Improving global stability analysis of Kolmogorov flows using enstrophy

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Kolmogorov Flows

$$\zeta_t + u\zeta_x + v\zeta_y + \beta\psi_x = -\mu\zeta + \cos x \;+\; \nu\nabla^2\zeta$$

velocity: $(u, v) = (-\psi_y, \psi_x)$ *(2-D periodic domain)*

vorticity: $\zeta(x, y) = v_x - u_y = \nabla^2\psi$

- *single-scaled* sinusoidal body force (at $k_f = 1$)
  - initially used by Kolmogorov (with $\beta = \mu = 0$) to study bifurcations as Reynolds number increases
  - subsequent work by others: viscous linear stability (*Meshalkin & Sinai*), weakly nonlinear theory (*Sivashinsky*), energy stability (*Fukuta & Murakami*)
  - quasi-2D laboratory experiments with approximate sinusoidal forcing (e.g. *Rivera & Wu, Burgess et al.*)

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- Two-dimensional flows:
  - dual conservation of energy E and enstrophy Z,

$$E = \frac{1}{2}\left\langle |\nabla\psi|^2 \right\rangle, \qquad Z = \frac{1}{2}\left\langle (\nabla^2\psi)^2 \right\rangle$$

  - nonlinear interactions transfer E simultaneously up ($k < 1$) and down ($k > 1$) scale
  - large-scale dissipation (e.g. sidewall drag, Ekman friction) needed to achieve statistically steady state

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- Geophysical flows:
  - variation of the Coriolis parameter with latitude modeled using the β-plane approximation
  - Kolmogorov flow on a β-plane as a model of zonal jet formation

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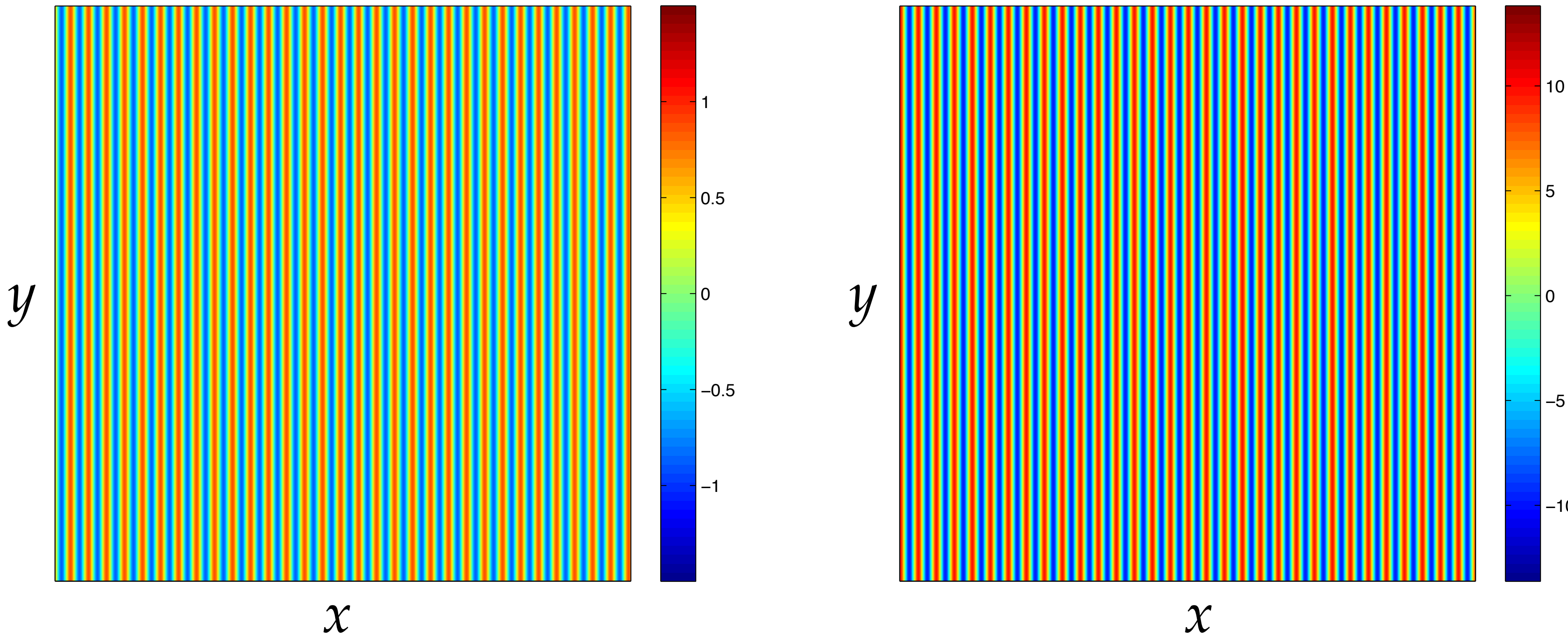
We shall first consider the inviscid case: $\nu = 0$

Stability of the Laminar Solution

$$\zeta_{\mathsf{L}}(x) = a\cos(x - x_\beta)$$

$$a = \frac{1}{\sqrt{\beta^2 + \mu^2}} \quad , \quad x_\beta = \tan^{-1}\frac{\beta}{\mu}$$



$\mu = 0.5 \quad \beta = 1.0$ $\mu = 0.1 \quad \beta = 0.0$

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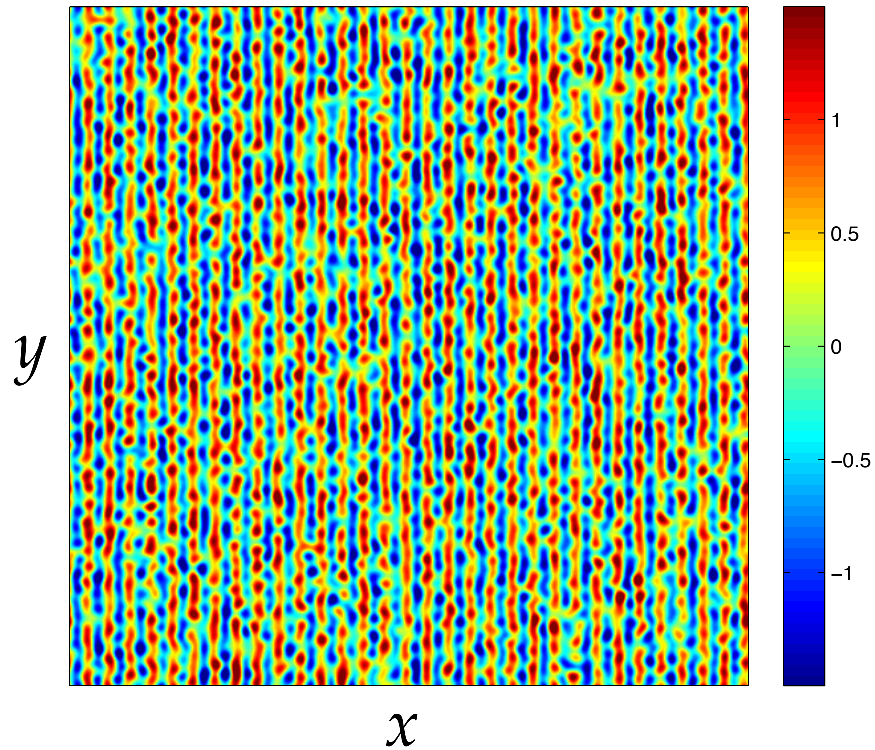

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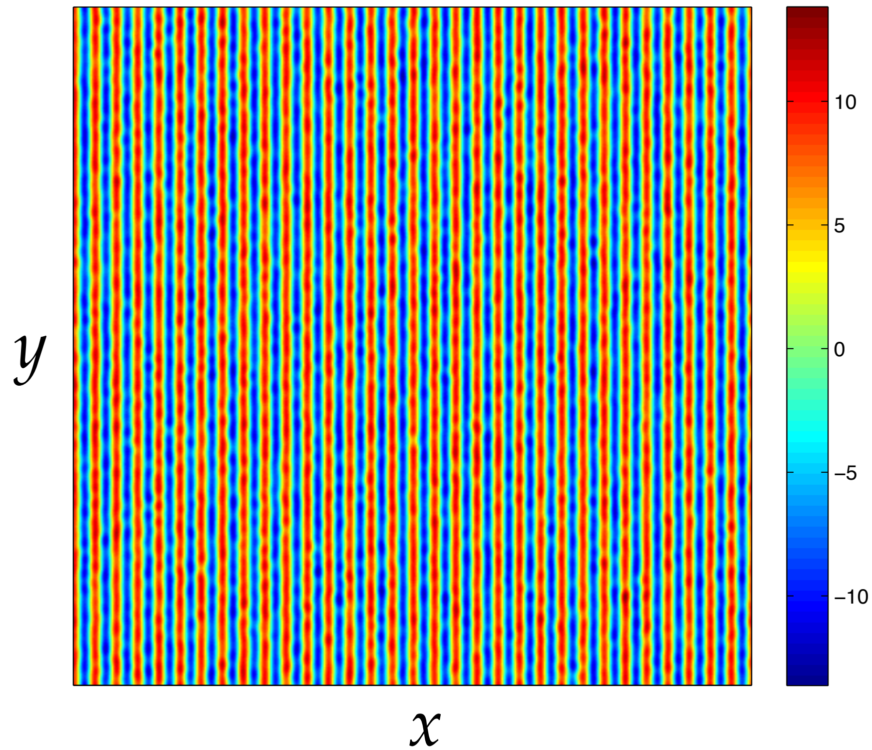

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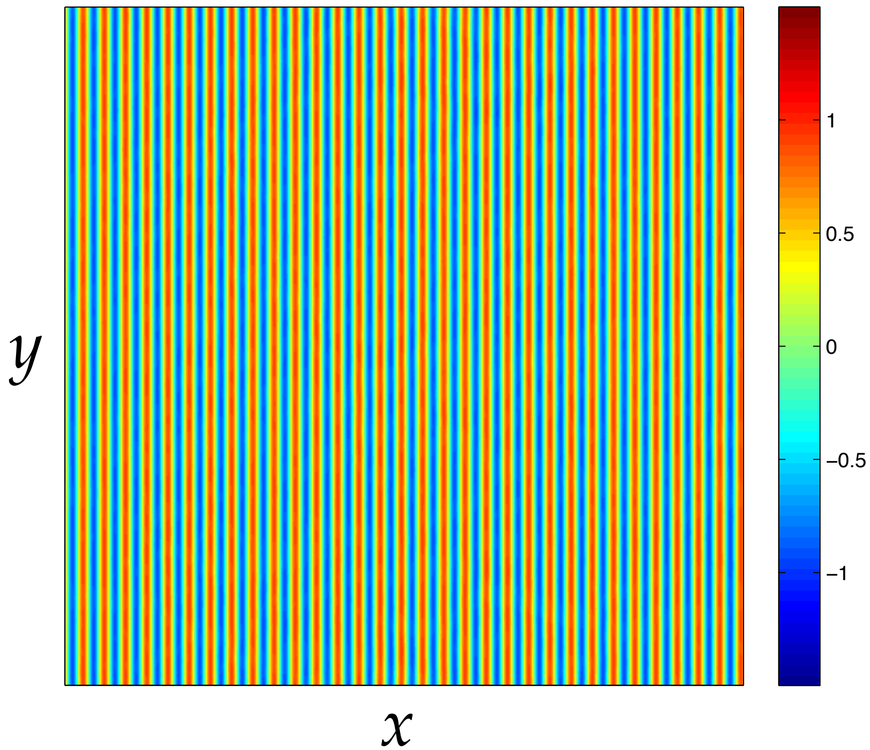

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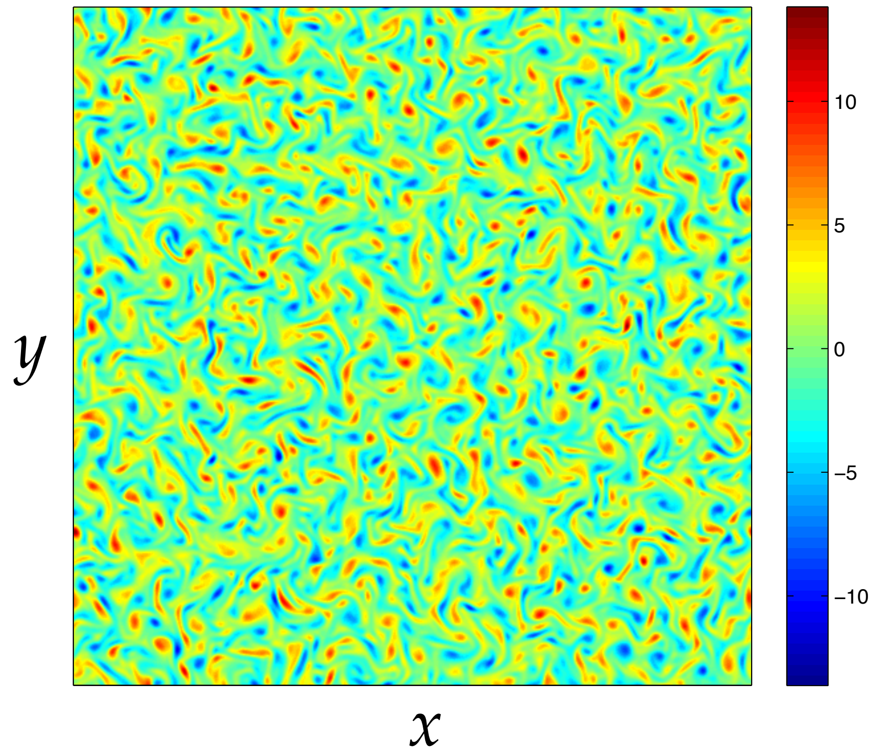
stable

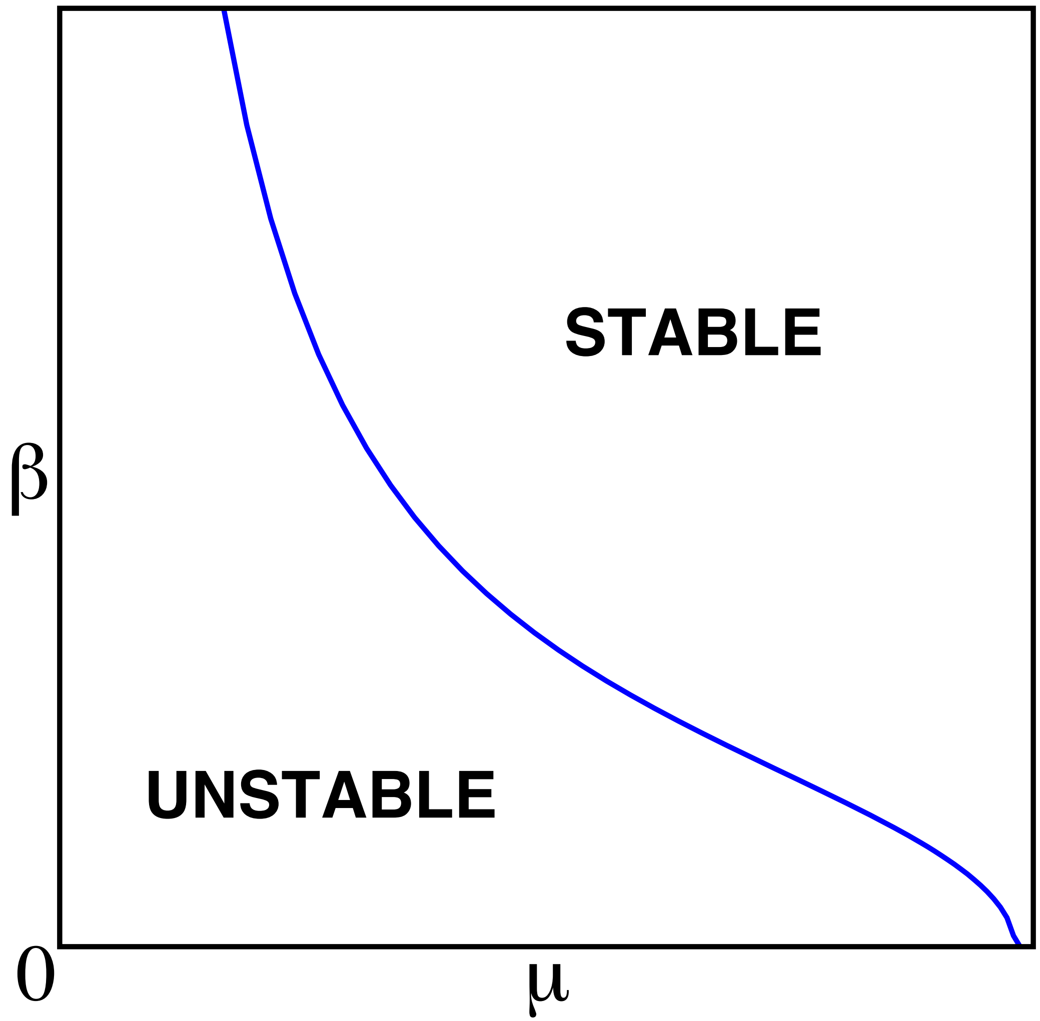


$\mu = 0.1 \quad \beta = 0.0$

unstable

Goal: Neutral Curve

$$\zeta_t + u\zeta_x + v\zeta_y + \beta\psi_x = -\mu\zeta + \cos x$$



Stability Analysis

$$\psi(x,y,t) = \psi_{\mathsf{L}}(x) + \varphi(x,y,t)$$

- Linear Instability
  - assume infinitesimal disturbance $\varphi \sim e^{-i\omega t}$
  - $\Im\{\omega\} > 0 \;\Rightarrow\; \psi_{\mathsf{L}}$ is unstable
  - gives sufficient condition for instability
- Global Stability (Asymptotic Stability)
  - φ is *not* assumed to be small
  - **disturbance energy**

$$E_{\varphi}(t) = \frac{1}{2}\left\langle |\nabla\varphi|^2 \right\rangle \to 0 \quad as \quad t \to \infty$$

  - gives sufficient condition for stability

Energy Method

$$\nabla^2\psi_t + J(\psi, \nabla^2\psi) + \beta\psi_x = -\mu\nabla^2\psi + \cos x$$

$$\psi_{\mathsf{L}}(x) = -a\cos(x - x_\beta)$$

Time evolution equation for φ $(\psi = \psi_{\mathsf{L}} + \varphi)$:

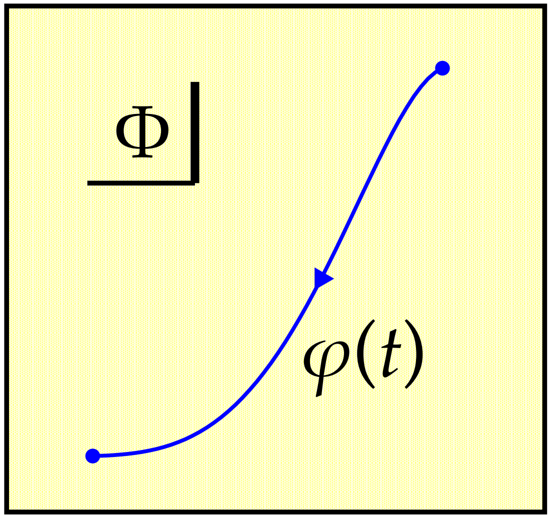
$$\nabla^2\varphi_t + J(\psi_{\mathsf{L}}, \nabla^2\varphi) + J(\varphi, \nabla^2\psi_{\mathsf{L}}) + J(\varphi, \nabla^2\varphi) + \beta\varphi_x = -\mu\nabla^2\varphi$$

$$\therefore \qquad \frac{dE_\varphi}{dt} = \left\langle \varphi J(\psi_{\mathsf{L}}, \nabla^2\varphi) \right\rangle - \mu\left\langle |\nabla\varphi|^2 \right\rangle$$

$$= a\left\langle \varphi_x\varphi_y\cos x \right\rangle - 2\mu E_\varphi$$

Energy Method

$$\frac{dE_\varphi}{dt} = 2\left(a\mathcal{R}[\varphi] - \mu \right) E_\varphi$$



where $$\mathcal{R}[\varphi] \equiv \frac{\left\langle \varphi_x \varphi_y \cos x \right\rangle}{\left\langle |\nabla\varphi|^2 \right\rangle}$$

Now define $$\mathcal{R}_* \equiv \max_{\varphi \in \Phi} \mathcal{R}[\varphi]$$

Φ : *set of all functions satisfying periodic boundary conditions*

Then,

$$\frac{dE_\varphi}{dt} < 2\left(a\mathcal{R}_* - \mu \right) E_\varphi$$

Energy Method

By Gronwall's inequality,

$$\frac{dE_\varphi}{dt} < 2\left(a\mathcal{R}_* - \mu\right) E_\varphi$$

$$\Rightarrow \quad E_\varphi(t) < E_\varphi(0)\, e^{2(a\mathcal{R}_* - \mu)t}$$

$$\therefore \quad E_\varphi(t \to \infty) \to 0 \quad \mathit{if} \quad a\mathcal{R}_* - \mu < 0$$

Neutral condition

$$a = \frac{1}{\mathcal{R}_*}\mu \quad \Rightarrow \quad \boxed{\beta = \sqrt{\frac{\mathcal{R}_*^2}{\mu^2} - \mu^2}}$$

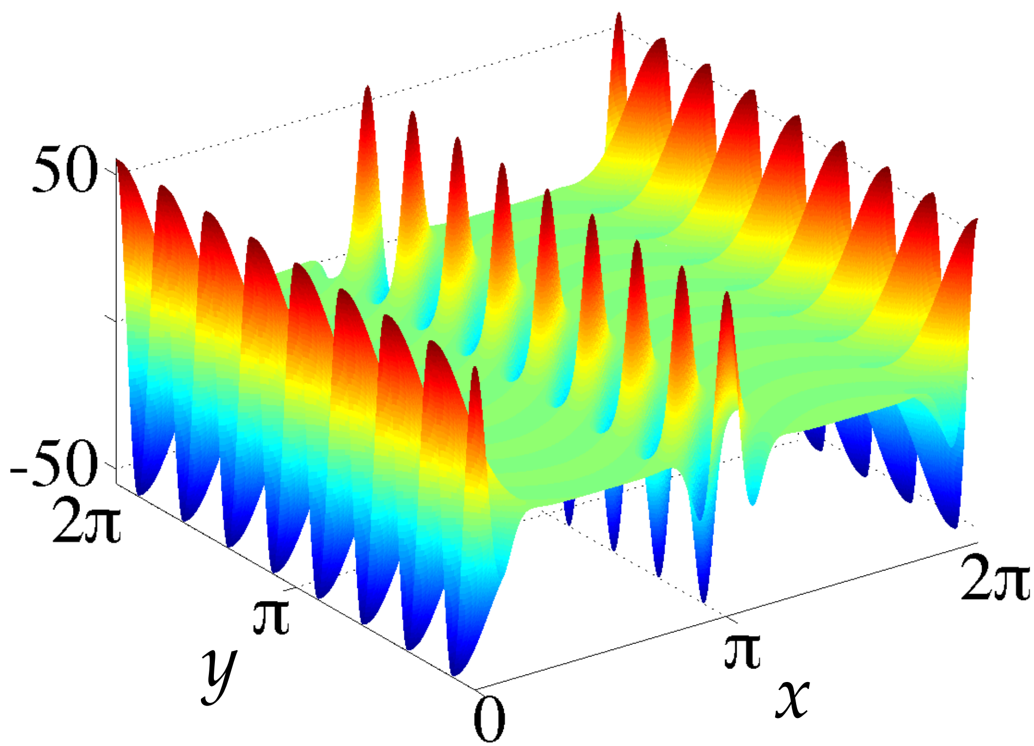
Variational Results

Maximize: $\quad \mathcal{R}[\varphi] \equiv \dfrac{\left\langle \varphi_x \, \varphi_y \, \cos x \right\rangle}{\langle |\nabla \varphi|^2 \rangle}$ over the set Φ.

Optimal solution

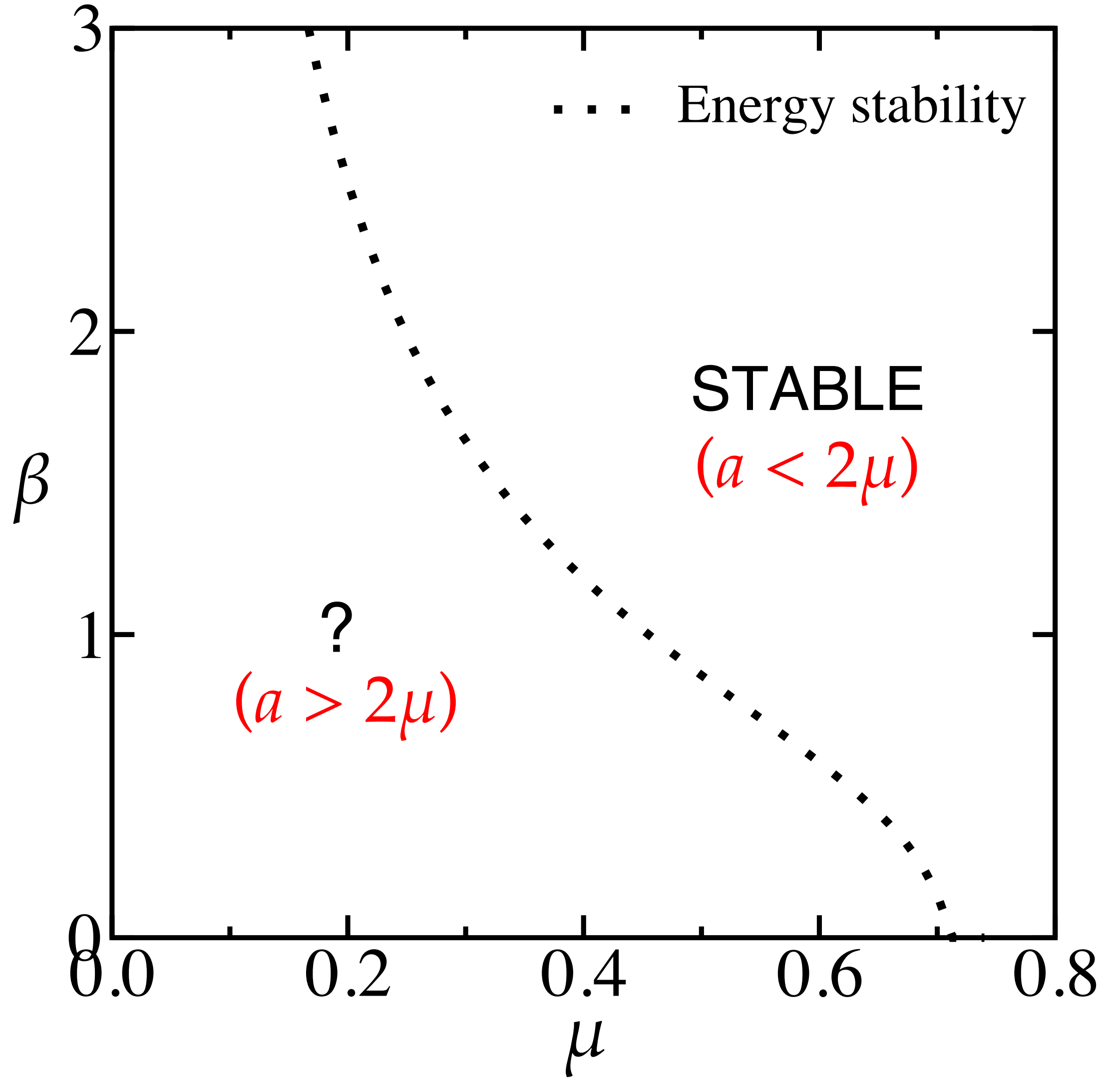
$$\mathcal{R}_* = \mathcal{R}[\varphi_*] = \frac{1}{2}$$

$$\varphi_*(x, y) \approx \lim_{l \to \infty} \cos\left[l(y + \sin x)\right] \exp\left(\frac{l}{2} \cos 2x\right)$$



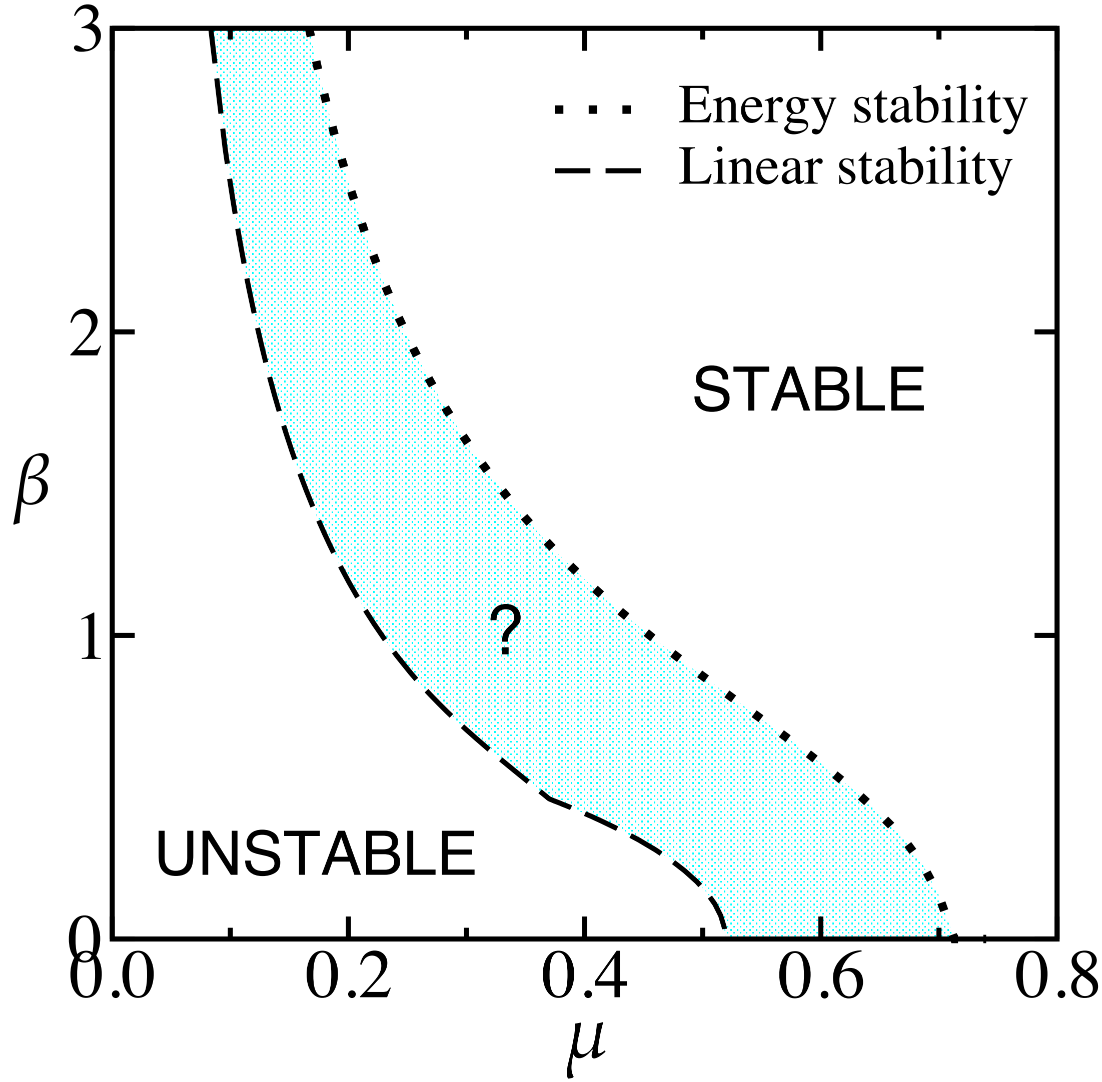
Energy Stability Curve

$$\beta = \sqrt{\frac{1}{4\mu^2} - \mu^2} \qquad (a = 2\mu)$$



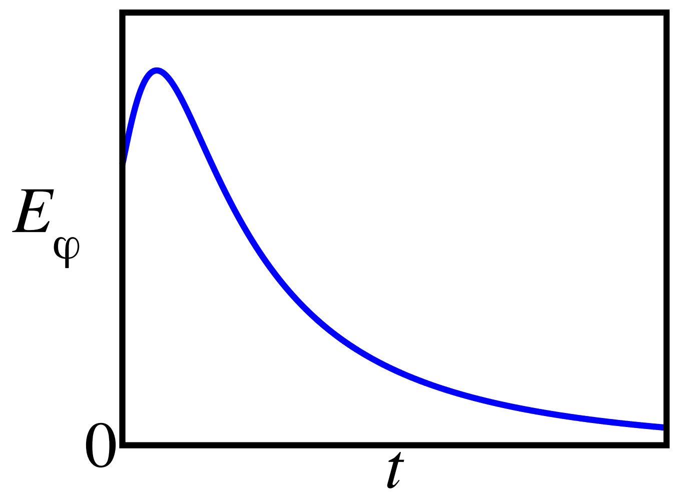
Energy Stability and Linear Stability Curve

$$\beta = \sqrt{\frac{1}{4\mu^2} - \mu^2} \qquad (a = 2\mu)$$



Limitations of the Energy Method

- requires $E_\varphi(t)$ to decrease monotonically for all φ, thus excludes transient growth of $E_\varphi(t)$



- the most efficient energy-releasing disturbance $\varphi_*(x, y)$ is unphysical: $l \to \infty$

- a gap between the energy stability curve and the neutral curve from linear stability analysis

Energy-Enstrophy Balance

Disturbance enstrophy: $Z_\varphi = \frac{1}{2}\left\langle (\nabla^2\varphi)^2 \right\rangle$

$$\frac{dZ_\varphi}{dt} = a\left\langle \varphi_x\,\varphi_y \cos x \right\rangle - 2\mu Z_\varphi$$

Recall,

$$\frac{dE_\varphi}{dt} = a\left\langle \varphi_x\,\varphi_y \cos x \right\rangle - 2\mu E_\varphi$$

Then,

$$\frac{d}{dt}(E_\varphi - Z_\varphi) = -2\mu(E_\varphi - Z_\varphi)$$

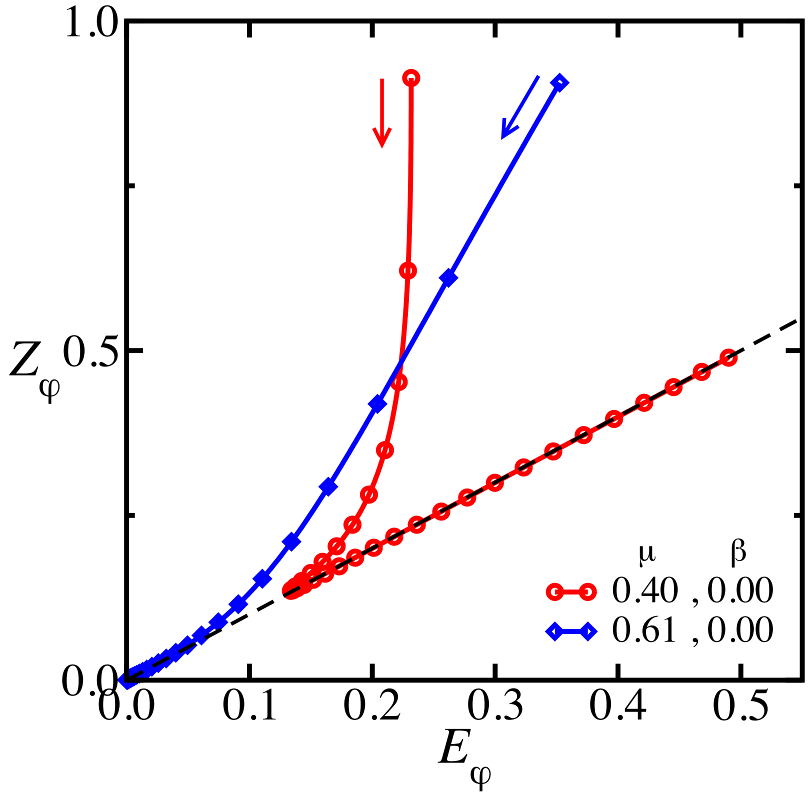
$$\boxed{E_\varphi(t) - Z_\varphi(t) = e^{-2\mu t}\left[E_\varphi(0) - Z_\varphi(0)\right]}$$

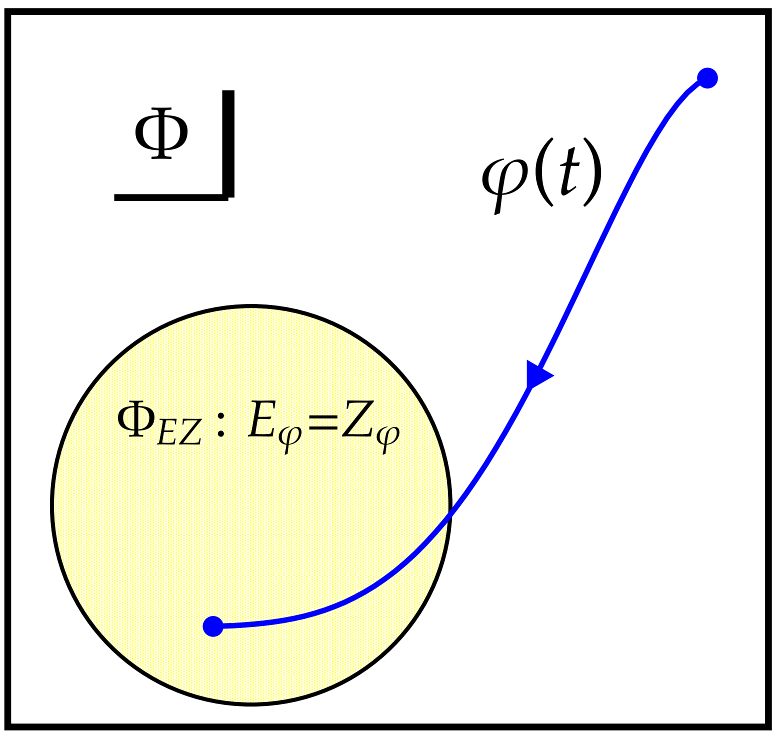
Energy-Enstrophy Balance

$$E_\varphi(t) - Z_\varphi(t) \to 0 \quad as \quad t \to \infty$$

$$\Phi_{EZ} = \{\varphi \in \Phi \ \text{such that} \ E_\varphi = Z_\varphi\}$$

$$\Rightarrow \Phi_{EZ} \ \text{attracts all initial conditions}$$





Optimization with Constraints

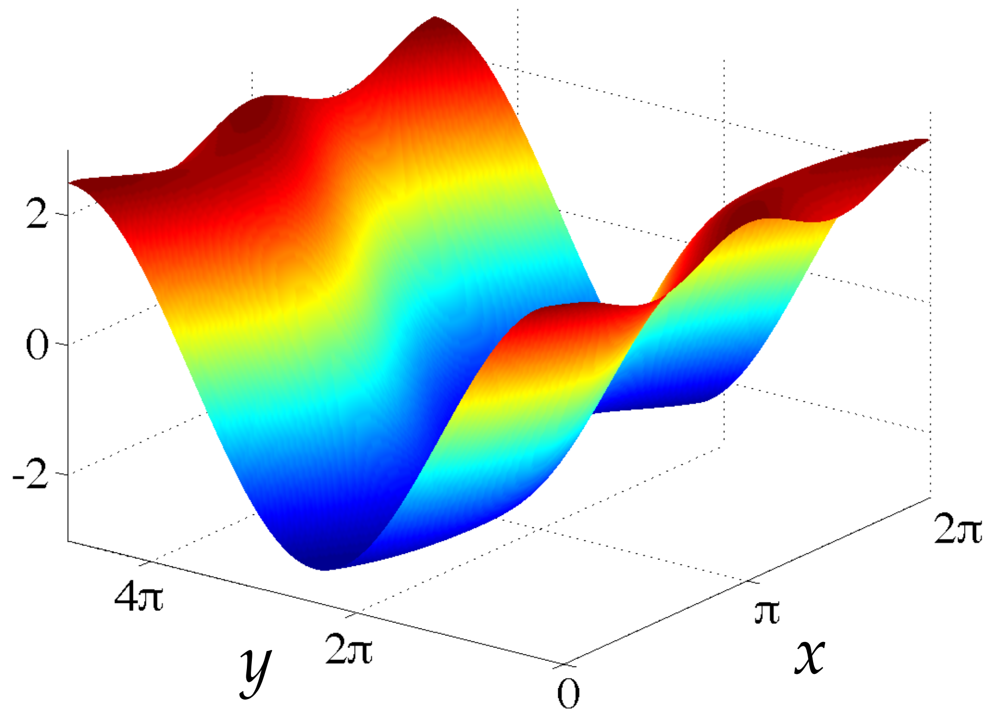
Maximize: $$\mathcal{R}[\varphi] \equiv \frac{\left\langle \varphi_x \, \varphi_y \cos x \right\rangle}{\langle |\nabla \varphi|^2 \rangle}$$

with constraint $$\langle |\nabla \varphi|^2 \rangle = \langle (\nabla^2 \varphi)^2 \rangle$$

Optimal solution

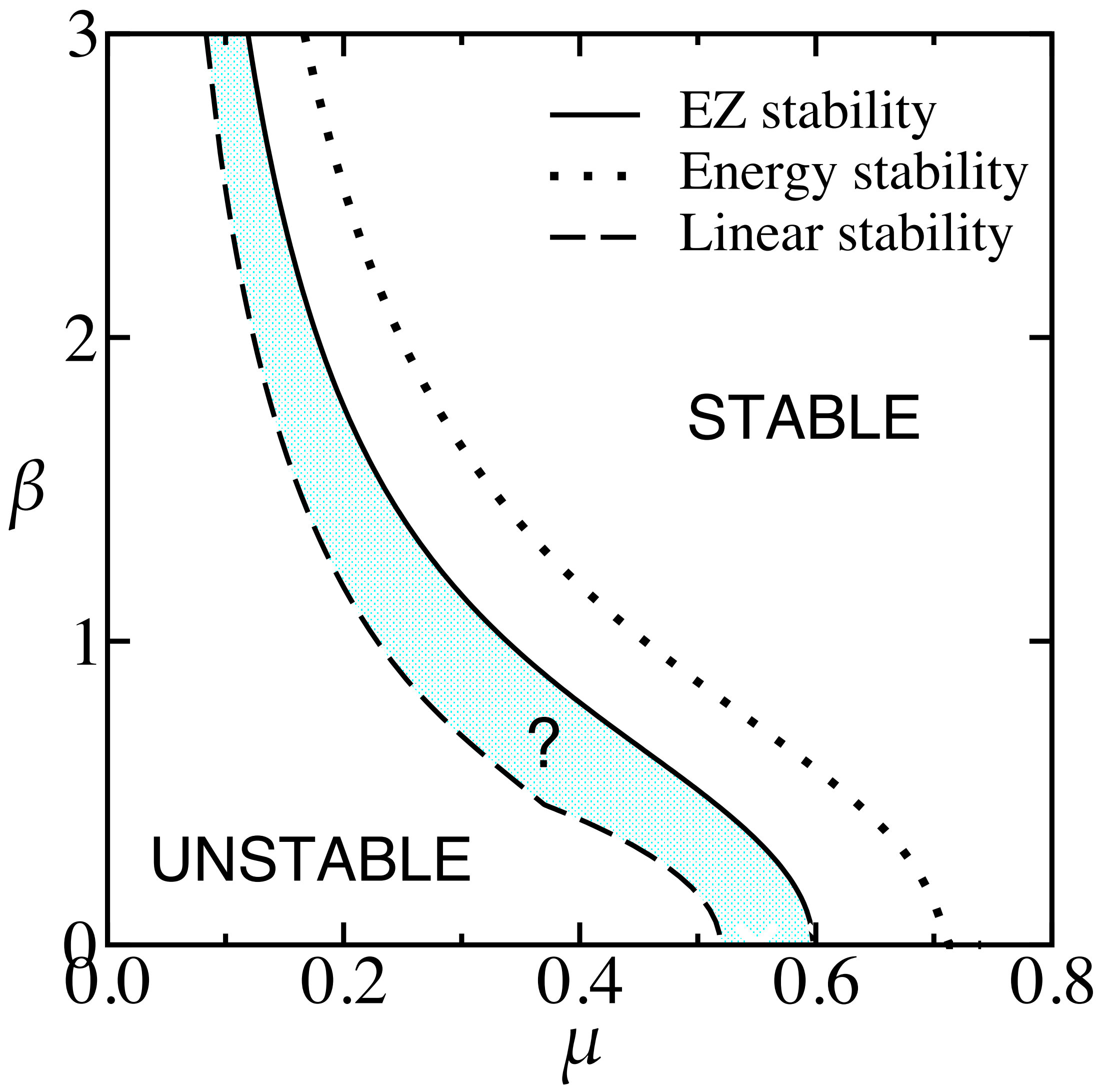
$$\mathcal{R}_* = \mathcal{R}[\varphi_*] = 0.3571$$

$$\varphi_*(x,y) = \mathfrak{R}\left\{ e^{\mathrm{i}\, l\, y} \, \tilde{\varphi}(x) \right\} \quad \textit{with} \quad l \approx 0.4166$$



Energy-Enstrophy (EZ) Stability $(\nu = 0)$

$$\beta = \sqrt{\frac{0.13}{\mu^2} - \mu^2} \qquad (a = 2.8\mu)$$



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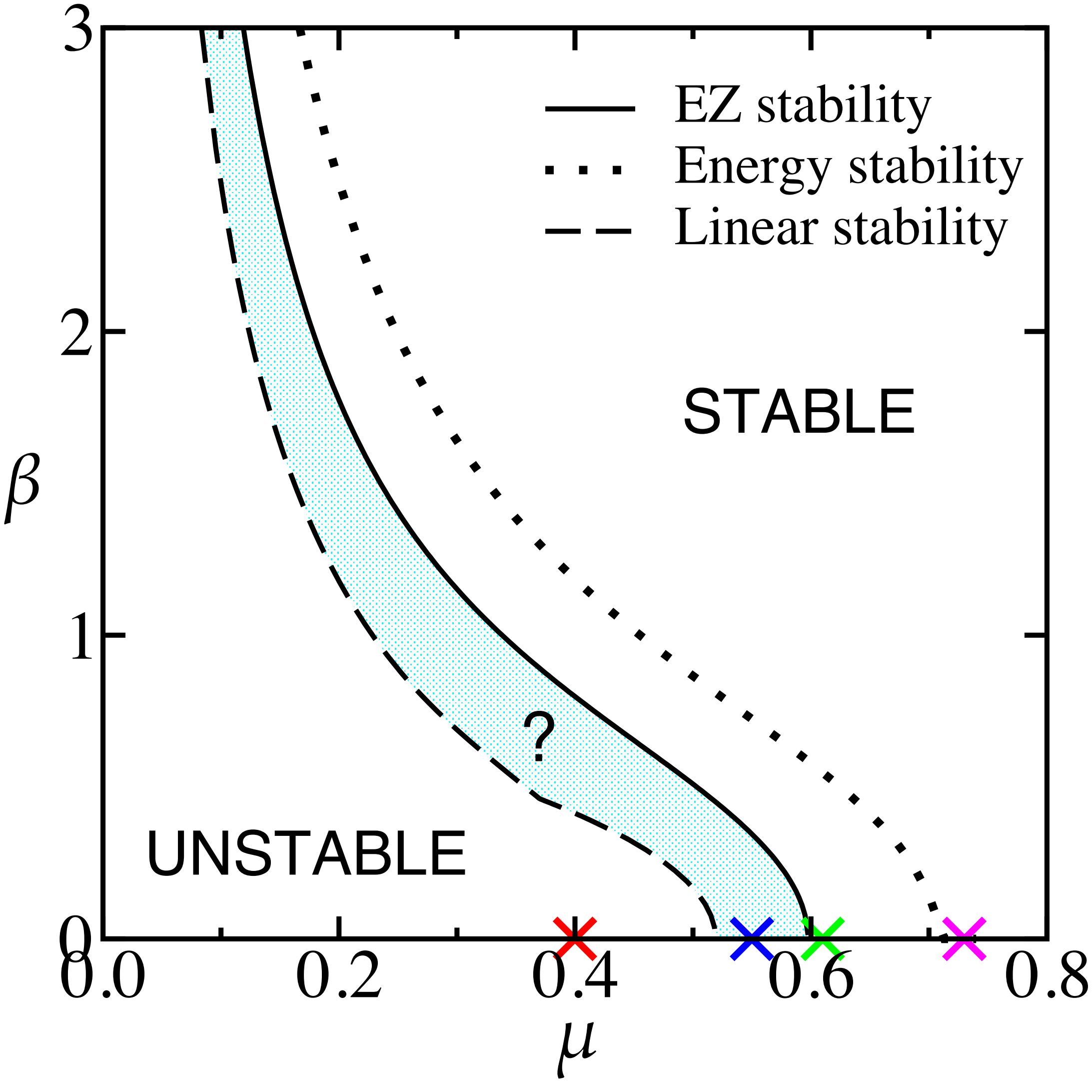

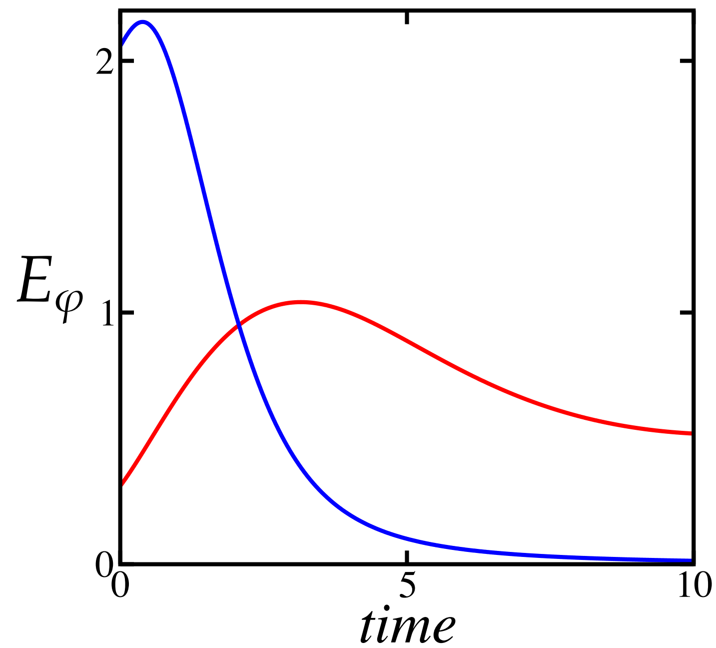

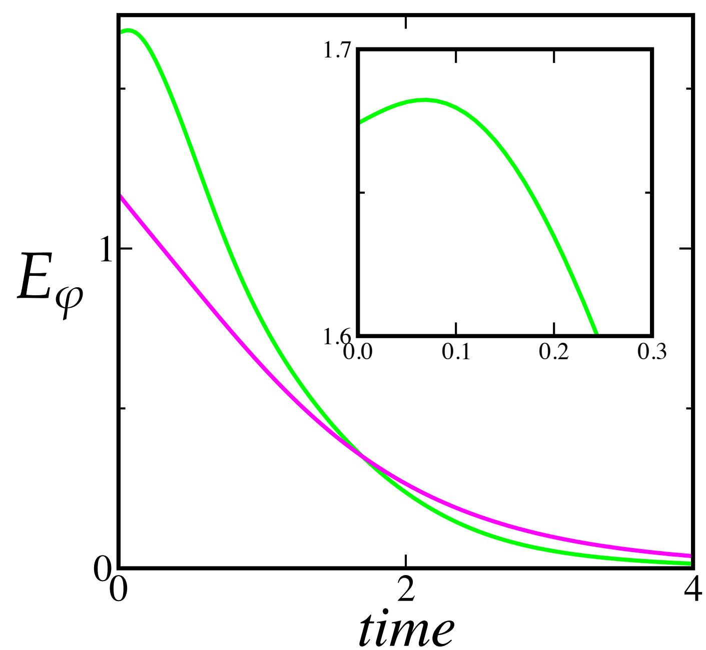

The viscous case: $\nu > 0$

$$\nabla^2\psi_t + J(\psi, \nabla^2\psi) + \beta\psi_x = -\mu\nabla^2\psi + \cos x \; + \; \nu\nabla^2\zeta$$

$$\psi_{\mathrm{L}}(x) = -a\cos(x - x_\beta)$$

$$a = \frac{1}{\sqrt{\beta^2 + (\mu+\nu)^2}}$$

$$\frac{dE_\varphi}{dt} = a\left\langle \varphi_x\,\varphi_y\cos x\right\rangle - 2\mu E_\varphi + 2\nu Z_\varphi$$

$$\frac{dZ_\varphi}{dt} = a\left\langle \varphi_x\,\varphi_y\cos x\right\rangle - 2\mu Z_\varphi + 2\nu P_\varphi$$

$$P_\varphi = \frac{1}{2}\left\langle |\nabla(\nabla^2\varphi)|^2\right\rangle$$

Extended Energy-Enstrophy (EEZ) Stability

Consider a family of norm with the parameter α:

$$Q(\alpha) = (1 - \alpha)\, E_{\varphi} + \alpha\, Z_{\varphi}\,, \quad 0 \leqslant \alpha \leqslant 1$$

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = 2\left\{ \mathcal{R}_Q[\varphi; \alpha, \nu, a] - \mu \right\} Q$$

Global stability : $Q(\alpha) \to 0$ as $t \to \infty$ for some α .

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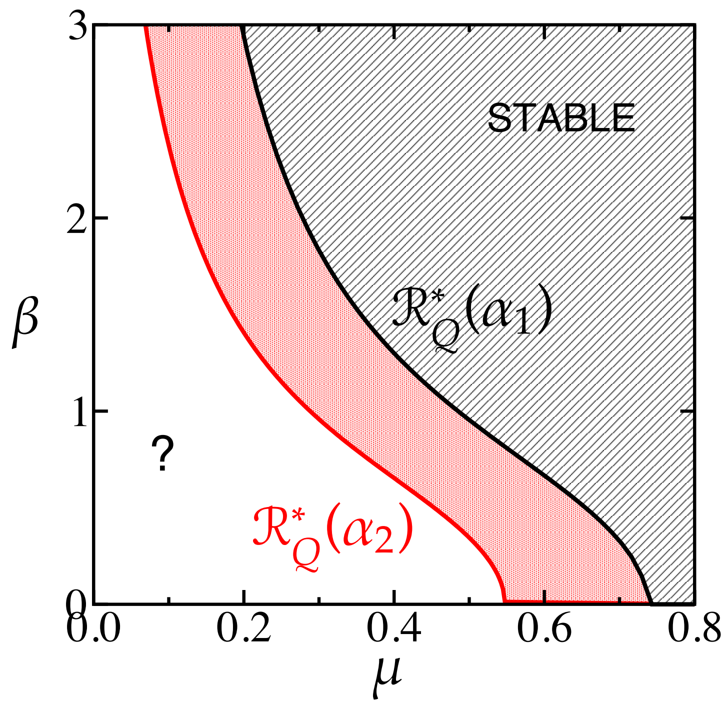
$$\mathcal{R}^*_Q(\alpha, \nu, a) = \max_{\varphi \in \Phi} \mathcal{R}_Q[\varphi; \alpha, \nu, a]$$

For each α, neutral condition : $\mathcal{R}^*_Q(\alpha, \nu, a) = \mu$



$\mathcal{R}^*_Q(\alpha_2) < \mathcal{R}^*_Q(\alpha_1)$

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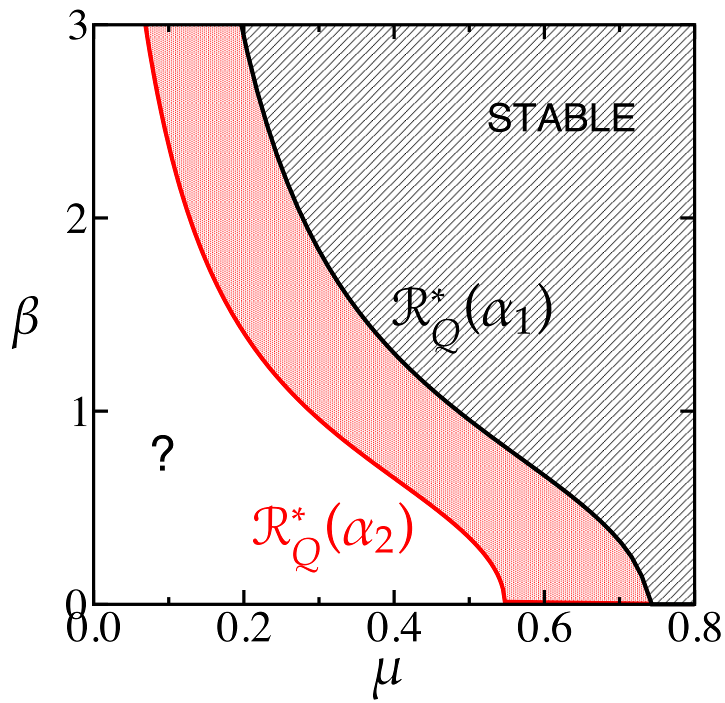
$$\mathcal{R}_Q^*(\alpha,\nu,a) = \max_{\varphi\in\Phi} \mathcal{R}_Q[\varphi;\alpha,\nu,a]$$

For each α, neutral condition : $\mathcal{R}_Q^*(\alpha,\nu,a) = \mu$

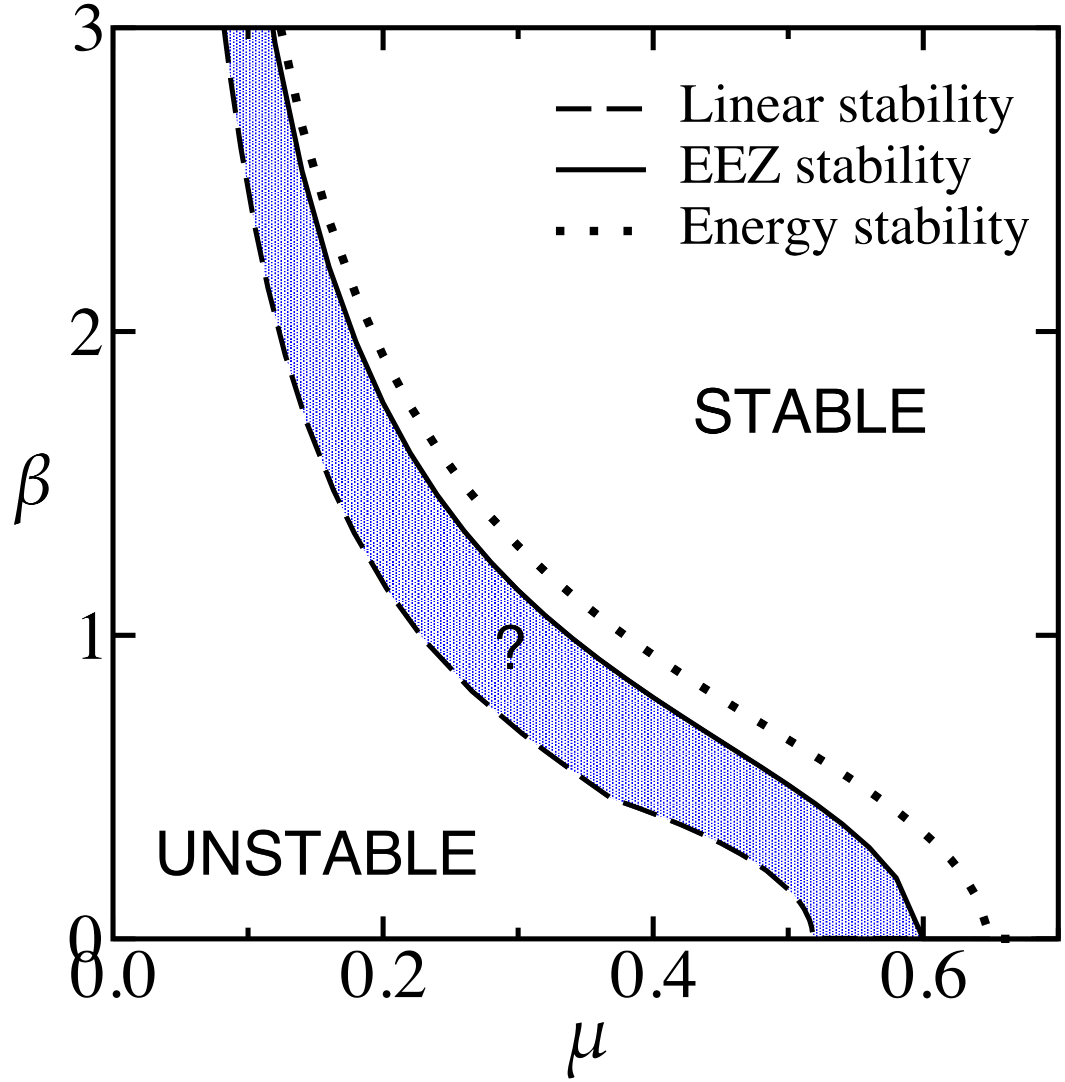
"Optimal" neutral condition : $\min_\alpha \mathcal{R}_Q^*(\alpha,\nu,a) = \mu$

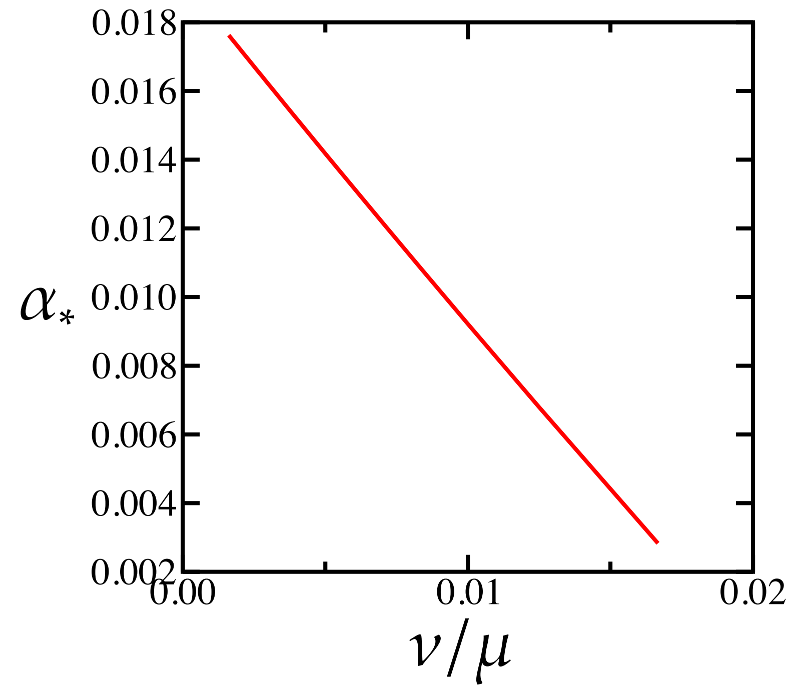


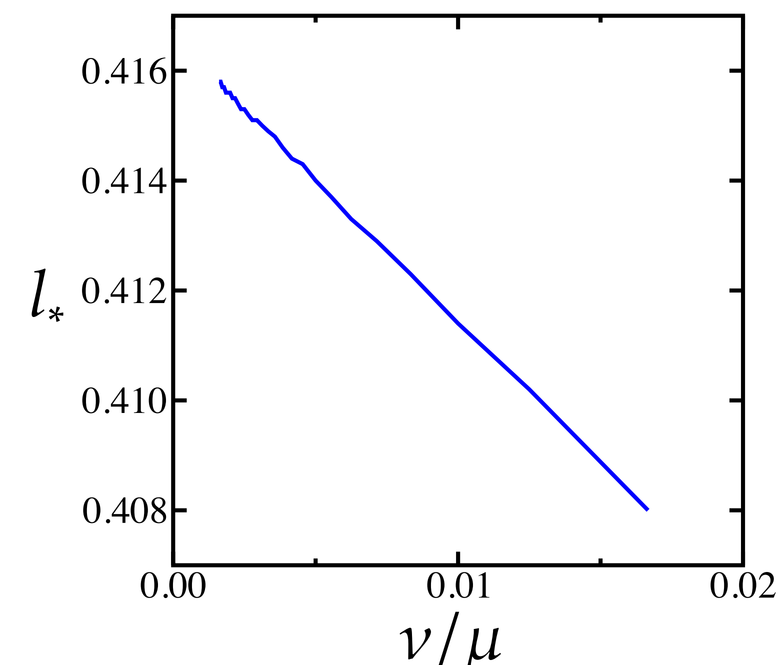
$\mathcal{R}_Q^*(\alpha_2) < \mathcal{R}_Q^*(\alpha_1)$

Extended EZ Stability $(\nu = 10^{-3})$

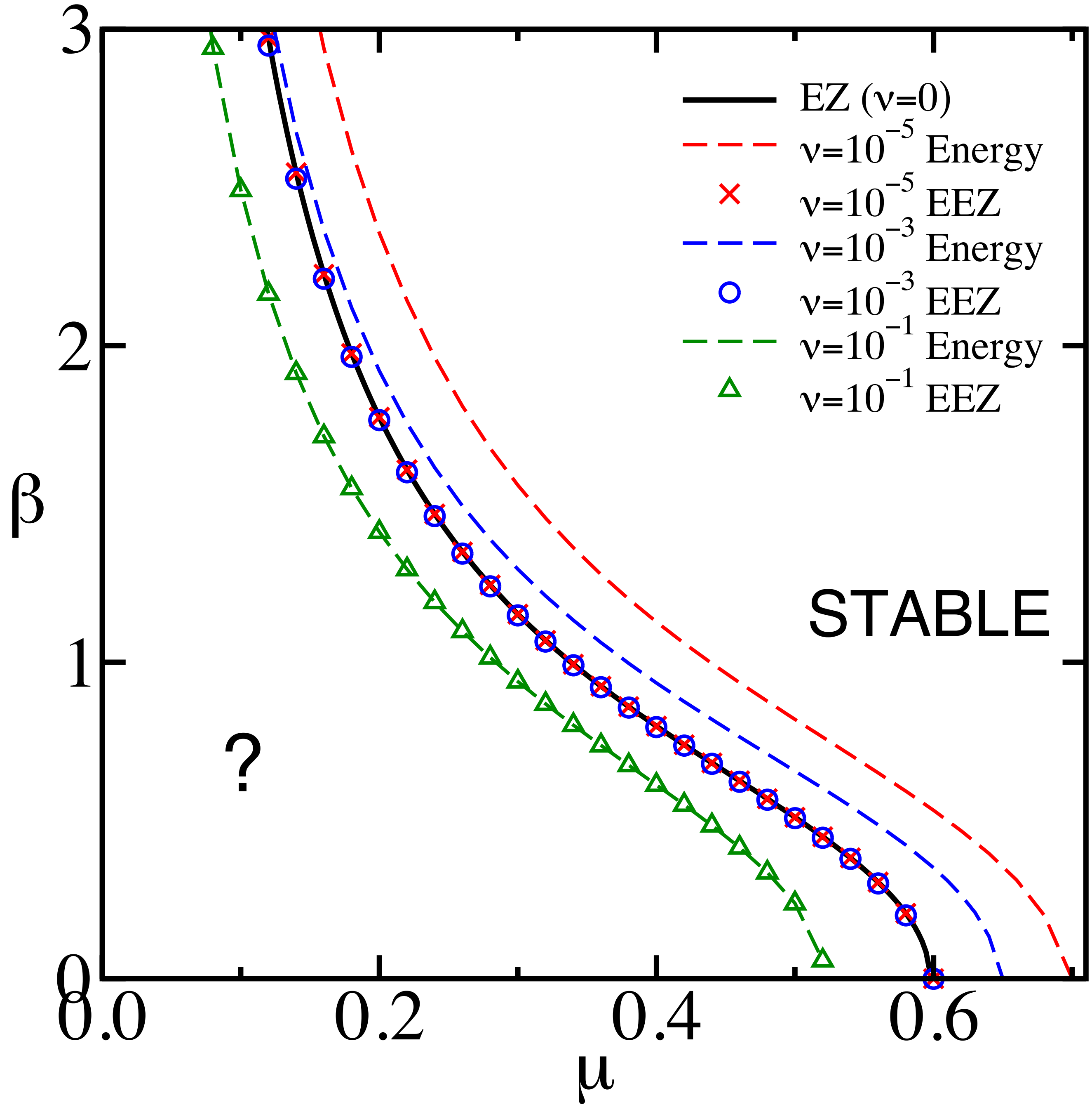
$$Q(\alpha) = (1-\alpha)\, E_\varphi + \alpha\, Z_\varphi$$







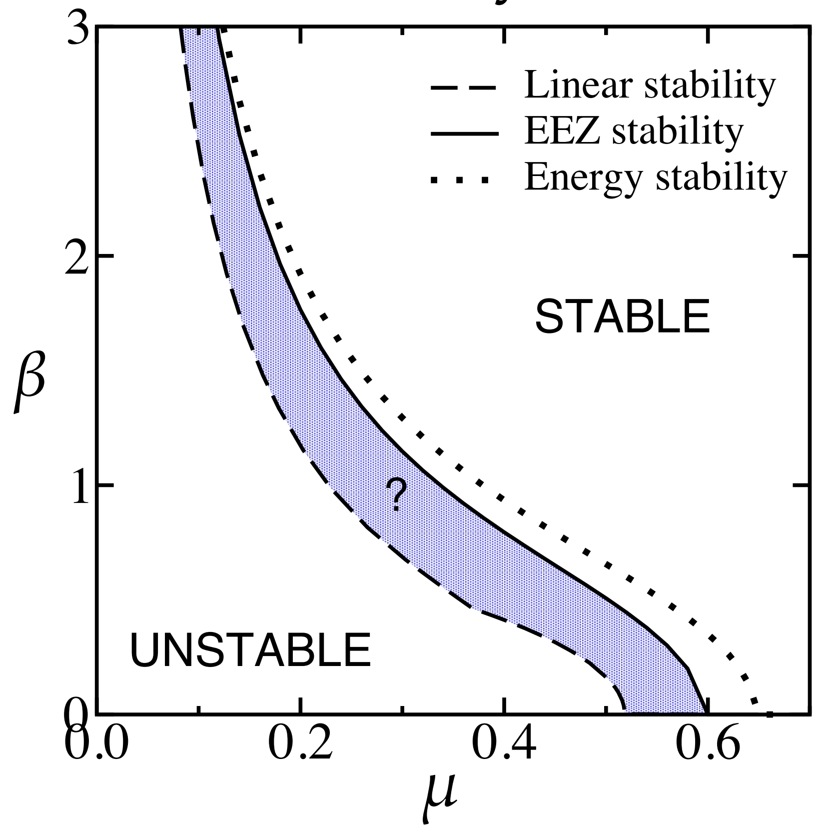
Extended EZ Stability for different ν



Summary

By incorporating information based on the enstrophy, we develop the EZ and EEZ stability method which

- allows transient growth in $E_{\varphi}(t)$ $\;(\,\varphi(t=0) \notin \Phi_{EZ}\,)$
- identifies a physically realistic most-unstable disturbance
- lies closer to the linear stability neutral curve



EZ stability: Tsang & Young, Phys. Fluids **20**, 084102 (2008)