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Impurity Parallel-Velocity-Gradient (i-PVG) instability

M. Lesur, J. Bourgeois, Y. Kosuga

29th IAEA Fusion Energy Conference

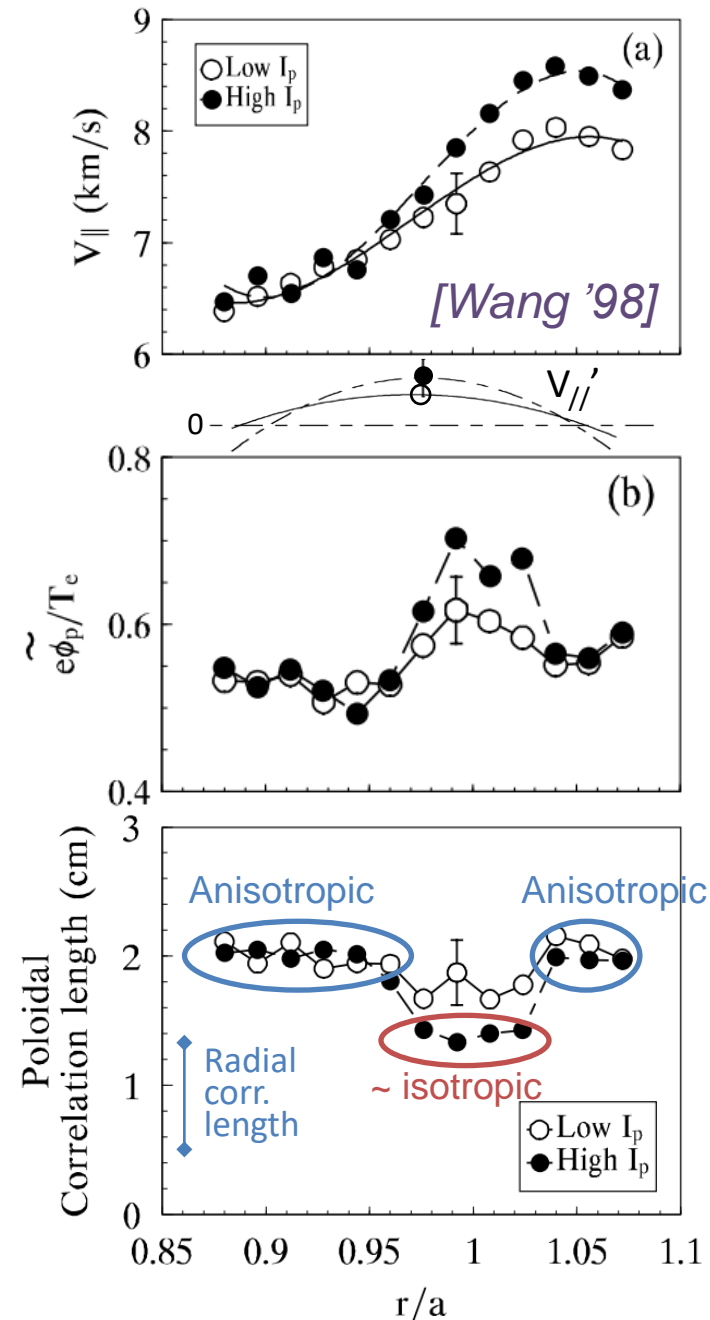
October 19th, 2023



Context: Parallel-Velocity-Gradient (PVG) instability

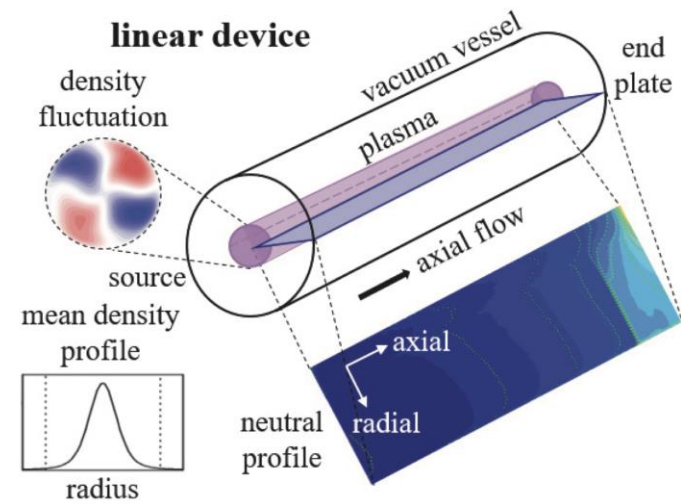
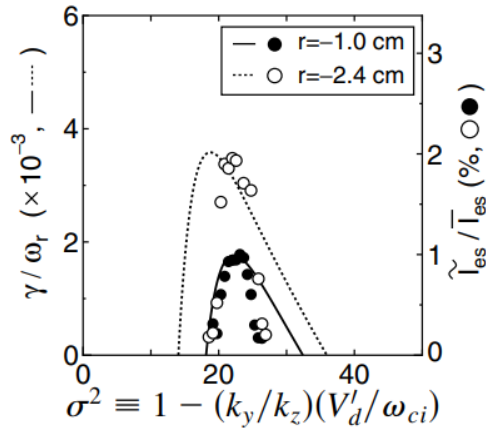
Radial gradient of parallel flows

- May drive Parallel Velocity Gradient (PVG) instability (Kelvin-Helmholtz-like)
- In tokamaks:
 - Maybe observed in edge (CT-6B) ▶ (hints from fluctuation level & isotropy)
 - Magnetic shear is stabilizing [Catto '73]
 - PVG can be expected in
 - SOL ($v_{||} \sim c_s$) [Drake '92]
 - Near transport barriers [McCarthy '02]
 - w. strong // beam injection [Garbet '02]
 - Spherical tokamaks [Chapman '12], [Wang '15]
 - May couple with ITG [Newton, Barnes, Highcock '10-12], [Field '12]
 - In experiments, no clear-cut, direct identification yet

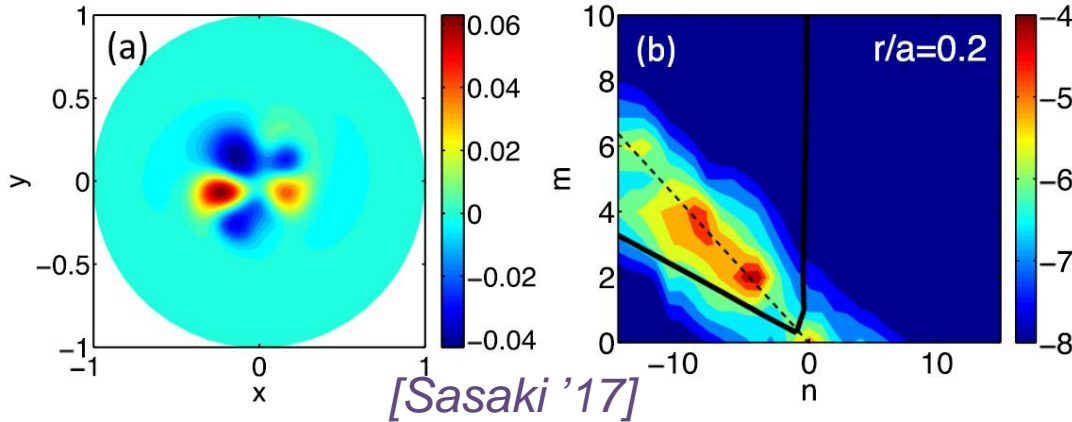


- In linear devices:

- Identified in experiments *[Kaneko '03]*

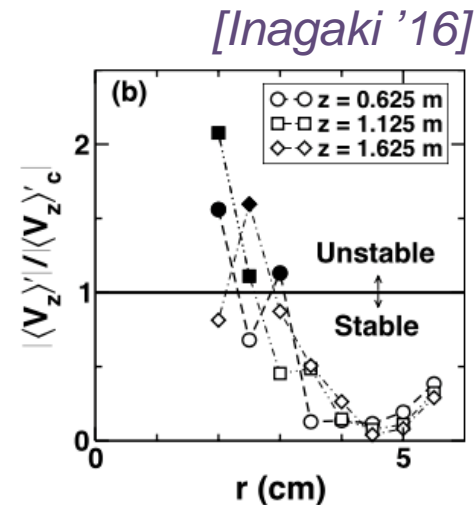


- Neglect role of ITG for now (cold ions)
- Fluid modeling *[D'Angelo '65], [Kosuga '15], [Sasaki '20]*



[Sasaki '17]

- Theory threshold agrees with observation on PANTA ▶
- Drives inward particle flux *[Kobayashi '16]*



[Inagaki '16]

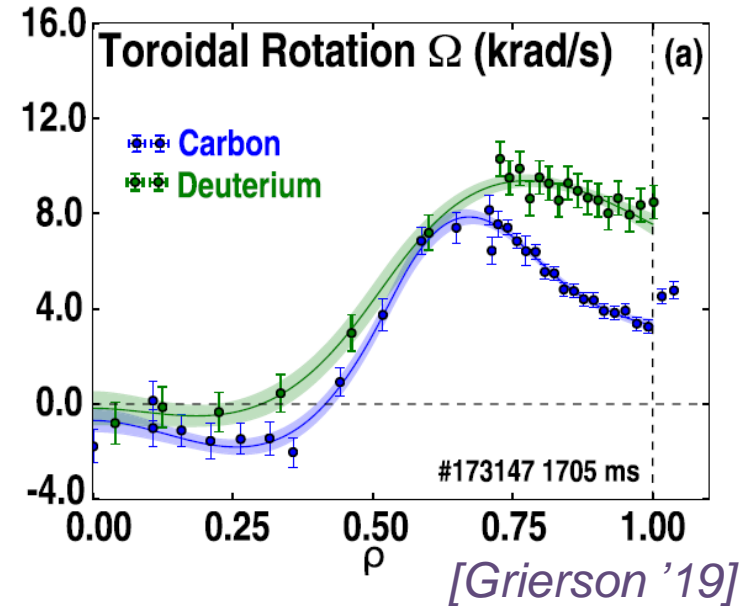
Role of impurities?

Strong radial gradient of impurity parallel flows in tokamaks

- May drive impurity-PVG (i-PVG)

Injection and control of impurity flow planned in future linear device

- Can be used to investigate i-PVG



Linear, local theory of the i-PVG

- Gyrokinetic dispersion relation for slab geometry with weak magnetic shear [Guo '19]
- Here, simpler model: generalization of Hasegawa-Mima with equilibrium and perturbed v_{\parallel}
 \Rightarrow **Parameter dependencies?**

Simplest i-PVG model

Assumptions

- Homogeneous, constant B field
- Assume one impurity species (main ion $s=i$, impurity $s=z$)
- Cold ions
- Retain polarization drift for ions

⇒ System of 4 fluid equations (2 for $s=i$, 2 for $s=z$)

$$\frac{\partial n_s}{\partial t} + \nabla_{\perp} \cdot [n_s(\mathbf{u}_E + \mathbf{u}_{p,s})] + \nabla_{\parallel}(n_s u_{\parallel,s}) = 0$$

polarisation // compressibility

$$\frac{\partial u_{\parallel,s}}{\partial t} + (\mathbf{u}_E + \mathbf{u}_{p,s}) \cdot \nabla_{\perp} u_{\parallel,s} + u_{\parallel,s} \nabla_{\parallel} u_{\parallel,s} = -\frac{q_s}{m_s} \nabla_{\parallel} \phi$$

closed by quasineutrality $\sum_{s \neq e} Z_s n_s = n_e = n_0 \exp\left(\frac{e\phi}{T_e}\right)$

Linear analysis

Additional assumptions

- Neglect $\mathbf{u}_{p,s} \cdot \nabla_{\perp} n_{s,0}$ and $\mathbf{u}_{p,s} \cdot \nabla_{\perp} u_{\parallel,s,0}$ (order $\omega/\omega_{c,s}$)
- Neglect $u_{\parallel,s,0} \nabla_{\parallel} \tilde{n}_s$ and $u_{\parallel,s,0} \nabla_{\parallel} \tilde{u}_{\parallel,s}$ (order $k_{\parallel} u_{\parallel,s,0}/\omega$, assumed small)

⇒ Linearized system can be reduced to 2 coupled equations

for effective variables $\Phi = e\phi/T_e = \sum Z_s \tilde{n}_s / n_{e,0}$

$$\tilde{u}_{\parallel} = \sum Z_s C_s \tilde{u}_{\parallel,s}$$

↑
concentration

$$\bar{\rho}^2 = \sum_{s \neq e} C_s Z_s^2 \rho_{c,s}^2$$

$$\partial_t (1 - \bar{\rho}^2 \nabla_{\perp}^2) \Phi + v_{*,e} \partial_y \Phi + \nabla_{\parallel} \tilde{u}_{\parallel} = 0$$

$$\partial_t \tilde{u}_{\parallel} - \overline{\nabla u_{\parallel}} \rho_{c,i} v_{T,i} \partial_y \Phi = -c_s^2 \nabla_{\parallel} \Phi$$

Hasegawa-Mima with
« effective PVG »

« Effective PVG »

$$\overline{\nabla u_{\parallel}} = \sum_{s \neq e} C_s Z_s \frac{\partial u_{\parallel,s,0}}{\partial x}$$

Dispersion relation

$$\omega^2 - \omega_{\text{iDW}} \omega - \frac{(k_{\parallel} c_s)^2}{1 + (k_{\perp} \bar{\rho})^2} \left(1 - \frac{k_y}{k_{\parallel}} \frac{\overline{\nabla u_{\parallel}}}{\bar{\omega}_c} \right) = 0$$

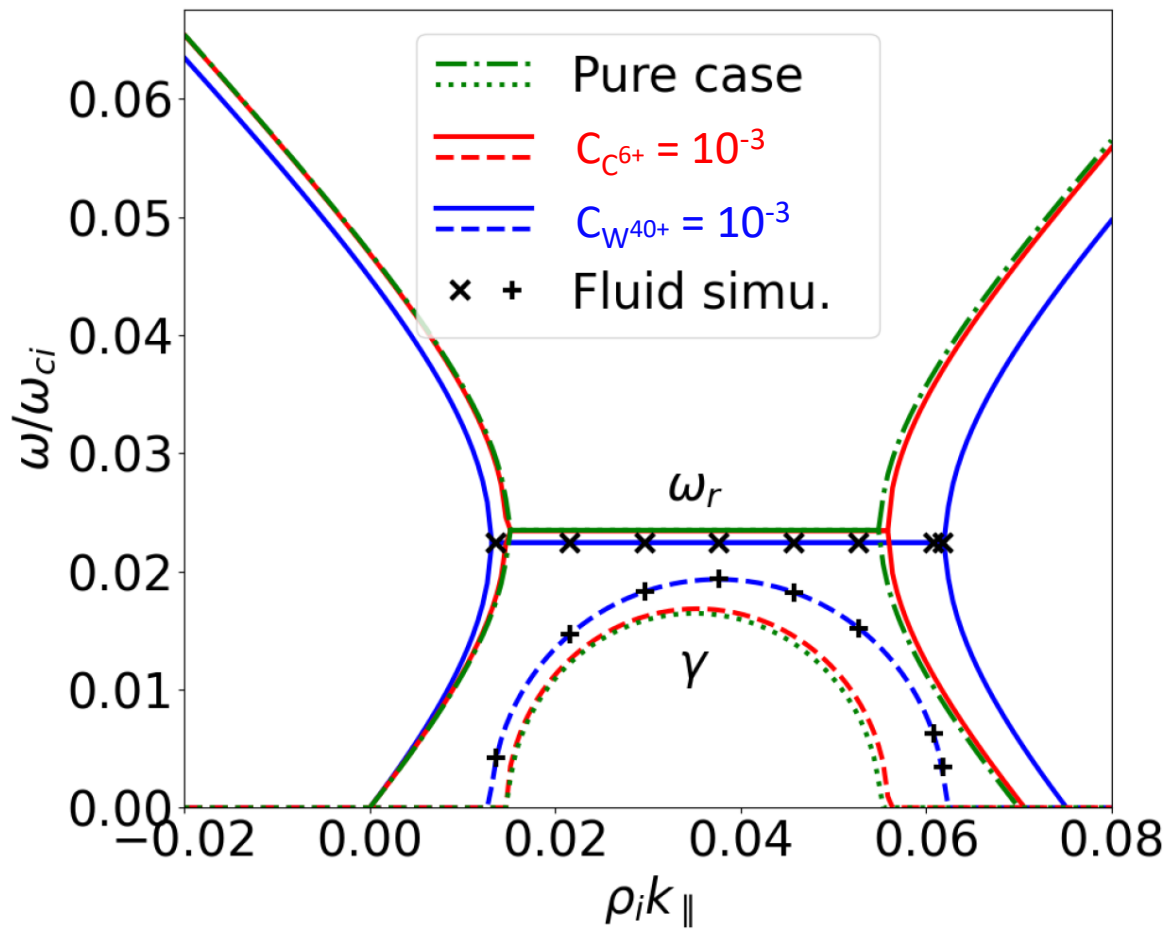
$$\omega_{\text{iDW}} = \frac{k_y v_{*,e}}{1 + (k_{\perp} \bar{\rho})^2}$$

$$\bar{\omega}_c = \sum_{s \neq e} C_s Z_s \omega_{c,s}$$

$$V = \nabla u_{\parallel,z,0} / \nabla u_{\parallel,i,0}$$

$L_n / \rho_{c,i}$	$\nabla u_{\parallel,i,0} / \omega_{c,i}$	V
10	0.1	2

$\rho_{c,i} k_x$	$\rho_{c,i} k_y$
0	0.7



[Bourgeois, in preparation]

The i-PVG instability

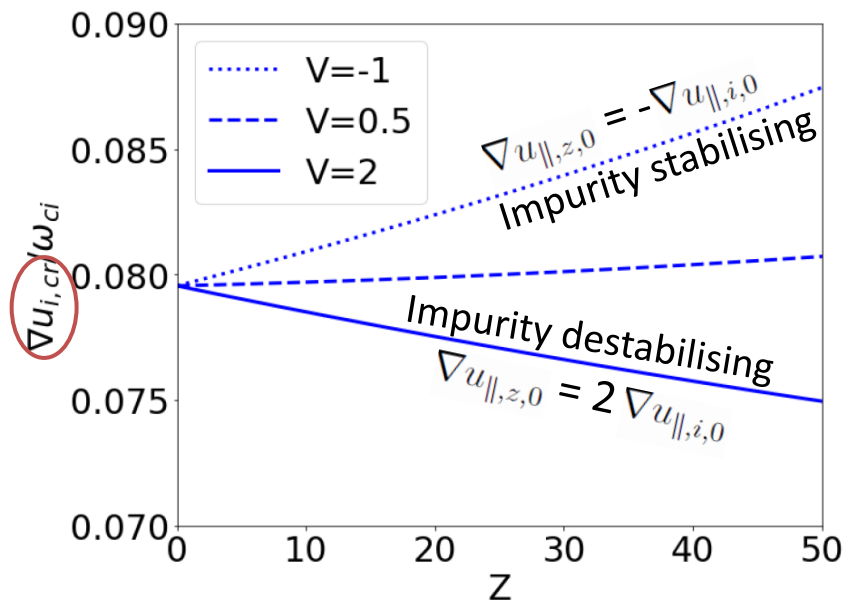
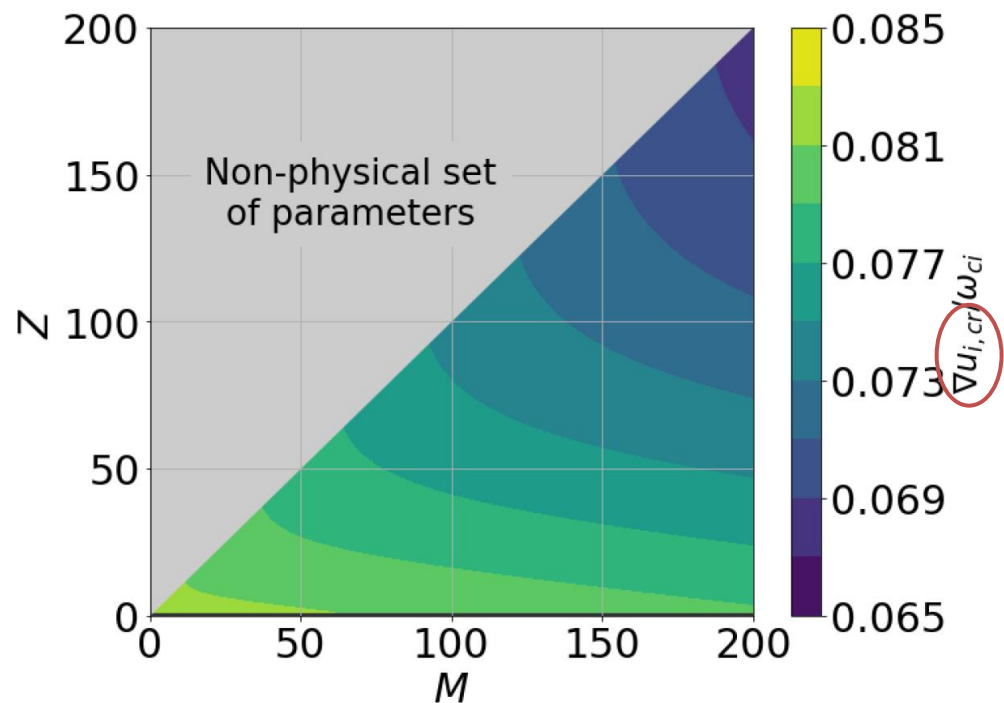
Instability condition

$$|\overline{\nabla u_{\parallel}}| > \overline{\nabla u_{\parallel,cr}} \quad \text{with} \quad \overline{\nabla u_{\parallel,cr}}^2 = \frac{(c_s/L_{n,e})^2}{1 + (k_{\perp}\bar{\rho})^2}$$

OR

$$|\partial_x u_{\parallel,i,0}| > \nabla u_{i,cr} \quad \text{with} \quad \nabla u_{i,cr} = \frac{1}{C_i + V C_Z Z_Z} \overline{\nabla u_{\parallel,cr}}$$

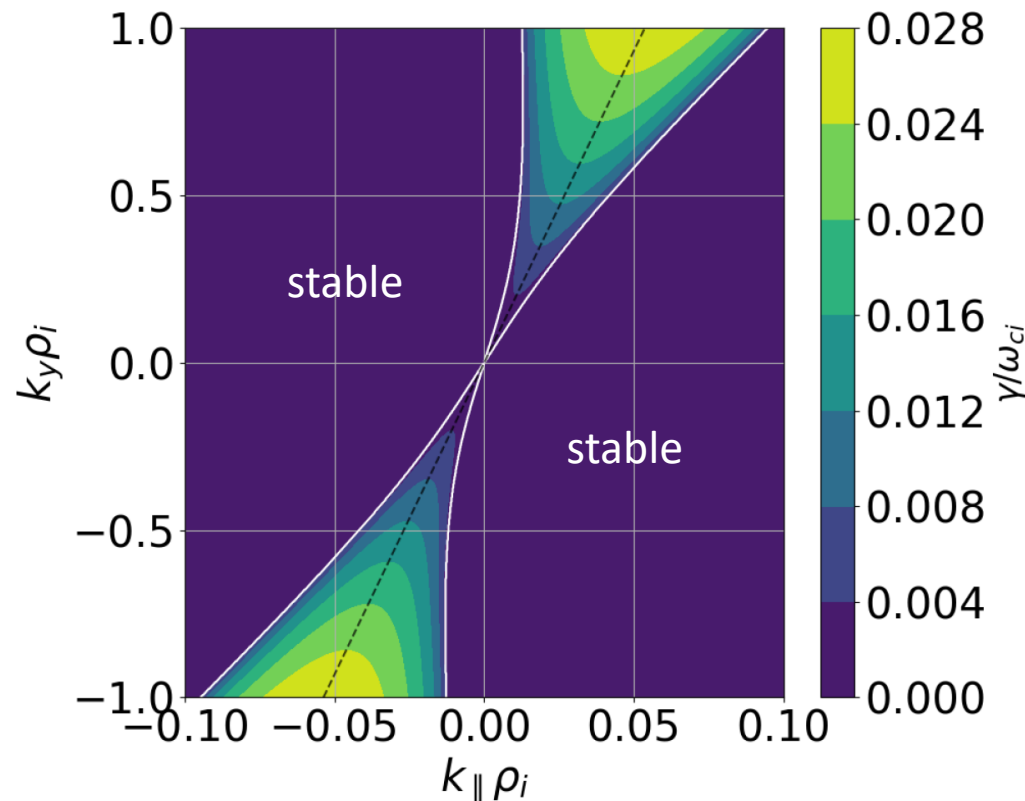
(equivalent)



Maximum growthrate

$$\gamma_{max} = \frac{k_{\perp} v_{*,e}/2}{1 + k_{\perp}^2 \bar{\rho}^2} \left[L_{n,e}^2 (1 + k_{\perp}^2 \bar{\rho}^2) \frac{\overline{\nabla u_{\parallel}}^2}{c_s^2} - 1 \right]^{1/2}$$

(reached for $k_{\parallel} = \frac{\overline{\nabla u_{\parallel}}}{2\bar{\omega}_c} k_y$ and $k_x = 0$)

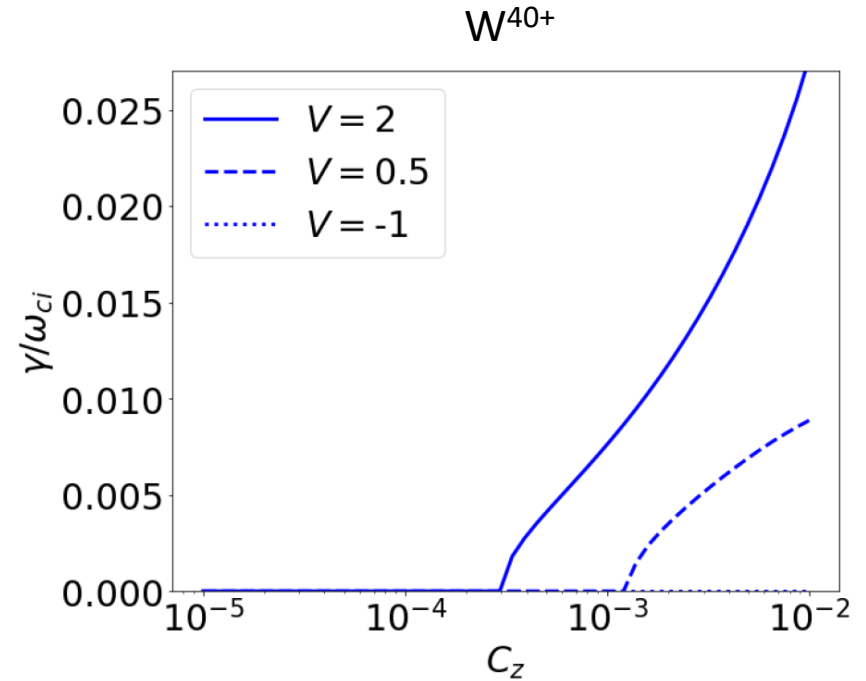
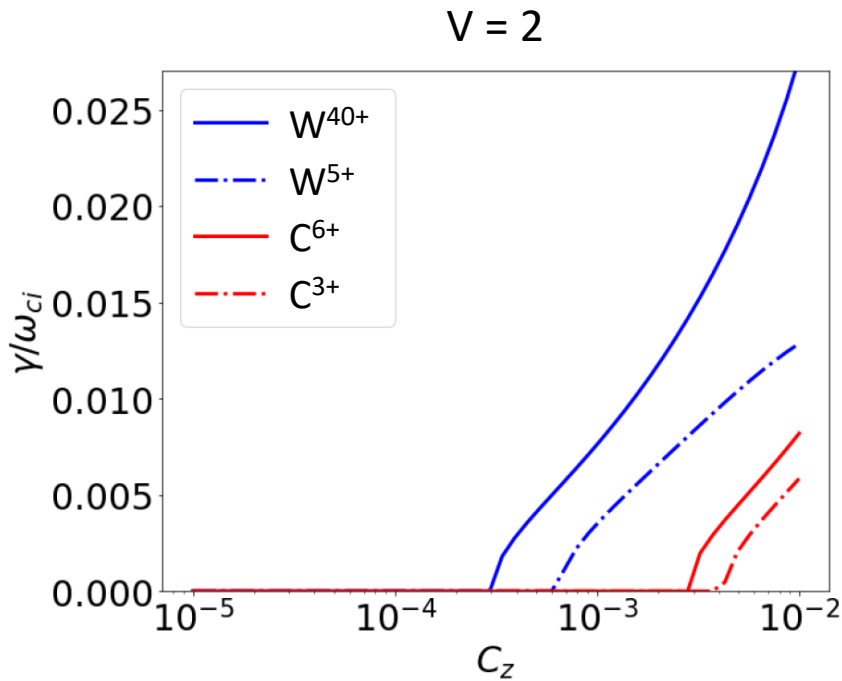


Effects of impurity close to PVG threshold

$L_n/\rho_{c,i}$	$\nabla u_{\parallel,i,0}/\omega_{c,i}$	V
10	0.1 0.08	2

\Rightarrow Pure PVG stable as long as $k_y < 0.75 \rho_{c,i}^{-1}$

Maximum growthrate



Summary & perspectives

Local, linear analysis of the (ideal) impurity-PVG

- Qualitatively: characteristics similar to pure PVG (ex: asym. in $k_y k_{//}$ plane)
- Close to threshold, impurities can have strong impact even at low concent.

Perspectives:

- Dissipative effects: resistivity, viscosity, drag [*Cuerva, in preparation*]
- Finite-Larmor-Radius effects
- Investigate nonlinear saturation and transport
- Coupling with ITG
- Global analysis with realistic boundary conditions



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