Lagrangian Analysis of Turbulent Rotating Convection

Herman Clercx

with Hadi Rajaei and Rudie Kunnen
Fluid Dynamics Laboratory
Physics Department
Eindhoven University of Technology
The Netherlands

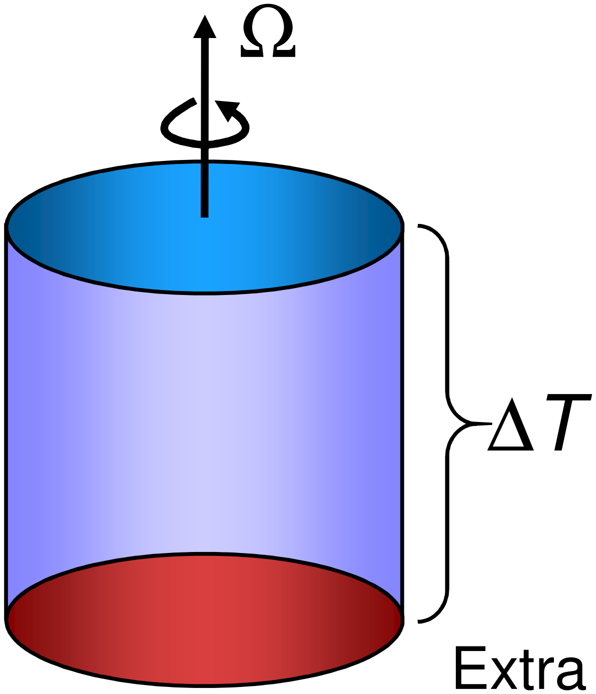
FOM

J.M. Burgerscentrum

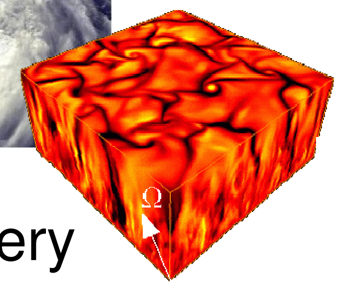
TU/e Technische Universiteit Eindhoven University of Technology

Where innovation starts

Motivation

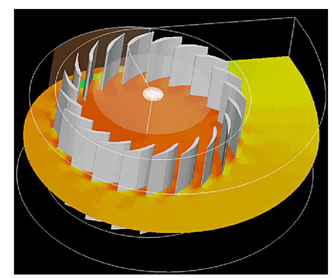


Relevant for geophysical flows:
> atmosphere
> oceans
> astrophysics



and in engineering:
> cooling in turbomachinery

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



$$\mathrm{Ro} = \sqrt{\frac{\mathrm{Ra}}{\sigma \mathrm{Ta}}}$$

$\frac{\text{buoyancy}}{\text{rotation}}$

Motivation

Non-rotating

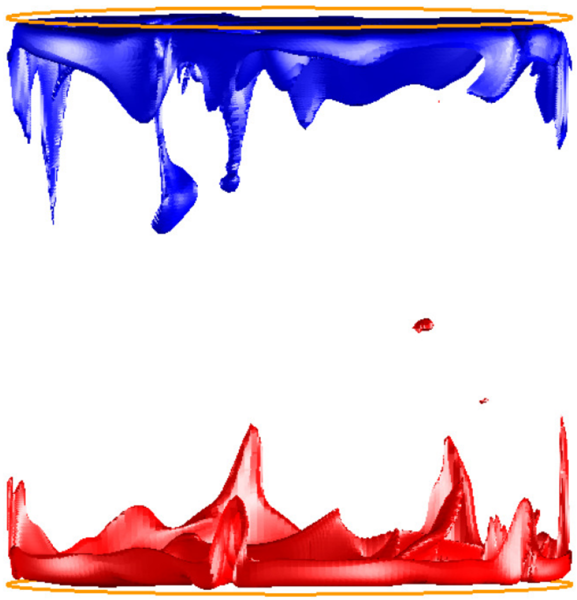
Ro=0.09

Rotating

Ra=10^8, Pr=4.38

Movies courtesy of Susanne Horn, Imperial College, London (private communication).

Motivation



Non-rotating (1/Ro=0)

Rotating (1/Ro=3.3)

$Ra = 10^8$, $Pr = 6.4$

Creation of vortices; Ekman pumping

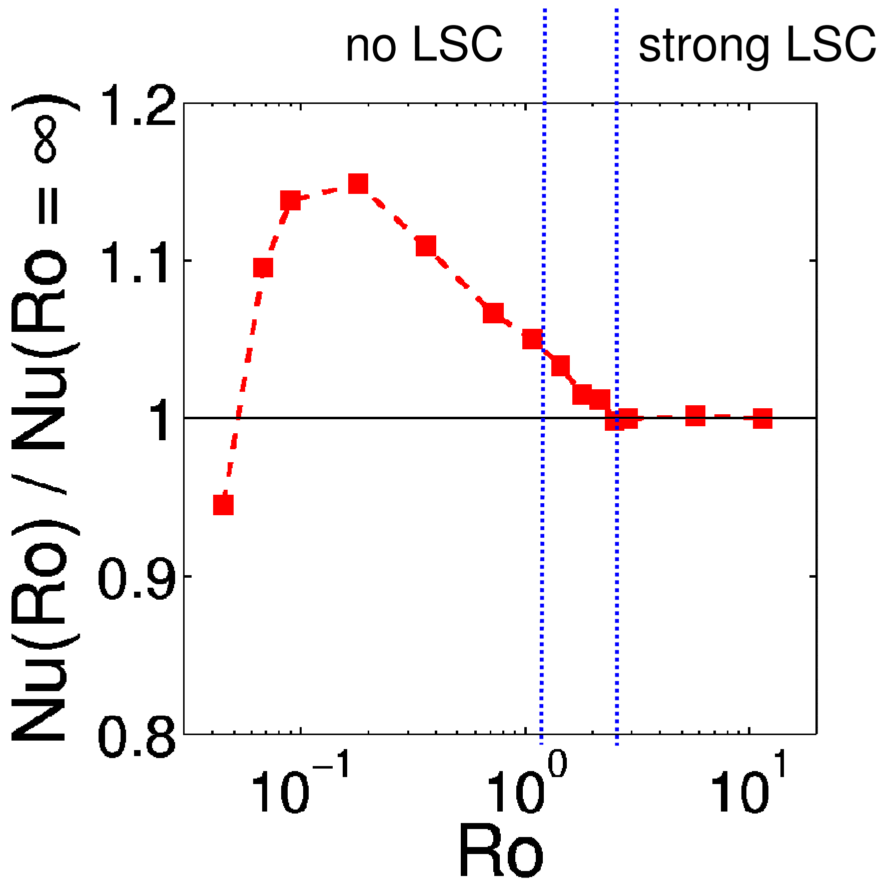
J.-Q. Zhong, R.J.A.M. Stevens, H.J.H. Clercx, R. Verzicco, D. Lohse and G. Ahlers, PRL **102**, 044502 (2009).

Motivation

Nusselt number scaled by non-rotating value at Ro =∞

Nu is larger in a range of Ro (no LSC effect) ⇒ vortical plumes!

At Ro < 0.2 ⇒ inhibition of convection by rotation



R.P.J. Kunnen, H.J.H. Clercx, and B.J. Geurts, EPL **84**, 24001 (2008).

Turbulent convection
3D-PTV measurements

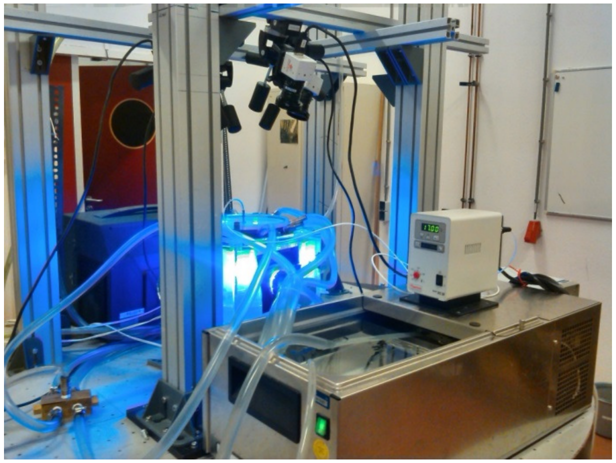
This investigation focusses on:

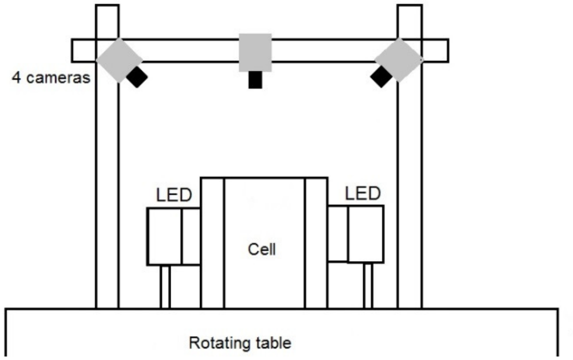
- Lagrangian dynamics of (fluid) particles for turbulent state characterization: LSC or vortical plumes

- transition between turbulent states at Ro_c and how it affects Lagrangian statistics of (fluid) particles

Turbulent convection
3D-PTV measurements

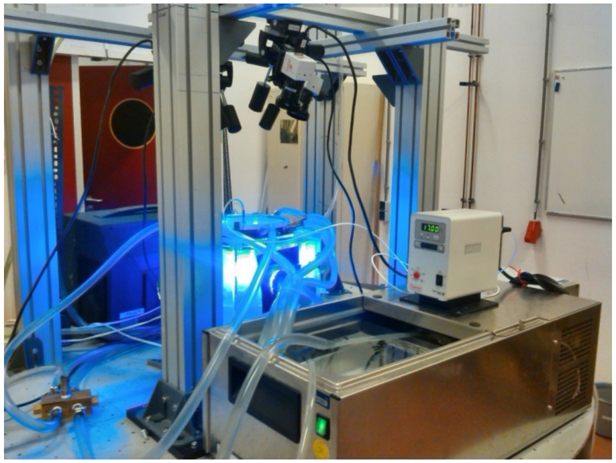
3D-PTV with 4 cameras, tracking individual neutrally buoyant particles





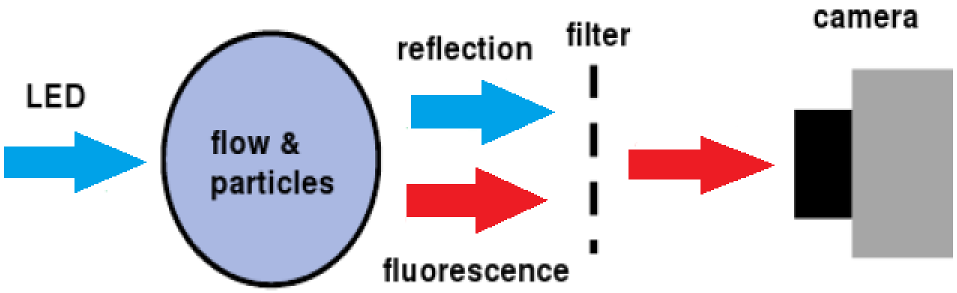
Turbulent convection
3D-PTV measurements

3D-PTV with 4 cameras, tracking individual neutrally buoyant particles



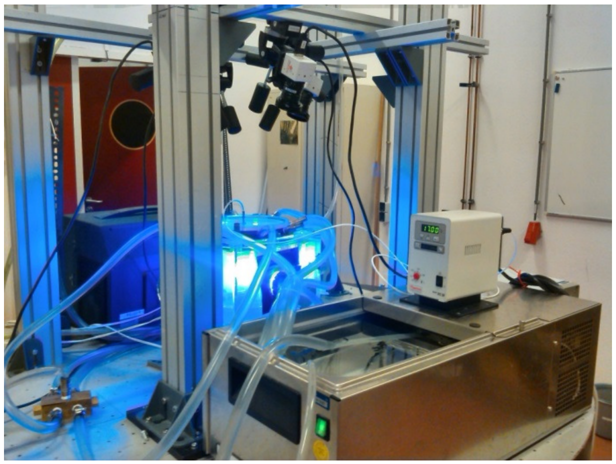
Particles : Fluorescent polyethylene,
emission wavelength: 600nm peak,
particle diameter: 75-90 μm
particles density: 1002 kg/cm^3

Illumination : blue LEDs with dominant wavelength of 455 nm



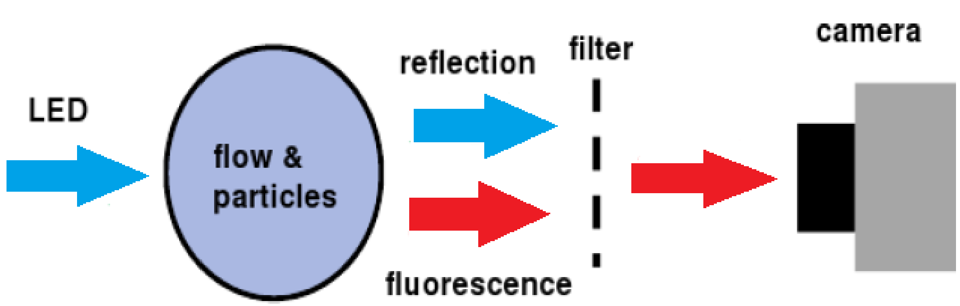
Turbulent convection
3D-PTV measurements

3D-PTV with 4 cameras, tracking individual neutrally buoyant particles



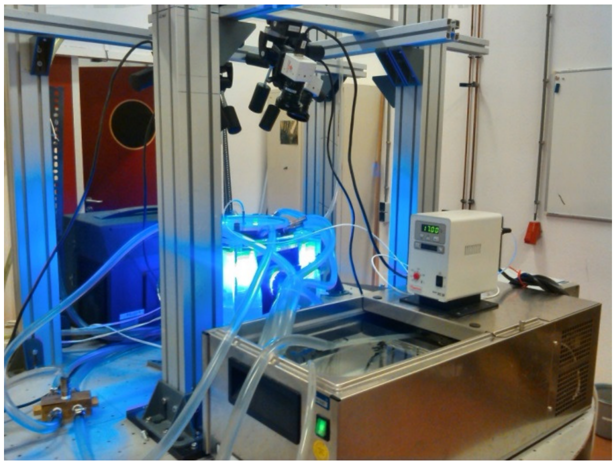
Particles : Fluorescent polyethylene,
emission wavelength: 600nm peak,
particle diameter: 75-90 μm
particles density: 1002 kg/cm^3

Illumination : blue LEDs with dominant wavelength of 455 nm



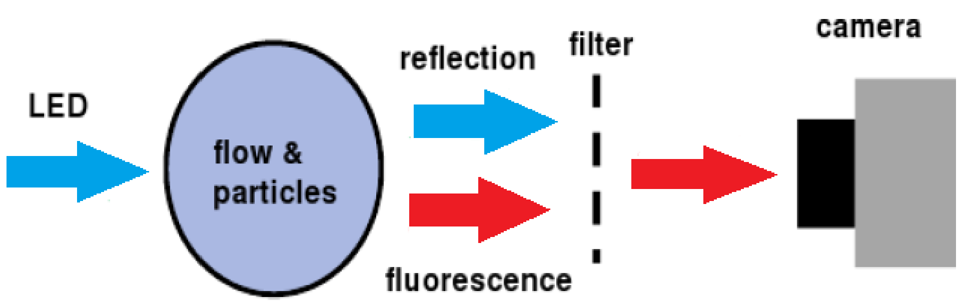
Turbulent convection
3D-PTV measurements

3D-PTV with 4 cameras, tracking individual neutrally buoyant particles



Particles : Fluorescent polyethylene, emission wavelength: 600nm peak, particle diameter: 75-90 μm particles density: 1002 kg/cm^3

Illumination : blue LEDs with dominant wavelength of 455 nm



Turbulent convection
3D-PTV measurements

Turbulent convection
3D-PTV measurements

Measurements in the center of the cell and near the top lid

$Ra = 1.3\times10^9$, $\Gamma = 1$, $Pr = 6.4$

Duration of the measurement = 400 min

Frame rate = 30 Hz

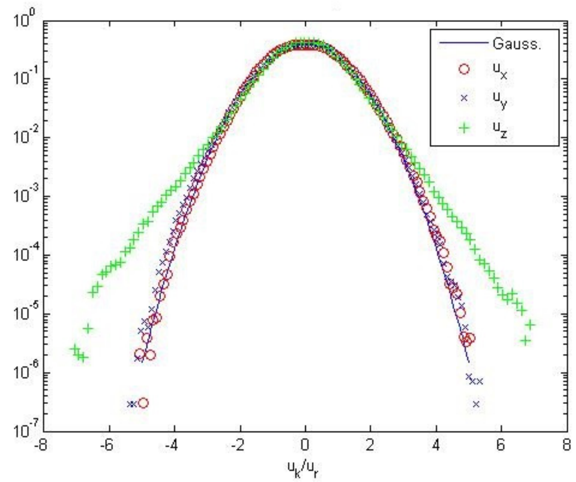
Number of data points in bulk 60-80 million; near top lid 30 million

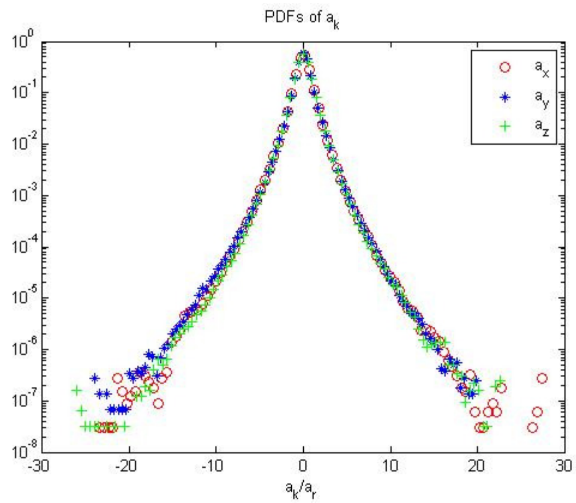
Measurement volume: 50*50*50 mm^3 in bulk and 50*50*10 mm^3 near top lid

Tracked almost 1000 particles in each time step

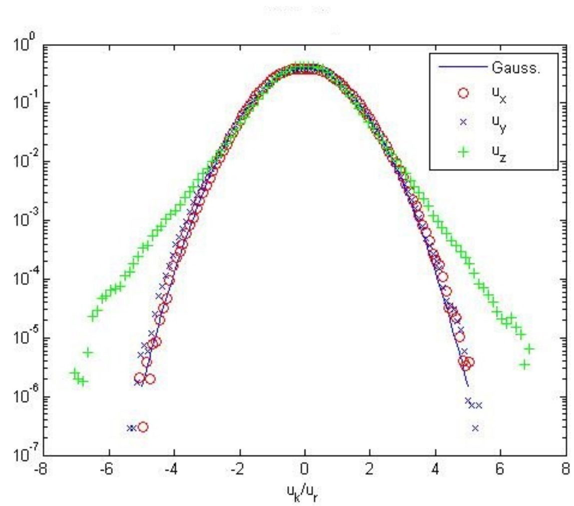
For 8 different rotation rates between 0 and 1.65 [rad/s] (corresponds to Rossby number between ∞ and 0.1)

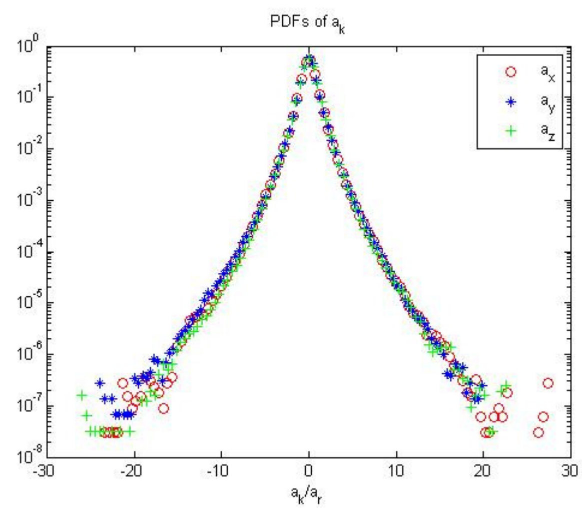
Turbulent convection
3D-PTV measurements

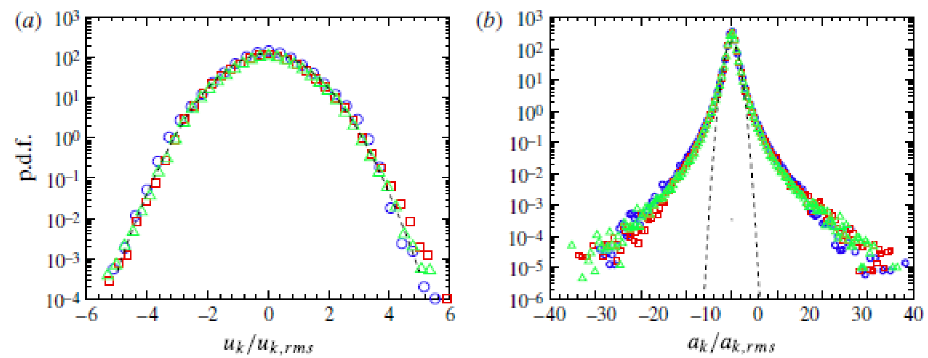




Turbulent convection
3D-PTV measurements



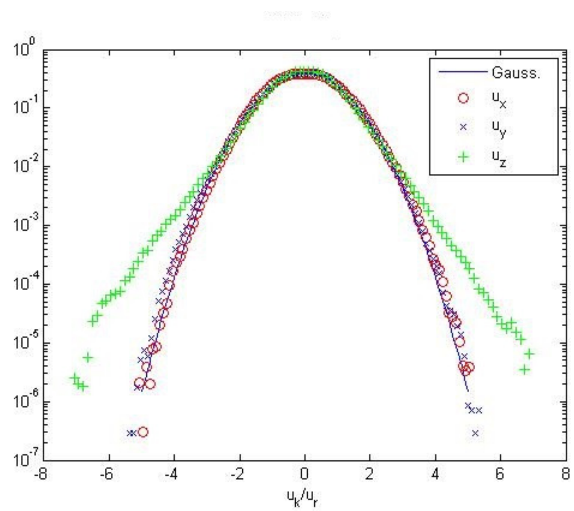


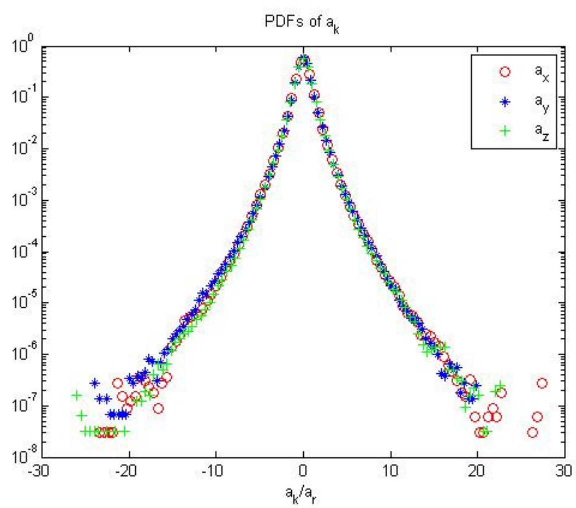


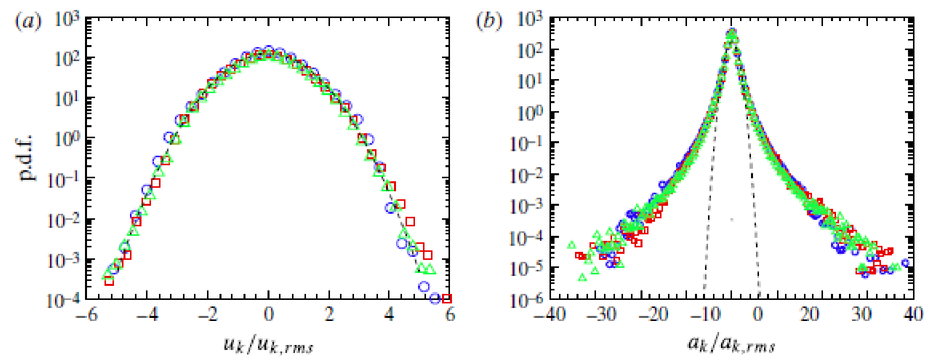
Experimental velocity and acceleration PDFs in the center of RB for Ra = 4.3×10^9 and Pr = 6. Circles, squares and triangles represent the z, x, and y components respectively.*

*Ni, R. Huang, Sh. D. , and Xia, K.-Q, J Fluid Mech. (2012), vol. 692, pp. 395-419.

Turbulent convection
3D-PTV measurements

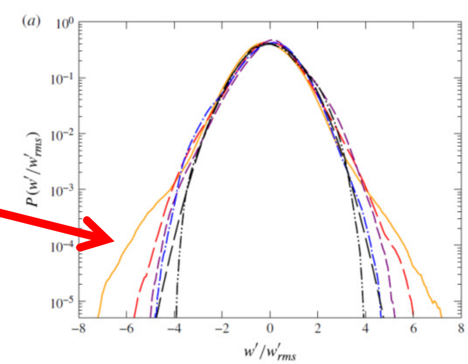






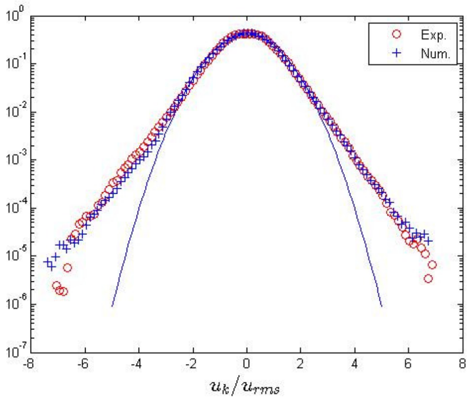
Experimental velocity and acceleration PDFs in the center of RB for Ra = 4.3×10^9 and Pr = 6. Circles, squares and triangles represent the z, x, and y components respectively.*

Numerical vertical velocity PDFs at the center of RB for different Γ (Ra = 10^9 , Pr = 4.38. The yellow line corresponds to Γ = 1).**

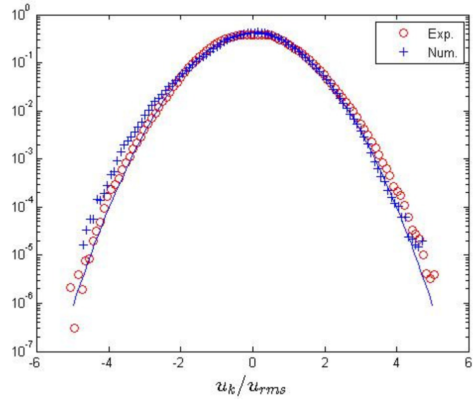


*Ni, R. Huang, Sh. D. , and Xia, K.-Q, J Fluid Mech. (2012), vol. 692, pp. 395-419.
** Kaczorowski M., Chong K.-L., and Xia K-Q, J. Fluid Mech. (2014), vol. 747, pp. 73–102.

Turbulent convection
3D-PTV measurements



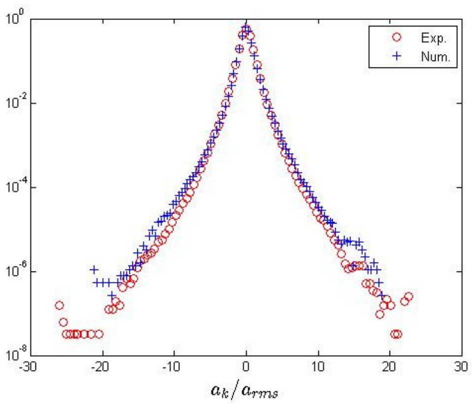
Vertical velocity PDF



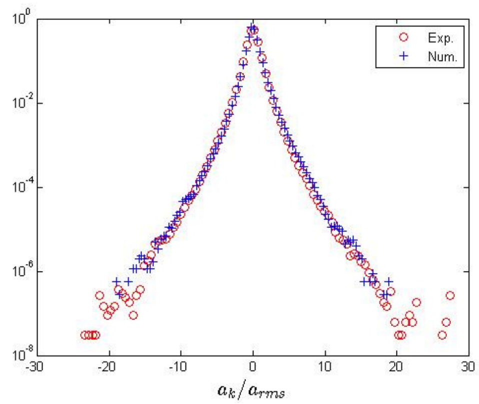
Horizontal velocity PDF

Excellent agree-ment between 3D-PTV and DNS!

(Verzicco-code)



Vertical acceleration PDF

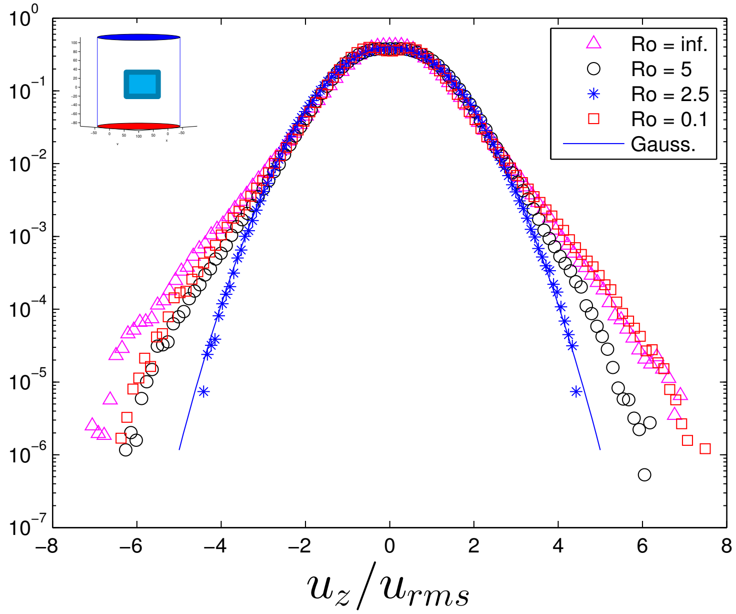


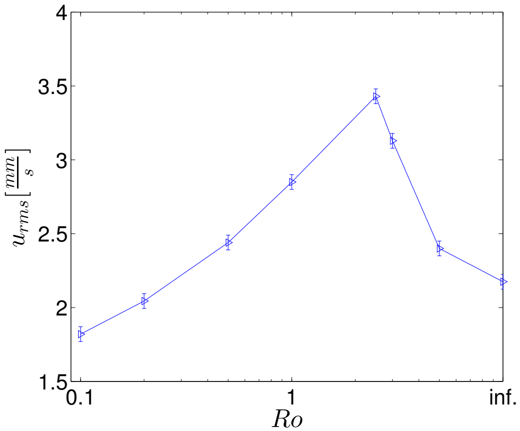
Horizontal acceleration PDF

Technische Universiteit Eindhoven University of Technology

Turbulent rotating convection
Lagrangian vertical velocity PDFs

normalized vertical velocity PDFs

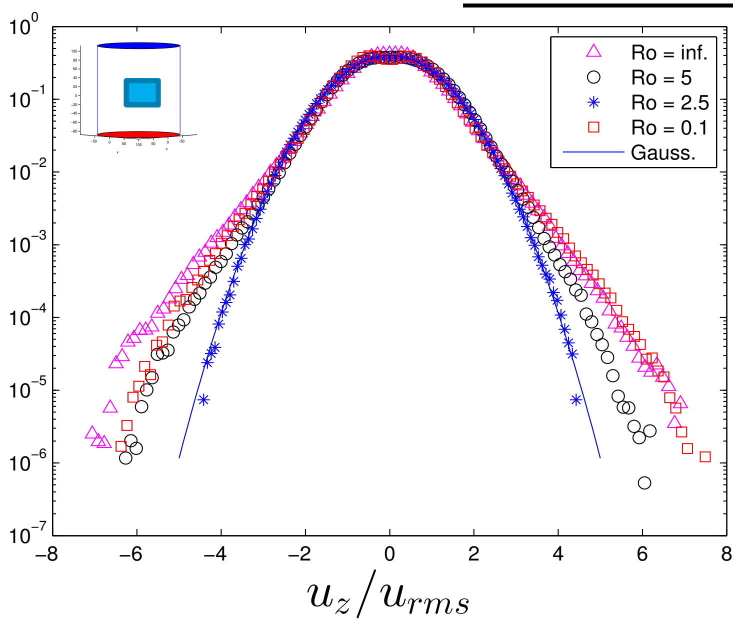


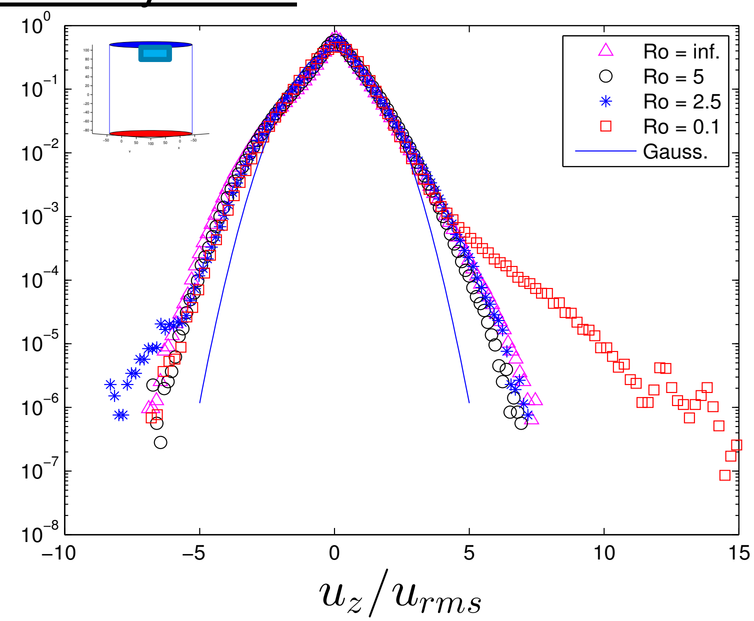


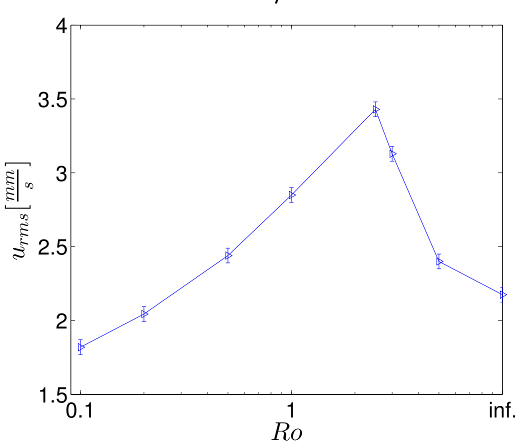
Vertical velocity RMS

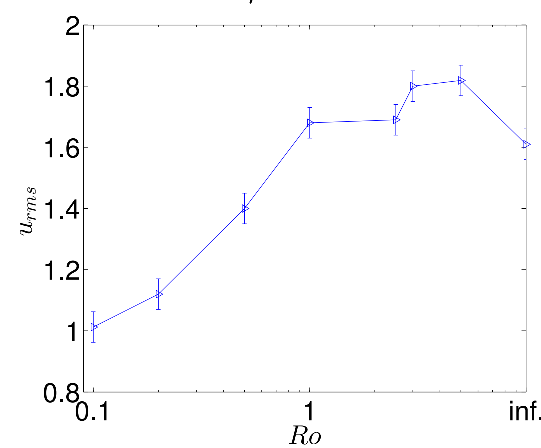
Turbulent rotating convection
Lagrangian vertical velocity PDFs

<u>normalized vertical velocity PDFs</u>





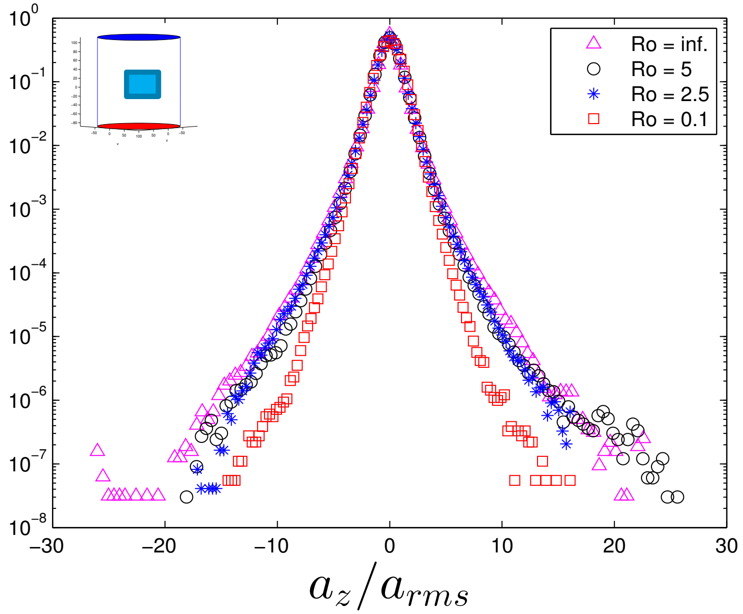


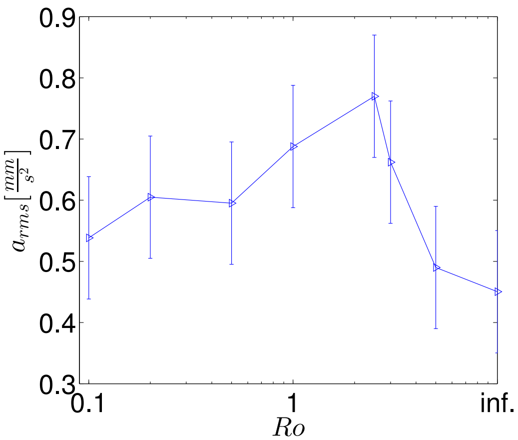


<u>Vertical velocity RMS</u>

Turbulent rotating convection
Lagrangian vertical acceleration PDFs

normalized vertical acceleration PDFs

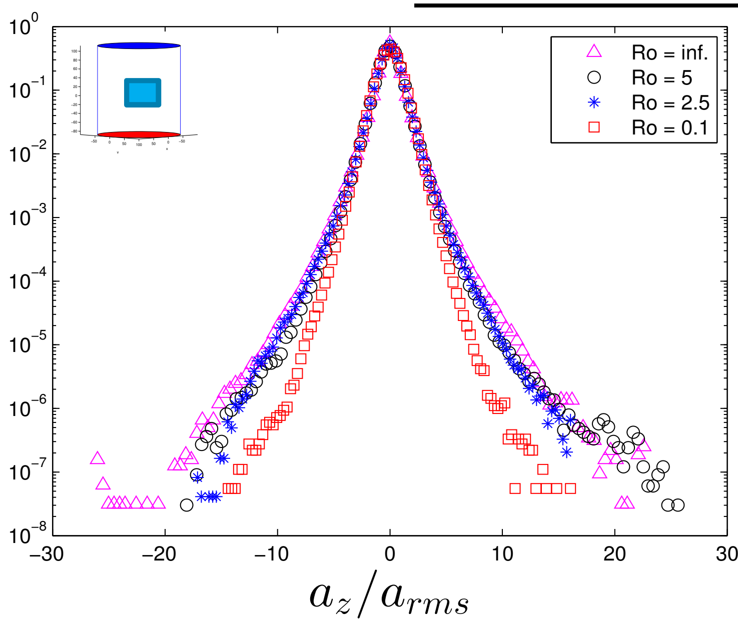


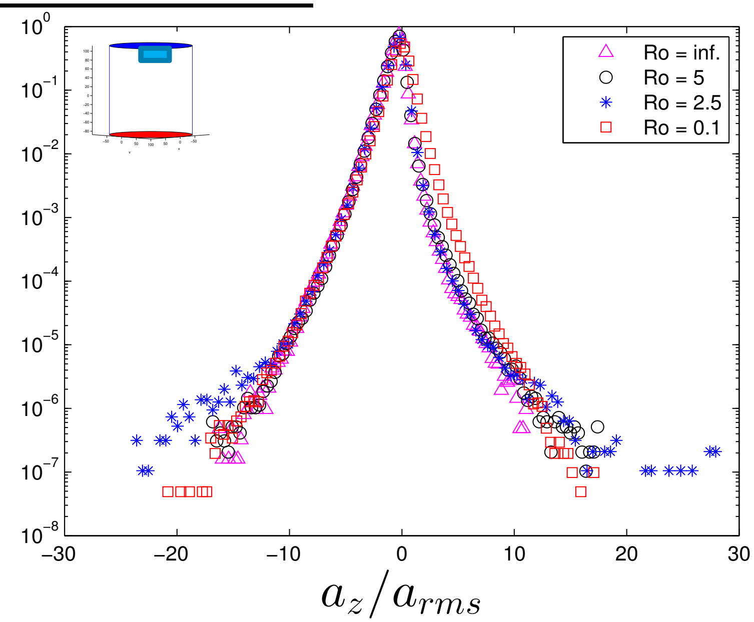


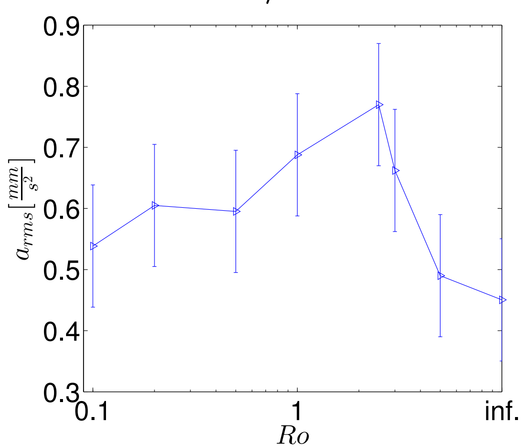
Vertical acceleration RMS

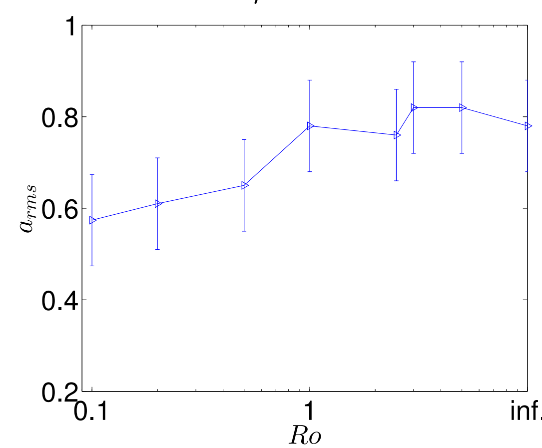
Turbulent rotating convection
Lagrangian vertical acceleration PDFs

normalized vertical acceleration PDFs



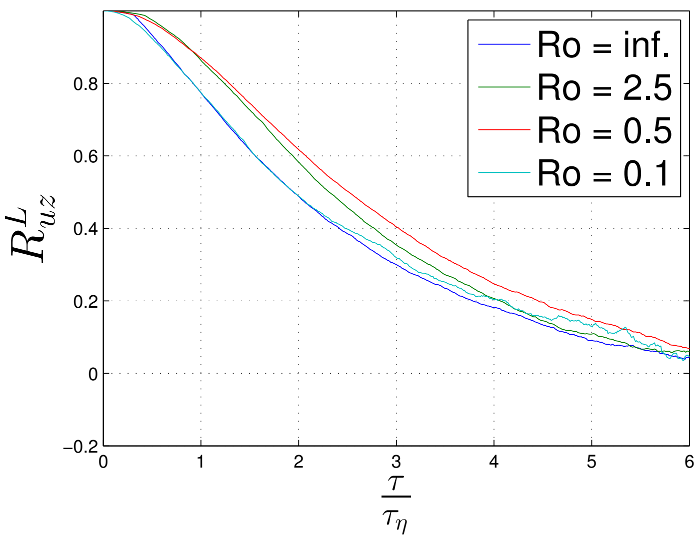




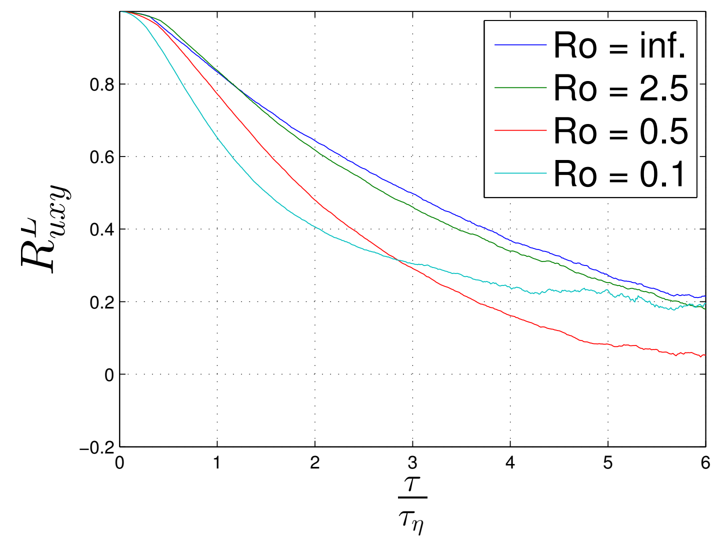


Vertical acceleration RMS

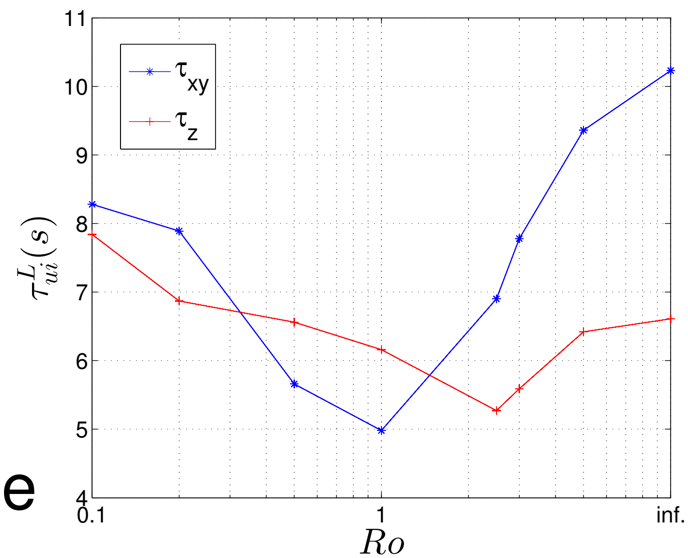
Turbulent rotating convection
Lagrangian velocity autocorrelation



Vertical-velocity autocorrelation

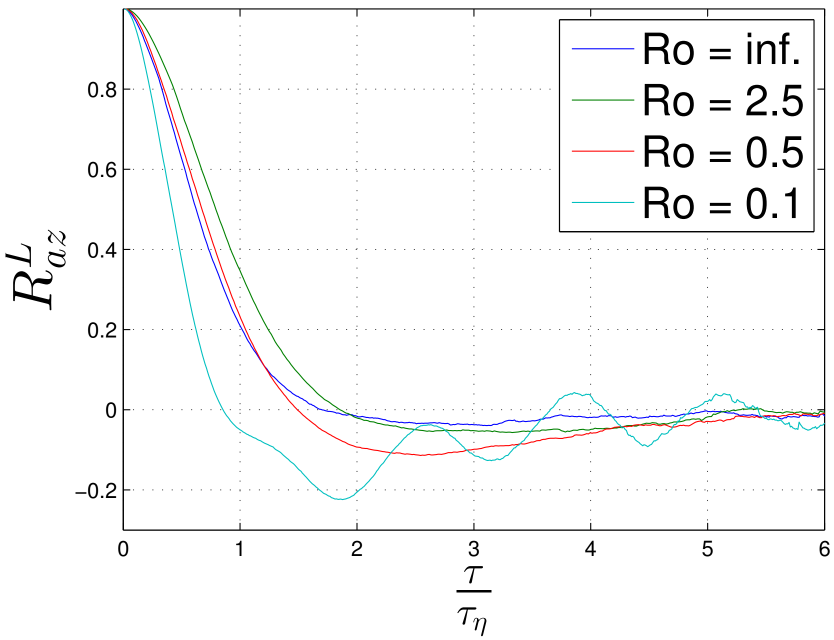


Horizontal-velocity autocorrelation

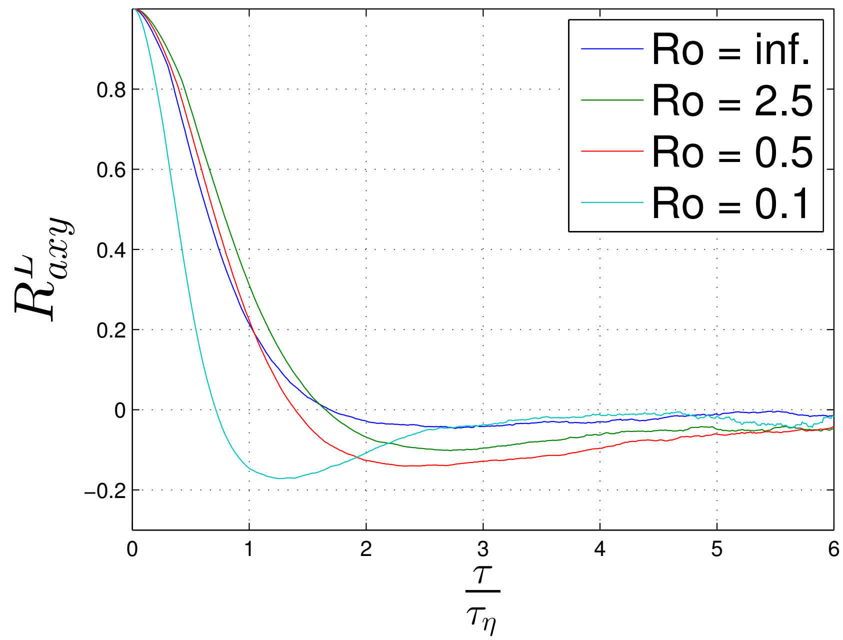


Integral time scale

Turbulent rotating convection
Lagrangian acceleration autocorrelation



Vertical-acceleration autocorrelation



Horizontal-acceleration autocorrelation

Inertial waves ?

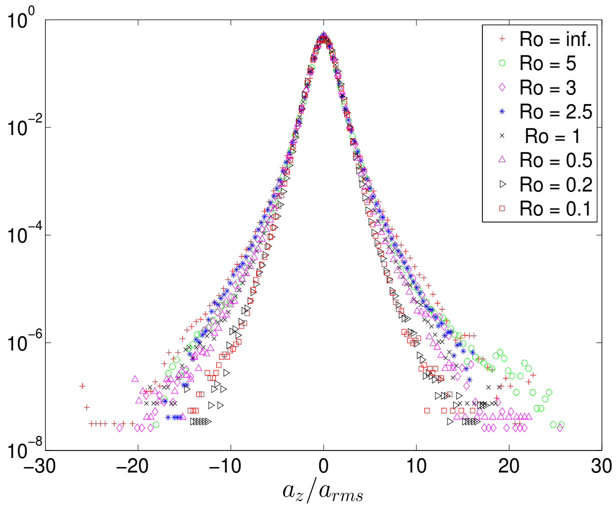
Conclusions

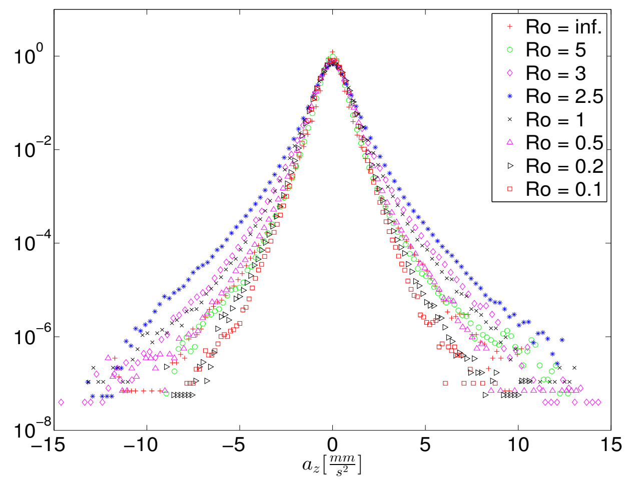
- Lagrangian acceleration and velocity measurements at the center and close to the top lid of a rotating Rayleigh-Bénard cell have been carried out
- At the center, the vertical velocity pdf has slightly wider tails for stationary and high rotation rate cases (coherent structures); approaches Gaussian distribution for intermediate Ro (nearby transition)
- Increasing rotation results in less intermittency in vertical acceleration of RB
- Indications of presence of internal waves

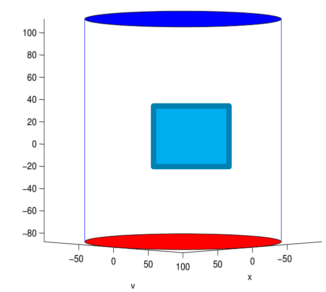
Lagrangian vertical-acceleration PDFs

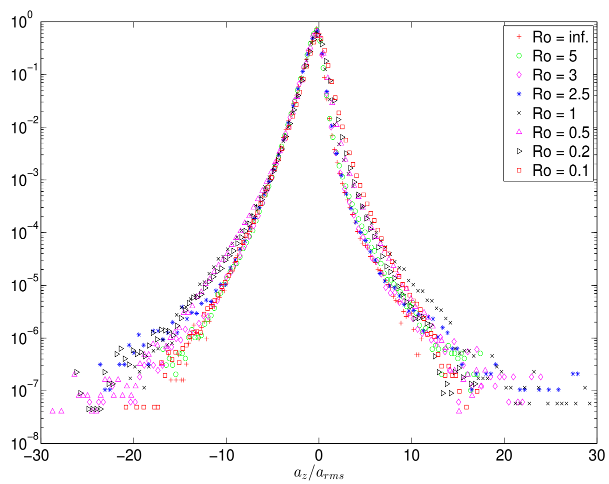
Normalized

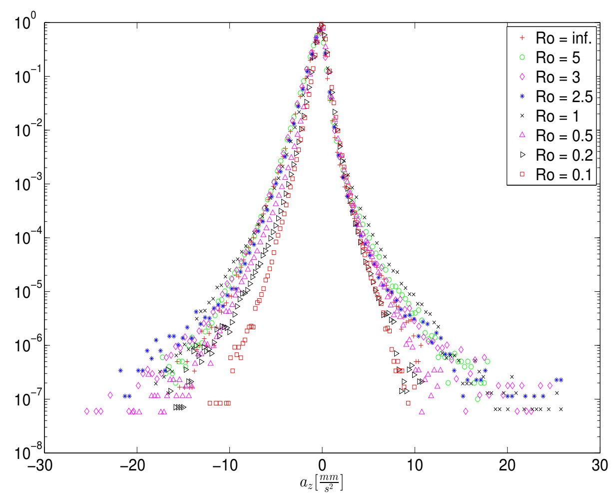
Magnitude

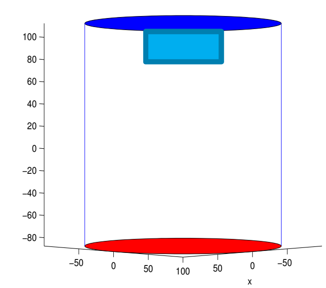












Lagrangian horizontal-acceleration PDFs

Normalized

Magnitude