Transport of heat by classical and quantum **turbulent flows** in **cryogenic helium ^{4}He**

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PřF MUNI: F3250 - Moderní témata fyziky kondenzované fáze :: 30.11.2022

research departments

New Technologies
Ing. Martin Zobač, Ph.D.

Medical Signals
Ing. Pavel Jurák, CSc.

Microphotonics
prof. RNDr. Pavel Zemánek, Ph.D.

Magnetic Resonance and Cryogenics
Ing. Zenon Starčuk, CSc.

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In 1967


In 2021

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Letní stáže na ÚPT v roce 2022

Ústav přístrojové techniky AV ČR nabízí studentům letní brigády ve špičkových laboratořích.

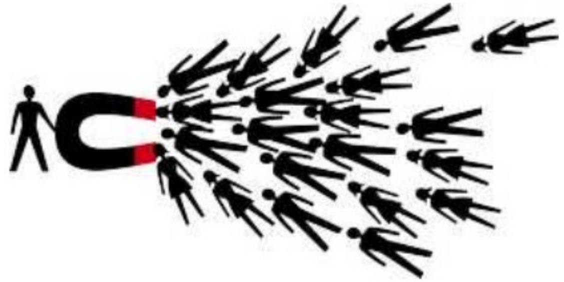
Vážení studenti,

chcete strávit letní brigádu ve špičkových laboratořích?
Máte zájem se něco užitečného naučit a přitom si i vydělat?
Zažít dobrodružství z objevování, pomáhat zprovoznit převratné technologie a posunout světovou vědu?
Využijte naši nabídku a staňte se v době prázdnin až 4 týdny součástí vědeckého týmu!
Podmínkou práce v laboratoři z důvodu bezpečnosti práce je věk nad 18 let.

Vyberte si některé z nabízených témat a neváhejte nás kontaktovat!

Cryogenics at ISI CAS Brno

Dny otevřených dveří



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Outline of Lecture #1

1. **Basic aspects**
    - [1 a] **Heat Transport**
    - [1 b] **Turbulent Flows**
    - [1 c] **Helium ^{4}He**

2. **Experiments in Brno: Classical turbulent Rayleigh-Benard convection**
    - [2 a] **Nu(Ra) - Heat transport efficiency**
    - [2 b] **Re(Ra) - Dynamics of coherent structures (wind)**

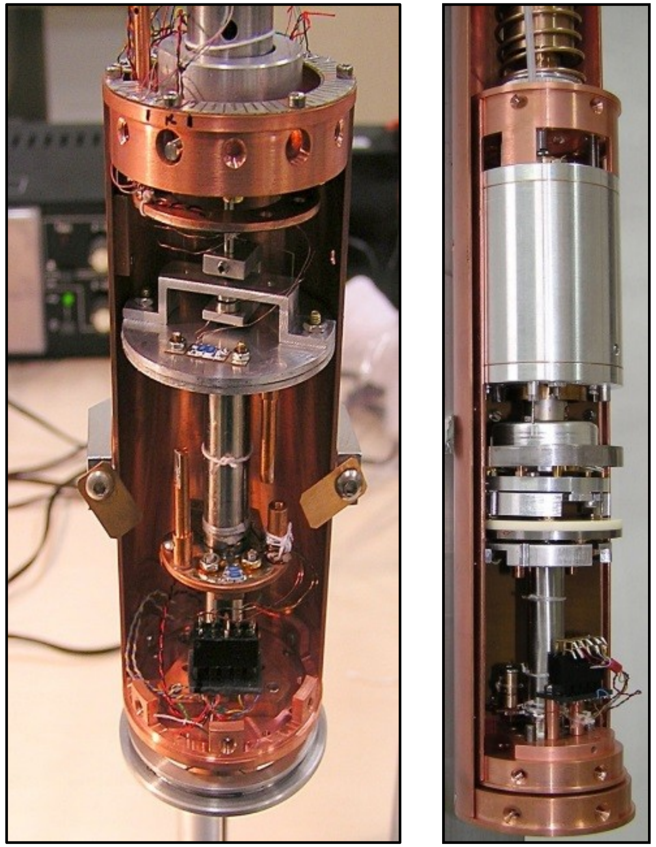
3. **New research directions**
    - [3 a] **Attractors in RBC**
    - [3 b] **Modulated Convection and Rotation**
    - [3 c] **Visualization of ^{4}He flows – metastable molecular excimers**
    - [3 d] **Classical and Quantum heat transfers - analogies**

Heat Transport at Low Temperatures (~5K)

- <u>Heat transport by **Radiation**</u>

Emister apparatus
(far-field regime)

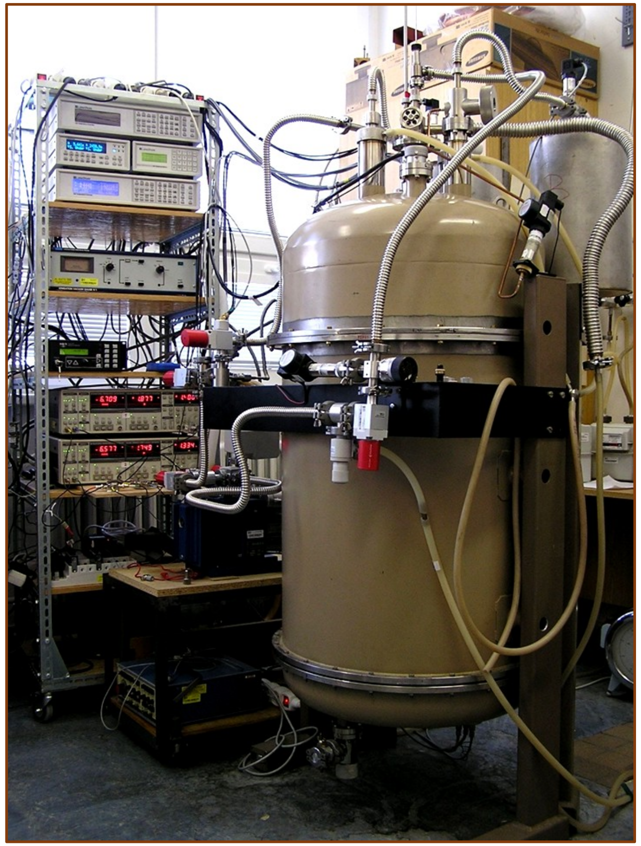
EWA apparatus
(near-field regime)



PRL **109**, 224302 (2012), PRB **99**, 024511 (2019)

- <u>Heat transport by **Convection**</u>

ConEV apparatus
(Rayleigh-Bénard convection)



… discussed in detail today

Basic Heat transport mechanisms: Recall…

- 1. ?

- 2. ??

- 3. ???

Basic Heat transport mechanisms: Recall…

- 1. Radiation (everywhere, including vacuum):

Stefan-Boltzmann's law: $\vec{q} = \sigma \varepsilon T^{4} \vec{n}$

σ black-body constant

ε surface emissivity

- 2. Conduction (all matter: solid bodies or motionless fluids):

Fourier's law: $\vec{q} = -\lambda \vec{\nabla} T$

λ microscopic conductivity

– depends on structure of the material (molecular/crystal lattice,…)

- 3. Convection (in flowing matter):

"Fourier-like law": $\vec{q} = -\lambda^{*} \vec{\nabla} T$

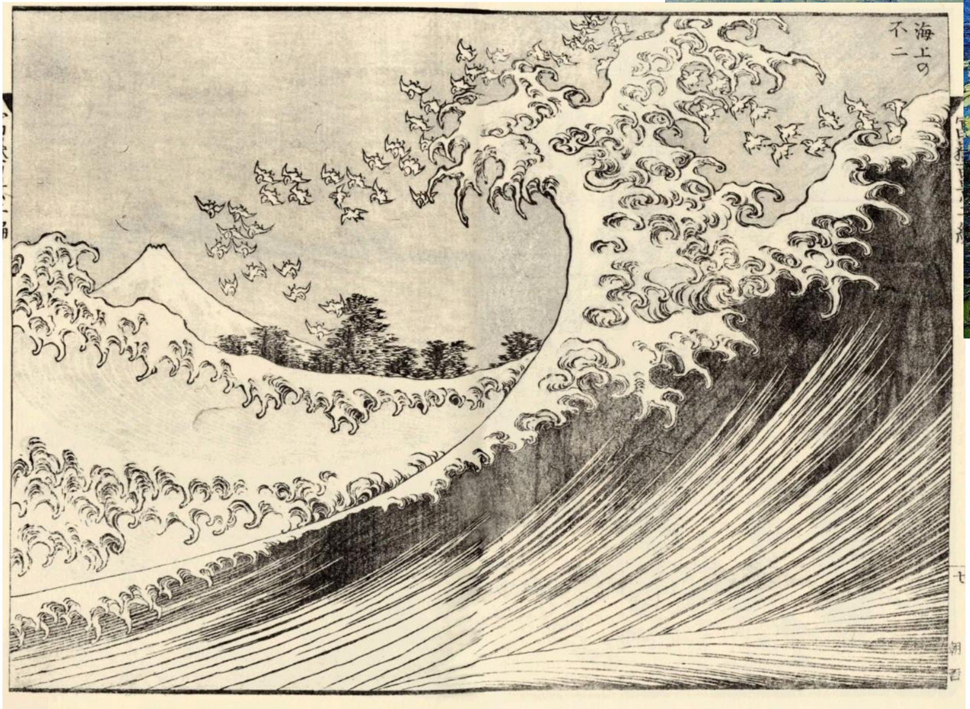
λ^{*} effective conductivity

– depends on the nature of the flow field (laminar/turbulent)

Turbulence

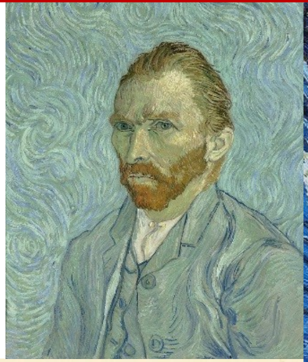
Leonardo da Vinci (1452-1519)

‘Drawing of Water Vortex,’
cca. 1510 - 1513.
Royal Collection Windsor, UK



‘Mount Fuji viewed from the sea,’
from One Hundred Views of Mount Fuji, ca. 1834.
British Museum

Katsushika Hokusai (1760-1849)



Vincent van Gogh (1853-1890)

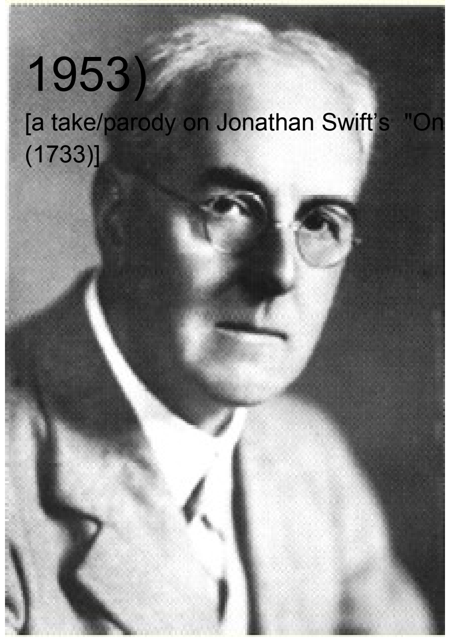
‘Starry Night’
1889.
MoMA, New York

Turbulence: Scales And Cascades

> “Big whirls have little whirls,
> That feed on their velocity,
> And little whirls have lesser whirls,
> And so on to viscosity.”
>
> Lewis Fry Richardson (1881 – 1953)

Leonardo da Vinci (1452-1519)

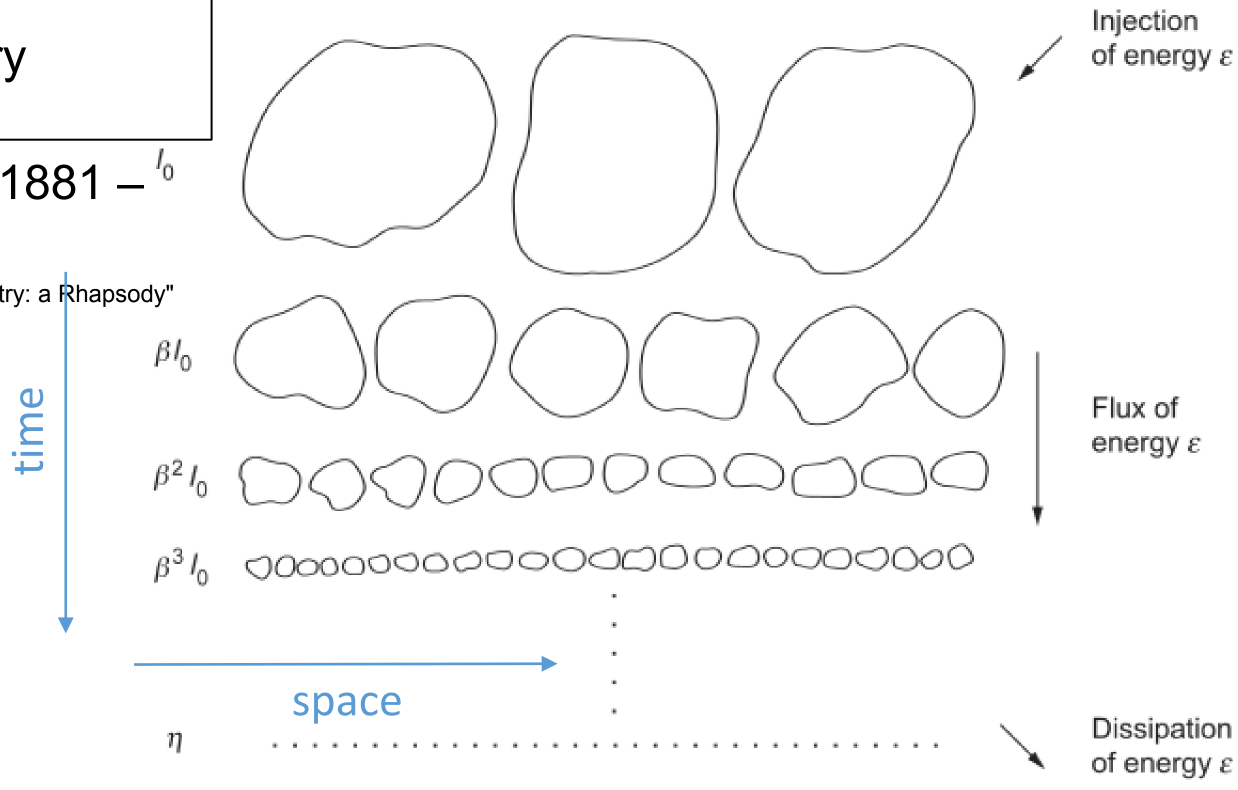
‘Drawing of Water Vortex,’
cca. 1510 - 1513.
Royal Collection Windsor, UK



[a take/parody on Jonathan Swift’s "On Poetry: a Rhapsody" (1733)]

Richardson cascade

- Starting at forcing scale
- Ending at viscous dissipation scale



Adapted from: Uriel Frisch. 1995. Turbulence: The Legacy of A. N. Kolmogorov.

Turbulence: Scales And Cascades

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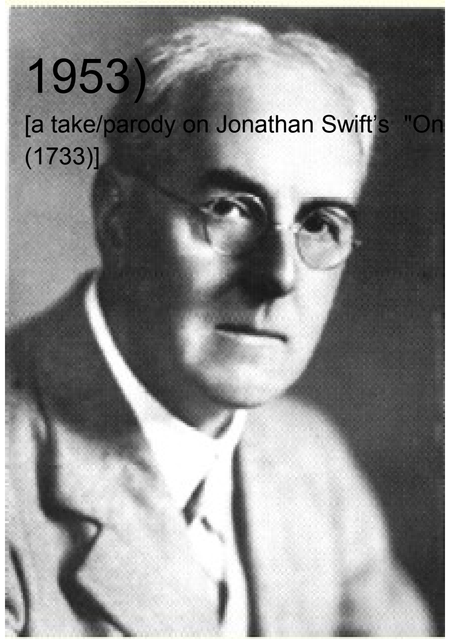


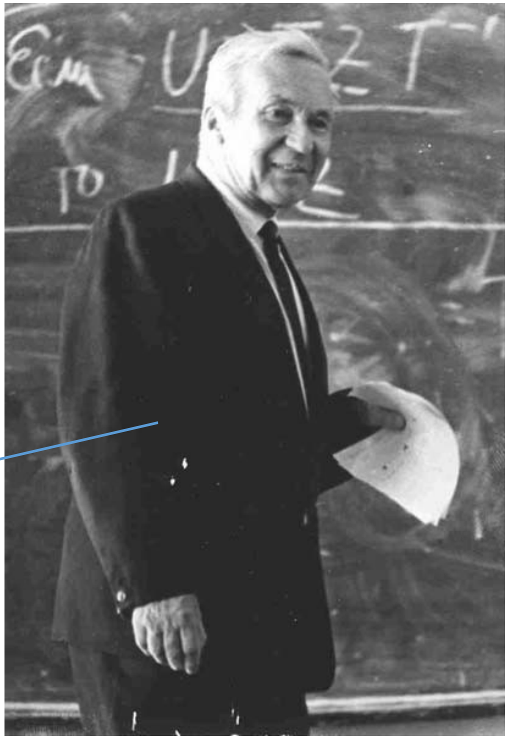
(1881 – 1953)

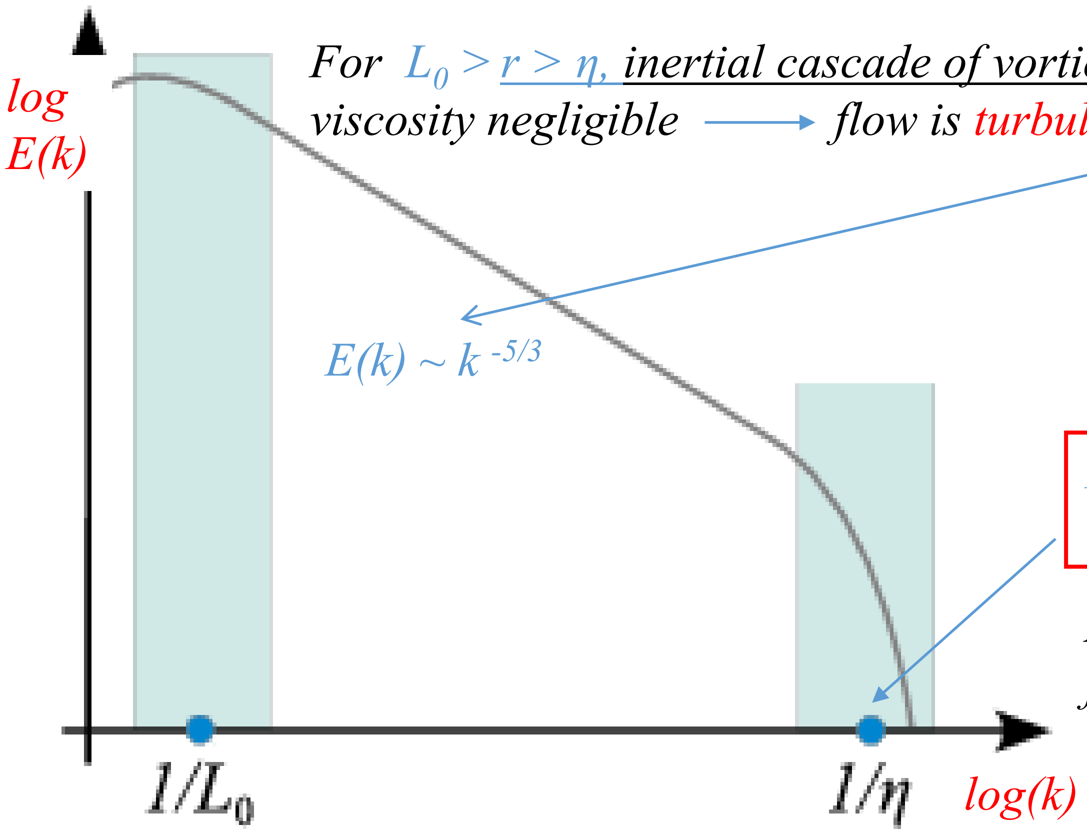
[a take/parody on Jonathan Swift’s "On Pc y" (1733)]

Richardson – Kolmogorov cascade

- Starting at forcing scale
- Ending at viscous dissipation scale
- Broad and smooth kinetic energy spectrum

Andrey Nikolaevich Kolmogorov (1903-1987)





For $L_0 > r > \eta$, *inertial cascade of vortices.*
viscosity negligible ⟶ *flow is turbulent*

$E(k) \sim k^{-5/3}$

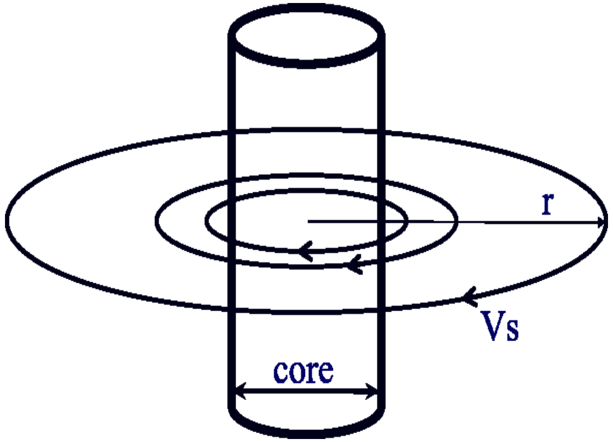
Kolmogorov scale:
$\eta = (\nu^3/\varepsilon)^{1/4}$

At $r < \eta$ *viscosity dominates,*
flow is laminar

Characteristic scales of turbulence in Nature

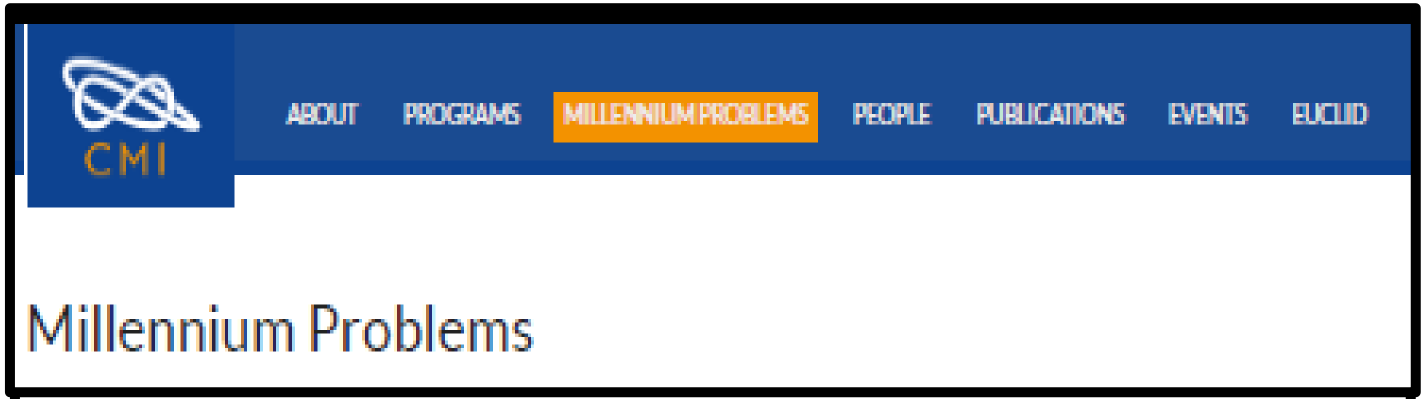
M100 galaxy
as seen through Hubble telescope

Maelstrom, Saltstraumen, Norway



Quantum vortex in superfluid He II

Turbulence: Major open scientific problem



Millennium Problems

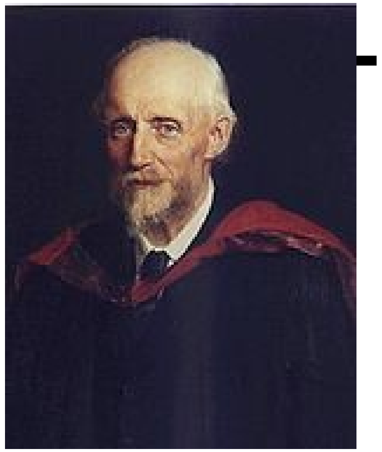
Clay Mathematics Institute **$1 000 000 prize**:

Navier–Stokes existence and smoothness problem:

Even basic properties of the solutions to Navier–Stokes have never been proven. For the three-dimensional system of equations, and given some initial conditions, mathematicians have not yet proved that smooth solutions always exist, or that if they do exist, they have bounded energy per unit mass.

Clear Ideas
by Rene Magritte,
1958

Turbulence onset and Reynolds nu

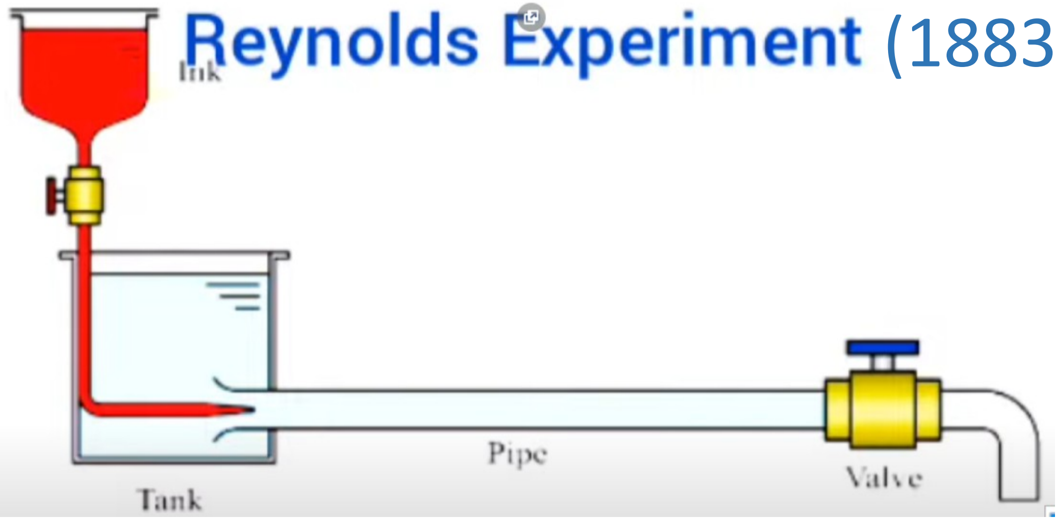


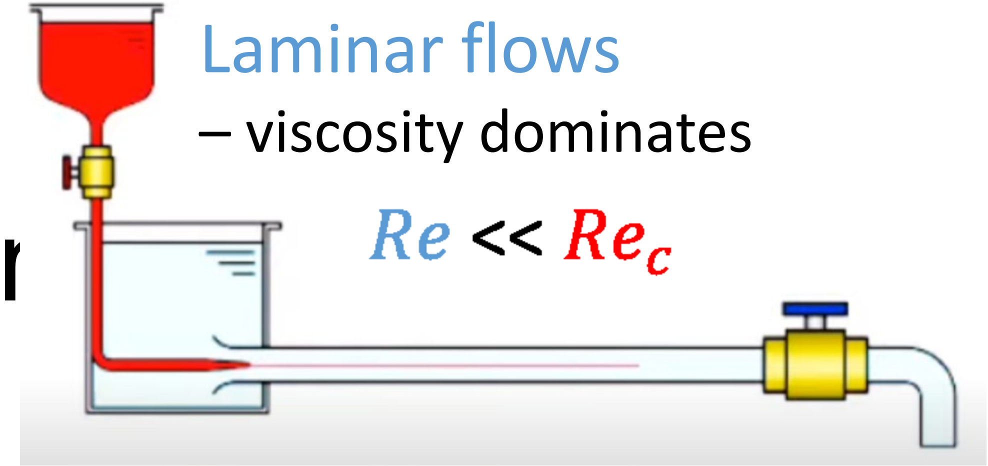
Osborne Reynolds
(1842-1912)

$$Re = \frac{U.L}{\nu}$$

Dimensionless “flow-similarity” number

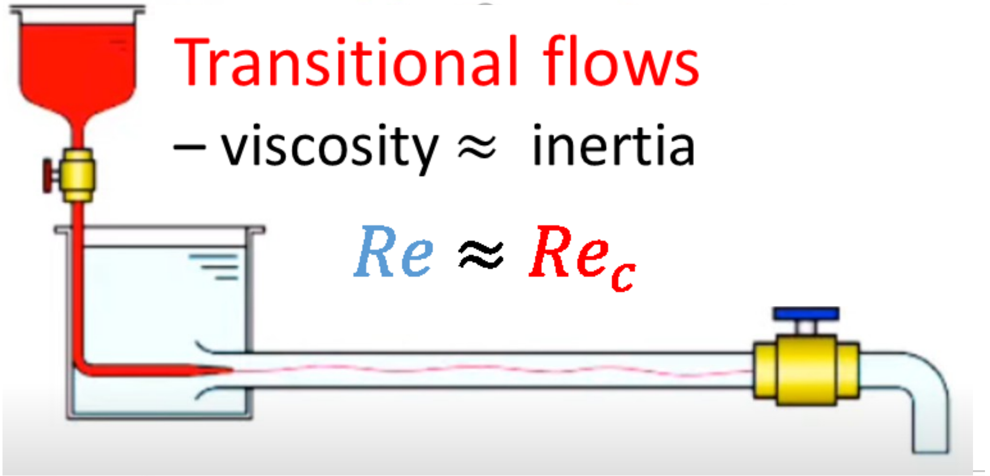
Reynolds Experiment (1883)





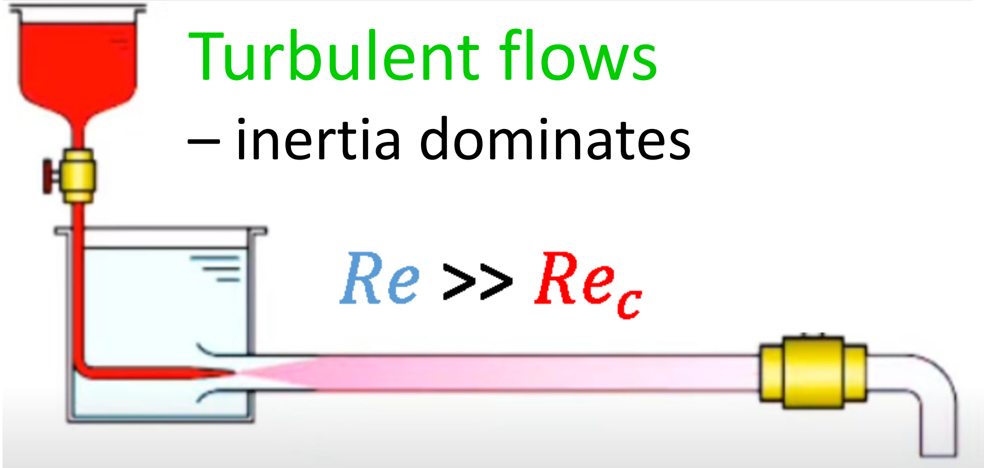
Laminar flows
– viscosity dominates

$Re \ll Re_c$



Transitional flows
– viscosity ≈ inertia

$Re \approx Re_c$



Turbulent flows
– inertia dominates

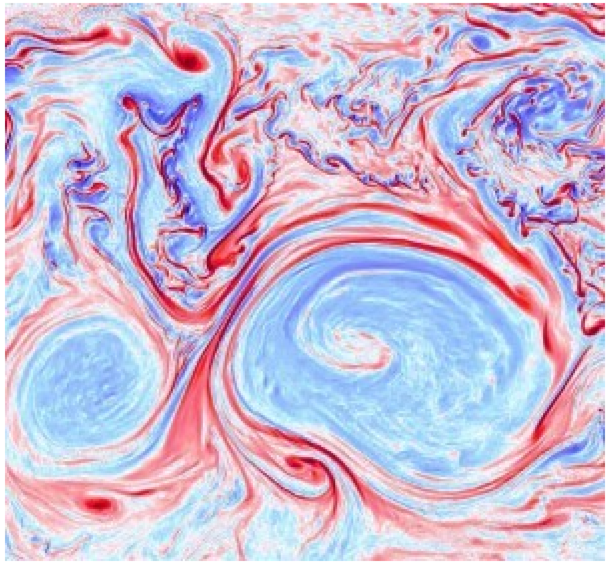
$Re \gg Re_c$

Turbulent mixing: very efficient heat transport

- Surface of the drop deforms and grows in area rapidly, due to turbulent flow fluctuations.

- Compared to transport by molecular diffusion, mixing by turbulent flows is thus able to enhance scalar transport by many orders of magnitude.

- Example: In a 1km thick atmospheric boundary layer, turbulent convection transfers heat at least **10^5 more efficiently(!)**



Helium

Huge helium discovery 'a life-saving find'

PUBLISHED

28 JUN 2016

A new approach to gas exploration has discovered a huge helium gas field, which could address the increasingly critical shortage of this vital yet rare element.

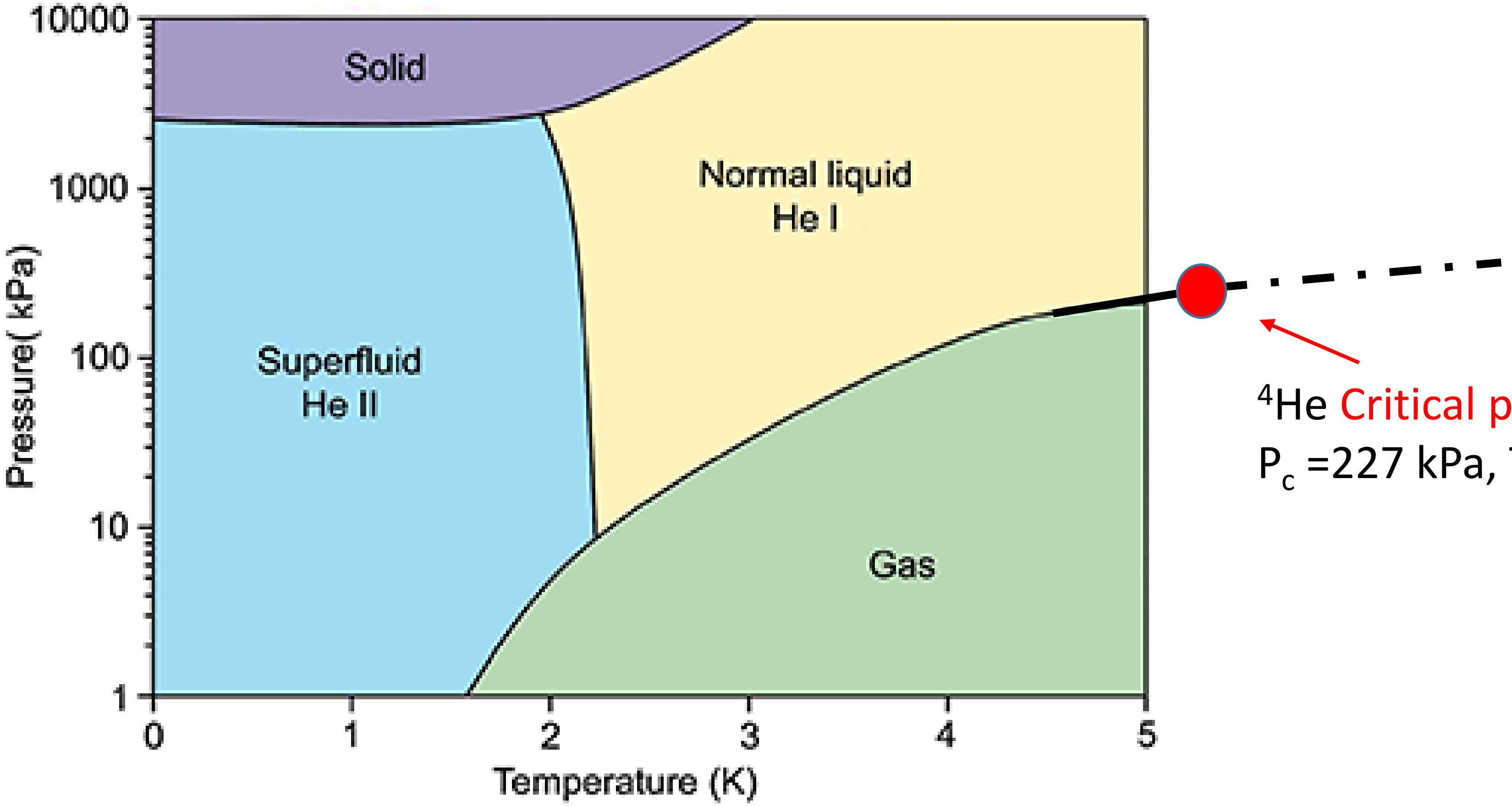
Helium ^{4}He: Three fluid phases

- **“Quantum flows”**

  in superfluid (He-II) phase

- **“Classical flows”**

  in liquid (He-I) and gaseous (GHe) phases



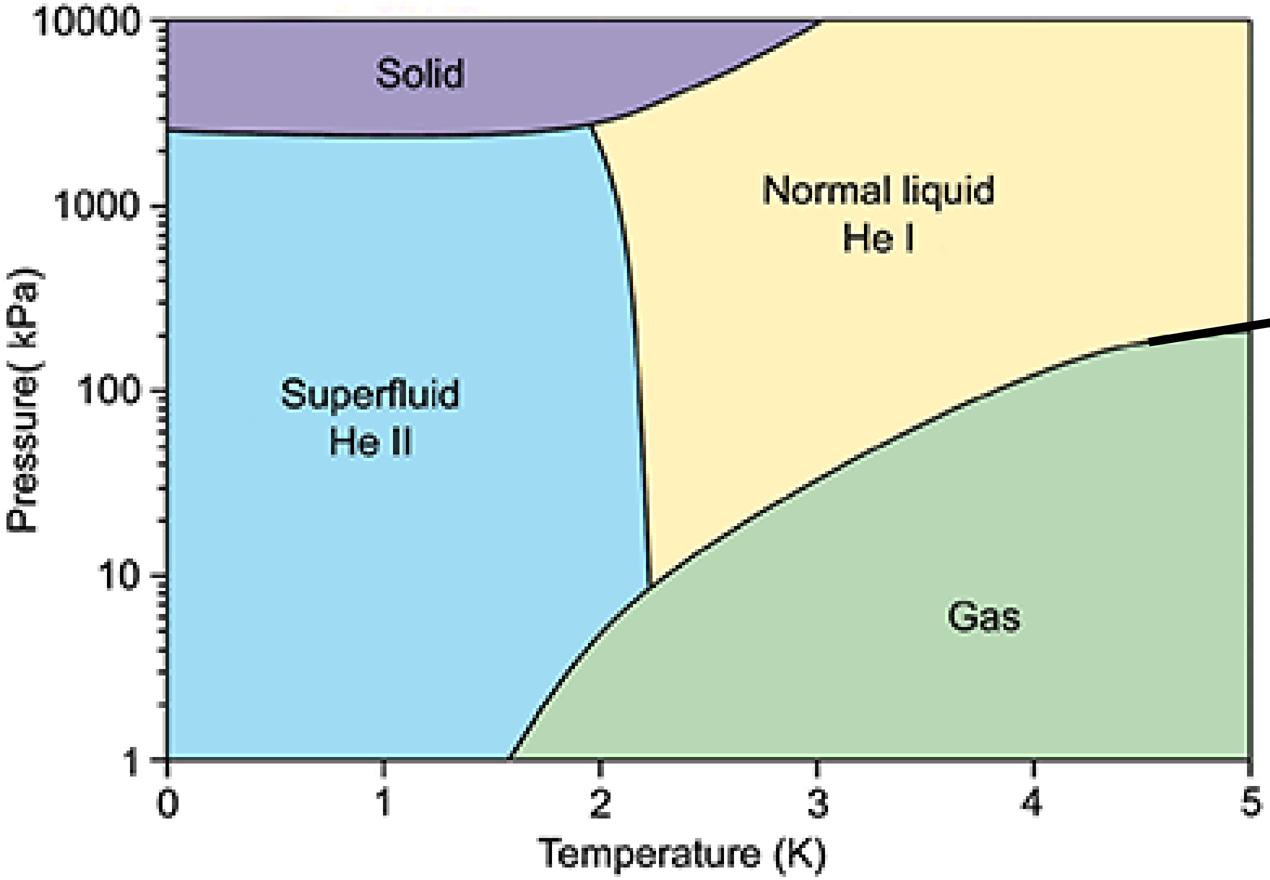
^{4}He Critical point (CP):

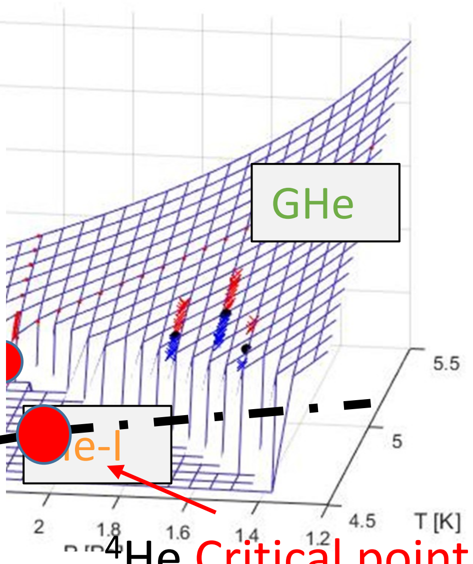
P_c =227 kPa, T_c = 5.20 K

Helium ^{4}He: Three fluid phases

- **<u>"Classical flows"</u>**

in liquid (He I) and gaseous (GHe) phases





^{4}He Critical point (CP):

P_c =227 kPa, T_c = 5.20 K

ar the critical point:

ematic viscosity $\nu \approx 10^{-8}$

pare: Air at T ~ 300K: 1.5E-5
Water at T ~ 300K: 1E-6

$\boxed{Re \sim 1/\nu}$ is high

Helium ^{4}He: Three fluid phases

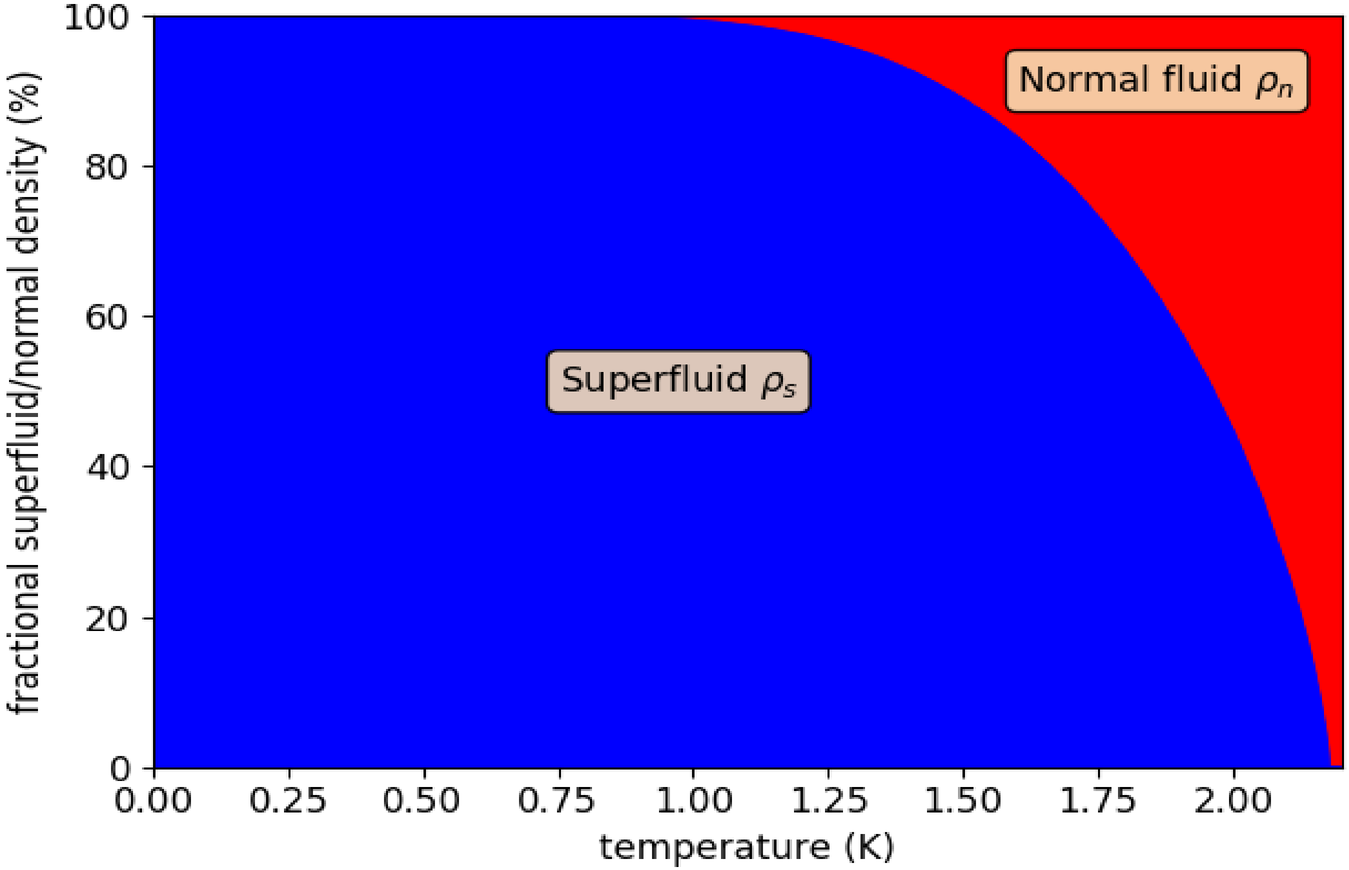
Superfluid Phase He-II ($T < T_\lambda \sim 2.2K$)

Does it mean that:

- $\nu \to 0$?
- $Re \to \infty$?

Actually NOT quite simply:

Two-fluid model of He-II (Tisza, Landau)

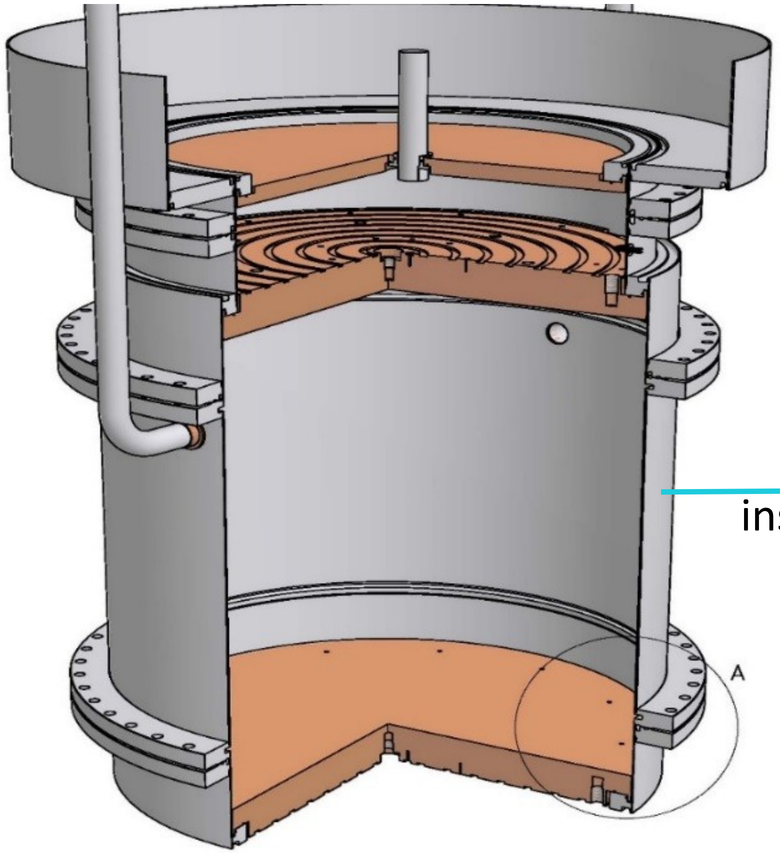


Cryogenics and Superconductivity group at ISI Brno

Long-time tradition in development and construction of cryogenic instruments for Basic Research:

Rayleigh Bénard convection (RBC) cell

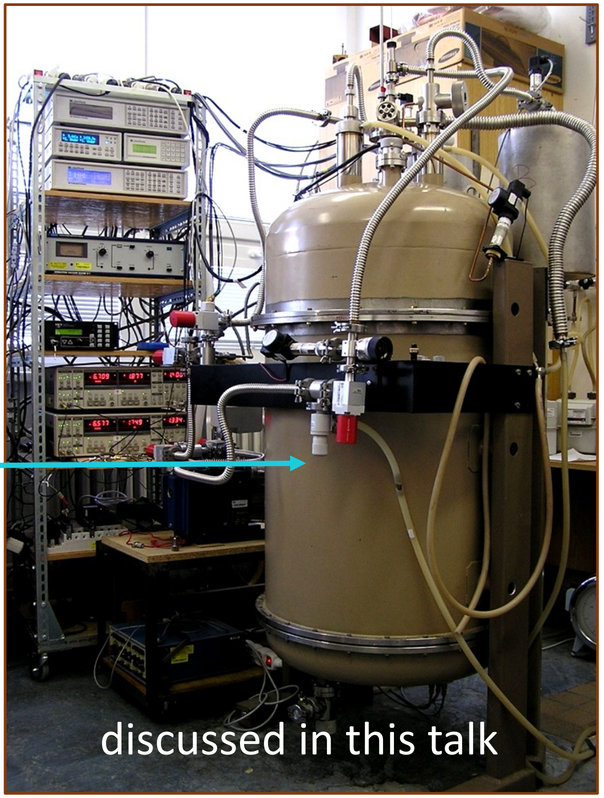
Size L = H = 30 cm



RBC cell
inside the cryostat

- Heat transport by Convection

ConEV apparatus (Convection Experimental Vessel)



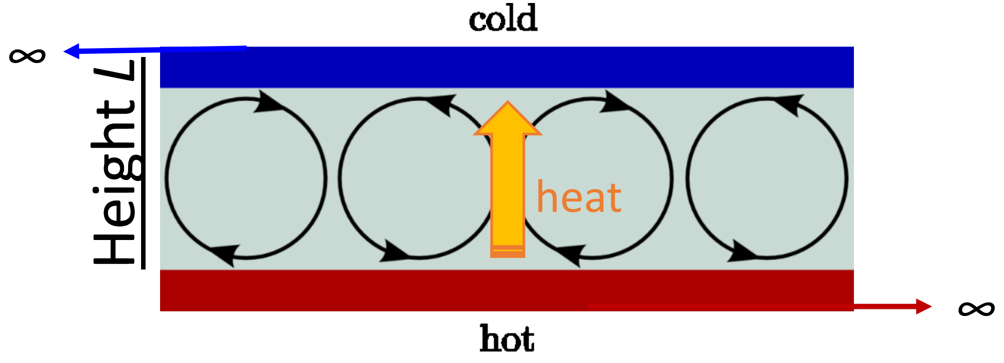
discussed in this talk

PRL **107** 014302 (2011),
PRL 109 154301 (2012),
PRL **110** 199402 (2013),
RSI **81** 085103 (2010),
PNAS **110** 8036 (2013),
JFM **785** 270 (2015),
JFM **832** 721 (2017),
PRE **99 (R)** 011101 (2019),
…

Rayleigh-Bénard model of convection

Finite Cell: Diameter *D*

$Ra \gtrsim Ra_c = 1708$



$$T_b = T_t + \Delta T$$

Oberbeck-Boussinesq (OB) fluid:

- constant **fluid properties** within ΔT:

α - thermal expansion coefficient
λ - fluid thermal conductivity
ν - kinematic viscosity
κ - thermal diffusivity

- density ρ is assumed to linearly depend on temperature T

Control parameters for RBC (adjustable):

Rayleigh number

Prandtl number

Aspect ratio

Order parameters for RBC (response of the system):

$$\boxed{Nu = \frac{Q_{\mathrm{turb}}}{Q_{\mathrm{cond}}}}$$

Nusselt number

$$\boxed{Re = \frac{UL}{\nu}}$$

Reynolds number

Ra, Pr, Nu, Re:
Dimensionless numbers related to intensity of turbulence

Equations a s

- Navier-Stokes equation = Newton equation for continuum - a viscous fluid with pressure and upward buoyancy forcing:

$$\left(\frac{\partial}{\partial t}+\boldsymbol{u}\cdot\nabla\right)\boldsymbol{u} = \nu\boldsymbol{\nabla}^2\boldsymbol{u} - \frac{1}{\rho_0}\nabla p + g\alpha\theta\hat{\boldsymbol{z}}$$

- Heat advection equation:

$$\left(\frac{\partial}{\partial t}+\boldsymbol{u}\cdot\nabla\right)\theta = \kappa\boldsymbol{\nabla}^2\theta$$

- Incompressibility condition:

$$\nabla\cdot\boldsymbol{u}=0$$

- Heat conduction: (Fourier's law)

$$Q_{\text{cond}} = \lambda\nabla\theta$$

"Boussinesq equations" of RBC

- Dynamical variables:

u - velocity field
θ - temperature field
p - pressure field

- Fluid properties: (considered constant!)

α - thermal expansion coefficient
ν - kinematic viscosity
κ - thermal diffusivity
λ - fluid thermal conductivity
ρ_0 - mean density
g - gravity acceleration

Equations and Scale-Similarity of solutions

"Non-dimensionalize" using
spatial, temporal, velocity, temperature and pressure scales:

$$t \rightarrow \frac{t}{T}, \boldsymbol{x} \rightarrow \frac{\boldsymbol{x}}{L},$$
$$\boldsymbol{v} \rightarrow \frac{\boldsymbol{v}}{U}, \theta \rightarrow \frac{\theta}{\Theta}, p \rightarrow \frac{p}{P}$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\nabla\right)\boldsymbol{u} = \sqrt{\frac{Pr}{Ra}}\boldsymbol{\nabla}^2\boldsymbol{u} - \nabla p + \theta\hat{\boldsymbol{z}}$$

$$\left(\frac{\partial}{\partial t} + \boldsymbol{u}\cdot\nabla\right)\theta = \frac{1}{\sqrt{RaPr}}\boldsymbol{\nabla}^2\theta$$

$$U = \sqrt{\alpha g \Delta\theta L}$$
$$T = \sqrt{L/\alpha g \Delta\theta}$$
$$\Theta = \Delta\theta \equiv T_b - T_t$$

Character of RBC solutions depends only on 2 essential parameters – *Ra* & *Pr* - instead of 5!

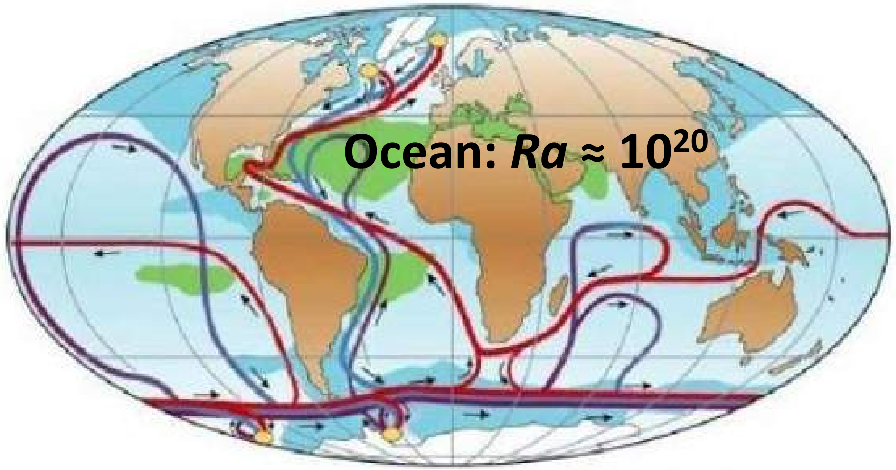
α ,ν, κ, ρ_0 (and g) ⟶ *Ra, Pr*

Large-scale Convection in Nature

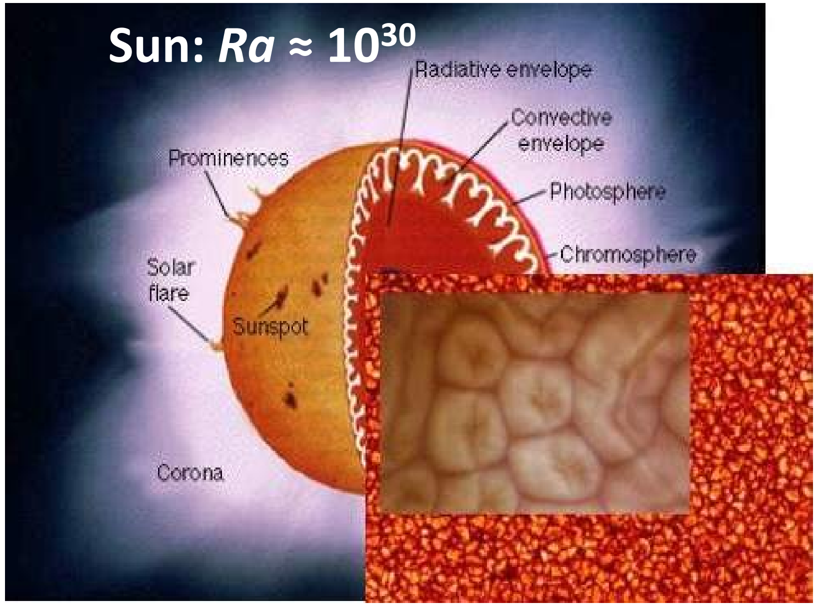
Natural convection often occurs on large scale distances ***L*** and thus is characterized by very high values of *Ra* number.

working fluid properties

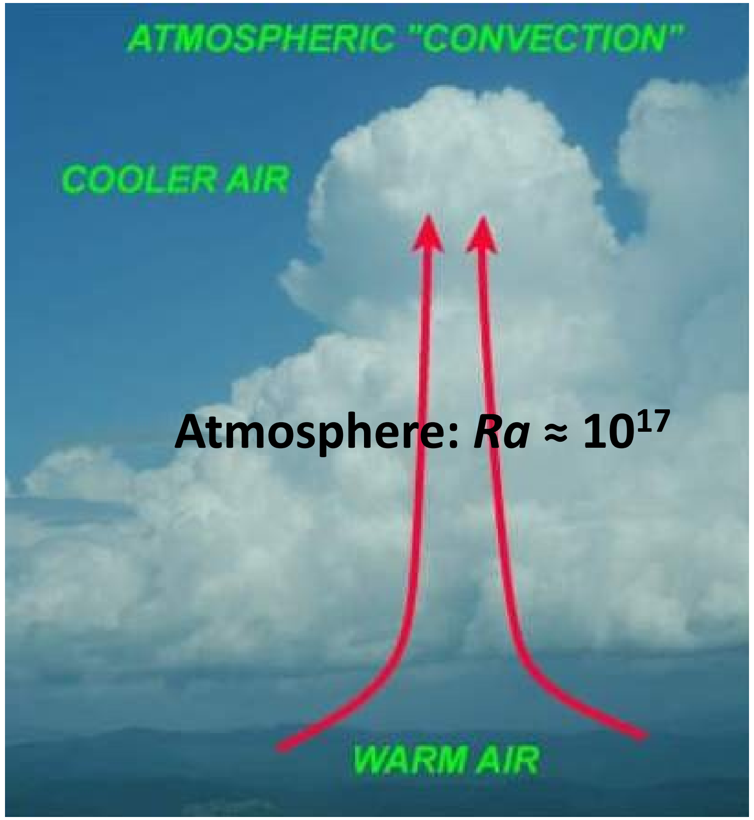
system size



Ocean: *Ra* ≈ 10^{20}



Sun: *Ra* ≈ 10^{30}



Atmosphere: *Ra* ≈ 10^{17}

Ra values attainable with different fluids

Examples	**Ra**
Atmosphere	$\approx 10^{17}$
Ocean	$\approx 10^{20}$
Laboratory	$\approx 10^{17}$
Computer	$\approx 10^{11}$

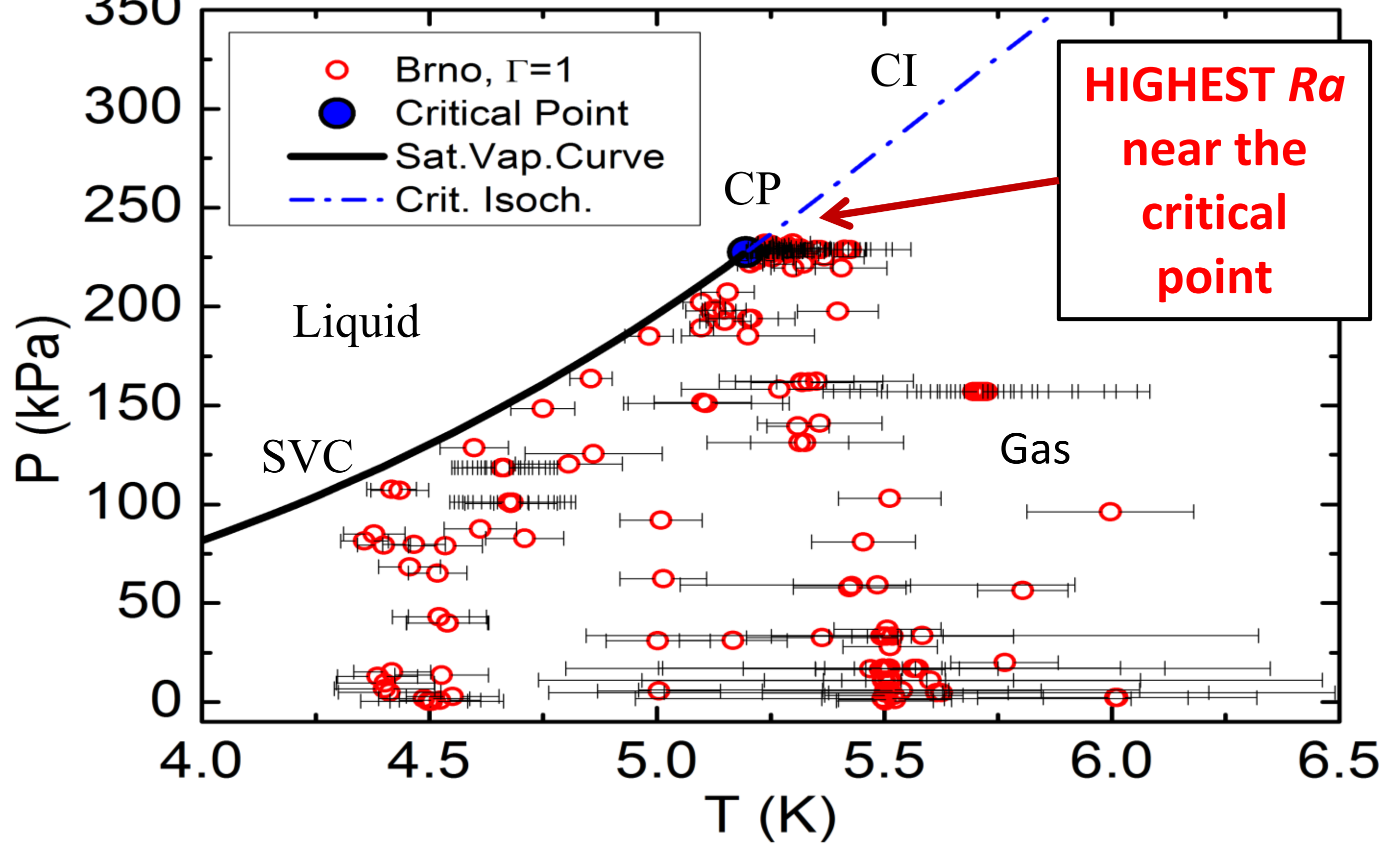
Laboratory experiments: high *Ra* at low *L*.

Fluid	**Temperature**	$\alpha/\nu\kappa$
Air	20 C	0.122
Water	20 C	14.4
Helium ^{4}He (gas)	5.5 K	$1.41\ \ 10^{8}$
Helium I (liquid)	2.25 K	$3.25\ \ 10^{-5}$

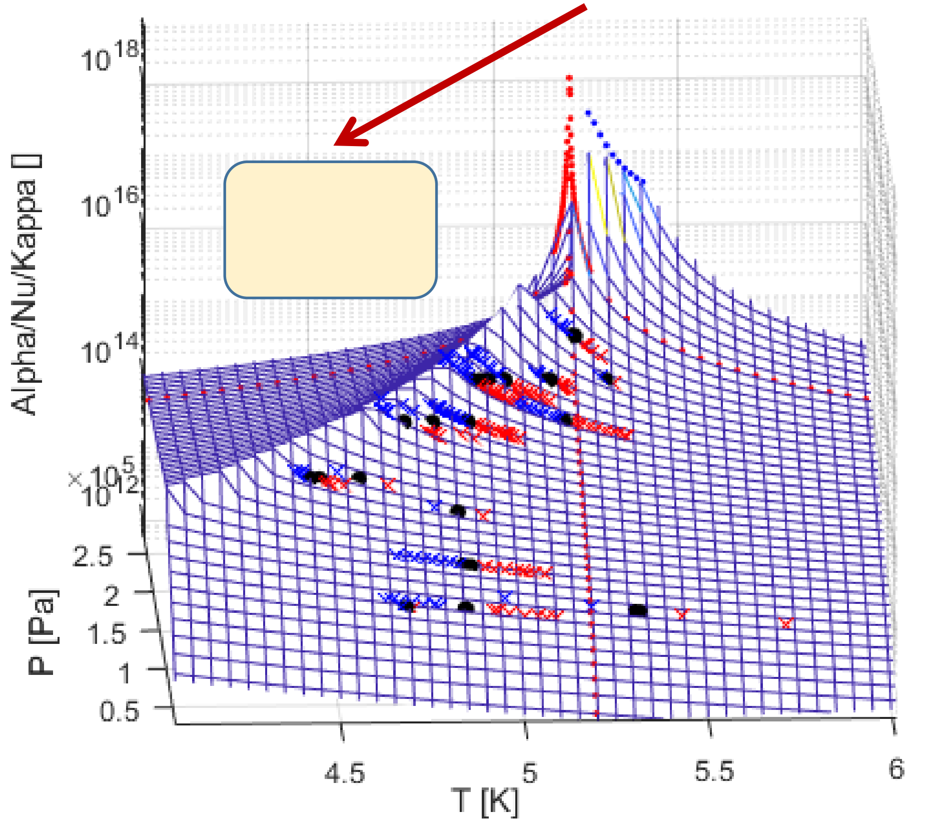
Rayleigh-Bénard Convection in ^{4}He

Brno cell L = 30 cm, Ra from 10^6 up to 10^{15}

^{4}He Critical point (CP): P_c =227 kPa, T_c = 5.20 K



HIGHEST *Ra* near the critical point

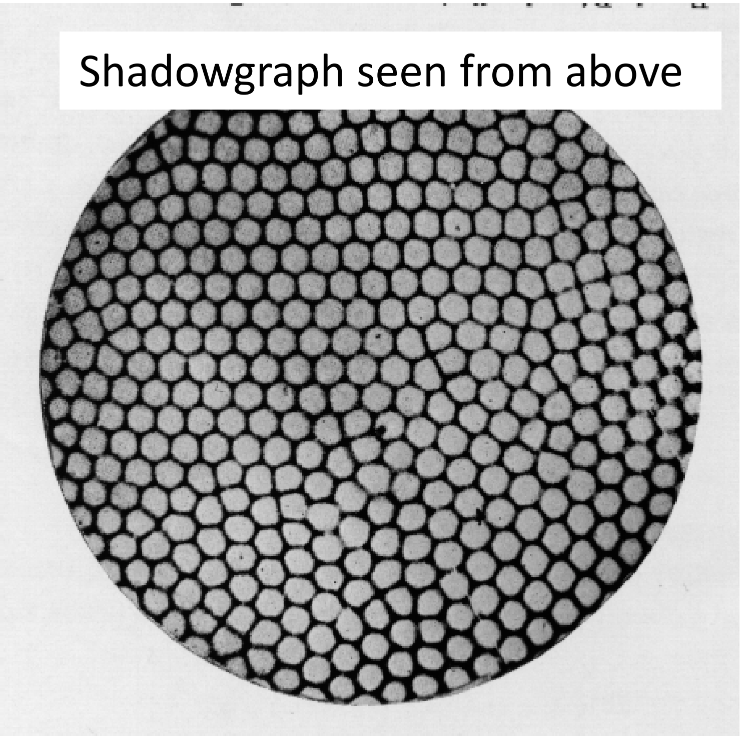


Other interesting regions besides CP:

1. Saturated Vapor Curve (SVC)
2. Critical Isochore (CI)

History
detour
#1:

Henri Benard (Ph.D. thesis, 1900)



Coherent structures / patterns observed in a fluid-filled pot heated from below

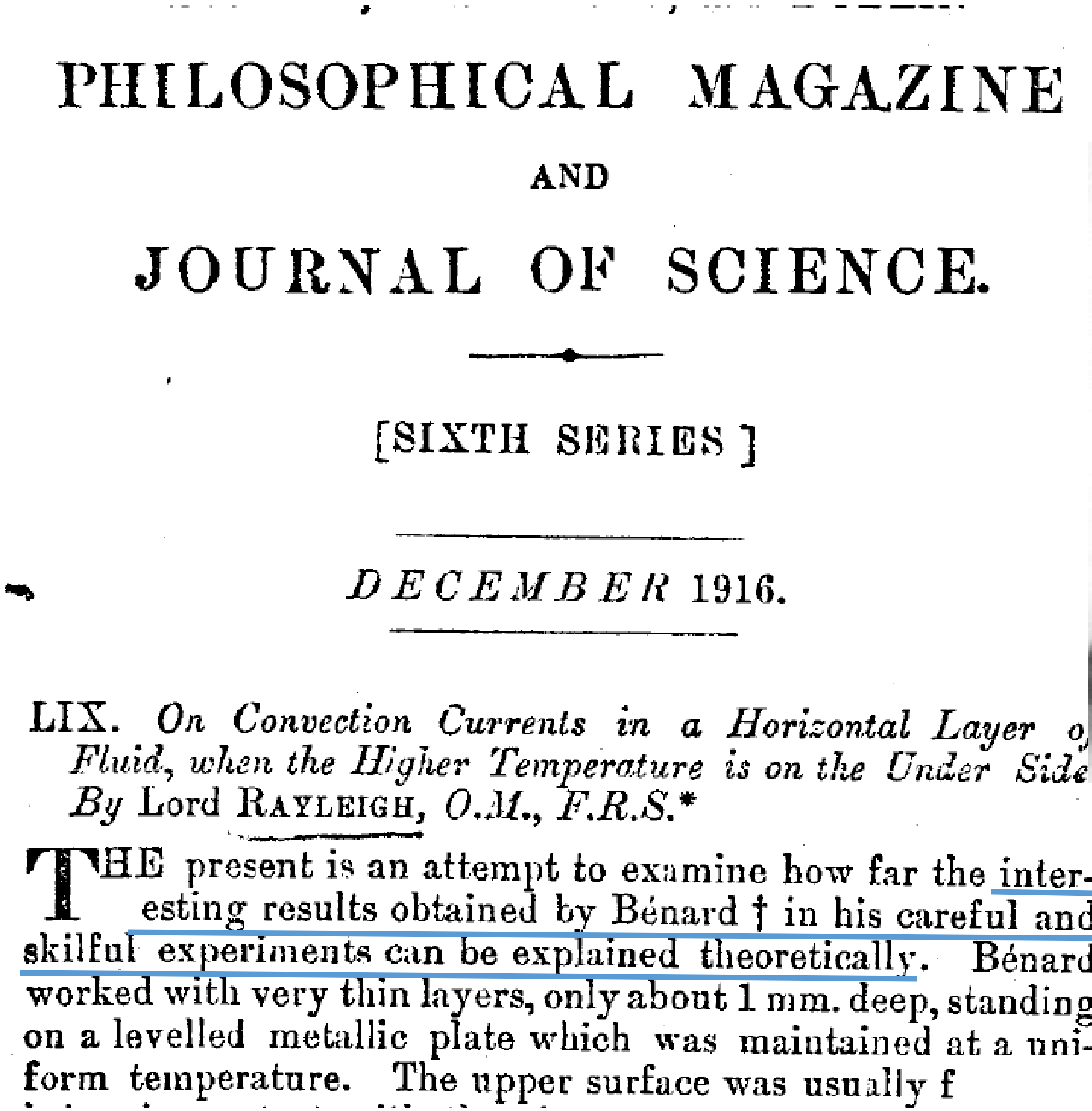
Carried out the first systematic and quantitative study of convection in a shallow layer heated from below, and studied the associated formation of convection **PATTERNS** systematically and quantitatively

E. Bouty : "*Bénard did not make any effort to provide general theoretical explanations …* ".

…it is not
as simple …

The report of the thesis committee stated "…. *though Bénard's main thesis was very peculiar, it did not bring significant elements to our knowledge. … the thesis should not to be considered as the best of what Bénard could produce.*"

History detour #2:



PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[SIXTH SERIES]

DECEMBER 1916.

LIX. *On Convection Currents in a Horizontal Layer o*
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. Bénard worked with very thin layers, only about 1 mm. deep, standing on a levelled metallic plate which was maintained at a uniform temperature. The upper surface was usually f

Lord Rayleigh

- Formulated eqations for system with ∞ plates
- Predicted critical value of the control parameter (now "Rayleigh number") for conduction - convection transition

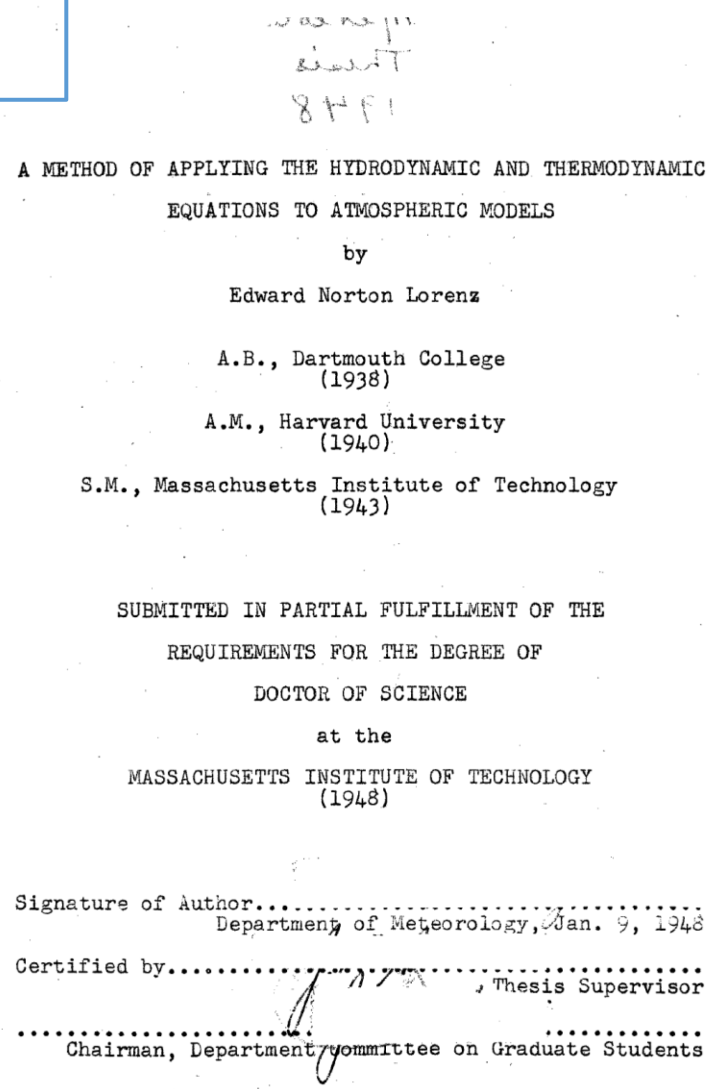
$Ra_c = 1708$

Experimentally confirmed with high accuracy

History
detour
#3:

Edward Lorer

ction



A METHOD OF APPLYING THE HYDRODYNAMIC AND THERMODYNAMIC
EQUATIONS TO ATMOSPHERIC MODELS

by

Edward Norton Lorenz

A.B., Dartmouth College
(1938)

A.M., Harvard University
(1940)

S.M., Massachusetts Institute of Technology
(1943)

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1948)

Signature of Author...
Department of Meteorology, Jan. 9, 1948

Certified by...
Thesis Supervisor

....
Chairman, Department Committee on Graduate Students

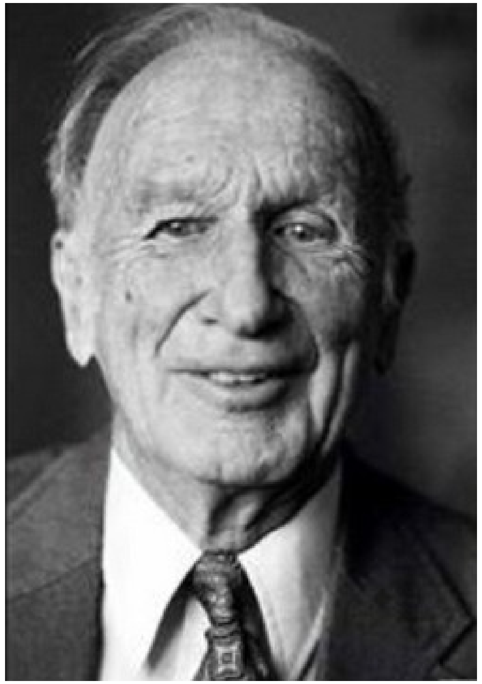
$$\frac{\mathrm{d}x}{\mathrm{d}t} = \sigma(y - x),$$

$$\frac{\mathrm{d}y}{\mathrm{d}t} = x(\rho - z) - y,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = xy - \beta z.$$

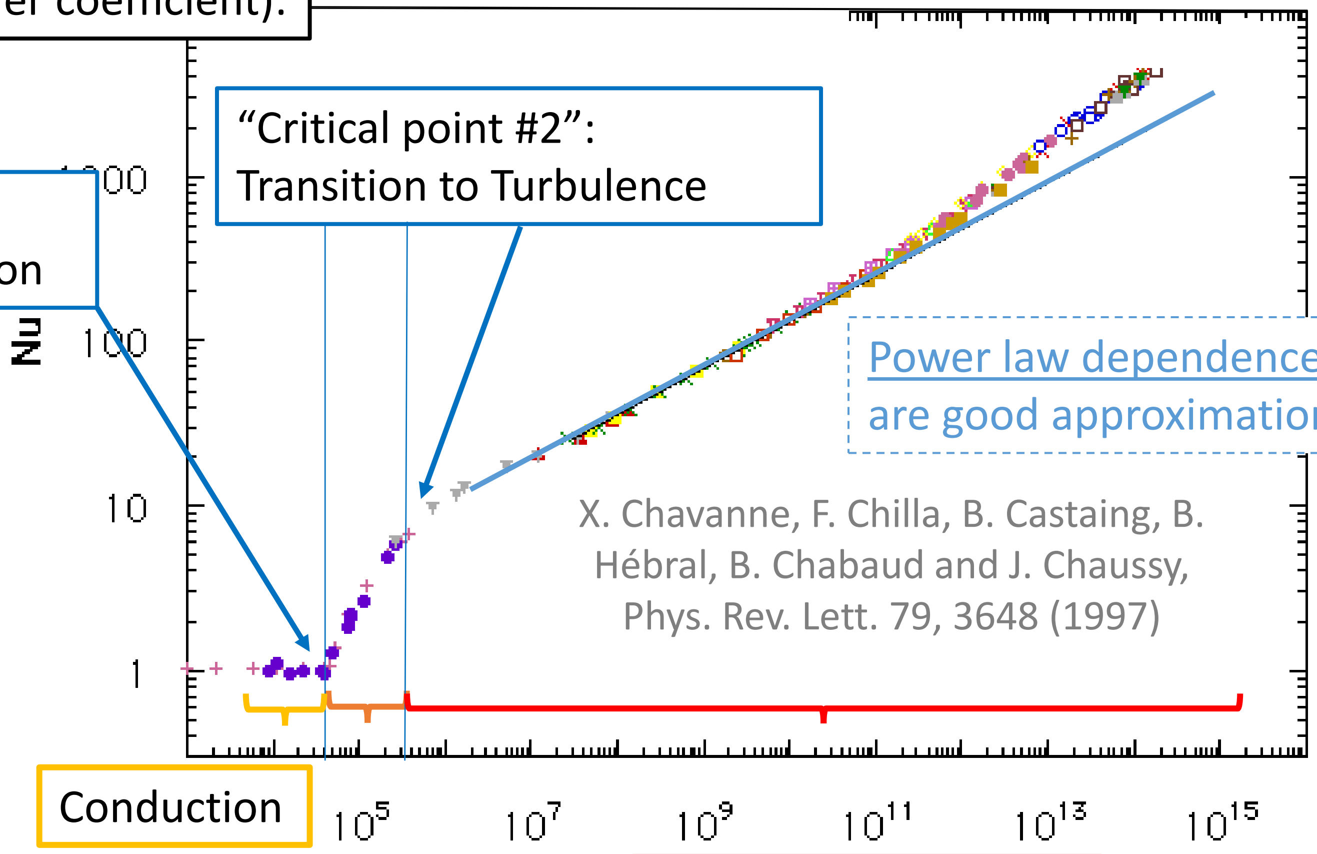
Simple 3D dynamical system derived from Boussinesq equations of RBC

“butterfly wing effect”
– sensitivity to initial conditions: deterministic chaos



Regimes of RBC: Heat Transport

Nusselt number *Nu*
(dimensionless heat transfer coefficient):



Critical point #1:
Onset of (laminar) Convection

"Critical point #2":
Transition to Turbulence

Power law dependences in turbulent regime(s) are good approximation

X. Chavanne, F. Chilla, B. Castaing, B. Hébral, B. Chabaud and J. Chaussy, Phys. Rev. Lett. 79, 3648 (1997)

Conduction

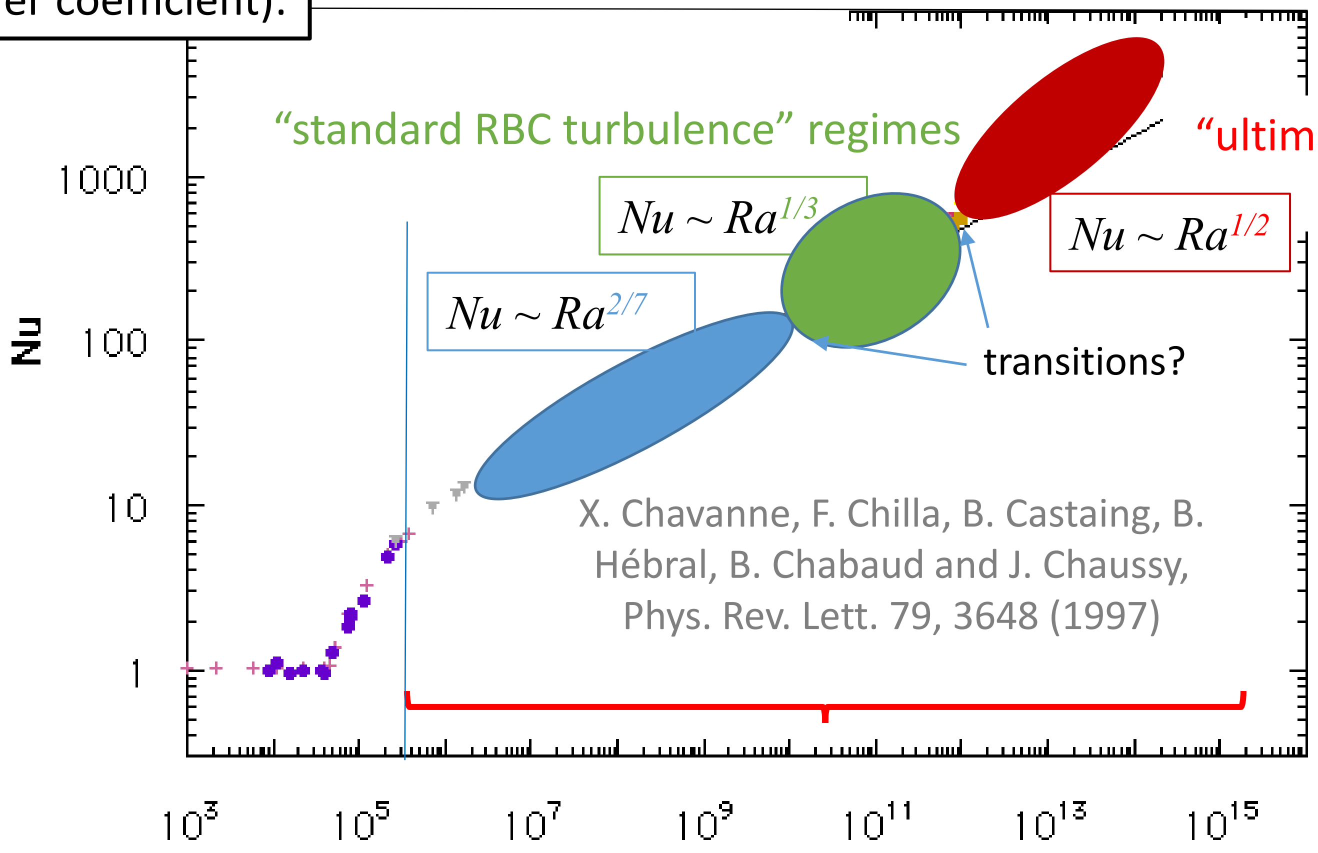
Laminar convection

Turbulent convection

Regimes of RBC: Heat Transport

Nusselt number *Nu*

(dimensionless heat transfer coefficient):



“standard RBC turbulence” regimes

$Nu \sim Ra^{2/7}$

$Nu \sim Ra^{1/3}$

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

“ultimate RBC turbulence” regime

transitions?

X. Chavanne, F. Chilla, B. Castaing, B. Hébral, B. Chabaud and J. Chaussy, Phys. Rev. Lett. 79, 3648 (1997)

Turbulent convection

Ultimate regime of heat transport in RBC

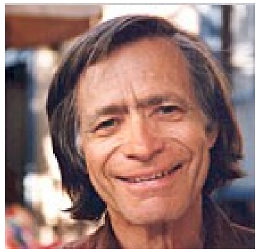
“Standard turbulent” RBC

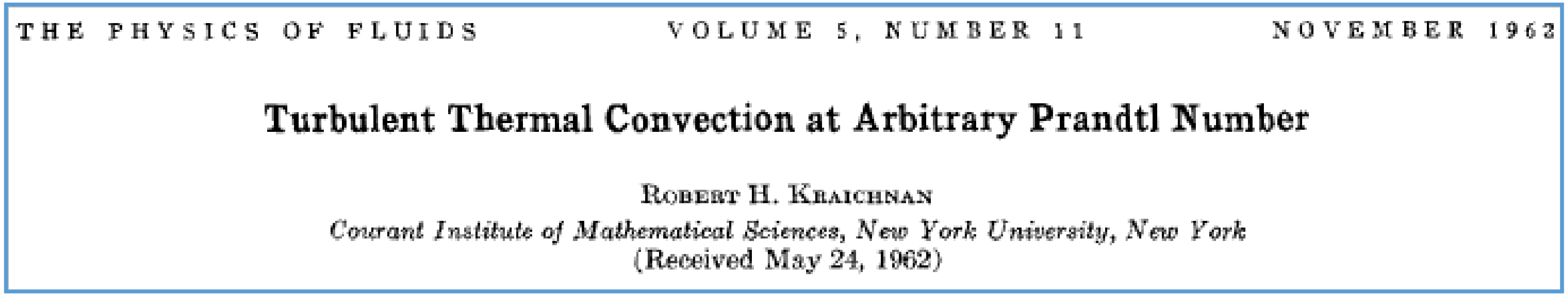
Malkus, Priestley, Spiegel (1954)

Shraiman and Siggia (1990)

laminar boundary layers (BL) + weak or no dependence on Pr

Ultimate / asymptotic turbulent RBC





THE PHYSICS OF FLUIDS VOLUME 5, NUMBER 11 NOVEMBER 1962

Turbulent Thermal Convection at Arbitrary Prandtl Number

Robert H. Kraichnan

Courant Institute of Mathematical Sciences, New York University, New York

(Received May 24, 1962)

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

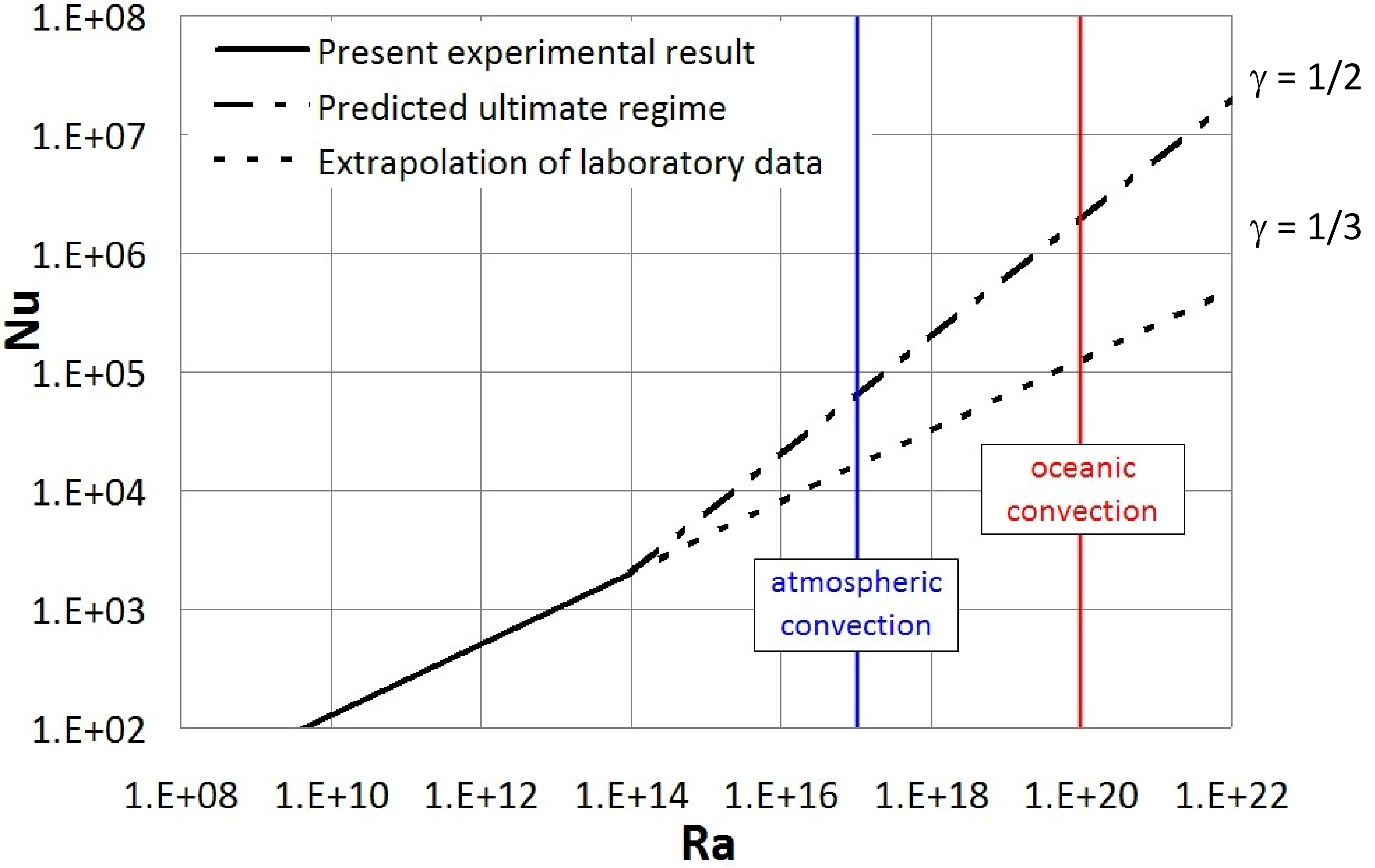
weak dependence on Pr

$Ra^* \approx 10^{21} - 10^{24}$

- fully turbulent boundary layers
- ballistic heat transfer independent of κ an ν

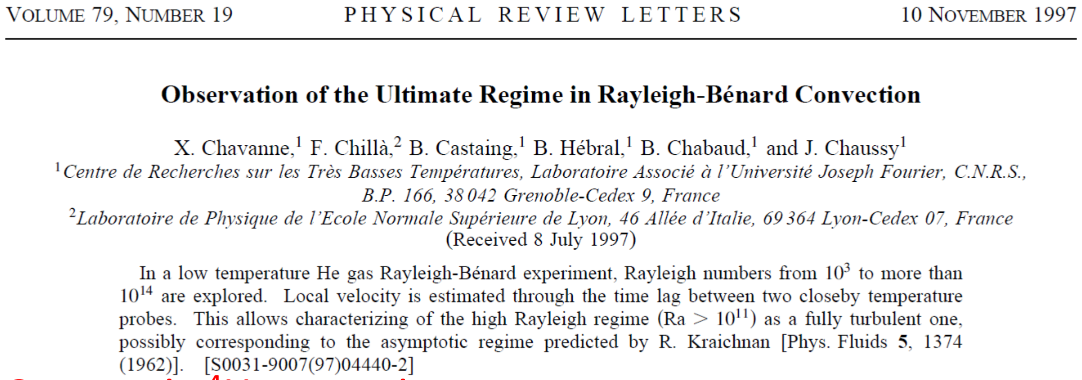
Extrapolations to large-scale flows?

exponents $\gamma = 1/3$ and $\gamma = 1/2$



Confirmation of existence of the ultimate regime is great challenge in this field of study!

OBSERVED...?



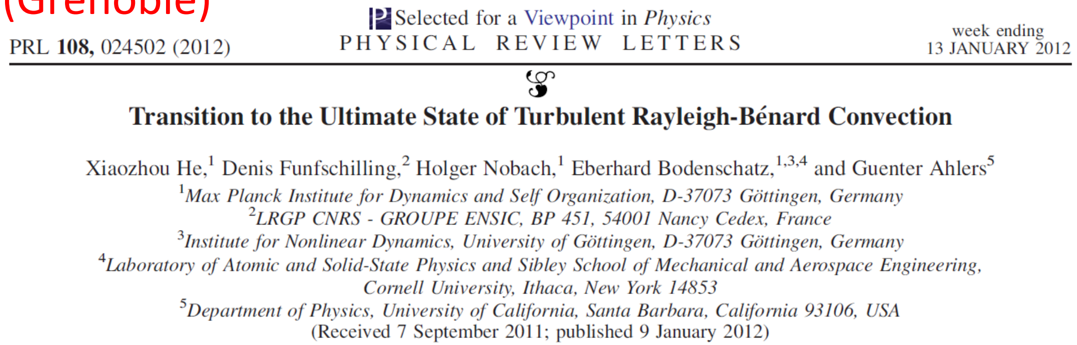
VOLUME 79, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1997

Observation of the Ultimate Regime in Rayleigh-Bénard Convection

X. Chavanne,[1] F. Chillà,[2] B. Castaing,[1] B. Hébral,[1] B. Chabaud,[1] and J. Chaussy[1]
[1]*Centre de Recherches sur les Très Basses Températures, Laboratoire Associé à l'Université Joseph Fourier, C.N.R.S., B.P. 166, 38 042 Grenoble-Cedex 9, France*
[2]*Laboratoire de Physique de l'Ecole Normale Supérieure de Lyon, 46 Allée d'Italie, 69 364 Lyon-Cedex 07, France*
(Received 8 July 1997)

In a low temperature He gas Rayleigh-Bénard experiment, Rayleigh numbers from 10^3 to more than 10^{14} are explored. Local velocity is estimated through the time lag between two closeby temperature probes. This allows characterizing of the high Rayleigh regime (Ra > 10^{11}) as a fully turbulent one, possibly corresponding to the asymptotic regime predicted by R. Kraichnan [Phys. Fluids **5**, 1374 (1962)]. [S0031-9007(97)04440-2]

Cryogenic ^{4}He experiment (Grenoble)



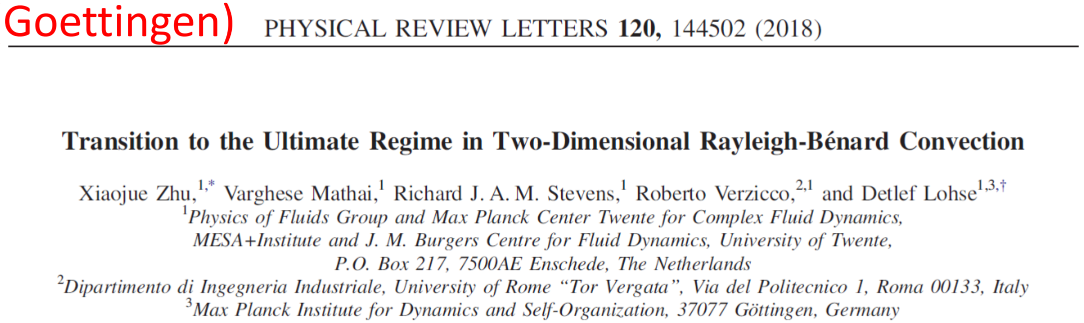
Selected for a Viewpoint in *Physics*

PRL **108,** 024502 (2012) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2012

Transition to the Ultimate State of Turbulent Rayleigh-Bénard Convection

Xiaozhou He,[1] Denis Funfschilling,[2] Holger Nobach,[1] Eberhard Bodenschatz,[1,3,4] and Guenter Ahlers[5]
[1]*Max Planck Institute for Dynamics and Self Organization, D-37073 Göttingen, Germany*
[2]*LRGP CNRS - GROUPE ENSIC, BP 451, 54001 Nancy Cedex, France*
[3]*Institute for Nonlinear Dynamics, University of Göttingen, D-37073 Göttingen, Germany*
[4]*Laboratory of Atomic and Solid-State Physics and Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York 14853*
[5]*Department of Physics, University of California, Santa Barbara, California 93106, USA*
(Received 7 September 2011; published 9 January 2012)

Room-temperature high-pressure SF$_6$ experiment (Goettingen)



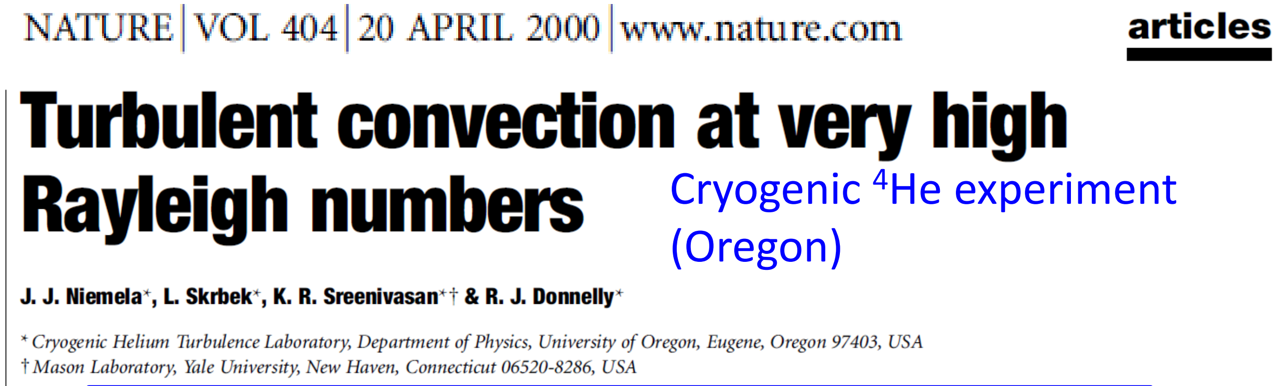
PHYSICAL REVIEW LETTERS **120,** 144502 (2018)

Transition to the Ultimate Regime in Two-Dimensional Rayleigh-Bénard Convection

Xiaojue Zhu,[1,*] Varghese Mathai,[1] Richard J. A. M. Stevens,[1] Roberto Verzicco,[2,1] and Detlef Lohse[1,3,†]
[1]*Physics of Fluids Group and Max Planck Center Twente for Complex Fluid Dynamics, MESA+Institute and J. M. Burgers Centre for Fluid Dynamics, University of Twente, P.O. Box 217, 7500AE Enschede, The Netherlands*
[2]*Dipartimento di Ingegneria Industriale, University of Rome "Tor Vergata", Via del Politecnico 1, Roma 00133, Italy*
[3]*Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany*

Numerical simulation in 2D (Twente, Rome, Goettingen)

NO...?



NATURE | VOL 404 | 20 APRIL 2000 | www.nature.com **articles**

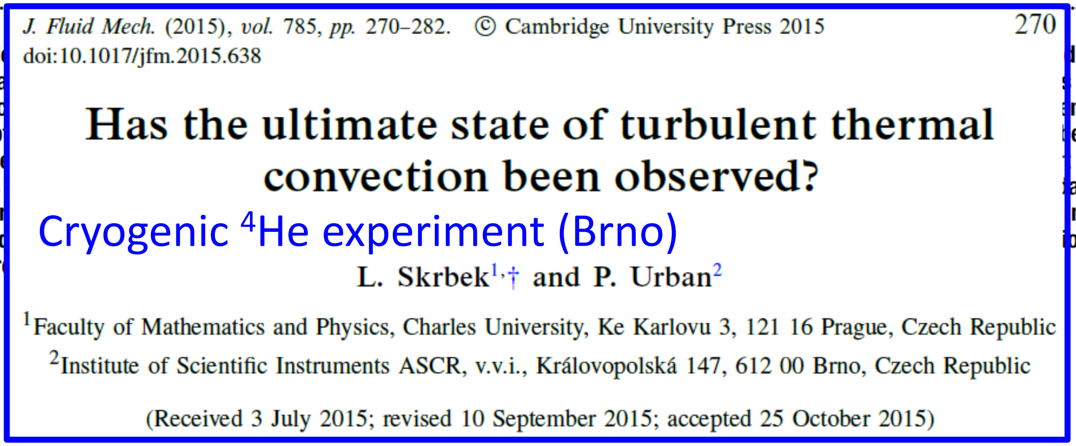
Turbulent convection at very high Rayleigh numbers

Cryogenic ^{4}He experiment (Oregon)

J. J. Niemela*, L. Skrbek*, K. R. Sreenivasan*† & R. J. Donnelly*
* *Cryogenic Helium Turbulence Laboratory, Department of Physics, University of Oregon, Eugene, Oregon 97403, USA*
† *Mason Laboratory, Yale University, New Haven, Connecticut 06520-8286, USA*

Turbul ... dissipa ... convec ... asymp ... repres ... orders ... entire ... we find ... and pr

driving to ... of turbulent ... nce of an ... er (Nu), ... over eleven ... ata, over the ... n particular, ... ons with Ra,



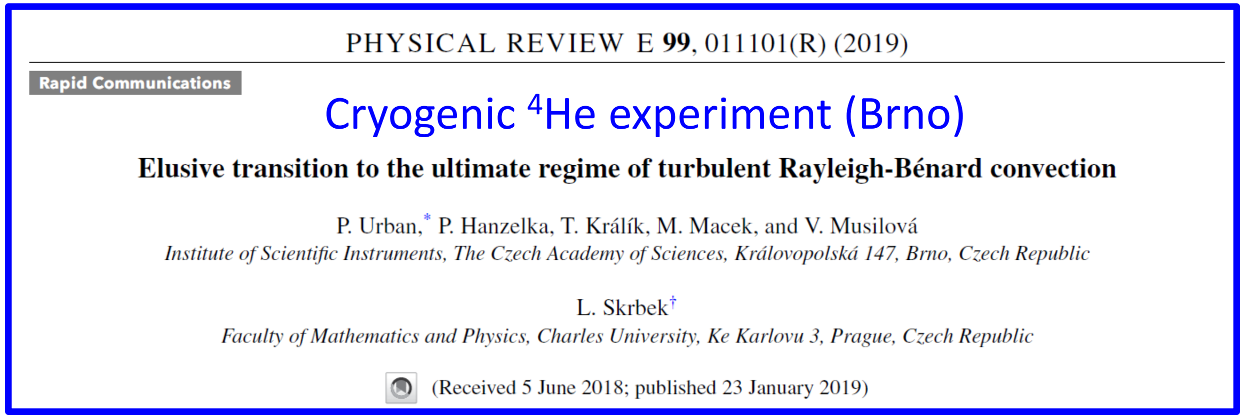
J. Fluid Mech. (2015), *vol.* 785, *pp.* 270–282. © Cambridge University Press 2015 270
doi:10.1017/jfm.2015.638

Has the ultimate state of turbulent thermal convection been observed?

Cryogenic ^{4}He experiment (Brno)

L. Skrbek[1,†] and P. Urban[2]
[1]Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Prague, Czech Republic
[2]Institute of Scientific Instruments ASCR, v.v.i., Královopolská 147, 612 00 Brno, Czech Republic

(Received 3 July 2015; revised 10 September 2015; accepted 25 October 2015)



PHYSICAL REVIEW E **99**, 011101(R) (2019)

Rapid Communications

Cryogenic ^{4}He experiment (Brno)

Elusive transition to the ultimate regime of turbulent Rayleigh-Bénard convection

P. Urban,* P. Hanzelka, T. Králík, M. Macek, and V. Musilová
Institute of Scientific Instruments, The Czech Academy of Sciences, Královopolská 147, Brno, Czech Republic

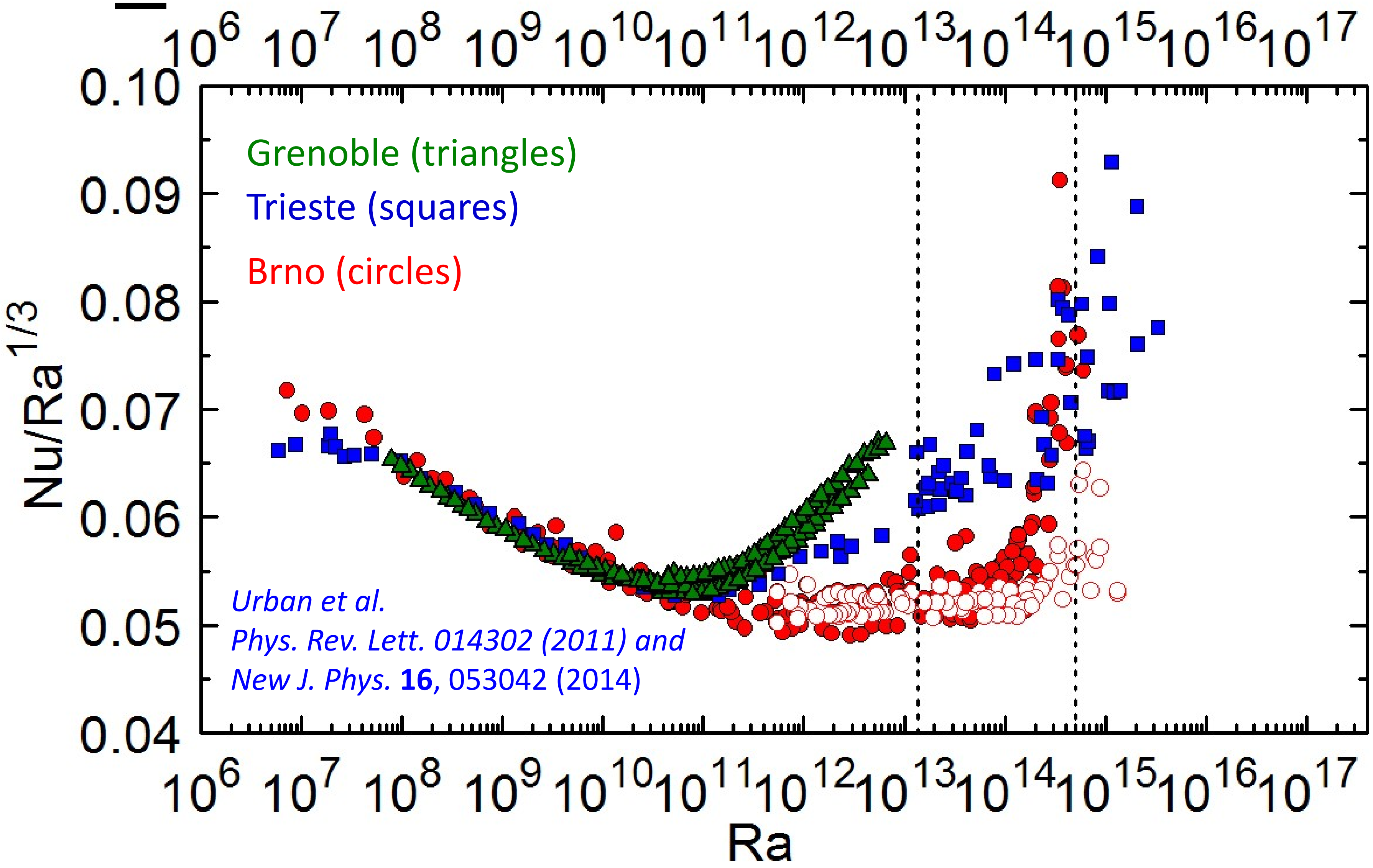
L. Skrbek†
Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, Prague, Czech Republic

(Received 5 June 2018; published 23 January 2019)

OBSERVED…? NO…?

Cryogenic Experiments with aspect ratio $\Gamma = 1$:

Nusselt no. reduced by $Ra^{1/3}$

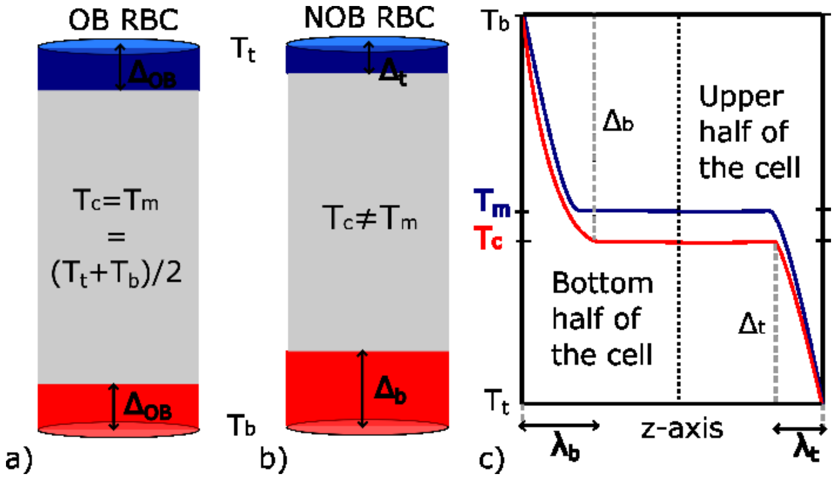


Urban et al.
Phys. Rev. Lett. 014302 (2011) and
New J. Phys. **16**, 053042 (2014)

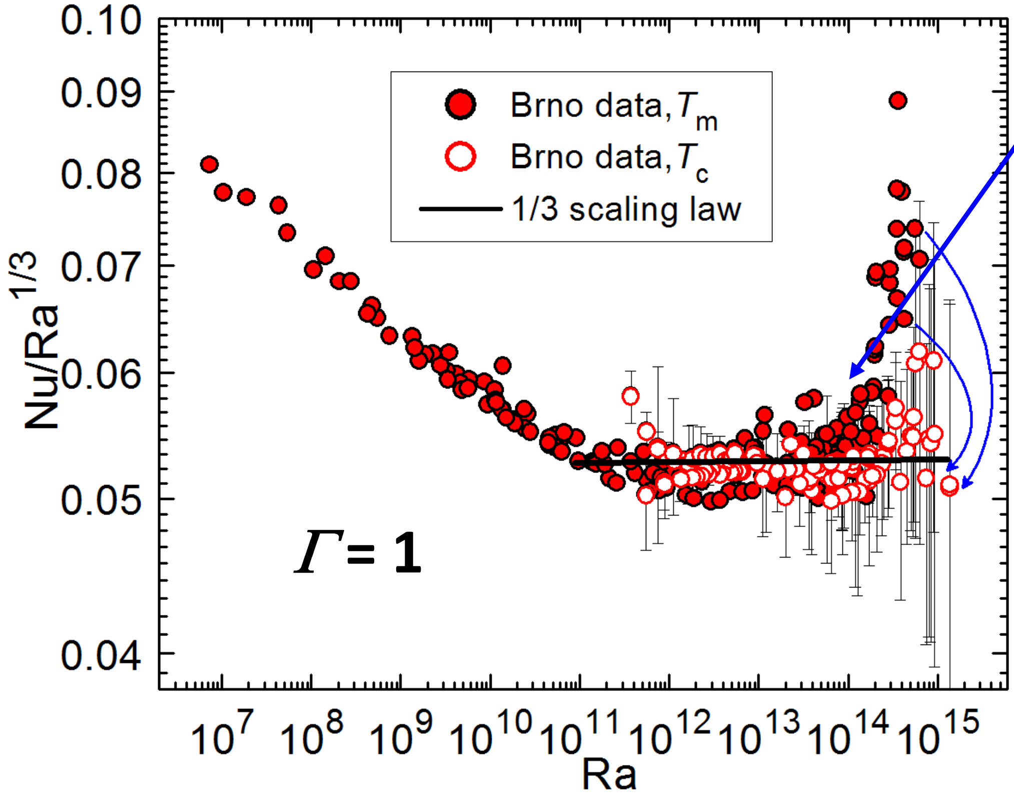
Transitions observed at ISI Brno:

1. Transition at Ra >~ 10^{14}: Ultimate regime transition or NOB effects ?
2. Transition at Ra~ 10^{10}-10^{11}: ?

NOB: $T_m \neq T_c$: BL asymmetry

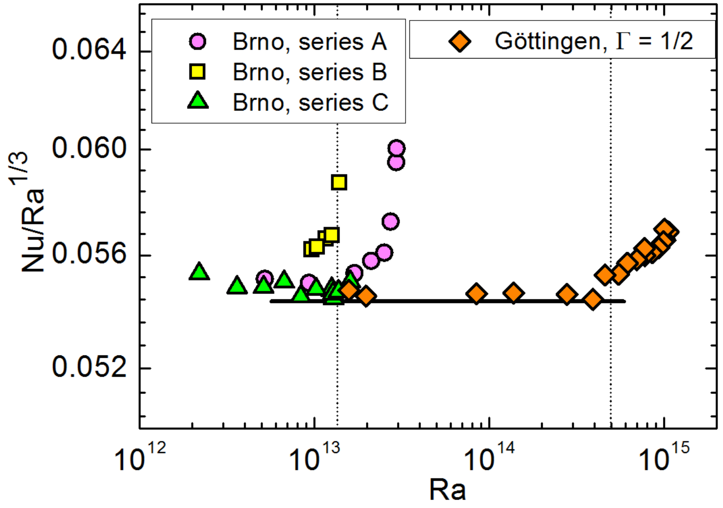


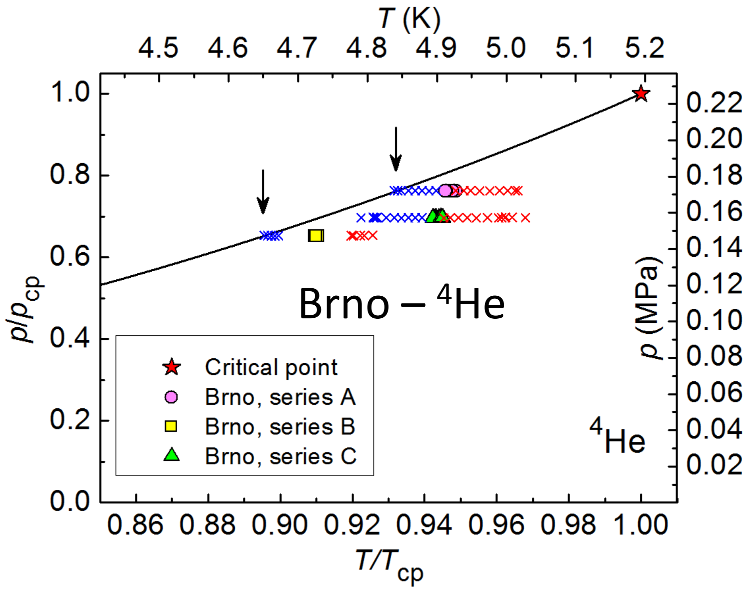
J.Drahotský, P. Hanzelka, V. Musilová, MM, R. du Puits and P. Urban
EPJ Conf S. ***180****, 02020 (2018)*

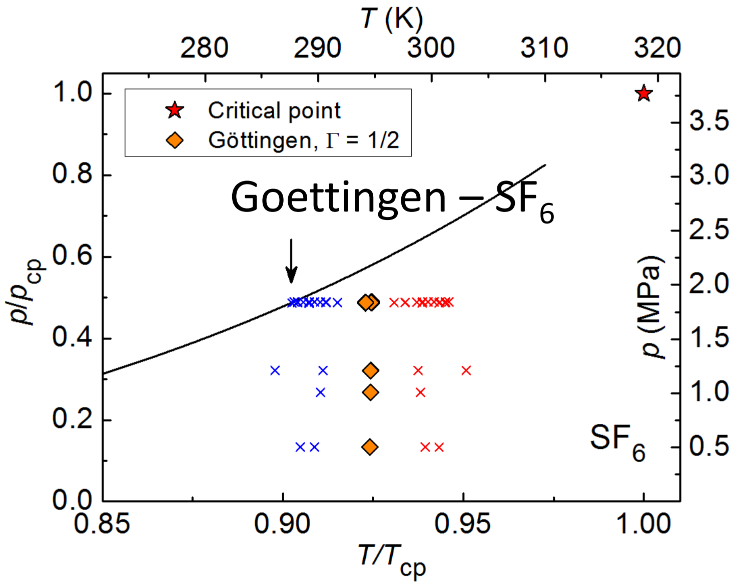


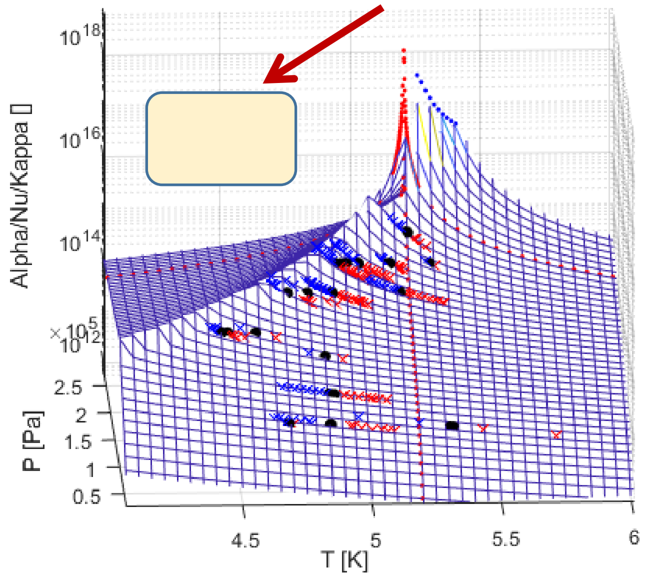
NOB effects
near the
Critical Point
of ^{4}He

P. Urban, P. Hanzelka, T. Kralik, V. Musilova, A. Srnka and L. Skrbek,
Phys. Rev. Lett. ***109****, 154301 (2012).*
P. Urban, P. Hanzelka, T. Králík, MM, V. Musilová, L. Skrbek
Phys. Rev. E ***99****, 011101 (R) (2019).*

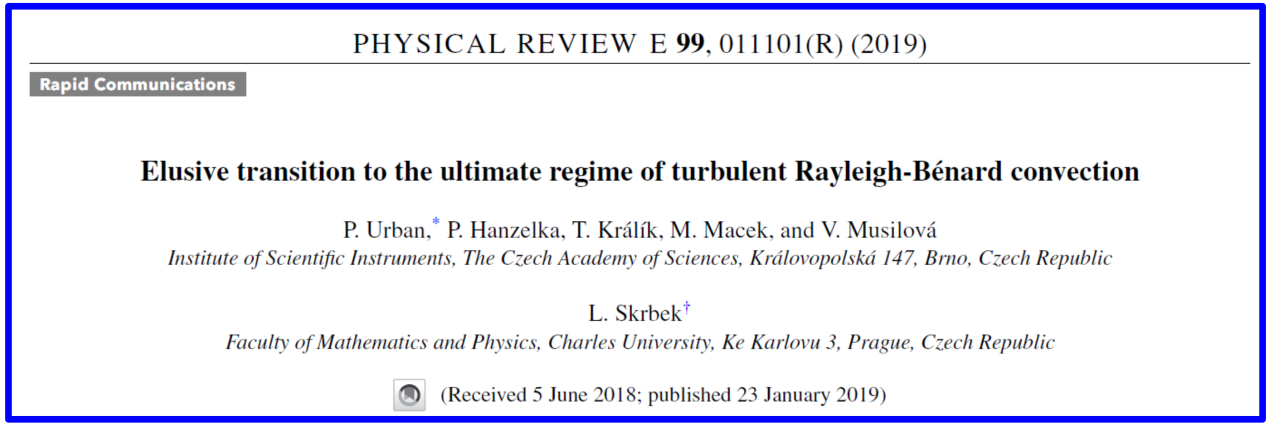








NOB effects
near the
Saturation Curves of
^{4}He and SF$_6$


PHYSICAL REVIEW E **99**, 011101(R) (2019)

Rapid Communications

Elusive transition to the ultimate regime of turbulent Rayleigh-Bénard convection

P. Urban,[*] P. Hanzelka, T. Králík, M. Macek, and V. Musilová
Institute of Scientific Instruments, The Czech Academy of Sciences, Královopolská 147, Brno, Czech Republic

L. Skrbek[†]
Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, Prague, Czech Republic

(Received 5 June 2018; published 23 January 2019)

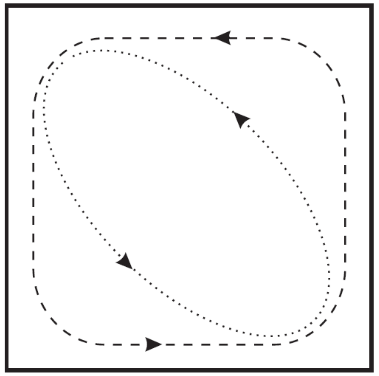
Transitions observed at ISI Brno:

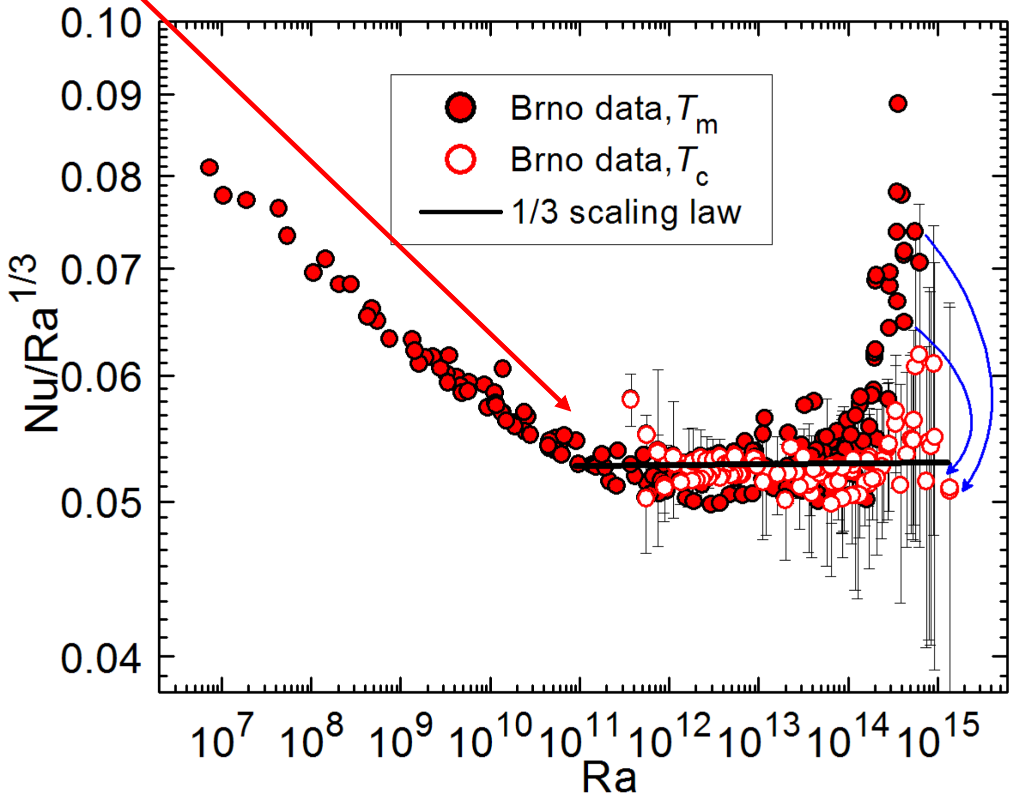
1. Transition at Ra >~ 10^{14}: Ultimate regime transition or NOB effects ?

2. Transition at Ra~ 10^{10}-10^{11}: ?

Transition: $Nu \sim Ra^{2/7}$ - $Ra^{1/3}$

Change in shape of the coherent flow structure - the mean wind

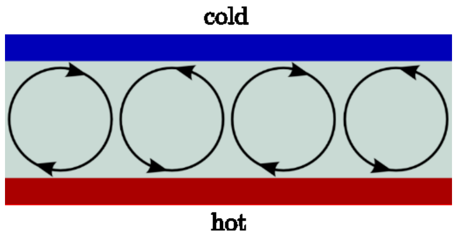




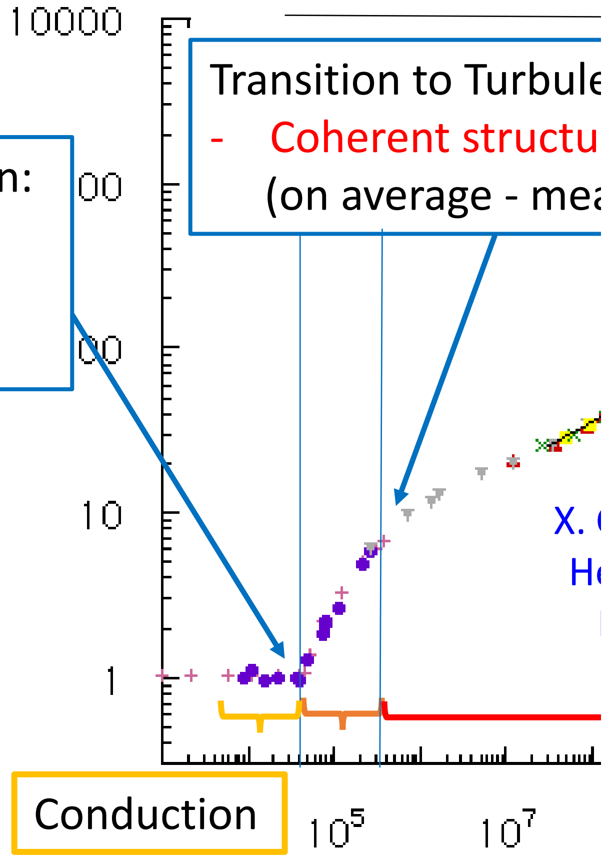
V. Musilová, T. Králík, M. La Mantia, MM., P. Urban, L. Skrbek.
J. Fluid. Mech. 832, 721 – 744 (2017).

Regimes of RBC: Coherent structures

Onset of (laminar) Convection:
- Different forms of coherent structures seen (Pattern formation)



Regimes near onset of convection:
Studied in cells with Γ >> 1.



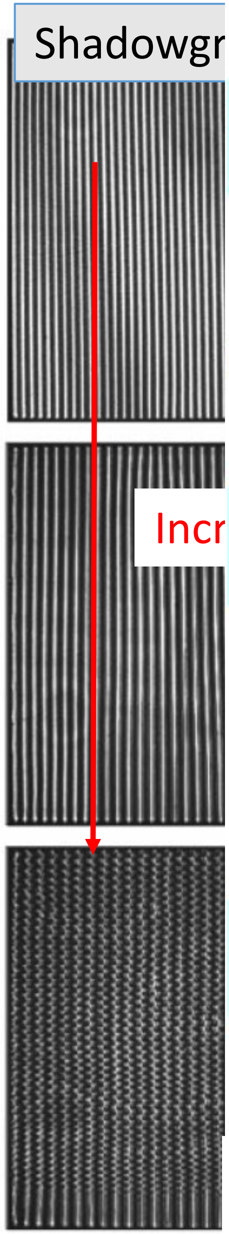
Transition to Turbule
- Coherent structu
(on average - mea

Conduction

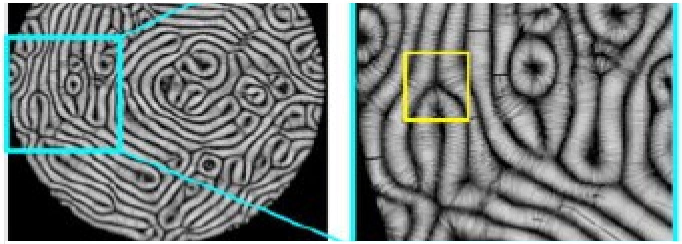
Laminar convection

Figure 5 (a) ISR and (b) SDC at ε = 0.92; (c) ISR at ε = 2.99 and (d) SDC at ε = 3.0; (e) oscillatory ISR and (f) oscillatory SDC at ε = 5.08. For this experiment Γ = 50 and σ = 1.03. For each pair of pictures only the initial conditions were different. The insets show a magnified view of the oscillating rolls. Whereas in (e) the oscillations travel from bottom to top, in (f) the oscillations are very disordered. Often rotating spoke pattern are found, as seen in the insert of (f). From Cakmur et al (1997a).

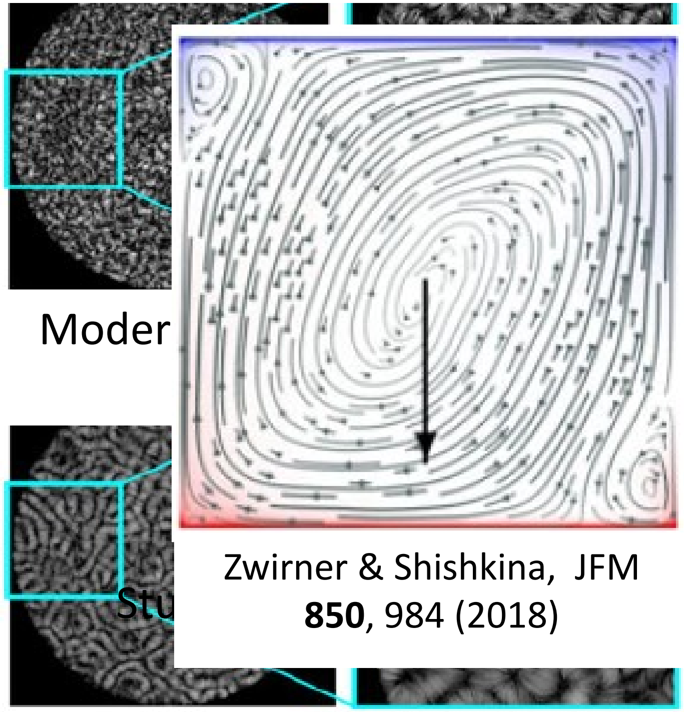
Adapted from Bodenschatz et al., Annu.Re.Fluid.Mech (2000)



Low Ra - instant. snapshot
(spiral defect chaos - SDC)



Moderate Ra - instant. snapshot
(disorder, strong fluctuations)



Zwirner & Shishkina, JFM **850**, 984 (2018)

Emran, Schumacher, JFM **776**, 96 (2015)
MM, Schumacher, in preparation

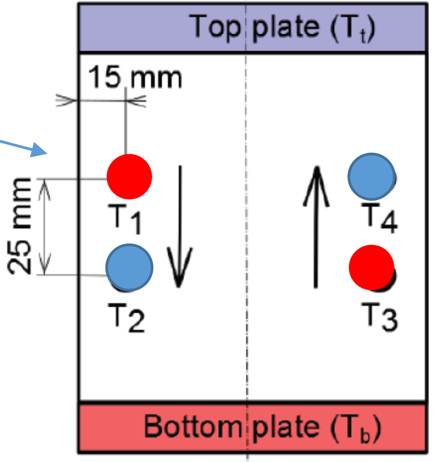
Reynolds measurements at ISI Brno: Temperature fluctuations in the turbulent bulk

Four small cubic Ge thermistors ($T_1 – T_4$) near sidewalls

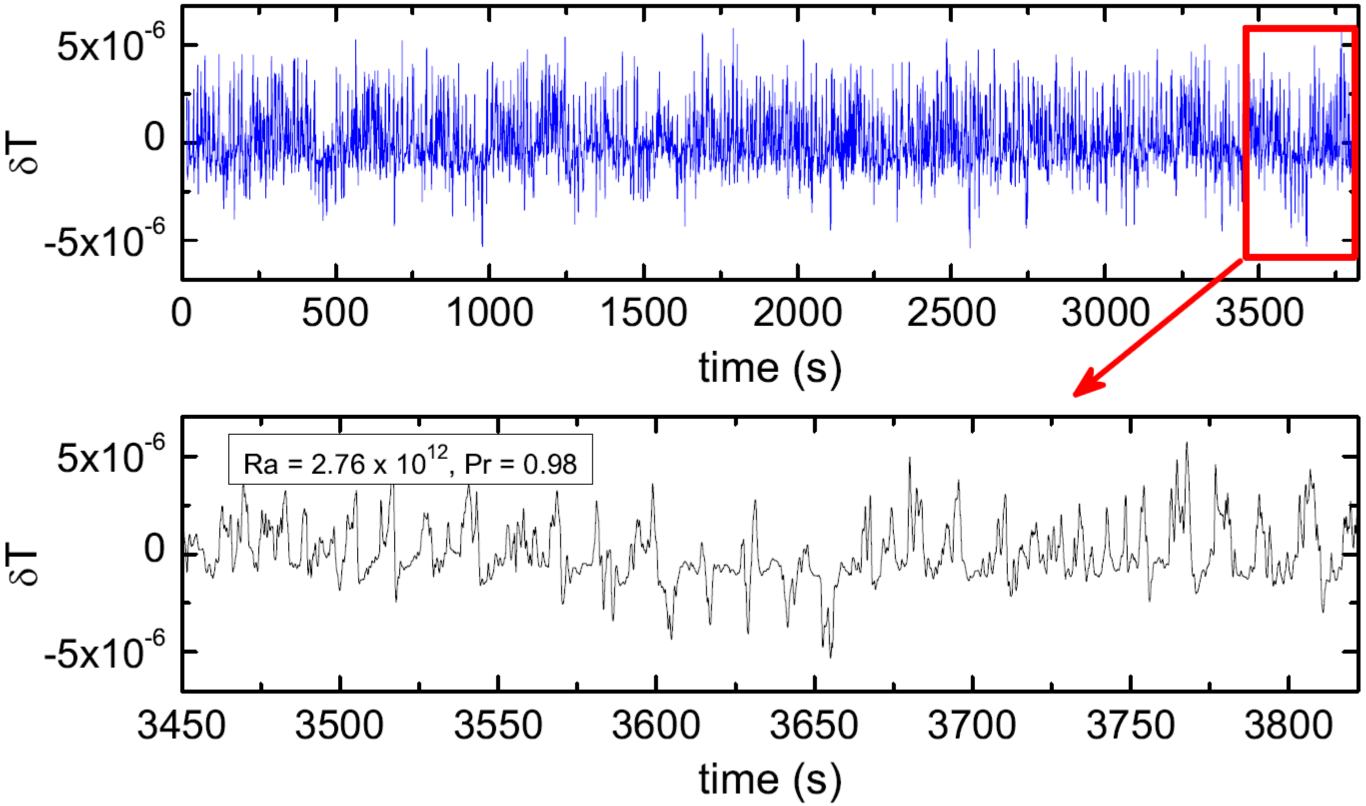
with respect to LSC direction:

T_1, T_3 – “leading sensors”

T_2, T_4 – “trailing sensors”



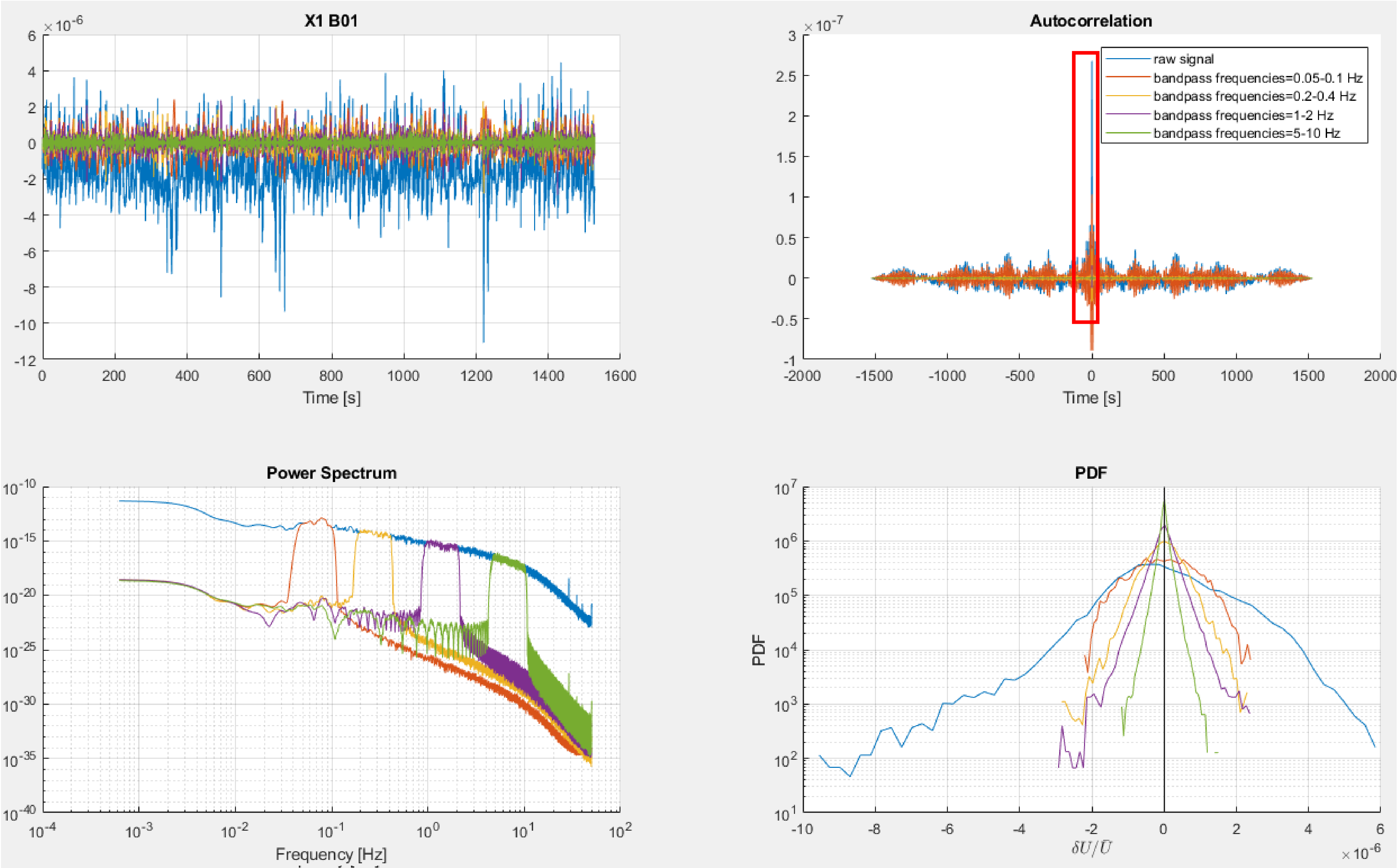
Temperature fluctuations time series (δT ~ 1mK)



Statistical analysis (see next slide)

- Temperature fluctuations PDFs
  (in turbulence: non-Gaussian, heavy tails, rare events)
- Power spectra
  (in turbulence: broad due to “Richardson cascade” transferring energy over wide range of scales)
- Auto- and Cross-correlations
  (Fourier transform of spectra)
- Reynolds numbers (different types)

Temperature fluctuations in the turbulent bulk



Reynolds numbers (one-point measurements)

One-point measurements:

- Frequency Reynolds number

$$\boxed{Re_{f0} = 2\frac{L^2 f_0}{\nu}}$$

Brno data fitted by a two-fold power law

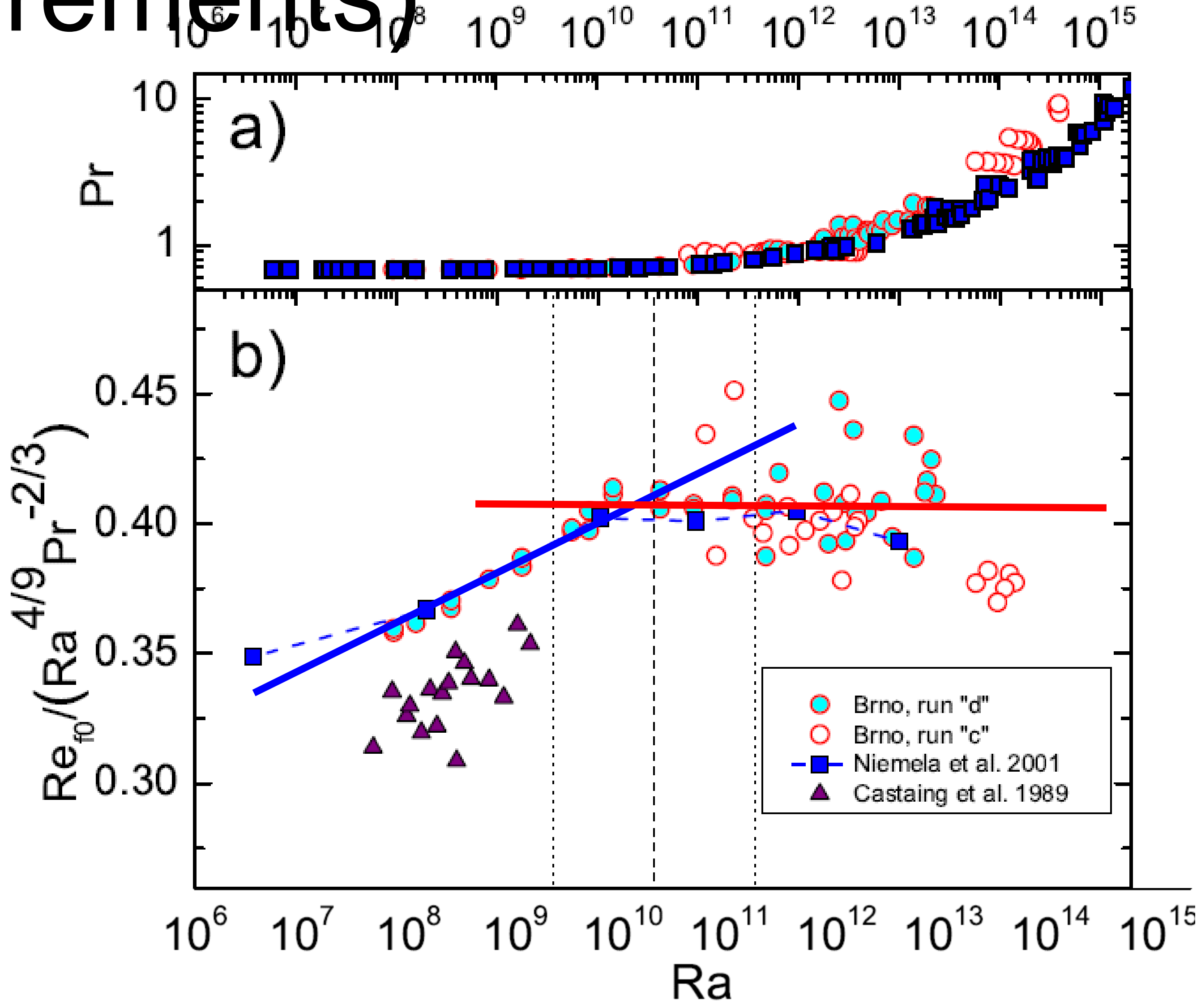
$$Re = \boxed{Ra^{\zeta}} Pr^{-2/3}$$

where

🟦 or 🟥

above / below the **transition point**

Ra = Ra$_c$



V. Musilová, T. Králík, M. La Mantia, MM., P. Urban, L. Skrbek.
J. Fluid. Mech. 832, 721 – 744 (2017).

Reynolds numbers (two-point measurements)

Two-point measurements:

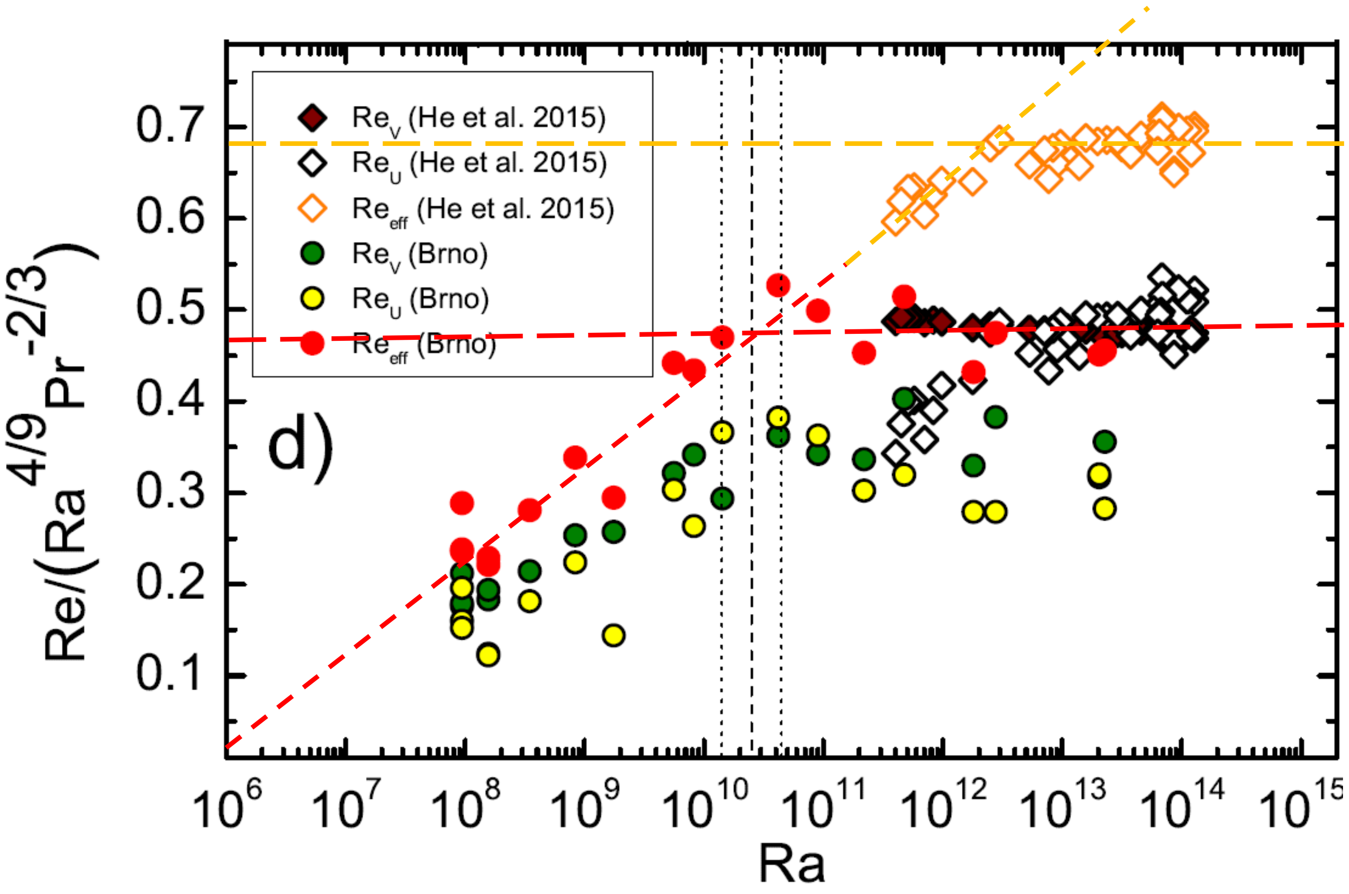
- “Elliptic approximation Reynolds numbers”

G.W. He & J.B.Zhang Phys.Rev. E 73 055303 (2006)

$$Re_U = \frac{LU}{\nu} \; ; \; U = d\frac{\tau_P}{\tau_0^2} = U_P\left(\frac{\tau_P}{\tau_0}\right)^2 \; ;$$

$$Re_V = \frac{LV}{\nu} \; ; \; V = \frac{d}{\tau_0}\sqrt{1-\left(\frac{\tau_P}{\tau_0}\right)^2} \; ;$$

$$Re_{\mathrm{eff}} = \frac{LU_{\mathrm{eff}}}{\nu} \; ; \; U_{\mathrm{eff}} = \sqrt{U^2+V^2} = \frac{d}{\tau_0}$$

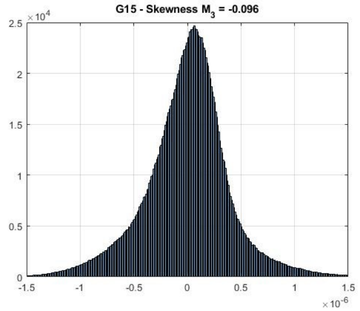


- Brno data compared with SF_6 data by

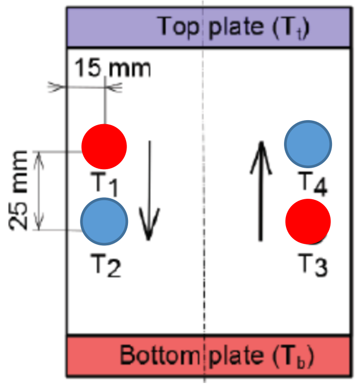
X. He et al. New J. Phys 17 063028 (2015)

V. Musilová, T. Králík, M. La Mantia, MM., P. Urban, L. Skrbek.
J. Fluid. Mech. 832, 721 – 744 (2017).

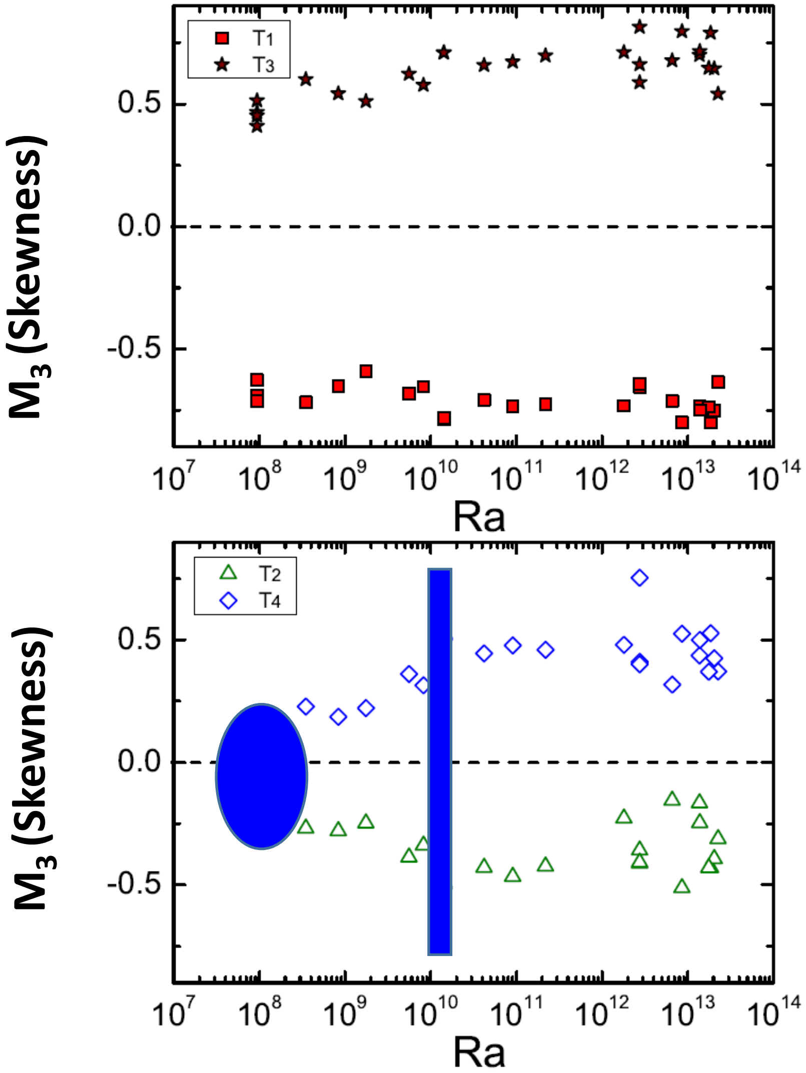
change



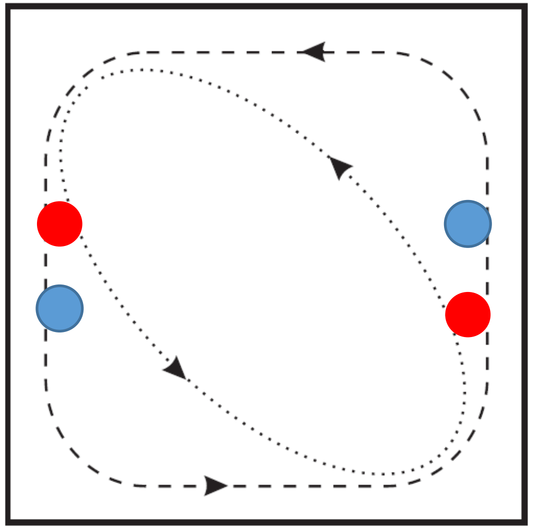
“leading sensors”



“trailing sensors”



Trailing sensors outside
main LSC roll for :
Tilted elliptical LSC



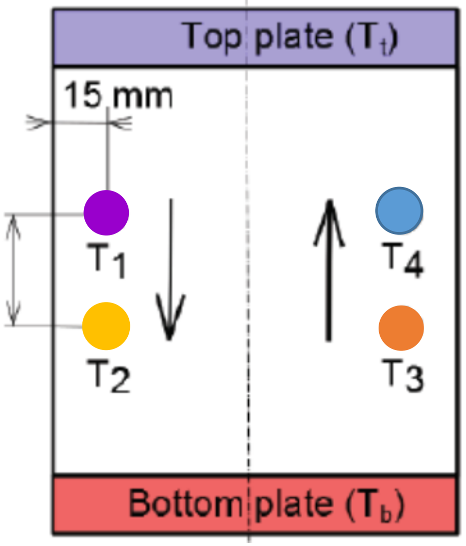
All sensors inside
the main LSC roll for :
Squarish LSC shape

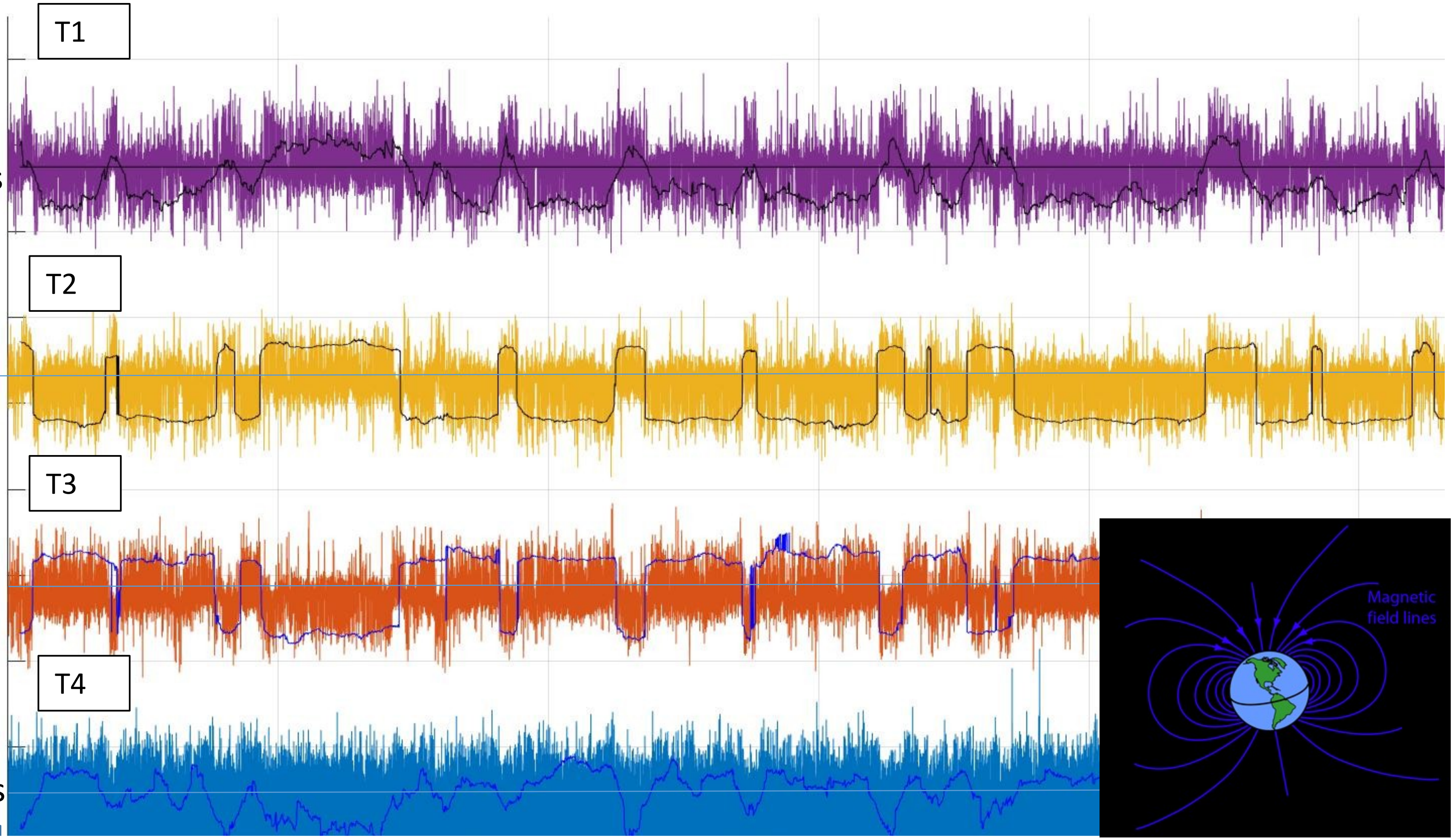
See also Niemela, Sreenivasan
Europhys. Lett. (2003) 62, 859

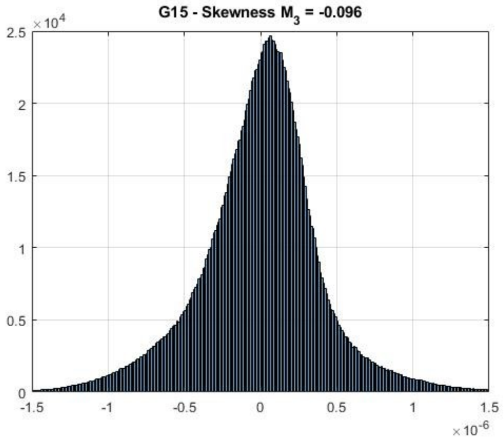
V. Musilová, T. Králík, M. La Mantia, MM., P. Urban, L. Skrbek.
J. Fluid. Mech. 832, 721 – 744 (2017).

Wind reversals

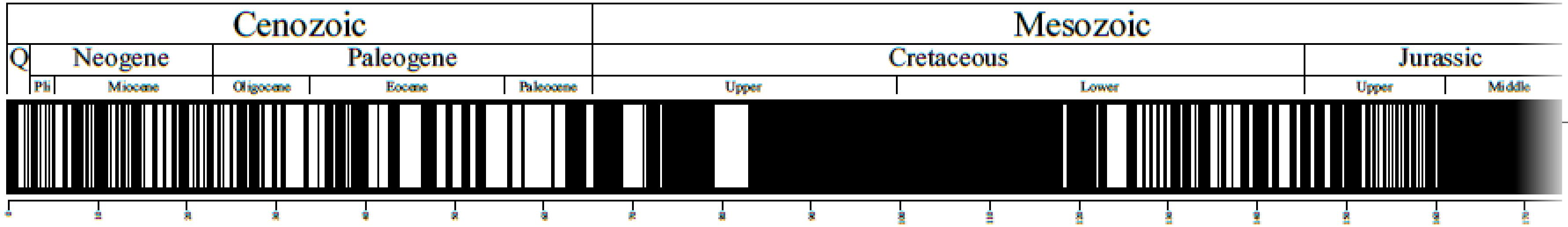
Bulk temperature fluctuations – measurement #f078:
$Ra = 8.86*10^{12}$, $Pr = 1.34$, $<Nu> = 1280$



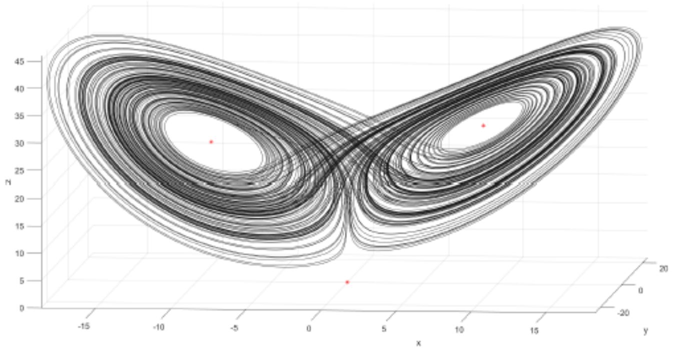




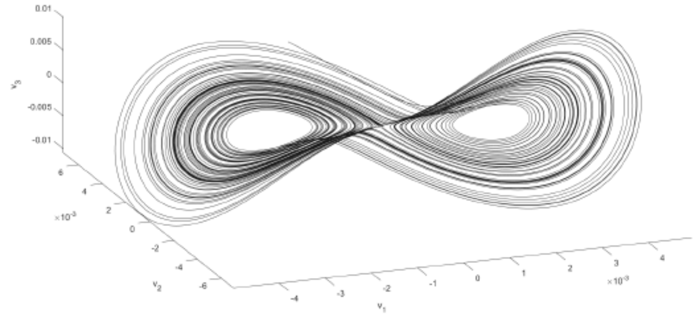
slidi
wind
analy



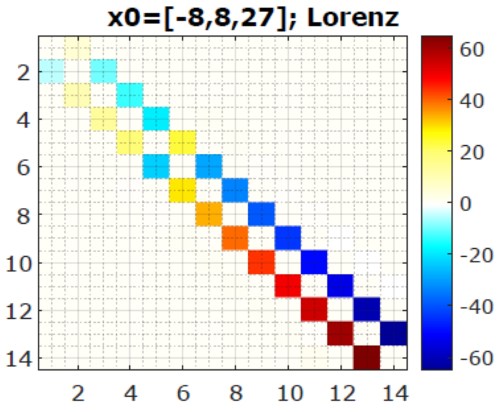
Outlook 1:
Attractors in RBC and Data-based Mathematical models



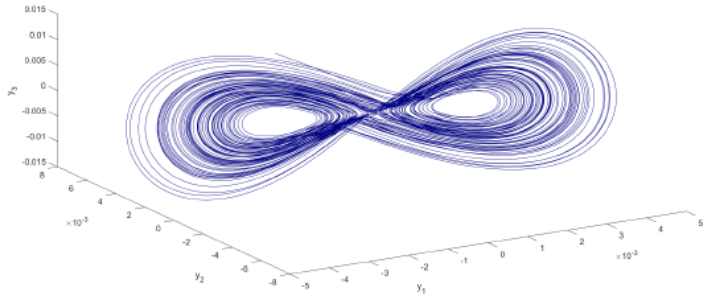
Obrázek: Původní atraktor.



Obrázek: Vnořený atraktor.



Obrázek: Barevně zobrazená matice soustavy.



Obrázek: Rekonstruovaný atraktor.

Jakub Kašný, FSI VUT
BP 2022,
to be submitted

Jakub Kašný 29. března 2022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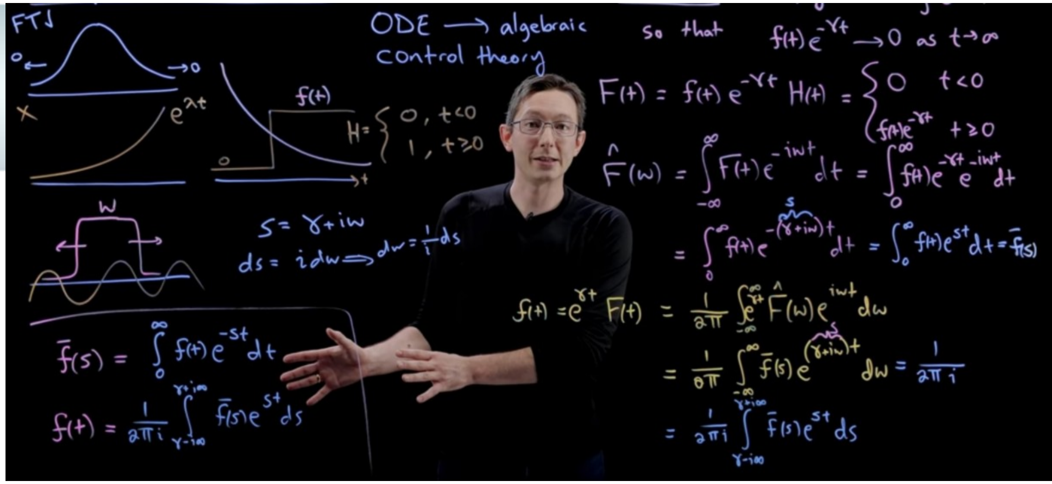
ARTICLE

DOI: 10.1038/s41467-017-00030-8

OPEN

Chaos as an intermittently forced linear system

Steven L. Brunton[1], Bingni W. Brunton[2], Joshua L. Proctor[3], Eurika Kaiser[1] & J. Nathan Kutz[4]


FTJ

ODE → algebraic
control theory

so that $f(t)e^{-\gamma t} \to 0$ as $t \to \infty$

$$H = \begin{cases} 0, & t<0 \\ 1, & t\geq 0 \end{cases}$$

$$F(t) = f(t)e^{-\gamma t}H(t) = \begin{cases} 0 & t<0 \\ f(t)e^{-\gamma t} & t\geq 0 \end{cases}$$

$$\hat{F}(\omega) = \int_{-\infty}^{\infty} F(t)e^{-i\omega t}\,dt = \int_0^{\infty} f(t)e^{-\gamma t}e^{-i\omega t}\,dt$$

$$= \int_0^{\infty} f(t)e^{-\overset{s}{\overbrace{(\gamma+i\omega)}}t}\,dt = \int_0^{\infty} f(t)e^{-st}\,dt = \bar{f}(s)$$

$s = \gamma + i\omega$

$ds = i\,d\omega \Rightarrow d\omega = \frac{1}{i}ds$

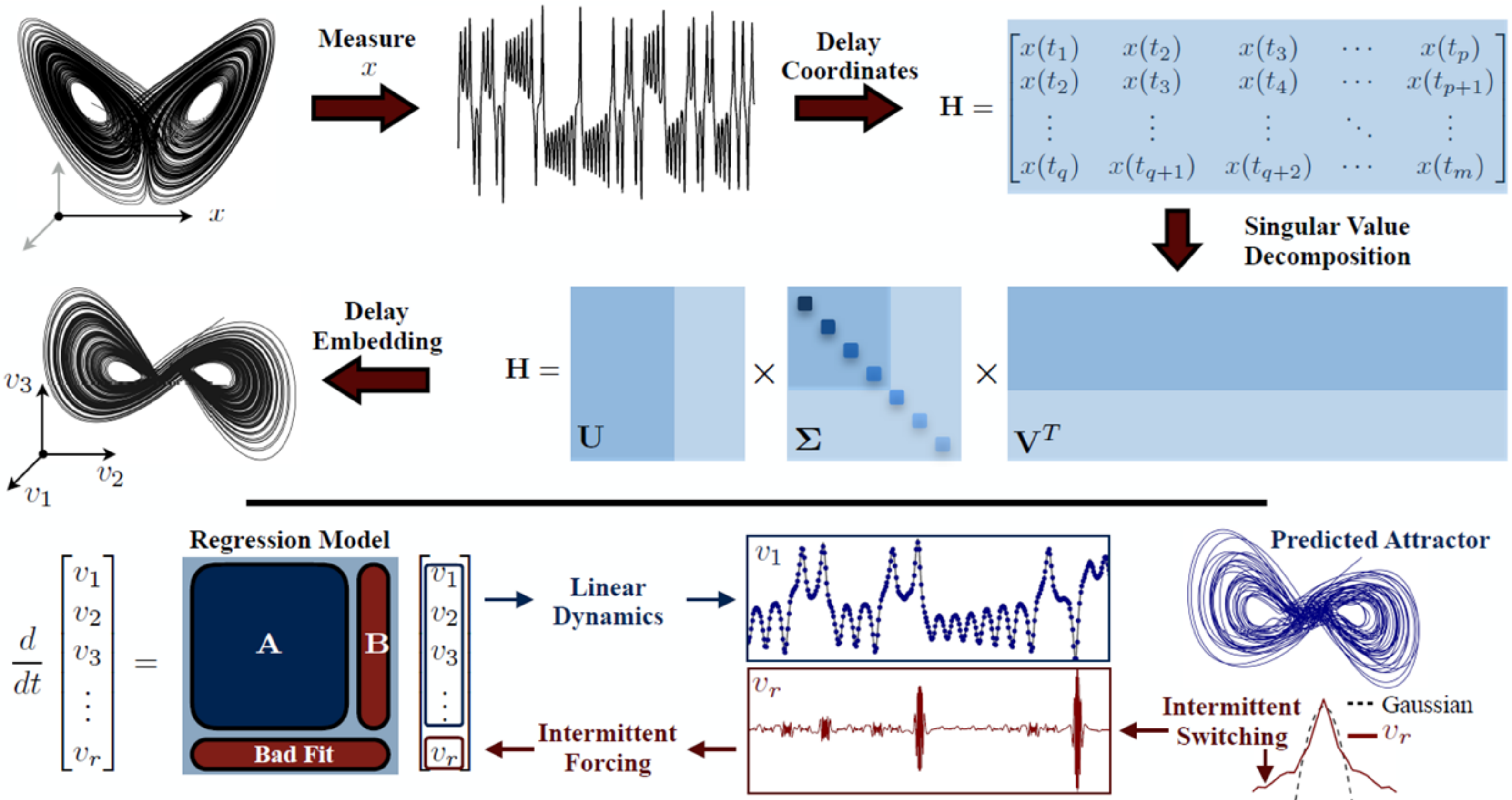
$$f(t) = e^{\gamma t}F(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} e^{\gamma t}\hat{F}(\omega)e^{i\omega t}\,d\omega$$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty} \bar{f}(s)e^{\overset{s}{\overbrace{(\gamma+i\omega)}}t}\,d\omega = \frac{1}{2\pi i}$$

$$= \frac{1}{2\pi i}\int_{\gamma-i\infty}^{\gamma+i\infty} \bar{f}(s)e^{st}\,ds$$

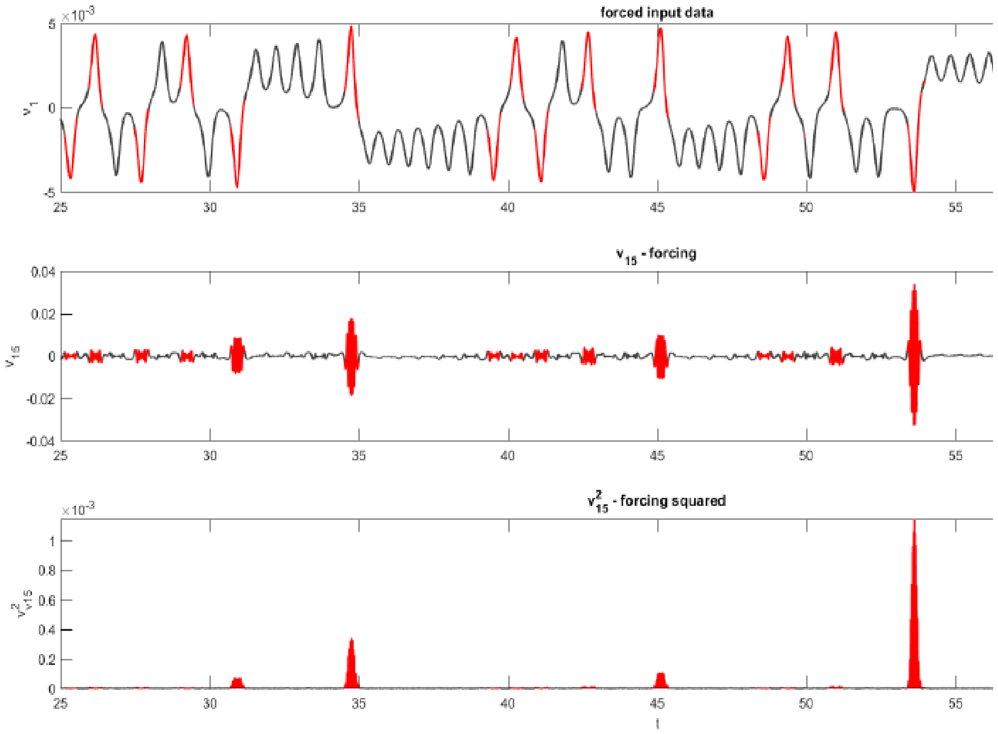
$$\bar{f}(s) = \int_0^{\infty} f(t)e^{-st}\,dt$$

$$f(t) = \frac{1}{2\pi i}\int_{\gamma-i\infty}^{\gamma+i\infty} \bar{f}(s)e^{st}\,ds$$



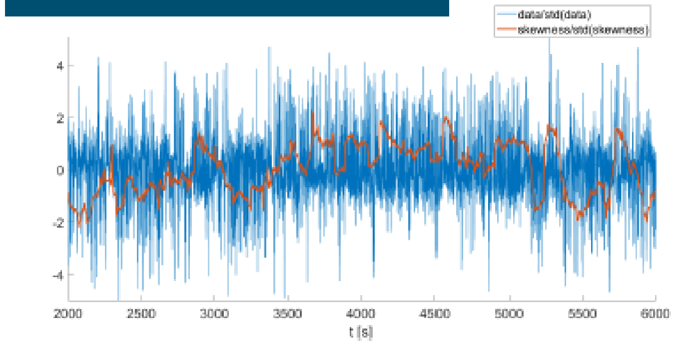
Outlook 1:
Attractors in RBC and Data-based Mathematical models

HAVOK na Lorenzově systému - predikce

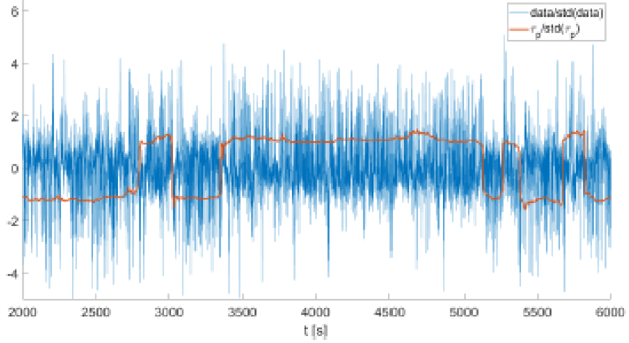


Obrázek: HAVOK predikce.

HAVOK na RBC



Obrázek: Signál šikmosti.



Obrázek: Signál τ_p

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BP 2022,
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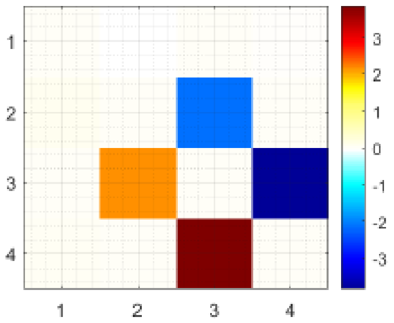
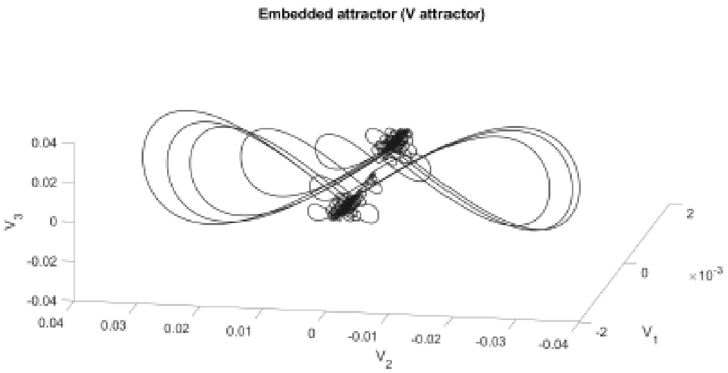
Outlook 1:
Attractors in RBC and Data-based Mathematical models

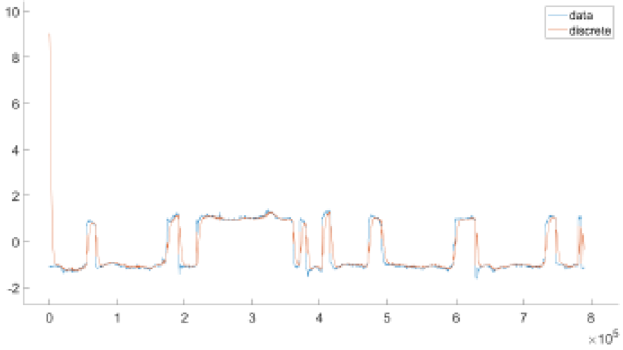
- Matice soustav a jejich stabilita.
- Atraktory.
- Atrakce řešení při změně počátečních podmínek.



Obrázek: Matice soustavy (τ_p signál).



Obrázek: Vnořený atraktor (τ_p signál).



Obrázek: Jiné počáteční podmínky (τ_p signál).

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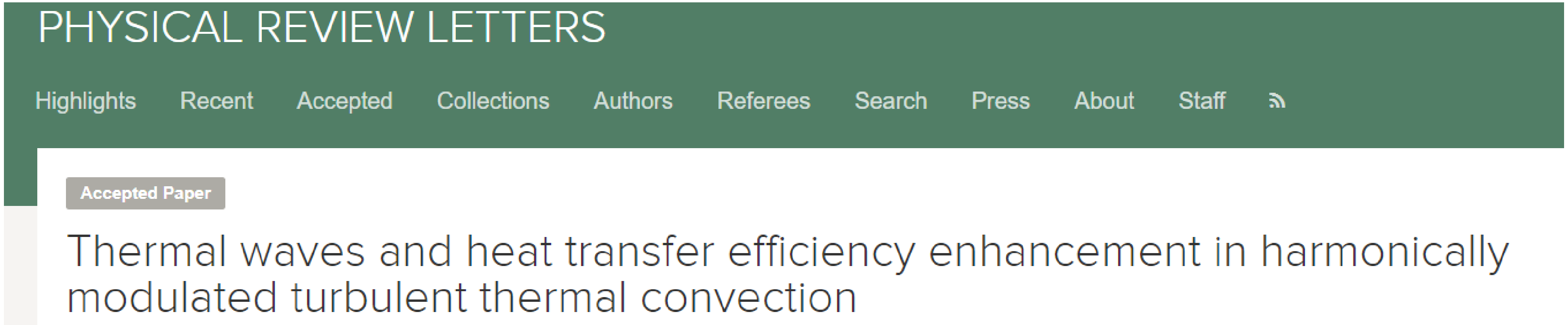
Outlook 2: Temperature modulation and rotation in Classical RBC and Quantum Counterflow



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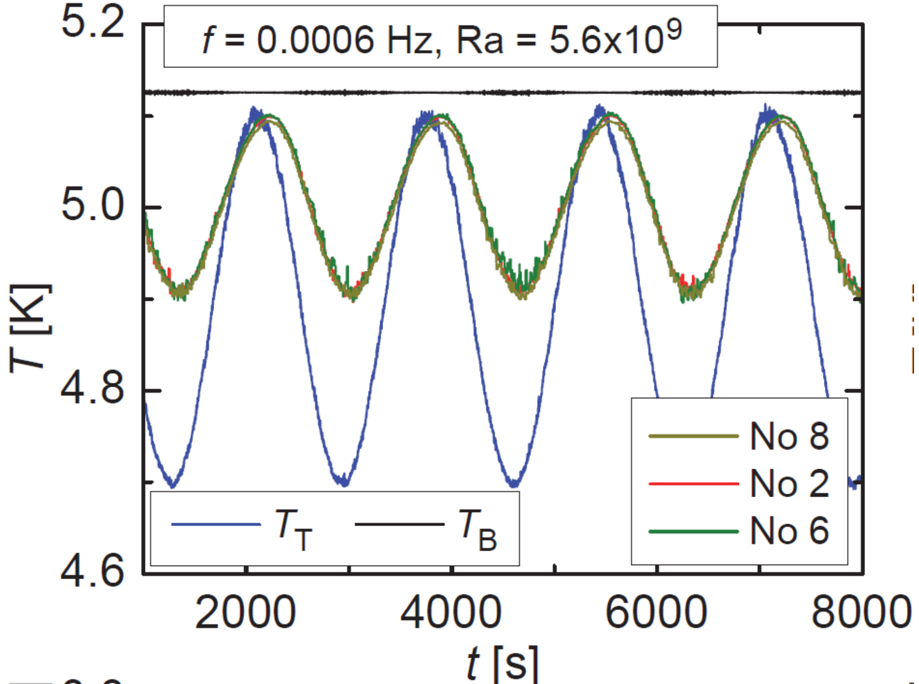
Accepted Paper

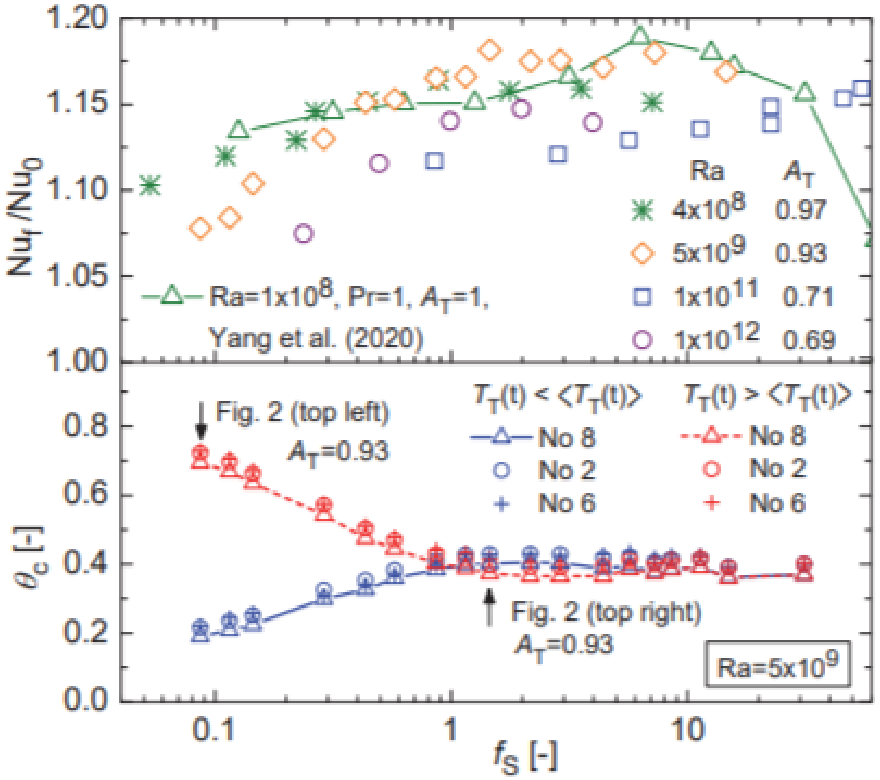
Thermal waves and heat transfer efficiency enhancement in harmonically modulated turbulent thermal convection

Phys. Rev. Lett.

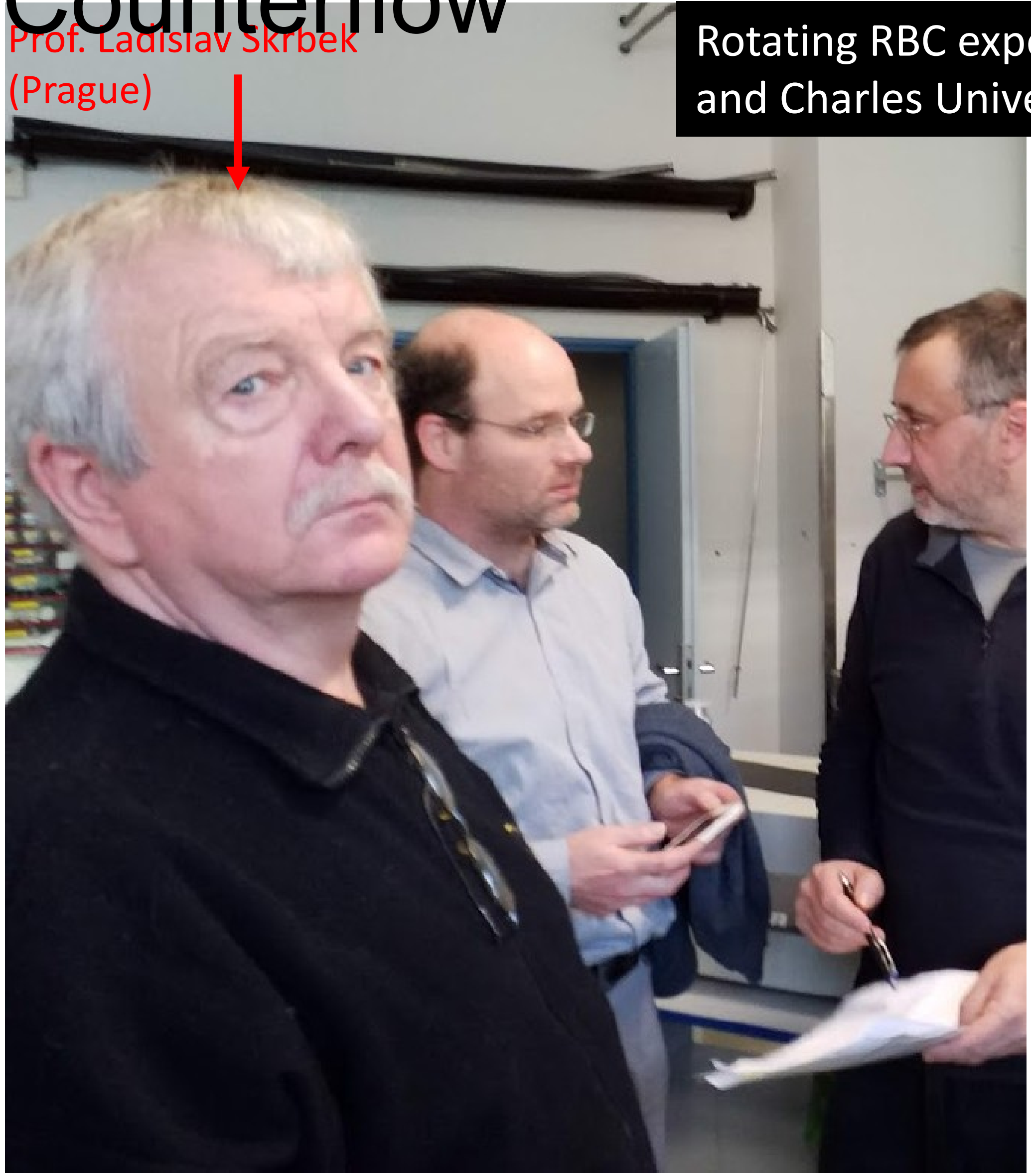
P. Urban, P. Hanzelka, T. Králik, V. Musilová, and L. Skrbek

Accepted 25 February 2022





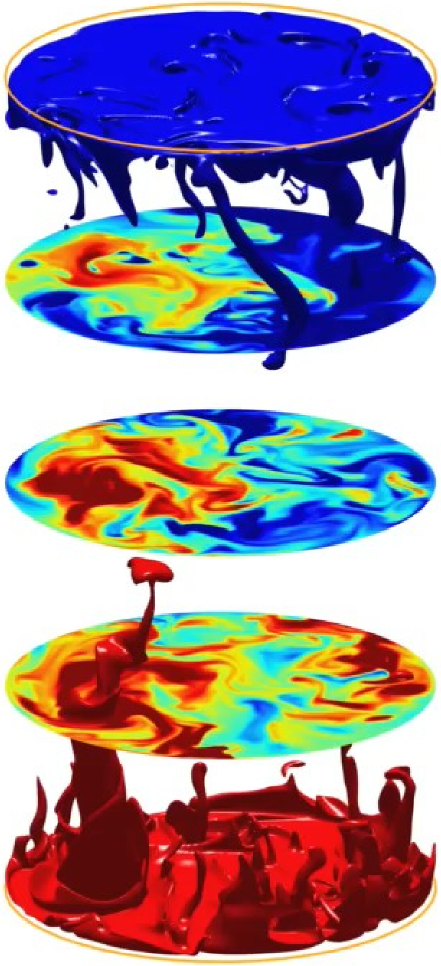
Outlook 2:
Rotating platforms for Classical RBC and Qua
Counterflow

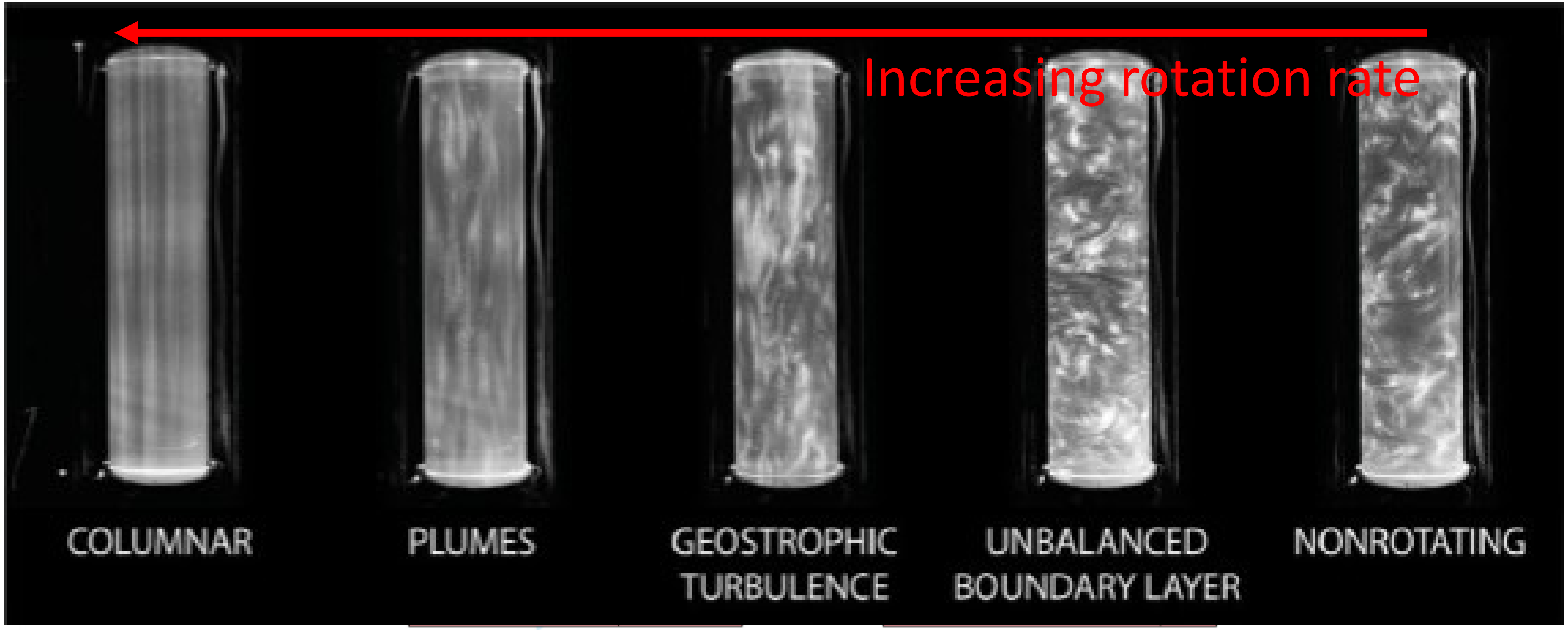


Rotating RBC experiment under preparation at ISI Brno and Charles University Prague

Outlook 2:
Rotating platforms for Classical RBC and Quantum Counterflow

Rotating RBC simulation from Richard Stevens
https://stevensrjam.github.io/Website/research_rrb.html]

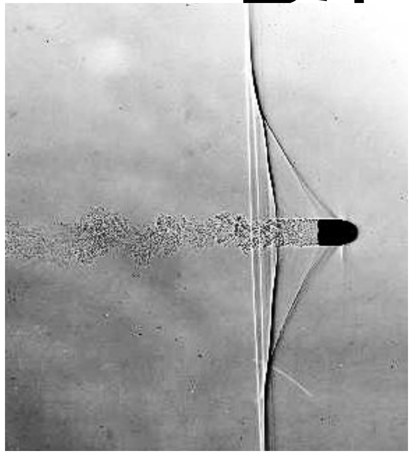




Increasing rotation rate

Figure 2. Schematic showing the distribution of rotating convection regimes in terms of Nusselt number (*Nu*) versus Rayleigh number (*Ra*) for a fixed Ekman number (*E*) and a) $Pr > 3$ and b) $Pr \lesssim 3$. Laboratory flow visualisations of each regime at $Pr \approx 7$, adapted from Cheng *et al.* (2015), are shown in the upper panel. In (a) and (b), the vertical lines indicate transition Rayleigh values: Ra_S denotes convective onset, Ra_{CP} denotes the transition between columnar-style convection and plumes, Ra_{PGT} between plumes and geostrophic turbulence, Ra_{GTU} between geostrophic turbulence and unbalanced boundary layers, and Ra_{UNR} to nonrotating-style convection. Though the transitions are delimited by lines, each likely occurs gradually over a range of *Ra* values. Their locations are not yet well-determined, and table 1 and figure 6 list various existing predictions. For $Pr \lesssim 3$, steady columnar convection does not occur (e.g. Julien *et al.* 2012b, Stellmach *et al.* 2014). (Colour online).

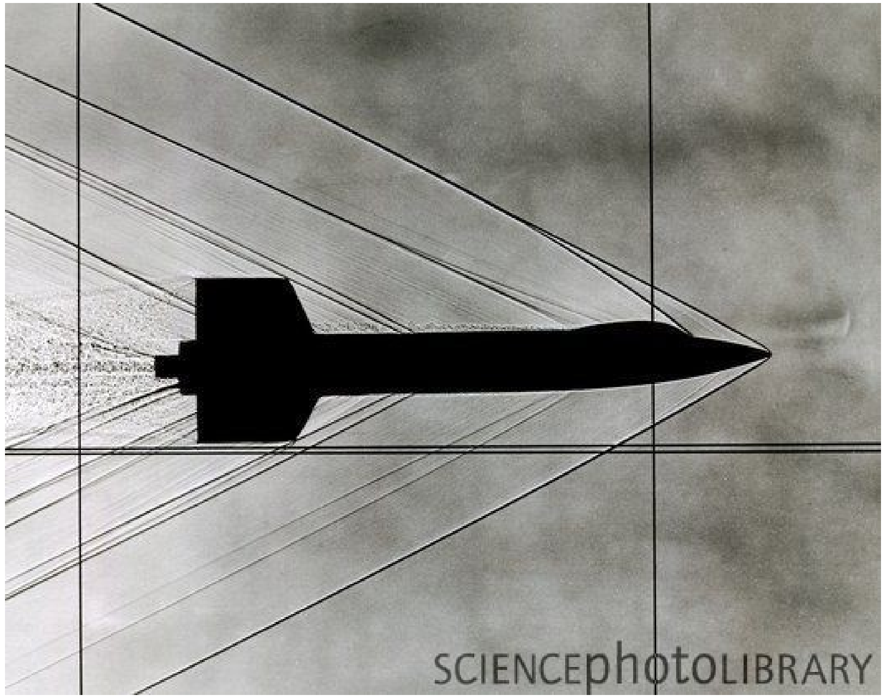
Outlook 3: Flow visualization at high Ra

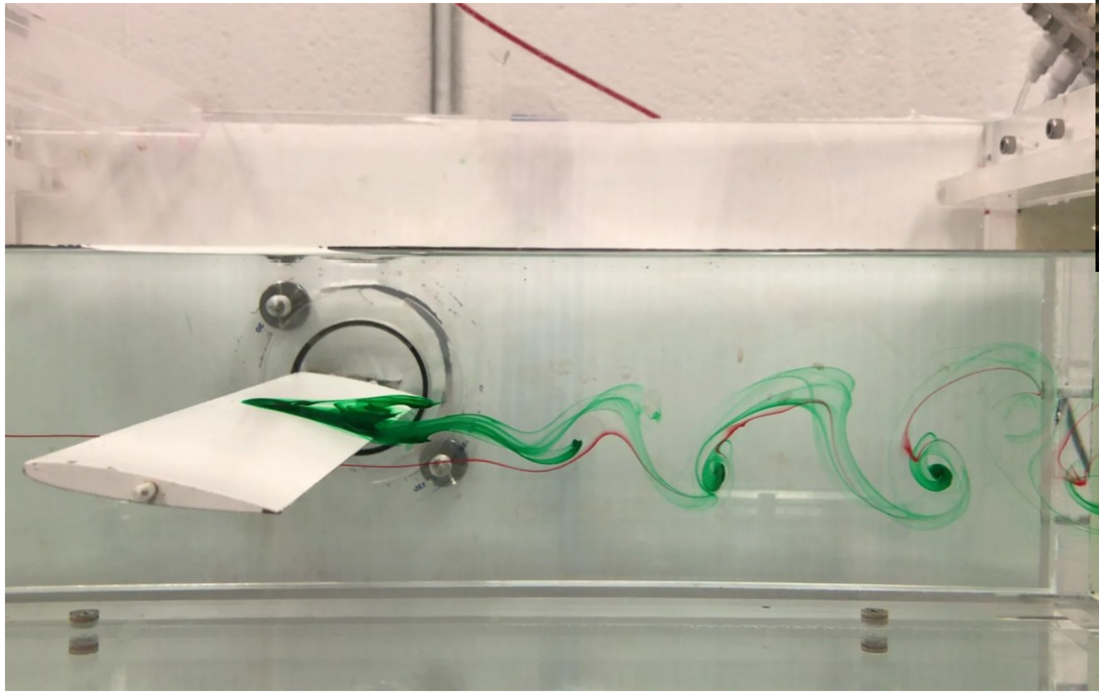

Ernst Mach &Peter Salcher, cca. 1890

<u>Many visualization methods exist:</u>

Smoke, Ink or Dye…
Particle Tracking Velocimetry,
Particle Image Velocimetry,
Laser Doppler Velocimetry
Shadograph, Schlieren, etc…

<u>None allow to reach “ultimate” *Ra*!</u>
(enabling direct velocity information in RBC)





Outlook 3: Flow visualization at high Ra

A promissing visualization method was developed

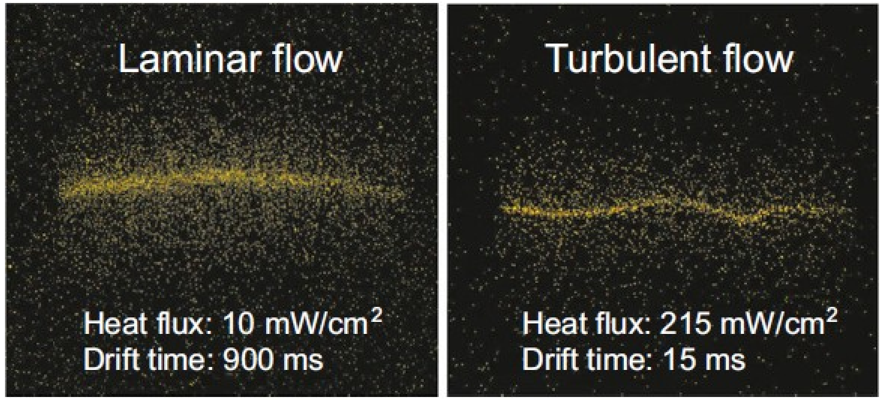
McKinsey et al. Phys. Rev. Lett. ***95****, 111101 (2005)*

W. Guo et al. Phys. Rev. Lett., 105, 045301 (2010)

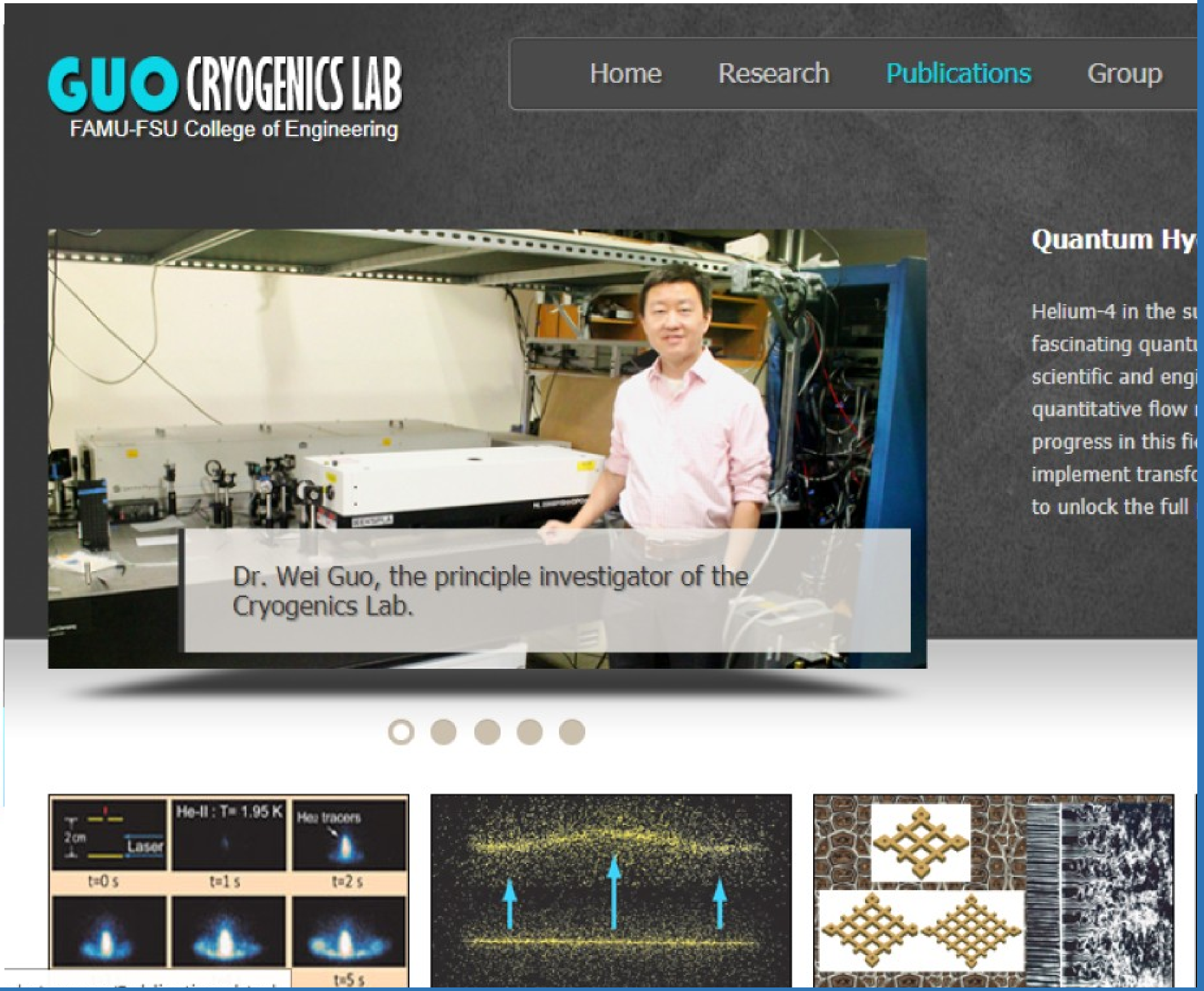
Long-living (> 10s) molecular triplet excimer He2*

McKinsey et al. Phys. Rev. A ***59****, 200 (1999)*

- Excimers form after He ionization
(by fs-lasers, radioactivity, intense electric field ionization, etc…)
- Can be visualized by molecular tagging via laser-induced fluorescence (LIF)



W. Guo et al. PNAS (2013)



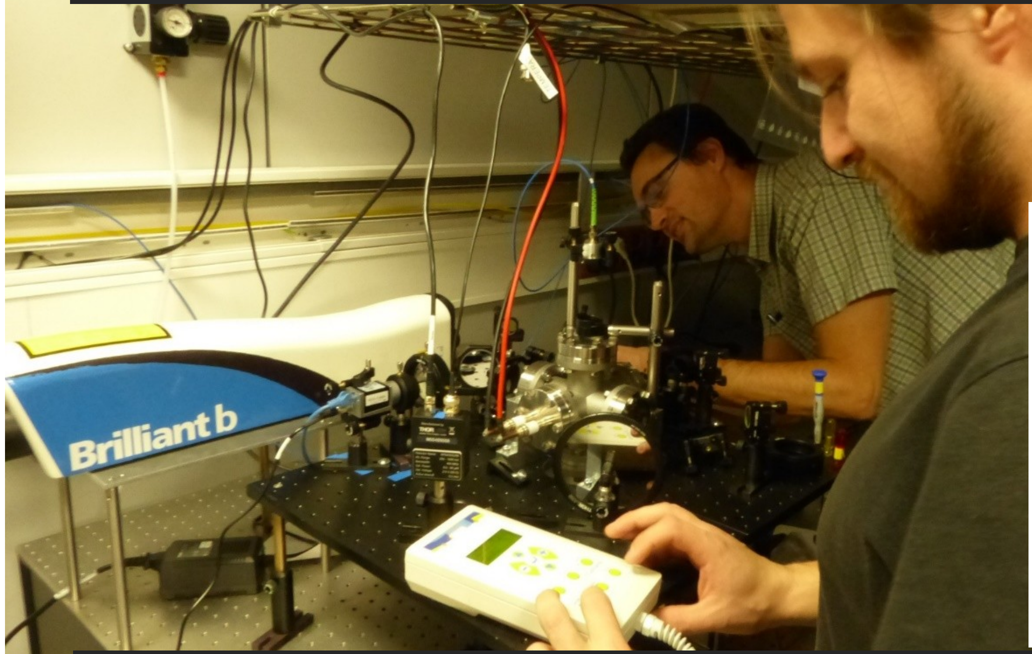
Quantum Hy

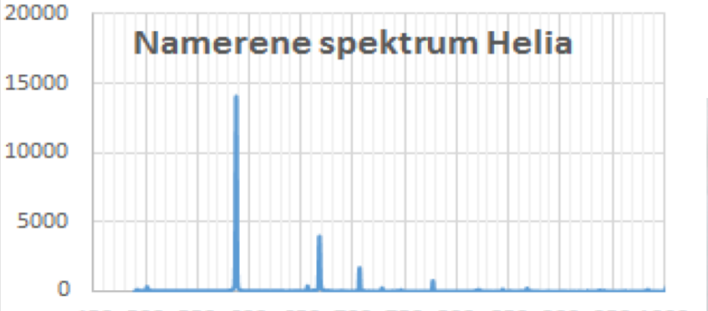
Helium-4 in the su
fascinating quantu
scientific and engi
quantitative flow
progress in this fi
implement transfo
to unlock the full

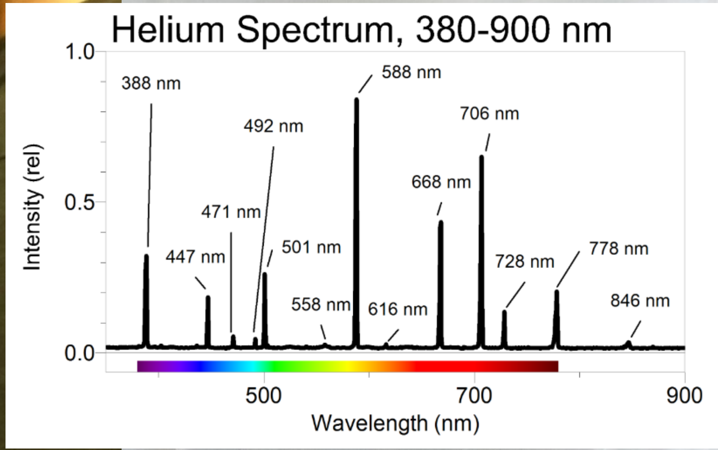
Dr. Wei Guo, the principle investigator of the Cryogenics Lab.

R&D for turbulent flow visualization in helium gas at ISI Brno

Laser ionization of Helium gas by the Brilliant nanosecond laser succesfully accomplished







Thanks to: Jan Ježek, Minh Tuan Pham, Jakub Grim


Mercur

and colleagues in Prague, Ilmenau, Florida…


Prague group of prof. Ladislav Skrbek


Ilmenau group of
prof. Joerg Schumacher

and
prof. Ronald du Puits

Summary:

- Turbulence is an open theoretical and experimental problem
- One of major open questions:
  Existence of the ultimate regime, relevant e.g. at extremely large spatial scales in Nature
- Can be studied in Lab in cryogenic Helium
- Information on velocity field missing at high Ra
  → Need for high *Ra* visualization experiments, possibly with He_2^* excimers
- Analogous transitions laws in classical and quantum heat transfer not well understood…

Thank You!

Open BSc. and MSc. Thesis Topics:

[Experiment]

- Rotating Rayleigh-Benard Convection (with Pavel Urban)

[Theory]

- Classical-Quantum Analogy for heat transport laws in Rayleigh-Benard Convection in GHe and Counter-Flow in He-II (with Michal Macek)

[Data Analysis]

- Attractors in turbulent Rayleigh Benard Convection (with Michal Macek)
- Ultimate Regime of Convection or NOB Convection? (with Michal Macek)

  Analyze and compare classical Rayleigh-Benard Convection data from:

  - Cryogenic GHe experiments at ISI Brno
  - Dry air experiments at Barrell of Ilmenau by group of prof. De Puits (DE)
  - Highly parallel direct numerical simulations by group of prof. Schumacher (TU Ilmenau, DE)

michal.macek@isibrno.cz