta_{xe}, p_{xe,j_p} - \Delta_{pe})$$

$$\Delta_{pe} = \frac{\Delta t}{2} V_{pe}(x_{j_x} - \Delta_{xe}, p_{xe,j_p} - \Delta_{pe})$$

with $\Delta_{xe} \equiv \dfrac{x_{j_x} - x(t_n)}{2}$ and $\Delta_{pe} \equiv \dfrac{p_{ej_p} - p_e(t_n)}{2}$

These are two implicit equations for Δ_{xe} and Δ_{pe}. They are solved iteratively. All phase-space quantities are interpolated using a tensor product of splines.

Finally, the distribution function is shifted along those characteristics.

The Ponderomotive Force (PF) Driven Vlasov-Poisson System of Equations

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Vlasov

$$\frac{\partial f_e^{1D}}{\partial \bar{t}} + \bar{\mathrm{v}} \frac{\partial f_e^{1D}}{\partial \bar{z}} - \left(E - \frac{\partial \psi_{PF}}{\partial \bar{z}} \right) \frac{\partial f_e^{1D}}{\partial \bar{\mathrm{v}}} = 0$$

$$\bar{t} = \omega_{pe} t;\ \bar{z} = z/\lambda_{De};\ \bar{\mathrm{v}} = \mathrm{v}/\mathrm{v}_{th}$$

$$\frac{\partial E}{\partial \bar{z}} = 1 - \int f_e^{1D}\, d\bar{\mathrm{v}}$$

Poisson

$$\int \mathrm{v}^2 f_e^{3D}\, d\mathrm{v}^3 = 3\mathrm{v}_{th}^2$$

$$\bar{\mathrm{v}} = \left(\mathrm{v} - \mathrm{v}_\phi \right) / \mathrm{v}_\phi$$

$$\psi_{PF} = \sum_{\#\,driver\ modes} \psi_{AMP}^{(i)} \cos\left(\bar{k}_i \bar{z} - \bar{\omega}_i \bar{t} \right)$$

$$\psi_{AMP} = \frac{\left(\frac{eE_0}{m\omega_0} \right)\left(\frac{eE_s}{m\omega_s} \right)}{\mathrm{v}_{th}^2}$$

$$\psi_{AMP} = \frac{0.037}{T_{e,keV}} \left(I_{0,10^{14}W/cm^2} \lambda_{0,\mu m}^2 \right) \sqrt{\frac{I_s}{I_0} \left(\frac{\lambda_s}{\lambda_0} \right)}$$

$$\frac{\partial \psi_{PF}}{\partial \bar{z}} = - \sum_{\#\,driver\ modes} \psi_{AMP}^{(i)} \bar{k}_i \sin\left(\bar{k}_i \bar{z} - \bar{\omega}_i \bar{t} \right)$$

What Are KEEN Waves?

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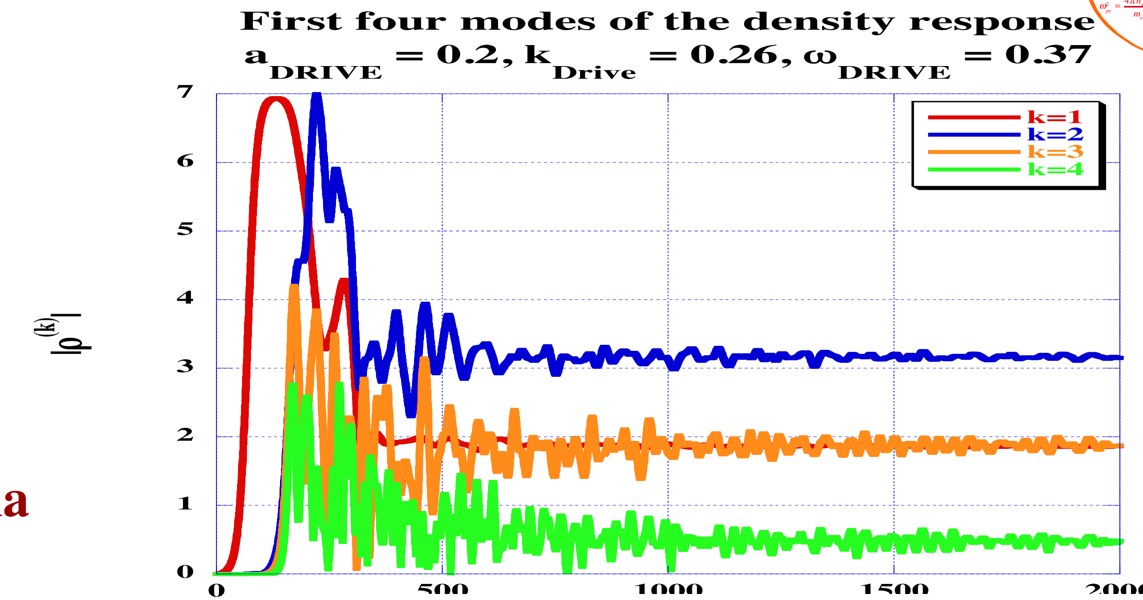
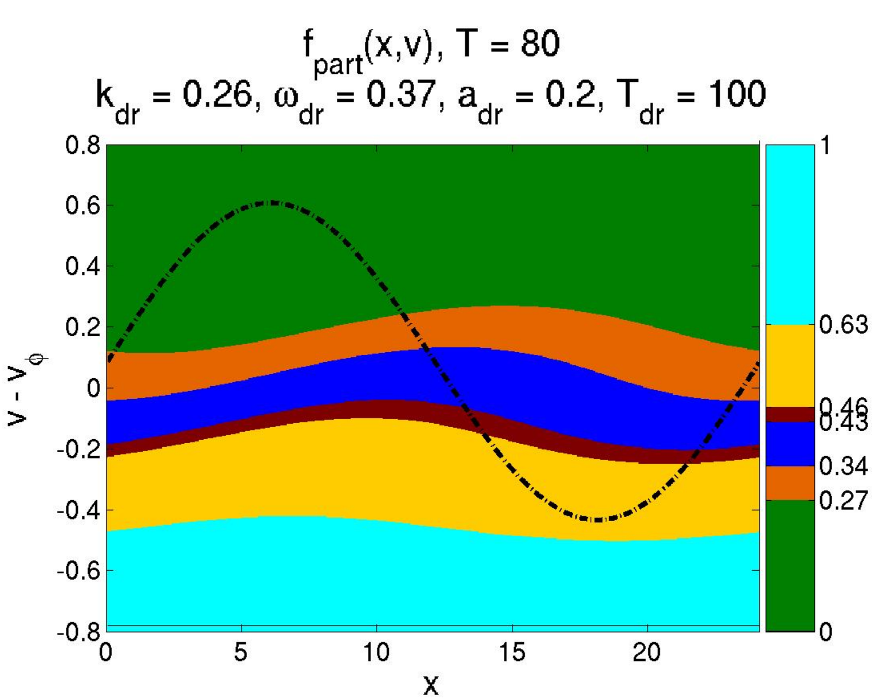
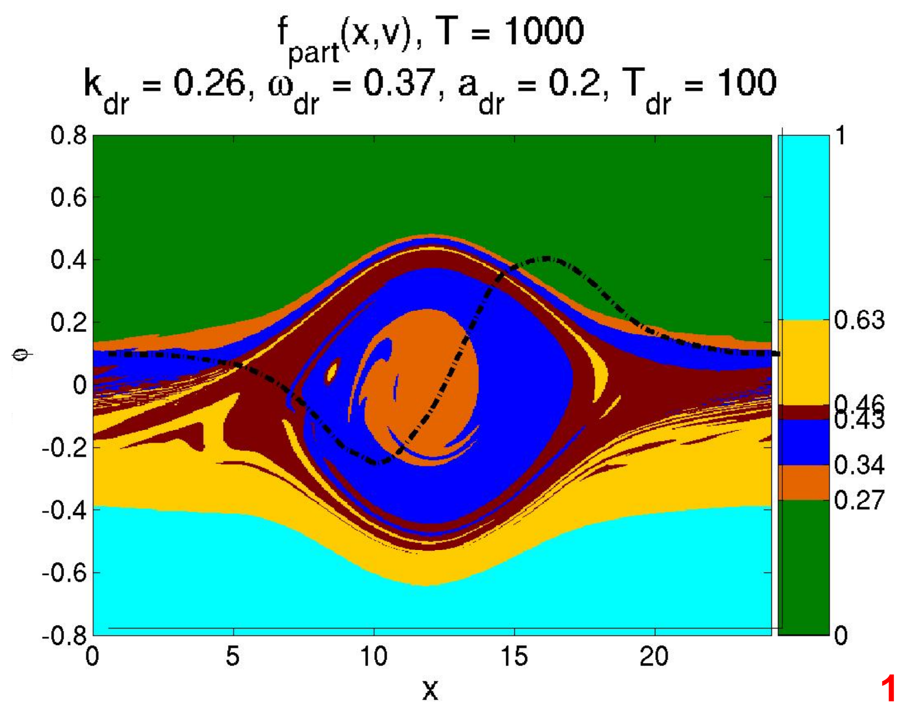
Nonlinear
Kinetic
Self-organized
Non-stationary
Coherent States
of a Vlasov Plasma







At a Higher Drive Frequency, More Intricate Entanglements in Phase Space Arise

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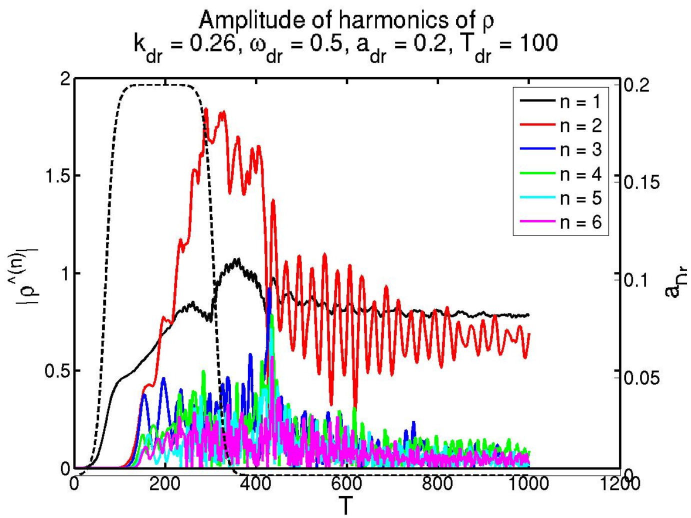
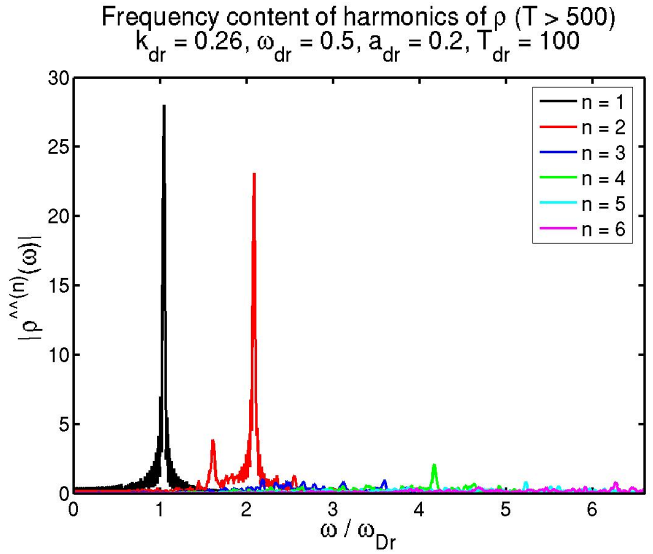
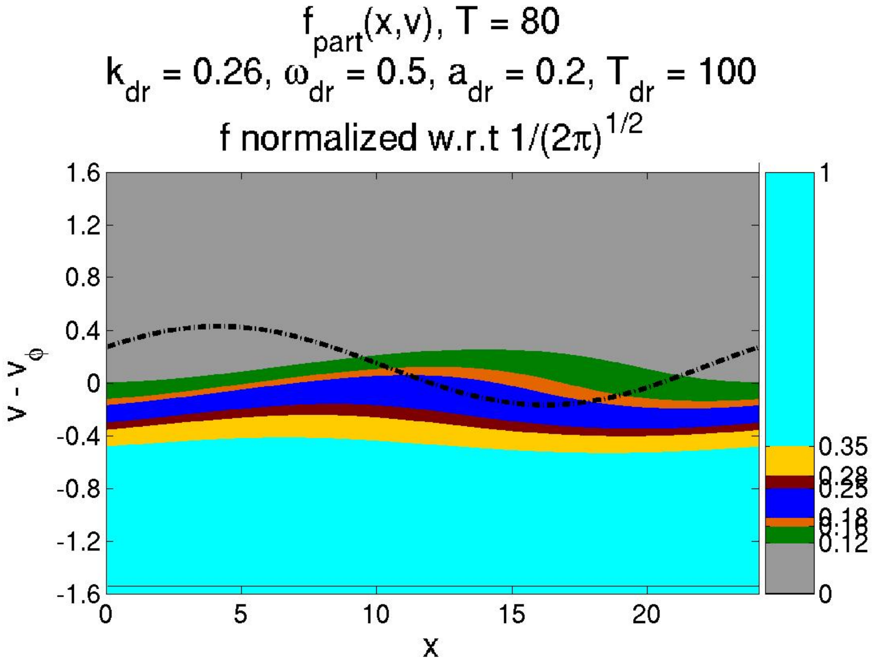
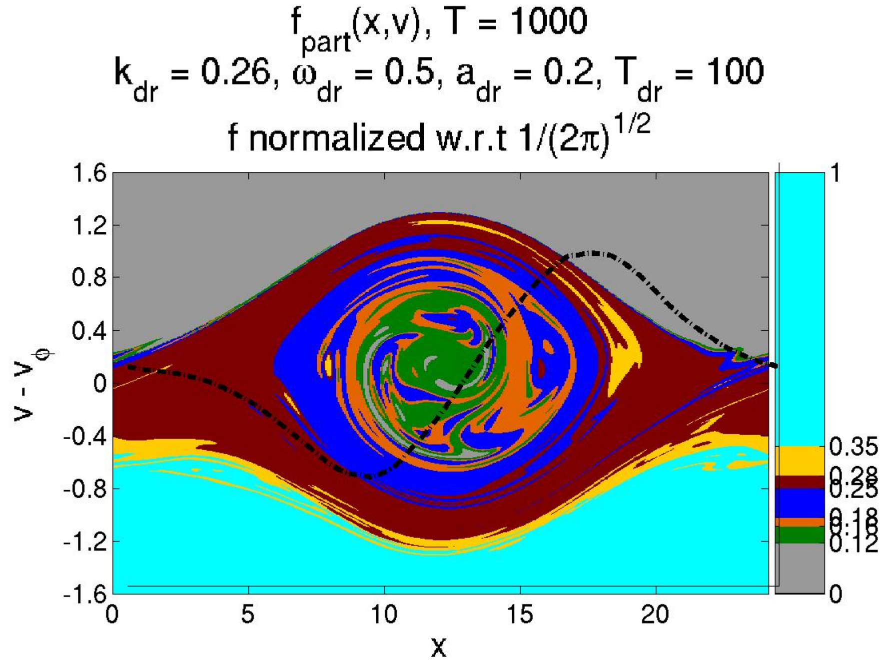
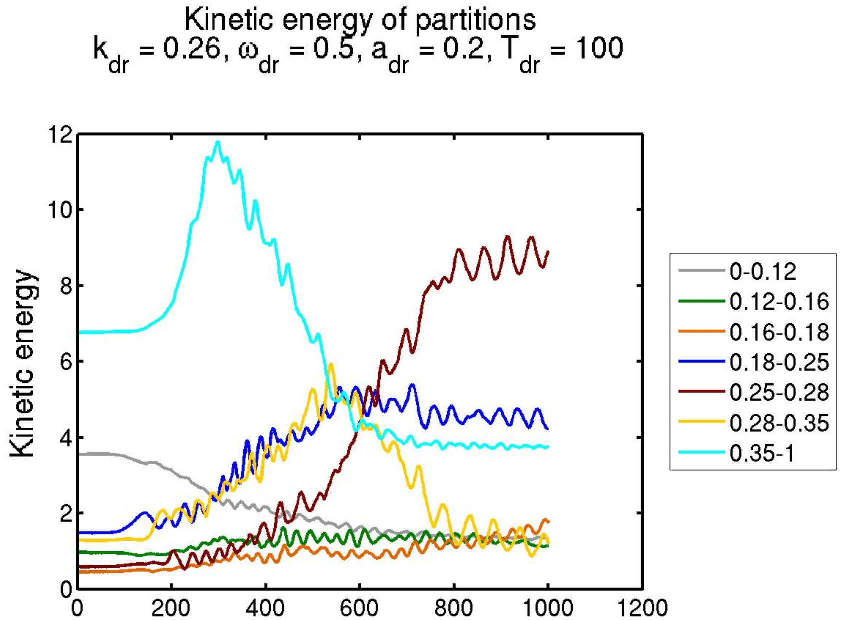


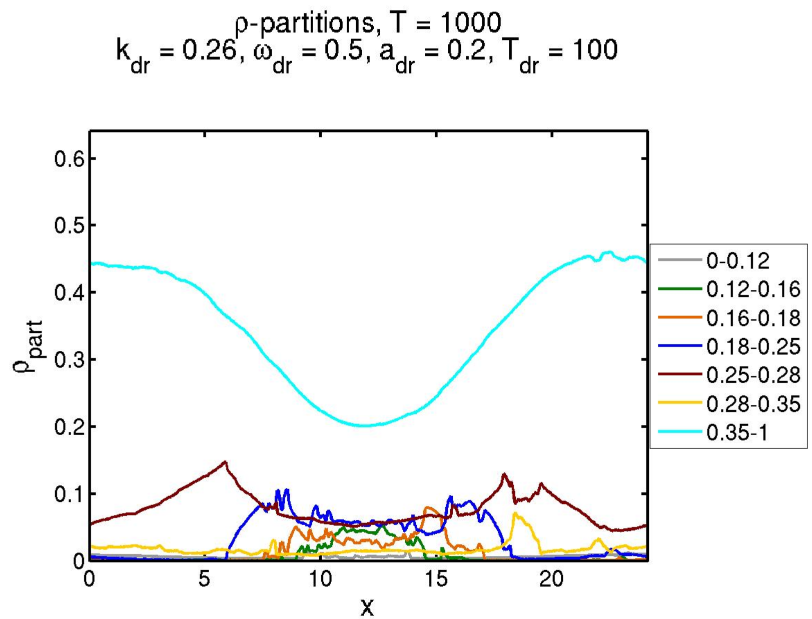


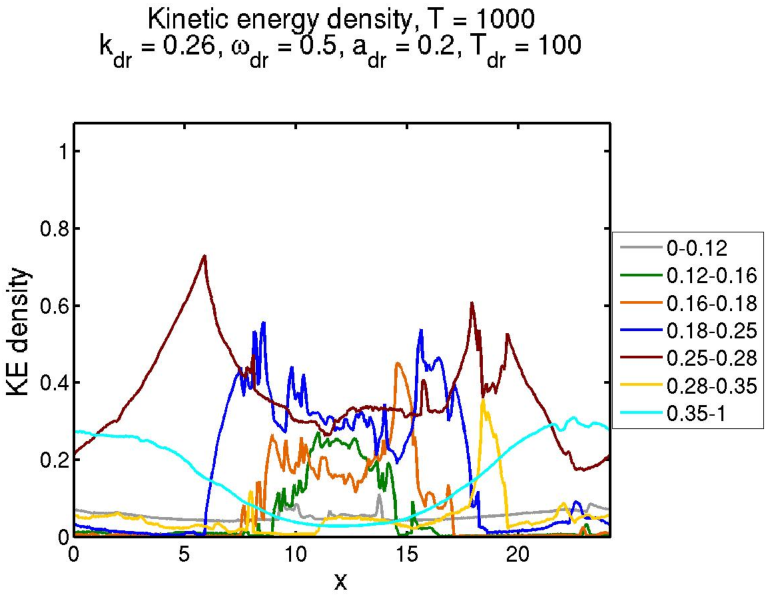


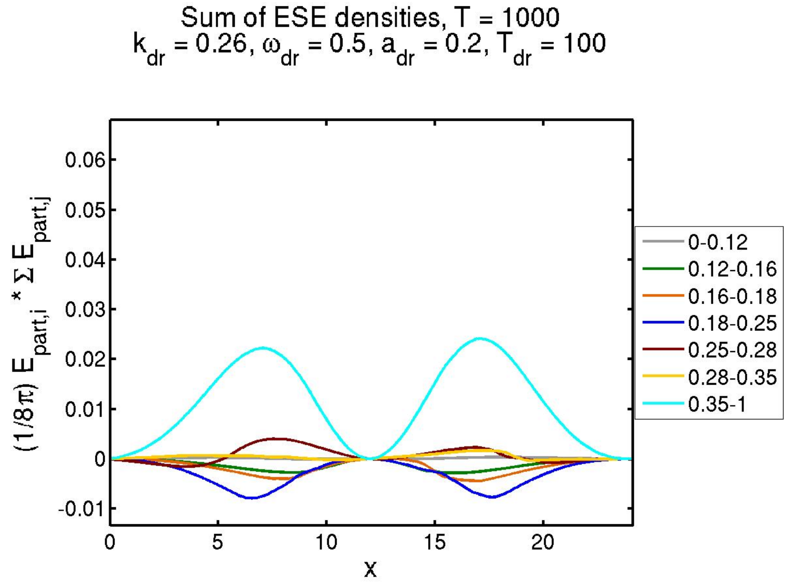


Detailed Diagnostics Reveal Classic Features of KEEN Waves at this $k_{Dr} = 0.26$. $\omega_{Dr}=0.5$

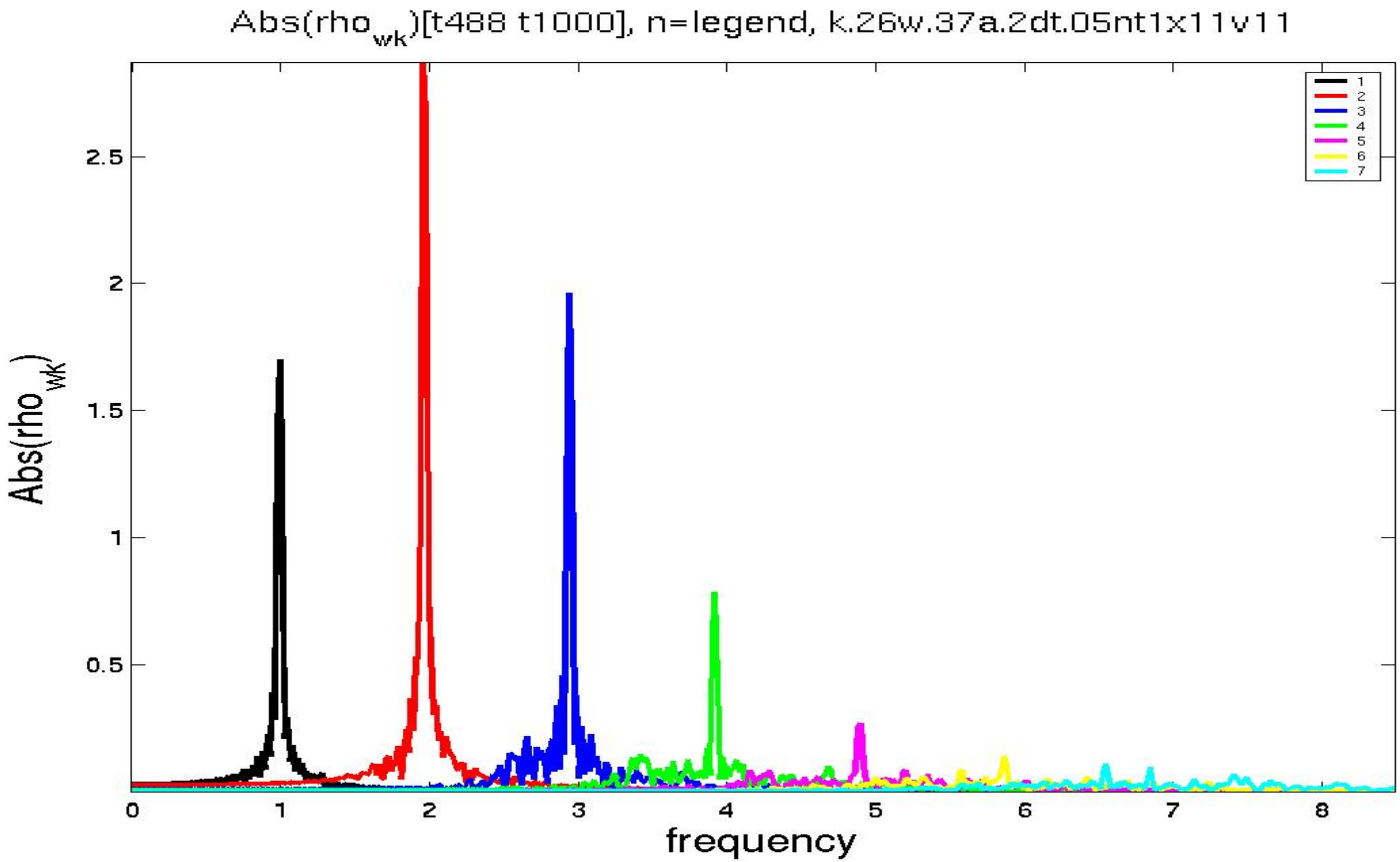




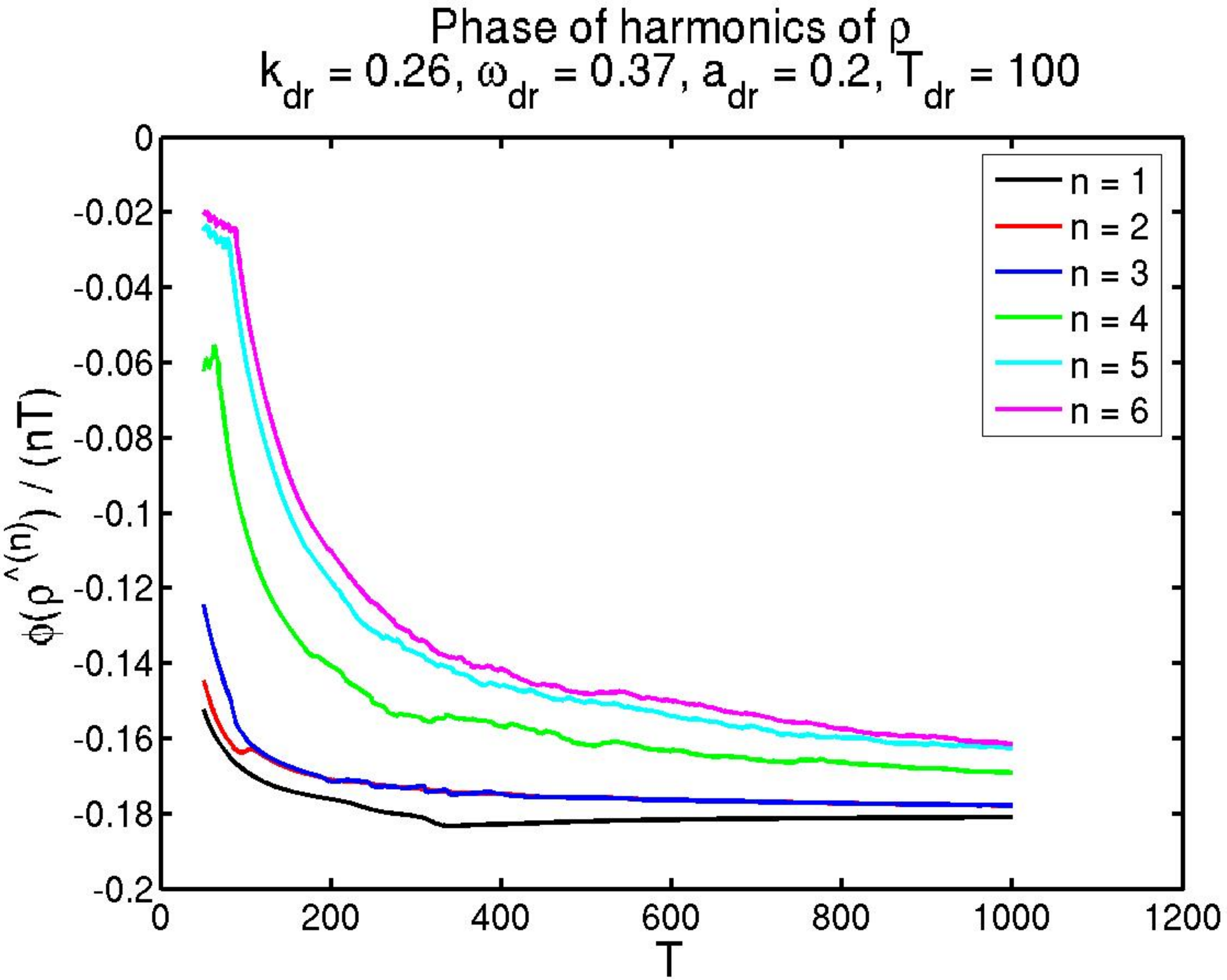




The Various Harmonic Modes of the Density Response of KEEN Waves: Higher Harmonics Have Wider Frequency Content as they are Chaotically Evolving

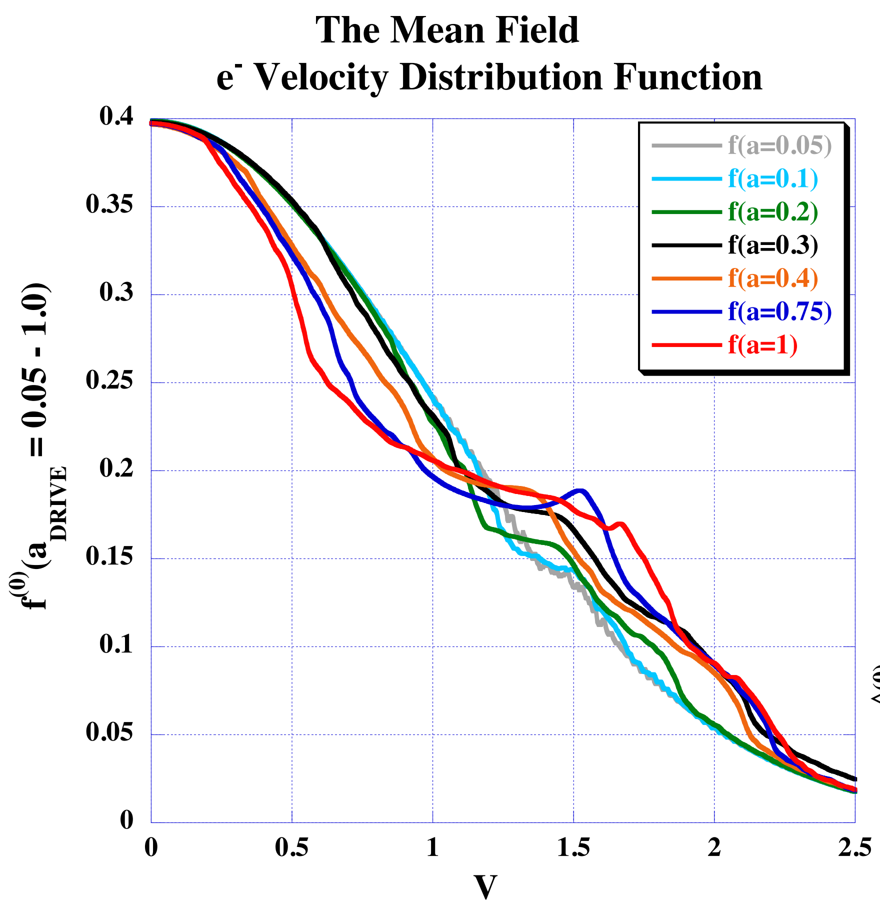


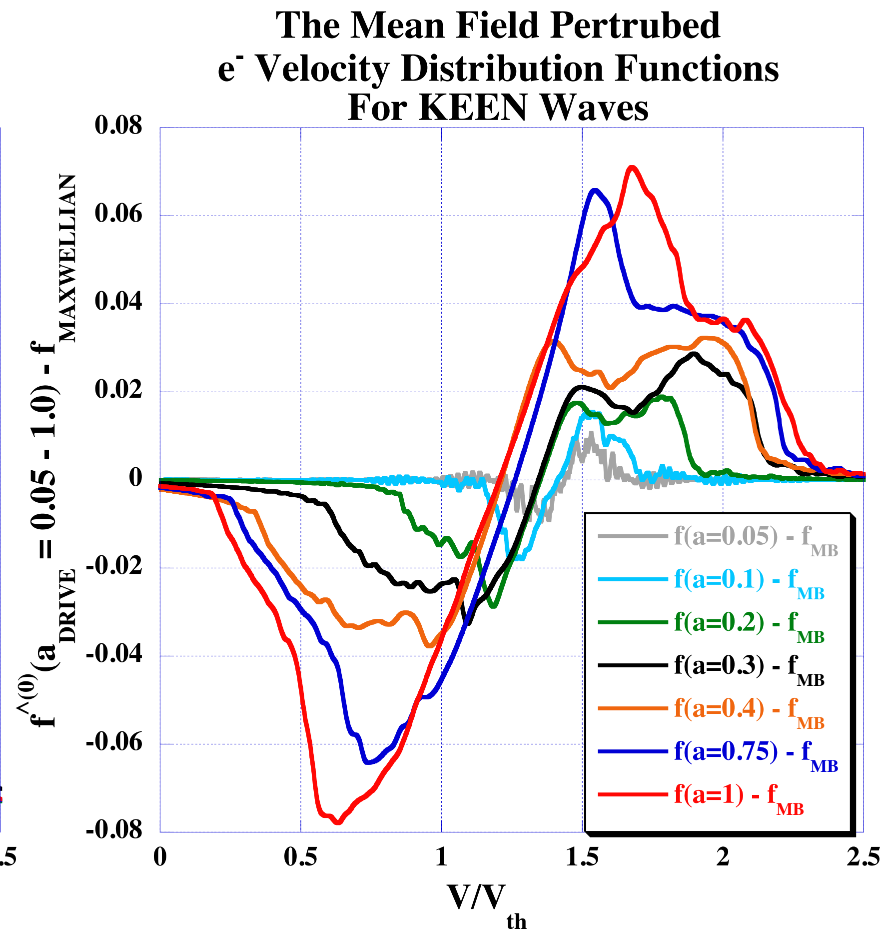
The First Few Harmonics Are Phase Locked and Evolve in Step



The e⁻ VDF in its Non-Oscillatory Component when a KEEN Wave Is Formed. As Expected a Wider and *Flatter* Region around $v_\phi = 1.423$ Is formed with Increasing a_{DRIVE}

$k_{DR} = 0.26$, $\omega_{DR} = 0.37$





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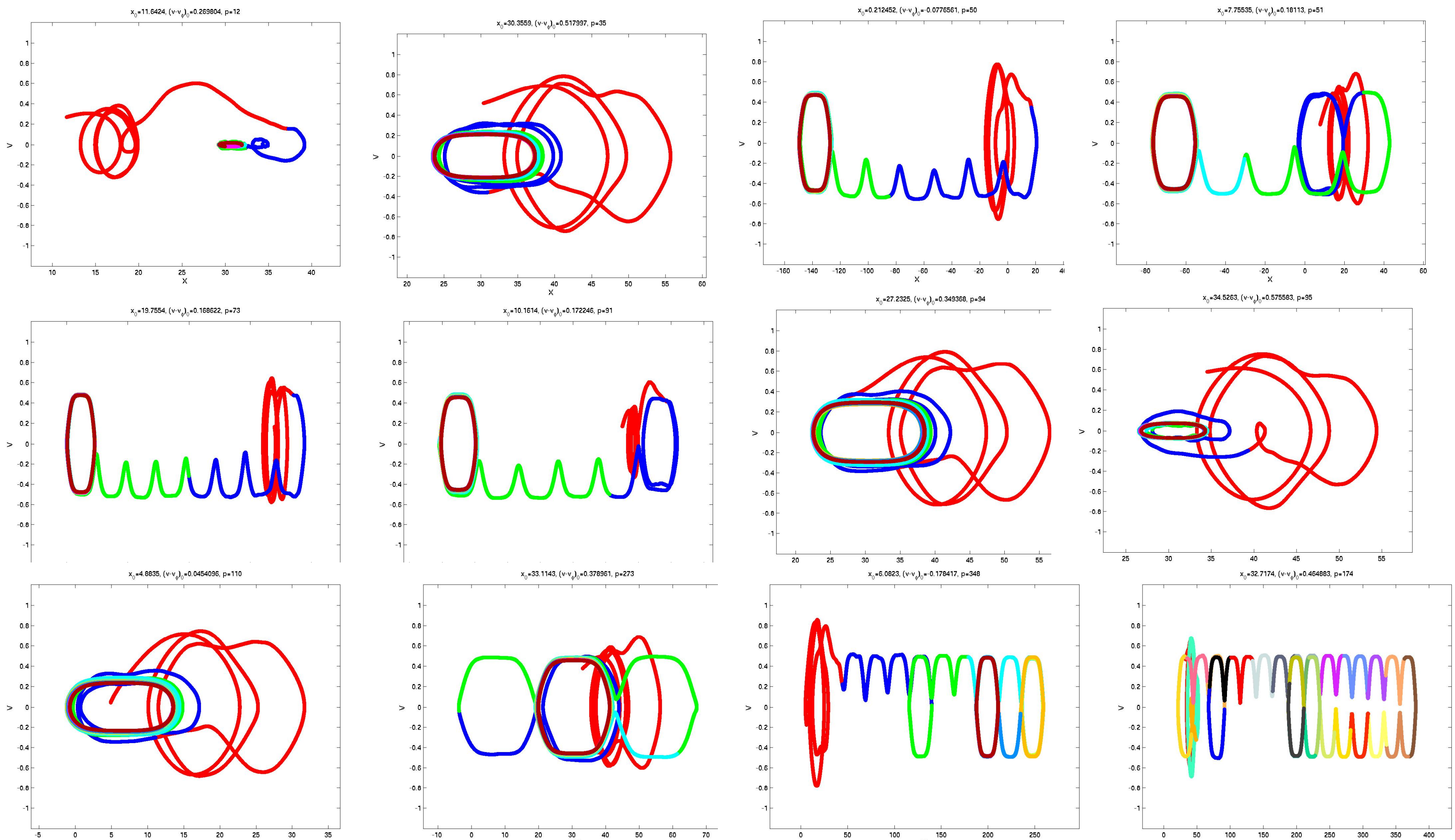
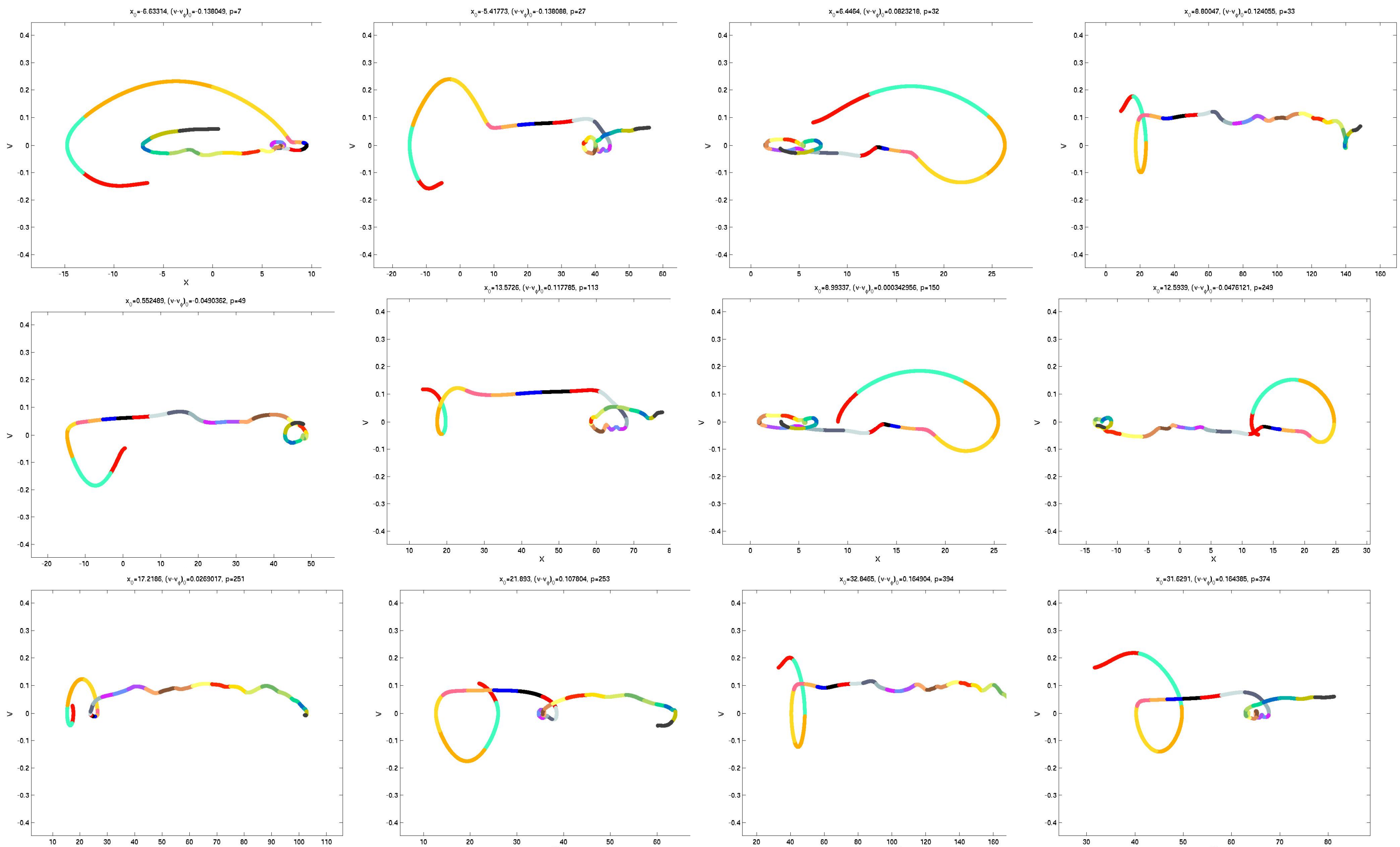
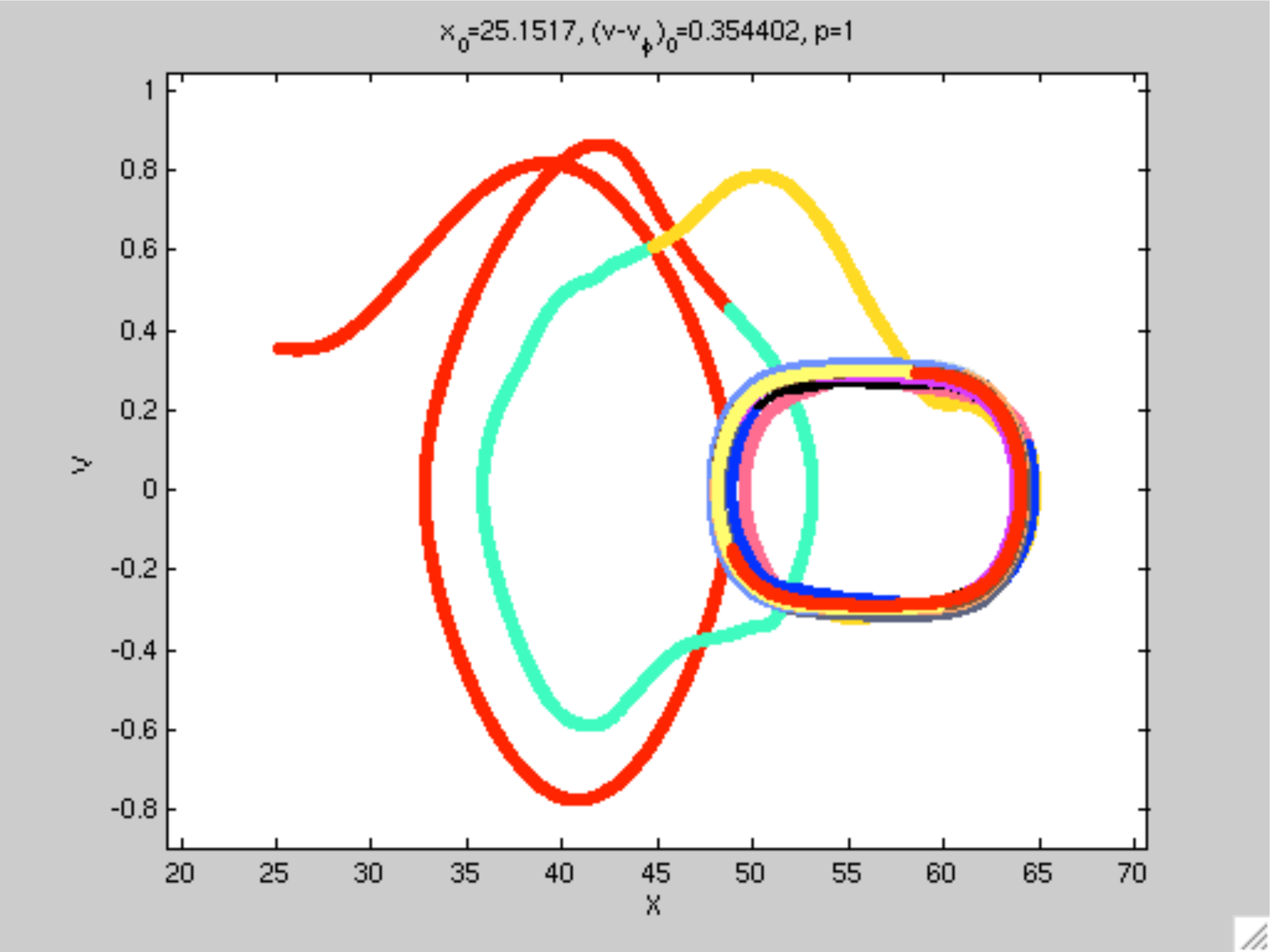
Unusual Trapped Particle Orbits Start Demystifying KEEN Wave Dynamics & Pointing Out Essential Differences with BGK Modes



Unusual Trapped Particle Orbits at Lower Amplitude Drive $a_{drive} = 0.0125$ and $t_{drive} = 100$: Left with Randomly Distributed "Action Loops"



Imagine Some Heavy Metal Music Accompanying this Movie of Particle Orbits Making Up the KEEN Wave



- Each color represents a 100 ω_p^{-1} units.
- 400 particle orbits with initial conditions in the v range

(- 0.896 to 1.046.)

Lagrangian Particle Statistics Gathered By Running them Backwards in the Self-Consistent Electric Field of a KEEN Wave Shows Differences btw Partitions

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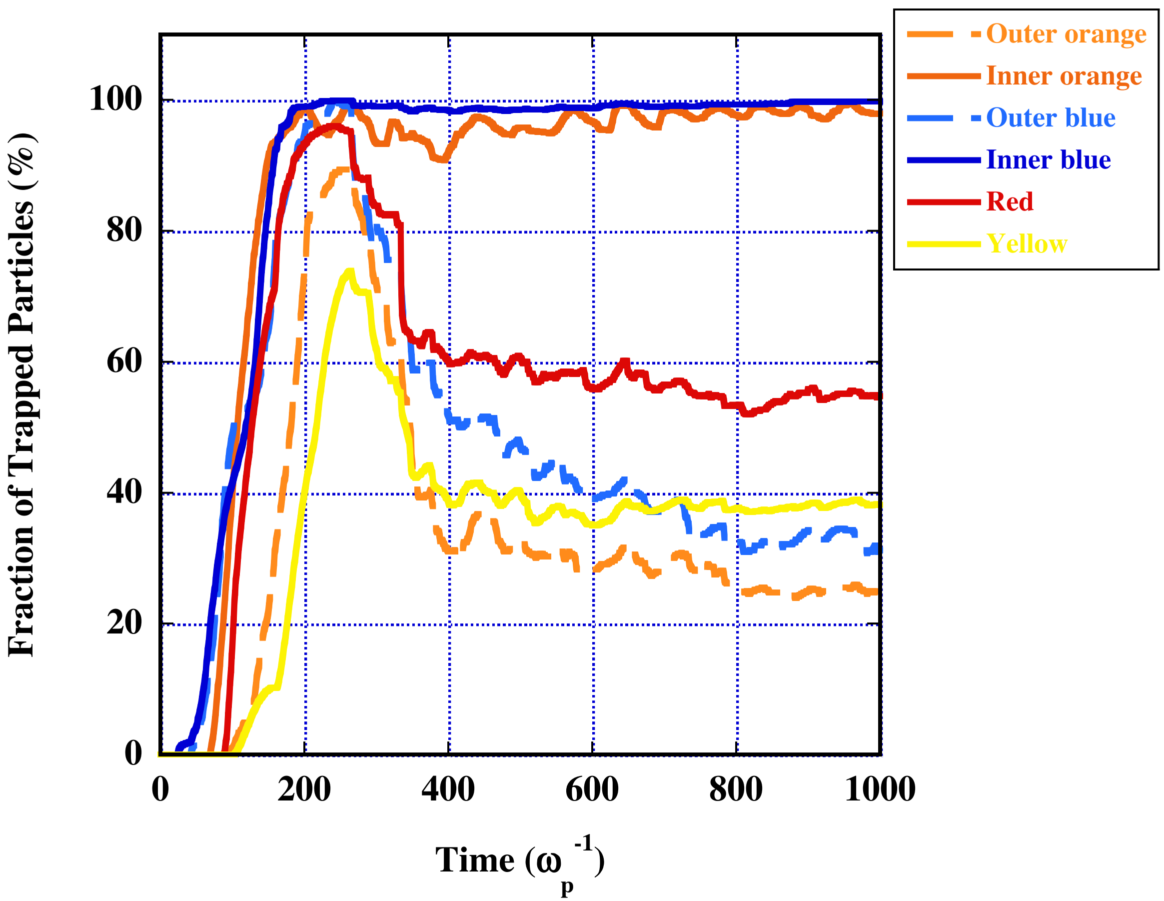
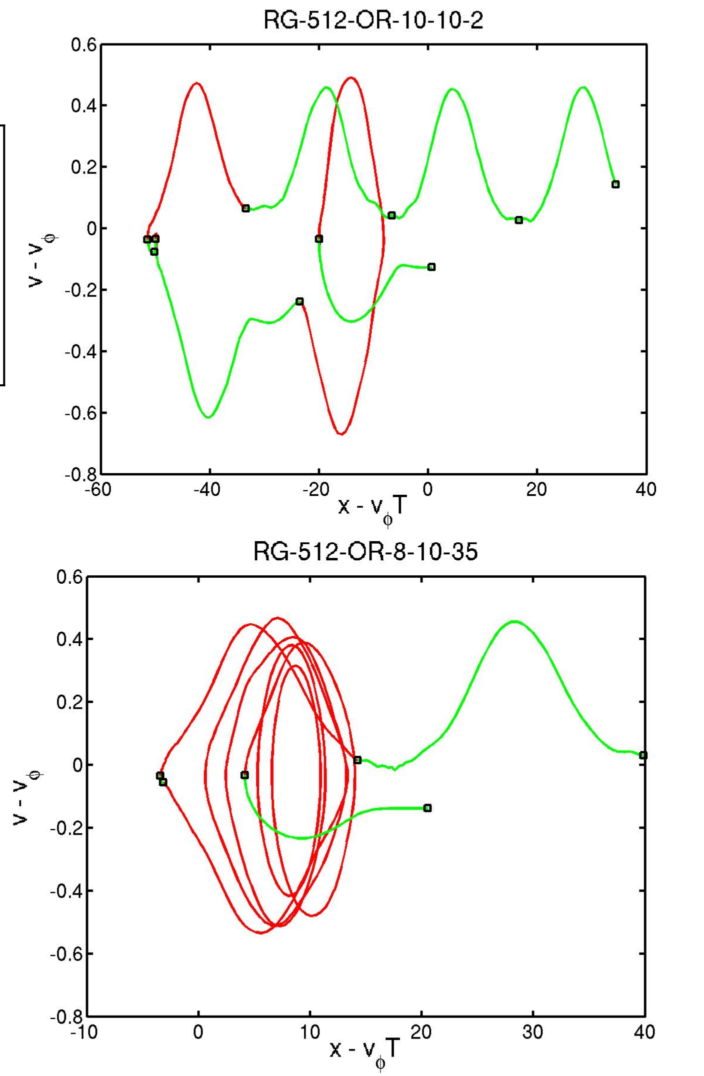
Fraction of Trapped Particles in the 6-Partition



Orange



A Useful Representation of the Time-Frequency Evolution of a Field Is Via its Wigner Transform

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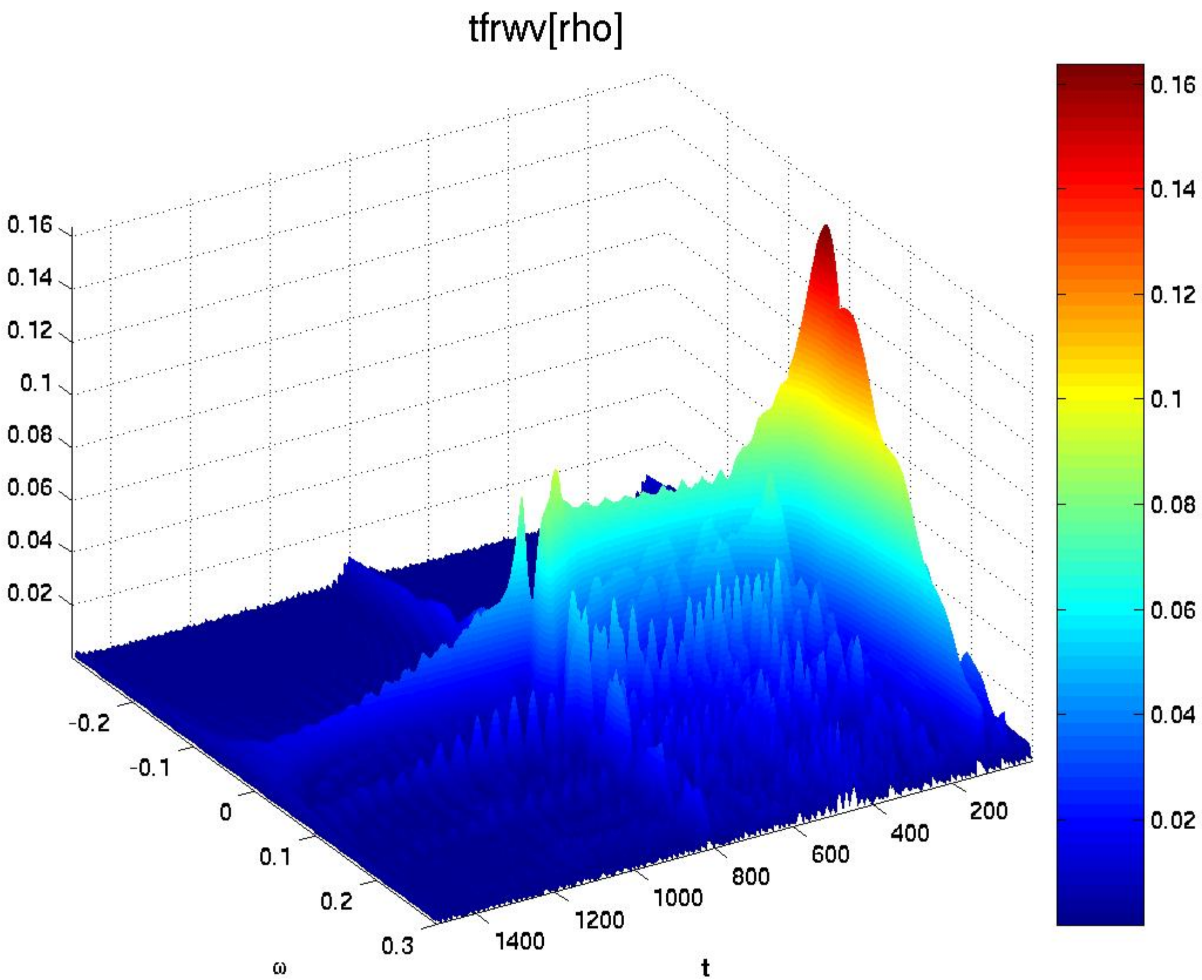
The Wigner transform $W_{\rho part}(t,\omega)$ is a bilinear functional of the scalar $\rho_{part}(t)$, (density field in one phase space partition), which represents the signal in (t, ω) ***phase space*** -- which is to say-- in time and frequency space simultaneously.

$$W_{\rho_k}(t,\omega) = \int_{-\infty}^{\infty} e^{-i\omega t'} \rho_k(t + t'/2)\, \rho_k^*(t - t'/2)$$

$$W_{\rho_k}(t,\omega) = FFT\{\, \rho_k(t + t'/2)\, \rho_k^*(t - t'/2)\}$$

We will track the evolution of the frequency of $\rho_{part}(t)$ as a function of time by studying its Wigner transform and showing how the various partitions have their own distinct temporal signatures.

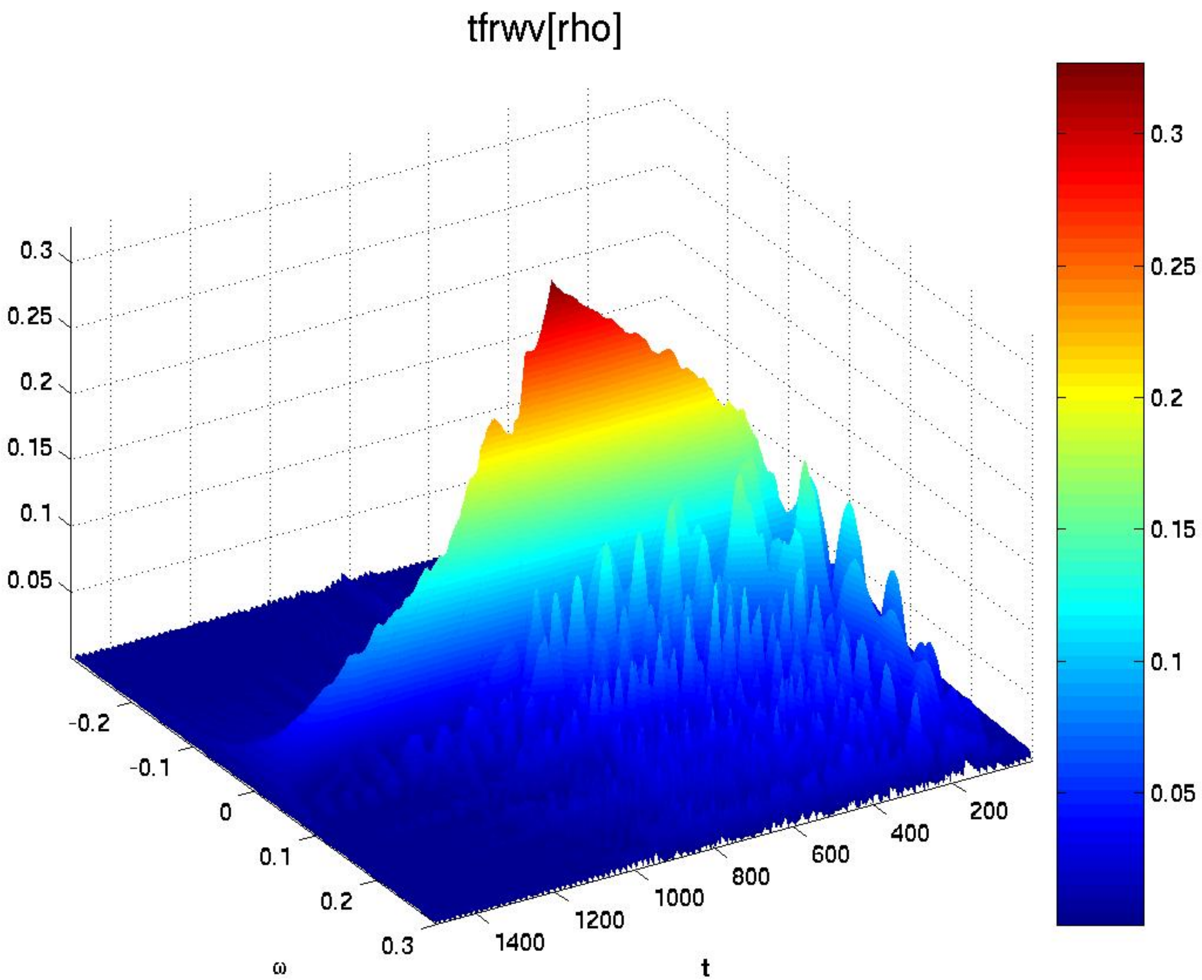
The 4 f-Partitions Engaged in Successively Trapping and Retarding Wayward Particles Have Their Own (t-ω) Signatures: Wigner Distribution Reveals Them



Orange ρ_{part}

f range **0.27-0.34**

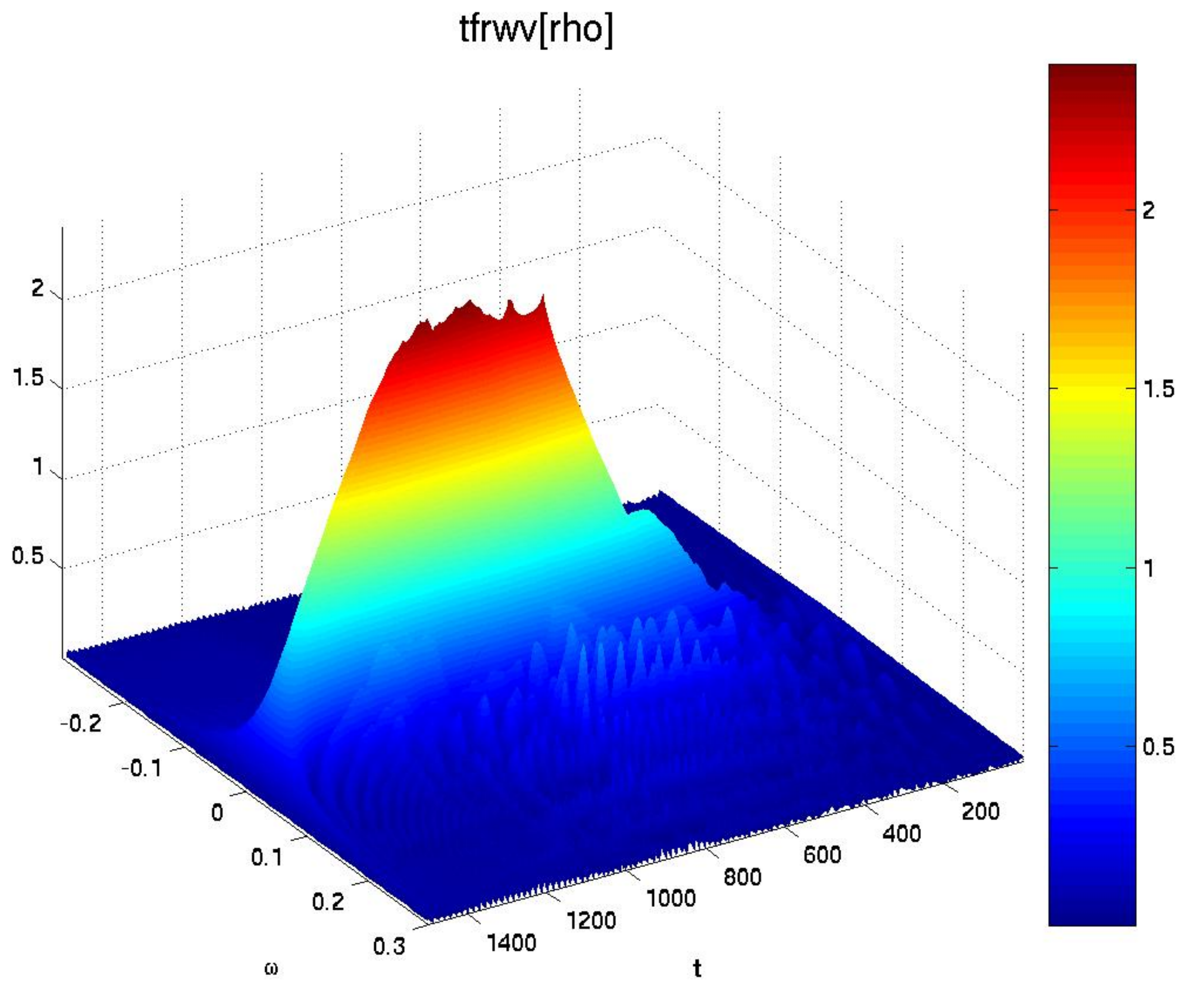
The 4 f Partitions Engaged in Successively Trapping and Retarding Wayward Particles Have Their Own (t-ω) Signatures: Wigner Distribution Reveals Them



Blue ρ_{part}

f range **0.34-0.43**

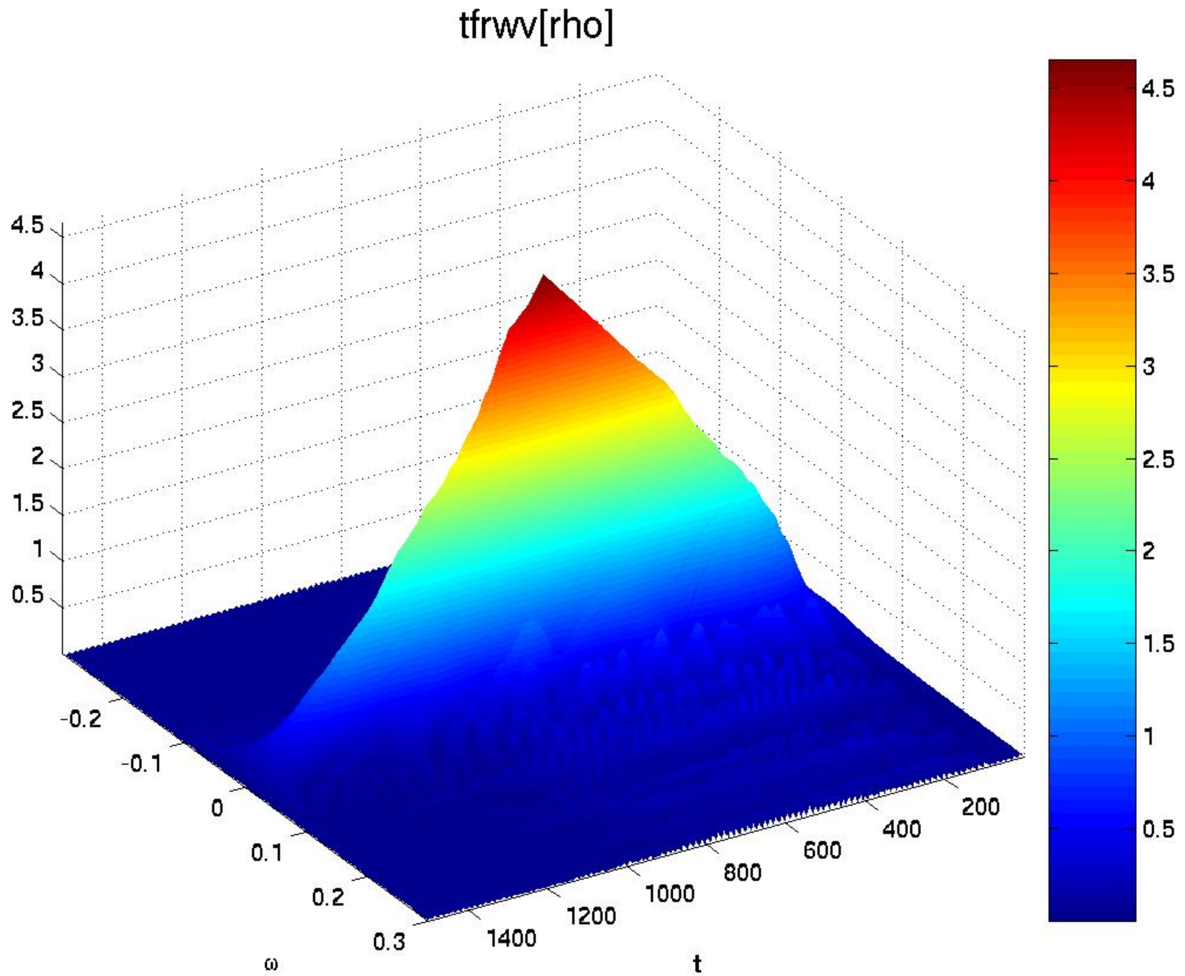
The 4 f Partitions Engaged in Successively Trapping and Retarding Wayward Particles Have Their Own (t-ω) Signatures: Wigner Distribution Reveals Them



Red ρ_{part}

f range **0.43-0.46**

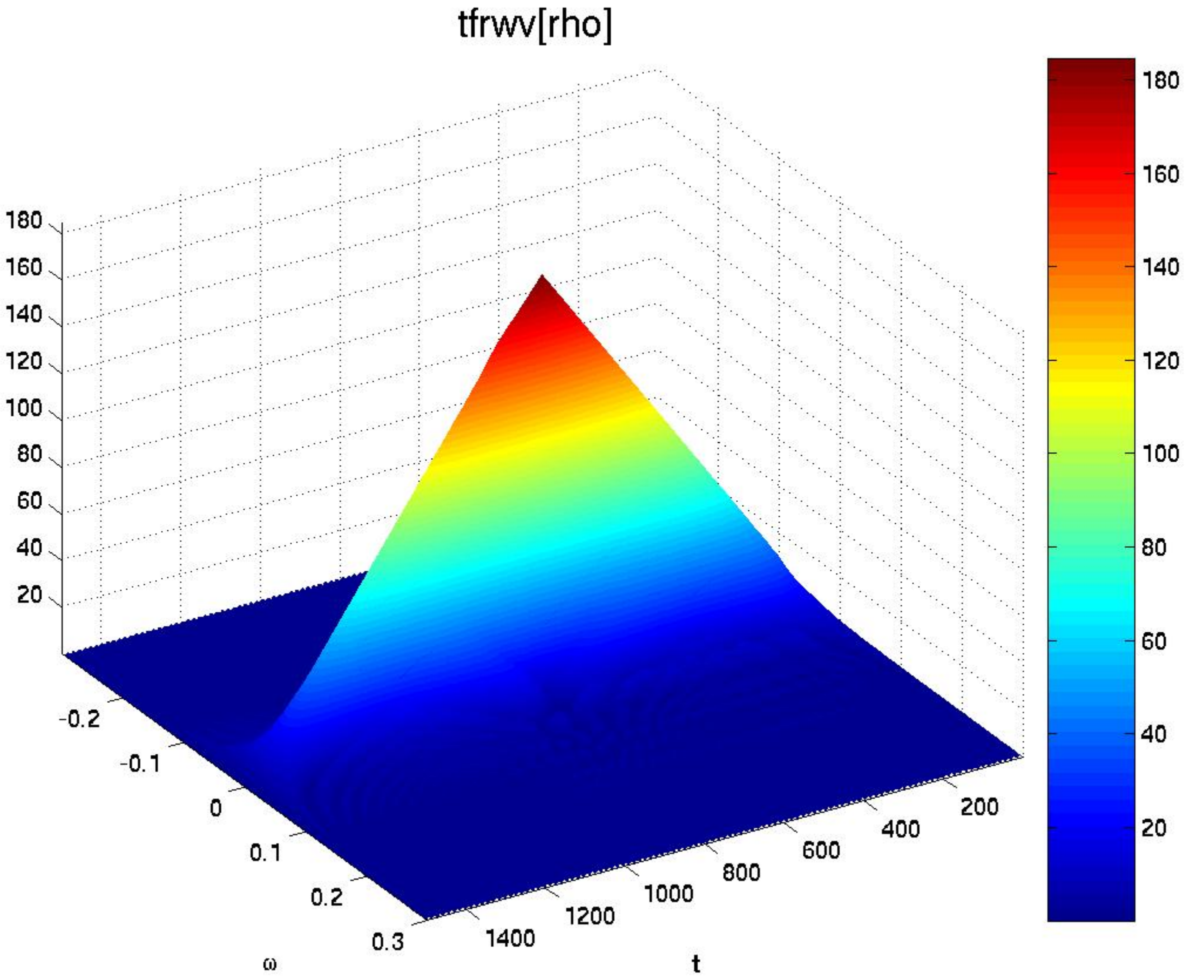
The 4 f Partitions Engaged in Successively Trapping and Retarding Wayward Particles Have Their Own (t-ω) Signatures: Wigner Distribution Reveals Them



Yellow ρ_{part}

f range **0.46-0.63**

The 4 f Partitions Engaged in Successively Trapping and Retarding Wayward Particles Have Their Own (t-ω) Signatures: Wigner Distribution Reveals Them



Turquoise ρ_{part}

f range **0.63-1.0**

Concrete Plan of Action for VP and VM Code Comparisons

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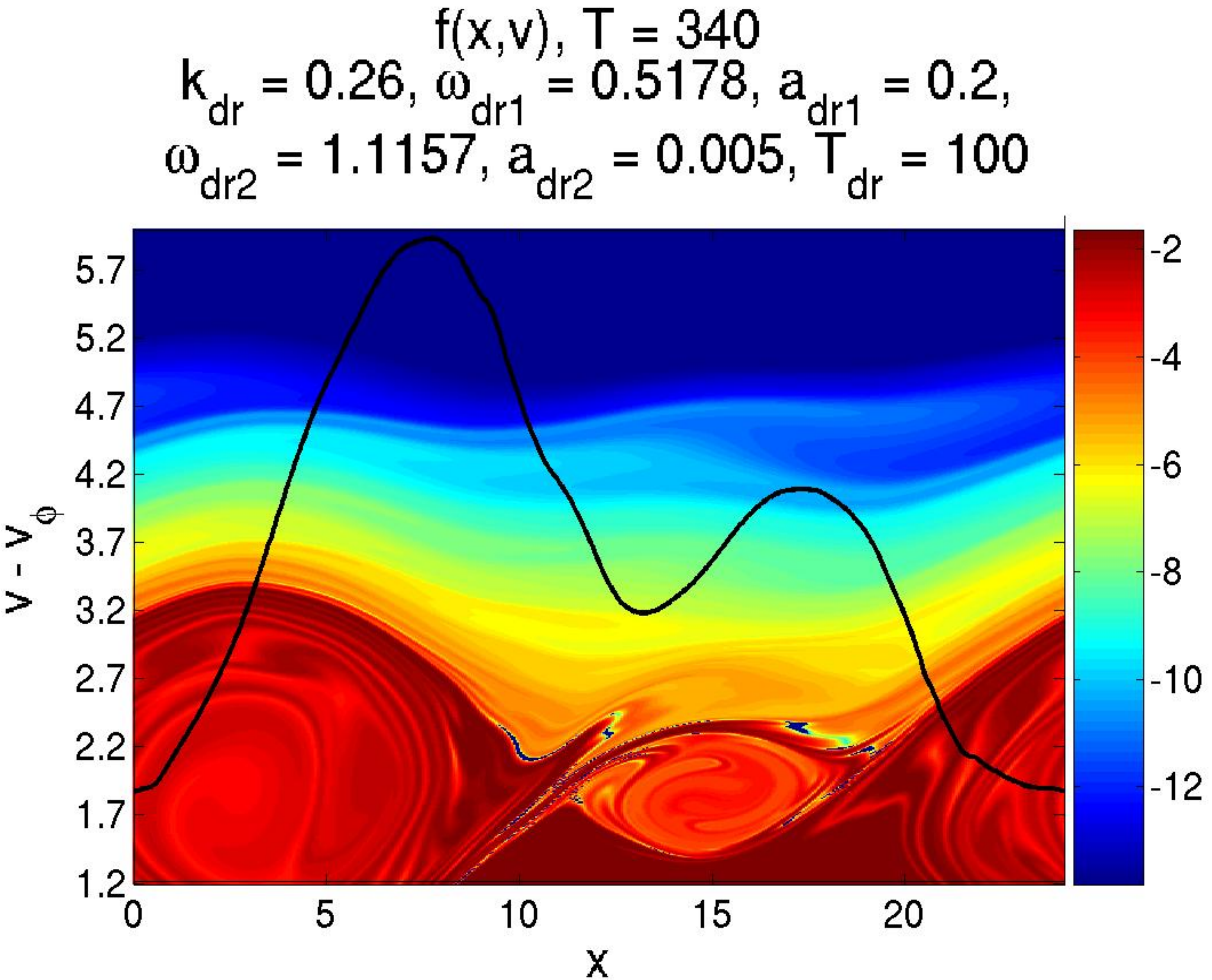
- Simulate 30 -100 vortex long trains in phase space driven by a prescribed ponderomotive force or by the crossing of counter-propagating laser beams.
- Vary the amplitude of the drive, $\mathbf{a_{Dr}}$, as well as the drive duration, $\mathbf{T_{Dr}}$, and drive location in $(\boldsymbol{\omega}_{\mathbf{Dr}}, \mathbf{k_{Dr}})$ space.
- Show long time states being created (KEEN waves, EPWs) after all drives are turned off.
- Run full suite of diagnostics up to partition of phase space and particle orbit statisticsgathering in those partitions.
- Ccompute the Wigner transform (t, ω) of the evolution of partitions of $\varrho_{part}{}^{\wedge(k)}(t)$ and $E_{part}{}^{\wedge(k)}(t)$ and $\langle f_{part}{}^{\wedge(k)}(t)\rangle_{rms,\, v}$. This is the l_2 norm in velocity of the spatial Fourier modes of $f_{part}(x, v, t)$.
- Establish compressibility of KEEN wave physics into low mode Fourier truncation and phase space partition condensation.

How Can We Use KEEN Waves?

Demonstration of the suppression of a PF driven EPW in the presence of a PF driven KEEN wave



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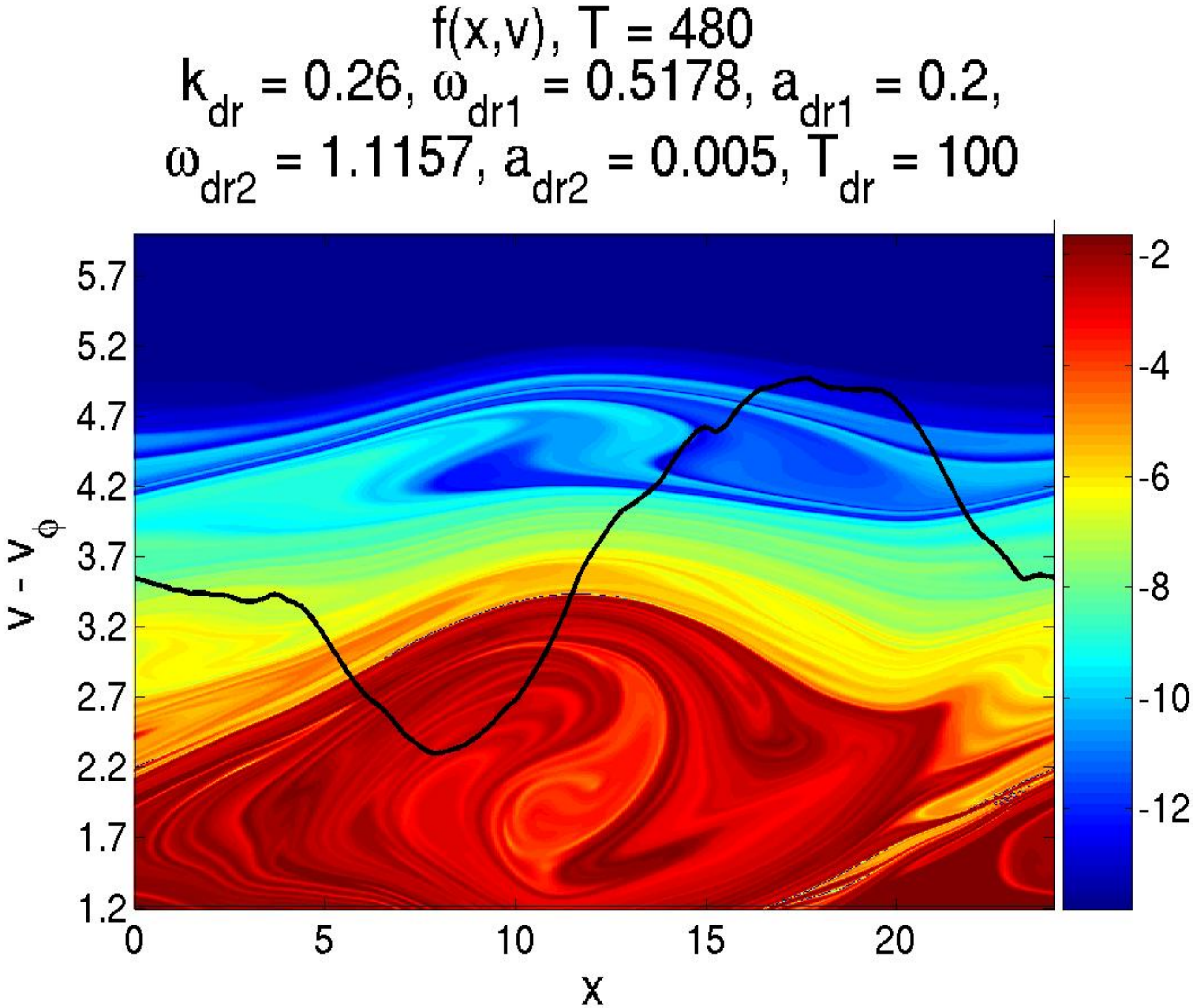

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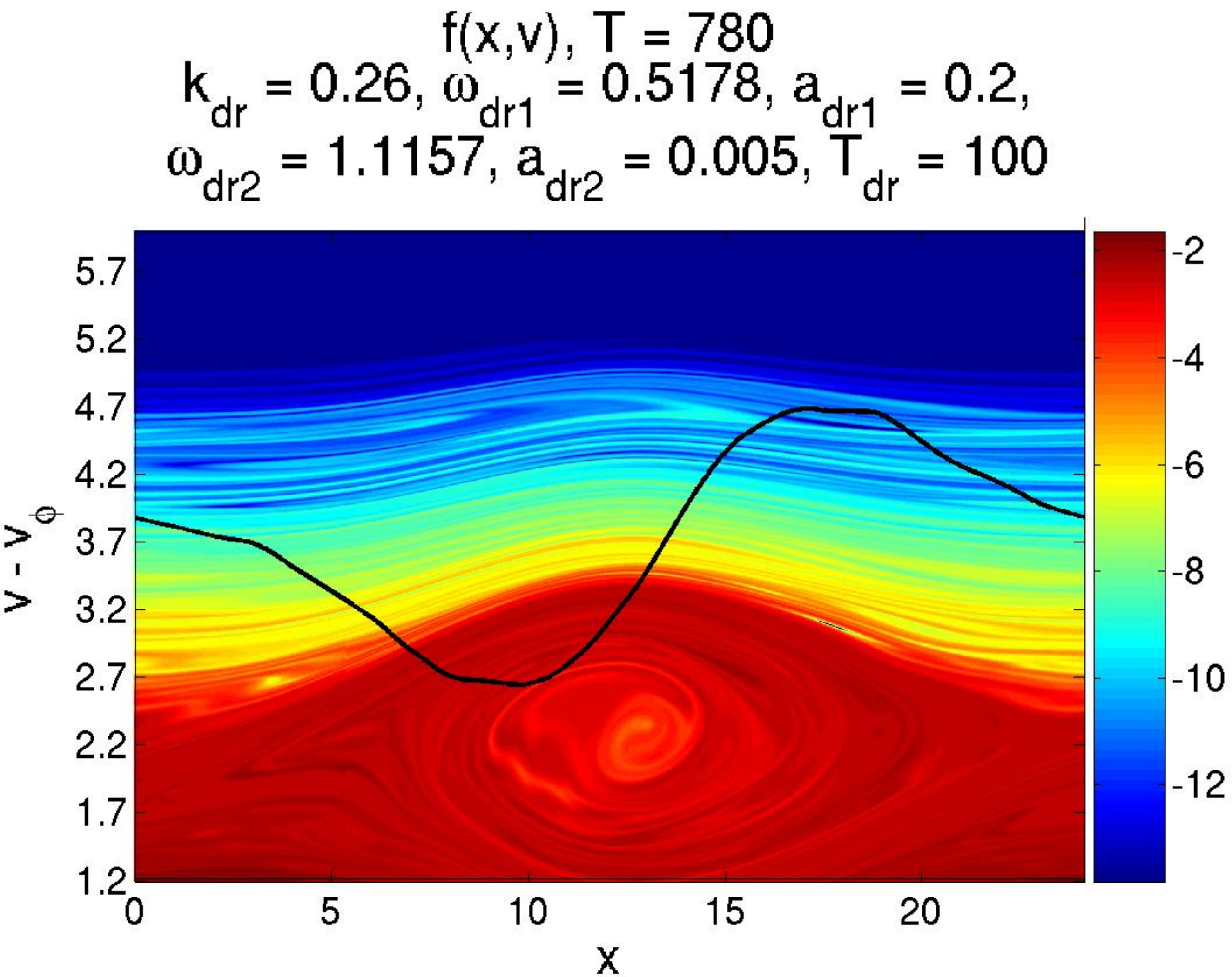

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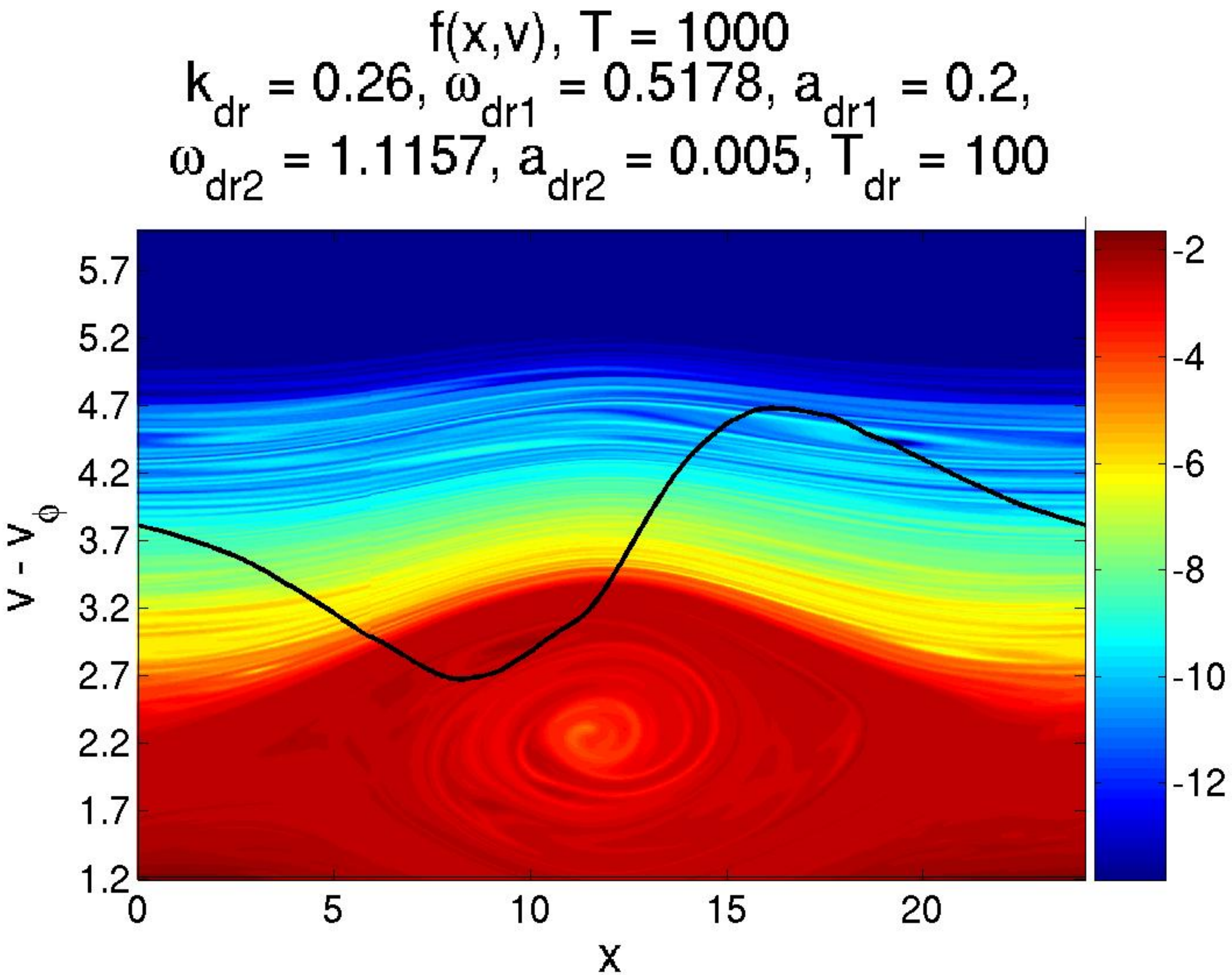

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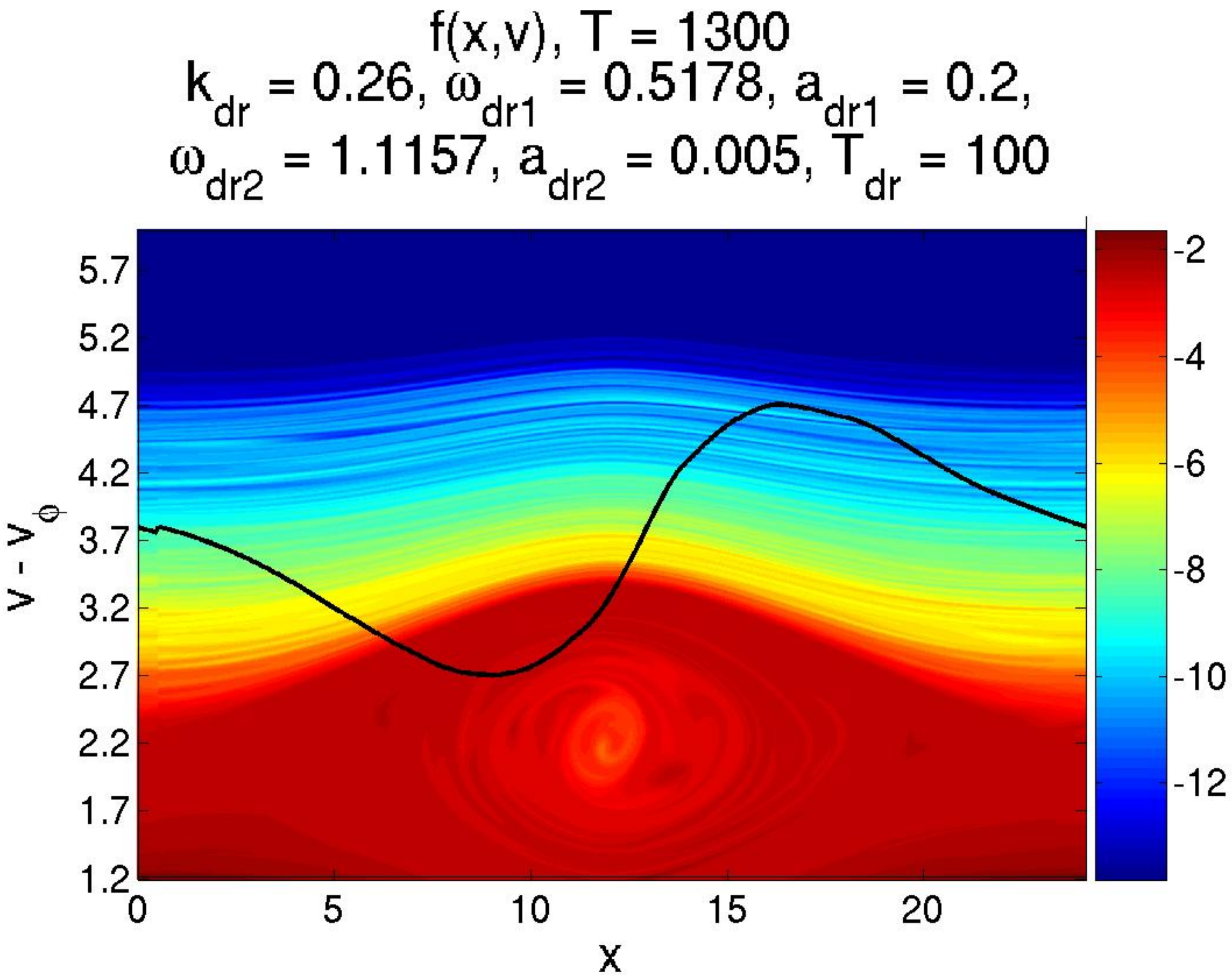

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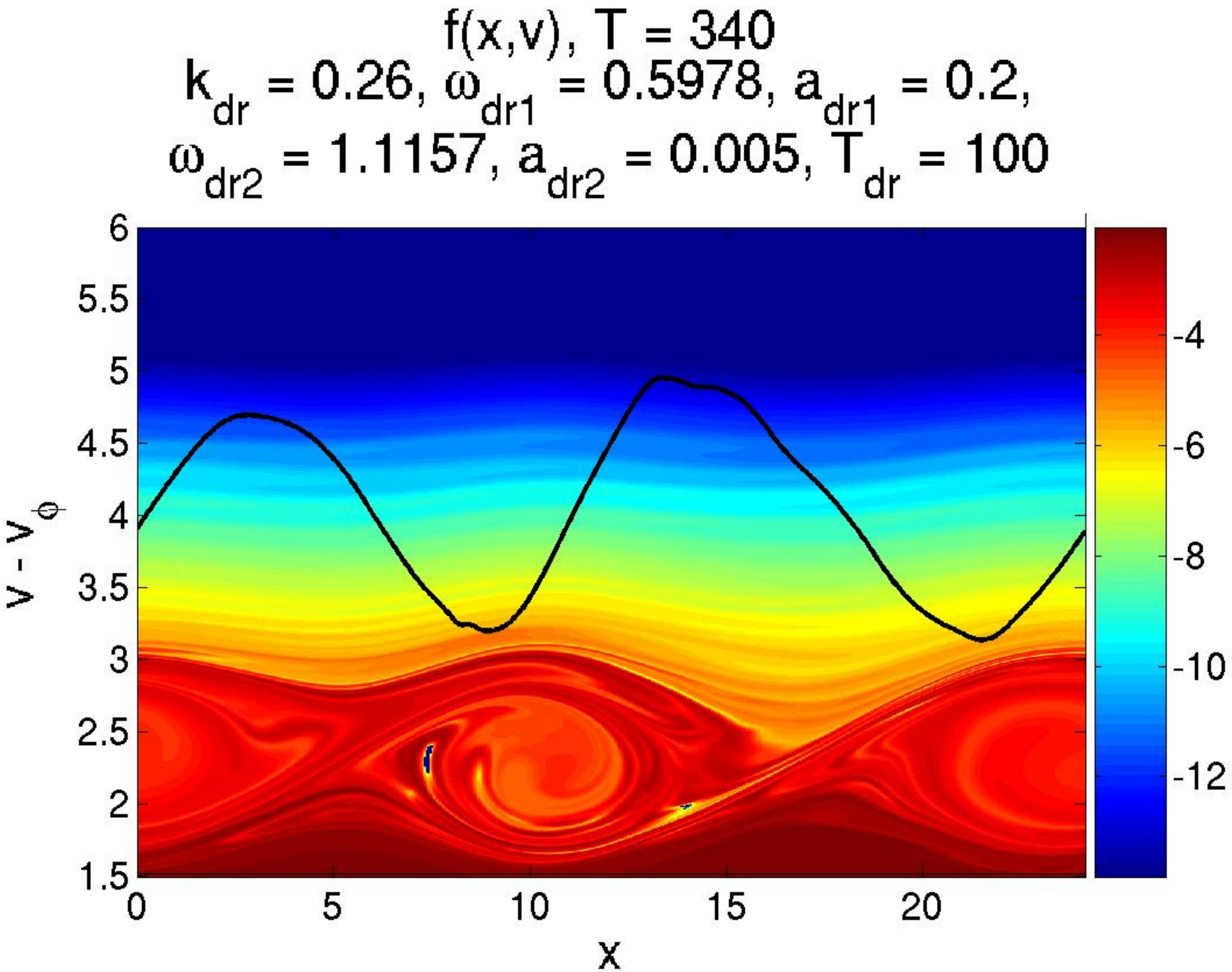

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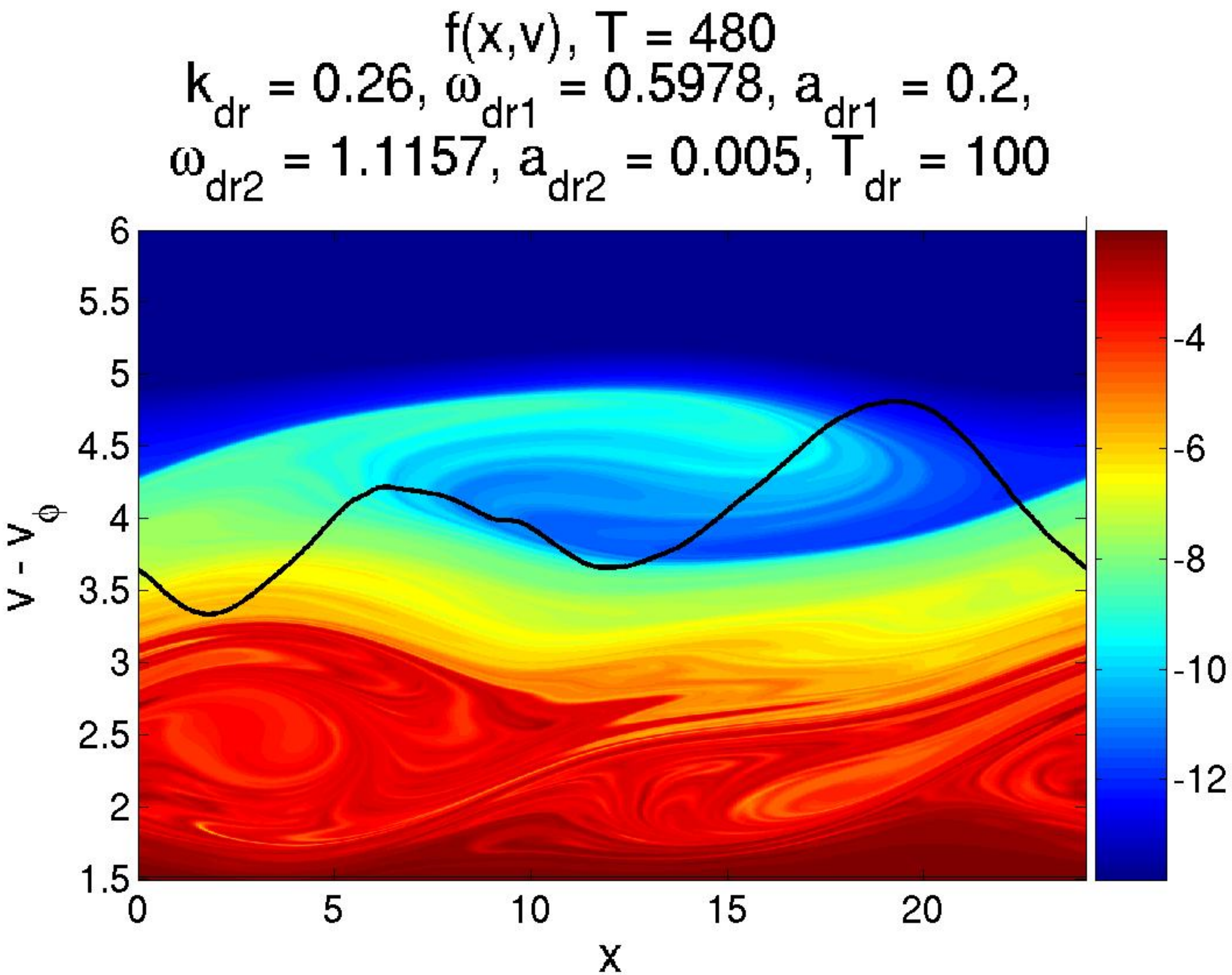

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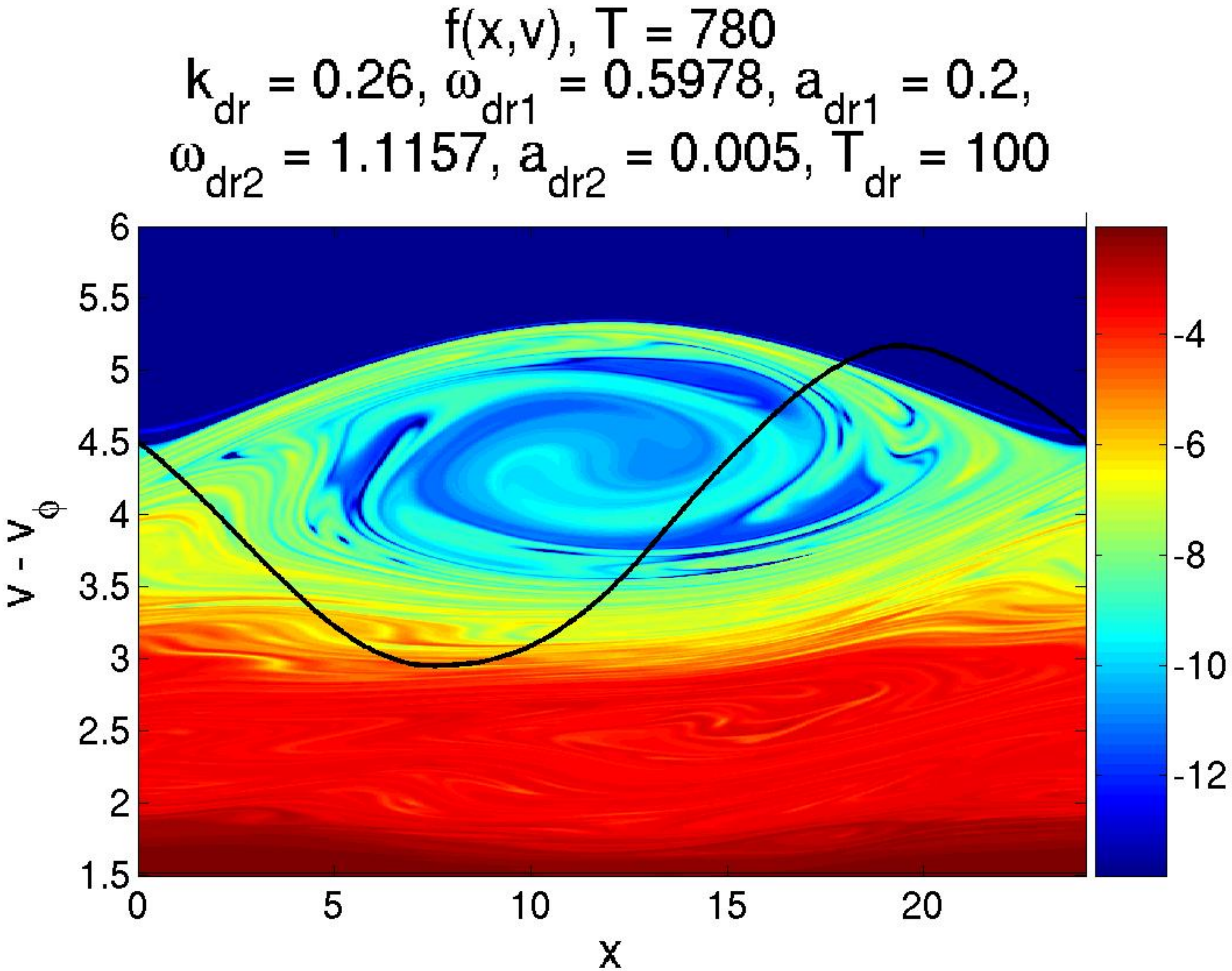

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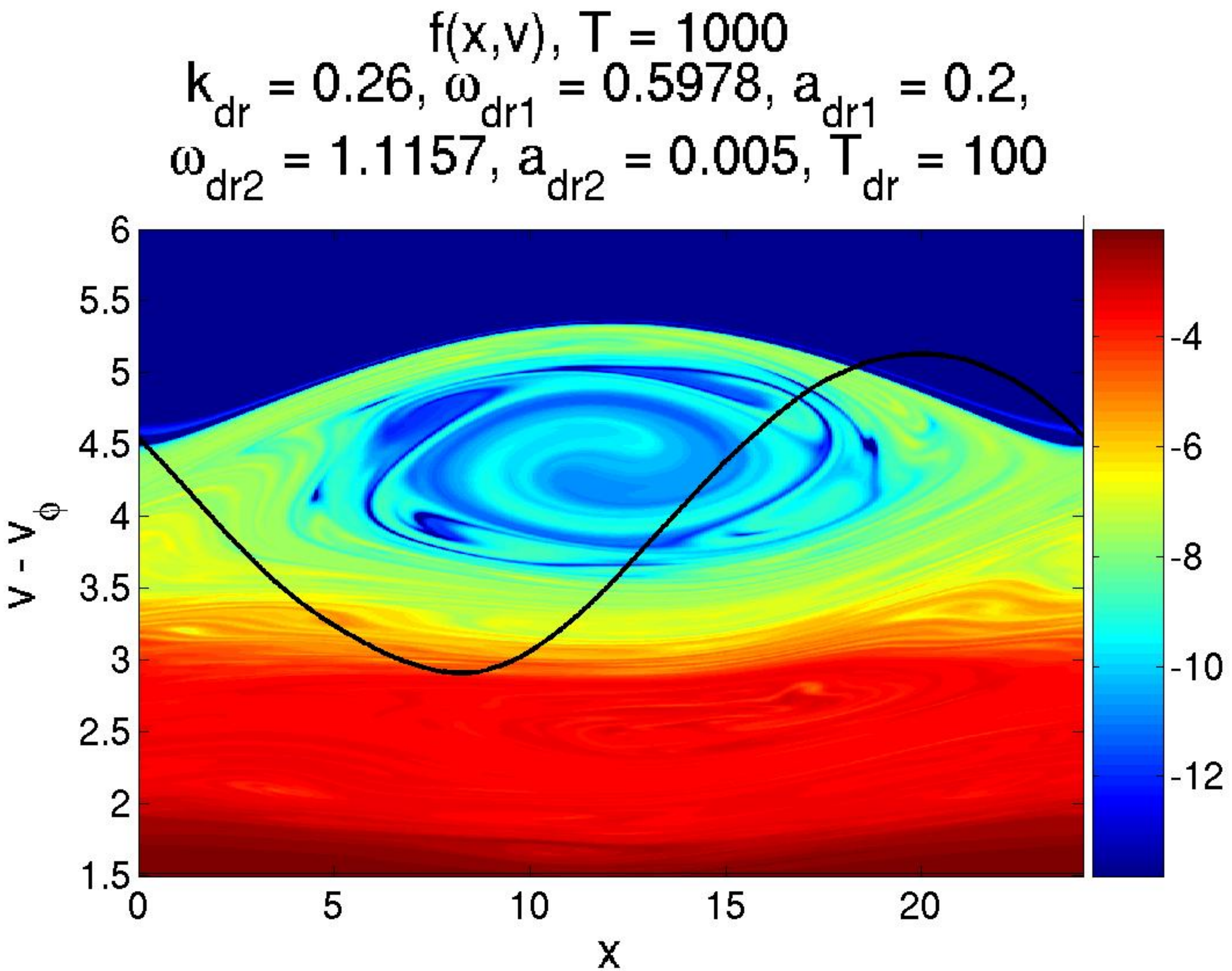

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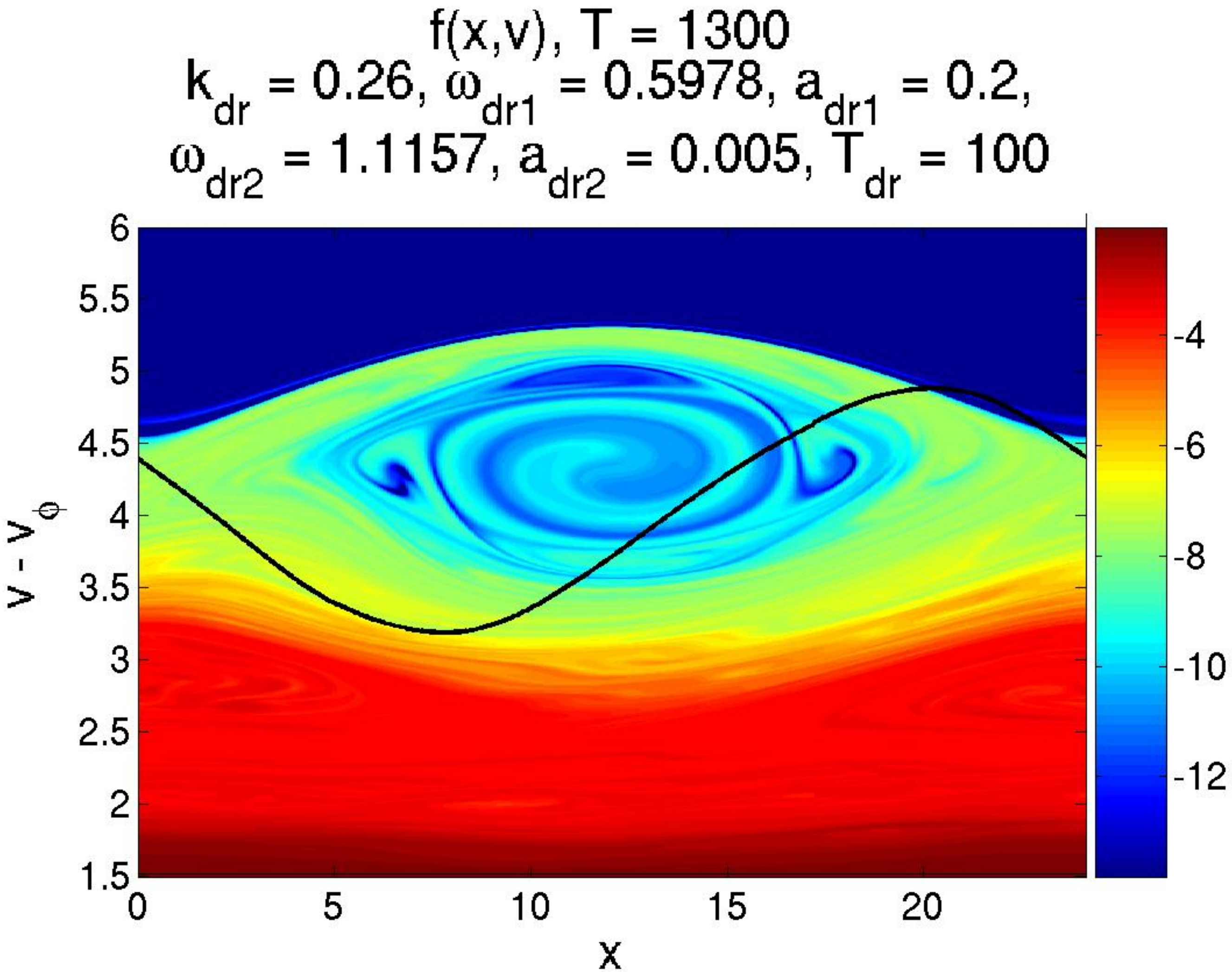
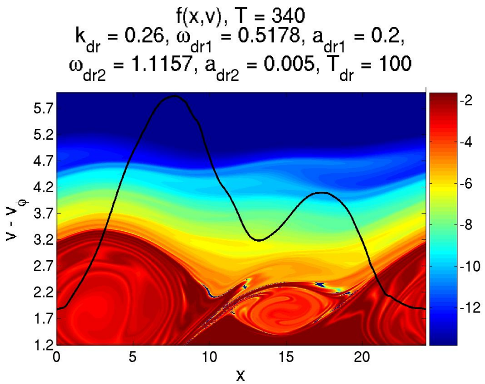
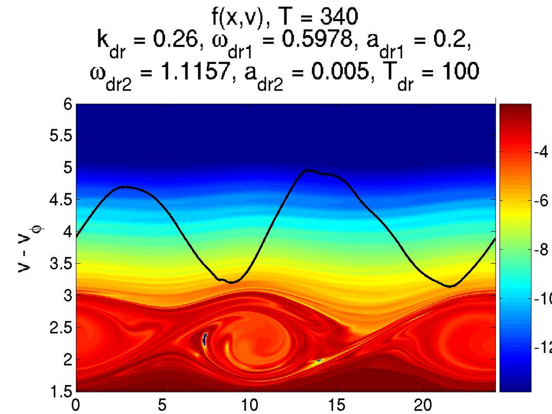


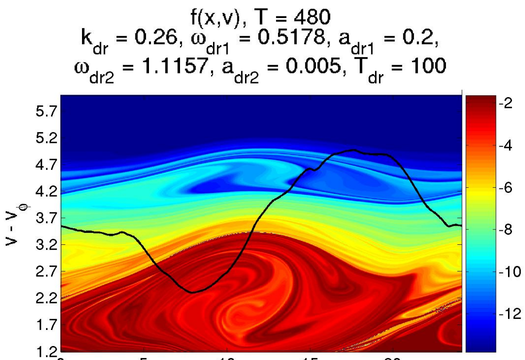
New Modes of Self-Organization in HED Plasma Can Destroy Old Undesirable Modes by a Novel 2:1 Resonance-- KEEN Waves Can Kill EPWs and SRS and Once Off Resonance, Coexist With Them

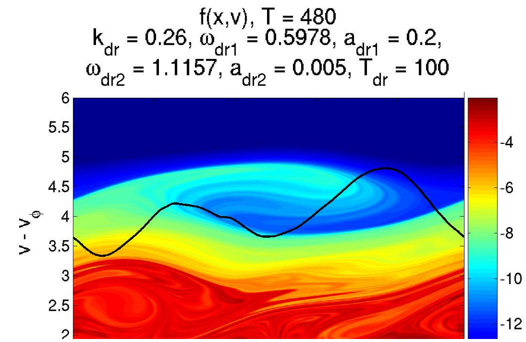


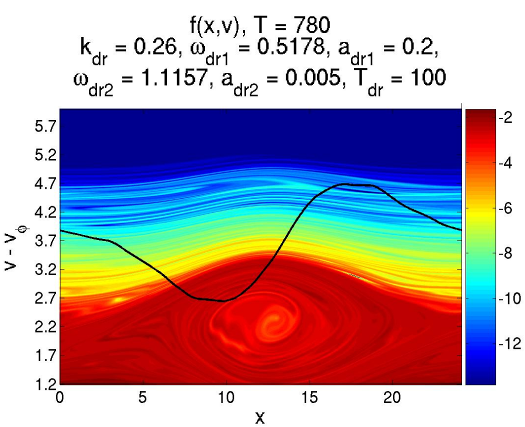
At 2:1 Frequency Resonance

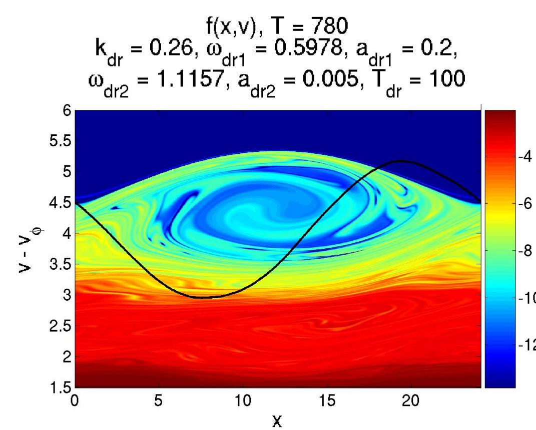


Past 2:1 Frequency Resonance

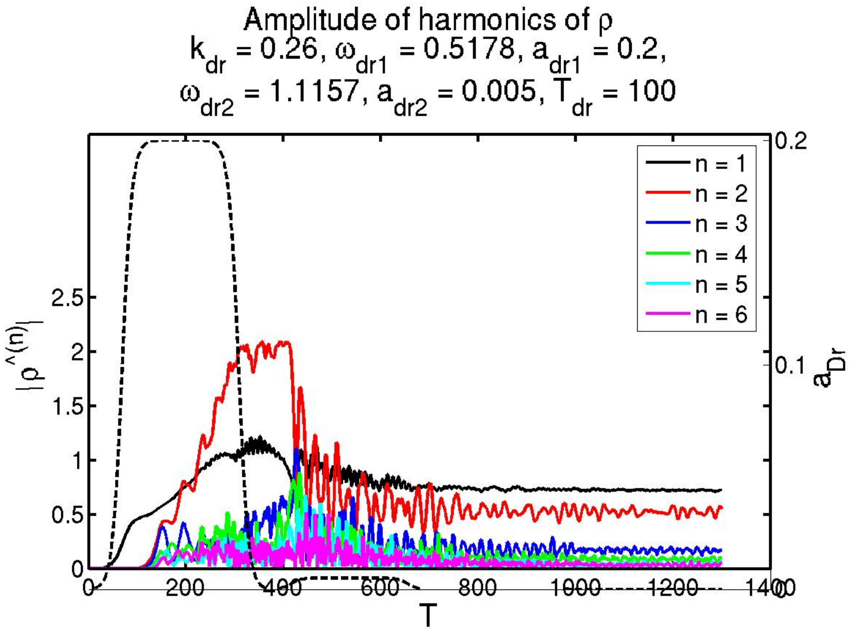


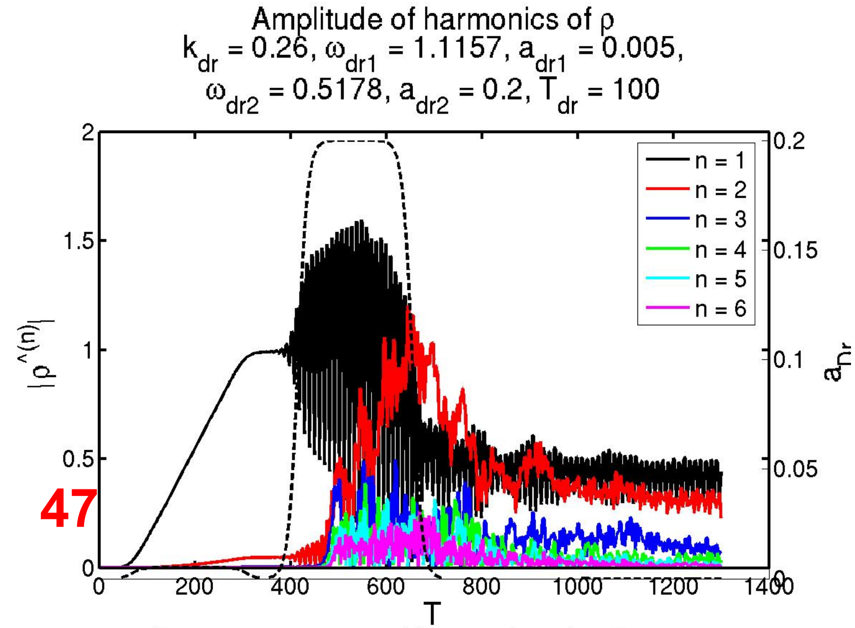


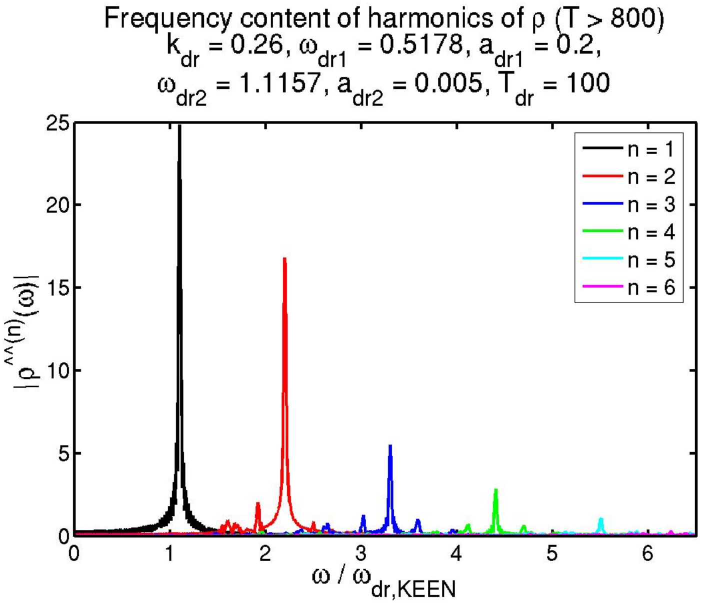


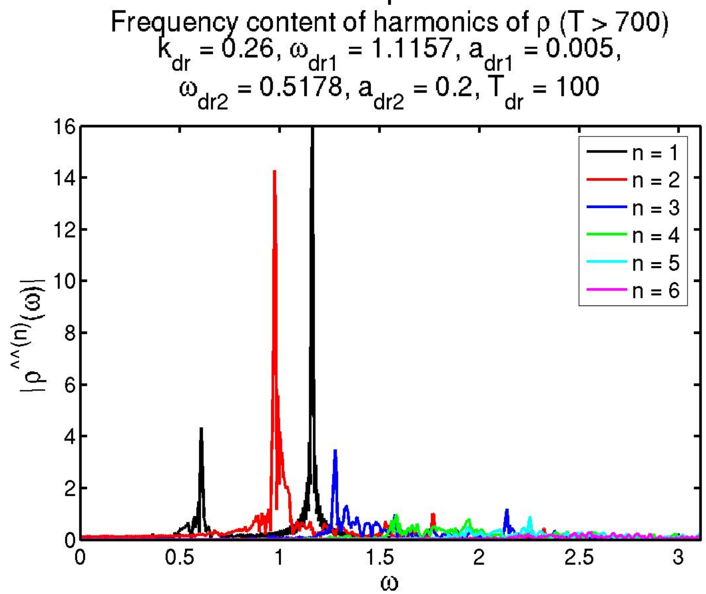


The Density Response to KEEN + EPW Drives ($\text{Commutator} \neq 0$) (Notice Difference in Scale btw L & R)









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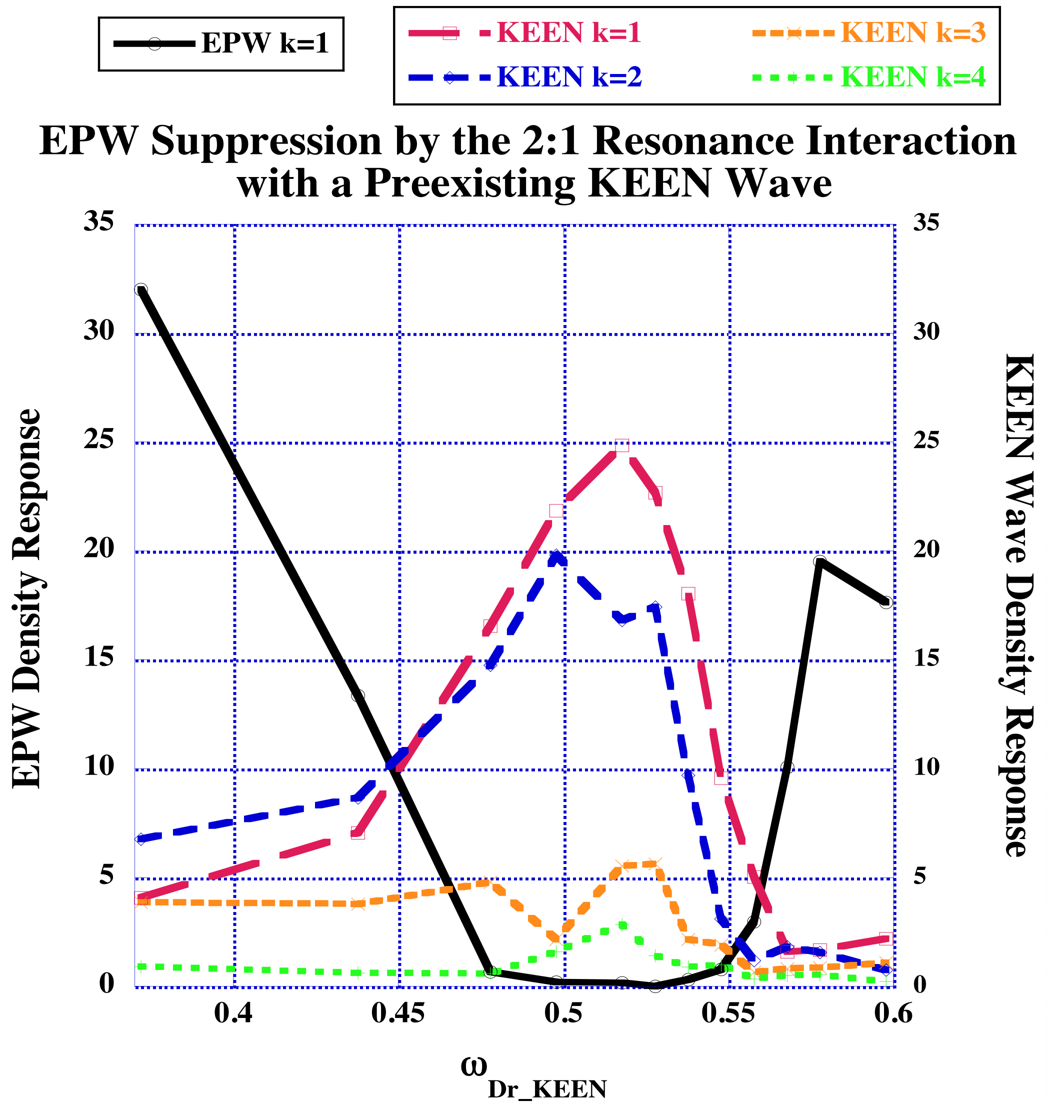
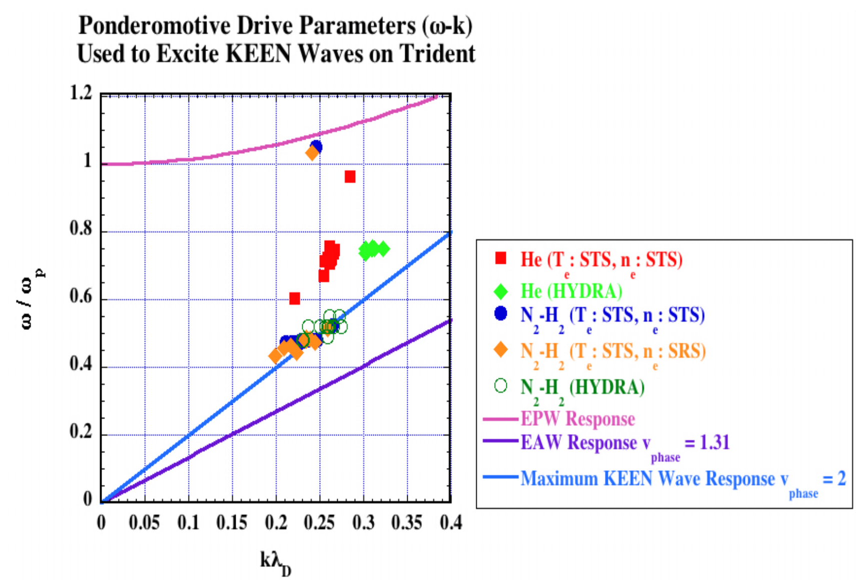
Using the 2:1 Resonance Make Multimode KEEN Wave Suppress Otherwise Stable NL Kinetic EPW

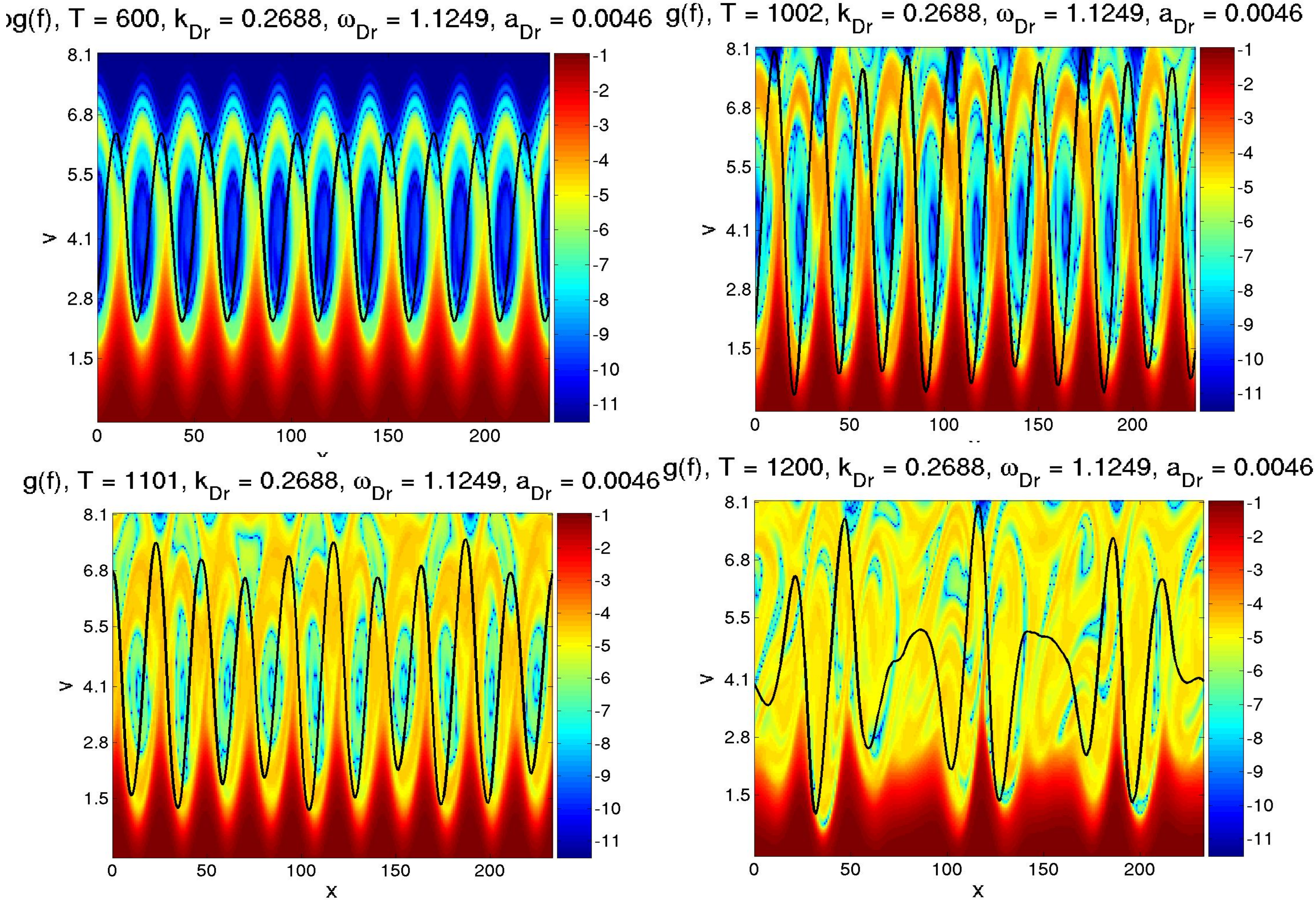


Now we can suppress Stimulated Raman Scattering and EPW growth! Use KEEN waves to make plasma phase space inhospitable to resonant (delicate, trapped particle frequency shift detuned/saturated) high frequency mode excitation.

- A good example of mode pruning, nonlinear structures suppressing each other and externally steered instability control.



Vortex Merging Is Commonly Observed in V-P & V-M Simulations of SRS, For Instance



SKEENS-SRBS Co-Evolution and Interactions in Fully Relativistic Vlasov-Maxwell Simulations

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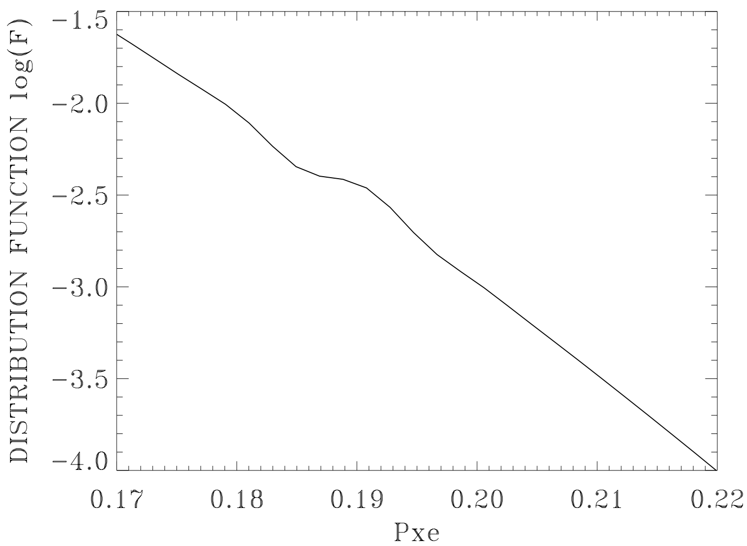

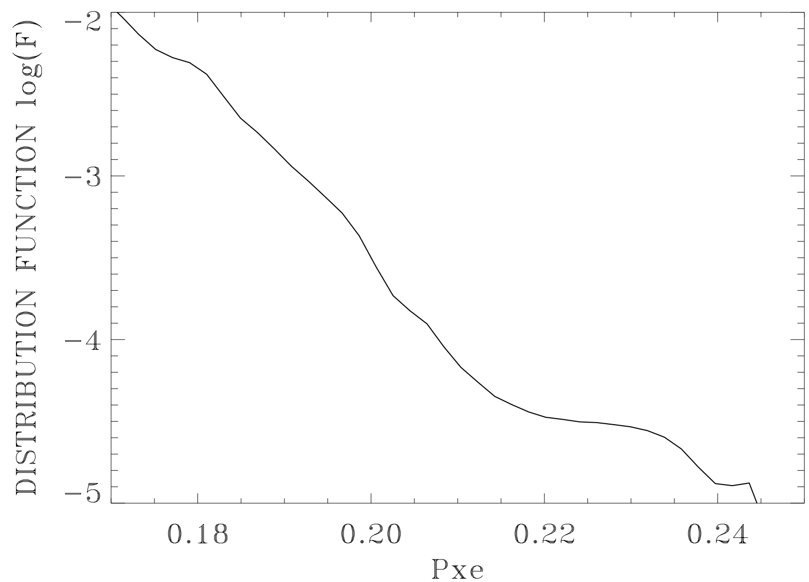

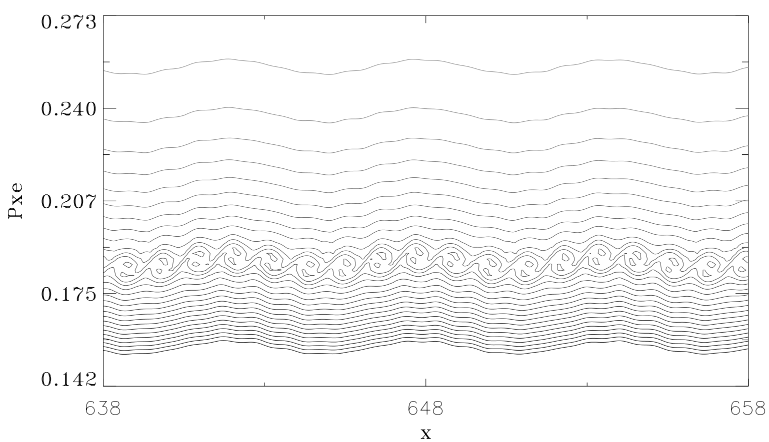

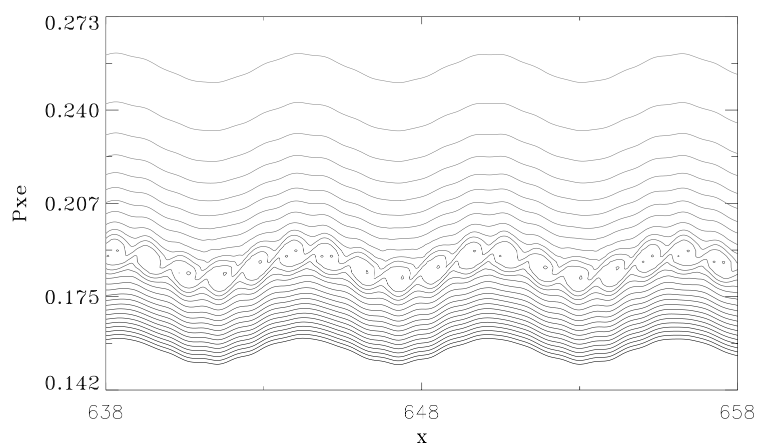

SKEENS-SRBS Co-Evolution and Interactions in Fully Relativistic Vlasov-Maxwell Simulations

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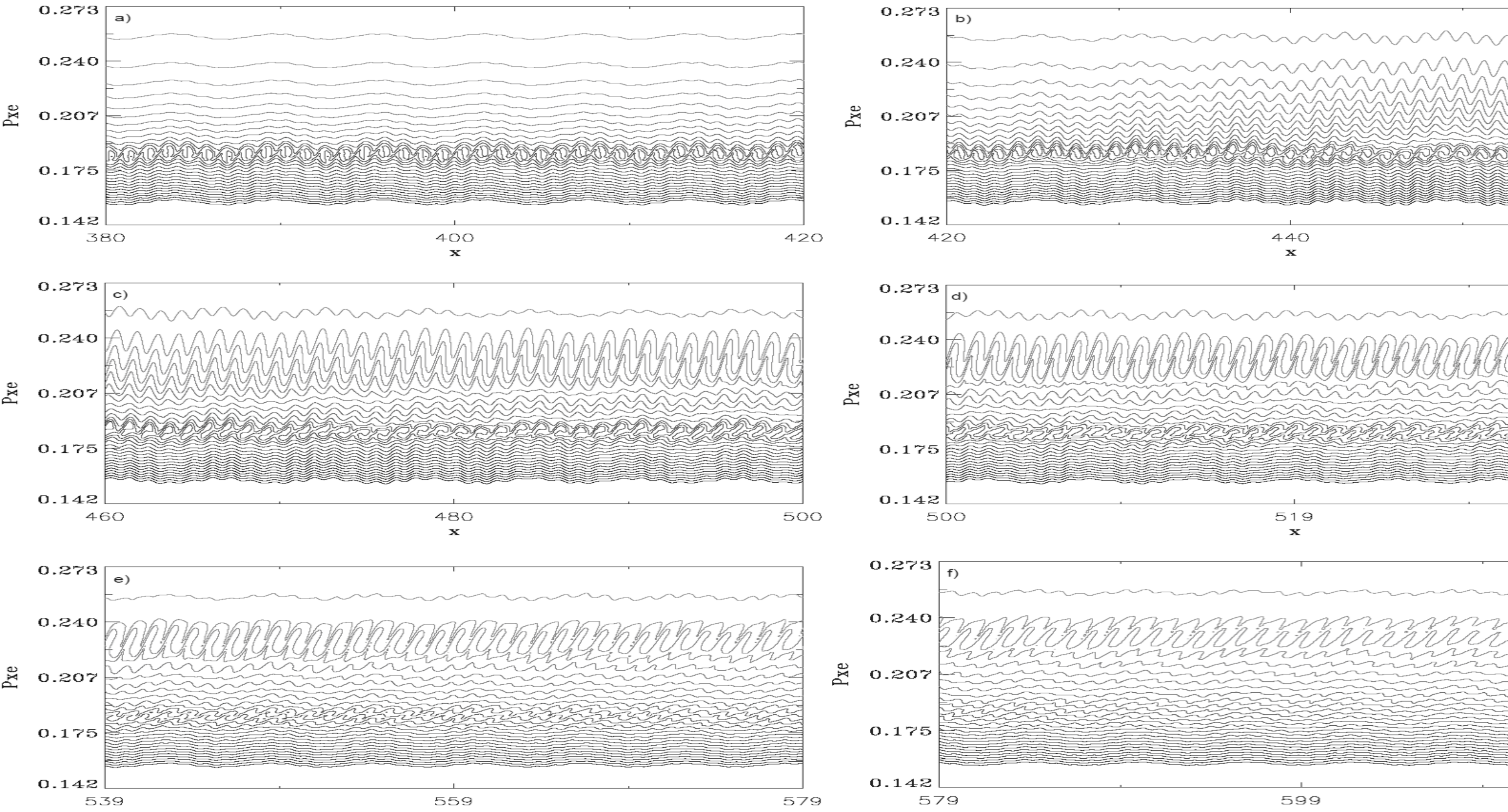

Figure 15. Phase-space contour plot of the electron distribution function in $x \in (380,619)$ at $t=820$.

Kinetic Modeling of HED Plasmas- A General Program Might Also Include:

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- Use adaptive grids and variational algorithms to preserve energy, momentum and entropy in discretized Lagrangian formulation of dynamics models. Make higher dimensional calculations possible (in 6 dimensional phase space). Do Vlasov right. Then add collisions.

- See how to disentangle complex dynamics projected down to low dimensional spaces such as the one body distribution function evolving in (x, v, t), by projecting back up to higher dimensional spaces.

- How high do you have to go before no meaningful collective (geometry, memory) effects are visible? Can computing just below that be optimal in terms of smooth tractable dynamics? Are sparse representations possible in that higher dimensional space?

- Is lower dimensional chaos an artifact of the downward projection? (Coifman’s dream) Can turbulence be so disentangles or parts thereof? (Jones’ truism: Everything looks like diffusion in high enough dimensions).