7 Nobeyama Wksp, Tokyo

The looming crisis in air traffic capacity – what can vortex dynamics do?

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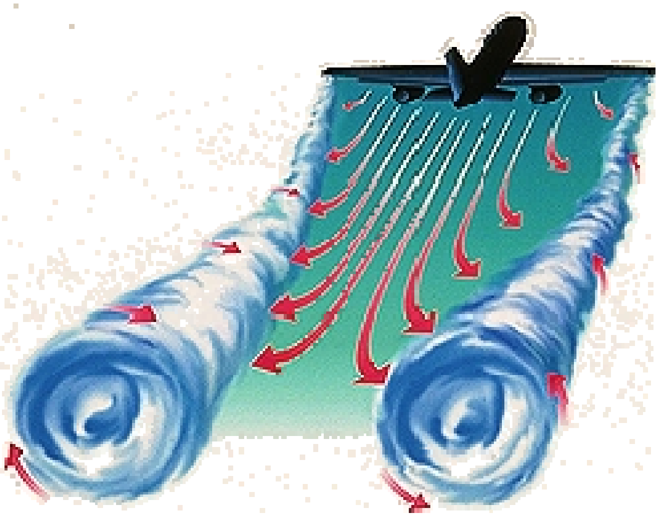
Dedicated to Kunio Kuwhara

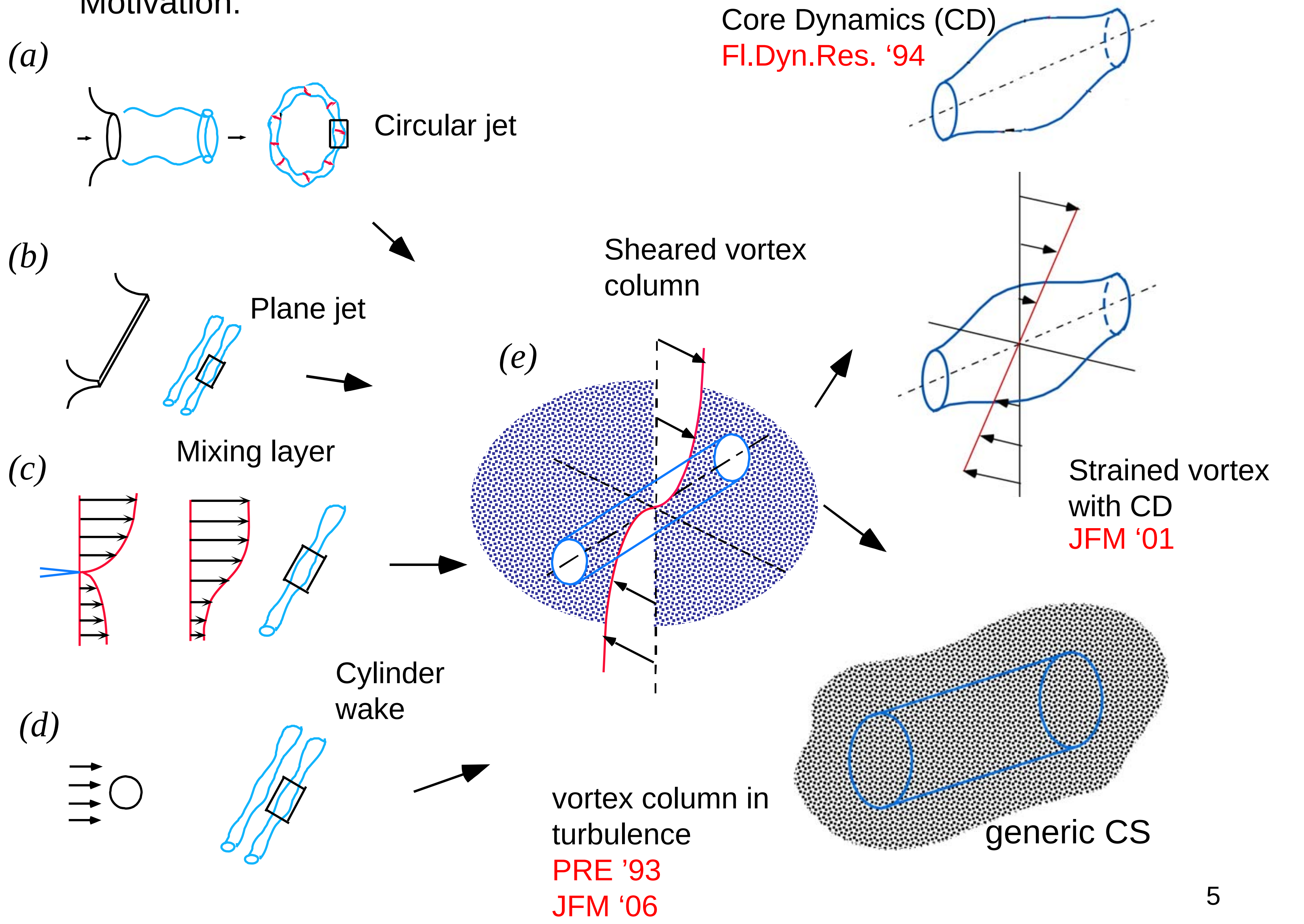
Funded by NSF



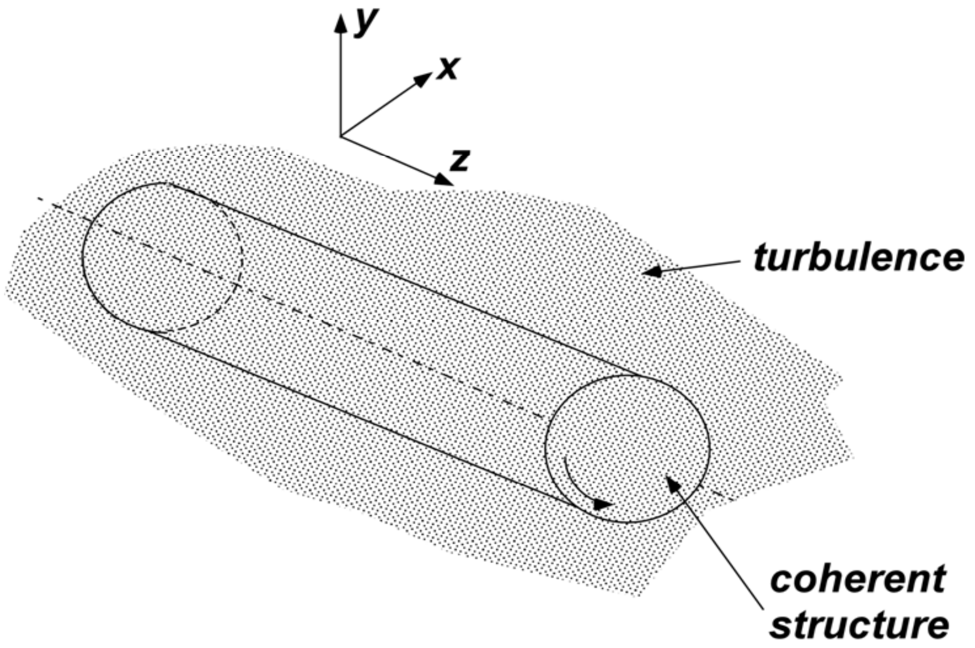

AIRLINES




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

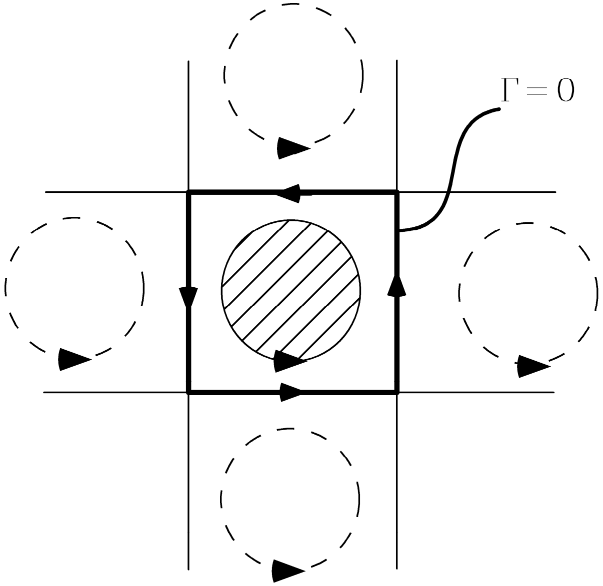
Oseen-Lamb
vortex

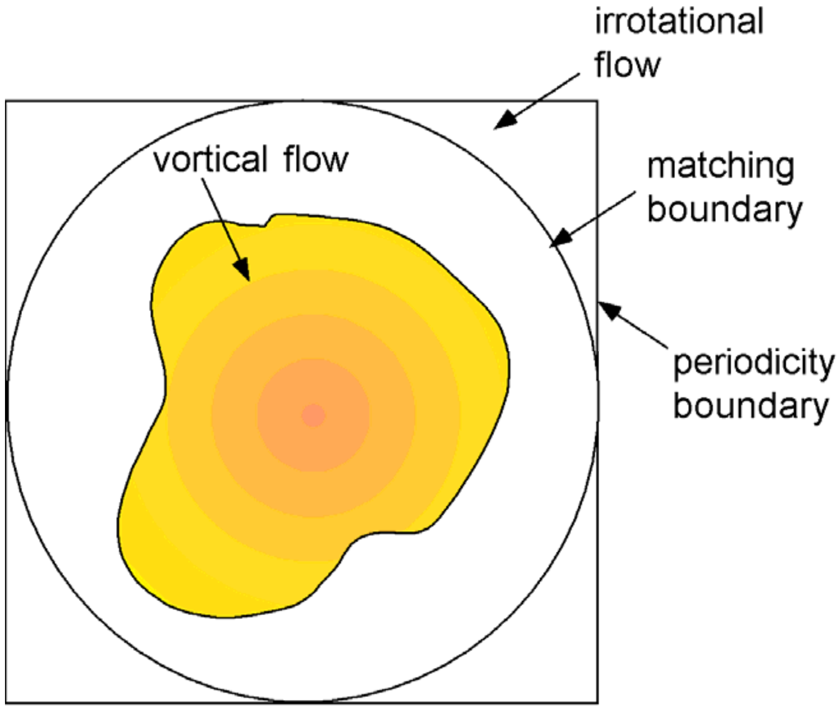
Idealizations:

- •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 @ $r \rightarrow \infty$

Numerical simulation method:



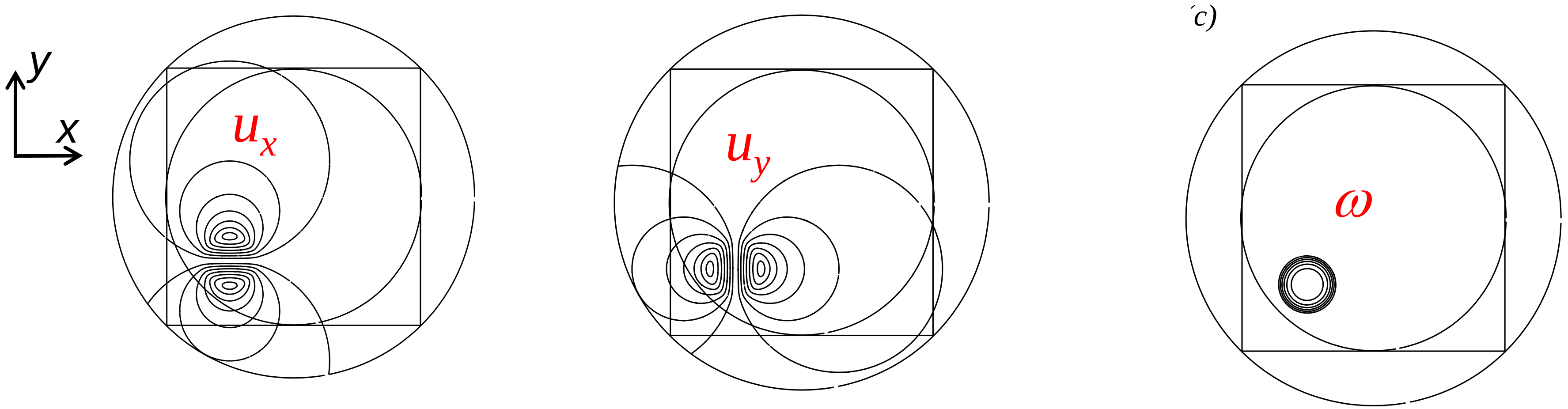


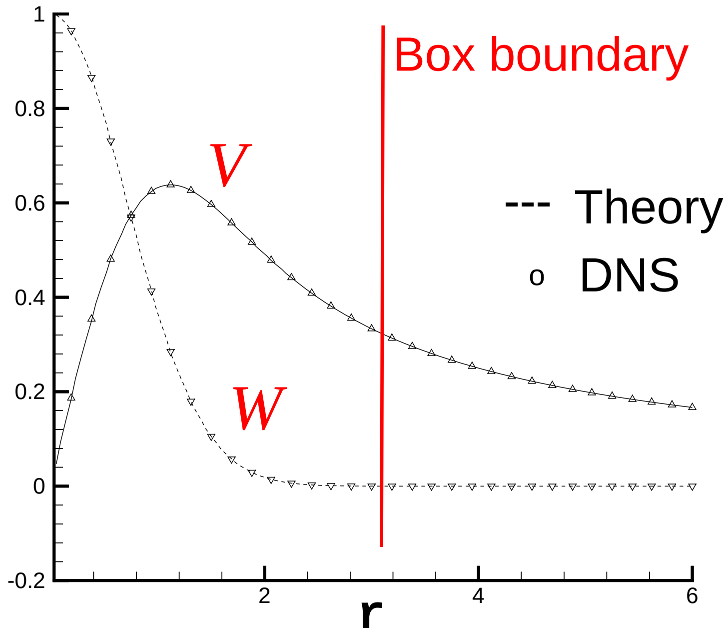
Triply-periodic

"unbounded" flow
(Rennich-Lele '97)

Pradeep & H. '04

<u>q-vortex</u>





o

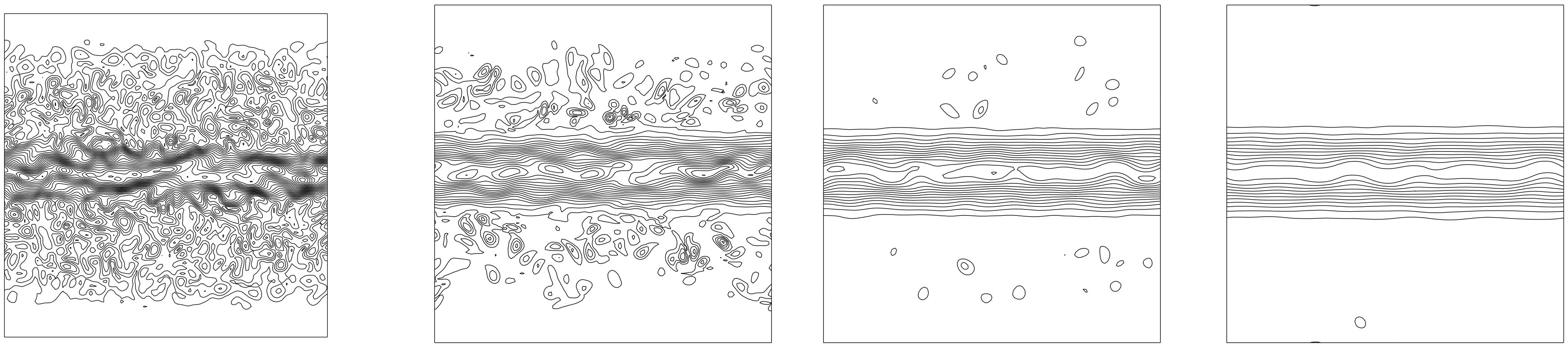
o

o

o

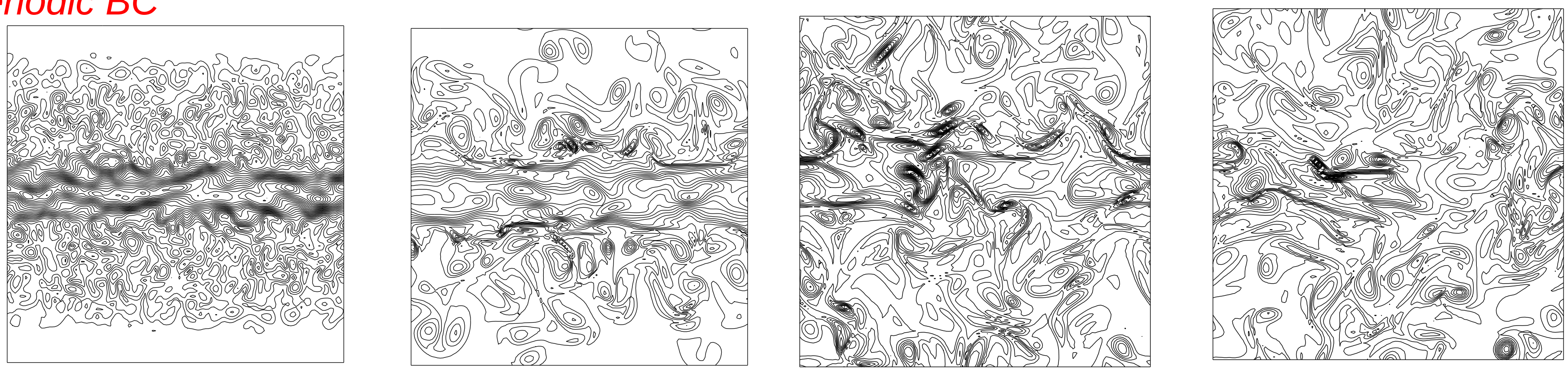
Comparison:

Unbounded BC

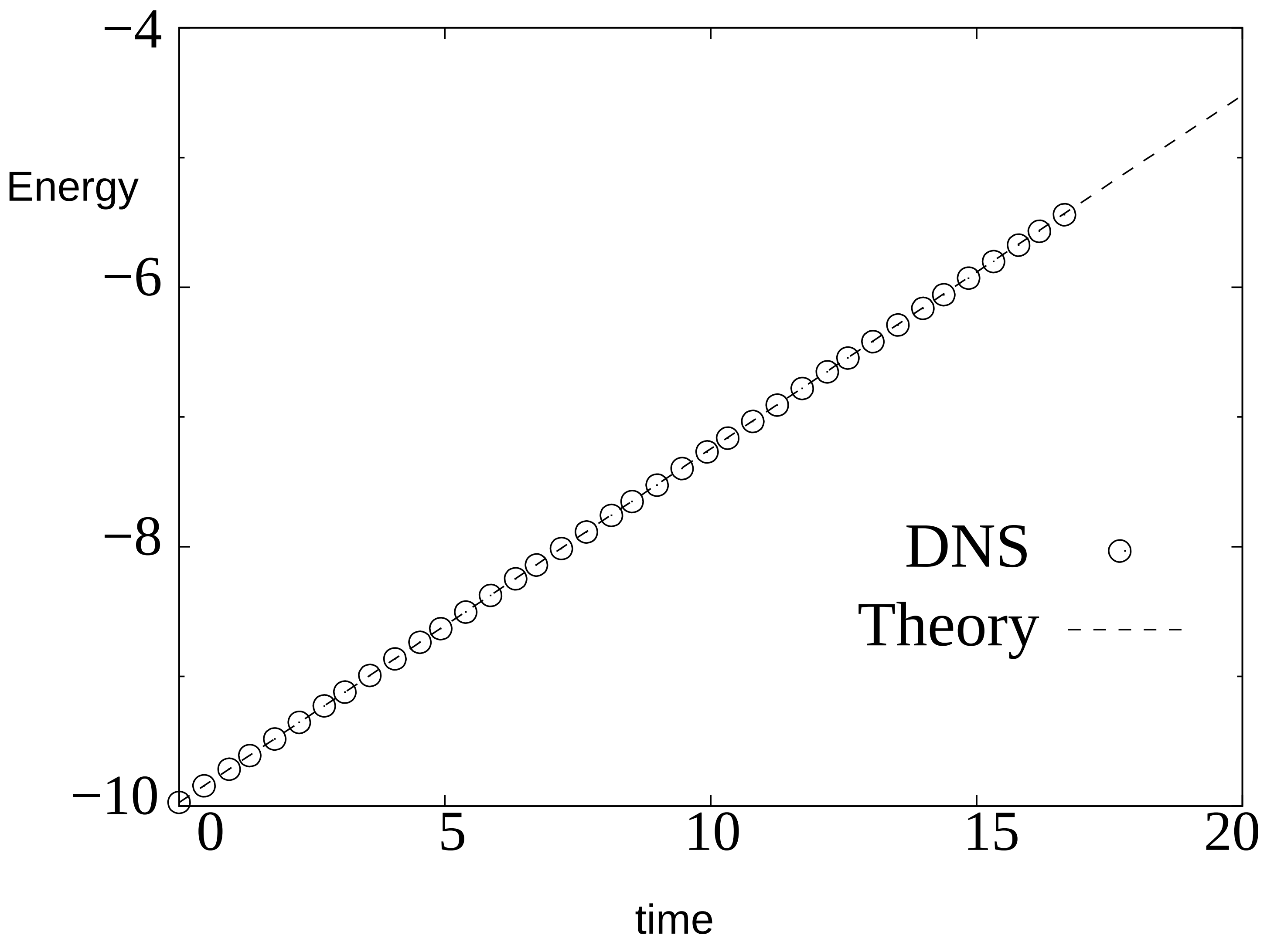


→ time

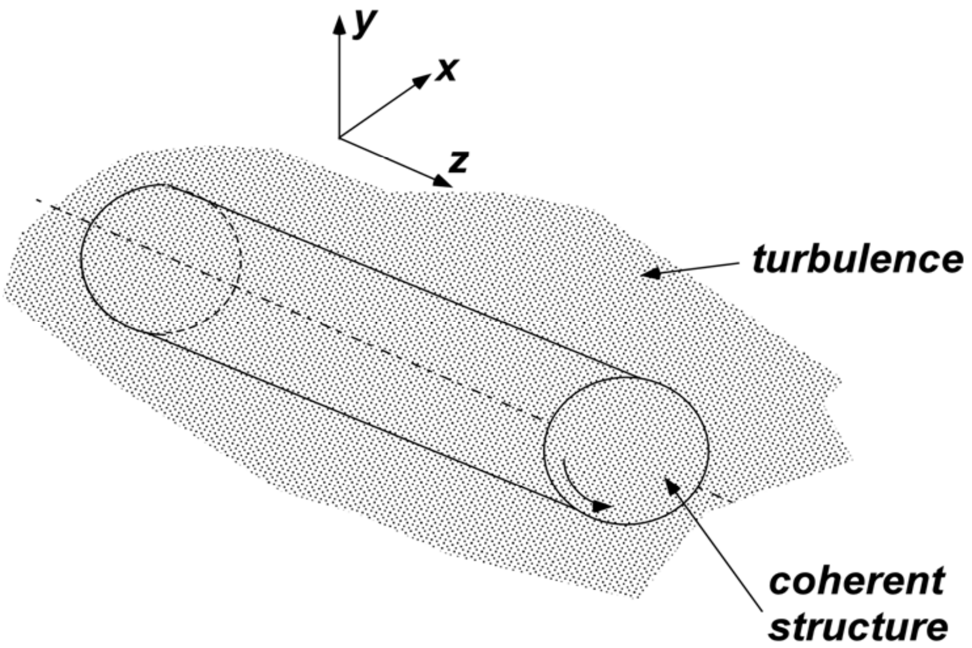
Periodic BC



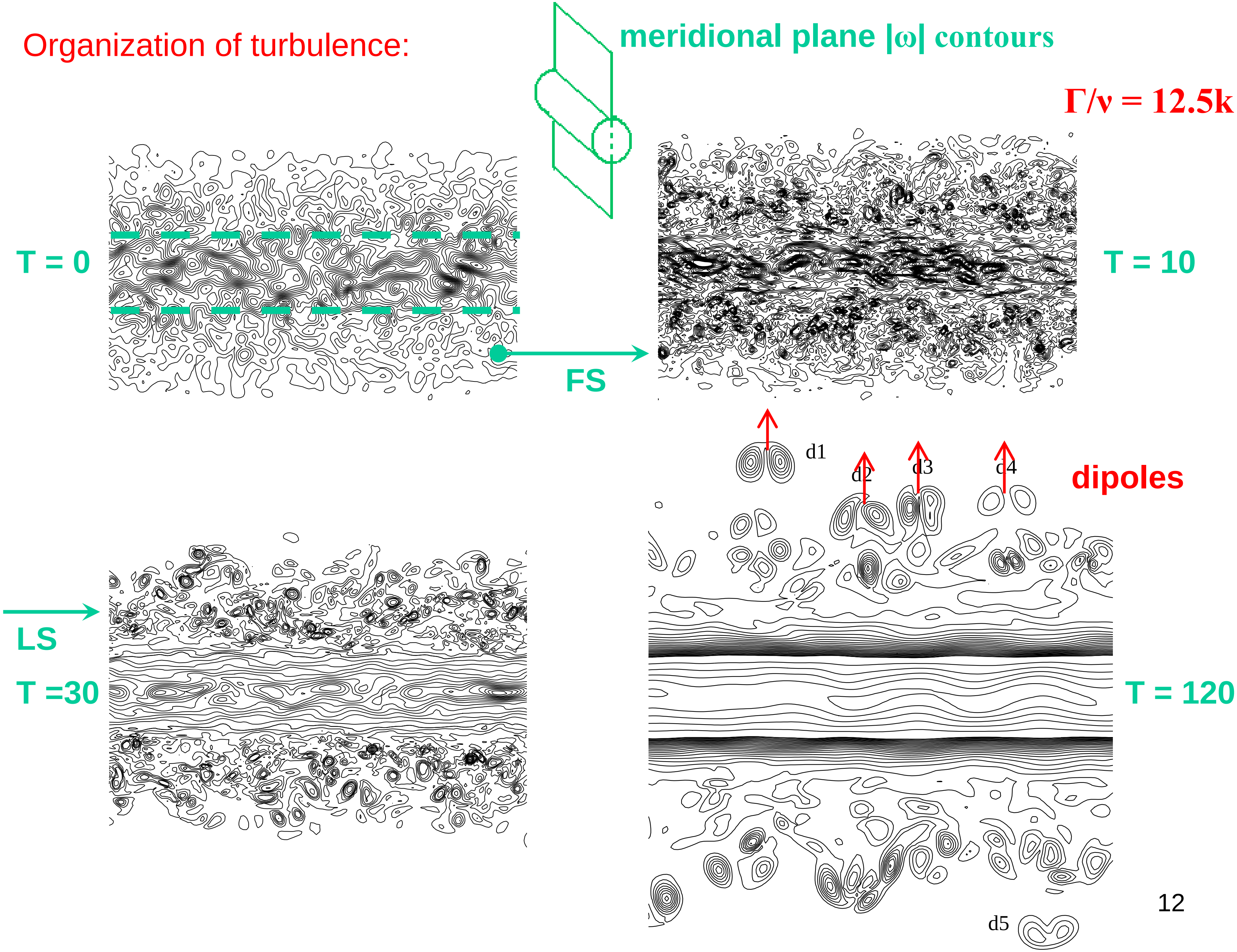
Growth of q-vortex instability mode: Bending wave   Re = 10^5 (DNS)

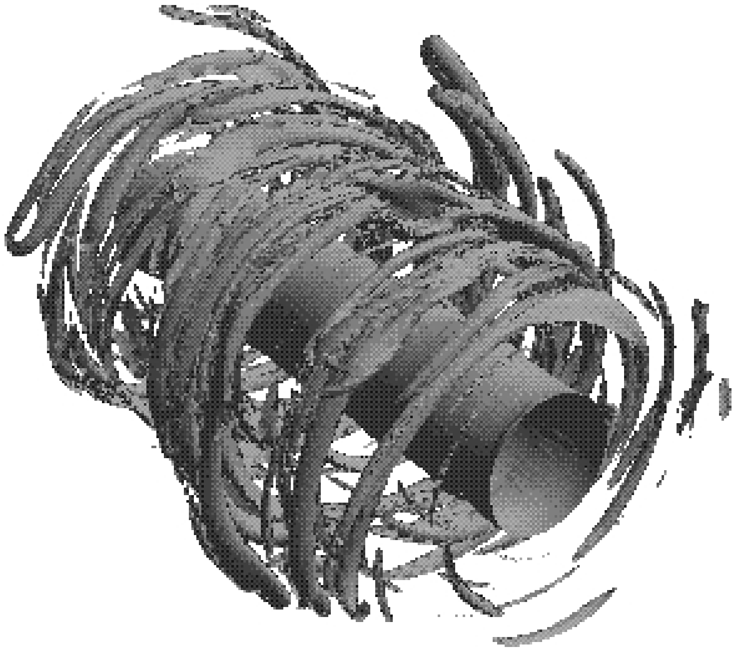


Vortex-Turbulence Interaction

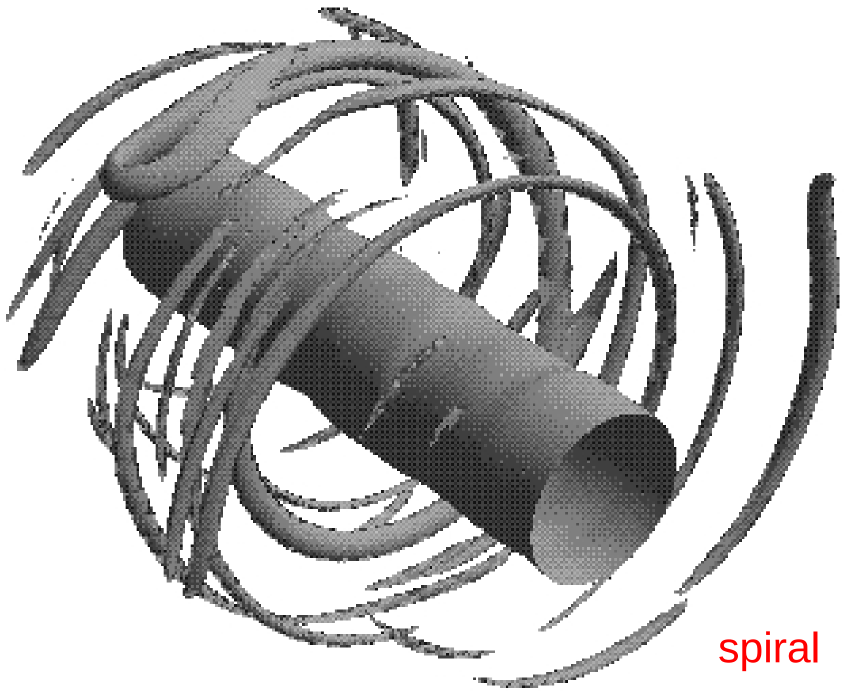


Organization of turbulence:





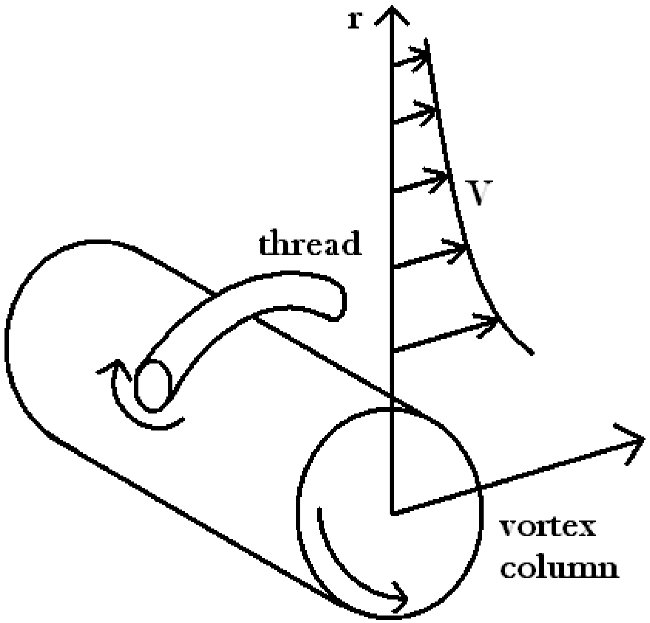
dipoles

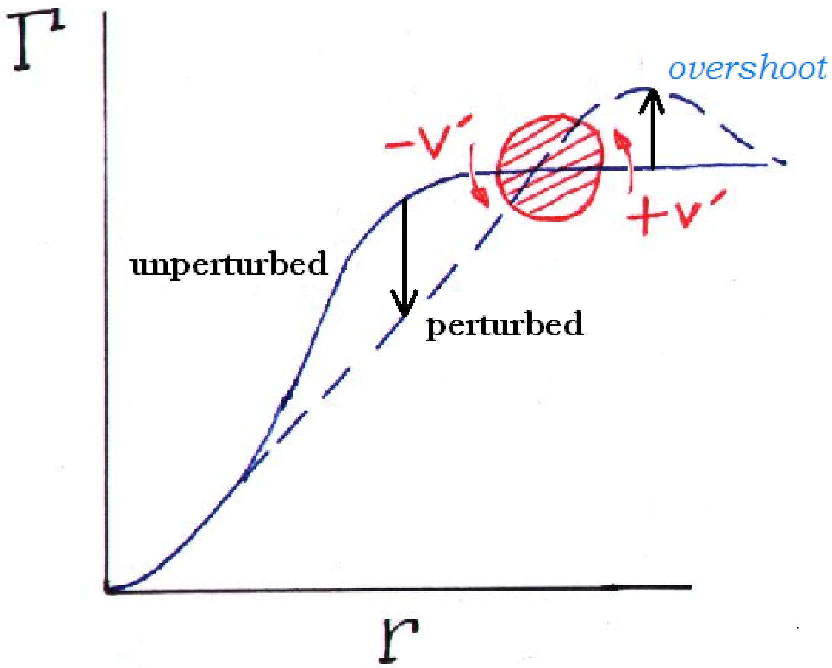


spiral

threads

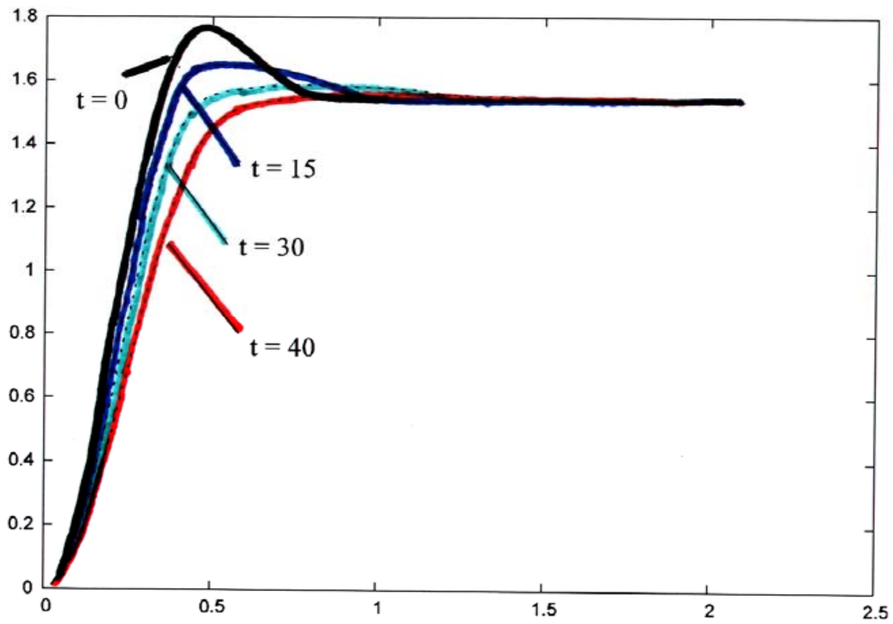
Transport effect of ***threads***:

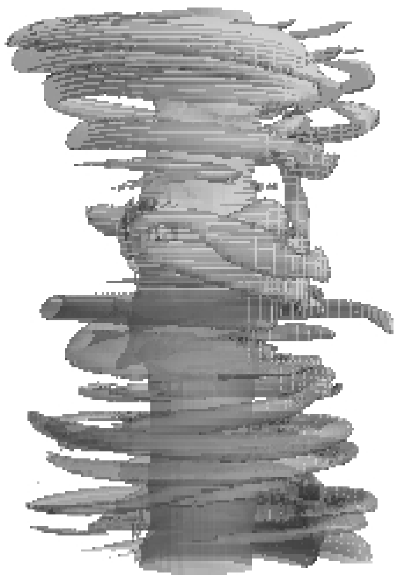


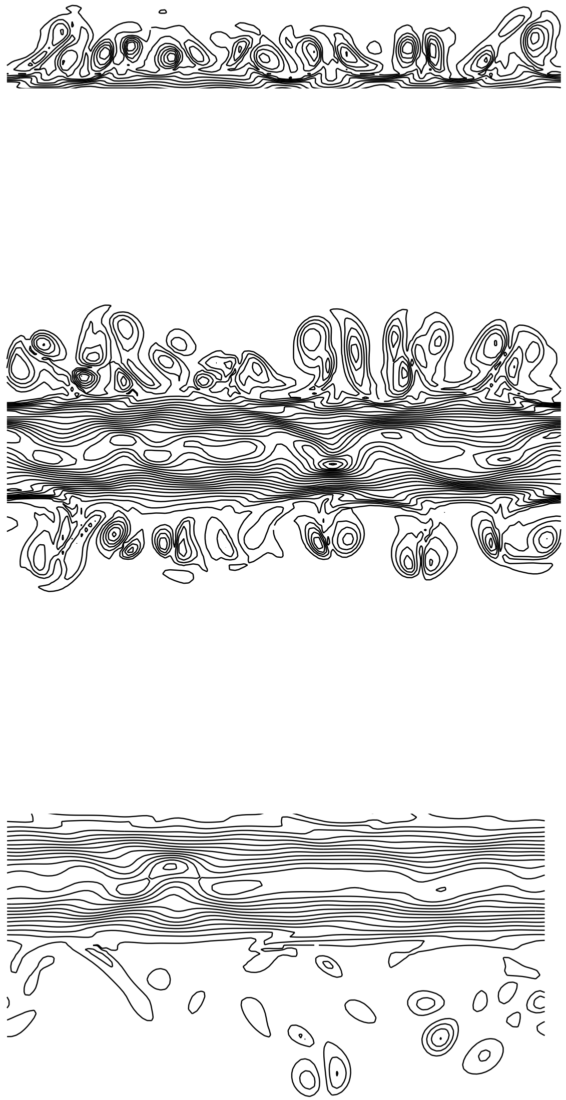


centrifugal instability

$Re = 5000$







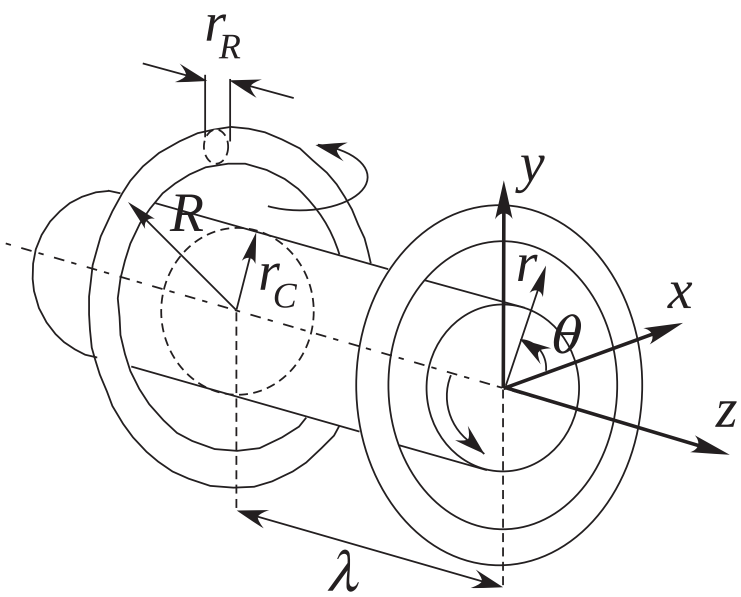
Self-limiting

Mechanisms of core perturbation growth:

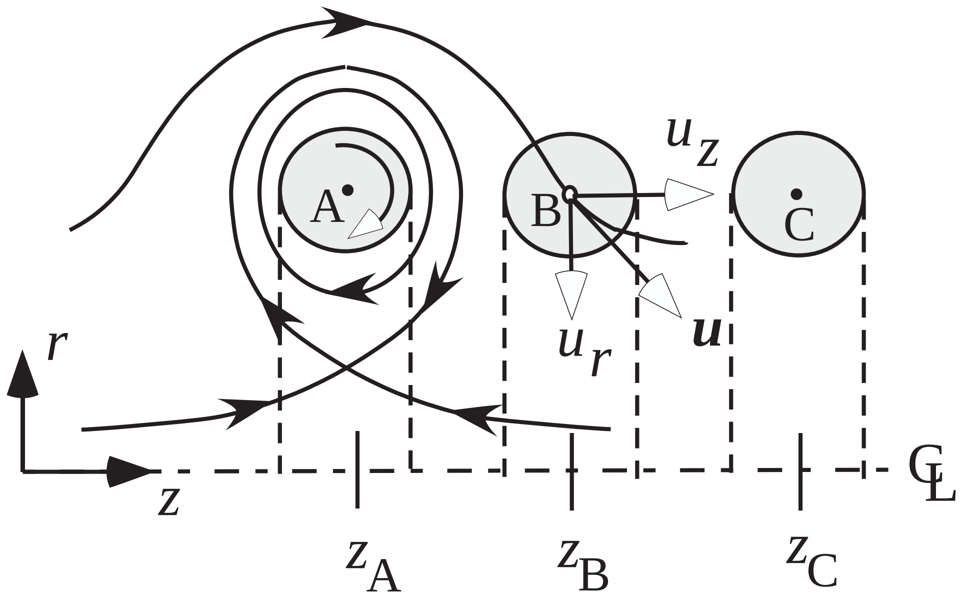
Centrifugal instability is self-limiting

Other mechanisms?

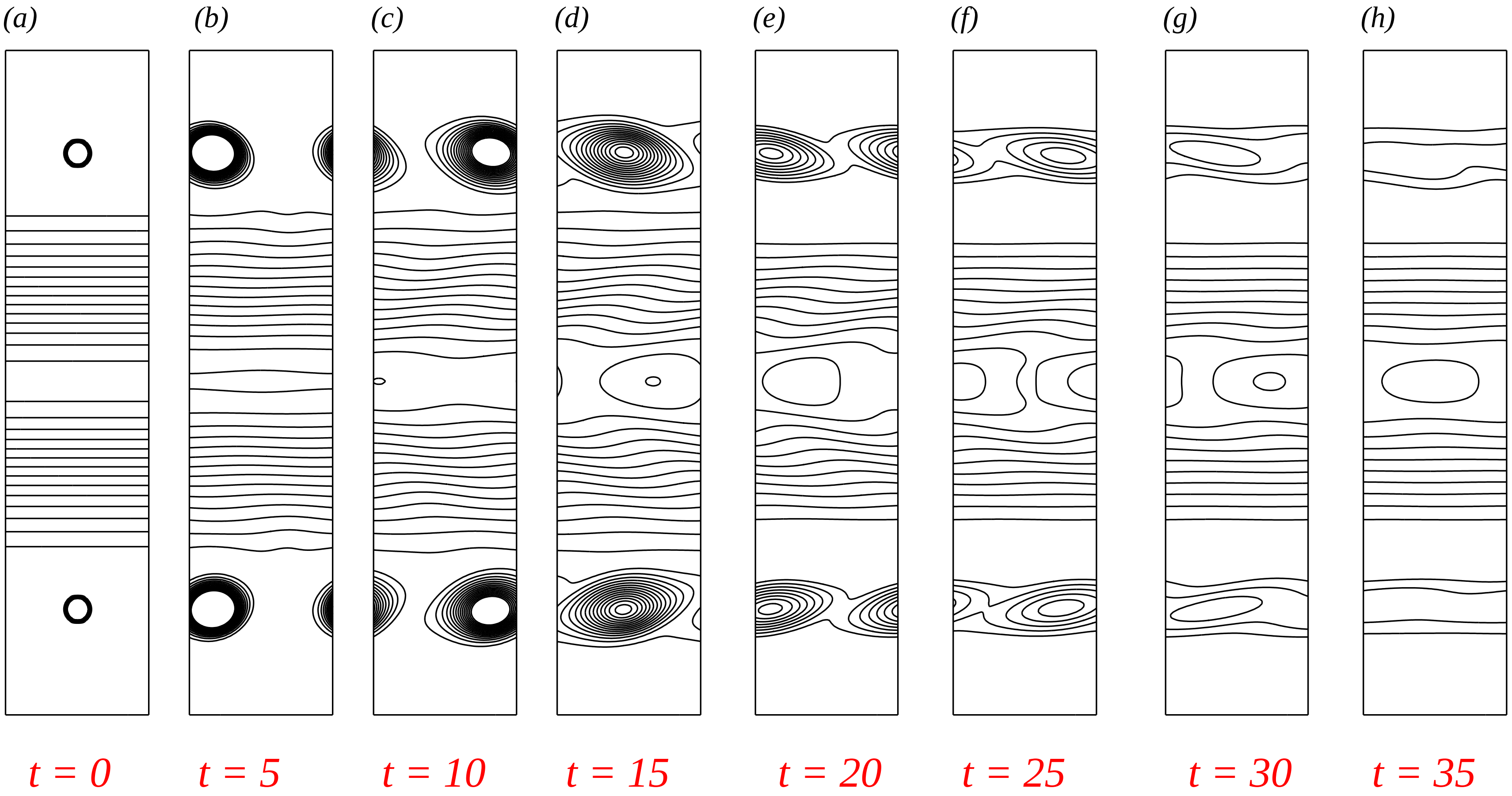
- Thread/Vortex wave resonance
- Transient growth



r_R
R
r_C
y
r
x
θ
z
λ

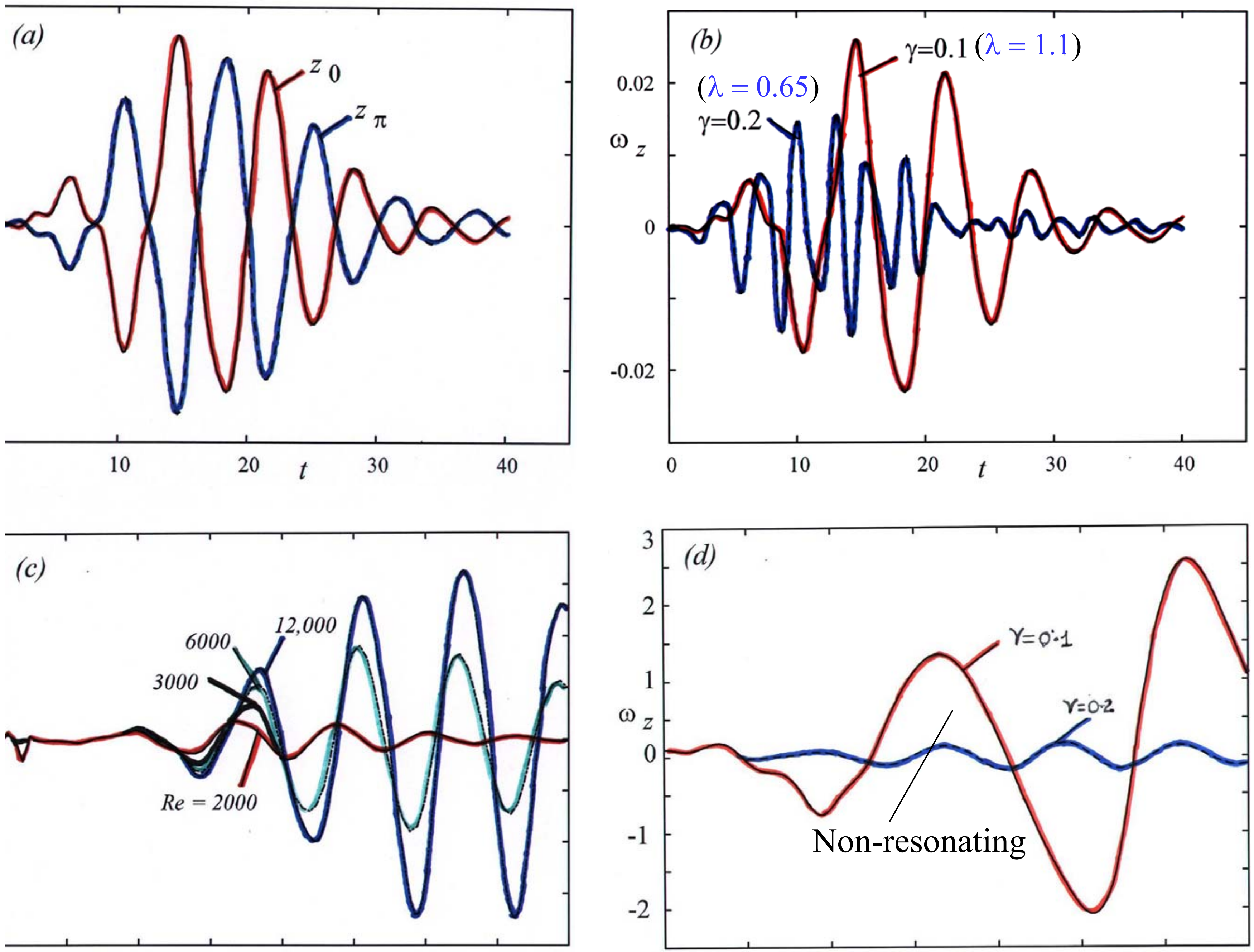


u_z
A
B
C
u_r
$\boldsymbol{u}$
r
z
z_A
z_B
z_C



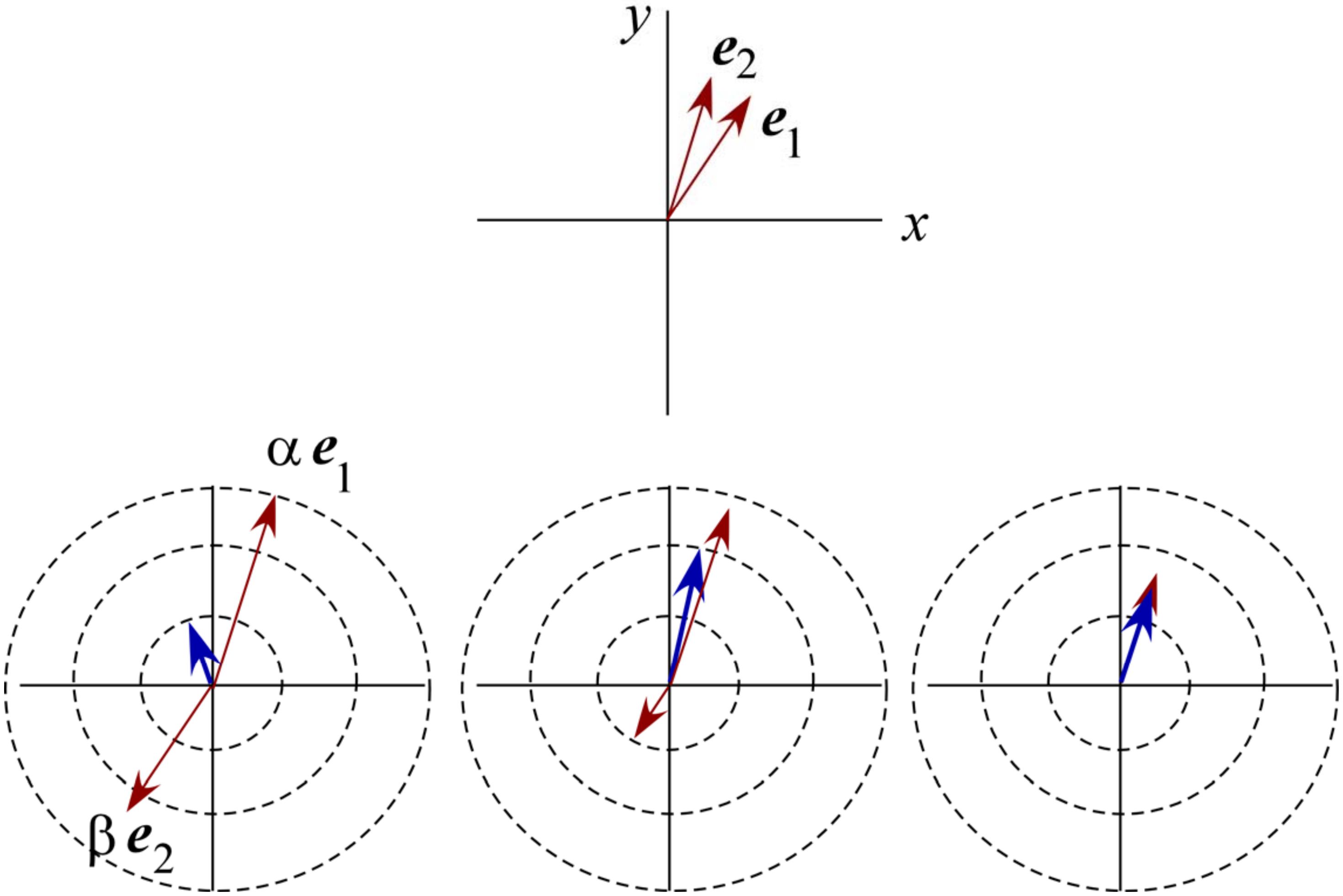
$\gamma = 0.1$

Re = 2000


(a)
z_0
z_π
10
20
30
40
t
(b)
γ=0.1 (λ = 1.1)
(λ = 0.65)
γ=0.2
0.02
0
-0.02
ω_z
0
10
20
30
40
t
(c)
12,000
6000
3000
Re = 2000
(d)
γ=0·1
γ=0·2
Non-resonating
3
2
1
0
-1
-2
ω_z

TRANSIENT GROWTH

A rudimentary example:



TG: Temporary growth followed by decay

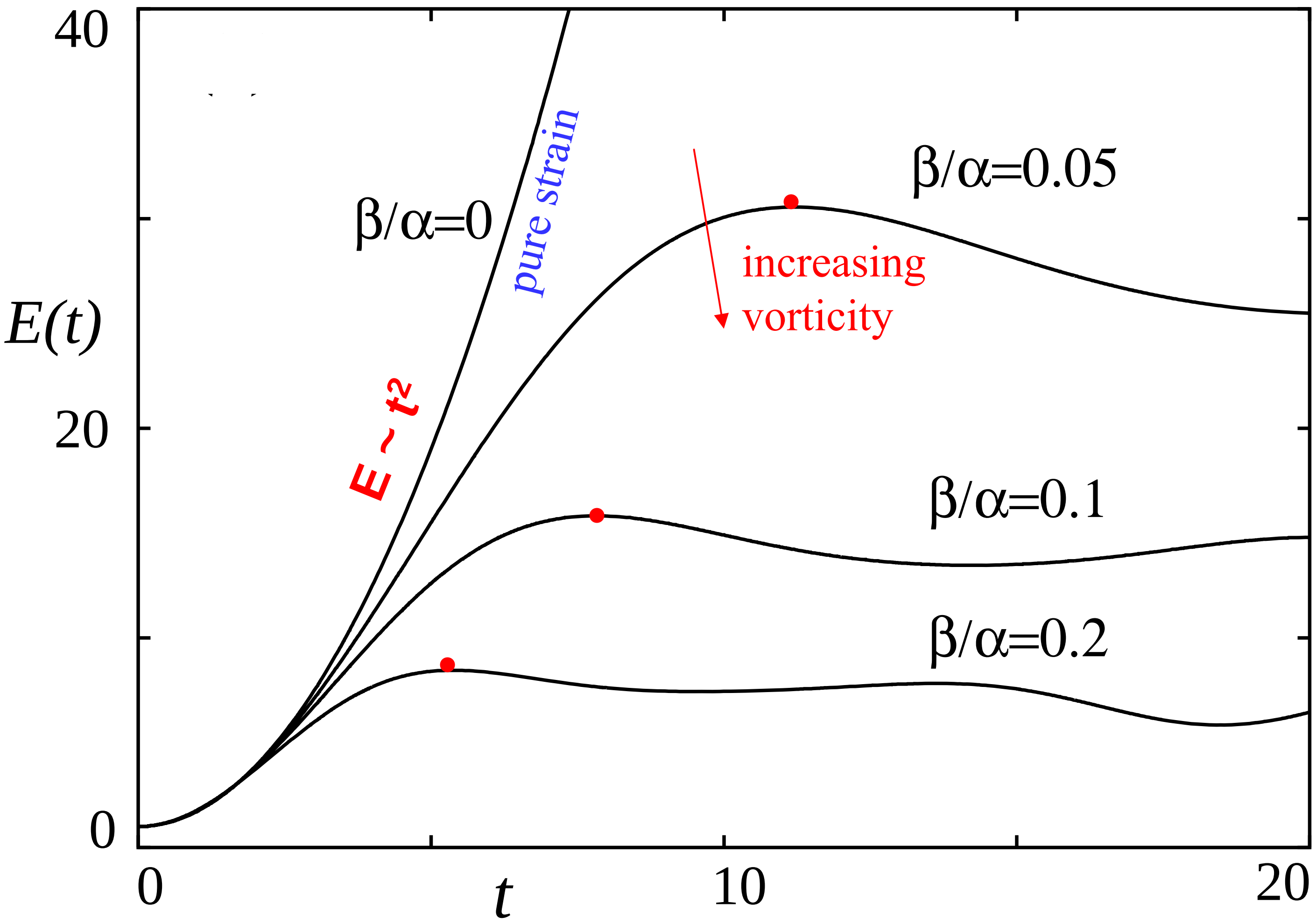
$$V = \frac{\alpha}{r} + \frac{\beta r}{2}$$

model flow

β/α = rotation/strain

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

Higher strain S
i.e. α ↑
$\Rightarrow \omega_\theta$ gen.
$\Rightarrow$ uv ↑
$\Rightarrow$E ↑
inc. vort(β)
$\Rightarrow$ arrest E ↑
sooner



LIN. INVISCID TG

Strain: unbounded growth (lin. sense)

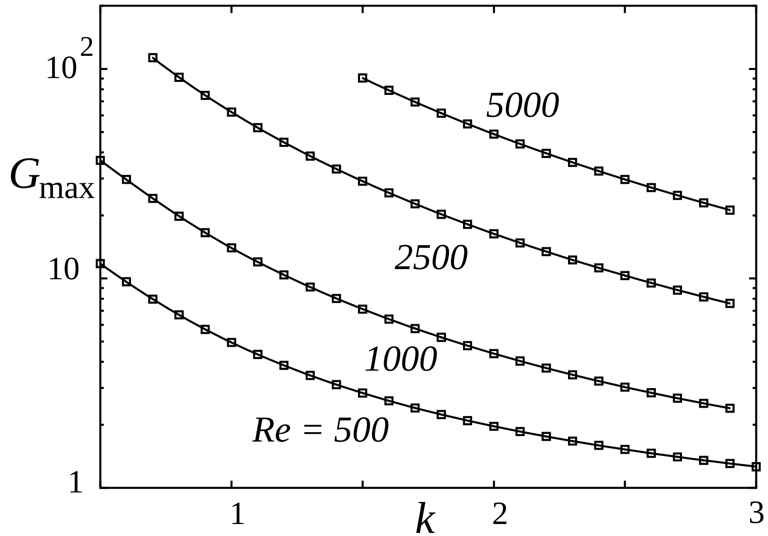
eventually saturate at NL level

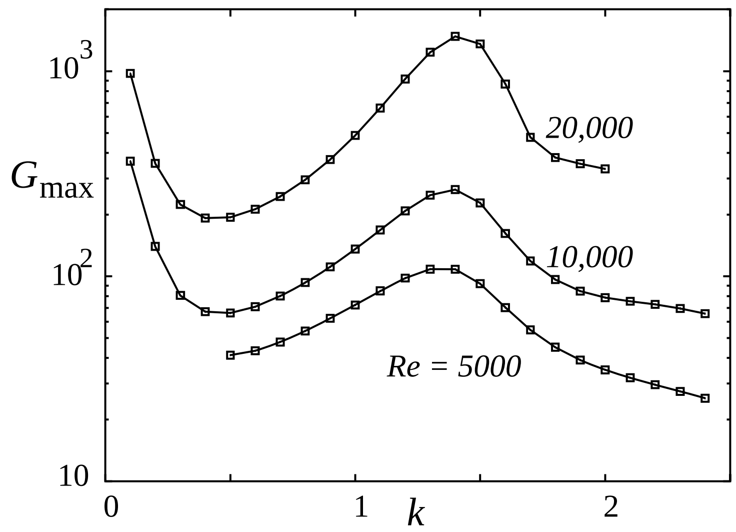
core vorticity: arrest growth & period of growth

$\longrightarrow$ core oscillation

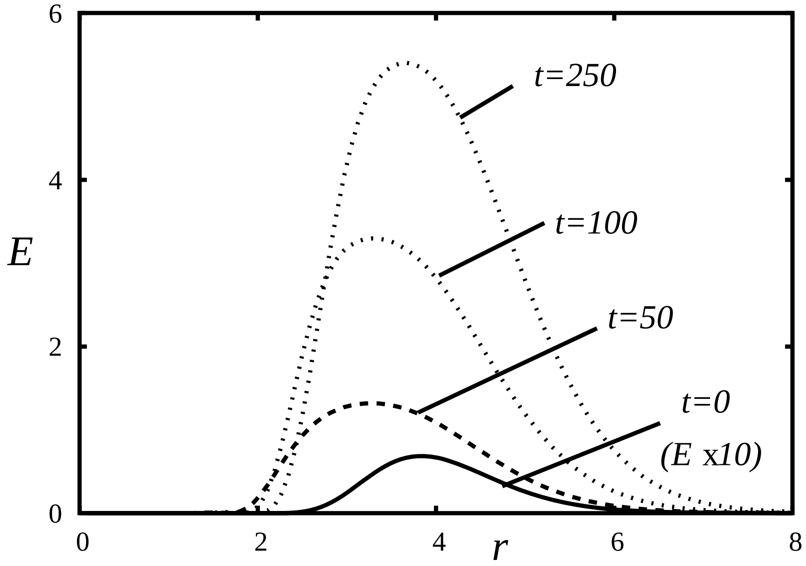
VISCOSITY damps both

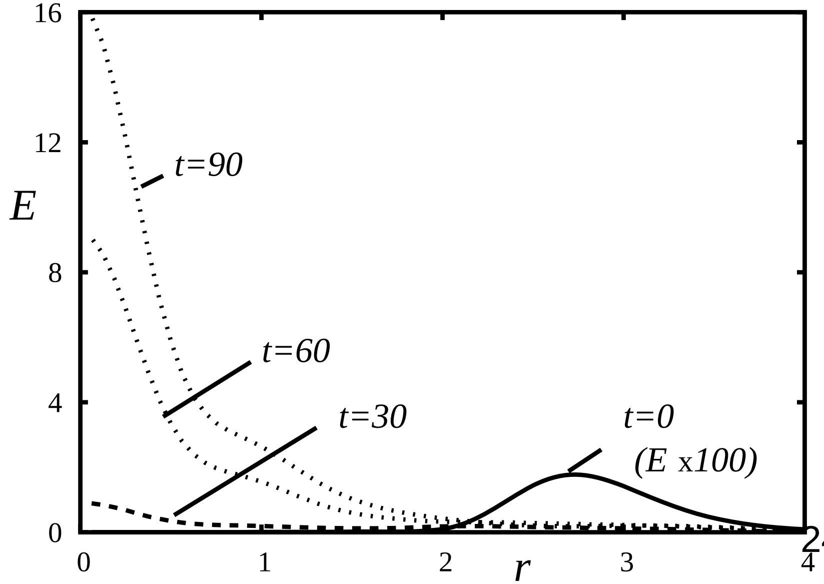
Optimal gains: *axi-sym* m = 0 *Bending* m = 1



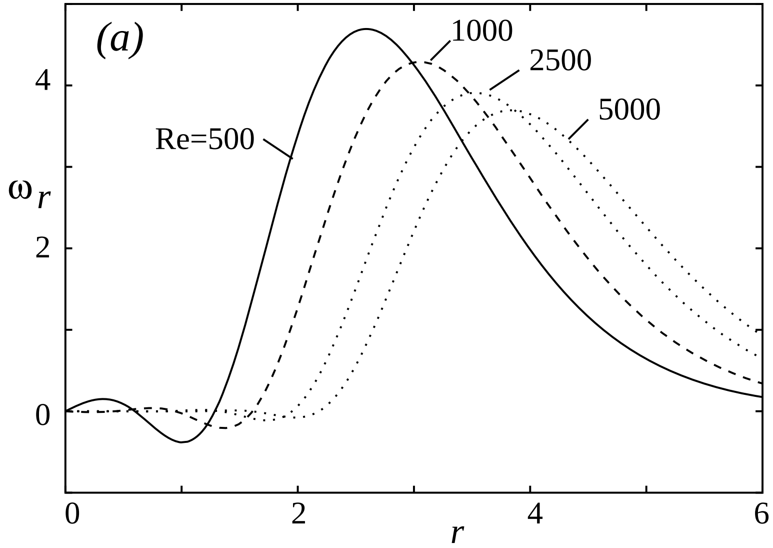


Energy evolution:

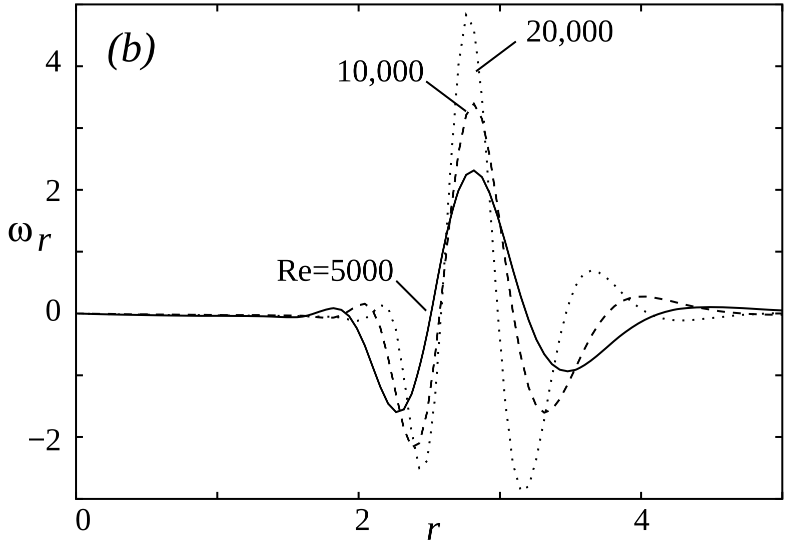




Re effect on tilting/stretching



m = 0



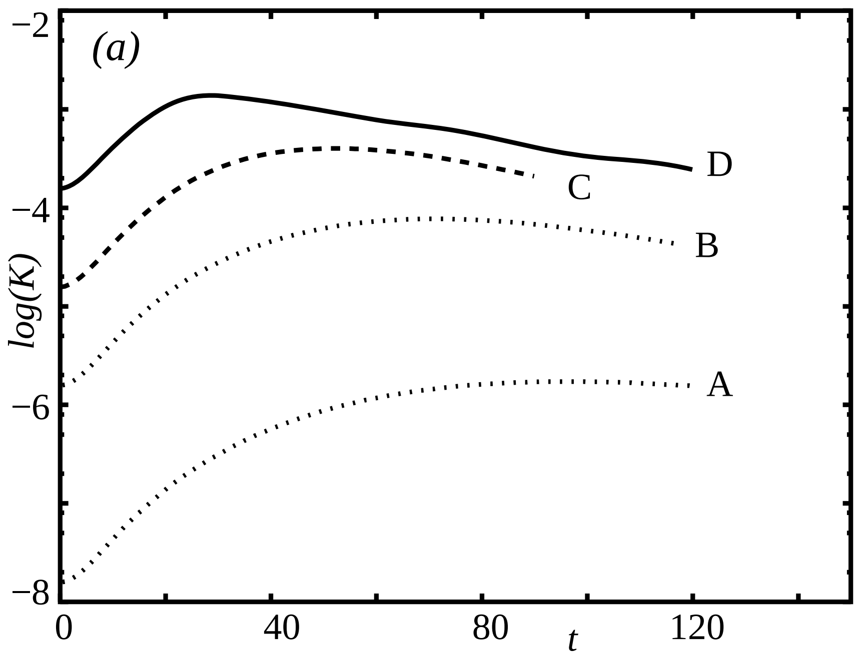
m = 1

TRANSIENT GROWTH

Nonlinear evolution of optimal modes

initial perturbation amplitude:

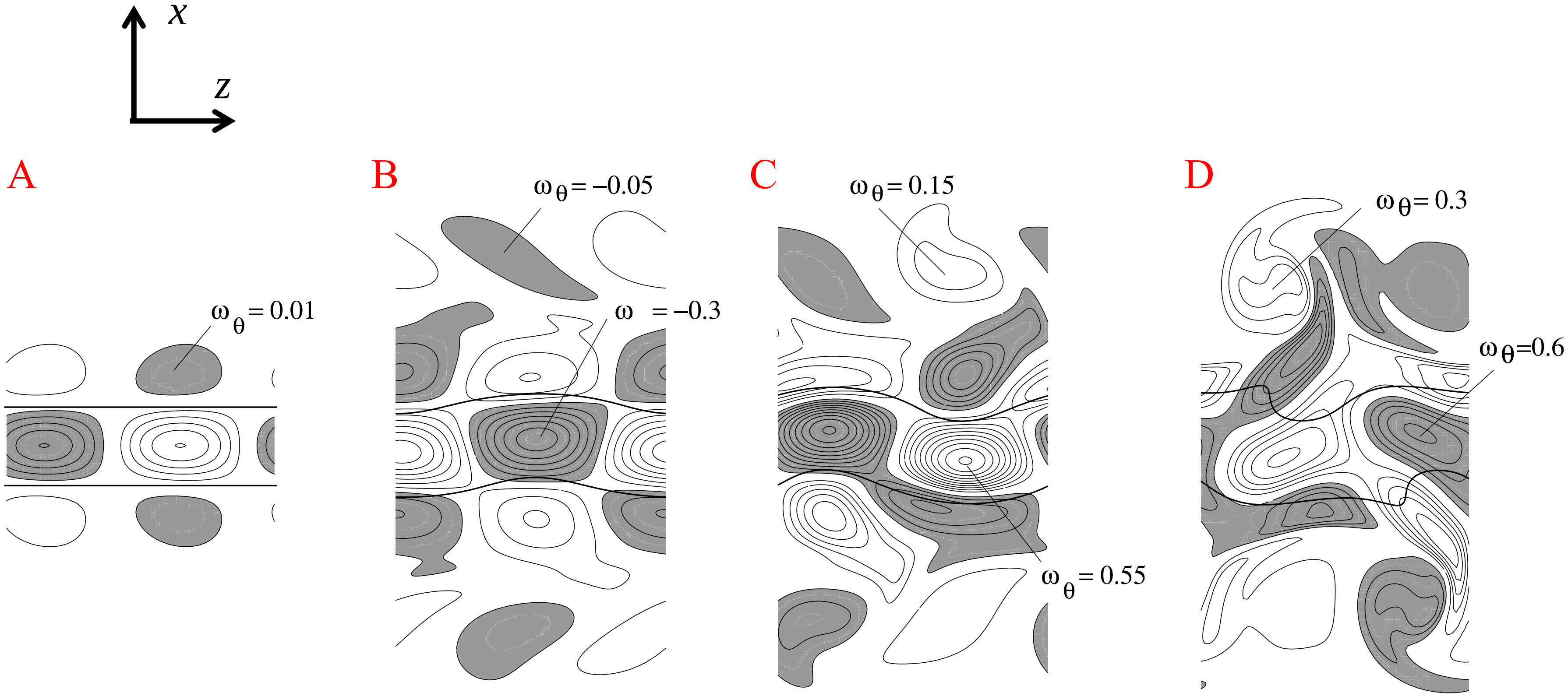
E



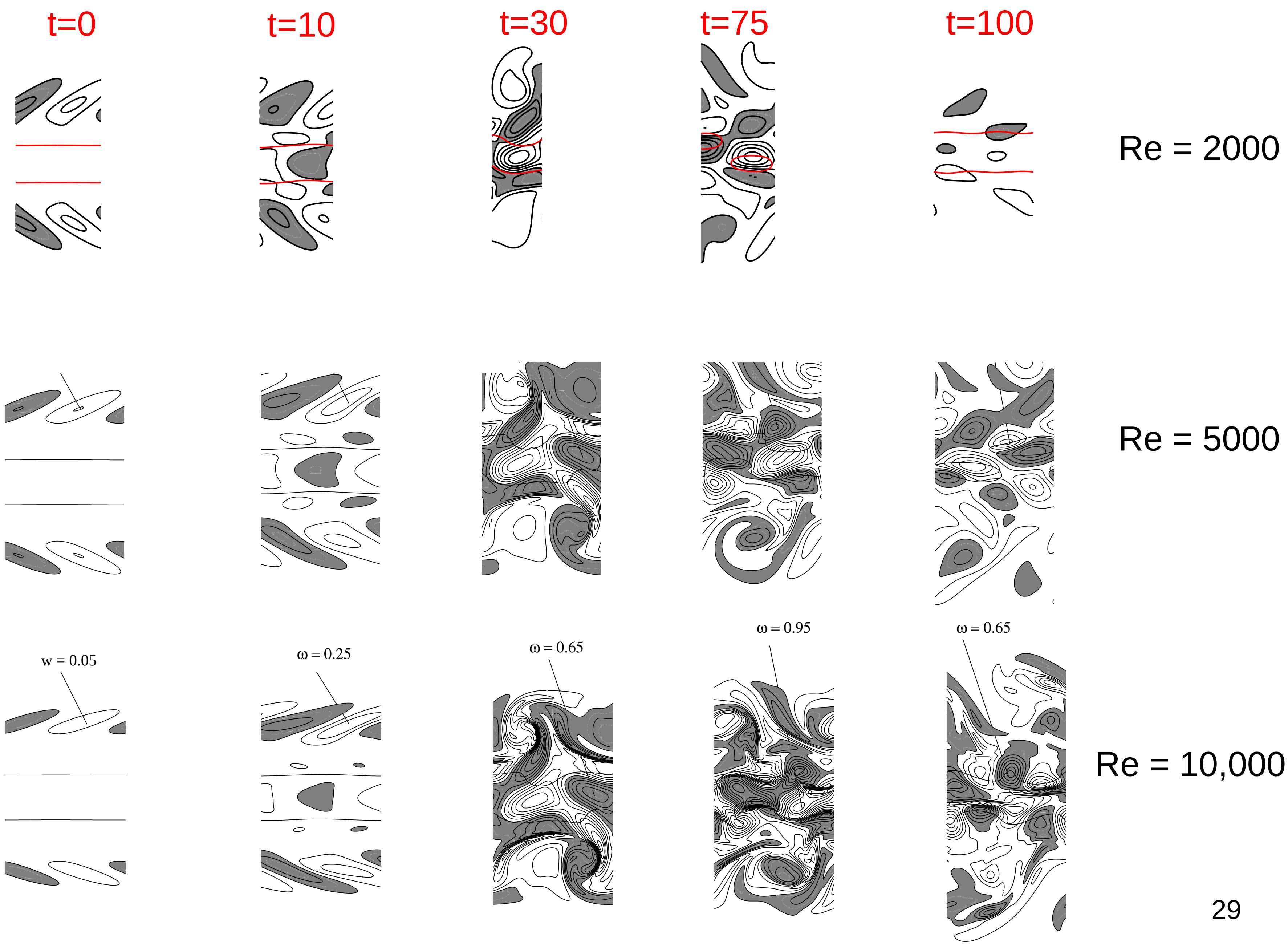
Case A	Linear
B	0.6%
C	2%
D	6%

Structure at time of max. energy: m = 1

Re = 5000



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



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

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