The Abdus Salam
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Conference and Euromech Colloquium #480

on

High Rayleigh Number Convection

4 - 8 Sept., 2006, ICTP, Trieste, Italy

Rotational effects on turbulent convection

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Rotational Effects on Turbulent Convection

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Euromech Colloquium on
High Rayleigh Number Convection
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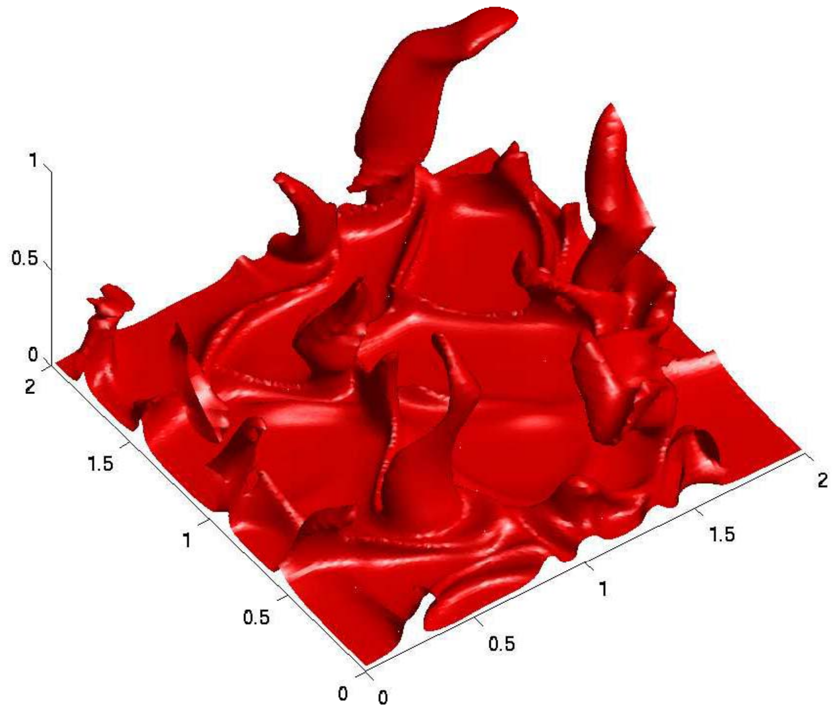
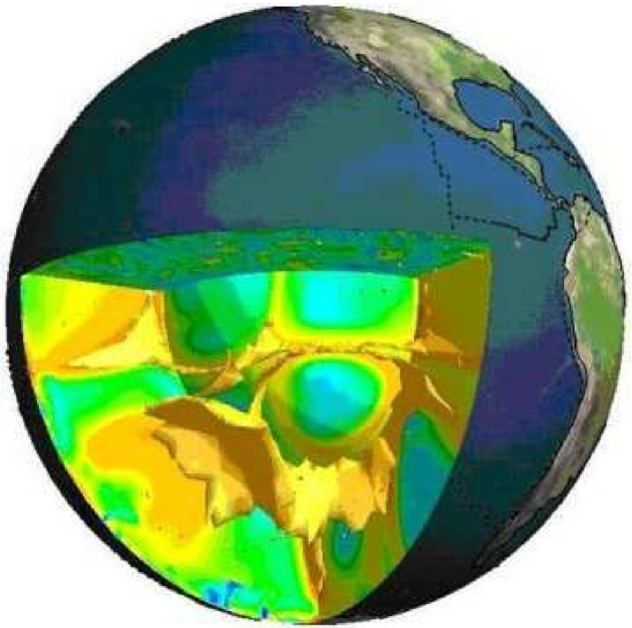
Convection influenced by rotation

in geophysical flow settings

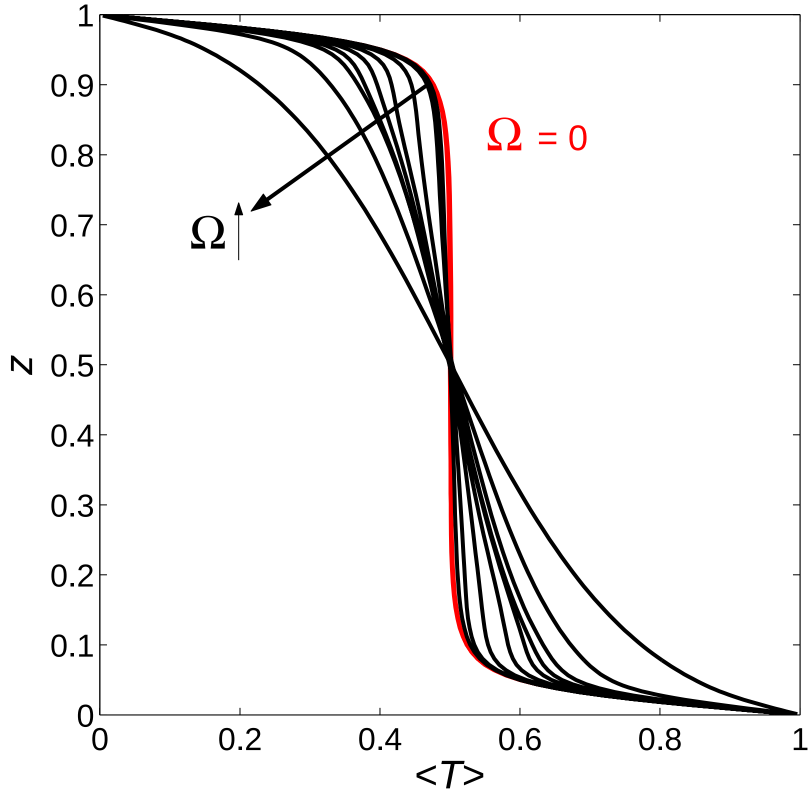




Rotational effects on convection

found in many statistical quantities using DNS:

- Temperature gradient over bulk
- Changes in heat transfer
- Skewness of vertical velocity (flow structuring)
- Boundary layers



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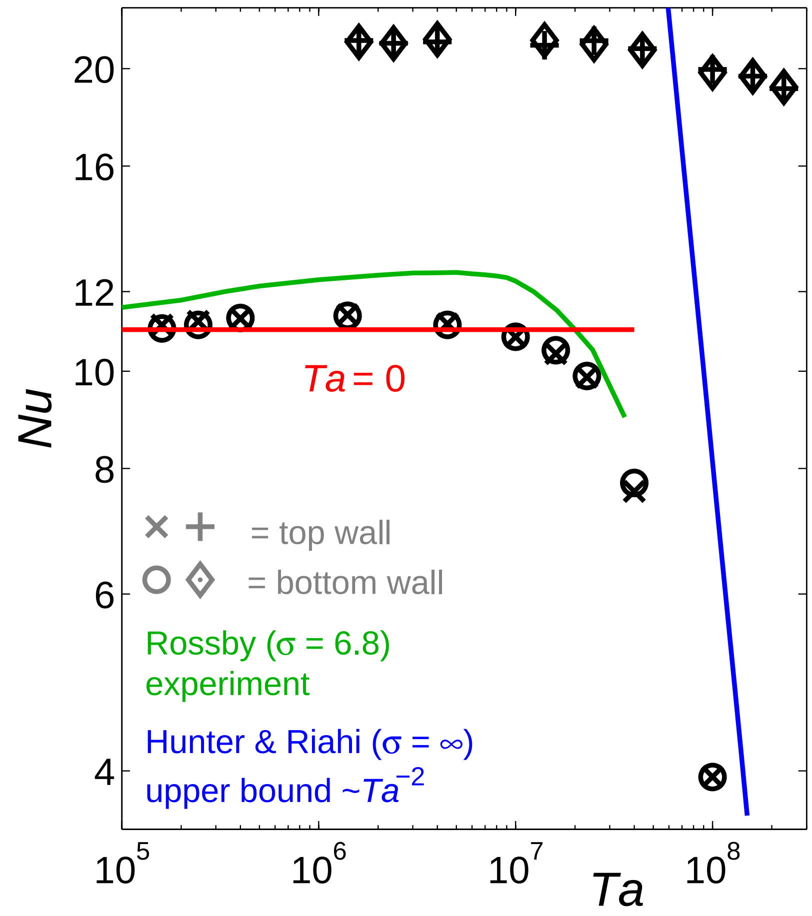

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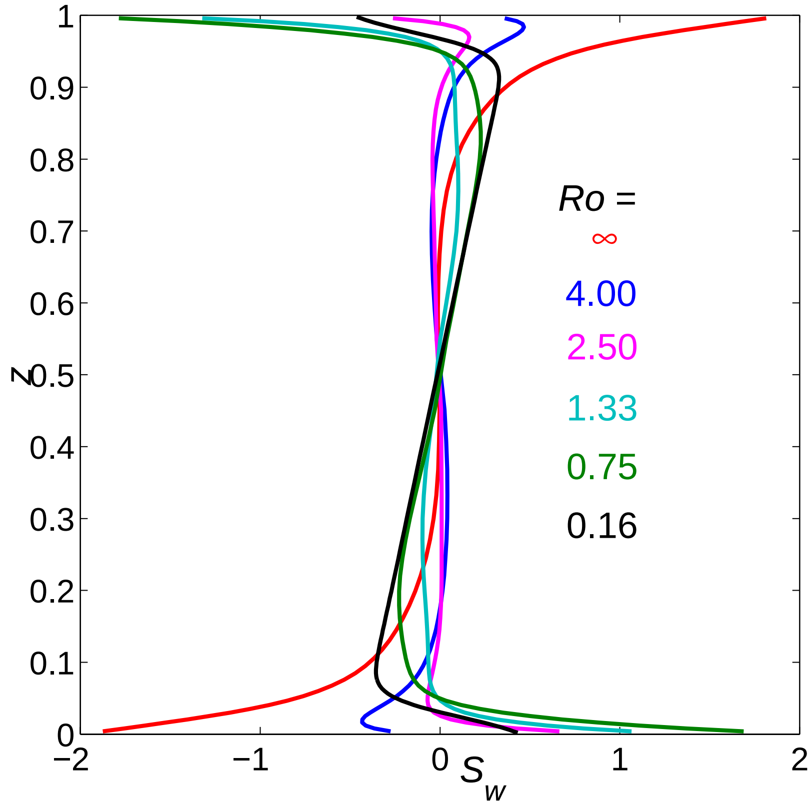

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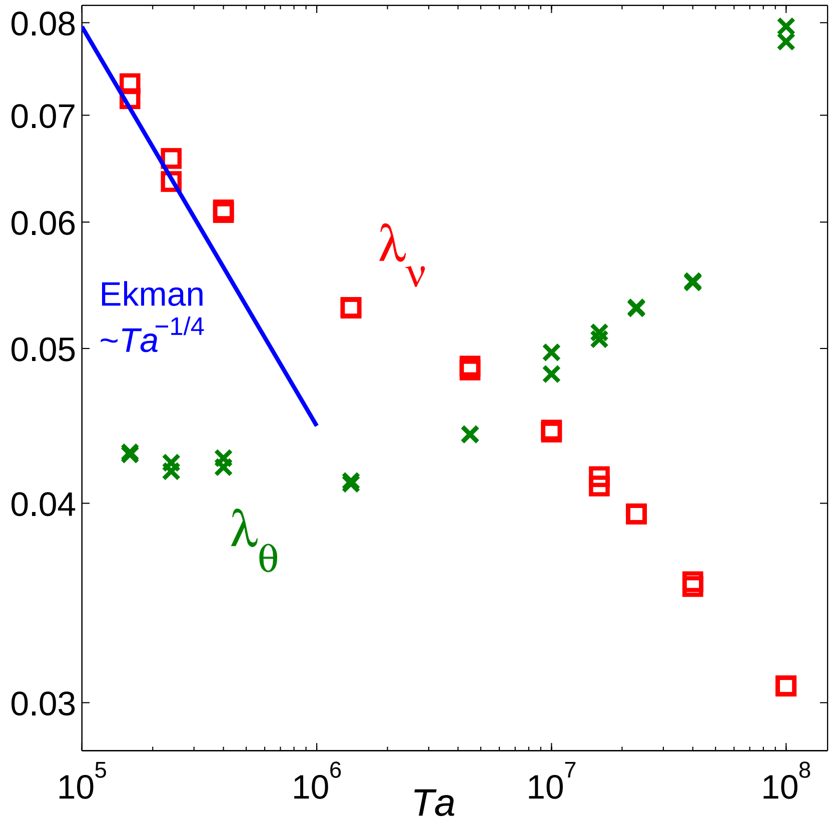


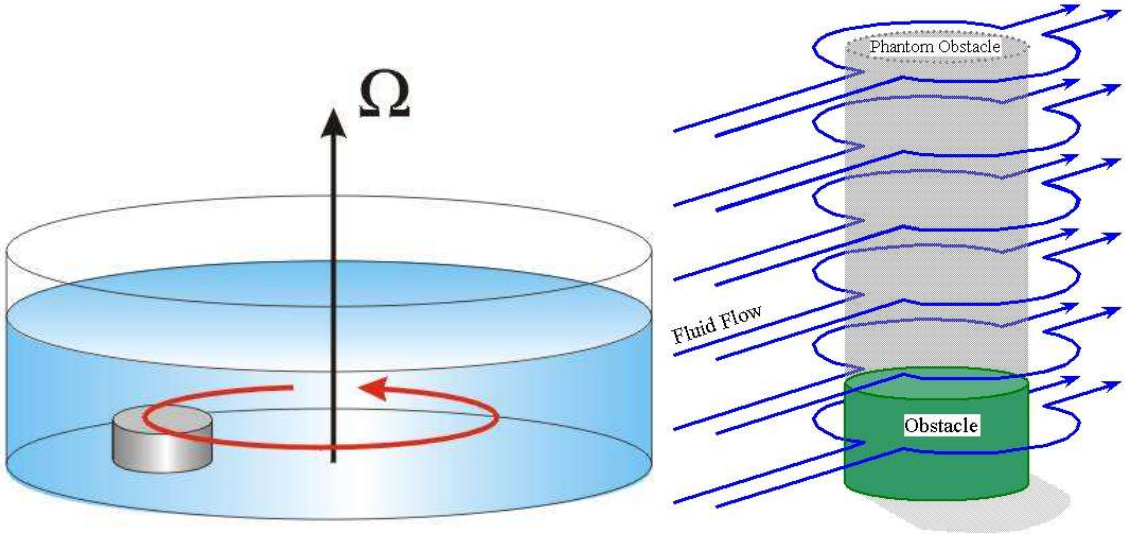
FOM TU/e

Influence of background rotation

Under geostrophic conditions no vertical variation of velocity

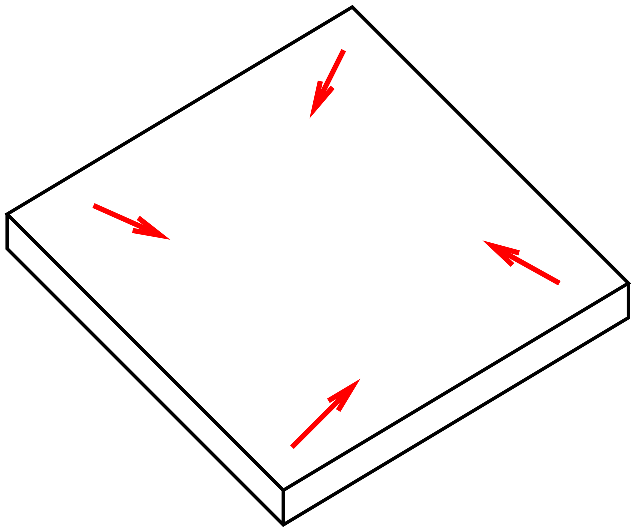
↕

Taylor–Proudman theorem



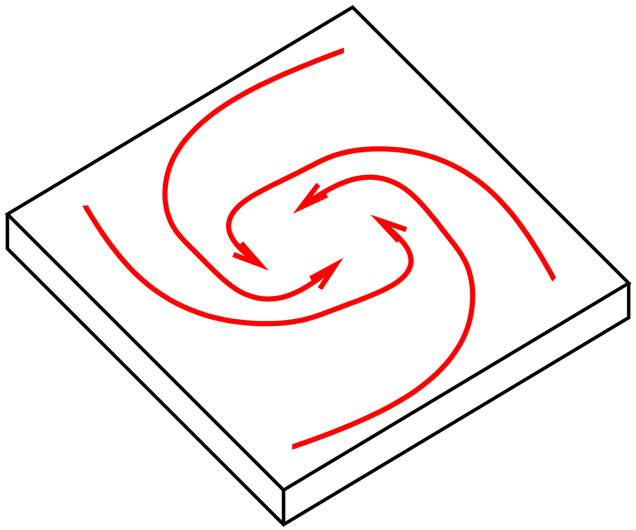
"Taylor column" above object dragged through rotating fluid

Thermal plumes under rotation



Thermal plumes spin up cyclonically → called thermal vortices

Thermal plumes under rotation



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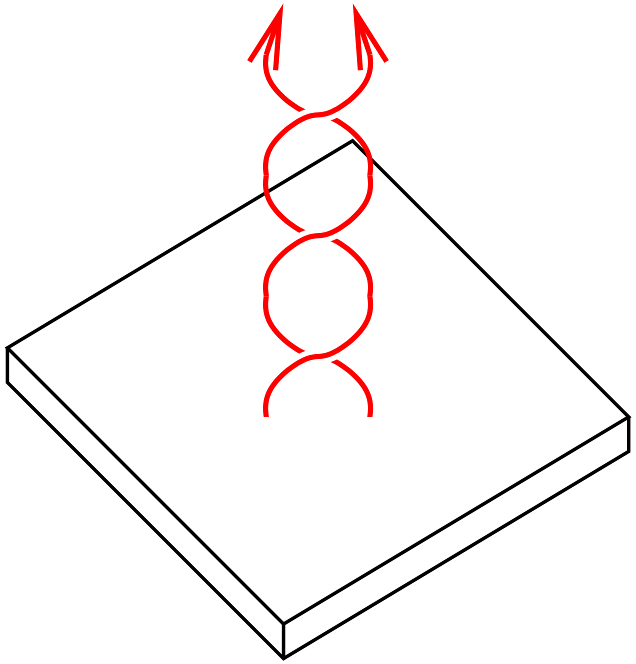
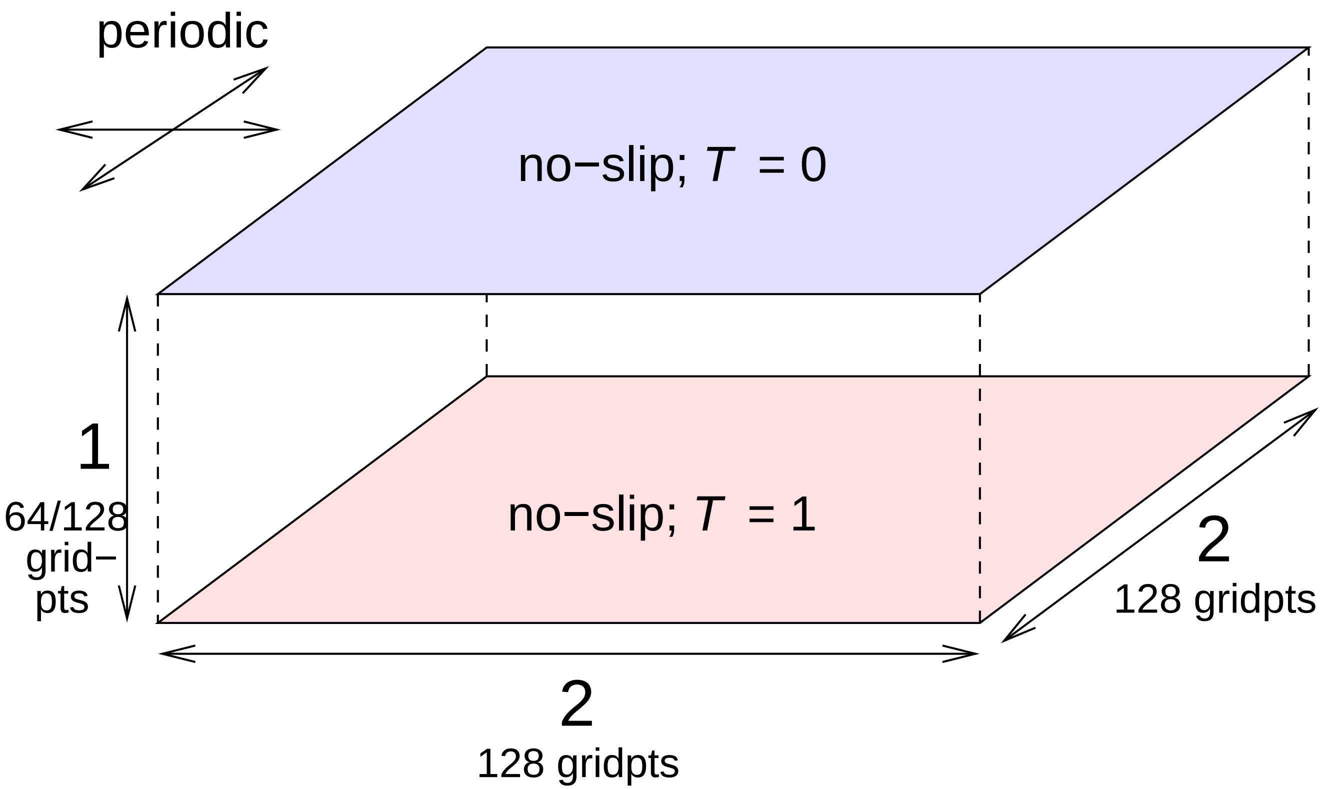


Thermal plumes spin up cyclonically → called thermal vortices

DNS: Domain and boundary conditions



- Symmetry-preserving fourth-order finite-volume discretisation
- Details: Verstappen & Veldman *J. Comput. Phys.* **187** (2003) 343–368

DNS: equations

Navier–Stokes and heat equations in Boussinesq approximation with incompressibility:

$$
\begin{aligned}
\frac{D\mathbf{u}}{Dt} + \sqrt{\frac{\sigma Ta}{Ra}}\ \hat{\mathbf{z}} \times \mathbf{u} &= -\nabla p + T\,\hat{\mathbf{z}} + \sqrt{\frac{\sigma}{Ra}}\ \nabla^2 \mathbf{u} \\
\frac{DT}{Dt} &= \frac{1}{\sqrt{\sigma Ra}}\ \nabla^2 T \\
\nabla \cdot \mathbf{u} &= 0
\end{aligned}
$$

Extra control parameter: Taylor number $Ta = \left(\frac{2\Omega H^2}{\nu}\right)^2$

Buoyancy/Coriolis ratio: Rossby number $Ro = \sqrt{\frac{Ra}{\sigma Ta}}$

Simulation values

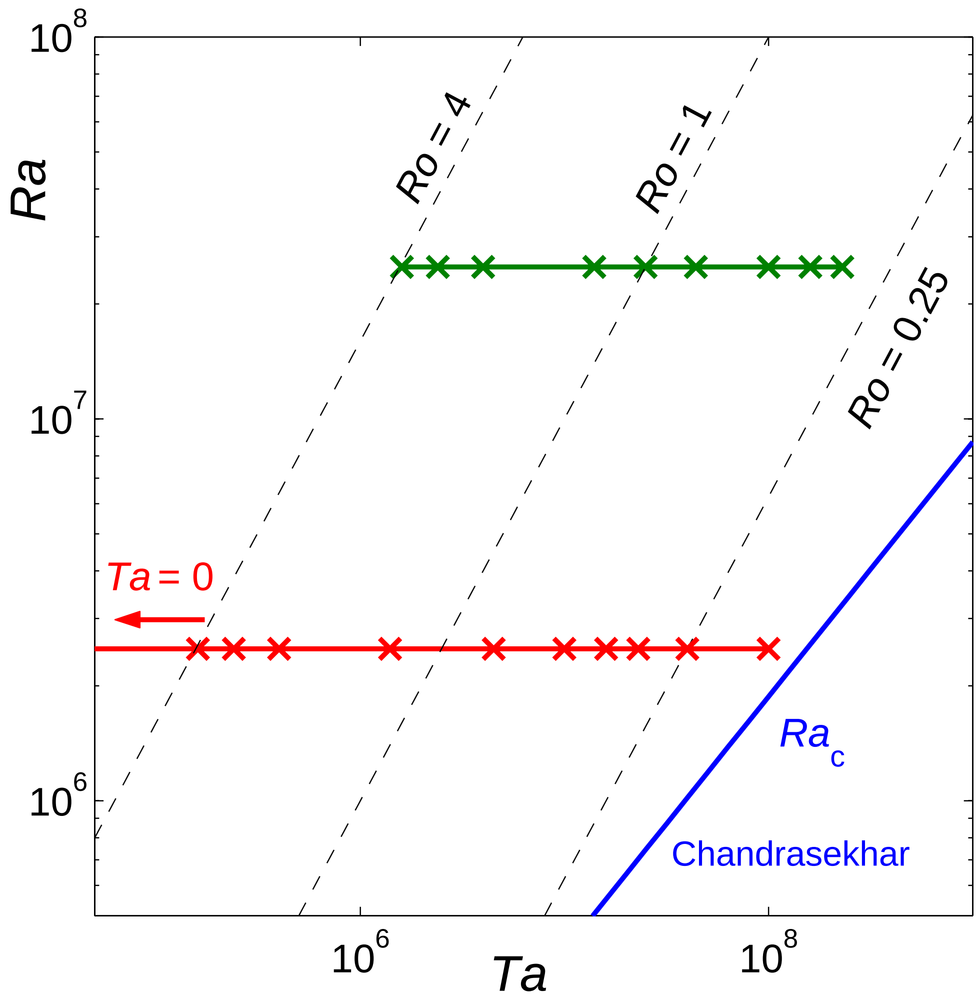
Two series: (both at $\sigma = 1$)

Red:

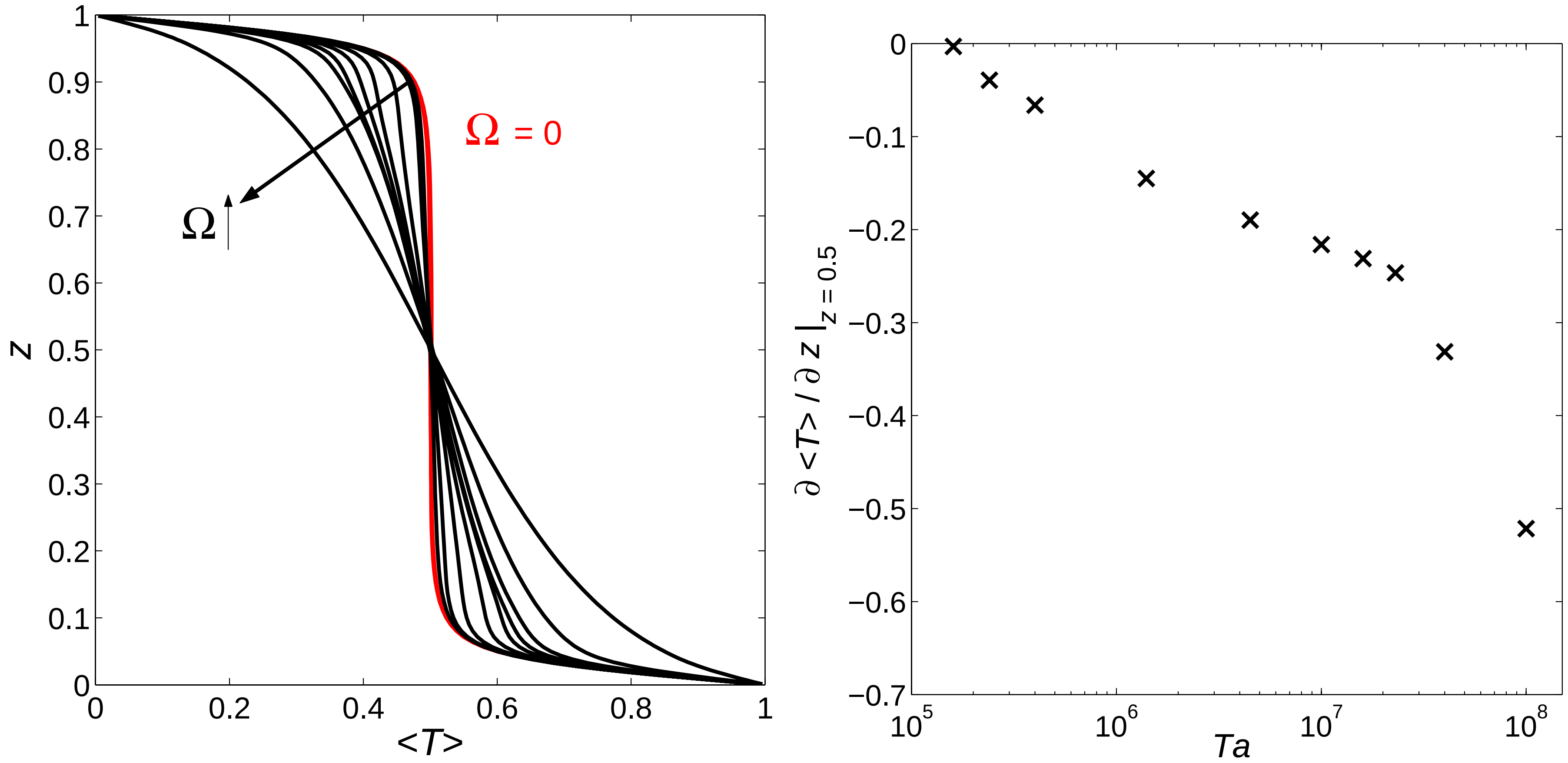
- $Ra = 2.5 \times 10^6$
- $Ta = 0 \ldots 10^8$
- $Ro = \infty \ldots 0.16$

Green:

- $Ra = 2.5 \times 10^7$
- $Ta = 1.6 \times 10^6 \ldots 2.3 \times 10^8$
- $Ro = 4.00 \ldots 0.33$



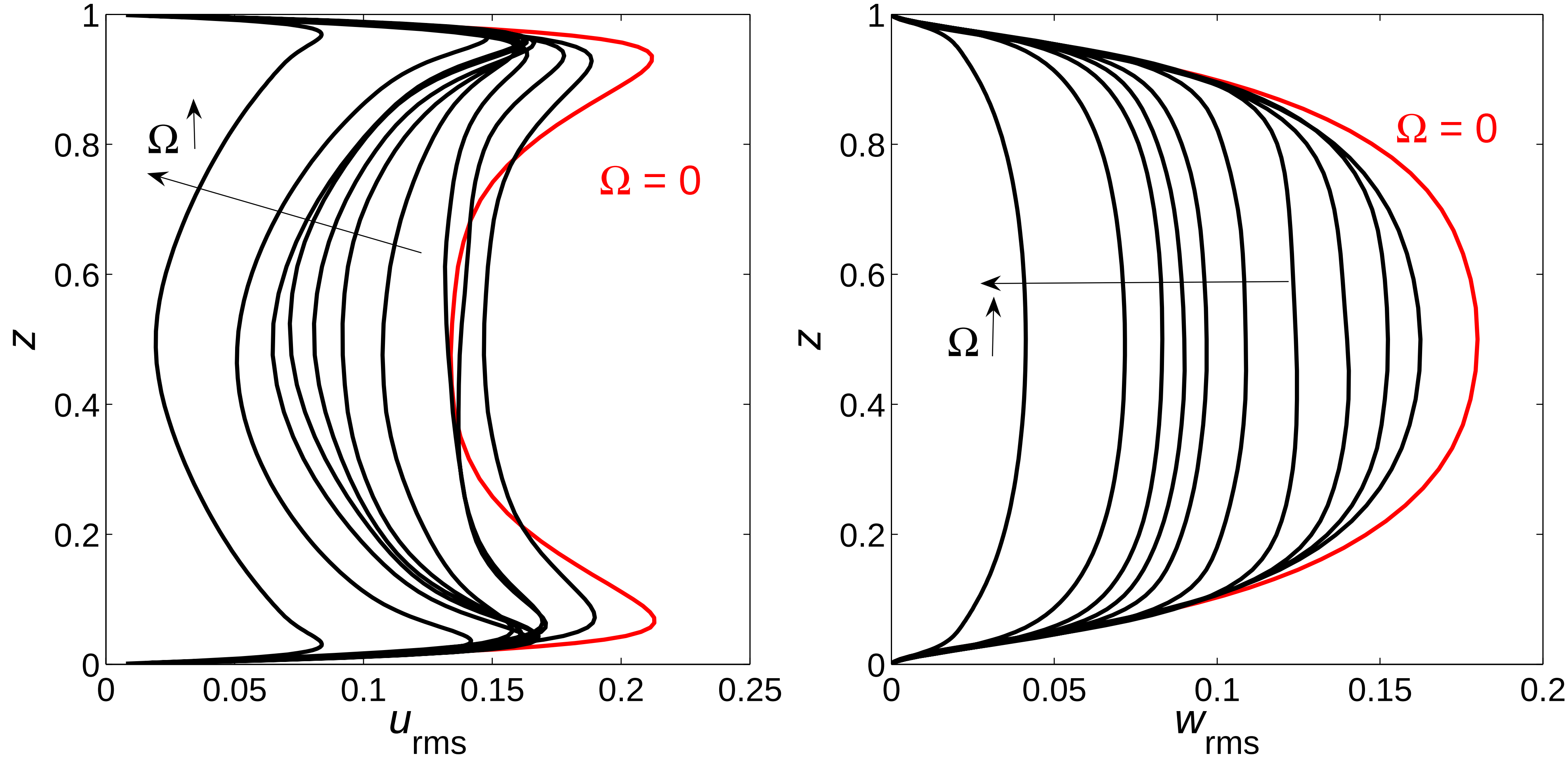
Average temperature and midplane gradient



$Ra = 2.5 \times 10^6$

Temperature gradient develops over bulk;
goes towards stable conductive state at high *Ta*

Horizontal and vertical rms velocities



Rotation lowers both horizontal
and vertical rms velocities

Heat transport — Nusselt number

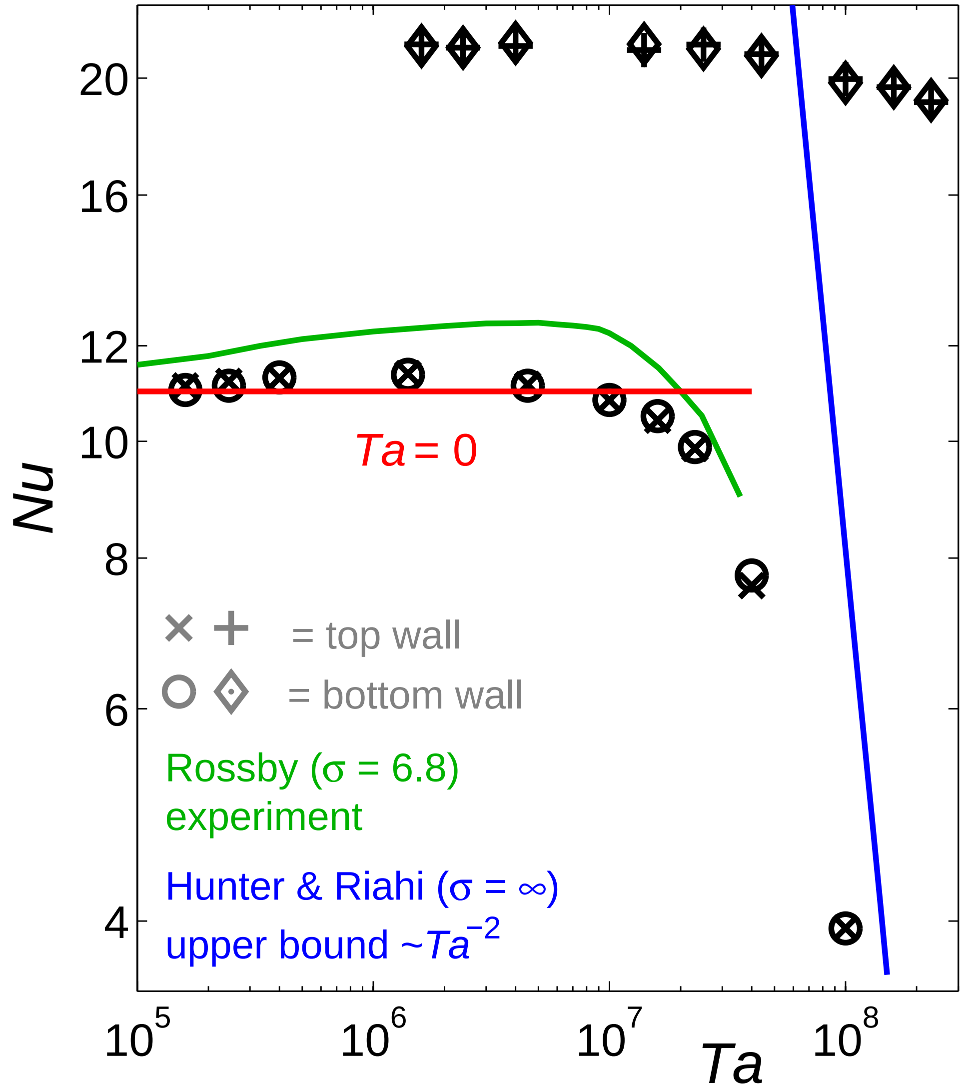
$$Nu = \left.\frac{\partial \langle T \rangle}{\partial z}\right|_{\text{wall}}$$

○, × $Ra = 2.5 \times 10^6$

◇, + $Ra = 2.5 \times 10^7$

Rossby *J. Fluid Mech.* **36** (1969)

Hunter & Riahi *J. Fluid Mech.* **72** (1975)



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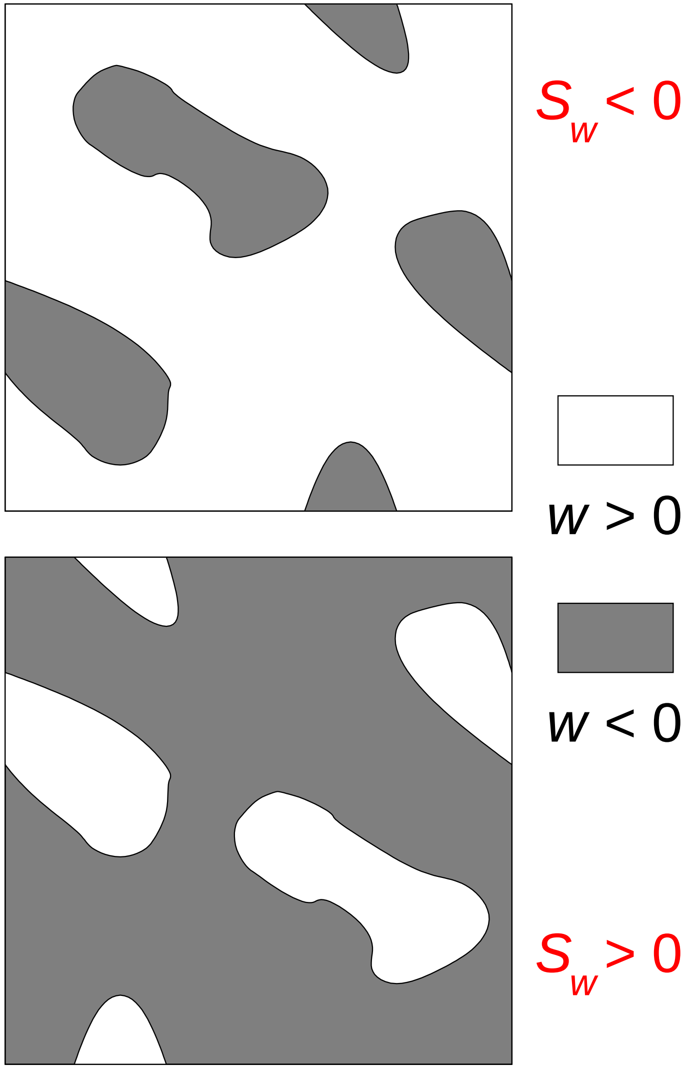
Vertical-velocity skewness

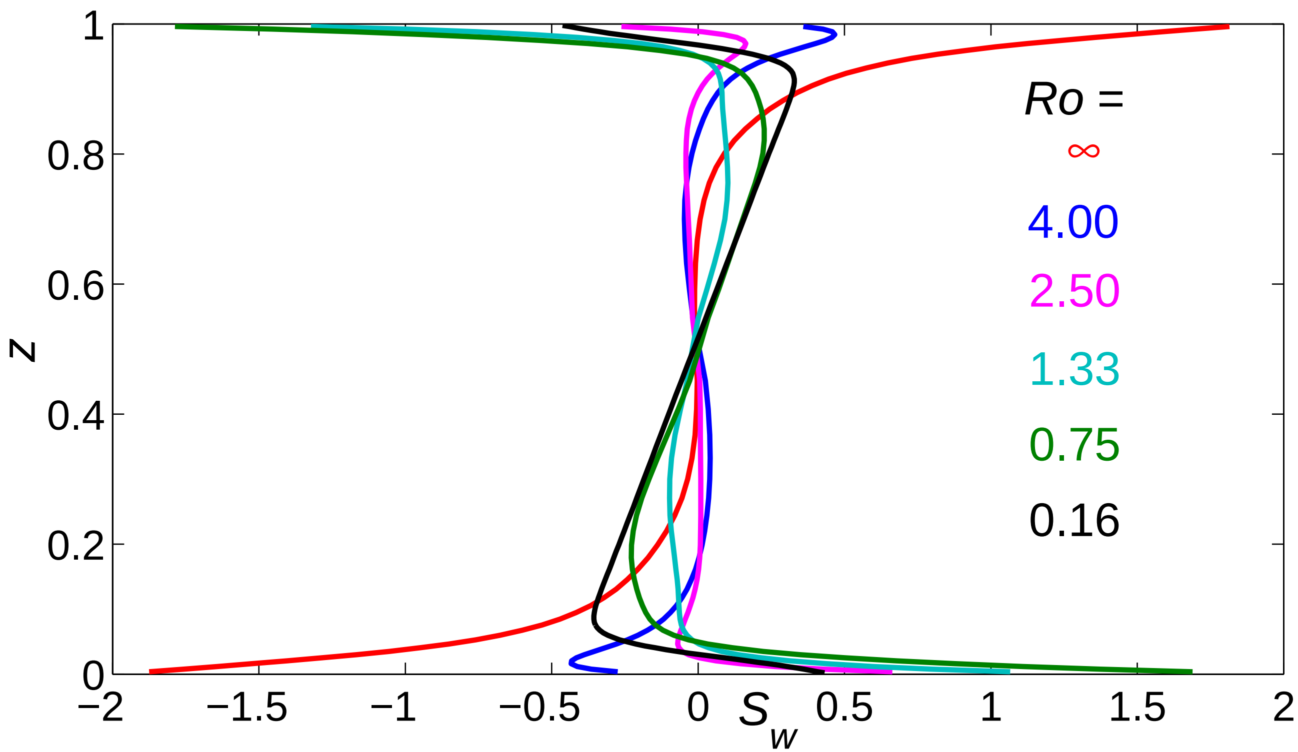
$$S_w = \frac{\left\langle (w - \langle w \rangle)^3 \right\rangle}{\left\langle (w - \langle w \rangle)^2 \right\rangle^{3/2}}$$

Indicates area fraction of horizontal cross-sections containing upward/downward motion.

$S_w > 0$: Fraction of cross-section containing upward motion smaller than fraction containing downward motion.



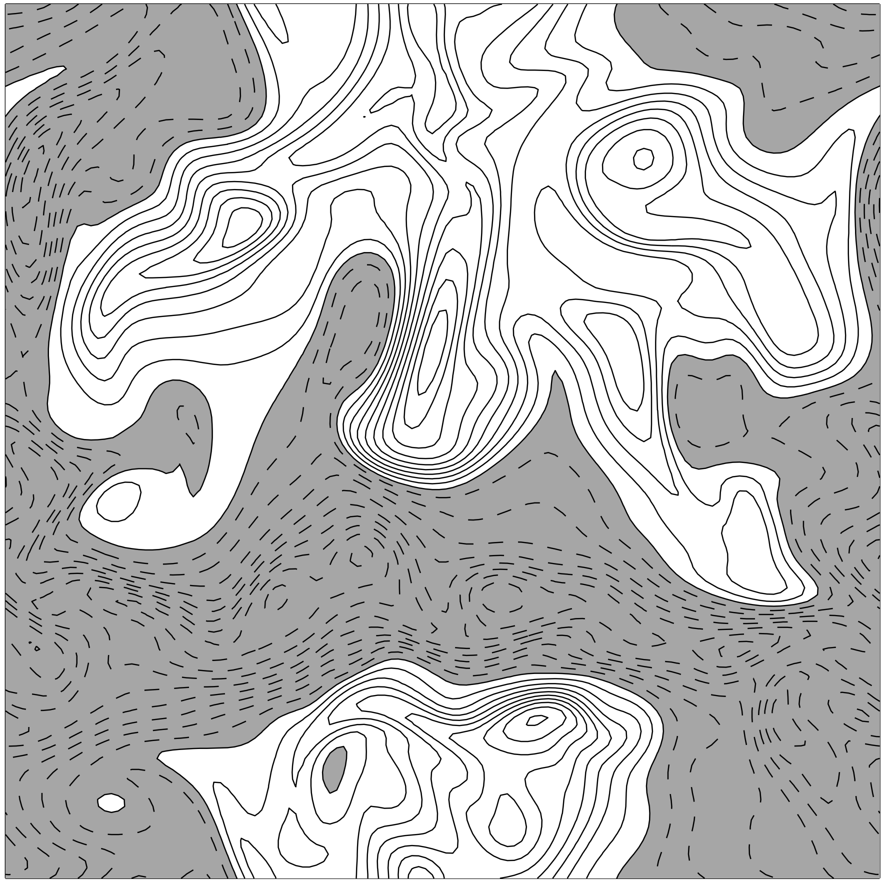
Vertical-velocity skewness for $Ra = 2.5 \times 10^6$

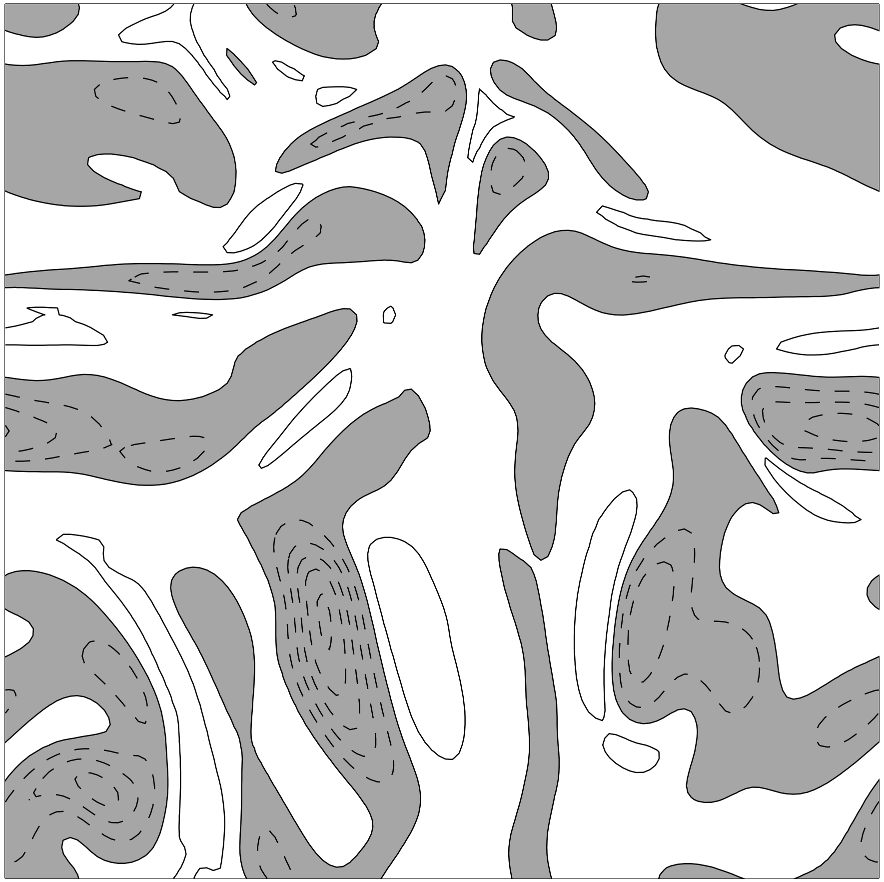


‘Switch’ of S_w near the walls points to different near-wall flow structure under rotation

No rotation ($Ro = \infty$)

Horizontal cross-sections, vertical-velocity contour plot

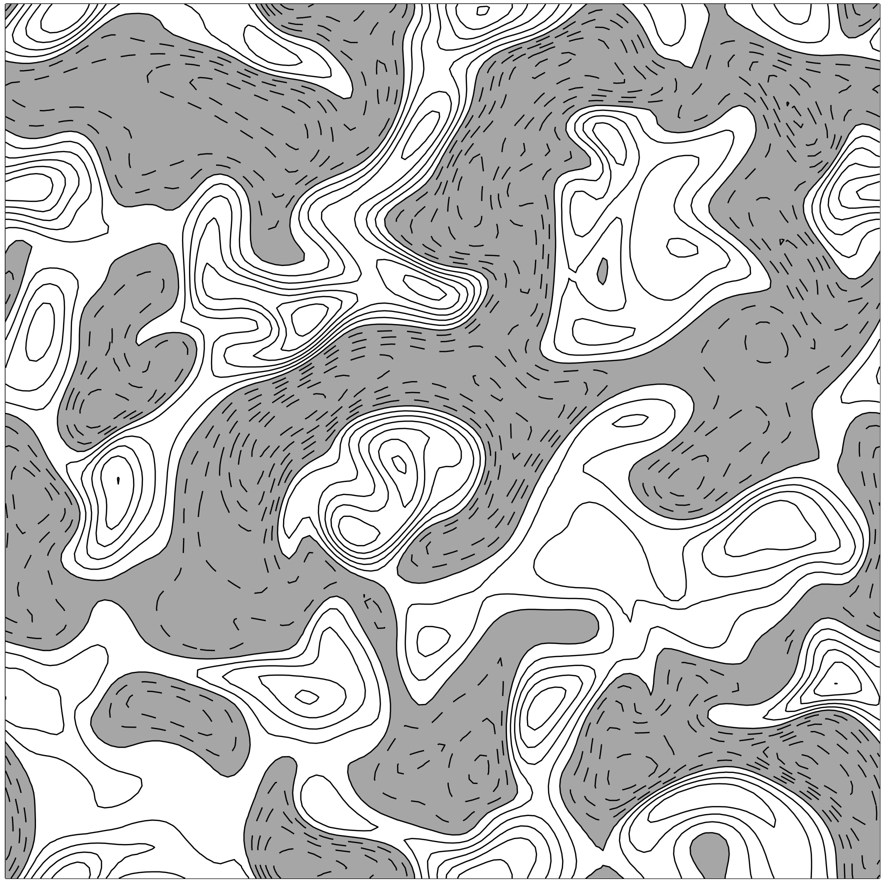




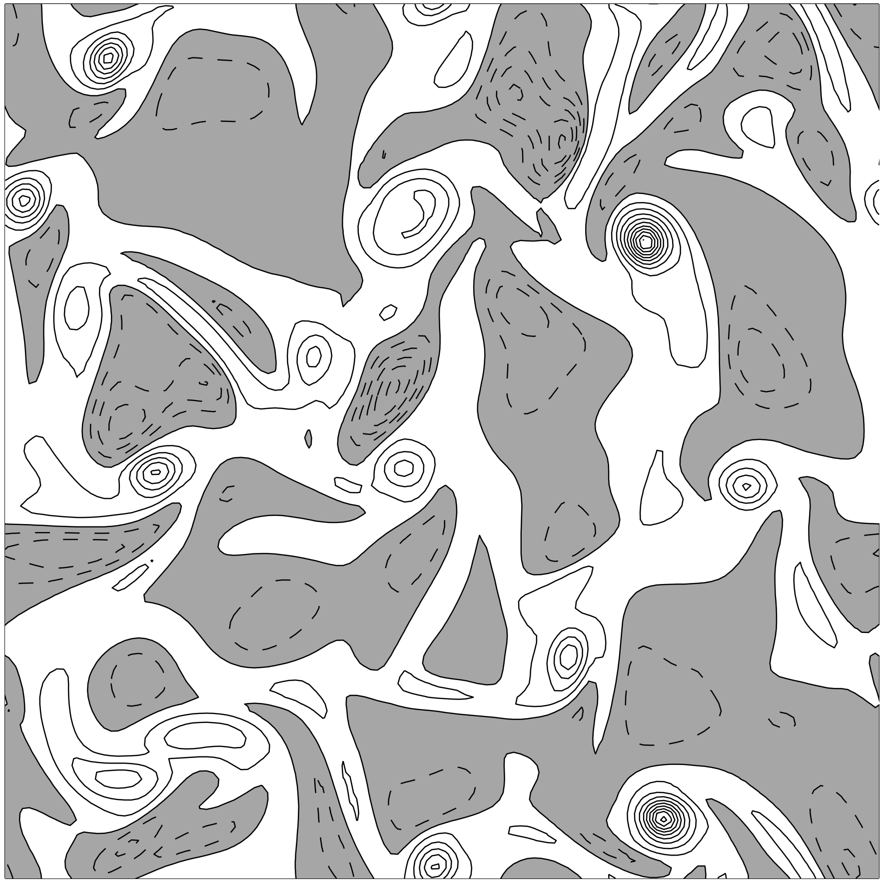
centre: $S_w = 0$ near-wall: $S_w = -1.5$

With rotation ($Ro = 0.75$)

Horizontal cross-sections, vertical-velocity contour plot



centre: $S_w = 0$

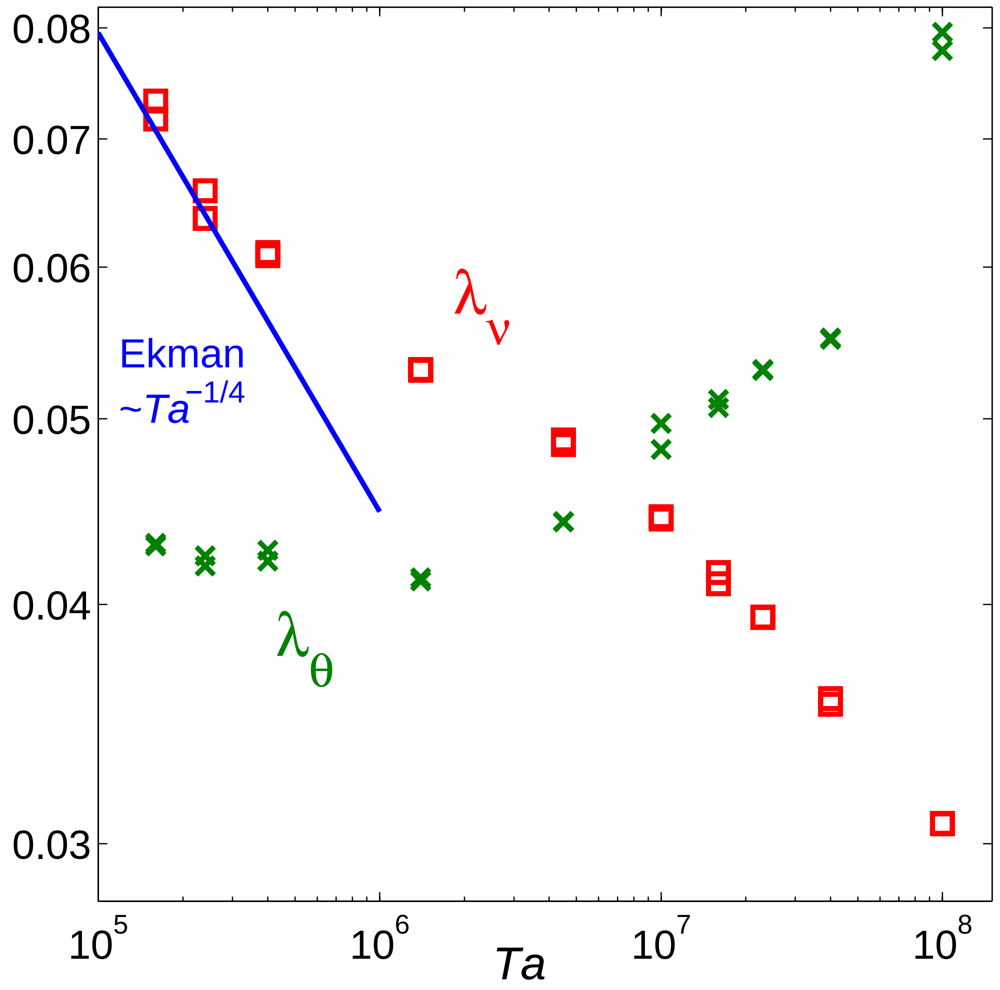


near-wall: $S_w = +0.5$

Boundary layer thicknesses ($Ra = 2.5 \times 10^6$)

λ_ν = viscous BL
λ_θ = thermal BL

BL thickness defined as height at which RMS value is largest



Conclusions

- Rotation alters flow structuring considerably $\longrightarrow$ vortical plumes
- At moderate rotation rates heat flux is increased by Ekman pumping
- At high rotation rates heat flux decreases rapidly due to geostrophic damping
- Rotation stabilises flow $\longrightarrow$ temperature gradient over bulk

Outlook

- Investigation of vortex structures and relation with heat transfer
- DNS on a cylindrical domain $\longrightarrow$ effect of sidewall; comparison with experiments
- Local velocity measurements in a cylindrical rotating-convection cell