Connecting boundary layer dynamics with extreme bulk dissipation events in Rayleigh-Bénard flow

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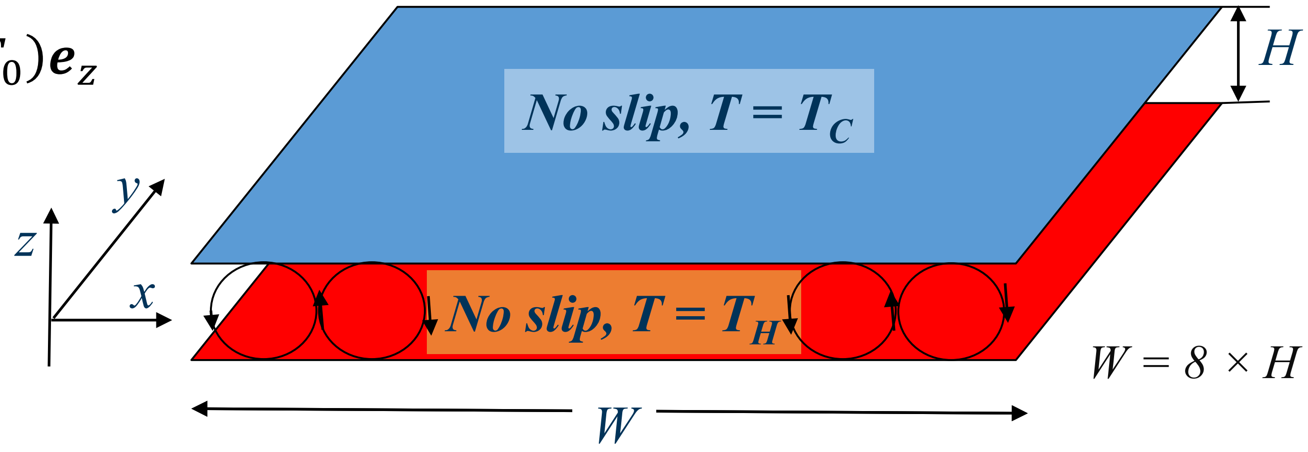
Direct Numerical Simulations (DNS)

High-resolved DNS of 3D Navier-Stokes and temperature equations are solved by a spectral element method using the Nek5000 software package at very high spectral resolution.

$$\begin{cases} \nabla \cdot \boldsymbol{u} = 0 \\ \dfrac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\dfrac{1}{\rho_0}\nabla p + \nu \nabla^2 \boldsymbol{u} + g\alpha(T - T_0)\boldsymbol{e}_z \\ \dfrac{\partial T}{\partial t} + (\boldsymbol{u} \cdot \nabla)T = \kappa \nabla^2 T \end{cases}$$

Periodic boundary conditions at the vertical walls.

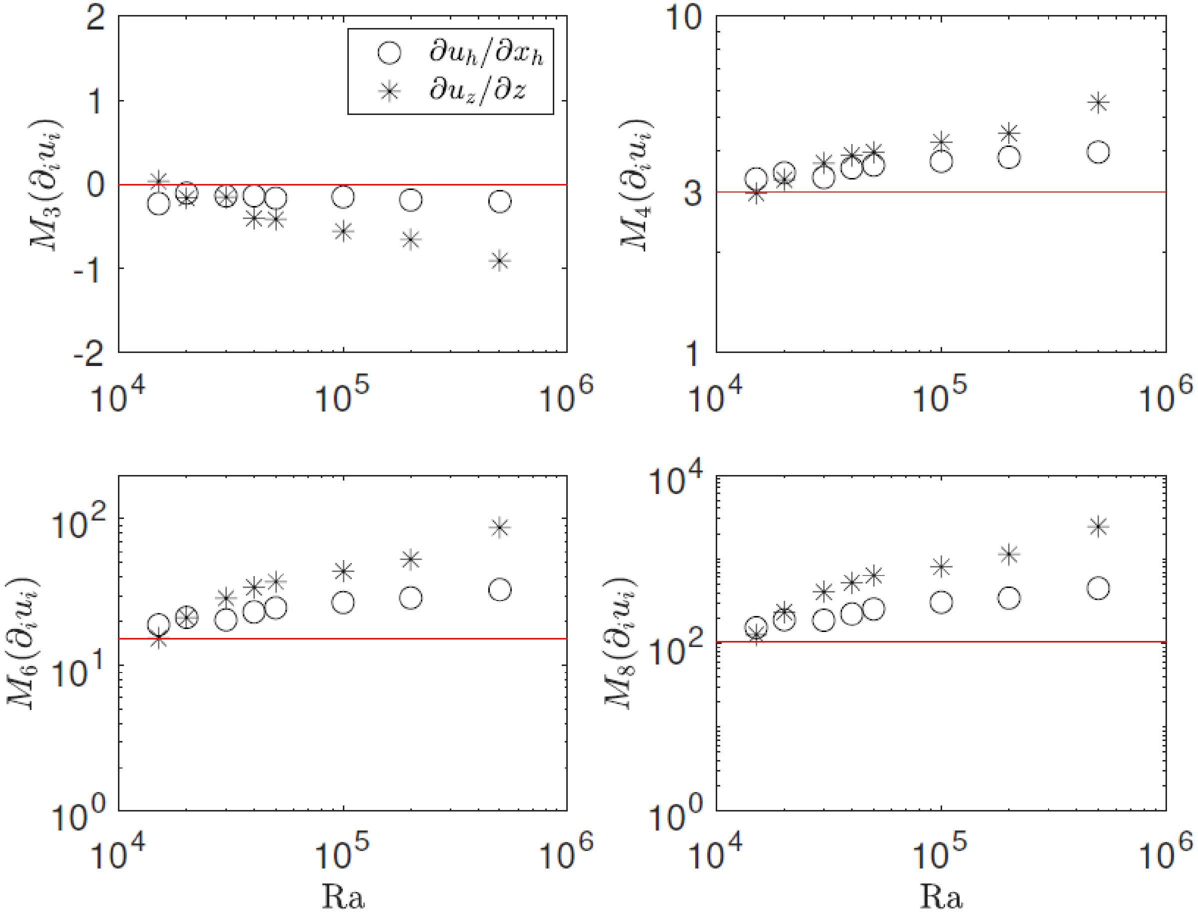


$$Ra = \frac{\alpha g (T_H - T_C) H^3}{\nu \kappa} = 1.5 \times 10^4 \div 5 \times 10^5$$

(low *Ra*, high resolution)

$$Pr = \frac{\nu}{\kappa} = 1$$

Transition from Gaussian to intermittent statistics



$$M_n(\partial_i u_i) = \frac{\langle(\partial u_i/\partial x_i)^n\rangle_b}{\langle(\partial u_i/\partial x_i)^2\rangle_b^{n/2}}$$

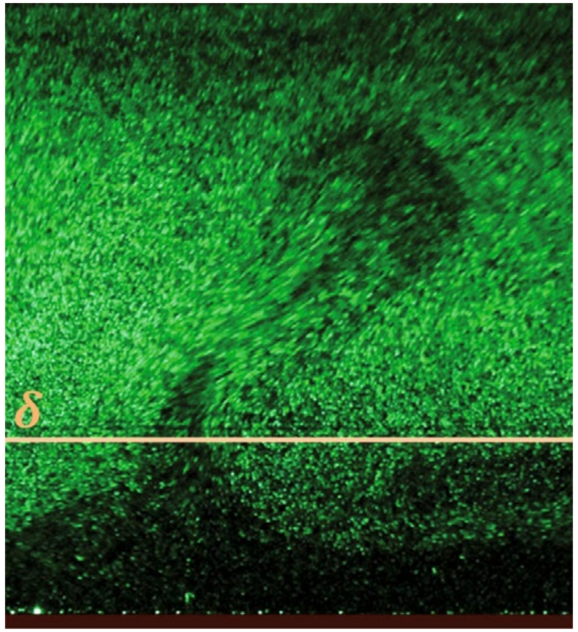
Red line: Gaussian moment amplitude

- The crossover is gradual and seems to be altered by increasingly intermittently appearing coherent structures;
- larger magnitudes of $\partial u_z/\partial z$ are connected to rising and falling of these thermal structures (thermal plumes).

Thermal plume

The most important near-wall structure is the **thermal plume** (a detached fragment of the thermal boundary layers (BLs)).

We want to investigate the link between derivative statistics in the bulk and the formation of plumes and plume clusters in the boundary layers.

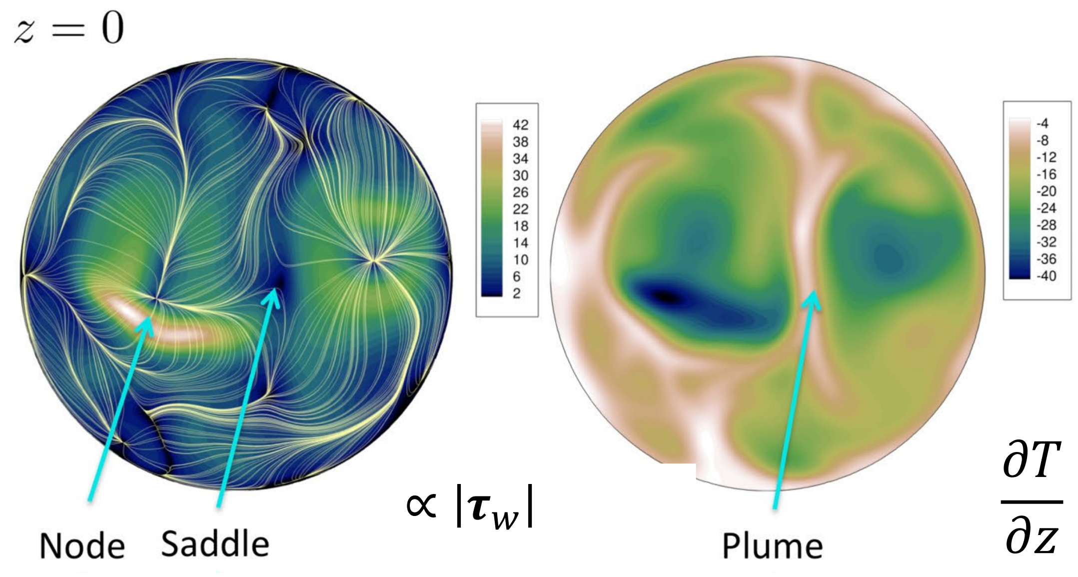


Thermal plume visualization with DEHS particles in the Barrel of Ilmenau [Figure from Ronald du Puits, TU Ilmenau]

Wall shear stress topology

The wall shear stress field is a two-dimensional vector field defined as:

$$\boldsymbol{\tau}_w = \rho_0 \nu \left. \frac{\partial \boldsymbol{u}_t}{\partial n} \right|_w$$



Bandaru *et al*. PRE 2015, studied the critical points of τ_w:

- Triplets of critical points composed of two unstable nodes and a saddle between them are identified as characteristic building blocks;
- saddle points are found where thermal plumes detach from the walls,
- and unstable nodes where thermal plumes impinge.

Thermal plumes detach from the plates in regions where the magnitude of $\partial T/\partial z$ is small.

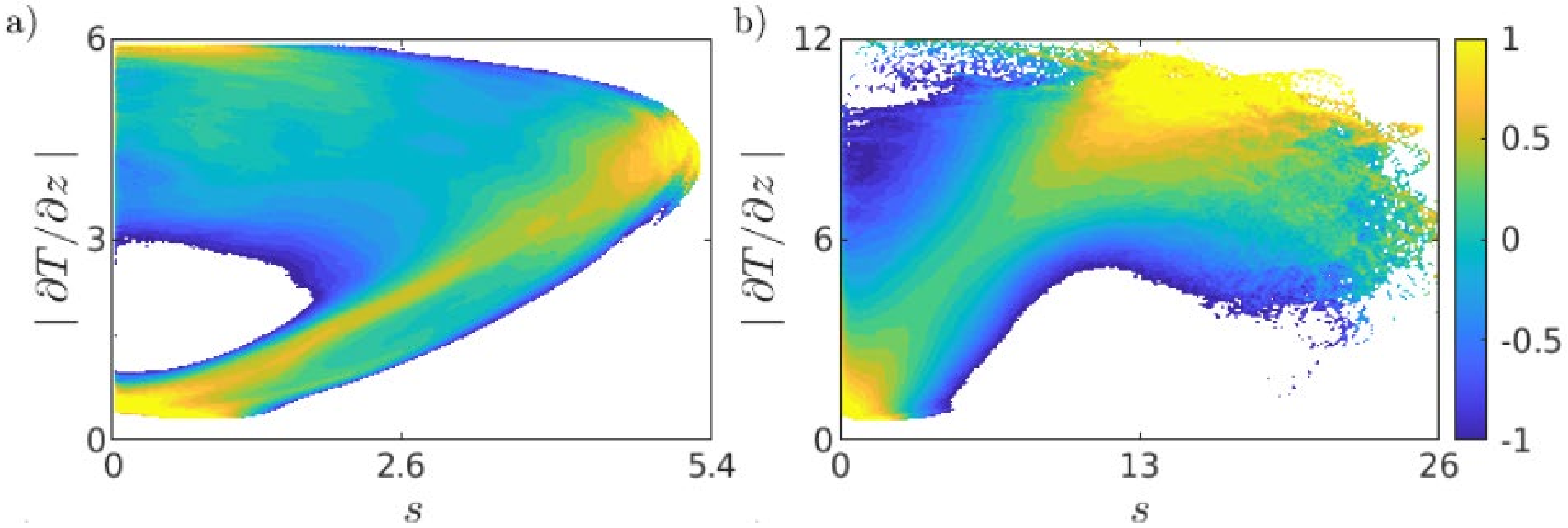
Statistical analysis

Statistics based on a sequence of snapshots at a time interval $\Delta t = 0.29\, T_f$ for $Ra\ = 1.5 \times 10^4$ and $\Delta t = 0.475\, T_f$ for $Ra\ = 5 \times 10^5$.

Joint probability density function (p) of the wall shear stress magnitude, $s = \left|\frac{\boldsymbol{\tau}_w}{\rho_0 \nu}\right|$ and $|\partial T/\partial z|$:

$$J(s, |\partial T/\partial z|\,) = \frac{p(s, |\partial T/\partial z|)}{p(s)p(|\partial T/\partial z|)}$$

If $J > 1$, the correlation is larger than if the two fields were statistically independent.

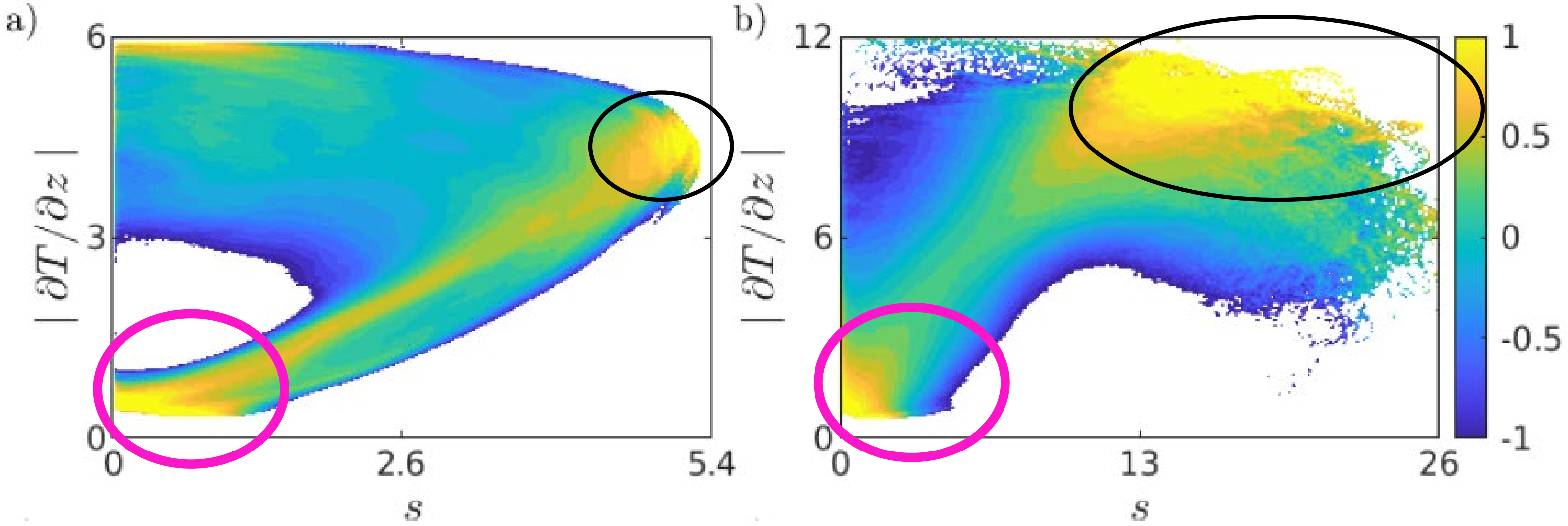


$Ra\ = 1.5 \times 10^4$ $\quad$ $Ra\ = 5 \times 10^5$

Statistical analysis

$J(s, |\partial T/\partial z|) > 1$:

1. for the smallest s magnitudes **in combination with plume detachments**, where $|\partial T/\partial z|$ is very small;
2. for the largest s magnitudes with local maxima of $|\partial T/\partial z|$.



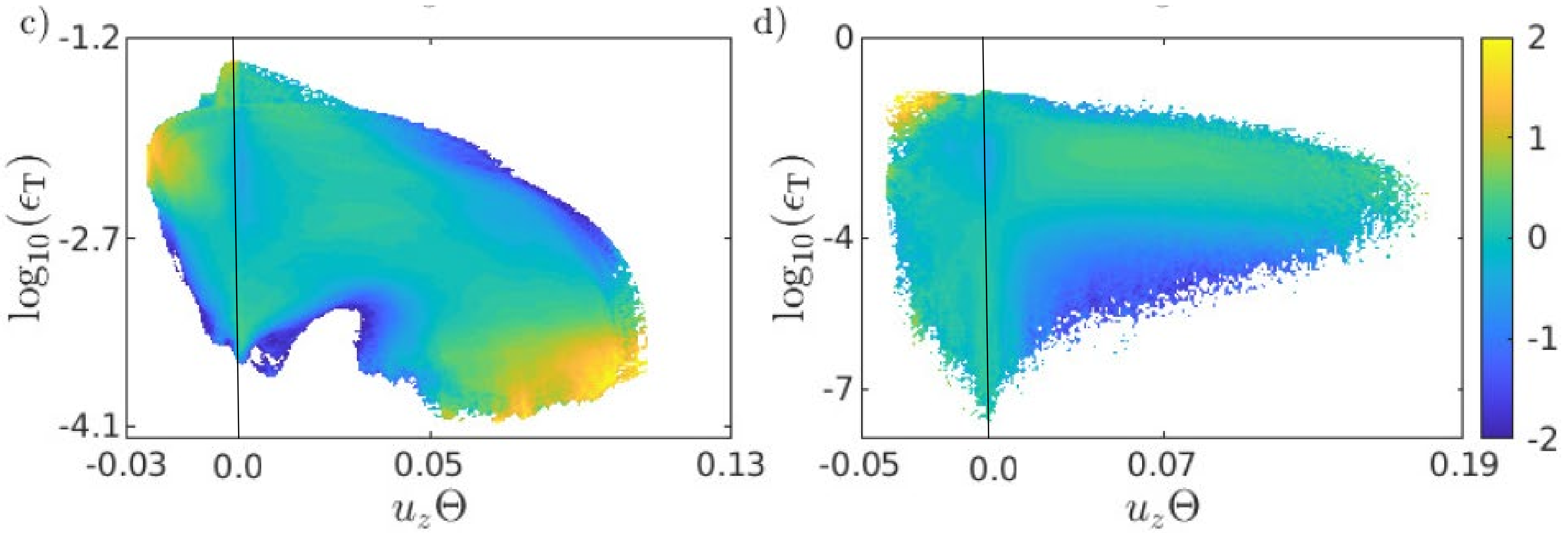
$Ra = 1.5 \times 10^4$ $Ra = 5 \times 10^5$

Statistical analysis

$J(u_z\Theta, \epsilon_T\ ),\ \ \Theta = T - \langle T\rangle_{V,t}$

$u_z\Theta$ determines the convective heat transfer, and $\epsilon_T(x, y, t) = \frac{1}{\sqrt{RaPr}}(\nabla T)^2$ is the thermal energy dissipation rate.

The largest values $u_z\Theta > 0$ correspond to rising or falling thermal plumes that reach the midplane.

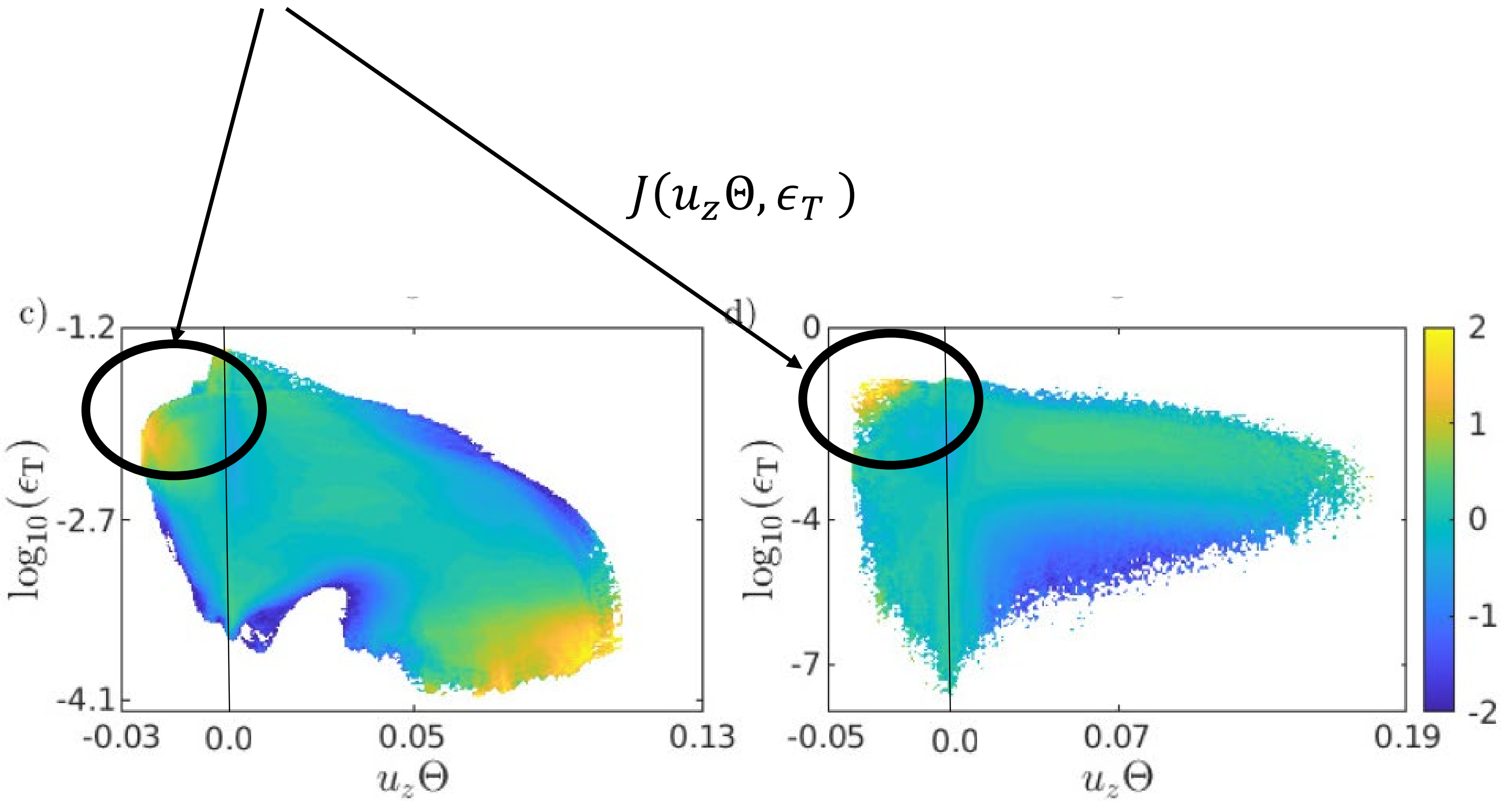


$Ra\ = 1.5 \times 10^4$ $Ra\ = 5 \times 10^5$

Statistical analysis

For both Rayleigh numbers local maxima of $J(u_z\Theta, \epsilon_T)$ with negative $u_z\Theta$ and high ϵ_T were identified.

- These events are associated to **plume collisions** that lead to **reversed transport events**;
- generation of **steep local temperature gradients**.



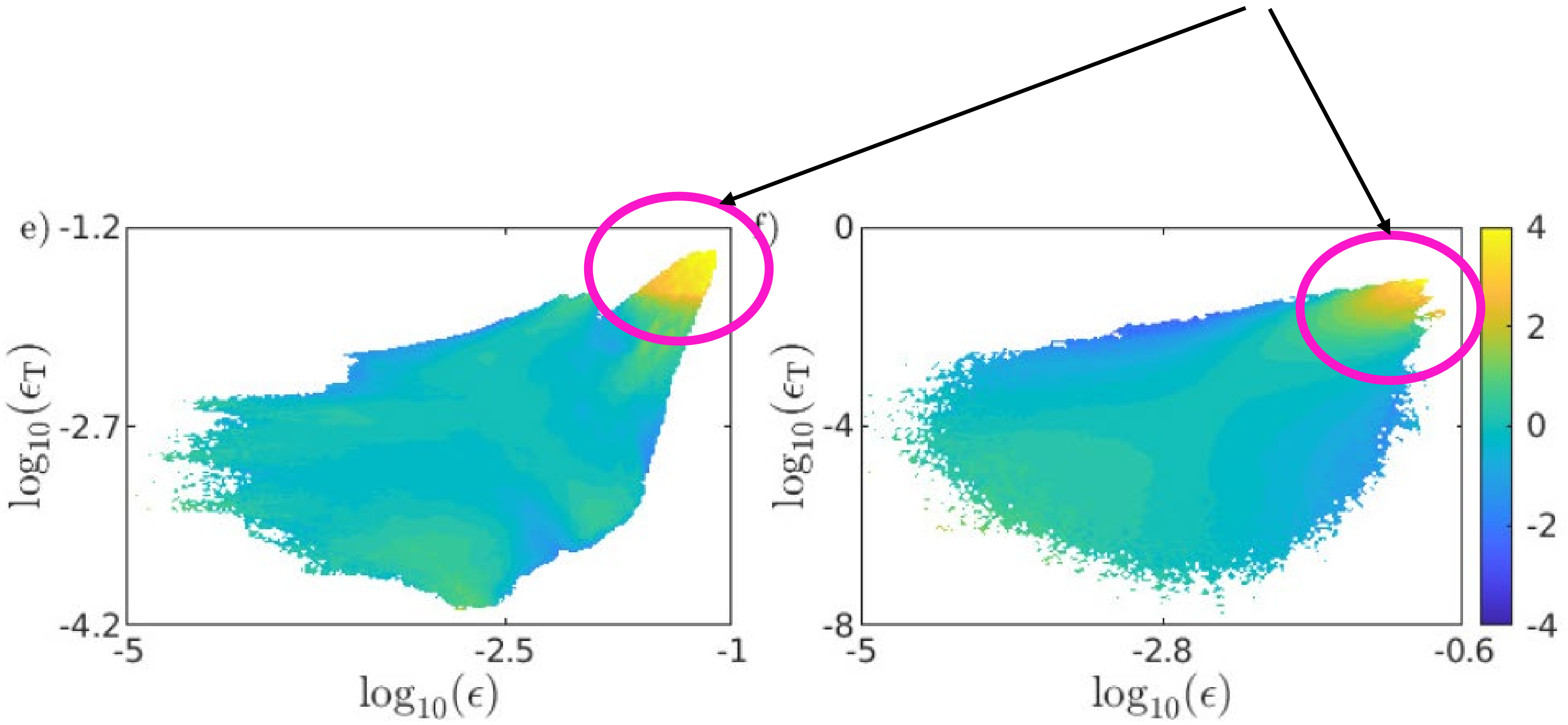
$Ra = 1.5 \times 10^4$

$Ra = 5 \times 10^5$

Statistical analysis

$J(\epsilon_T, \epsilon\,)$ correlates the thermal and the kinetic energy dissipation rate $\epsilon(x,y,t) = \frac{1}{2}\sqrt{\frac{Pr}{Ra}}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T)^2$ for both Rayleigh numbers show a strong statistical correlation at their maximum amplitudes:

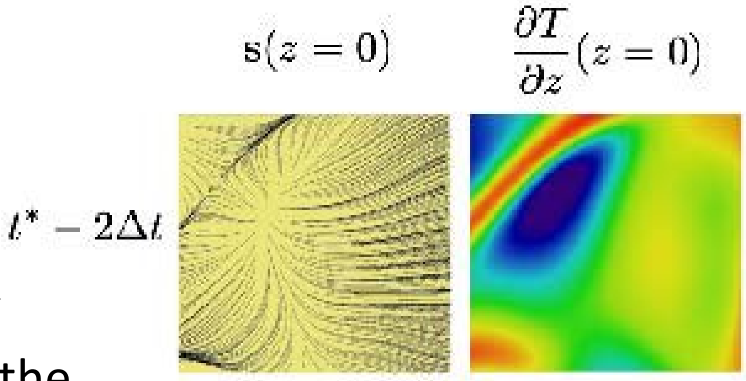
Plume collisions in the bulk generate **steep temperature gradients** (and thus high amplitudes of ϵ_T), and **subsequently local shear layers** (and thus high amplitudes of ϵ)

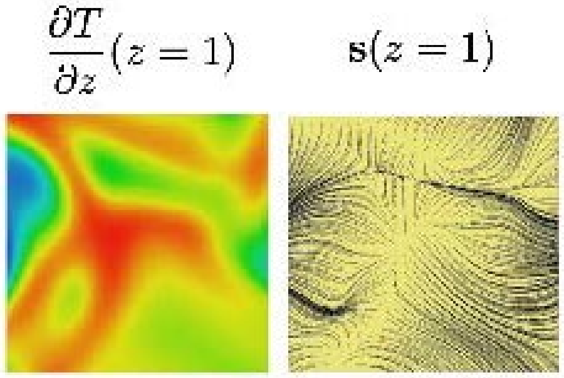


$Ra\ = 1.5 \times 10^4$

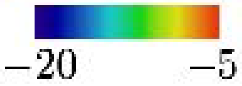
$Ra\ = 5 \times 10^5$

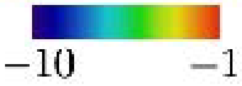
Formation of an event at $Ra\ = 5 \times 10^5$





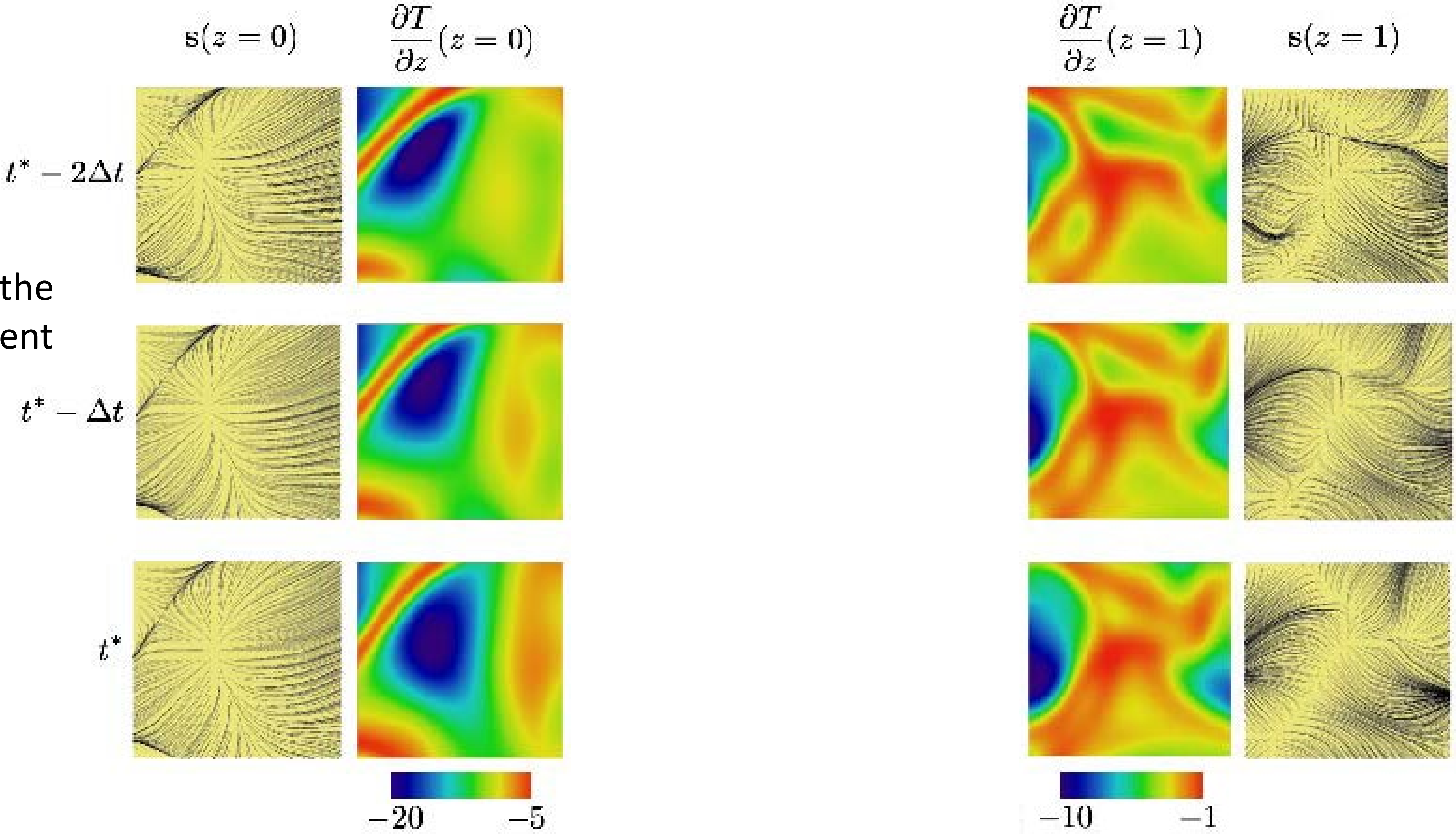
Section $H \times H$ centered at the (x,y) of the event





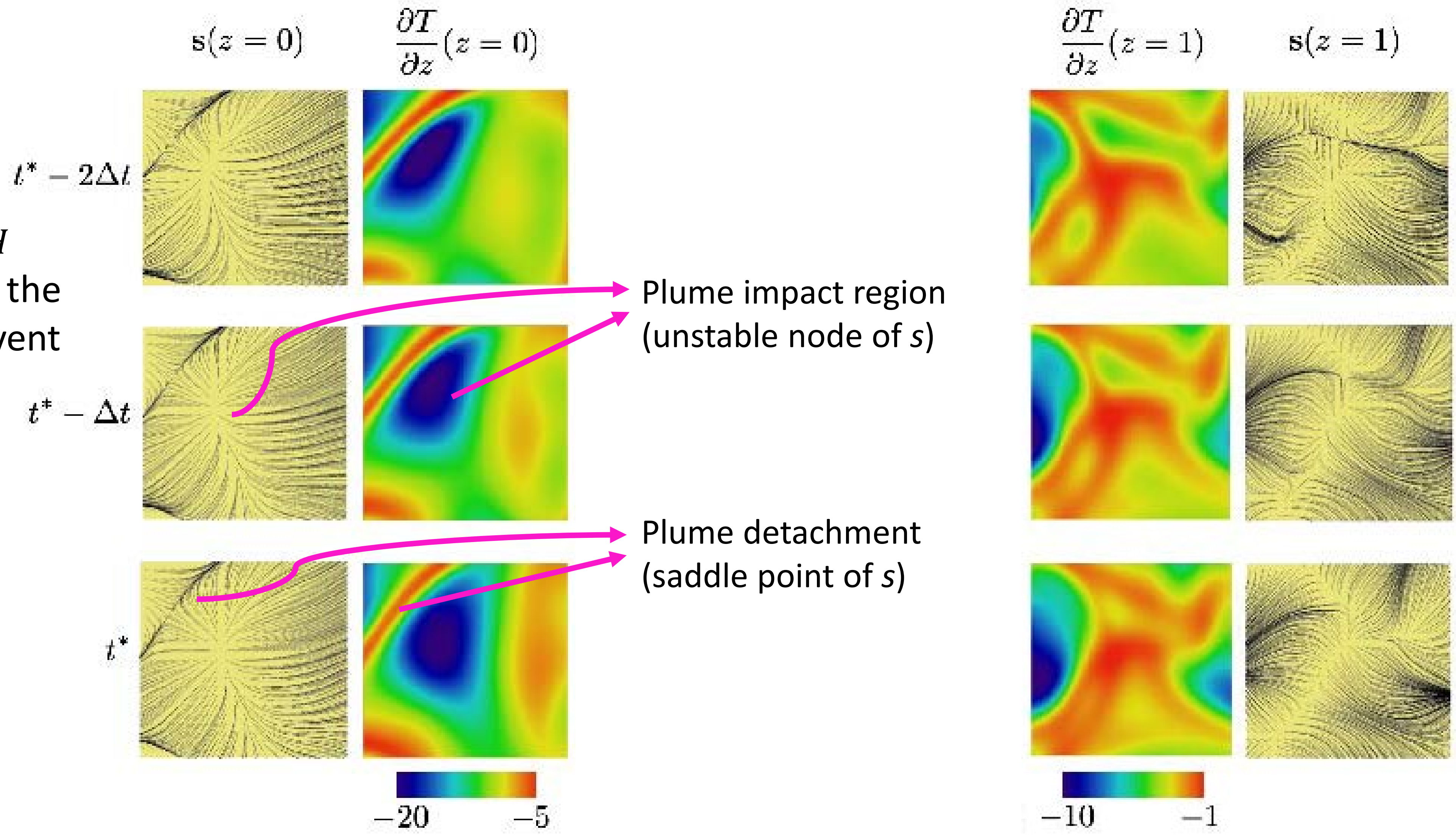
Formation of an event at $Ra = 5 \times 10^5$

Section $H \times H$ centered at the (*x*,*y*) of the event



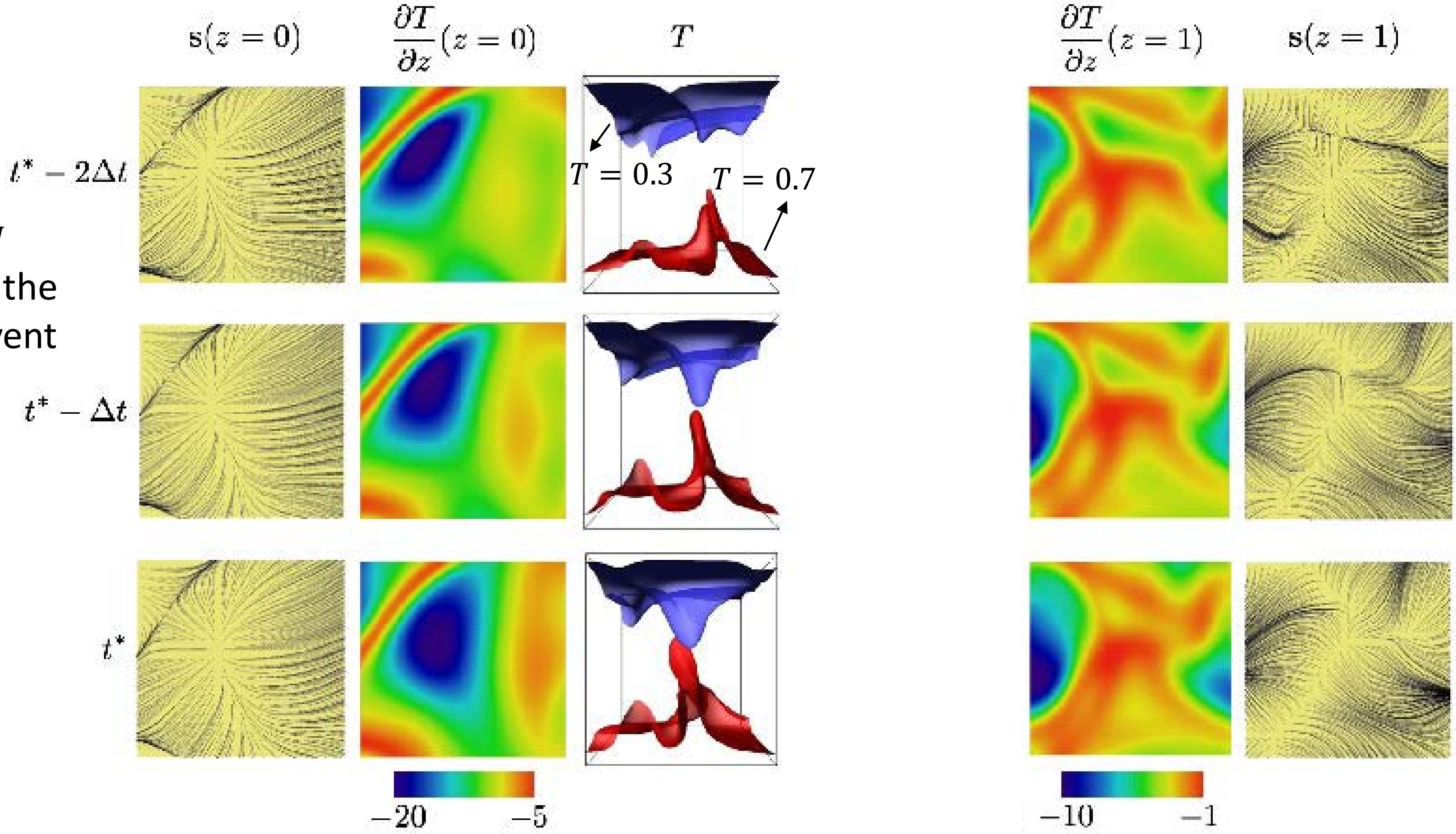
Formation of an event at $Ra = 5 \times 10^5$

Section $H \times H$ centered at the (x,y) of the event



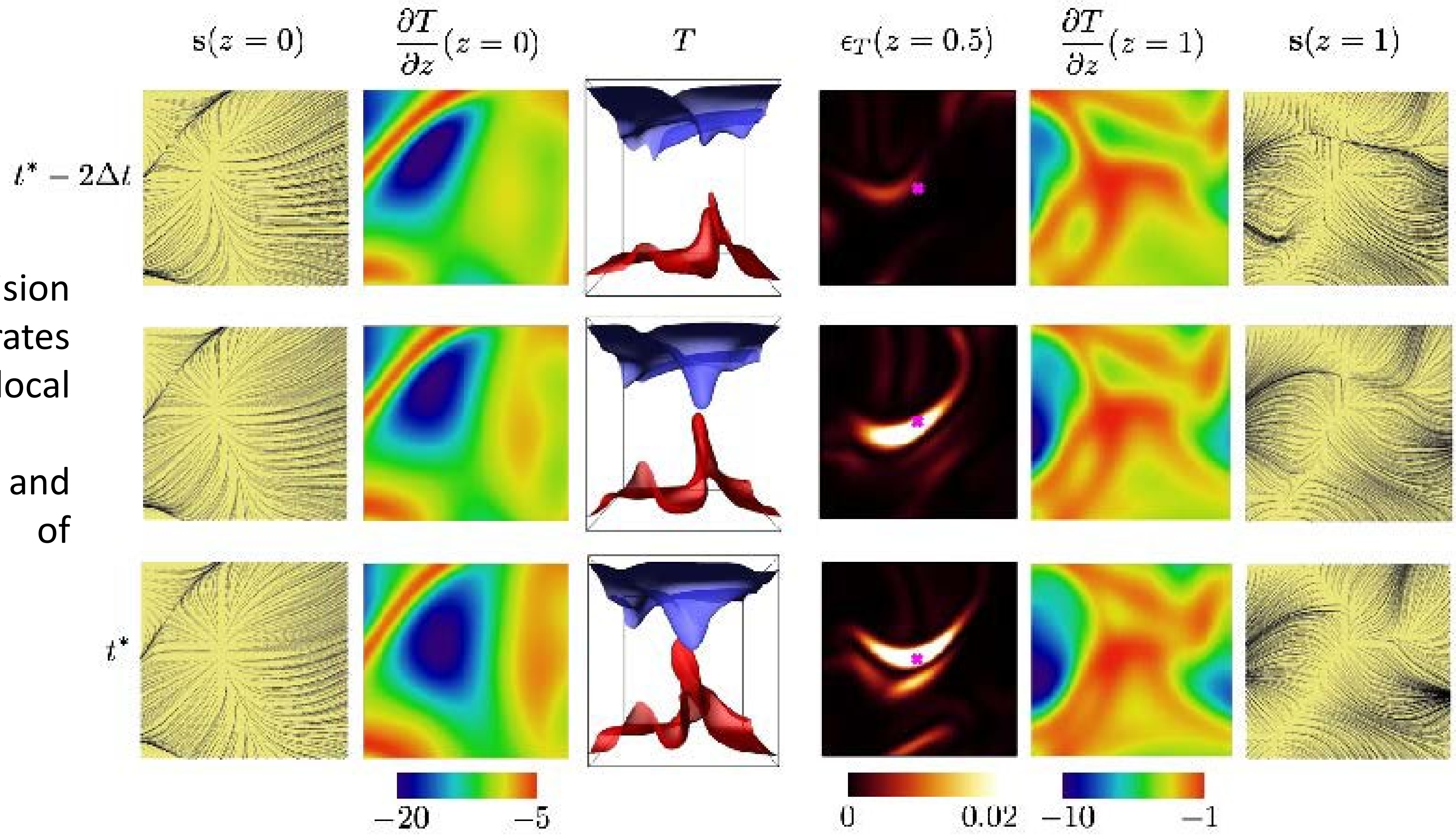
Formation of an event at $Ra = 5 \times 10^5$

Section $H \times H$ centered at the (x,y) of the event



Formation of an event at $Ra = 5 \times 10^5$

A frontal collision plumes generates strong local temperature gradients and large values of ϵ_T.



Boundary layer precursors

$|\partial T/\partial z| < c_{1,2}$ at the top and bottom BL simultaneously.
\+ (*x,y*) position of the extreme event.

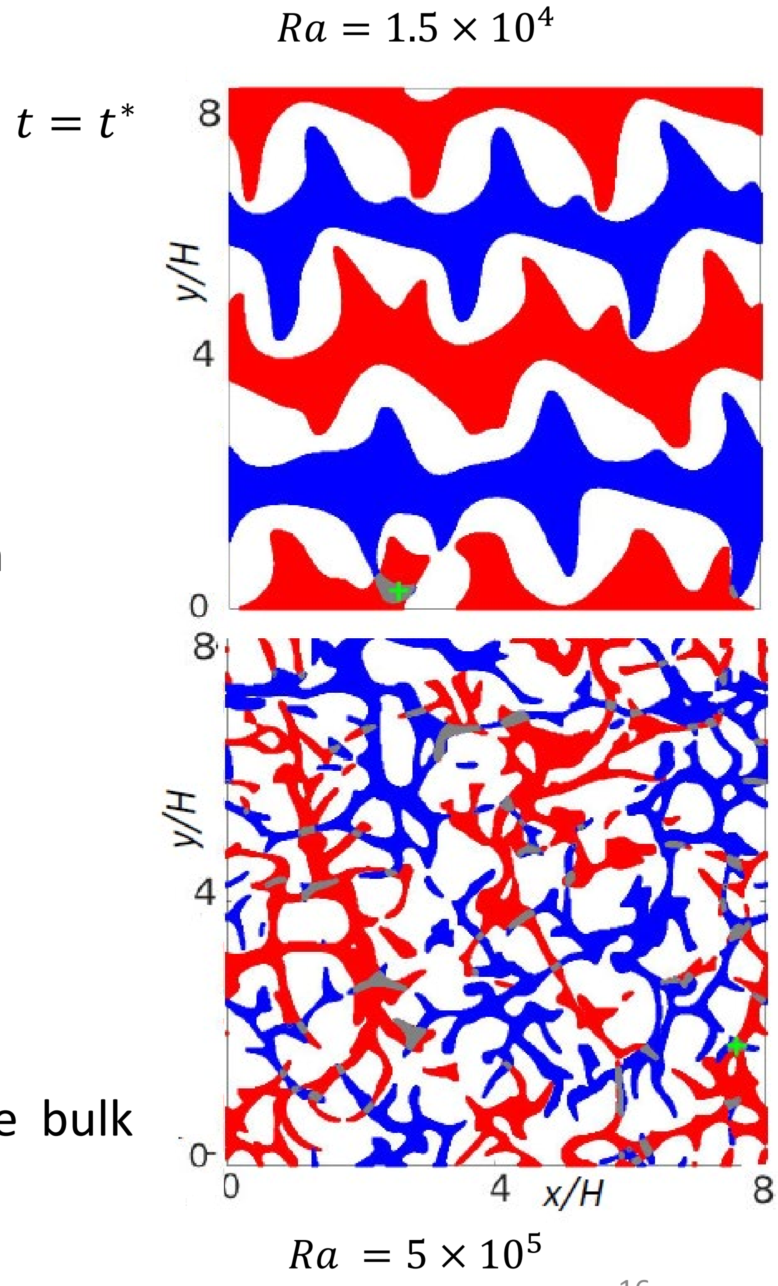
At the lower Ra:

- The plume detachment regions do not overlap, except at the location of the largest event, where the synchronicity is broken.

At the largest Ra:

- The synchronicity is not visible: we can detect several intersections in the horizontal position of simultaneous plume detachments from the BLs.

The number of **intersections** can be thought as **precursors** for extreme bulk dissipation events;

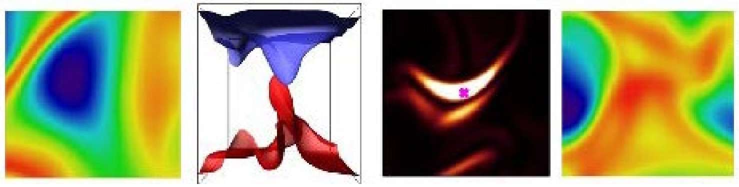


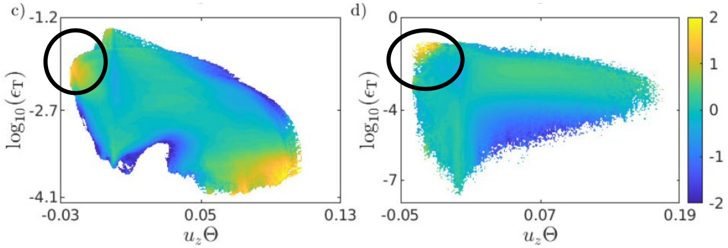
Summary

- We studied the **formation of extreme events** of the derivatives of velocity and temperature in the bulk of a **thermal convection layer**;

- based on high-resolution DNS data at Pr = 1 in a range of **moderate Rayleigh numbers**, for which the **derivative statistics proceeds a crossover from Gaussian to intermittent behaviour**.

- The **breaking of the synchronicity between the plume detachment dynamics at the top and bottom walls enhances the probability of** plume collisions in the center of the convection layer, and thus of **dissipation rate events in the far tails** of their distributions.



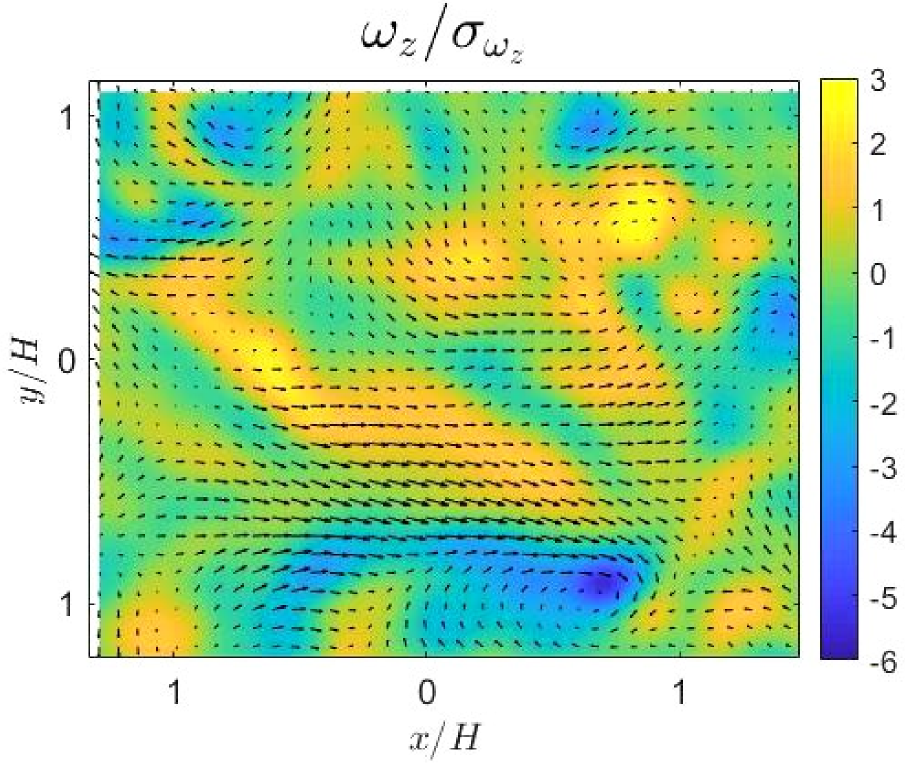


- These intermittency generation mechanisms might change as we increase the Rayleigh number further.

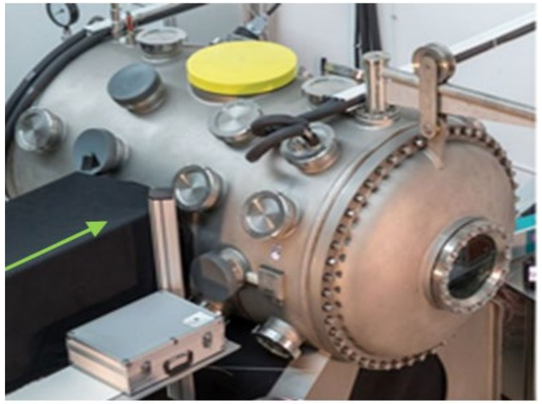
Future work

- **Experimental study** of thermal convection in gases, $Pr \sim 1$;
- available data: **stereo PIV velocity measurements** on a plane at half height of the cell;
- not all 9 components of the velocity gradient are measured;
- **Recurrent neural networks** can be used to design models for the detection of precursors to extreme bulk dissipation events, **which use the present DNS data base for training**.

Ra = 2.5 × 10^5



https://arxiv.org/pdf/2104.04222.pdf



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