KTH Workshop
April 30, 2010

CS-Turbulence Interaction

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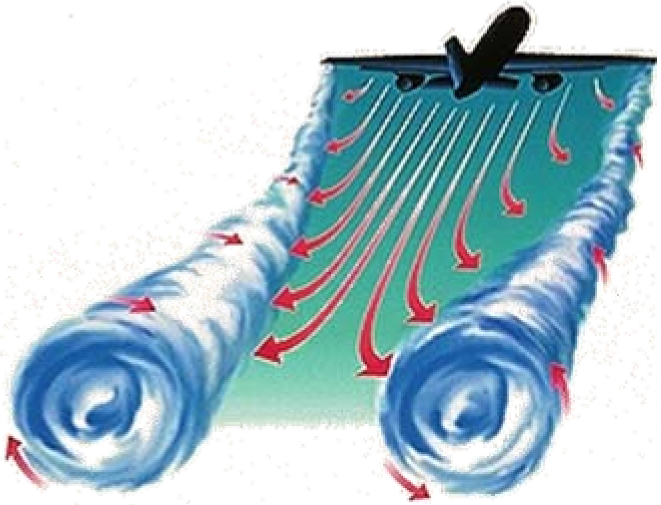
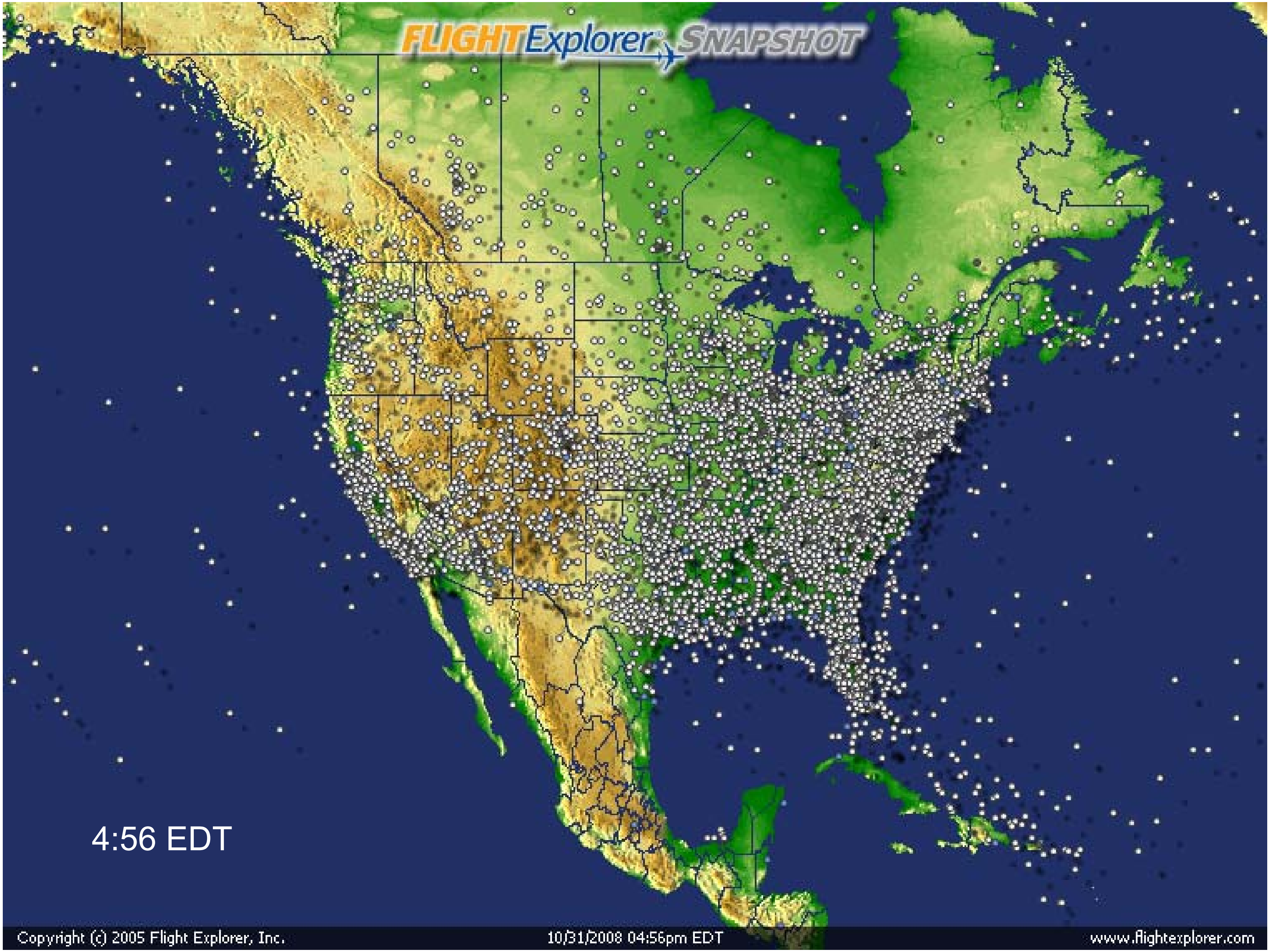
University of Houston

Funded by NSF





AIRLINES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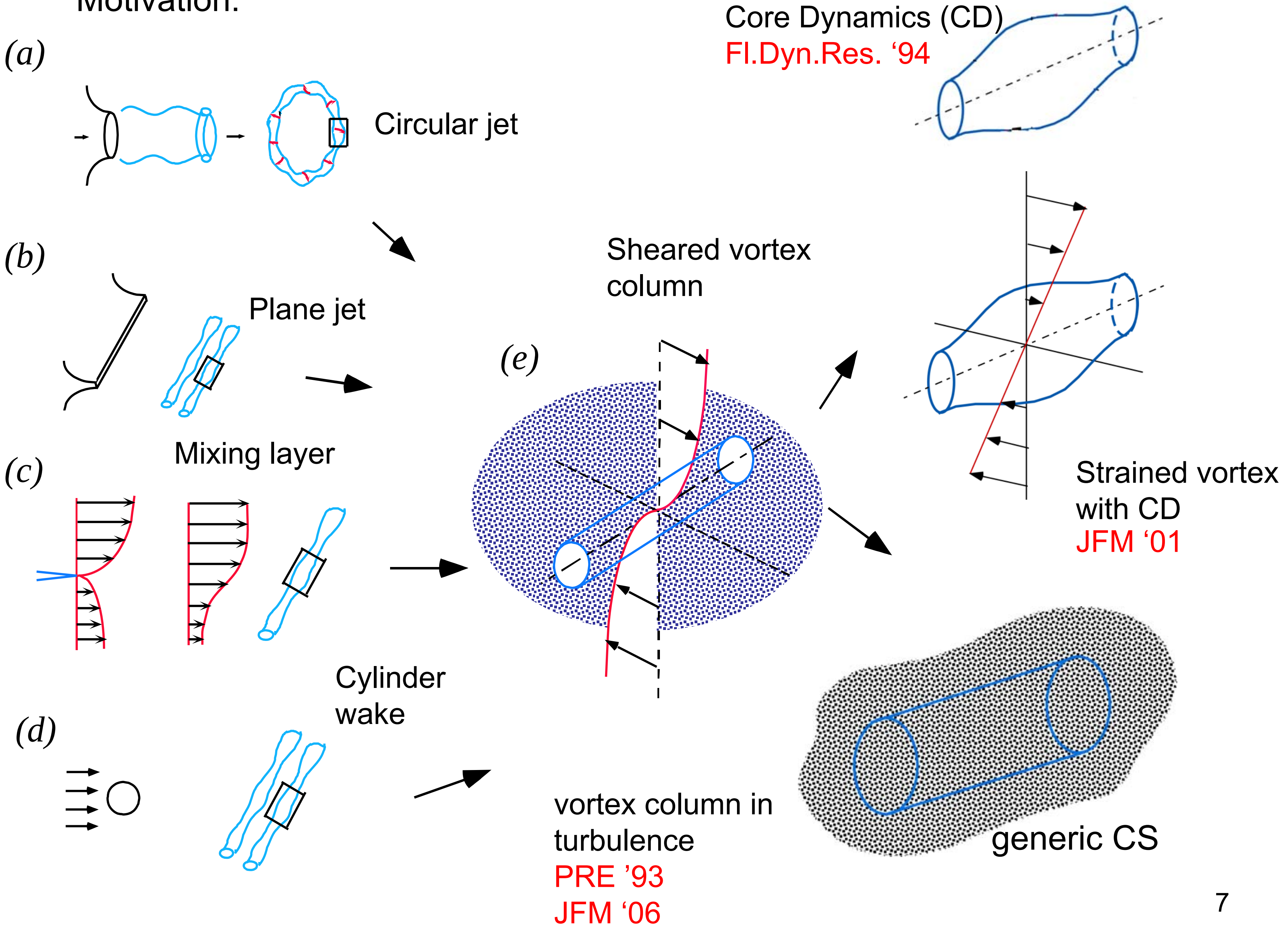
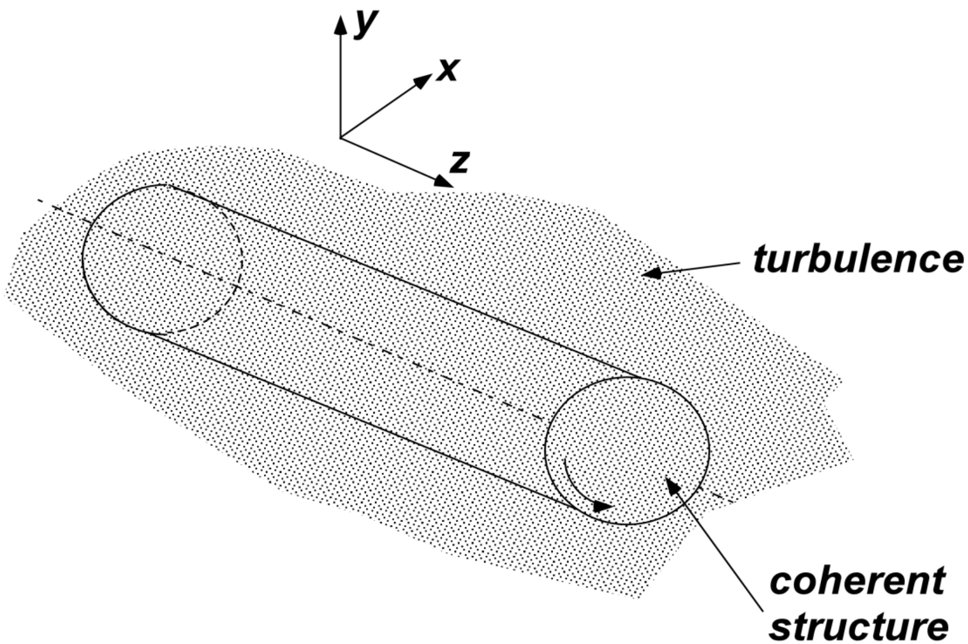
Trailing vortex:

A simple example of **coherent structure**

Motivation:


(a)
Circular jet
(b)
Plane jet
(c)
Mixing layer
(d)
Cylinder
wake
(e)
Sheared vortex
column
vortex column in
turbulence
PRE '93
JFM '06
Core Dynamics (CD)
Fl.Dyn.Res. '94
Strained vortex
with CD
JFM '01
generic CS

CS-turbulence interaction: Idealized flow



DNS

Re ≡ Γ/ν

1k – 20k

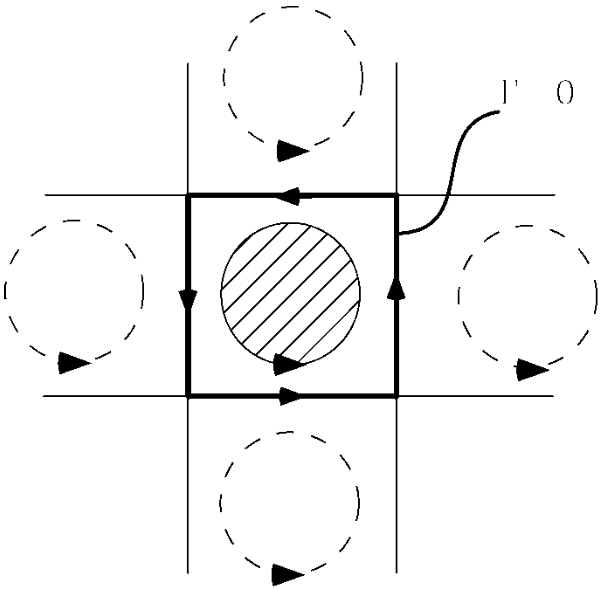
Oseen-Lamb
vortex

Idealizations:

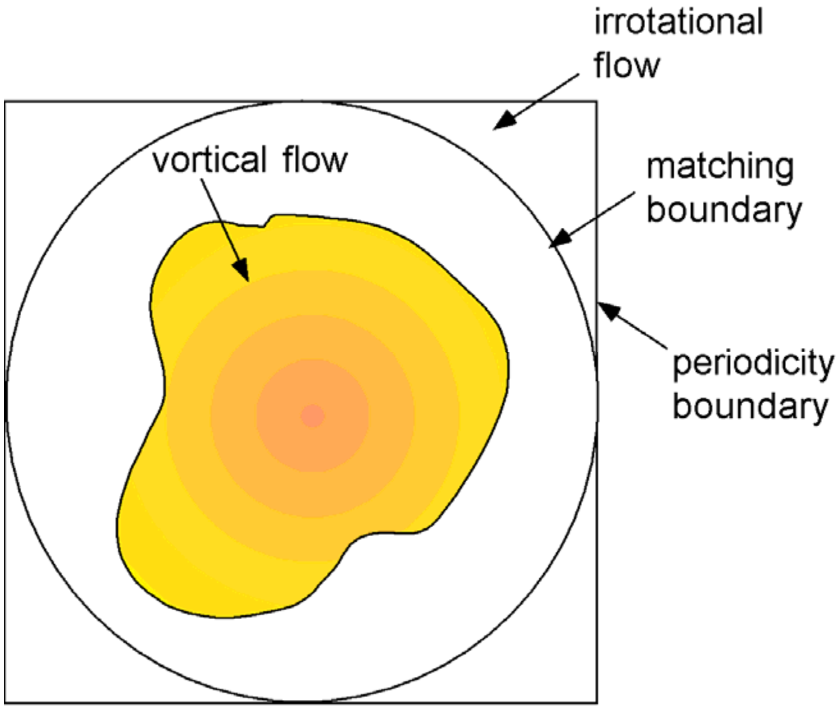
•No interaction with other CS	no pairing or reconnection
•No background shear	no elliptic instability
•Rectilinear, cylindrical CS	no self-induced motion
•Random, fine-scale fluctuations	homog., isotrop. k – sep.

Flow evolution using DNS initialized with 3-D vort. from lin. analysis
Pseudo-spectral method (Rennich & Lele '97; Pradeep & Hussain '04)
periodic in z, pot. flow @ r → ∞

Numerical simulation method:



Triply-periodic

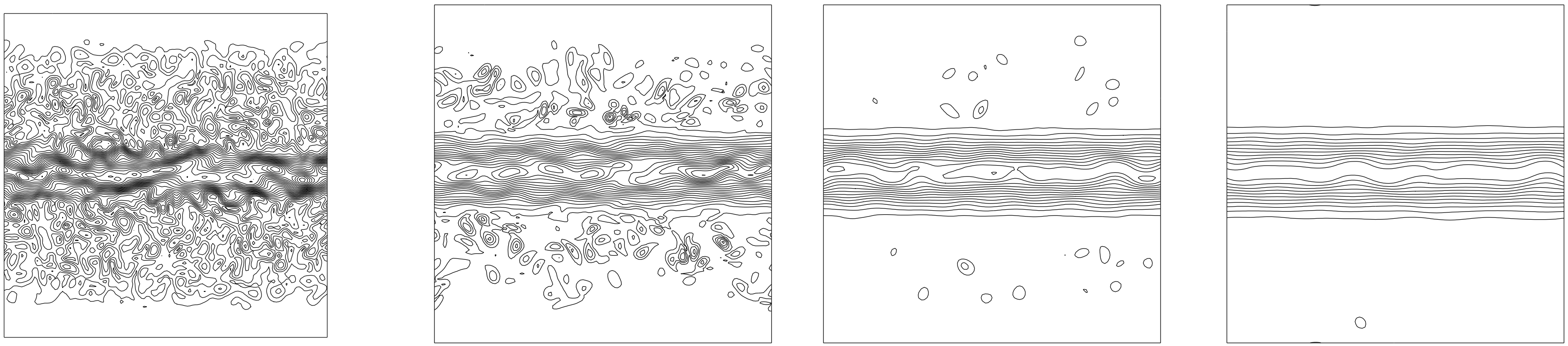


"unbounded" flow
(Rennich-Lele '97)

Pradeep & H. '04

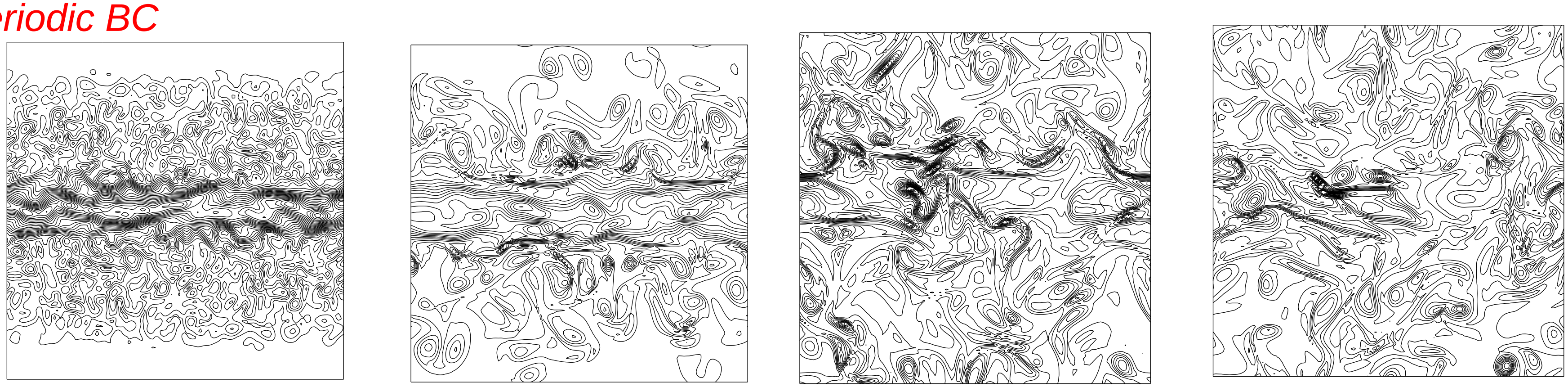
Comparison:

Unbounded BC

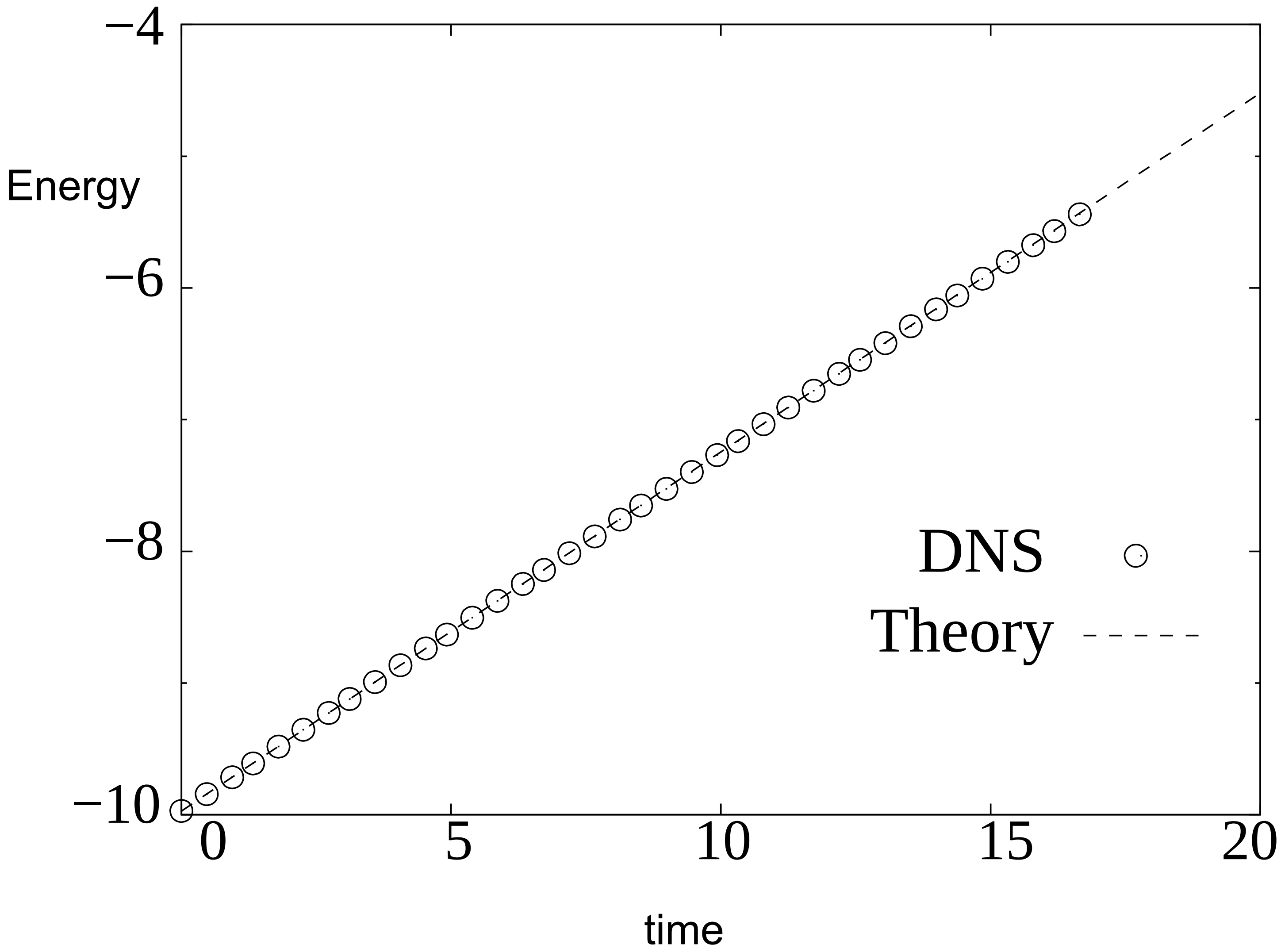


time

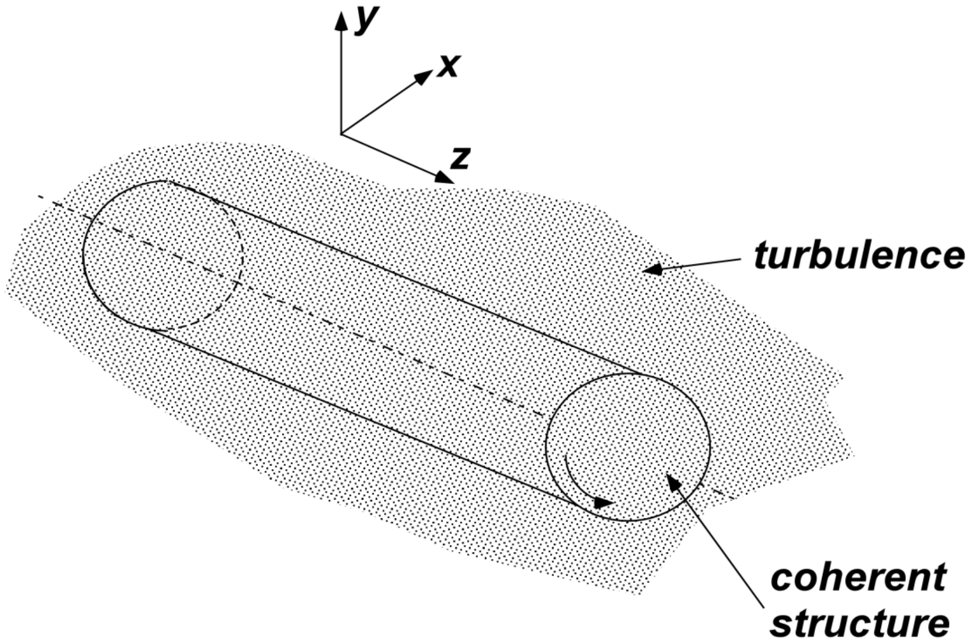
Periodic BC



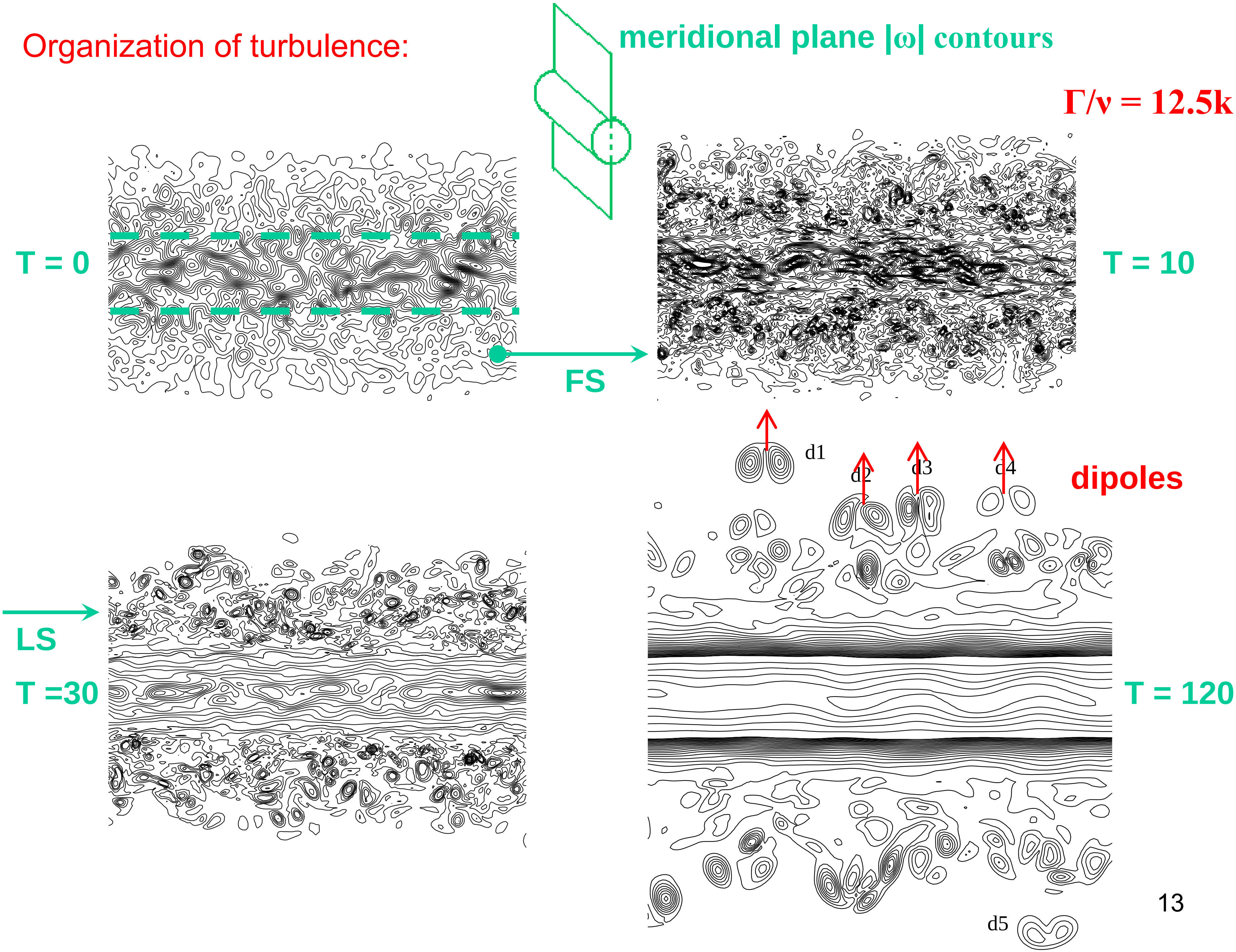
Growth of q-vortex instability mode: Bending wave $Re = 10^5$ (DNS)

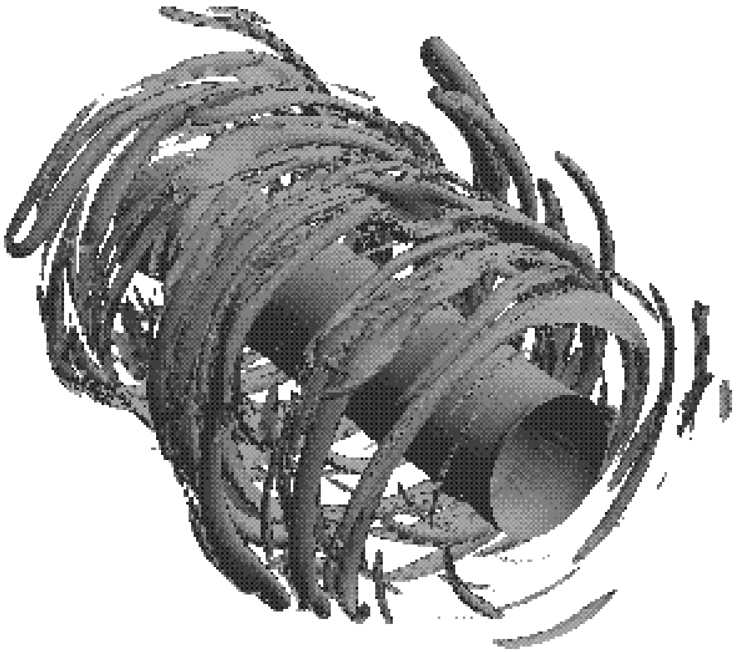


Vortex-Turbulence Interaction

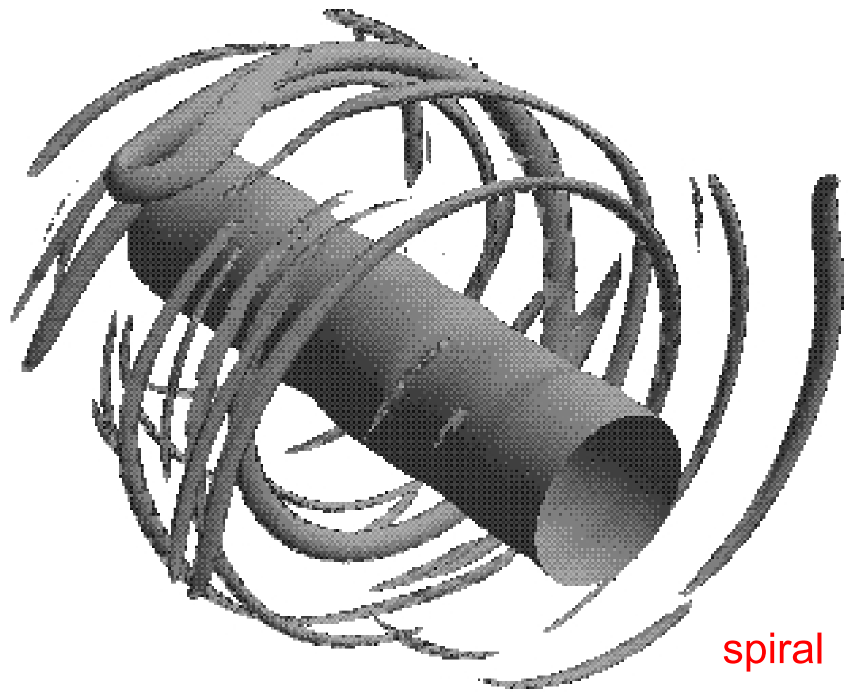


Organization of turbulence:





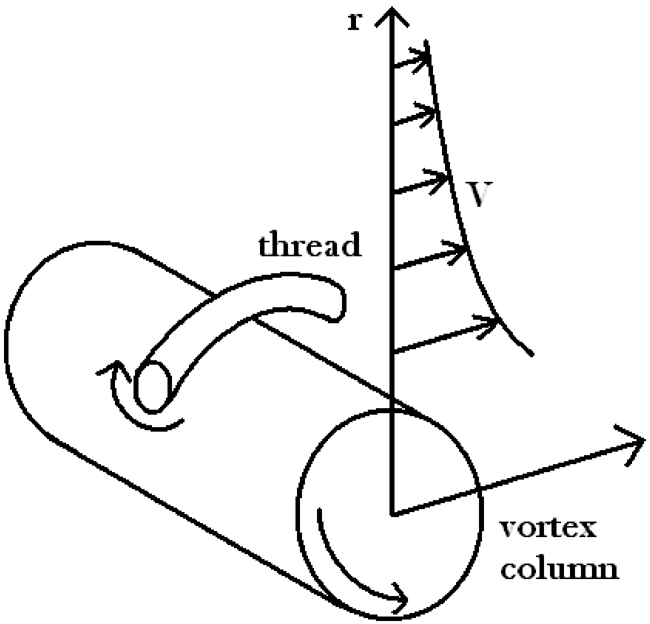
dipoles

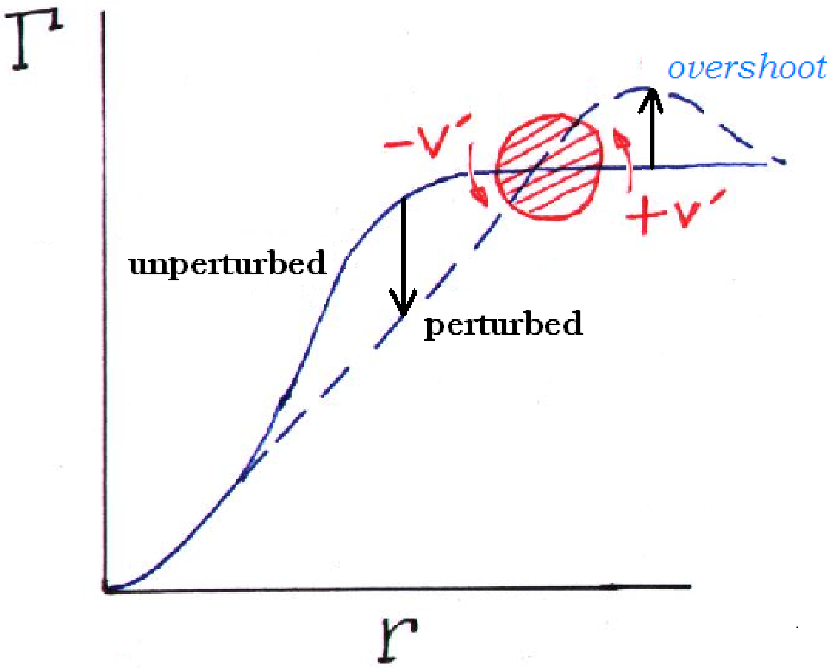


spiral

threads

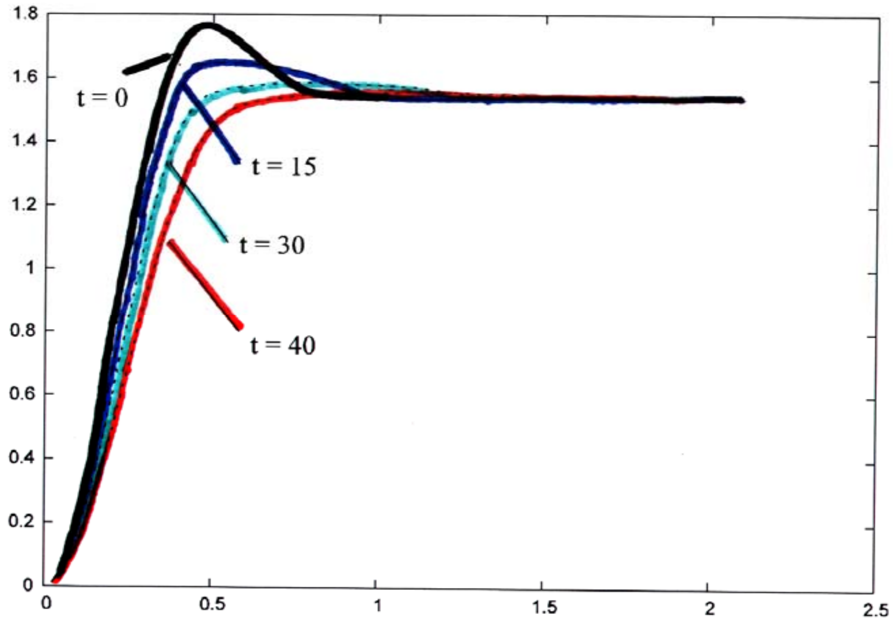
Transport effect of ***threads***:

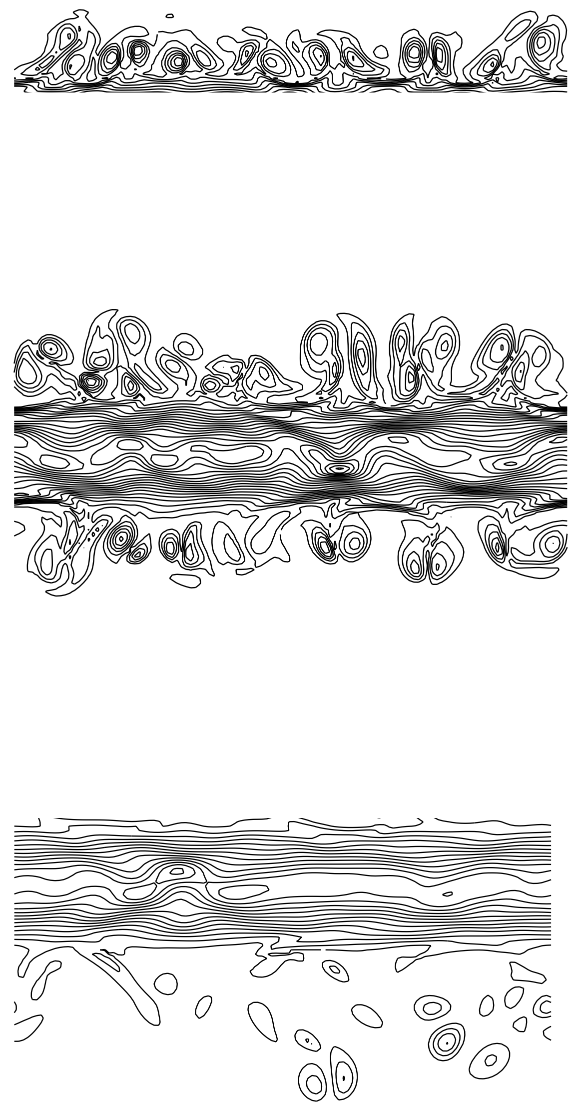


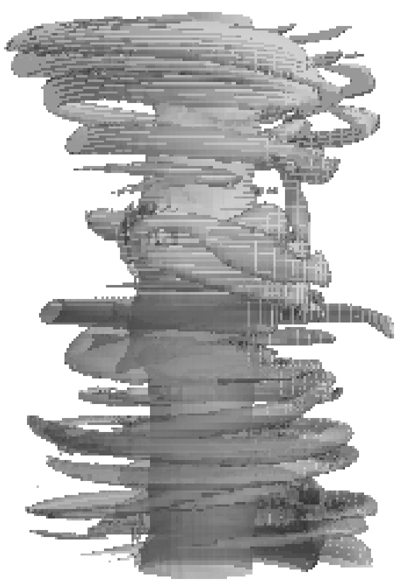


centrifugal instability

Re = 5000

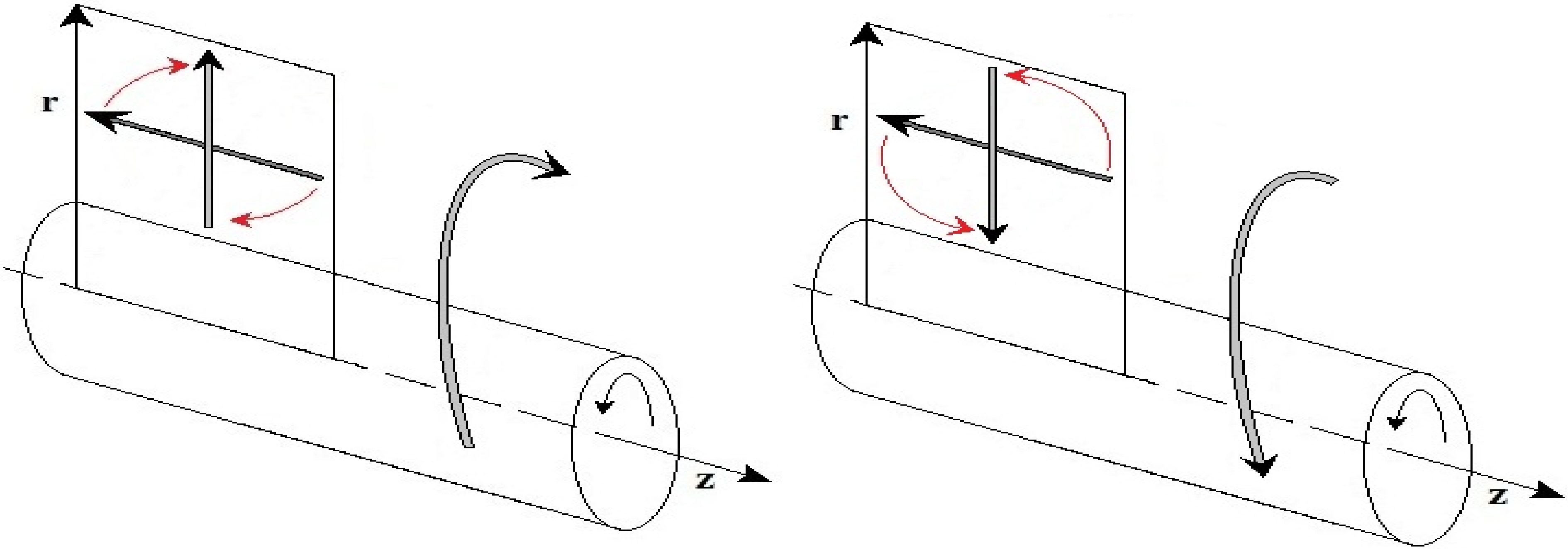


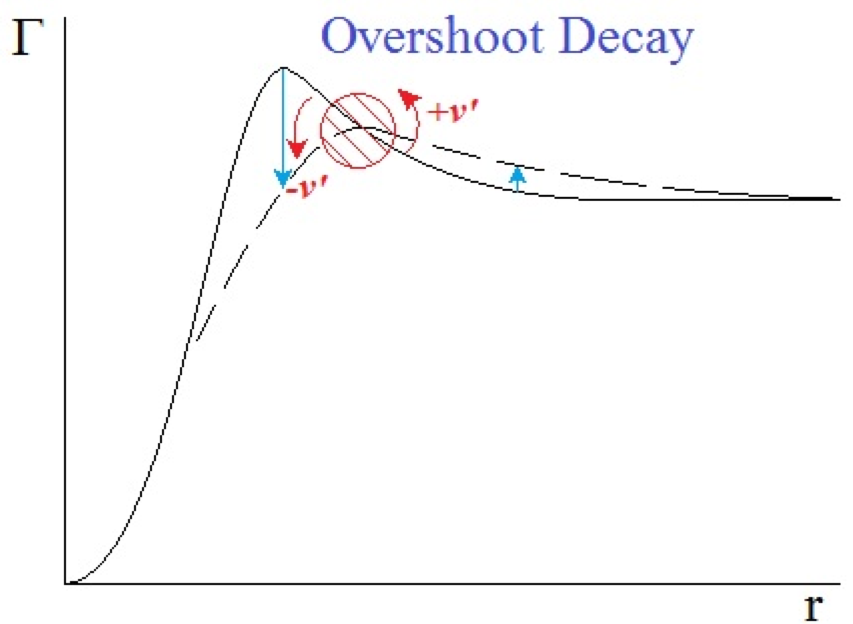


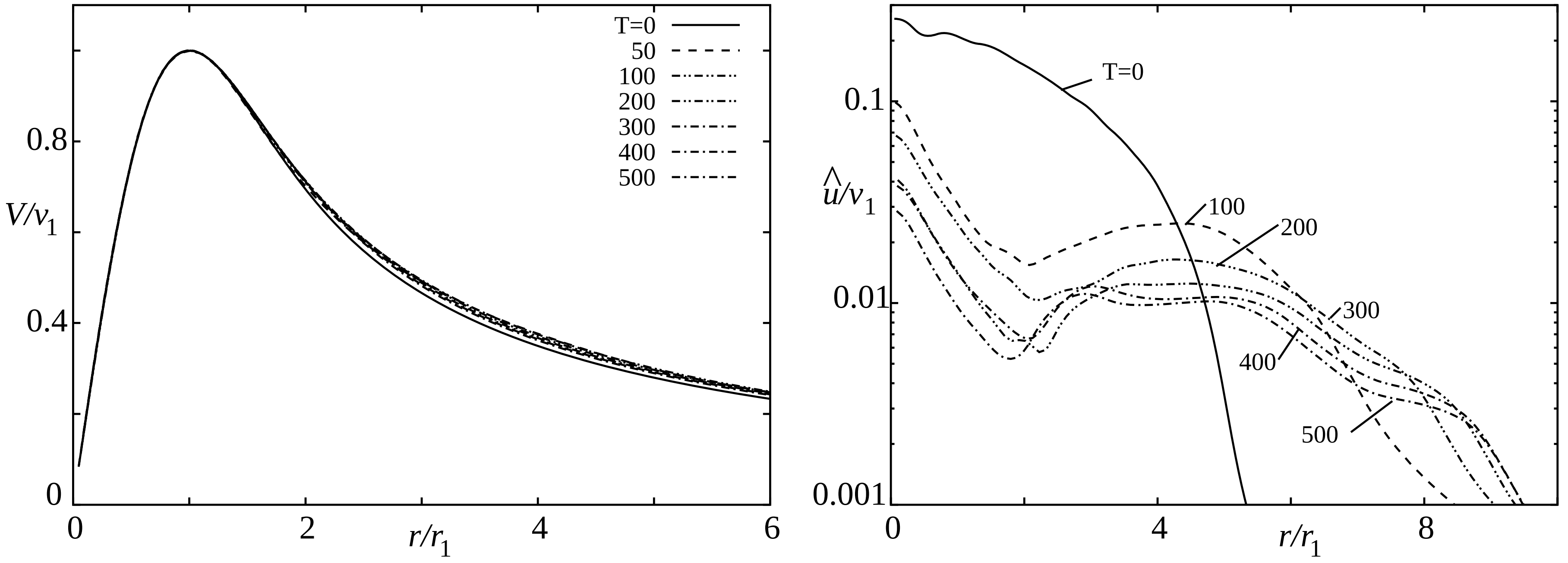


Self-limiting

Instability Driven Intensification:





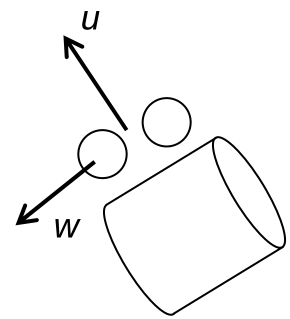


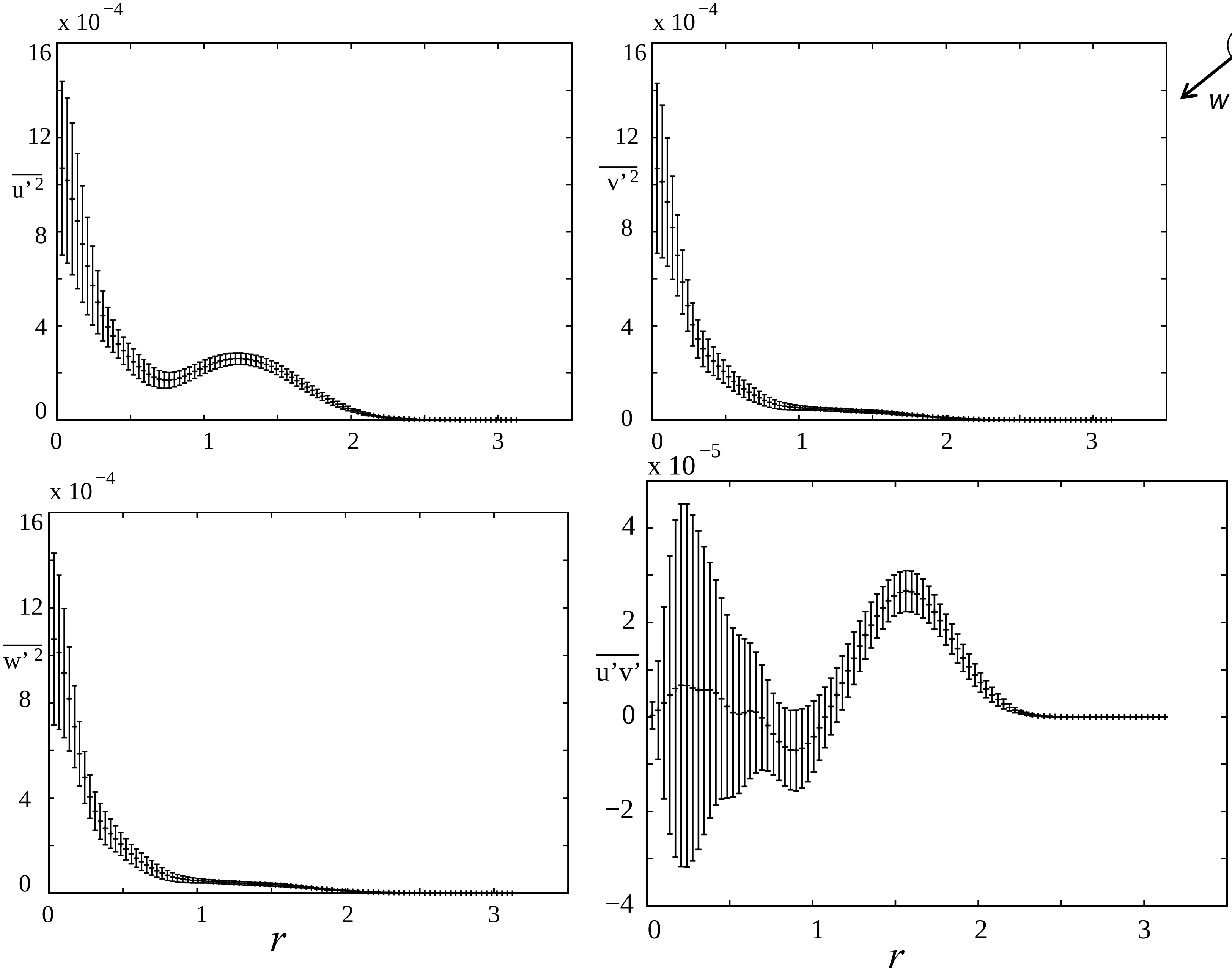
- surprisingly little effect of turbulence on vortex decay

More rapid decay possible?

Turb. statistics:

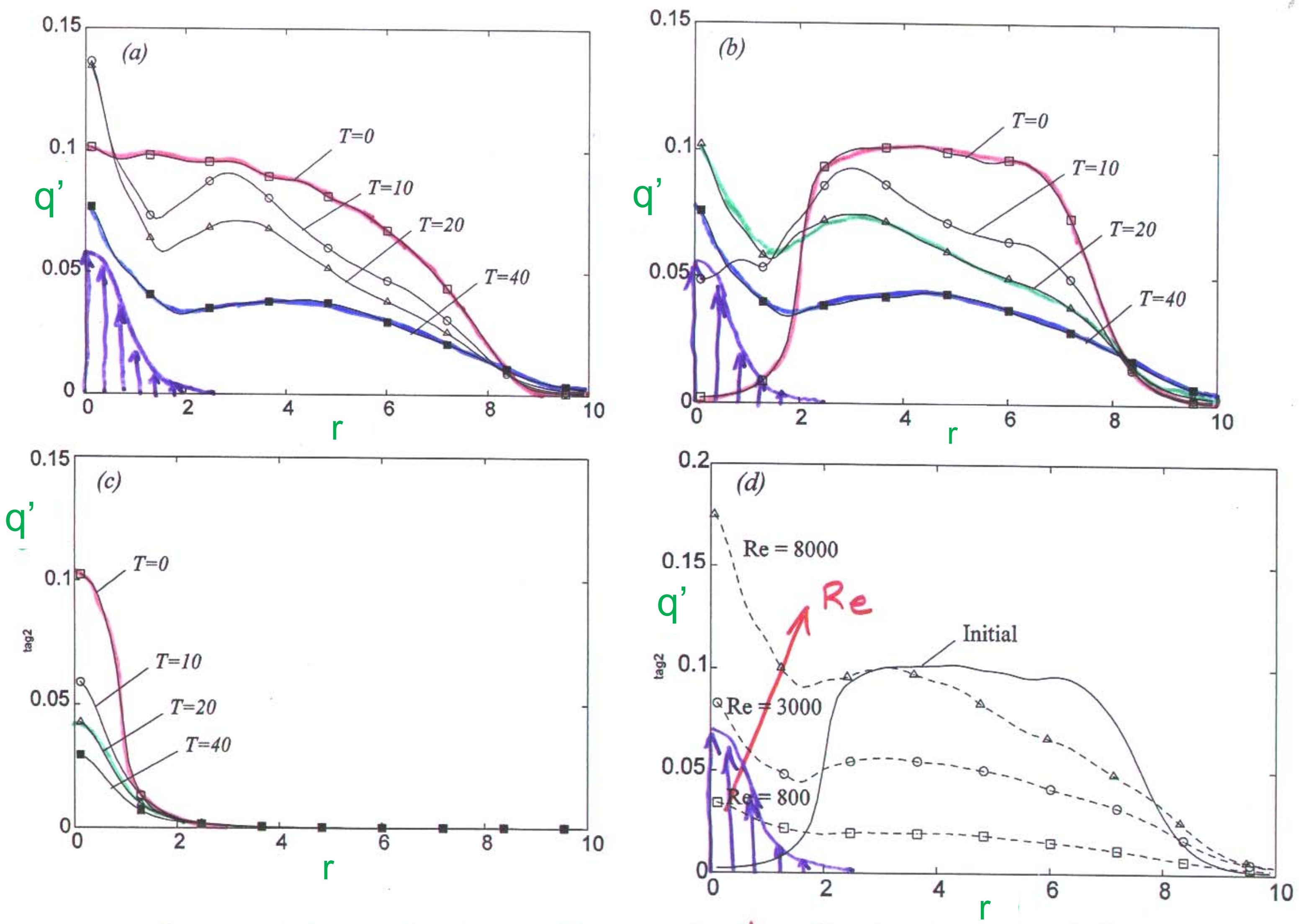
T = 15





Re=3000

Growth of core fluctuations:



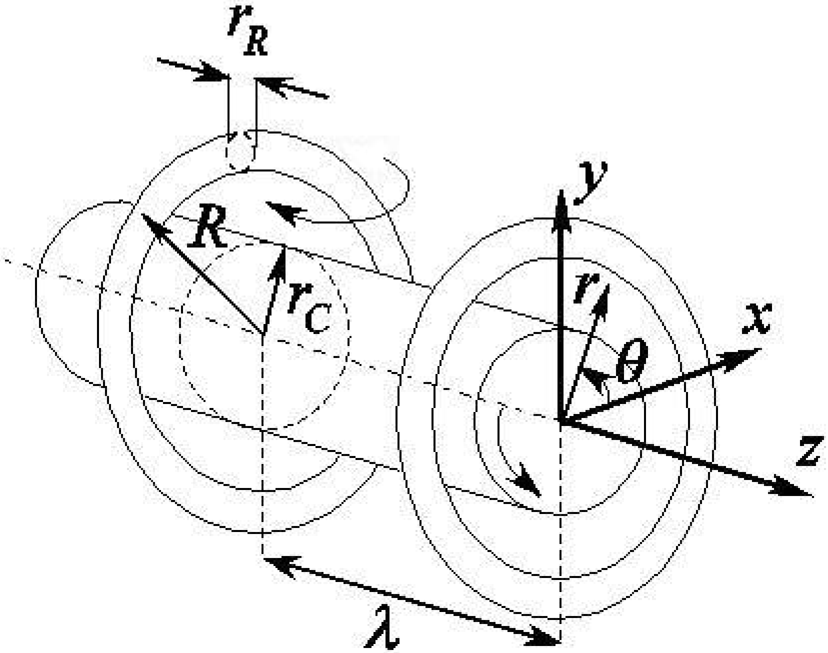
Oseen vortex stable; Γ overshoot effect damped?
Why E ↑ Transient Growth?

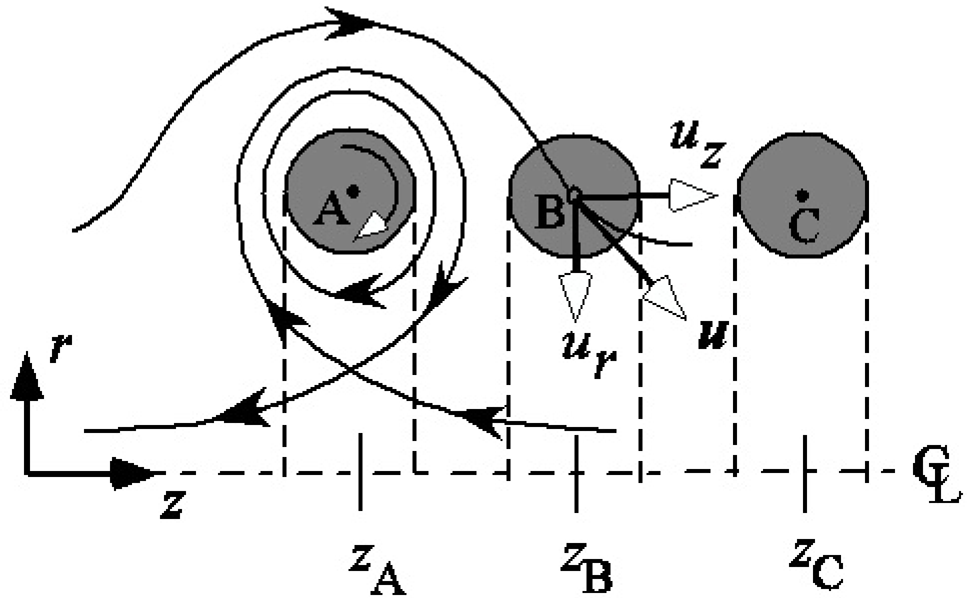
Mechanisms of core perturbation growth:

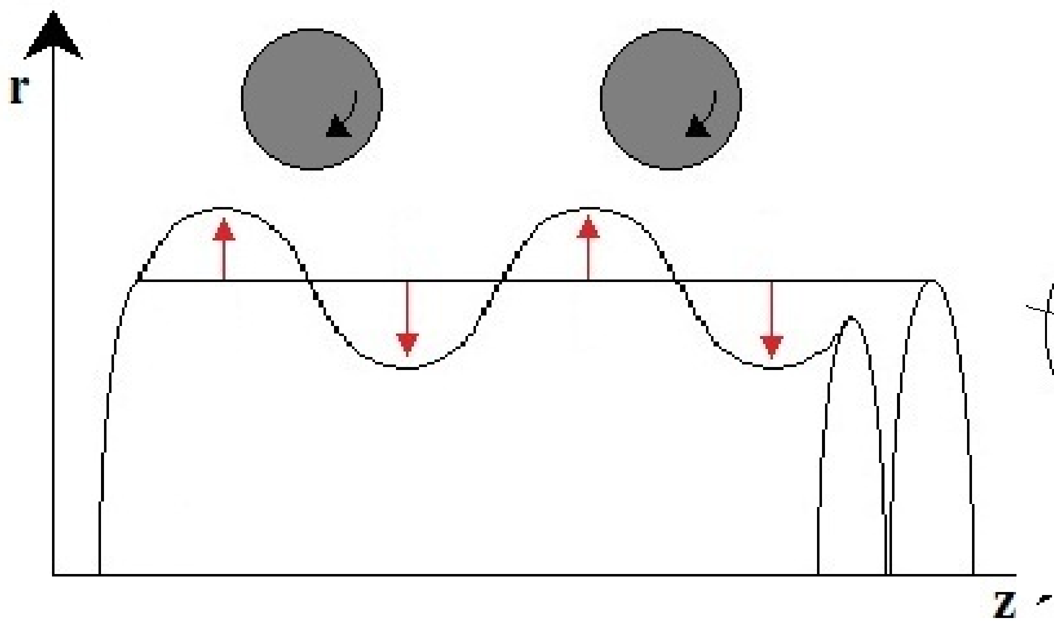
Centrifugal instability is self-limiting

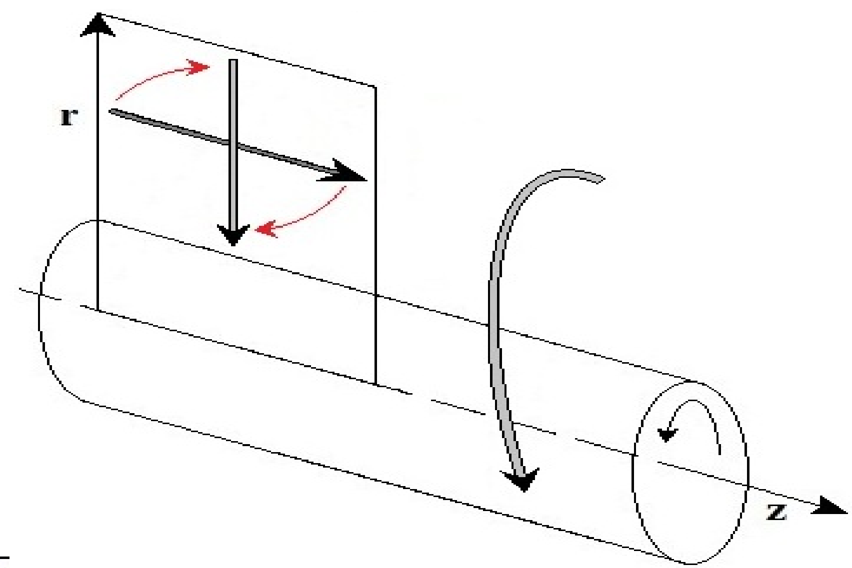
Other mechanisms?

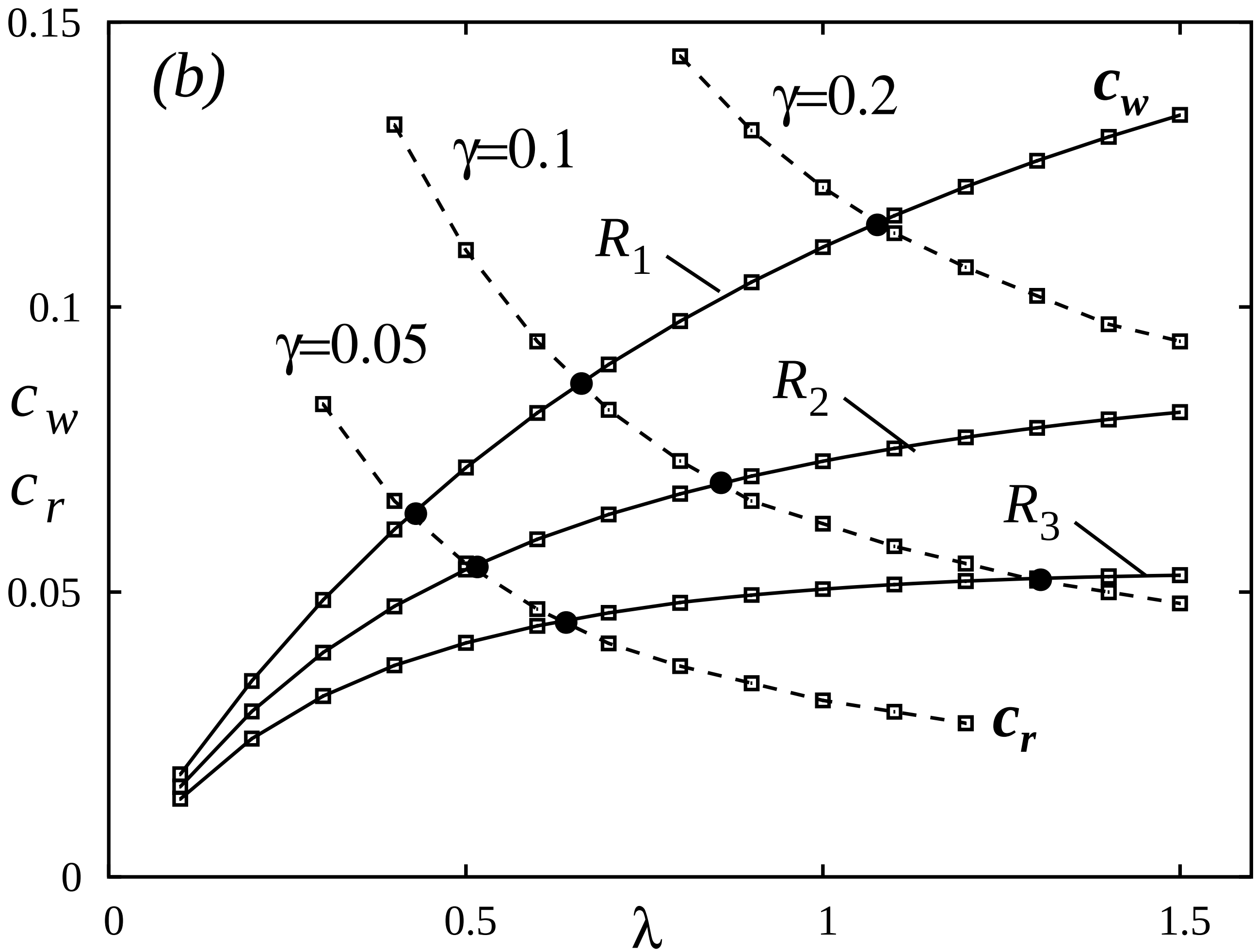
- Thread/Vortex wave resonance
- Transient growth

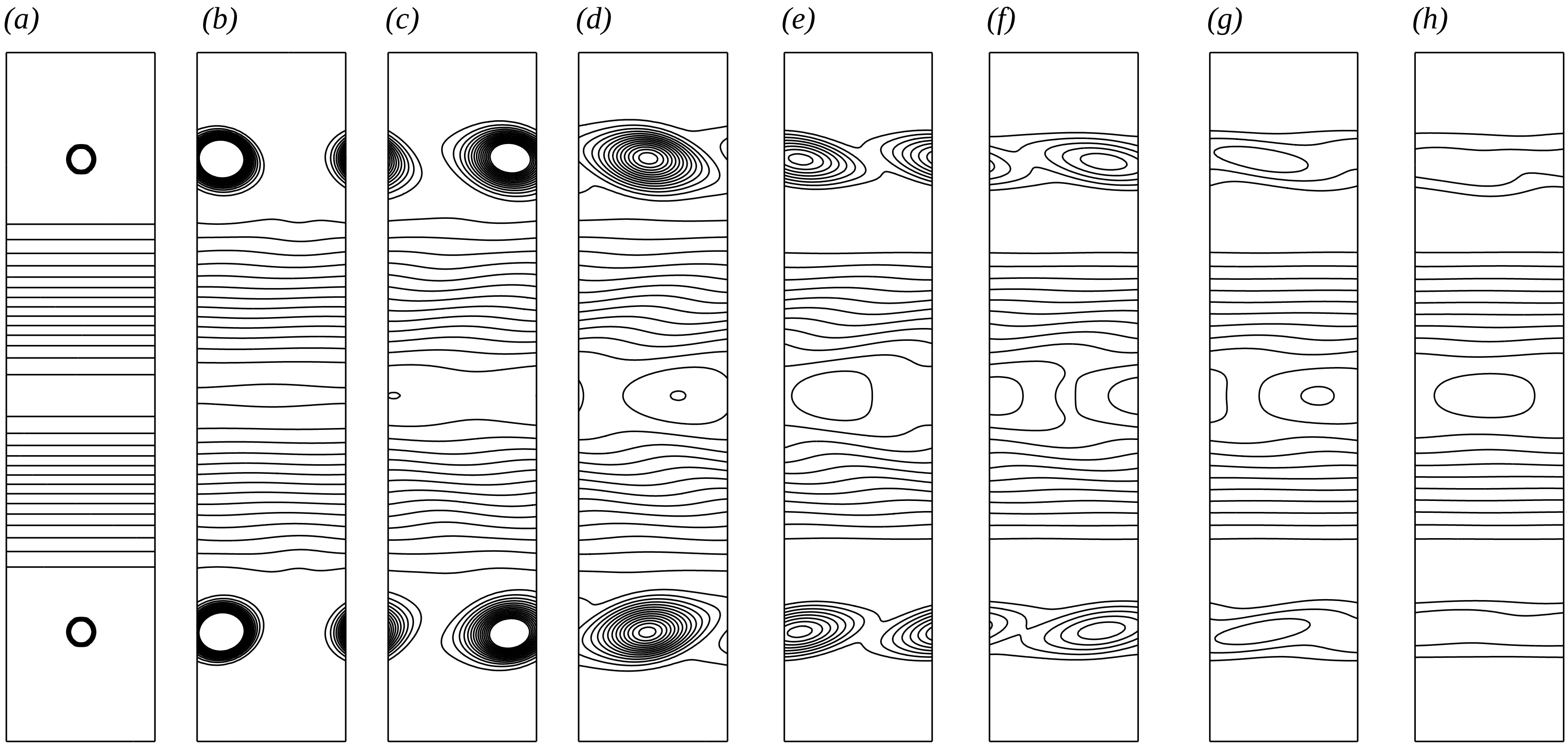

r_R
R
r_C
y
r
x
θ
z
λ


u_z
A
B
C
u_r
u
r
z
z_A
z_B
z_C
C_L


r
z


r
z

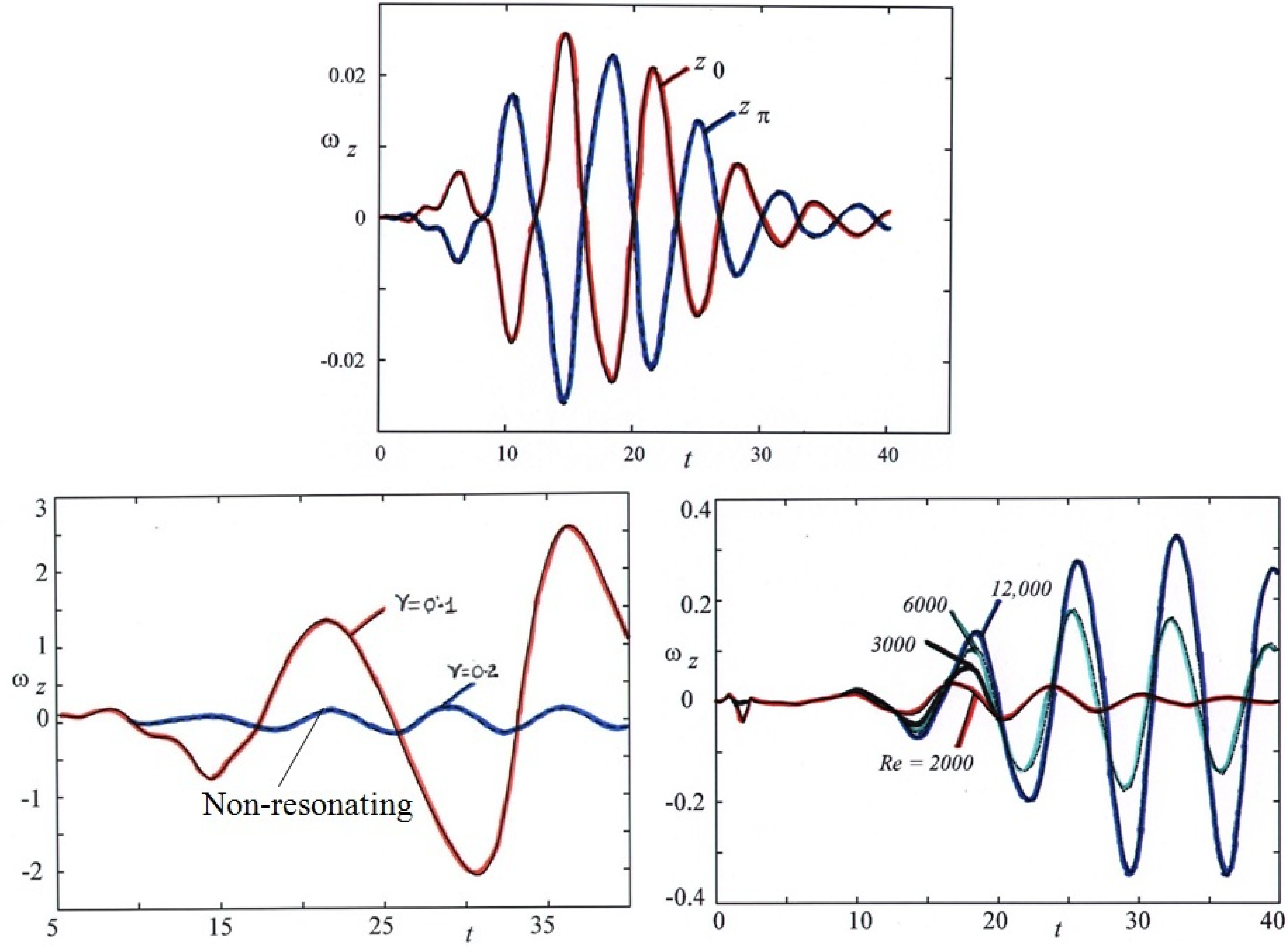

(b)
γ=0.2
γ=0.1
γ=0.05
c_w
R_1
R_2
R_3
c_r
c_w
c_r
0.15
0.1
0.05
0
0
0.5
1
1.5
λ



$t = 0$ $t = 5$ $t = 10$ $t = 15$ $t = 20$ $t = 25$ $t = 30$ $t = 35$

$\gamma = 0.1$

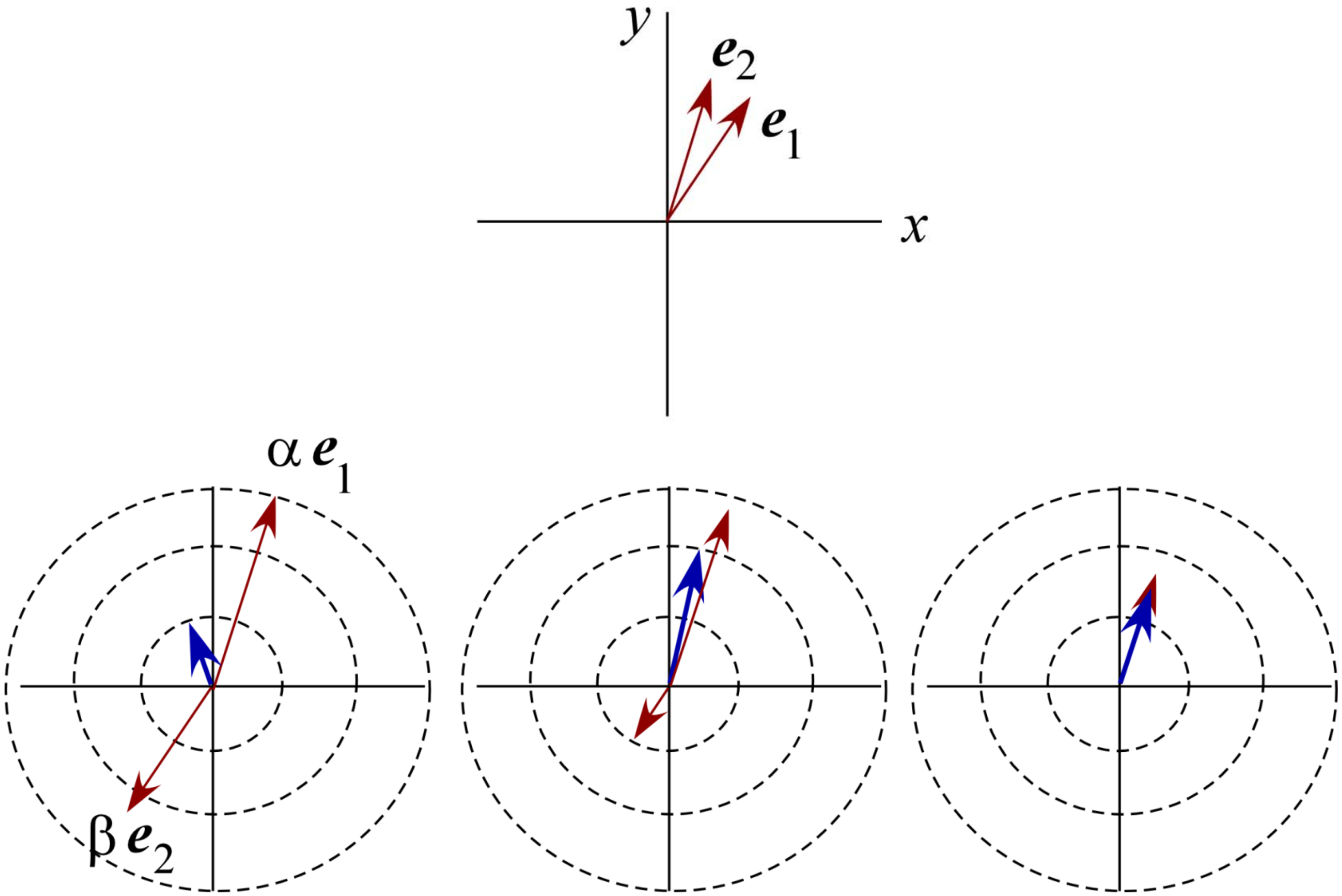
Re = 2000



ω z
z 0
z π
0.02
0
-0.02
0
10
20
30
40
t
3
2
1
0
-1
-2
ω z
γ=0·1
γ=0·2
Non-resonating
5
15
25
35
t
0.4
0.2
0
-0.2
-0.4
ω z
12,000
6000
3000
Re = 2000
0
10
20
30
40
t

TRANSIENT GROWTH

A rudimentary example:



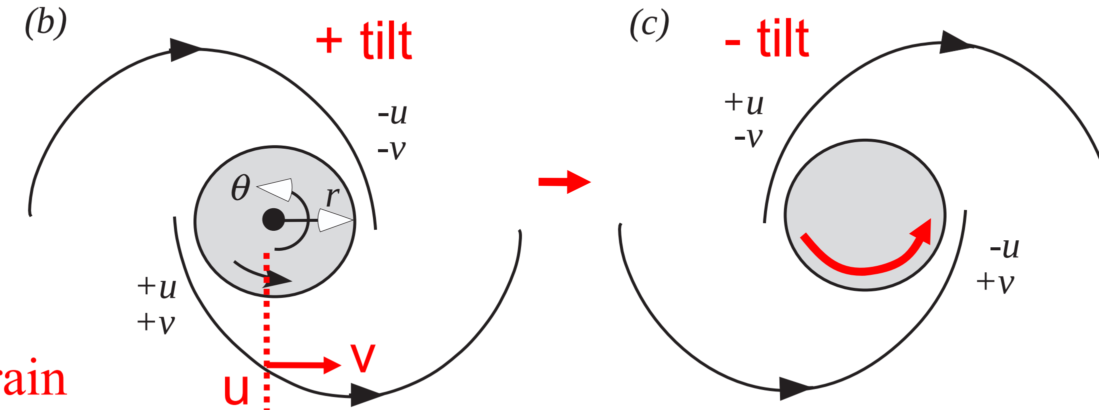
TG: Temporary growth followed by decay

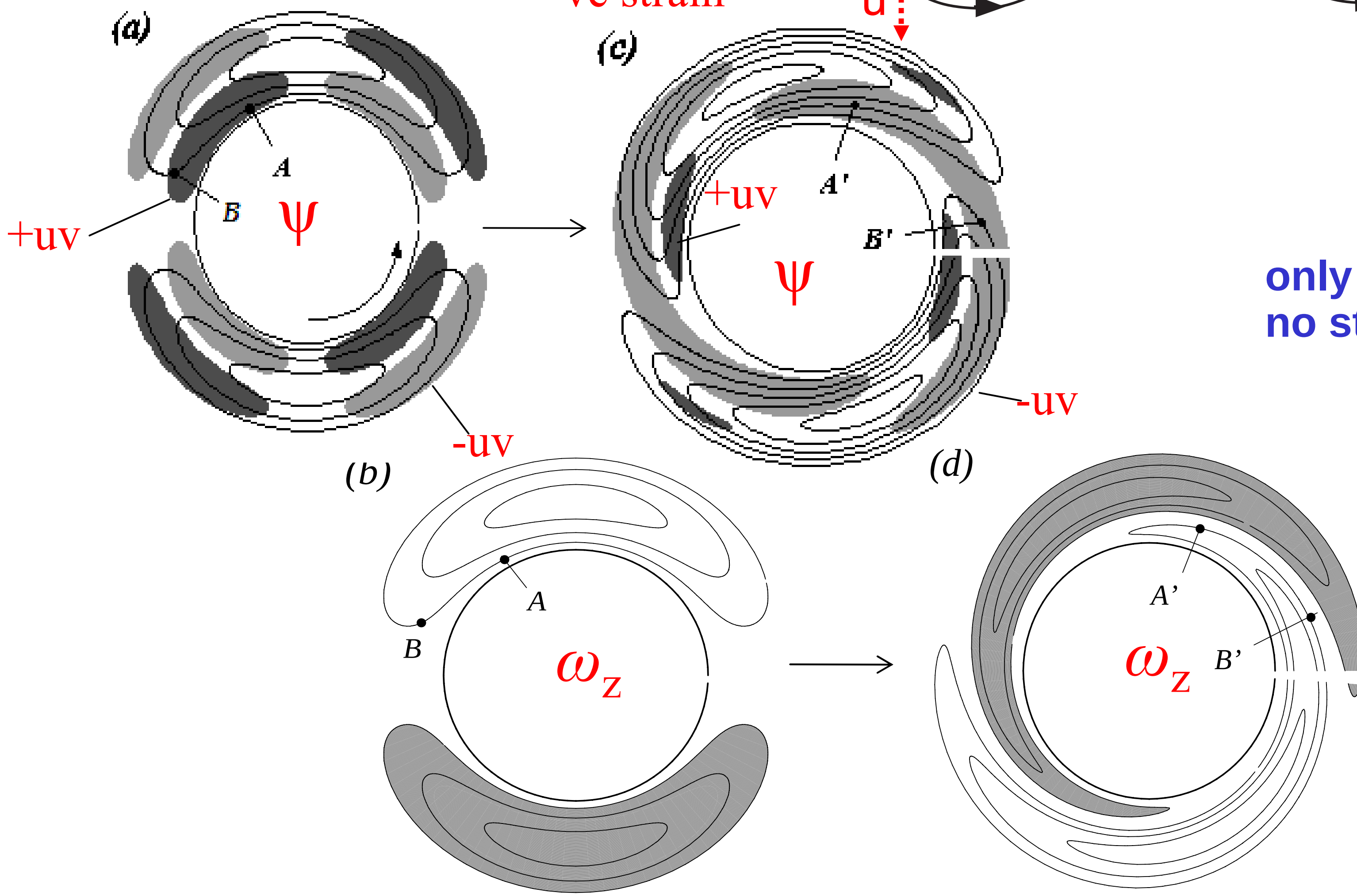
2-D mechanism:

Rigid Rotating Rod

$$\frac{dE}{dt} \sim -\int uv \, \underline{r(V/r)'} \, dV$$

-ve strain





only shearing, no stretching

Three-dimensional mechanism:

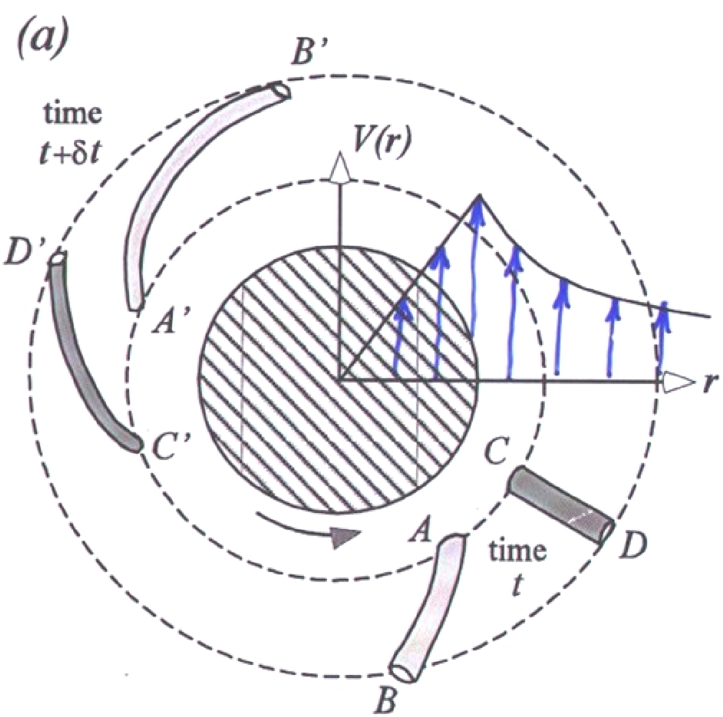
mean vorticity & strain: opposite effects

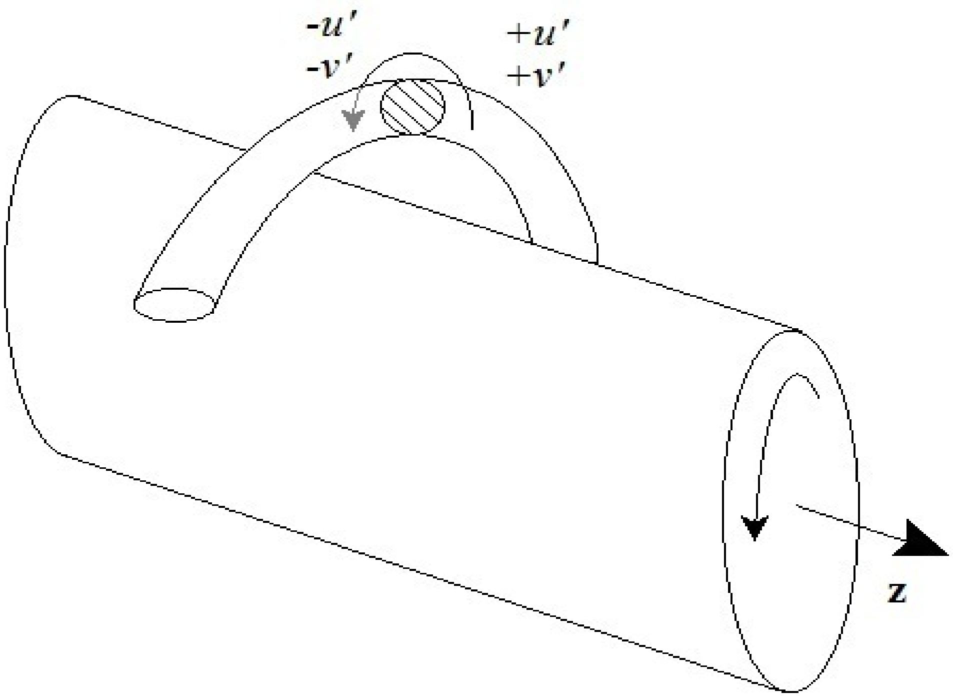
vorticity ⇒ limits growth (mag. & period) ← core

strain ⇒ growth ← outside

$$\frac{\partial \omega_r}{\partial t} = 0; \quad \frac{\partial \omega_z}{\partial t} = 0; \quad \frac{\partial \omega_\theta}{\partial t} = \omega_r S$$

Pure straining flow



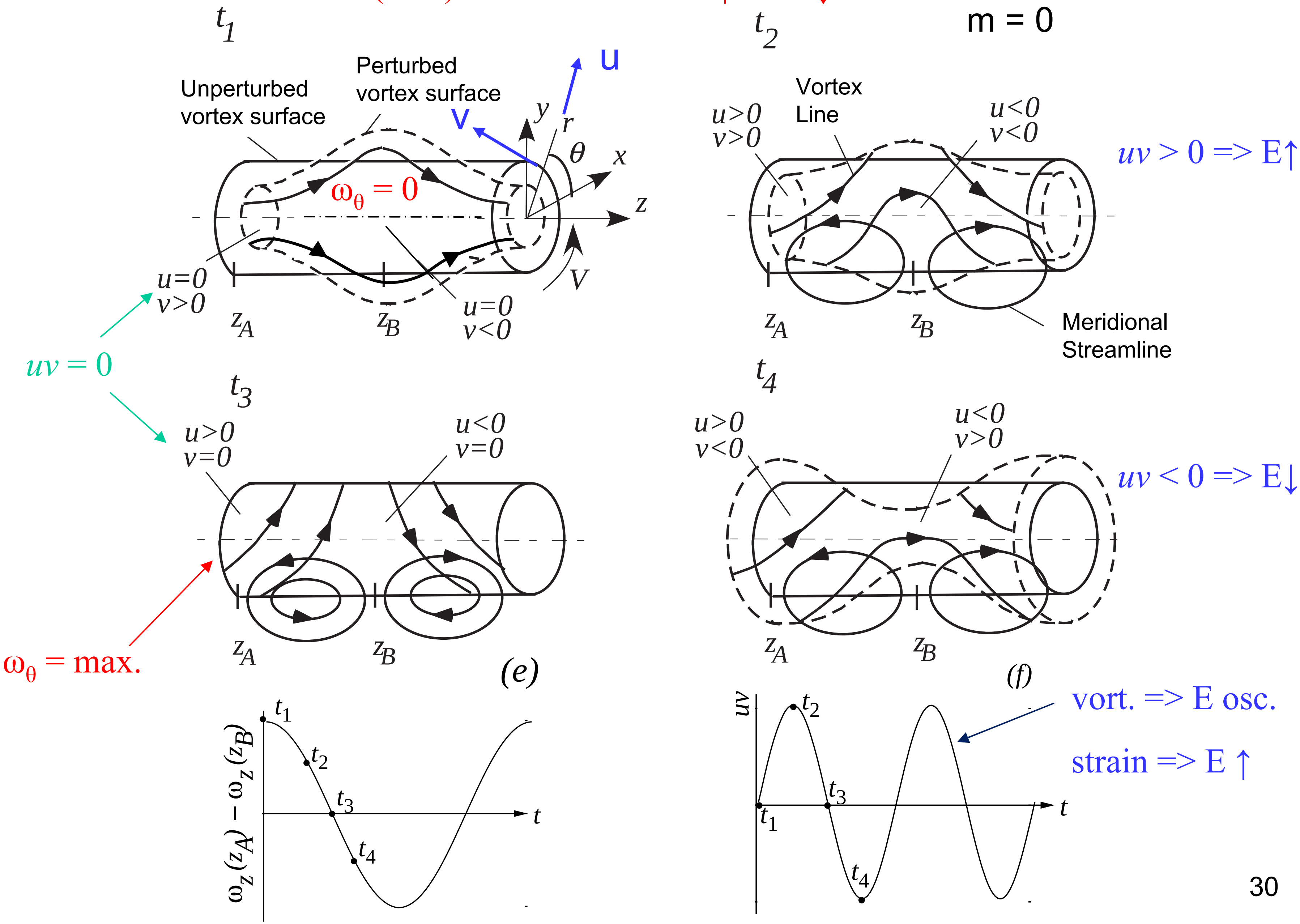


Rotation only

@ vort. Surface
$\Gamma = 2\pi r(V+v) = \text{const.}$ ⇒ $r\downarrow \Rightarrow v\uparrow$
$r\uparrow \Rightarrow v\downarrow$

Core dynamics

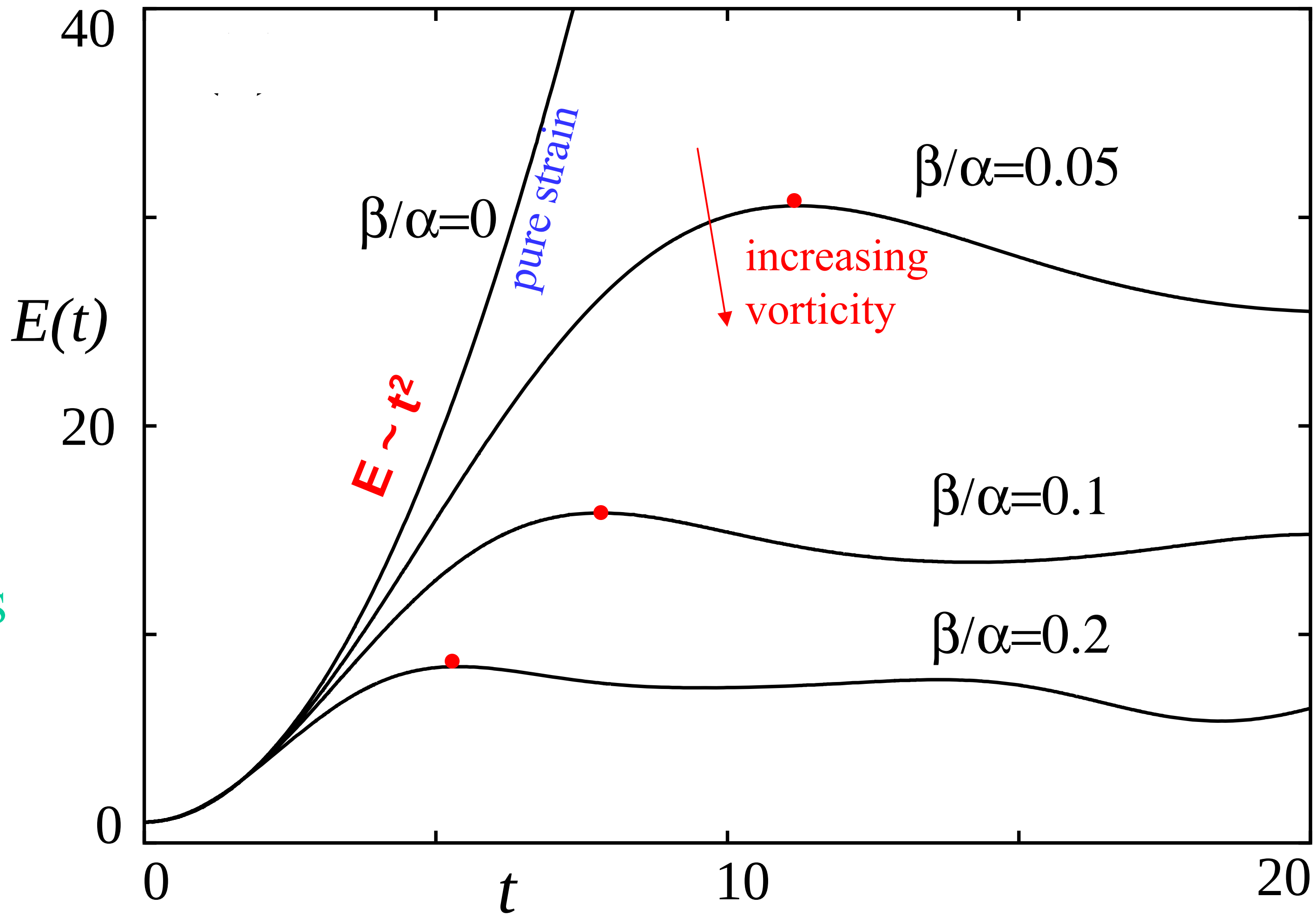
m = 0



$$V = \frac{\alpha}{r} + \frac{\beta r}{2}$$

model flow

β/α = rotation/strain



$$\frac{\partial \omega_\theta}{\partial t} = \omega_r S$$

Higher strain S

i.e. α ↑

⇒ω_θ gen.

⇒ uv ↑

⇒E ↑

inc. vort(β)

⇒ arrest E ↑

sooner

LIN. INVISCID TG

Strain: unbounded growth (lin. sense)

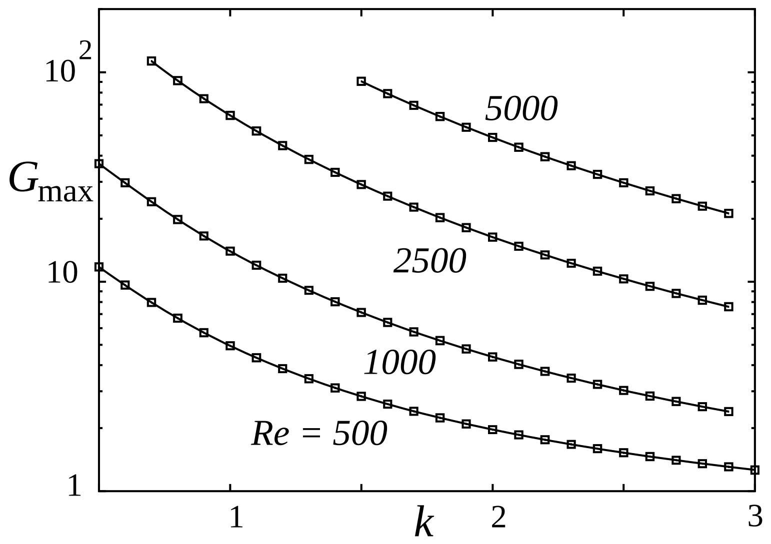
eventually saturate at NL level

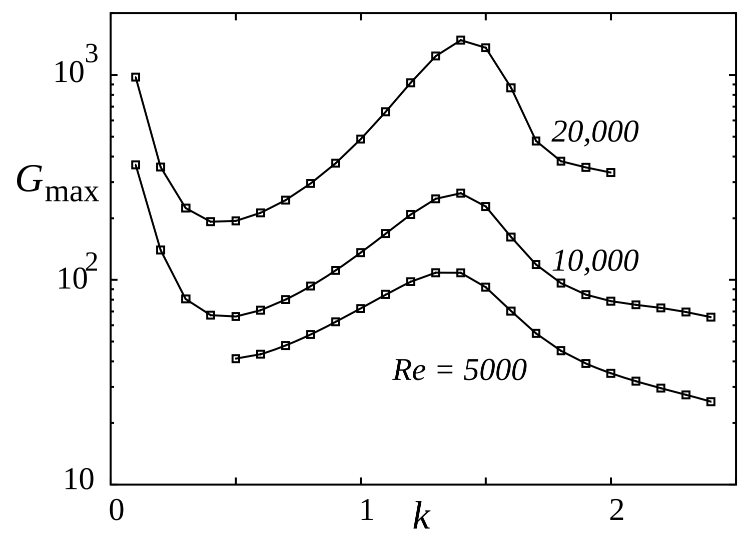
core vorticity: arrest growth & period of growth

$\longrightarrow$ core oscillation

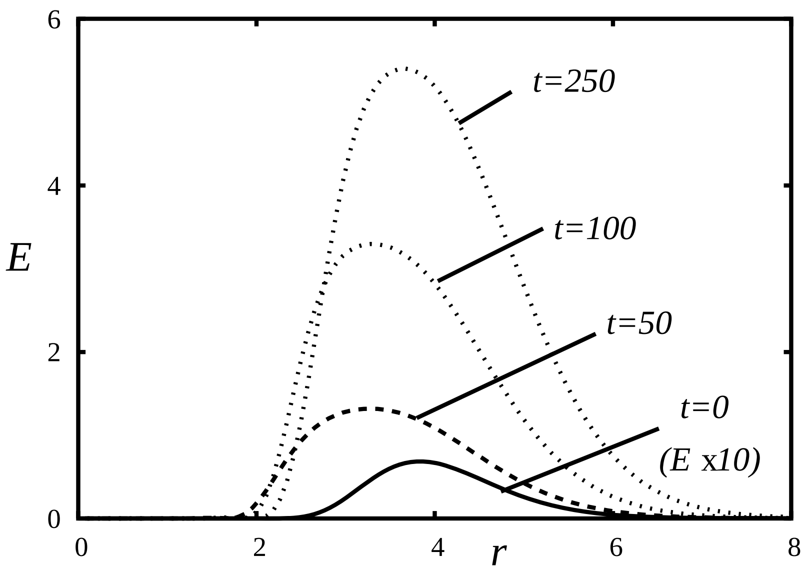
VISCOSITY damps both

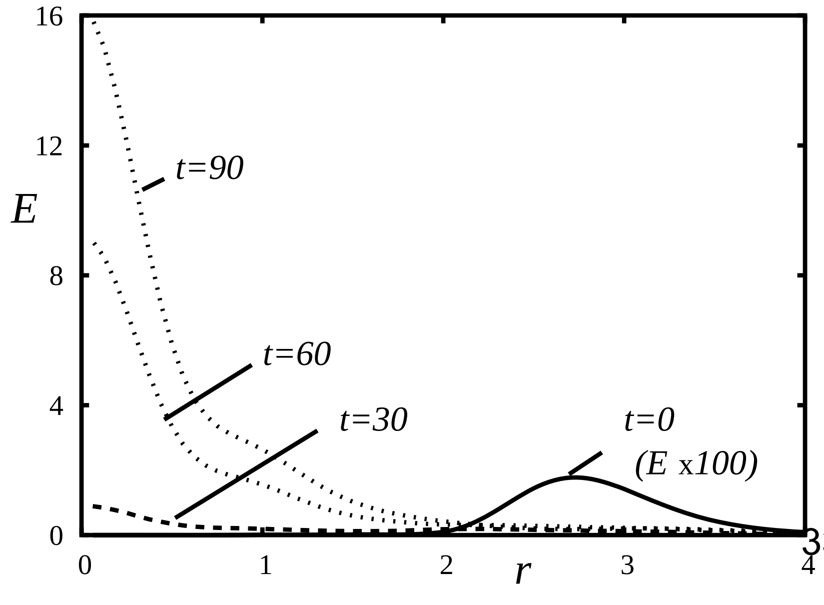
Optimal gains: *axi-sym* m = 0 *Bending* m = 1



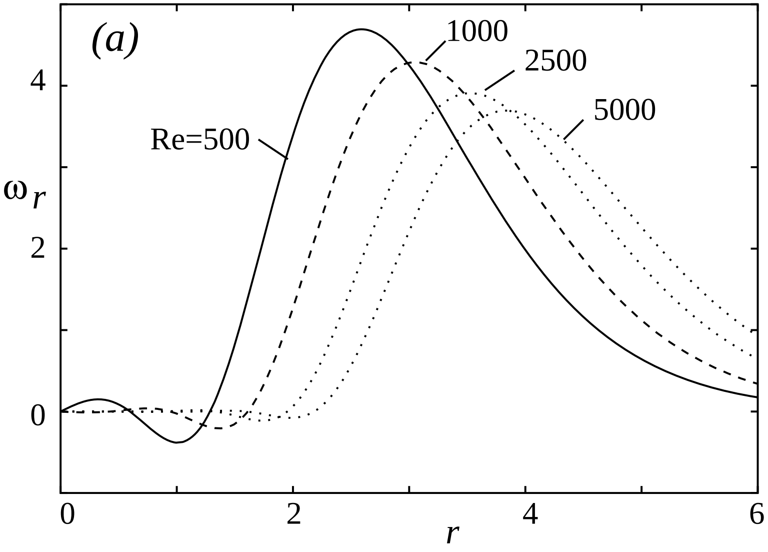


Energy evolution:

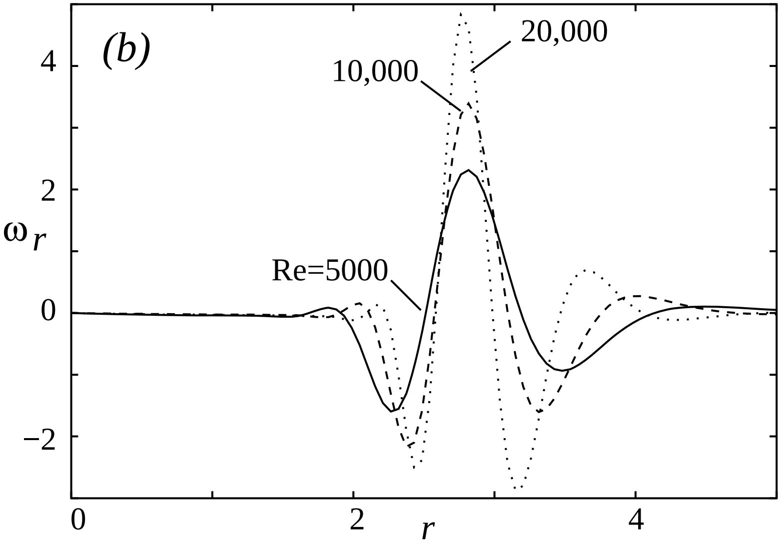




Re effect on tilting/stretching



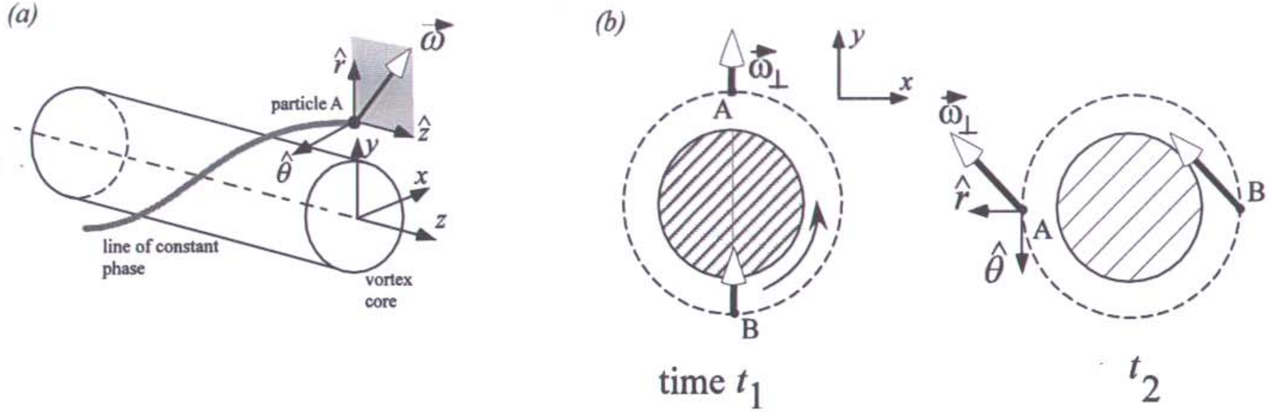
m = 0

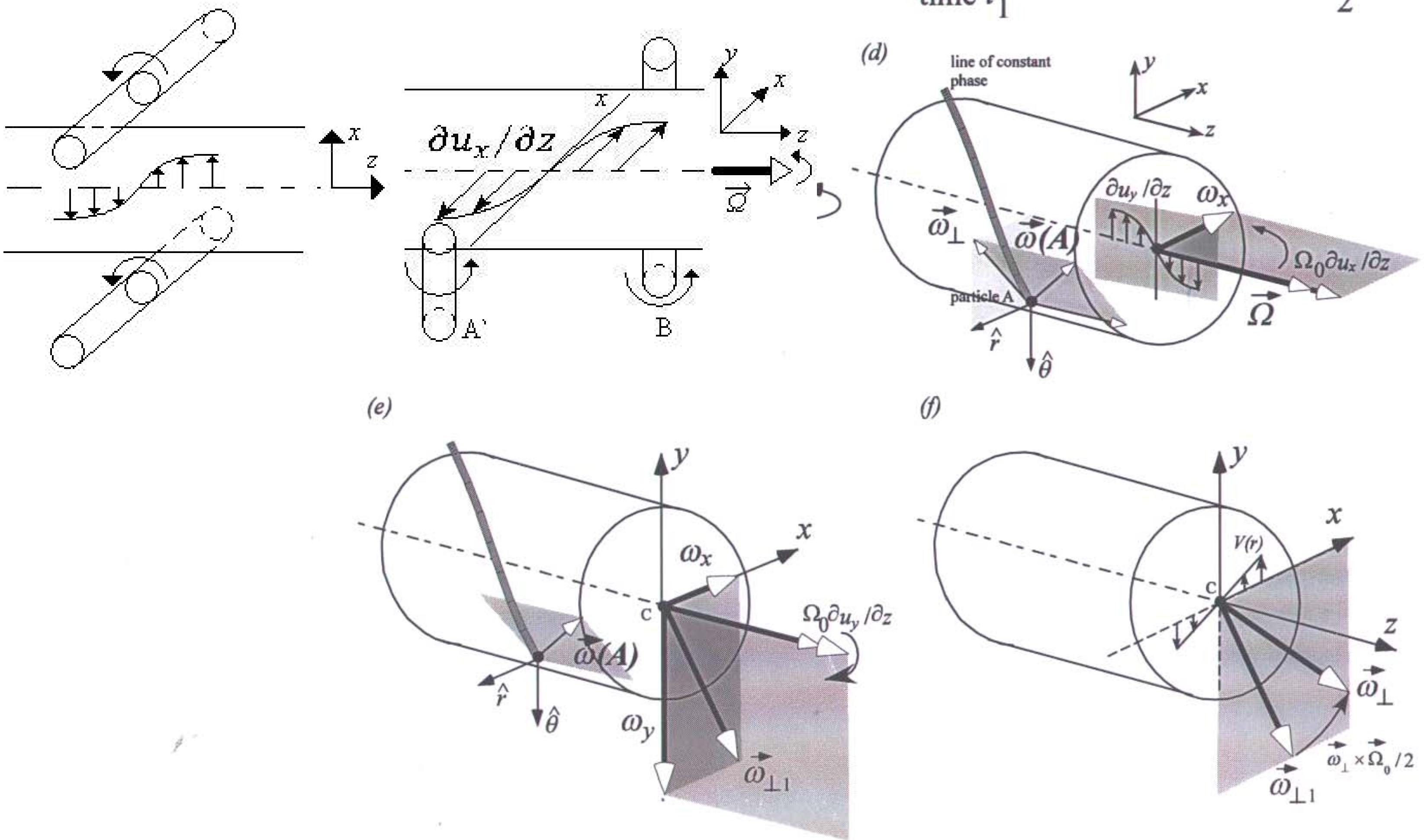


m = 1

Mechanism of core fluctuation growth:

m = 1



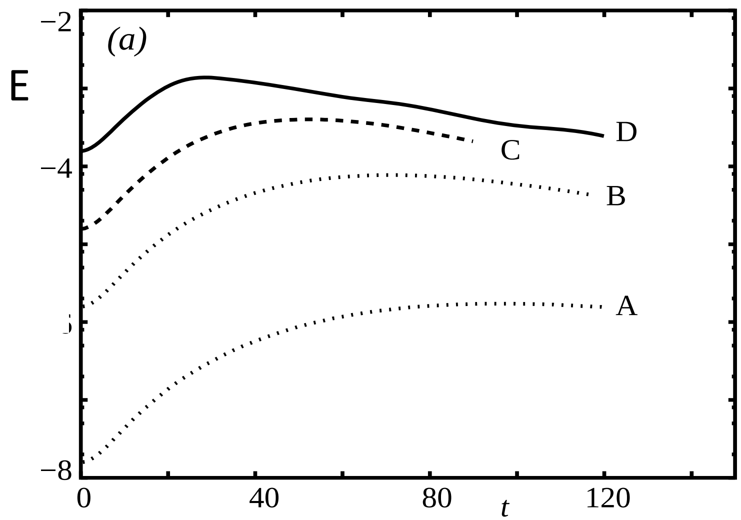


NONLINEAR TRANSIENT GROWTH

of optimal modes

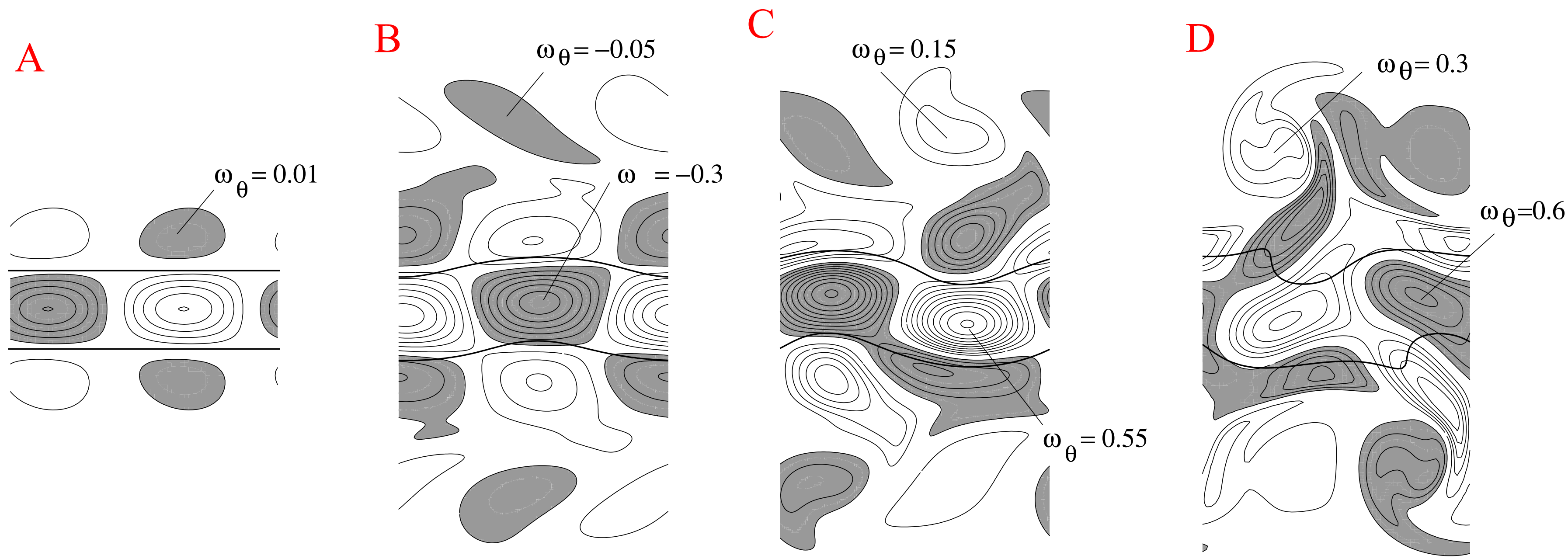
initial perturbation amplitude: $m = 1$

Re = 5000

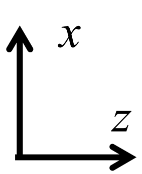


Case	
A	Linear
B	0.6%
C	2%
D	6%

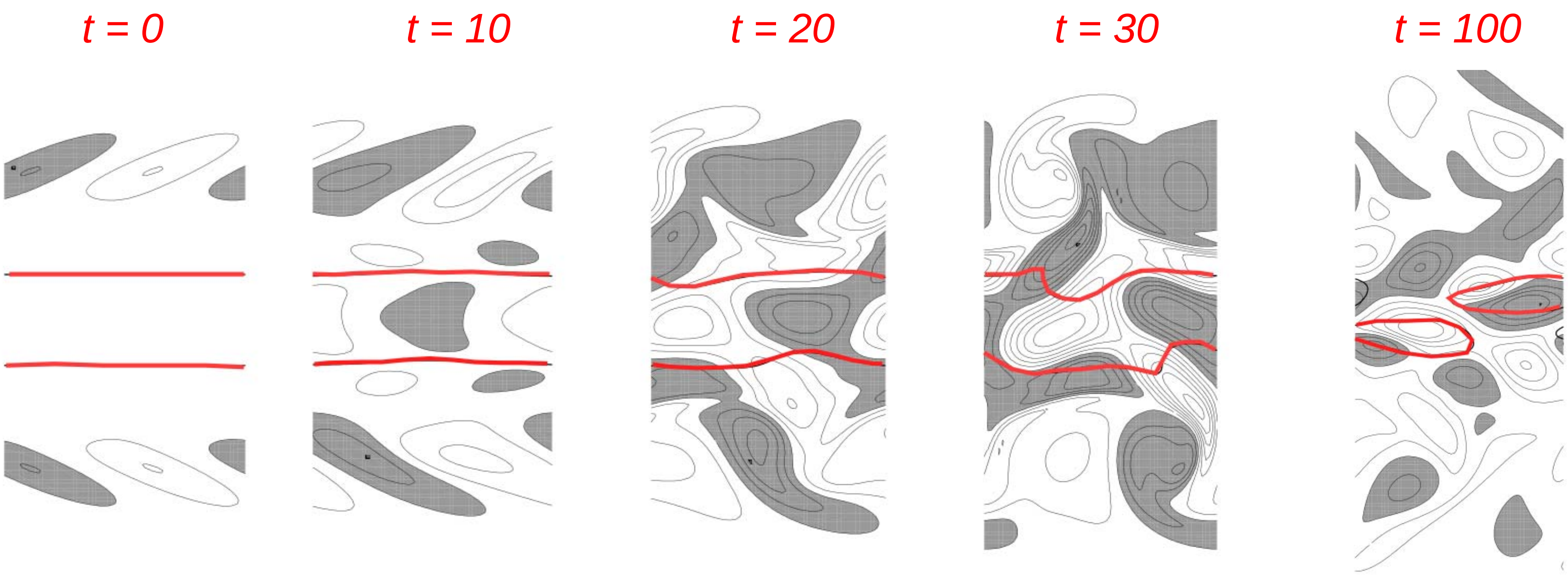
Structure at time of max. energy:

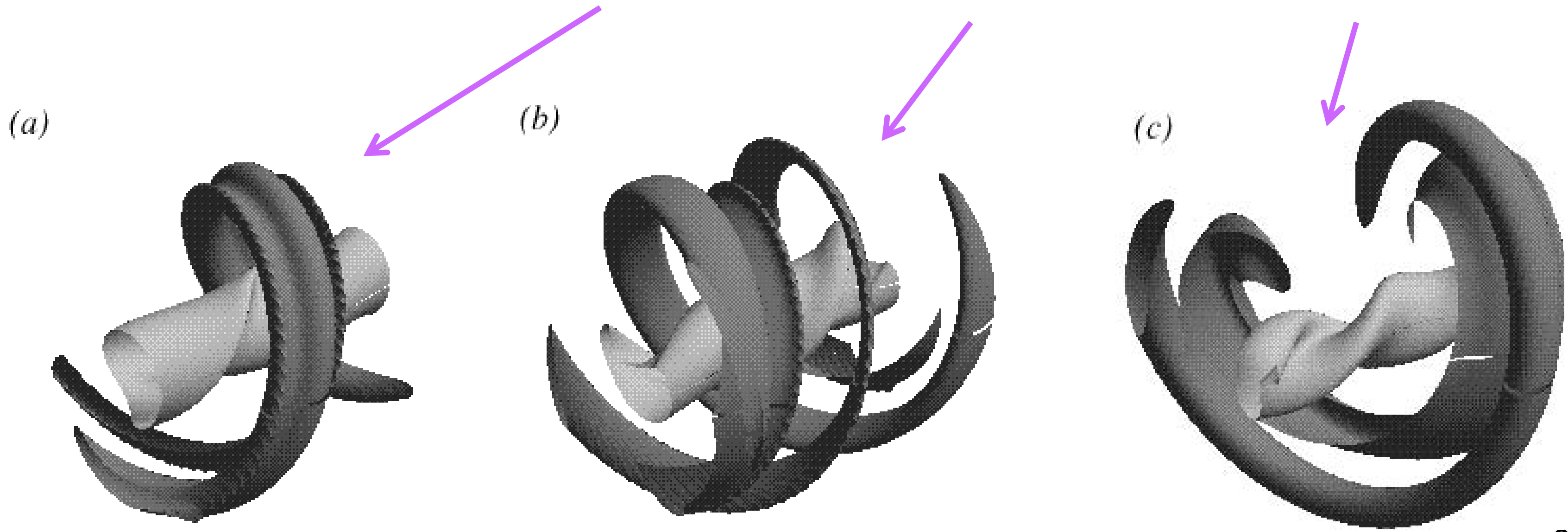


t = 90 *t = 70* *t = 50* *t = 30*

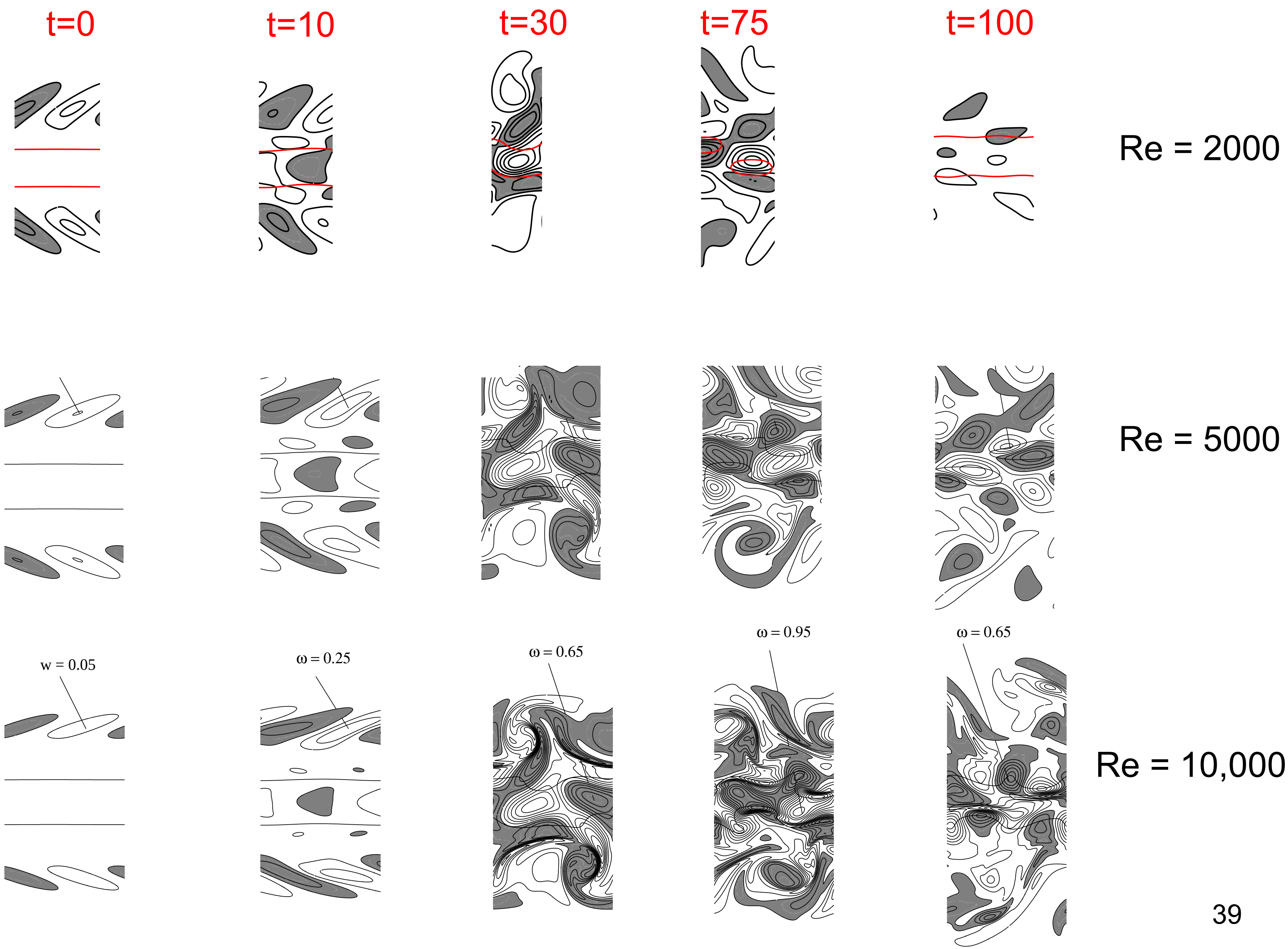


<u>High-amplitude perturbation evolution</u>: Case D, m = 1 Re = 5000

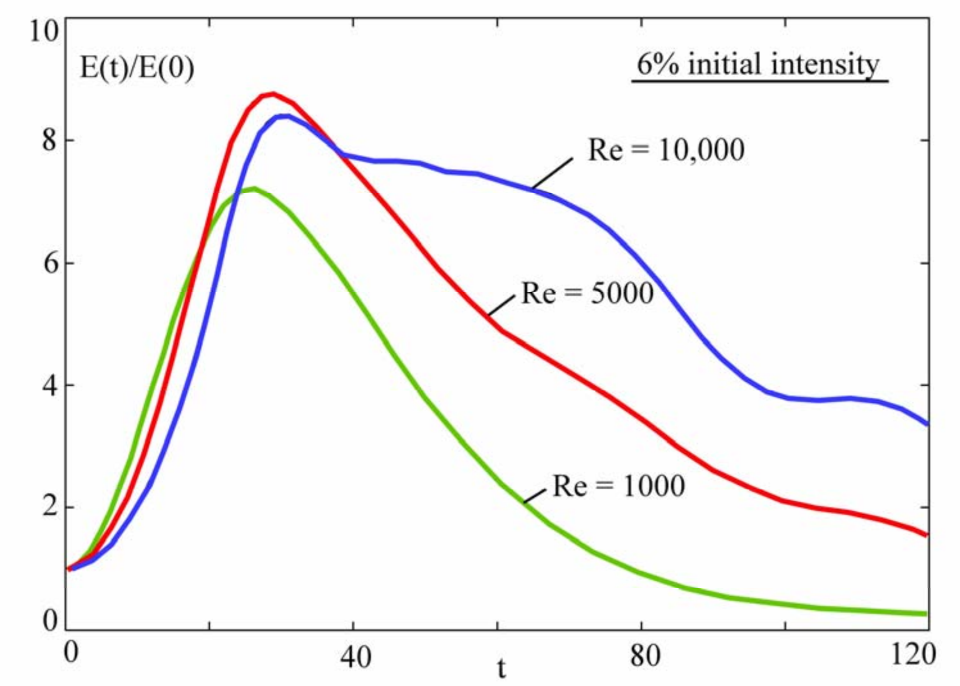




Re effect:

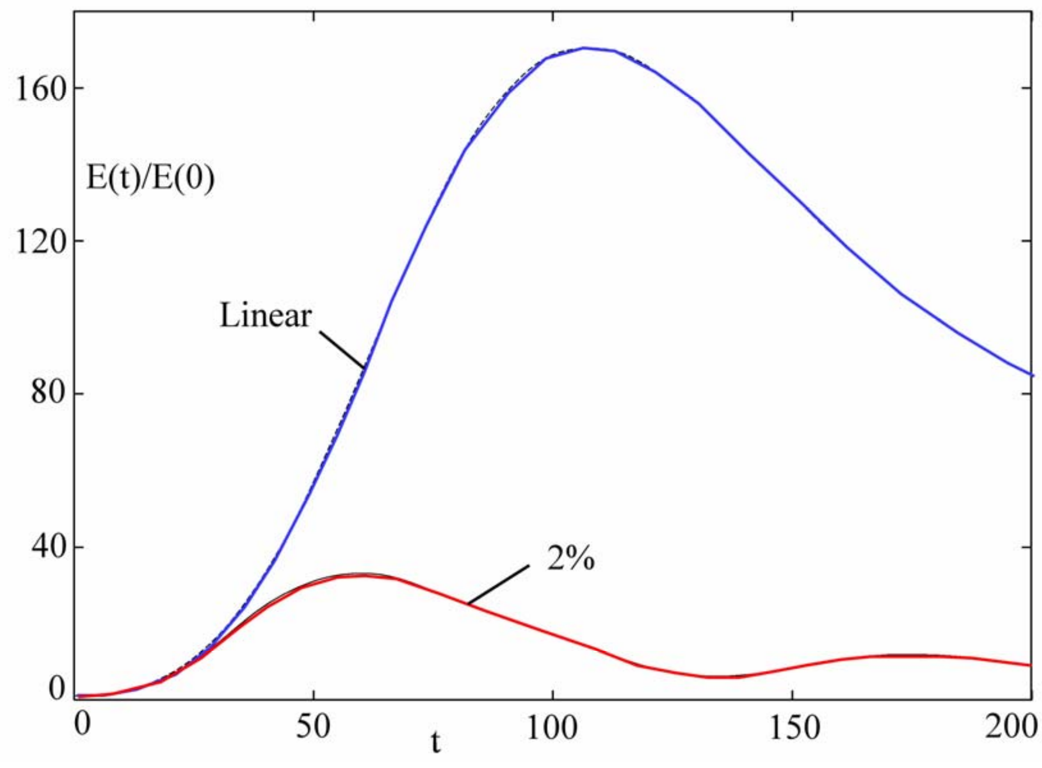

t=0
t=10
t=30
t=75
t=100
Re = 2000
Re = 5000
Re = 10,000
w = 0.05
ω = 0.25
ω = 0.65
ω = 0.95
ω = 0.65

***Re*-effect in time**

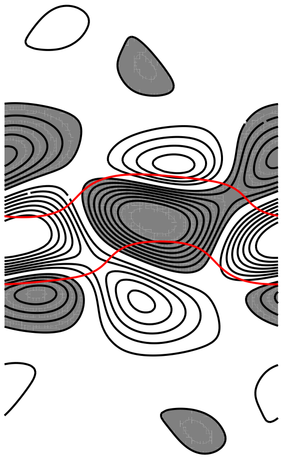


Regenerative Transient Growth?

Re = 5000



Regenerative Transient Growth?



t = 100 t = 120 t = 140 t = 160 t = 180

Some conclusions

- Turbulence induces and amplifies core fluctuations – amplitudes exceeding those of external perturbations.
- Several potential mechanisms of core transition / accelerated vortex decay studied.
- Circulation overshoot => centrifugal instability: amplifies perturbations, but inherently self-limiting.
- Weak “threads” can resonate with vortex core dynamics waves, but not strong perturbations.
- Transient growth: orders-of-magnitude amplification
- Strongest transient growth for bending waves.

Further study

Nonlinear transient growth, regenerative transient growth,

vortex breakup and turbulence self-sustenance