Dynamical systems analysis of transition in boundary layer flows

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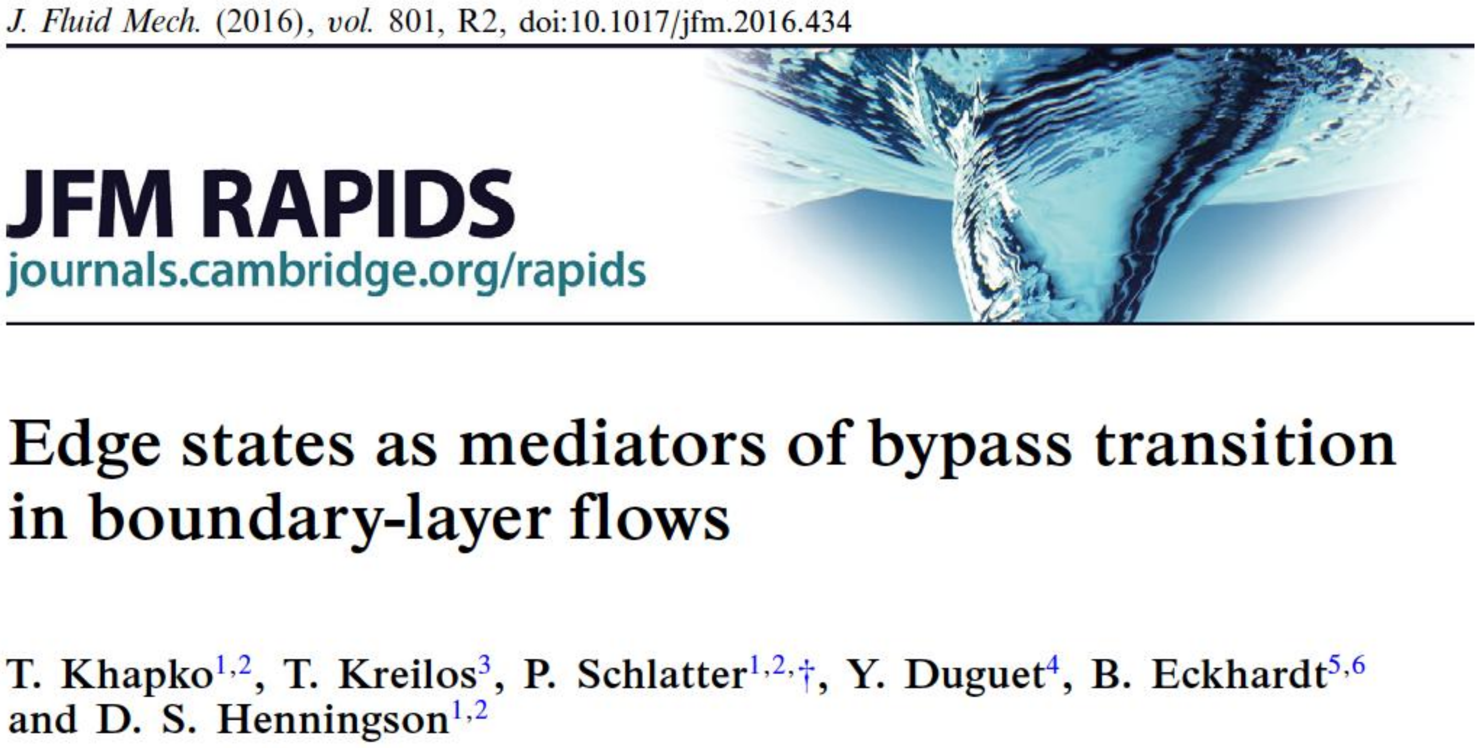
Published papers



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JFM RAPIDS
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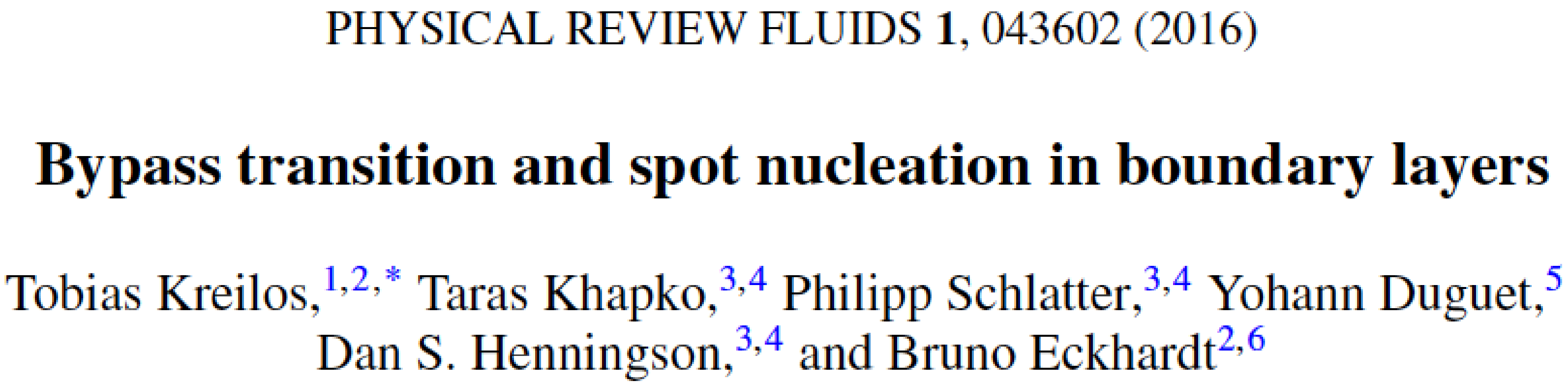
Edge states as mediators of bypass transition in boundary-layer flows

T. Khapko[1,2], T. Kreilos[3], P. Schlatter[1,2,†], Y. Duguet[4], B. Eckhardt[5,6] and D. S. Henningson[1,2]

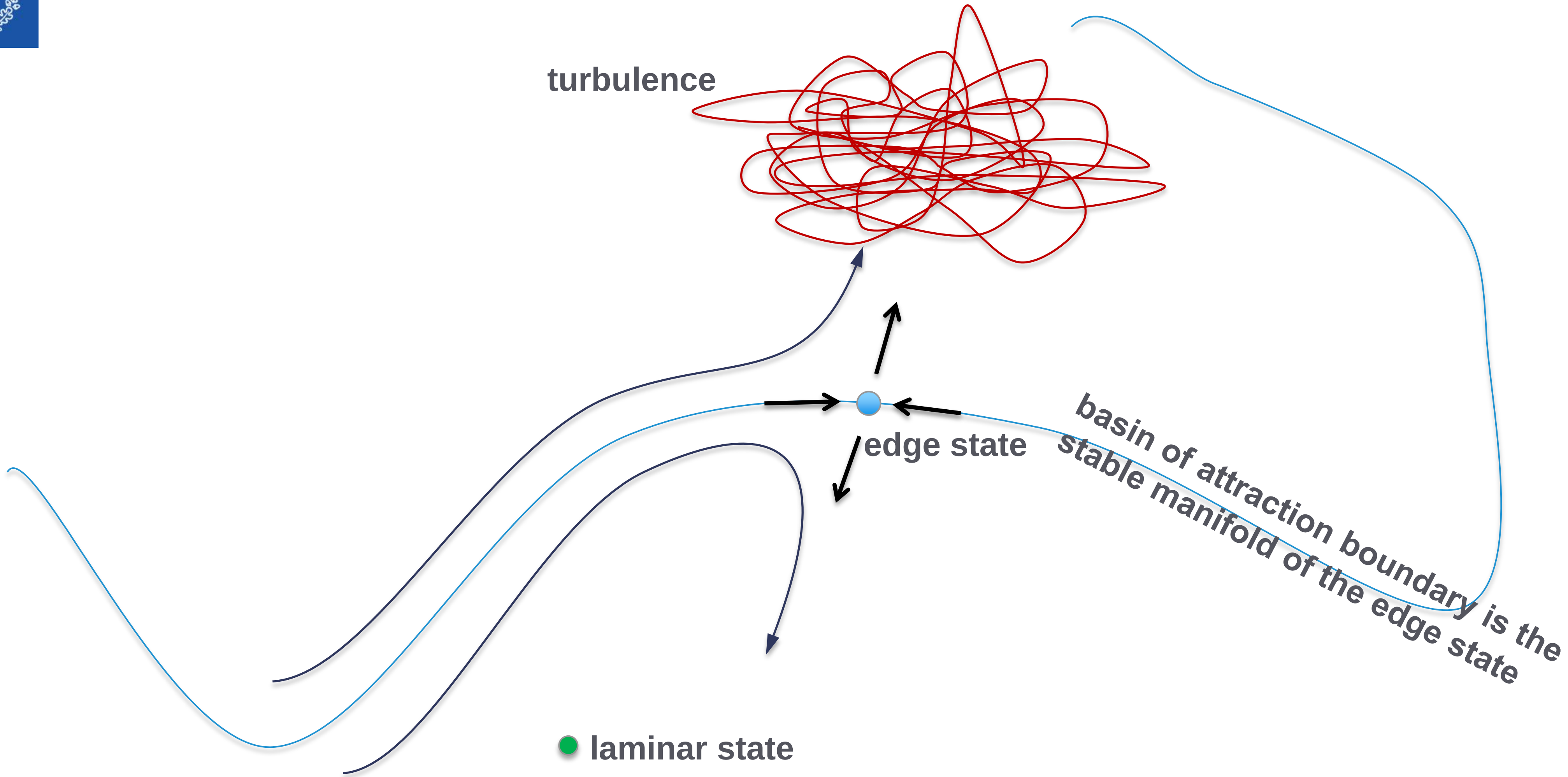


PHYSICAL REVIEW FLUIDS **1**, 043602 (2016)

Bypass transition and spot nucleation in boundary layers

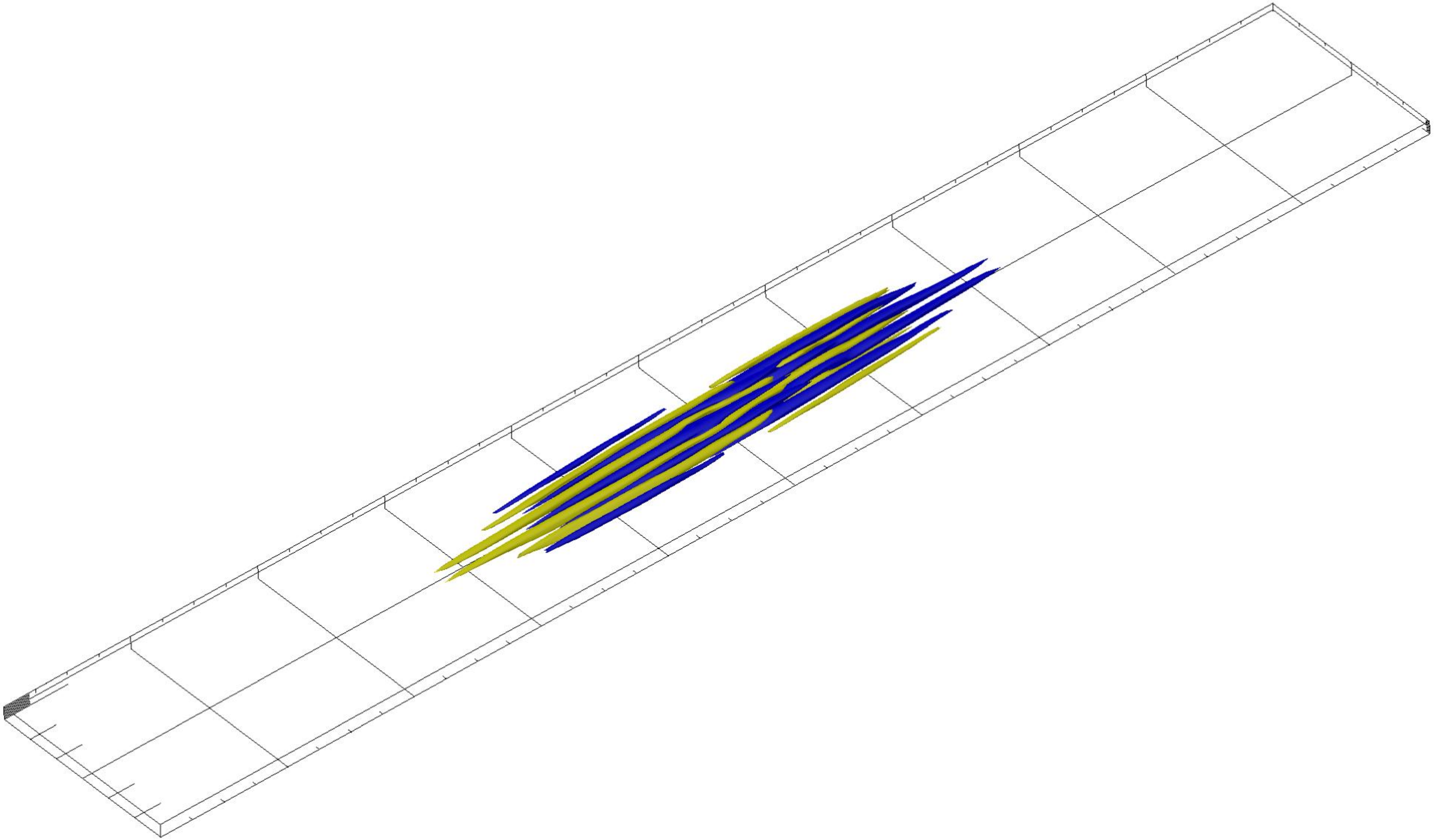
Tobias Kreilos,[1,2,*] Taras Khapko,[3,4] Philipp Schlatter,[3,4] Yohann Duguet,[5]
Dan S. Henningson,[3,4] and Bruno Eckhardt[2,6]

Dynamical systems picture in state space



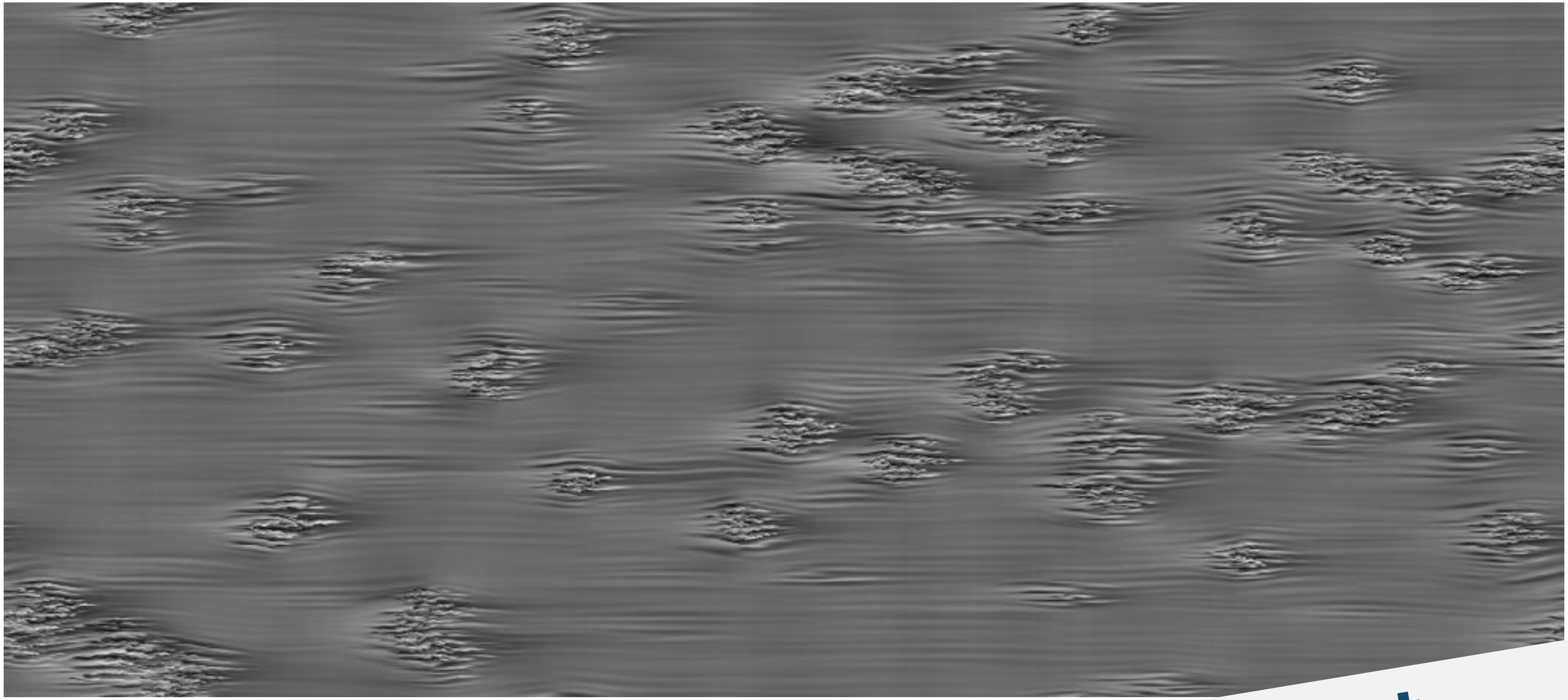
- edge instability governs transition in the vicinity of the basin of attraction boundary

Plane Couette flow – localised edge state



[5] Duguet, Schlatter and Henningson, *Phys. Fluids* (2009)

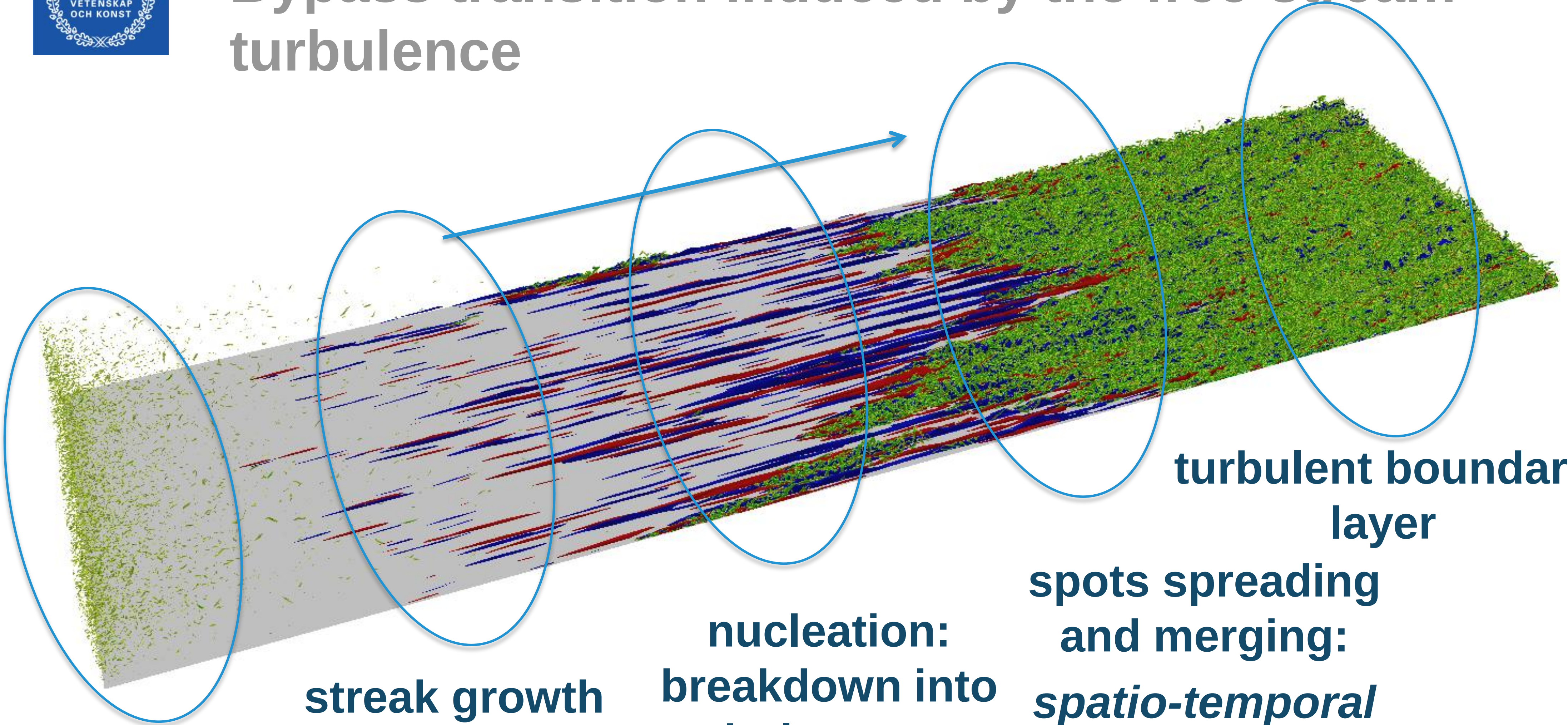
Plane Couette flow – nucleation of spots associated with edge states in noise transition



What about boundary layers?

[6] Duguet, Schlatter and Henningson, *J. Fluid Mech.* (2010)

Bypass transition induced by the free-stream turbulence



free-stream turbulence

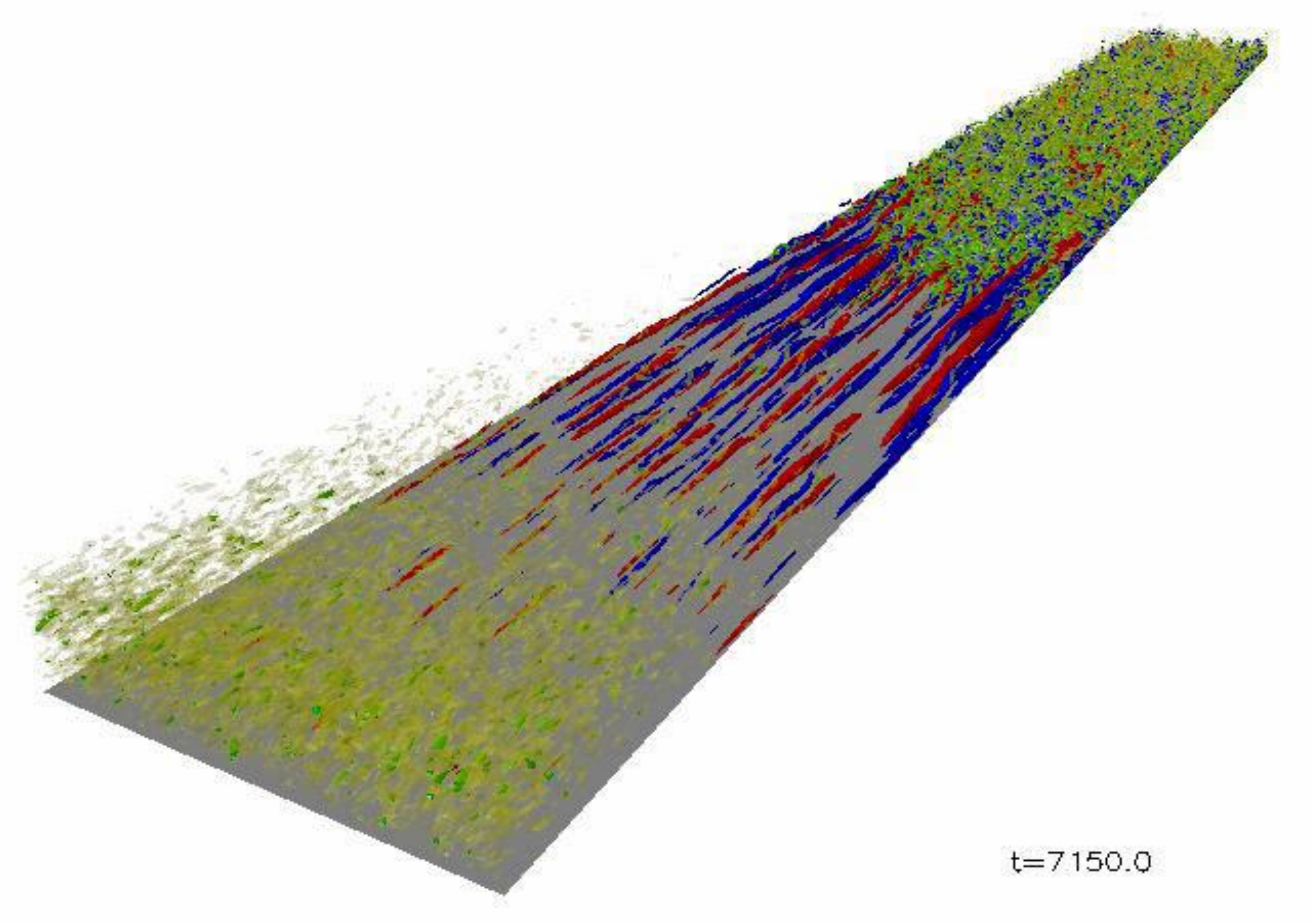
streak growth

nucleation: breakdown into turbulent spots

spots spreading and merging: *spatio-temporal intermittency*

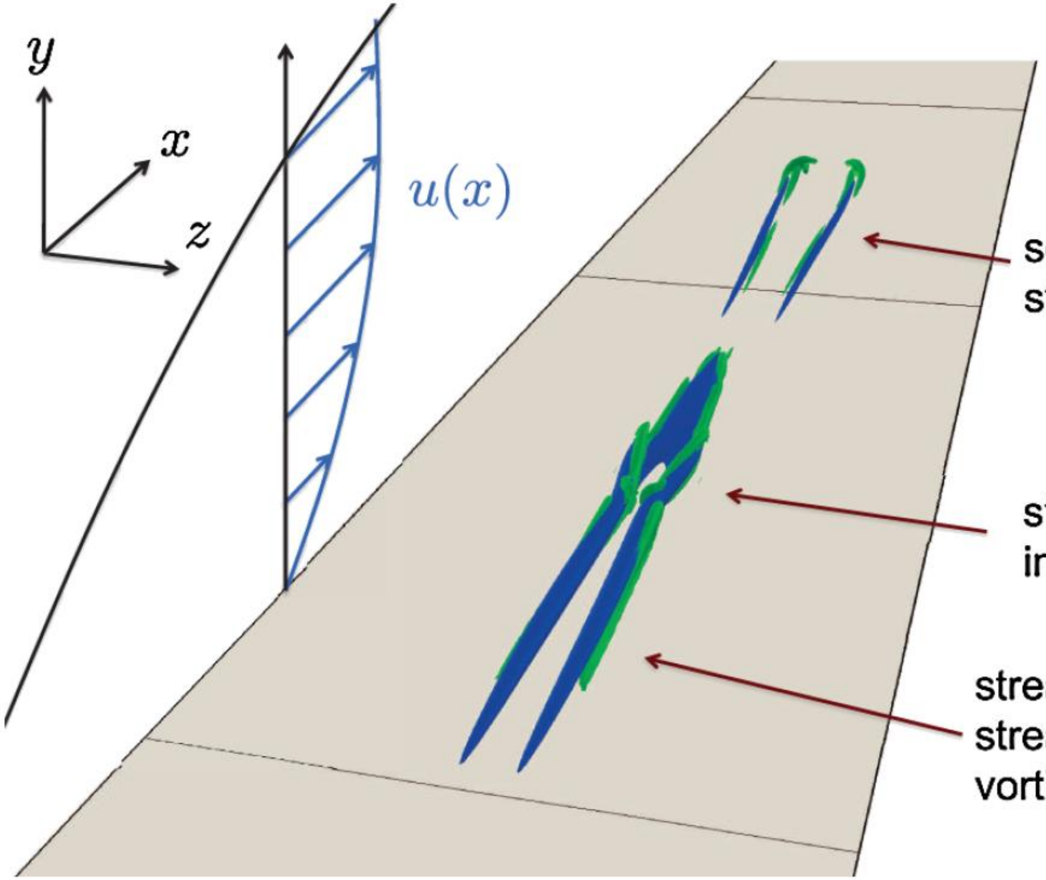
turbulent boundary layer

Boundary layers



P. Schlatter,
KTH

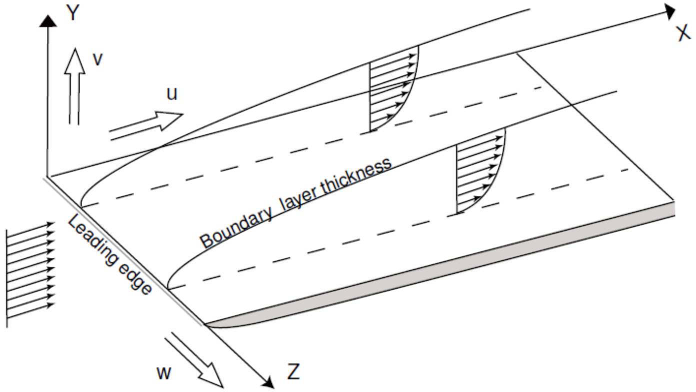
Edge tracking in the Blasius boundary-layer flow



secondary structures

streak instability

streaks + streamwise vortices



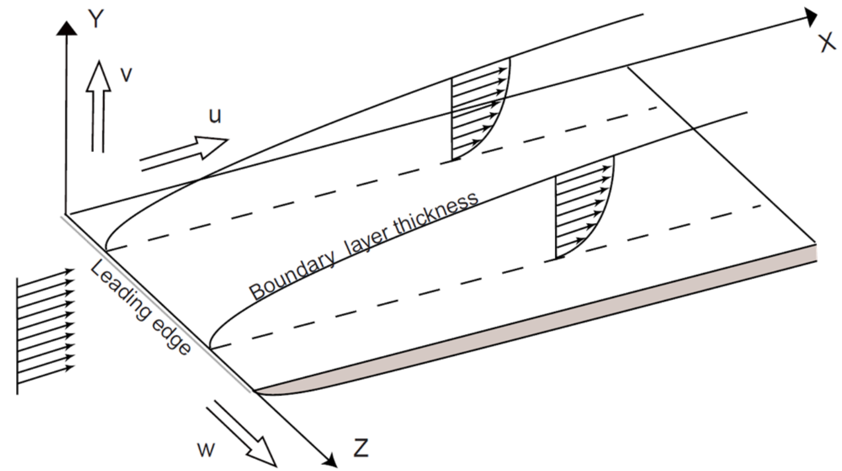
$$[L_x,L_y,L_z]=[3000\delta_0^*,60\delta_0^*,100\delta_0^*]$$

- costly due to spatial growth
- difficulty accessing asymptotic dynamics

[7] Duguet, Schlatter, Henningson and Eckhardt, *Phys. Rev. Lett.* (2012)

Applying suction

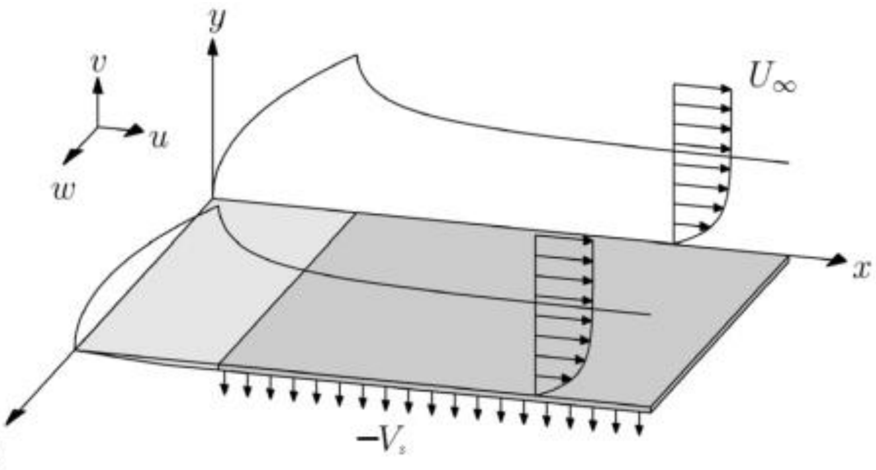
Asymptotic Suction Boundary Layer

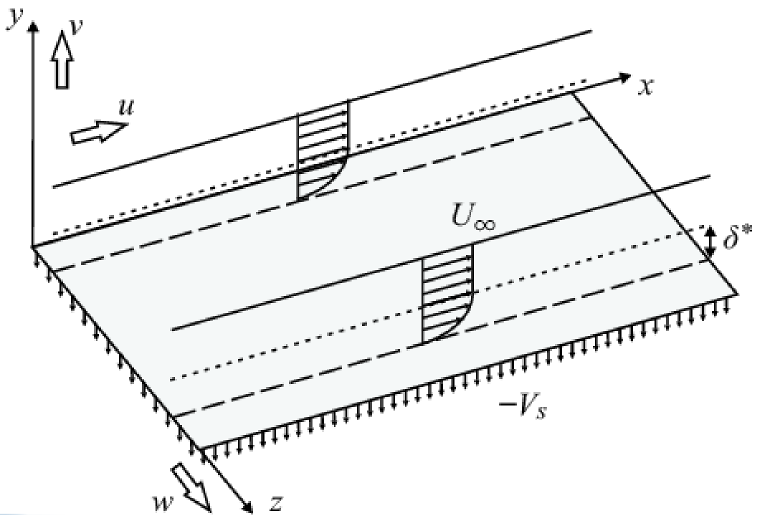


$$u = U_\infty\left(1 - e^{-\frac{yV_S}{\nu}}\right)$$
$$v = -V_S$$

$$Re = \frac{U_\infty \delta^*}{\nu} = \frac{U_\infty}{V_S}$$

- Experimentally realizable (Antonia *et al.* 1983, Fransson & Alfredsson 2003)
- Linearly stable up to Re_c=54370 (Hocking 1975)
- Turbulence observed at Re=270 (Khapko *et al.* 2016)

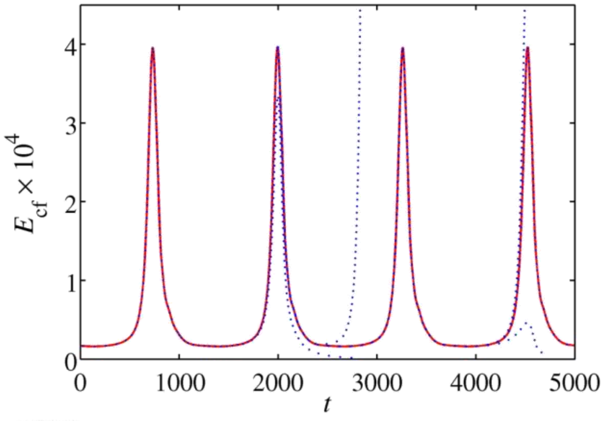


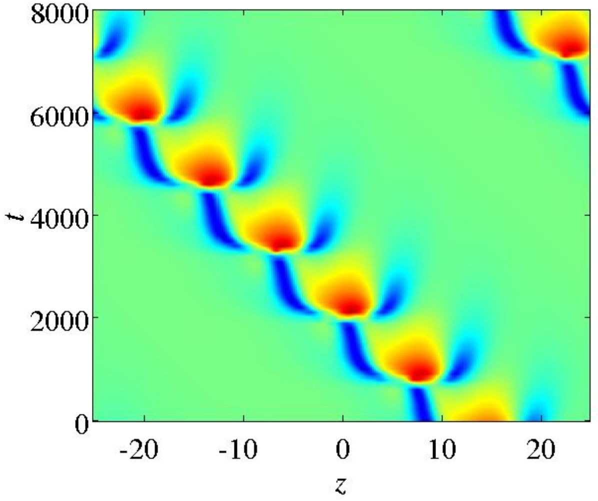


[8] Sketch from Levin, PhD thesis (2005)

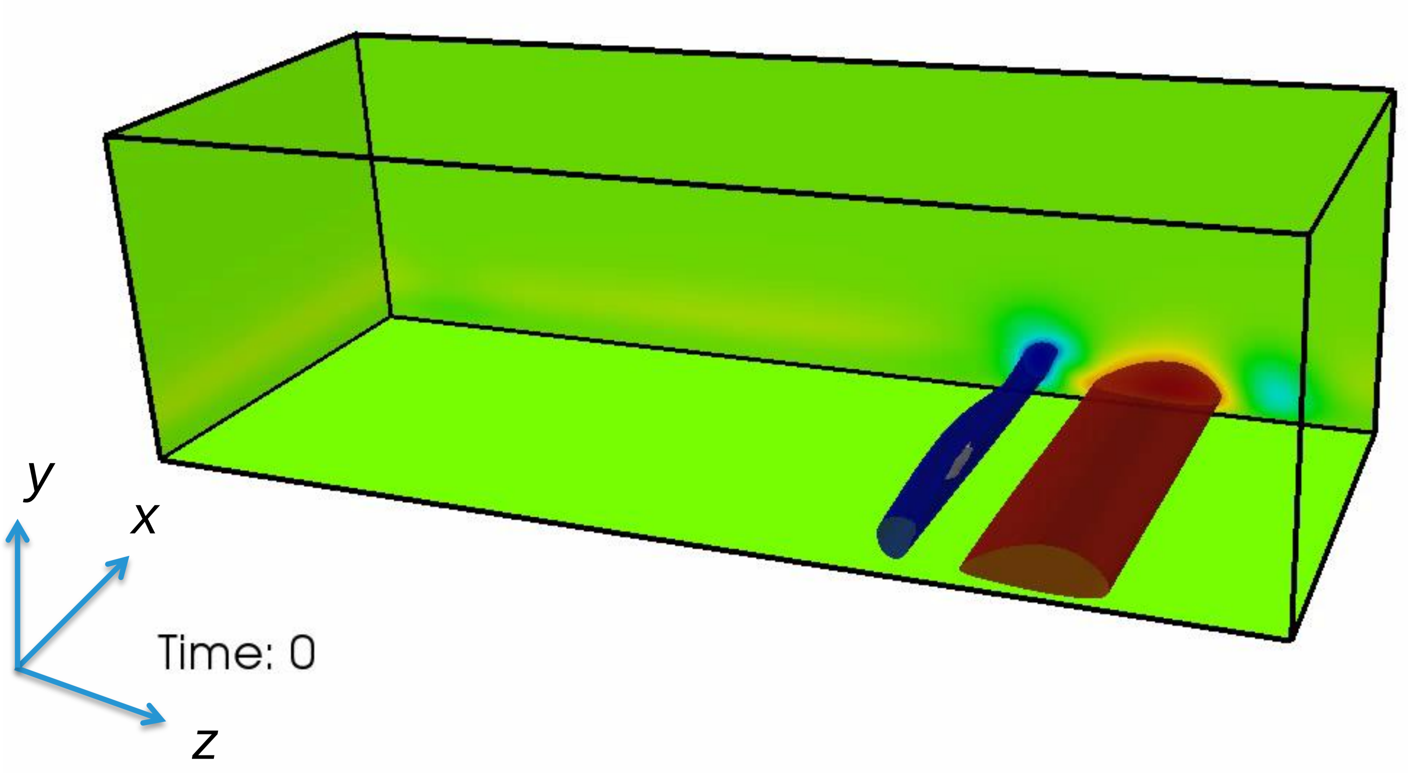
Edge states in short-wide domains in ASBL

$$E_{cf} = \frac{1}{L_x L_z}\int_{\Omega} (v'^2 + w'^2)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$





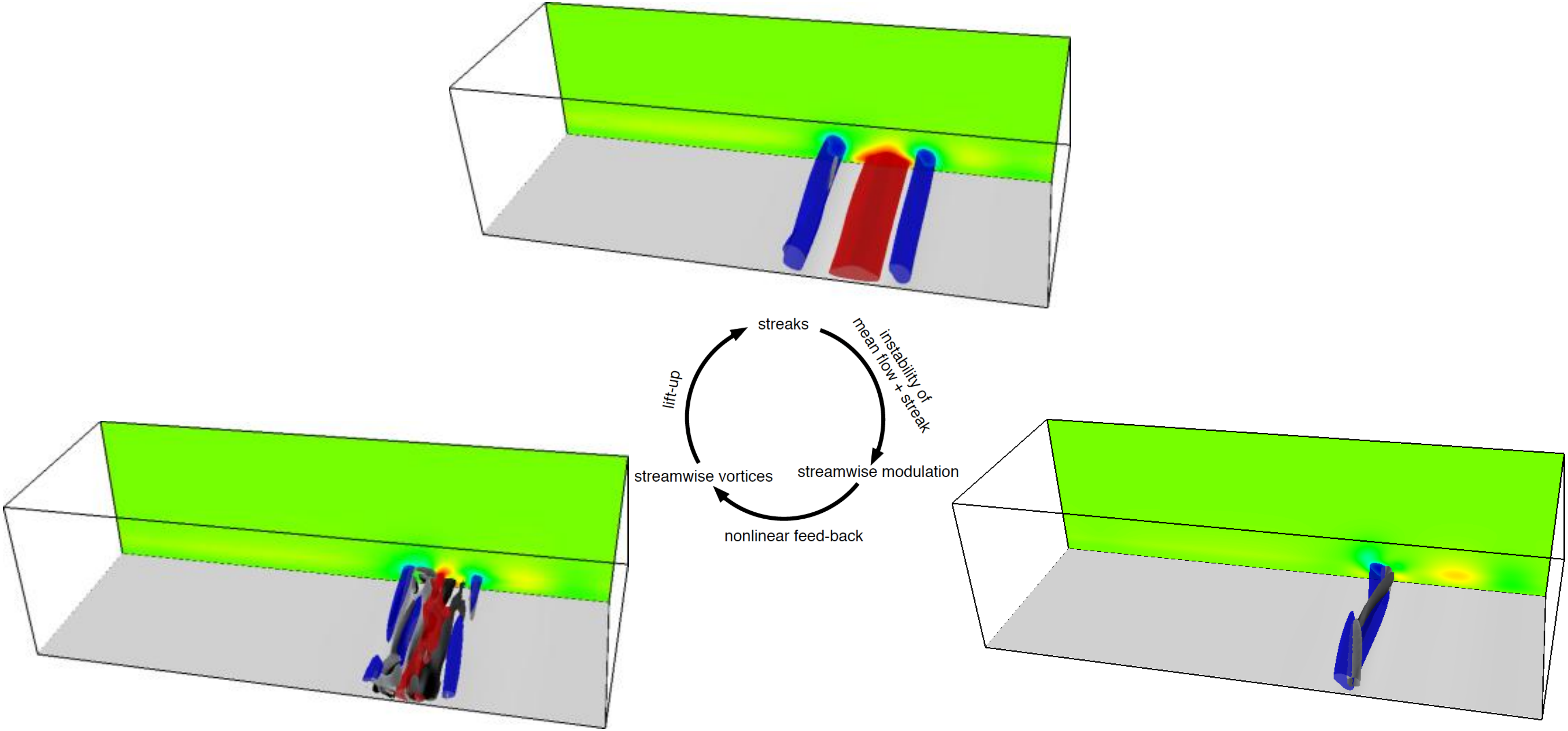
$[L_x, L_y, L_z] = [6\pi\delta^*, 15\delta^*, 50\delta^*]$ $Re = 500$



[10] Khapko, Kreilos, Schlatter, Duguet, Eckhardt and Henningson, *J. Fluid Mech.* (2013)

[11] Khapko, Duguet, Kreilos, Schlatter, Eckhardt and Henningson, *Eur. Phys. J. E* (2014)

Self-sustaining mechanism



streaks

instability of mean flow + streak

streamwise modulation

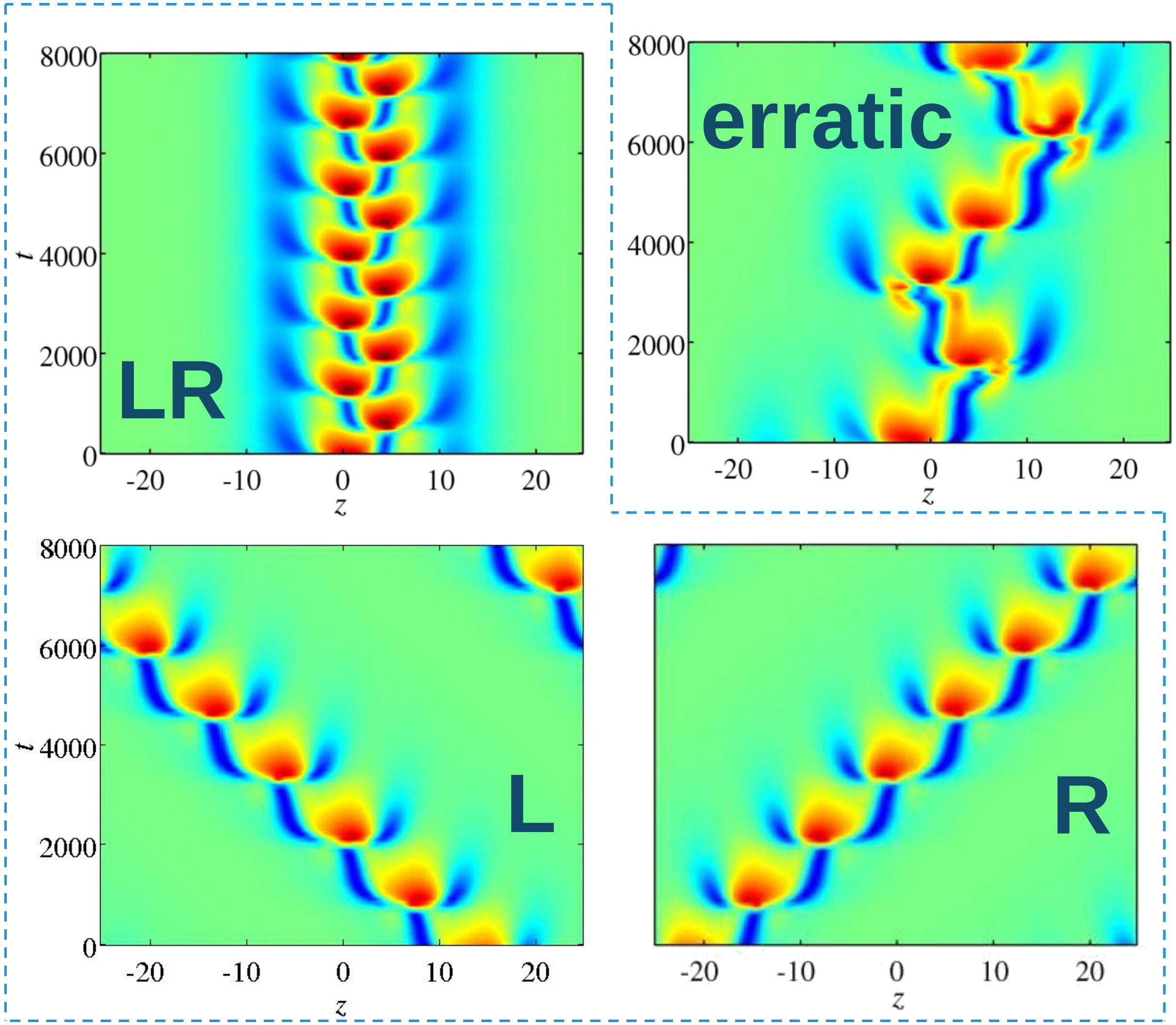
nonlinear feed-back

streamwise vortices

lift-up

[12] Hamilton, Kim and Waleffe, *J. Fluid Mech.* (1995)

Edge states in short-wide domains in ASBL



- multitude of periodic and erratic edge states sharing the same dynamics
- periodic edge states help identify phases in self-sustaining mechanism of near-wall turbulence

- **the dynamics in streamwise direction is constrained**

- **next step – large domains with fully localized states**

[10] Khapko, Kreilos, Schlatter, Duguet, Eckhardt and Henningson, *J. Fluid Mech.* (2013)

[12] Khapko, Duguet, Kreilos, Schlatter, Eckhardt and Henningson, *Eur. Phys. J. E* (2014)

Edge state in large domains in ASBL

Spanwise-localized edge state

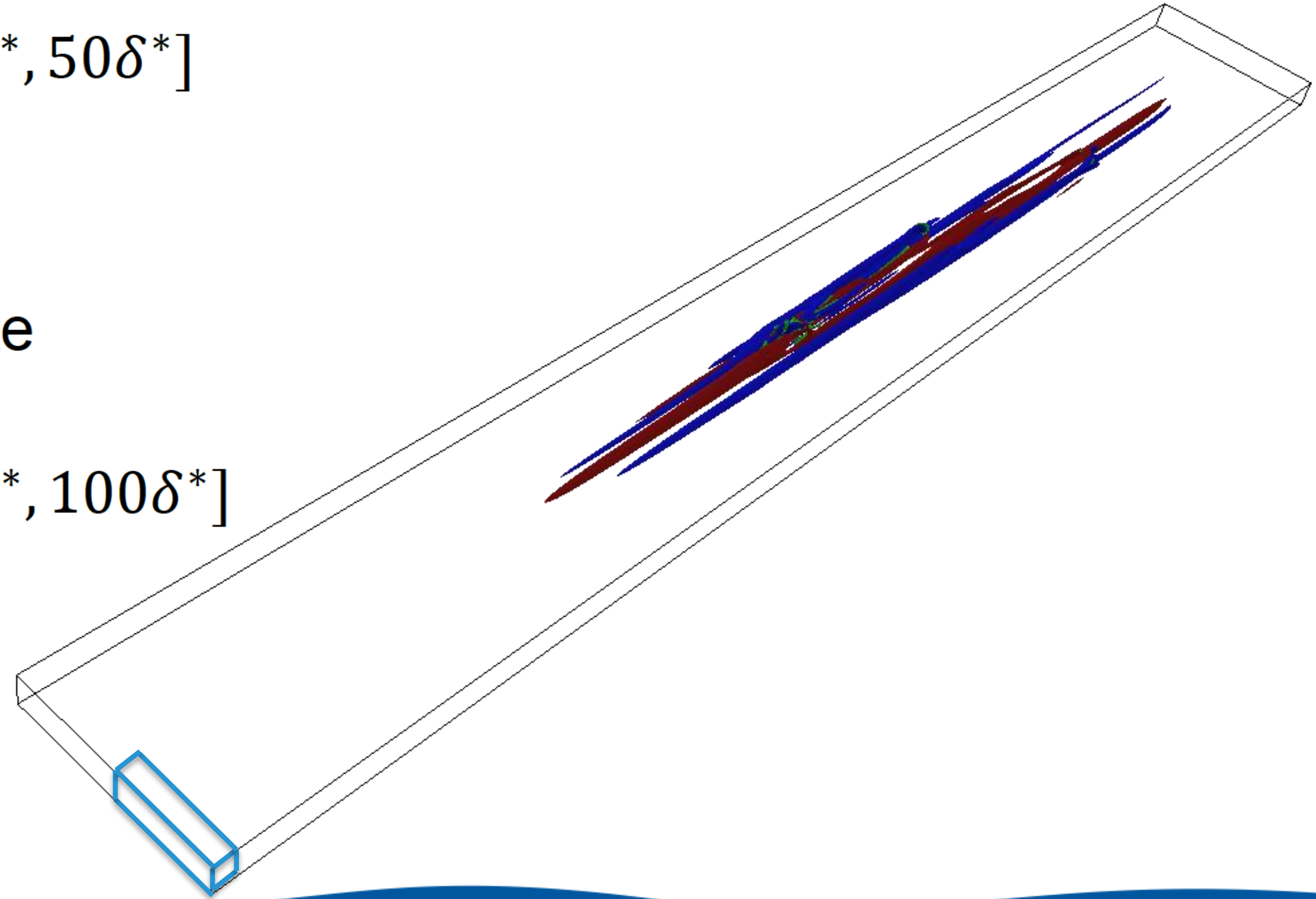
Domain size:

$[\mathrm{L_x}, \mathrm{L_y}, \mathrm{L_z}] = [6\pi\delta^*, 15\delta^*, 50\delta^*]$

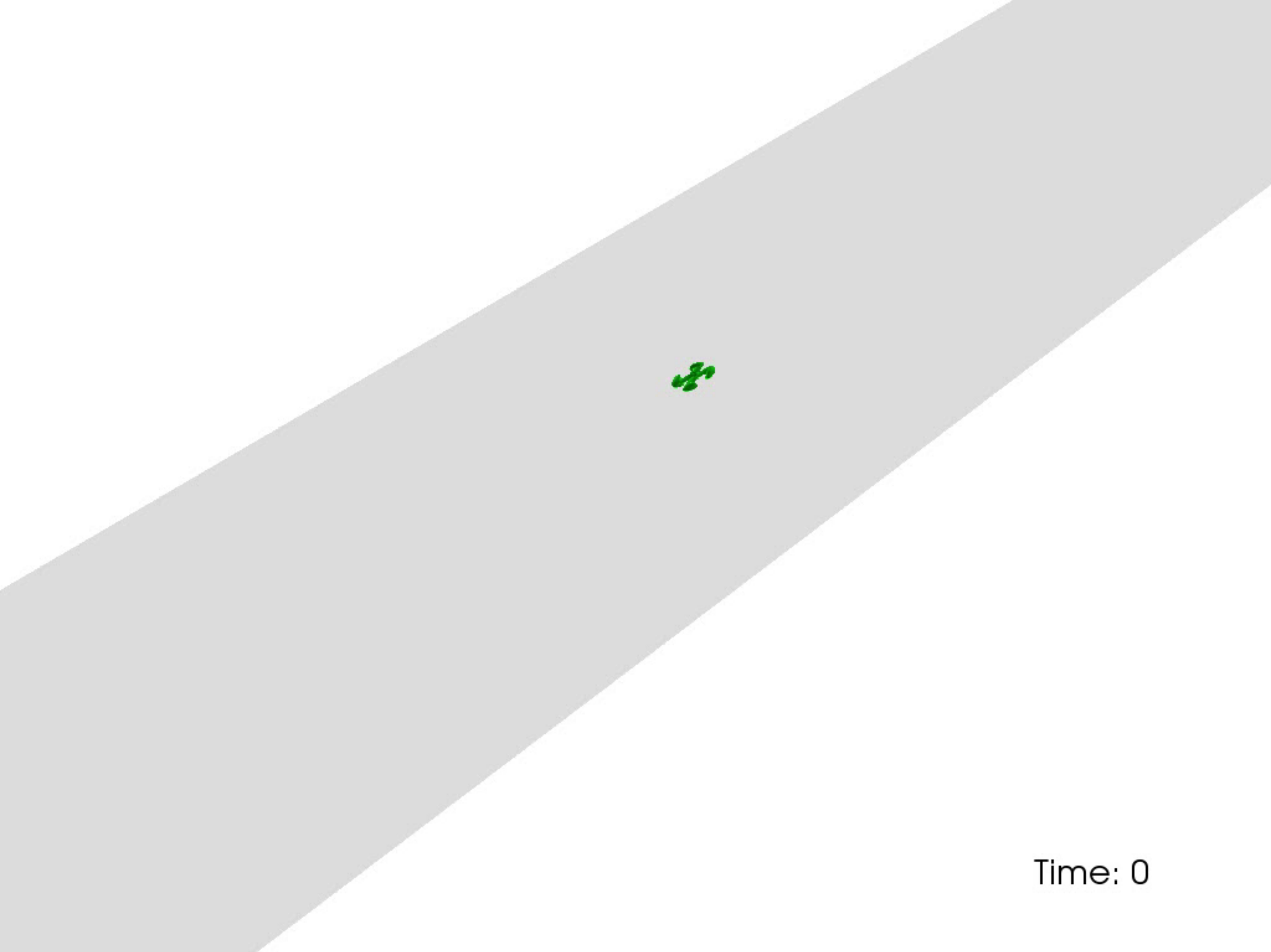
Fully-localized edge state

Domain size:

$[\mathrm{L_x}, \mathrm{L_y}, \mathrm{L_z}] = [800\delta^*, 15\delta^*, 100\delta^*]$

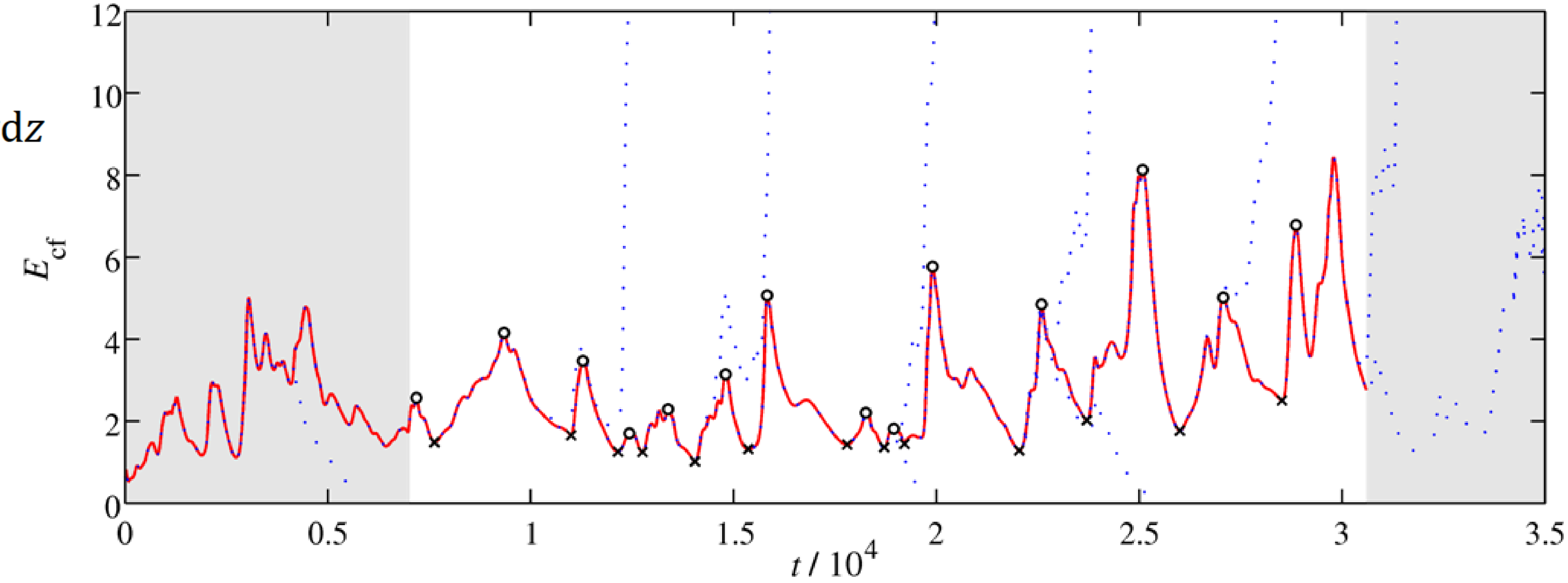


Edge state in large domains in ASBL



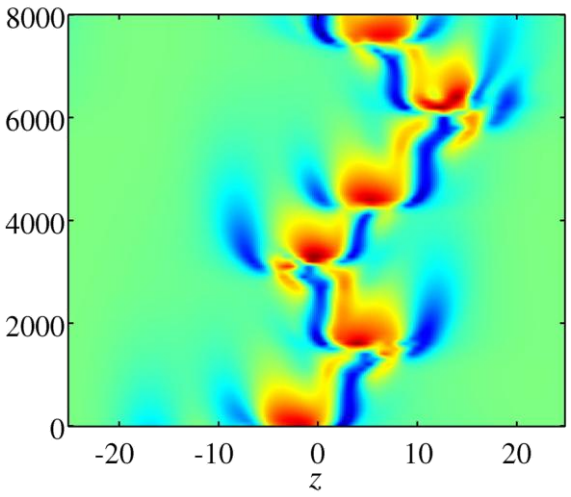
Time evolution of the localized edge state

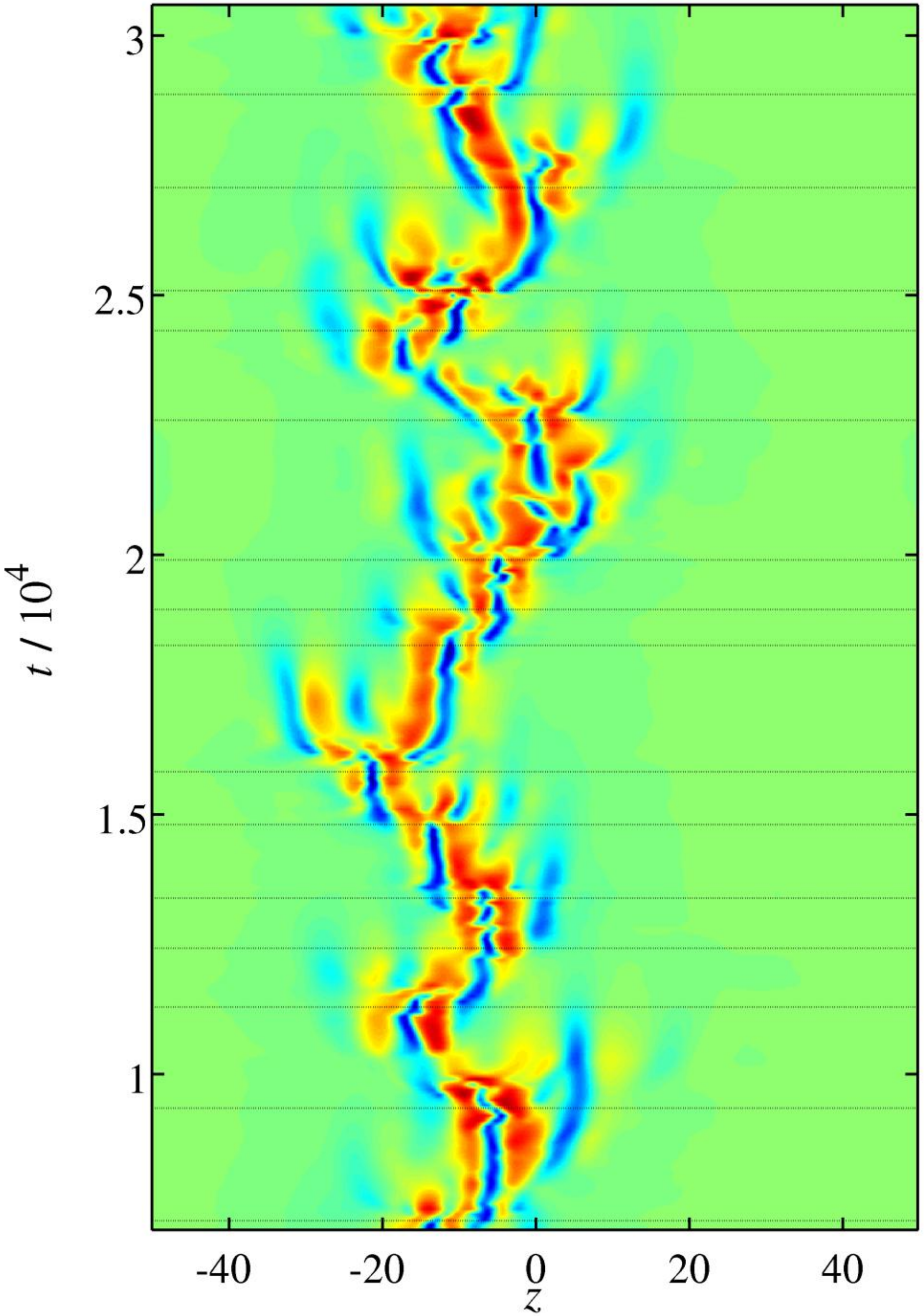
$$E_{cf} = \int_{\Omega} (v'^2 + w'^2)\mathrm{d}x\mathrm{d}y\mathrm{d}z$$



Space-time diagrams

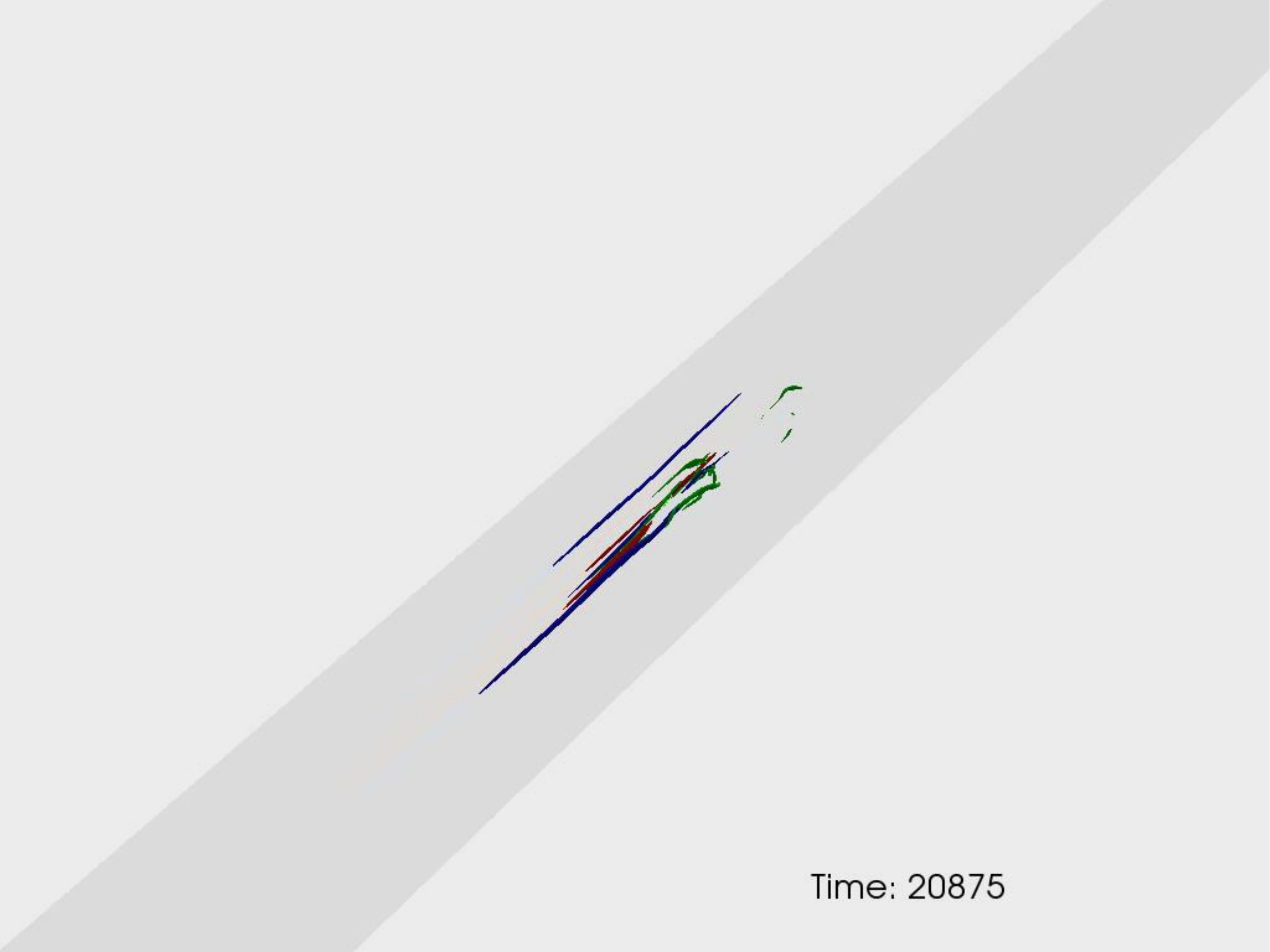
- bursts leading to spanwise shifts in all set-ups: general feature of ASBL



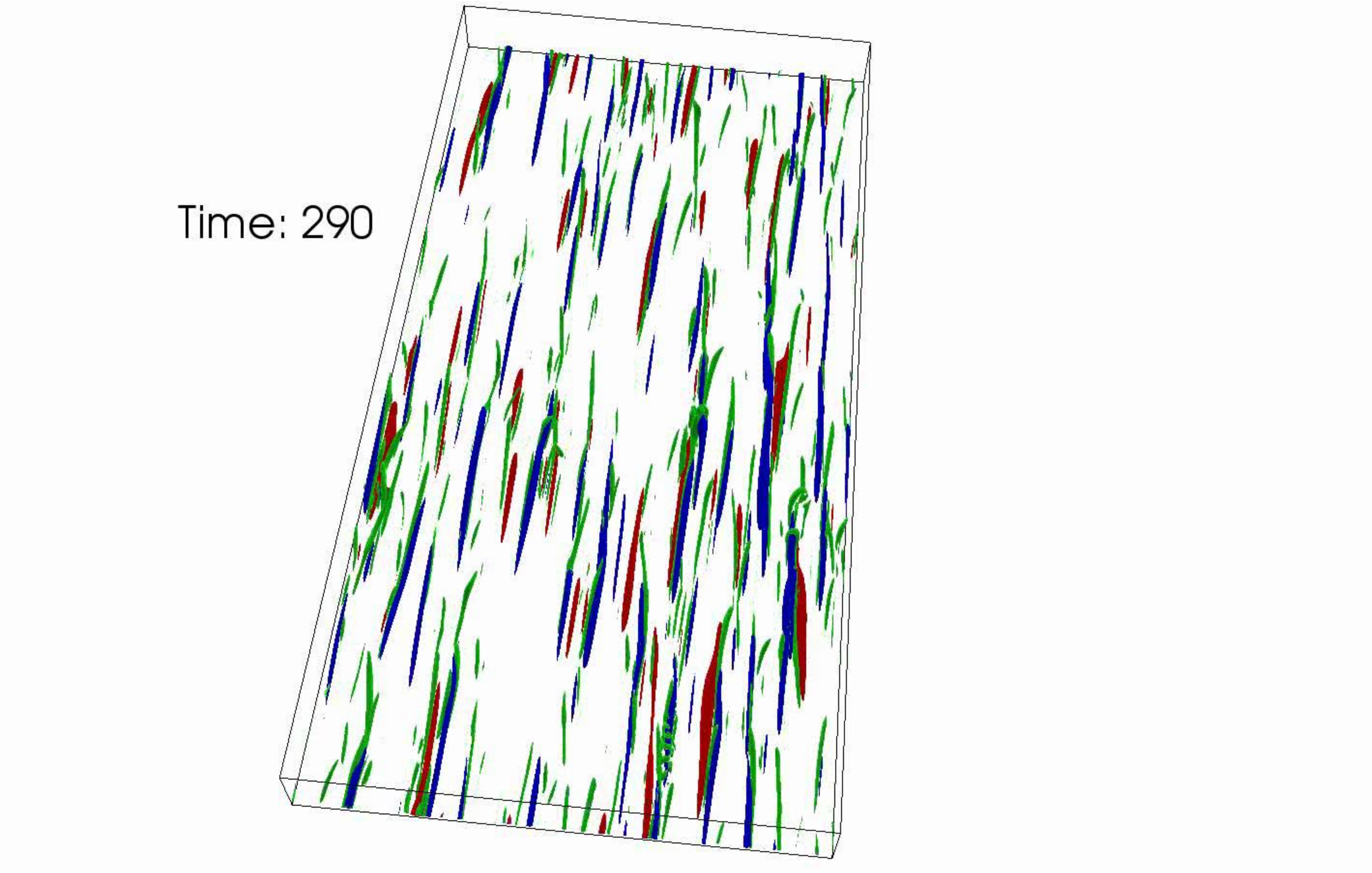


u' averaged in x at $y = 1$ plane

Departure to turbulence



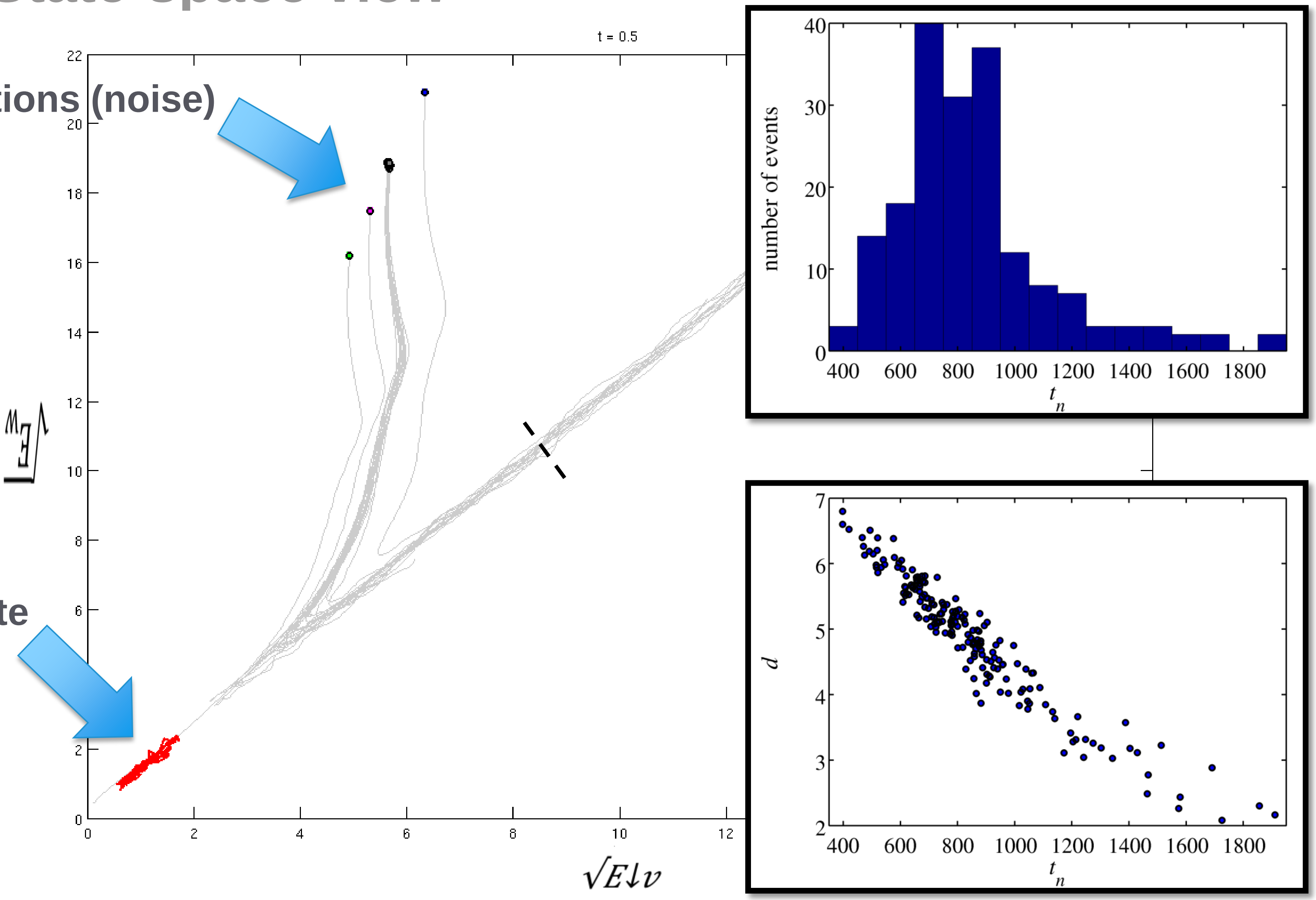
Identifying edge states in transition from noise?



Comparison between edge state and nucleation events

	edge state in calm phase	noise nucleation events
streak width	3.46 ± 0.52	3.75 ± 0.63
strength of the streak	-0.25 ± 0.03	-0.25 ± 0.04
sinuous instability wavelength	33 ± 10	27.5 ± 6

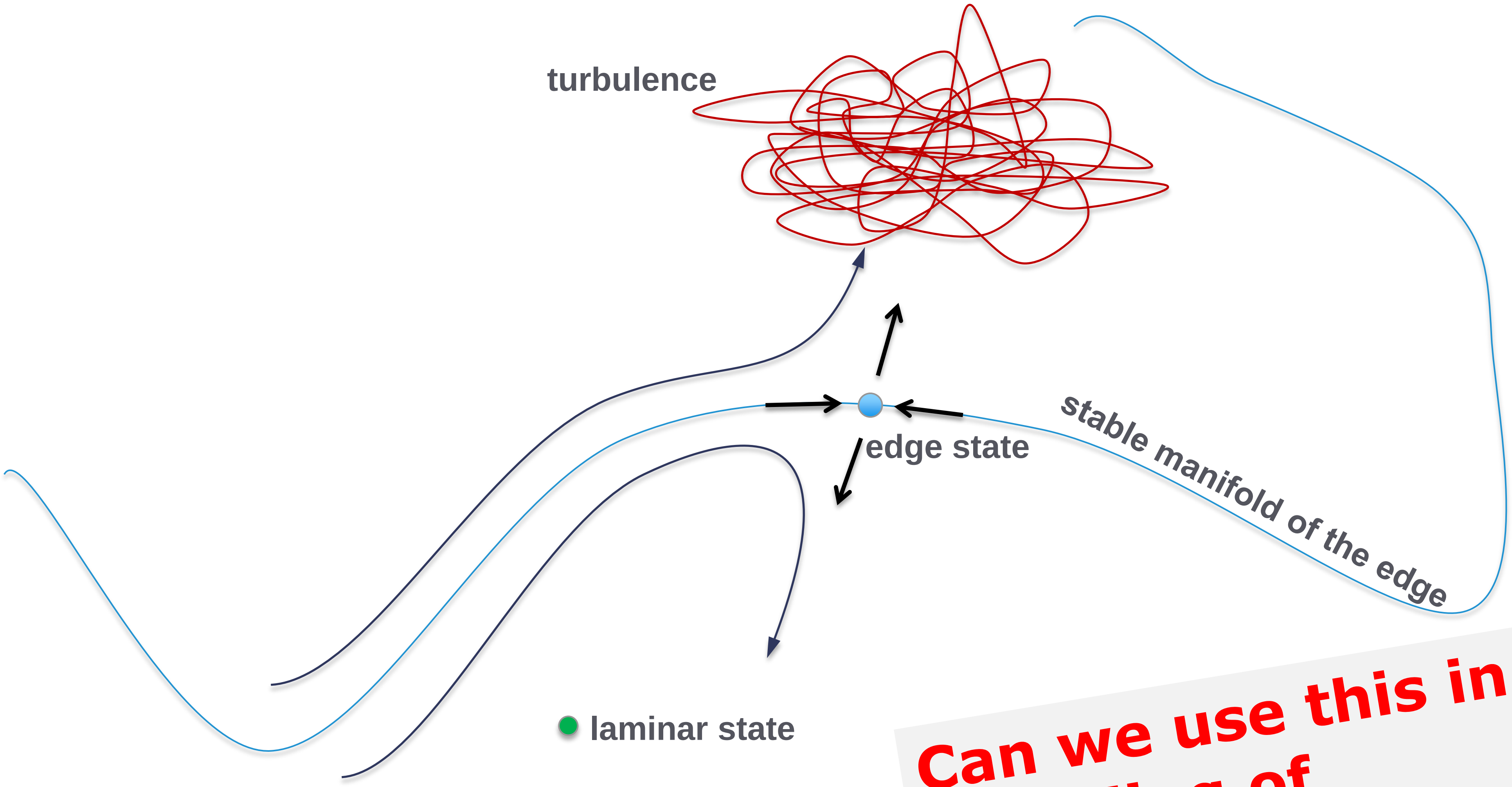
State-space view



initial conditions (noise)

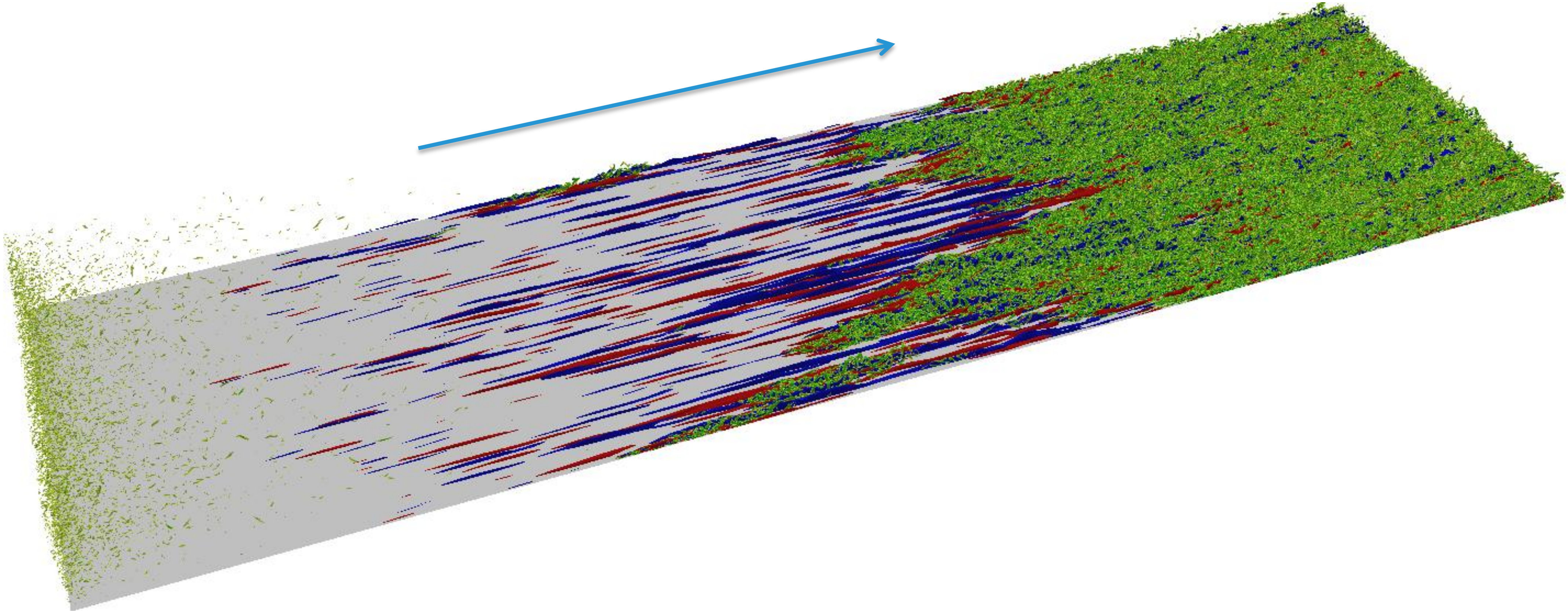
edge state

Edge instability leading to turbulence – valid scenario when starting in a vicinity of the edge



Can we use this in modeling of bypass transition?

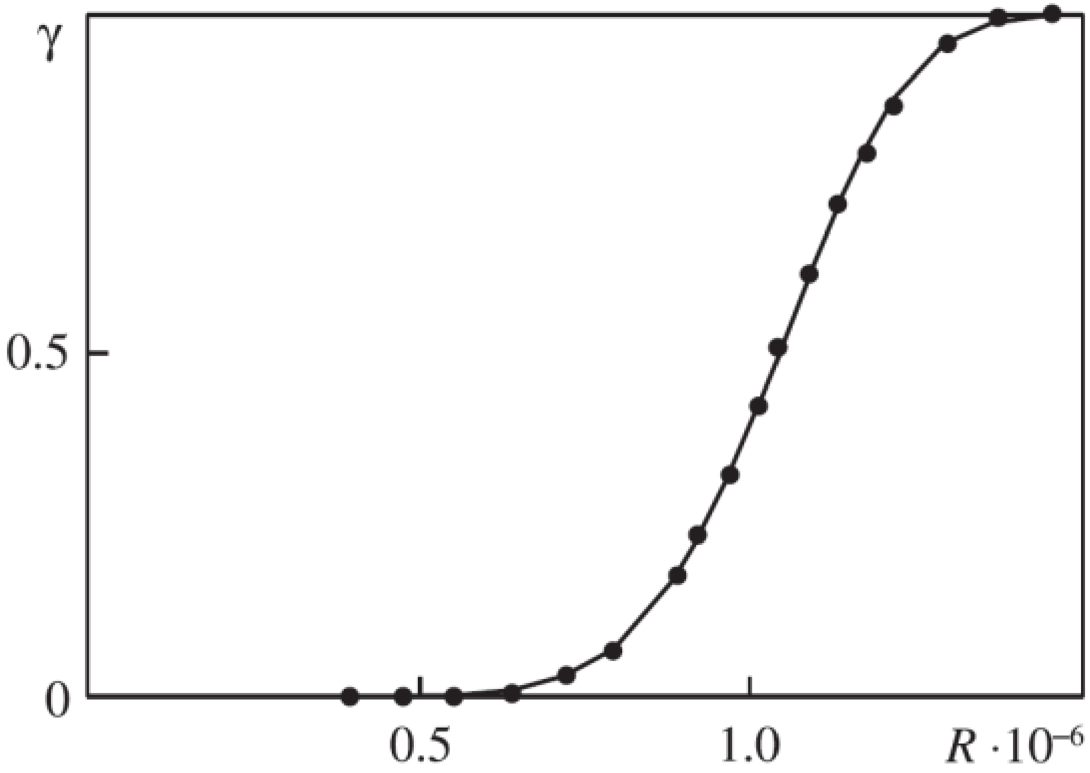
Bypass transition induced by the free-stream turbulence



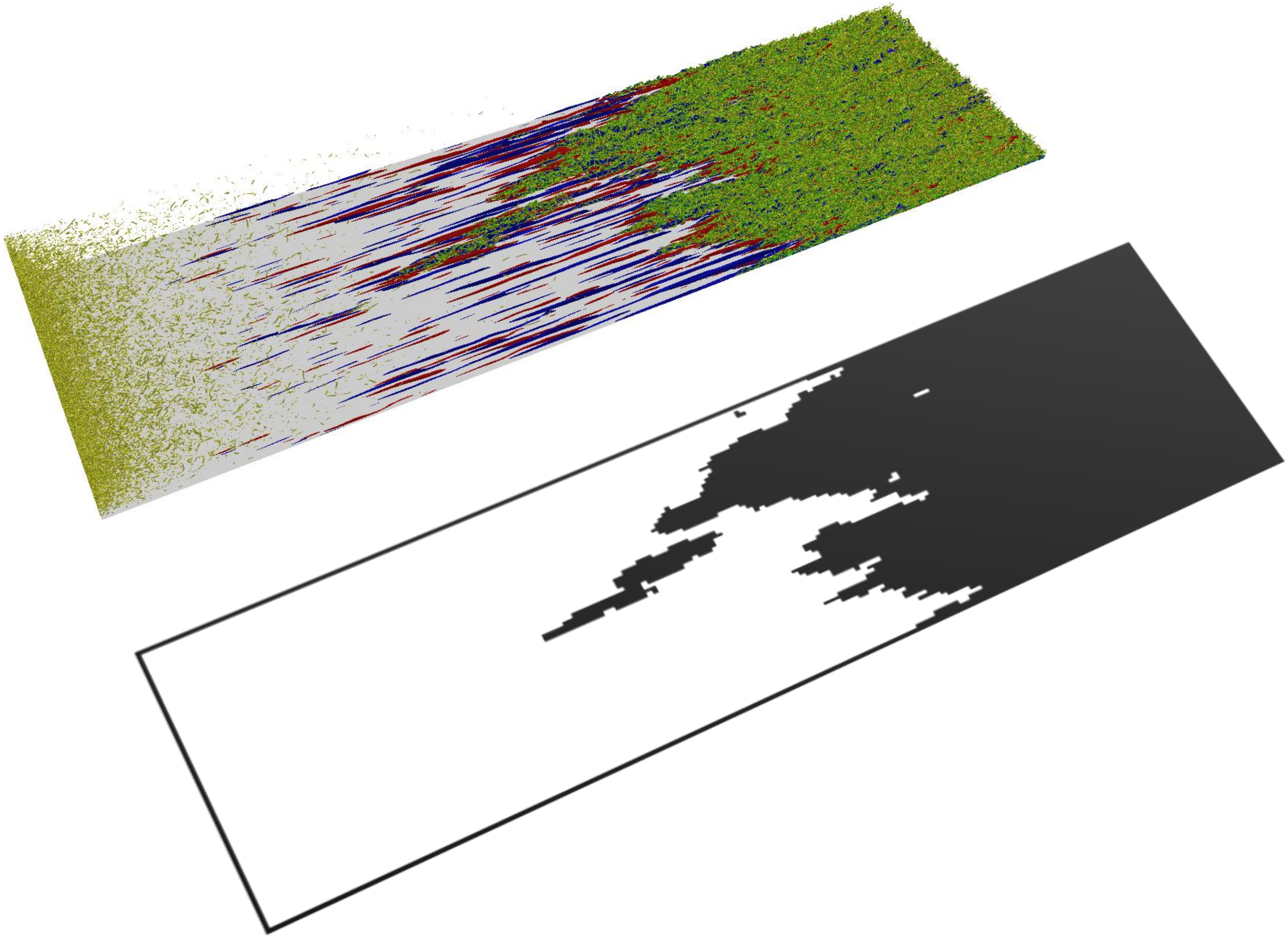
Modelling bypass transition

- Emmons, 1951
- Narasimha, 1985
- Johnson and Fashifar, 1994
- Vinod and Govindarajan, 2004
- Ustinov, 2013

✓ estimating intermittency by modelling all aspects of transition: nucleation, spreading and merging of turbulent spots



Binary representation of bypass transition



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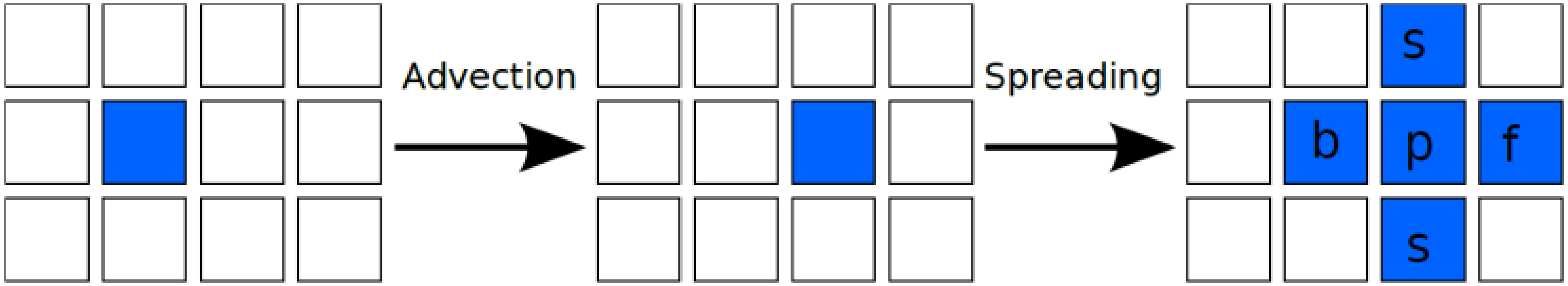
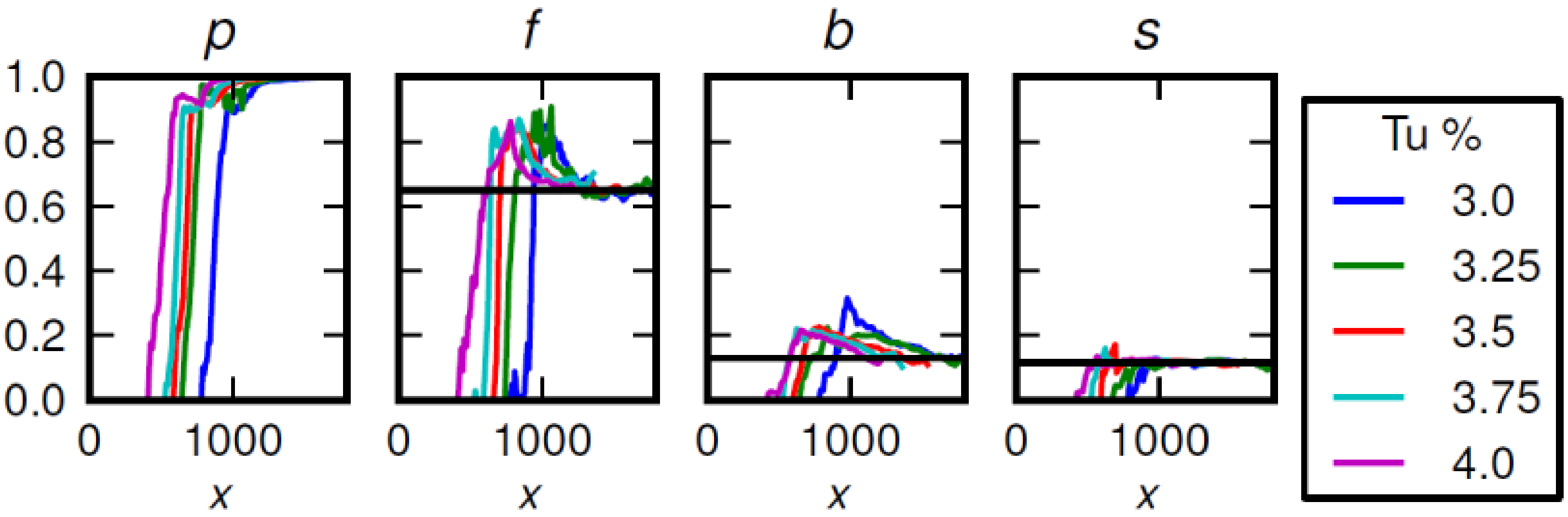
Probabilistic cellular automaton model

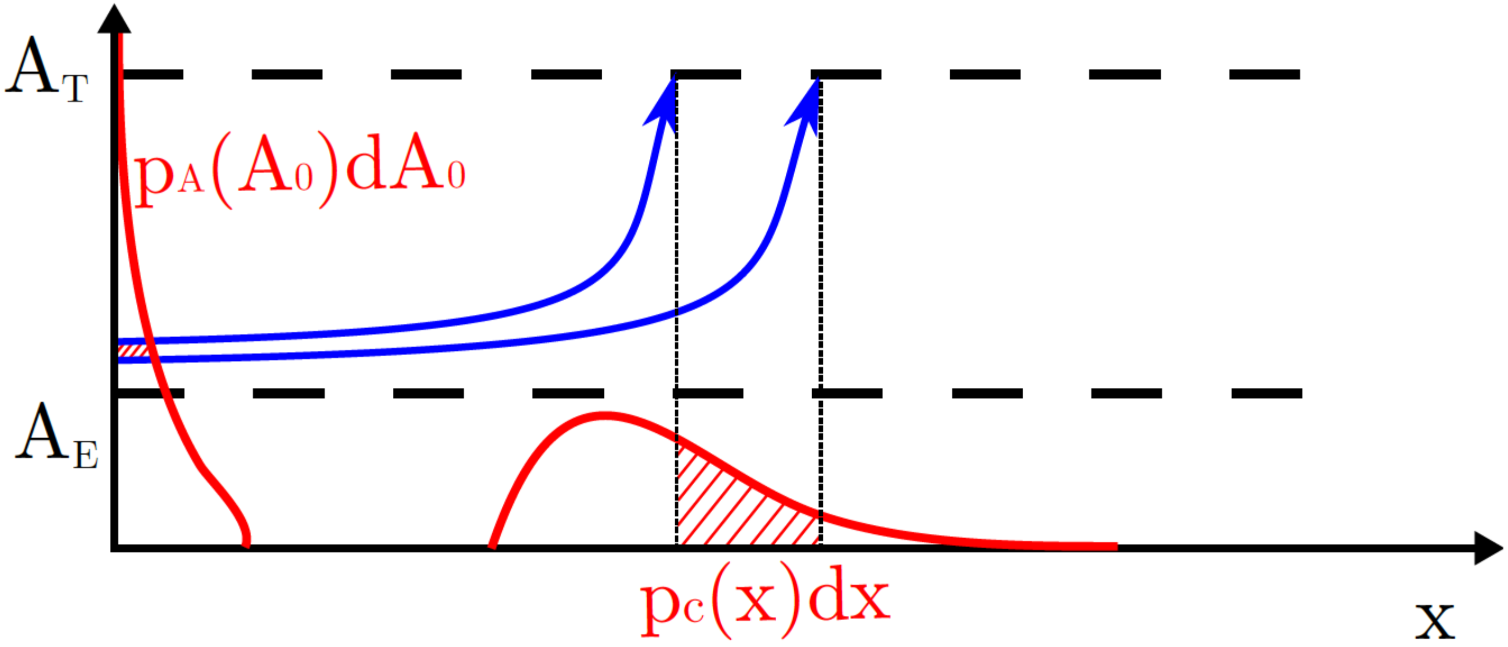




- the only difference between different Tu's is the nucleation probability

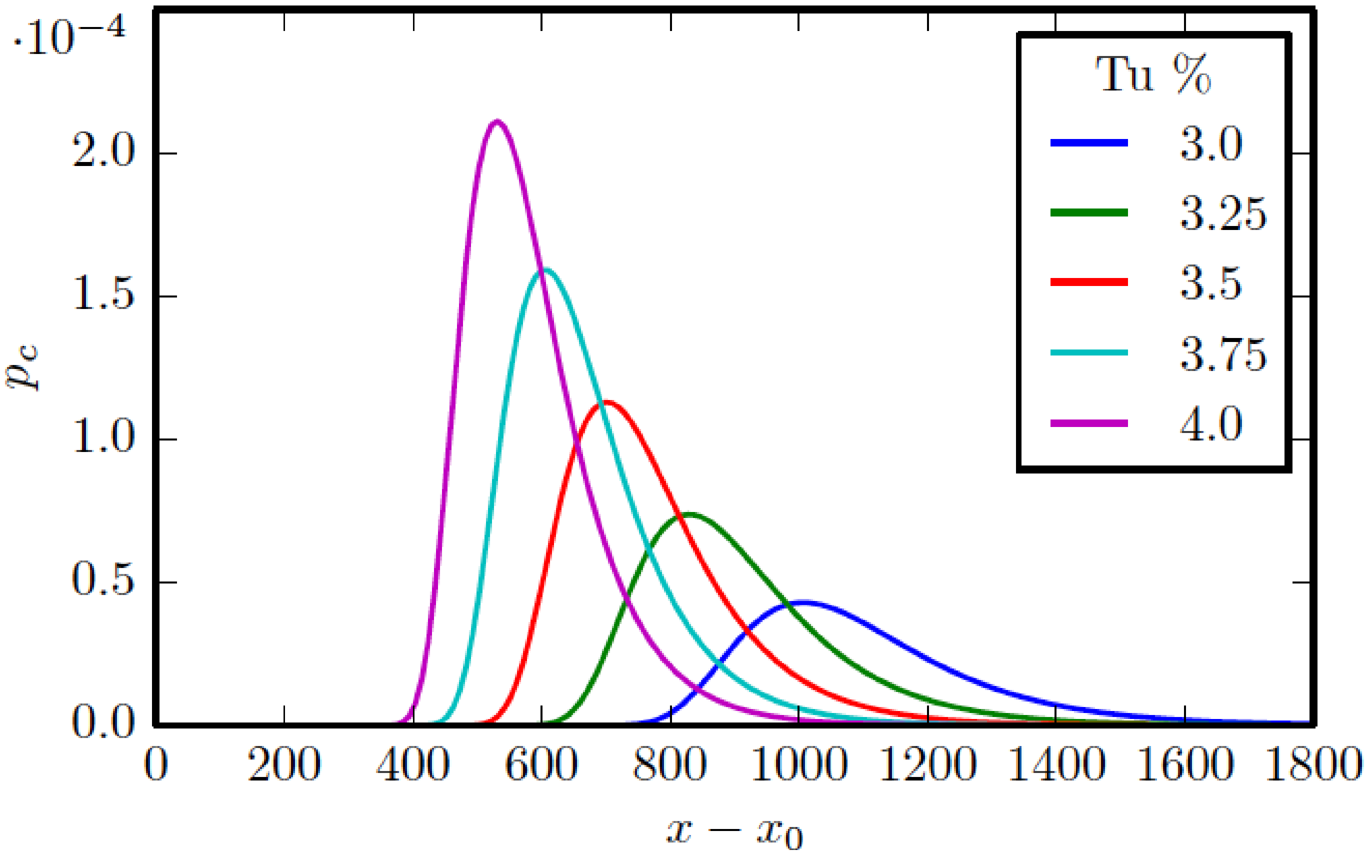
Modelling the nucleation rate: exponential departure from the edge

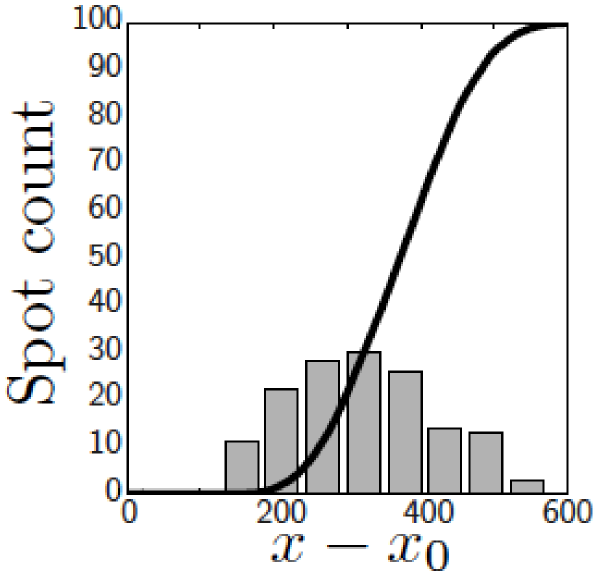
$$A_0(x) = A_E + (A_T - A_E)\exp(-\lambda x)$$



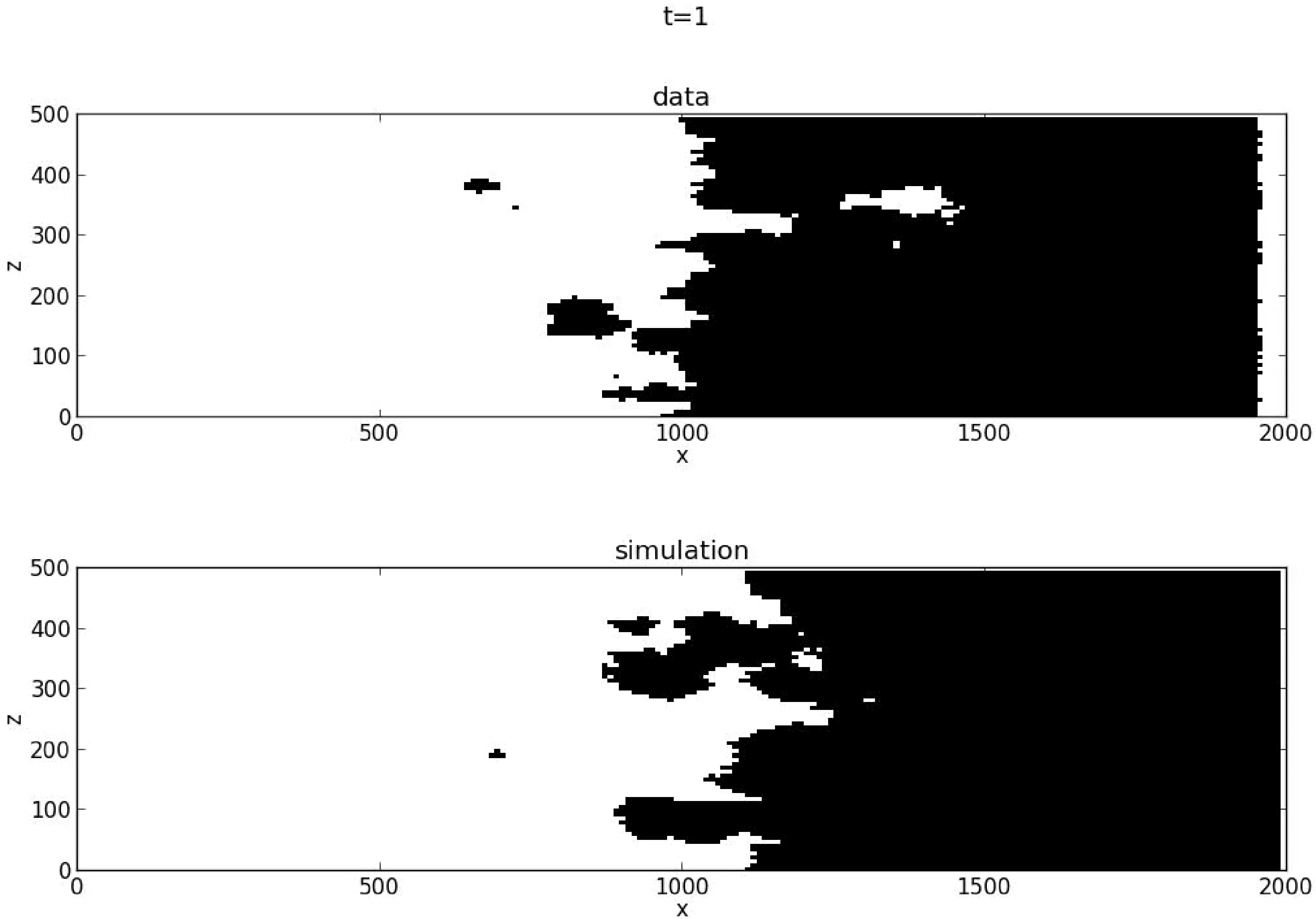
$$p_c(x)dx = p_A(A_0(x))\left|\frac{dA_0}{dx}\right|dx$$

Modelling the nucleation rate – curve fitted to numerical experiments

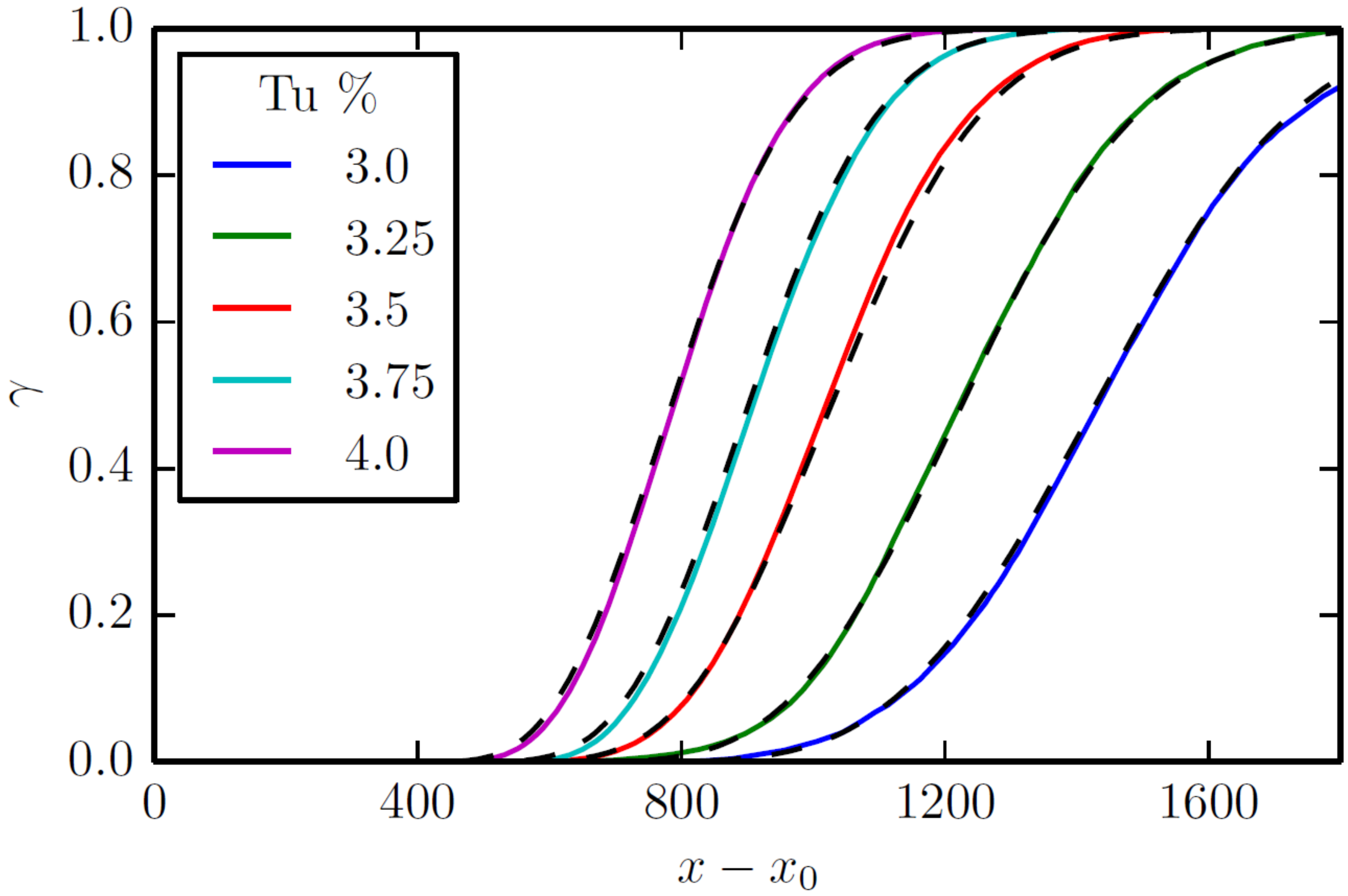




Comparing the model and the simulations



Comparing the model and the simulations

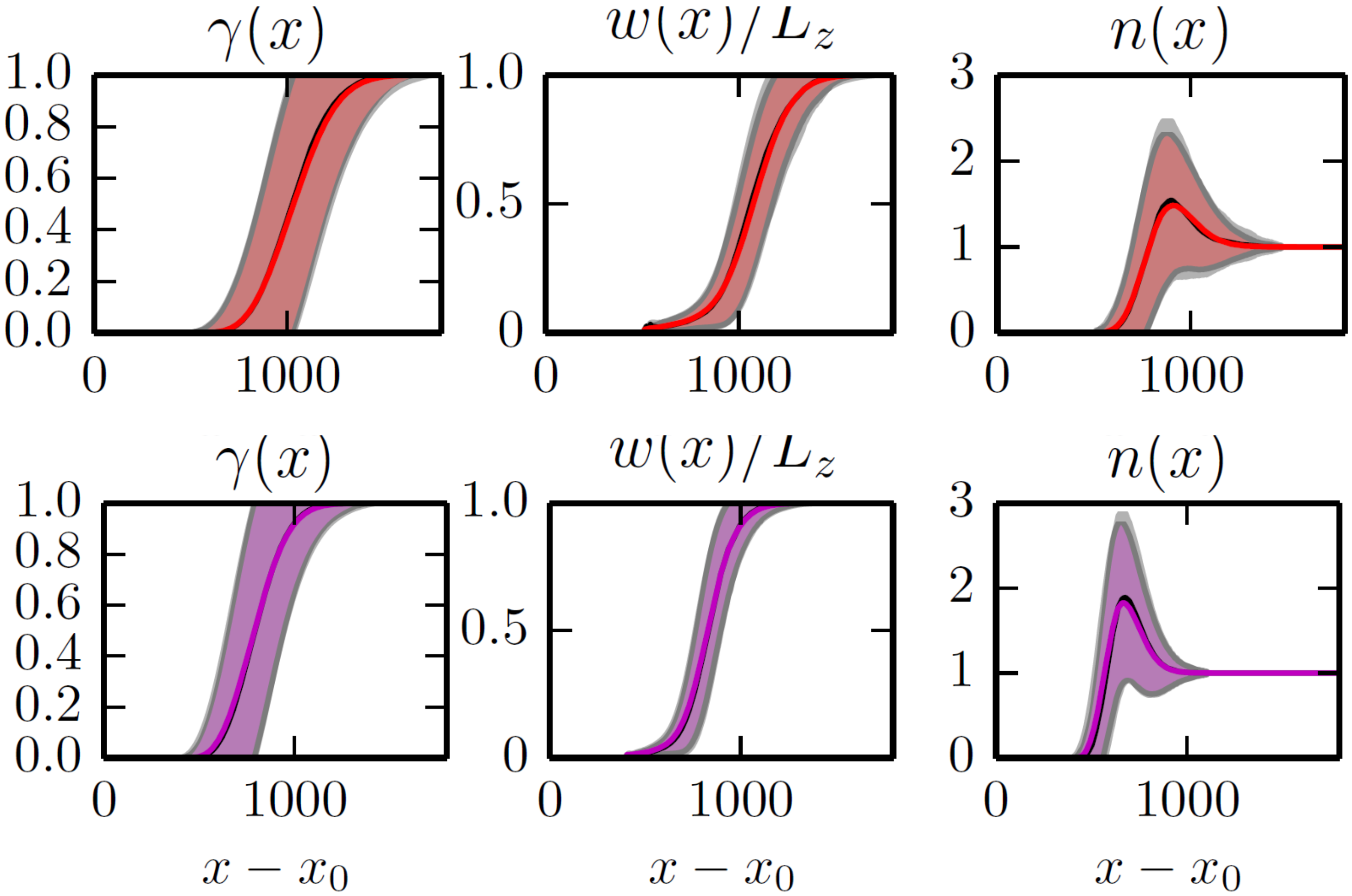


[15] Kreilos, Khapko, Schlatter, Duguet, Henningson and Eckhardt *(submitted)*

Comparing the model and the simulations

$Tu = 3.5\%$

$Tu = 4.0\%$



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[15] Kreilos, Khapko, Schlatter, Duguet, Henningson and Eckhardt *PR Fluids (2016)*

Conclusions

- In boundary layers the edge states are characterized by recurrent bursts leading to spanwise shifts
- The self-sustaining mechanism of the edge state bears many similarities to the regeneration cycle of the near-wall turbulence
- During transition the flow approaches the edge for finite time
- Nucleation model constructed based on this transition process
- Nucleation model + Probabilistic cellular automaton
  = very good description of bypass transition

ETC16 in Stockholm Aug 21-24 2017
Deadline for abstracts is extended to Jan 22

- For information see www.etc16.se