Search for the "**ULTIMATE STATE**" in turbulent Rayleigh-Benard convection

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Ra = 4.6×10^8
Pr = 6.0

KITP, March 28 2011

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A progress report

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Supported by the Max Planck Society and the Volkswagen Stiftung
Work at UCSB supported by NSF Grant DMR07-02111

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$\eta_K = (\nu^3/\varepsilon_u)^{-1/4}$

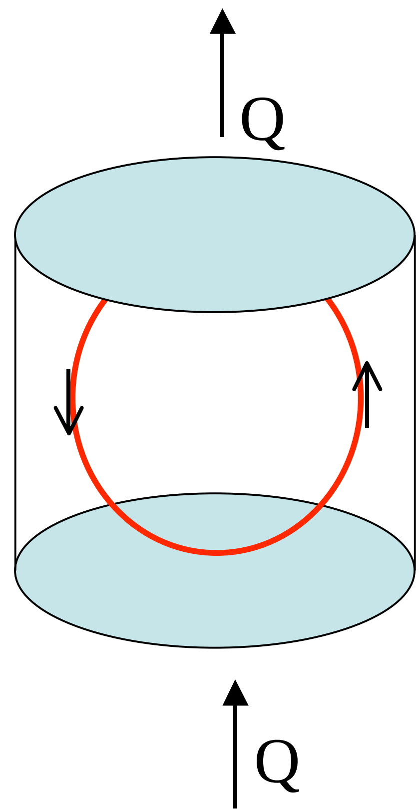
$\eta_K/L = Pr^{1/2}[Ra(Nu-1)]^{-1/4}$

(see, e.g., Lohse and Xia, Annu. Rev. Fluid Mech. **42**, 335 (2009))

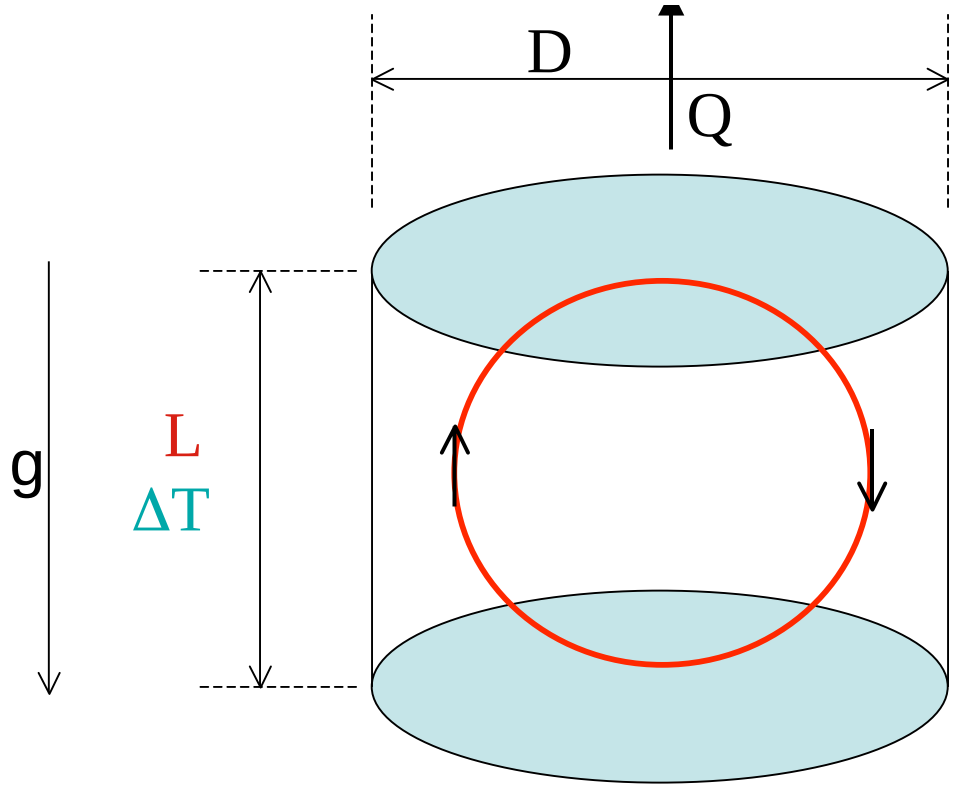
$Ra = 4.6\times10^8$
$Pr = 6.0$
$\eta_K/L = 6\times10^{-3}$
$(\eta_K \sim 0.5$ mm)

Some [e.g. Sugiyama et al., EPL **80**, 34002 (2007)] argue that the System is turbulent when $\ell_{coher}/L = 10\eta_K/L < 0.1$

Viewed from the top



KITP, March 28 2011



Pr = 596, Ra = 6.8x10^8, Nu = 55

$\eta_K/L = 6x10^{-2}$ Movie by K.Q. Xia et al.

Fluid properties

$$Ra = \overbrace{(\alpha / \kappa \nu)} \; g \, L^3 \, \Delta T$$

Q

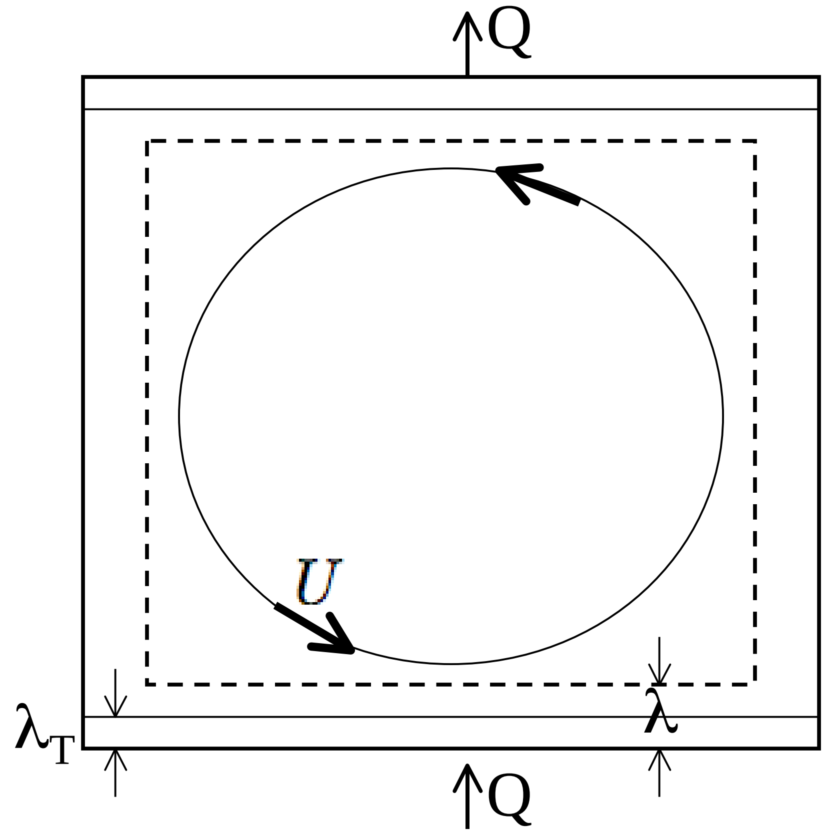
$g = 9.8$ m / s^2

Aspect ratio $\Gamma = D/L = 1/2$

Nusselt number $Nu = (QL/\Delta T) / \lambda$

Prandtl number $Pr = \nu/\kappa$

See e.g. Ahlers, Grossmann, and Lohse, Rev.Mod.Phys. **81**, 503 (2009).
D. Lohse and K.-Q. Xia, Annu. Rev. Fluid Mech. **42**, 459 (2010).
G. Ahlers, Physics **2**, 74 (2009).



$$Ra < Ra^{*} \simeq 10^{14} :$$

Thin thermal boundary layers above (below) the bottom (top) plate control the heat transport when Ra is not too large. Then, from experiment,

$$Nu \sim Ra^{\gamma_{eff}} Pr^{0.0} \qquad \gamma_{eff} \simeq 0.31$$

$$Re_s > Re_s^* \simeq 400$$

(or equivalent fluctuations):

The "Kraichnan" regime

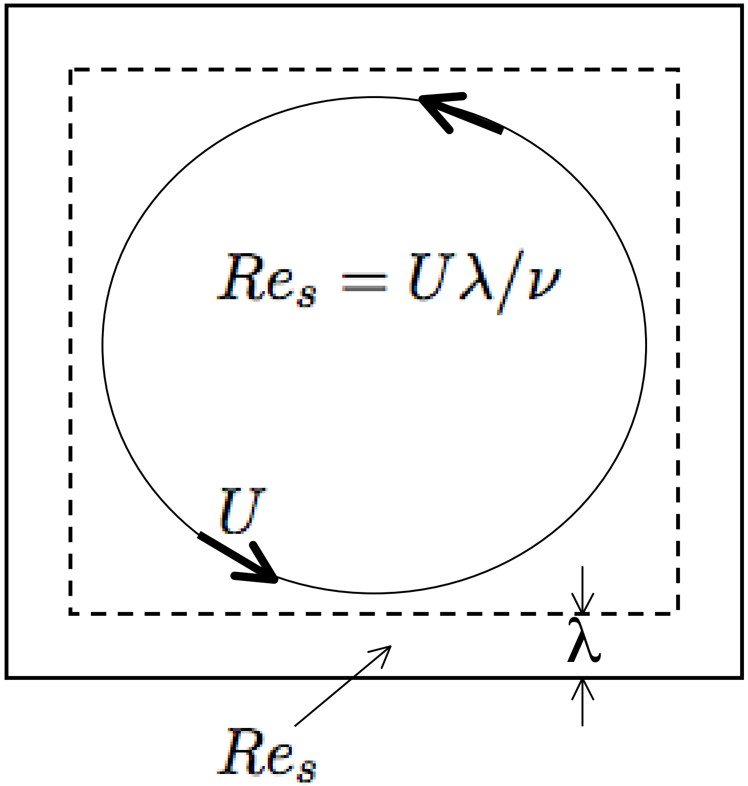
$$Nu \sim Ra^{1/2}$$

with logarithmic corrections due to the viscous sublayer:

$$Nu \sim Ra^{1/2}(lnRa)^{-3/2}Pr^{-1/4}$$

for $0.1 \leq Pr \leq 1$

R. H. Kraichnan, Turbulent thermal convection at arbitrary Prandtl numbers, Phys. Fluids **5**, 1374 (1962)



The LSC applies a shear to the boundary layers (BL) and is expected to cause a BL shear instability when the shear Reynolds number Re_s exceeds a critical value Re_s^* ~= 400.

Various attempts to observe the Kraichnan predictions:

A.) Systems "without" boundaries where Nu ~ $Ra^{1/2}$ is expected:

1.) DNS for RBC with periodic BCs

2.) DNS for Rayleigh-Taylor instability

3.) salt diffusion in a vertical pipe

4.) RBC in a vertical column with wide top and bottom entrance sections

5.) Local heat flux measurements for RBC

B.) Systems with boundaries where Nu ~ $Ra^{1/2}/[\log(Ra)]^{3/2} \sim Ra^{0.39}$ is expected:

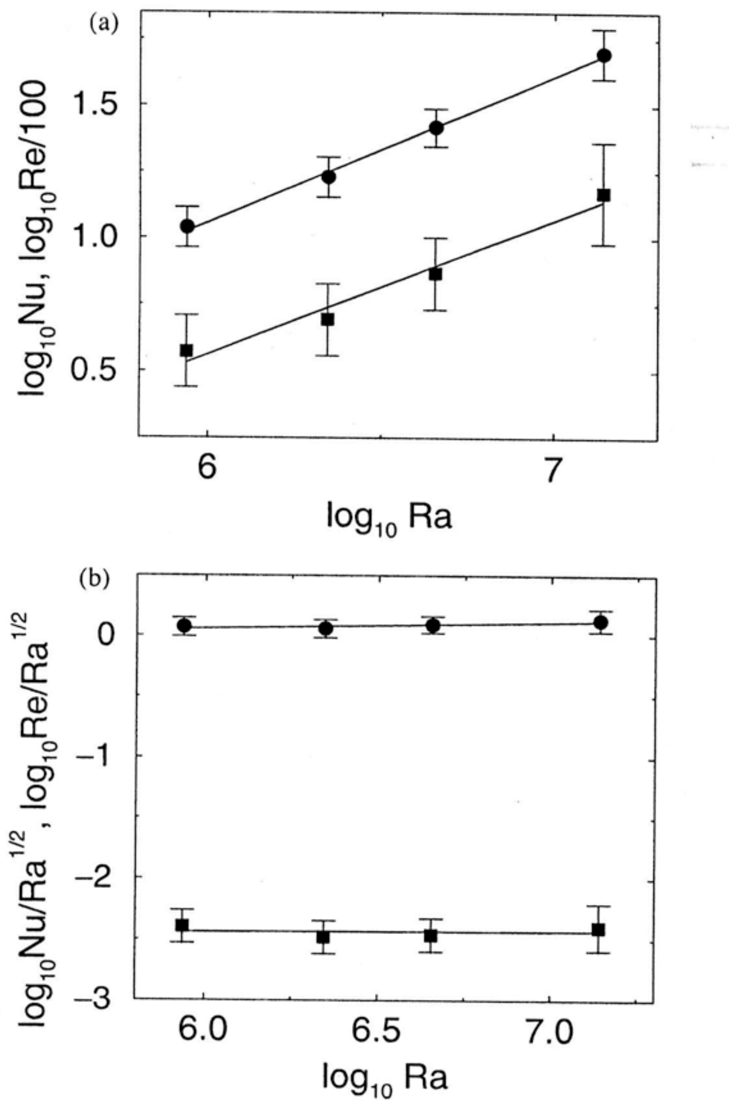
6.) Turbulent Taylor-Couette flow

7.) RBC experiments using He near its critical point

8.) RBC experiments using classical gases under pressure

D. Lohse and F. Toschi,
Phys. Rev. Lett. **90**, 034502 (2003).

DNS, using periodic BCs in the vertical direction



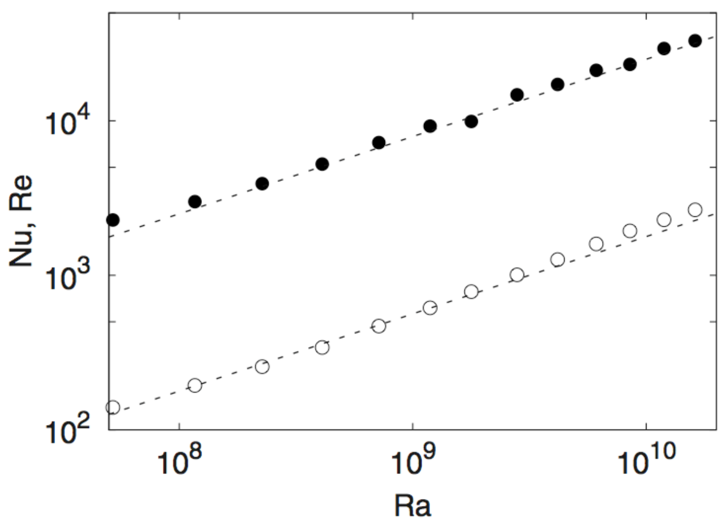
Kolmogorov scaling and Intermittency in Rayleigh-Taylor turbulence

Boffetta, Mazzino, Musaccio, and Vozella, Phys. Rev. 79, 065301R (2009).

Cold fluid above hot fluid

No boundaries!

Nu ~ $Ra^{0.5}$



M.R. Cholemari and J.H. Arakeri,
Int. J. Heat Mass trans. 48, 4467 (2005);
J. Fluid Mech. **621**, 69 (2009)

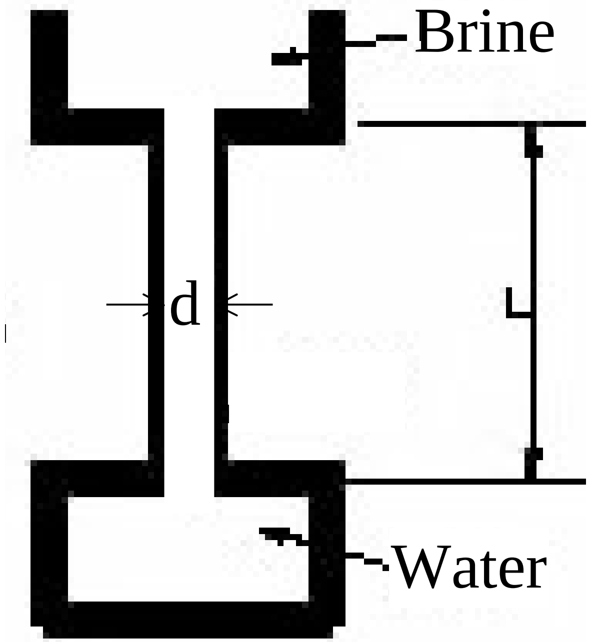
$$Ra = \frac{g(\Delta\rho/(\rho_0 L)d^4}{\nu\alpha}$$

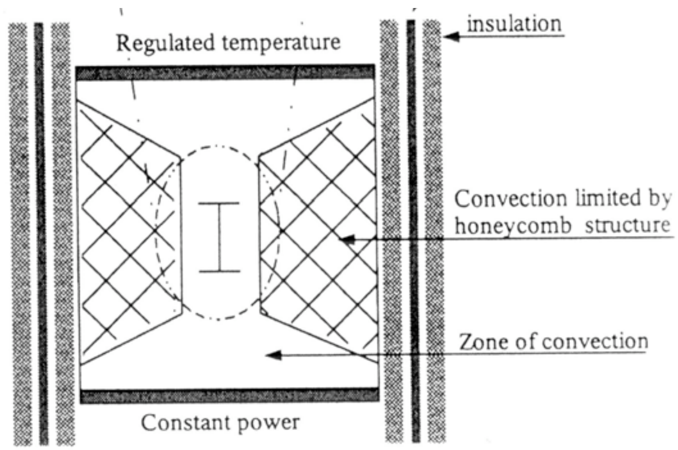
d = slot width

Nu defined in terms of concentration flux

$$Nu = \frac{\langle flux \rangle}{\alpha \Delta C / L}$$

They claim to get Nu ~ $Ra^{0.5}$





So they tried

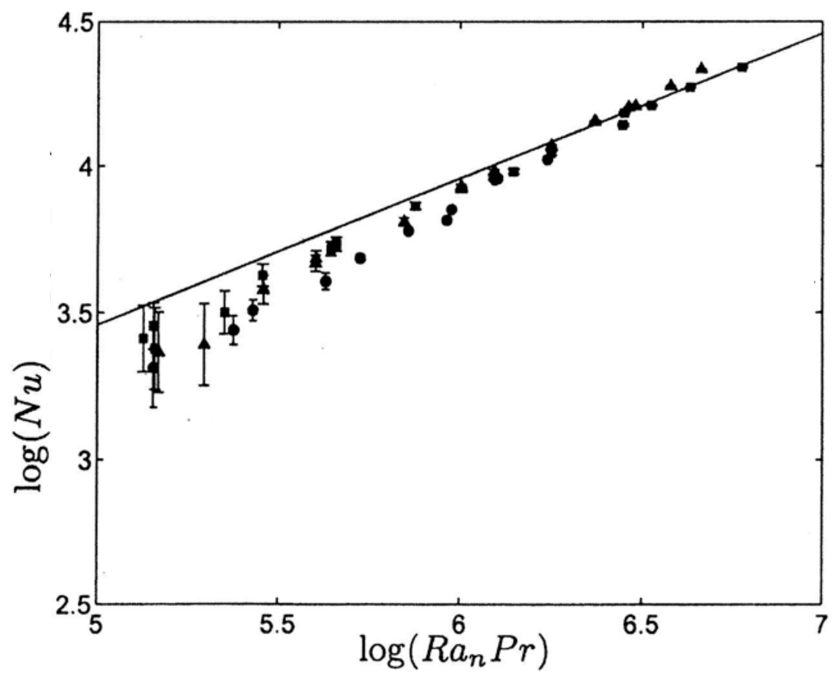
$$d = \theta / \beta$$

θ = rms fluct. of T

Note that d depends on Ra !
Kraichnan assumes a length that depends only on the geometry.

$$Ra = \frac{g \alpha \beta d^4}{\kappa \nu} \qquad Nu = Q / \lambda \beta$$

$$\beta = dT/dz$$



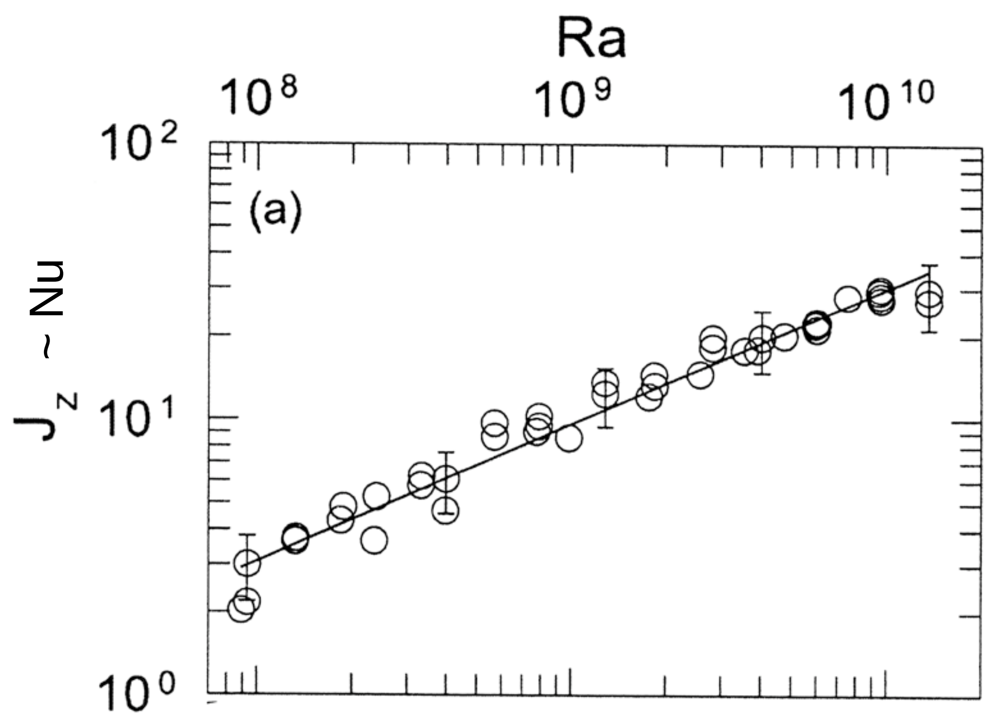
Using the slot width for d did not give a power law for Nu(Ra).

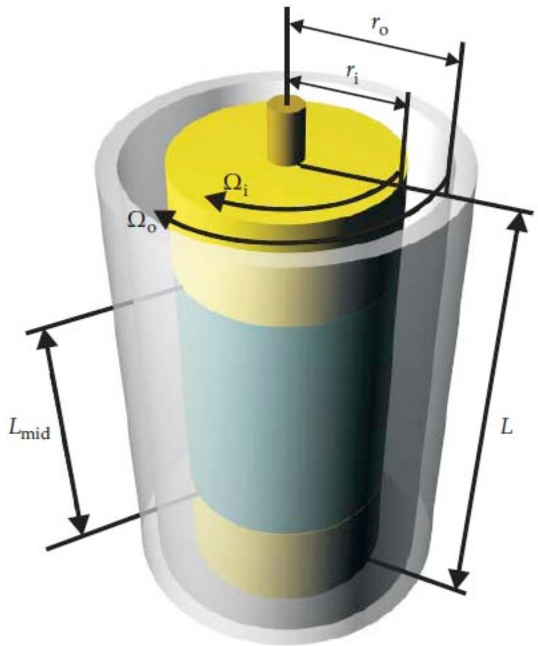
M. Gibert, H. Pabiou, F. Chilla, and B. Castaing, "High-Rayleigh-number convection in a vertical ch
Phys. Rev. Lett. **96**, 084501 (2006),
Gibert et al., Phys. Fluids **21**, 035019 (2009).

X.D. Shang,P. Tong, and K.Q. Xia,
Phys. Rev. Lett. **100**, 244503 (2008)
[see also S. Grossmann and D. Lohse,
Phys. Fluids **16**, 4462 (2004)].

$$Nu(x,y) = \frac{\langle w(x,y,t)\theta(x,y,t)\rangle_t}{\kappa\nu}$$

At half height on the vertical sample center line:





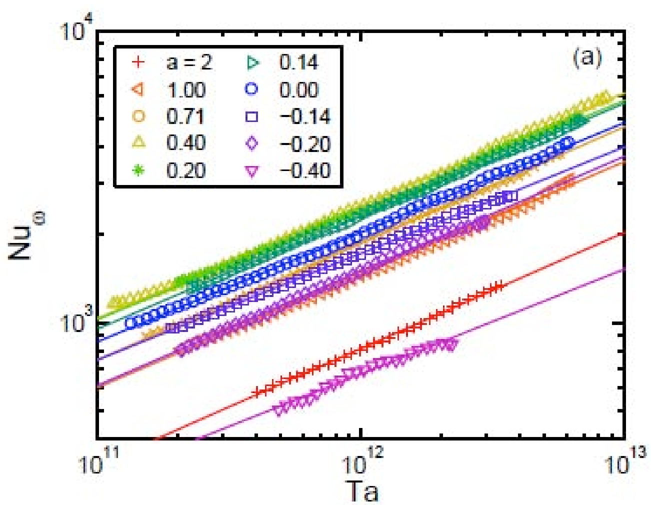
Torque scaling in turbulent Taylor-Couette flow
D.P.M. van Gils, S.G. Huisman, G.-W. Bruggert, C. Sun, and D. Lohse, Phys. Rev. Lett. **106**, 024502 (2011)

Nu_ω ~ flux of angular velocity from the inner to the outer cylinder $\longrightarrow$ Nu

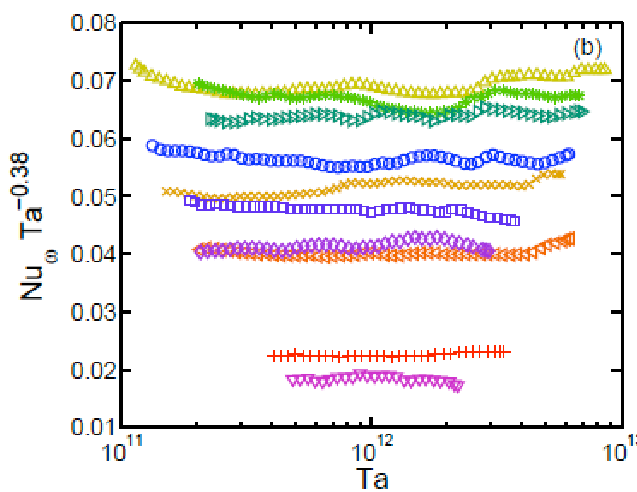
Ta ~ $(\Omega_i - \Omega_o)^2$ $\longrightarrow$ Ra

B. Eckhardt, S. Grossmann, and D. Lohse, J. Fluid Mech. **581**, 221 (2007).

van Gils et al. find $Nu_\omega \sim Ta^{0.38}$, consistent with turbulent BLs. In Taylor-Couette flow, the driving applies shear directly to the BLs; thus the BLs are driven into the turbulent state more easily than is the case for RBC where the thermal driving induces a large-scale circulation (or fluctuations) which in turn (as a secondary effect) applies the shear to the BLs.



$a = -\Omega_o / \Omega_i$



How to get large Ra:

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

To get large Ra, use a sample with large L
(then Γ will necessarily be small).

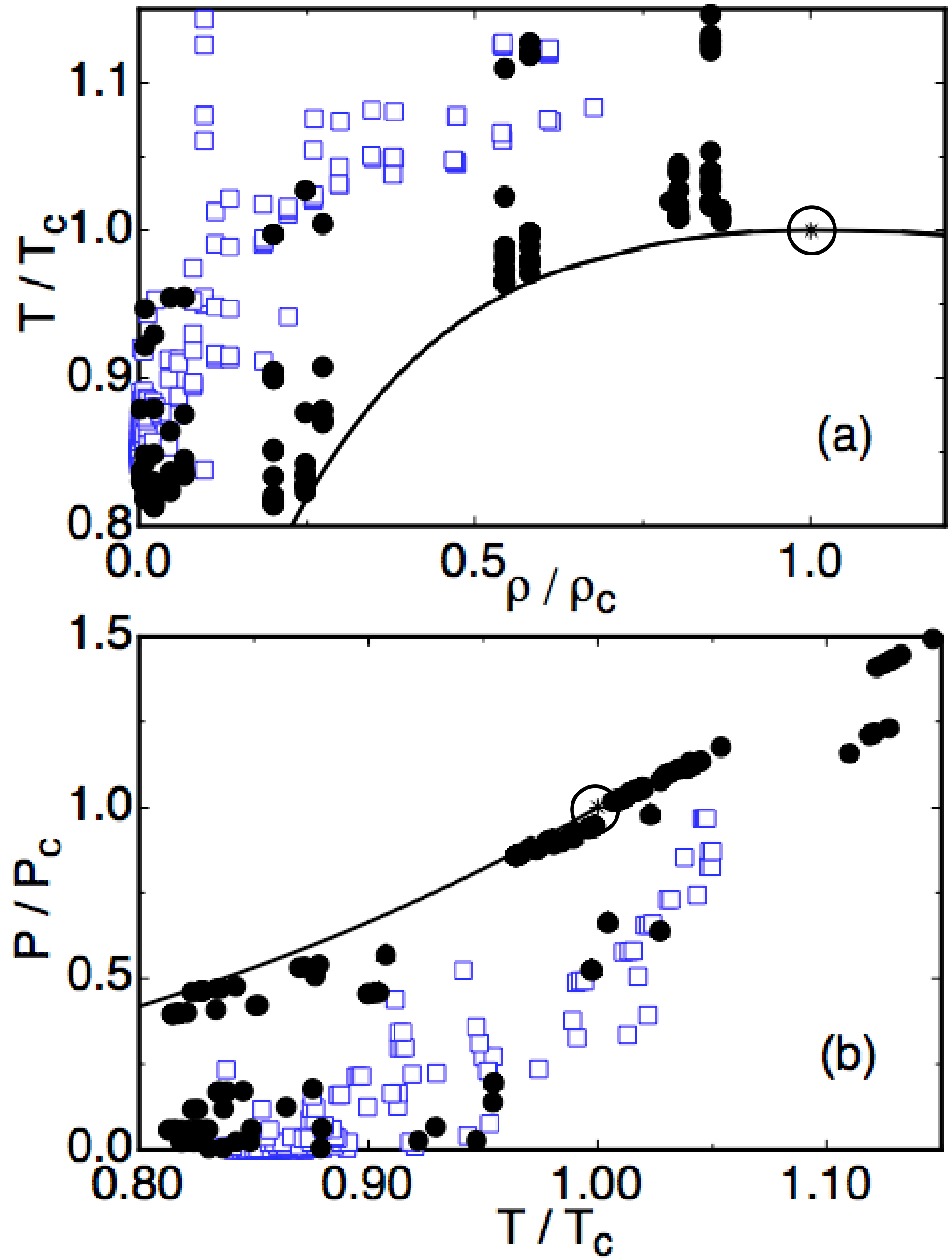
Use a fluid with large $\alpha/\kappa\nu$

RBC in aspect ratio D/L = 1/2, using He^4 near its CP (~5K)

At CP:

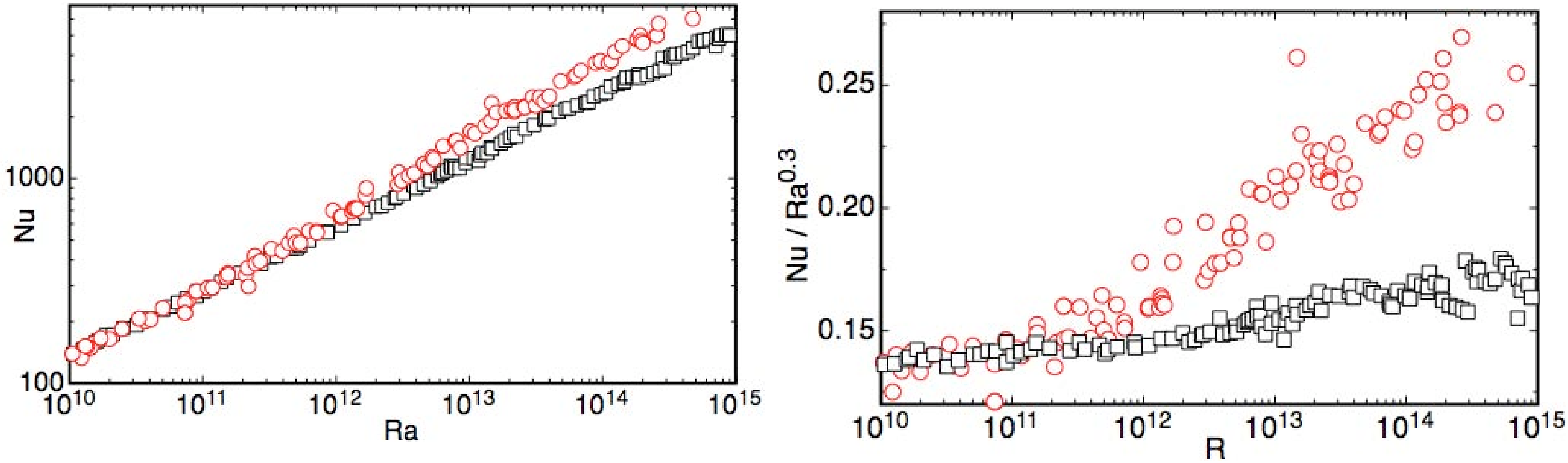
$$Ra \rightarrow \infty$$

$$Pr \rightarrow \infty$$



Solid circles:
X. Chavanne,
F. Chilla, B. Chabaud,
B. Castaing, and B. Hebral,
Phys, Fluids **13**, 1300 (2001)

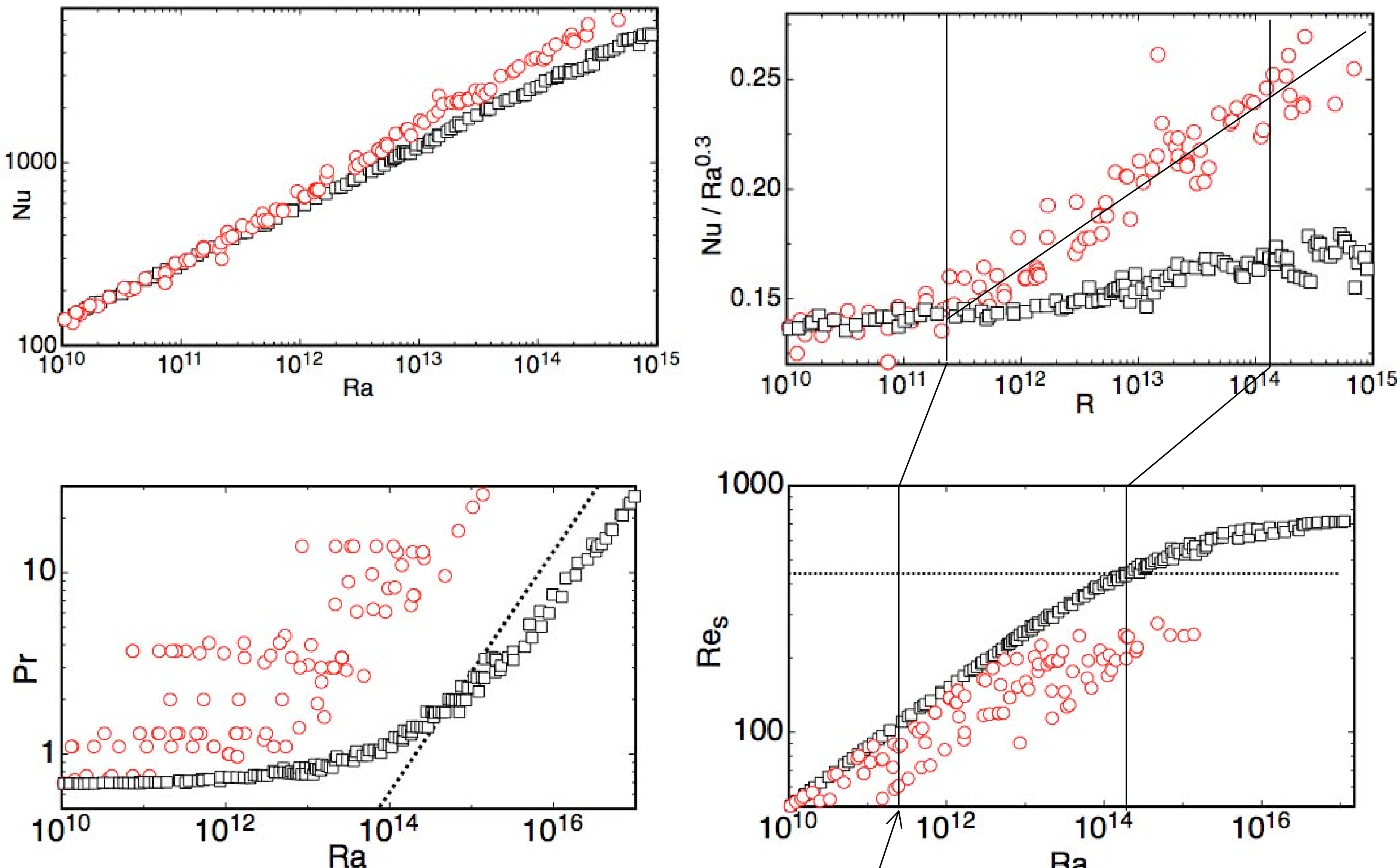
Open squares:
J. Niemela, L. Skrbek,
K. R. Sreenivasan,
and R.J. Donnelly,
Nature 404, 837 (2000)
L = 1 m!



X. Chavanne, F. Chilla, B. Castaing, B. Hebral, B. Chabaud, and J. Chaussy, Phys. Rev. Lett. 79, 3648 (1997), ``Observation of the ultimate regime in Rayleigh-B\'enard convection".

Red circles: Chavanne, X., F. Chilla, B. Chabaud, B. Castaing, and
B. Hebral, Phys, Fluids 13, 1300 (2001)
(the "**GRENOBLE**" data).

Black squares: Niemela, J., L. Skrbek, K. R. Sreenivasan,
and R. Donnelly, Nature 404, 837 (2000)
(the "**OREGON**" data).



Dotted line: $Re_s^* = 400$

$Ra^*_{Grenoble}$ ~ 2×10^{11} where Rs_s ~ 80 !

Both experiments were done with helium near 5 K.
It seemed desirable to have another set of measurements, preferably not with helium at low temperatures but rather at ambient temperatures with more classical experimental techniques.

March 2007: Eberhard said to me “I will build a very large pressure vessel at my Institute in Goettingen for various experiments. Why not put a very large convection cell into it?”

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How to get large Ra:

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

$$Ra = \frac{\alpha g \Delta T L^3 \rho^2 C_P}{\lambda \eta}$$

$$Ra \propto \frac{\rho^2}{\lambda \eta} \propto \frac{P^2 M^2 L^3}{\lambda \eta}$$

$$\eta \lambda \propto \sigma^{-4}$$

$$\sigma = scattering\ radius$$

To get large Ra, use a high molecular weight gas at high pressure in a sample with large L.

SF_6 at pressures up to 19 bars !

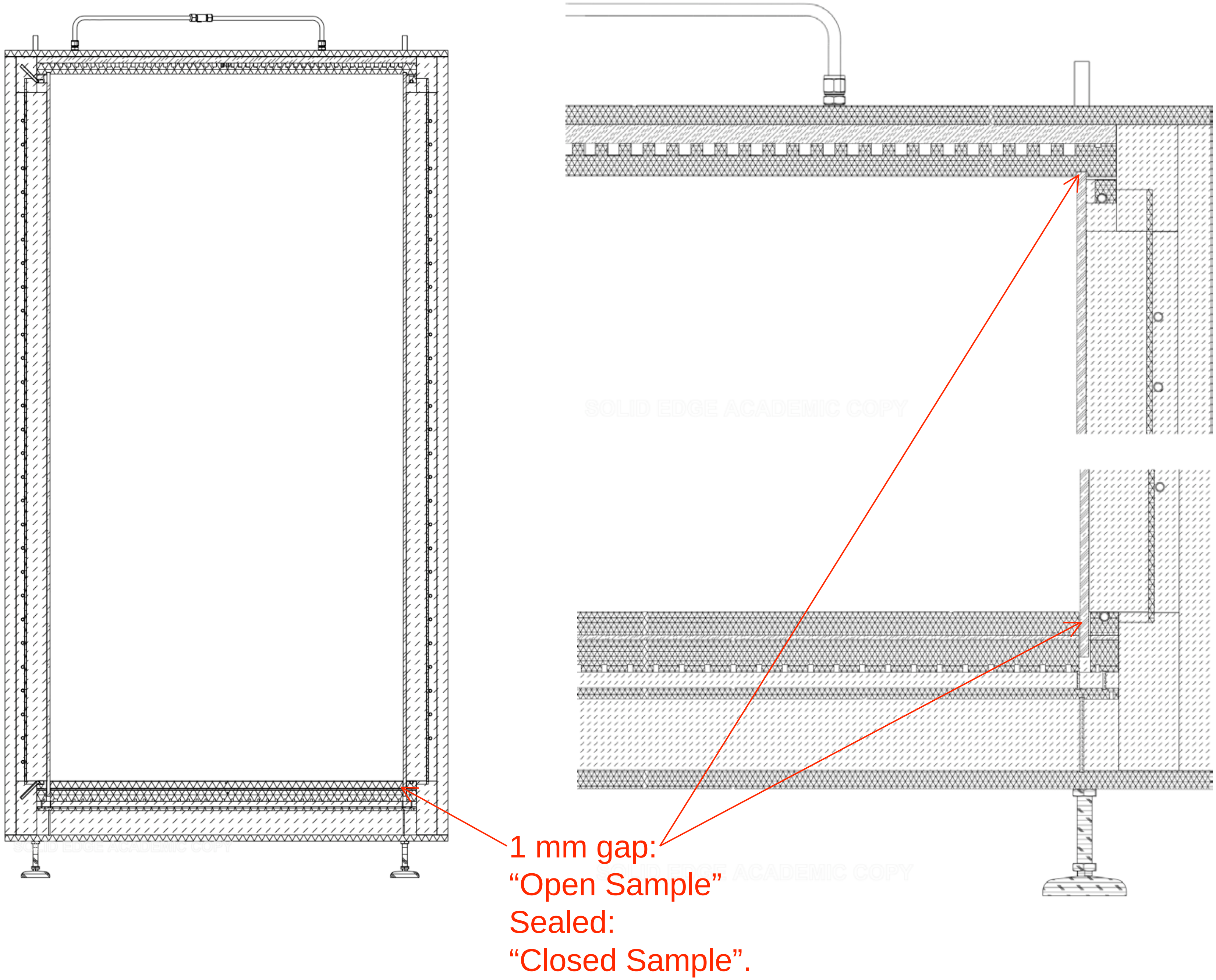
The Uboot of Goettingen

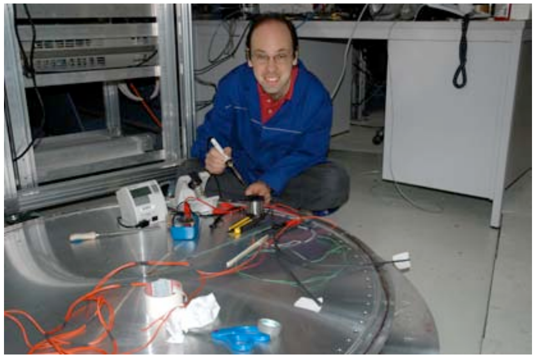
P up to 19 bars

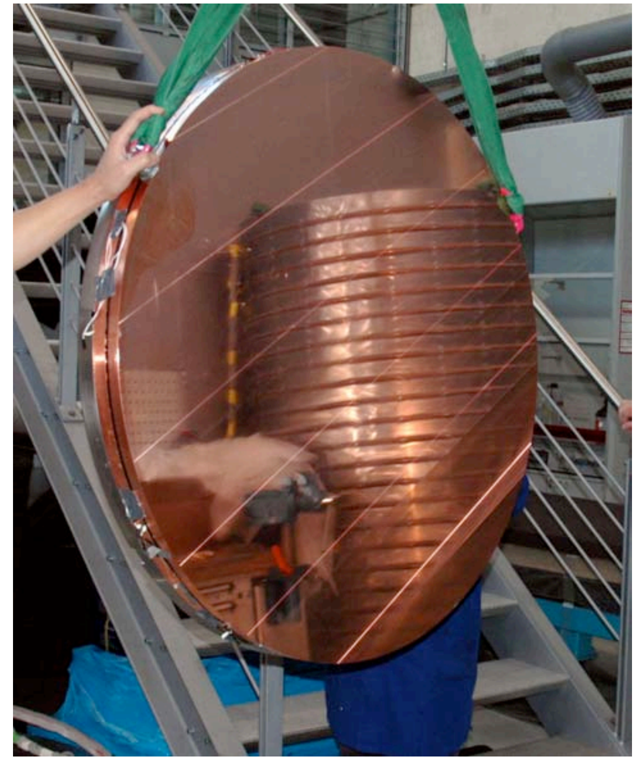
Gases: He, N2, Air, SF_6

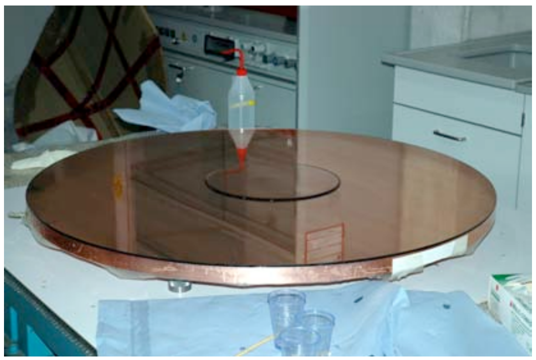
Under turret, 1.5m X 4m

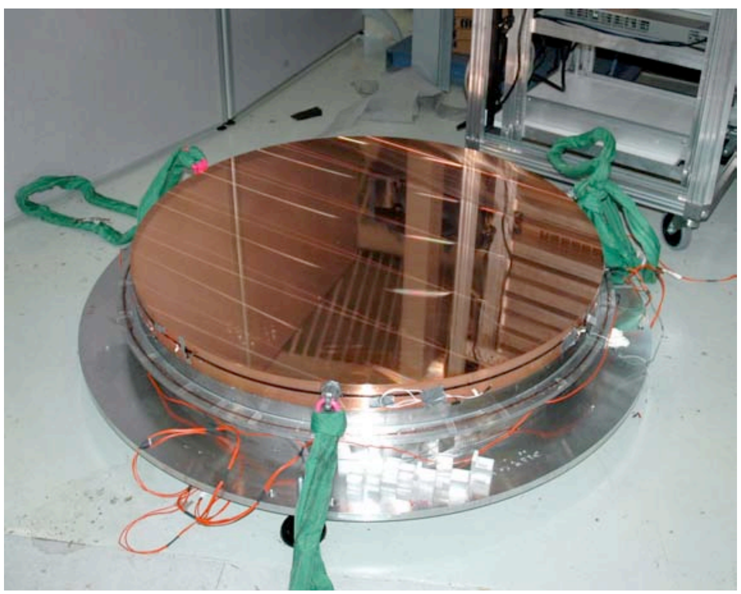
G. Ahlers, D. Funfschilling, and E. Bodenschatz, New J. Phys. **11**, 123001 (2009).


1 mm gap:
“Open Sample”
Sealed:
“Closed Sample”.



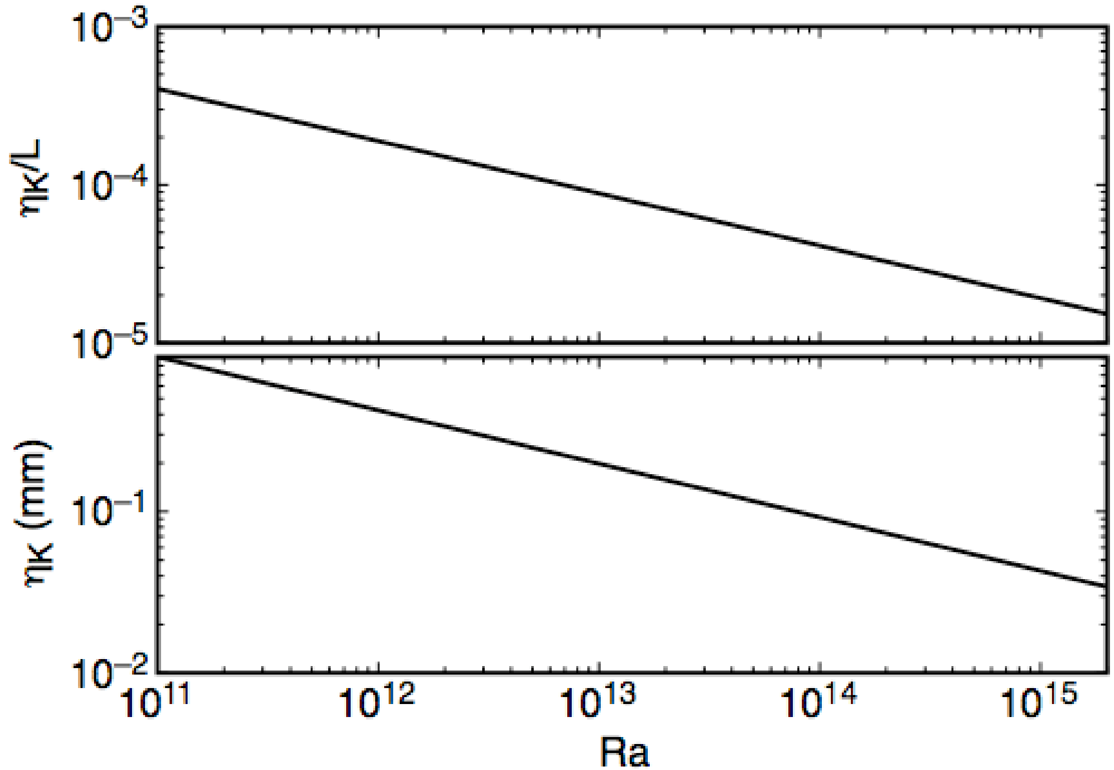




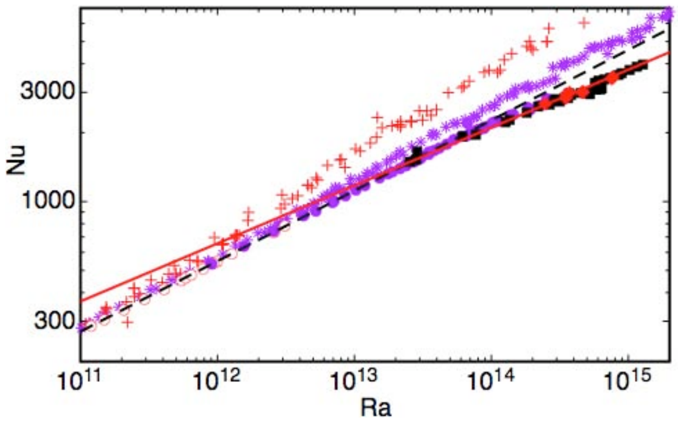








Size of smallest coherent structures (eddies?)
is expected to be ℓ_{coher} ~= 10η_K
Which is of order half a mm near Ra = 10^{15}.
But ℓ_{coher}/L ~= 2×10^{-4}.
Re_s ~= 800.



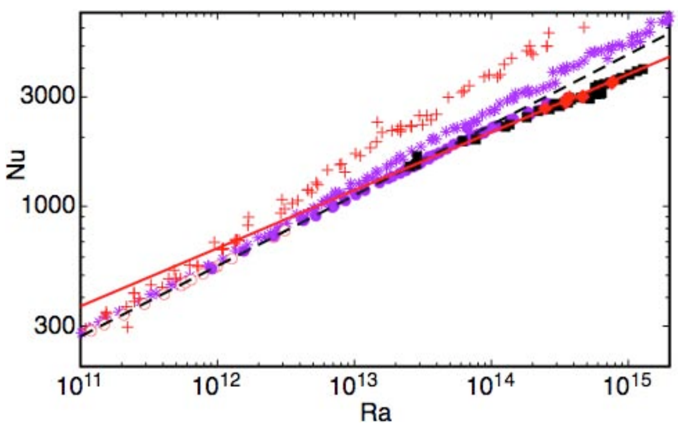
Plusses: Chavanne et al.,
Phys. Fluids **13**, 1300 (2001).
Stars: Niemela et al.,
Nature 404, **837** (2001).

D. Funfschilling, E. Bodenschatz, G. Ahlers,
Phys. Rev. Lett.**103**, 014503 (2009).

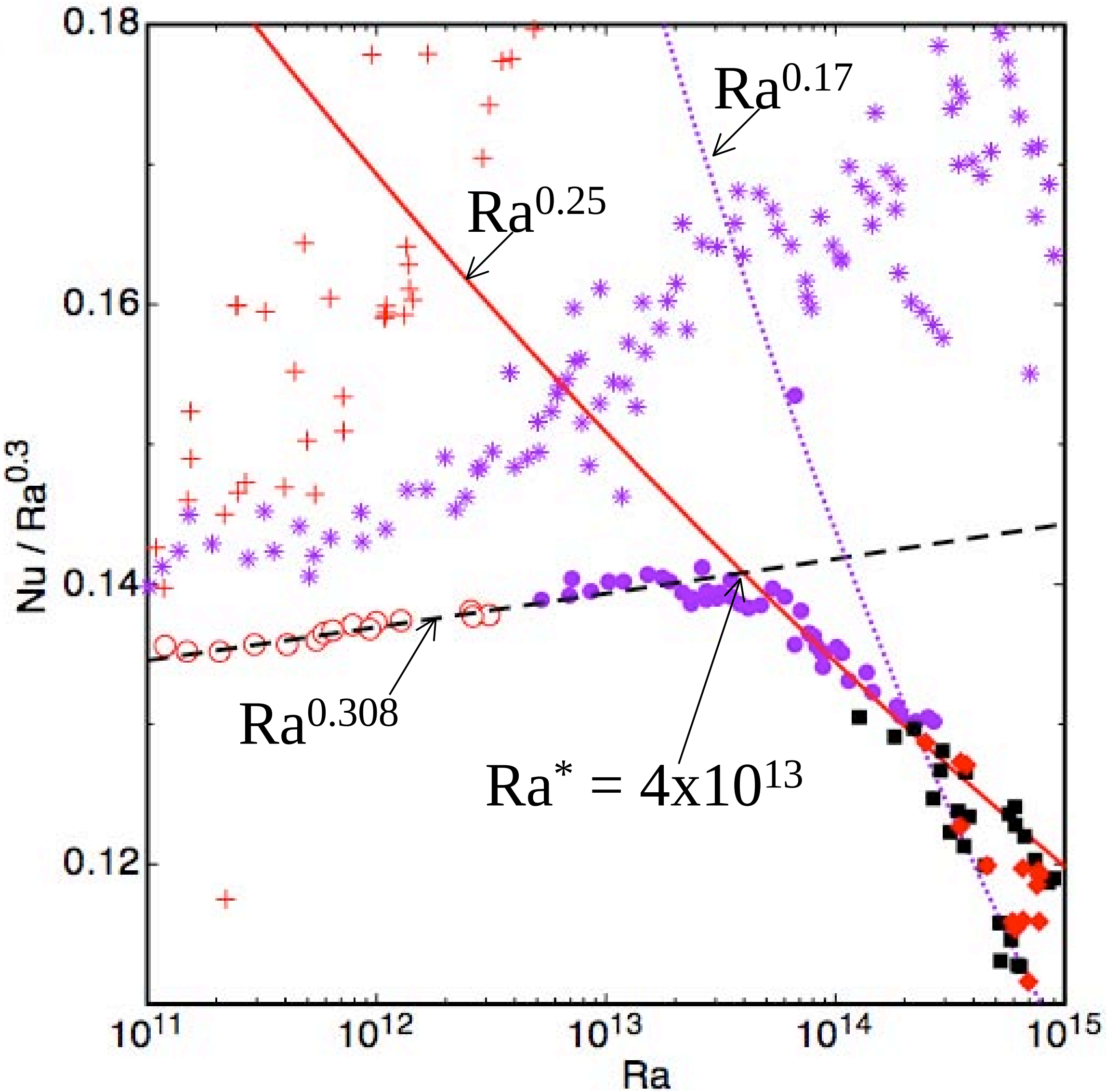
G. Ahlers, E. Bodenschatz, D. Funfschilling,
and J. Hogg, J. Fluid Mech. **641**, 157 (2009).

G. Ahlers, D. Funfschilling, and E. Bodenschatz,
New J. Phys. **11**, 123001 (2009).

“Open Sample”



Plusses: Chavanne et al.,
Phys. Fluids **13**, 1300 (2001).
Stars: Niemela et al.,
Nature 404, **837** (2001).

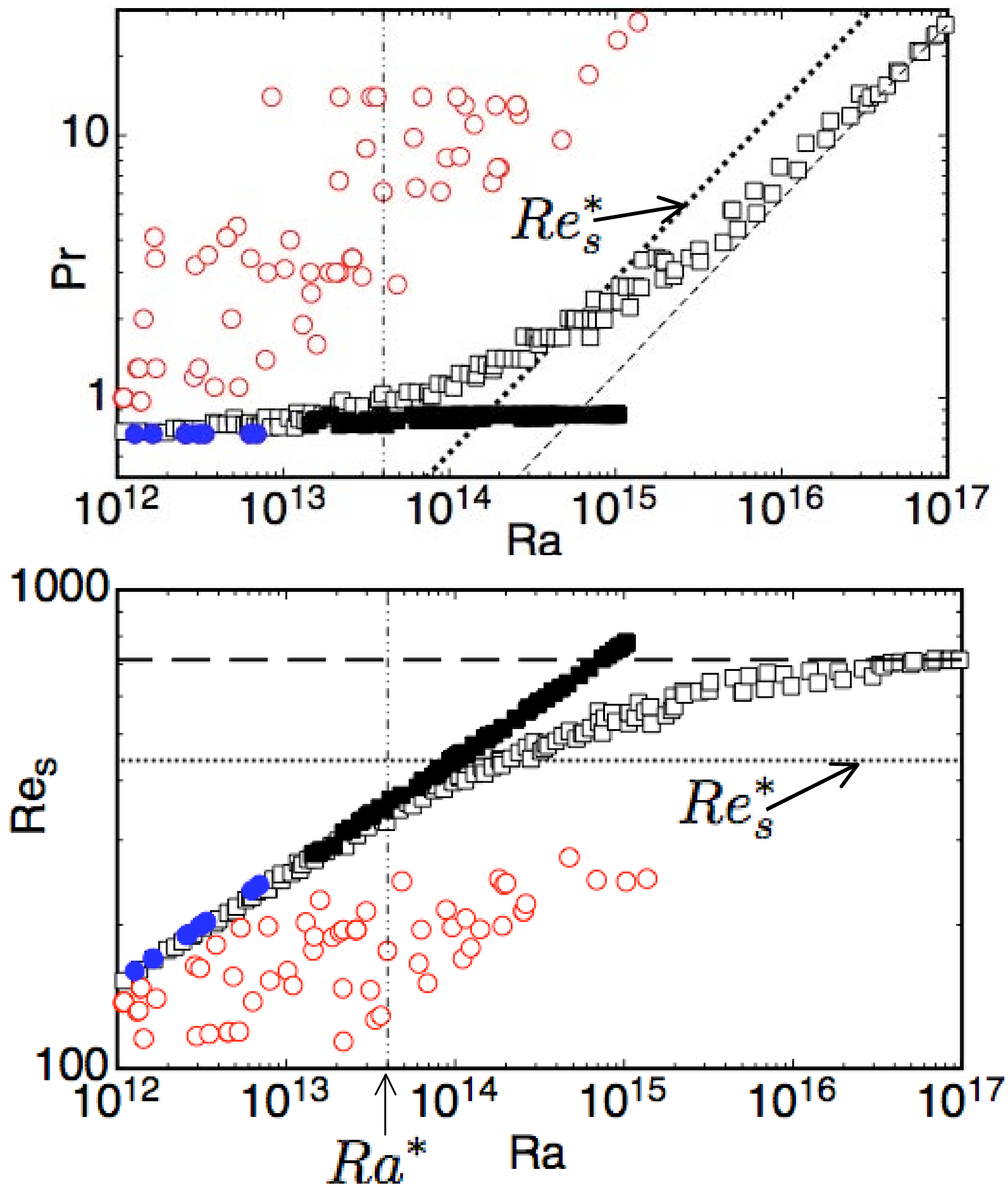


D. Funfschilling, E. Bodenschatz, G. Ahlers, Phys. Rev. Lett.**103**, 014503 (2009).

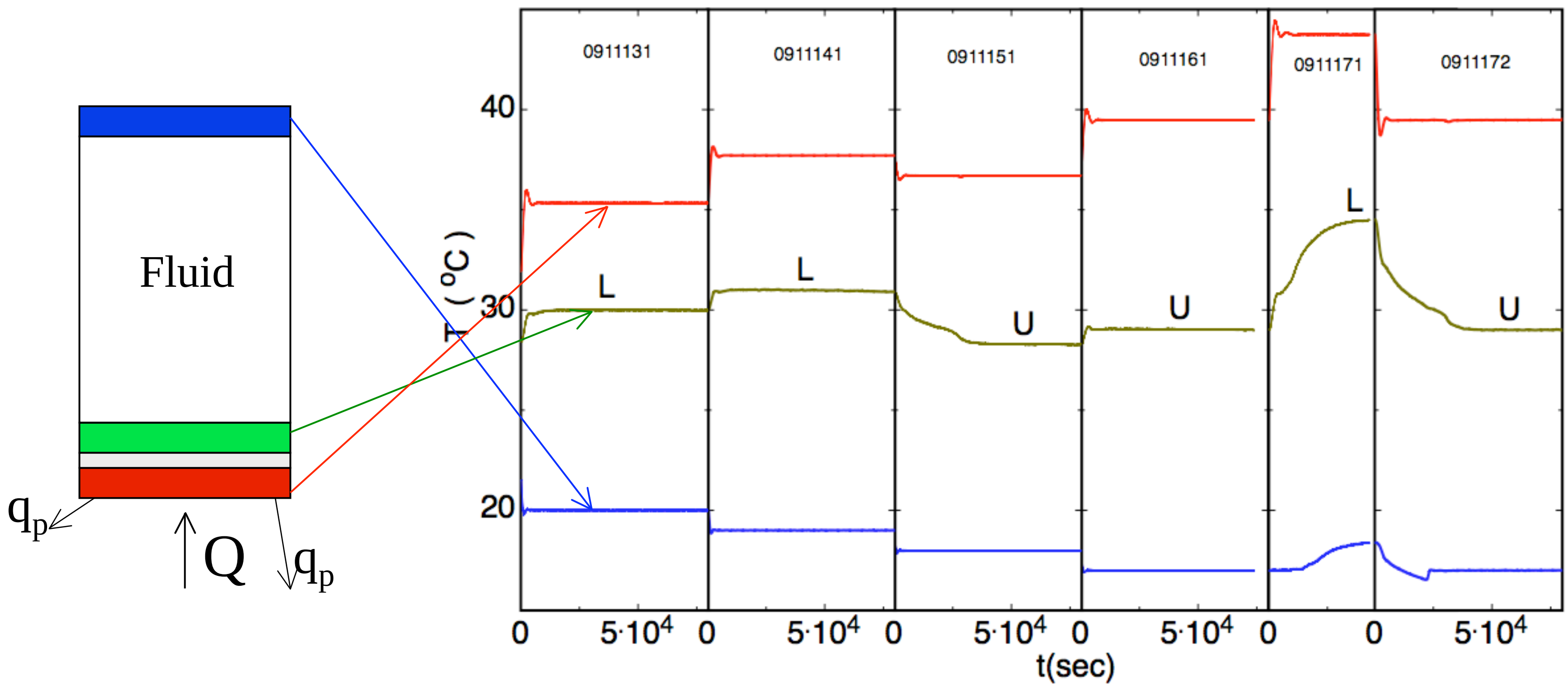
G. Ahlers, E. Bodenschatz, D. Funfschilling, and J. Hogg, J. Fluid Mech. **641**, 157 (2009).

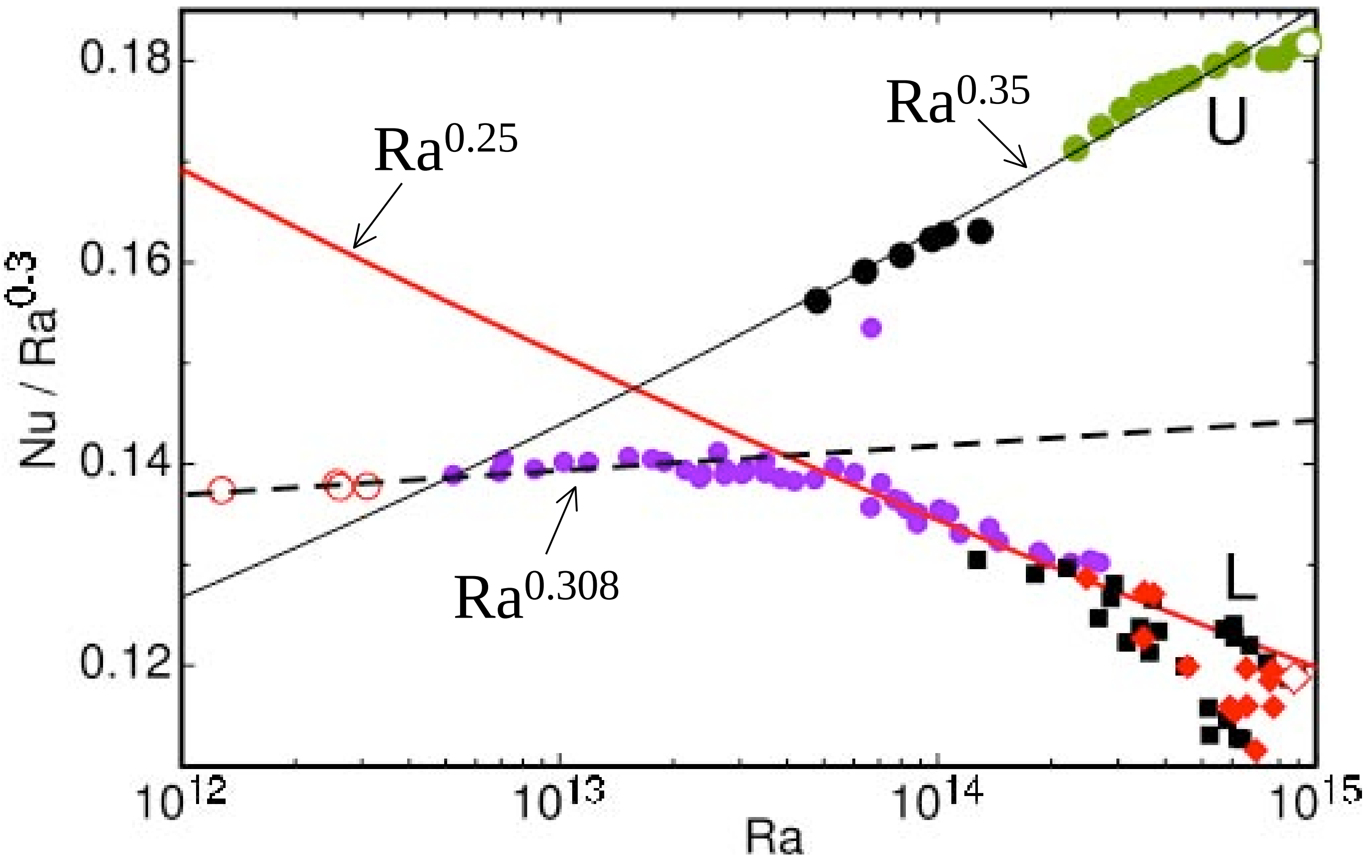
G. Ahlers, D. Funfschilling, and E. Bodenschatz, New J. Phys. **11**, 123001 (2009).

"Open Sample"



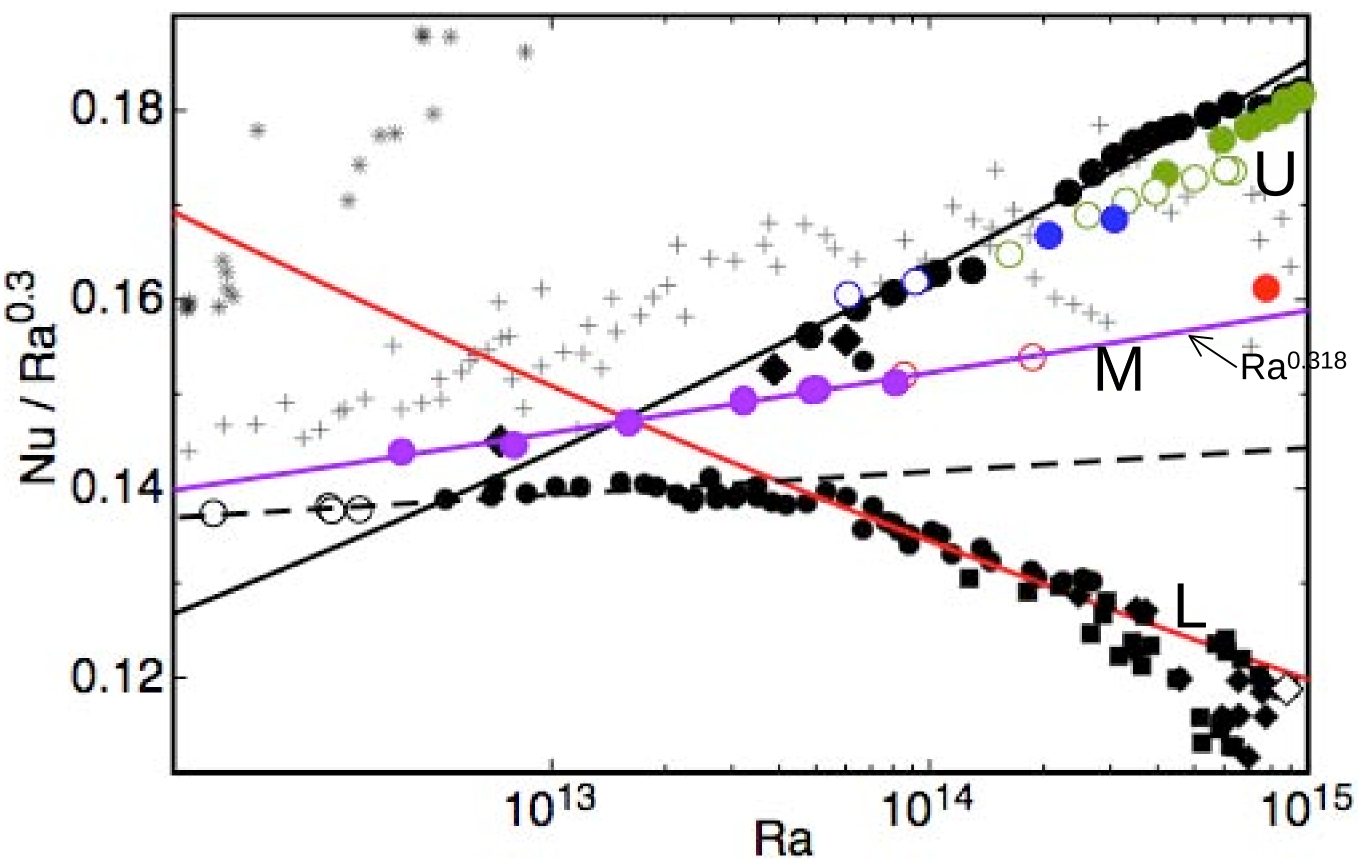
Pr
10
1
10^12
10^13
10^14
10^15
10^16
10^17
Ra
Re_s^*
1000
100
Re_s
Re_s^*
10^12
10^13
10^14
10^15
10^16
10^17
Ra^*
Ra


Fluid
q_p
Q
q_p
0911131
0911141
0911151
0911161
0911171
0911172
40
30
20
T (°C)
L
L
U
U
L
U
0
5·10^4
t(sec)



“Multiple scaling in the ultimate regime of thermal convection”
S. Grossmann and D. Lohse, Phys. Fluids, in print.

These data are for the “Open Sample”.
In June 2010 the gap between the sidewall and the plates was sealed to create the “Closed Sample”.

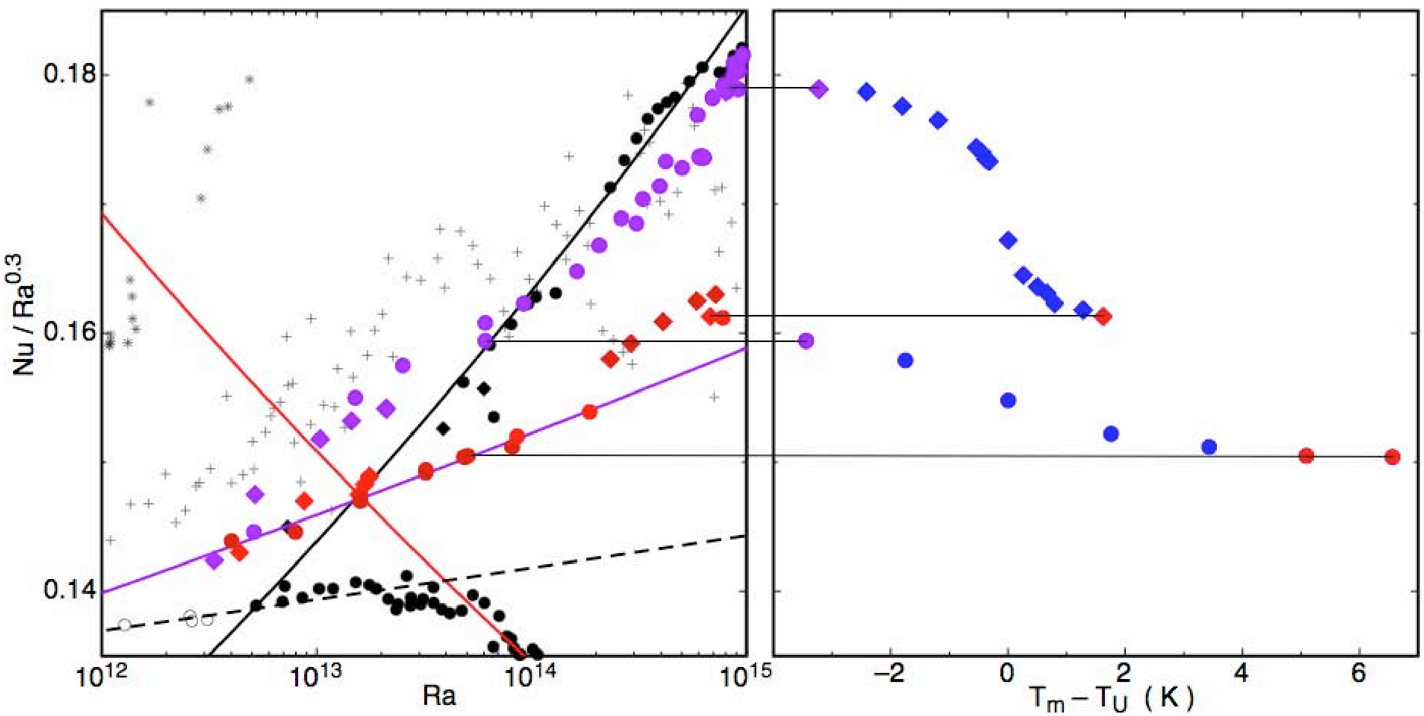


Black symbols: Open sample

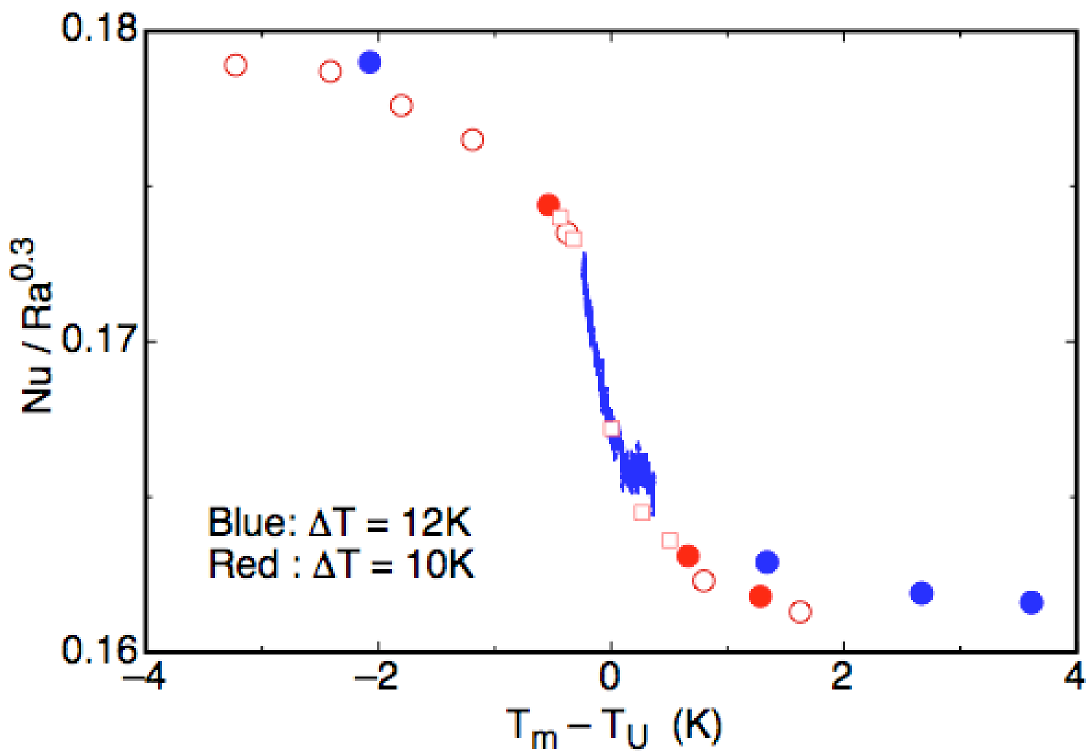
Colored symbols: Closed sample

Middle branch “M”: $T_m - T_U > 0$

Upper branch “U”: $T_m - T_U < 0$



Circles: leveled cell
Diamonds: cell tilted through 0.8 degrees
Purple: Upper branch
Red: Middle branch



There is a similarity to a subcritical bifurcation (or first-order phase transition) "unfolded" by a "field" h, with h ~ T_m - T_U.

But it is unknown why T_m - T_U should couple to the system and act like a field.

Although there is a continuity of states at relatively small Ra, the "pure" system (h=0) would have two distinct states.

Summary

"Open" Sample:

1.) There is a sharp transition in the heat transport at $Ra^* = 4x10^{13}$.

2.) For $Ra < Ra^*$ we find $Nu \sim Ra^{0.308}$.

3.) For $Ra > Ra^*$ there is a **L**ower branch with $Nu \sim Ra^{0.25}$.

4.) For $Ra > Ra^*$ there is an **U**pper branch where $Nu \sim Ra^{0.35}$.

5.) The transition from one branch to the other occurs when the temperature difference between the sample and the Uboot is changed.

Summary

"Closed" Sample:

1.) The lower branch seen with the open sample no longer exists.

2.) The upper branch seen with the open sample still exists.

3.) There is a "Middle" branch with Nu ~ $Ra^{0.318}$.

4.) The transition from one branch to the other occurs when the temperature difference $T_m - T_U$ between the sample and the Uboot is changed.

5.) For relatively small Ra all Nu between the two branches can be reached by varying $T_m - T_U$.

6.) For relatively large Ra Nu changes discontinuously as $T_m - T_U$ passes through zero, indicating that there are two distinct states.

7.) There are similarities to a continuous phase transition in the presence of a field, with $T_m - T_U$ playing the role of the field; but it remains unknown how this field couples to the system.