Structure-Driven Turbulence in `No Man's Land': A Bound for Fluctuation Amplitude in Drift Hole - Zonal Flow System

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Ads:

This conference: EP session, Thur. Afternoon. (over...)
Paper: Y.K. + P.D. PoP '11, M.L. + P.D. '12 (submitted), Y.K. + P.D. '12 (submitted)
WCI Center web cite: Collection of talks, papers, etc

Outline

- Background and Motivation

  → Drive in No Man's Land: Incoming Holes?!

  Eg) density blob/hole, phase space density hole (Vlasov + 3D magnetized)

  → Role of zonal flow in drift hole driven turbulence?

- Revisiting drift hole calculation with zonal flow coupling

  → Structure: shift of potential, hole-flow resonance

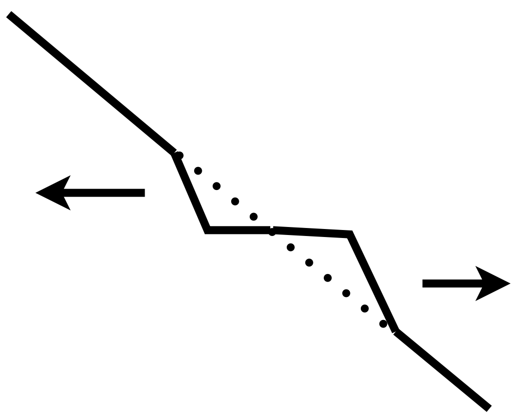
  → Dynamics: coupled DH-ZF system, self-regulating predator-prey behavior

- An application: amplitude bound in DH-ZF system

- Conclusion

Structure driven turbulence:

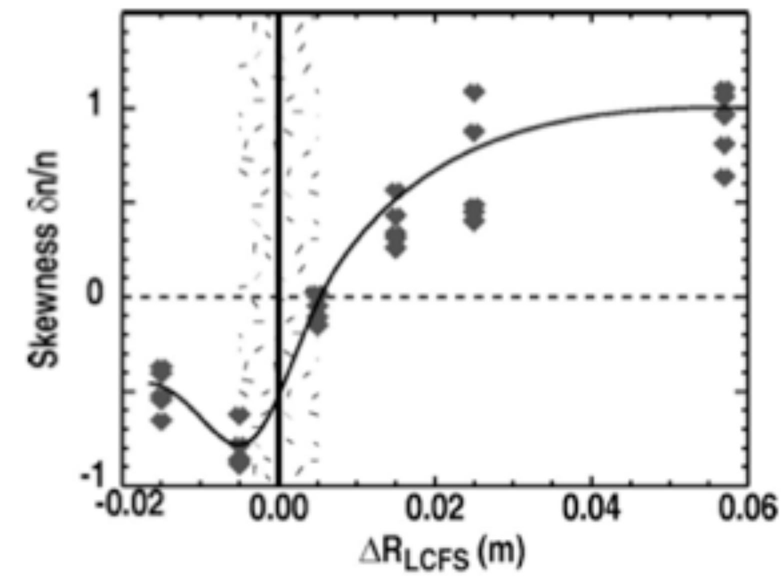
- Structure as drive for No Man's Land turbulence??
- Real space structure: Density blob/hole (Boedo '01, '03)



→ Edge turbulence

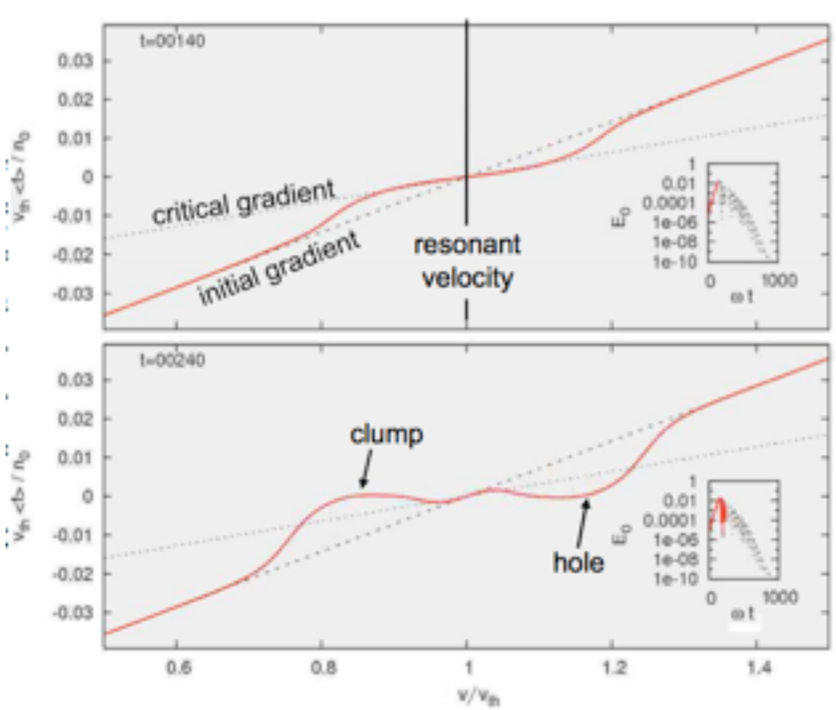
→ Blob ejection

→ Hole creation



→ Incoming hole as drive for turbulence in No Man's Land??

- Analogous to Hole-Clump (phase space structures, ala B+B) driven turbulence in EP problem



→ Resonance, Velocity gradient flattening

→ clump-hole pair creation

→ Subcritical Instability, observed numerically
(B+B '97 Lesur '12, Lesur EP session, this meeting)

Structure driven turbulence:

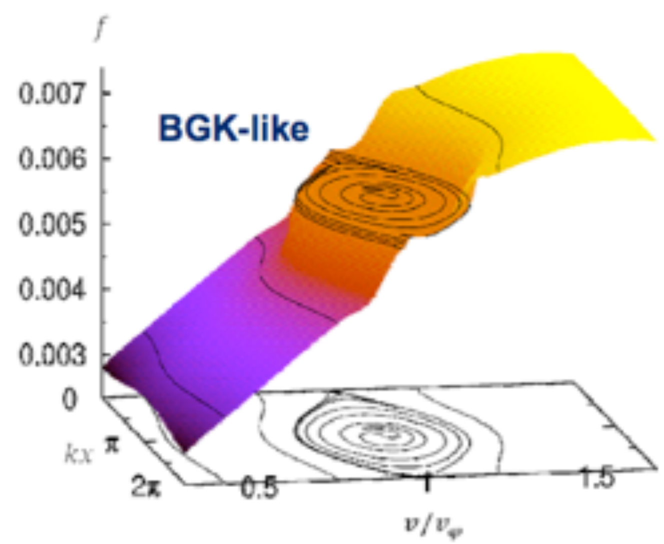
- Structure as drive for No Man's Land turbulence??

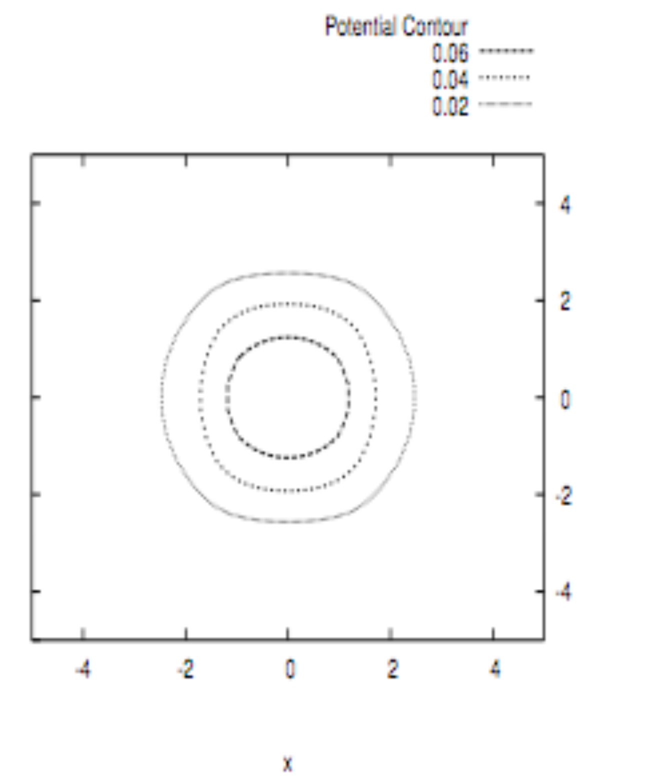
- Phase space structure: Drift Hole (Terry + Diamond + Hahm '83)

  → BGK solution for inhomogeneous, 3D magnetized plasmas

parallel → akin to 1D

perpendicular → ExB vortex





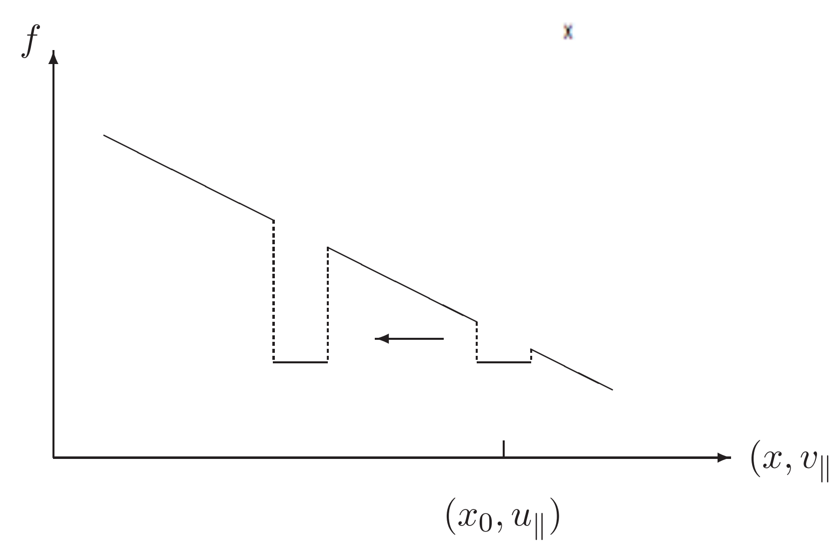
- Taping of free energy:

  → Spatial scattering of other species

  (Quasi-neutral constraint)

  → Displacement, Growth

  → Can be subcritical!



Extension of drift hole paradigm:

- Zonal flow coupling in drift hole physics?

  → Impact on saturation of drift hole growth and evaluation of saturation amplitude

  → MUST include ZF effect for precise evaluation!

- How was it missed?

  → Naively, Reynolds stress via drift hole potential:

$$\langle \tilde{v}_x \tilde{v}_y \rangle = \mathrm{Re} \sum_k i k_y \phi_{-k} \frac{1}{\lambda_k} \phi_k \to 0$$

- However: DH growth → Scattering of polarization charge → ZF coupling (P.D. '91,'08, Y.K. '11)

$$\langle \tilde{v}_x \nabla_\perp^2 \tilde{\phi} \rangle = \partial_x \langle \tilde{v}_x \tilde{v}_y \rangle \neq 0 \quad \text{in general...}$$

➔ will show: Hole-Flow resonance provides proper phase, allows DH-ZF coupling!

➔ revisiting drift hole problem with zonal flow coupling!

Structure: dressing potential & screening length

- Resonance/Trapping of electron → Screening → Dressing potential

- Dressing potential → GK Poisson Eq.
  (Terry, Diamond, Hahm '83)

Trapped electrons

$$\left(\partial_x^2 - \lambda_k^{-2}[\langle v_y\rangle]\right)\frac{e\phi_k}{T_e} = \frac{1}{\rho_s^2} f_H \Delta v_\parallel \frac{\Delta y}{L_y}\frac{2}{k_y \Delta y}\sin\frac{k_y \Delta y}{2}$$

Screening charges: guiding center ions, polarization ions, adiabatic electrons

- Localized potential $\phi \sim e^{-x/\lambda_k}$ when $\lambda_k^2 > 0$ → otherwise ($\lambda_k^2 < 0$) $\phi \sim e^{ik_x x}$

→ Potential not-localized,
Dressed potential radiated away

- Flow → Screening length:

χ : susceptibility

Flow-Hole resonance → phase 'i'

$$\lambda_k^{-2} \propto \chi(\mathbf{k}, k_\parallel u_\parallel, \langle v_y\rangle)$$

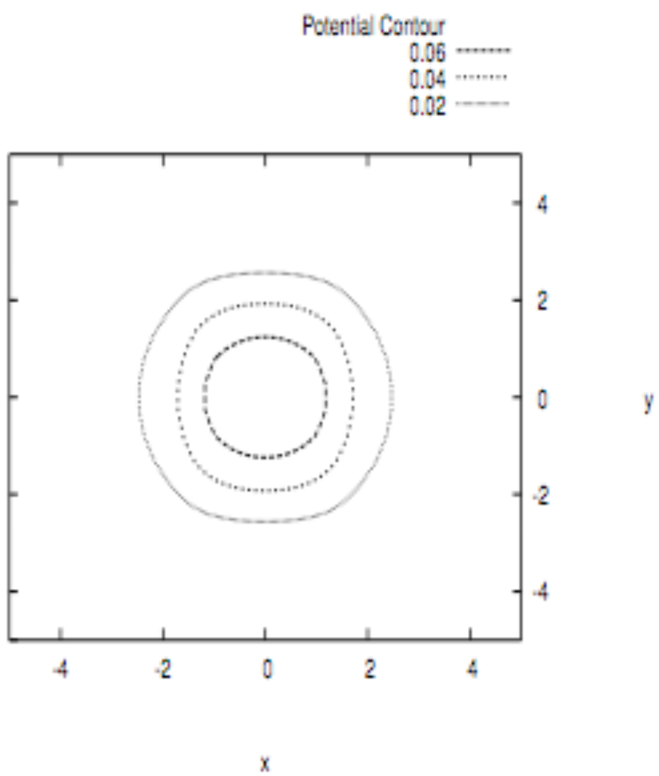
$$\cong \chi^{(0)}(\mathbf{k}, k_\parallel u_\parallel) - \boxed{\left(\frac{k_y c_s}{k_\parallel u_\parallel}\right)^2 \frac{\langle v_y\rangle}{c_s}} + \boxed{i\omega_{*e}\pi\delta(k_\parallel u_\parallel - k_y\langle v_y\rangle)}$$

From expansion: different screening for x>0 and x<0, potential not screened symmetrically

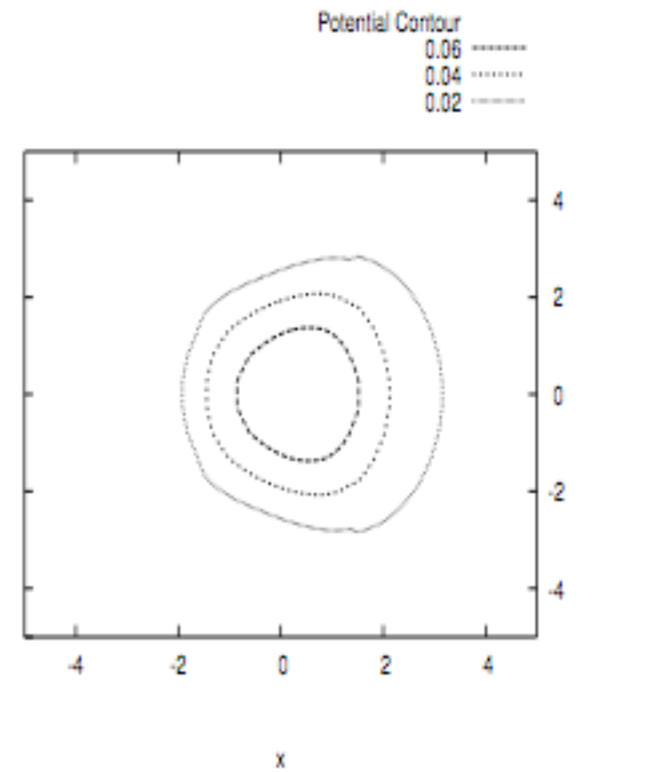
Potential with Flow

- Dressing Potential: $\phi = \phi^{(0)} + \phi^{shift} + \phi^{res}$

- $\phi^{(0)}$:Up to Flow → Isotropic ExB Vortex



- ϕ^{shift} : Shift to Isotropic ExB Vortex



→ Analogous to Shift of Drift Wave Eigenmode Structure by Shear Flow

- ϕ^{res} : Resonance

→ Non-Zero Reynolds Forcing:

$$\langle \tilde{v}_x \tilde{v}_y \rangle = \frac{c^2}{B^2} \mathrm{Re} \sum_k i k_y (\phi^{(0)}_{-k} + \phi^{shift}_{-k}) \partial_x \phi^{res}_k + \frac{c^2}{B^2} \mathrm{Re} \sum_k i k_y \phi^{res}_{-k} \partial_x (\phi^{(0)}_k + \phi^{shift}_k)$$

→ Plausible: Resonance → absorption
→ zonal flow drive!

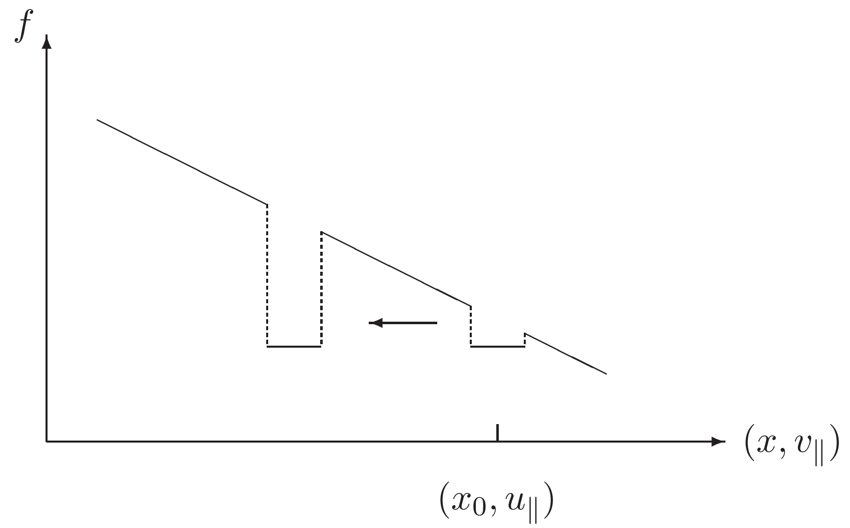
Dynamics:

- Non-Zero Reynolds Forcing → Drift Hole Potential dressed by Zonal Flow

- Zonal Flow Effects on Dynamics?

→ Displacement of phase space density blob

$$\frac{\partial}{\partial t}\int dv_{\parallel}\frac{\langle \delta f_e^2\rangle}{2} = -\left\langle \tilde{v}_x \frac{\delta n_e}{n_0}\right\rangle \frac{\partial \langle f_e\rangle}{\partial x}\bigg|_0 + \frac{|e|}{m_e}\left\langle \tilde{E}_{\parallel}\frac{\delta n_e}{n_0}\right\rangle \frac{\partial\langle f_e\rangle}{\partial v_{\parallel}}\bigg|_0$$



→ Quasi-neutral constraint:
Electron DH must scatter ions, polarization charge

$$\delta n_e = \delta n_i^{GC} + n_0 \rho_s^2 \nabla_{\perp}^2 e\tilde{\phi}/T_e$$

→ Overall Growth:

$$\frac{\partial}{\partial t}\int dv_{\parallel}\frac{\langle \delta f_e^2\rangle}{2} = -\langle f_e\rangle|_0 \sum_{\mathbf{k}} (\omega_{*e}|_0 - k_{\parallel}u_{\parallel})\mathrm{Im}\chi_i \left|\frac{e\tilde{\phi}}{T_e}\right|^2_{\mathbf{k}}$$

Guiding center ions

$$-\frac{1}{\omega_{ci}}\partial_x\langle \tilde{v}_x\tilde{v}_y\rangle \frac{\partial\langle f_e\rangle}{\partial x}\bigg|_0 - \frac{m_i}{m_e}\frac{c^2}{B^2}\partial_x\langle \tilde{E}_x \tilde{E}_{\parallel}\rangle \frac{\partial \langle f_e\rangle}{\partial v_{\parallel}}\bigg|_0$$

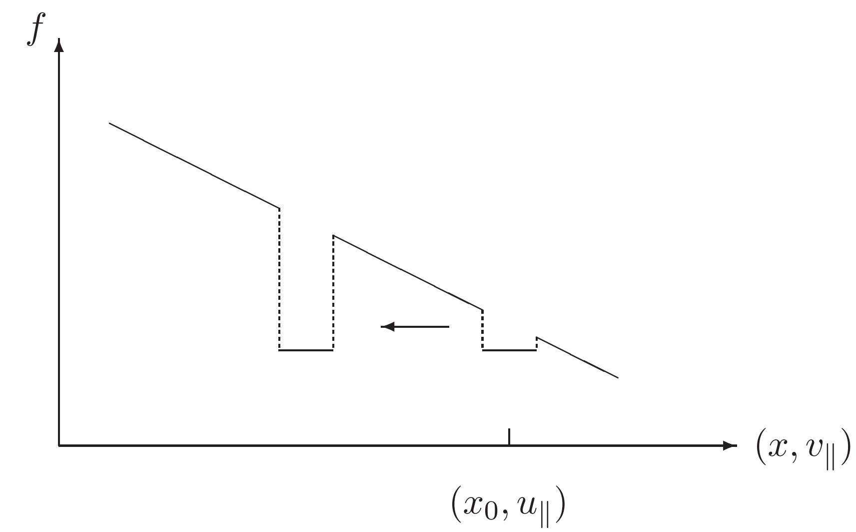
Polarization ions
→ zonal flow + toroidal flow
(McDevitt '09)

→ couples to intrinsic rotation

Subcritical Instability

- Up to Flow → `Bare' Growth of Drift Hole, Subcritical Instability

$$\gamma \sim \langle f_e \rangle|_0 \Delta v_{\|} (\omega_{*e}|_0 - k_{\|} u_{\|}) \frac{|\mathrm{Im}\chi_i|}{|\chi|^2} \sim k_{\|} \Delta v_{\|} \frac{|\mathrm{Im}\chi_e \mathrm{Im}\chi_i|}{|\chi|^2}$$



→ Free Energy Required: $\omega_{*e}|_0 > k_{\|} u_{\|}$

→ Nonlinear: $\Delta v_{\|} \propto \sqrt{\phi}$

→ Ion Dissipation as Drive: Scattering of Ions Required for Growth

- Comparison to Linear Drift Wave Growth:

	Electron drift wave instability	Electron drift hole instability
Growth rate	$\gamma_L \sim \|\partial\chi/\partial\omega_k\|^{-1}(\|\mathrm{Im}\chi_e\| - \|\mathrm{Im}\chi_i\|)$	$\gamma \sim k_{\|}\Delta v_{\|}\|\mathrm{Im}\chi_e \mathrm{Im}\chi_i\|/\|\chi\|^2$
Access to free energy	$\omega_* > \omega$	$\omega_{*e}\|_0 > k_{\|} u_{\|}$
Amplitude dependence	No	Yes, $\propto \Delta v_{\|} \sim \sqrt{\tilde{\phi}}$
Ion Landau Damping	Stabilizing	Destabilizing
Type of instability	Supercritical, exponential growth	Subcritical, explosive growth

TABLE I. Comparison between linear and nonlinear instabilities.

Coupled Evolution: Closed Feedback Loop

- Drift Hole Dynamics with Zonal Flow → Coupled Evolution, Self-Regulating Behavior

$$\frac{\partial}{\partial t}\int dv_{\parallel}\frac{\langle\delta f_e^2\rangle}{2} = -\,\langle f_e\rangle|_0\sum_{\mathbf{k}}(\omega_{*e}|_0 - k_{\parallel}u_{\parallel})\mathrm{Im}\chi_i\left|\frac{e\tilde{\phi}}{T_e}\right|^2_{\mathbf{k}}$$

$$\rightarrow\quad \frac{\partial}{\partial t}\left(\int dv_{\parallel}\frac{\omega_{ci}\langle\delta f_e^2\rangle}{2\partial\langle f_e\rangle/\partial x|_0} - \langle v_y\rangle\right) = \frac{c_s^2}{v_*}\sum_{\mathbf{k}}(\omega_{*e}|_0 - k_{\parallel}u_{\parallel})\mathrm{Im}\chi_i\left|\frac{e\tilde{\phi}}{T_e}\right|^2_{\mathbf{k}} + \nu_d^{\perp}\langle v_y\rangle$$

→ Momentum budget for flow and turbulence pseudomomentum
→ akin to Momentum Theorems by Charney & Drazin:

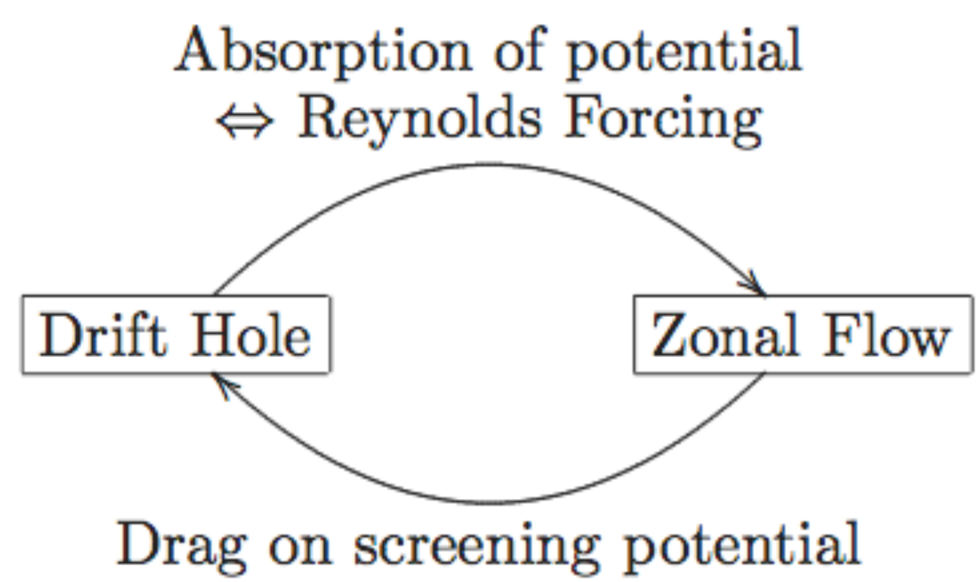
$$\int dv_{\parallel}\langle\delta f_e^2\rangle/\langle f_e\rangle'|_0$$

→ kinetic extension of pseudomomentum

→ Self-Regulating Predator-Prey Behavior

Prey: Drift Hole

Predator: Zonal Flow



→ Analogous to self-regulation of DW-ZF with energy conservation

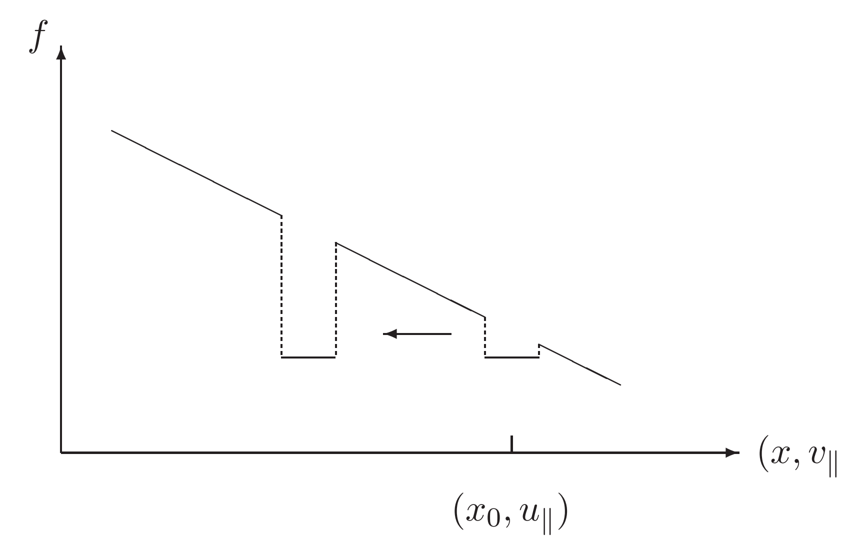
$$\partial_t(\mathcal{E}_{DW} + {V'_{ZF}}^2) = \gamma\mathcal{E}_{DW} - \nu V'_{ZF}$$

Saturation

- Coupled Drift Hole+Zonal Flow Evolution → Saturation with Flows

$$\frac{\langle v_y \rangle}{c_s} = -\frac{1}{\nu_d^{\perp}} \frac{c_s}{v_*} \sum_{\mathbf{k}} (\omega_{*e}|_0 - k_{\parallel} u_{\parallel}) \mathrm{Im}\chi_i \left| \frac{e\tilde{\phi}}{T_e} \right|_{\mathbf{k}}^2$$

→ Stationary State with Non-Zero Flow: Akin to Enhanced State in Predator-Prey



→ Hole Mixing ceases via Turbulent Drag from Flow

→ Zonal Flow Driven by a single coherent phase space structure: Does not Require Inverse Cascade, Wave based Mechanisms (Coherent, W.K.E.) etc.

An Application: Bound on Amplitude

- Non-Zero Flow Results at Stationary State → Feedback to Structure itself? i.e. $\lambda[\langle v_y \rangle]$

- Screening must be positive even with flows for localized dressing potential to form

→ Flows may undress DH potential...

$$\lambda^{-2} \propto \chi[\langle v_y \rangle] > 0 \qquad \Rightarrow \qquad \frac{\langle v_y \rangle}{c_s} < \min\left(\frac{u_\parallel}{c_s}\frac{k_\parallel}{k_y}\frac{\chi^{(0)}}{1+k_y^2\rho_s^2}\right)$$

- Turbulent driven zonal flow must satisfy the condition

- Bound on Amplitude

$$\left|\frac{e\tilde{\phi}}{T_e}\right|^2 < \frac{\nu_d^\perp}{\omega_{ci}}\frac{1}{\rho_s k_y \mathrm{Im}\chi_i}\min\left(\frac{u_\parallel}{c_s}\frac{k_\parallel}{k_y}\frac{\chi^{(0)}}{1+k_y^2\rho_s^2}\right)$$

→ ZF damping as controlling parameter: akin to Predator-Prey

→ increases toward edge

Conclusion

- Drive in No Man's Land turbulence: Incoming Drift Hole?

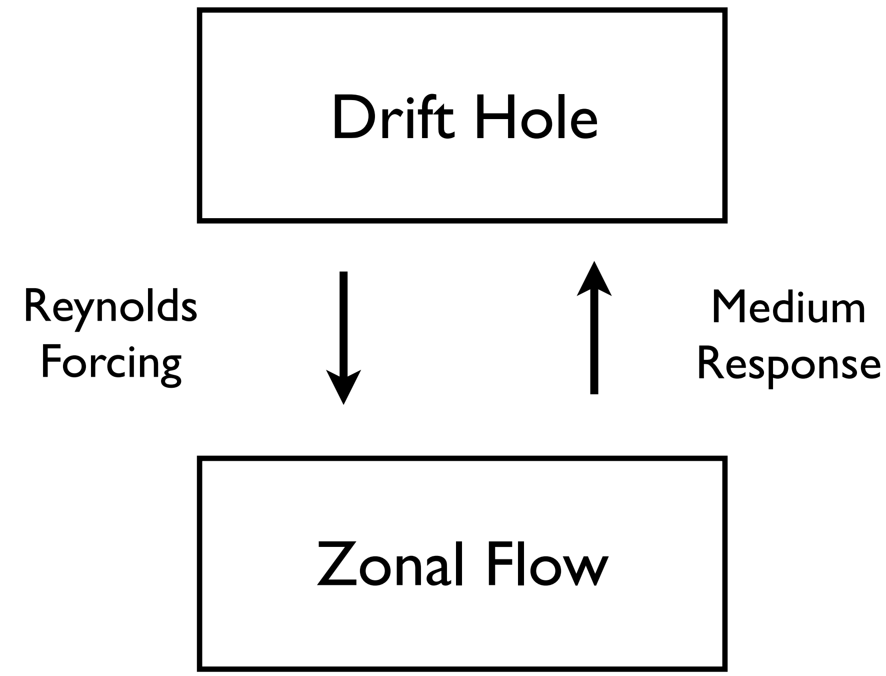
- Drift Hole coupled to Zonal Flow

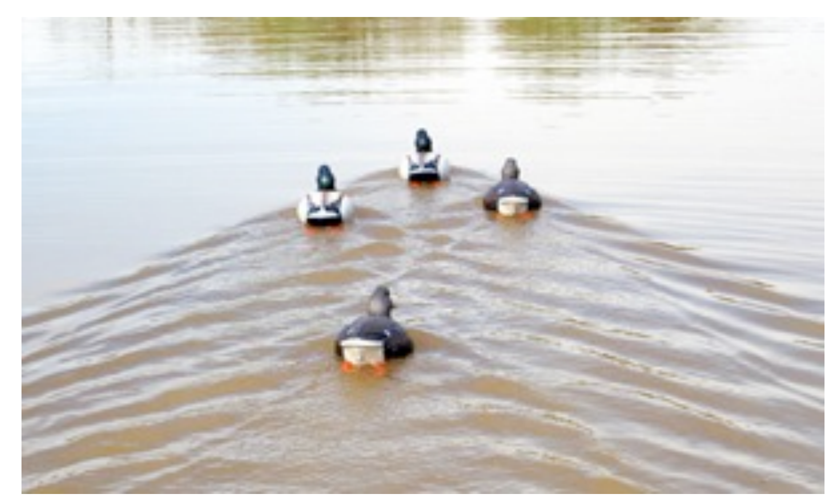
  → made possible with flow-hole resonance

  → self-regulating behavior of DH-ZF system

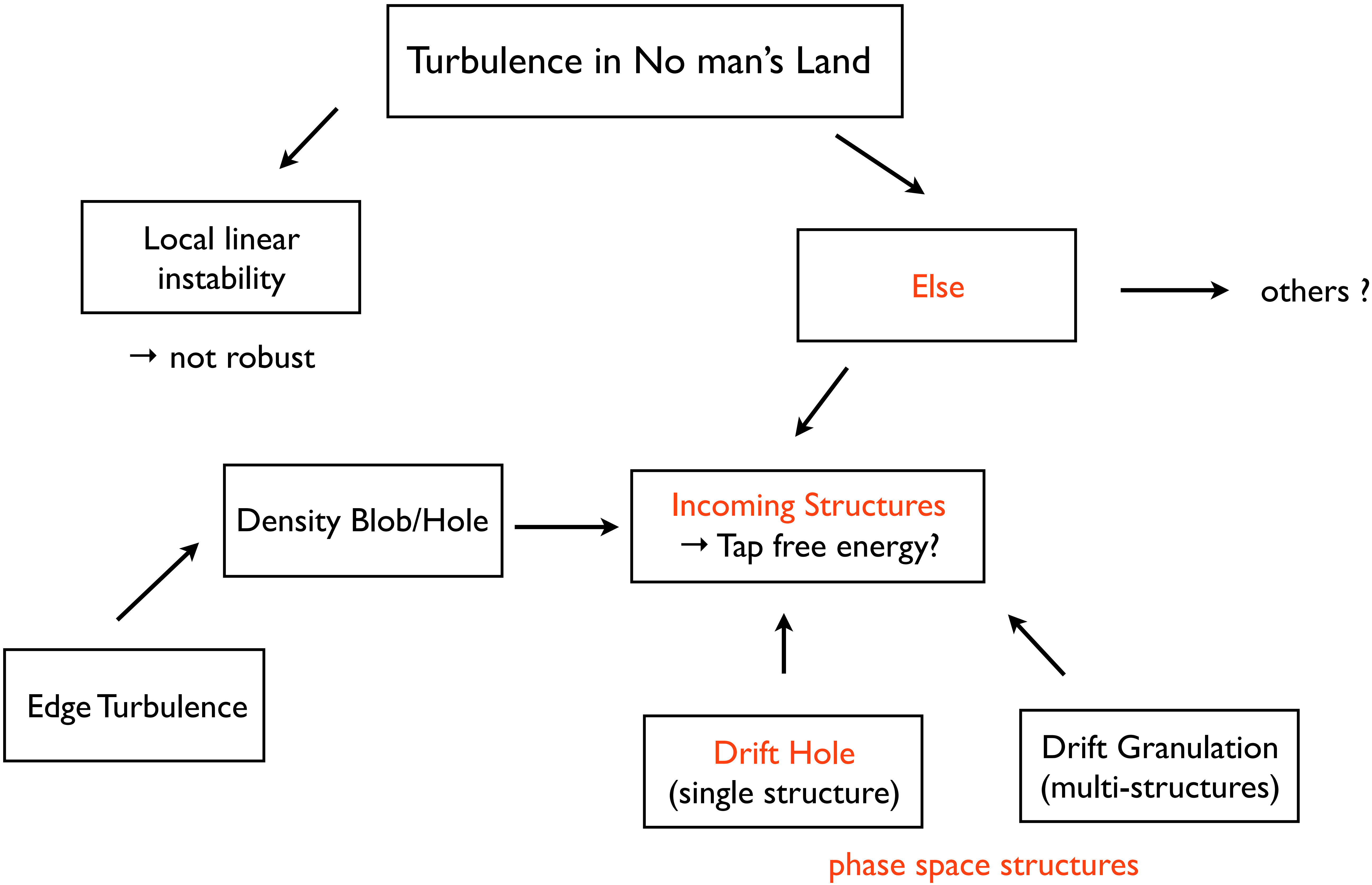
  → Amplitude bound in DH-ZF system: DH effects become increasing important toward edge

- Other mechanisms: Real space density hole? Granulation (multiple structures)?



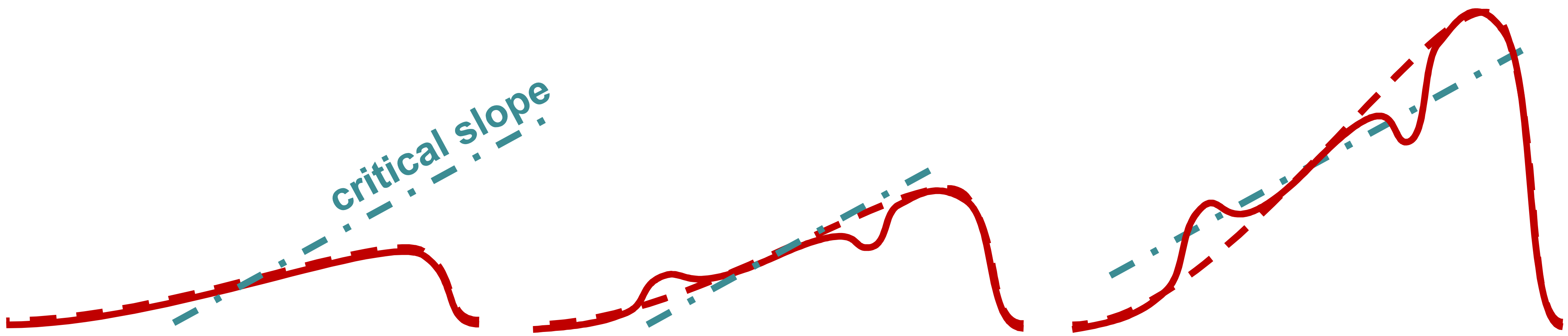


Bird's Eye View:



Subcritical instability

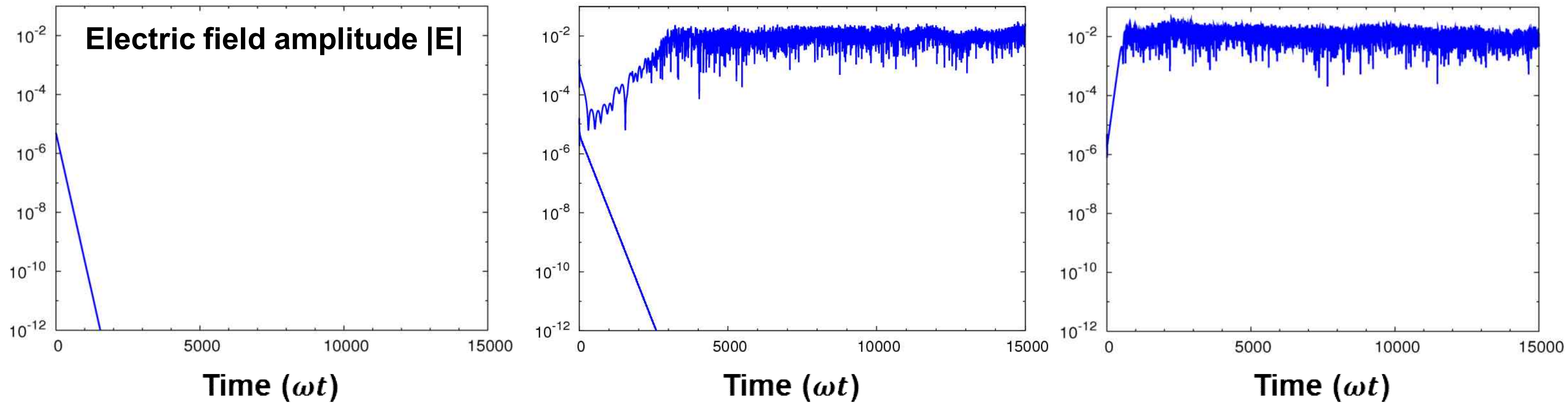
Linear growth rate $\gamma \approx \gamma_L - \gamma_d \quad \Rightarrow \quad$ Critical slope $\gamma_L = \gamma_d$



Stable, $\gamma < 0$

Nonlinearly unstable, $\gamma < 0$
(Subcritical instability)

Unstable, $\gamma > 0$



Zonal Flow Coupling

- Flux of polarization charge:

$$\langle \tilde{v}_x \nabla_\perp^2 \tilde{\phi} \rangle = \frac{c}{B} \mathrm{Re} \sum_k i k_y (\phi_{-k}^{(0)} + \phi_{-k}^{shift} + \phi_{-k}^{res}) \partial_x^2 (\phi_k^{(0)} + \phi_k^{shift} + \phi_k^{res})$$

- Phase: $\phi^{(0)}$ ϕ^{shift} pure real ϕ^{res} pure imaginary

- Non-zero polarization charge flux

$$\langle \tilde{v}_x \nabla_\perp^2 \tilde{\phi} \rangle = \frac{c}{B} \mathrm{Re} \sum_k i k_y \{ (\phi_{-k}^{(0)} + \phi_{-k}^{shift}) \partial_x^2 \phi_k^{res} + \phi_{-k}^{res} \partial_x^2 (\phi_k^{(0)} + \phi_k^{shift}) \} \neq 0$$

→ Non-zero Reynolds Forcing, ZF coupling

$$\therefore \partial_x \langle \tilde{v}_x \tilde{v}_y \rangle \propto \langle \tilde{v}_x \nabla_\perp^2 \tilde{\phi} \rangle \neq 0$$