Ruminations on a convective theme

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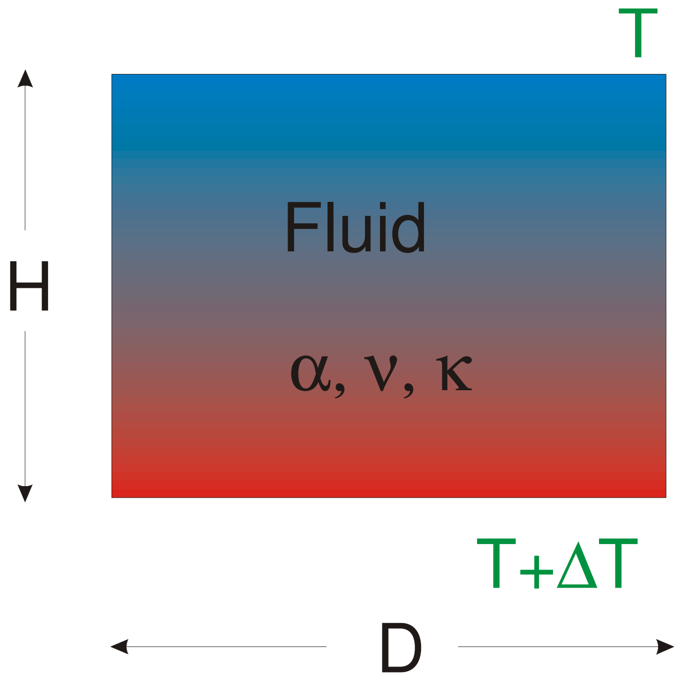
Sreeni helping celebrate Russ Donnelly's 65th birthday in 1995 in Boulder CO. Carl Weiman was also there to talk about his BEC observations a few weeks earlier

Rayleigh-Benard Convection

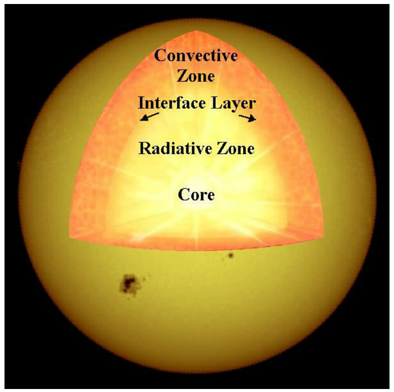


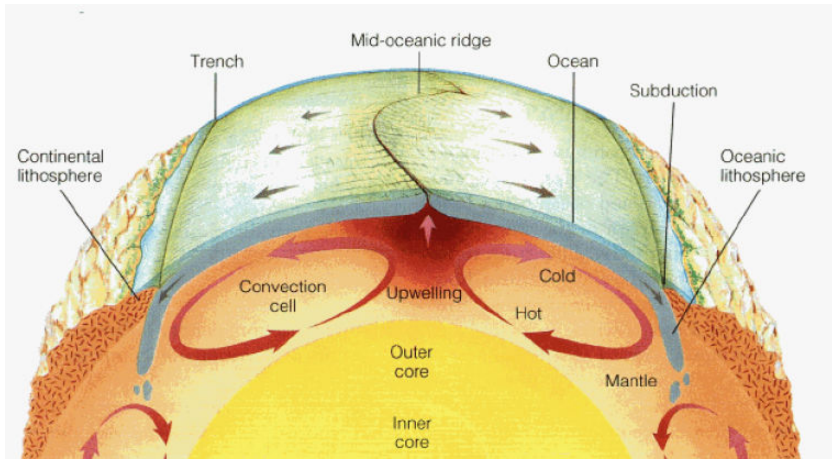
Notation used in this talk

$$\mathrm{Ra} = \frac{g\alpha\Delta T H^3}{\nu\kappa}$$ Rayleigh number

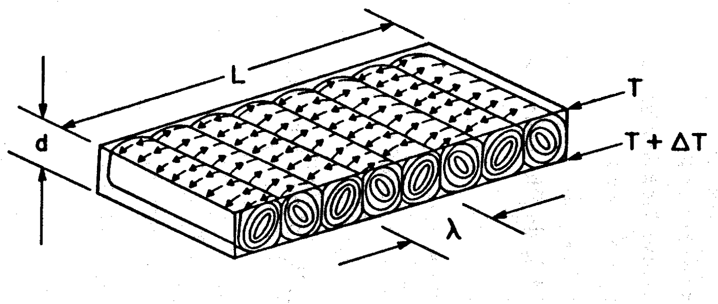
$$\mathbf{Pr} = \frac{\nu}{\kappa}$$ Prandtl number

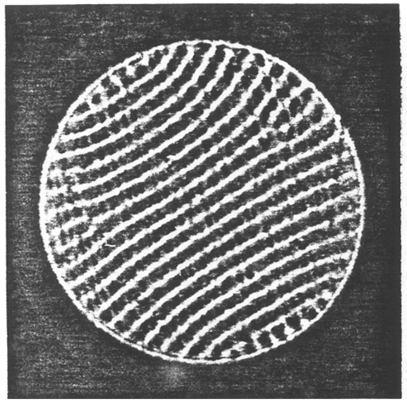
$$\Gamma = \frac{D}{H}$$ Aspect ratio

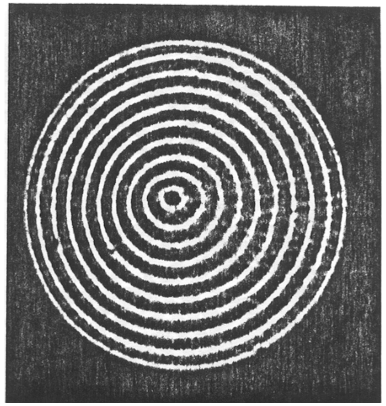




Rayleigh Benard convection (RBC)*near onset*: For the most part, a completely understood problem







Boundary conditions make a difference

RBC at very high Ra: Plumes figure prominently

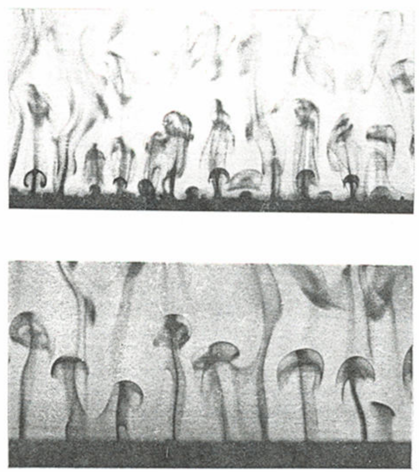
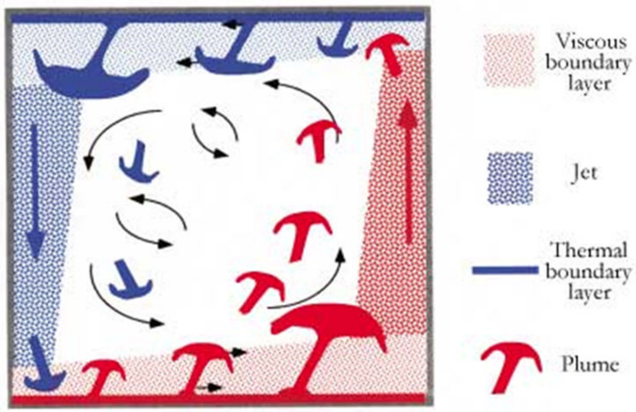
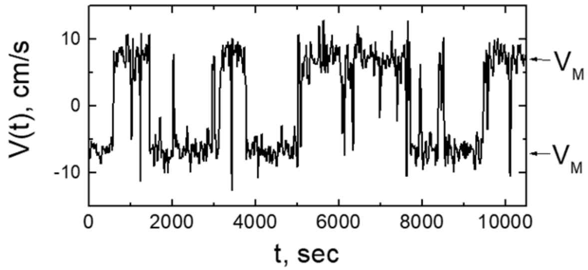


FIGURE 1. Photographs of thermals rising from a heated horizontal surface.

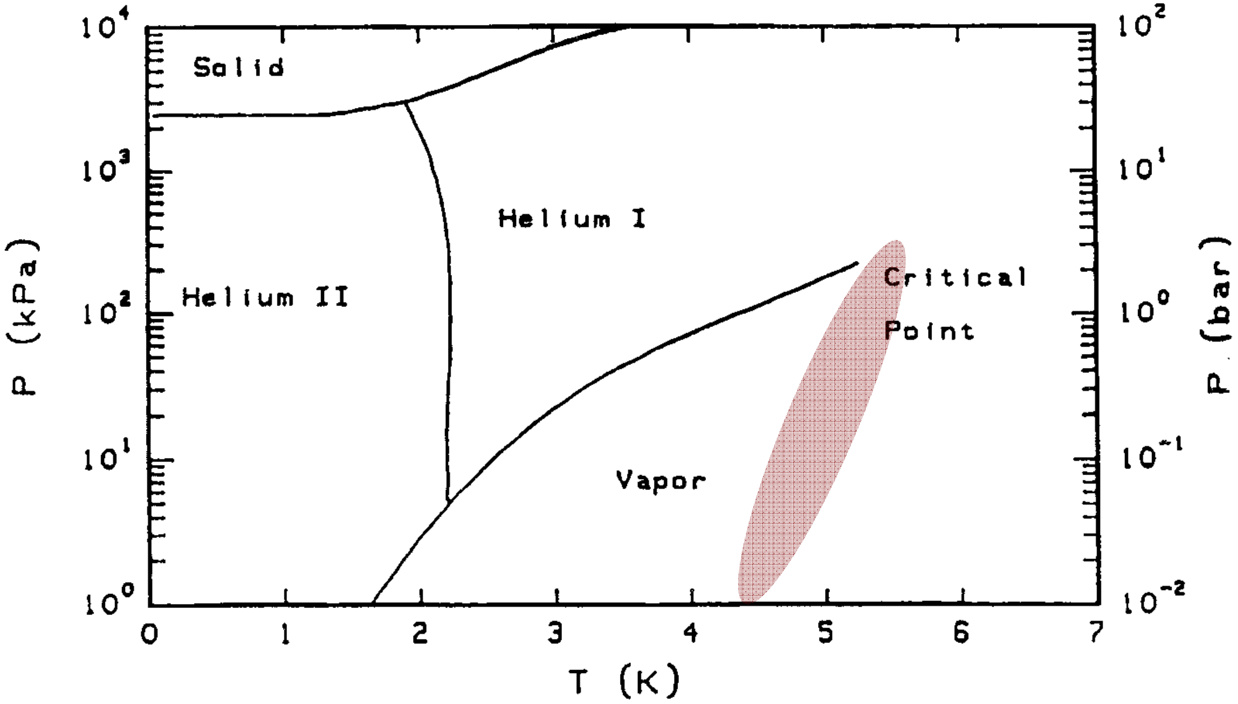


(from L. Kadanoff, Physics Today, August 2001)

Mean wind "reversals"



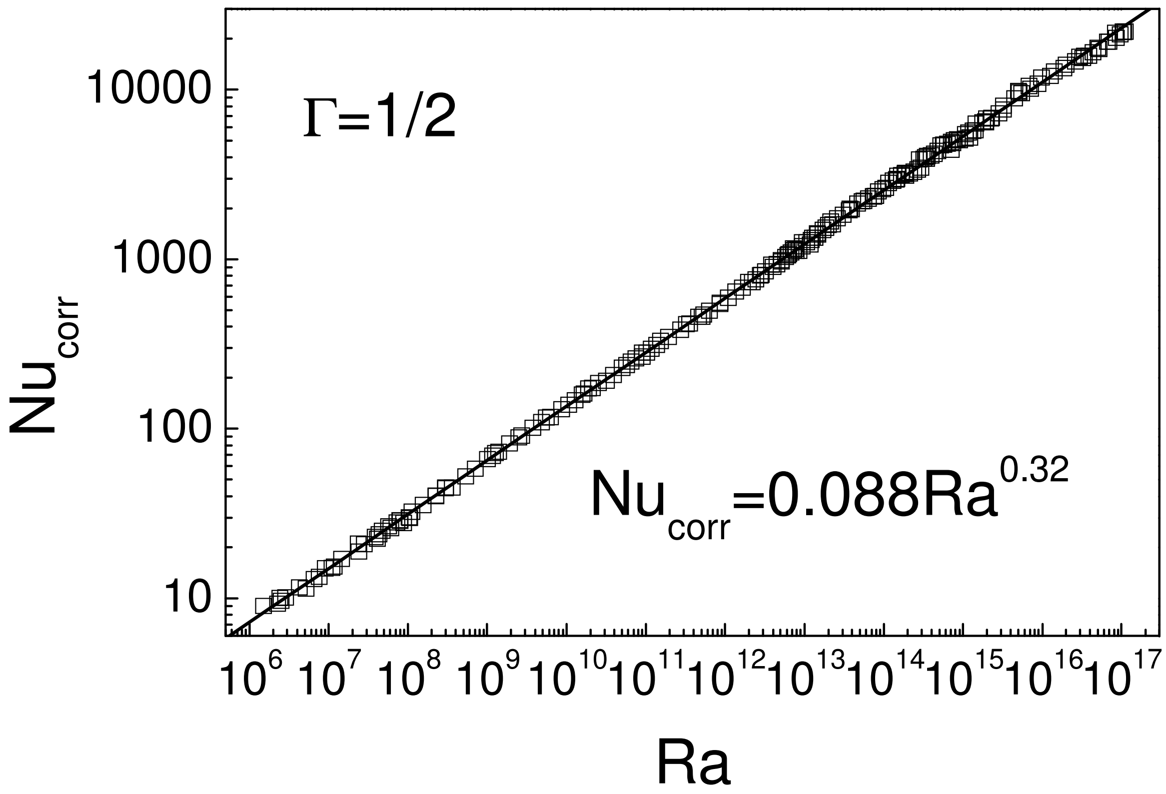
Using helium to obtain high Ra



12 orders of magnitude variation in Ra in shaded region. Desire all *12 in the turbulent regime (scaling and high Ra)*

Turbulent Heat Transfer I

Conductivity enhancement by a factor of 20,000



"From a distance all *cows* look black"

(1) JJN, L. Skrbek, K.R. Sreenivasan & R.J. Donnelly, *Nature,* **404**, 837 (2000)

(2) JJN & K.R. Sreenivasan*, J. Fluid Mech.,* **557** 411-422 (2006).

Turbulent heat transfer II (with slight hand motions)

advection-diffusion equation

$$\frac{\partial T}{\partial t} + U_j \frac{\partial T}{\partial x_j} = \kappa \frac{\partial^2 T}{\partial x_j \partial x_j}$$

Decomposition and averaging over fluctuations yields for the vertical heat flux

$$q_3 = \rho c_P \left(\overline{\theta u_3} - \kappa \frac{\partial \overline{T}}{\partial x_3} \right)$$

$$\overline{\theta u_3} \equiv -\kappa_T \frac{\partial \overline{T}}{\partial x_3}$$

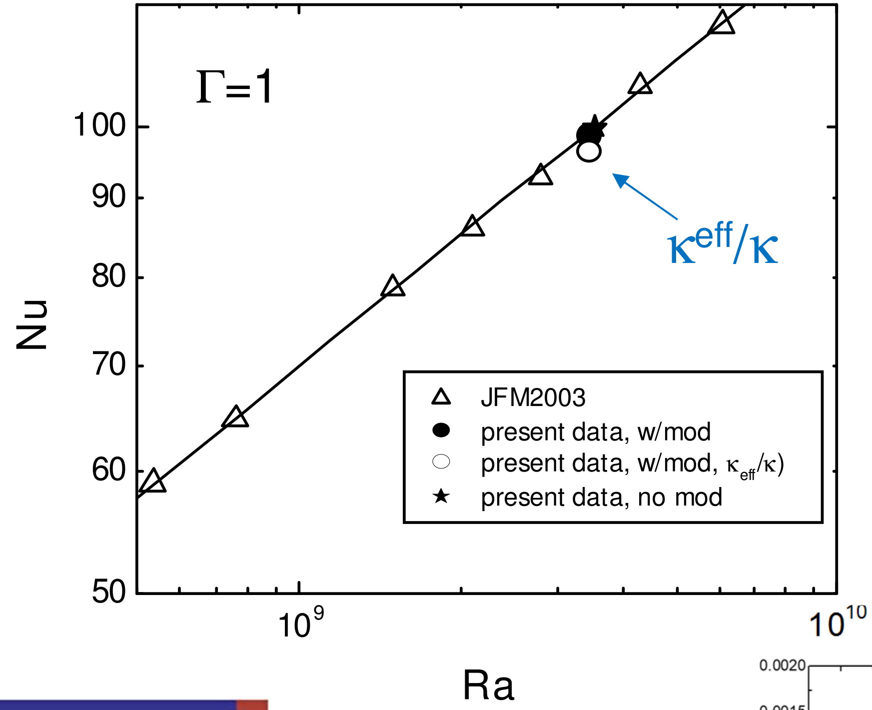
a *convenient definition* treating turbulence as a diffusive "fluid" (thanks Charles, for opening up the "can of sand")

$$\boxed{Nu = \frac{\kappa^{eff}}{\kappa}}$$

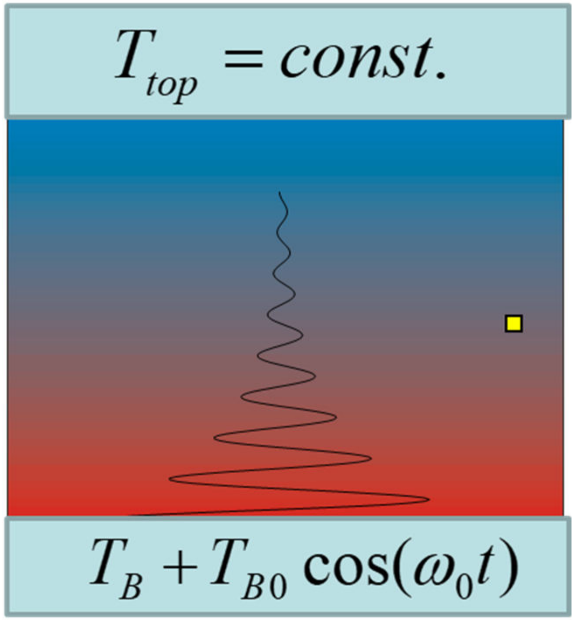
$$\kappa^{eff} \equiv (\kappa + \kappa_T)$$

,

Works pretty well….(open circle)



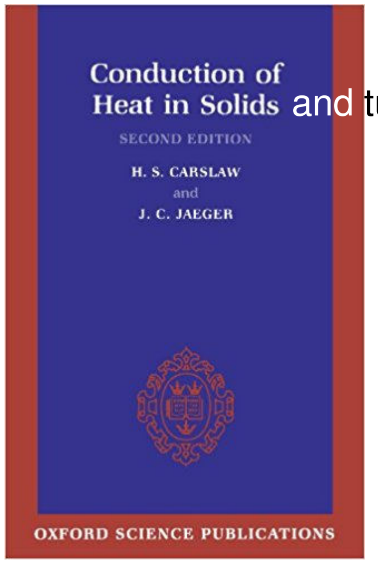
How was κ^{eff} measured?



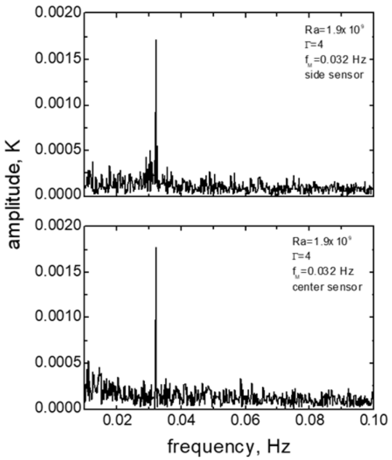
$$\frac{\partial T}{\partial t} = \kappa^{eff} \frac{\partial^2 T}{\partial x_j \partial x_j}$$

$$T(z, \omega_0) = (T_{B0}) \exp(-z/\delta_S)$$

$$\delta_S = \sqrt{\frac{2\kappa^{eff}}{\omega_0}}$$



and turbulent "fluids"...maybe.



JJN, K.R. Sreenivasan, Phys Rev. Lett., **100,** 184502 (2008)

Rotation about vertical axis:

Rotation plays a large role in large scale geophysical turbulent flows

Rotation rate: Ω_D (rad/s) ⟶ *Dimensionless* rotation rate: $\Omega \equiv \left(\frac{2\Omega_D H^2}{\nu} \right) = Ek^{-1}$

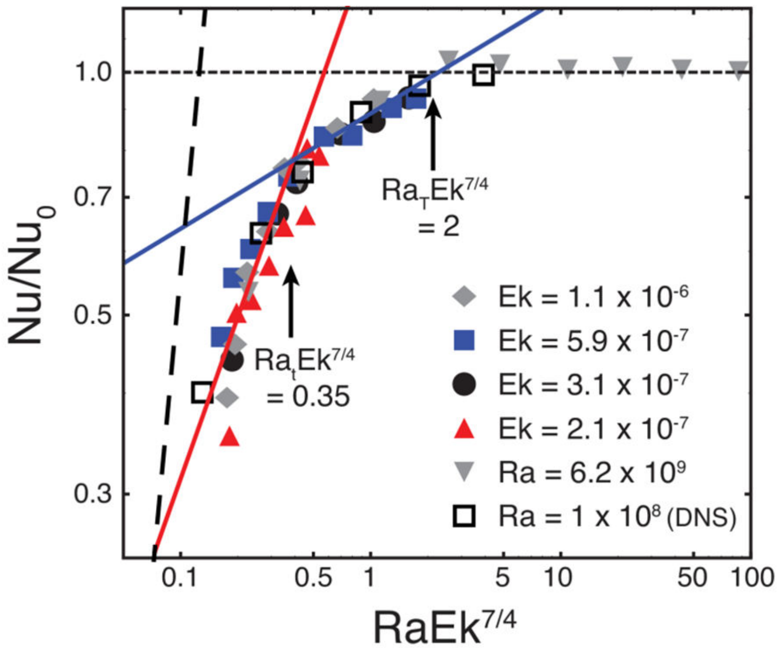
Taylor number: $Ta = \Omega^2 = Ek^{-2}$

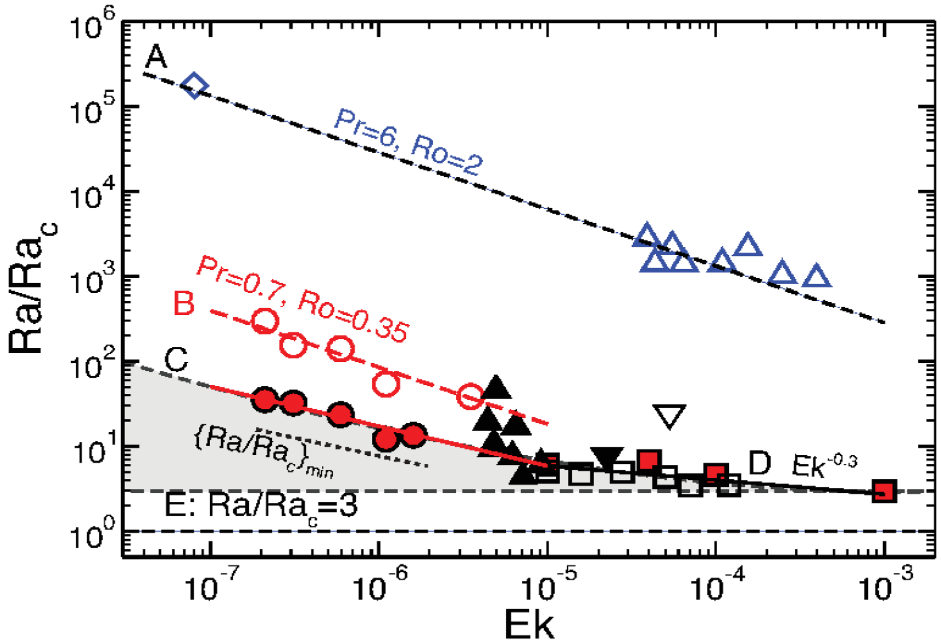
Convective Rossby number: $Ro = \left[\frac{Ra}{PrTa} \right]^{1/2} = (2\Omega_D)^{-1} \left(\frac{g\alpha\Delta T}{H} \right)^{1/2}$

Turbulent heat transfer III

Heat transport in the geostrophic (rotation-dominated) regime

At constant Ek, or Ra





Nu~Ra^1 in geostrophic regime (but limited range for scaling)

JJN, S. Babuin, K.R. Sreenivasan, J. Fluid Mech. **649** , 509-522 (2010)

R.E. Ecke, JJN, Phys. Rev. Lett. **113**, 114301 (2014)

Here are some of the things Najmeh Foroozani might have talked about:

Effect of wall roughness on the large scale circulation in turbulent convection with cubic confinement

N. Foroozani[1], JJN, V. Armenio[2], K. R. Sreenivasan[3]

[1]International Centre for Theoretical Physics (ICTP), [2]University of Trieste, [3]New York University USA (NYU)

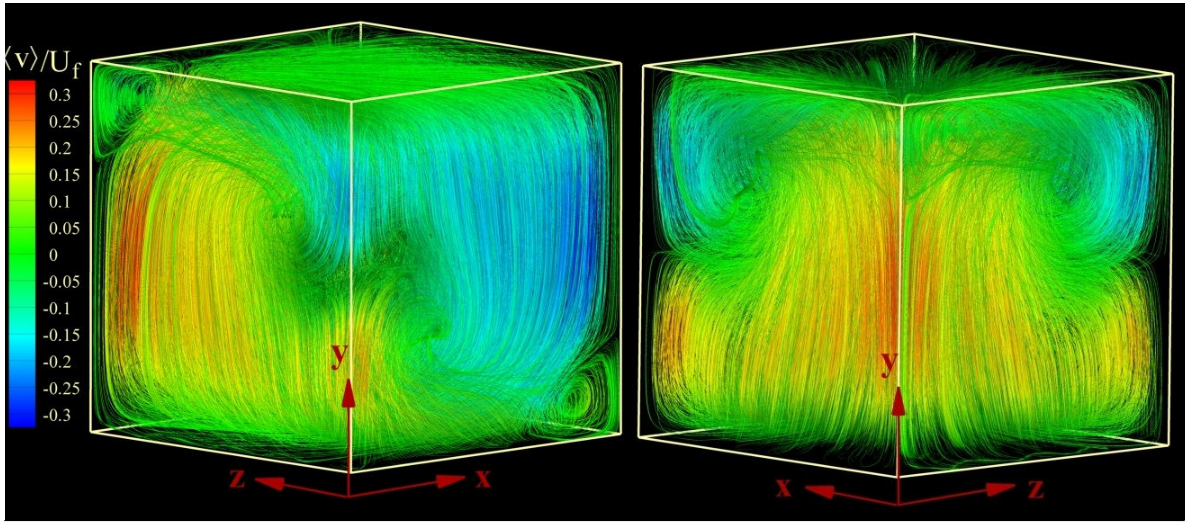
Mathematical Model

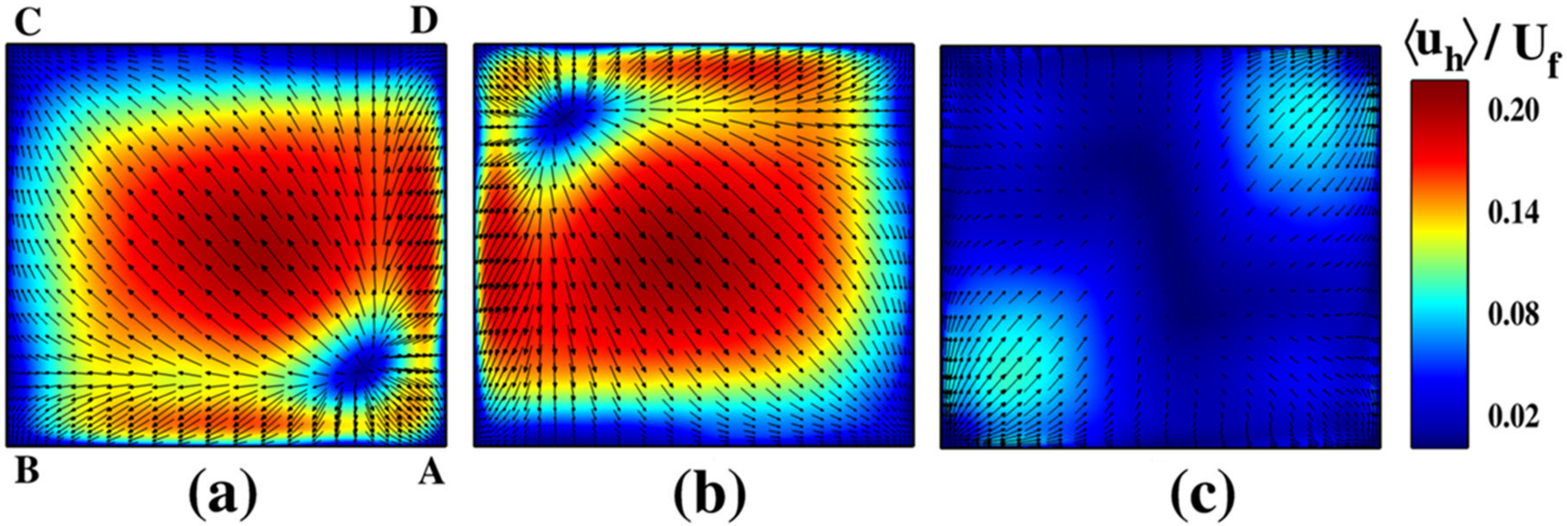
Large Eddy Simulations (LES) are used, solving the spatially filtered Boussinesq approximation of the unsteady NS equations in 3D (Armenio, Meneveau,…)

Boundary conditions and computational domain

- Cubic cell (Γ=1), **No slip** condition, **adiabatic** side walls**, isothermal** top and bottom walls with $Pr = 0.7, Ra = 10^6$ & 10^8.
- Density is a linear function of temperature: $\rho = \rho_0[1 - \alpha(T - T_{0)})]$
- For ***low Ra***, grid mesh $32 \times 64 \times 32$ & for ***high Ra*** $64 \times 96 \times 64$.
- Grid cells clustered near walls to resolve properly momentum and thermal boundary layers.
- Normalization scales for lengths, velocity, density, time respectively: ***H,*** $\boldsymbol{U_f} = \sqrt{\alpha g \Delta T H}$, $\boldsymbol{\Delta\rho} = \rho_{top} - \rho_{bot}$ and $\boldsymbol{T_{eddy}} = 2H/v_{rms}$

Features of the Large Scale Flow in a Cube (Ra=10^8)



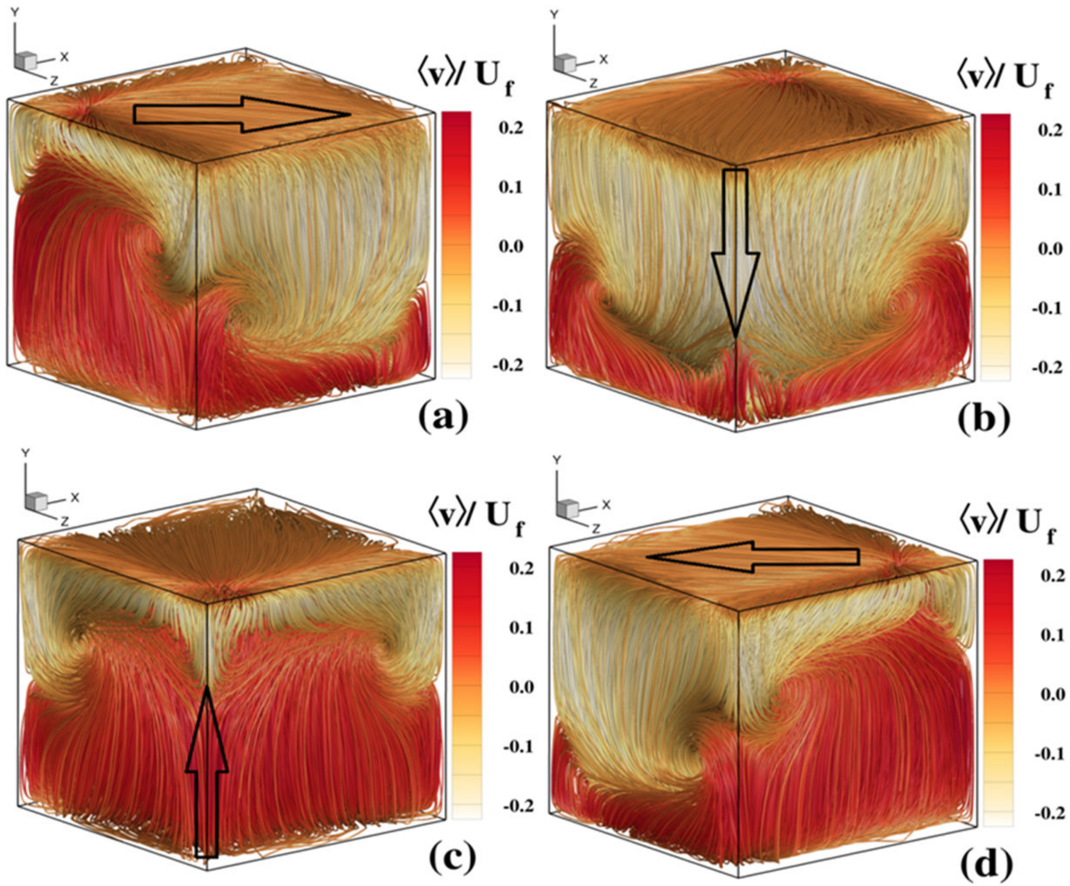


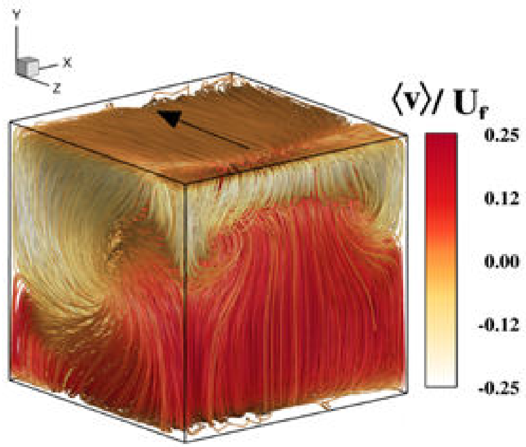
N. Foroozani, JJN, V. Armenio, and K. R. Sreenivasan, Phys. Rev. E **90**, 063003 (2014)

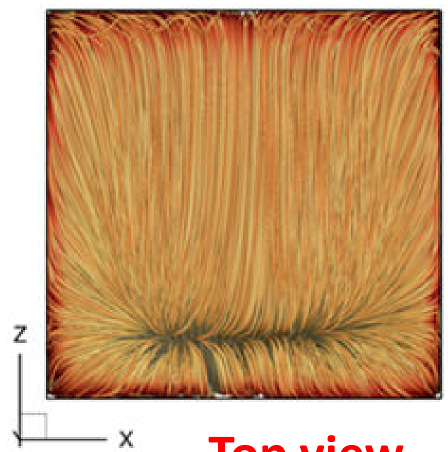
N Foroozani, JJN, V Armenio, KR Sreenivasan, Physical Review E **95** (3), 033107 (2017)

Re-orientations of the Large Scale Flow in a Cube, Ra=10^8

Transient states in between, parallel to side wall







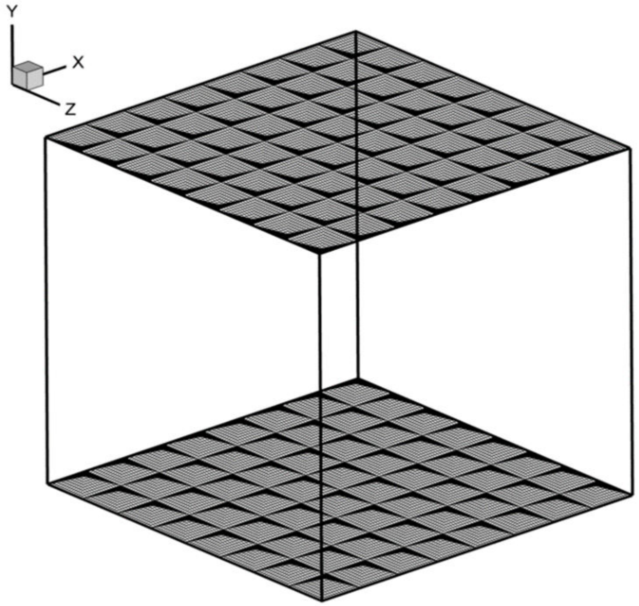
Top view

8 discrete flow states in total

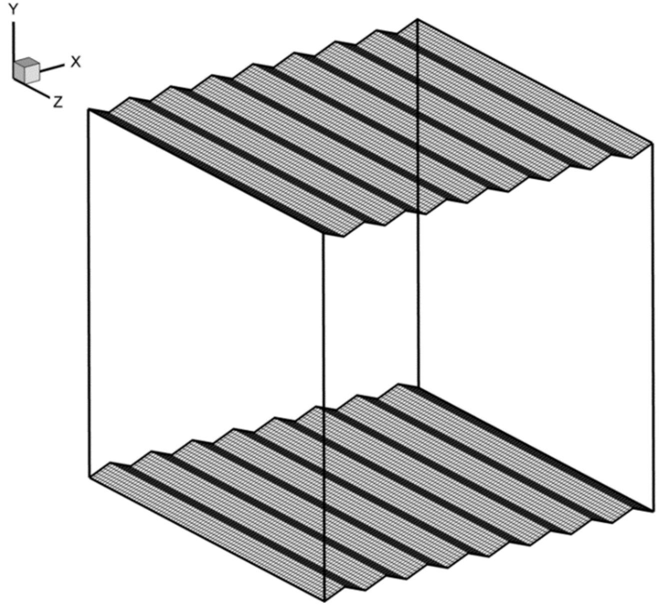
N. Foroozani, J. J. Niemela, V. Armenio, and K. R. Sreenivasan Phys. Rev. E 95, 033107 (2017)

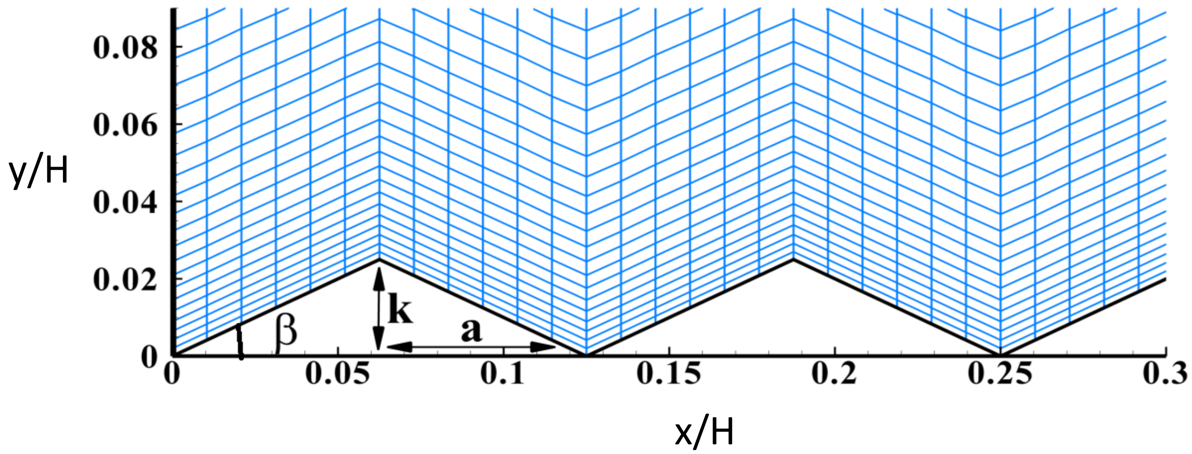
Adding “2D” and 3D roughness elements

Pyramids (64)



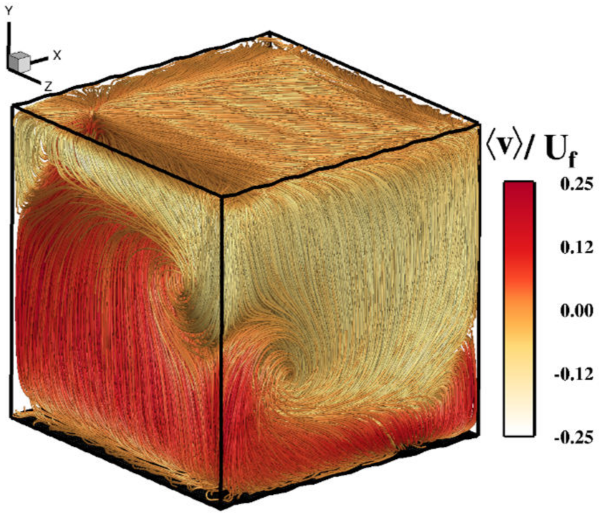
Grooves (8)



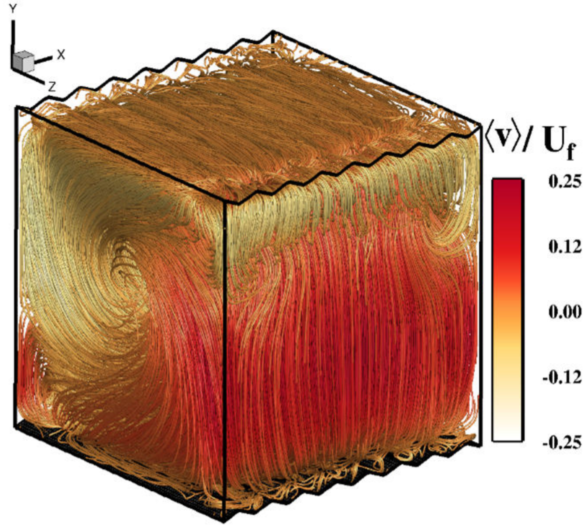


Grid mesh:
$96 \times 96 \times 96$

Grooves

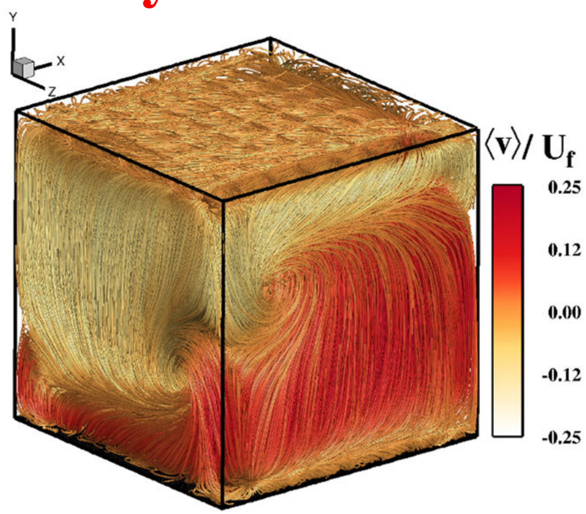


Hydrodynamically smooth



Hydrodynamically rough

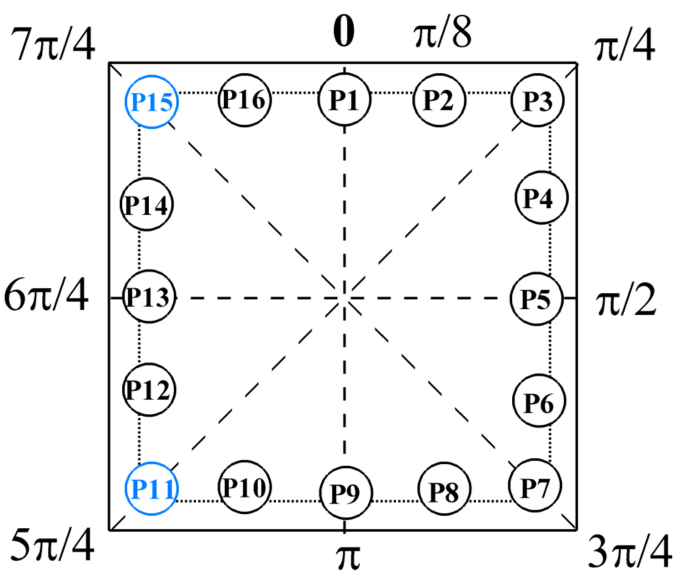
Pyramids



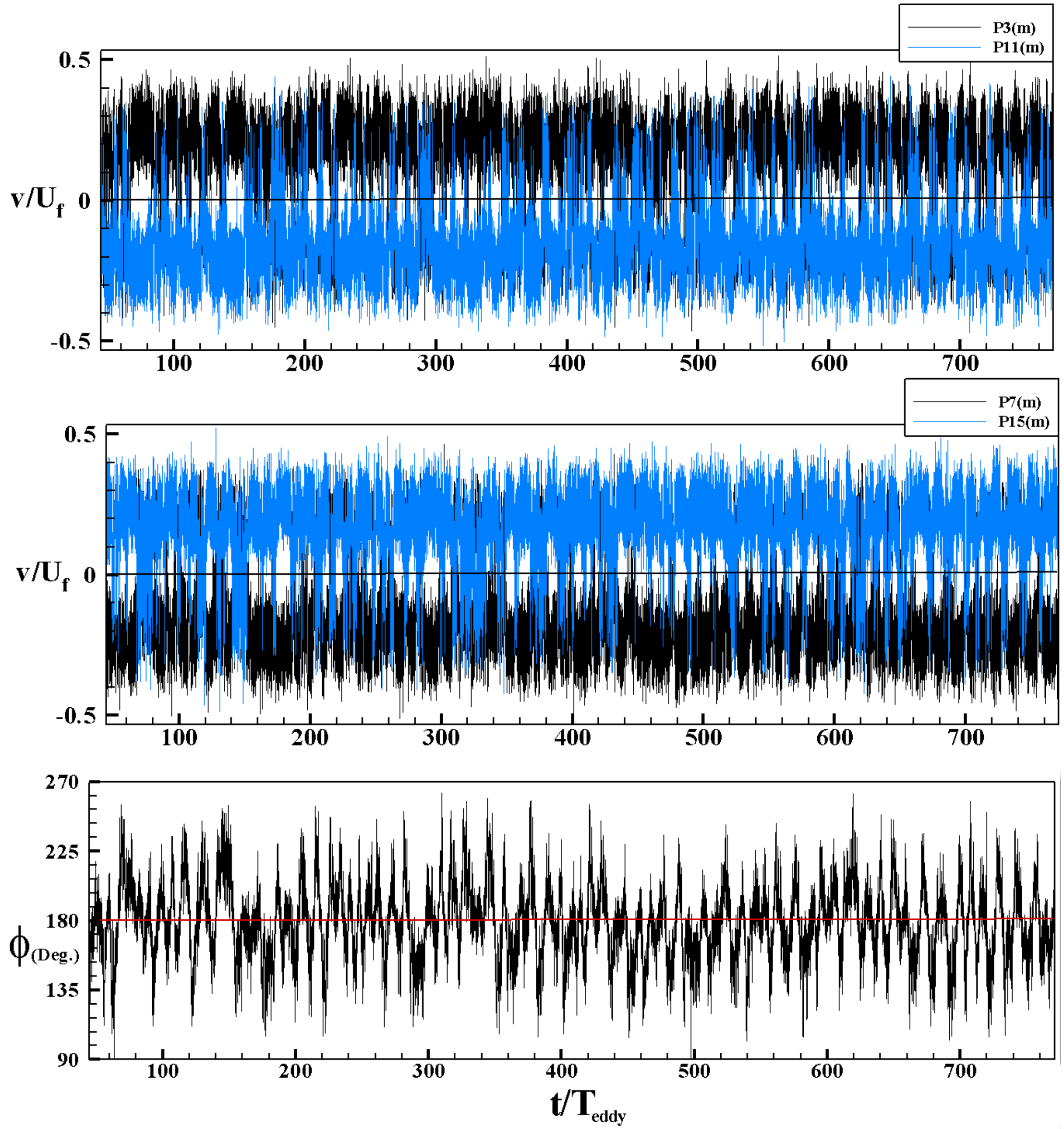
Hydrodynamically rough (same configuration as for smooth)

Unsteady flow states with (hydrodynamically rough) *grooves*

Velocity probe placement



(horizontal plane H/2)

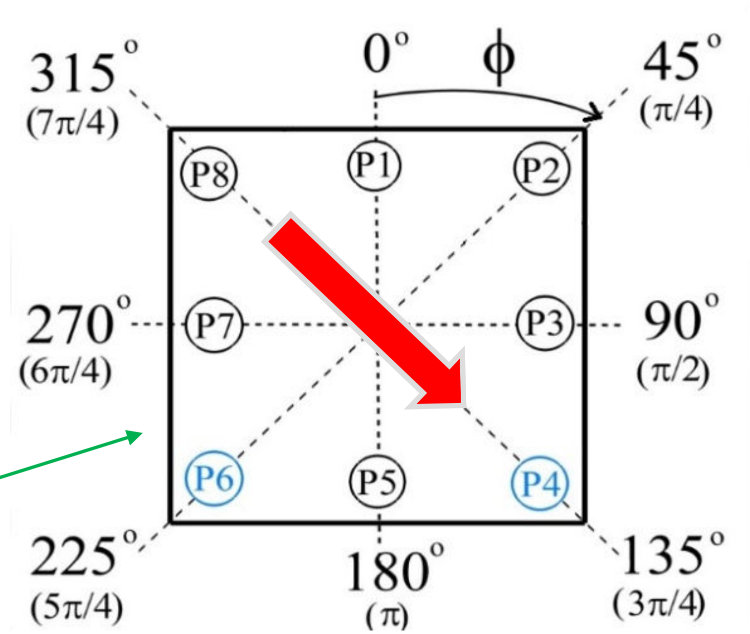


Time averaged flow is parallel to side wall

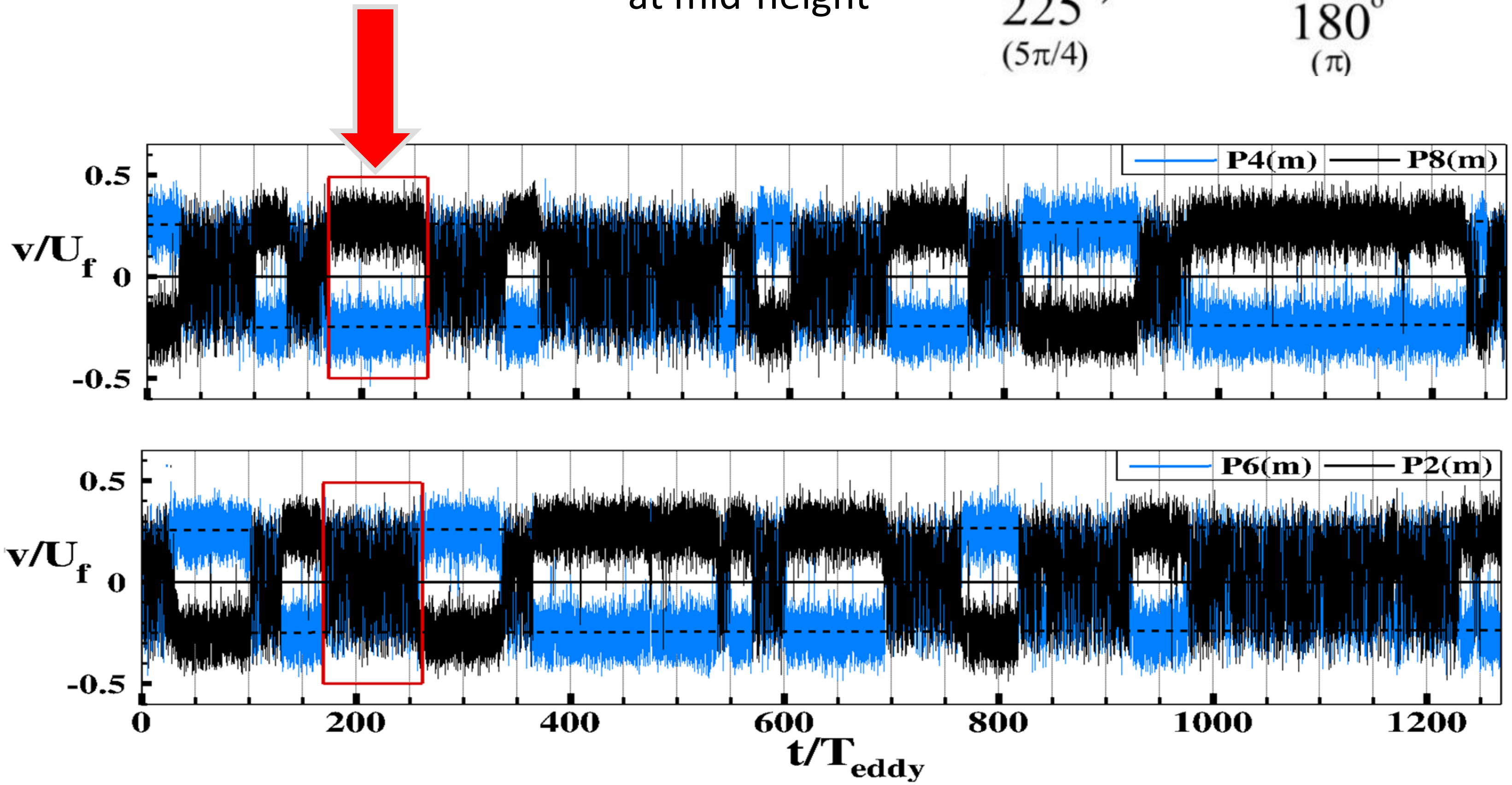
Fourier Transform

Flow with smooth boundaries:

Non-periodic re-orientations observed
but no direct reversals

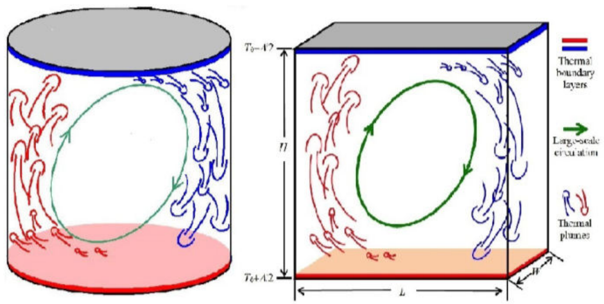


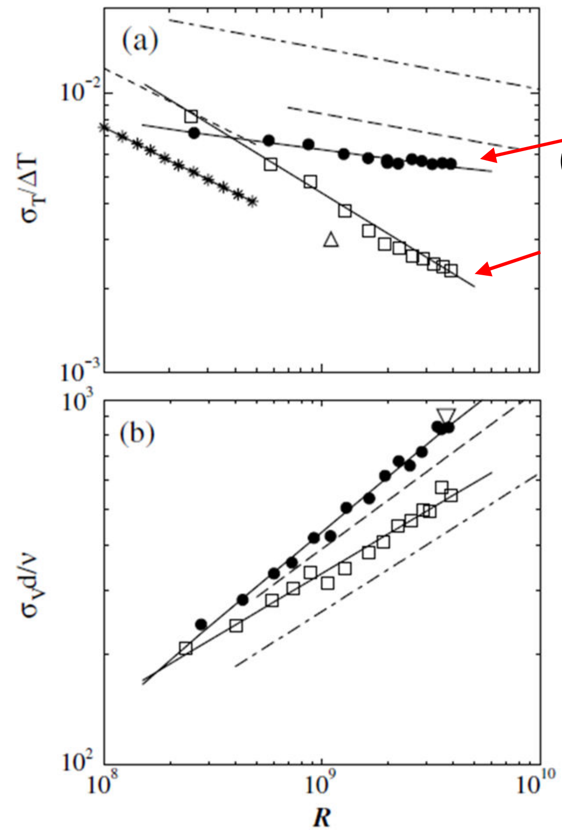
Horizontal plane
at mid-height



ASIDE: Q. Does container shape affect rms statistics in the bulk?

A. Yes (Daya and Ecke [*Phys. Rev. Lett.* **87**, 184501 (2001))





From Daya and Ecke 2001

Daya and Ecke found in **cube**:

$$\frac{\sigma_T}{\Delta T} \propto Ra^{-0.48\pm0.03} \qquad \frac{\sigma_V H}{\nu} \propto Ra^{-0.36\pm0.05}$$

Our results in a cube:

$$\frac{\sigma_\rho}{\Delta\rho} = 0.59 Ra^{-0.46} \qquad \frac{\sigma_V H}{\nu} = 0.32 Ra^{0.39}$$

N. Foroozani, JJN, V. Armenio, and K. R. Sreenivasan, Phys. Rev. E **90**, 063003 (2014).

Conclusions

"Simple fluids are easier to drink than understand."

--**A.C. Newell** and **V. E. Zakharov**, in Turbulence: A Tentative Dictionary (Plenum Press, NY 1994)

"Simple fluids are easier to understand if you drink."

J. Dudley and JJN, (somewhere in London 2016)

THANKS!