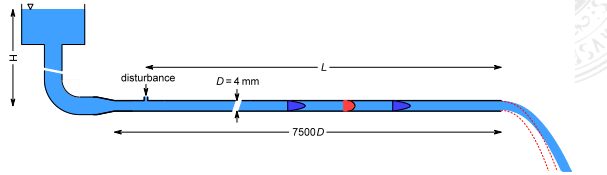
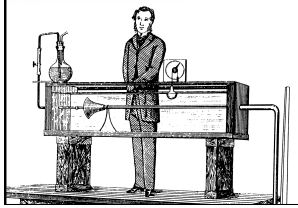
Transition: transients

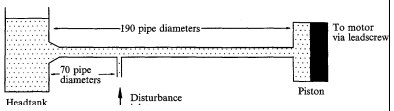
Bruno Eckhardt

Philipps Universität Marburg & TU Delft 3TU.

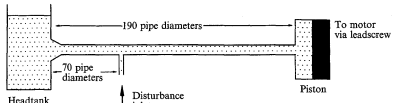
Experiments:

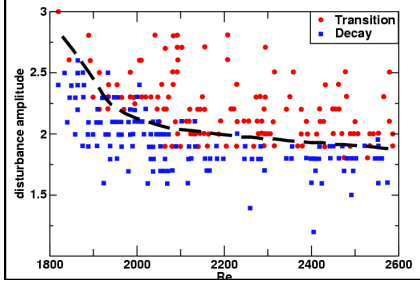




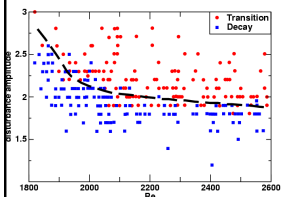


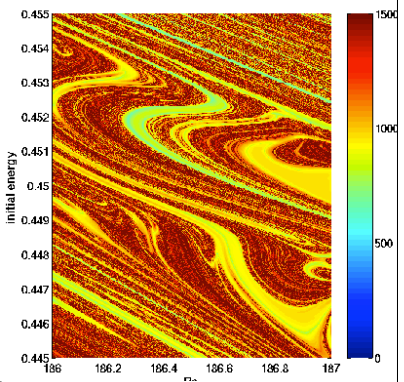
Experiments on transition Darbyshire and Mullin 1995





Lifetimes in a model

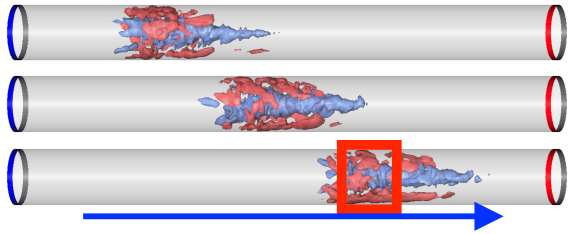




NJP **6**, 56 (2004)

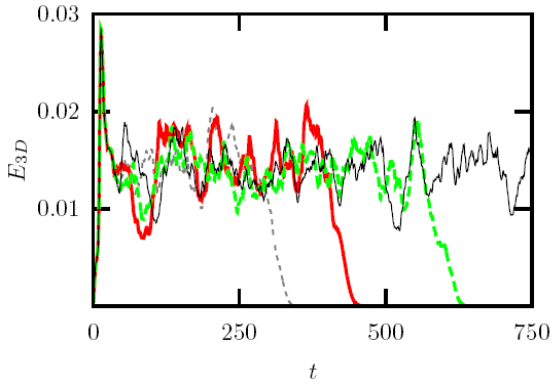
Localized turbulence at low Re

Re=1900

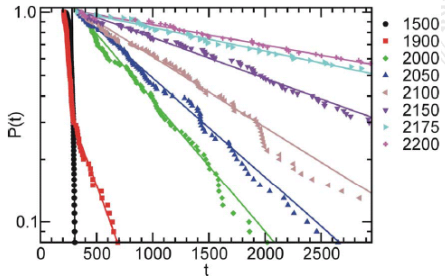


TM Schneider and BE, EPJB **64**, 457 (2008)

Time trace



Lifetime statistics for fixed Re:



Lifetimes show exponential tails:

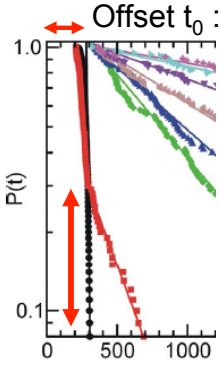
JFM **504** (2004) 343

$$P(t,\mathrm{Re}) \propto \exp(-t/\tau(\mathrm{Re}))$$

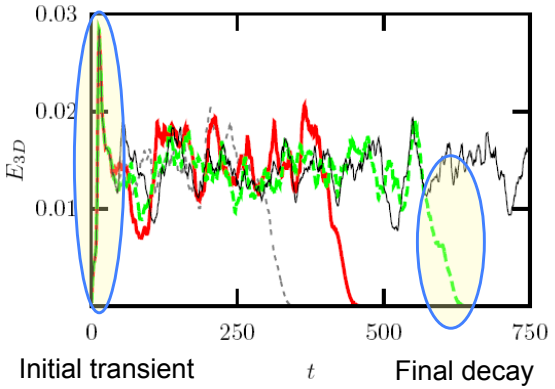
Imperfections to be considered:

Offset t_0 : due to initial transient and final decay

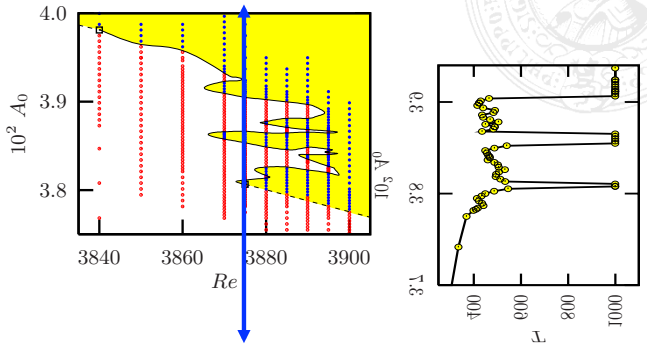
Fraction of states or weight of pdf: Due to initial conditions



Time trace

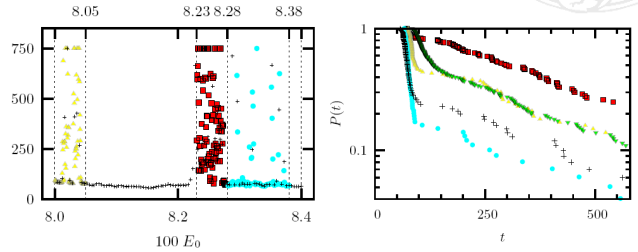


Folds and lifetimes



Weight of pdf:

Initial conditions from an interval that crosses several folds:

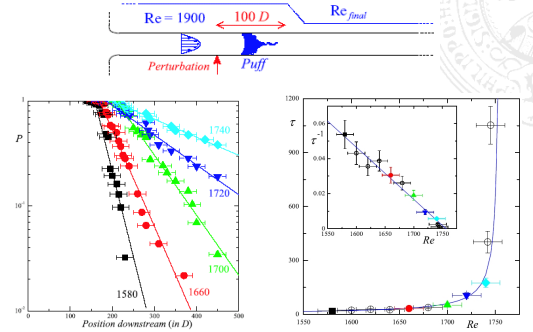


TM Schneider and BE, PRE 2010

So P(t) is exponential:

But how does τ vary with Re?

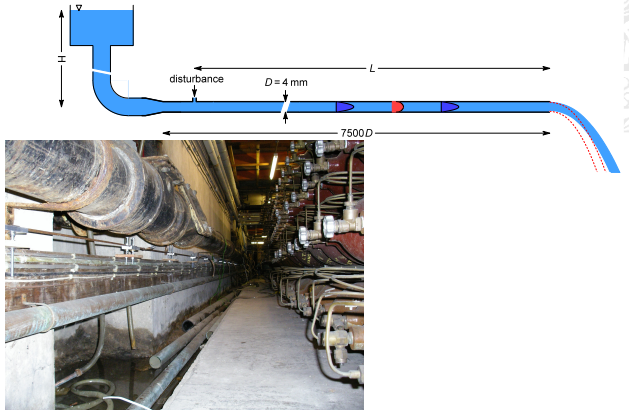
Transient life times



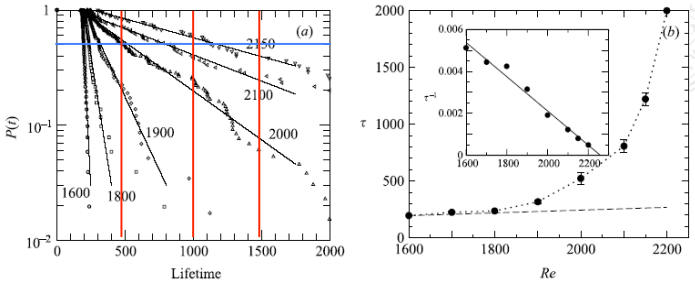
Divergence ?

Peixinho & Mullin, PRL **96** (2006) 094501

Measurement principle

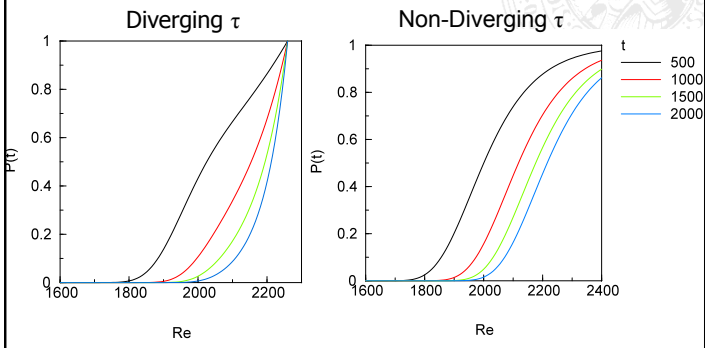


Transient life times

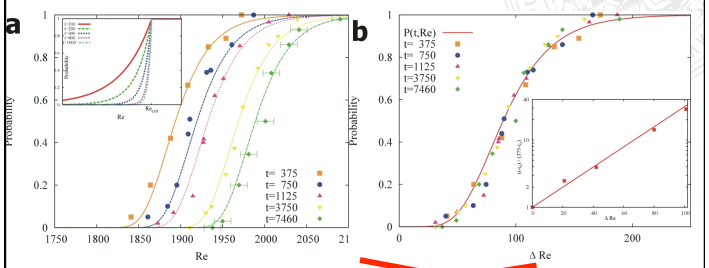


Faisst & Eckhardt *J. Fluid Mech.* **504** (2004) 343

P(t, Re) for fixed t



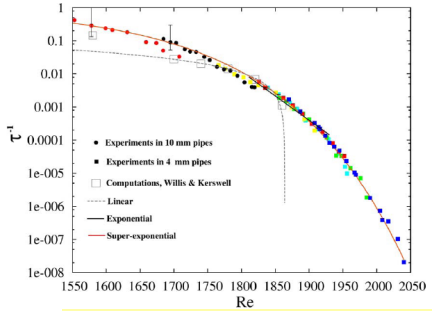
Turbulent lifetimes II



$$P(t,\mathrm{Re}) = \exp(-t/\tau(\mathrm{Re})) = \begin{cases} \exp(-t(\mathrm{Re}_c - \mathrm{Re})) \\ \exp(-t\exp(-a\,\mathrm{Re})) \end{cases}$$

No divergence in τ No transition to attractor !

Variation of lifetime with Re



Rapidly growing lifetimes, but no divergence!
No transition to attractor !

Nature **443** (2006) 59
Hof et al PRL 2008 & JFM 2010, Kuik et al JFM 2010

Conclusion

- Life time distributions are **exponential** for fixed pipe length and Re
- Life times **increase** with increasing Reynolds number …
- but do **not** diverge for finite Reynolds number

Is pipe flow asymptotically stable?

$$\tau^{-1}(\mathrm{Re}) = \exp\left(59.28 - 0.0344\,\mathrm{Re}\right)$$

$$\left.\begin{array}{l} D = 1\ \mathrm{cm} \\ \mathrm{Re} = 2365 \\ Q = 1\ \ell\ \mathrm{min}^{-1} \end{array}\right\} \Rightarrow \tau^{-1} = 2.6\times10^{-10} \Rightarrow L \cong 39\times10^{3}\ \mathrm{km}\ !$$

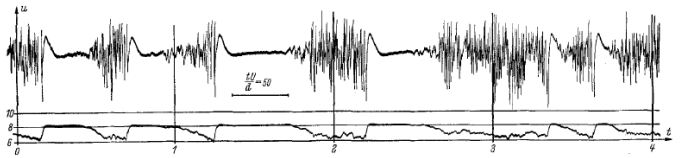
$$\tau = 5\ \mathrm{yr}\ !$$

$$P = 35\times10^{3}\ \mathrm{bar!}$$

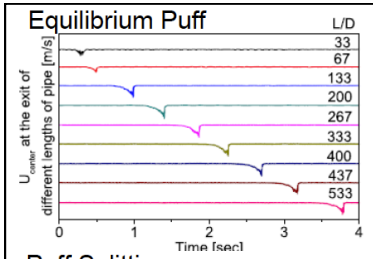
Spatial aspects

Rotta 1956

- Spatio-temporal intermittency



- Intrinsic switches between turbulence and laminar flow
- Persistent !



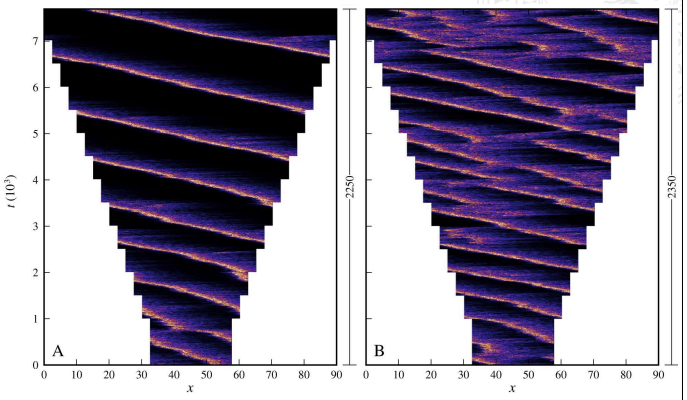
Re=2310

Re=2495

Nishi, Ünsal, Durst, Biswas
JFM 614 (2008) 425

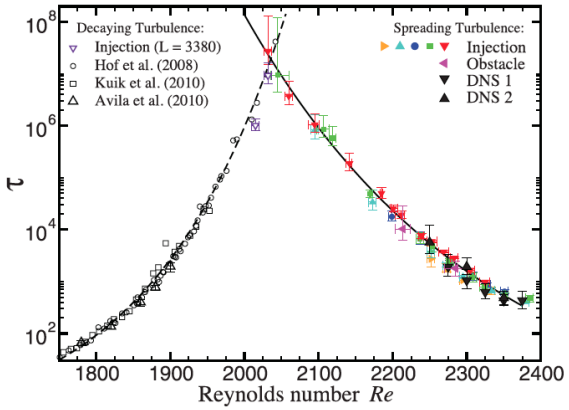
Spatial aspects

Moxey and Barkley,
PNAS **107**, 8091 (2010)



Re=2250

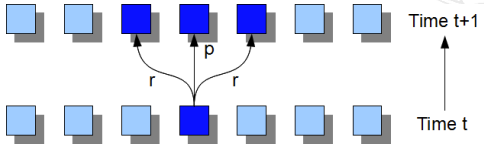
Re=2350



Connection to (directed) percolation

Percolation model

- Probability p to survive
- Probability r to spread to neighboring cells

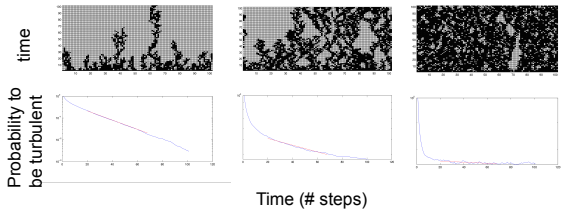


- p,r small: decay
- p,r large enough: persistence

Phase transition to sustained turbulence

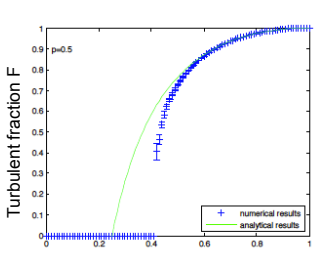
Transition to persistent turbulence

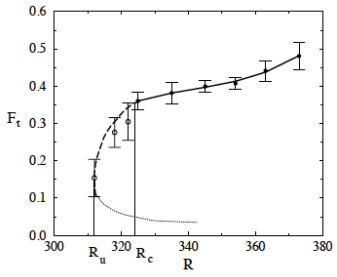
p=0.7 r=0.2 r=0.3 r=0.35



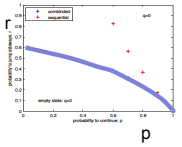
K. Allhoff, BE

Phase diagram





Plane Couette flow,
Bottin et al, EPL **43**, 171 (1998)



K. Allhoff, BE,

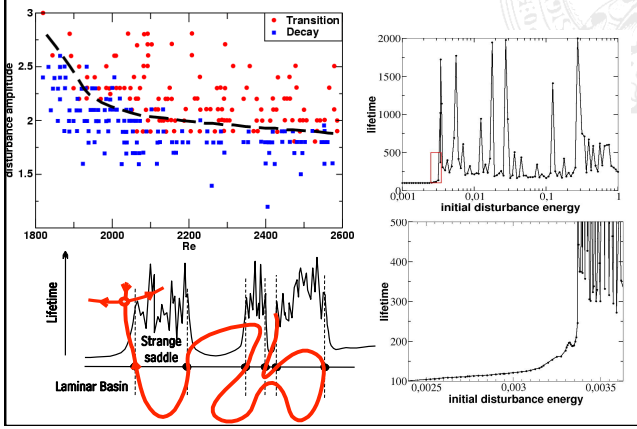
Spatial aspects

- Persistent turbulence as a consequence of seeding by surviving spots
- Relation to directed percolation (Pomeau 1986, Manneville 2009)
- Would be in line with Rotta (1956), who found Re_c=2320

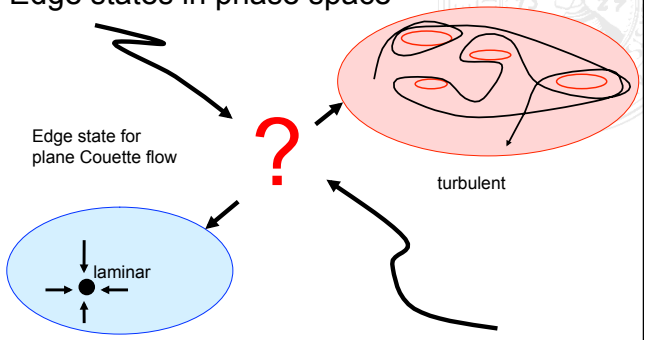
Laminar-turbulent boundary

Edge of chaos
Edge states

The edge of chaos



Edge states in phase space



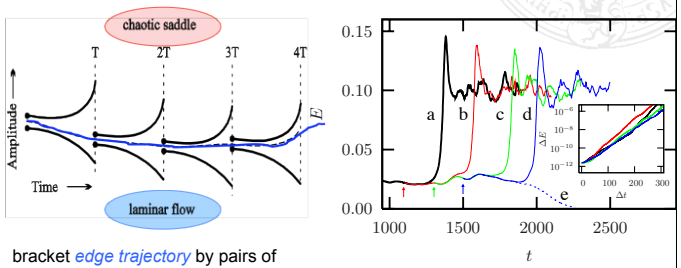
Annual Reviews Fluid Mechanics 39 (2007) 447-468

Dynamics in the Edge of Chaos

Keeping a trajectory in the Edge of Chaos

Aim: Analyze dynamics of *'edge trajectories'* in the boundary

Concept: approximate edge trajectory



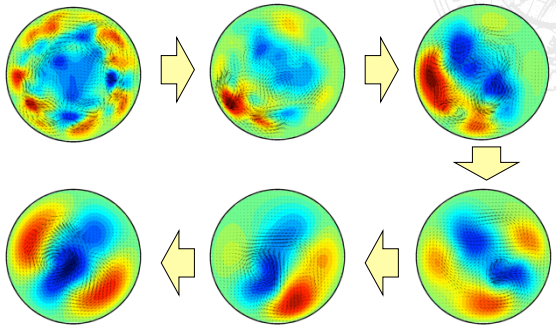
bracket *edge trajectory* by pairs of trajectories that decay or turn turbulent

Skufca, Yorke & Eckhardt *PRL* 2006

Dynamics in the Edge of Chaos

Local attractors - the Edge state

Approach: Follow arbitrary trajectories in the edge of chaos



Result: Edge trajectories collapse onto relative attractor - the *'edge state'*

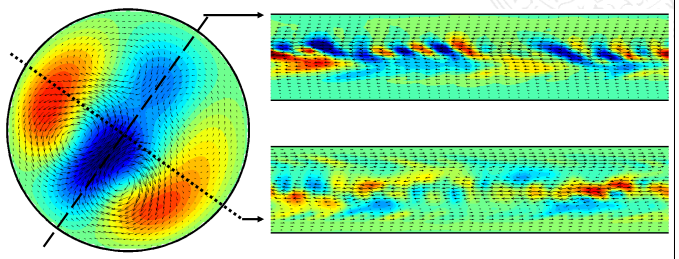
T.M. Schneider & B. Eckhardt *Chaos* 2006

The Edge State

Dynamical features

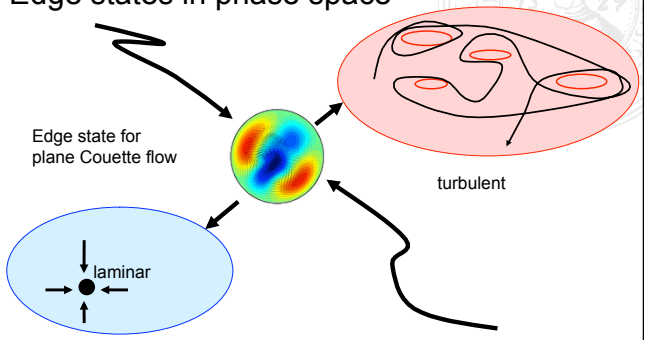
cross-section perp. to axis (time-averaged)

cross-section in downstream direction (instantaneous)



Features: - Asymmetric pair of vortices
- persistently active, perhaps chaotic

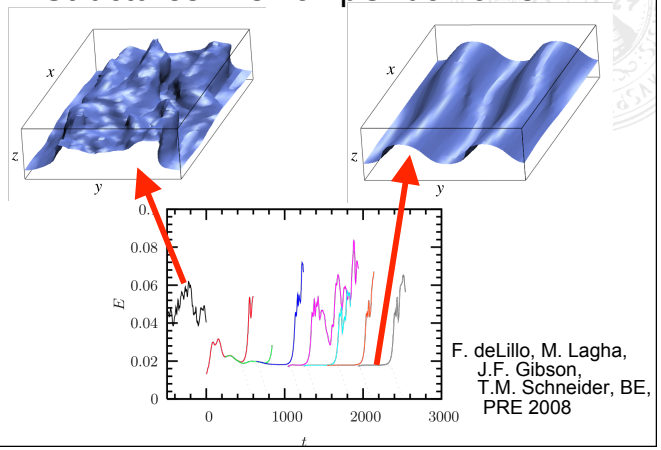
Edge states in phase space



Annual Reviews Fluid Mechanics 39 (2007) 447-468

Localized structures

Structures in small pCf domains…



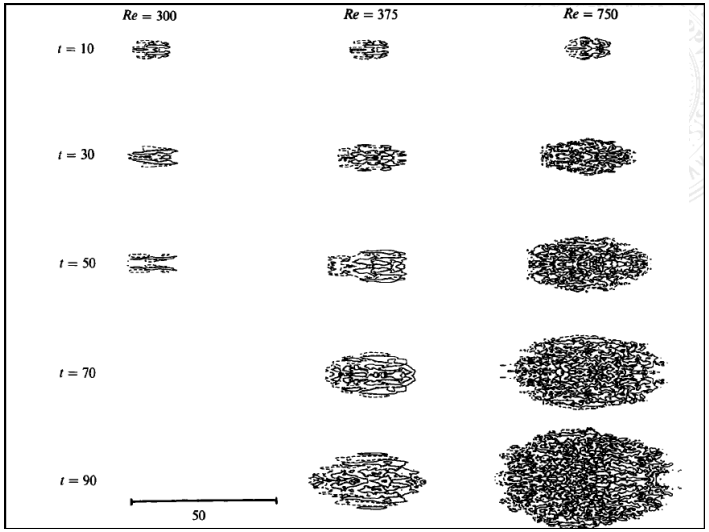
F. deLillo, M. Lagha, J.F. Gibson, T.M. Schneider, BE, PRE 2008

J. Fluid Mech. (1991), *vol.* 229, *pp.* 499–516
Printed in Great Britain

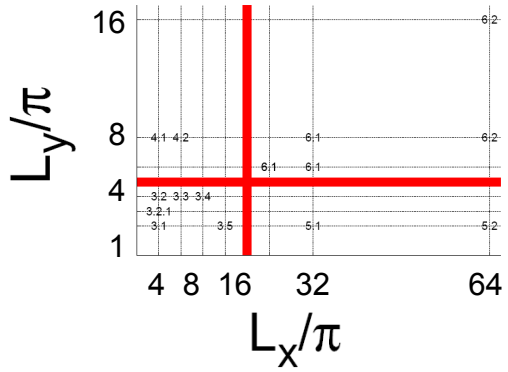
Direct simulation of turbulent spots in plane Couette flow

By ANDERS LUNDBLADH† AND ARNE V. JOHANSSON
Department of Mechanics, Royal Institute of Technology, S-100 44 Stockholm, Sweden

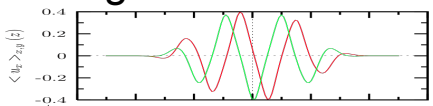
- fix localized perturbation
- Study time evolution for different Re
- Determine Re_c above which it keeps growing



Increasing box size



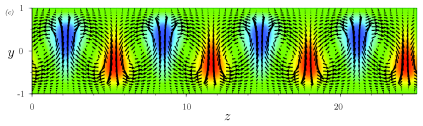
Edge states in wide boxes



Symmetry:

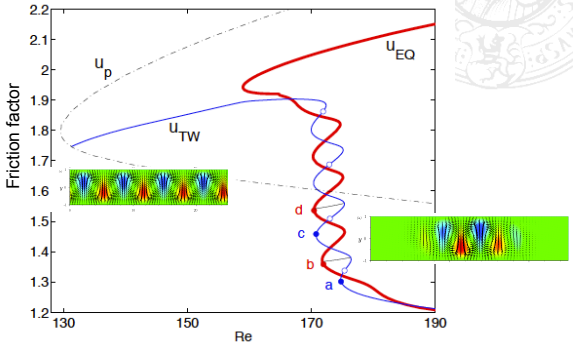
reflection

rotation



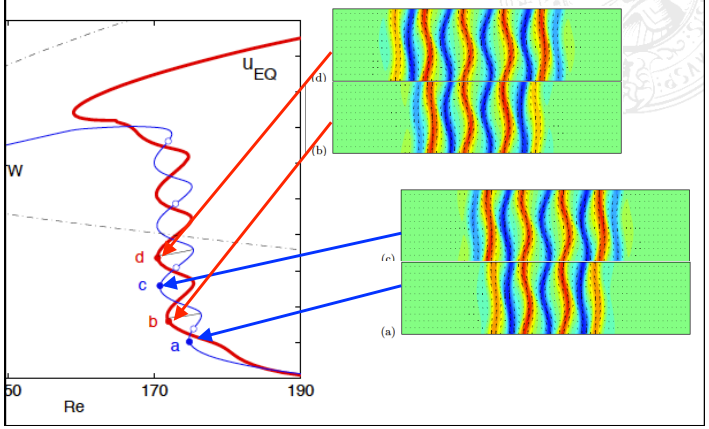
JFM **646,** 441 (2010)

Snaking and localization (I)

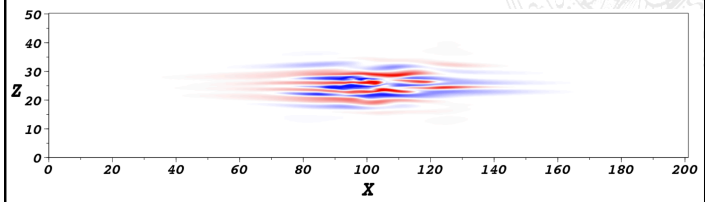


Schneider, Gibson, Burke, PRL 2010

Snaking and localization (II)



Increasing lengths and widths

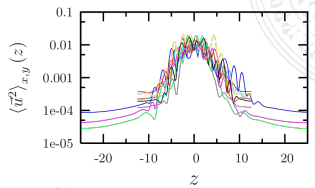


Localized marginally stable spot:
stronger will become turbulent
weaker will decay

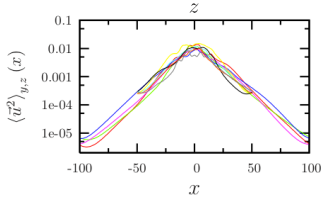
JFM **646,** 441 (2010)

Localization properties

spanwise



streamwise



Immediate collaborators:

Marburg:	Korinna Allhoff, Tobias Madré, Marina Pausch, Matthew Salewski, Stefan Zammert
	Daniel Marinc (now RWTH Aachen)
	Tobias M Schneider (now Harvard)
Barcelona:	Fernando Mellibovsky
	Alvaro Meseguer
Delft:	Dirk Jan Kuik
	Rene Delfos, Jerry Westerweel