Problems in highly turbulent flow:

1. Rayleigh-Benard
2. Taylor-Couette
3. Boundary layers
4. 2-phase flow
5. Turbulence with phase transitions

I. RB

- Oregon vs Grenoble controversy: origin?
- Ultimate RB convection: Kraichnan regime?
- Better understanding of aspect ratio dependence
- Understanding of non-Oberbeck-Boussinesq effects
- Understanding of the large scale wind dynamics
- BLs!
- RB with rotation

II. Taylor-Couette

- Torque vs Reynolds
- Role of BLs
- Ultimate regime

III. Boundary layers

- Log-law vs Barenblatt
- Coupling BL-bulk
- Role of plumes, structures: exchange of momentum: statistical description
- Roughness of wall: drag reduction

IV. 2-phase flow: particles & drops in turbulence, clouds

- Clustering, coalescence
- 2-way coupling, 4-way coupling
- sink velocity of particles in turbulence
- effective forece models
- Lagrangian vs Eulerian view

V. Turbulence with phase-transition

Instrumentation

Probes on microscale: bolometers, aneometers

High-speed 3D PIV: resolution!

Radio particles

Temperature control crucial

Why now?

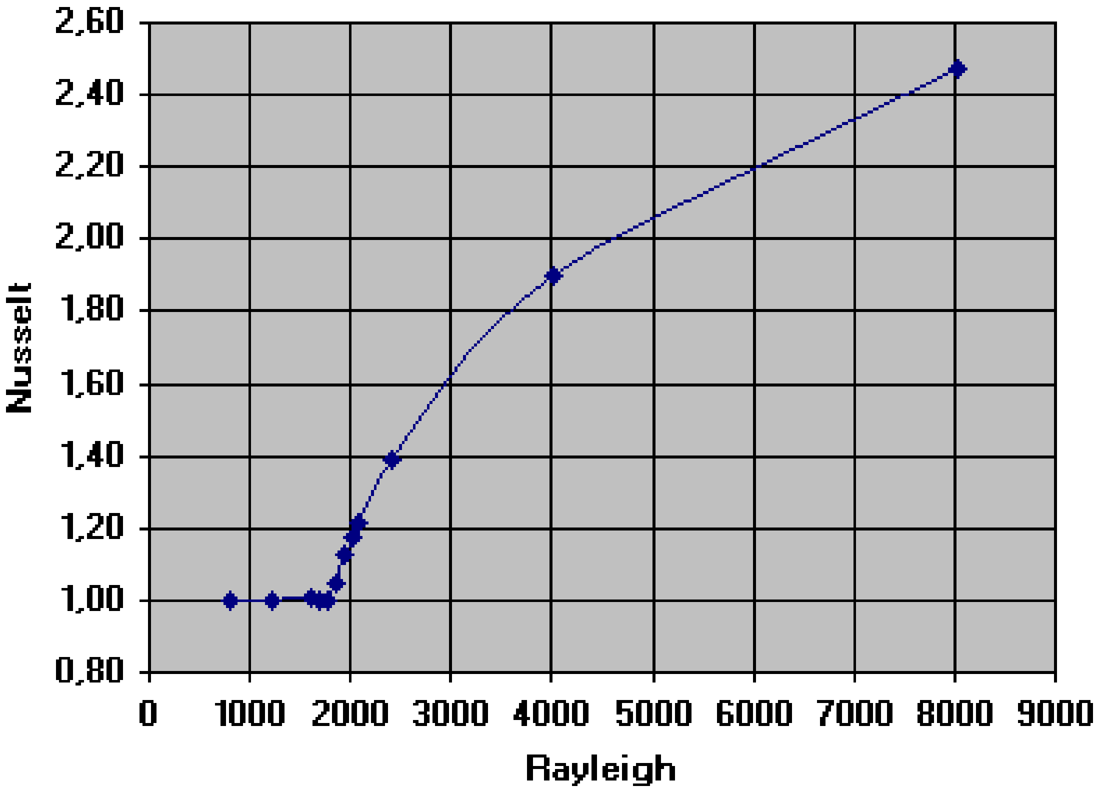
High-speed cameras

Data storage and handling in Tbytes

I. Rayleigh-Benard convection

RB system “drosophila” of fluid dynamics & pattern formation

Onset of convection: rolls



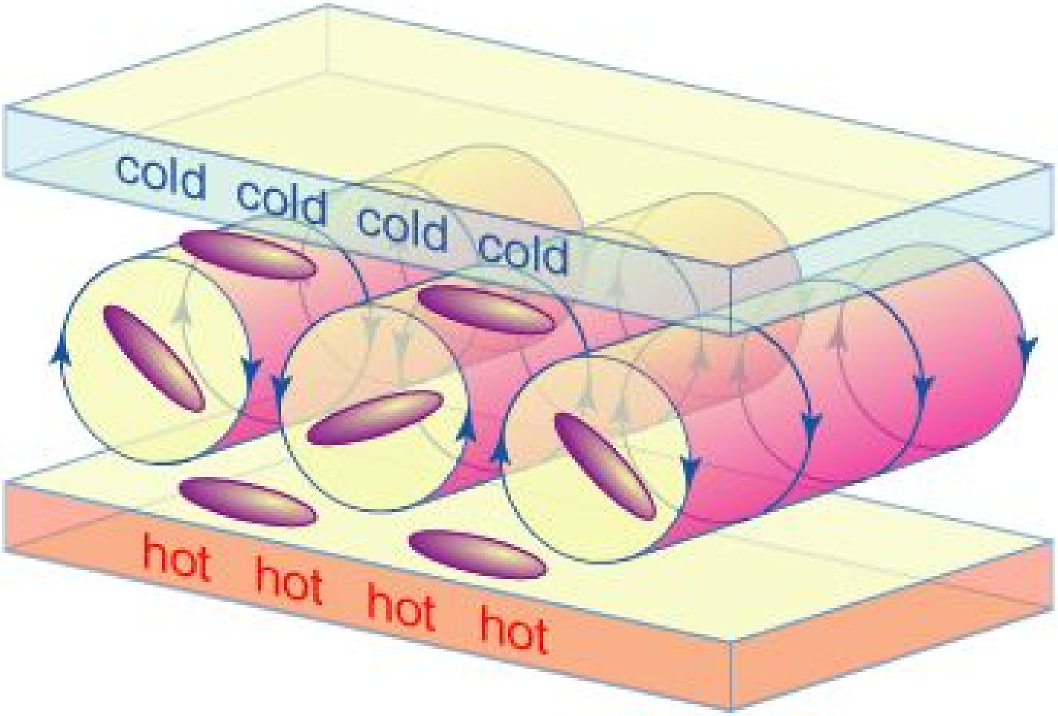
$$Ra_c = 1708$$

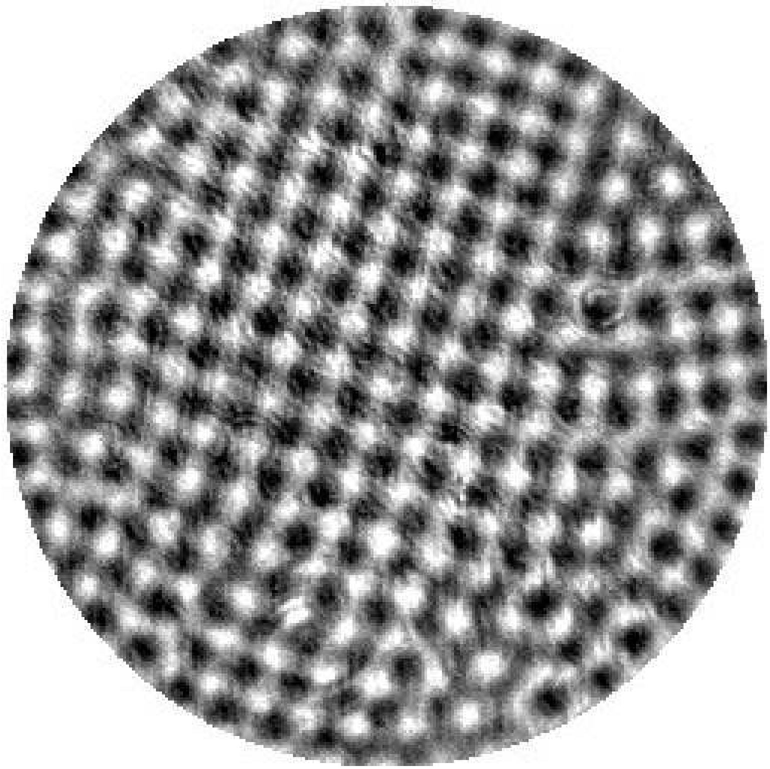
(independent of Pr)

Chandrasekhar, Taylor,

late 1930s

Convection rolls

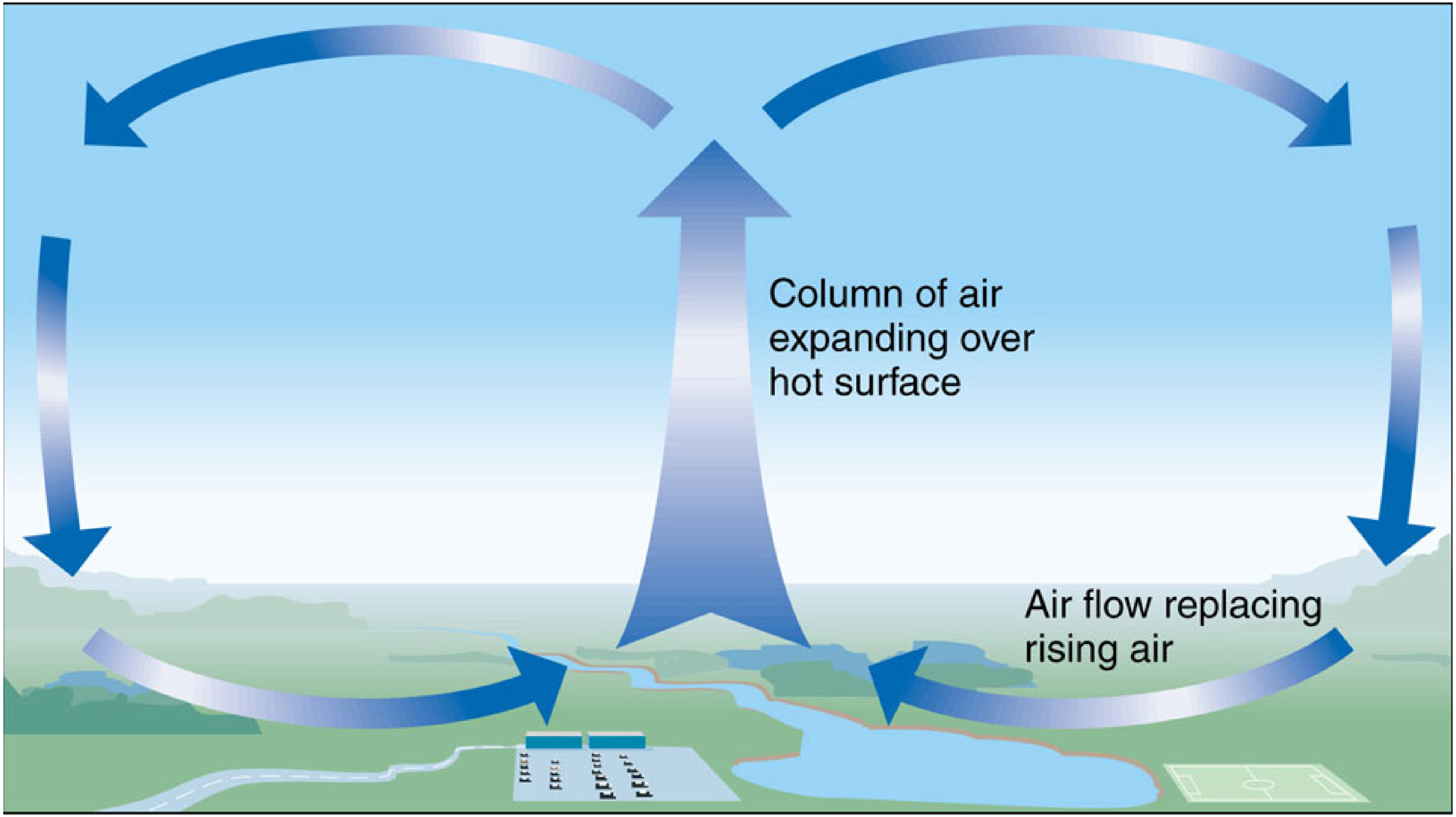




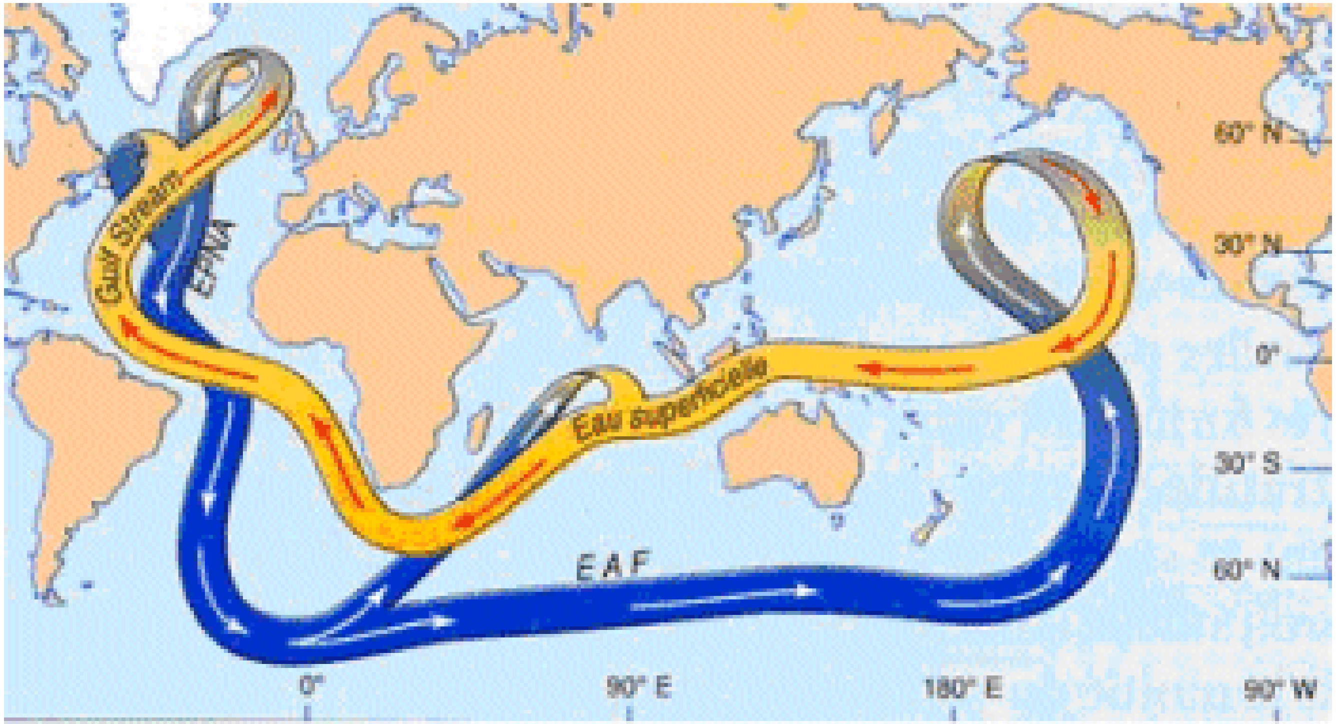
Applications

- Convection in earth mantle (Pr = 10^{21})
- Convection in earth kernal
- Convection in stars
- Convection in the ocean (including thermohaline)
- Convection in the atmosphere
- Metal production
- ….

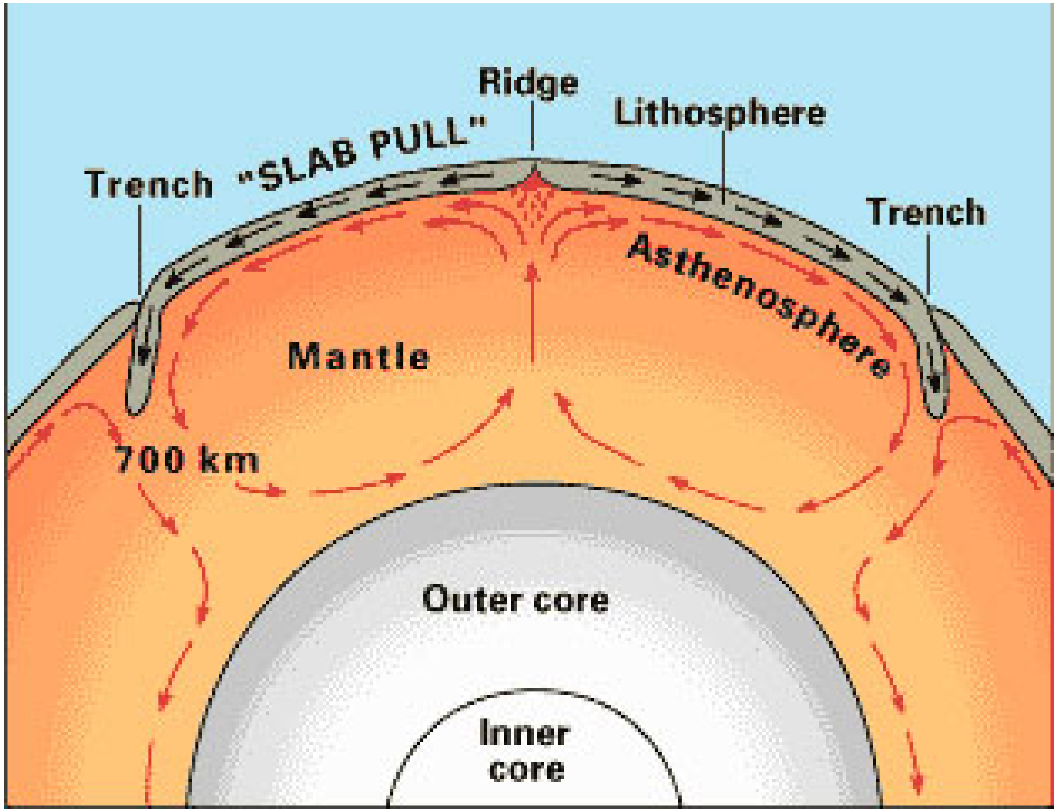
Convection in atmosphere

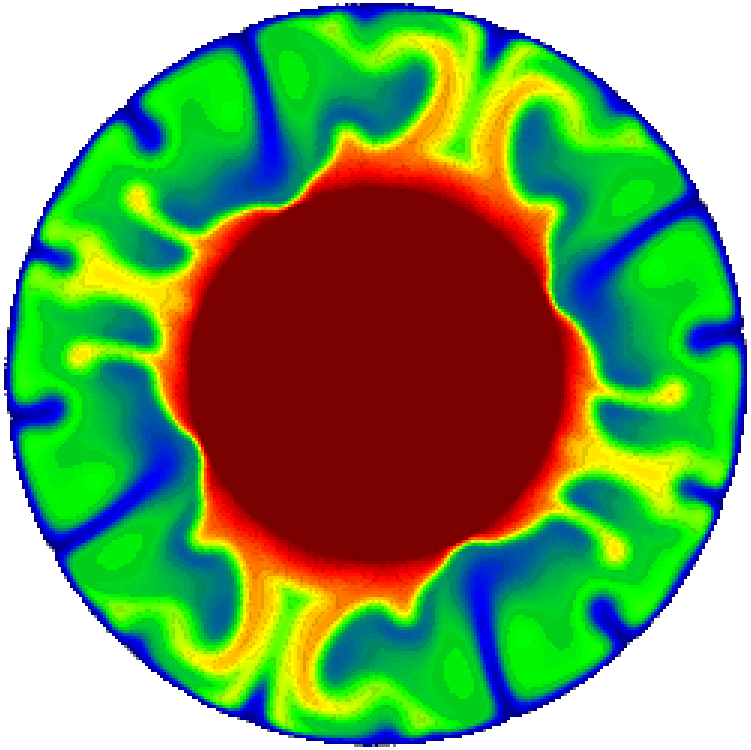


Convection in the ocean



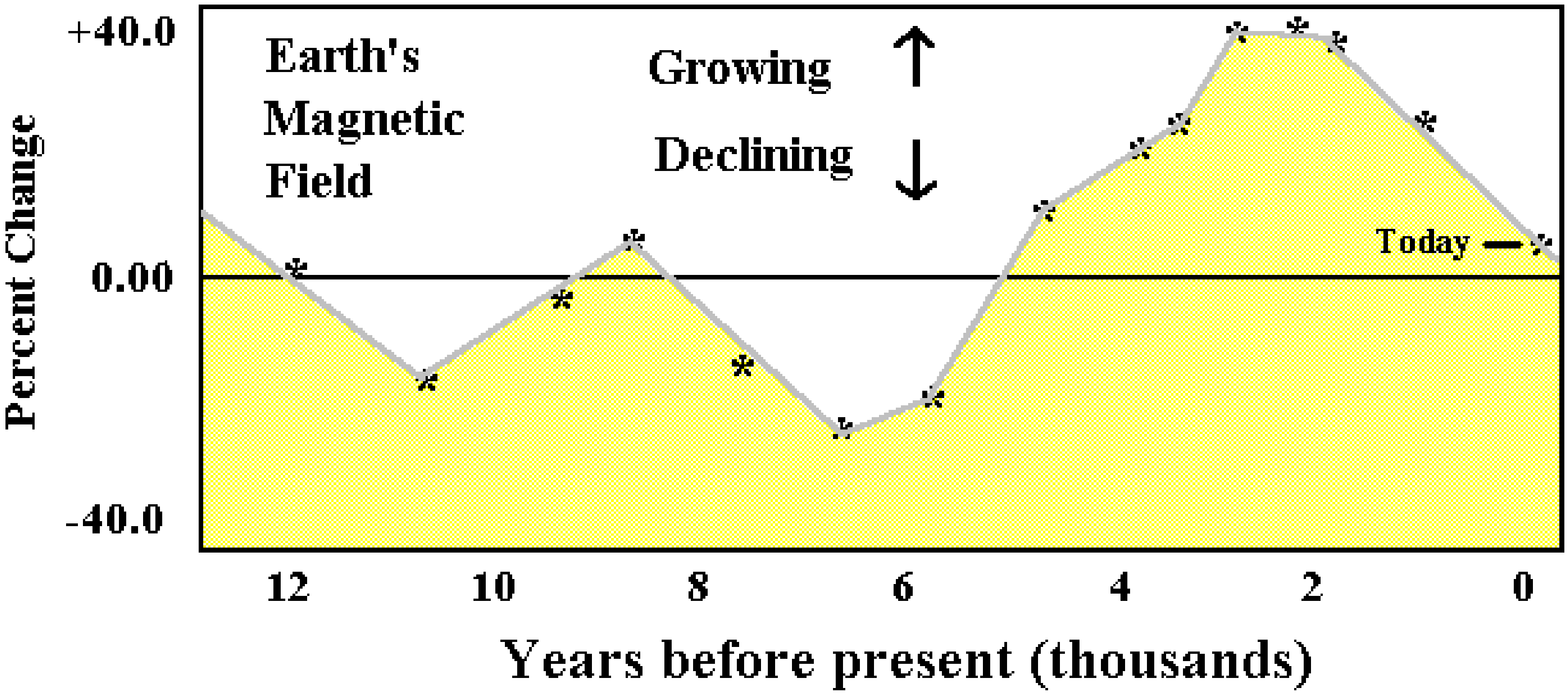
Mantle convection



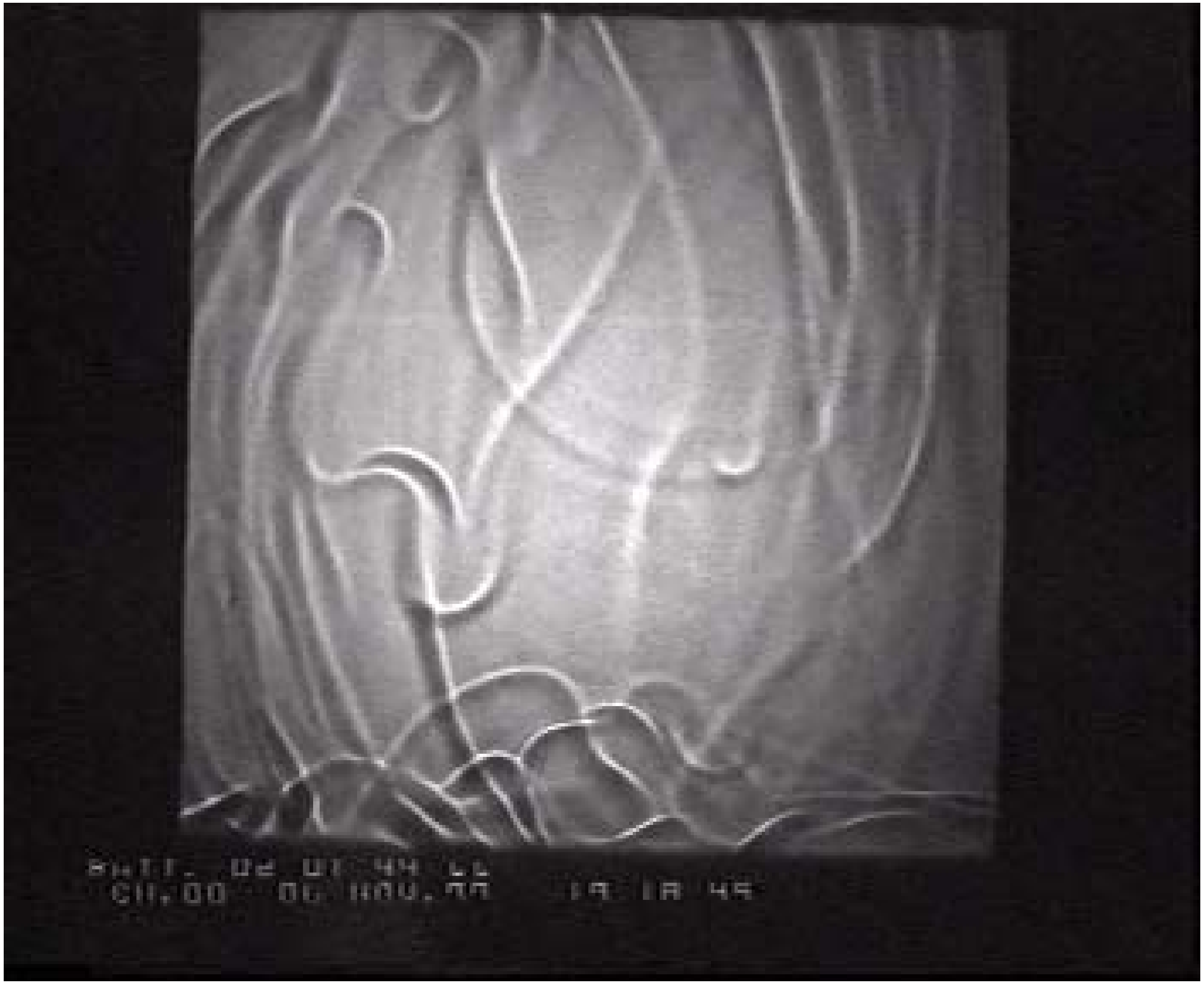


Glatzmeier

Reversal of magnet field of earth



Schlieren visualization of global flow



water,

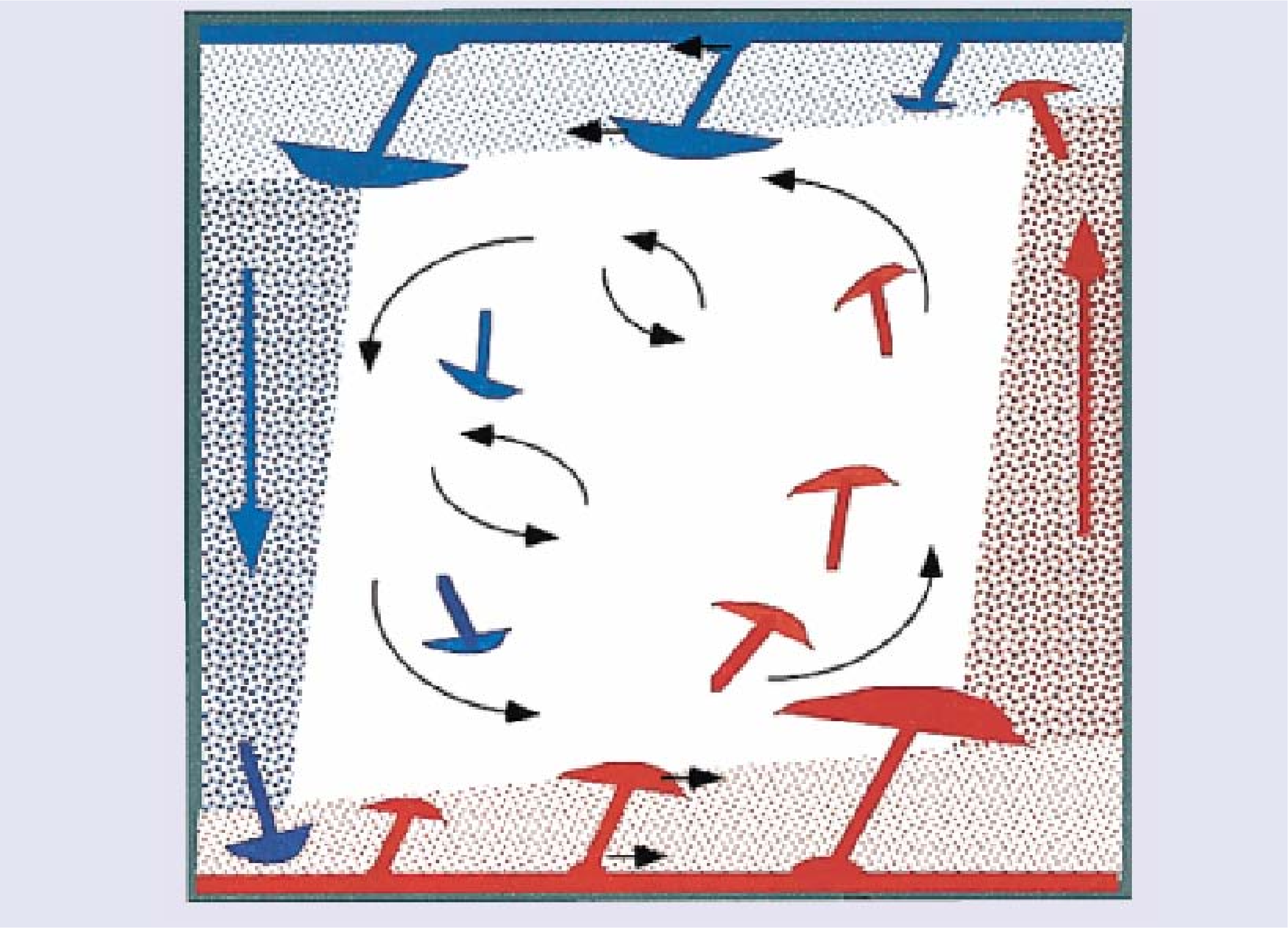
Pr=4,

Ra=5 10^9

Tong, Xia et al.,

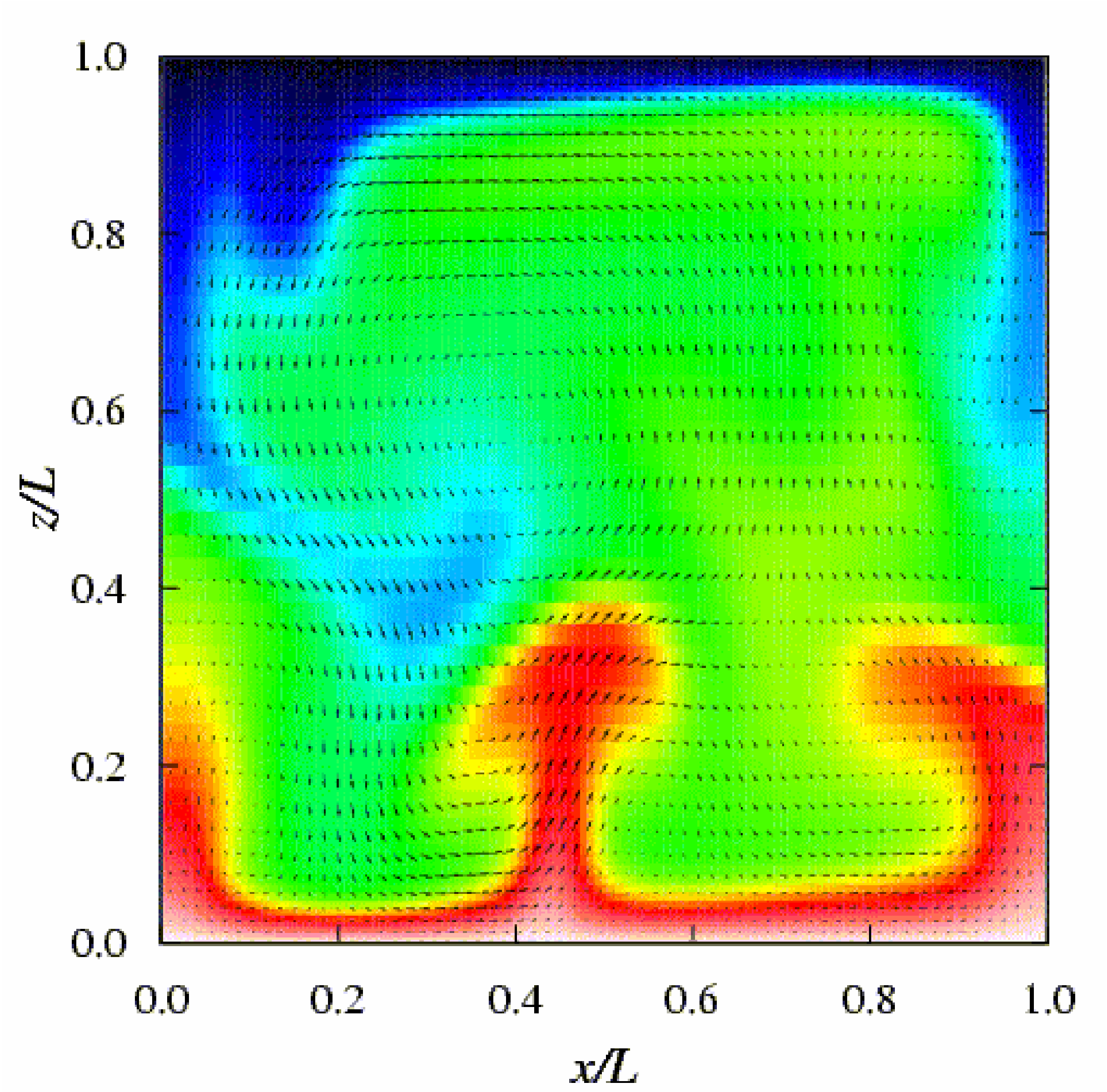
Hongkong

Role of plumes in RB convection



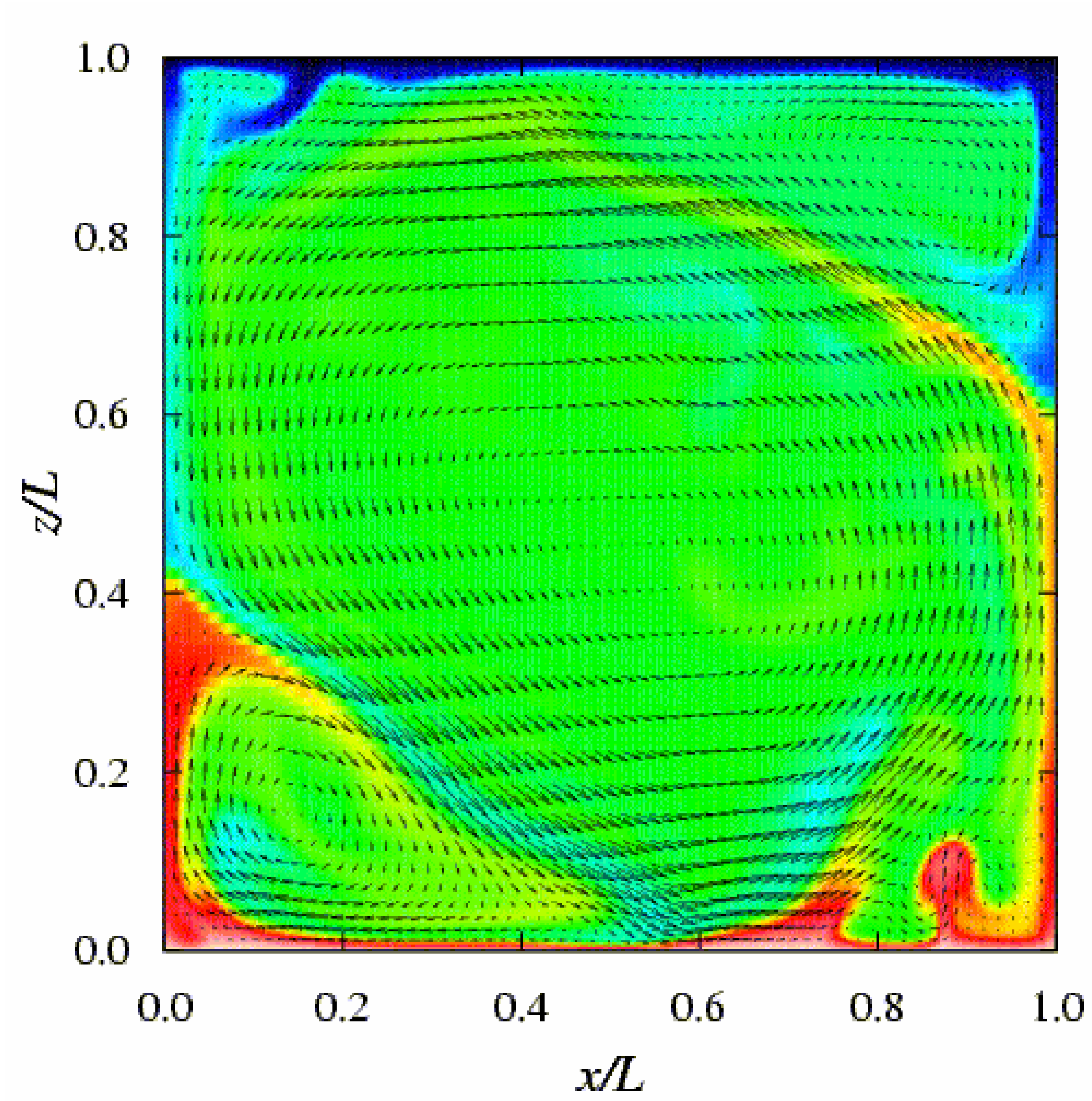
L.P. Kadanoff, Phys. Today 54(8), 34 (2001)

2D OB-simulation, Pr=4, Ra=10^6



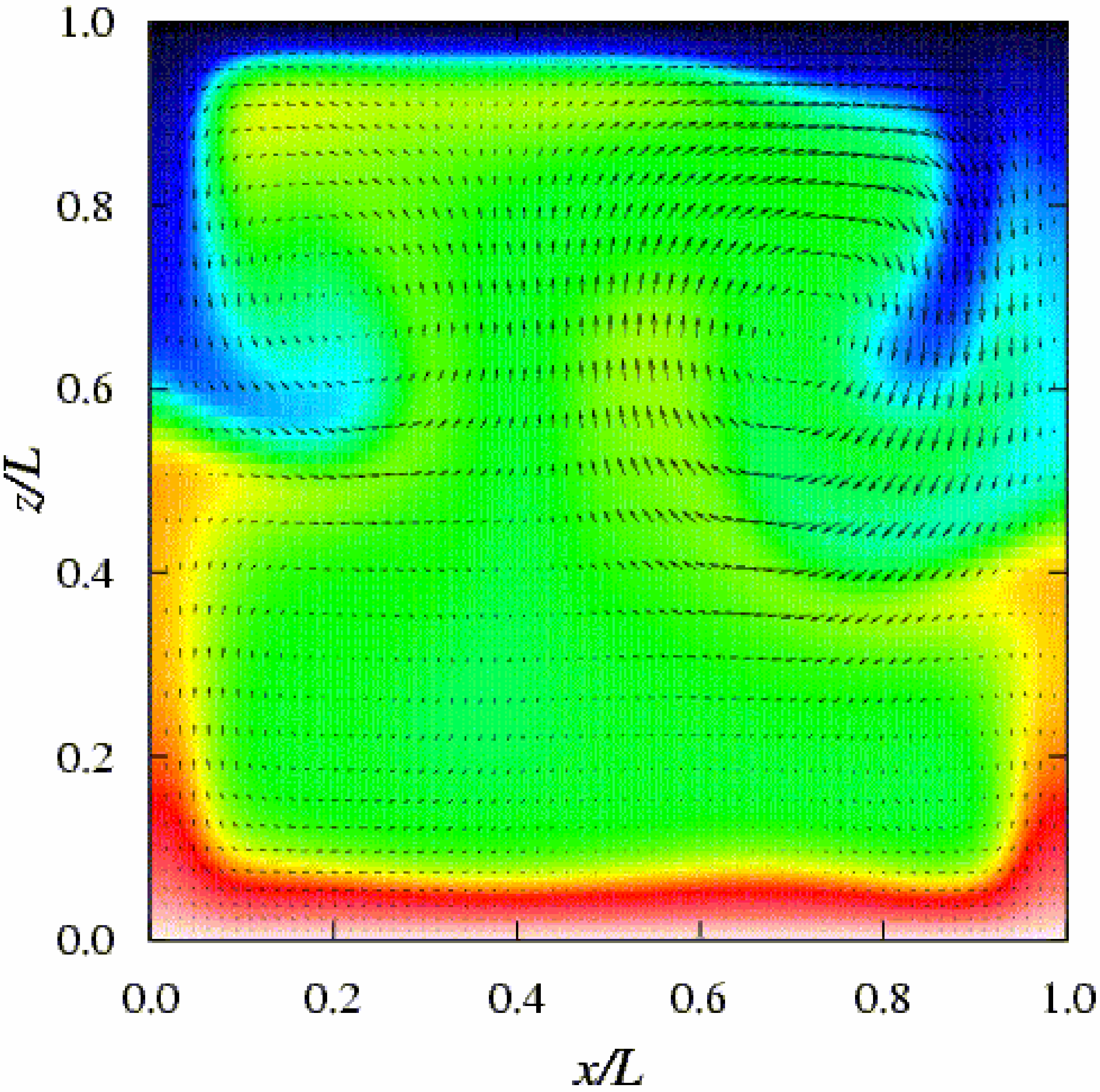
Kazu Sugiyama, Twente

2D OB-simulation, Pr=4, Ra=10^8



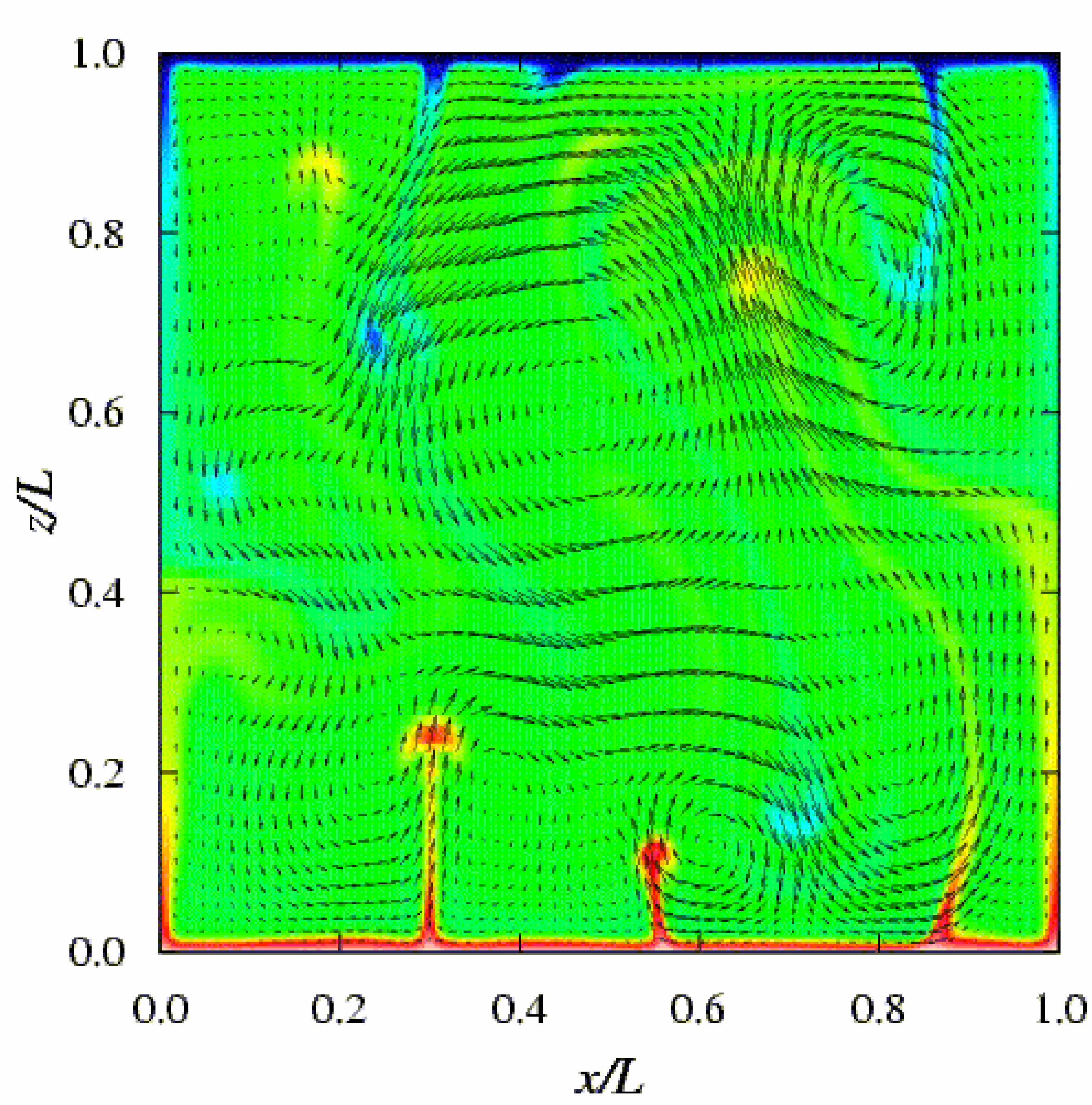
Kazu Sugiyama, Twente

2D OB-simulation, Pr=2540, Ra=10^6



Glycerol, Kazu Sugiyama, Twente

2D OB-simulation, Pr=2540, Ra=10^8



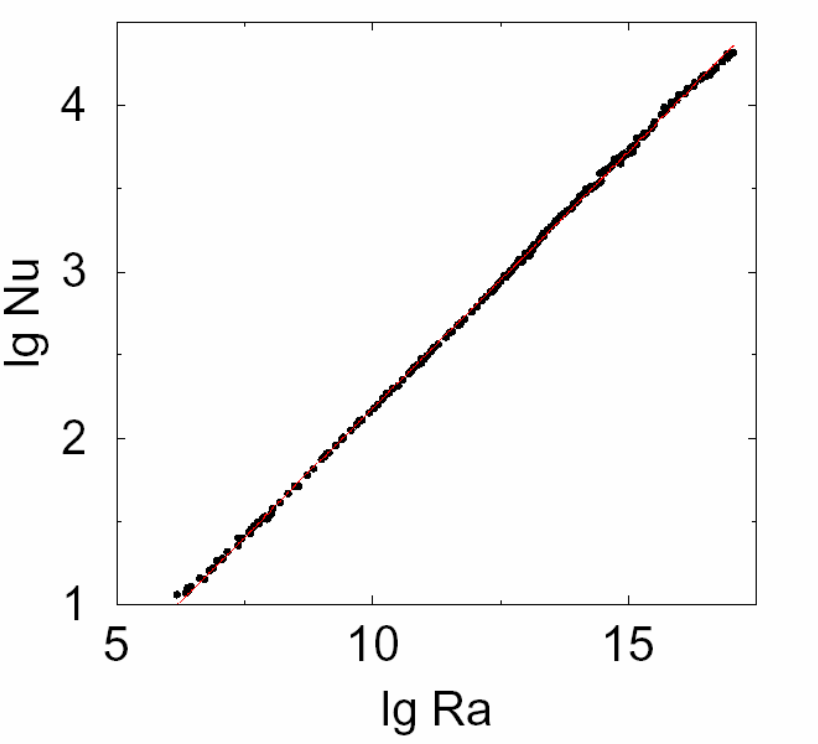
Glycerol, Kazu Sugiyama, Twente

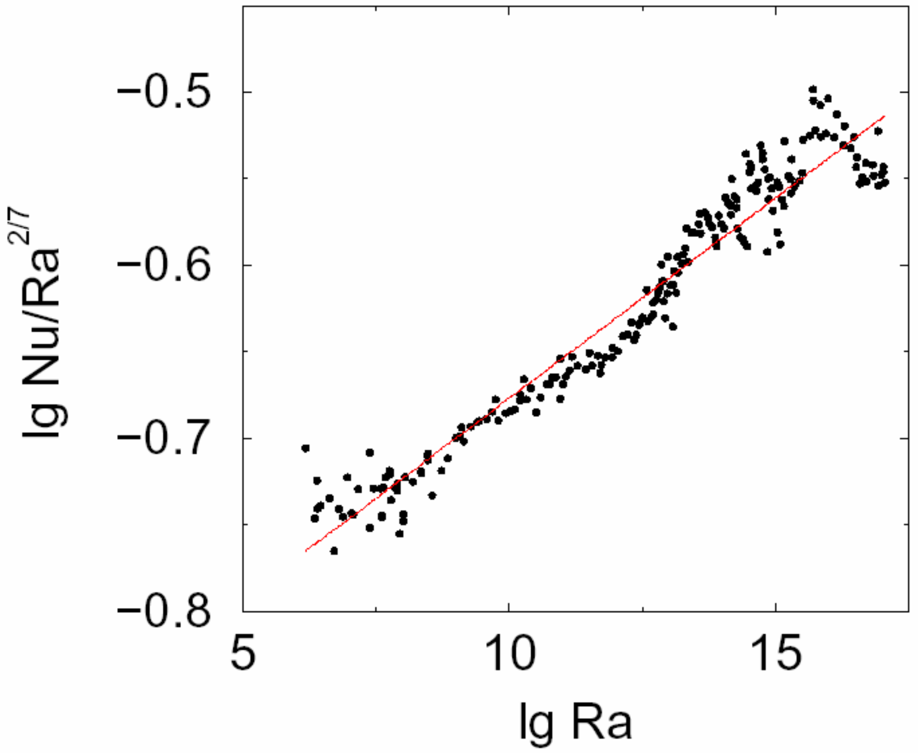
Focus on global scaling laws

Nu(Ra): Scaling Nu~Ra$^{\gamma}$

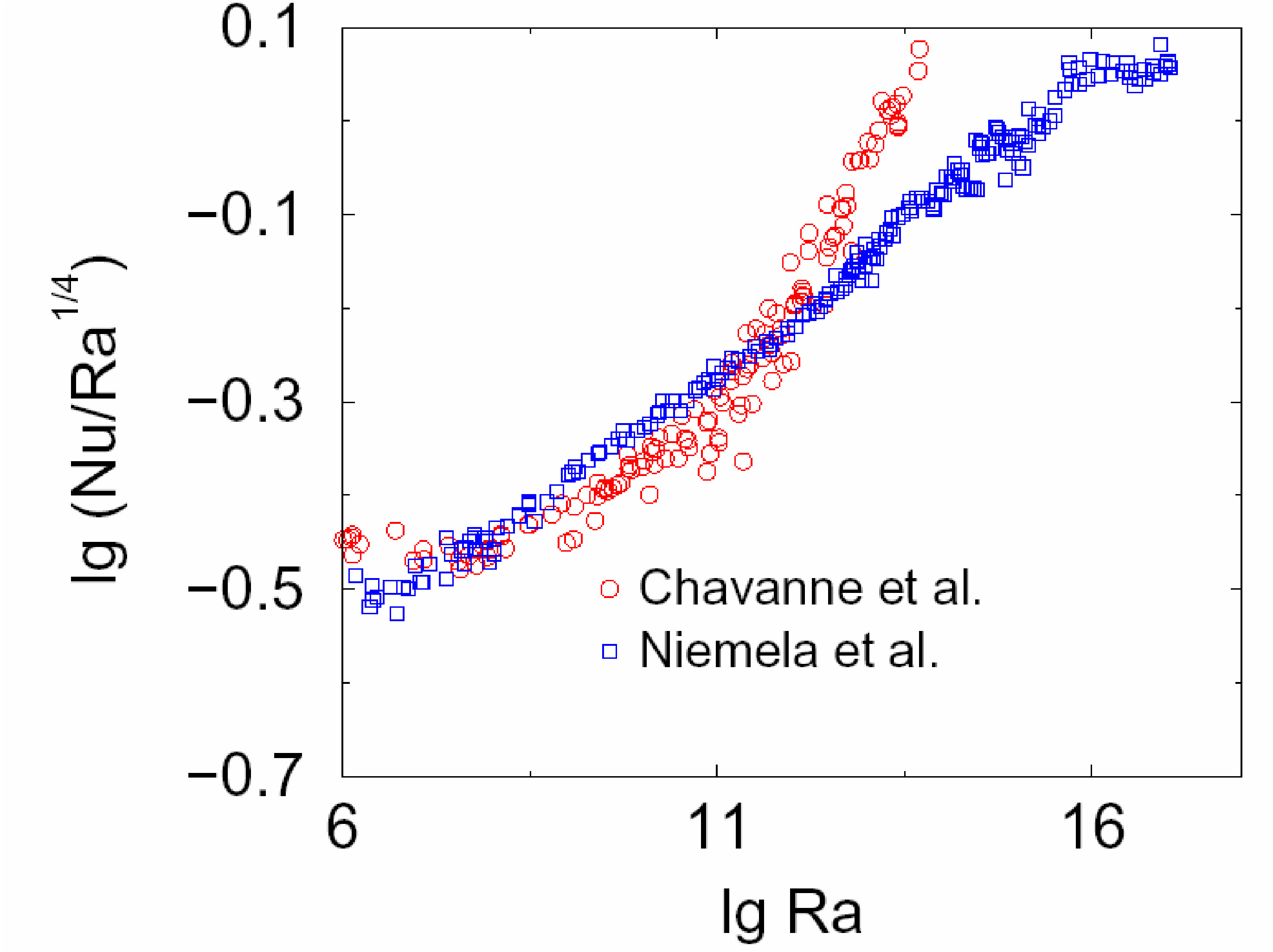
$\gamma = 2/7$ (Castaing, Libchaber, Kadanoff, et al., JFM, 1989, Siggia, ARFM 1994)

$\gamma = 0.31$ (Sreenivasan., Nature, 2000)





Nu(Ra) for large Ra



Chavanne et al., PRL79, 3648 (1997); Niemela et al., Nature 404, 837 (2000)

Reference	fluid	Pr	Ra range	γ
Ashkenazi & Steinberg (1999)	SF_6	1–93	10^9–10^{14}	0.30 ± 0.03
Garon & Goldstein (1973)	H_2O	5.5	10^7–3×10^9	0.293
Tanaka & Miyata (1980)	H_2O	6.8	3×10^7–4×10^9	0.290
Goldstein & Tokuda (1980)	H_2O	6.5	10^9–2×10^{11}	$\frac{1}{3}$
Qiu & Xia (1998)	H_2O	≈ 7	2×10^8–2×10^{10}	0.28
Lui & Xia (1998)	H_2O	≈ 7	2×10^8–2×10^{10}	0.28 ± 0.06
Shen *et al.* (1996)	H_2O	≈ 7	8×10^7–7×10^9	0.281 ± 0.015
Threlfall (1975)	He	0.8	4×10^5–2×10^9	0.280
Castaing *et al.* (1989)	He	0.7–1	$\lesssim 10^{11}$	0.282 ± 0.006
Wu & Libchaber (1991)	He	0.6–1.2	4×10^7–10^{12}	0.285
Chavanne *et al.* (1997)	He	0.6–0.73	3×10^7–10^{11}	$\frac{2}{7}$
Davis (1922)	air	≈ 1	$\lesssim 10^8$	0.25
Rossby (1969)	Hg	0.025	2×10^4–5×10^5	0.247
Takeshita *et al.* (1996)	Hg	0.025	10^6–10^8	0.27
Cioni *et al.* (1997)	Hg	0.025	5×10^6–5×10^8	0.26 ± 0.02
Cioni *et al.* (1997)	Hg	0.025	4×10^8–2×10^9	0.20
Glazier *et al.* (1999)	Hg	0.025	2×10^5–8×10^{10}	0.29 ± 0.01
Horanyi *et al.* (1998)	Na	0.005	$\lesssim 10^6$	0.25

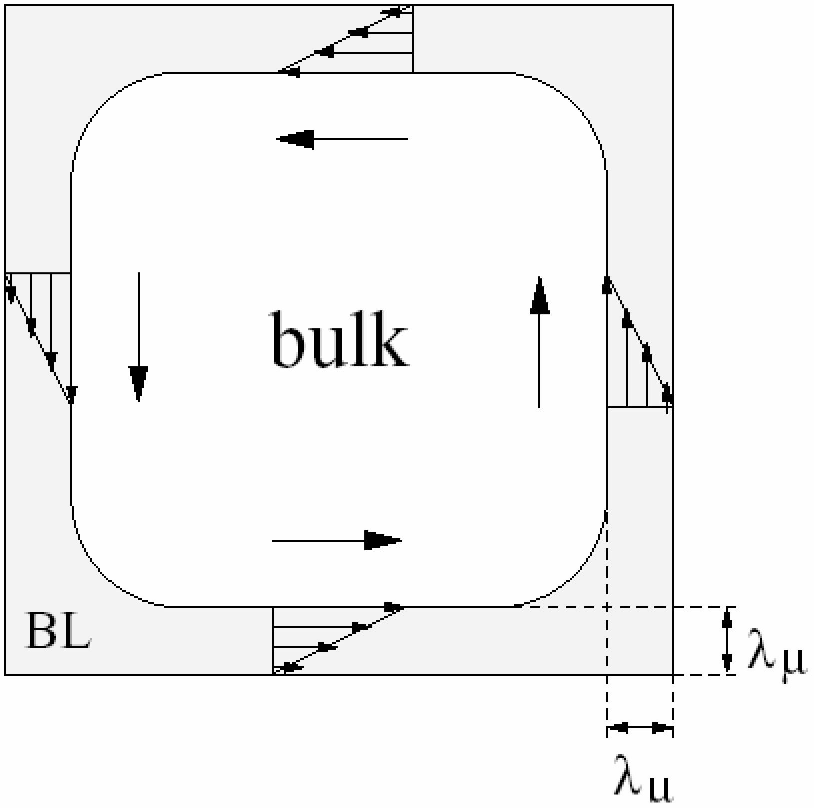
TABLE 1. Power-law exponents γ of the power law $Nu \sim Ra^{\gamma}$ for various experiments. The experiments were done with different aspect ratios; however, no strong dependence of the scaling exponent γ on the aspect ratio is expected (in contrast to the prefactors, which do have an aspect ratio dependence as found by Wu & Libchaber 1992).

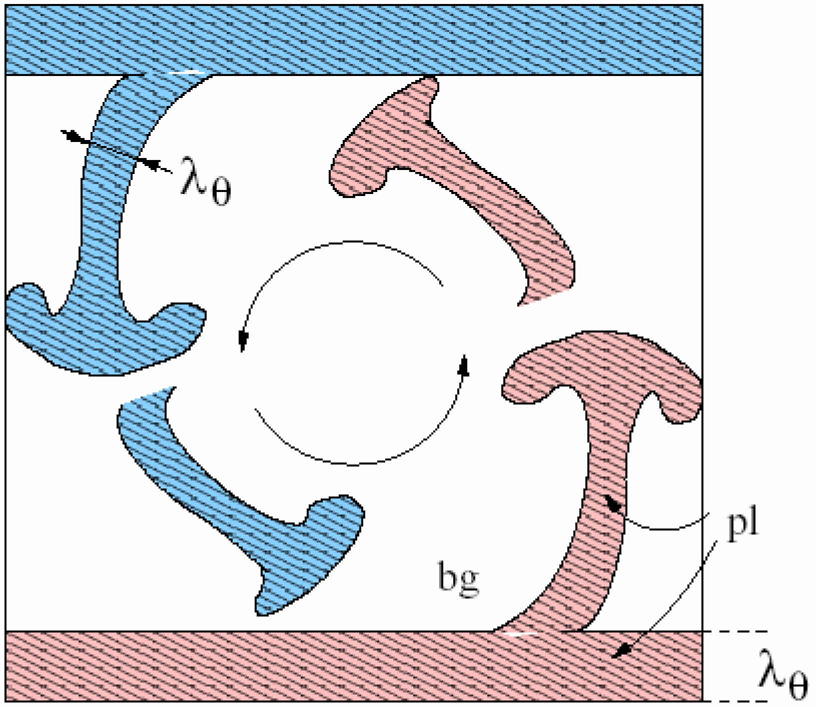
Central idea: Splitting of dissipations into bulk and BL contribution

$$\epsilon_u = \epsilon_{u,BL} + \epsilon_{u,bulk}$$

$$\epsilon_\theta = \epsilon_{\theta,BL} + \epsilon_{\theta,bulk}$$

Decomposition of kinetic and thermal dissipation

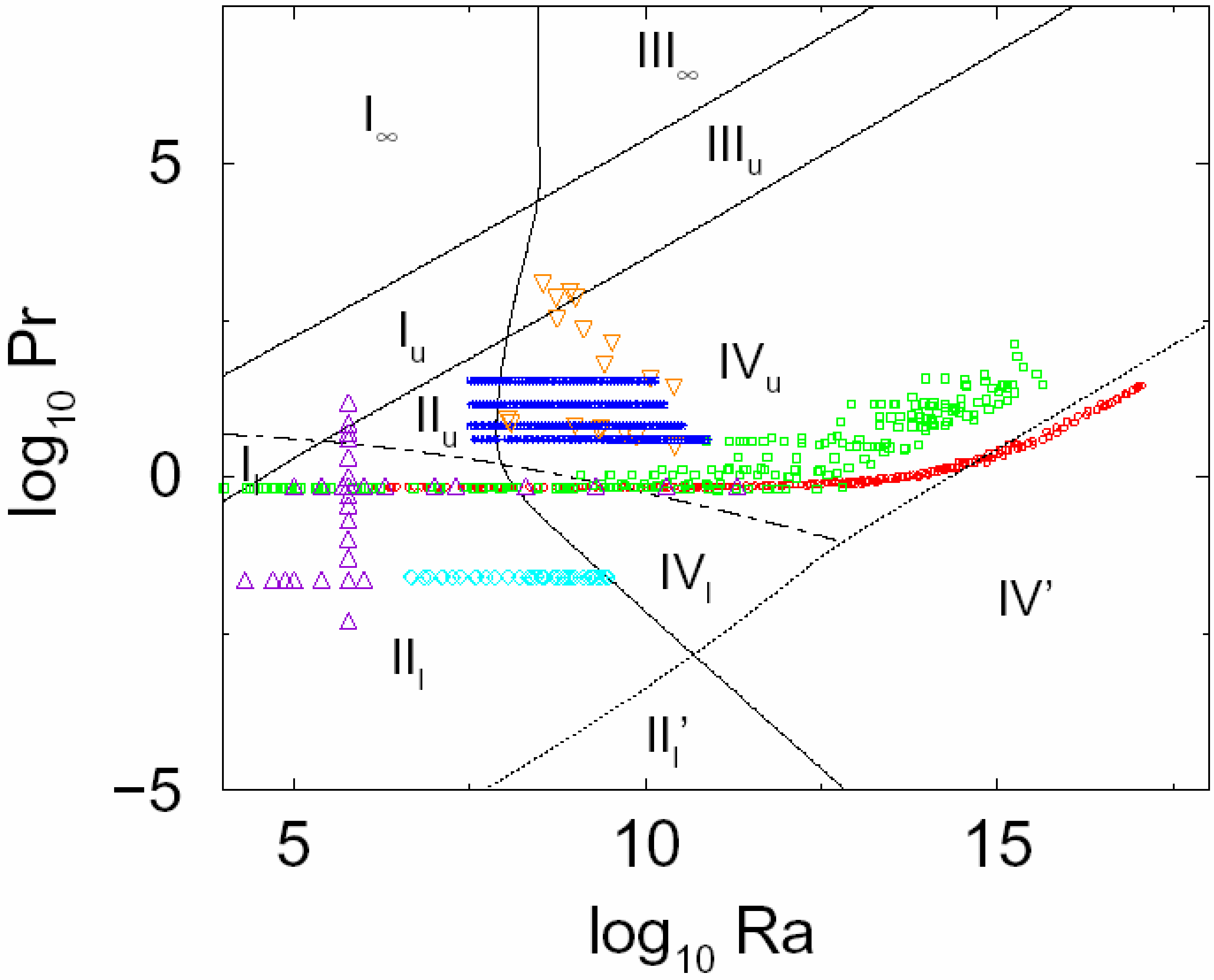




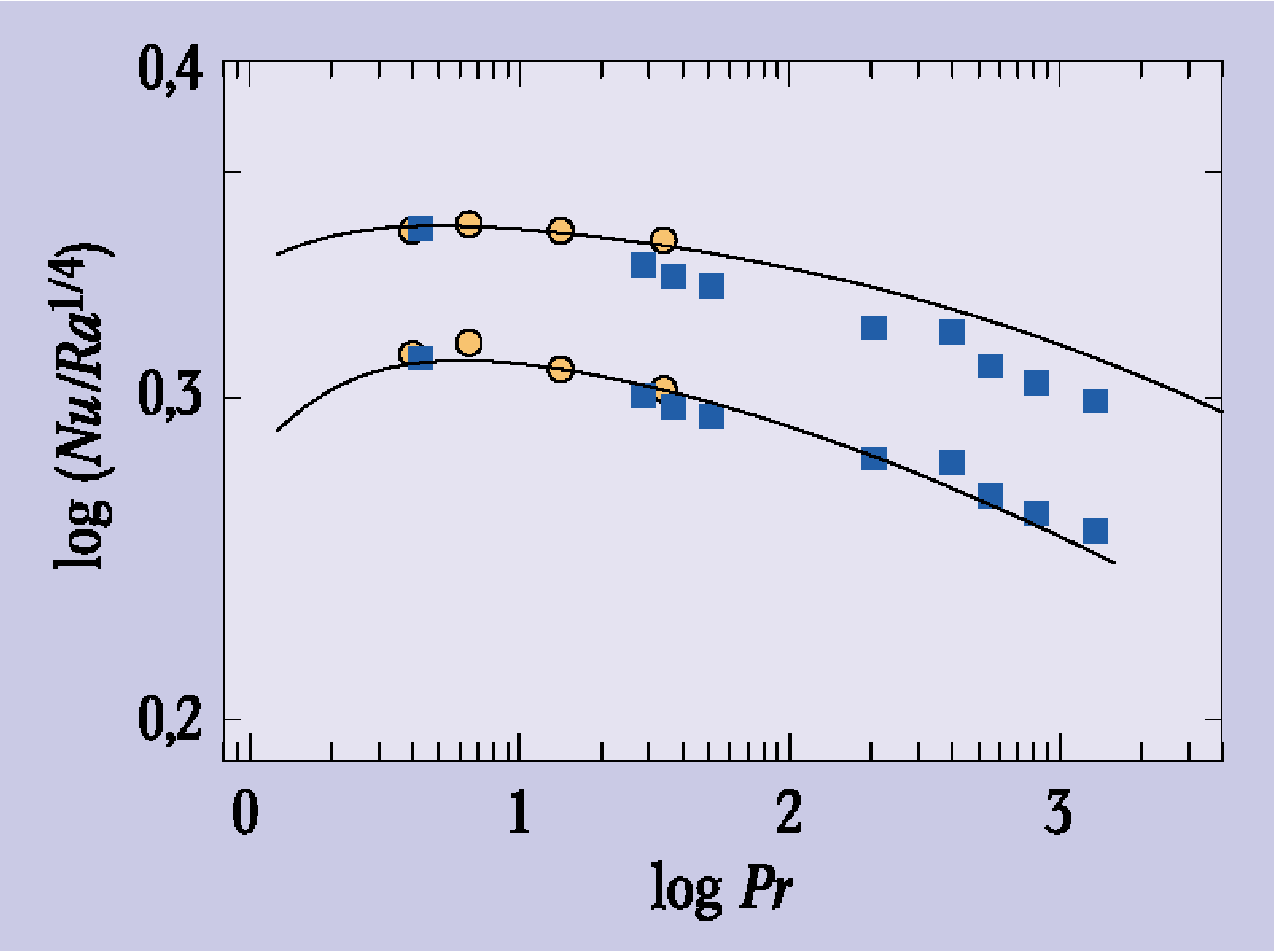
$$\boxed{\epsilon_u = \epsilon_{u,BL} + \epsilon_{u,bulk}}$$

$$\boxed{\epsilon_\theta = \epsilon_{\theta,pl} + \epsilon_{\theta,bg}}$$

Phase diagram with data points



Prediciton of Nu(Pr) for large Pr

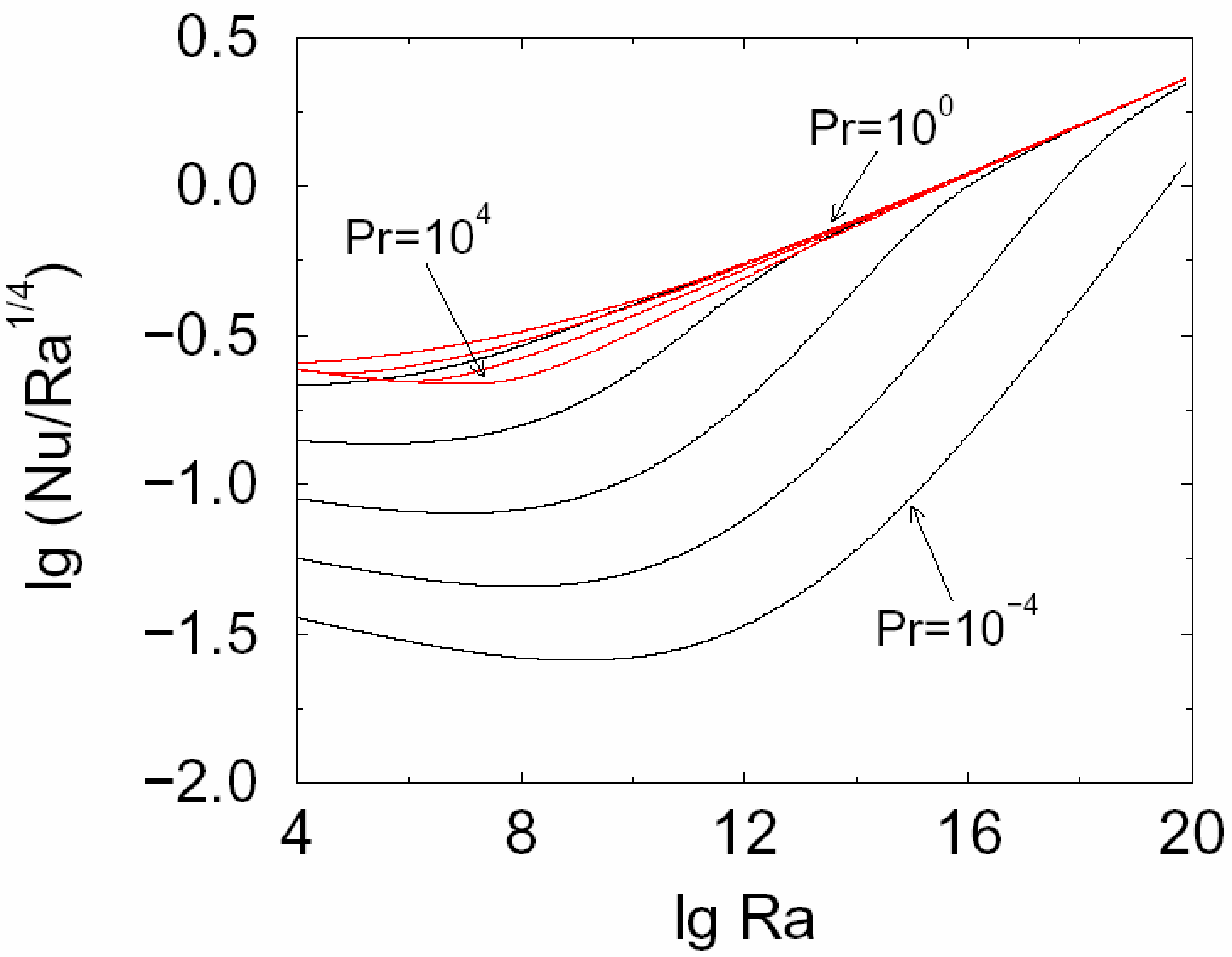


Ra=1.78 10^9

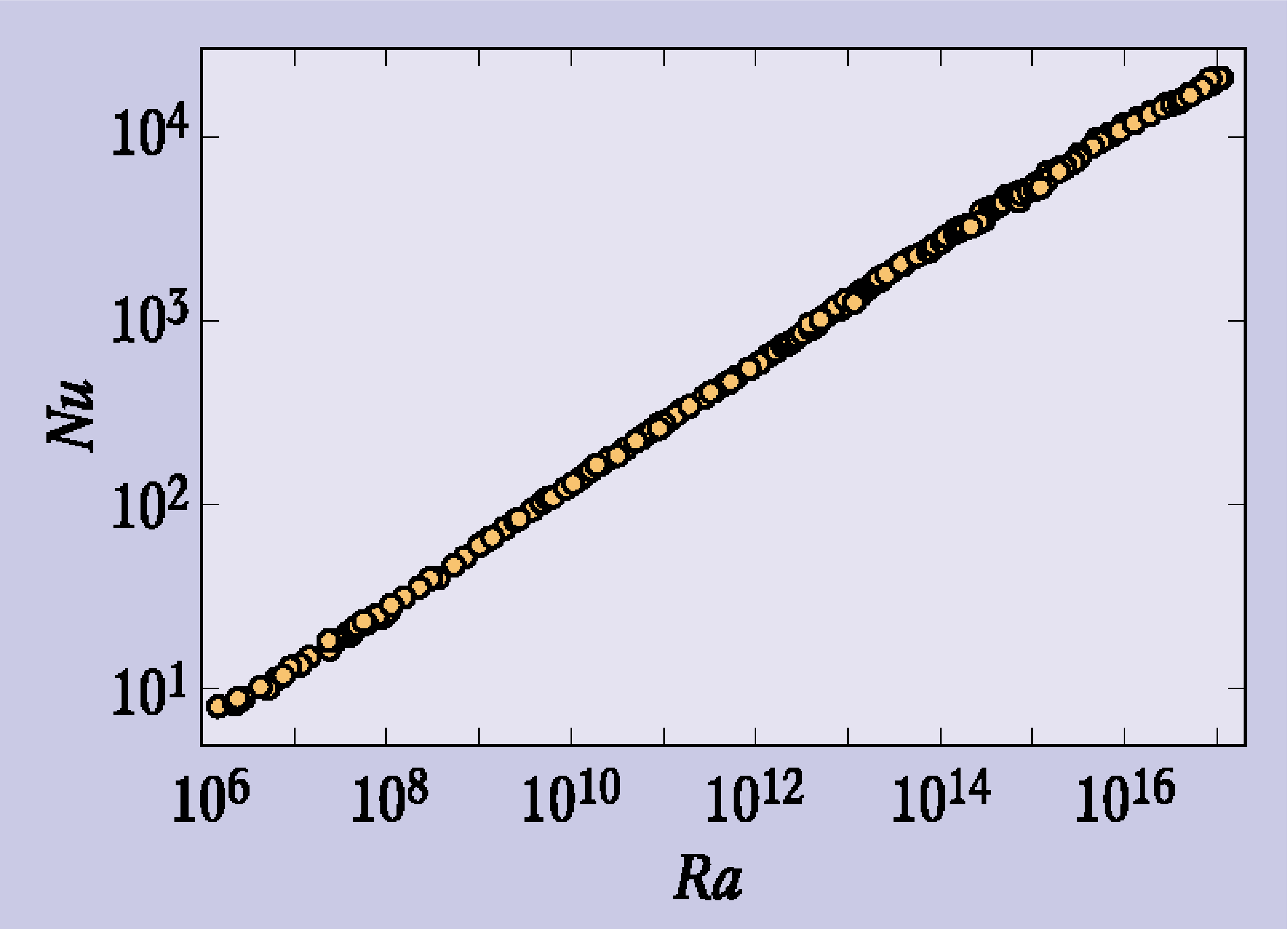
Ra=5.62 10^7

Xia et al, PRL, 2002

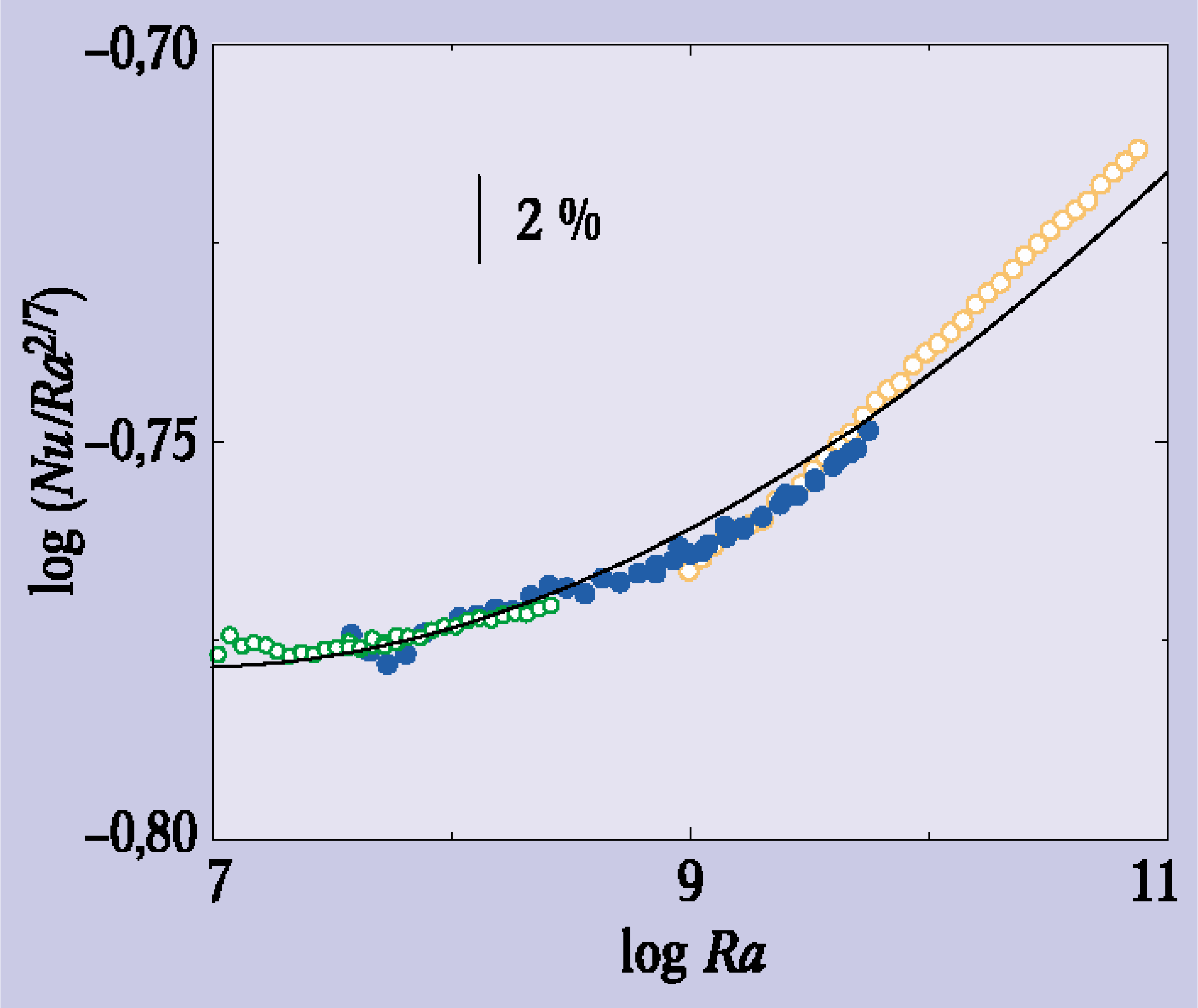
Also Nu(Ra): no (pure) power law!



Nu(Ra)



Ahlers et al., PRL 2001



Experimental confirmation that there is no power law in Nu(Ra)!

Summary of GL theory

- Systematic, Boussinesq-eq. & Prandtl-Blasius based theory → **Phase space of RB convection**
- No power laws as in general BL and bulk contribute
- Power laws only recover asymptotically
- Consistent with experimental observations

Nu (Ra, Pr)

Re (Ra, Pr)