The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1771 - 14

Conference and Euromech Colloquium #480

on

High Rayleigh Number Convection

4 - 8 Sept., 2006, ICTP, Trieste, Italy

Recent experiments on turbulent RBC by the Santa Barbara group

G. Ahlers
University of California at Santa Barbara
USA

Non-Boussinesq Effects on Turbulent Rayleigh-Benard Convection in Gases

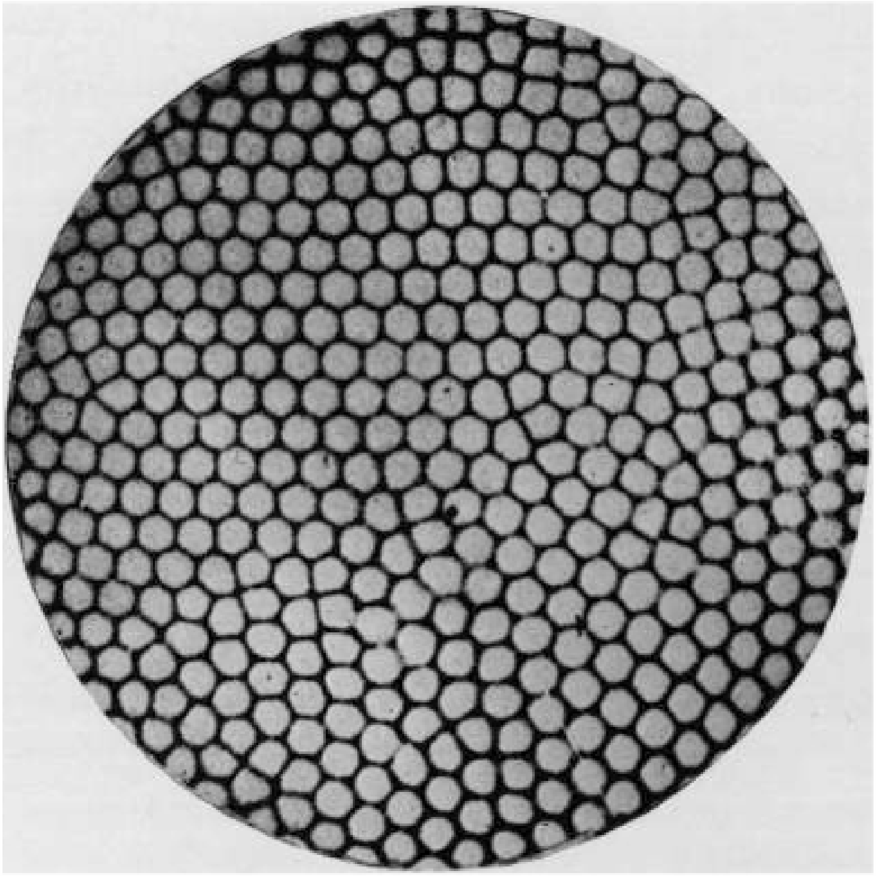
Guenter Ahlers
Denis Funfschilling

Department of Physics
and iQCD
University of California
Santa Barbara CA USA

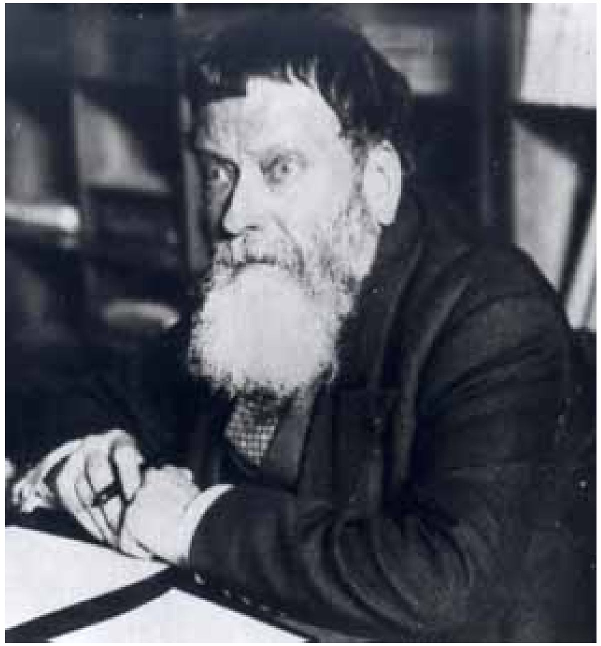
Pattern Formation in Convection: The Legacy of Henry Benard, Lord Rayleigh and **Fritz Busse**

Les Tourbillons Cellulaires dans une Nappe Liquide

Henri Benard



Revue generale des Sciences XII, 1261 (1900)



Ph.D. March 15 1901 College de France

Lord Rayleigh

THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

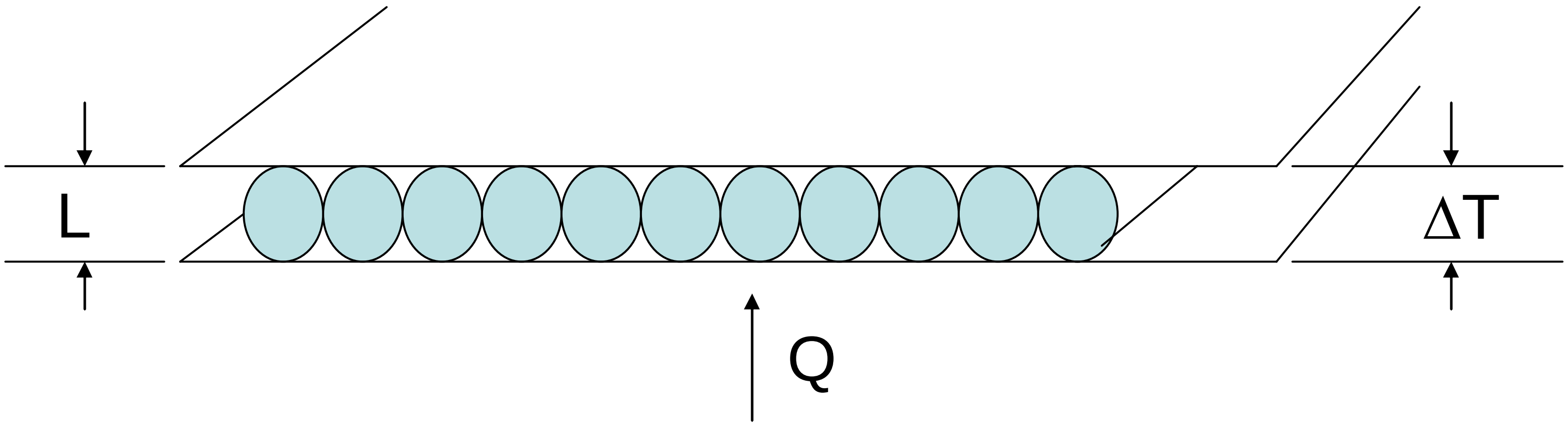
JOURNAL OF SCIENCE.

[SIXTH SERIES]

DECEMBER 1916.

LIX. *On Convection Currents in a Horizontal Layer of Fluid, when the Higher Temperature is on the Under Side. By* Lord RAYLEIGH, *O.M., F.R.S.**

THE present is an attempt to examine how far the interesting results obtained by Bénard † in his careful and skilful experiments can be explained theoretically.



$\varepsilon = \Delta T/\Delta T_c - 1$

Rayleigh carried out a stability analysis of the quiescent fluid layer. He used slip boundary conditions at top and bottom in order to permit an analytic solution.

He found that the bifurcation is stationary (i.e. that the lowest eigenvalue is real), and calculated the neutral curve $R_c(k)$ and k_c. However, this does not give the nature of the bifurcation and the pattern above onset.

Next milestones:

nonlinear effects:

nature of the bifurcation

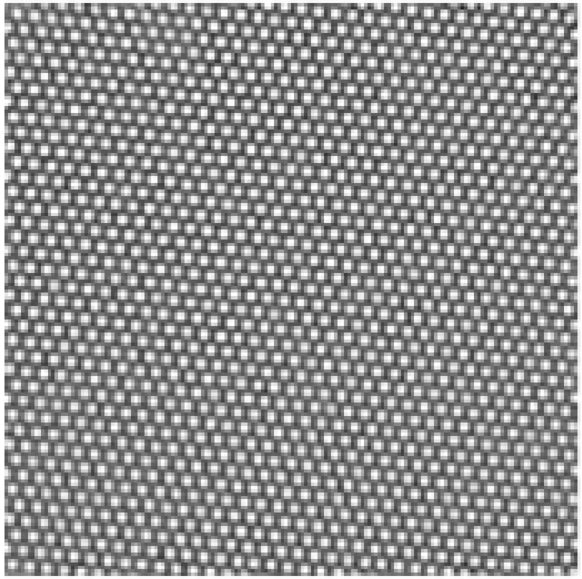
pattern just above onset

Schluter, Lortz, and **Busse** (1965):

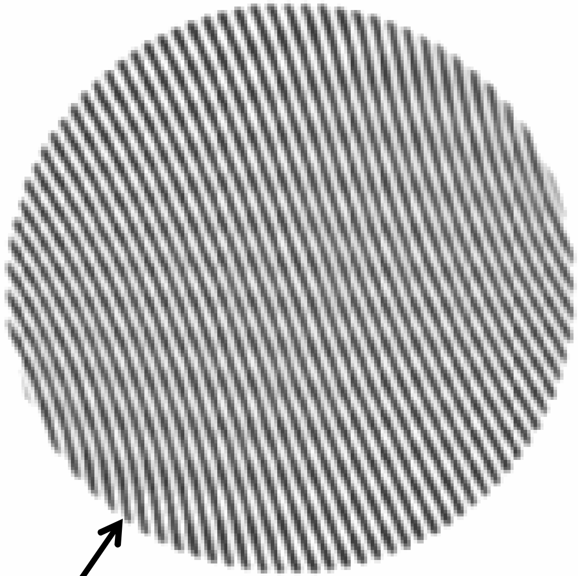
ridgid BCs, Boussinesq samples:

super-critical

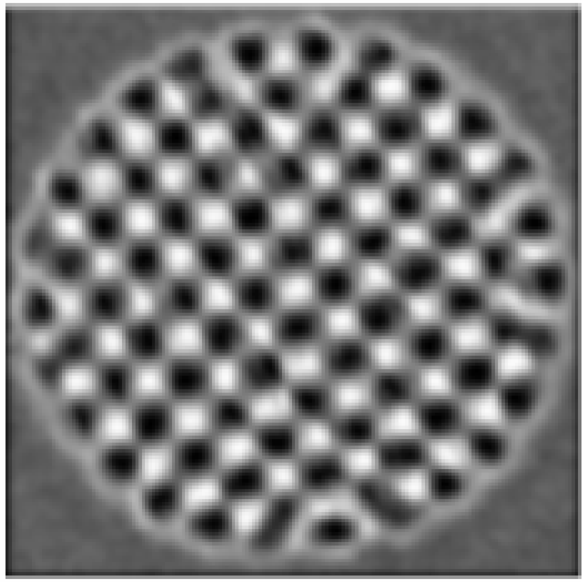
rolls (or stripes)



Non-Boussinesq



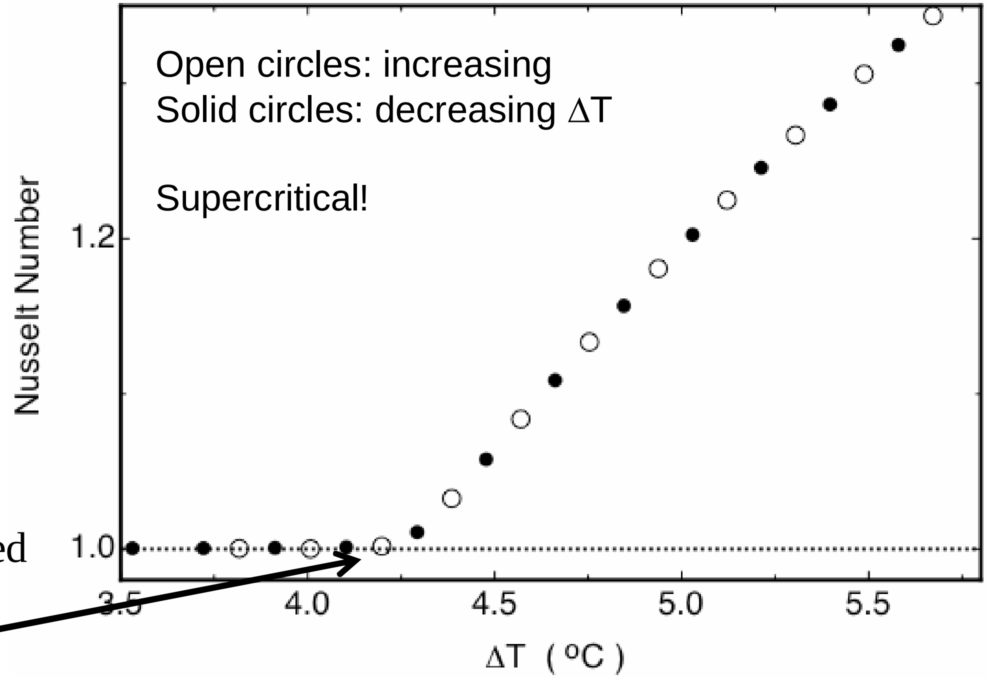
Boussinesq



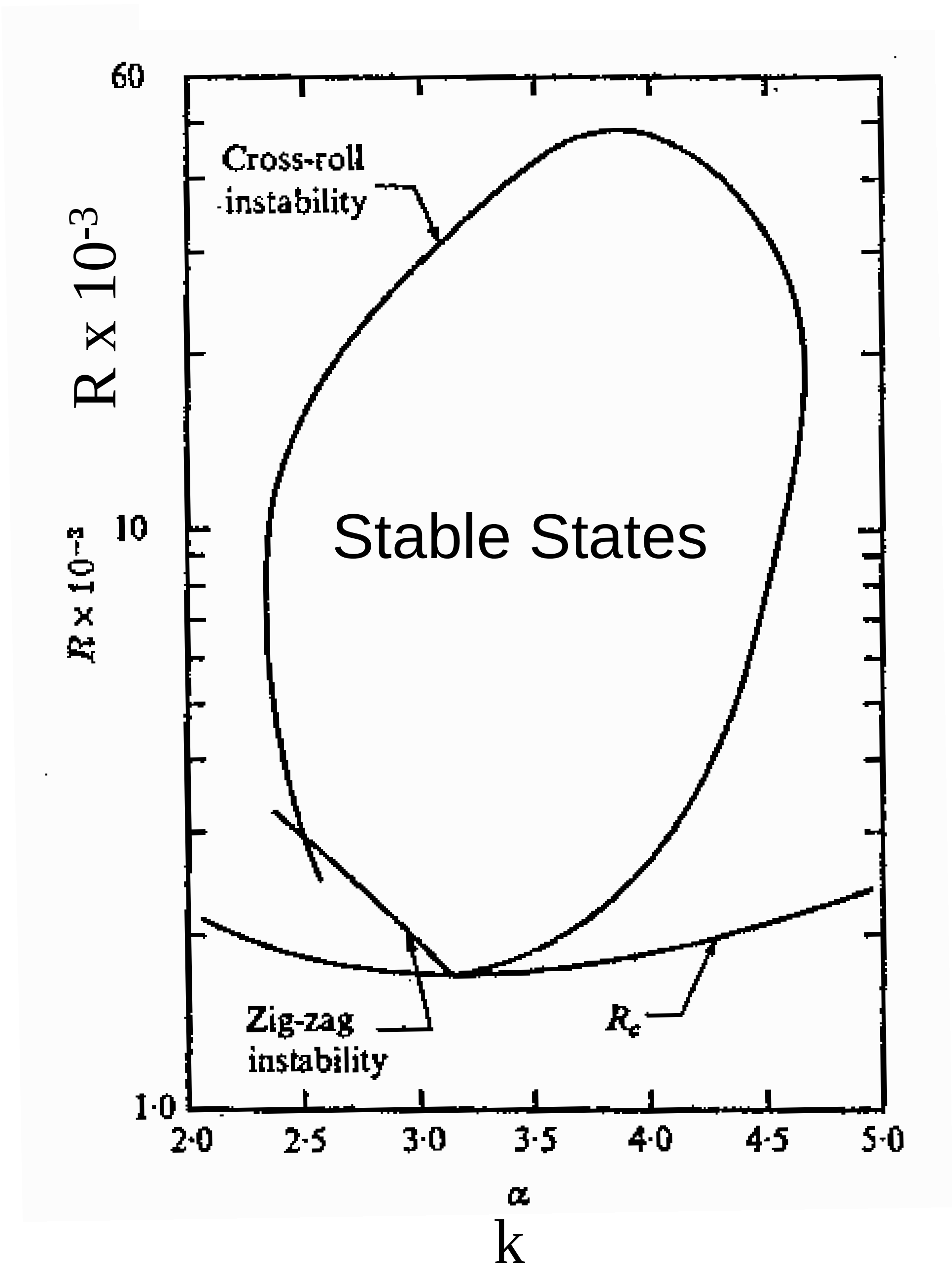
Binary mixtures (diffusion driven)

Rolls, as predicted
by **Busse** et al. (1965)
for Boussinesq RBC

Hexagons, as predicted
by **Busse** (1967) for
non-Boussinesq RBC



Supercritical, as predicted
by **Busse** et al. (1965)
for Boussinesq RBC



In the 1970's and thereafter Fritz, largely with his long-time friend Richard Clever, calculated the various stability boundaries for the straight-roll state. This gave us the **Busse Balloon** which soon became the "playground" of experimentalists and theorists with an interest in nonlinear physics and pattern formation.

No extremum principle

Any state inside the Balloon is attainable if the phase of the pattern is pinned, e.g. by sidewalls, in an experiment.

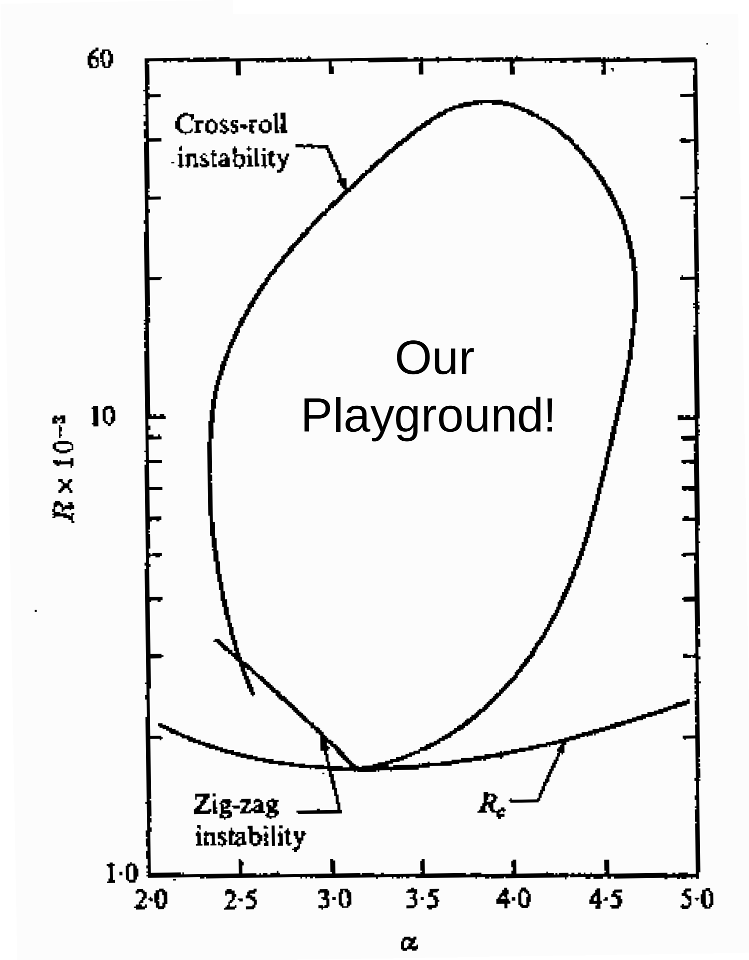
Wavenumber-selection processes occur when the phase can slip at some point in the pattern

Spatio-temporal chaos can be found

Many other things:

- upper bounds for heat or momentum flux
  in turbulent flows
- geophysical fluid dynamics
- convection in rotating systems
- dynamo theory
- turbulent RB convection

Our Heroes:



Henri Benard

Lord Rayleigh

AND

Fritz Busse

Thank you, Fritz, and

best wishes for many more

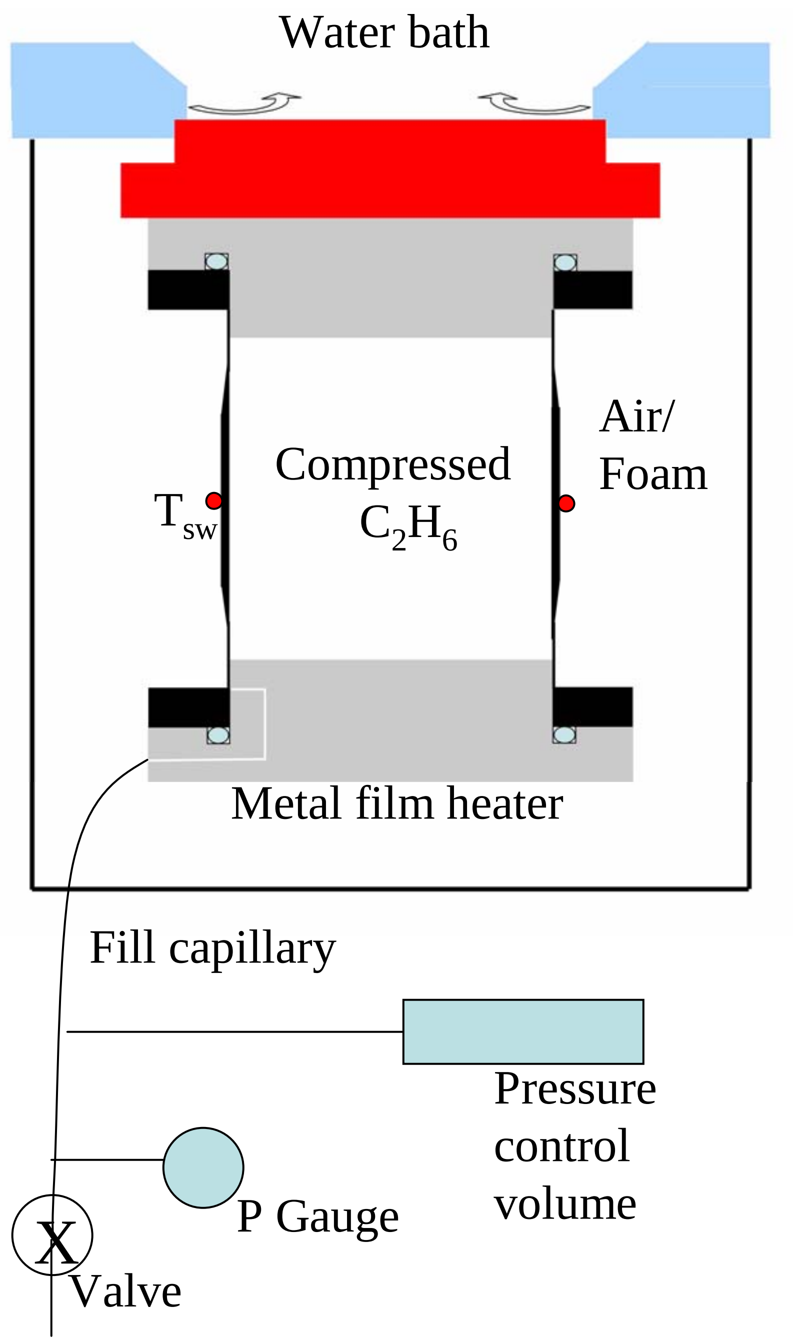
Birthdays and

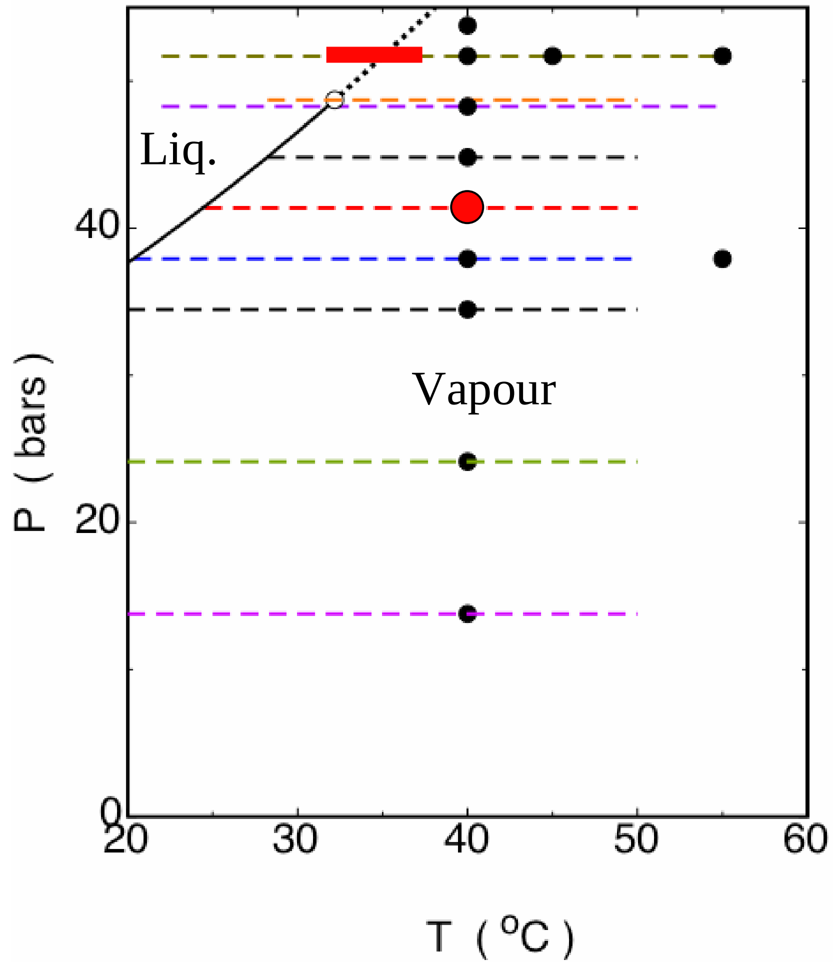
many more

papers in JFM and elsewhere!

Turbulent convection in Gases under pressure and Near their critical points

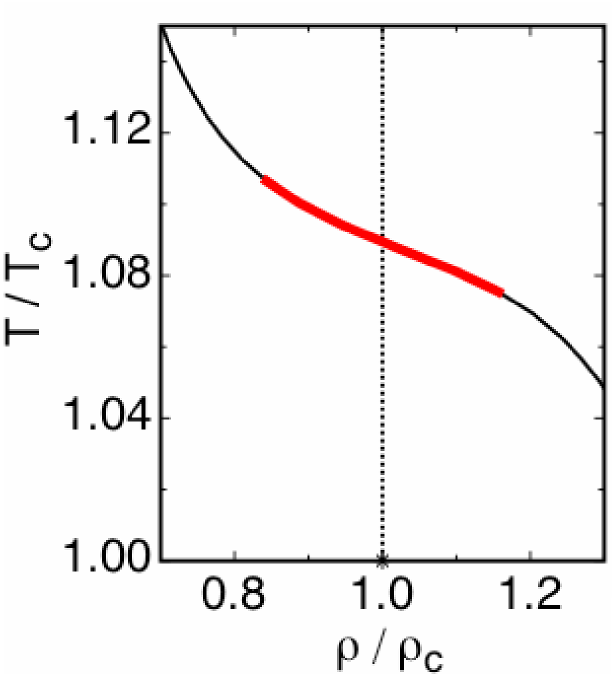
Denis Funfschilling and G.A.

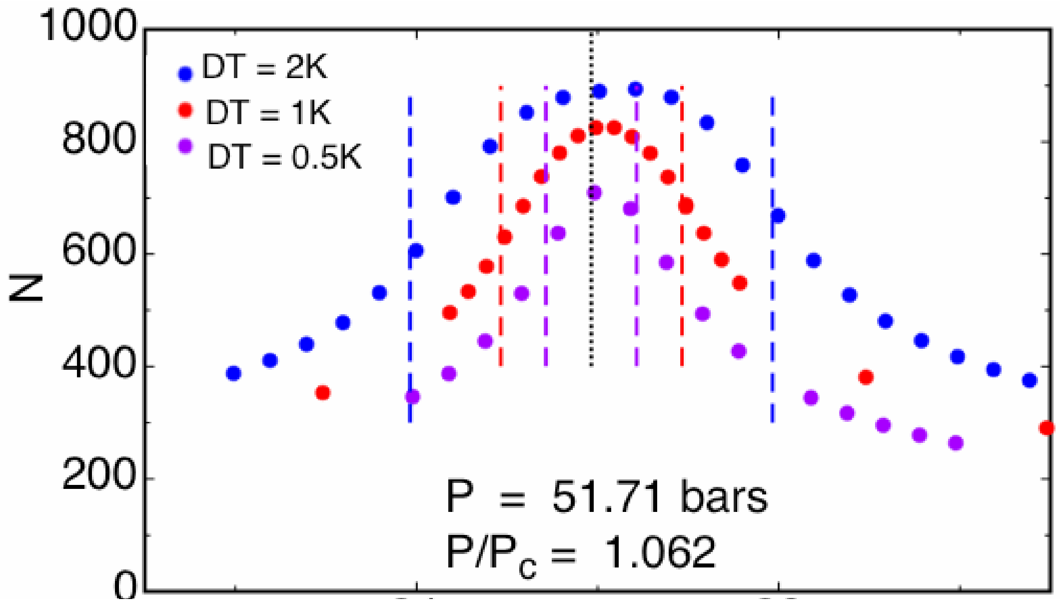




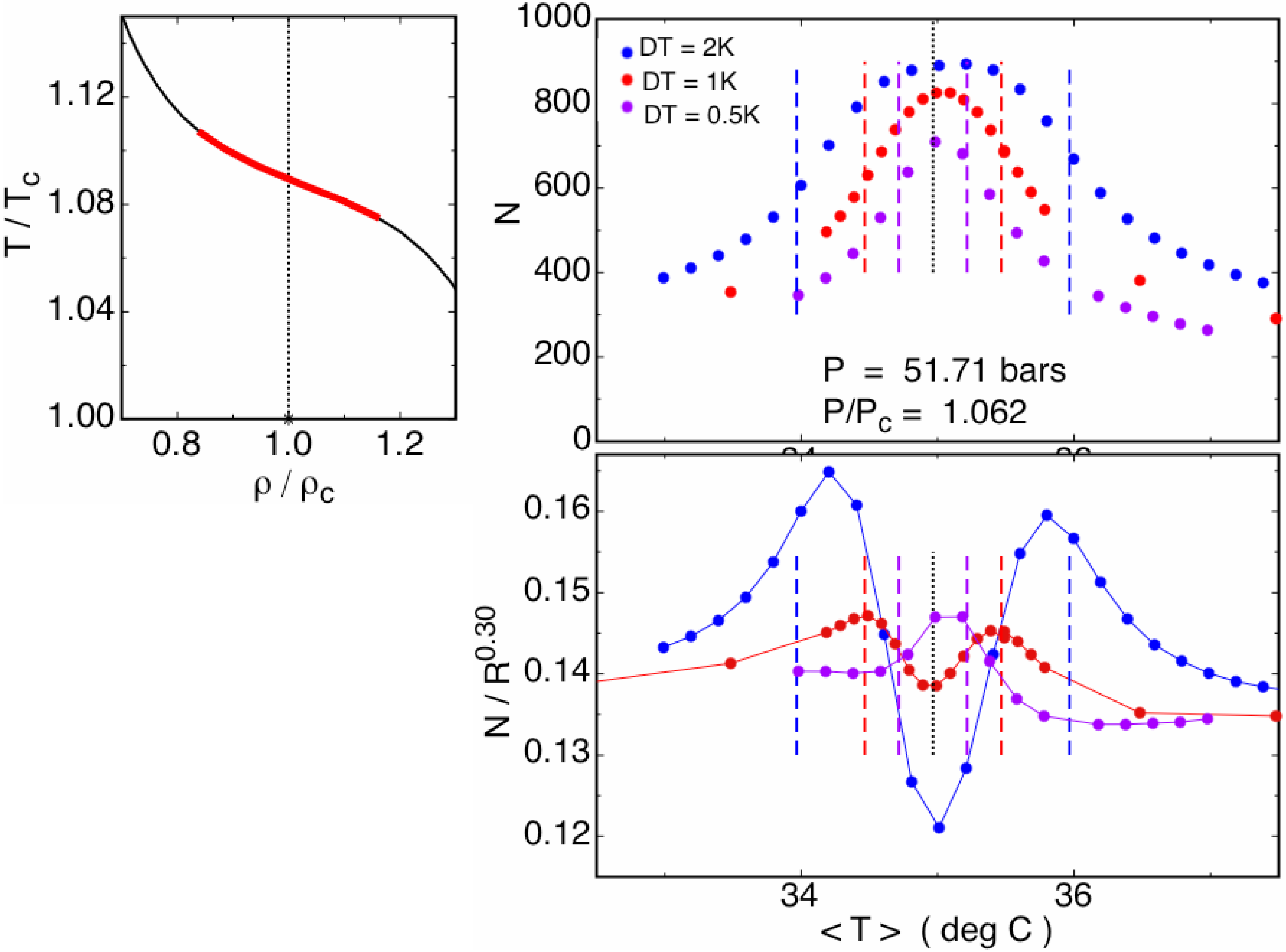
P constant to +/- 1 mBar
T constant to +/- 1 mK

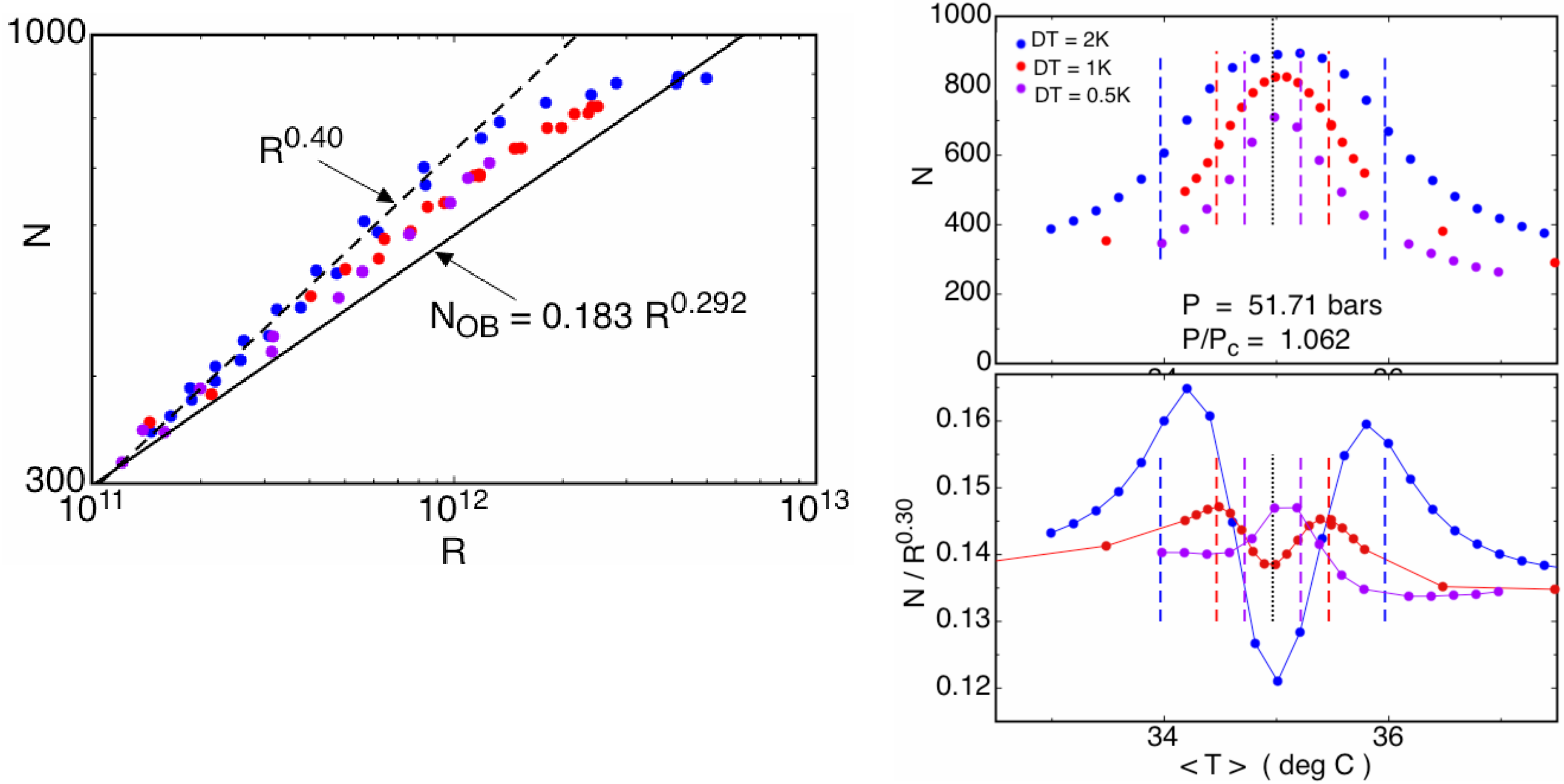
1.) Isobars at constant ΔT
2.) Constant <T>, varying ΔT





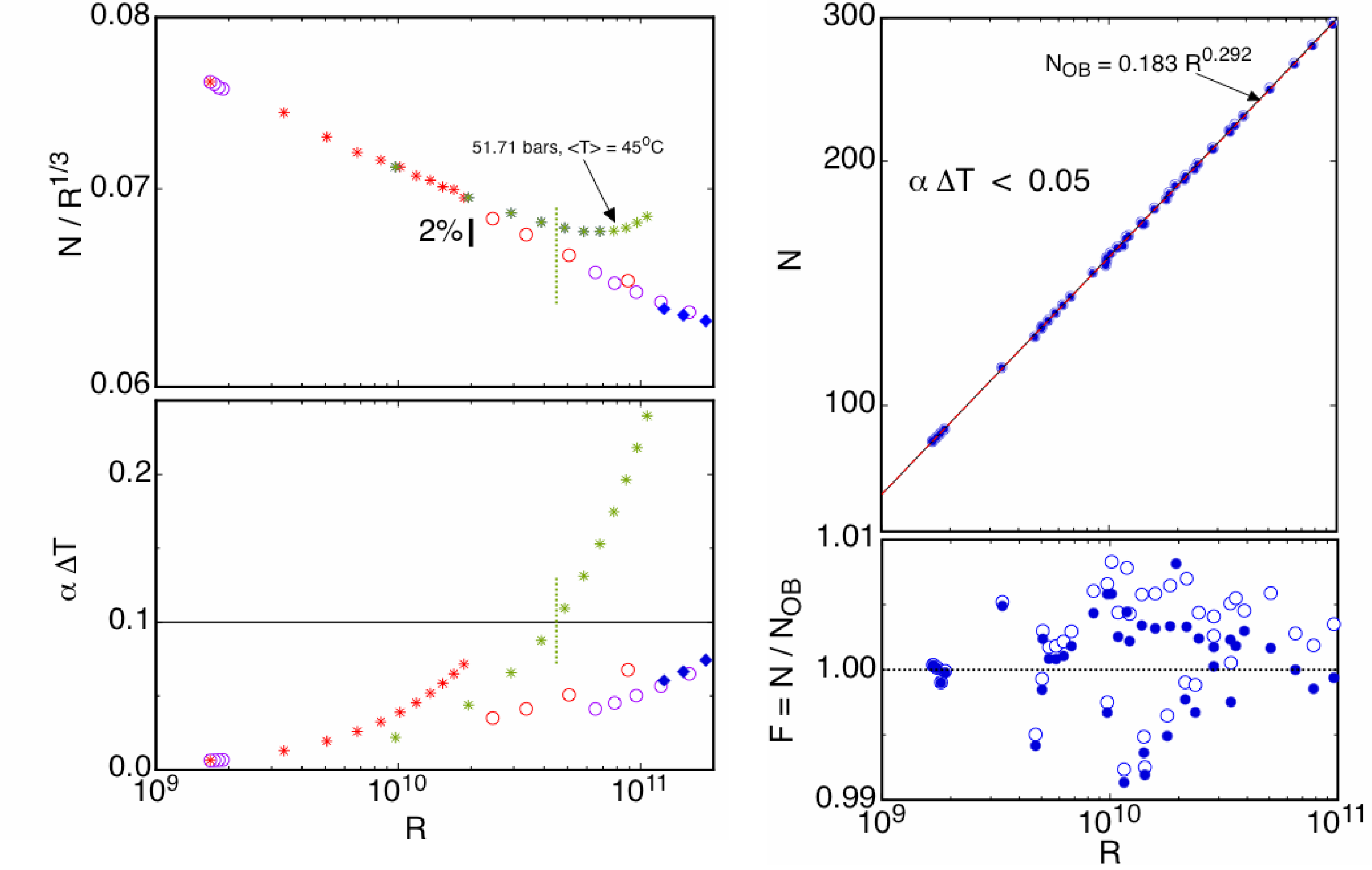
Isobars, constant Delta T,
crossing the critical isochore


T / T_c
ρ / ρ_c
1.12
1.08
1.04
1.00
0.8
1.0
1.2
DT = 2K
DT = 1K
DT = 0.5K
N
P = 51.71 bars
P/P_c = 1.062
N / R^0.30
< T > (deg C)
34
36



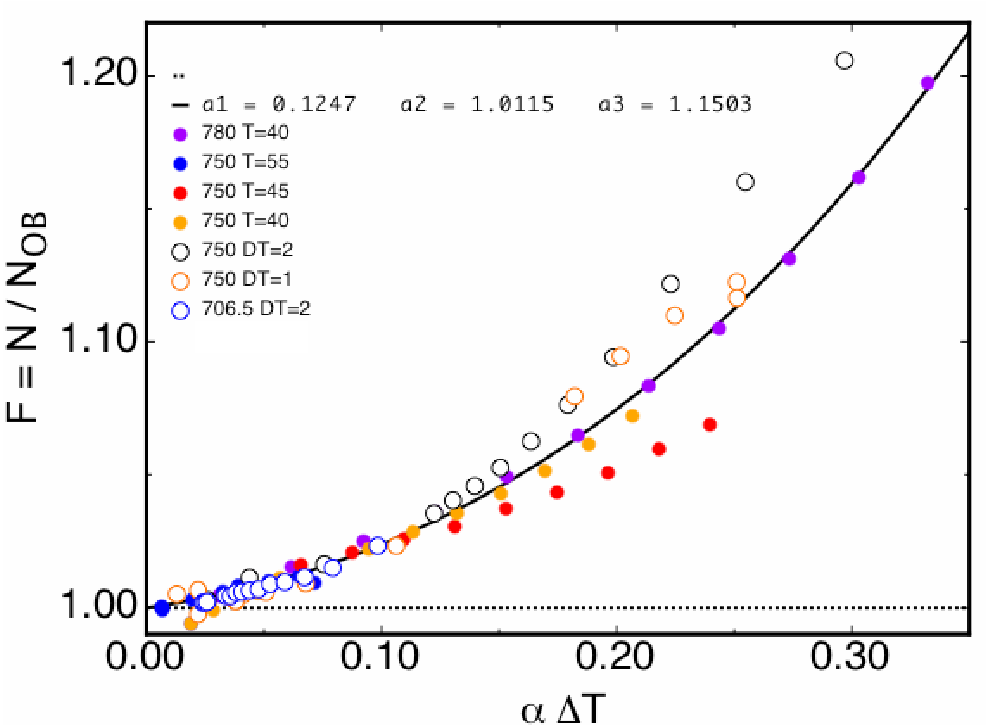
1000
300
N
R
10^{11}
10^{12}
10^{13}
$R^{0.40}$
$N_{OB} = 0.183\ R^{0.292}$
DT = 2K
DT = 1K
DT = 0.5K
P = 51.71 bars
P/P_c = 1.062
N
1000
800
600
400
200
0
0.16
0.15
0.14
0.13
0.12
$N / R^{0.30}$
34
36
< T > (deg C)

Non-Oberbeck-Boussinesq (NOB) effects in the vapour phase

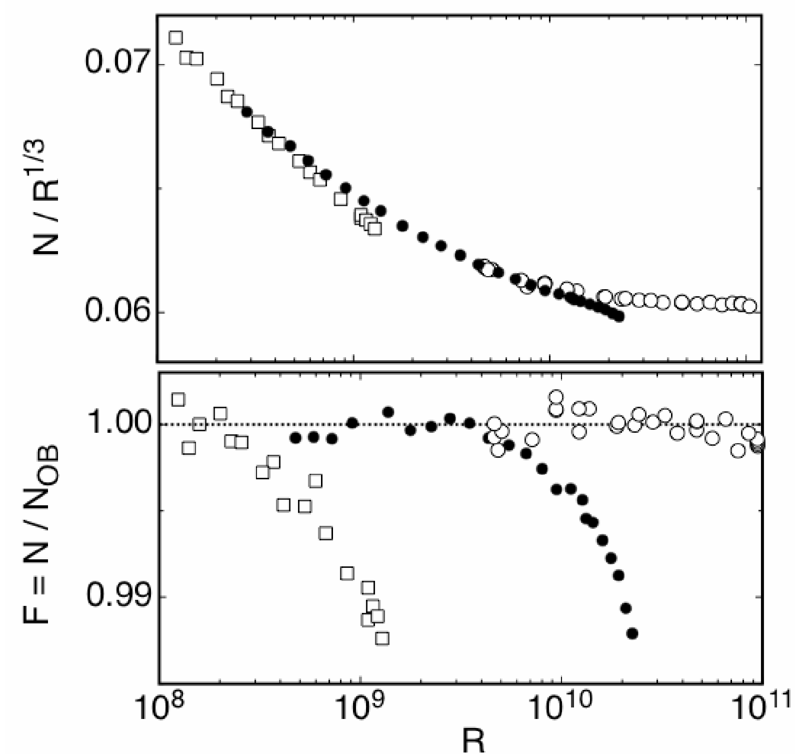


For NOB effects in liquids, especially water, see
G Ahlers, E. Brown, F. Fontenele Araujo, D. Funfschilling, S. Grossmann, and D. Lohse, J. Fluid Mech., in press.

ethane



water

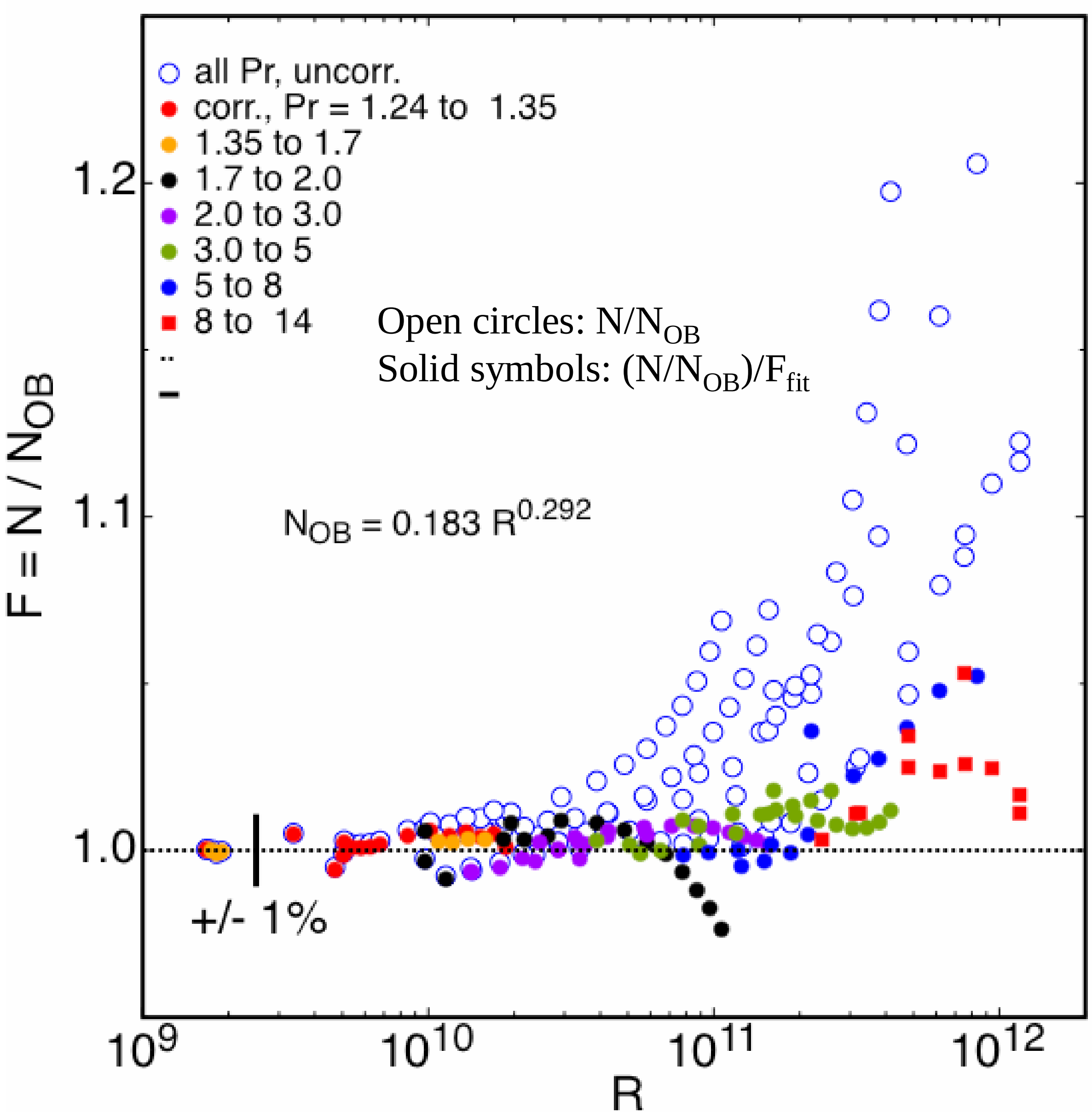


Solid line:

$F_{fit} = 1 + a_1 (\alpha\, \Delta T) + a_2 (\alpha\, \Delta T)^2 + a_3 (\alpha\, \Delta T)^3$

From G Ahlers, E. Brown, F. Fontenele Araujo, D. Funfschilling, S. Grossmann, and D. Lohse, J. Fluid Mech., in press. .

$a_1 = 0.125,\ a_2 = 1.01,\ a_3 = 1.15$



Note:

No significant Prandtl-number dependence.

Agrees with

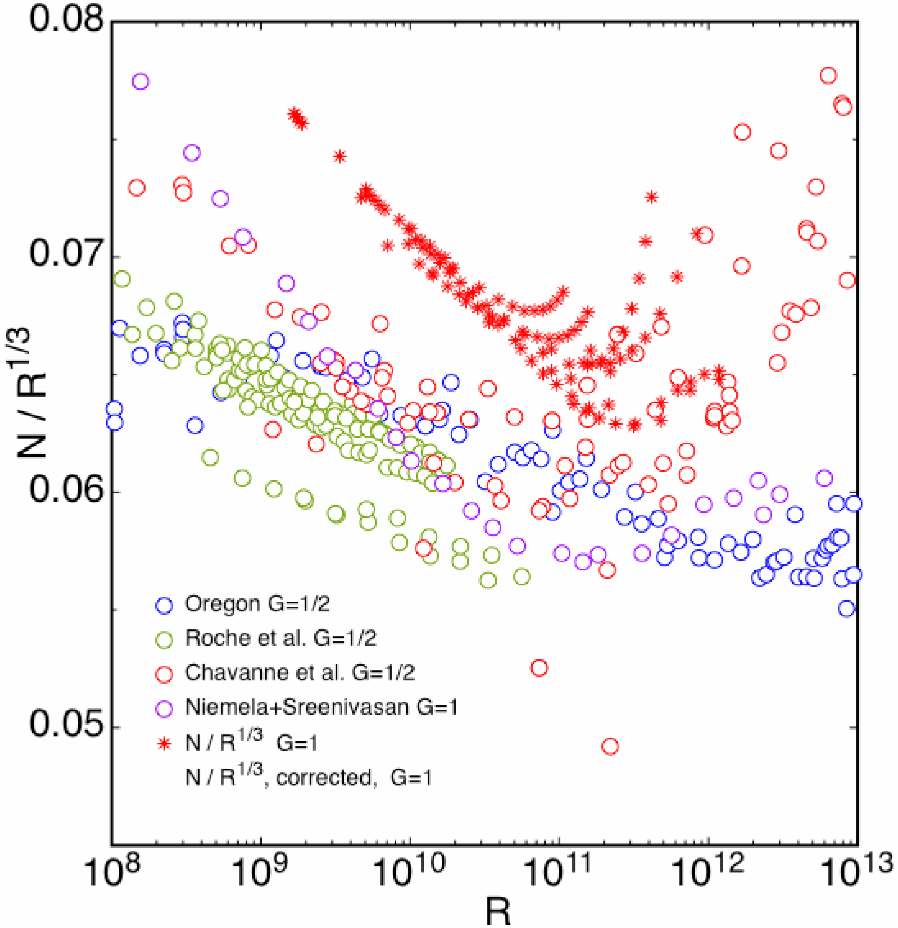
A.+ Xu, PRL **86**, 3320 (2001);

Roche et al., Europhys. Lett. **58**, 693 (2002);

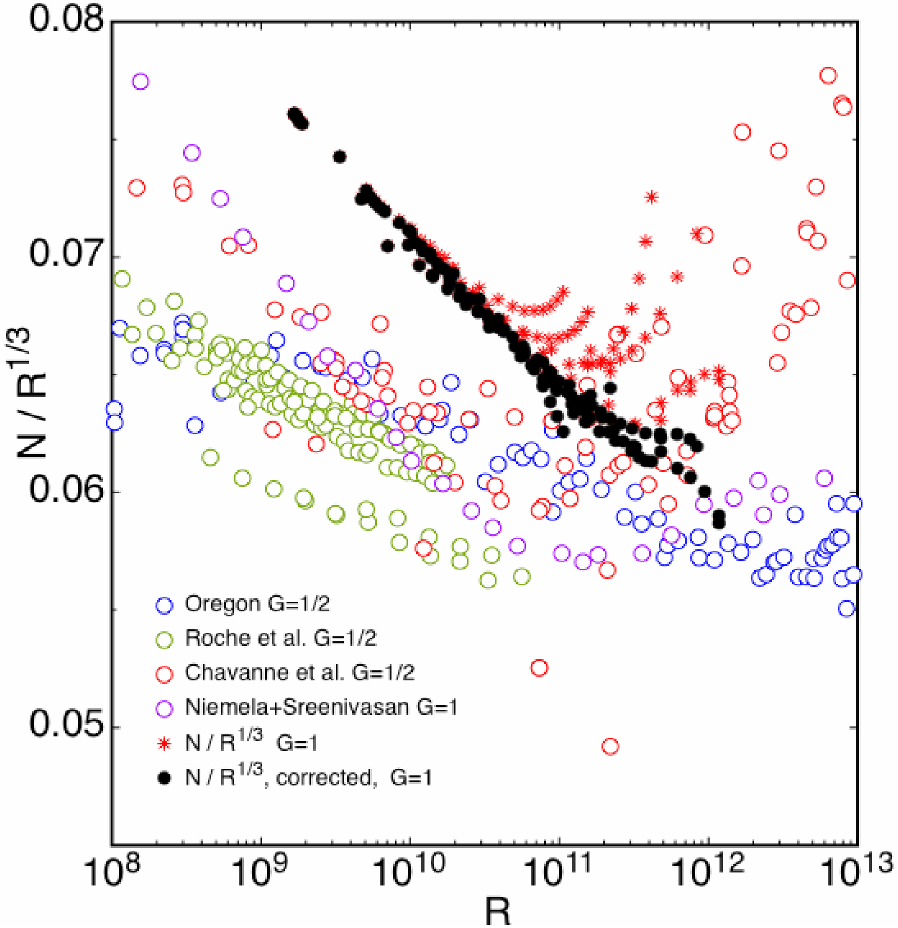
Xia et al., PRL **88**, 064501 (2002).

Disagrees with

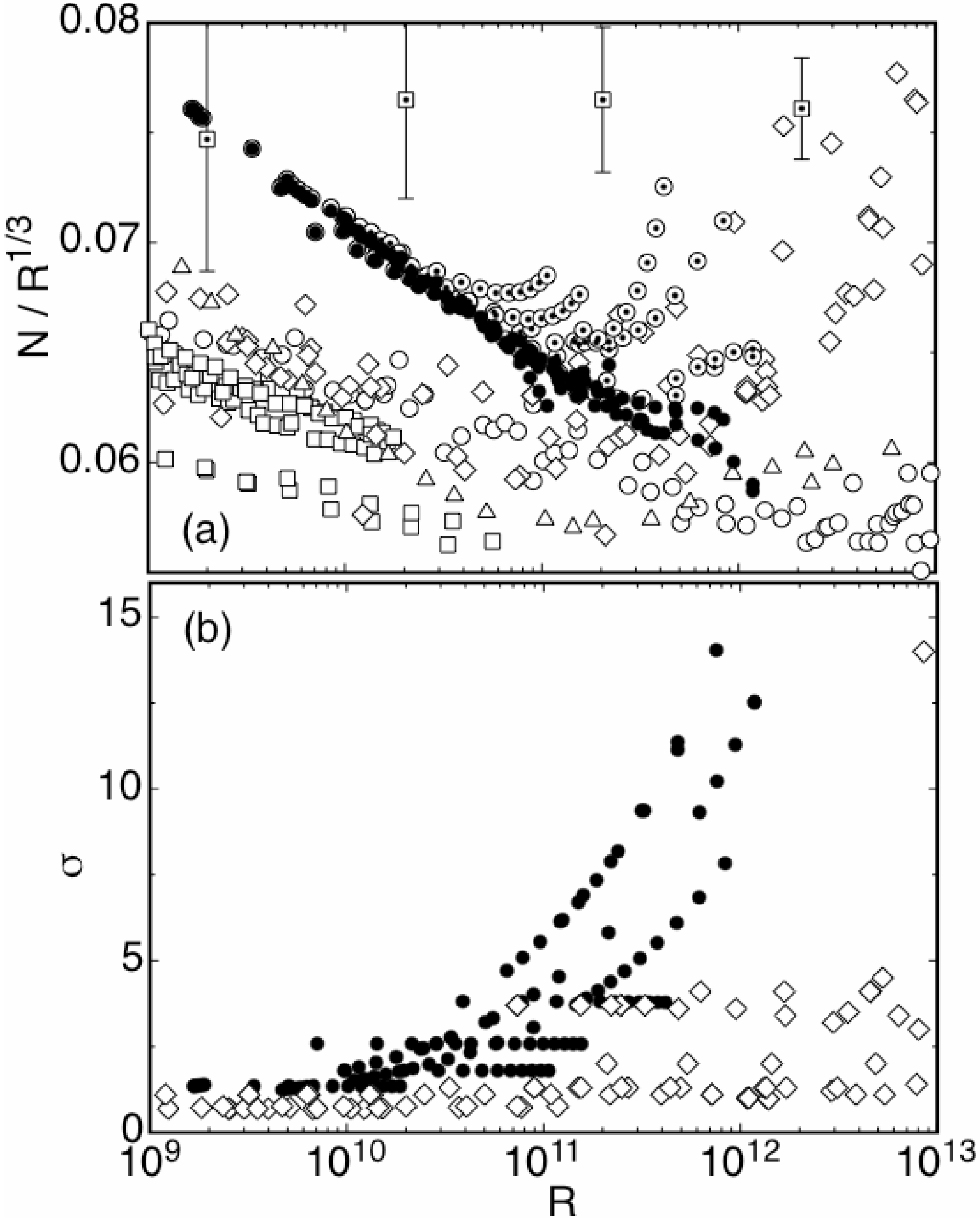
Ashkenazi and Steinberg, PRL **83**, 3641 (1999).



0.08
0.07
0.06
0.05
N / R^1/3
10^8
10^9
10^10
10^11
10^12
10^13
R
Oregon G=1/2
Roche et al. G=1/2
Chavanne et al. G=1/2
Niemela+Sreenivasan G=1
N / R^1/3 G=1
N / R^1/3, corrected, G=1



0.08
0.07
0.06
0.05
N / R^1/3
10^8
10^9
10^10
10^11
10^12
10^13
R
Oregon G=1/2
Roche et al. G=1/2
Chavanne et al. G=1/2
Niemela+Sreenivasan G=1
N / R^1/3 G=1
N / R^1/3, corrected, G=1

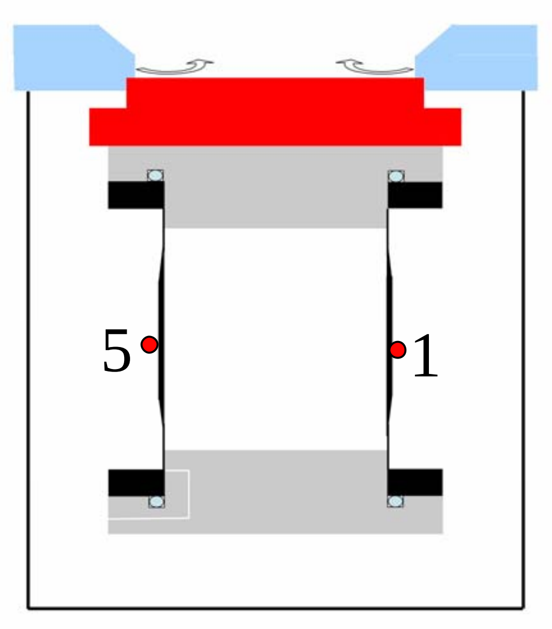

0.08
0.07
0.06
N / R^1/3
(a)
15
10
5
0
σ
(b)
10^9
10^10
10^11
10^12
10^13
R

Summary:

NOB effects cause an INCREASE of Nuselt; this differs from liquids like water where N decreases, albeit by a much smaller amount.

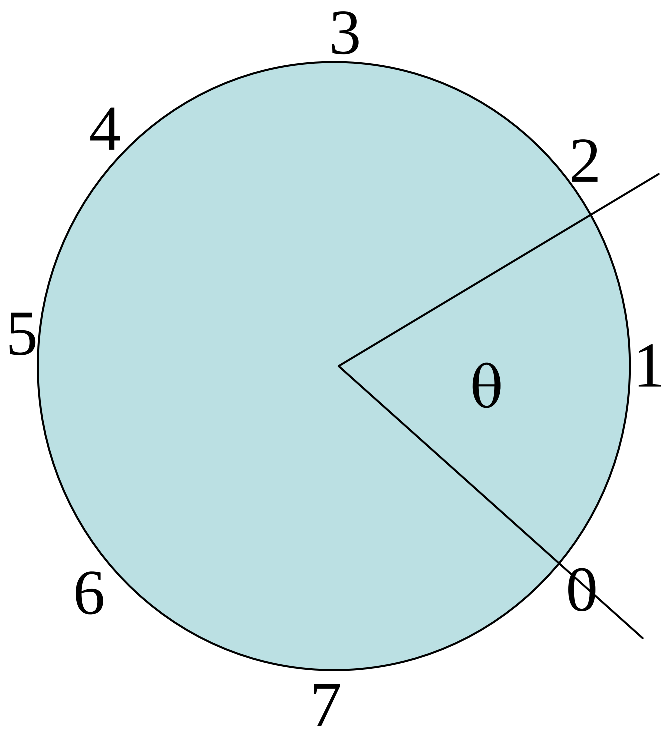
$\alpha\Delta T$ by itself does not completely determine the size of the NOB effect, but for $\alpha\Delta T < 0.15$ is does so reasonably well.

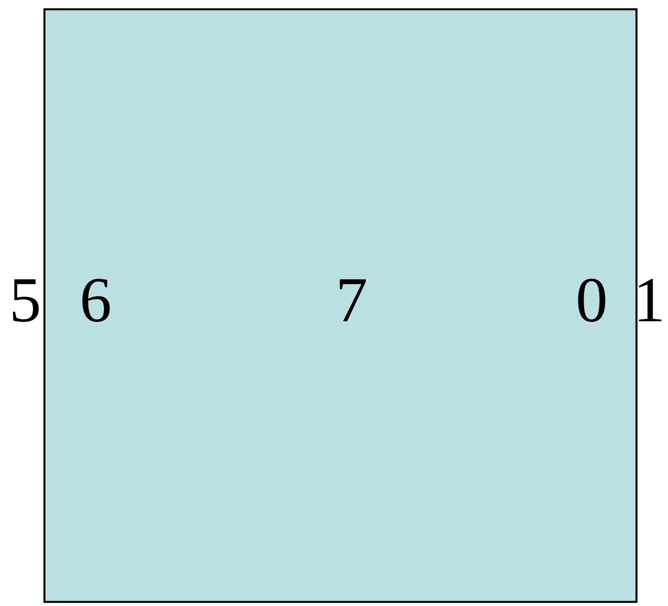
After NOB corrections, our data reach $R \sim= 10^{12}$, but are not yet sufficient to enter the range where the Oregon and the Grenoble data differ so dramatically.



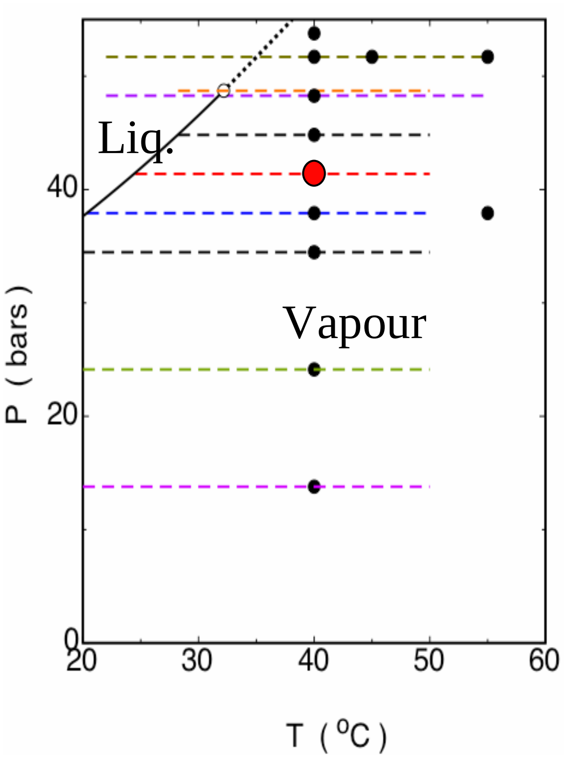
Sidewall Thermometers

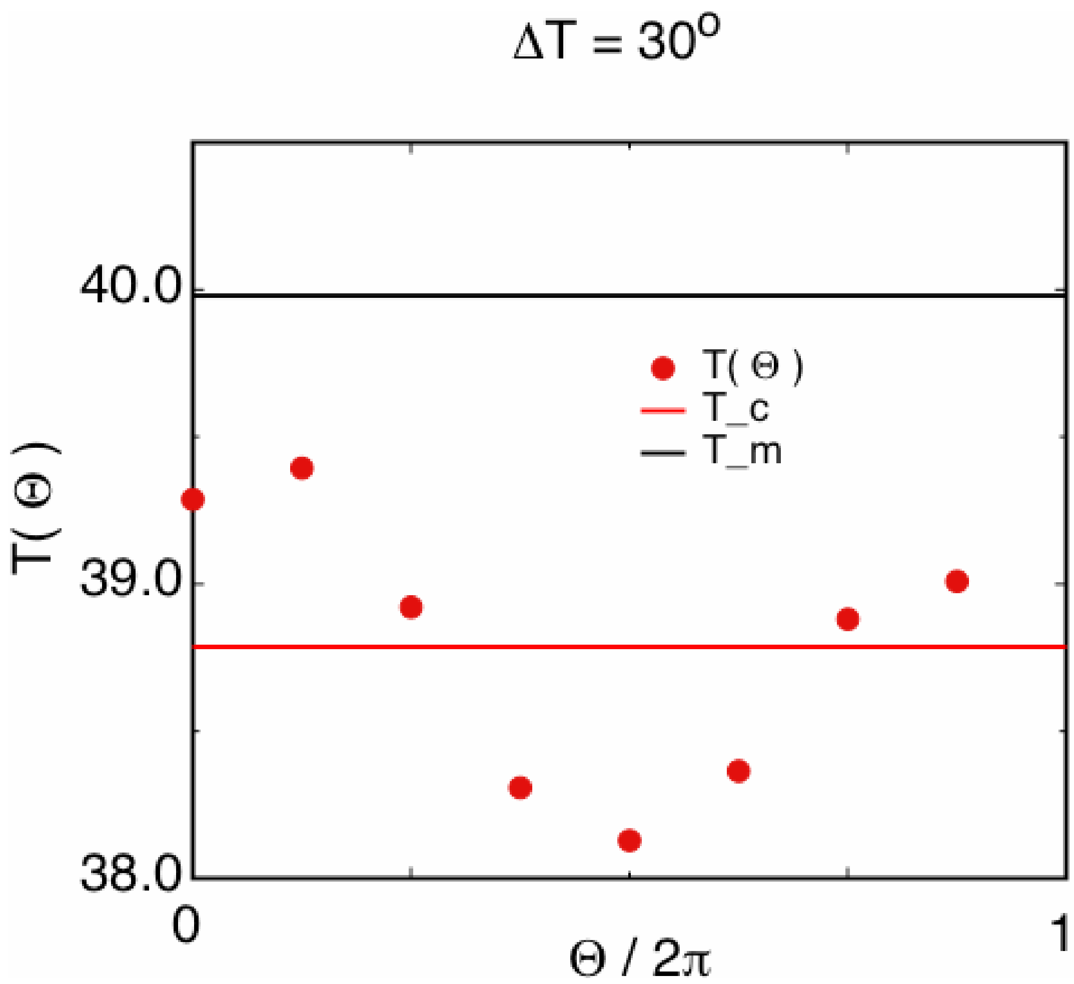
Side view



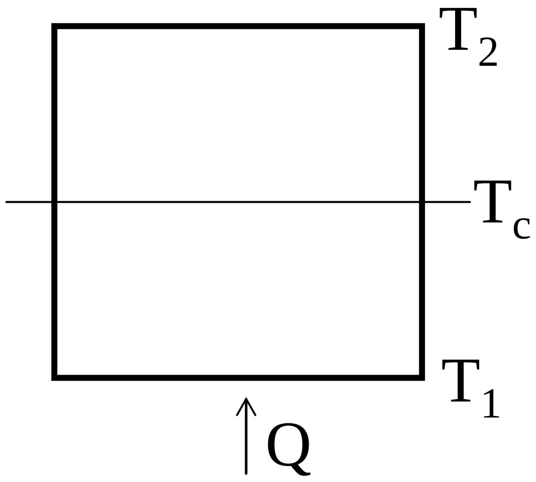


L/2 (middle)



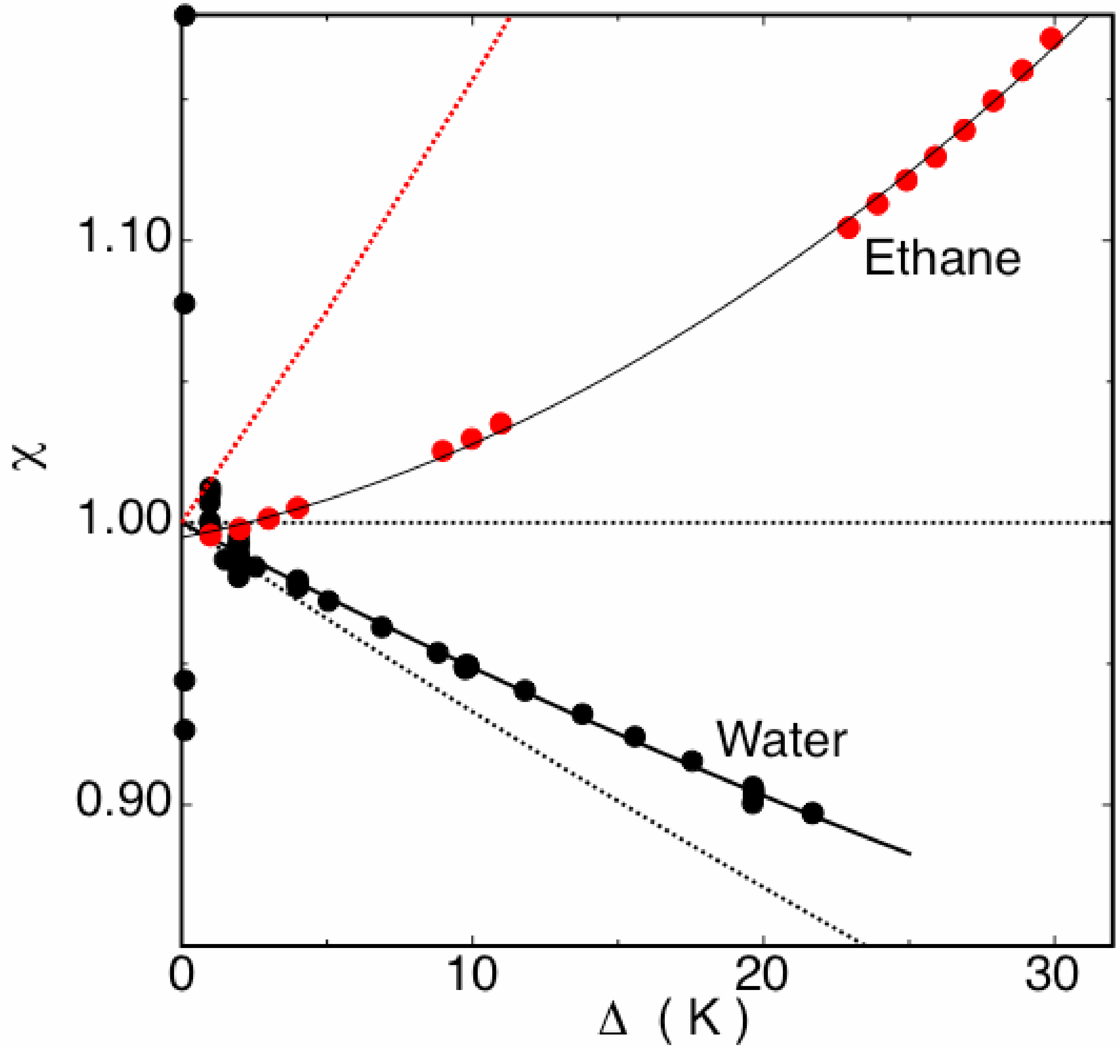


P = 41.37 bars, $P/P_c = 0.85$, <T> = 40°C



$$\Delta = T_1 - T_2$$

$$\chi = \frac{T_1 - T_c}{T_c - T_2}$$



See Francisco Fontenele Araujo’s talk yesterday.

Summary:

The temperature T_c at the horizontal midplane is decreased by NOB effects. This differs from liquids, where T_c is increased. A quantitative comparison with Fontenele Araujo et al.
has yet to be made.

Reorientations of the large-scale circulation of turbulent RBC in aspect-ratio one samples

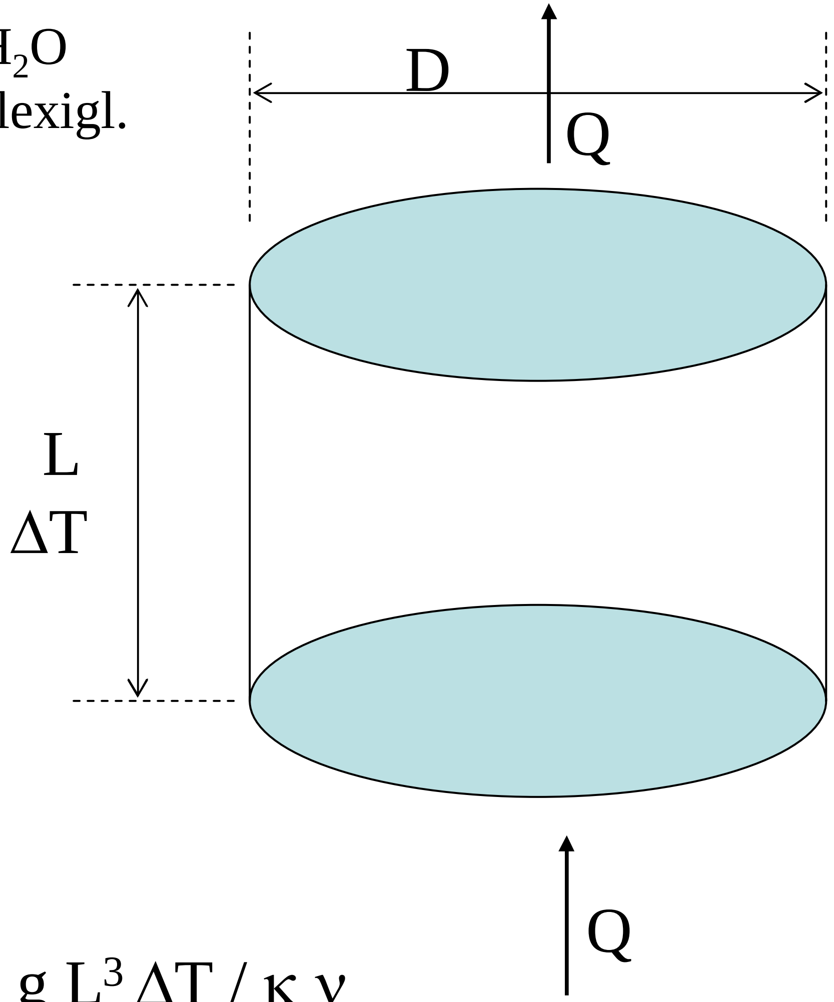
E. Brown, A. Nikolaenko, and G.Ahlers,
Phys. Rev. Lett. 95, 084503 (2005).

E. Brown and G. Ahlers,
J.Fluid Mech., in press.

For preprints or reprints, go to
http://www.nls.physics.ucsb.edu/

Rayleigh-Benard Convection Cell

Fluid: H_2O
Wall: Plexigl.



$\Gamma = D/L = 1.0$

Three samples:

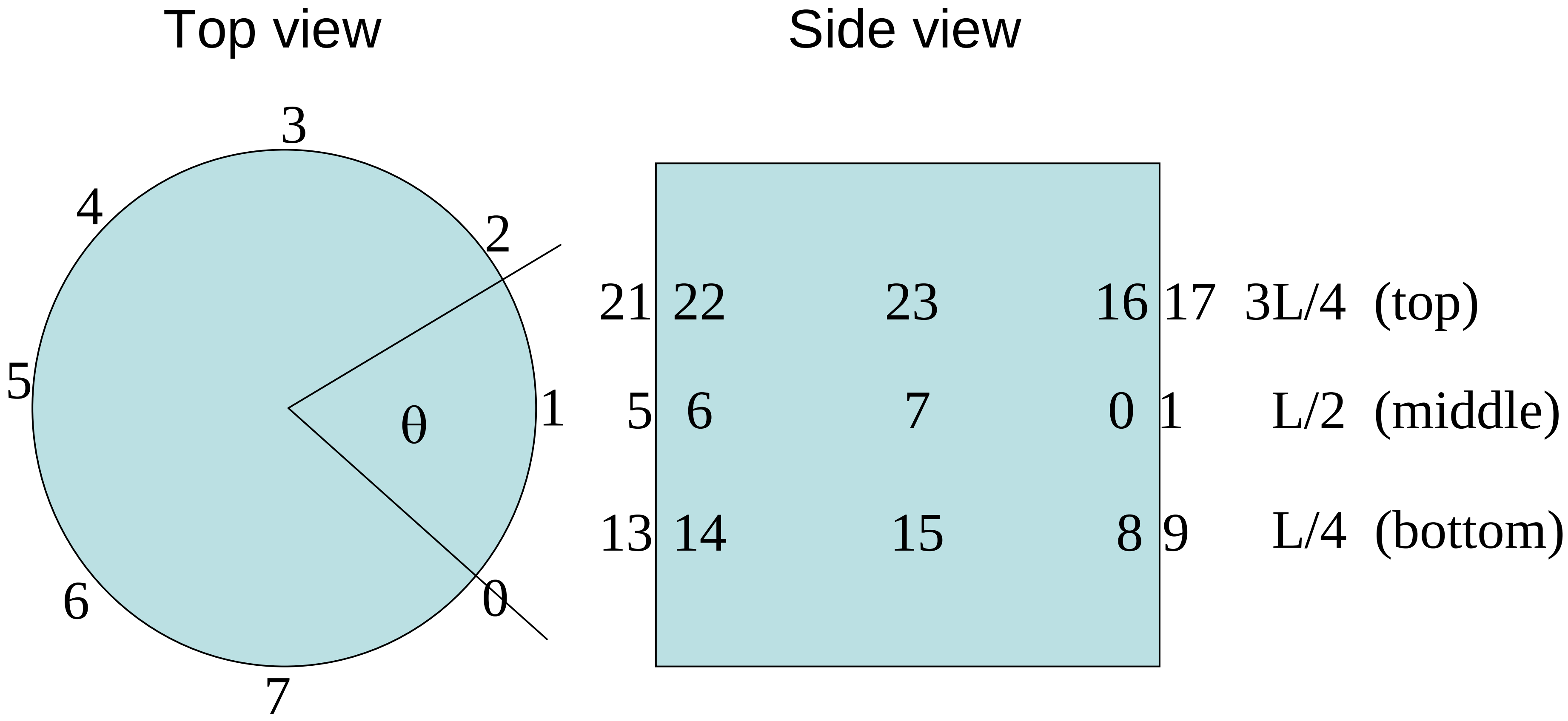
Small: D = L = 9 cm

Medium: D = L = 25 cm

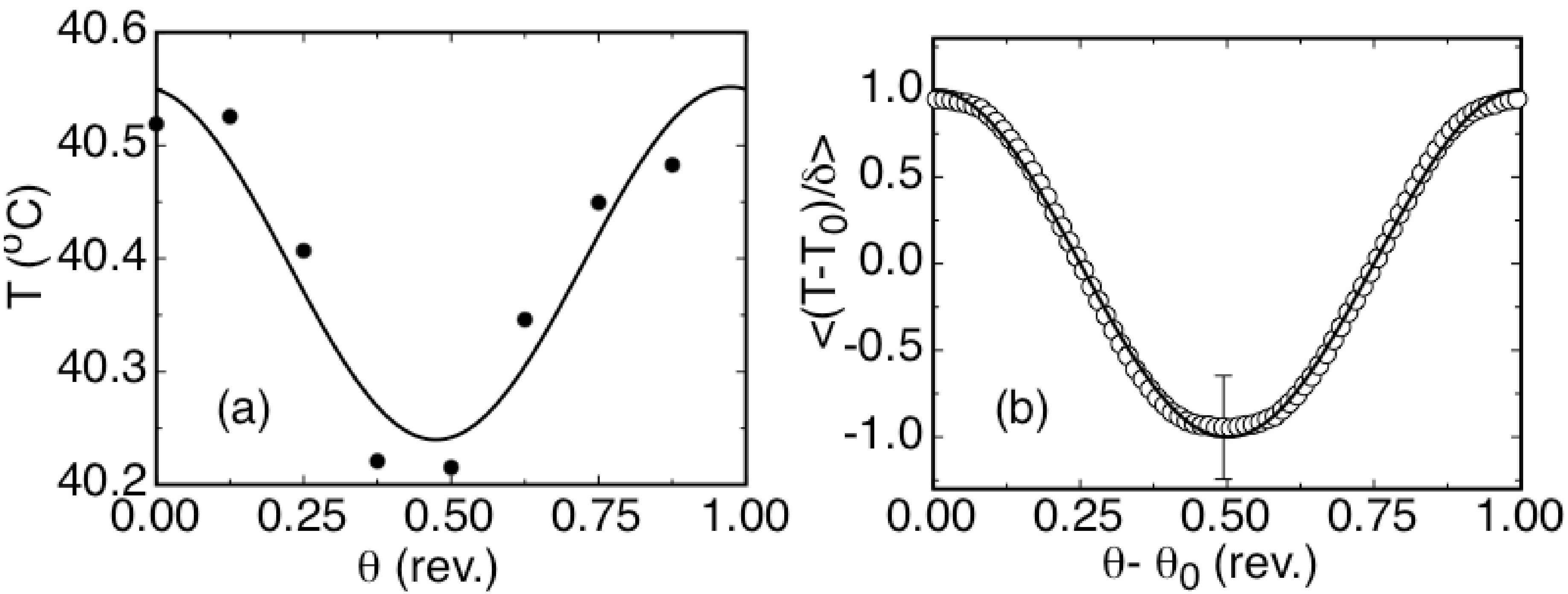
Large: D = L = 50 cm
$\Delta T = 20\ {}^{o}C$: $R = 10^{11}$
Q = 1500 W

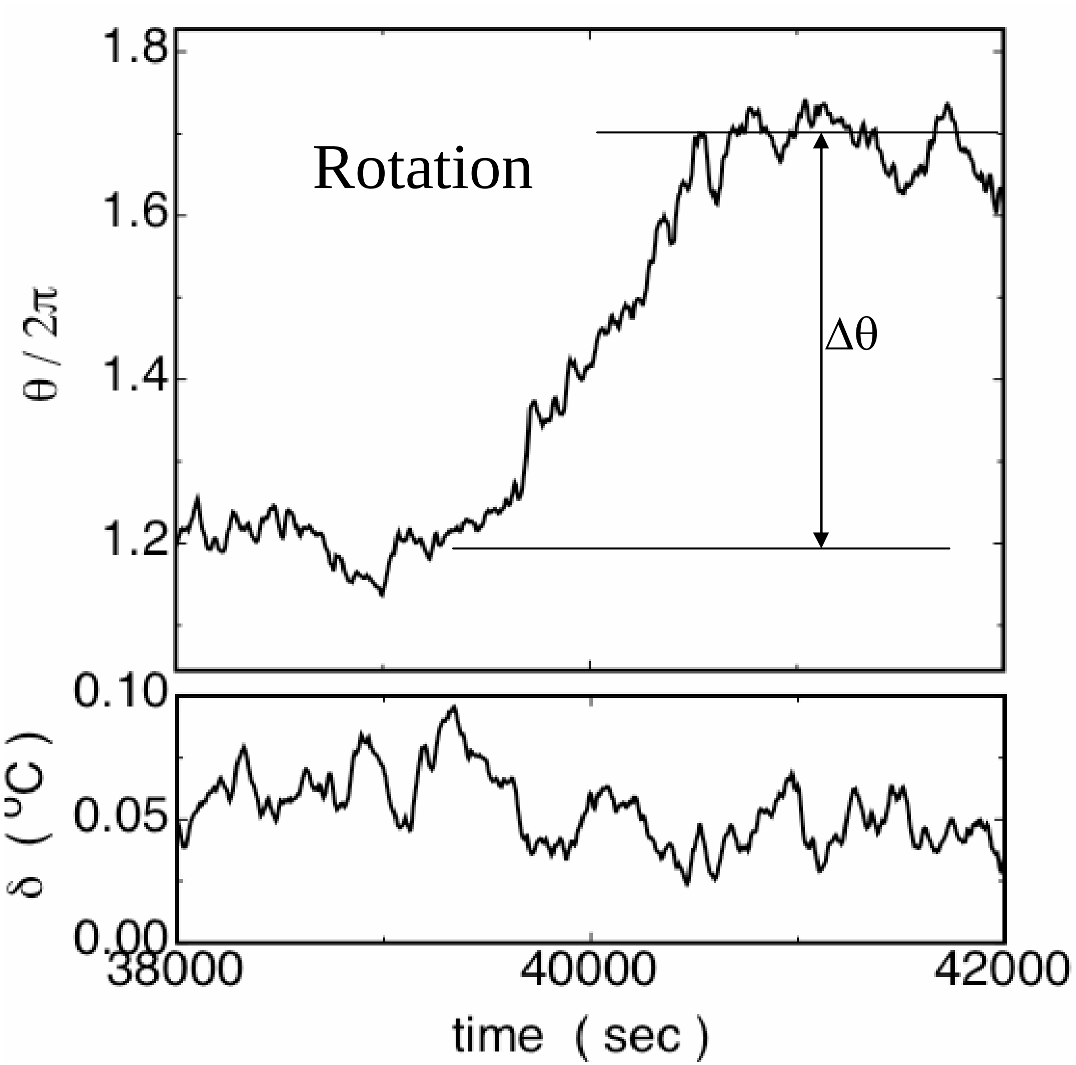
$R = \alpha\, g\, L^3\, \Delta T / \kappa\, \nu$

Prandtl No. $\sigma = \nu/\kappa = 4.4$
(H_2O, 40 ^{o}C)


Top view
Side view
3
4
2
5
θ
1
6
0
7
21 22 23 16 17 3L/4 (top)
5 6 7 0 1 L/2 (middle)
13 14 15 8 9 L/4 (bottom)

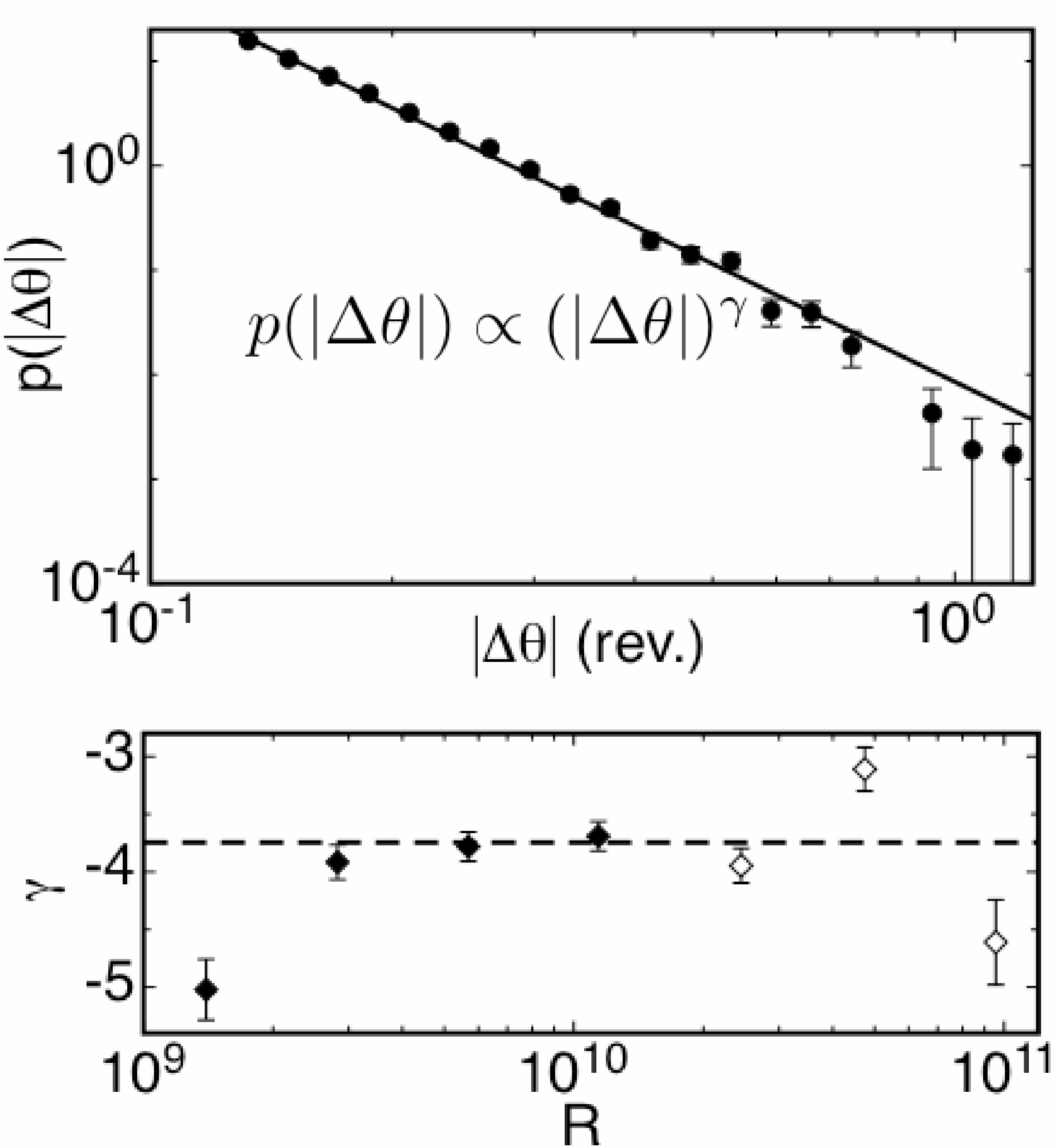
$$T_i = T_0 + \delta \cos(i\pi/4 + \theta_0), \quad i = 0, \ldots, 7$$
$$i = 8, \ldots, 15$$
$$i = 16, \ldots, 23$$





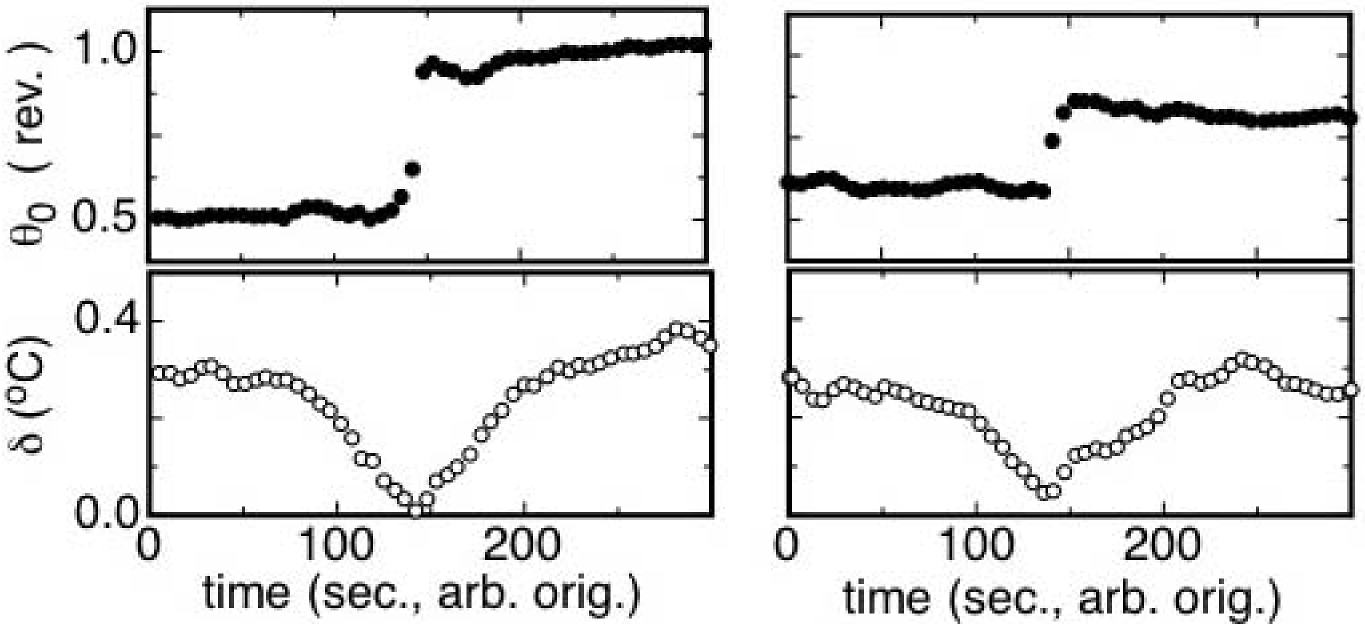
Rotation
Δθ
θ / 2π
1.8
1.6
1.4
1.2
δ (°C)
0.10
0.05
0.00
38000
40000
42000
time (sec)

Rotations



$p(|\Delta\theta|) \propto (|\Delta\theta|)^{\gamma}$
p(|Δθ|)
10^0
10^-4
10^-1
10^0
|Δθ| (rev.)
-3
-4
-5
γ
10^9
10^10
10^11
R

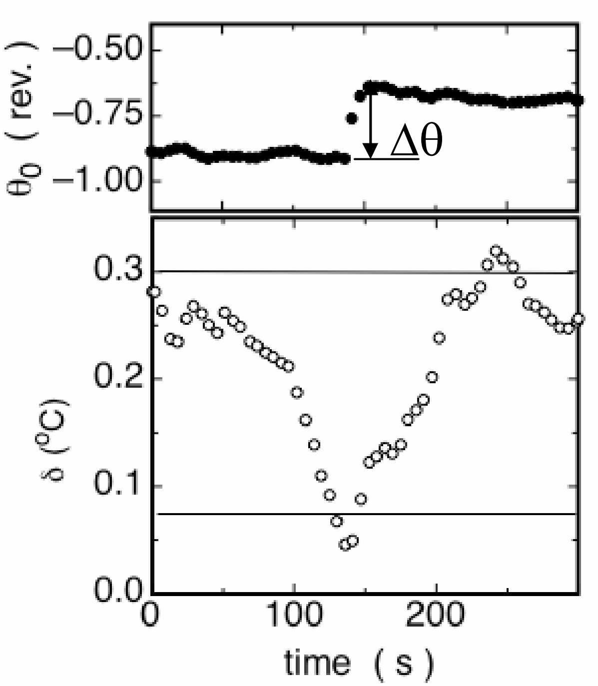
Cessation

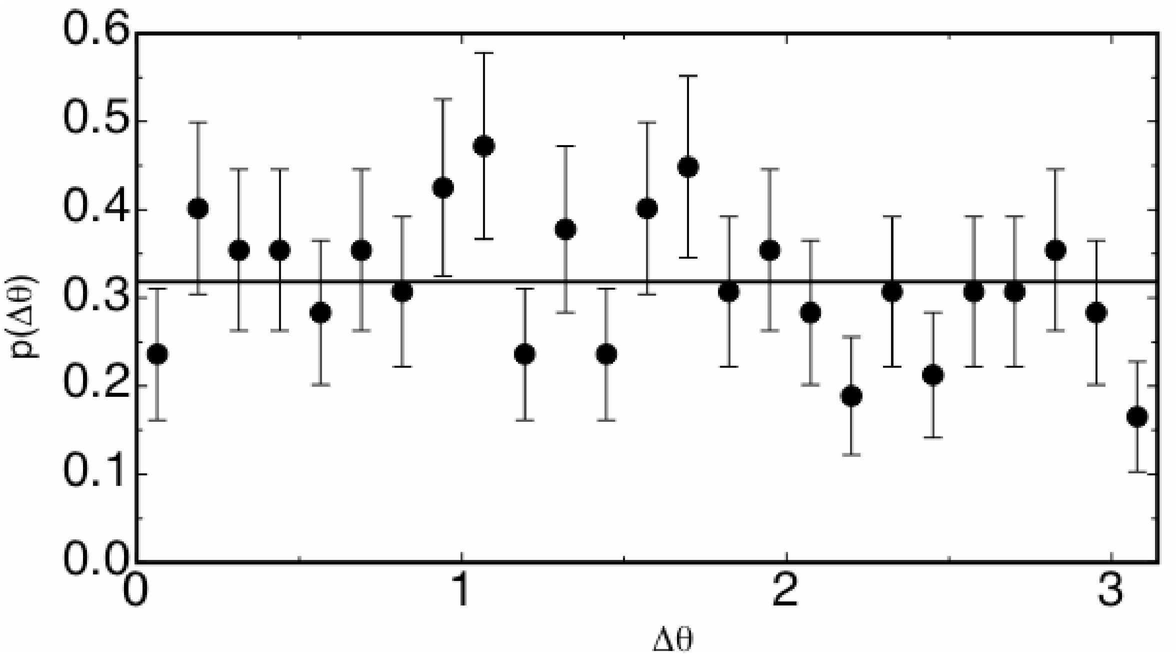


θ_0 (rev.)
1.0
0.5
δ (°C)
0.4
0.0
0
100
200
time (sec., arb. orig.)
0
100
200
time (sec., arb. orig.)

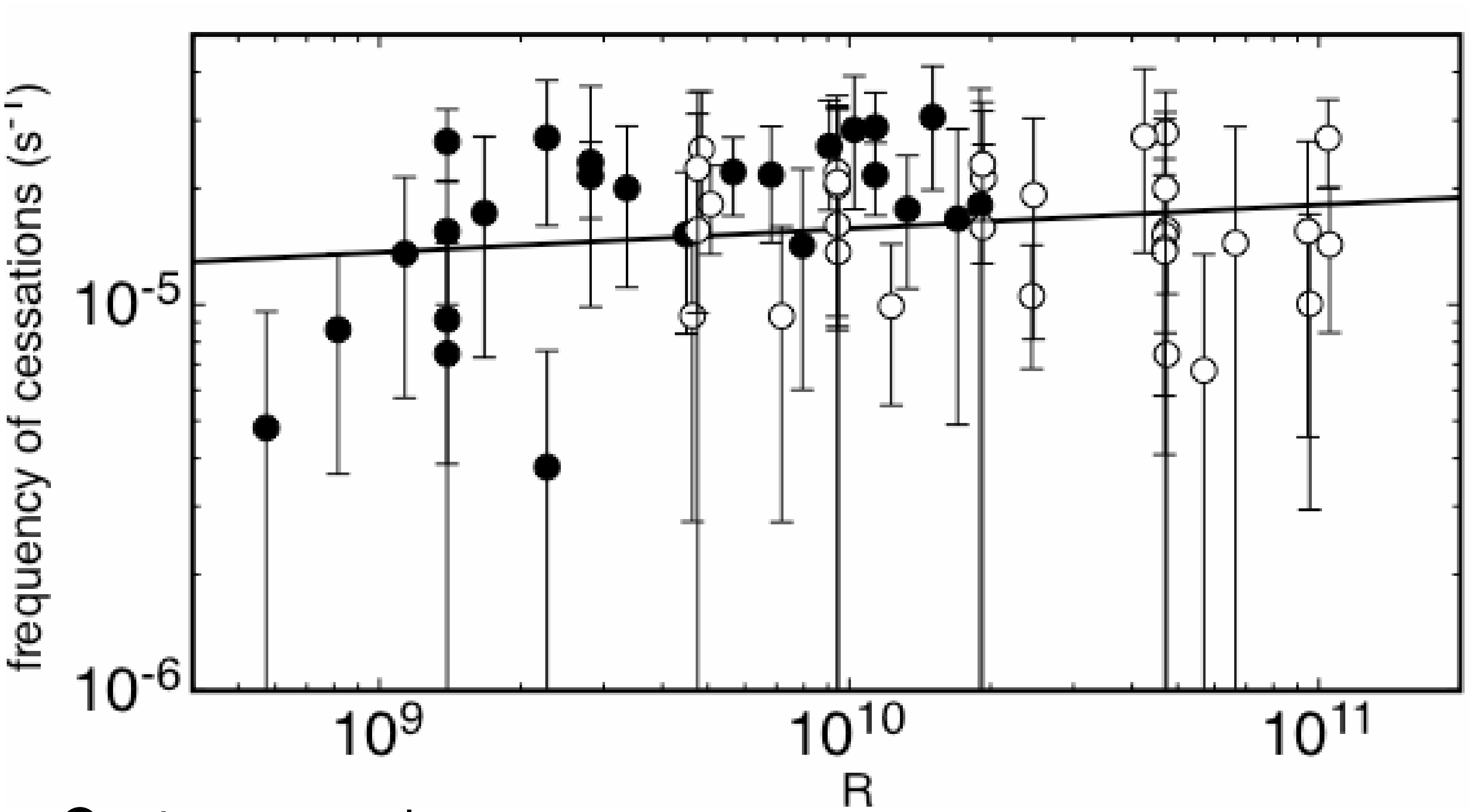
Cessations

probability distribution of $|\Delta\theta|$ for reorientations with $\delta/\langle\delta\rangle < 0.25$



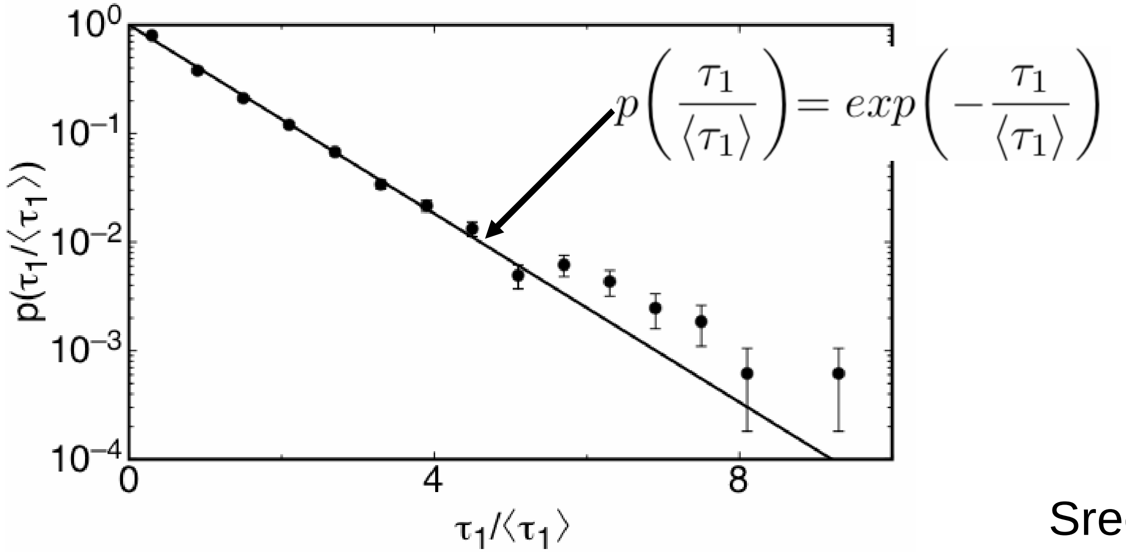


Properties in the time domain

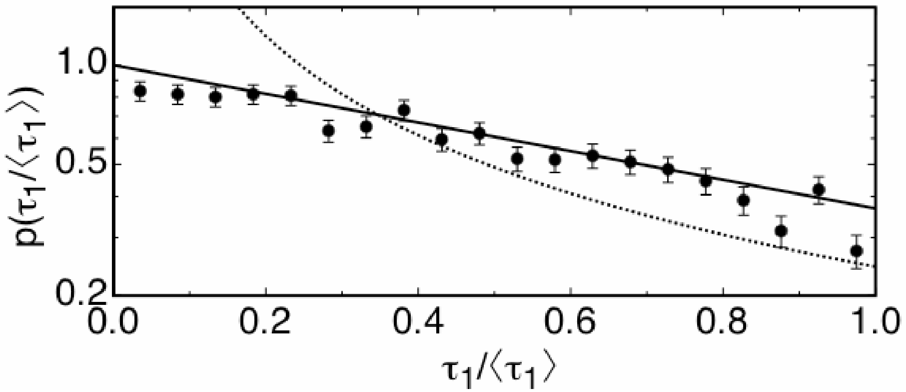


○ Large sample

● Medium sample



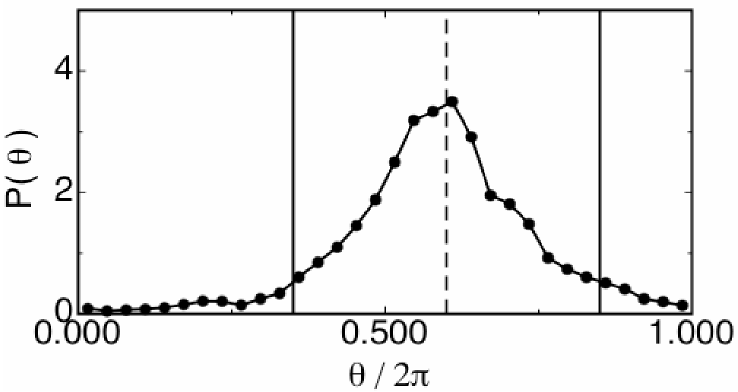
Poisson distributed, in agreeent with Sreenivasan et al. for large τ_1



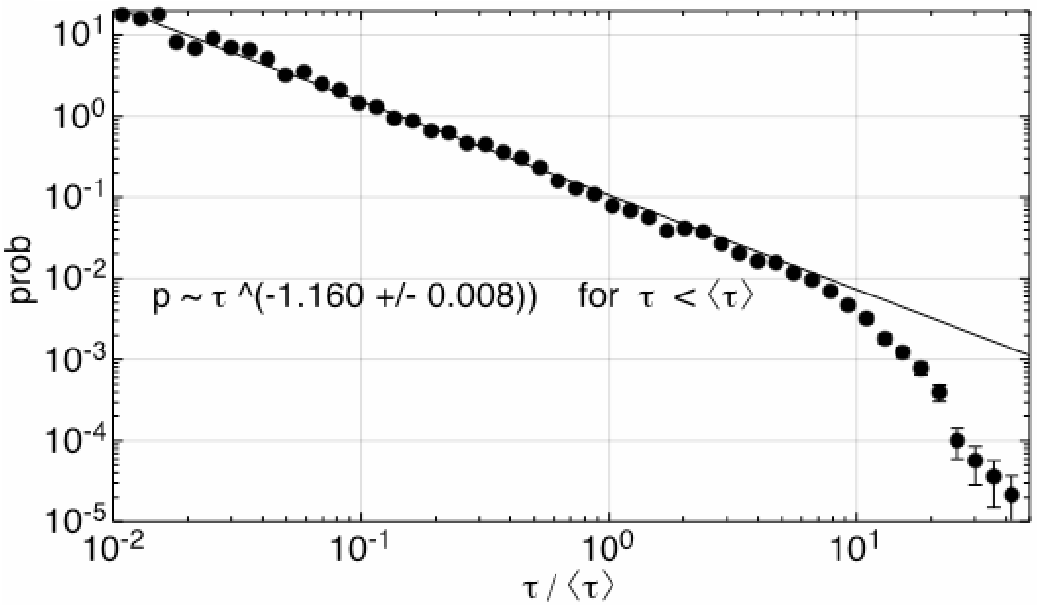
Sreenivasan et al. found power law $P(\tau_1/<\tau_1>) \sim \tau_1^{-1}$ for small τ_1 (dotted line)

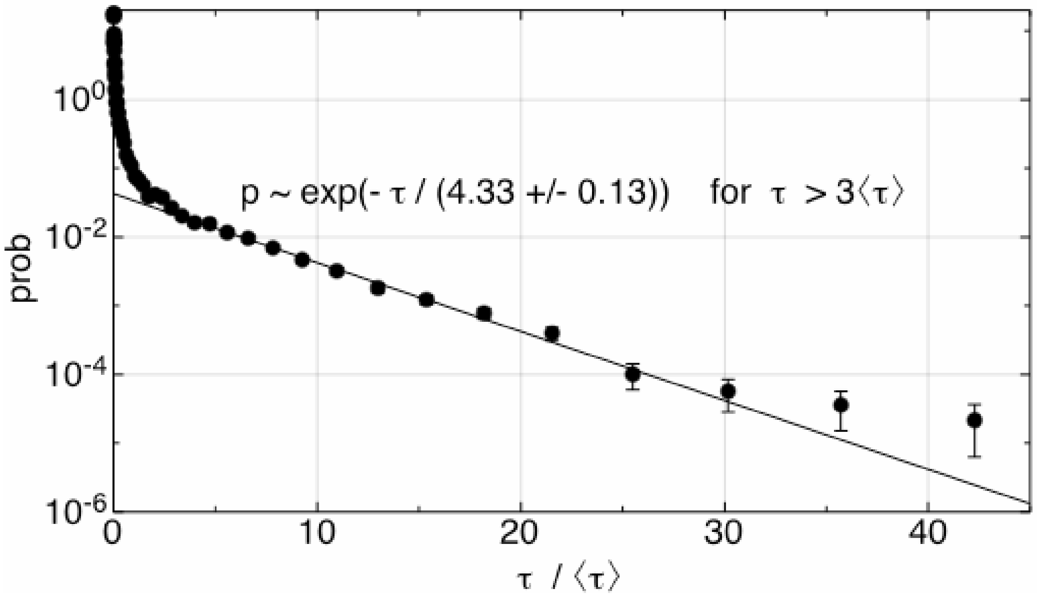
Following
K, Sreenivasan, A. Bershadskii, and J. Niemela, Phys. Rev. E 65, 056306 (2002):

- τ_1 = time between i^{th} and $(i+1)^{th}$ re-orientation



probability distribution of the time interval τ between reversals,
using a criterion more similar to SBN's





A.) The azimuthal dynamics of the LSC is diffusive, with interspersed reorientations of relatively short duration.

B.) LSC reorientations can occur via

1.) rotation of the vorticity vector ("rotation")

2.) shrinking of the vorticity vector, followed by re-development with a new orientation ("cessation")

C.) Cessation is followed by re-development of the LSC in a circulation plane with an arbitrary new orientation, i.e. $P(\Delta\theta) = 1/\pi$.

D.) Rotation through an angle $\Delta\theta$ has a powerlaw probability distribution $P(\Delta\theta) \sim \Delta\theta^{-\gamma}$ with $\gamma \sim 4$ (i.e. rotations through smaller angles are more likely). "Heavy tail" distrib. as in forest fires and stock markets.

E.) Rotations and Cessations are each Poisson distributed in time.

F.) Small-amplitude high-frequency diffusive "jitter" of θ can give a power-law distribution in time for small time intervals τ as observed by Sreenivasan et al.