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The strain field of light jets

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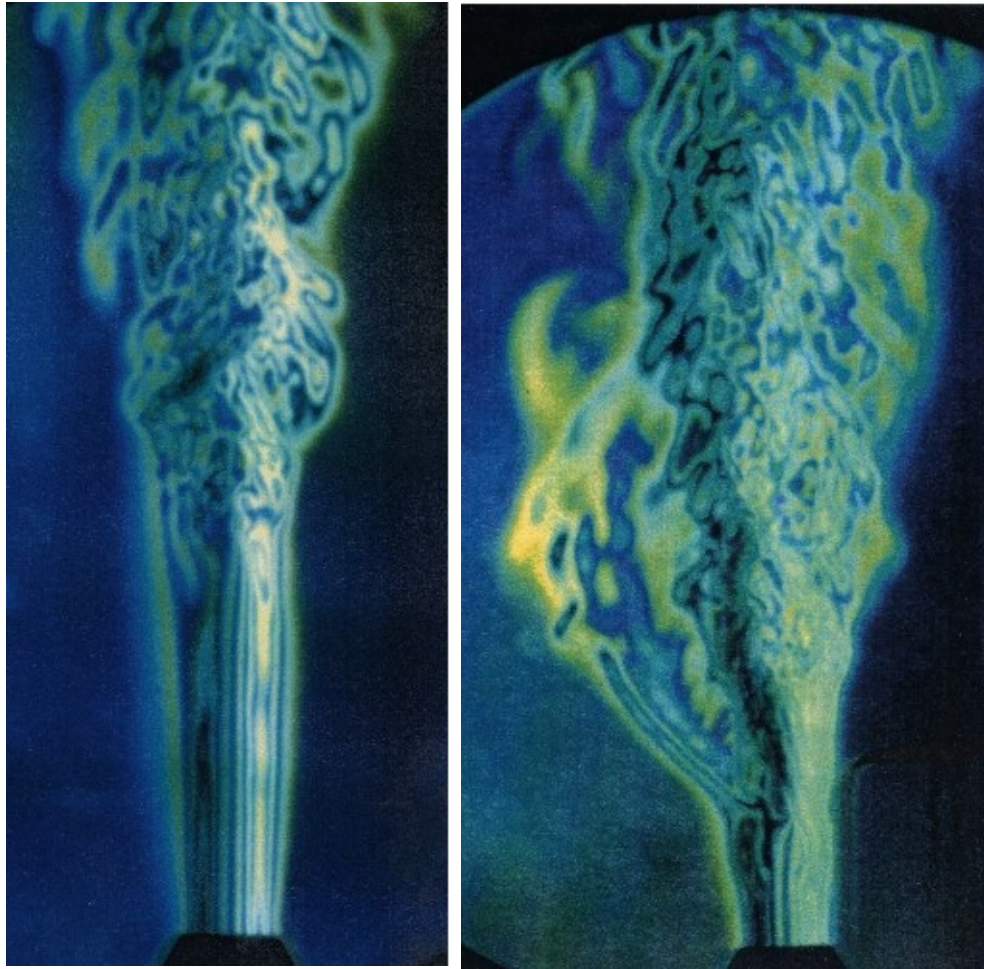
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Outline

- Specific features of light jets
- Basics of the 2D development of KH billow in inhomogeneous jets and mixing layers
- The strain field of a light jet with pairing
- Potential growth rate of oblique modes according to the Caufield and Kerswell's criterion

Specific features of light jets : absolute column mode and side jets

First observation by Monkewitz & Bechert (Album of Fluid Motion - 1988)



1. Side jets occur when the jet is absolutely unstable,
2. The jet is absolutely unstable under a critical density ratio $s < 0.7$,
3. Side jets acknowledged within some range of Reynolds number,
4. Side Jets induced by counter-rotative streamwise vortices lying in the braid region between successive vortex rings (Brancher et al. Phys Fluids 1994)
5. A shorter route to the mixing transition and a large increase of the mixing rate,
6. Side Jets recovered in a pulsed homogeneous jet by Monkewitz and Pfizenmaier (1991)

Question: why vortex induction naturally produces side jets in round light jets only ?

Side ejections on helium jets from Hermouche, *Imft* (1996)

Re = 750

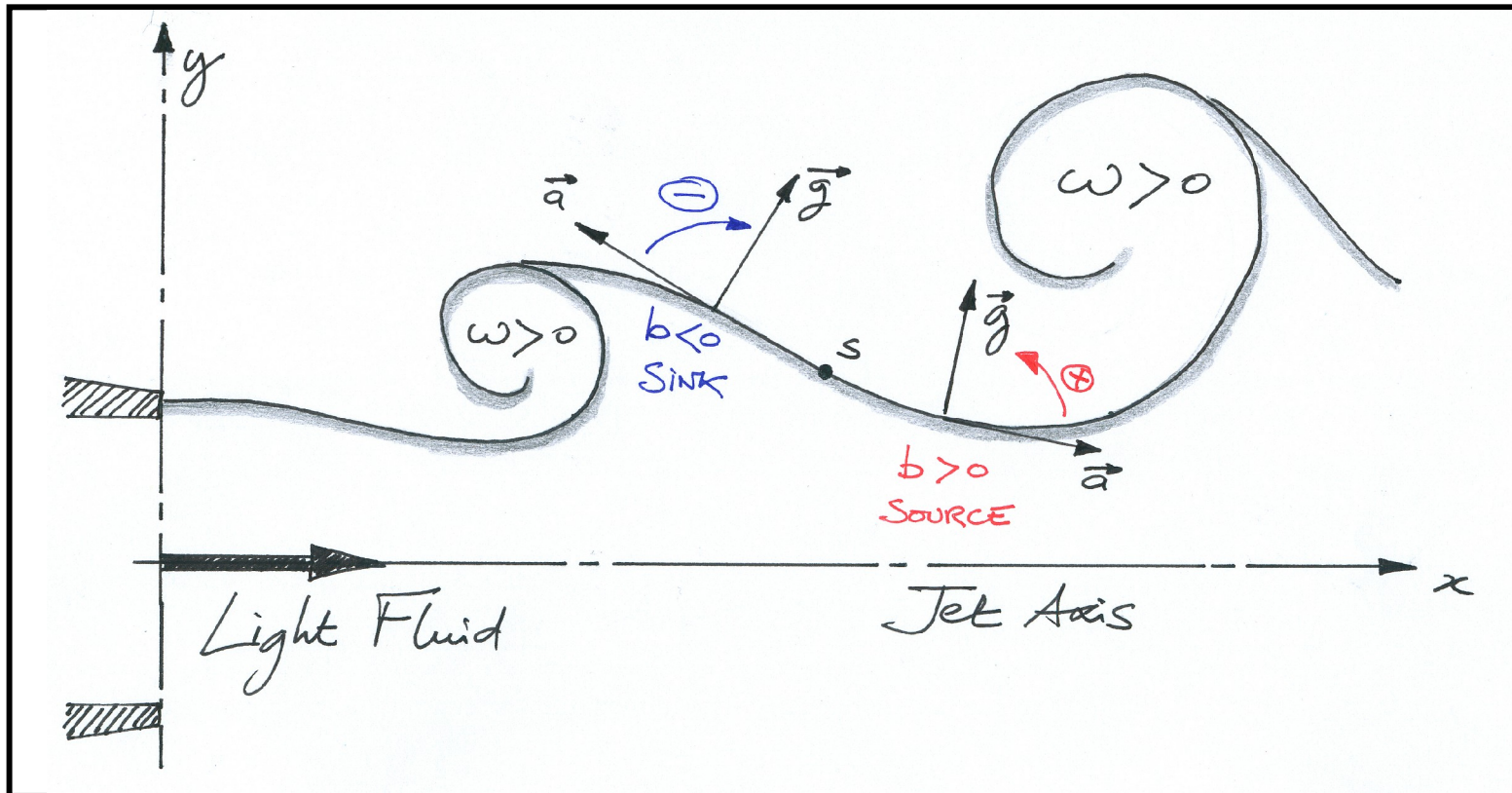
Re = 1000

The nature of the baroclinic torque in infinite Froude number jets

$$\frac{d\omega}{dt} = \underbrace{(\omega \cdot \nabla) \mathbf{u}}_{\text{green}} - \frac{1}{\rho^2} \nabla P \times \nabla \rho - \underbrace{d\omega}_{\text{blue}} + \underbrace{\nu \Delta \omega}_{\text{yellow}}$$

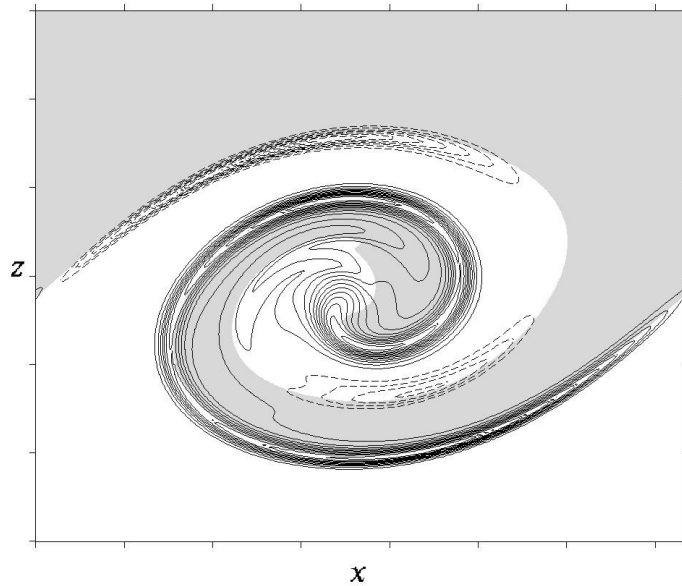
$$\mathbf{b} = \mathbf{a} \times \frac{1}{\rho} \nabla \rho$$

- vanishes in barotropic flows
- signature of inertia difference



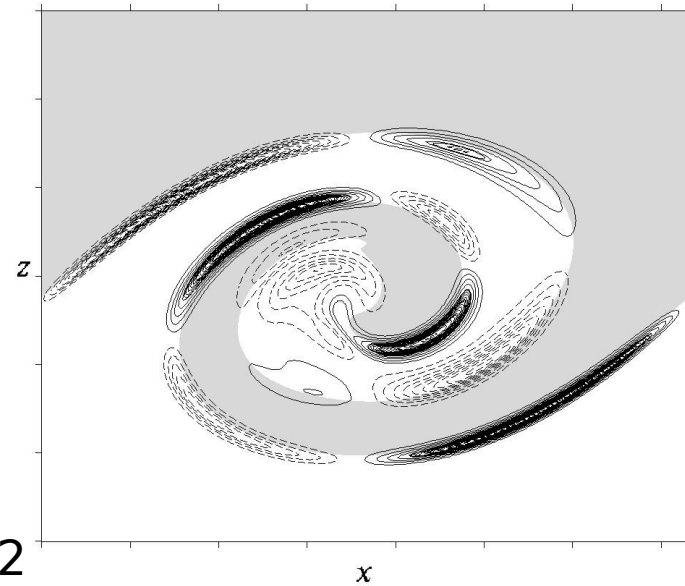
The baroclinic torque in the inhomogeneous mixing layer

Kelvin-Helmoltz Instability in the temporal mixing layer $s=3$, $Re = U\delta/\nu = 1500$



Vorticity

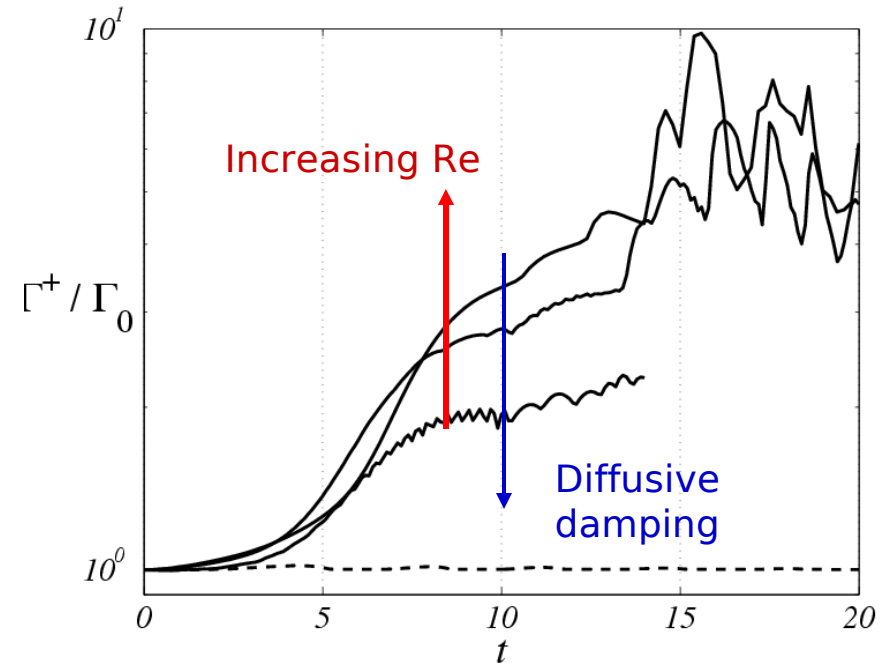
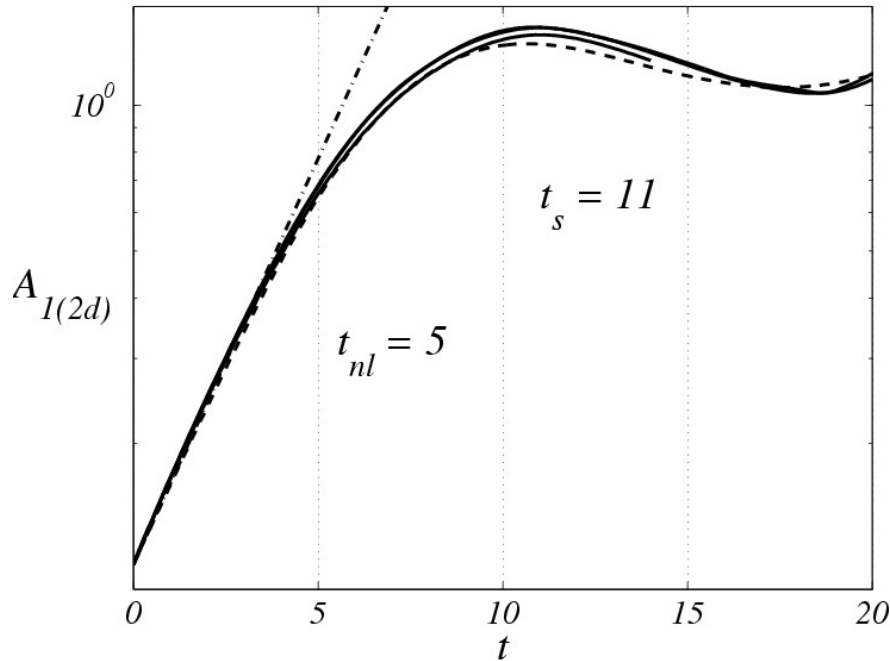
$t=12$



Baroclinic torque

The order of magnitude of the baroclinic torque

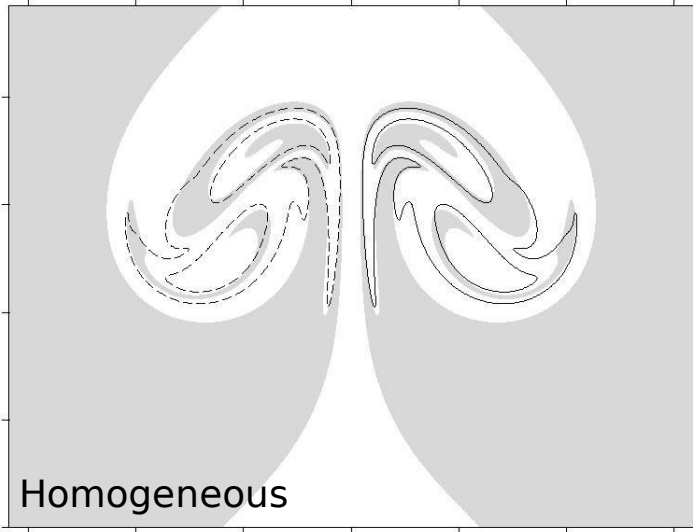
Temporal mixing layer $s=3$, $Re = Ud/n = 500, 1500, 3000$



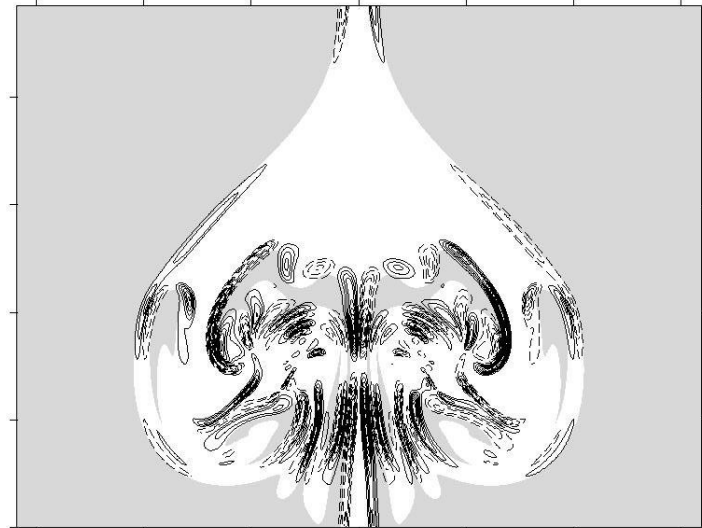
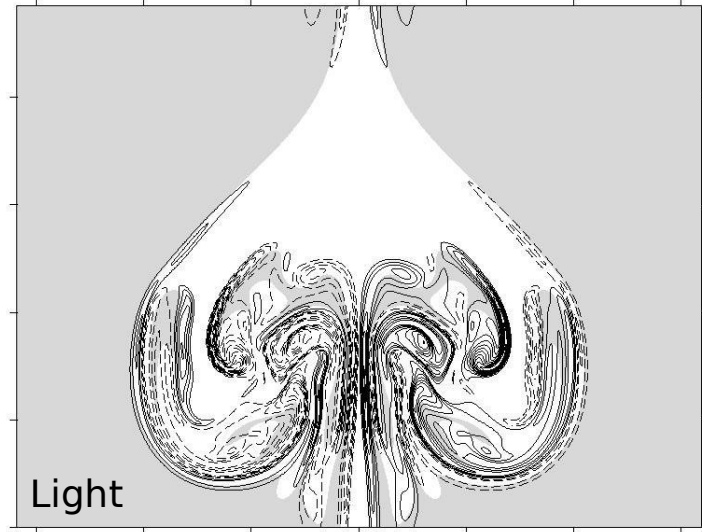
- Small changes in the growth rate
- Vorticity redistribution **within one KH wavelength**
- Positive/negative generated circulation increases with the **Reynolds/Schmidt numbers**

The structure of the 2D light Jet (with pairing)

Temporal jet $s=1/3$, $Re = UD/\nu = 2500$



Vorticity

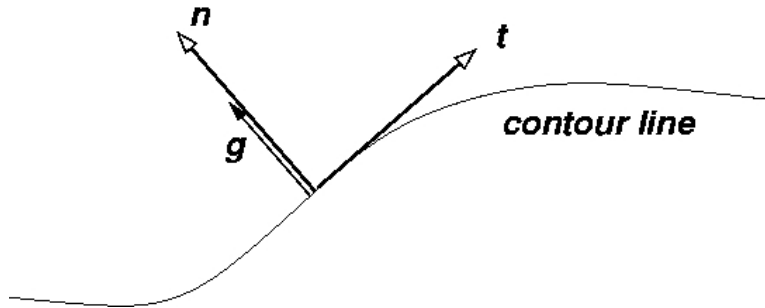


Kyle et Sreenivasan JFM 249 (1993)

Baroclinic Torque

Analysis of the strain field

The shear and the strain rate across a contour line



$$\lambda = \frac{\partial u_t}{\partial n} \quad , \quad \gamma = \frac{\partial u_t}{\partial t}$$

$$\lambda = \mathbf{n} \cdot \nabla \mathbf{u} \cdot \mathbf{t} \quad , \quad \gamma = \mathbf{t} \cdot \nabla \mathbf{u} \cdot \mathbf{t}$$

The model of the braid region according to Caulfield and Kerswell (PoF vol 12, 2000)

Model flow with strain rate γ and rotation rate $r = \frac{\omega}{2}$

$$\mathbf{u} = \begin{pmatrix} \gamma & -r \\ r & -\gamma \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \equiv \mathbf{A} \cdot \mathbf{x} \quad |\gamma| > |r|, \Delta \text{ real} \quad \textit{Hyperbolic region}$$

$$\Delta^2 = \gamma^2 - r^2 = -\det \mathbf{A} \quad |\gamma| < |r|, \Delta \text{ imaginary} \quad \textit{Elliptic region}$$

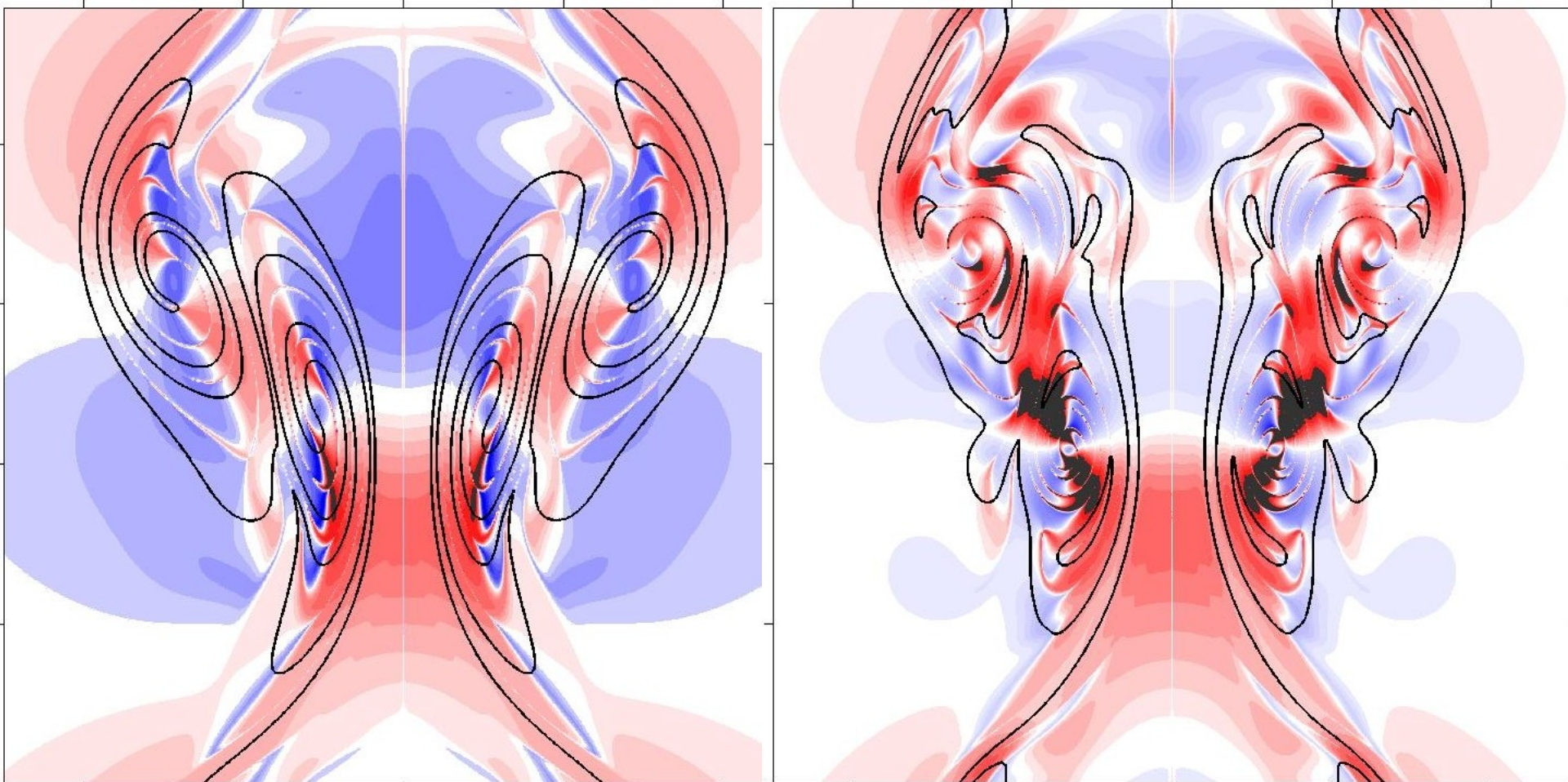
Application to real flows

$$r = \frac{\omega}{2} \quad \Delta^2 = \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} + \left(\frac{\partial v}{\partial y} \right)^2 \quad \gamma_{ck}^2 = \Delta^2 + r^2$$

The strain field along material lines

Temporal jet $s=1/3$, $Re = UD/\nu = 2500$

Red : positive γ (**stretching**) - Blue : negative γ (**compression**) - Shaded : above same positive level



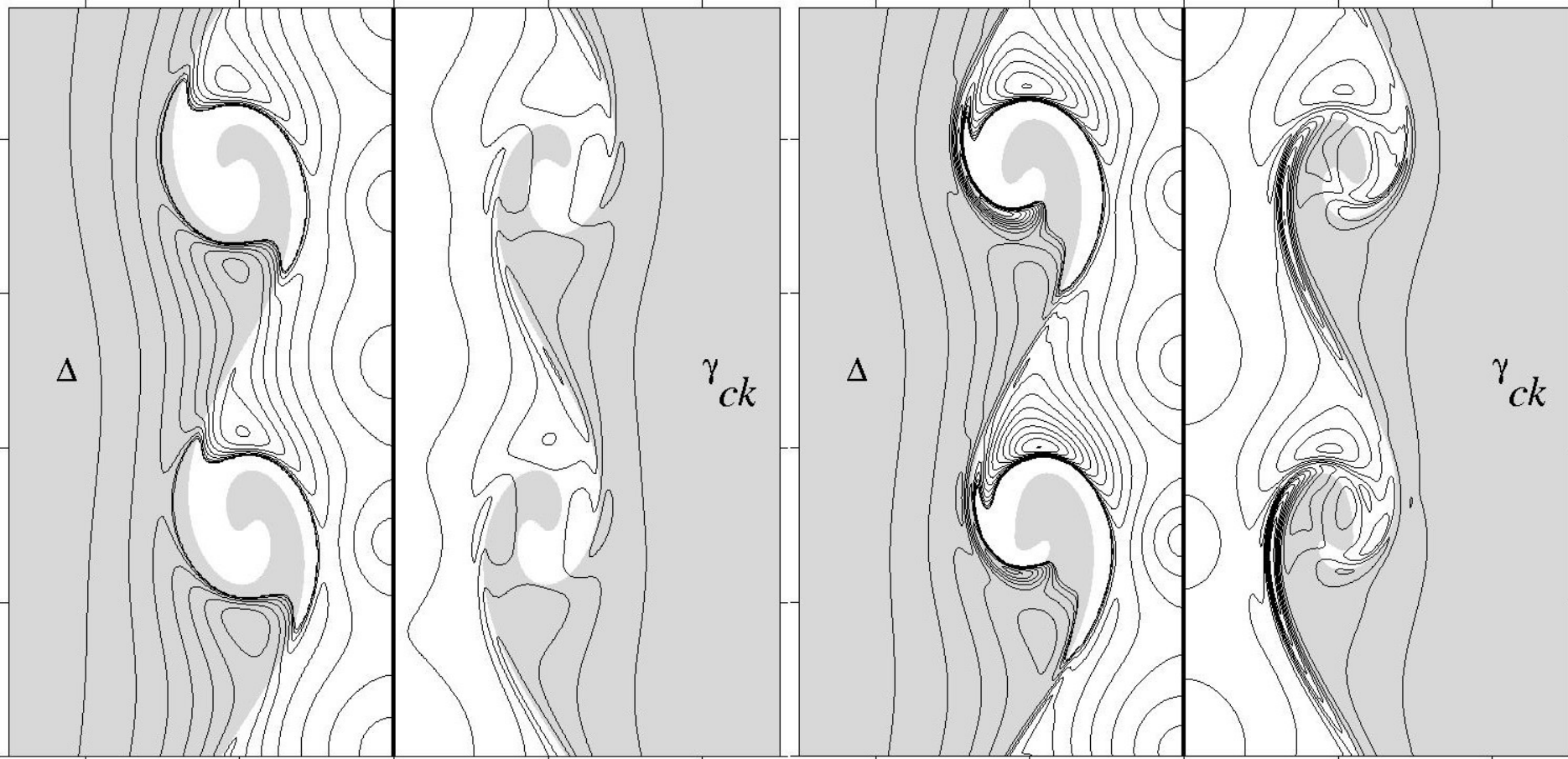
Passive scalar

t = 12

Light jet

The strain field according to the Caulfield and Kerswell's analysis

Temporal jet $s=1/3$, $Re = UD/\nu = 2500$



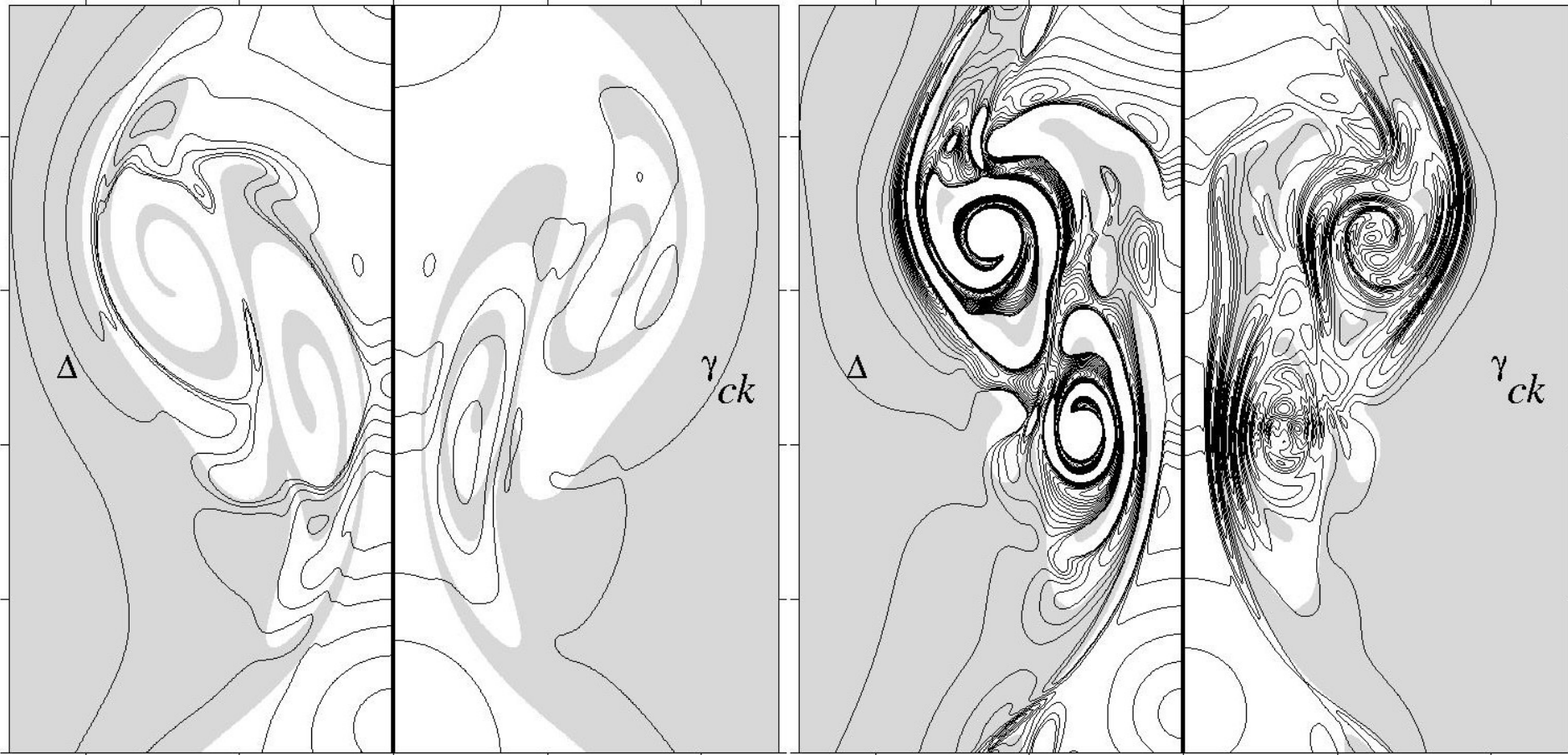
Passive scalar

t = 4,5

Light jet

The strain field according to the Caulfield and Kerswell's analysis

Temporal jet $s=1/3$, $Re = UD/\nu = 2500$



Passive scalar

t = 12

Light jet

Transient and asymptotic growth rates of 3D disturbances according to CK2000

Before the pairing - $t = 4.5\tau$

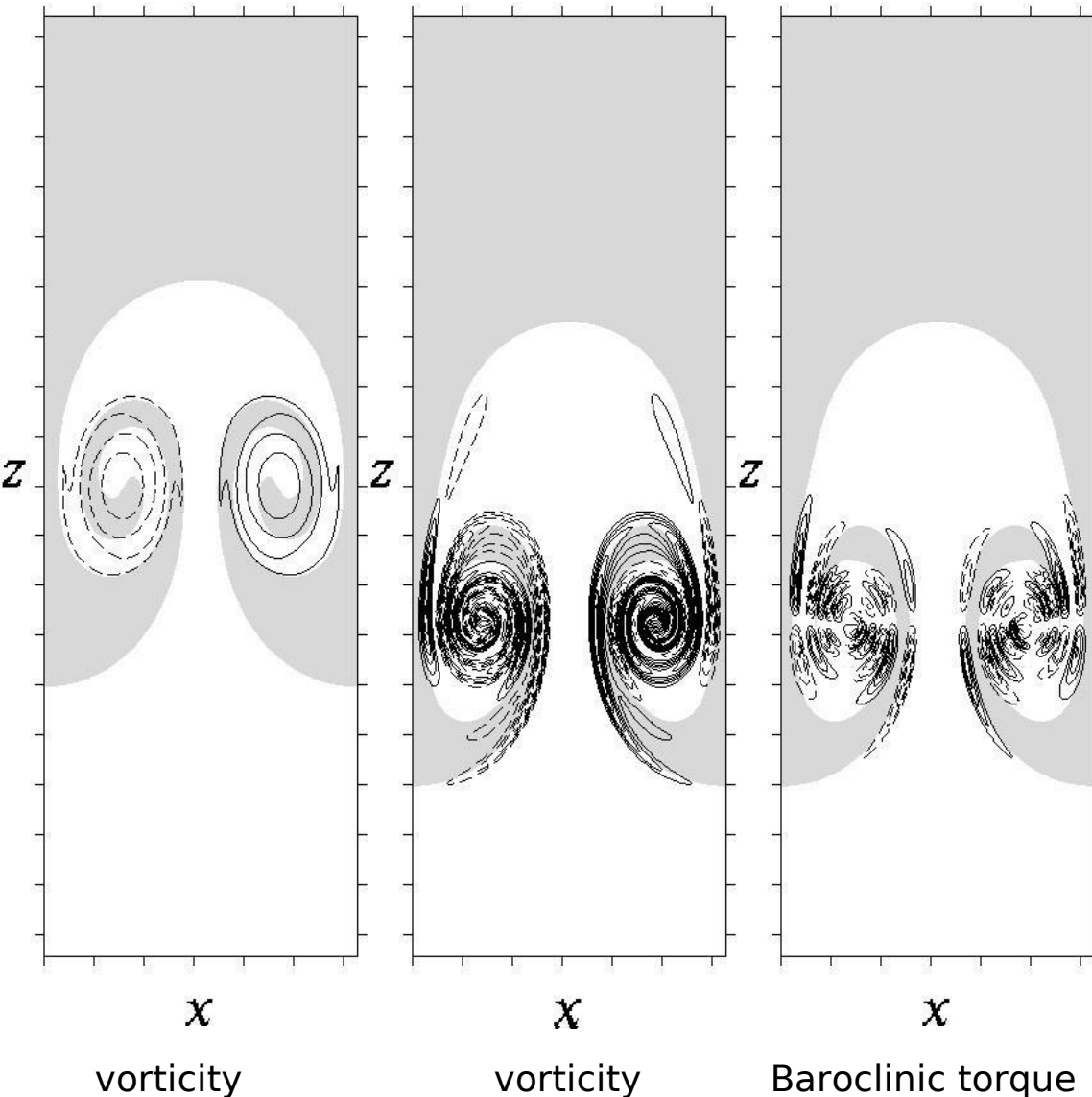
During the pairing - $t = 12.0\tau$

	γ_{ck}	$r = \frac{\omega}{2}$	Δ		γ_{ck}	$r = \frac{\omega}{2}$	Δ	
Homogeneous Jet								
Elliptic	0.52	1.33	<0		0.57	1.37	<0	
Hyperbolic	1.22	0.96	0.75		0.27	0.11	0.25	
Light Jet								
Elliptic	0.71	1.53	<0		0.34	3.83	<0	
Hyperbolic	1.00 to 2.47	1.04	0.51 to 0.73		0.49	0.45	0.18	
Homogeneous Jet								
Elliptic	$\sigma \sim \gamma_{ck}$	0.52			$\sigma \sim$	0.57		
Hyperbolic	$\sigma_{tr} \leq 2\gamma_{ck}$	2.44	$\sigma_{as} \sim 2\Delta$	1.5	$\sigma_{tr} \leq$	0.54	$\sigma_{as} \sim$	0.5
Light Jet								
Elliptic	$\sigma \sim$	0.71			$\sigma \sim$	0.34		
Hyperbolic	$\sigma_{tr} \leq$	2. to 5.	$\sigma_{as} \sim$	1. to 1.46	$\sigma_{tr} \leq$	0.98	$\sigma_{as} \sim$	0.36

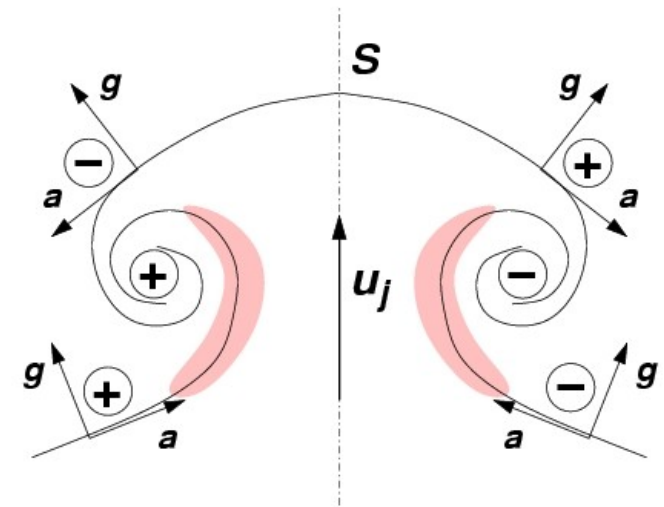
- The structure of the infinite Froude number inhomogeneous jet is biased by the baroclinic torque,
- The baroclinic torque is Reynolds-number and density-ratio sensitive,
- The strain fields of light jets present a folded layered structure and higher pick values,
- According to the theoretical prediction by CK00 the growth rate of transient « pressureless modes » is bounded above by $\sigma_{tr} \leq 2\gamma_{ck}$.
- Growth rates of transient modes may be up to twice more than their homogeneous counterpart before and during the pairing process,
- This may ensure the rapid growth of streamwise-aligned structures yielding side ejections of light fluid,
- The baroclinic torque mechanism produces thinner braids indicating higher spanwise or azimuthal wavenumbers,
- A need for an (ongoing) direct stability approach « à la » Klaassen and Peltier JFM 227 (1991).

Streamwise baroclinic torque on a pair of counter-rotating vortices

Counter-rotating vortices on a density-gradient layer



Spatial structure of the baroclinic torque on the pattern of counter-rotating vortices



- **Offset** of vortex centers toward the light side Potential
- Potential amplification by the strain field via the density-gradient