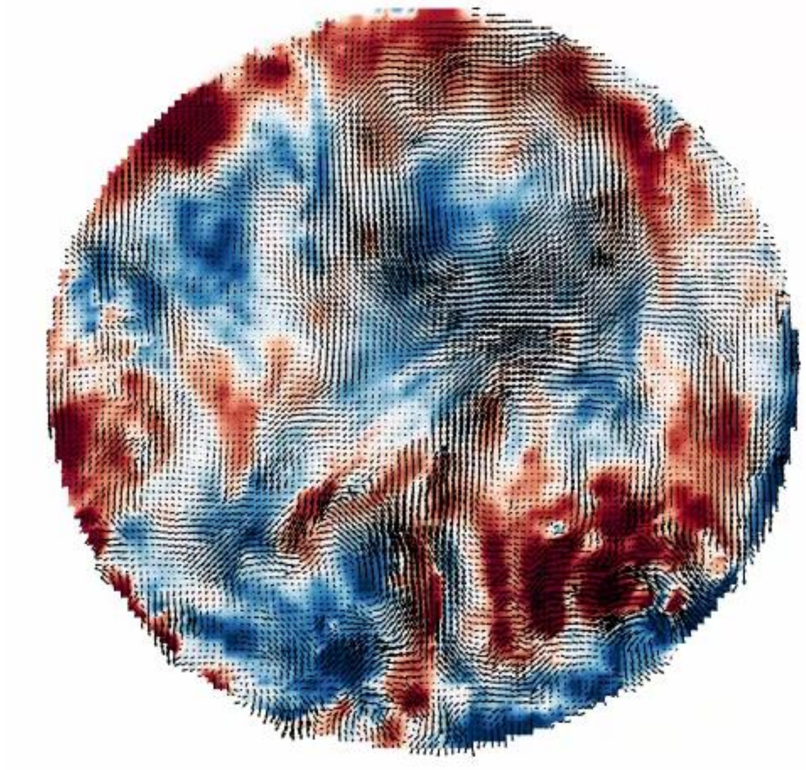
Confined rotating convection: a laboratory perspective

Rudie Kunnen

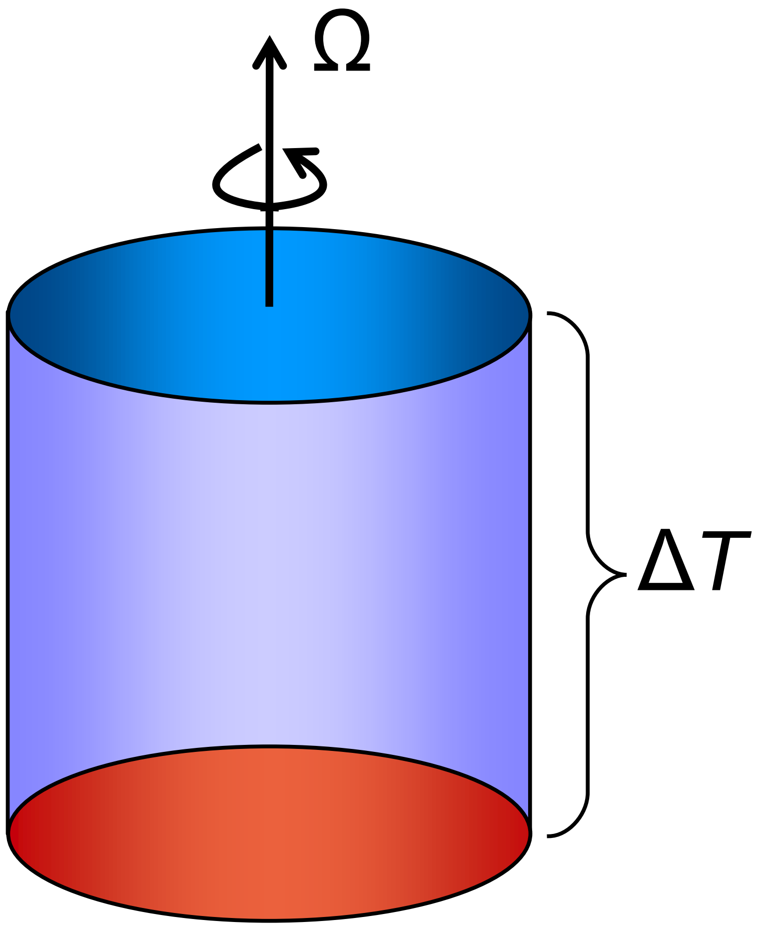


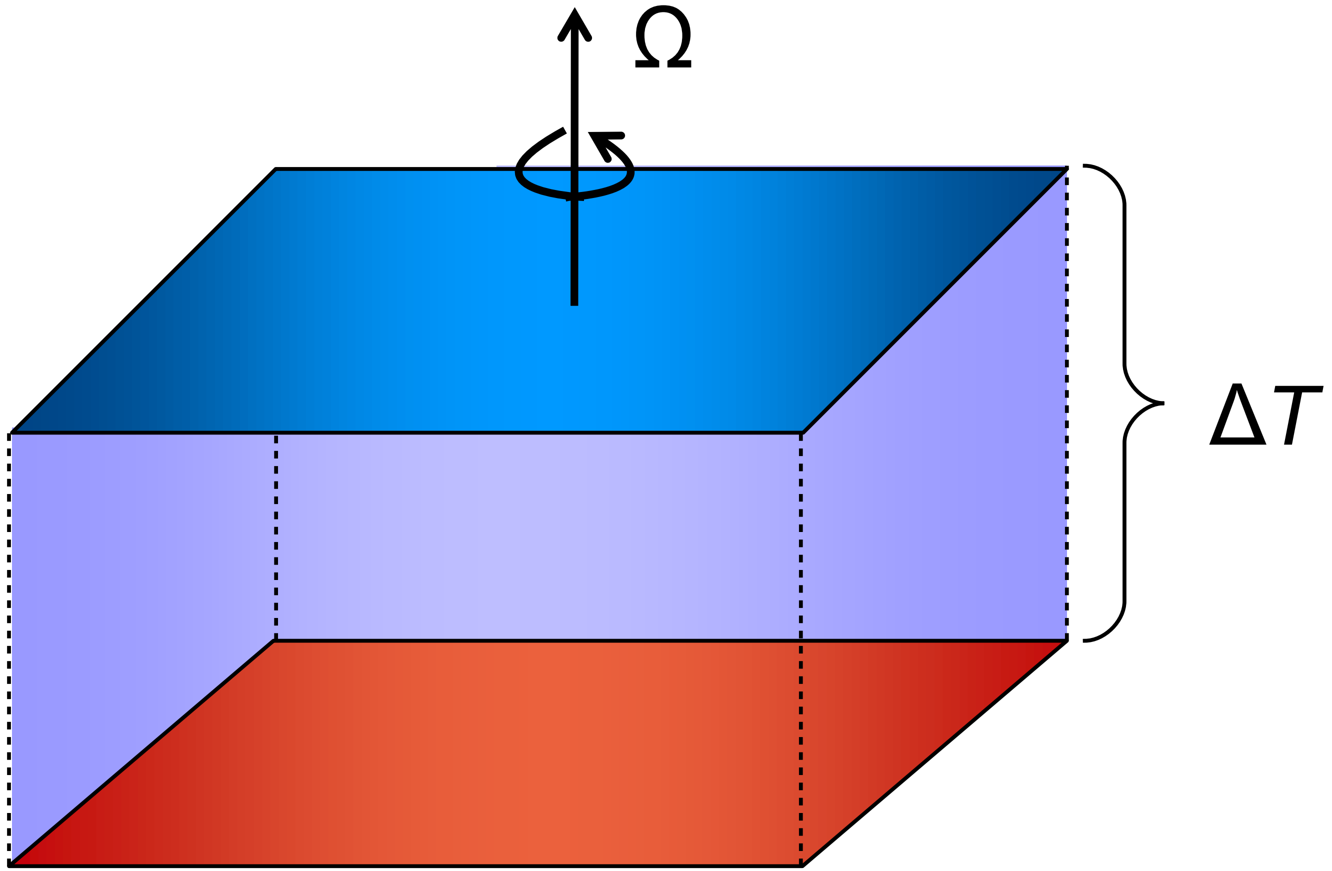
27 January 2025

Workshop at IPAM

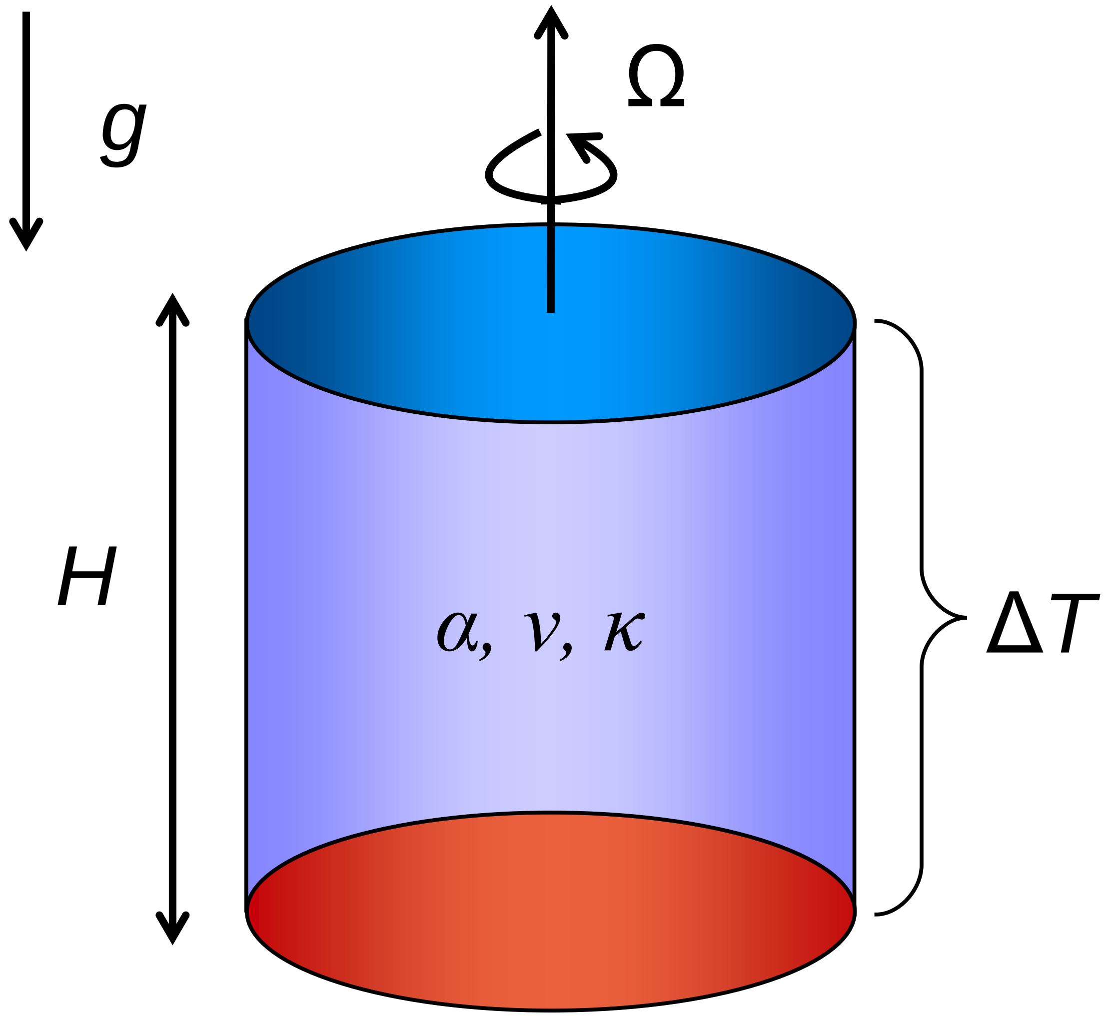
Rotating Turbulence: Interplay and Separability of Bulk and Boundary Dynamics

Rotating Rayleigh-Bénard convection





Rotating Rayleigh-Bénard convection



Rayleigh: thermal forcing

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

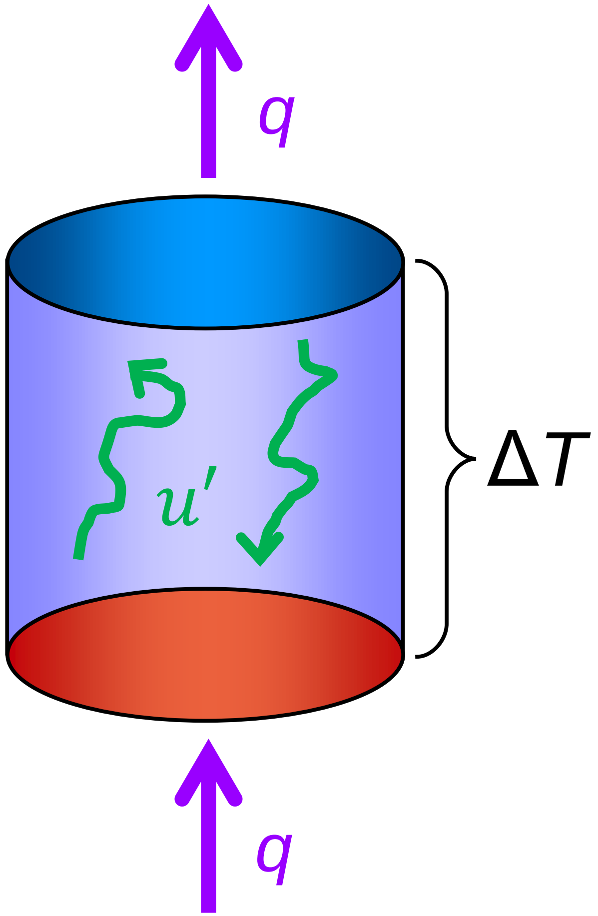
Prandtl: fluid properties

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

Ekman: $\dfrac{\text{viscous}}{\text{Coriolis}}$

$$Ek = \frac{\nu}{2\Omega H^2}$$

Response parameters: Nusselt and Reynolds



Nusselt:

efficiency of convective heat transfer

Nu = Total heat transfer / Conduction

$$Nu = \frac{q}{k\,\Delta T/H}$$

Reynolds:

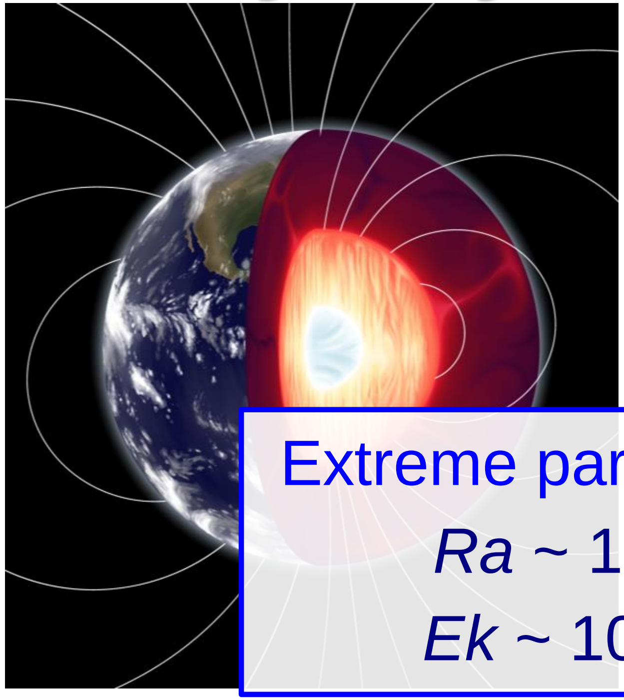
magnitude of velocity fluctuations

Re = Inertia / Viscosity

$$Re = \frac{u'H}{\nu}$$

Goal: know $Nu(Ra, Pr, Ek)$ and $Re(Ra, Pr, Ek)$

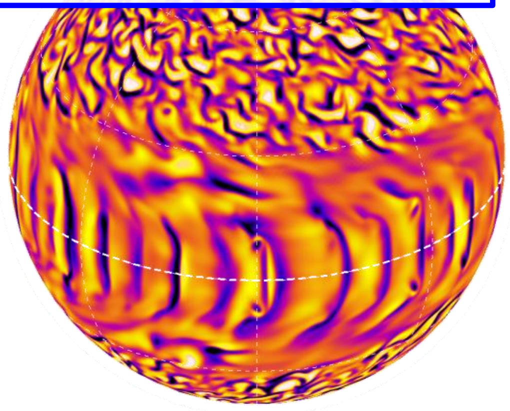
Rotation and buoyancy: shaping flows in nature

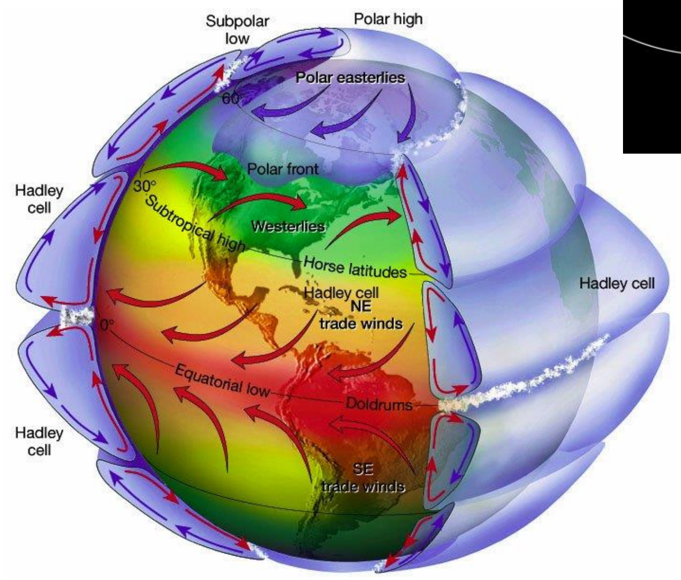


Extreme parameter values:

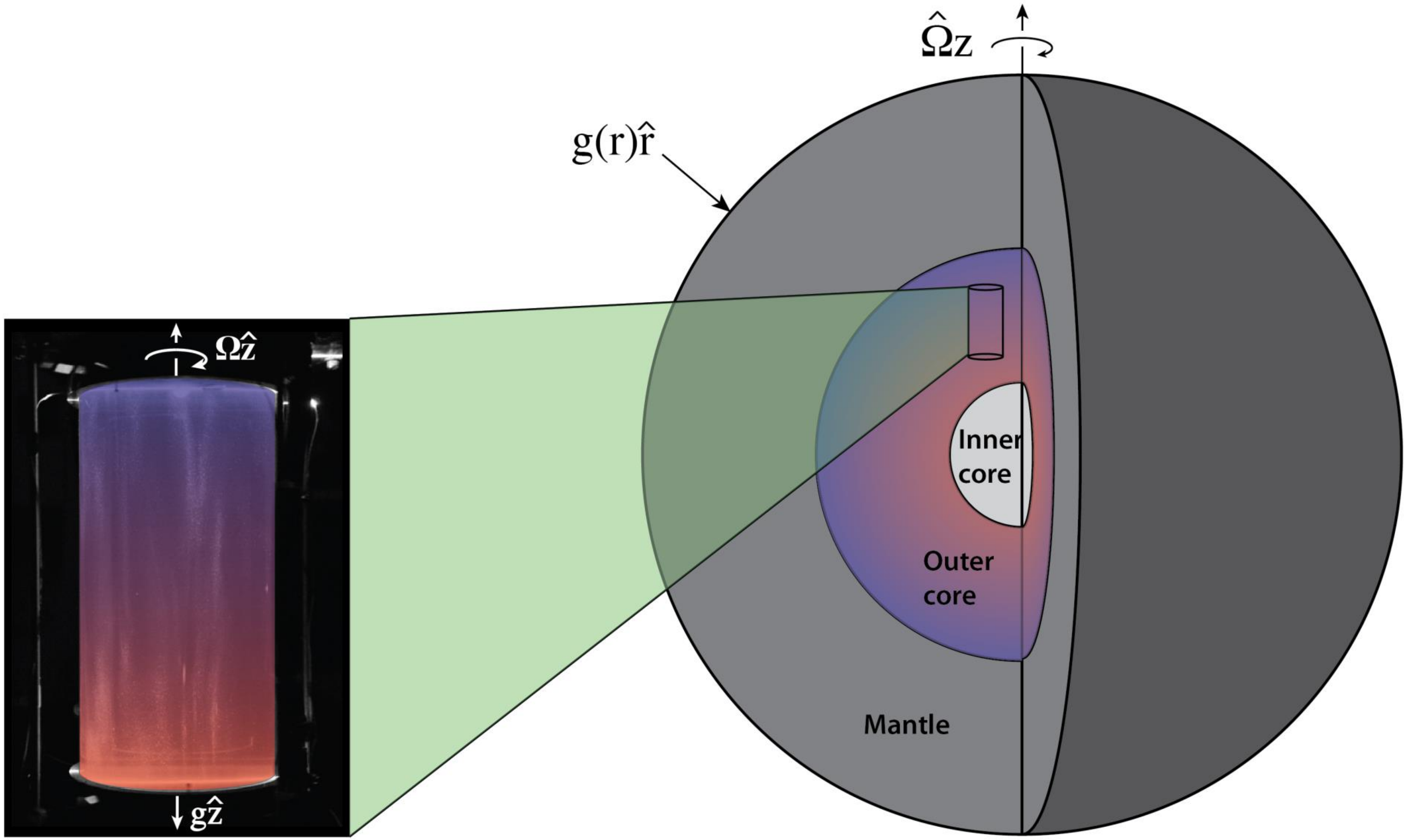
$Ra \sim 10^{20} - 10^{25}$

$Ek \sim 10^{-15} - 10^{-12}$





Sphere vs. Cylinder



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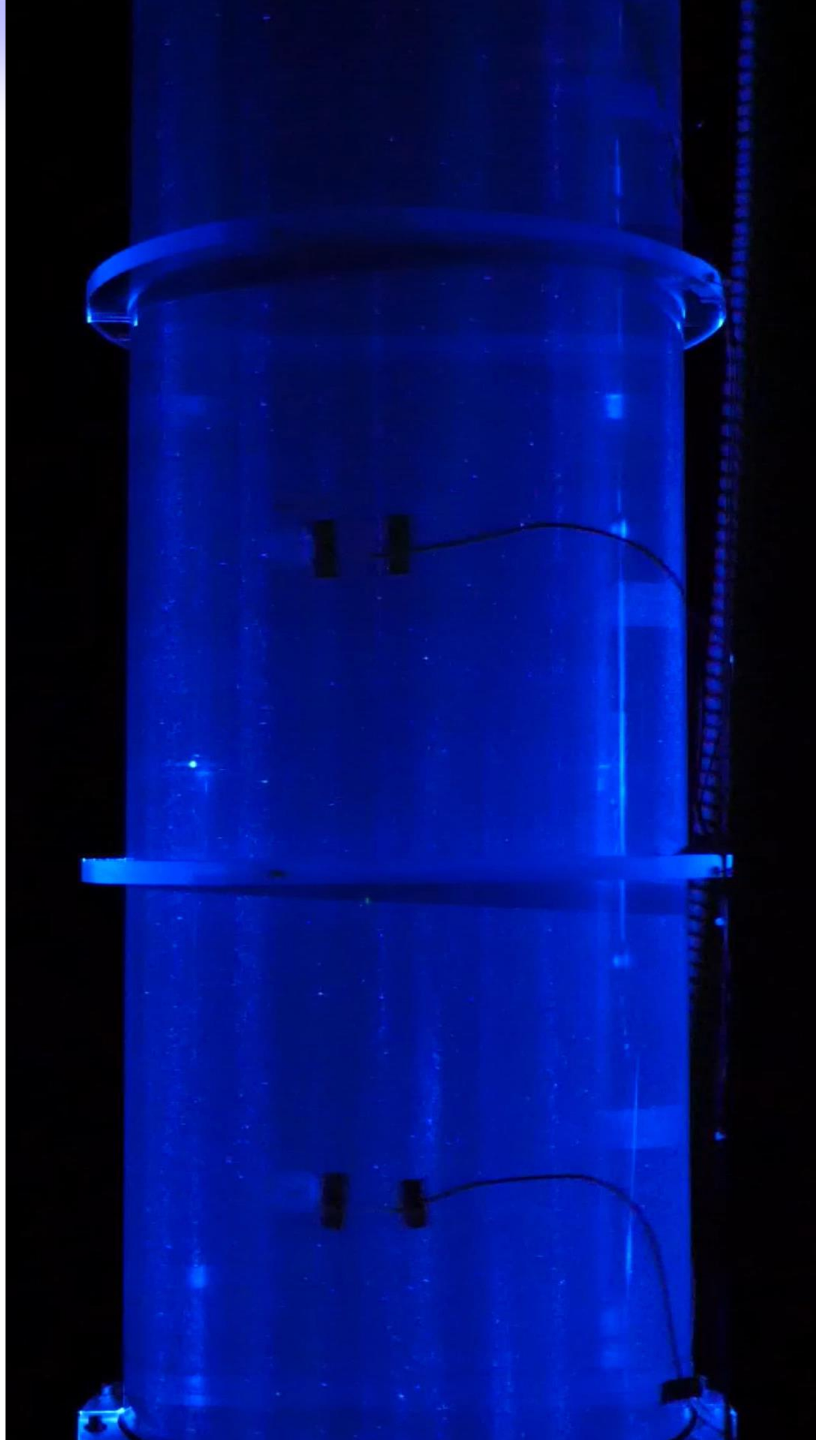
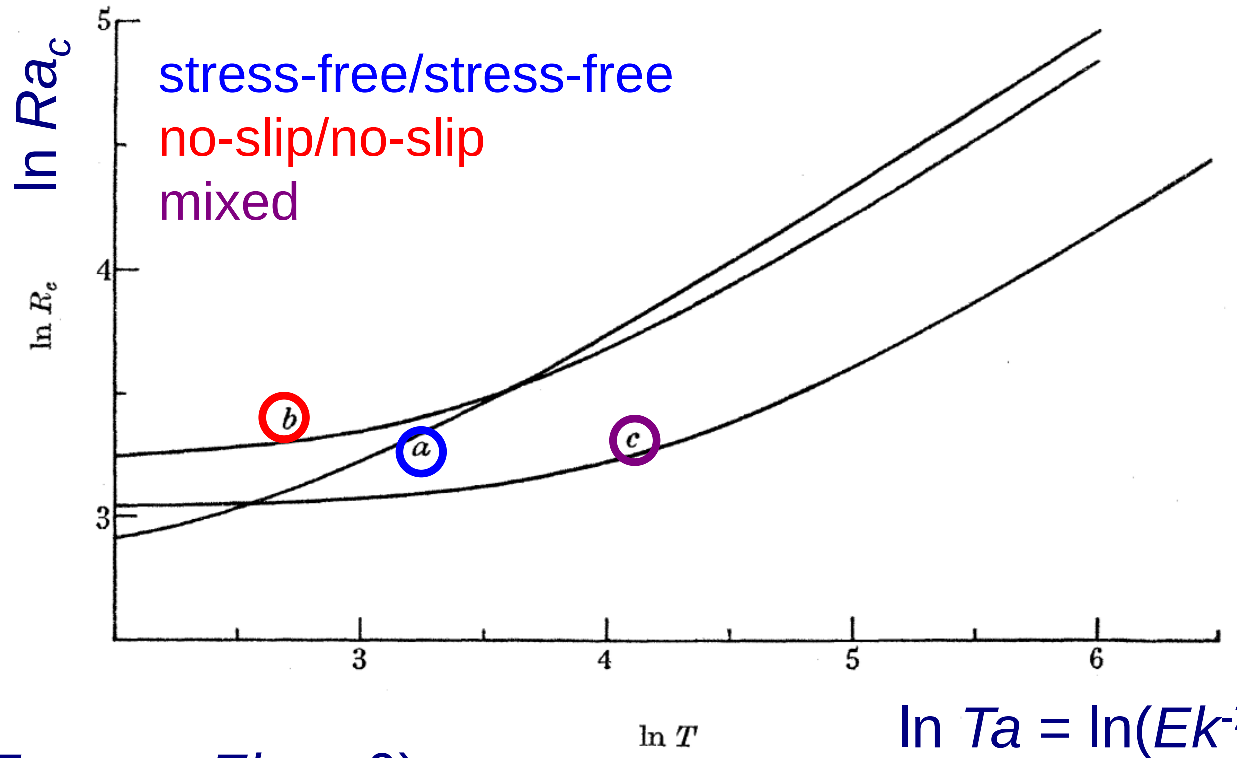


Rotation and linear stability of RB

Chandrasekhar (1953)



ln Ta = ln(Ek^{-2})

Rotation increases →

Rotation *stabilizes* convection!

Asymptote for rapid rotation ($Ta \to \infty$, $Ek \to 0$):

$Ra_c = 8.7\ Ta^{2/3} = 8.7\ Ek^{-4/3}$

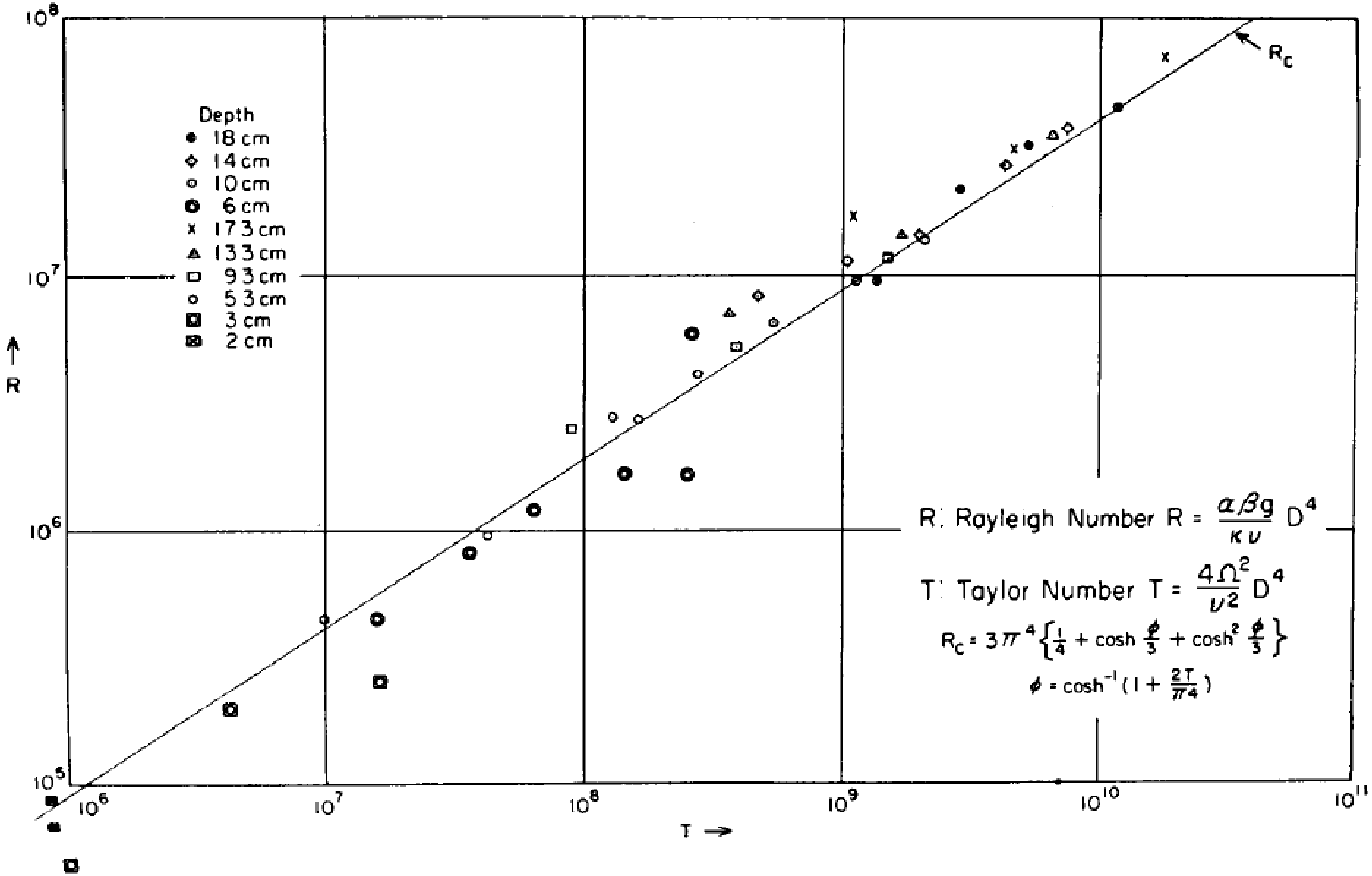
$L_c/H = 4.8\ Ta^{-1/6} = 4.8\ Ek^{1/3}$ (most unstable wavelength)

Chandrasekhar, *Proc. R. Soc. Lond. A* **217**, 306-327 (1953)

Nakagawa & Frenzen (1955)

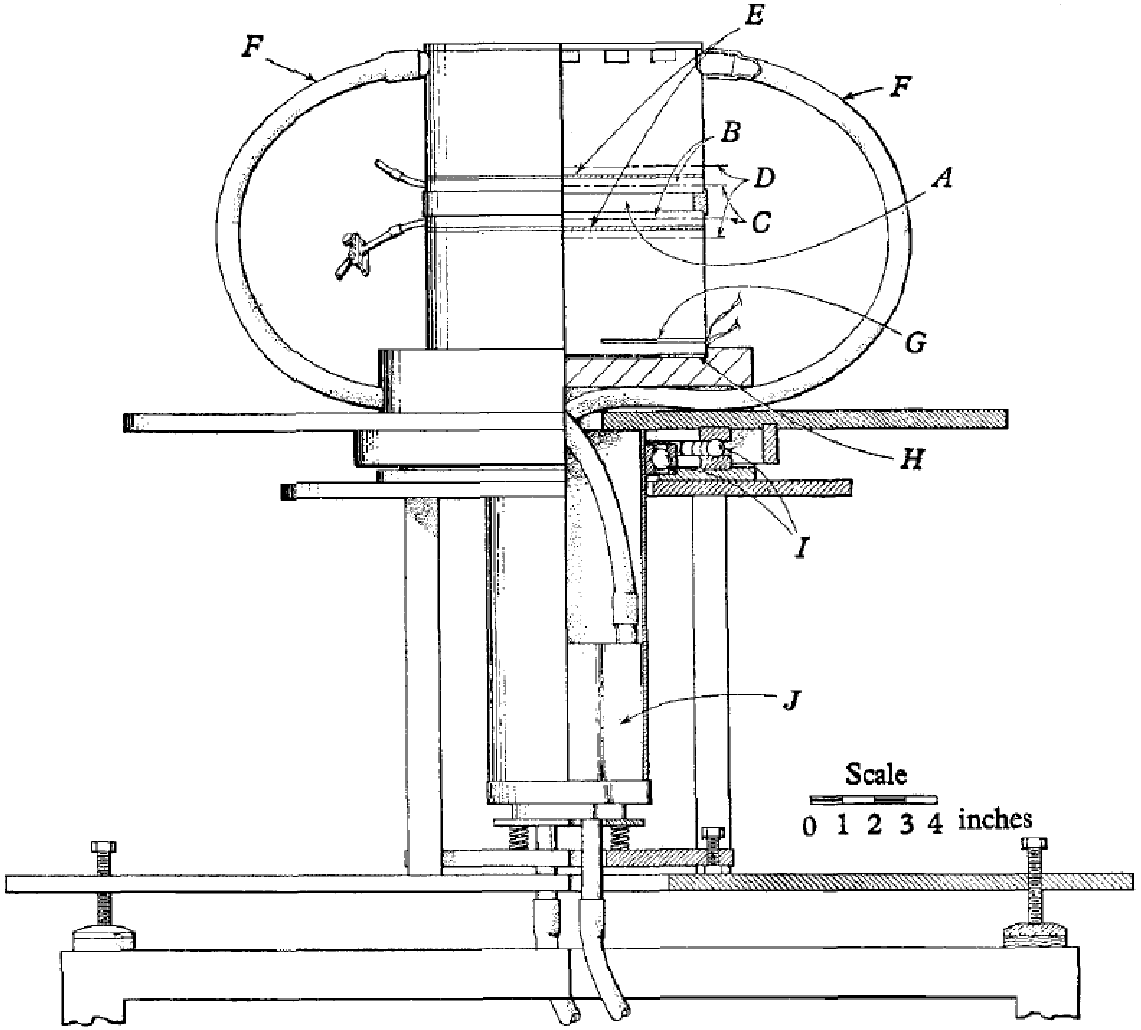
Temperature measurements in rotating water layer show convective instability

Visual confirmation



Nakagawa & Frenzen, *Tellus* **7**, 1-21 (1955)

Rossby (1969)



First extensive exploration of heat transfer in turbulent rotating convection:

Three fluids:

- mercury (*Pr* = 0.025)
- water (*Pr* = 6.8)
- [silicone oil (*Pr* = 200)]

For water:

- *Ra* up to ~ 4 x 10^6
- *Ek* down to ~ 10^{-4}

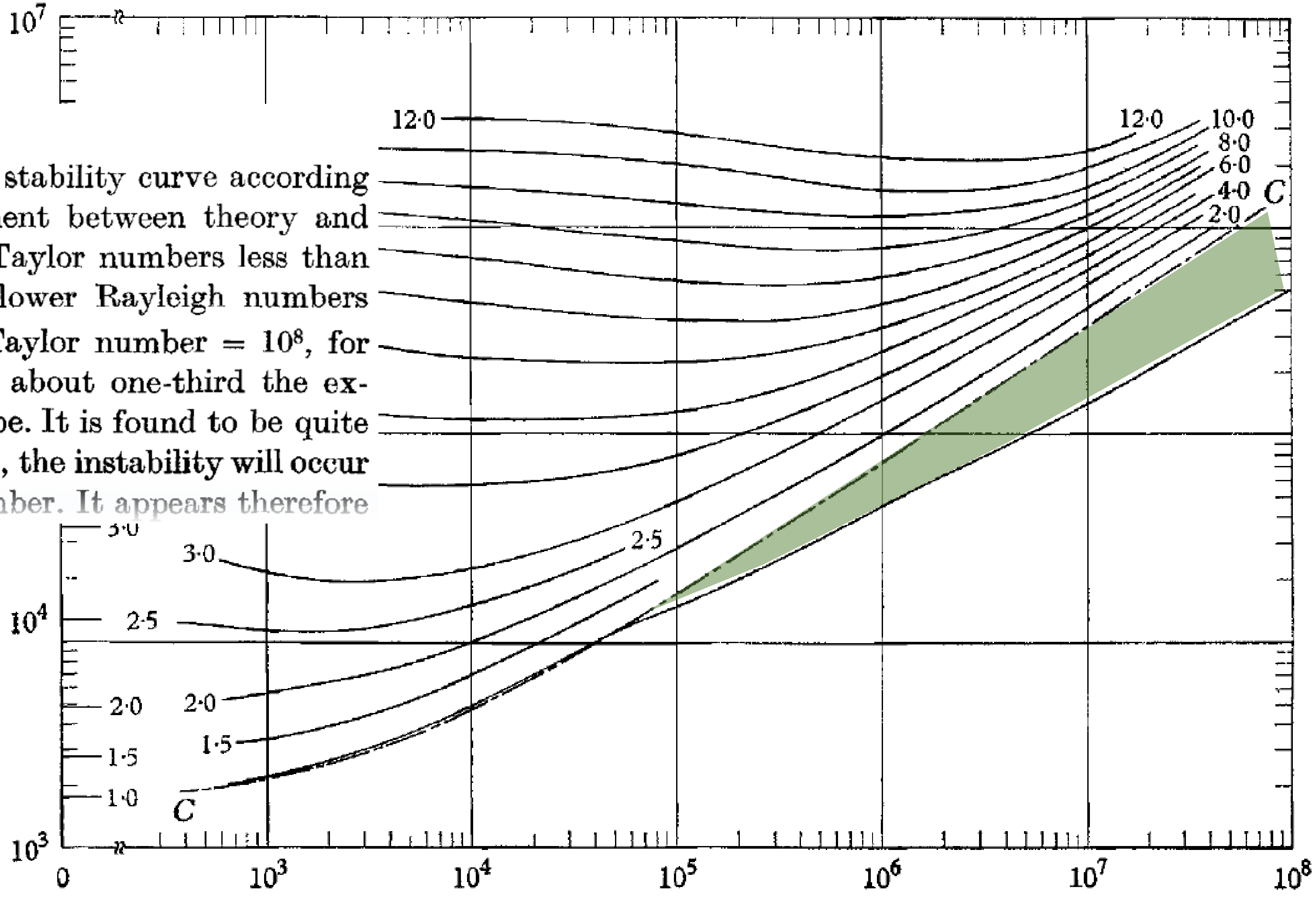
Rossby, *J. Fluid Mech.* **36**, 309-335 (1969)

Rossby (1969)

Contours of *Nu*

Water

The dot-dashed line C–C in figure 11 is the marginal stability curve according to Chandrasekhar (1961). We find excellent agreement between theory and experiment for the critical Rayleigh number at all Taylor numbers less than 5×10^4; beyond this the fluid becomes unstable at lower Rayleigh numbers than the marginal stability theory predicts. At a Taylor number $= 10^8$, for example, the measured critical Rayleigh number is about one-third the expected value. We do not understand why this should be. It is found to be quite reproducible; i.e. if one changes the depth of the fluid, the instability will occur at the same Rayleigh number for a given Taylor number. It appears therefore

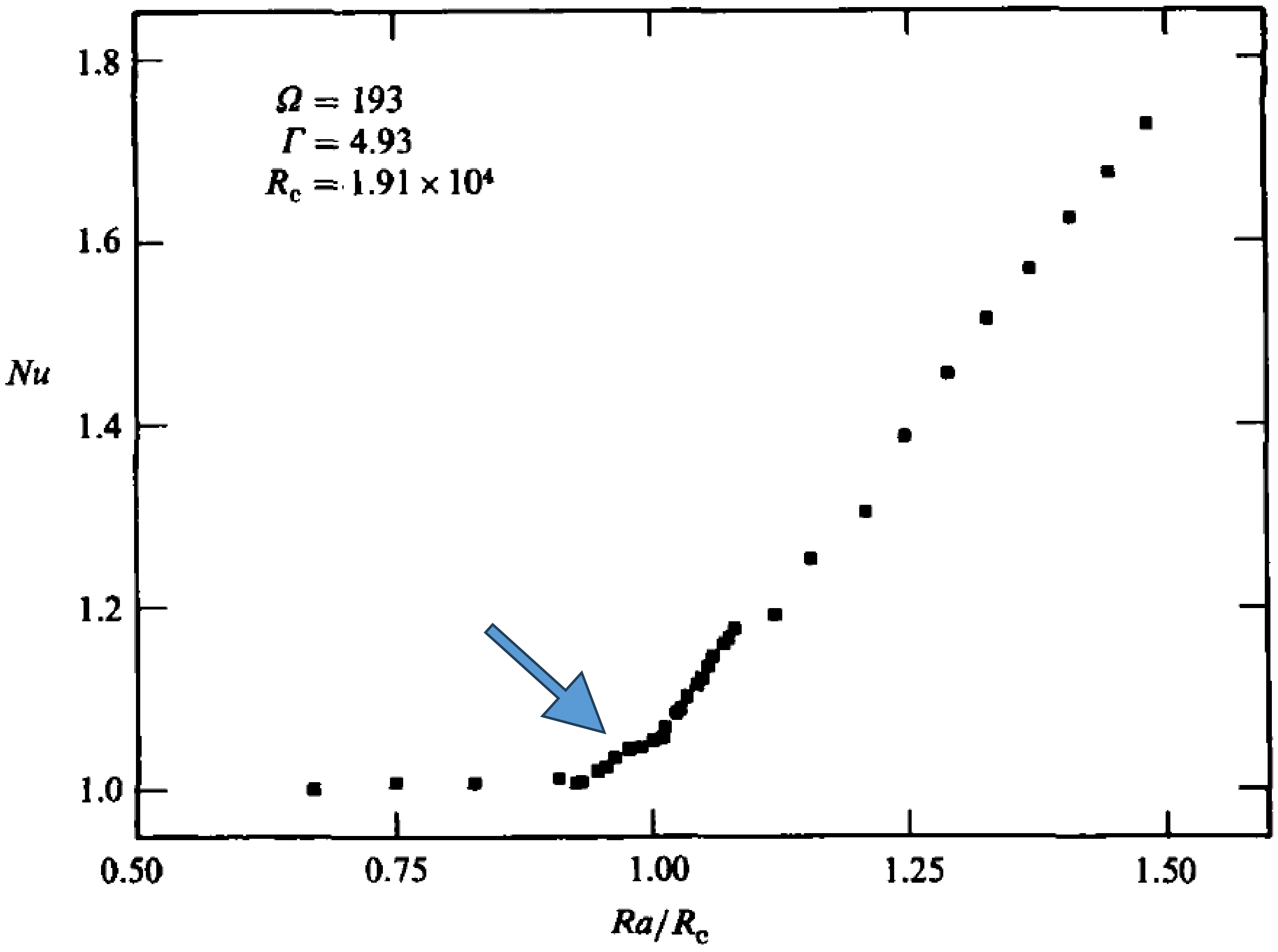


$Ta = Ek^{-2}$

Rossby, *J. Fluid Mech.* **36**, 309-335 (1969)

Pfotenhauer et al. (1987)

Rotating convection in liquid helium; onset below Ra_C confirmed

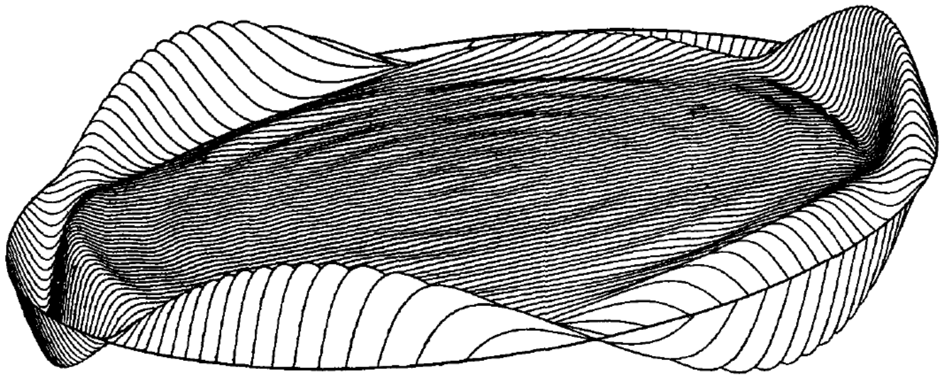


Pfotenhauer et al., *J. Fluid Mech.* **175**, 85-96 (1987)

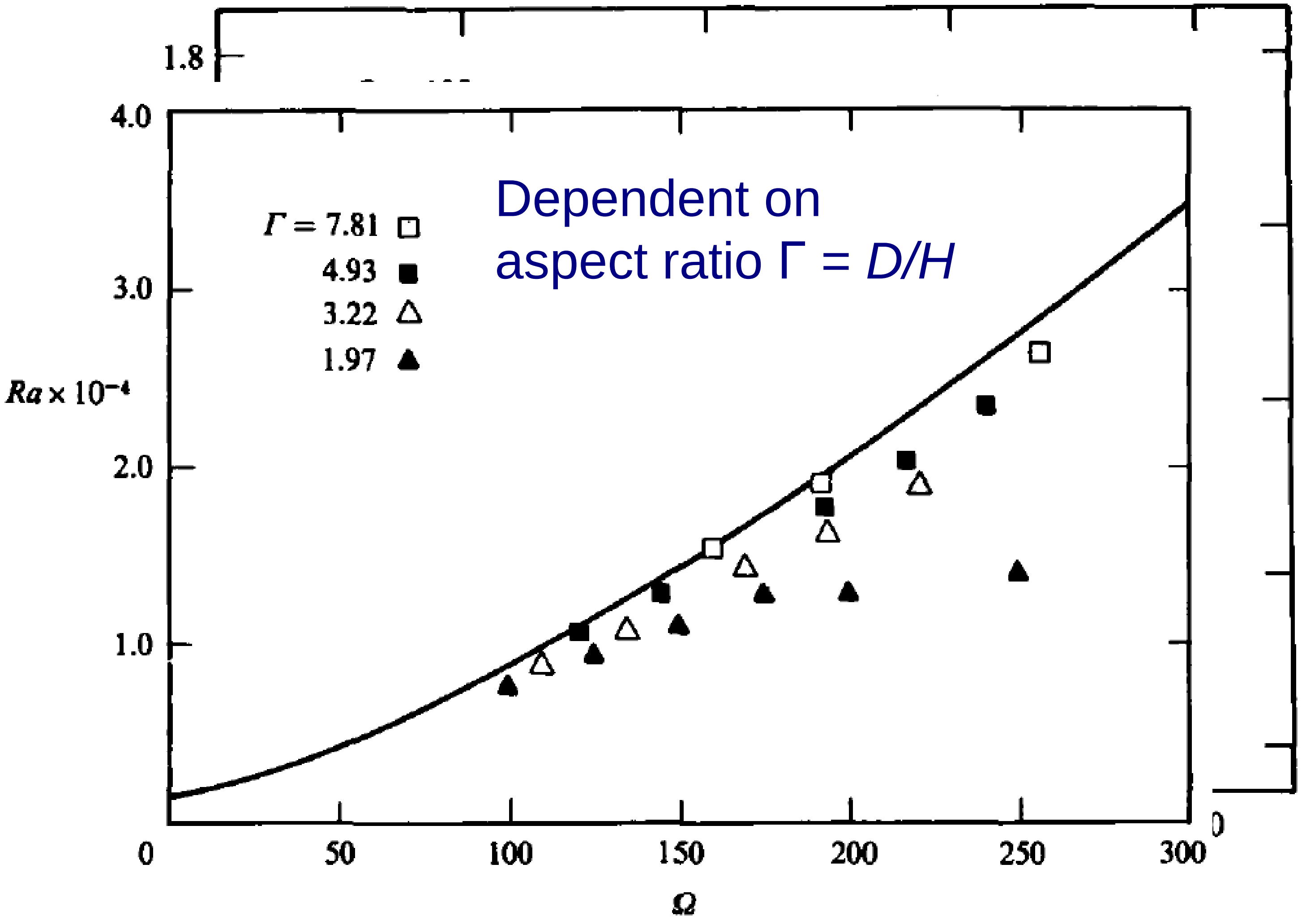
Pfotenhauer et al. (1987)

Rotating convection in liquid helium; onset below Ra_C confirmed

Postulate link with non-axisymmetric modes of convection in cylinder (Buell & Catton 1983)



Dependent on aspect ratio $\Gamma = D/H$



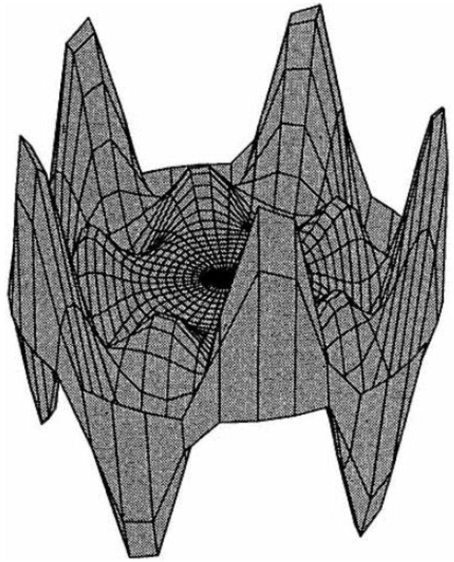
Pfotenhauer et al., *J. Fluid Mech.* **175**, 85-96 (1987) Buell & Catton, *Phys. Fluids* **26**, 892-896 (1983)

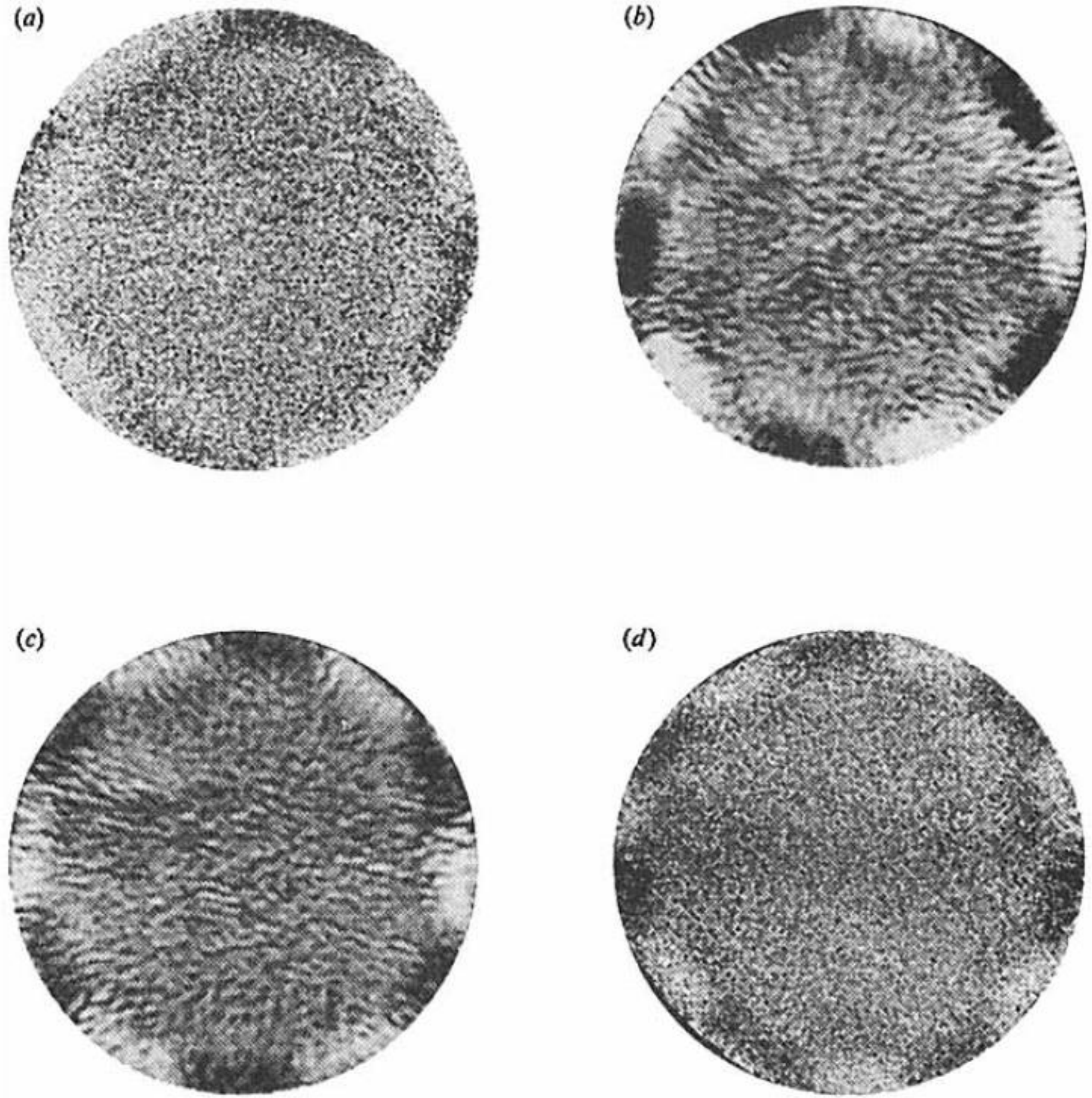
Zhong et al. (1991, 1993)

Shadowgraph confirmation of wall mode precessing anticyclonically

Not *static* asymmetric modes of Buell & Catton (1983),

but *precessing* modes of Goldstein et al. (1993)





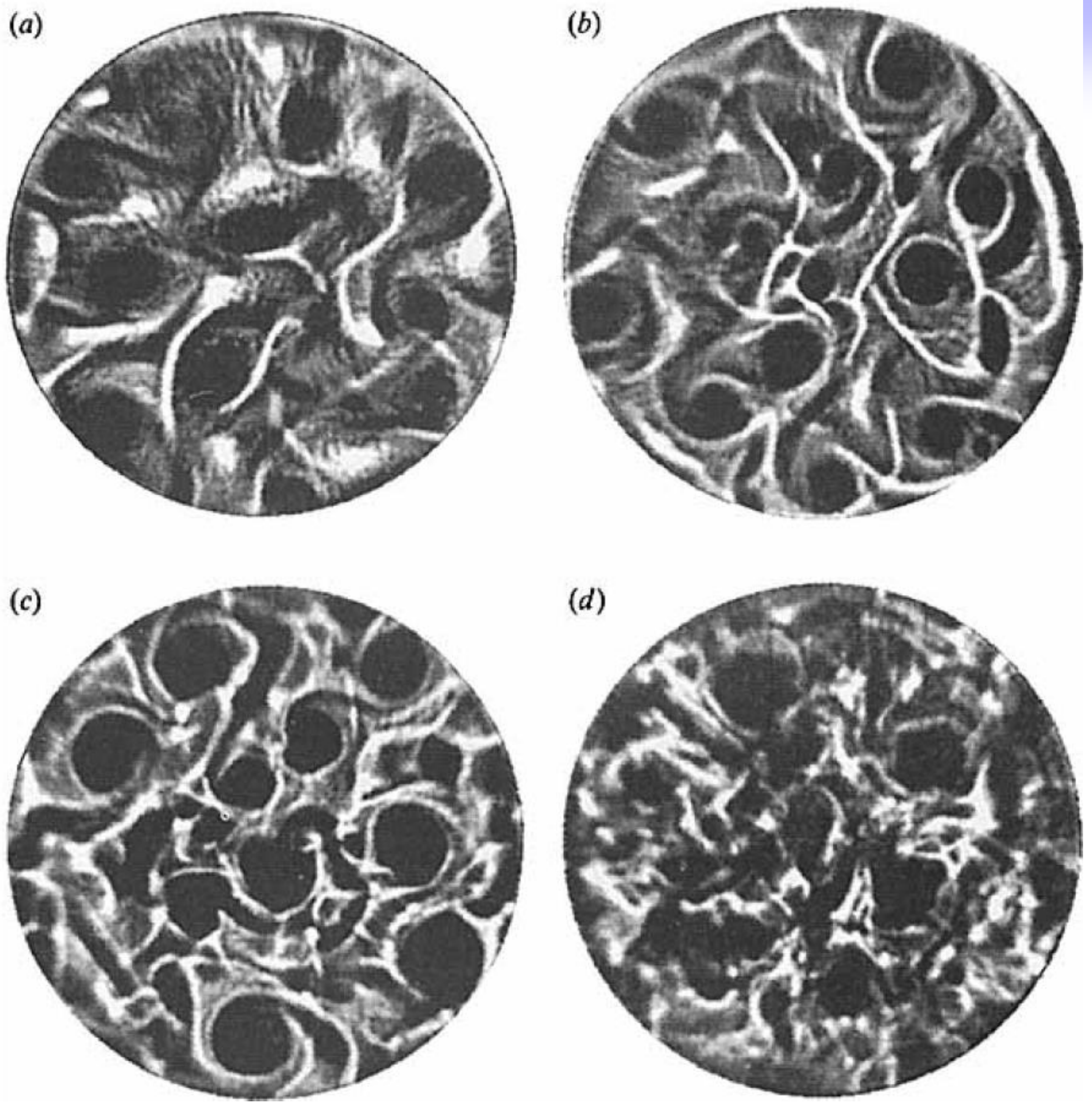
Goldstein et al., *J. Fluid Mech.* **248**, 583-604 (1993)

Zhong et al., *Phys. Rev. Lett.* **67**, 2473-2476 (1991); *J. Fluid Mech.* **249**, 135-159 (1993)

Zhong et al. (1991, 1993)

Shadowgraph confirmation of wall mode precessing anticyclonically

… and turbulence at higher *Ra*



Zhong et al., *Phys. Rev. Lett.* **67**, 2473-2476 (1991); *J. Fluid Mech.* **249**, 135-159 (1993)

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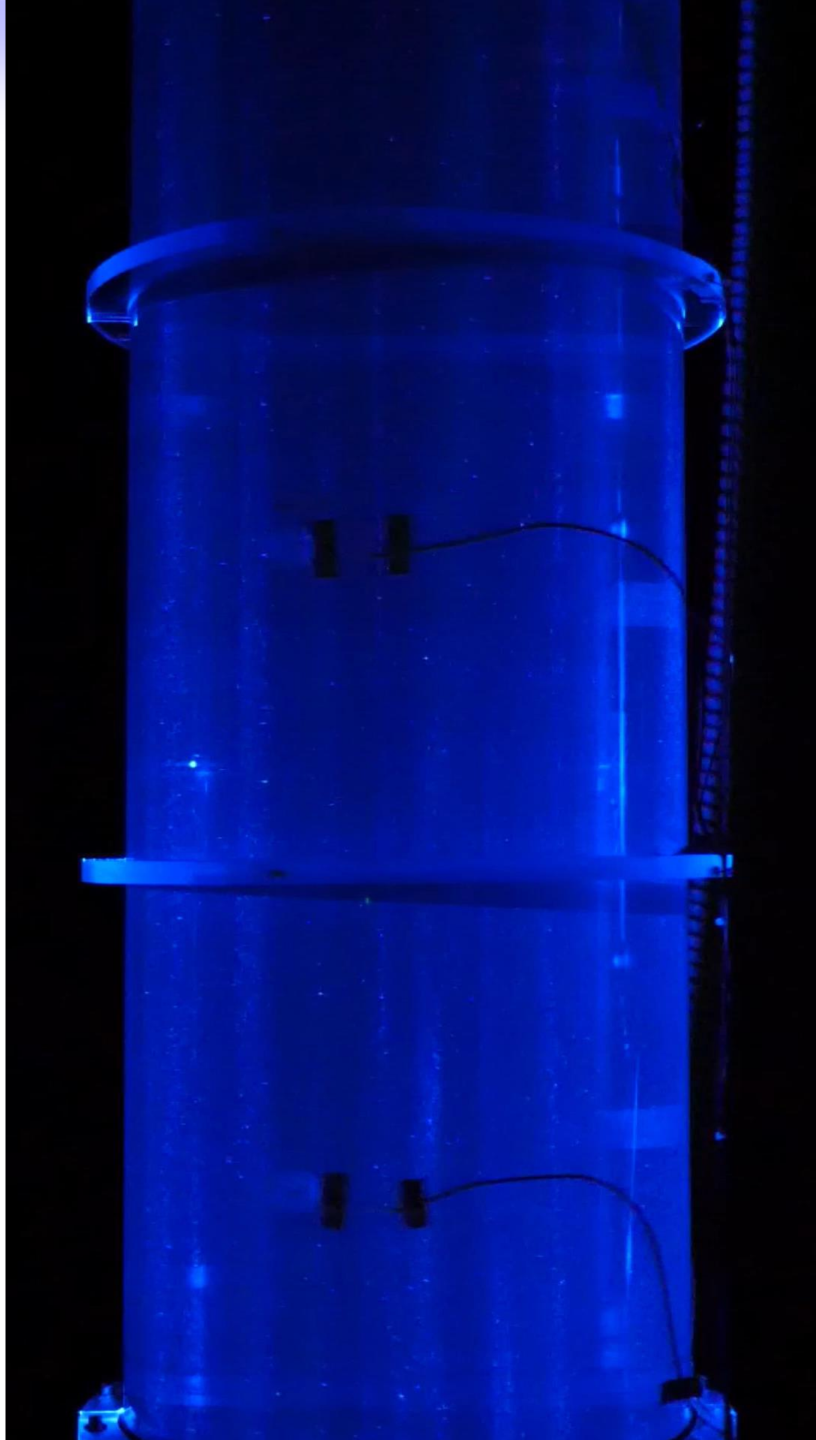
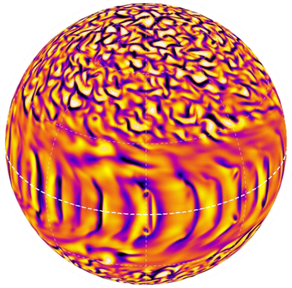


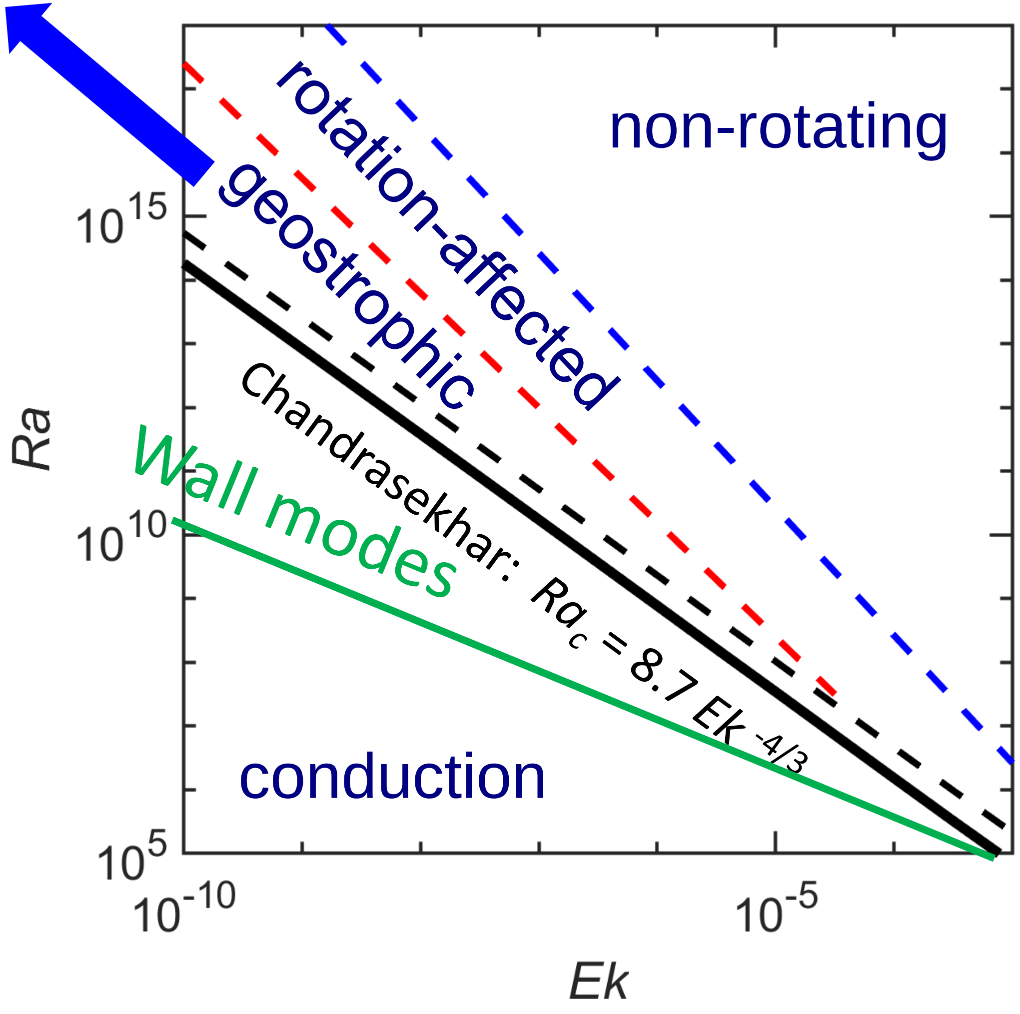
Phase diagram of rotating convection

Geo-/astrophysics:

Ra ~ $10^{20} – 10^{25}$

Ek ~ $10^{-15} – 10^{-12}$





← Rotation increases

Need to understand geostrophic convection for accurate extrapolation!

Ecke & Niemela, *Phys. Rev. Lett.* **113**, 114301 (2014)
Kunnen et al., *J. Fluid Mech.* **799**, 413-432 (2016)
Kunnen, *J. Turbul.* **22**, 267-296 (2021)

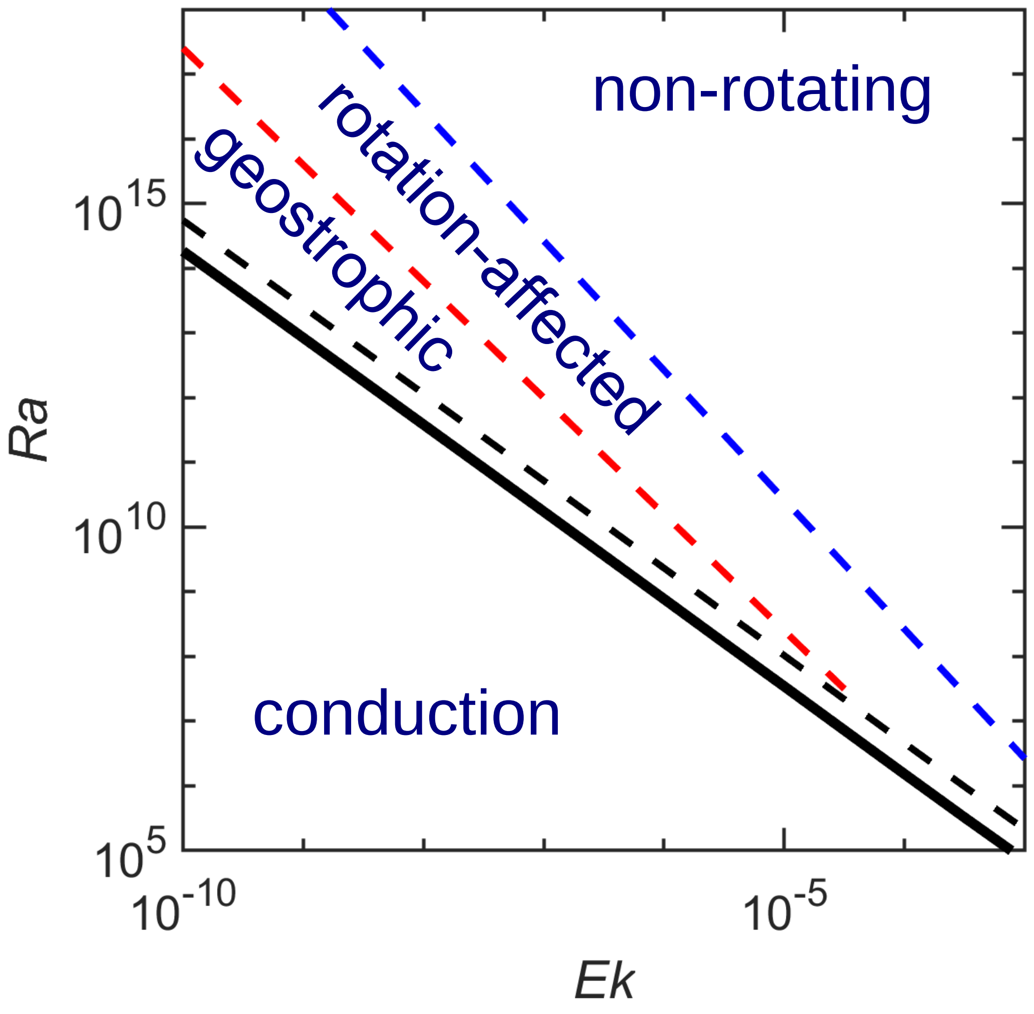
Realizing geostrophic convection in the lab

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

$$Ek = \frac{\nu}{2\Omega H^2}$$

Size matters!

However, there are practical constraints



← Rotation increases

Realizing geostrophic convection in the lab

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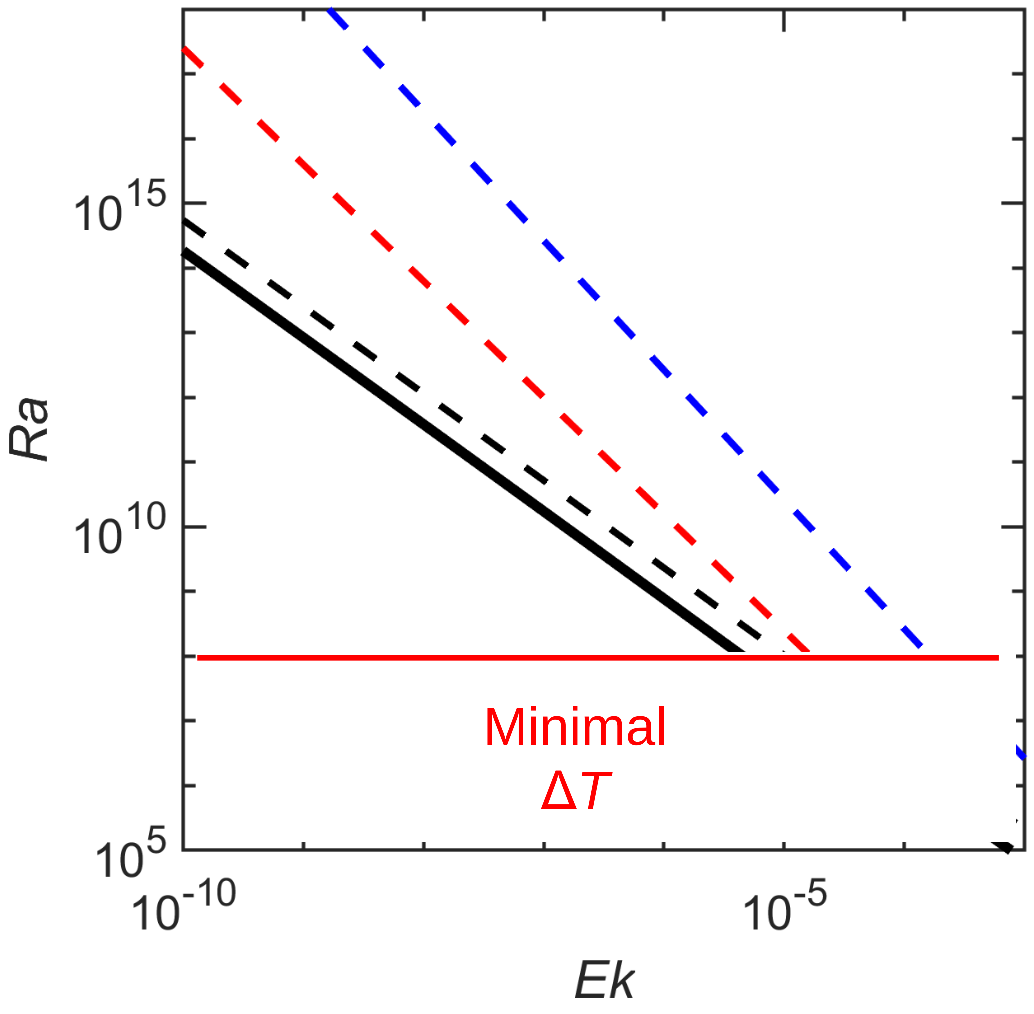

Constraint #1:

Minimal Δ*T*
in practice

Minimal heat flux

Realizing geostrophic convection in the lab

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

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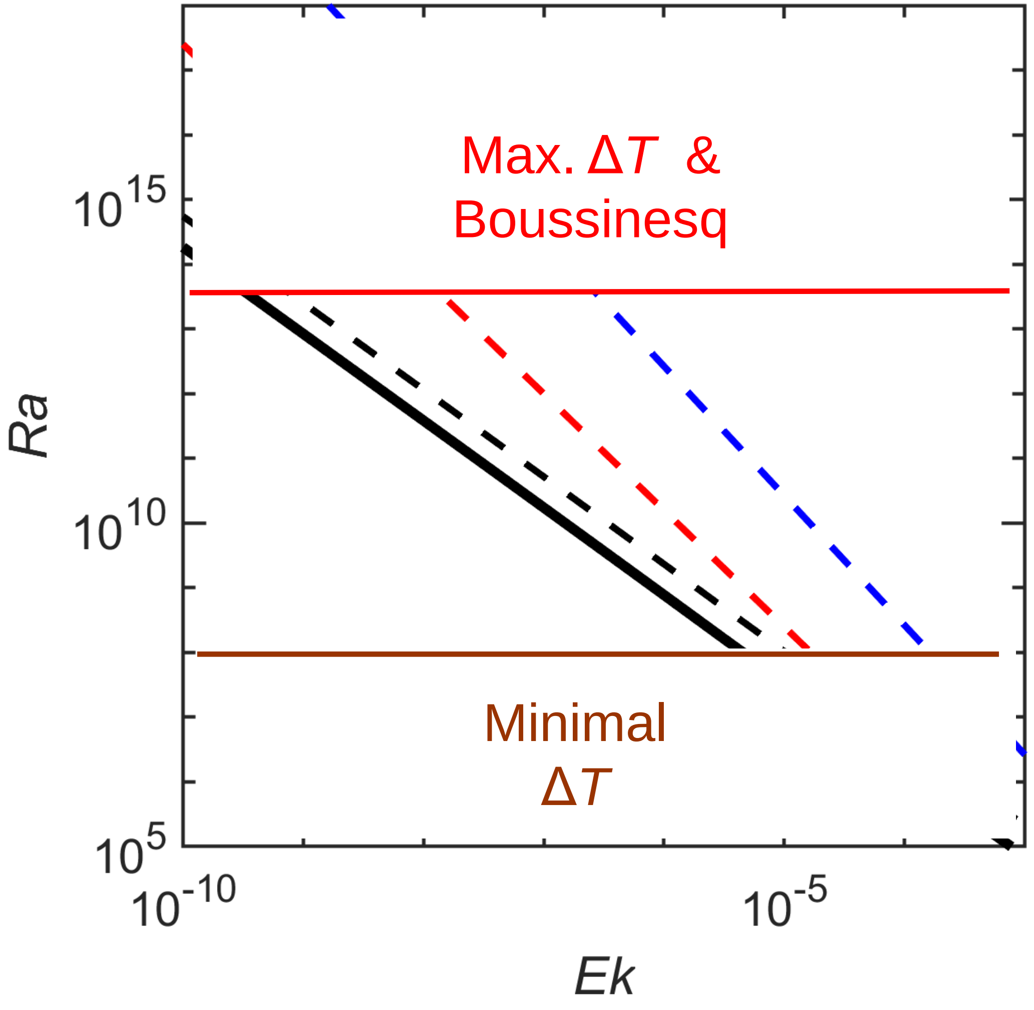


Constraint #2:

Maximal ΔT in practice

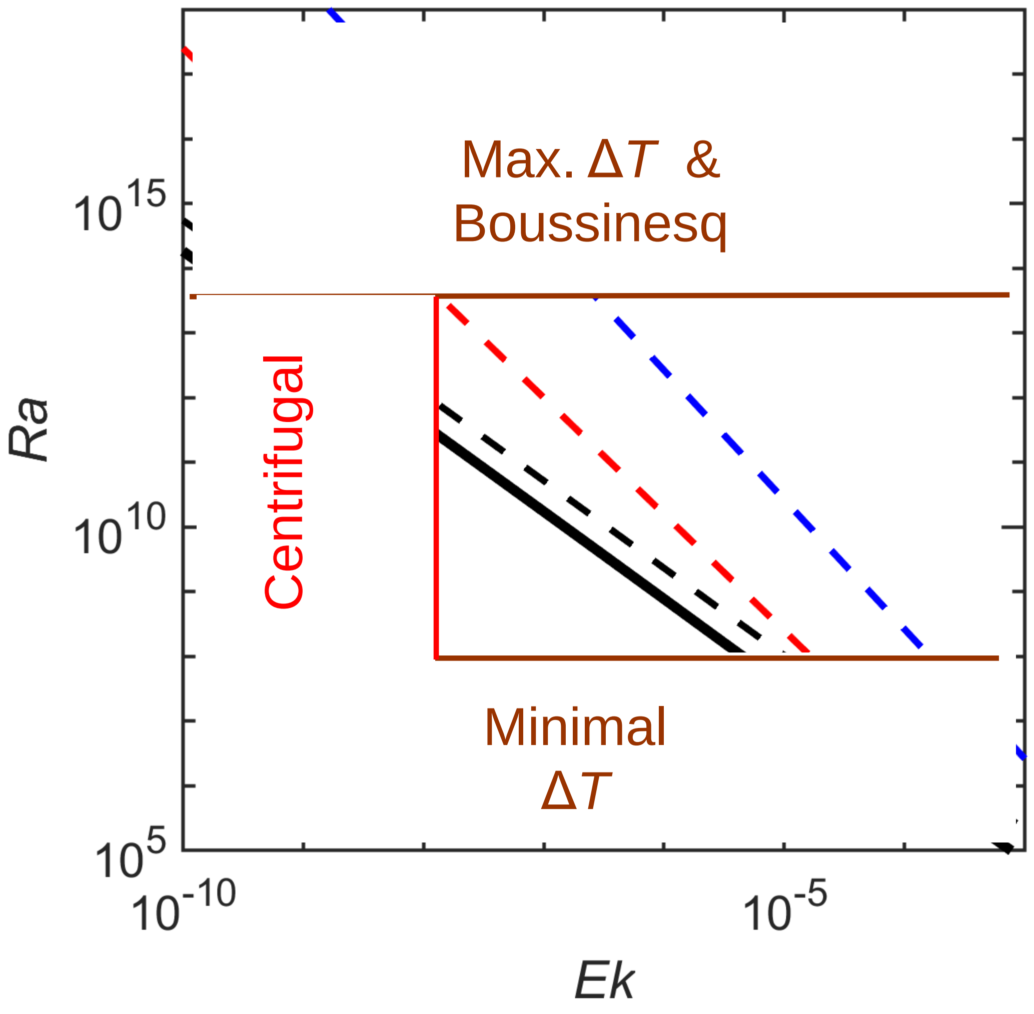
Maximal heat flux

Retain Boussinesq conditions

Realizing geostrophic convection in the lab

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

$$Ek = \frac{\nu}{2\Omega H^2}$$



Constraint #3:

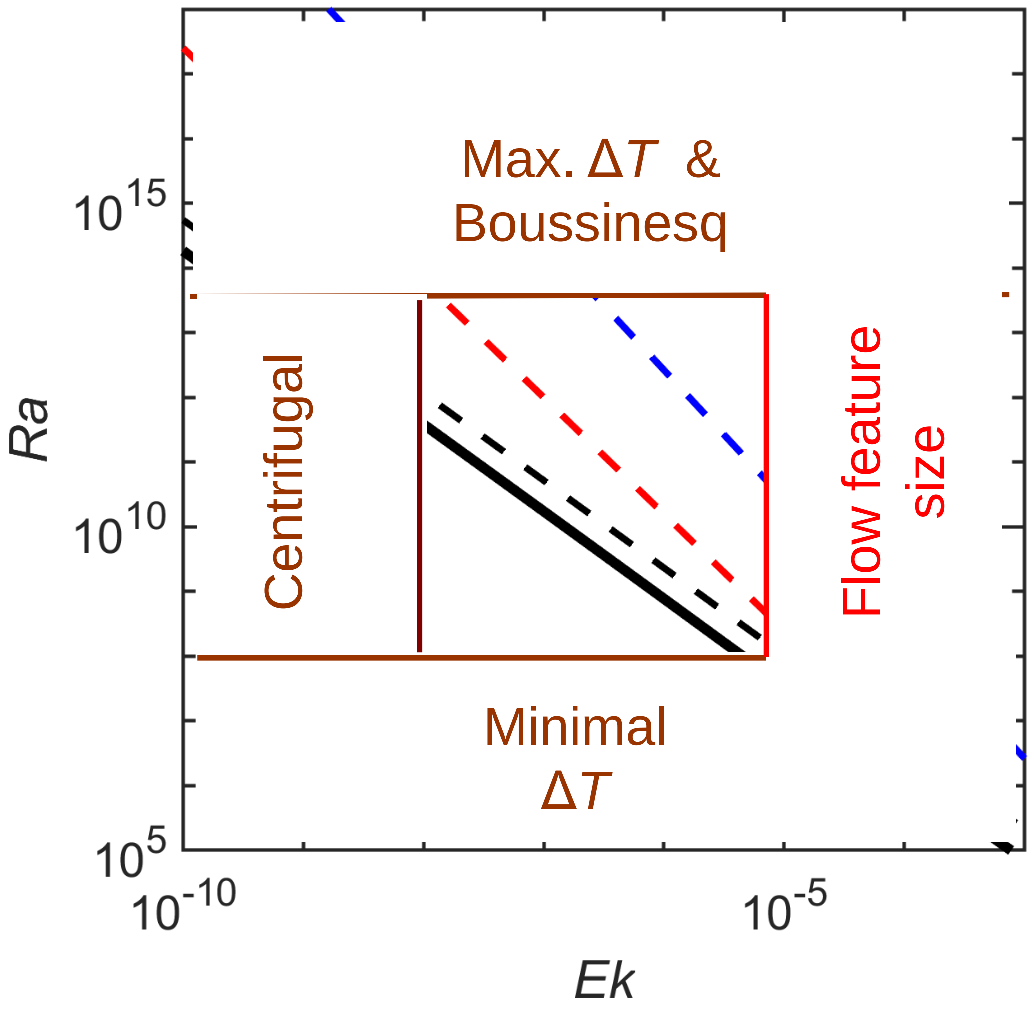
Centrifugal effects:

$Fr = \Omega^2 R / g < 0.1$

Realizing geostrophic convection in the lab

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

$$Ek = \frac{\nu}{2\Omega H^2}$$



Constraint #4:

Diameter vs. size of flow features:

$D/L_c > \sim 10$

$$L_c = 4.8\, Ek^{1/3} H$$

Tall, slender setups

Cheng et al. (2018)

a. RoMag, UCLA, liquid Ga

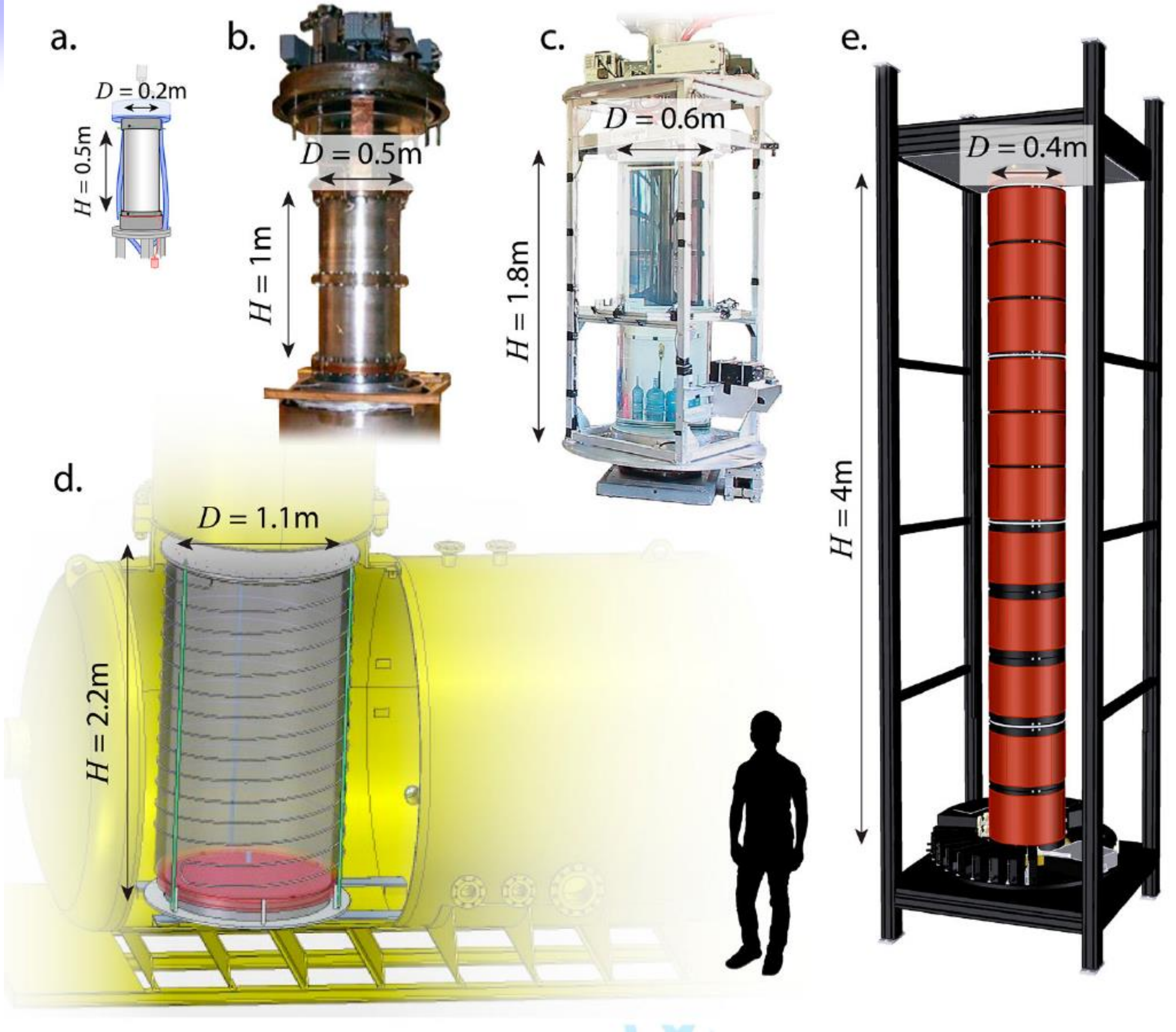
b. ICTP (Trieste), cryogenic He

c. NoMag, UCLA, water

d. U-Boot, MPI-DS Göttingen, $SF_6/N_2/He$

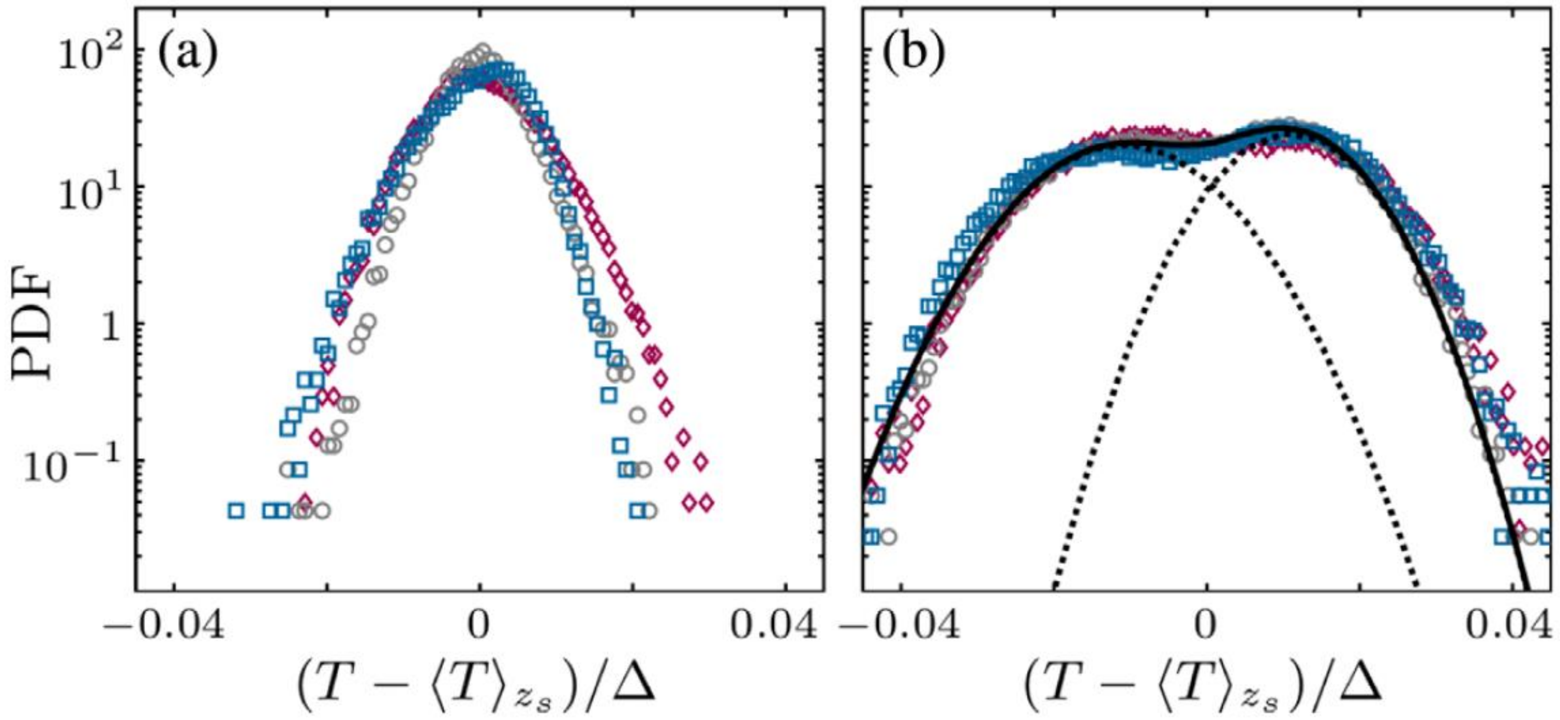
e. TROCONVEX, Eindhoven, water

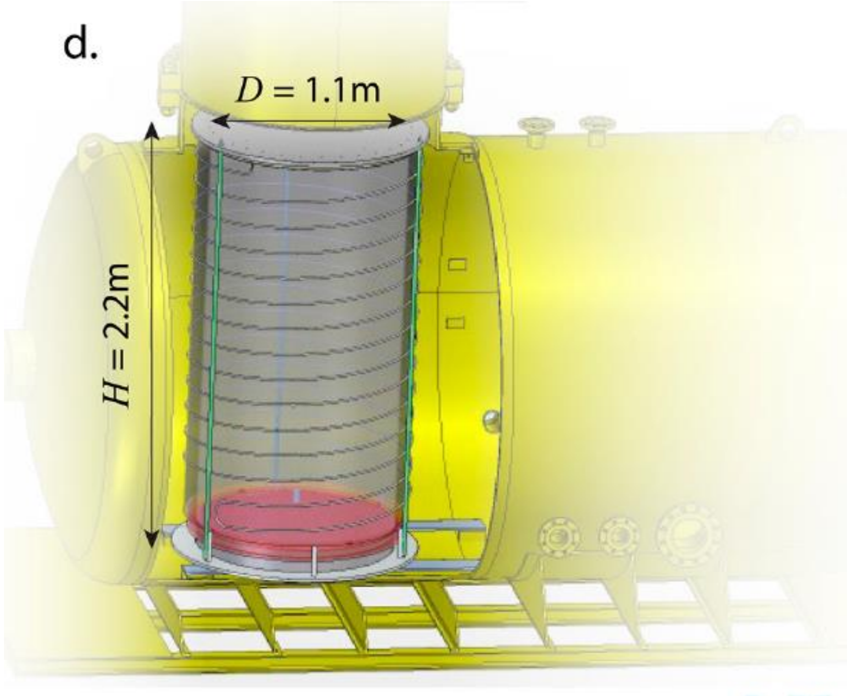
Cheng et al., *GAFD* **112**, 277-300 (2018)



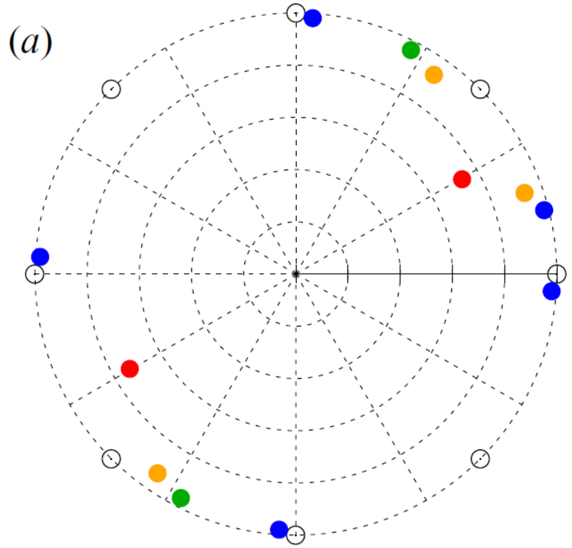
Göttingen U-Boot

No rotation (Zhang et al 2020) Rotation





Temperature probes near sidewall
(Wedi et al 2021)



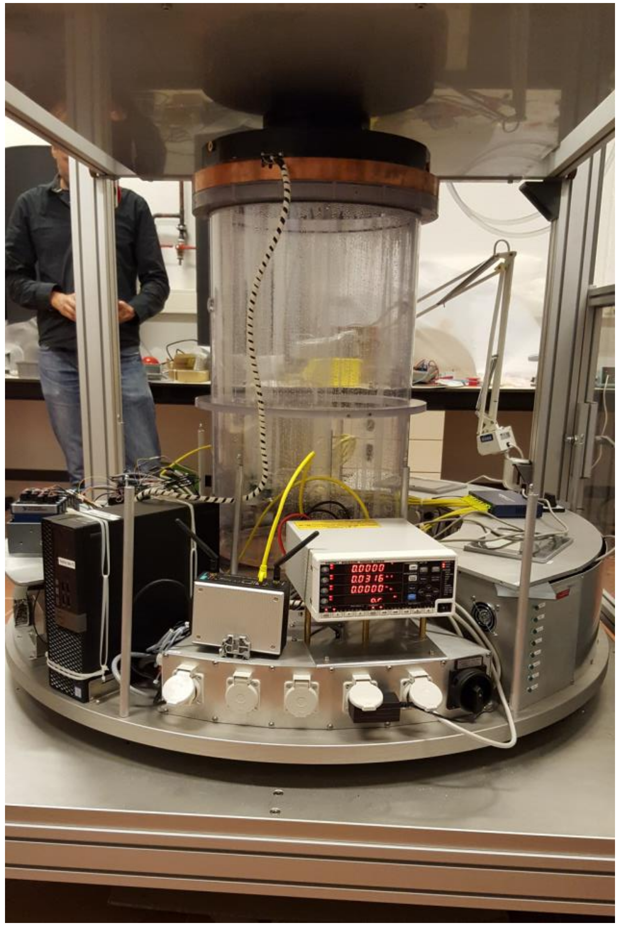
Zhang et al., *Phys. Rev. Lett.* **124**, 084505 (2020); Wedi et al., *J. Fluid Mech.* **912**, A30 (2021)

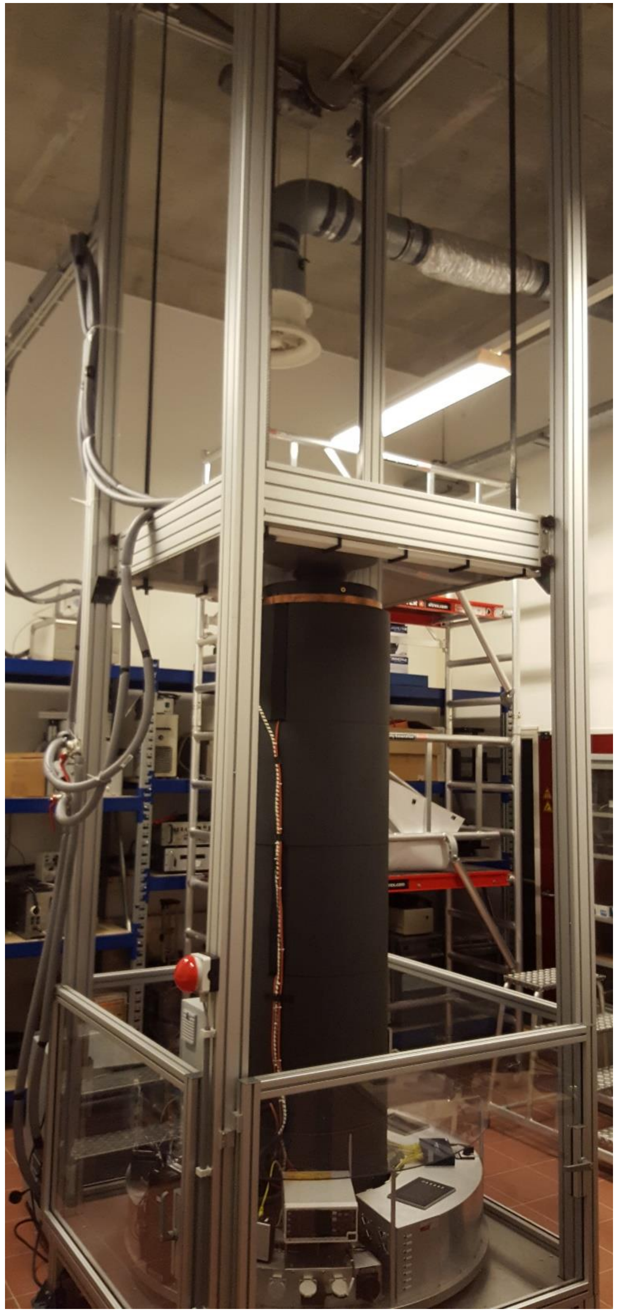
Eindhoven: TROCONVEX

Variable height: 0.8 – 4 m at constant diameter 0.4 m

Active heat shields on side & bottom

Can also use optical flow diagnostics (stereo-PIV)





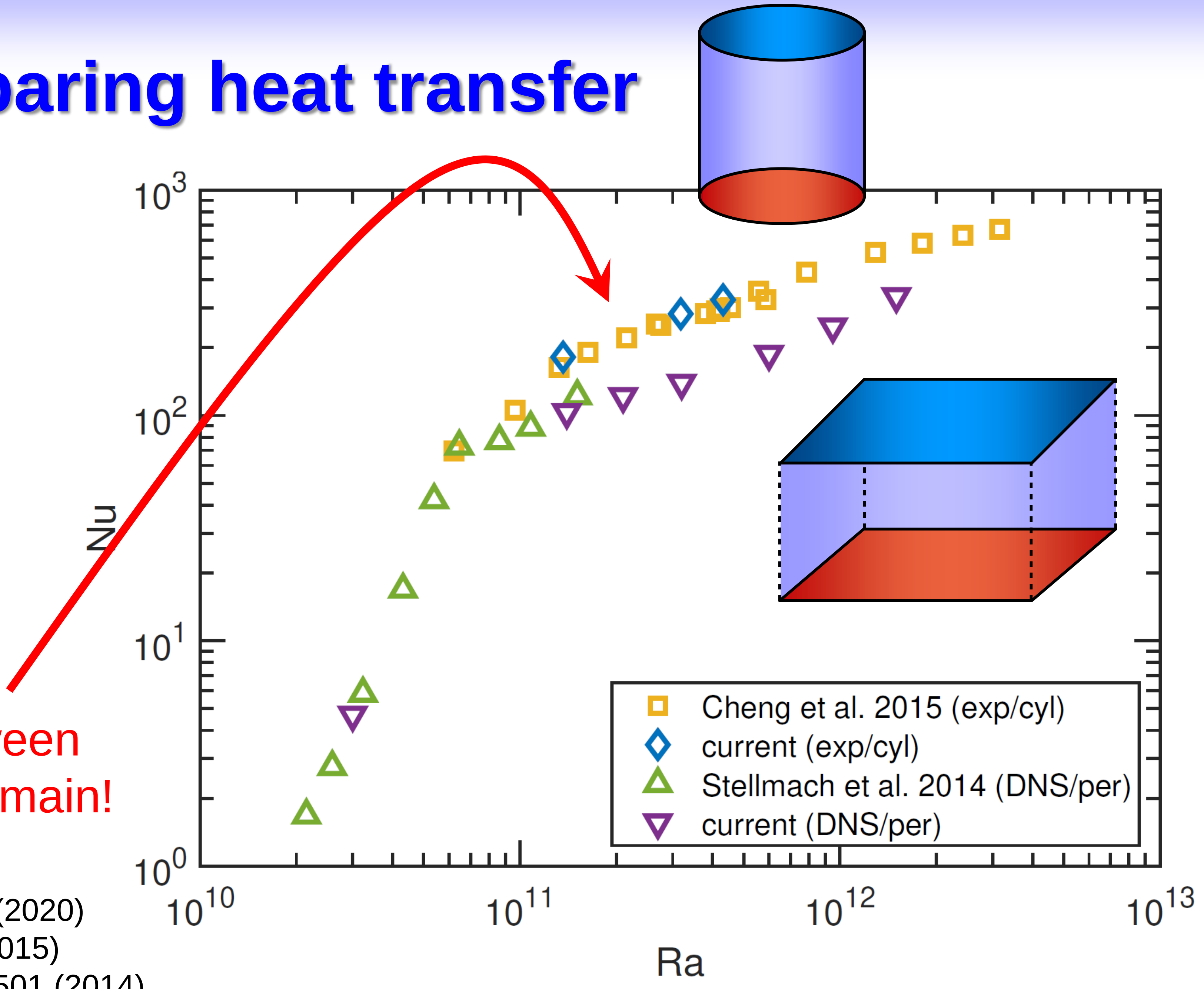
Eindhoven: comparing heat transfer

Nusselt number:

$$Nu = \frac{\text{total heat flux}}{\text{conduction}}$$

At constant $Ek = 10^{-7}$

Nu differs by factor 2 between cylinder & hor. periodic domain!



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)
Cheng et al., *Geophys. J. Int.* **201**, 1-17 (2015)
Stellmach et al., *Phys. Rev. Lett.* **113**, 254501 (2014)

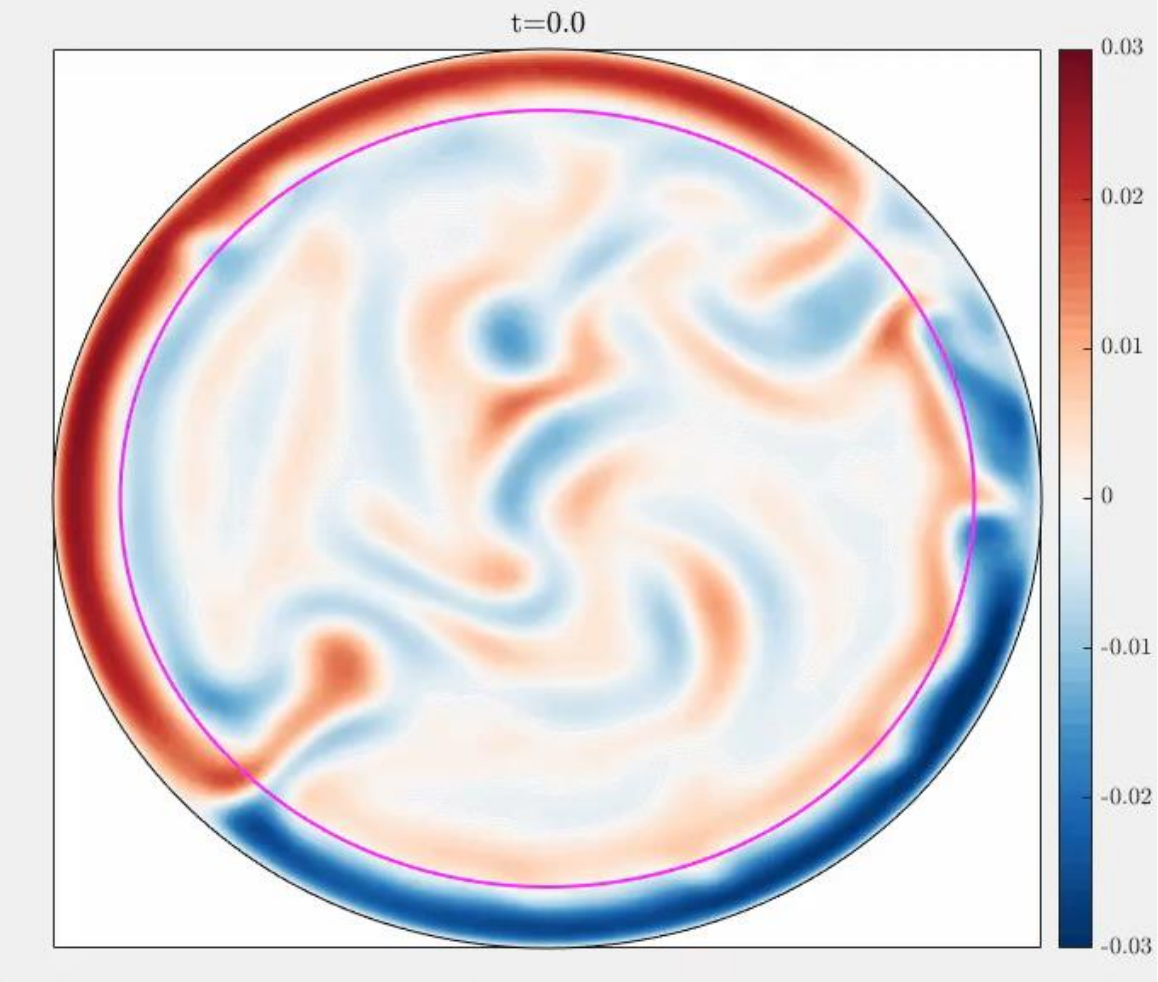
What is going on?

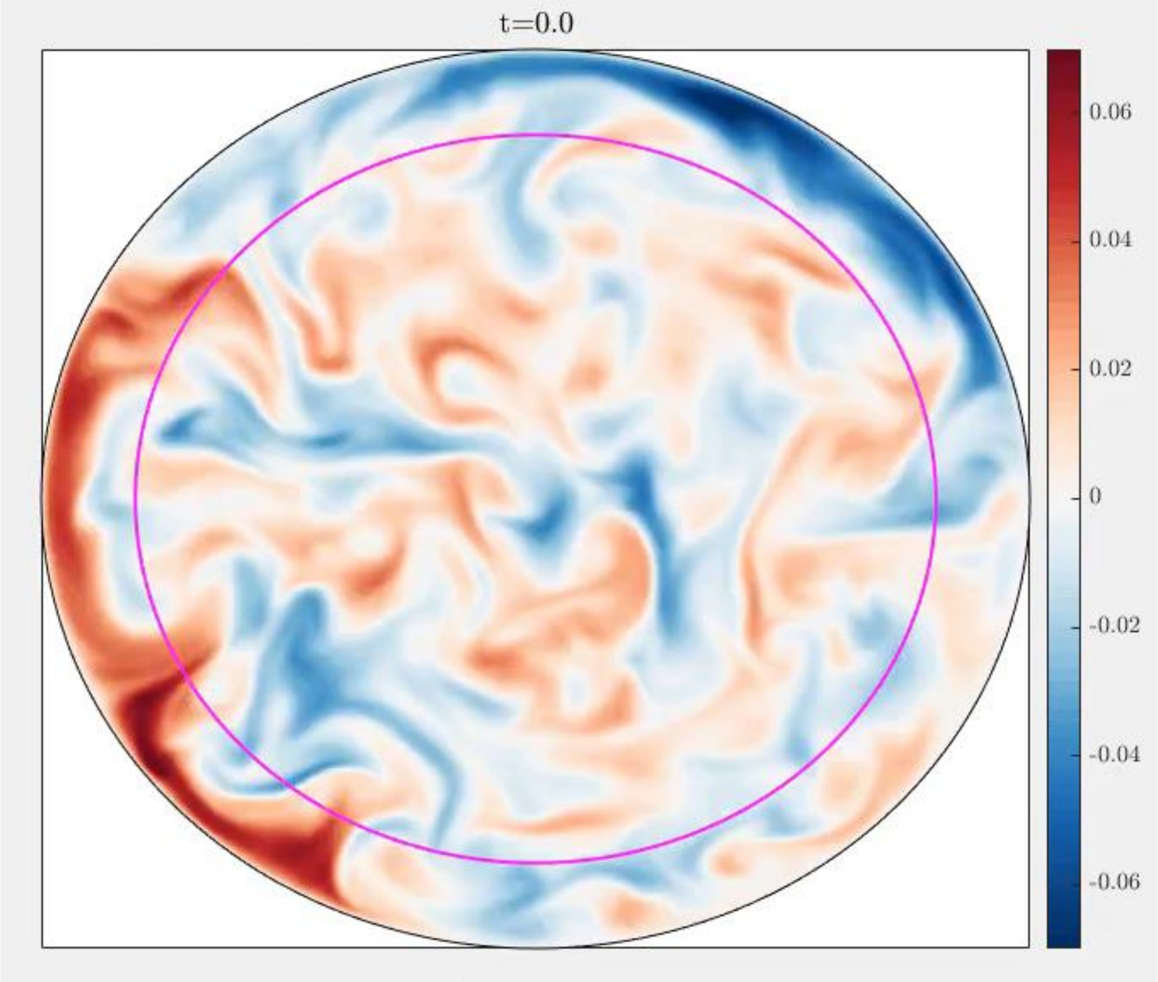
cylinder simulations – vertical velocity at mid-height

What is going on?

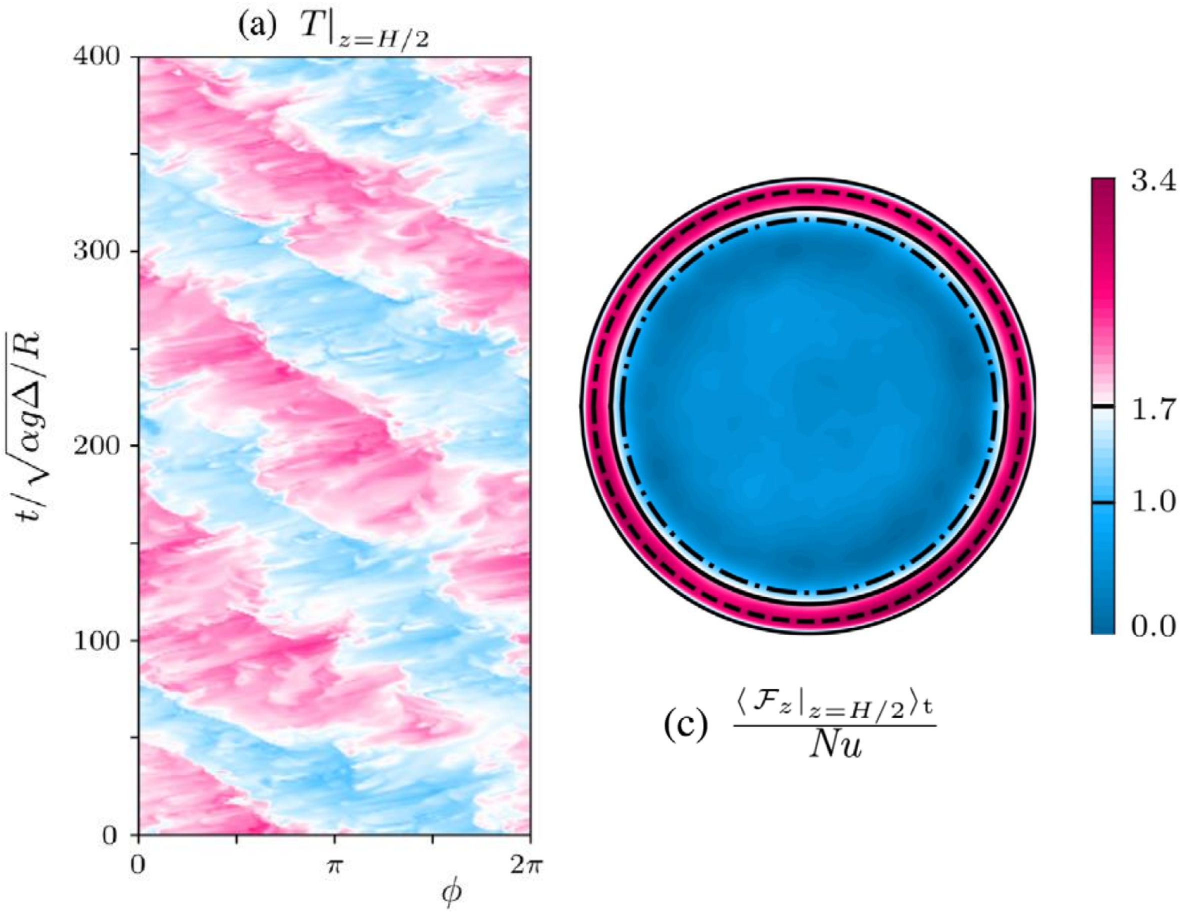
cylinder simulations – vertical velocity at mid-height

Ra = 5.0 x 10^{10} *Ek* = 10^{-7} *Ra* = 4.3 x 10^{11}



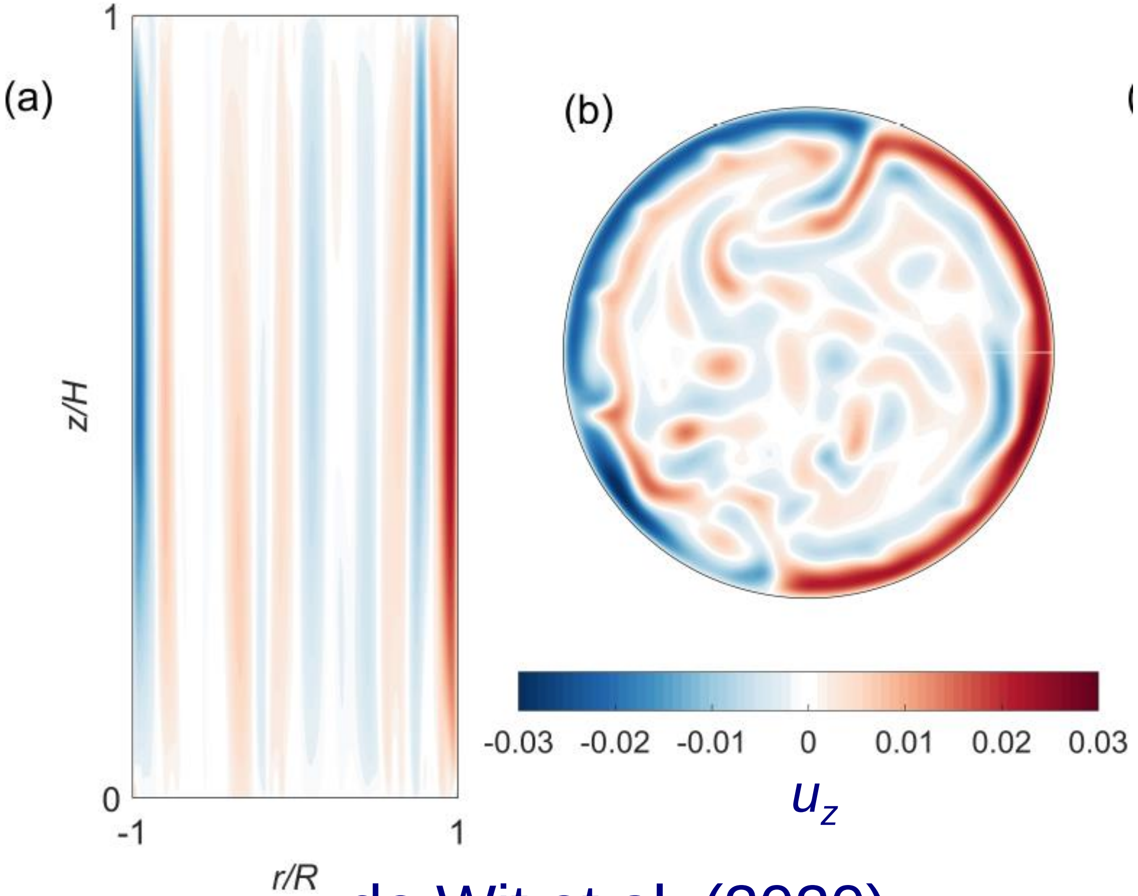


Wall modes persist!



Zhang et al. (2020)

$Ra = 10^9$ $Pr = 0.8$ $Ek = 3 \times 10^{-6}$ $D/H = 1/2$



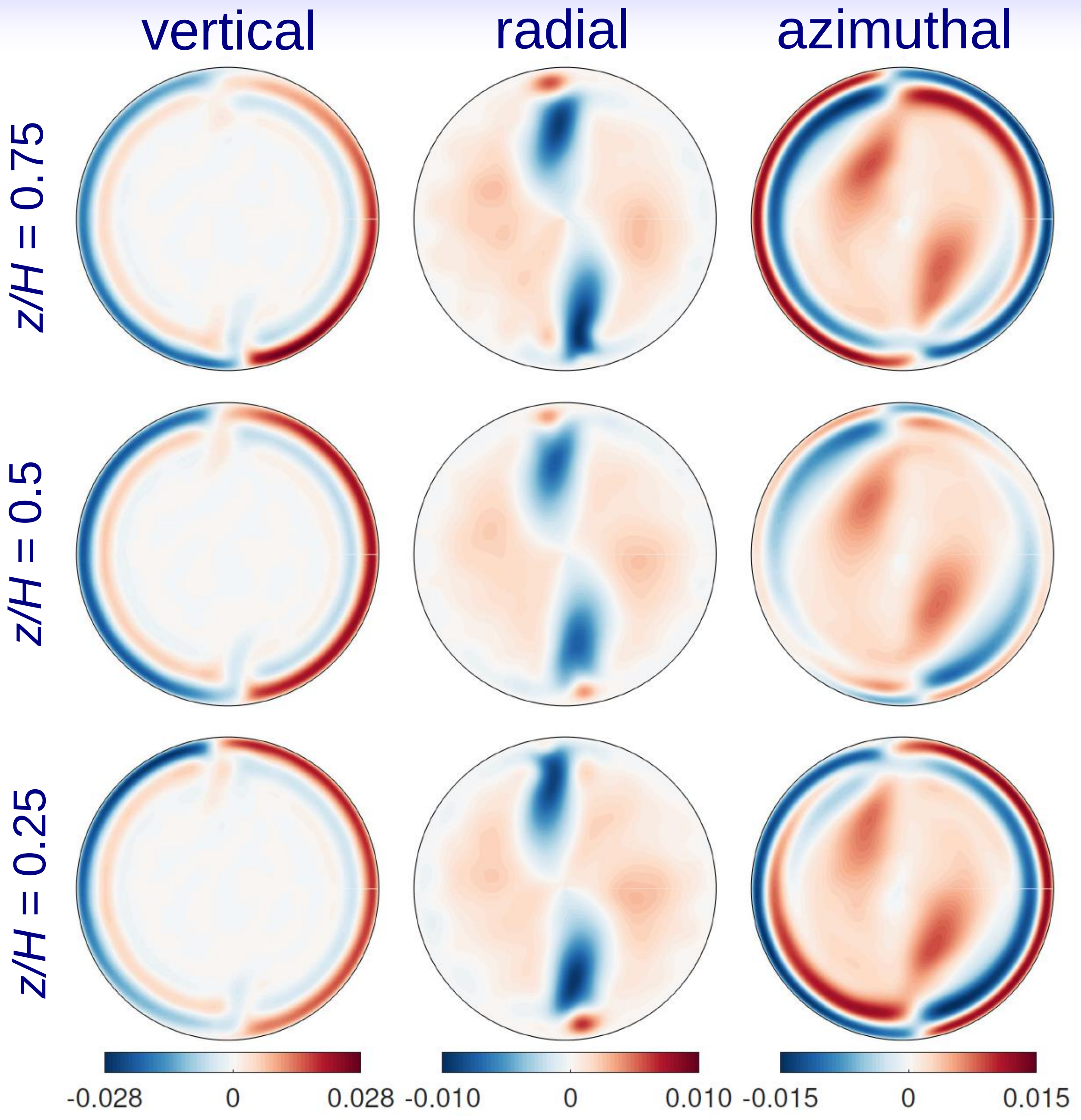
de Wit et al. (2020)

$Ra = 5 \times 10^{10}$ $Pr = 6.4$ $Ek = 10^{-7}$ $D/H = 1/5$

Zhang et al., *Phys. Rev. Lett.* **124**, 084505 (2020); de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

Orientation-compensated mean flow - ”low” *Ra*

- Bulk: mean flow is geostrophic (independent of z)
- Strong two-layer sidewall circulation with jets directed into bulk



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

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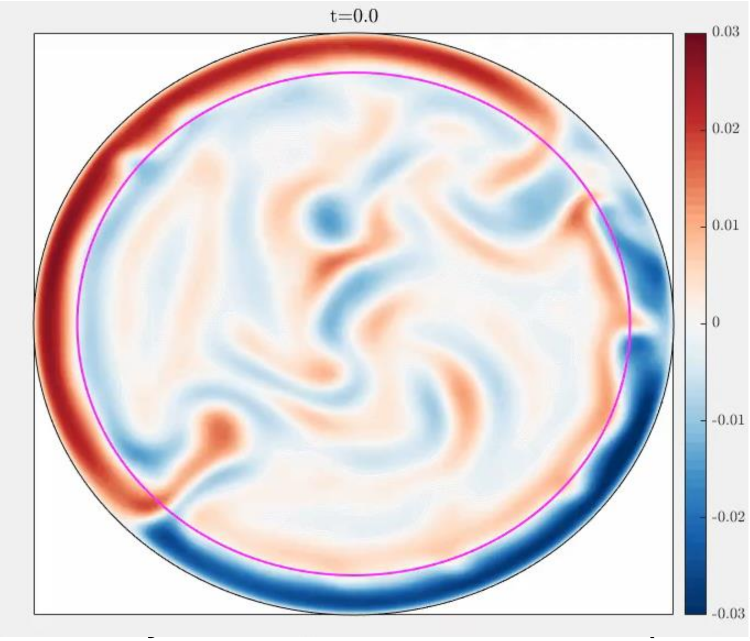
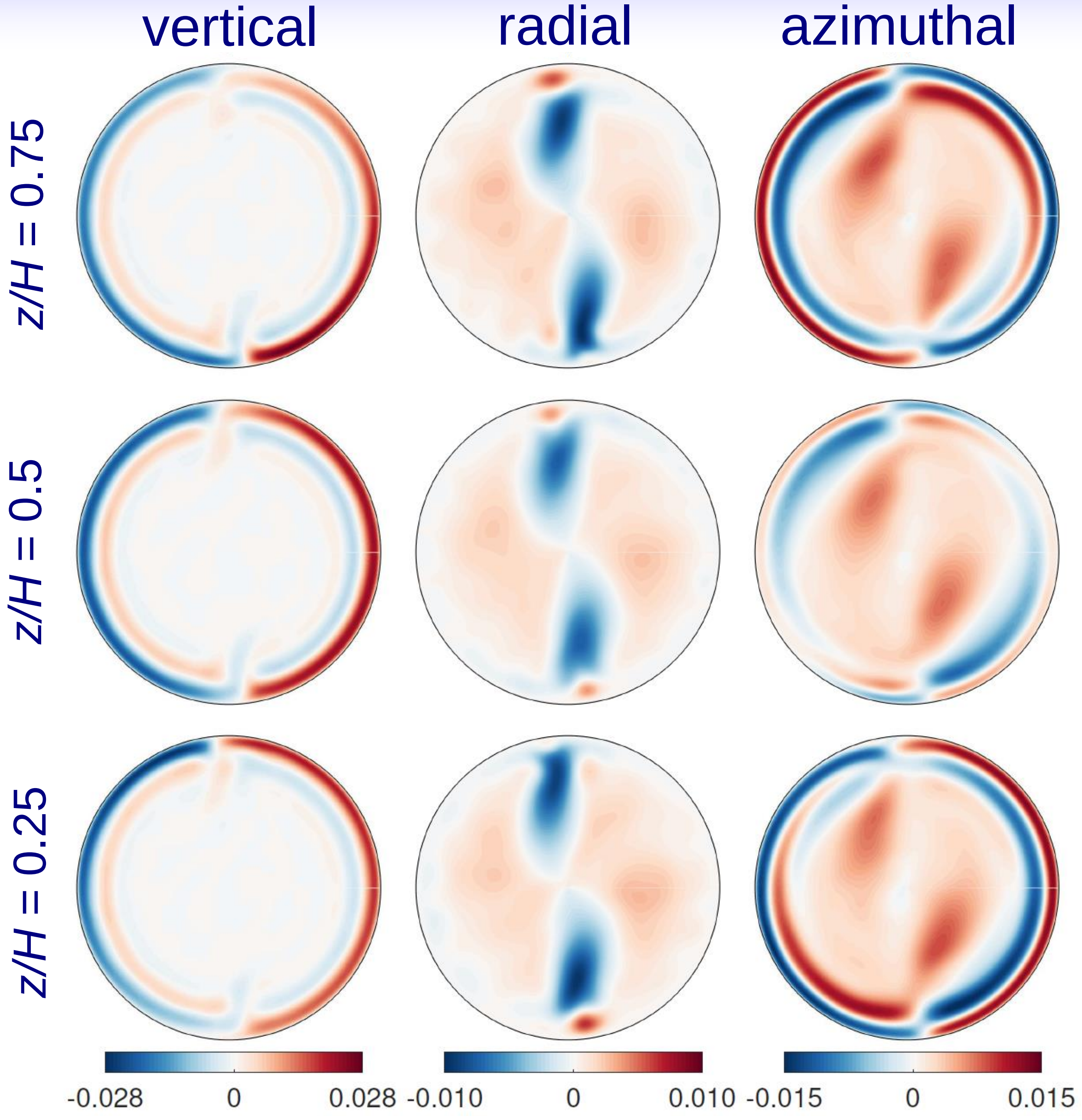
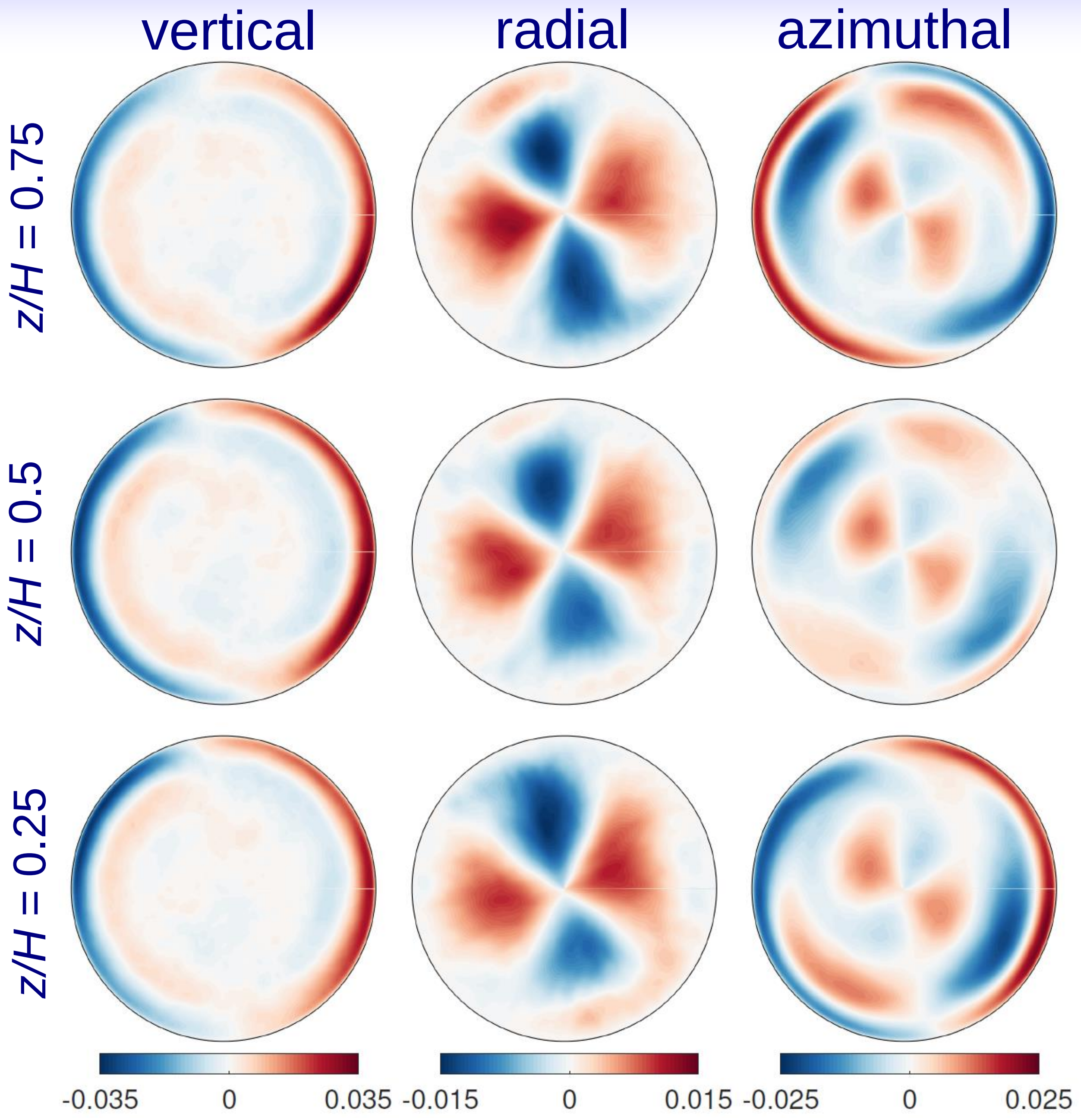




de Wit e)

Orientation-compensated mean flow - ”high” *Ra*

- Bulk: geostrophic with distinct mean flow pattern
- Weaker, wider two-layer sidewall circulation



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

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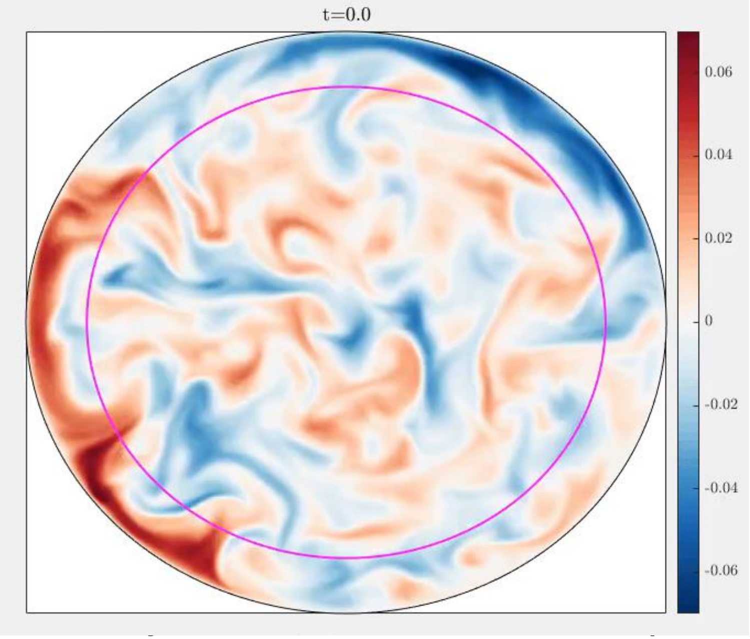

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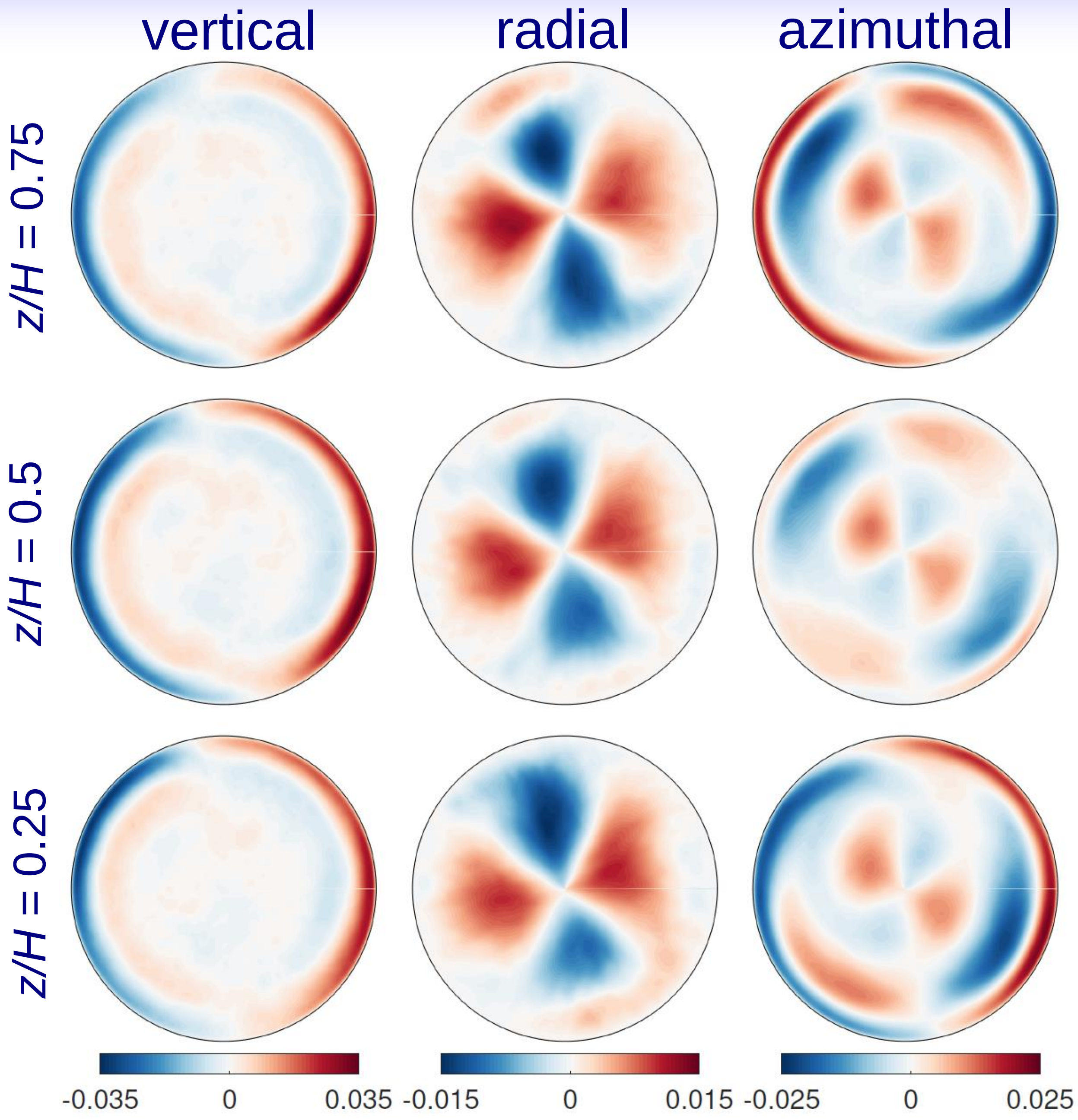
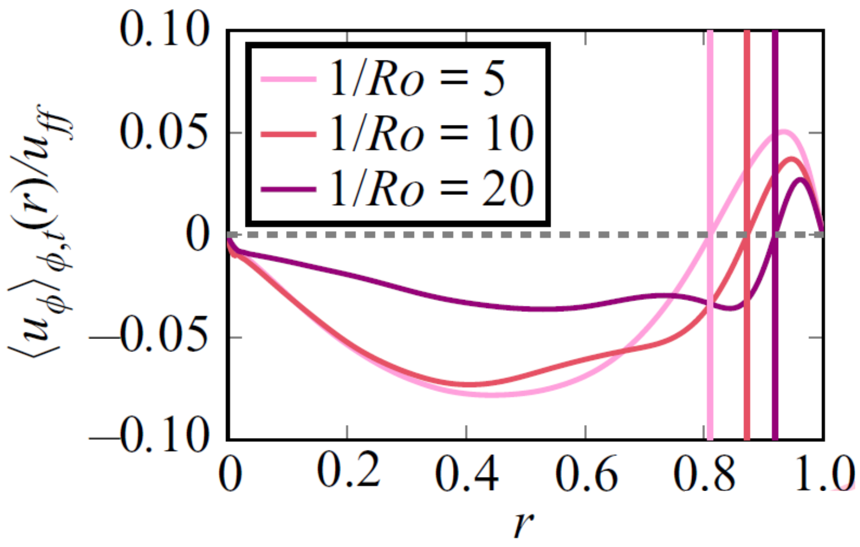
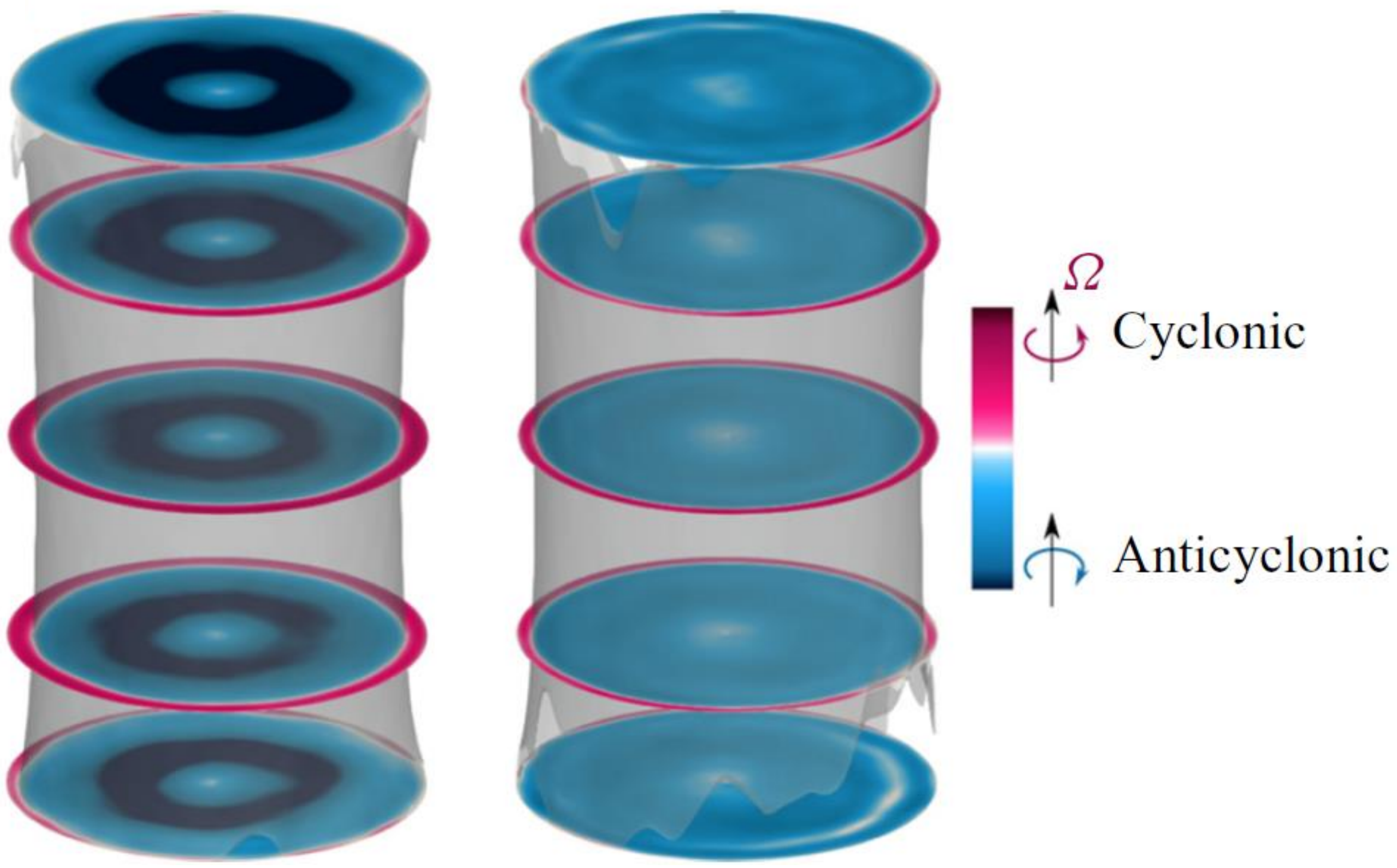


Time/azimuthal average: boundary zonal flow

Zhang et al.
(2020, 2021, 2024)
Ecke et al. (2022)





Zhang et al., *Phys. Rev. Lett.* **124**, 084505 (2020); *J. Fluid Mech.* **915**, A62 (2021); *Phys. Rev. Fluids* **9**, 053501 (2024)
Ecke et al., *Phys. Rev. Fluids* **7**, L011501 (2022)

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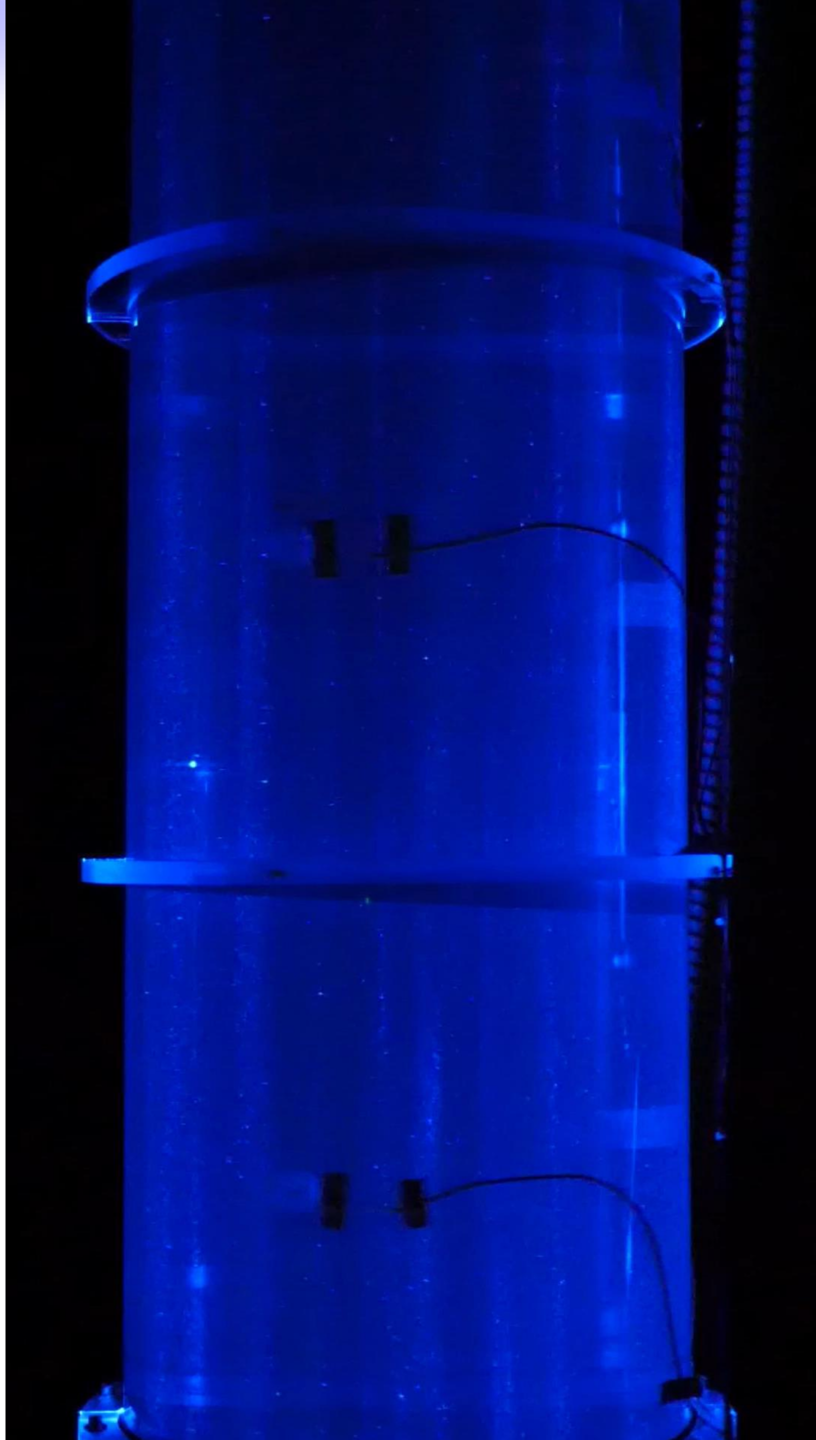
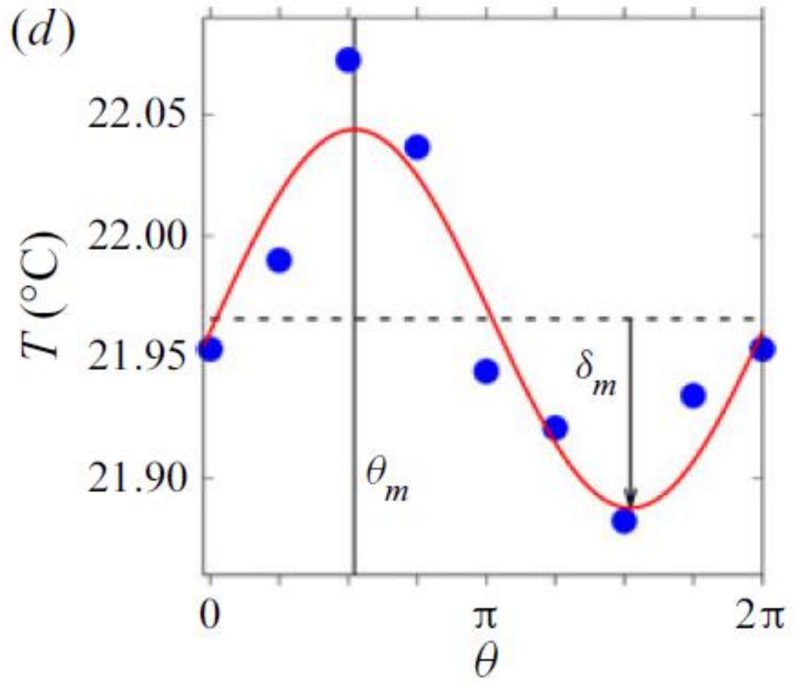


Temperature probes

Göttingen U-Boot
Wedi et al. (2021)



Wedi et al., *J. Fluid Mech.* **912**, A30 (2021)

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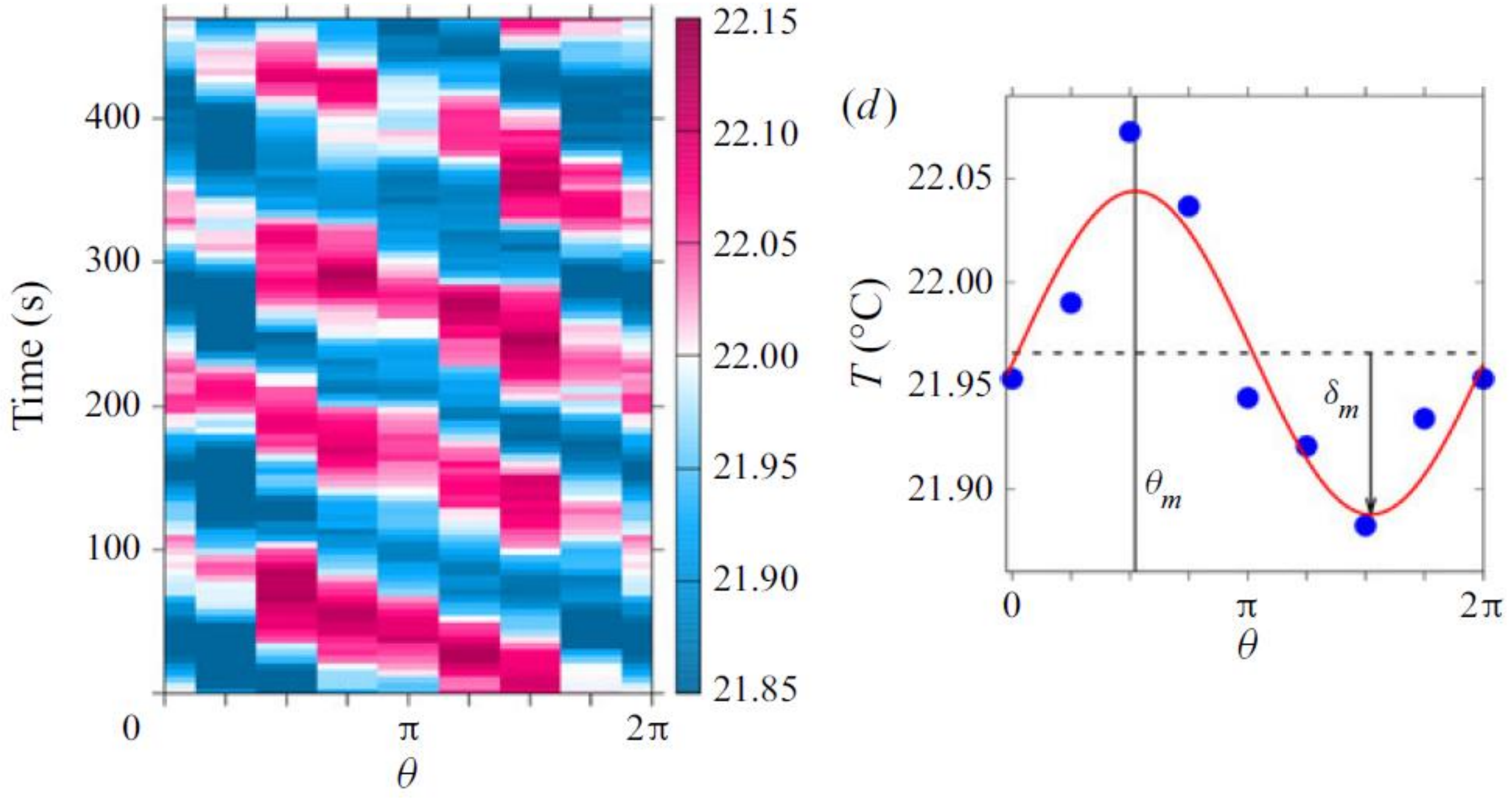
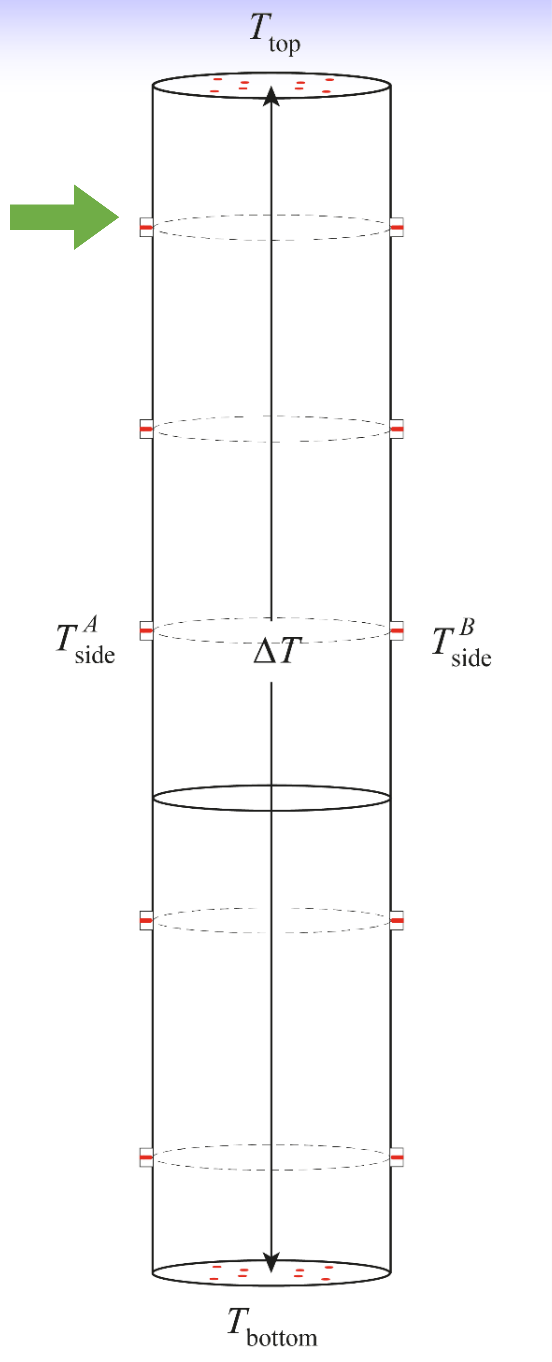
Wedi et al. (2021)

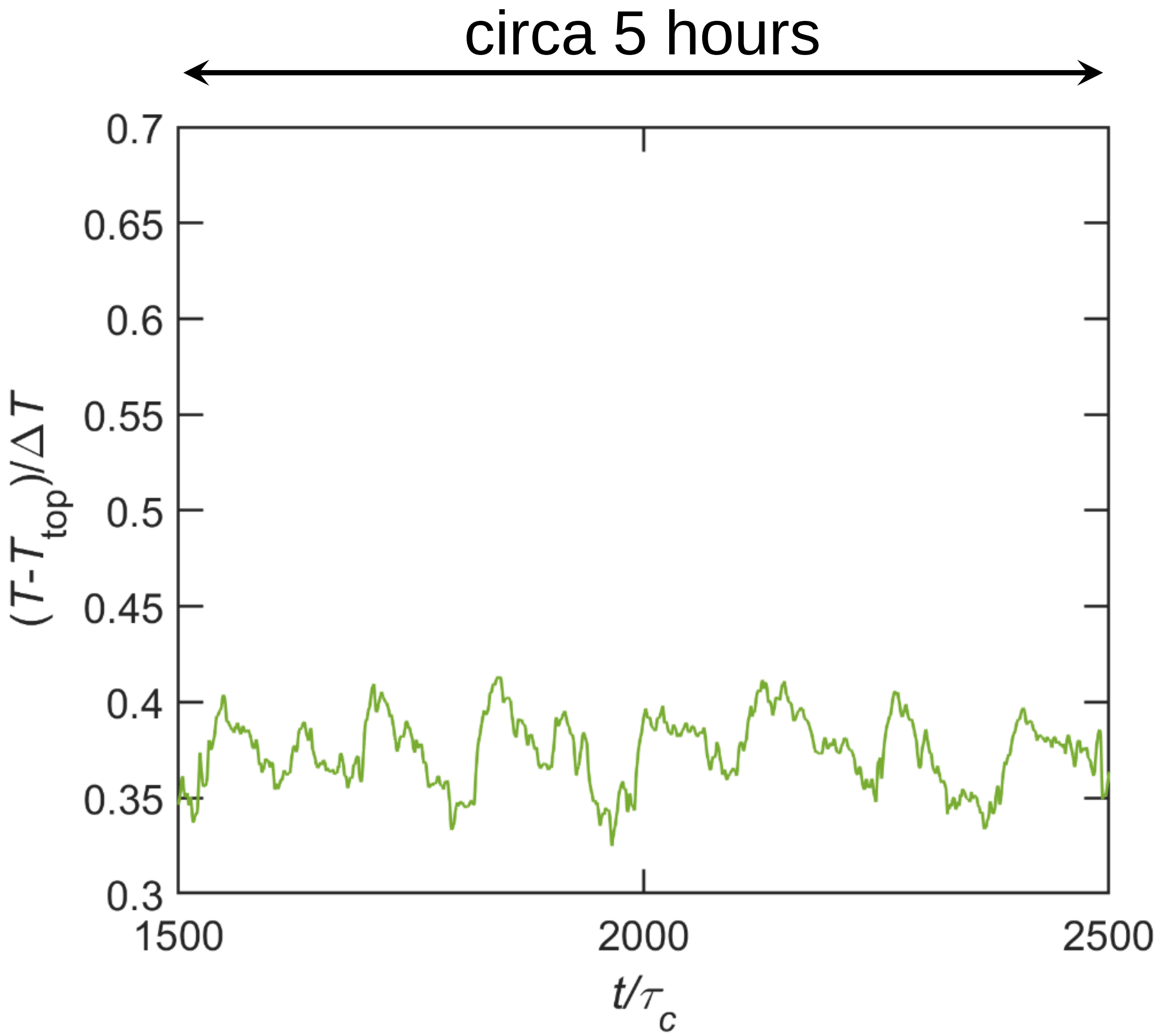


Wedi et al., *J. Fluid Mech.* **912**, A30 (2021)

Temperature probes

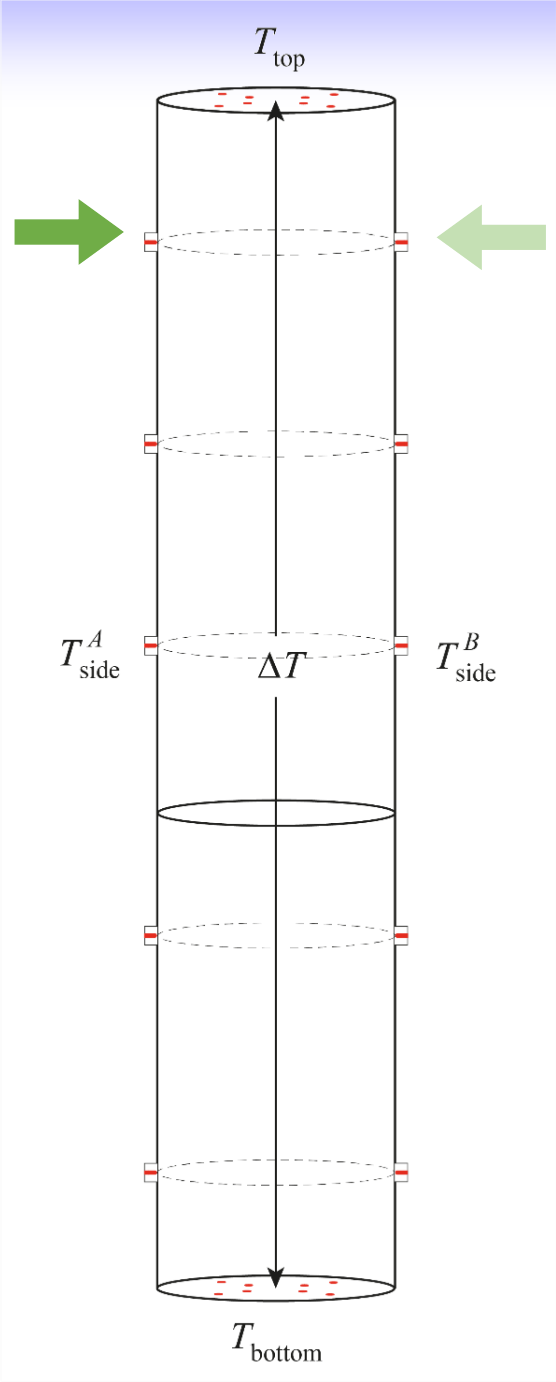


Eindhoven
TROCONVEX
de Wit et al. (2020)

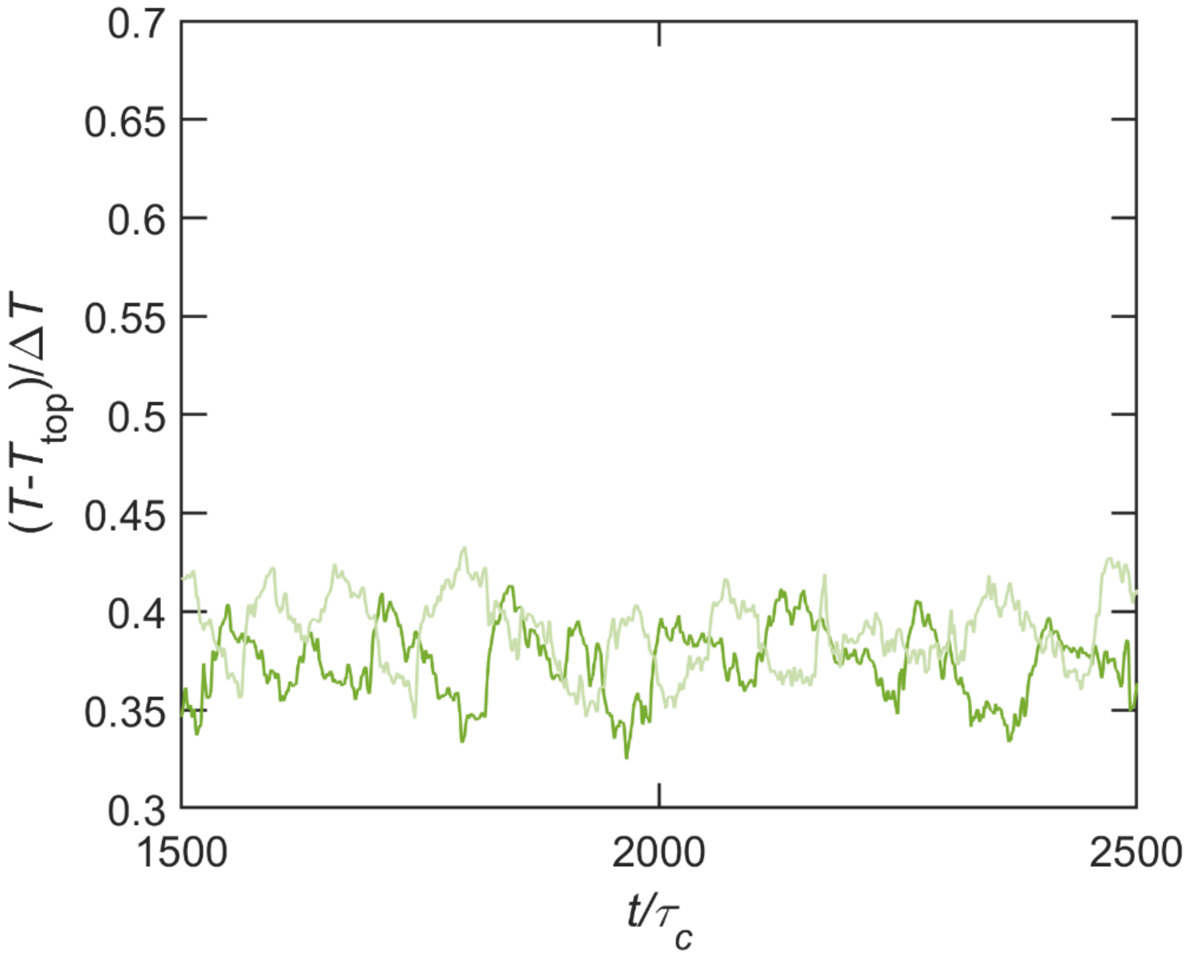


de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

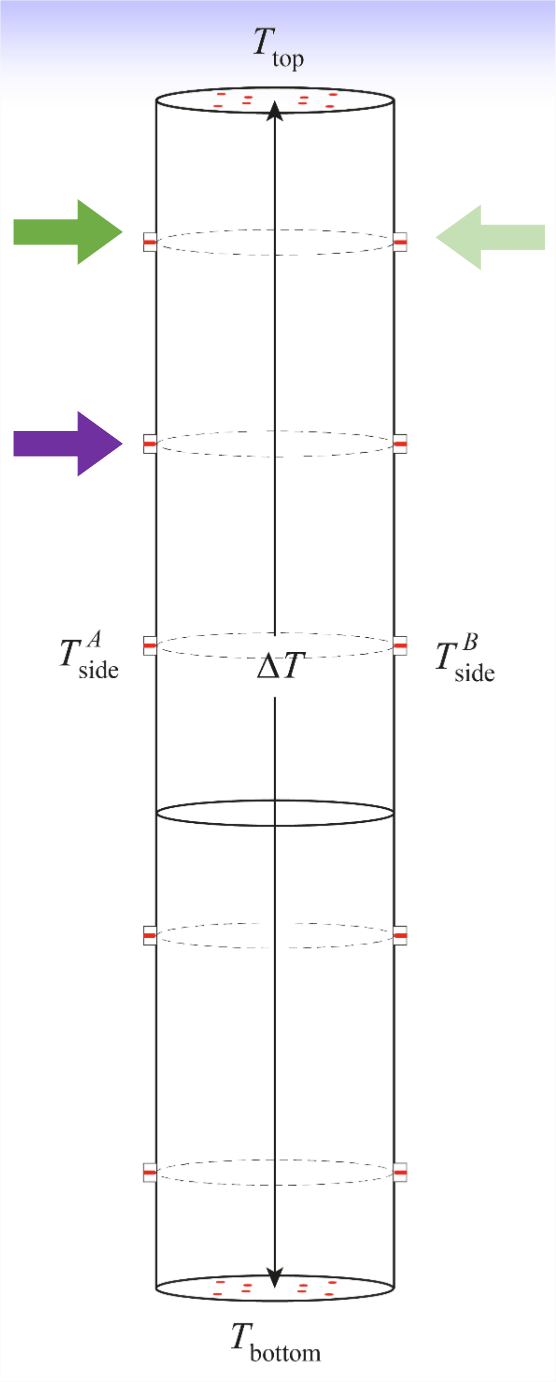
Temperature probes



Eindhoven
TROCONVEX
de Wit et al. (2020)



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)



Temperature probes

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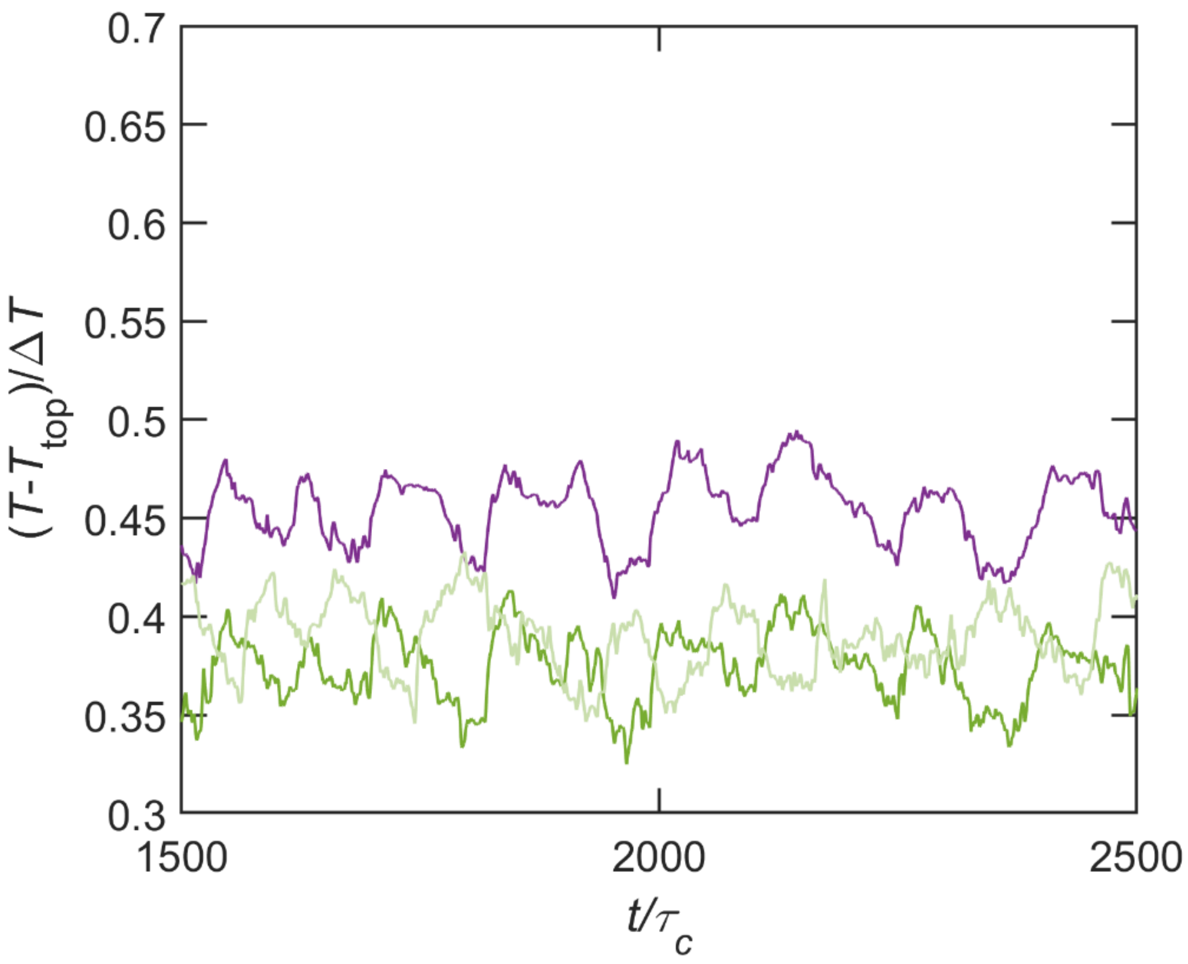
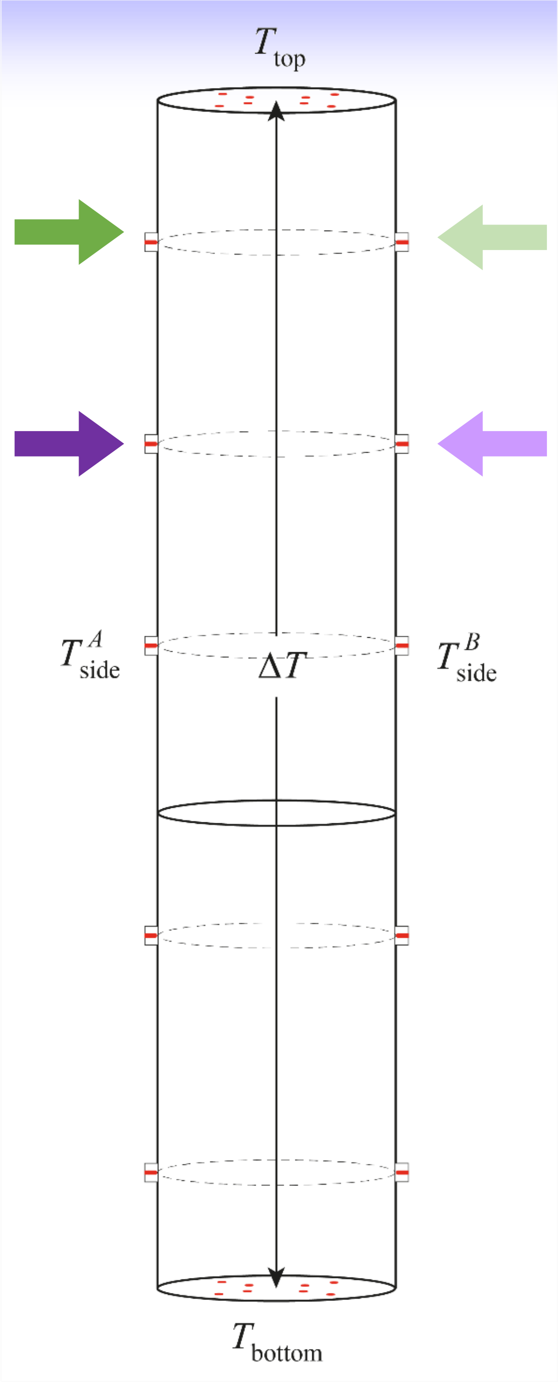


de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

Temperature probes



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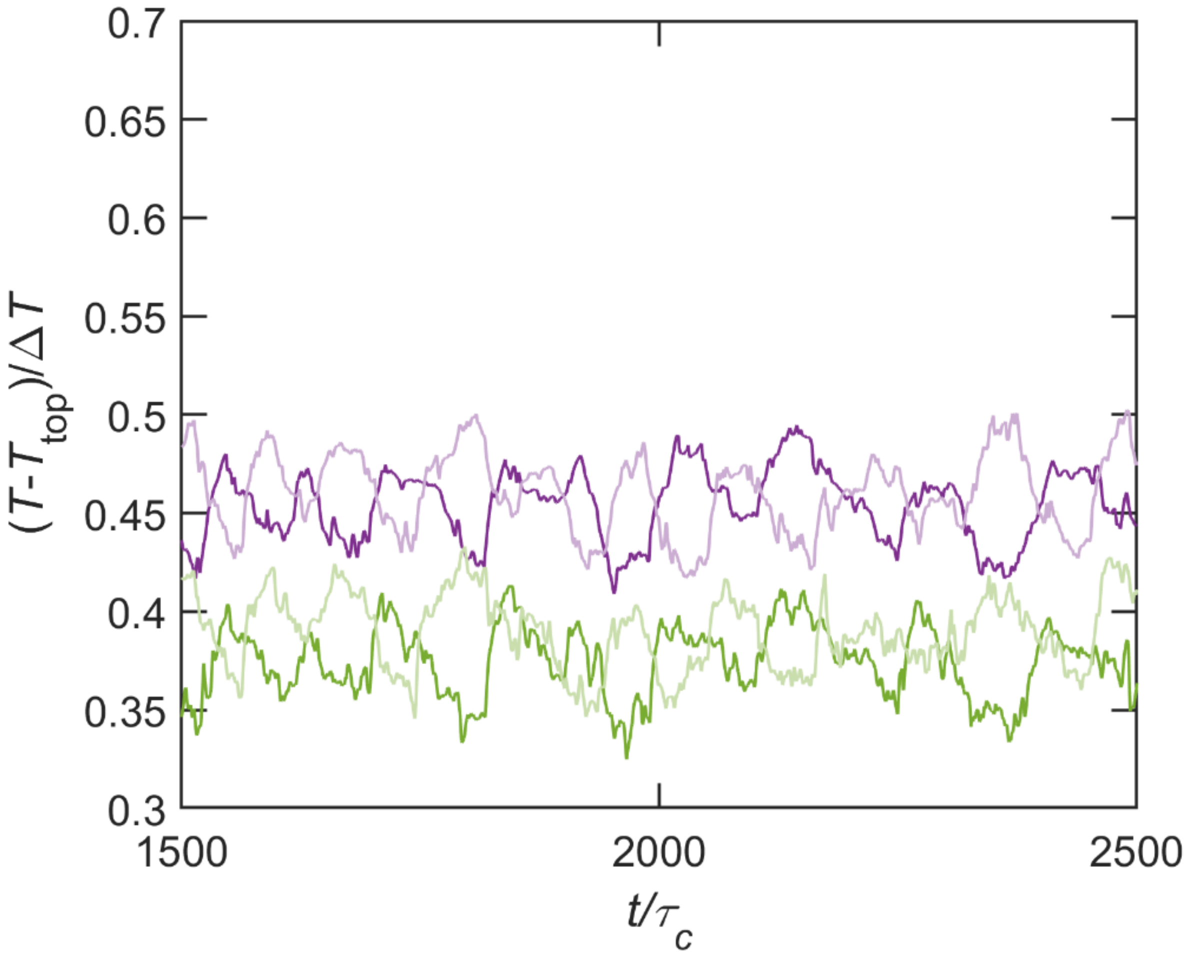
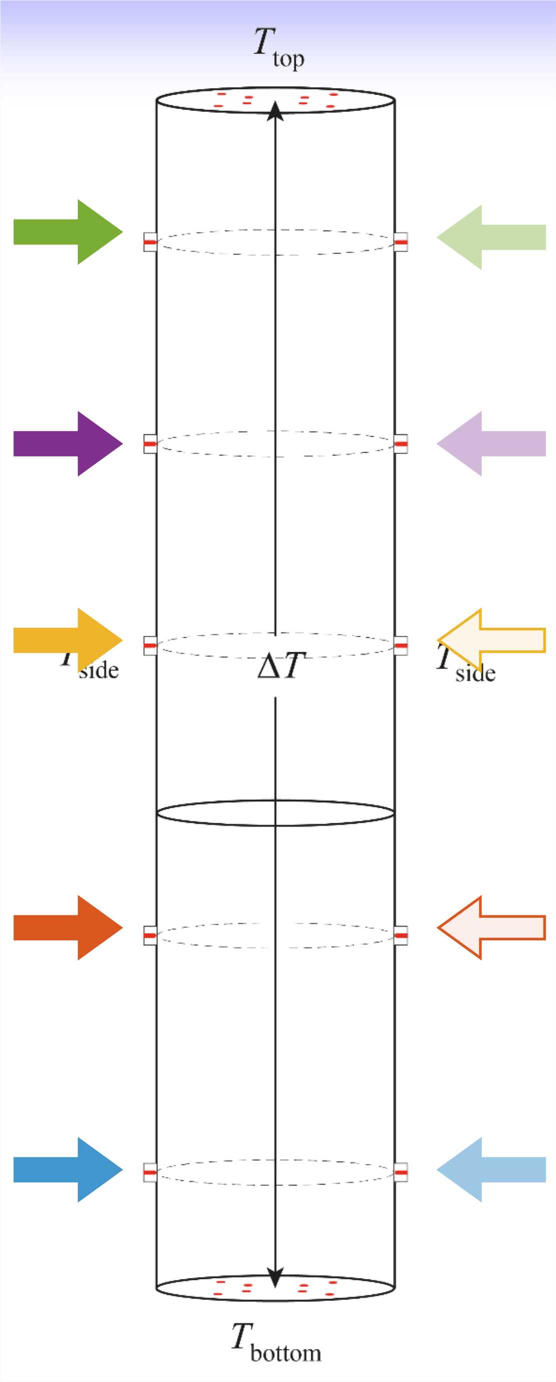
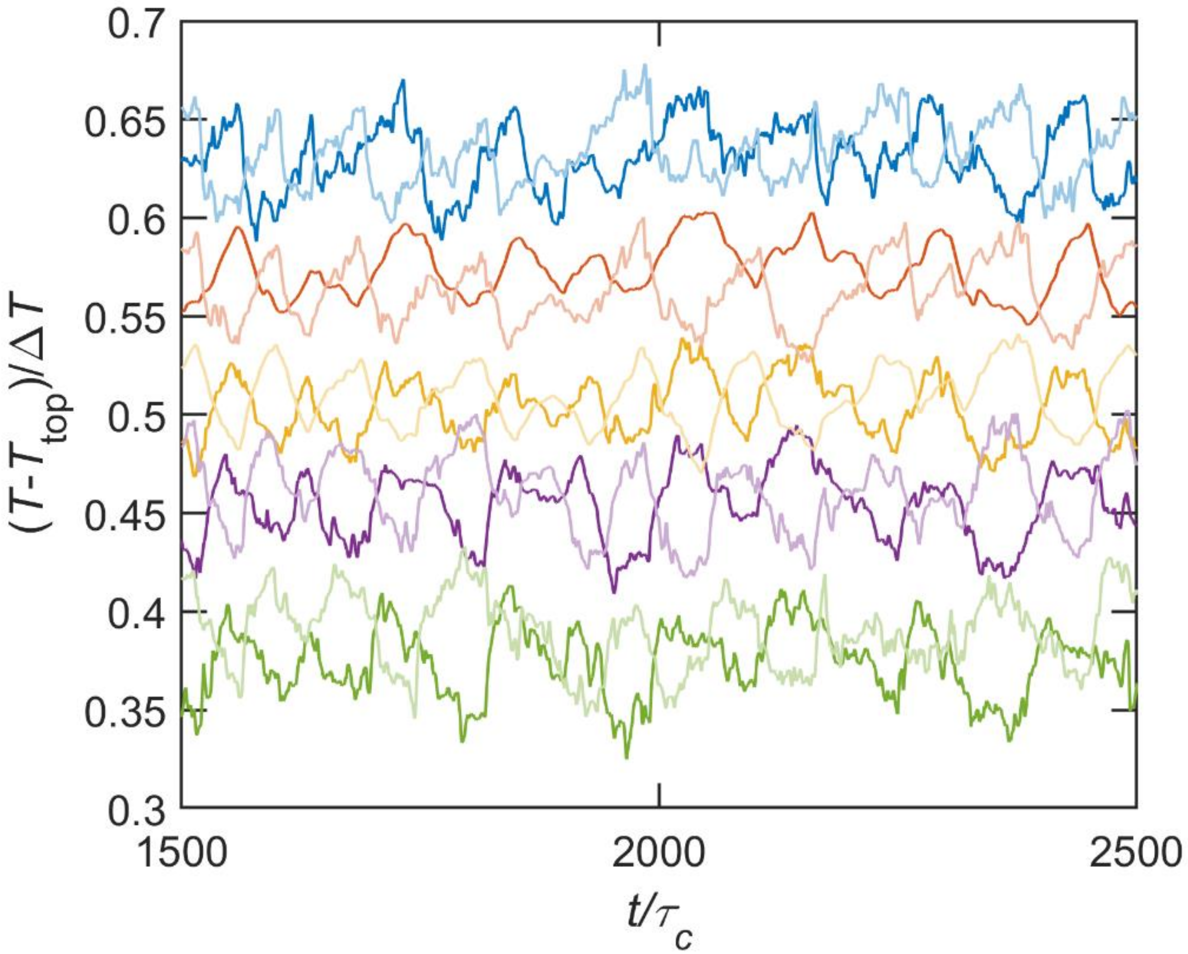


de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)



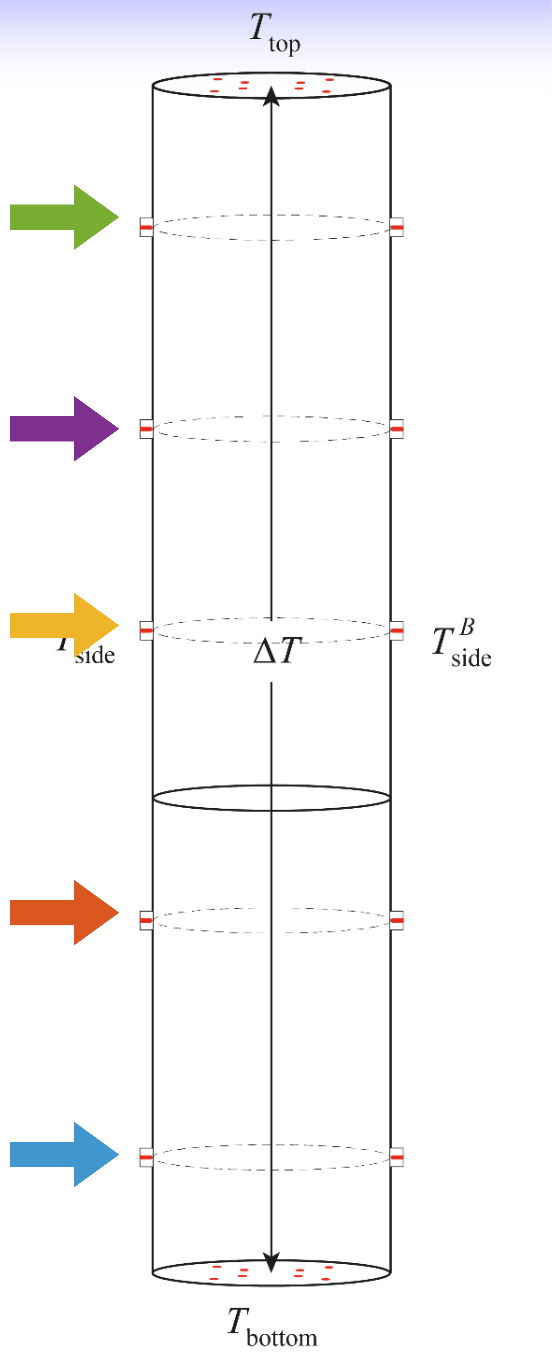
Temperature probes

Eindhoven
TROCONVEX
de Wit et al. (2020)



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

Temperature probes



Eindhoven
TROCONVEX
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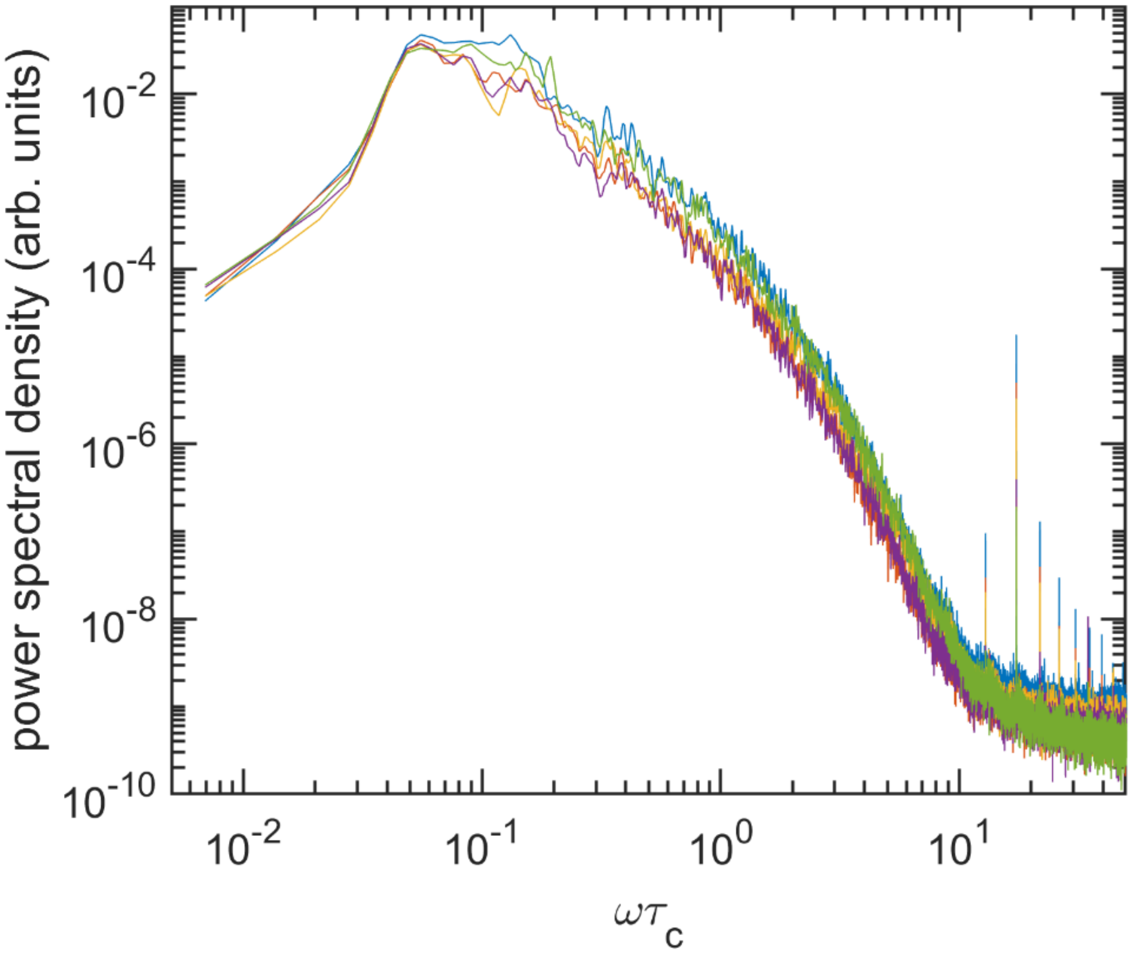
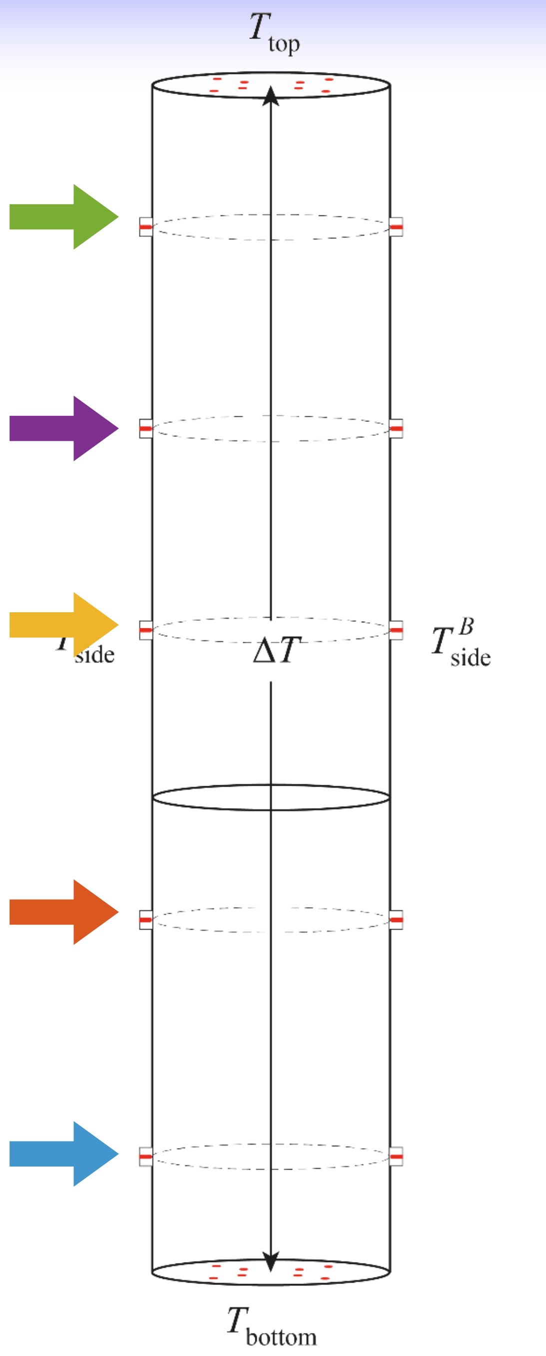
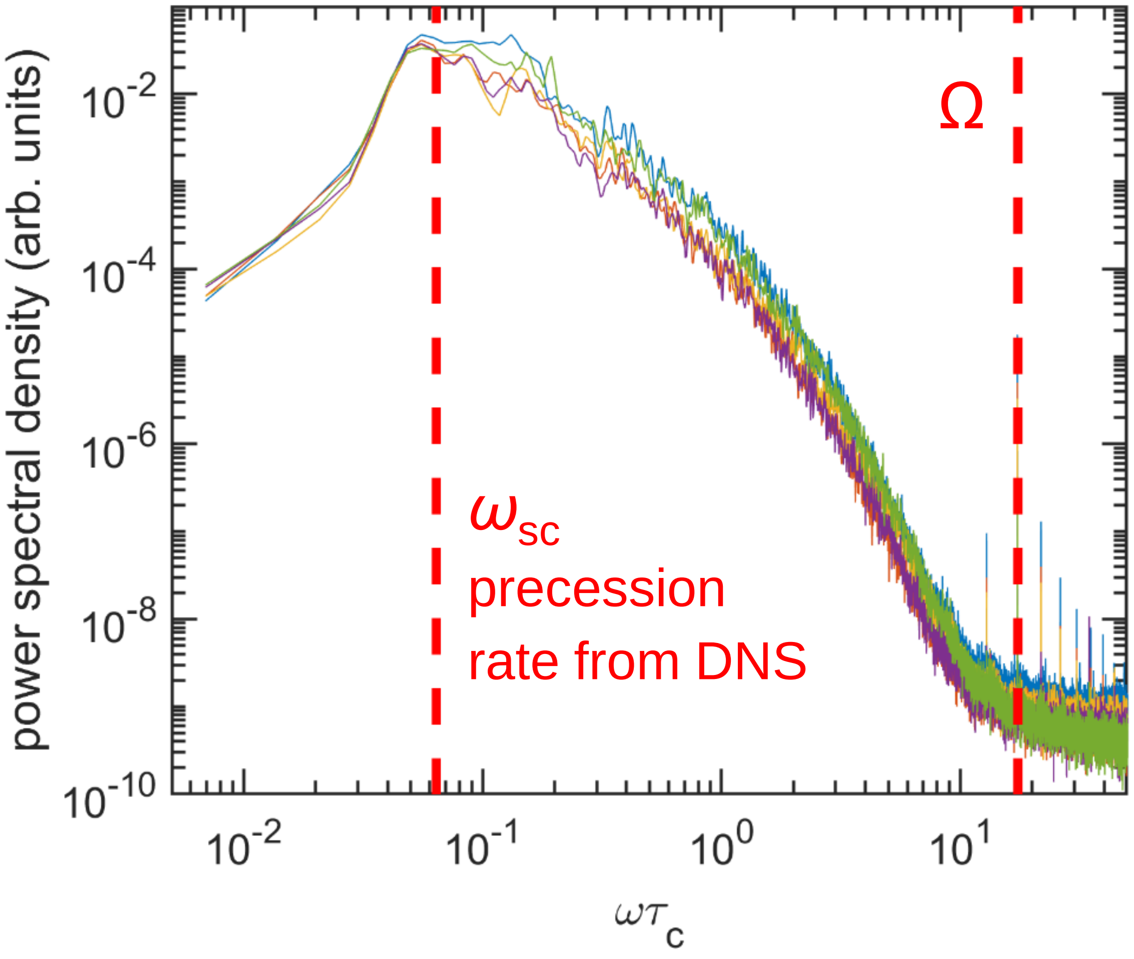


de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

Temperature probes

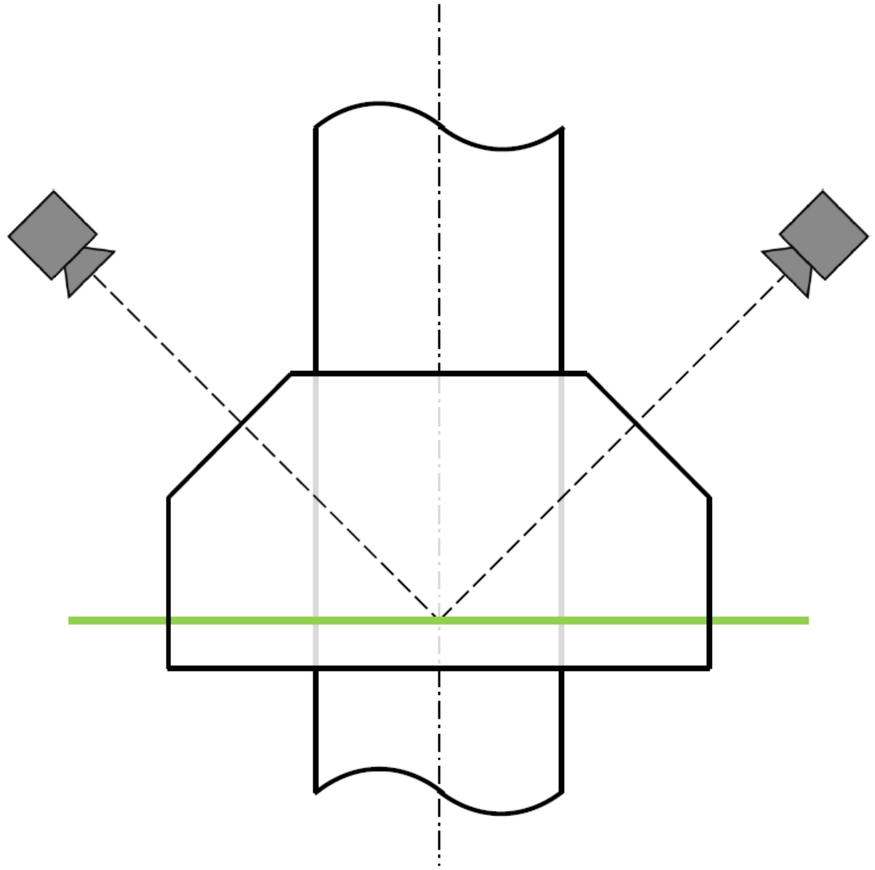


Eindhoven
TROCONVEX
de Wit et al. (2020)



de Wit et al., *Phys. Rev. Fluids* **5**, 023502 (2020)

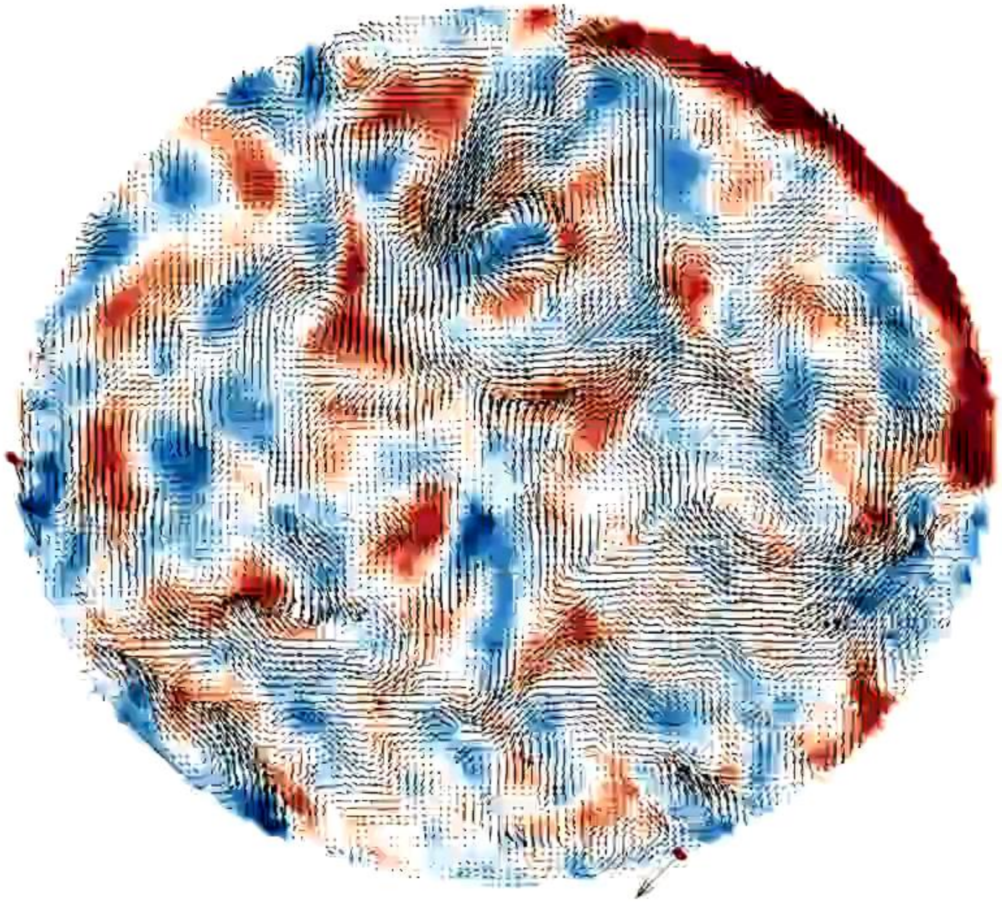
TROCONVEX – stereo-PIV mode

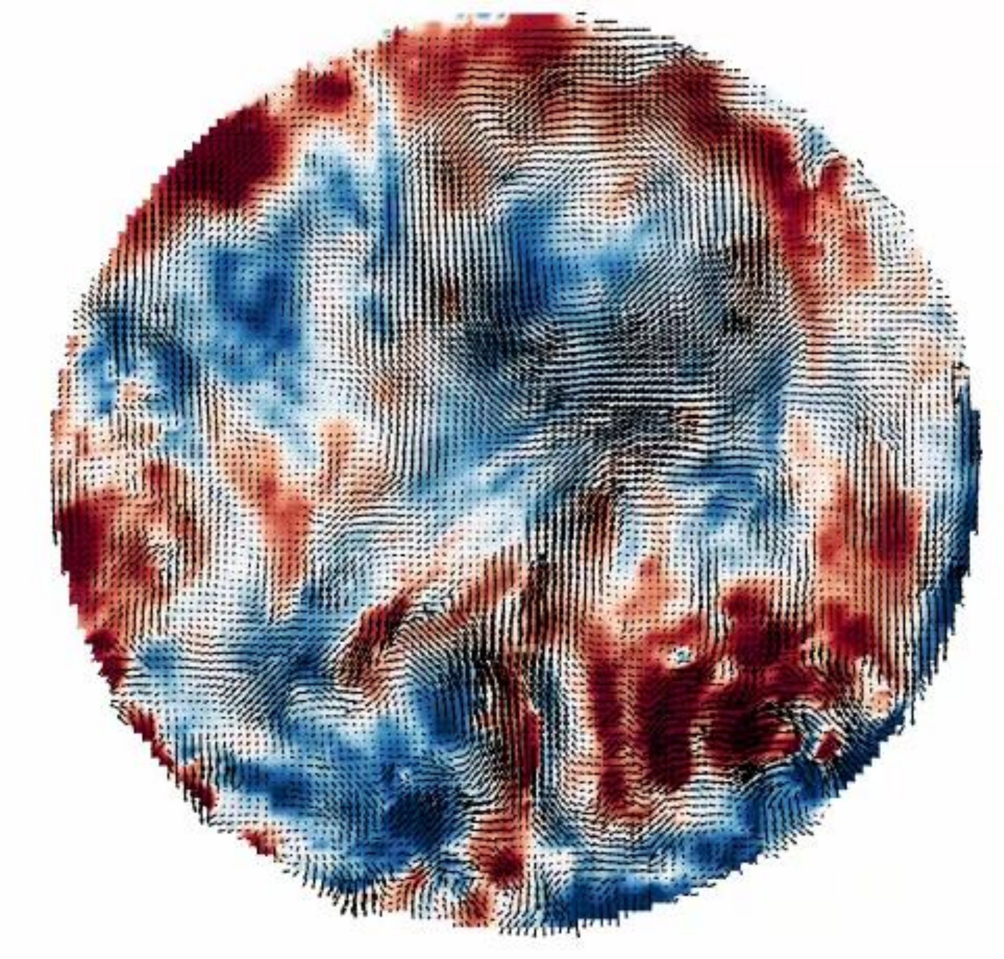


Madonia et al., *EPL* **135**, 54002 (2021)
Madonia et al., *J. Fluid Mech.* **962**, A36 (2023)

Flow measurements – wall modes (Madonia et al. (2021, 2023)

"low" *Ra* = 2.2×10^{11} *Ek* = 5×10^{-8} "high" *Ra* = 4.3×10^{12}

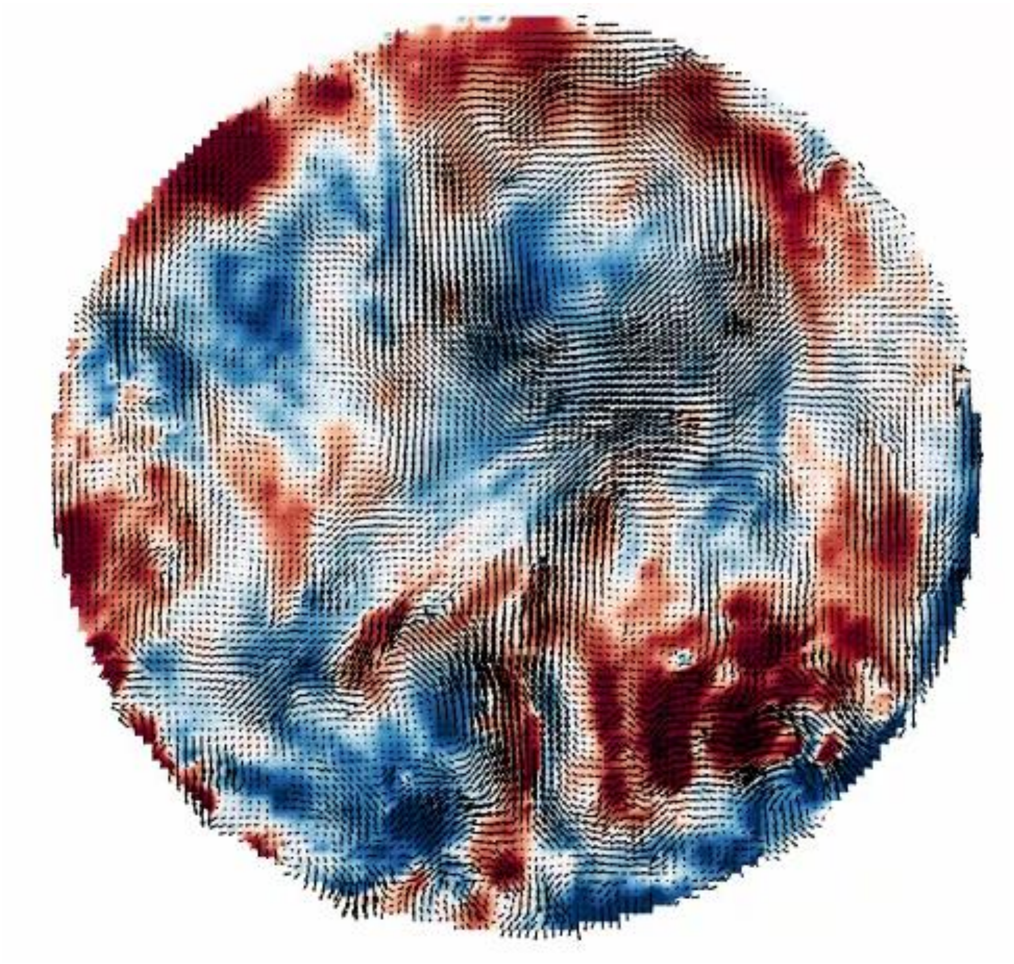


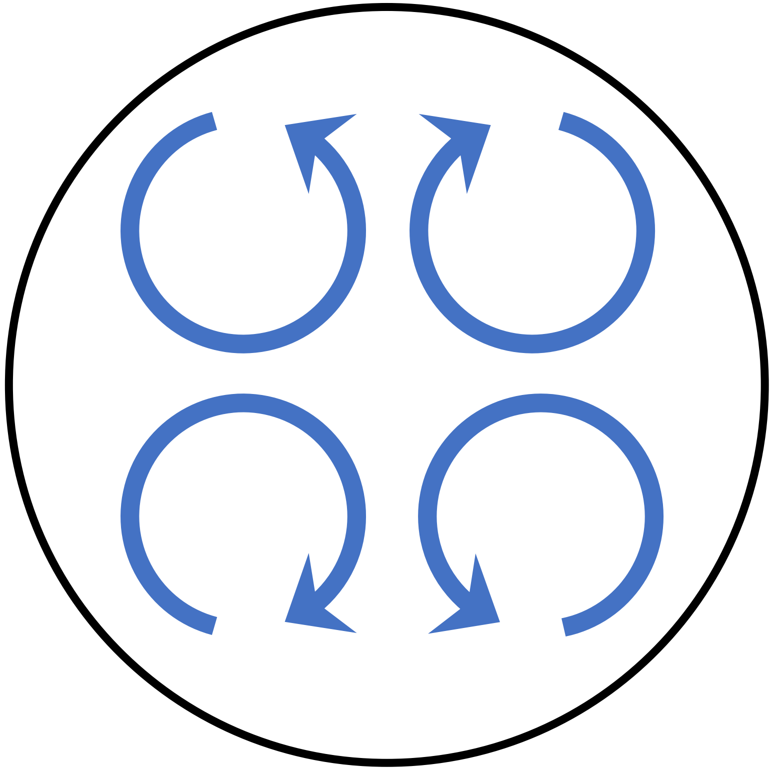


Madonia et al., *EPL* **135**, 54002 (2021); Madonia et al., *J. Fluid Mech.* **962**, A36 (2023)

Jets lead to quadrupolar vortex

Ra = 4.3×10^{12}



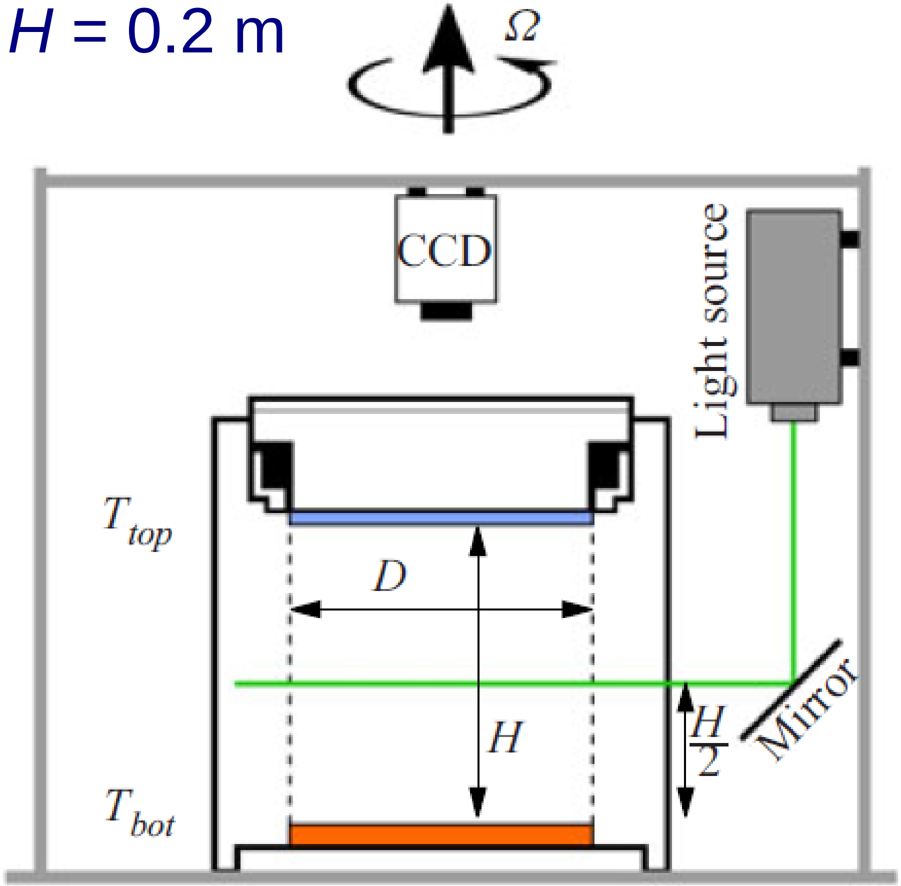


Madonia et al., *EPL* **135**, 54002 (2021); Madonia et al., *J. Fluid Mech.* **962**, A36 (2023)

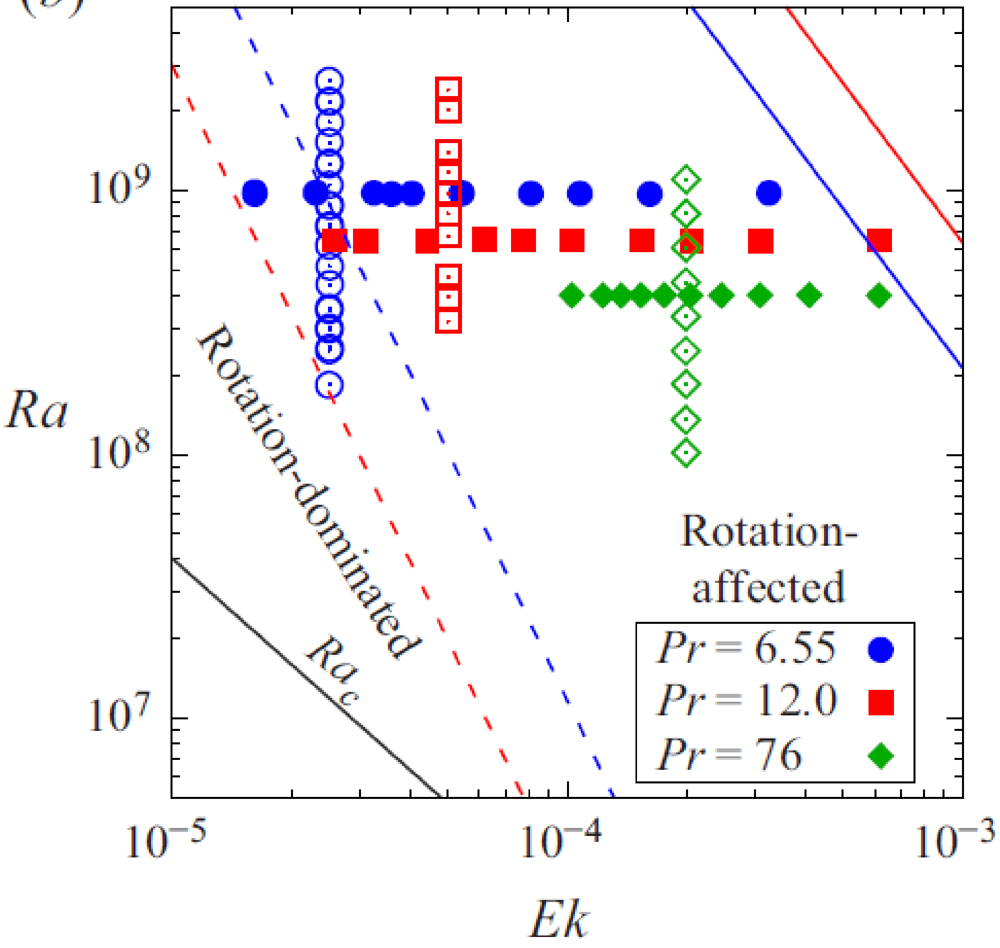
PIV reveals boundary zonal flow

Wedi et al. (2022)

$D = H = 0.2$ m



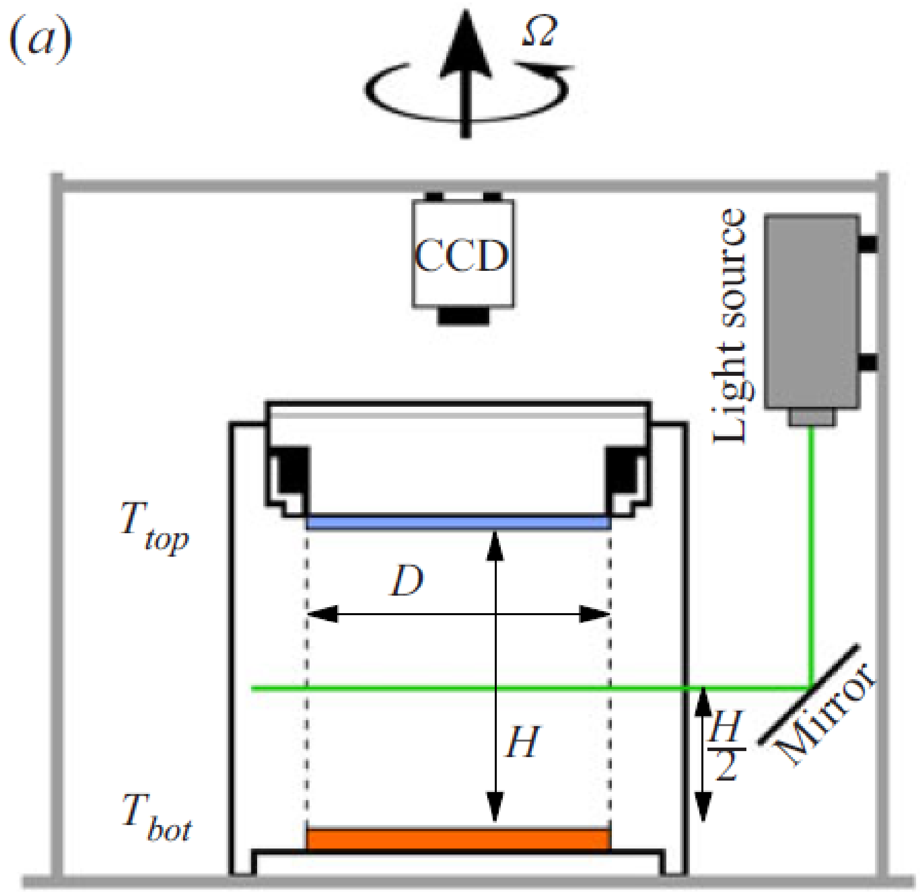
(b)

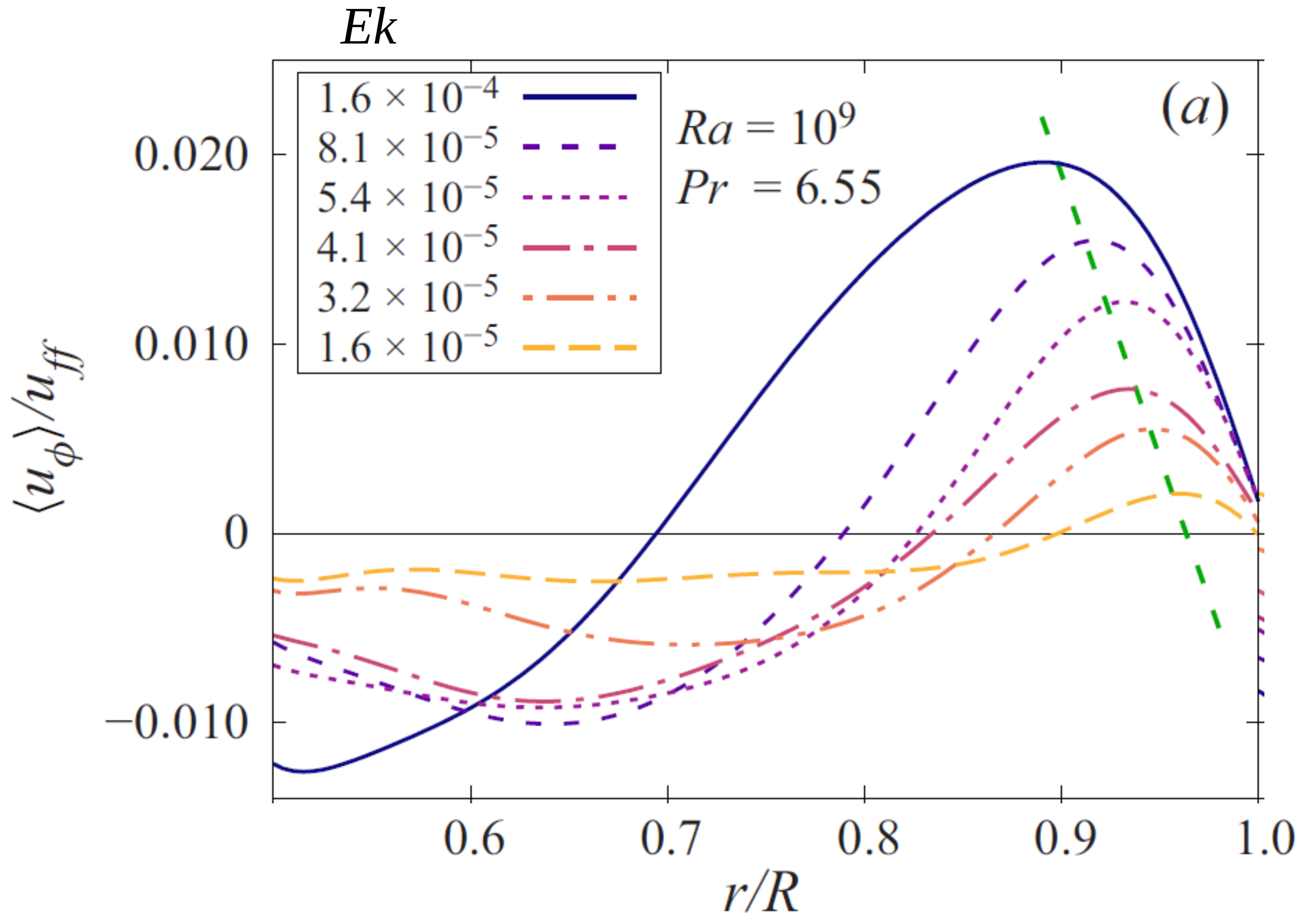


Wedi et al., *J. Fluid Mech.* **939**, A14 (2022)

PIV reveals boundary zonal flow

Wedi et al. (2022)





Wedi et al., *J. Fluid Mech.* **939**, A14 (2022)

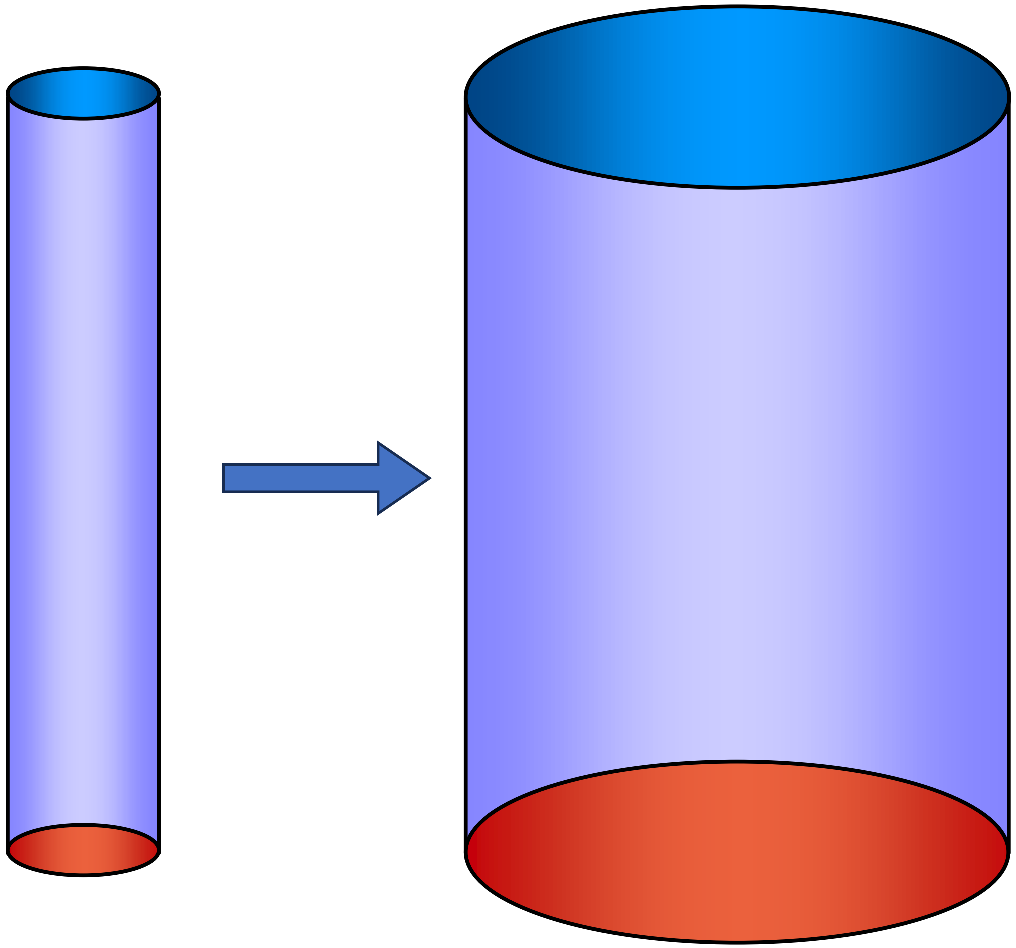
Can we reduce the effects of wall modes...

Wider cylinder?

$$\Gamma = \frac{D}{H} = 0.2$$

to

$$\Gamma = 0.72$$

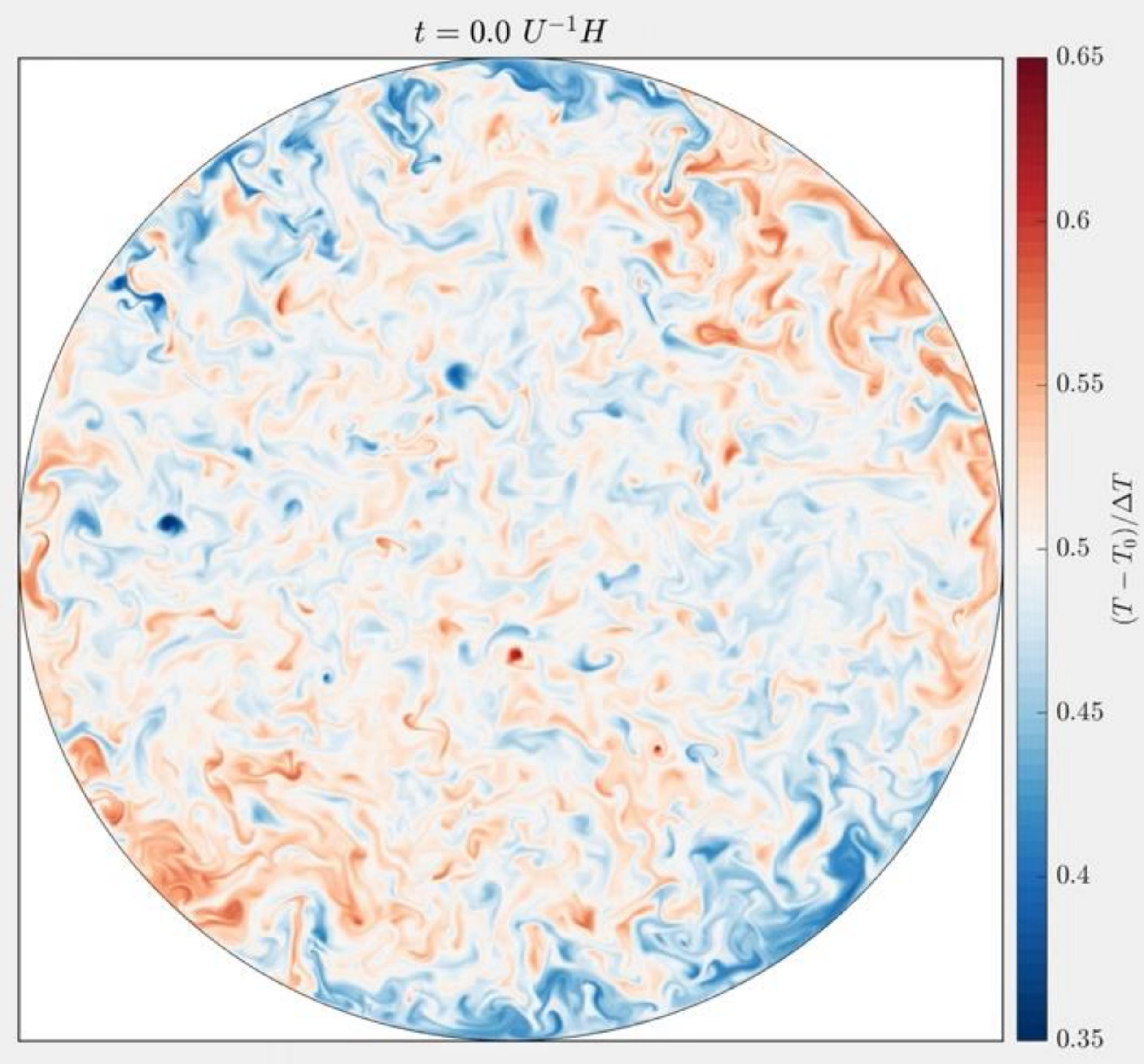


De Wit et al., *Phys. Rev. Fluids* **8**, 073501 (2023)

Can we reduce the effects of wall modes...

$\Gamma = 0.72$

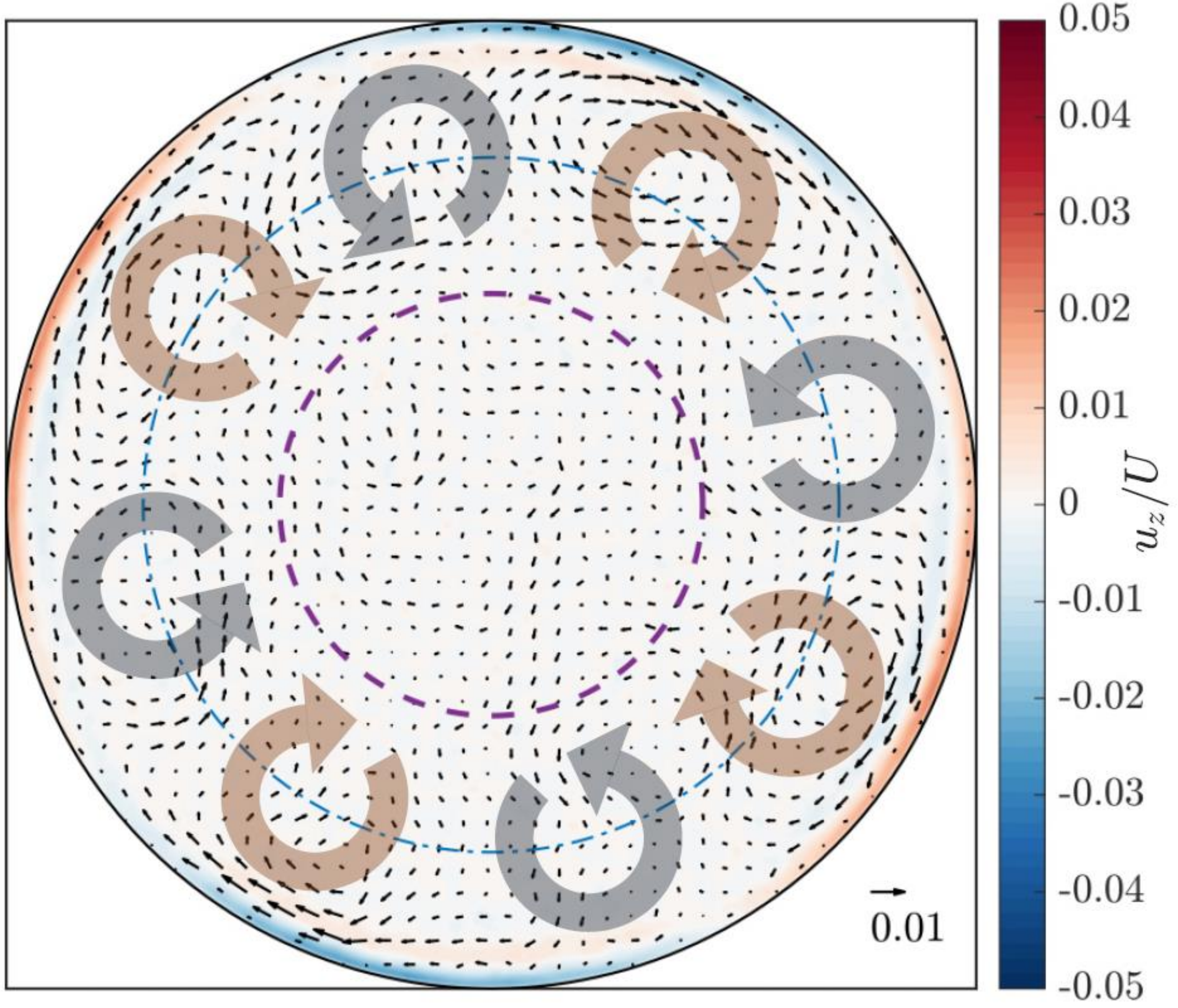
DNS
de Wit et al. (2023)



De Wit et al., *Phys. Rev. Fluids* **8**, 073501 (2023)

Can we reduce the effects of wall modes...

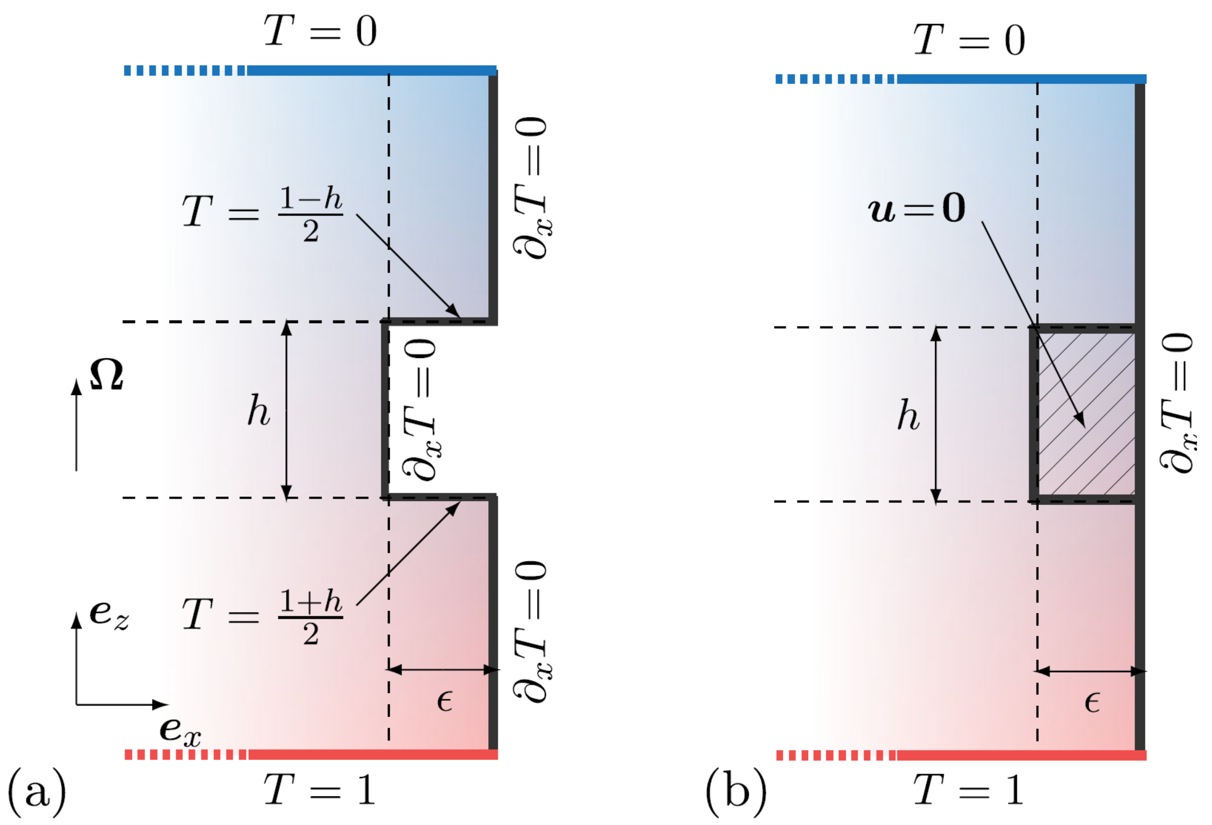
$\Gamma = 0.72$



De Wit et al., *Phys. Rev. Fluids* **8**, 073501 (2023)

...or get rid of them entirely?

Terrien et al. (2023): horizontal fins on sidewall



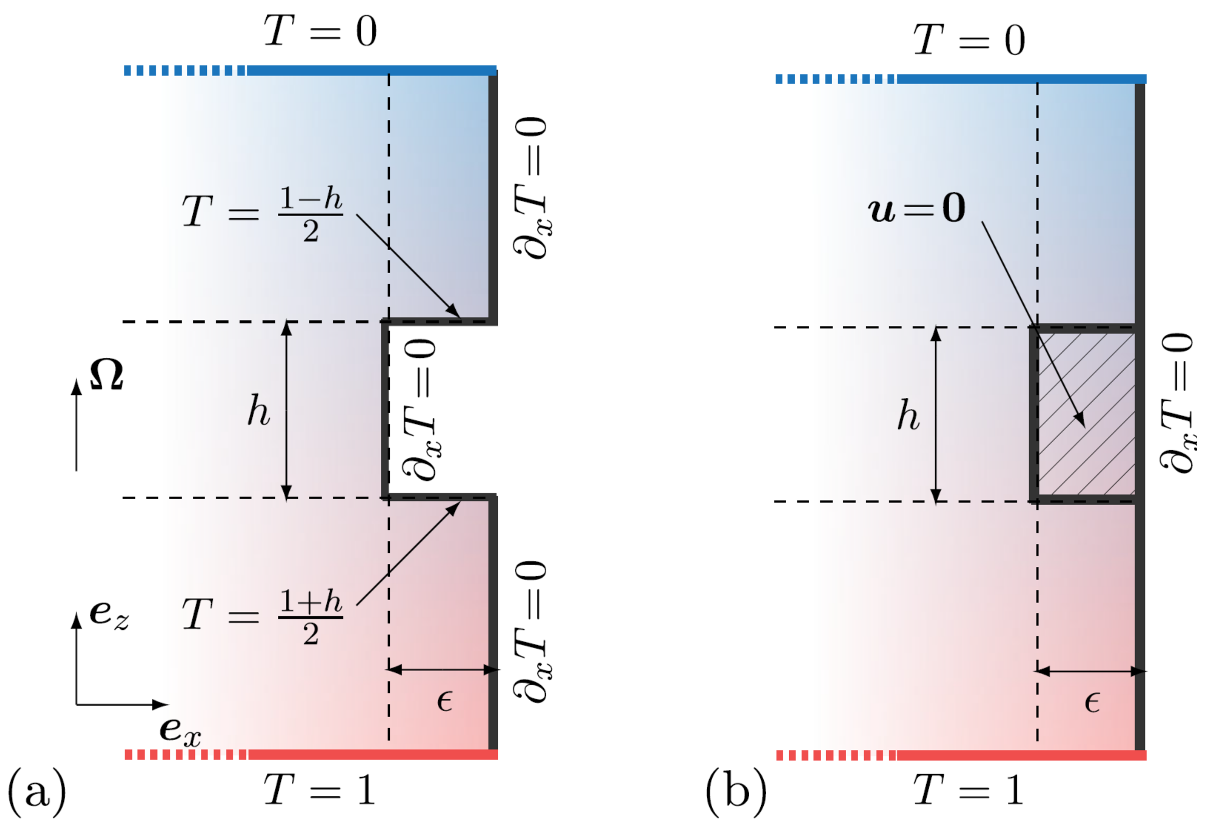
Fixed temperature or conducting barrier

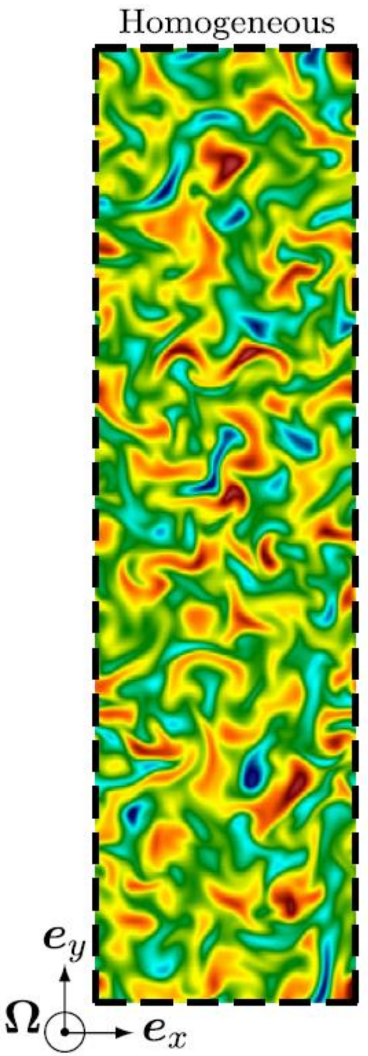
Terrien et al., *Phys. Rev. Lett.* **130**, 174002 (2023)

...or get rid of them entirely?

Terrien et al. (2023): horizontal fins on sidewall

(top view)





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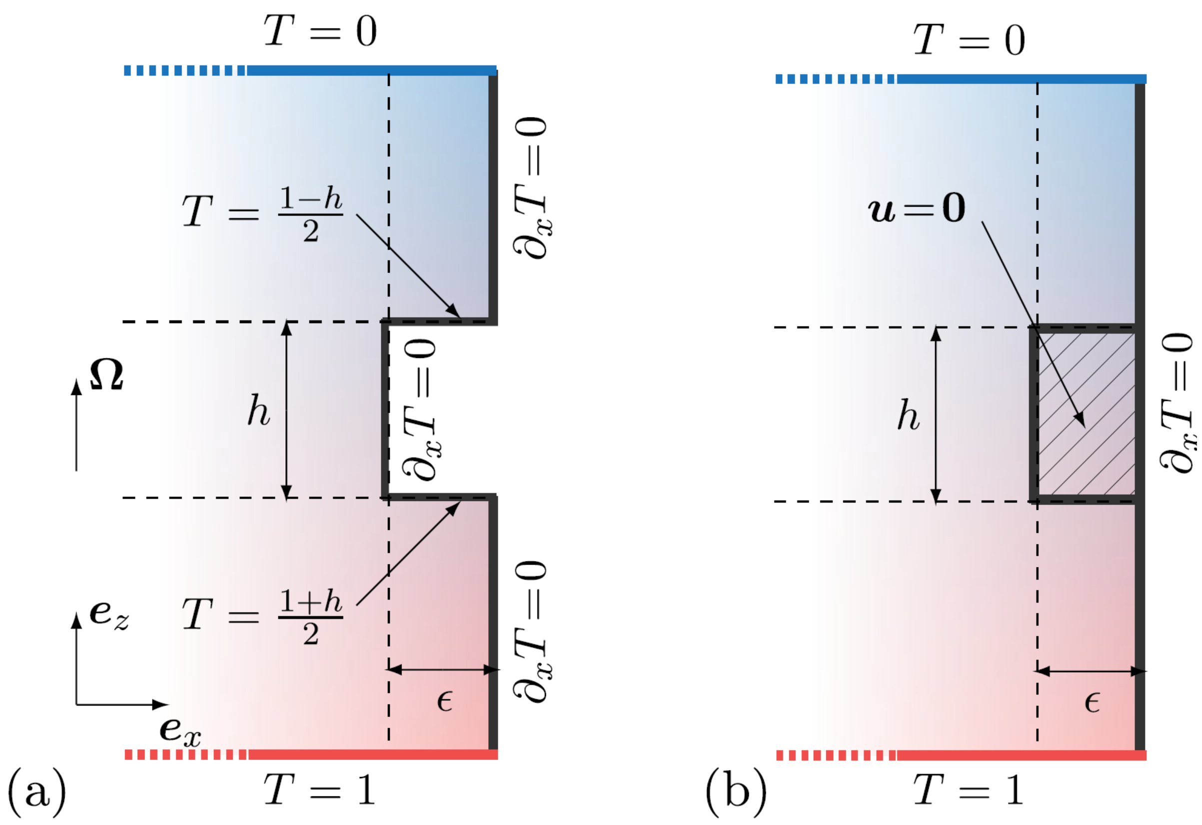
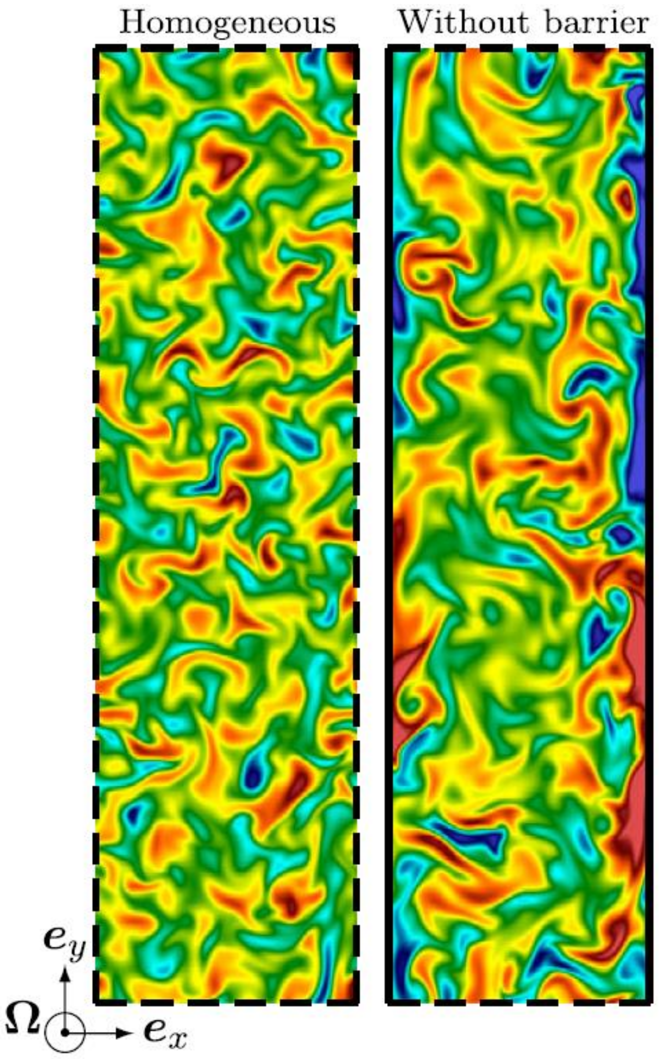


(top view)



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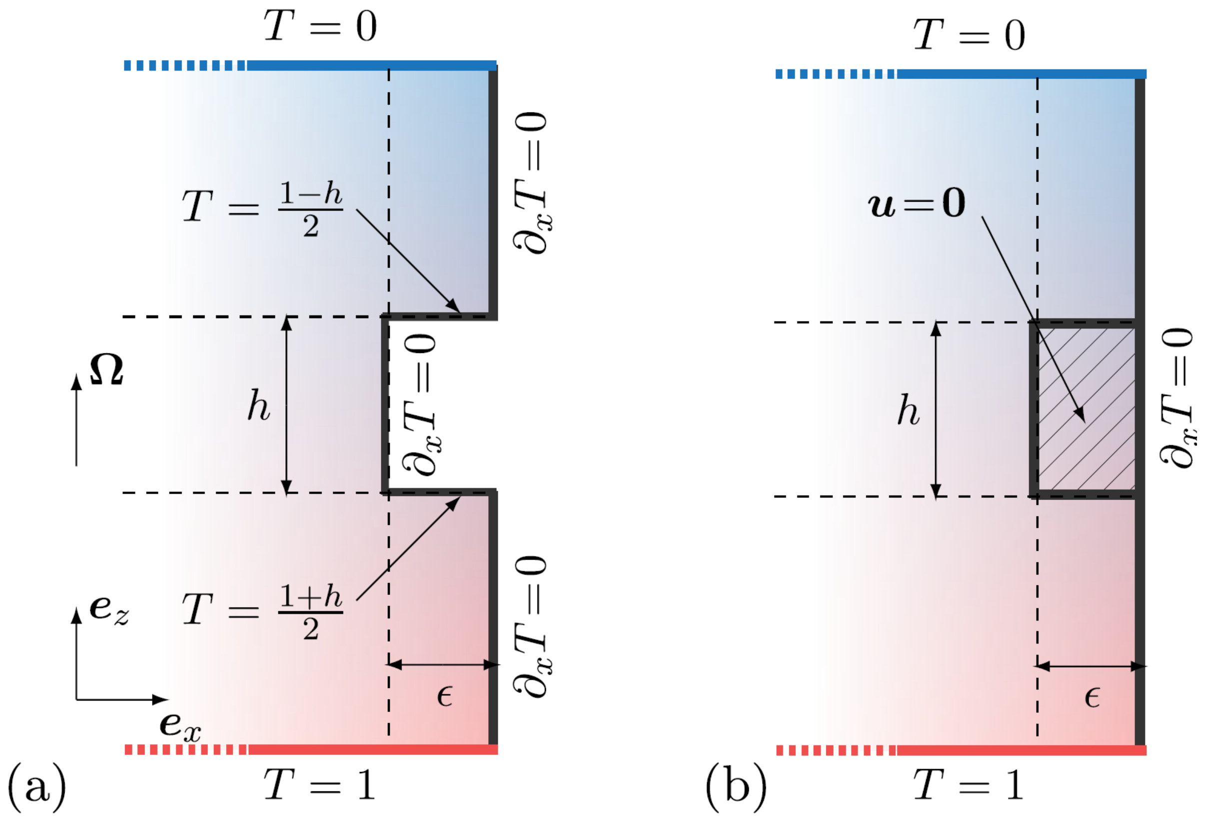
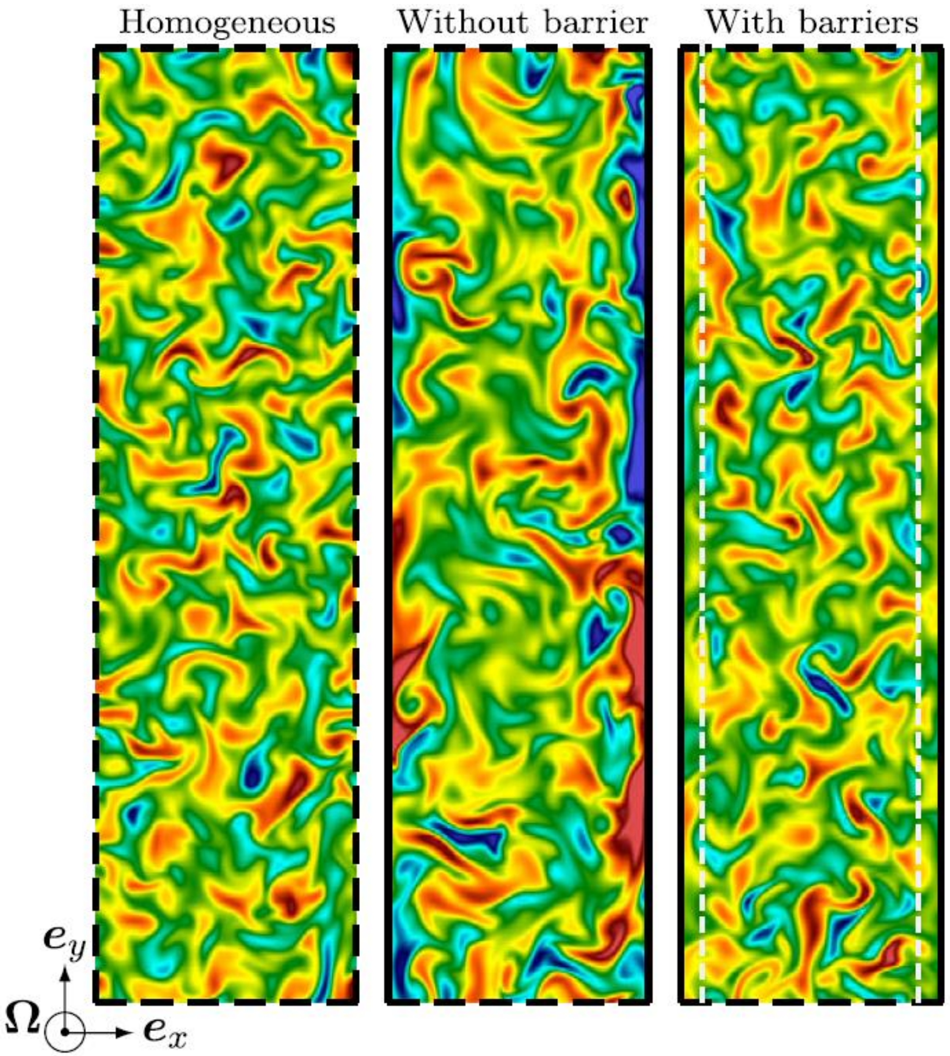


(top view)



Fixed temperature or conducting barrier

Terrien et al., *Phys. Rev. Lett.* **130**, 174002 (2023)

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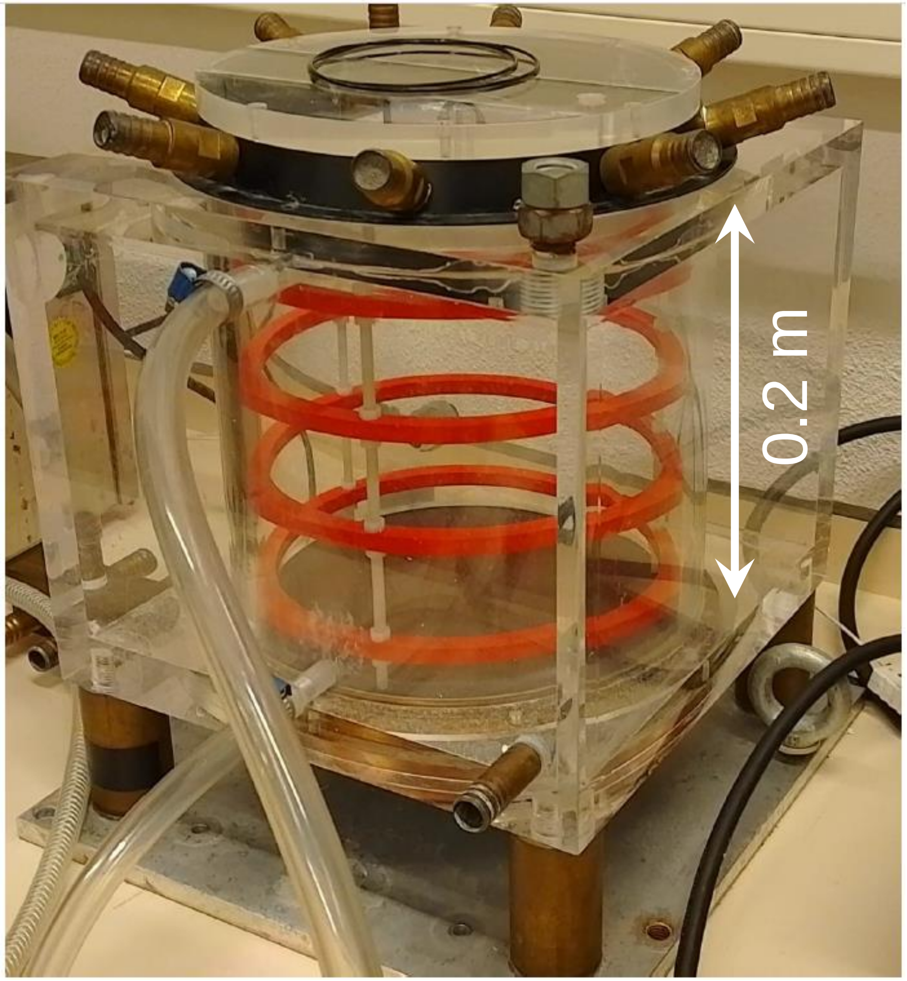
Wouter Vereijssen, Lázaro Martínez: PIV experiments with fins on sidewall (prelim)



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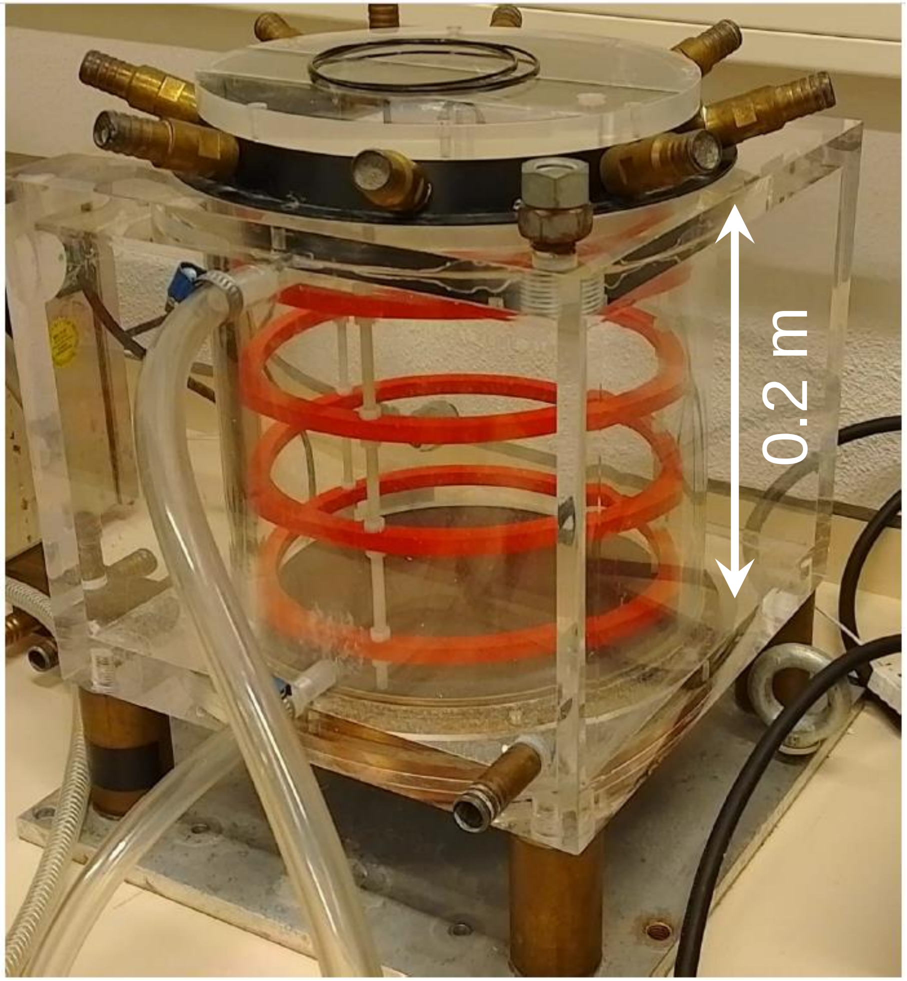
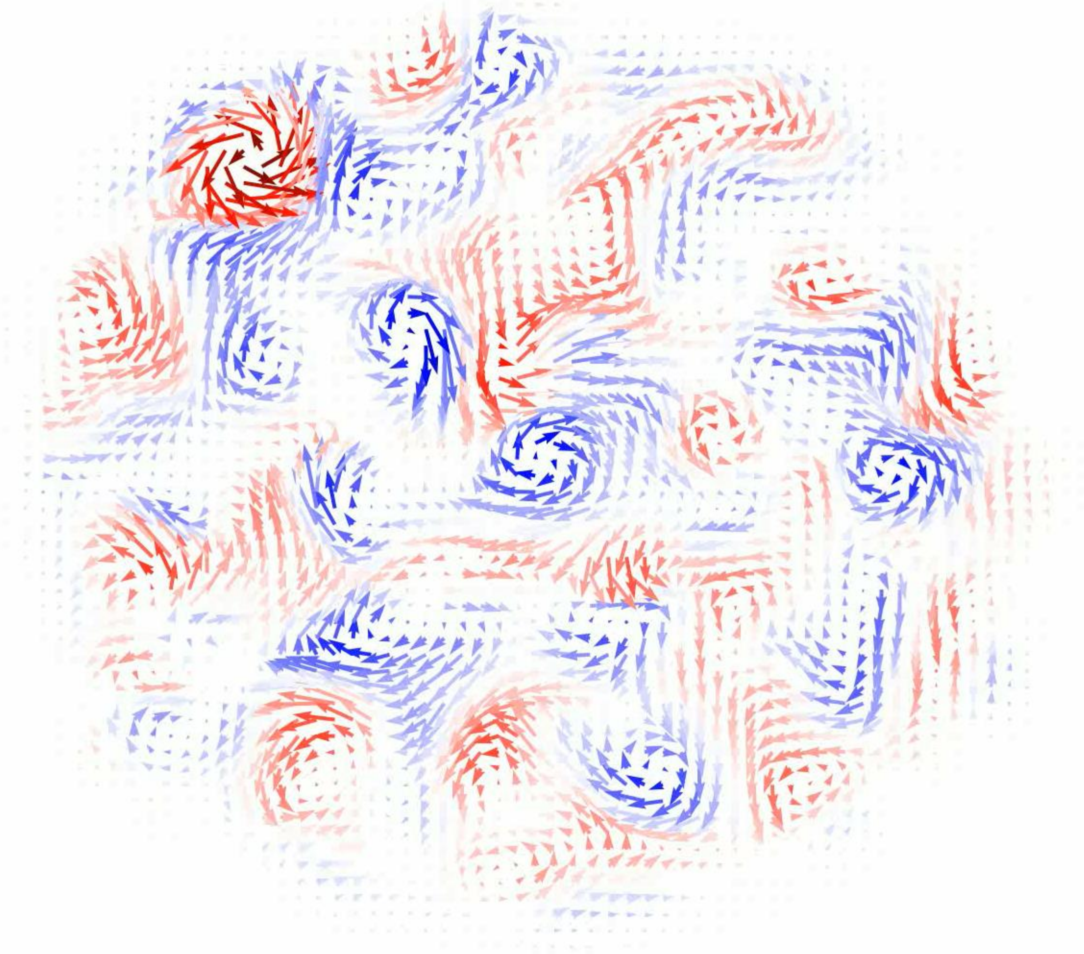


Horizontal cross-section (1 fin)



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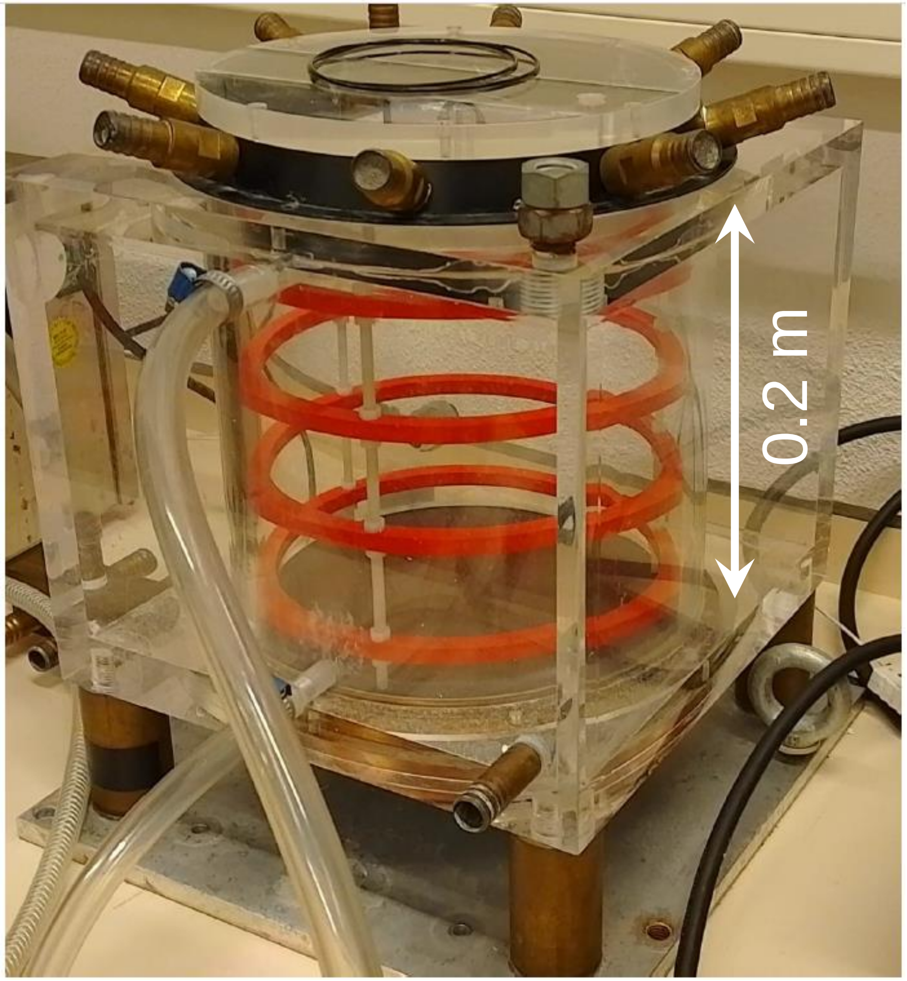
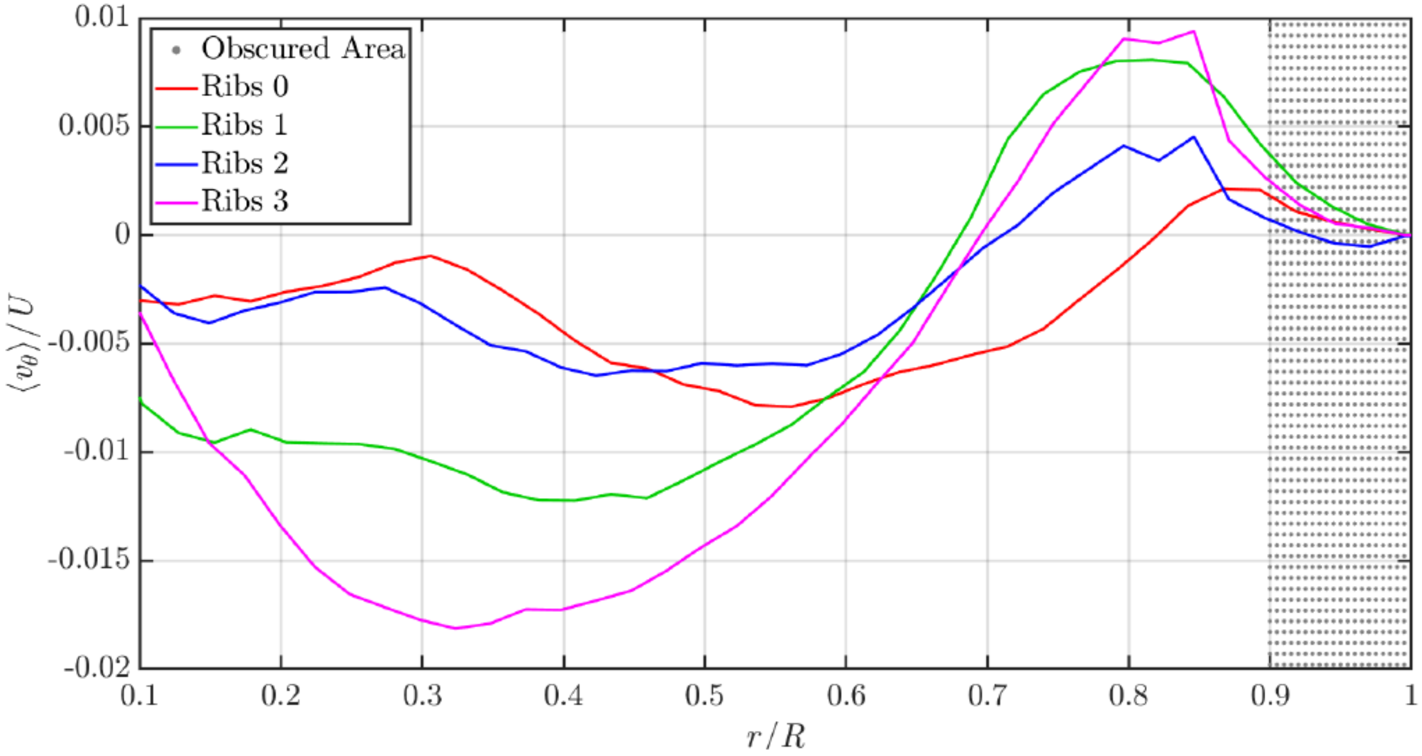


Averaged azimuthal velocity



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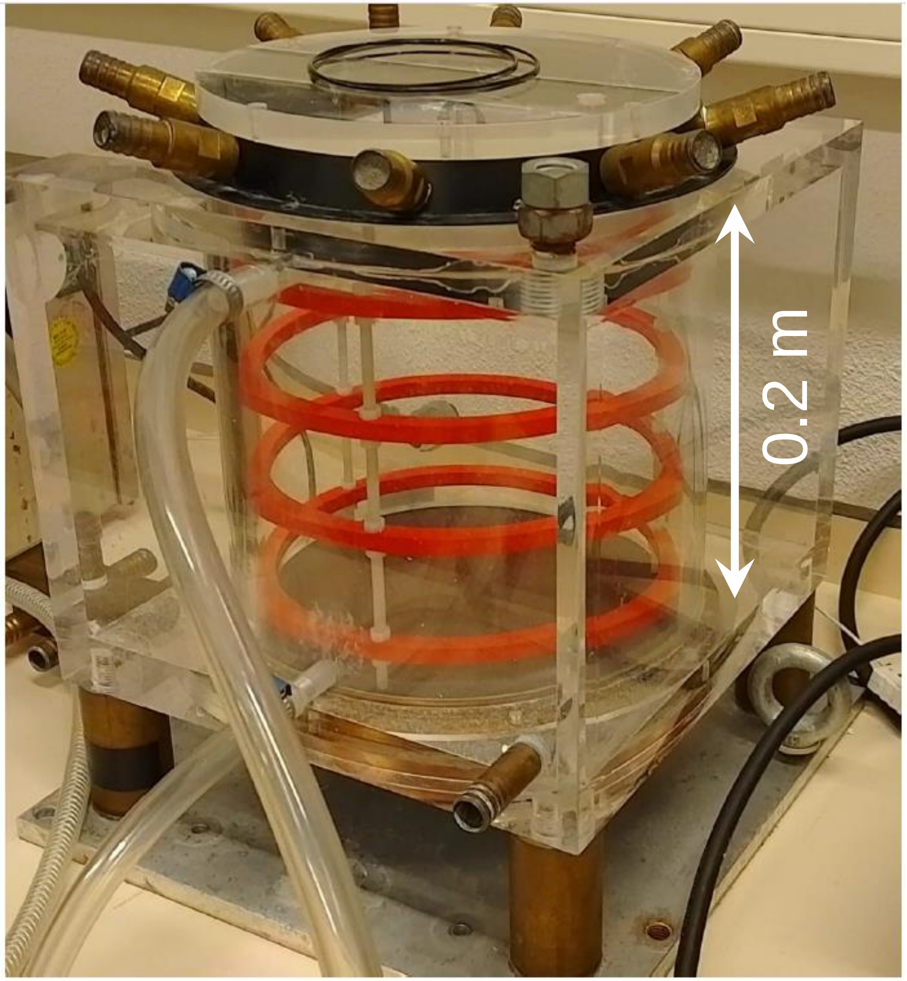
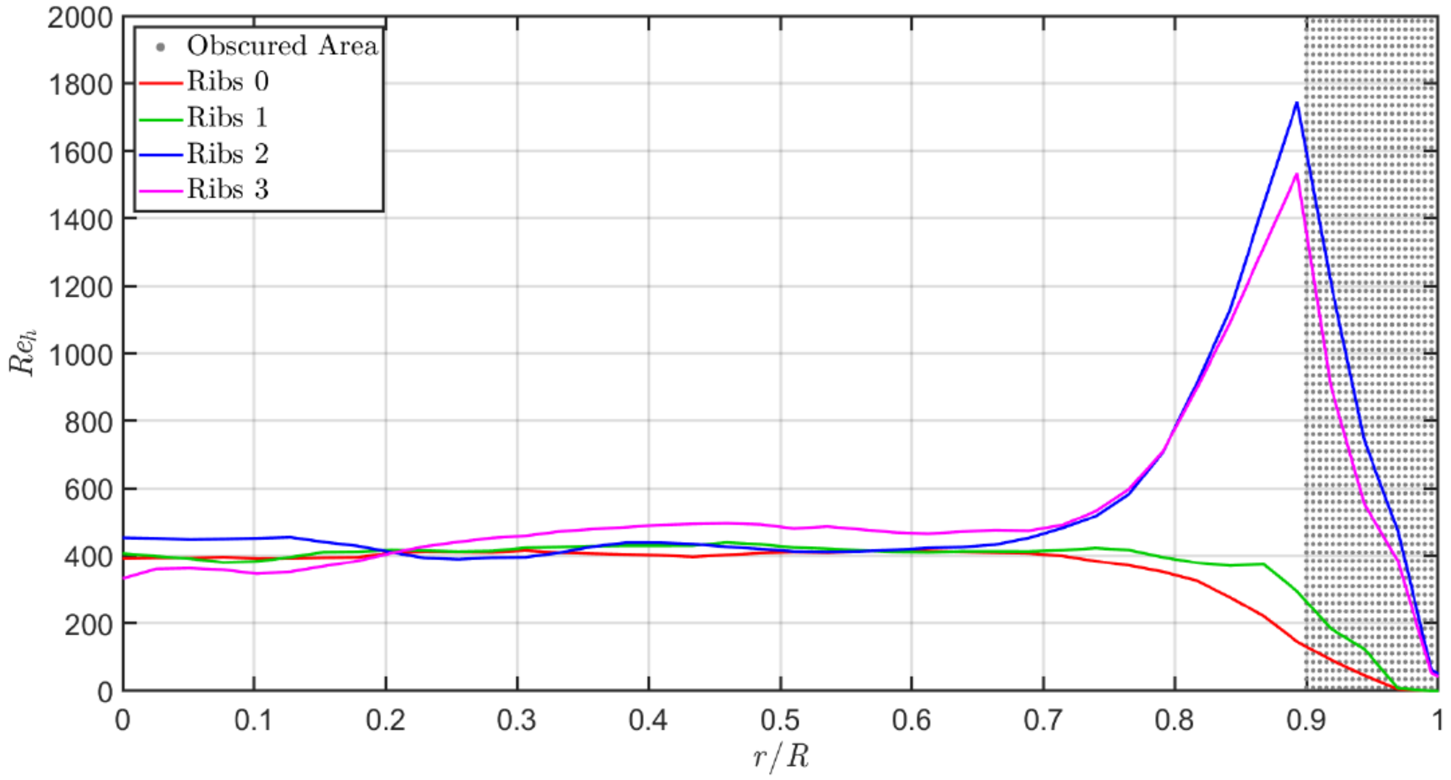


Reynolds number based on horizontal fluctuation velocity



Conclusion

Wall modes: *unexpected*, *persistent*
part of confined turbulent rotating convection

- Strong convective heat transfer

- Jet-like intrusions shape interior flow

How to deal with them?

- …uncertain:

    - Wider flow domains (?)
    - Horizontal fins at sidewall (?)