(Nearly) Large Scale Facilities Part II:
Turbulent (Cryogenic) Thermal Convection at ICTP

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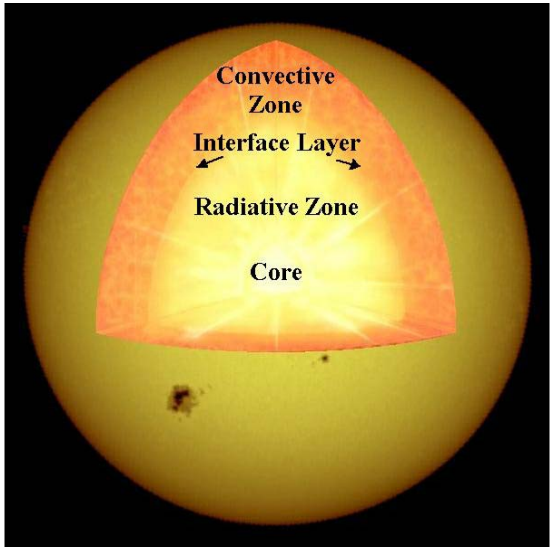
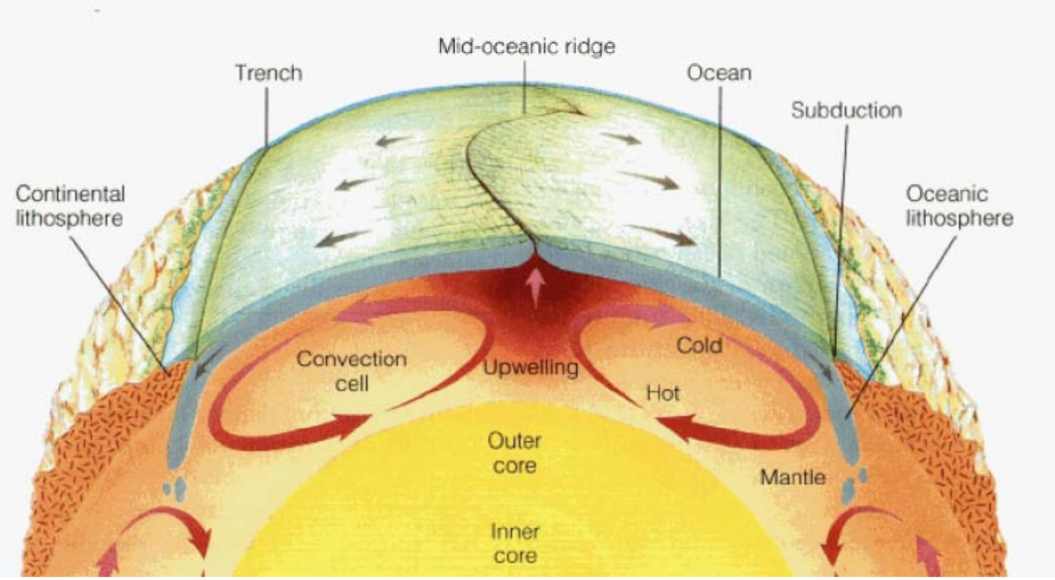
Some of the motivating examples of thermal convection at limiting values of the control parameters in Nature



Sun

Ra ~10^{22}

10^{-3}<Pr<10^{-10}



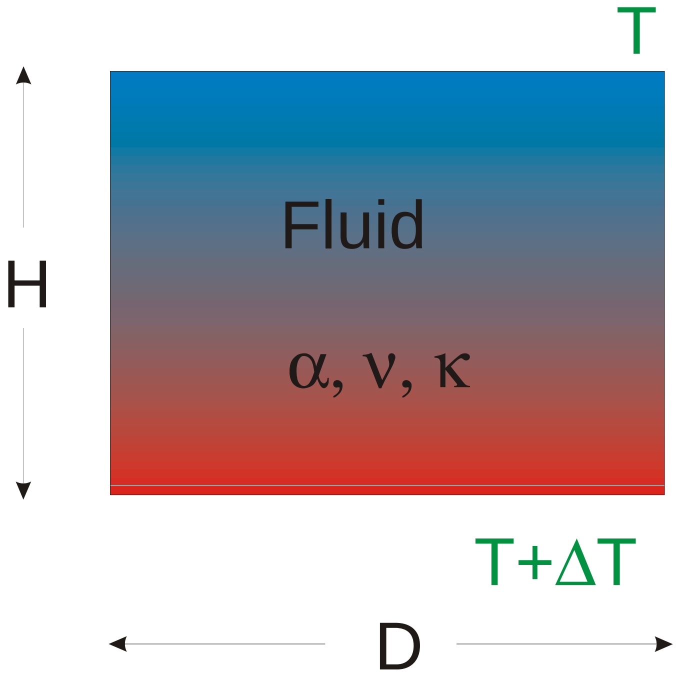
Mantle

Ra ~ 10^6

Pr~10^{21}

(Pr~10^3,magma)

Rayleigh-Benard Convection



α fluid thermal expansion coefficient

ν fluid kinematic viscosity

κ fluid thermal diffusivity

Control parameters for convection

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

$$Pr = \nu/\kappa$$

$$\Gamma = D/H$$

Global heat transfer: Nusselt number

$$\mathrm{Nu} \equiv \frac{\text{measured heat flux}}{\text{heat flux due to pure conduction}} = \frac{QH}{k_f \Delta T}$$

Q = applied heat flux;
k_f= fluid thermal conductivity

$$\mathrm{Nu} = f(\mathrm{Ra};\ \mathrm{Pr};\ \Gamma;\ \ldots..)$$

$$\mathrm{Nu} = C\,\mathrm{Ra}^{\beta} + \ldots.\ (\text{large Ra, constant Pr, } \Gamma, \ldots)$$

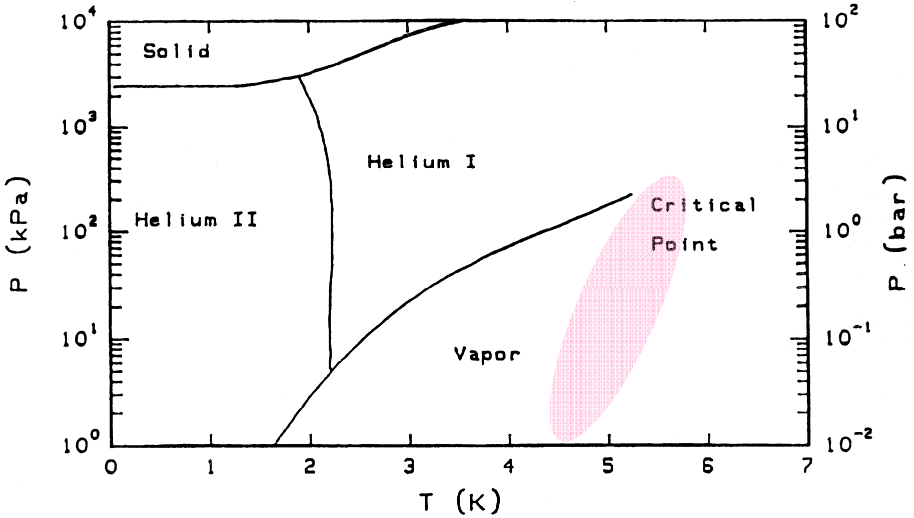
“classical” results

$\beta=1/3$: boundary layers (uncoupled) important (Priestley, Howard, Malkus, 1954); limit of infinite Prandtl number (Constantin and Doering 2001).

$\beta=1/2$: Kraichnan (1962) for moderate Pr (with logarithmic correcions); Toschi & Lohse bulk simulations.

Recent treatment: Lohse and Grossmann (2002) – β determined in Ra-Pr space, implies no pure scaling.

Using L-T helium gas as the working fluid



$$Ra = g \cdot \left(\frac{\alpha}{\nu\kappa} \right) \cdot \Delta T \cdot H^3$$

↙ ↘

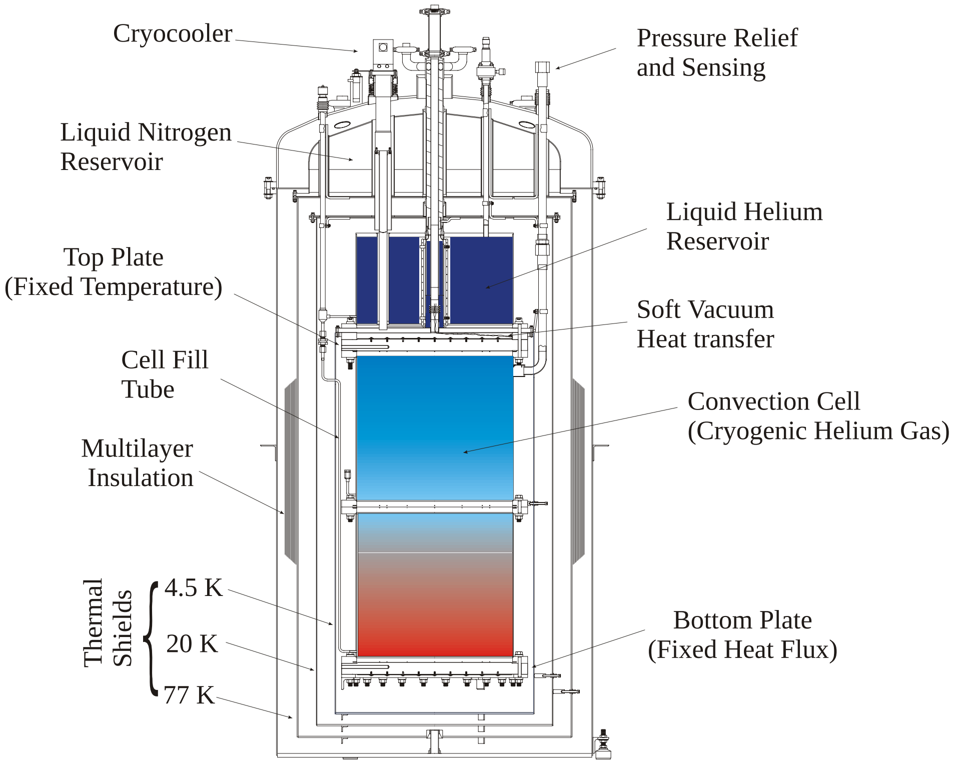
4.4 K , 2 mbar:

$\alpha / \nu\kappa = 5.8 \times 10^{-3}$

5.25 K, 2.4 bar:

$\alpha / \nu\kappa = 6.5 \times 10^{9}$

Ra ~ ($\rho^2 \alpha C_P$). Away from critical point the Prandtl number is approximately constant of order unity. 12 decades of Ra possible, *but which 12 depends mostly on H.* The shaded region gives an approximate area of operation with the P-T plane.

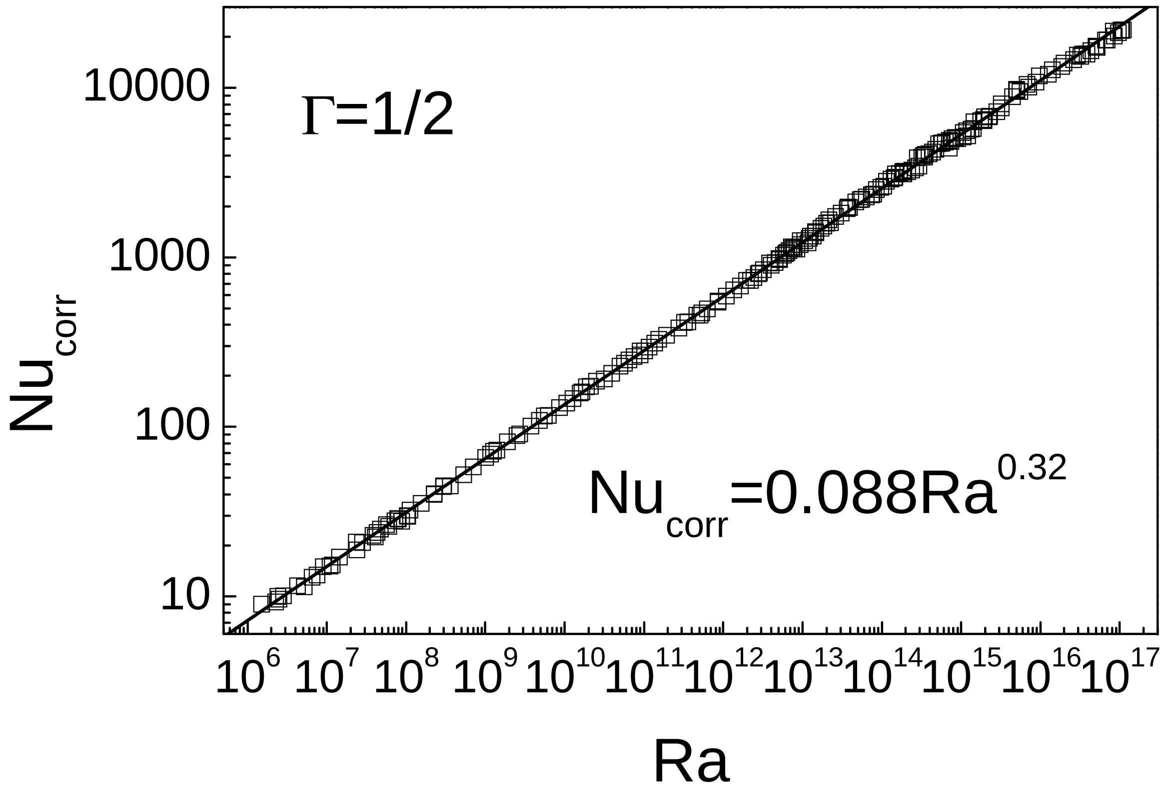


H_{max} = 1 meter
D = 0.5 meter

Facilities located at Elettra Synchrotron Laboratory


E30
Linde

Turbulent Heat Transfer

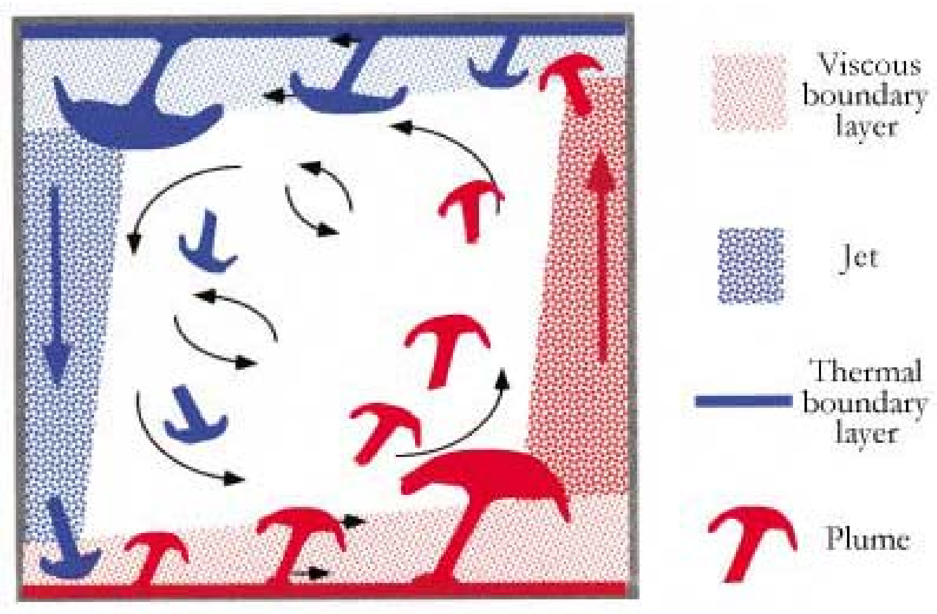


Log-log plot of the Nusselt number versus Rayleigh number

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

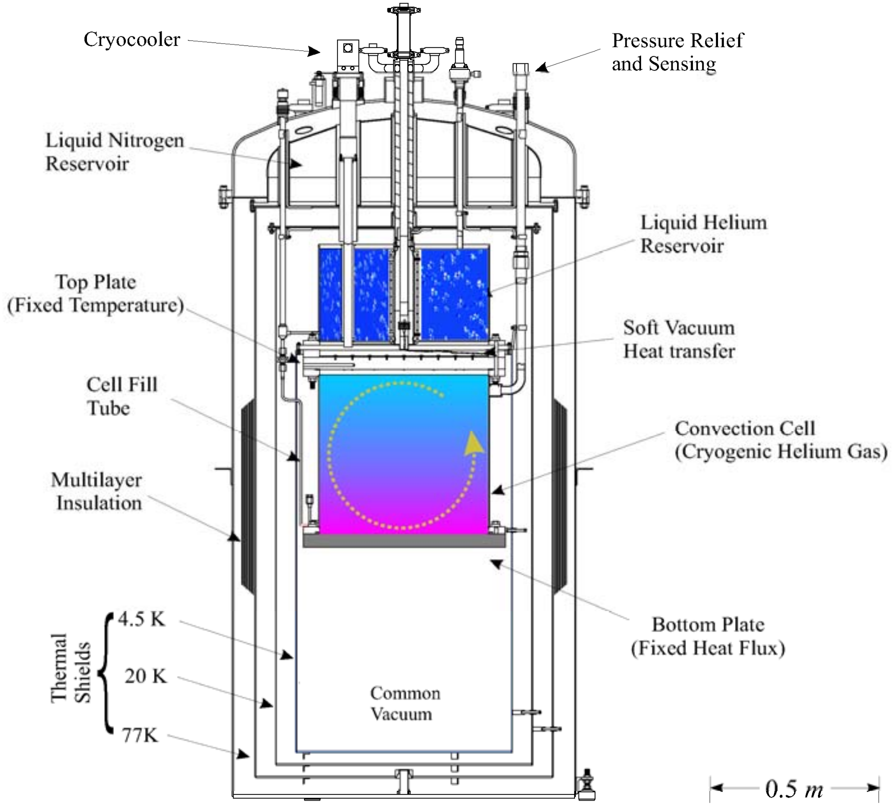
(2) J.J. Niemela & K.R. Sreenivasan, *J. Fluid Mech.,* **557** 411-422 (2006).

A coherent "mean wind"



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

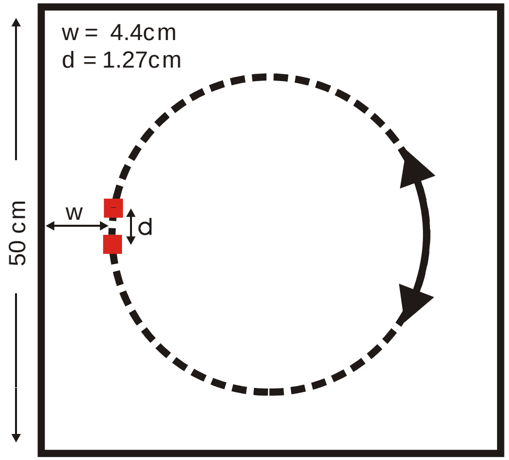
An aspect ratio unity cell



Some issues for consideration:

- *coupling of top and bottom boundary layers due to wind*
- *importance of thermal conditions on sidewalls in presence of wind*
- *ability of heating plates to supply needed rate of plume formation*

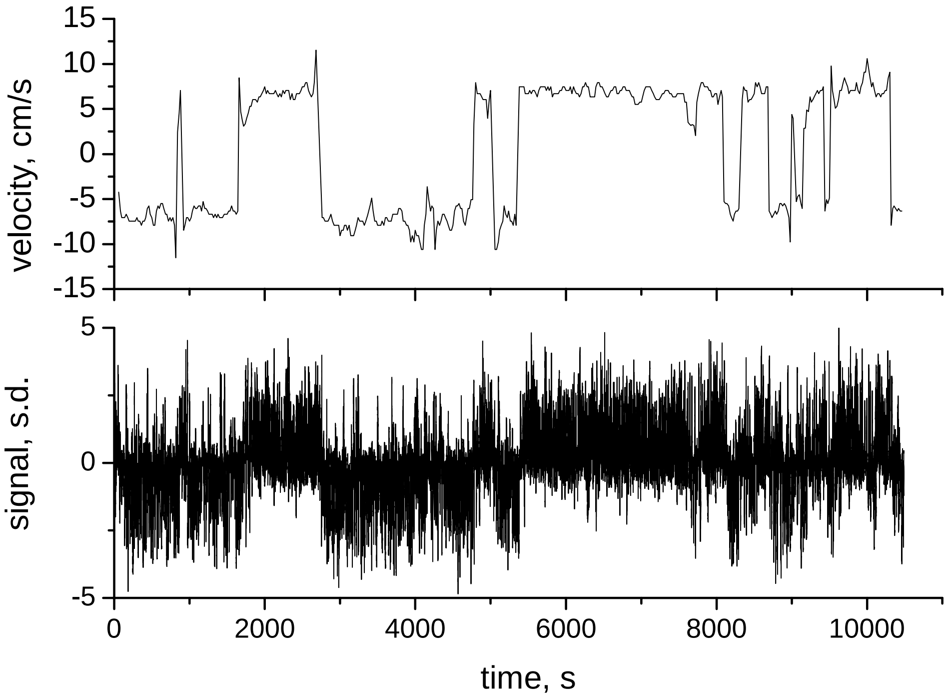
An aspect ratio unity cell for enhancing the mean wind



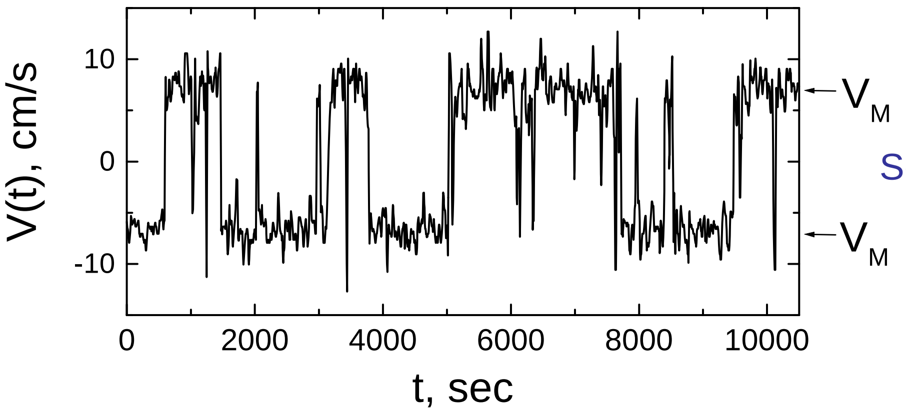
250-micrometer NTD-doped Ge sensors are placed in various positions in the flow.

Stabilization: 10^5 turn-over times of the wind

Run times: 10^4 turn-over times of the wind

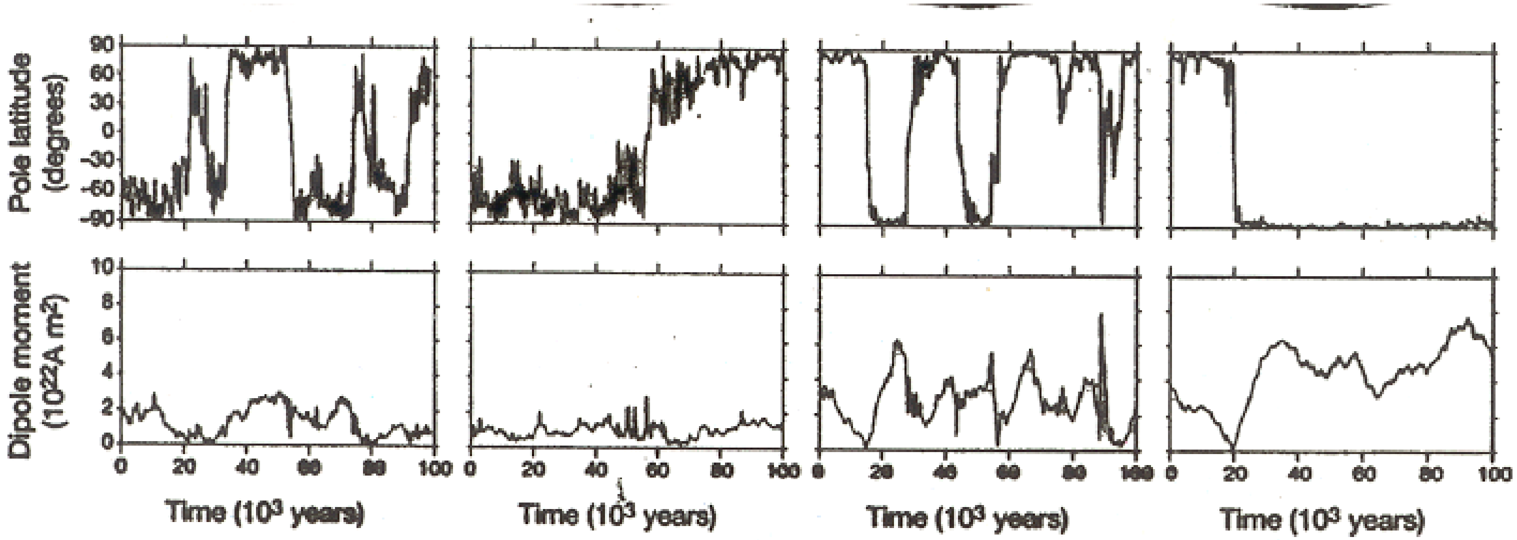


The mean wind and its reversals



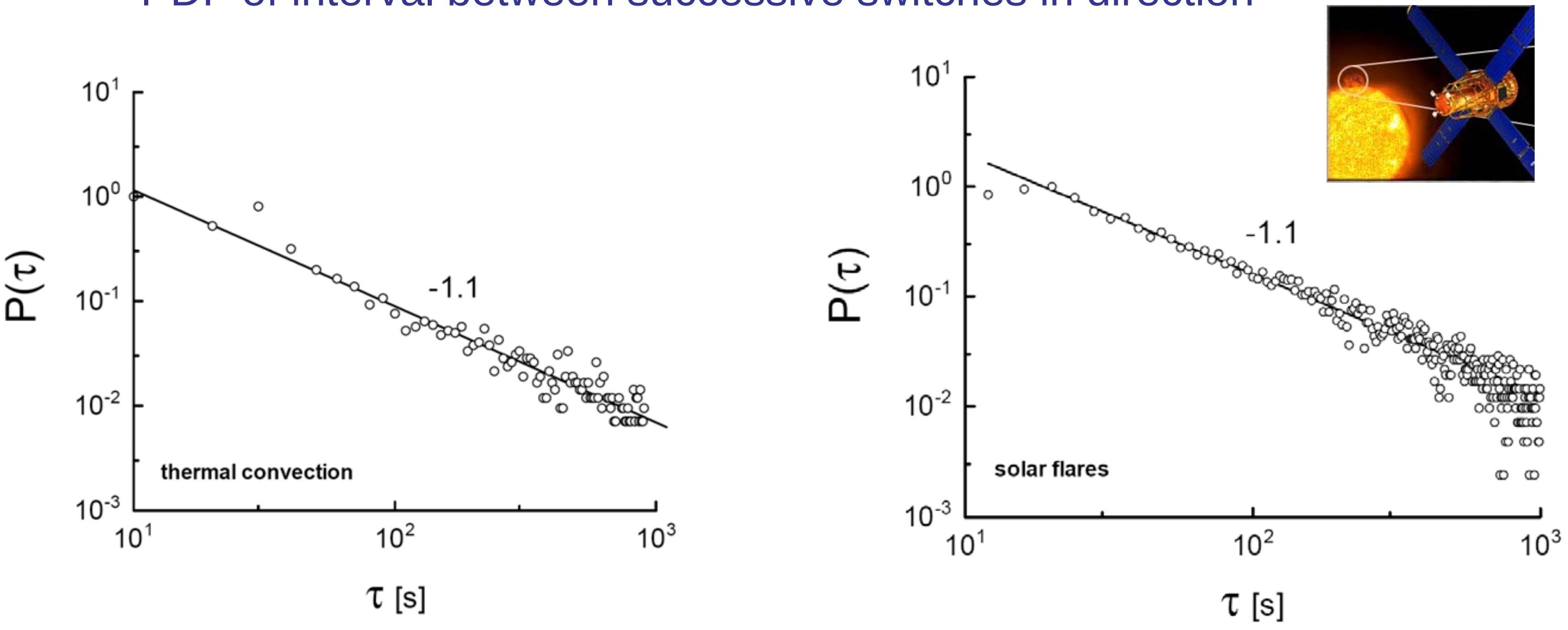
Segment of continuous 5.5-day time series.

Geomagnetic polarity reversals: range of time scales~ 10^3-10^5 years.

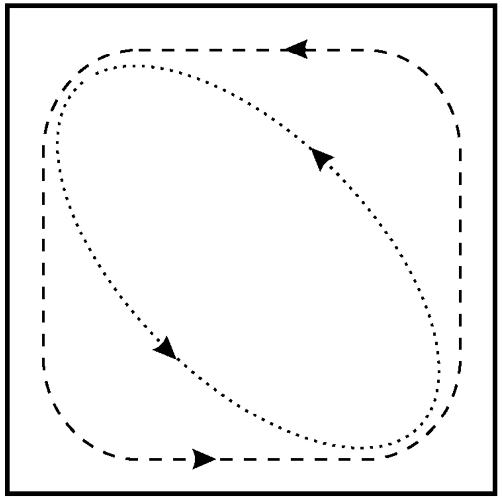


Glatzmaier, Coe, Hongre and Roberts *Nature* **401**, p. 885-890**,** 1999

PDF of interval between successive switches in direction



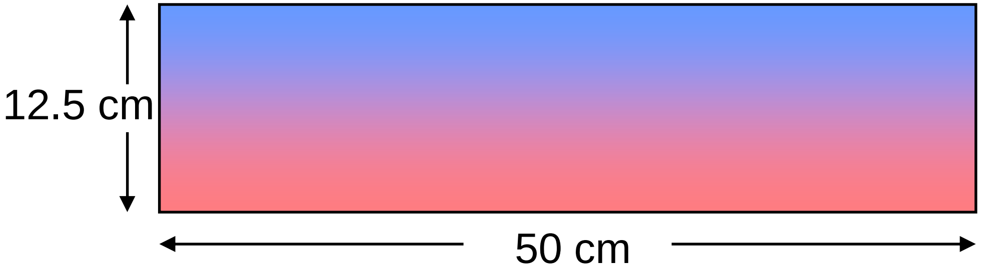
A. Bershadskii, J.J. Niemela, K.R. Sreenivasan *Physics Letters* A **331** 15-19. (2004)

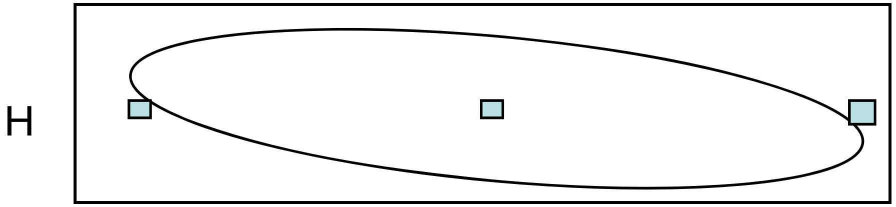


From measurements of the cycling time and the velocity magnitude, the overall shape of the mean flow appears to change as a function of Ra, from a tilted ellipse at lower Ra to a more squarish shape at high Ra.

J.J. Niemela and K.R. Sreenivasan, *Europhysics Letters* **62,** 829-833 (2003)

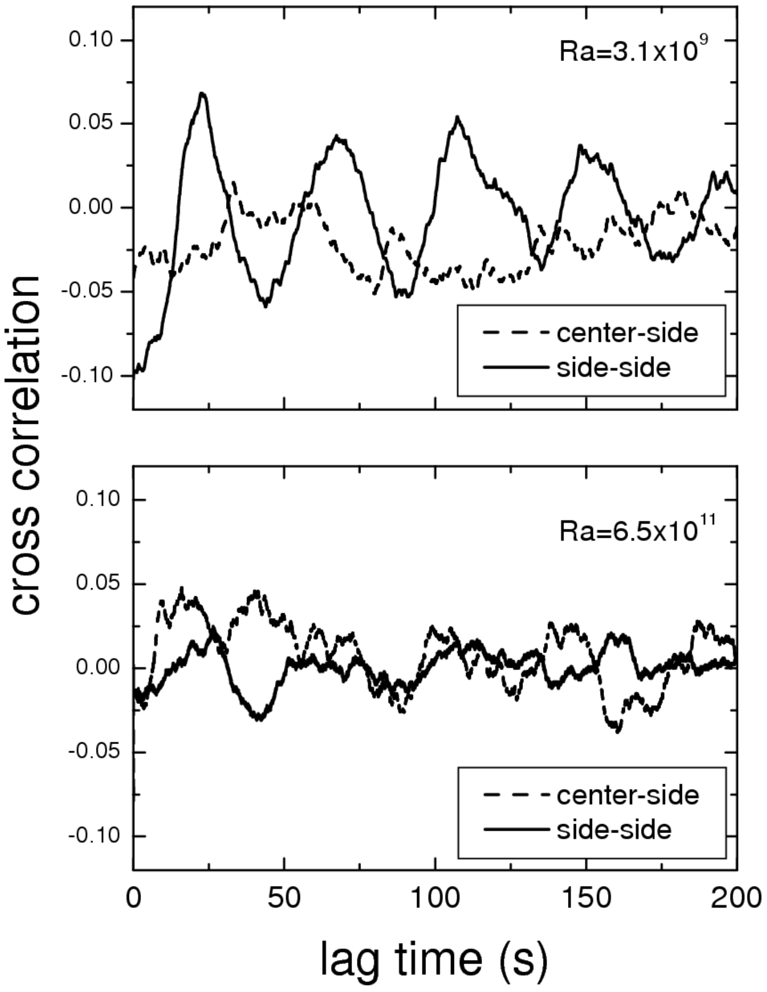
An Γ=4 cell capable of attaining high Ra

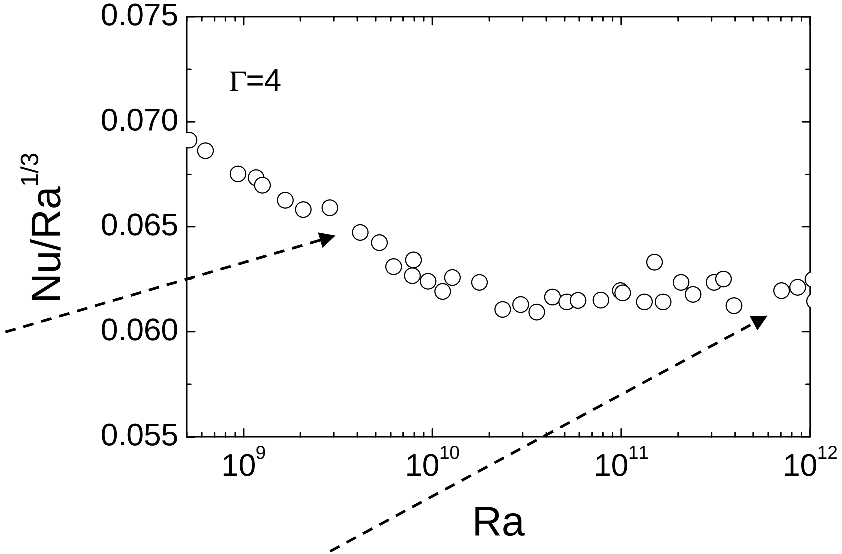




Side view/sensor arrangement, $\Gamma = 4$ cell

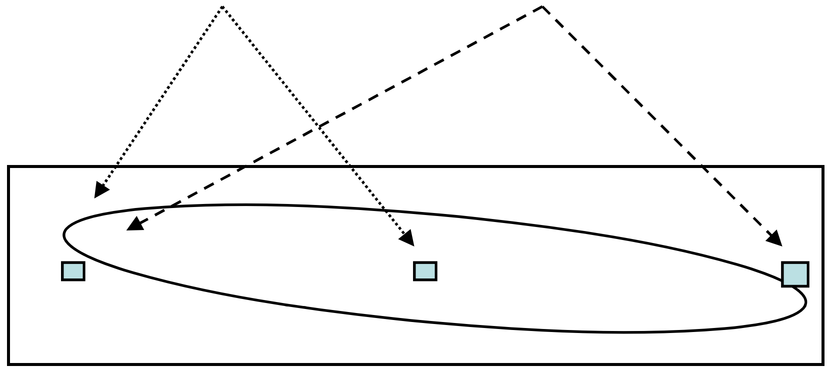
Loss of coherence of the mean wind

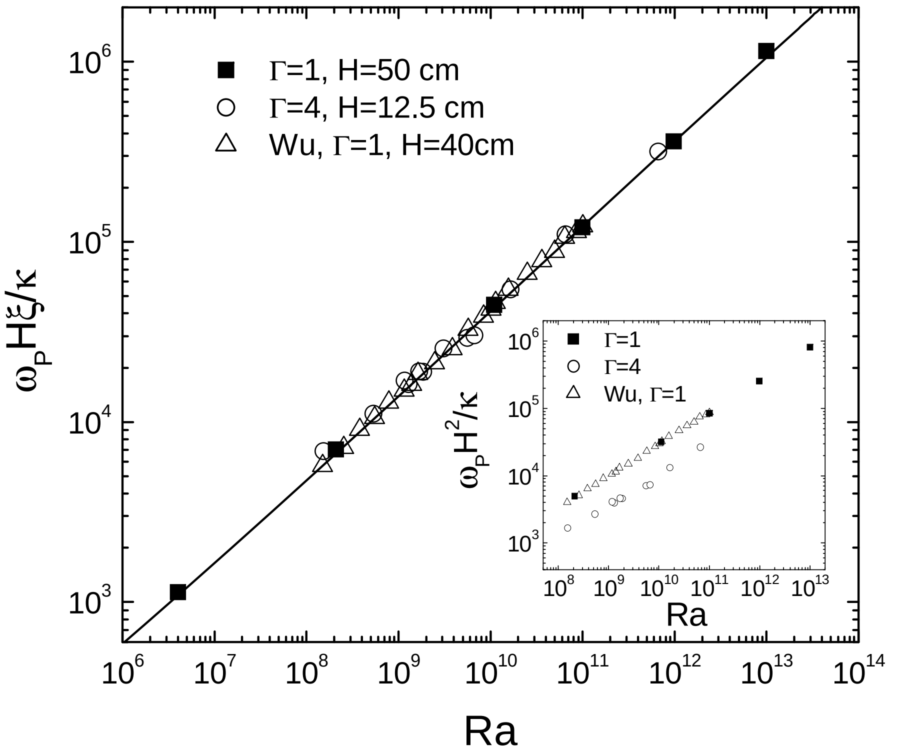




Cross-correlations between:

side and center/ opposite side





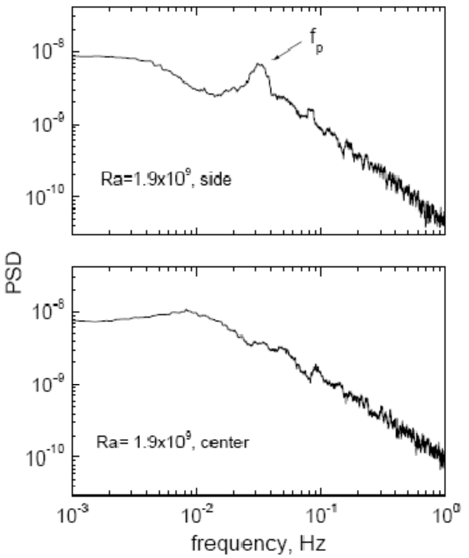


FIGURE 4. The power spectral density (PSD) for temperature fluctuations measured at the horizontal midplane of the apparatus along the sidewall (top) and in the center (bottom). The peak in the sidewall data, labelled as f_p, indicates the advection of plumes by a large-scale coherent wind. The broad and weak peak in the lower panel is roughly centered at $f_p/4$.

$$Re^*_f Pr^{2/3} = 0.44 Ra^{0.453}$$

Grossmann & Lohse: $RePr^{2/3} \sim Ra^{4/9}$

Note on corrections due to finite conductivity of the plates

Verzicco (2004)

- $Nu = F(X)Nu_{inf}$, where Nu_{inf} is achieved with "ideal" plates
- $X=R_f/R_p= k_pH/(k_f*Nu*e)$

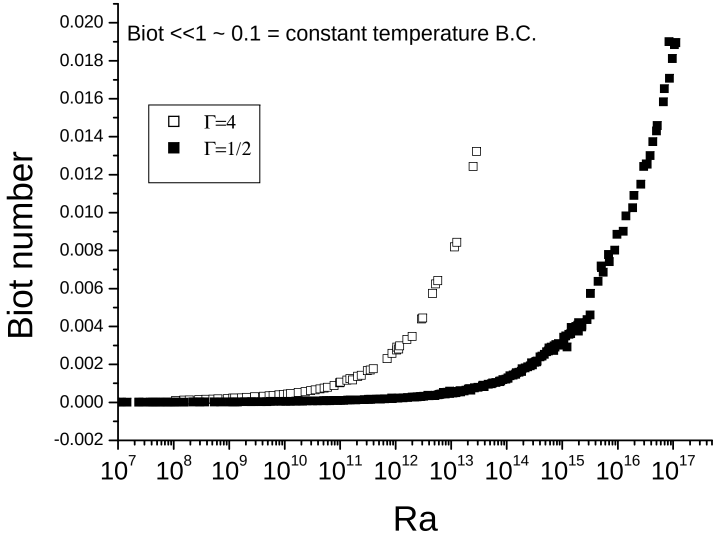
k_p= thermal conductivity of plates
k_f= thermal conductivity of fluid
e= thickness of the plates.

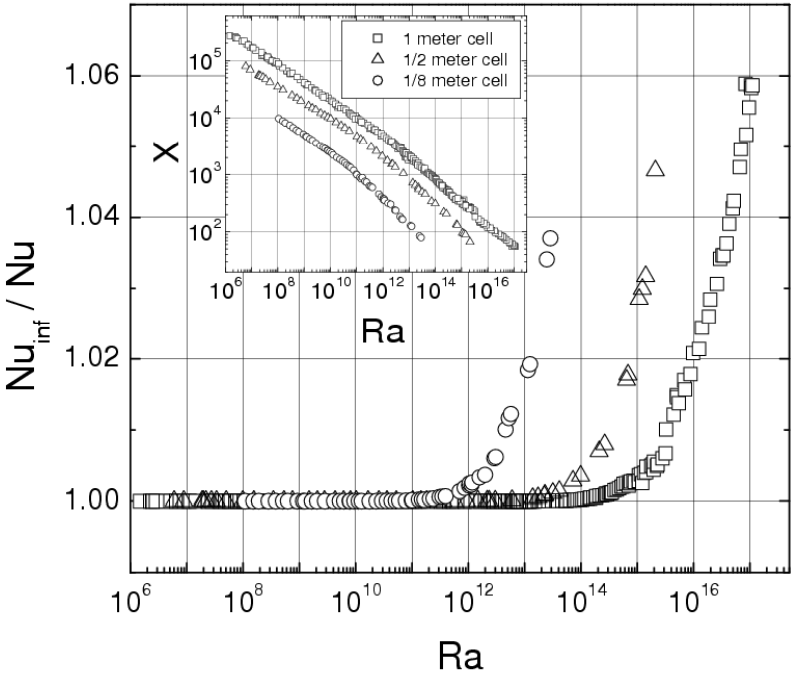
- $F(X) =1-exp[-(X/4)^{1/3}]$

An empirical relation was derived subsequently by Ahlers (2005):

- $F(X) =1-exp[-aX^b]$ with a=0.275, b=0.39

Effect is small for helium experiments and affects *only the last half decade of results* no matter what the height—this is because lowering H lowers X just enough to compensate for the reduced range of Ra. We may consider that this effect is relatively negligible in helium experiments.





Sidewall conduction effects

[Ahlers (2001), Roche (2001), Roche et al (2002), Verzicco (2002), Niemela and Sreenivasan, (2002)],

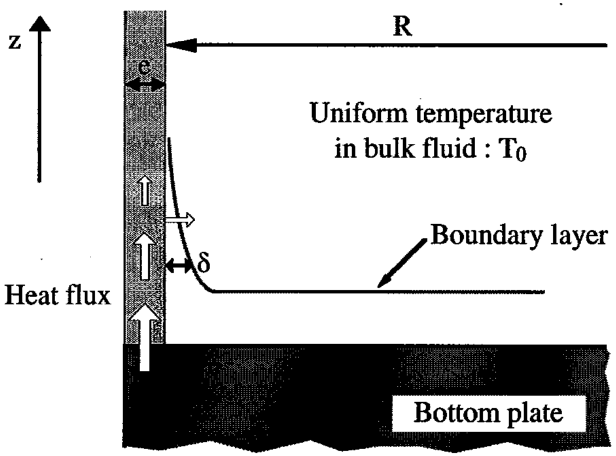
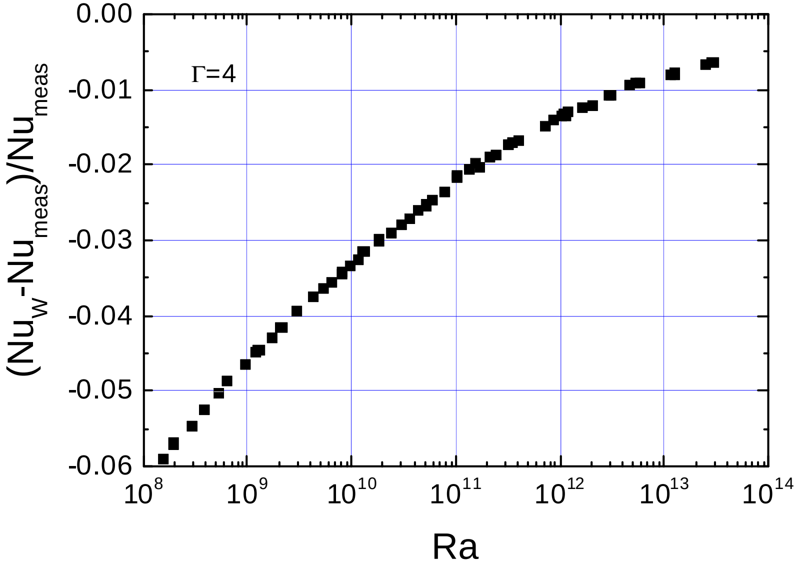


Fig. 1. Heat balance in the wall



Using the correction proposed by Roche, et al.

Discussion

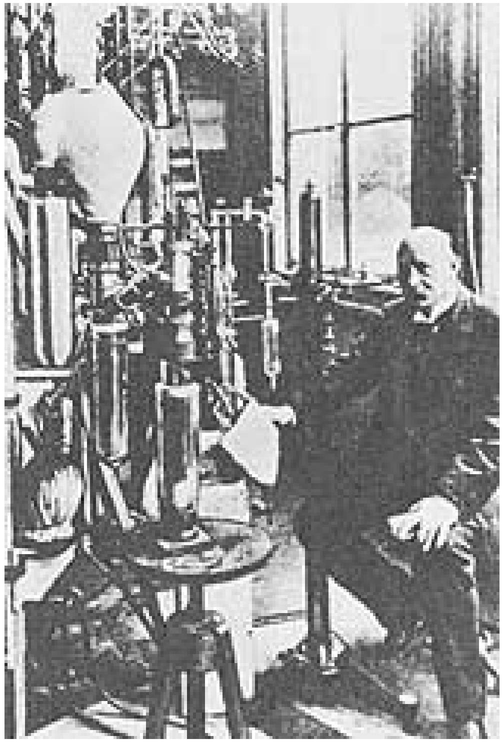
•In these helium experiments, ranges of high Ra can be investigated where it is difficult to apply numerical techniques. This is especially true of large aspect ratio experiments, for which little data exists of any kind at high Ra. There the loss of correlation between opposite wall sensors at high Ra is consistent with the relatively large observed 1/3 power law scaling region, indicative of the randomization generally prescribed for its attainment.

•A high Ra experiment under constant Pr and strictly Boussinesq conditions would be desirable---with a 5 meter tall sample, for instance, Ra > 10^{15} could be achieved in the laboratory *under these ideal conditions*. Such an experiment would also satisfy necessary criteria for observing the so-called “ultimate regime” in heat transfer. *This is not to say that the same apparatus could not be pushed further***.** It appears that effects due to plate conduction will never be significant in any helium gas experiment, regardless of Ra, except perhaps for the last half-decade. There are many problems imbedded in “simple” RB convection—the Nusselt number gives the integrated answer, but an apparatus should be designed to shed light on as many of the details as possible.

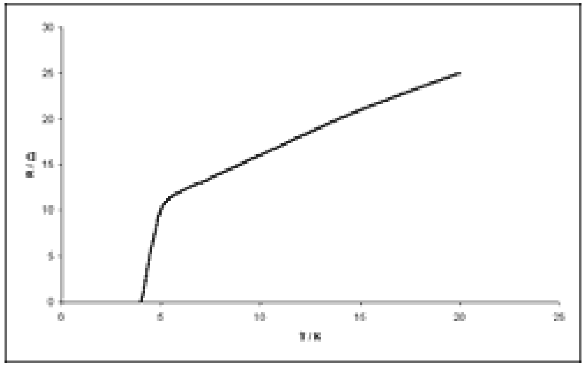
•Interaction of the buoyancy-induced turbulent convection and the Coriolis forces is interesting. An example is the dynamo generating the magnetic field of the earth. From Richardson (1922):

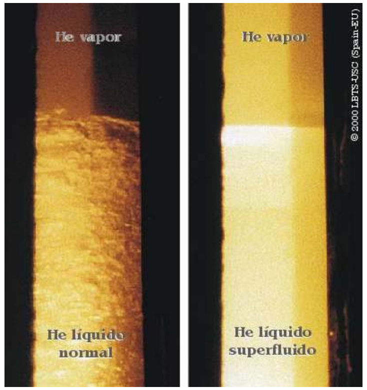
Convection and diffusion
In turb’lence with helicity,
Yields order from confusion
In cosmic electricity!

A short historical digression….

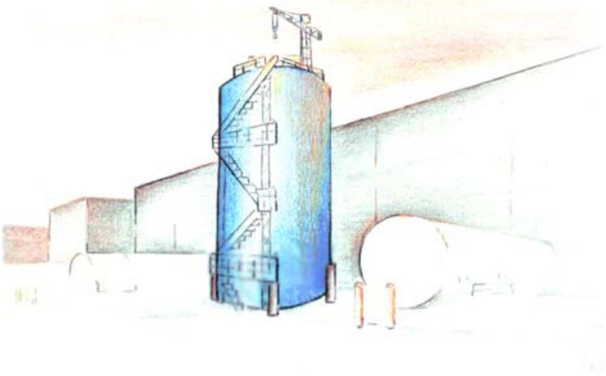


Leiden, 1908: Kamerlingh Onnes succeeds in liquifying helium, an element first identified spectroscopically in India in 1868 during a total eclipse of the sun. This leads to the discovery of **superconductivity** a few years later and **superfluidity** a few decades later.





Left: Onnes seated by his cryostat.
His motto: *“Door meten tot weten*“
(knowledge through measurement)



“Simple fluids are easier to drink than understand.”

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

Corrollary:

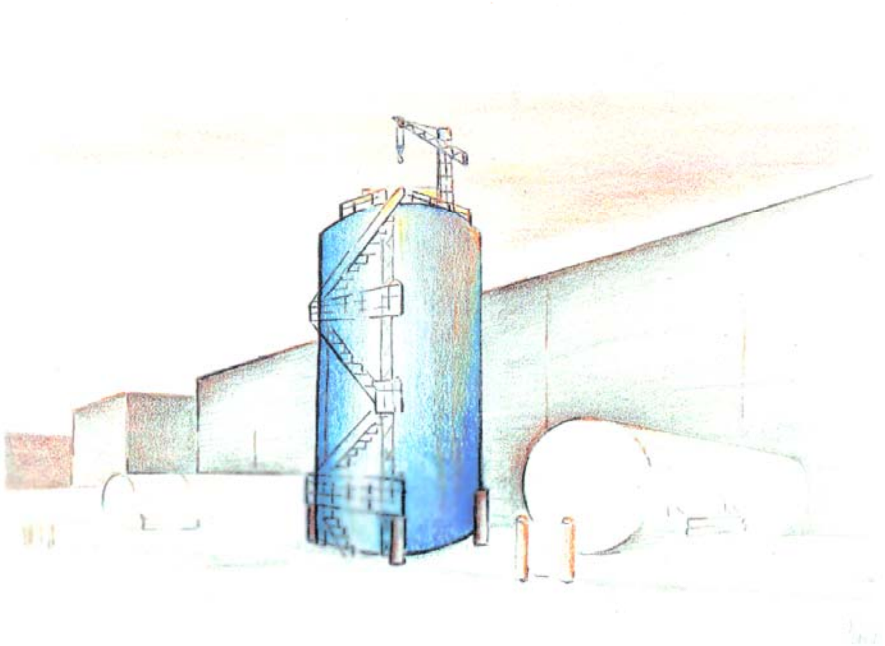
“Simple fluids are easier to understand if you drink.”

A proposed experiment: a 10m high convection cell capable of $Ra \sim 10^{21}$ nearly comparable to that of the Sun.

Inside cell dimensions
D = 5m, L = 10m,
Max volume ~ 25,000 gallons of liquid helium equivalent

Outside dimensions
~7 m dia and ~20 m high

Refrigeration needed
< 200 W



RHIC, BNL

Huge accelerator facilities like CERN or BNL would have plenty of liquid helium on hand, used to cool superconducting magnets.