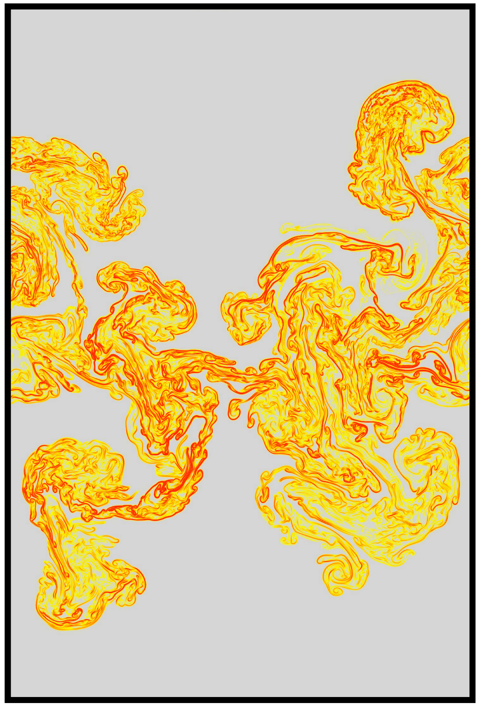
Rayleigh-Taylor Turbulence in stratified and unstratified flows

Luca Biferale
Dept. of Physics & INFN, University of Rome "Tor Vergata"
International Collaboration for Turbulence Research



with: F. Mantovani, L. Tripiccione (Ferrara, Italy)
M. Sbragaglia (Rome, Italy)
A. Scagliarini (Barcellona, Spain)
F. Toschi (Eindhoven, The Netherlands)

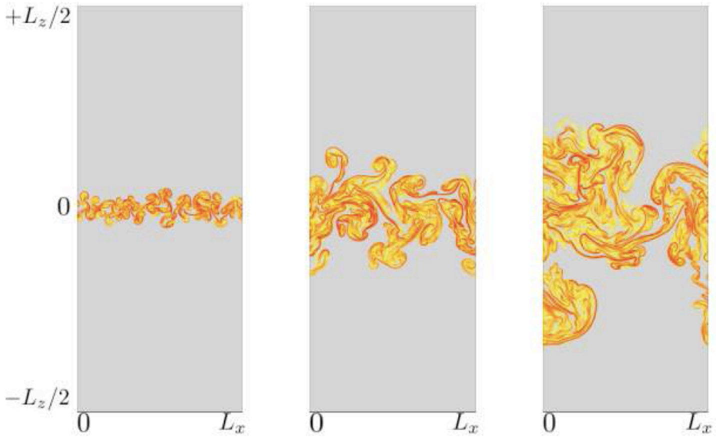
Rayleigh Taylor systems in 2d:

-) Incompressible unstratified at large Reynolds
-) Compressible unstratified at “moderate” Reynolds
-) Incompressible stratified at large Reynolds
-) Incompressbile unstratified + reaction at large Reynolds

High resolution (4096x10000) 2D Rayleigh-Taylor turbulence

Why 2D:

- to test thermal Lattice Boltzmann at high resolution and fully developed turbulence
- to study Bolgiano small-scales physics, a case relevant for 3d convection close to the wall
- to study overshooting between turbulent and stratified layers
- To study conspiracy between reactions and RT instability



-Lattice Boltzmann Methods for thermal flows: continuum limit and applications to compressible Rayleigh-Taylor systems. A. Scagliarini, L. B, M. Sbragaglia, K. Sugiyama, and F. Toschi, PoF (2010)

-High Resolution study of Rayleigh-Taylor turbulence: small scales statistics. L. B, F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PoF (2010)

-Second order closure for stratified convection: bulk region and overshooting: L.B., F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PRE (2011)

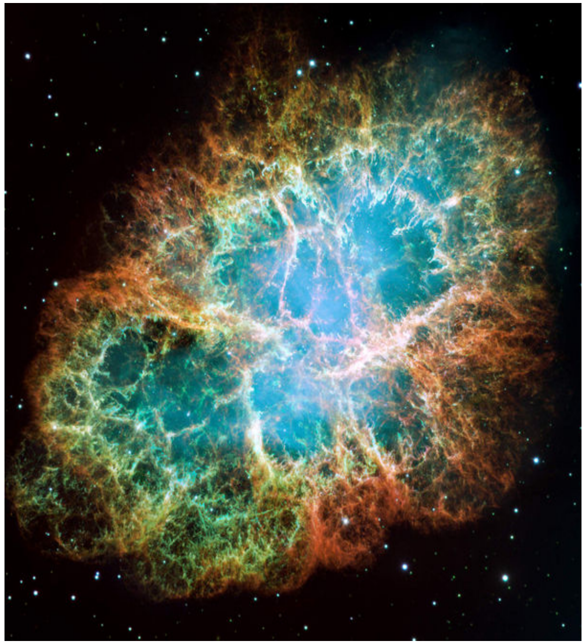
-Reactive RT systems: front propagation and non-stationarity; L.B. F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, EPL (2011)

The Rayleigh-Taylor instability

DEFINITION: **We talk about a Rayleigh-Taylor instability when a denser fluid is accelerated against a lighter one.**

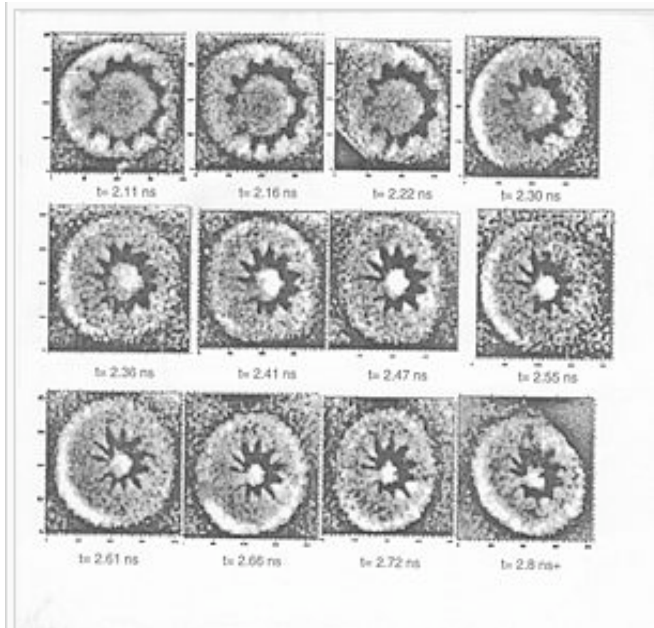
EXAMPLES:

Supernova explosion



"Mammatus clouds"

Inertial confinement nuclear fusion



<u>Kolmogorov (3d) vs Bolgiano (2d)</u>

M. Chertkov, Phys. Rev. Lett. **91**, 115001 (2003).

in 2d: kinetic energy dissipation is vanishing small

$$\partial_t\langle(\delta_r u)^2\rangle + \frac{d}{dr}\langle(\delta_r u)^3\rangle = -\epsilon_{diss} + g\langle\delta_r u\delta_r T\rangle \qquad L_B \to 0$$

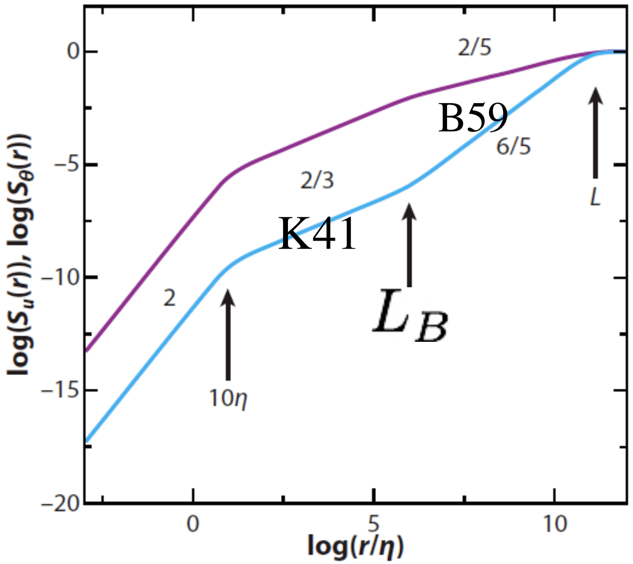
$$L_B \sim \epsilon_\nu^{5/4}\epsilon_\theta^{-3/4}g^{-3/2}$$

BOLGIANO THEORY 2D

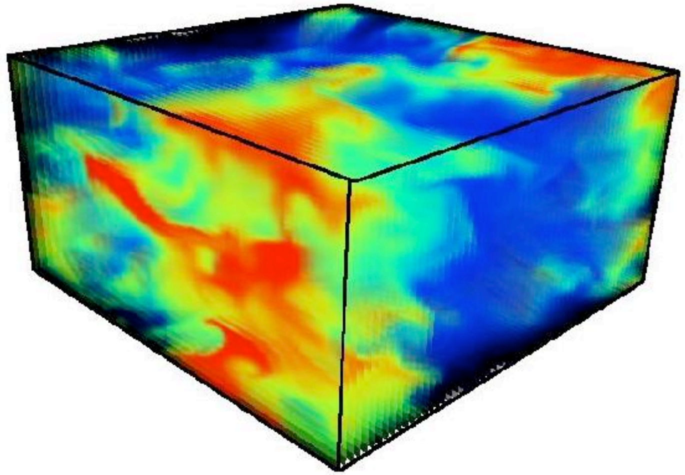
$$\begin{cases}\langle(\delta_r u)^2\rangle \sim r^{6/5}\\ \langle(\delta_r T)^2\rangle \sim r^{2/5}\end{cases}$$

KOLMOGOROV THEORY 3D

$$\begin{cases}\langle(\delta_r u)^2\rangle \sim r^{2/3}\\ \langle(\delta_r T)^2\rangle \sim r^{2/3}\end{cases}$$



3d convection



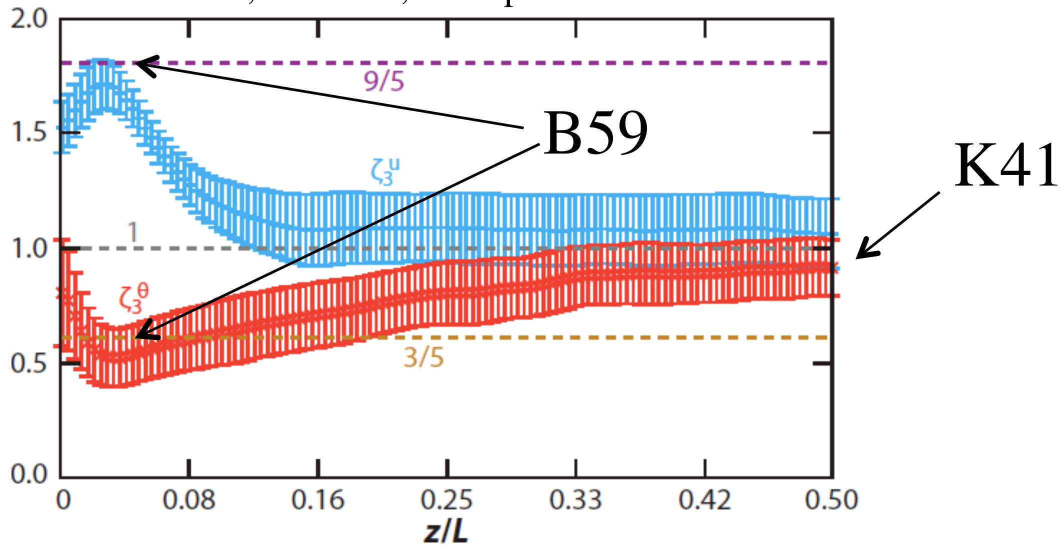
$$L_B \sim \epsilon_\nu^{5/4} \epsilon_\theta^{-3/4} g^{-3/2}$$

$$\langle (\delta_r u)^3 \rangle \sim r^{\zeta_v(3)}$$

$$\langle |\delta_r T|^3 \rangle \sim r^{\zeta_T(3)}$$

Lohse & Xia ARFM 2010

E. Calzavarini, F. Toschi, R. Tripiccione et al PRE 2002



$$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0$$

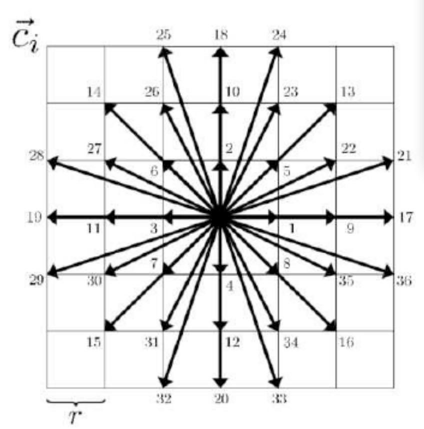
$$\rho(\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla P + \nabla \cdot \hat{D}$$

$$\rho(\partial_t T + \mathbf{u} \cdot \nabla T) = -P \nabla \cdot \mathbf{u} + \nabla \cdot (\kappa \nabla T) + \hat{D} : (\nabla \otimes \mathbf{u})$$

$$P = \rho T$$

$$f_l(\mathbf{x} + \mathbf{c}_l \Delta t, t + \Delta t) - f_l(\mathbf{x}, t) = -\frac{\Delta t}{\tau}(f_l(\mathbf{x}, t) - \bar{f}_l^{(eq)})$$

$$\bar{f}_l^{(eq)} \equiv f_l^{(eq)}(\rho, \mathbf{u} + \tau \mathbf{K}, T - \tau^2 K^2 / D)$$



Examples:

External body-force (e.g.: gravity):
Rayleigh-Bénard and Rayleigh-Taylor systems +
Stratifications + Compressibility

Internal force from pseudo-potentials (Shan-Chen model):
multiphase fluids

(Shan et al., **J. Fluid. Mech. 550**, 413 (2006))
(Sbragaglia et al., **J. Fluid. Mech. 628**, 299 (2009))

$$\bar{\boldsymbol{u}}^{(L)} = \boldsymbol{u}^{(L)} + \tau \boldsymbol{g} \qquad \bar{T}^{(L)} = T^{(L)} + \frac{\tau(\Delta t - \tau)g^2}{D} + \mathcal{O}(\Delta t)^2.$$

$$\boldsymbol{u}^{(H)} = \boldsymbol{u}^{(L)} + \frac{\Delta t}{2}\boldsymbol{g} \qquad T^{(H)} = T^{(L)} + \frac{(\Delta t)^2 g^2}{4D}.$$

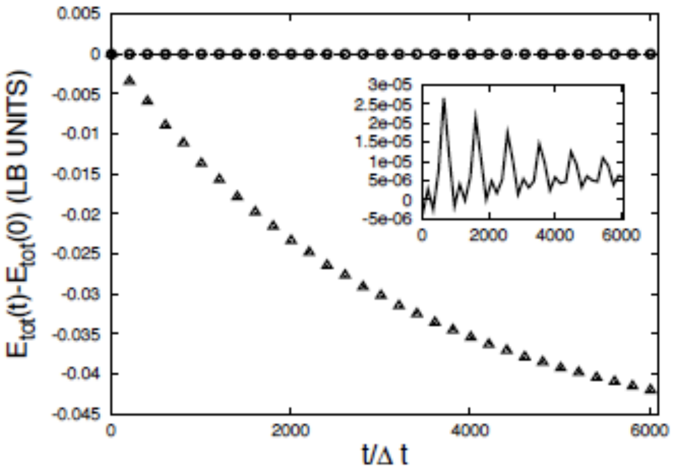


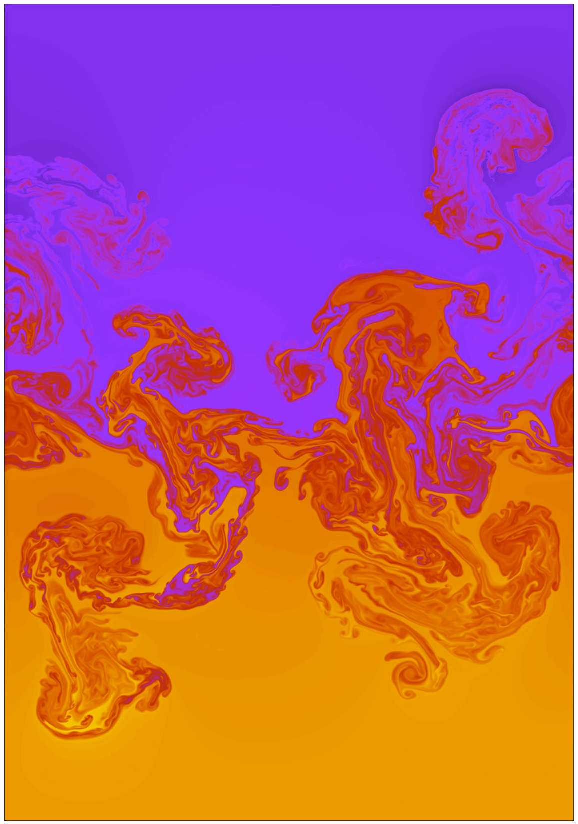
FIGURE 1. Variations of total energy for a non ideal system with an initial sinusoidal wave in the temperature field $\theta^{(H)}(x, y, t = 0) = 1.0 + \epsilon \sin(2\pi y/L_y)$ with $\epsilon = 0.01$ and smooth hydrodynamical velocity fields. The lattice Boltzmann parameters in (4.1) and (1.5) are such that $\tau/\Delta t = 0.6$, $\mathcal{G} = -3.0$. Two simulations are carried out. The first simulation is only with shifted momentum ($\triangle$). A second one with shifted momentum and temperature ($\circ$), enlarged in the inset.

initial state

$$T(x,z,t) = \bar{T}(z,t) + \theta(x,z,t)$$

$$\begin{cases} \partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0 \\ \rho(\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u}) = -\nabla P + \nabla \cdot \hat{D} \\ \rho(\partial_t T + \mathbf{u} \cdot \nabla T) = -P \nabla \cdot \mathbf{u} + \nabla \cdot (\kappa \nabla T) + \hat{D} : (\nabla \otimes \mathbf{u}) \end{cases}$$

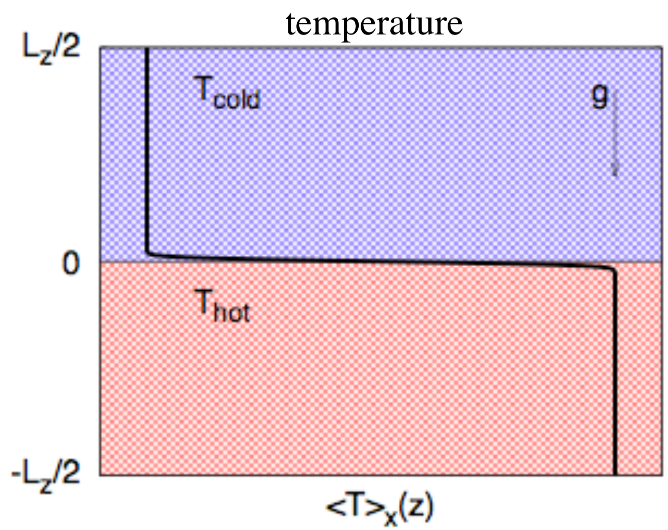
g

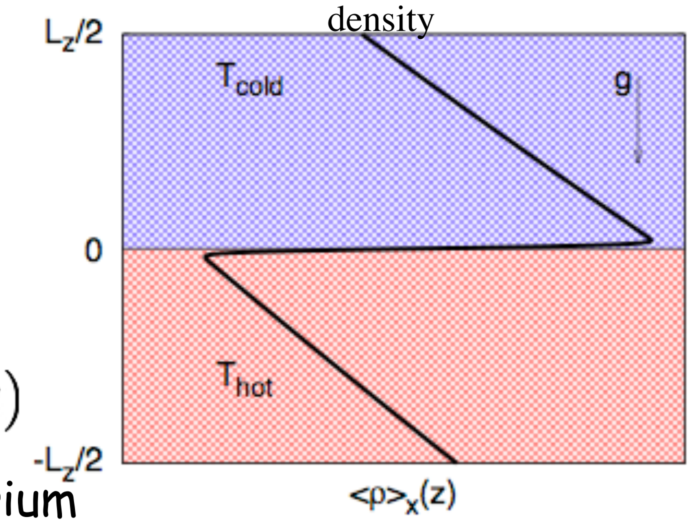


$L(t)$

$$\partial_z p(z) = -g\rho(z)$$

hydrostatic equilibrium



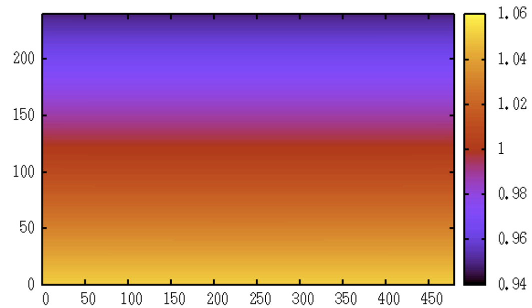


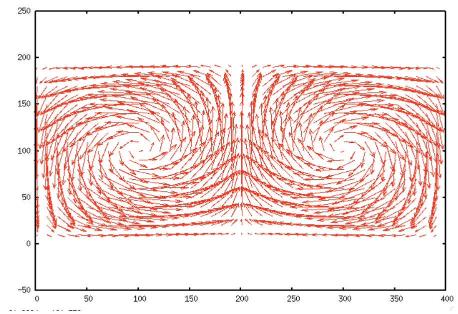
Transition to convection

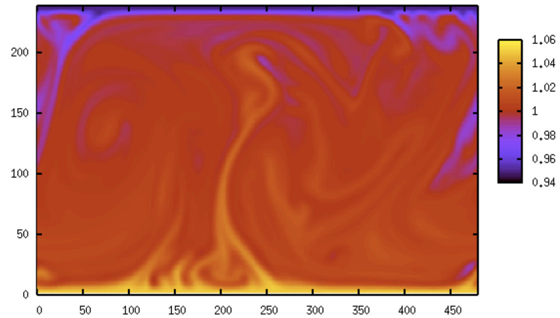
The dimensionless controlling parameter is the **Rayleigh number**

$$\mathcal{R}a = \frac{\alpha g \Delta T H^3}{\nu \kappa}$$

Conductive state → $\mathcal{R}a_c$ → Convective state → Turbulent convection







$\mathcal{R}a$ →

The response of the system to the increase of the Rayleigh number can be checked by measuring the **Nusselt number**

$$Nu = \frac{\langle u_z T \rangle - \kappa \langle \partial_z T \rangle}{\kappa \frac{\Delta T}{H}}$$

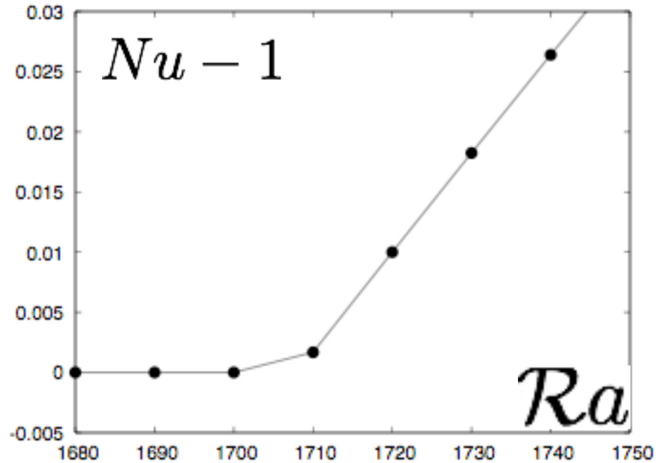
it is the **dimensionless heat flux!**

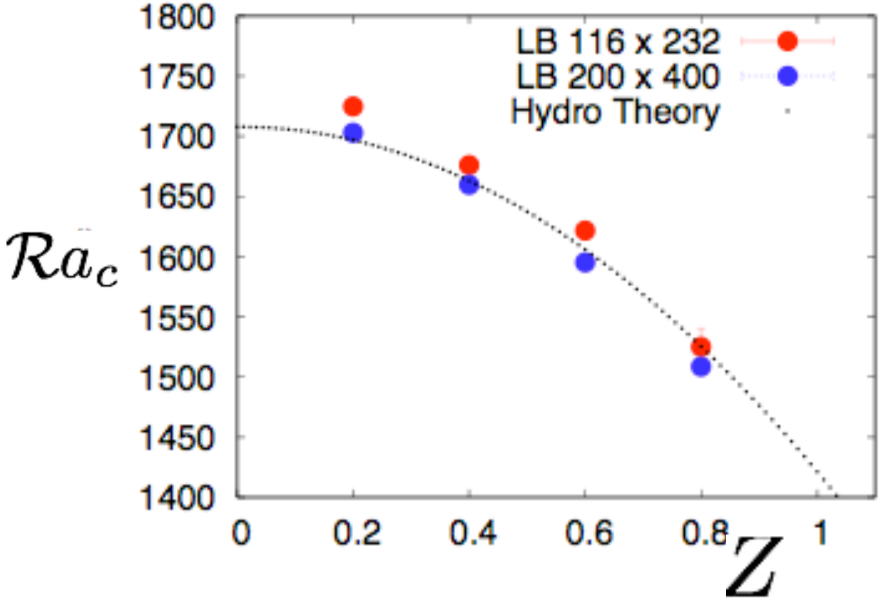
NOB and compressibility effects

Data from numerical simulations based on a 2D LB algorithm with 37 lattice speeds.

The departure from the OB regime can be controlled by the so called **depth parameter**

$$Z = \frac{\Delta T}{T_{up}}$$





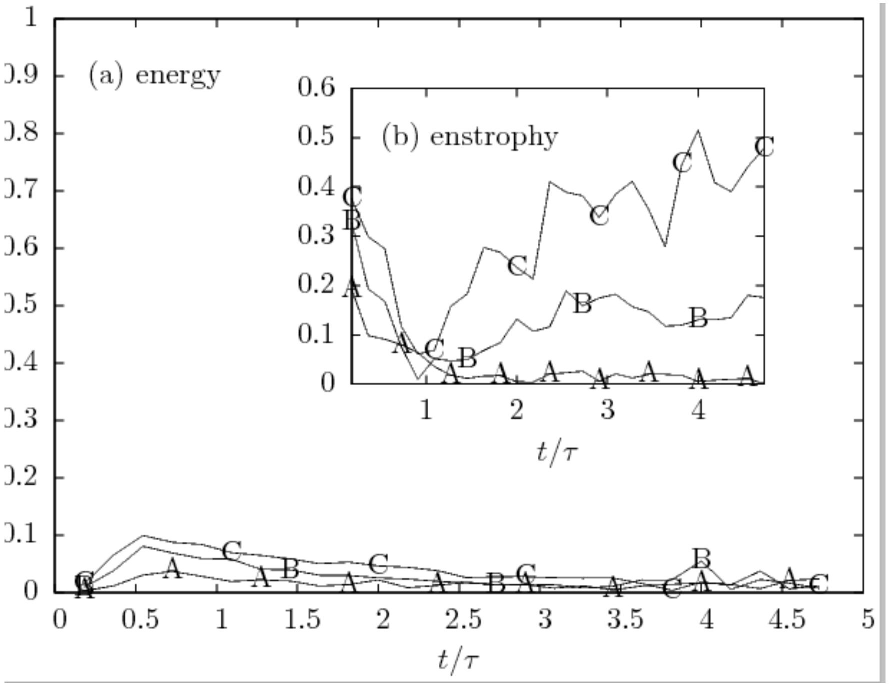
The theoretical prediction results from a linear stability analysis of the hydrodynamic equations.

Nie **et al.**, **PRE 77**, 035701 (2008)
Spiegel, **Ap. J. 141**, 1068 (1965)
Gough **et al.**, **Ap. J. 206**, 536 (1976)

LBM ACCURACY

	At	L_x	L_z	ν	k	g	T_{up}	T_{down}	τ	L_γ	$\eta(\tau)$	Ra_{max}	N_{conf}
run (A)	0.05	4096	10000	0.005	0.005	2×10^{-5}	0.95	1.05	6.4×10^4	10000	4.3	8×10^9	18
run (B)	0.05	4096	6000	0.0025	0.0025	2.67×10^{-5}	0.95	1.05	5.5×10^4	7500	2.2	2×10^{10}	5
run (C)	0.05	4096	6000	0.001	0.001	2.67×10^{-5}	0.95	1.05	5.5×10^4	7500	1.5	1×10^{11}	23

$$\begin{cases} \partial_t \frac{1}{2}\langle u^2 \rangle_V = -\epsilon_\nu + g\langle \theta u_z \rangle_V \\ \partial_t \frac{1}{2}\langle w^2 \rangle_V = -\epsilon_\omega + g\langle \partial_x \theta w \rangle_V , \end{cases}$$



Rayleigh Taylor systems in 2d:

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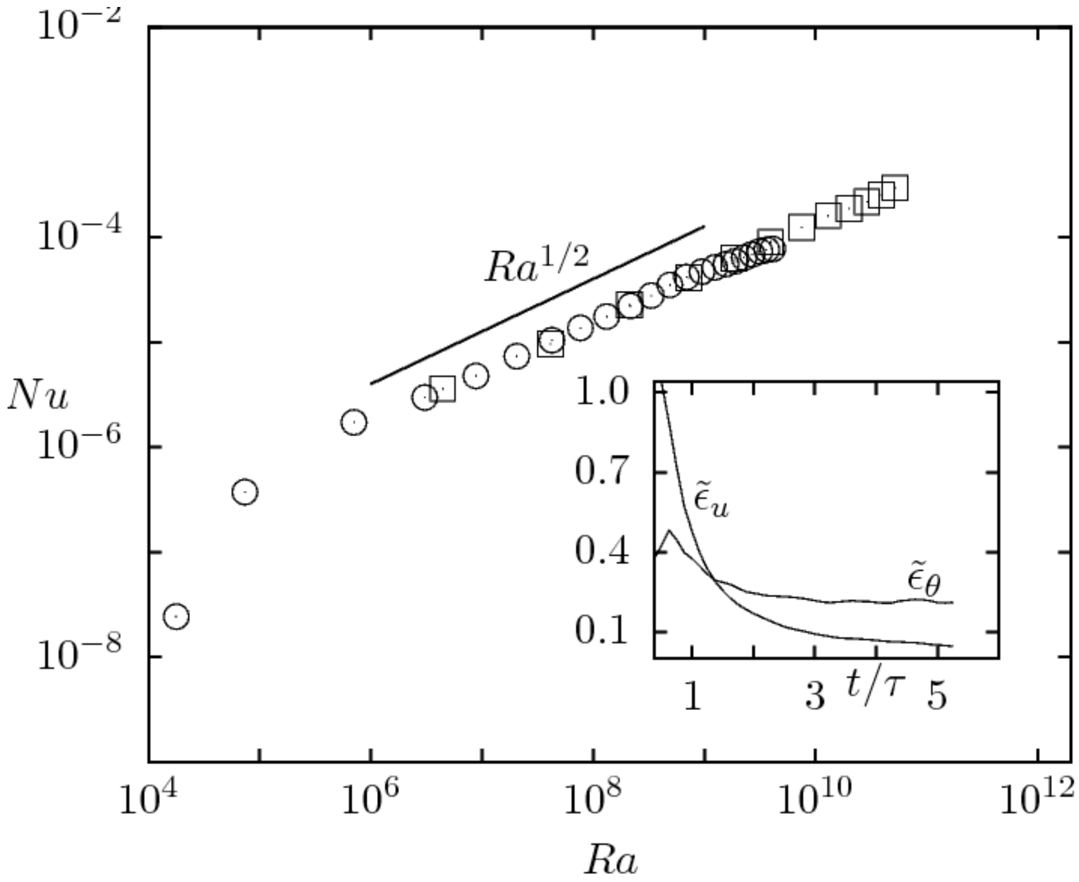


1. Kraichnan ultimate regime: $Nu \sim Ra^{1/2}$
2. absence of kinetic energy anomaly: $\epsilon_\nu \to 0$

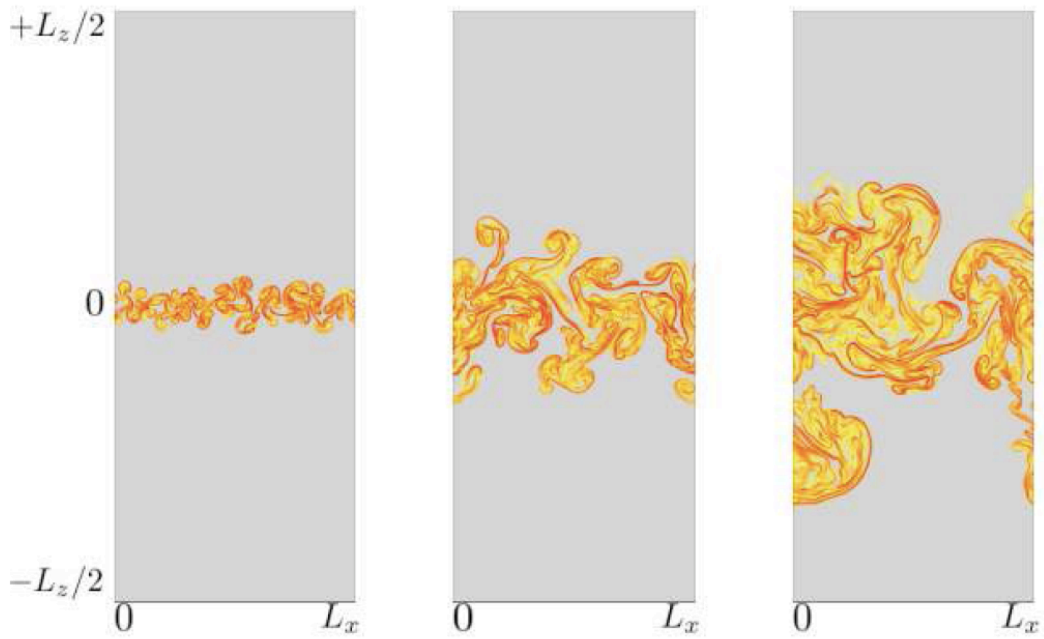
$$L_B \sim \epsilon_\nu^{5/4} \epsilon_\theta^{-3/4} g^{-3/2} \to 0$$

$$\delta_R \theta = \theta(\mathbf{x} + R) - \theta(\mathbf{x})$$

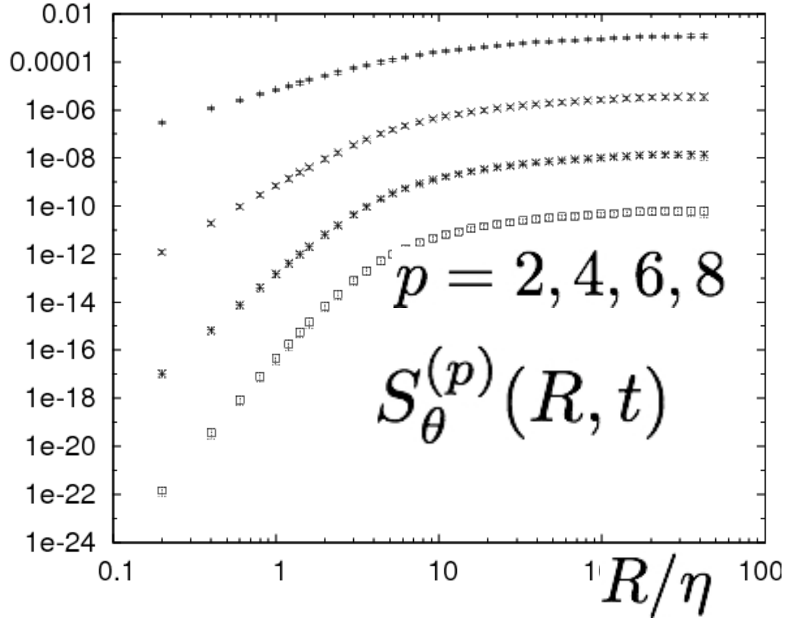
$$\delta_R u_i = u_i(\mathbf{x} + R) - u_i(\mathbf{x})$$

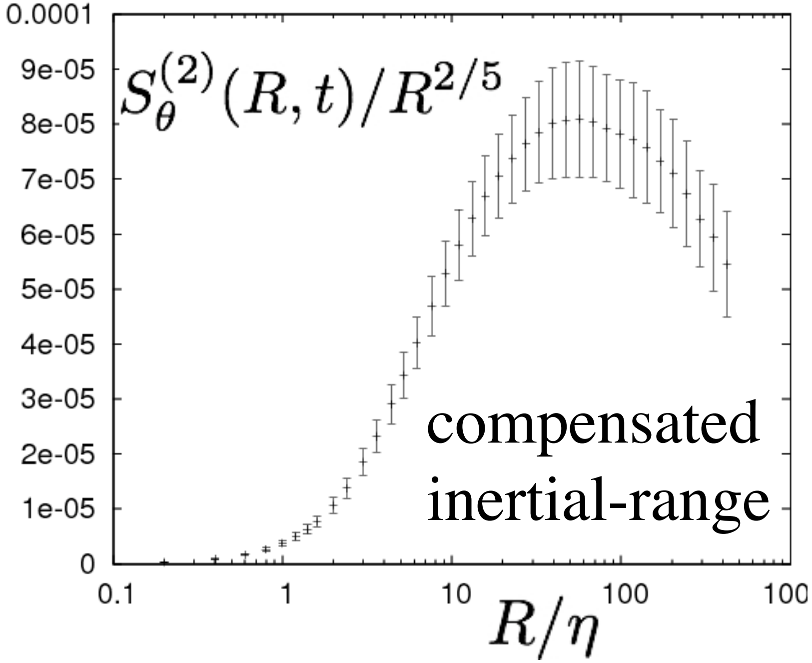
$$S_\theta^{(p)}(R,t) = \langle |\delta_R \theta|^p \rangle$$

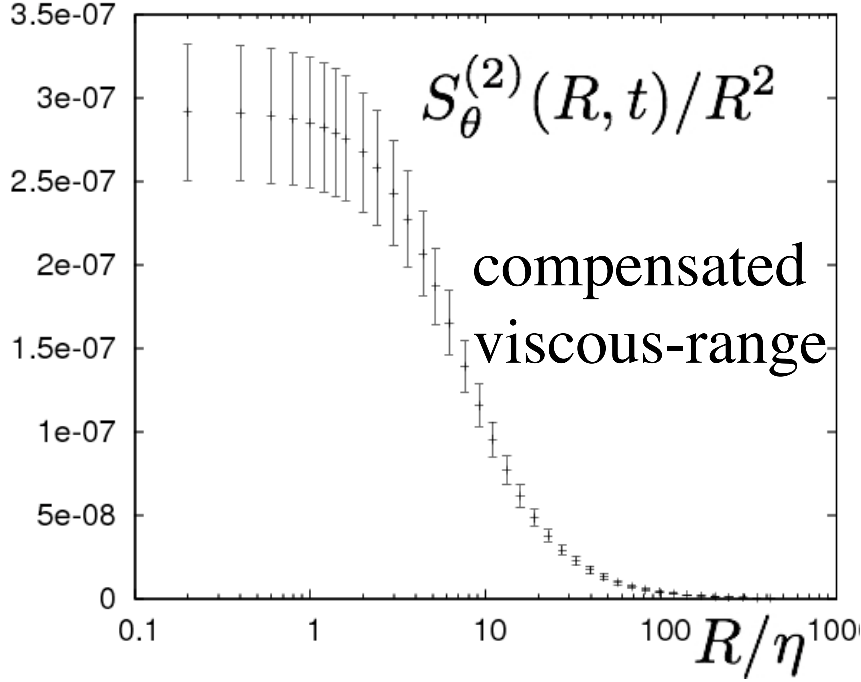
$$S_{u_i}^{(p)}(R,t) = \langle |\delta_R u_i|^p \rangle; \qquad i = x, z$$

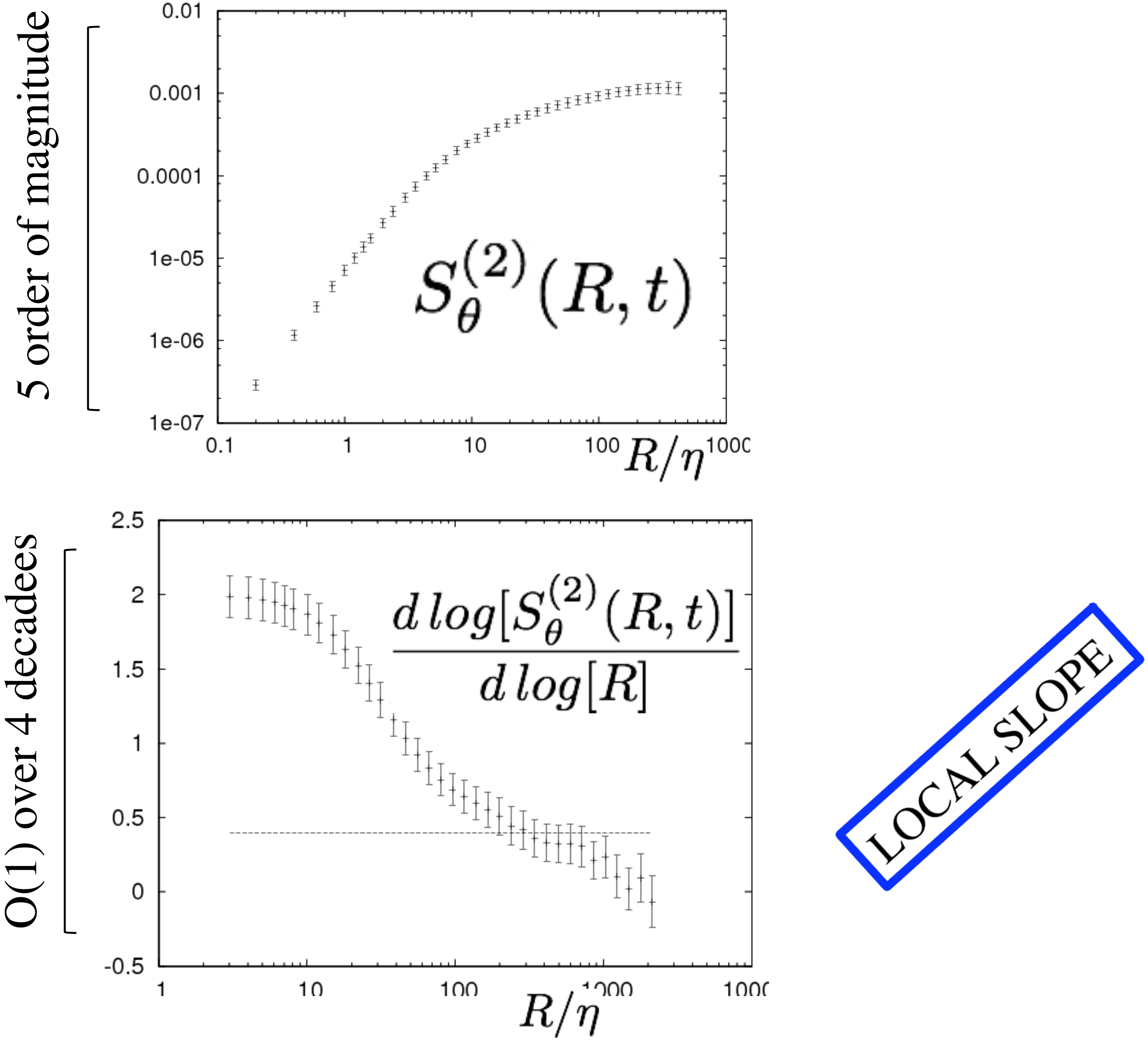


How to probe physics varying over 24 order of magnitude?







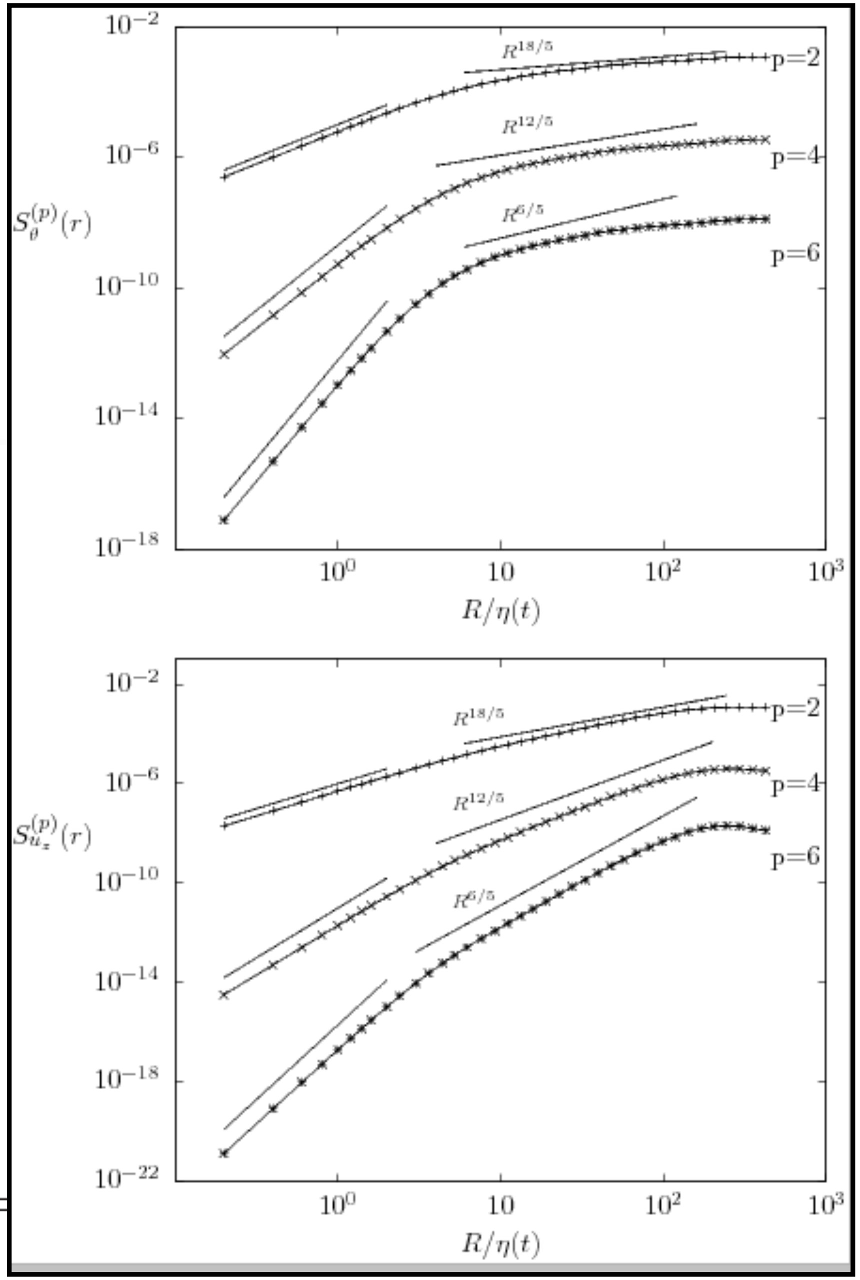


5 order of magnitude
0.01
0.001
0.0001
1e-05
1e-06
1e-07
0.1
1
10
100
1000
$S_\theta^{(2)}(R,t)$
R/η
O(1) over 4 decadees
2.5
2
1.5
1
0.5
0
-0.5
1
10
100
1000
$\frac{d\,log[S_\theta^{(2)}(R,t)]}{d\,log[R]}$
R/η
LOCAL SLOPE

$$S_\theta^{(p)}(R,t) = \langle |\delta_R \theta|^p \rangle$$
$$S_{u_i}^{(p)}(R,t) = \langle |\delta_R u_i|^p \rangle; \qquad i = x, z$$

$$\eta(t) < R < L(t)$$

$$S_\theta^{(p)}(R,t) \sim \left(\frac{R}{L(t)}\right)^{\zeta_\theta(p)}$$
$$S_{u_x,u_z}^{(p)}(R,t) \sim K(t)^p \left(\frac{R}{L(t)}\right)^{\zeta_u(p)}$$



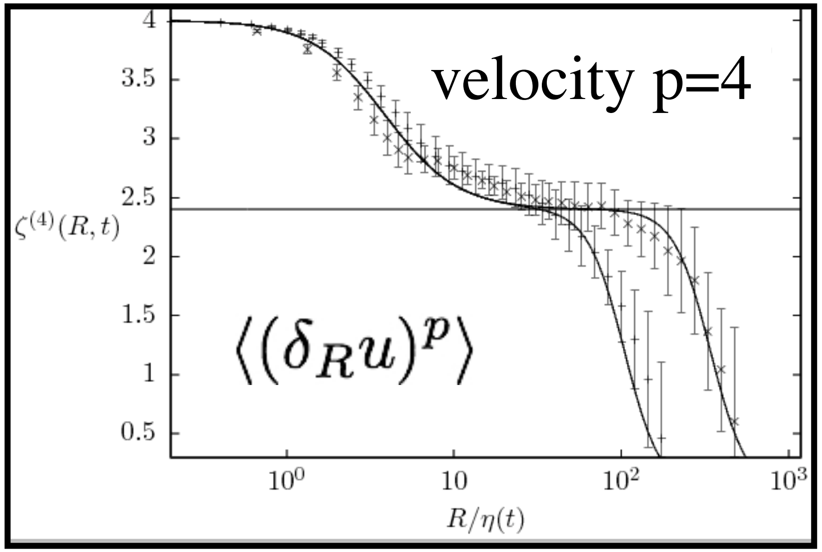
Bolgiano scaling:

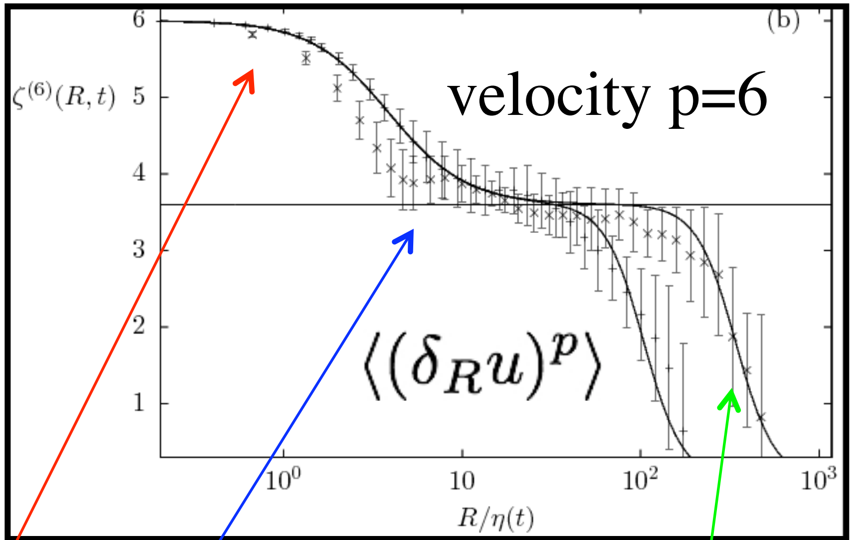
$$\zeta_\theta(p) = \frac{p}{5}; \qquad \zeta_u(p) = \frac{3p}{5};$$

-High Resolution study of Rayleigh-Taylor turbulence: small scales statistics. L. B, F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PoF (2010)

$$f^{(p)}(R,t) \sim R^{\zeta(p|R,t)}$$

$$\zeta(p|R,t) = \frac{d\,log(f^{(p)}(R,t))}{d\,log(R)}.$$

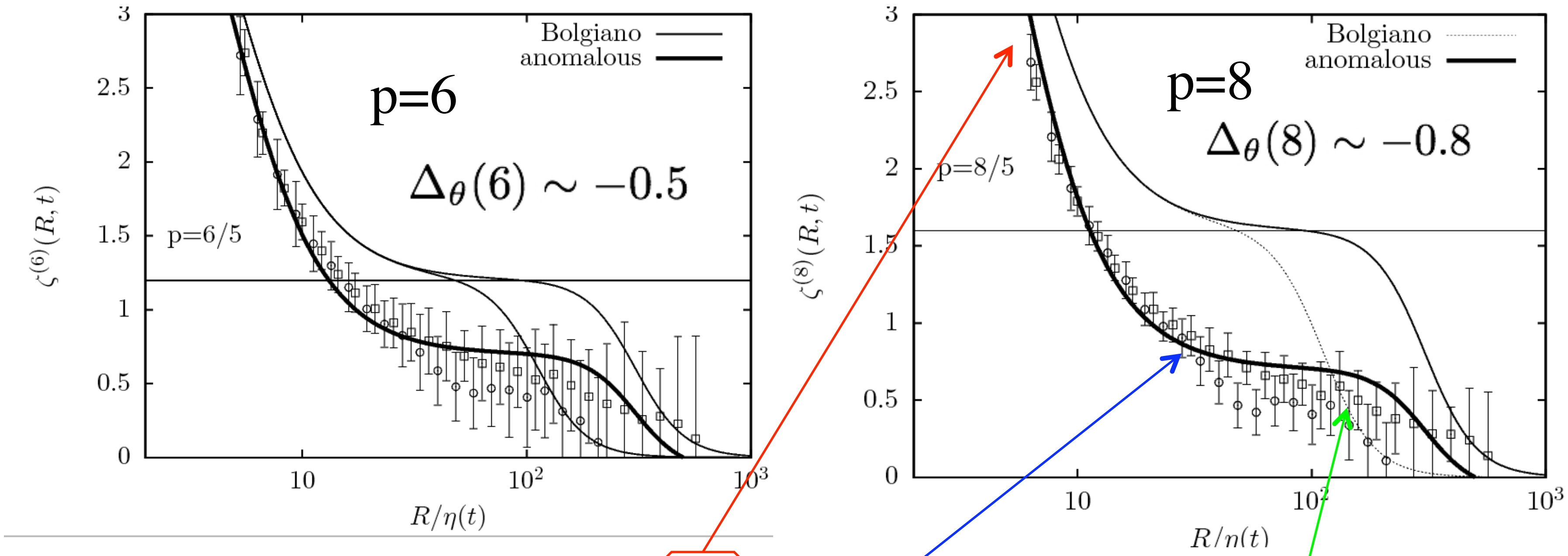




$$f^{(p)}(R,t) = C_p \frac{R^p}{(R^2 + A_p \eta(t)^2)^{\frac{p-\zeta(p)}{2}}} (R^a + L(t)^a)^{-\zeta(p)/a},$$

BATCHELOR PARAMETRIZATION + BOLGIANO DIMENSIONAL SCALING: $\zeta_{u_z}(p) = 3p/5$

temperature $\langle(\delta_R\theta)^p\rangle$



$$f^{(p)}(R,t) = C_p \frac{R^p}{(R^2 + A_p\eta(t)^2)^{\frac{p-\zeta(p)}{2}}}(R^a + L(t)^a)^{-\zeta(p)/a},$$

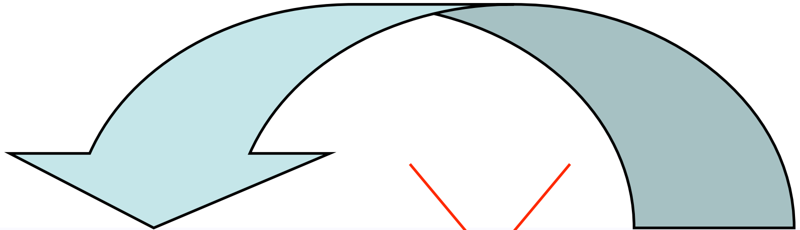
$$\zeta_\theta(p) = \frac{p}{5}; \qquad \zeta_\theta(p) = p/5 + \Delta_\theta(p).$$

BATCHELOR PARAMETRIZATION + ANOMALOUS SCALING

$\zeta_\theta(p)$	Bolgiano	Ref.[15]	here
p=4	0.8	0.6	0.6 ± 0.06
p=6	1.2	0.7	0.7 ± 0.07
p=8	1.6	—	0.8 ± 0.1

[15] A. Celani, A. Mazzino, and L. Vozella, Phys. Rev. Lett. **96**, 134504 (2006).

energy transfer driven by buoyancy forcing at all scales:
a case of **power law forcing** with high intermittent statistics



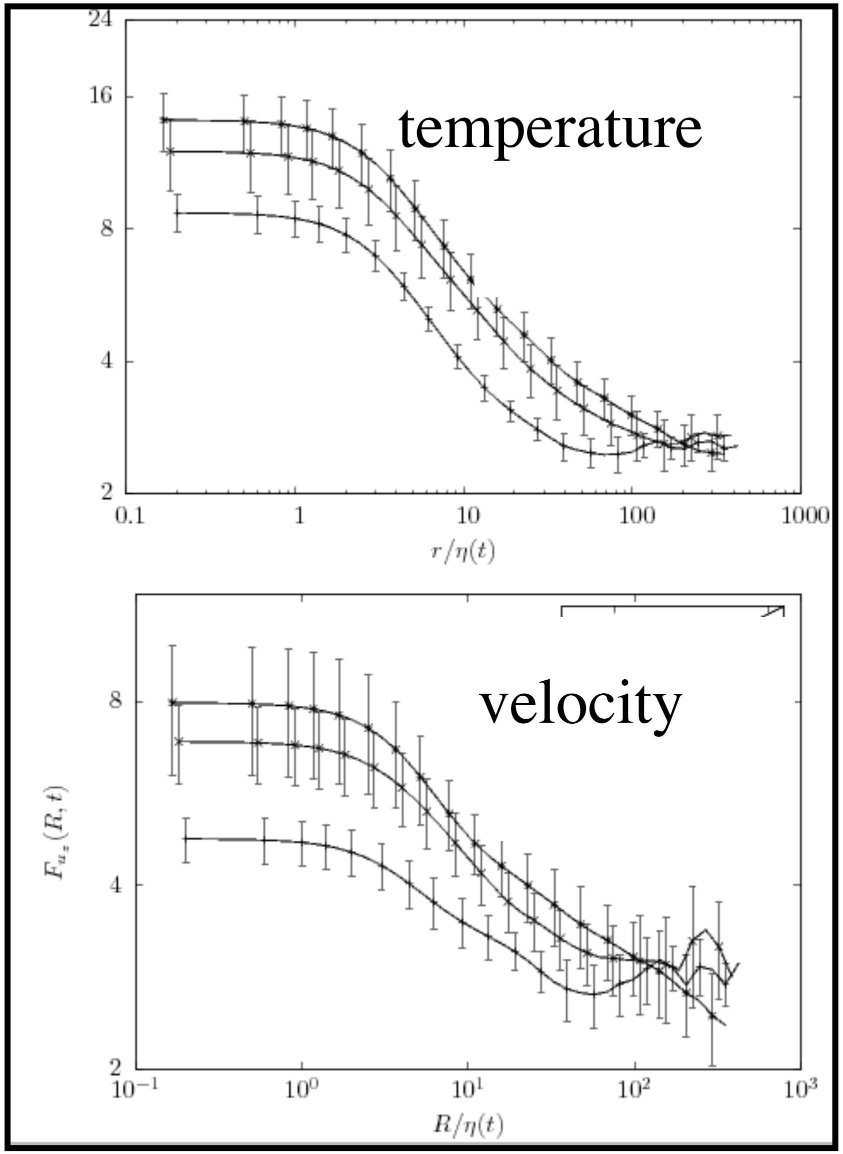
$$\partial_t \langle (\delta_r u)^2 \rangle + \frac{d}{dr} \langle (\delta_r u)^3 \rangle = -\epsilon_{diss} + g \langle \delta_r u \delta_r T \rangle$$

can we observe non-Gaussian velocity in 2d?

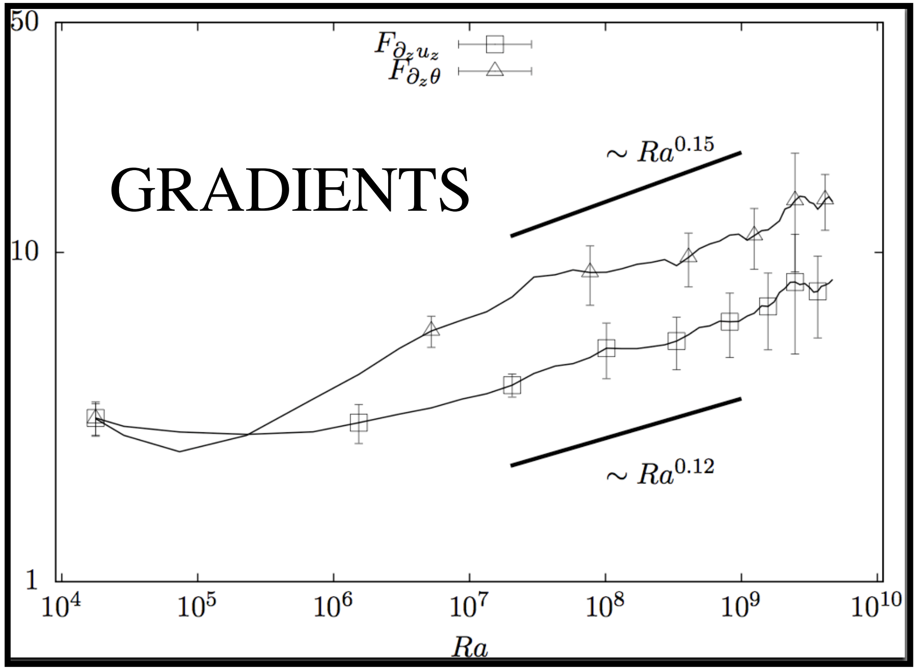
$$F_{u_z}(R,t) = \frac{S^{(4)}_{u_z}(R,t)}{(S^{(2)}_{u_z}(R,t))^2}; \qquad F_\theta(R,t) = \frac{S^{(4)}_\theta(R,t)}{(S^{(2)}_\theta(R,t))^2}.$$

FLATNESS

High Resolution study of Rayleigh-Taylor turbulence: small scales statistics. L. B, F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PoF (2010)



$R \to 0$



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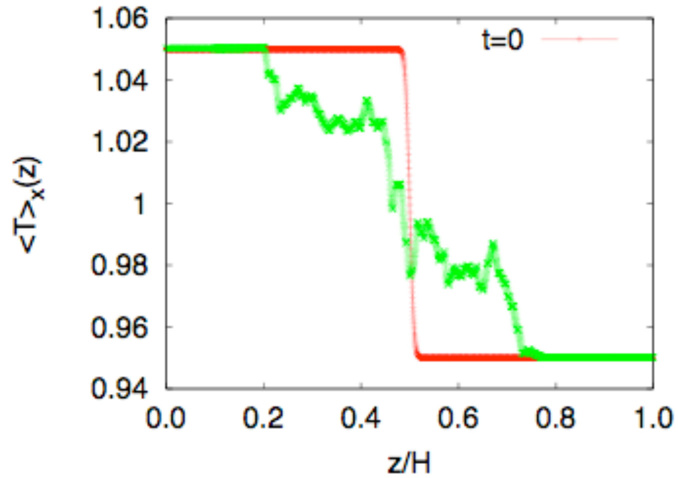
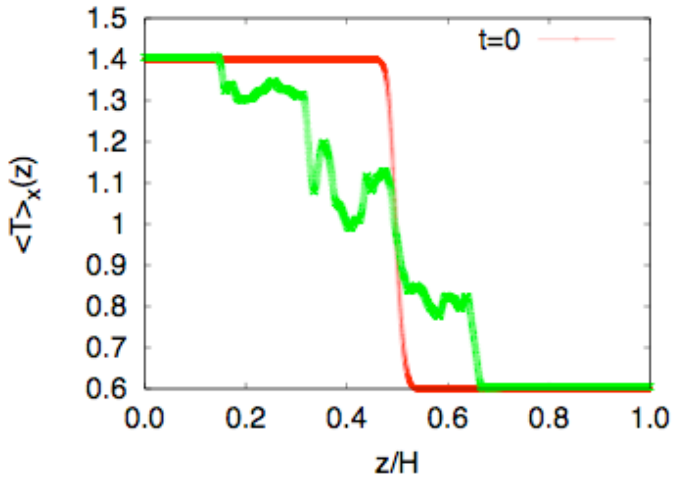
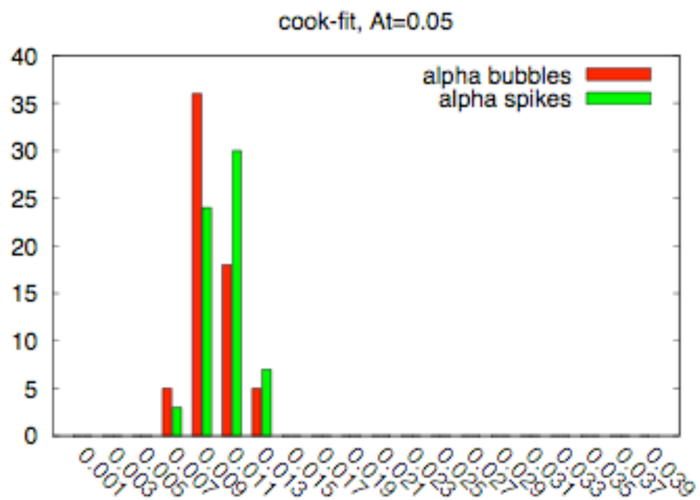
Effects of compressibility:

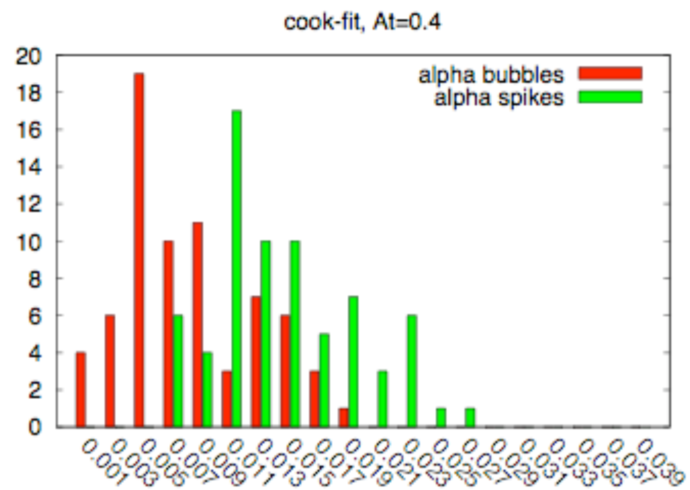
Lattice Boltzmann Methods for thermal flows: continuum limit and applications to compressible Rayleigh-Taylor systems. A. Scagliarini, L. B, M. Sbragaglia, K. Sugiyama, and F. Toschi, PoF (2010)



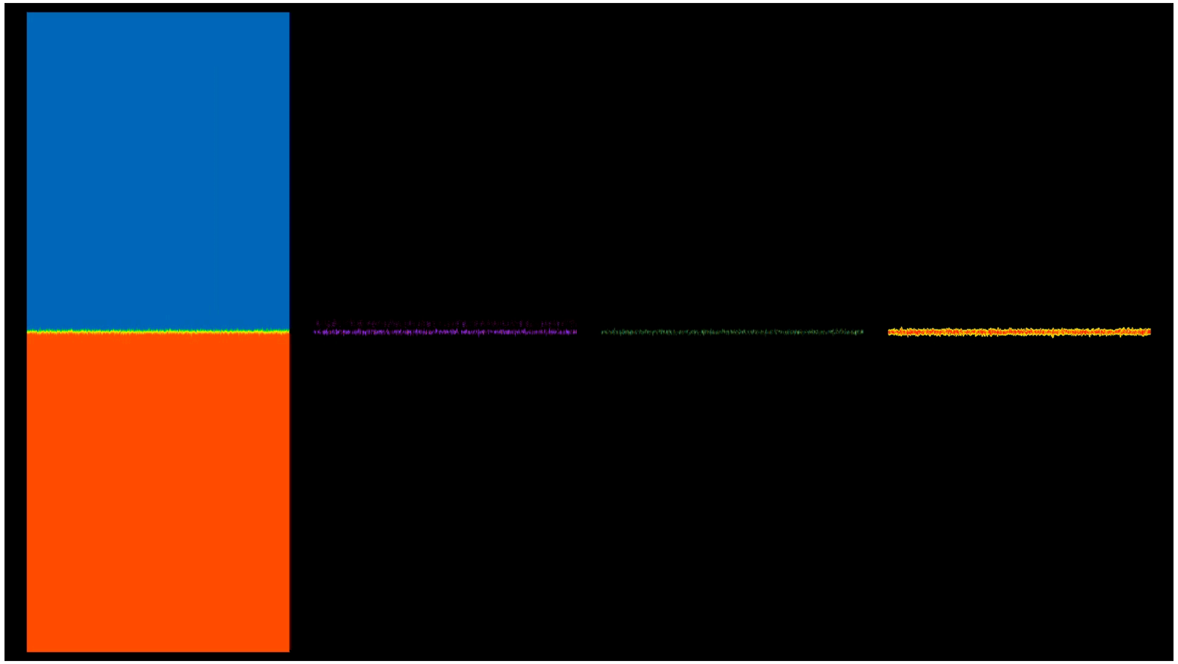


$$L(t) = L_0 + 2\sqrt{\alpha \mathcal{A} g L_0}t + \alpha g \mathcal{A} t^2$$

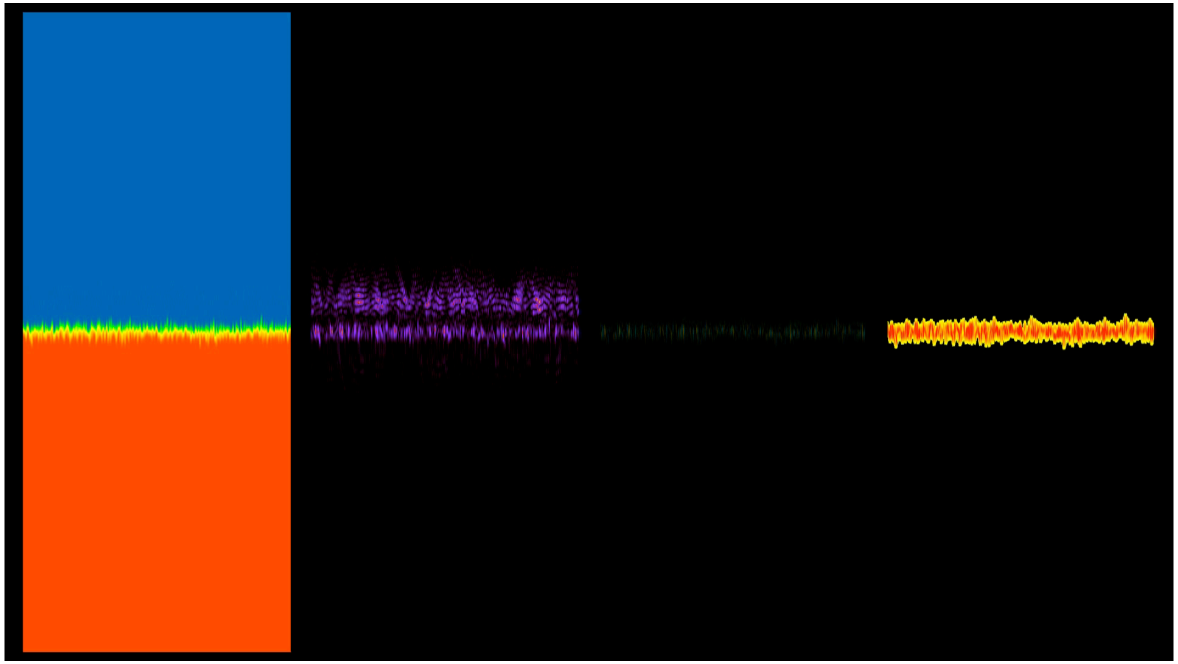




Second order closure for stratified convection: bulk region and overshooting: L.B., F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PRL submitted (2010)



Large stratification



Small stratification

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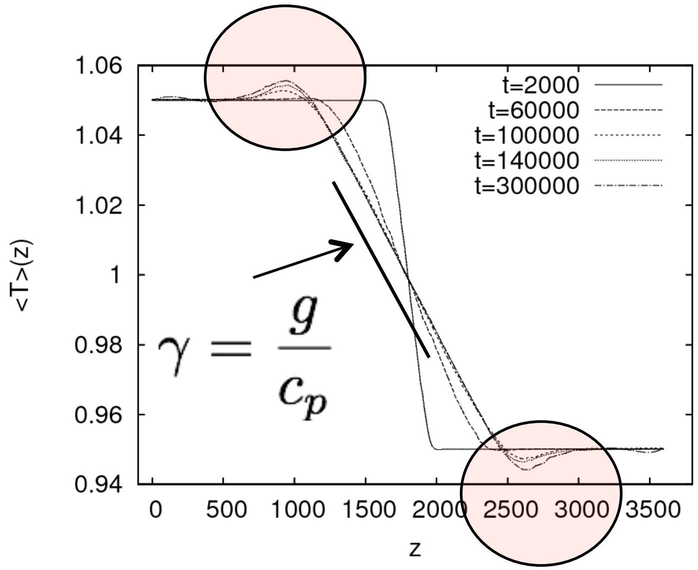
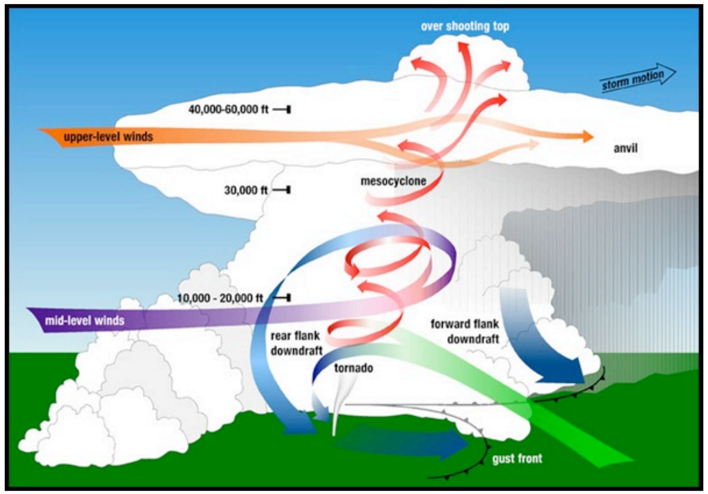
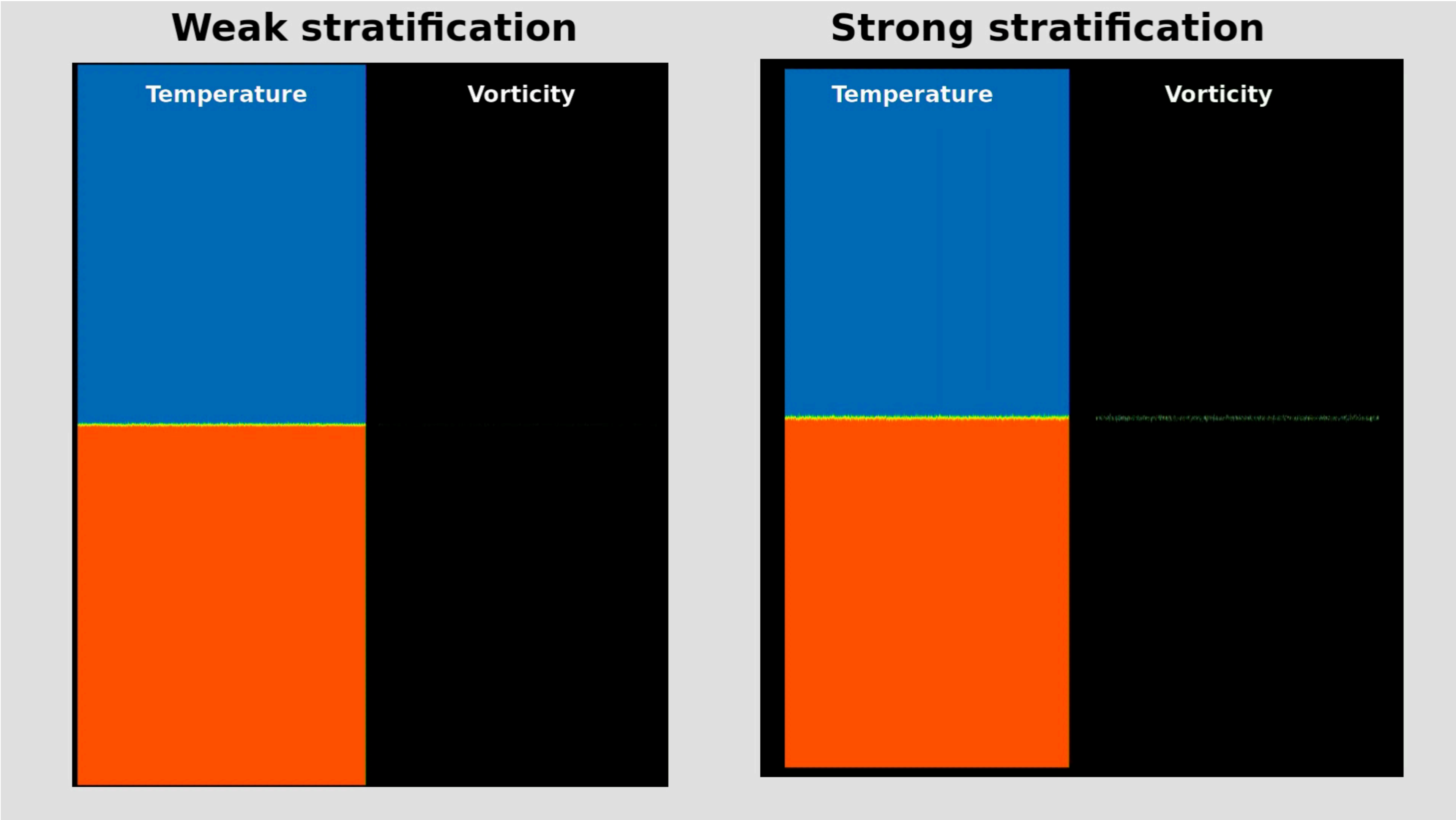
Large scales: arrest at the adiabatic atmosphere and overshoot



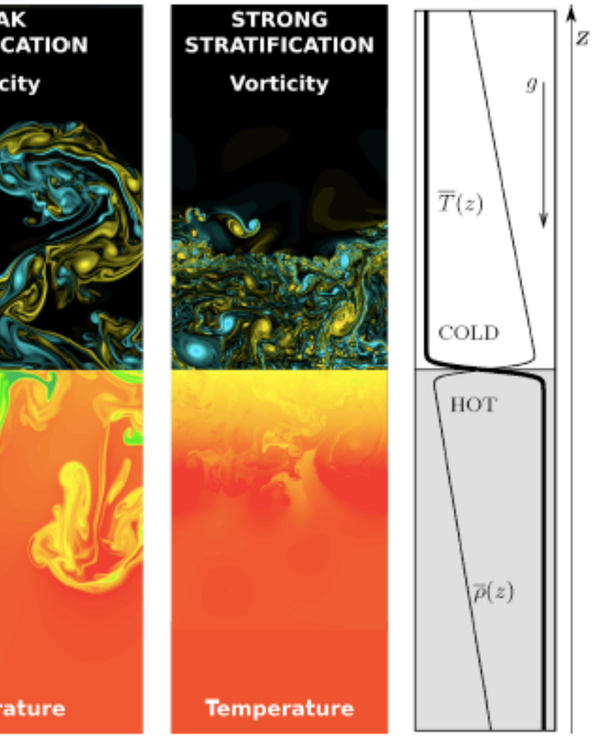


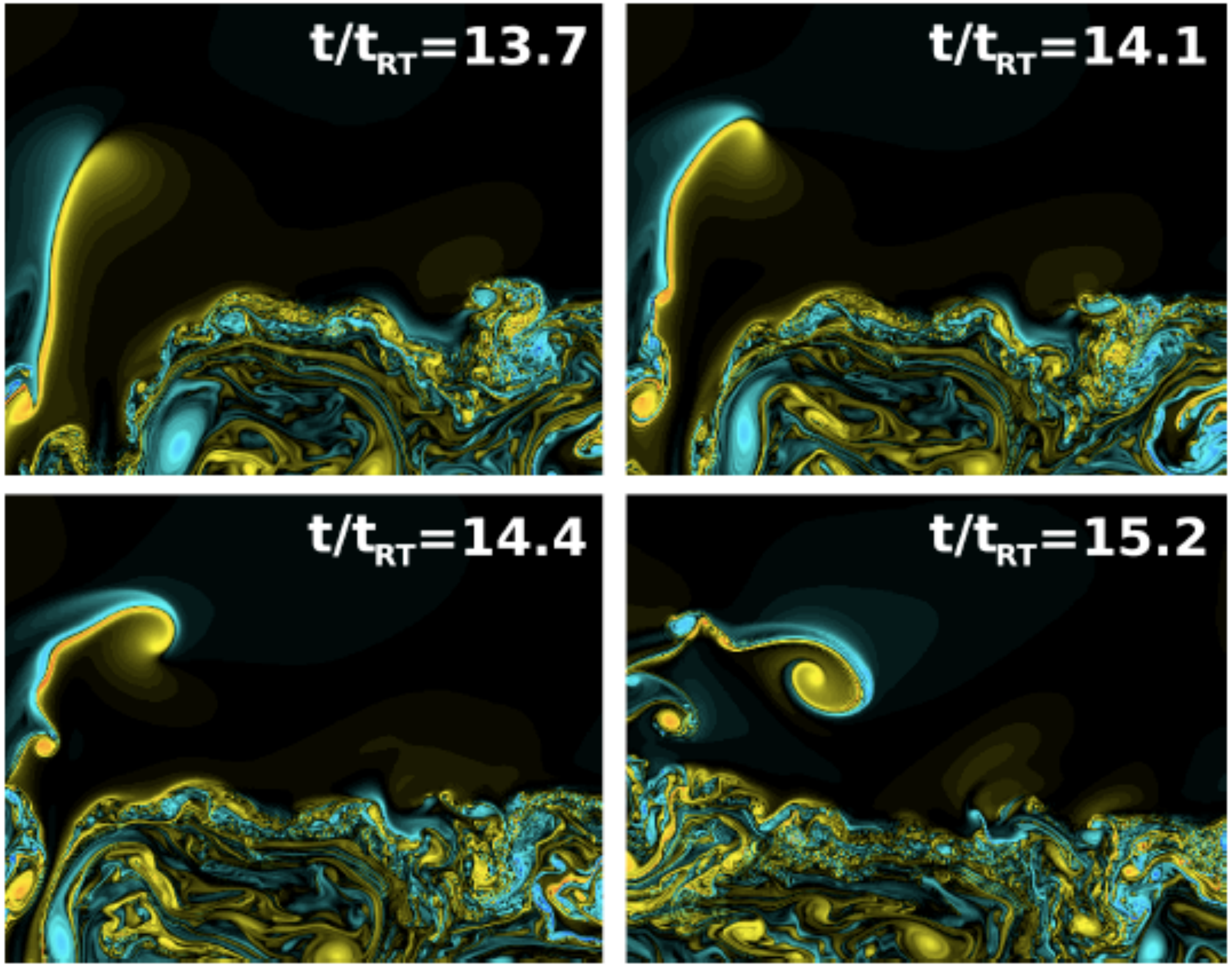
$$\partial_t T + v_i \partial_i T - v_z \gamma = \kappa \partial_{ii} T$$

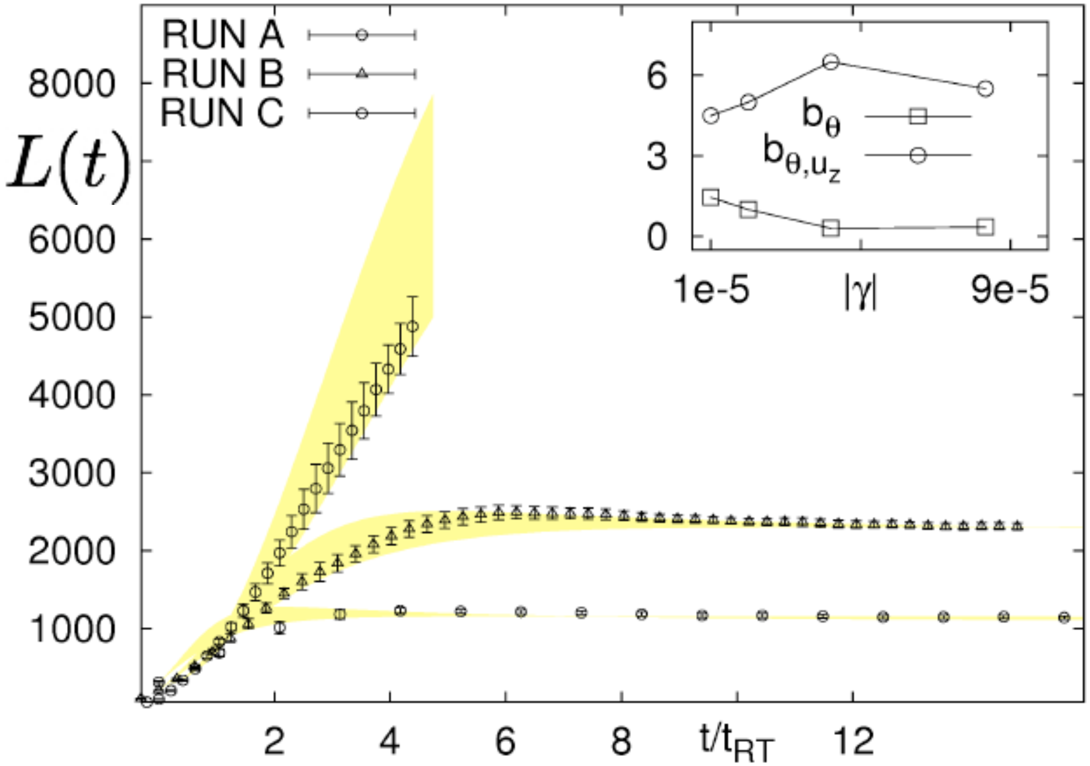
$$\gamma = \frac{\alpha T g}{c_p} = \frac{g}{c_p} \equiv \frac{\Delta T}{L_{ad}}$$



Weak stratification
Temperature
Vorticity
Strong stratification
Temperature
Vorticity

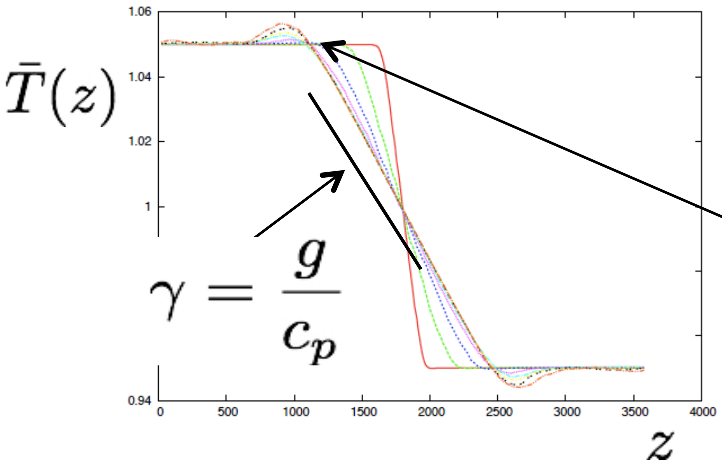

STRONG
STRATIFICATION
Vorticity
Temperature
z
g
$\overline{T}(z)$
COLD
HOT
$\overline{\rho}(z)$

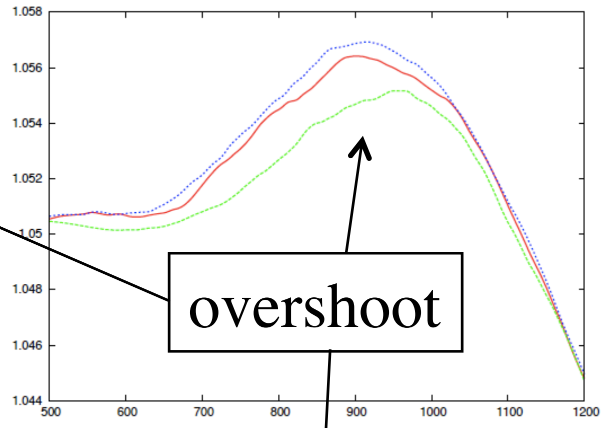

$t/t_{RT}=13.7$
$t/t_{RT}=14.1$
$t/t_{RT}=14.4$
$t/t_{RT}=15.2$

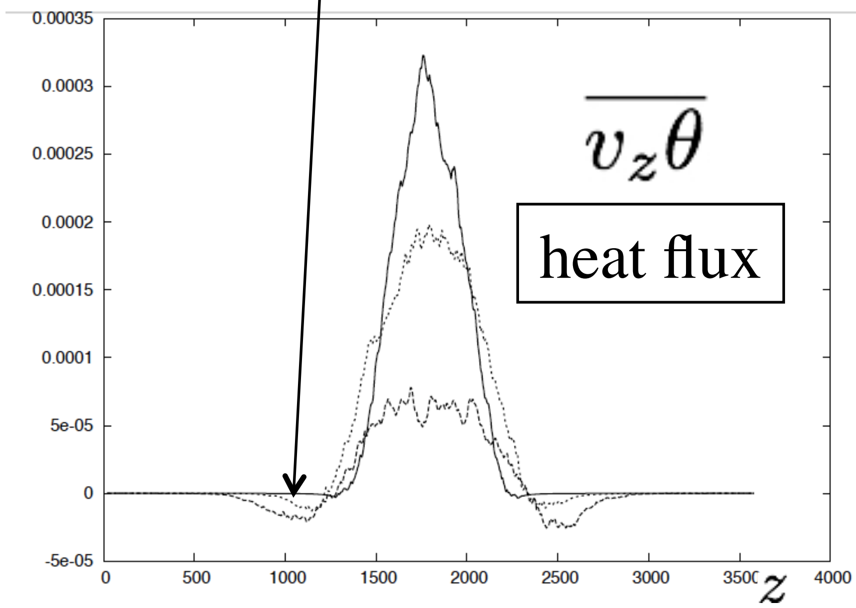


$$L(t) = \frac{1}{L_x} \int dxdz\, \chi \left[\frac{T(x,z) - T_u}{T_d - T_u} \right]. \qquad \begin{cases} \chi[\xi] = 2\xi; & 0 \le \xi \le 1/2 \\ \chi[\xi] = 2\,(1-\xi); & 1/2 \le \xi \le 1 \end{cases}$$

Stratification: role of adiabatic gradient:
arrest and overshoot: troubles for Prandtl mixing length theory







$$T(x, z, t) = \bar{T}(z, t) + \theta(x, z, t)$$

$$\partial_t \bar{T} + \partial_z \overline{v_z \theta} = \kappa \partial_{zz} \bar{T}$$

$$\overline{v_z \theta} = -K(z, t) \partial_z \bar{T}$$

$$\partial_t \overline{\theta^2} + \partial_z \overline{\theta^2 v_z} + \overline{v_z \theta}(\partial_z \bar{T} - \gamma) = \kappa \overline{\theta \partial_{jj} \theta}$$

NEGLIGABLE STRATIFICATION

$$\partial_t \bar{T} + \partial_z \overline{v_z \theta} = \kappa \partial_{zz} \bar{T}$$

$$\overline{v_z \theta} = -K(z,t)\partial_z \bar{T}$$

$$\boxed{\partial_t \bar{T} = \partial_z K(z,t) \partial_z \bar{T}}$$

homogeneous eddy diffusivity $K(z,t) = L_{ml}(t)V(t) \sim (L_{ml}(t))^{3/2} \qquad (A)$

Prandtl mixing lenght: $K(z,t) = (L_{ml}(t))^{5/2}\partial_z \bar{T} \qquad (B)$

Spiegel mixing lenght: $K(z,t) = (L_{ml}(t))^{2}(\partial_z \bar{T})^{1/2} \qquad (C)$

P. Odier, J. Chen, M. K. Rivera, and R. E. Ecke, Phys. Rev. Lett. **102**, 134504 (2009).

G. Boffetta, F. De Lillo and S. Musacchio,"Nonlinear diffusion model for Rayleigh-Taylor mixing", *Phys. Rev. Lett.* **104**, 034505 (2010)

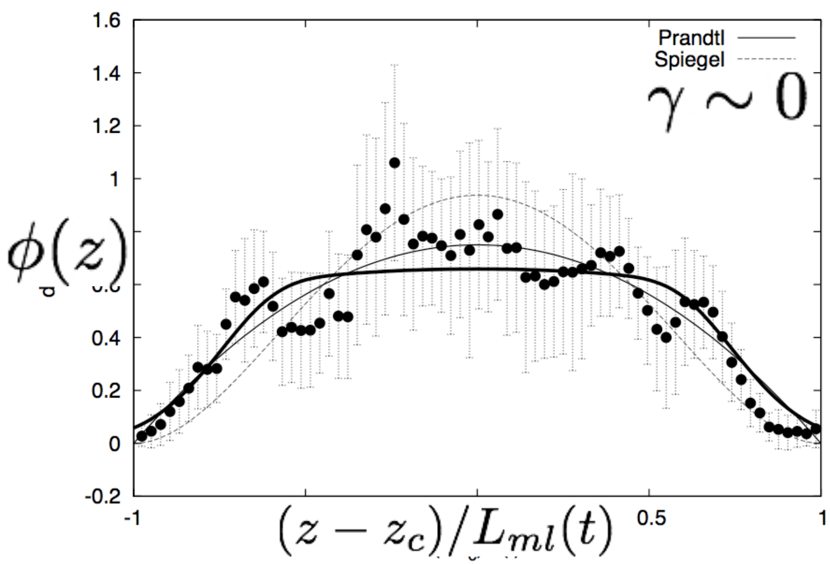
E.A. Spiegel"Convective instability in a comprssible atmosphere", *Astrophys. J.* **141**, 1068 (1965)

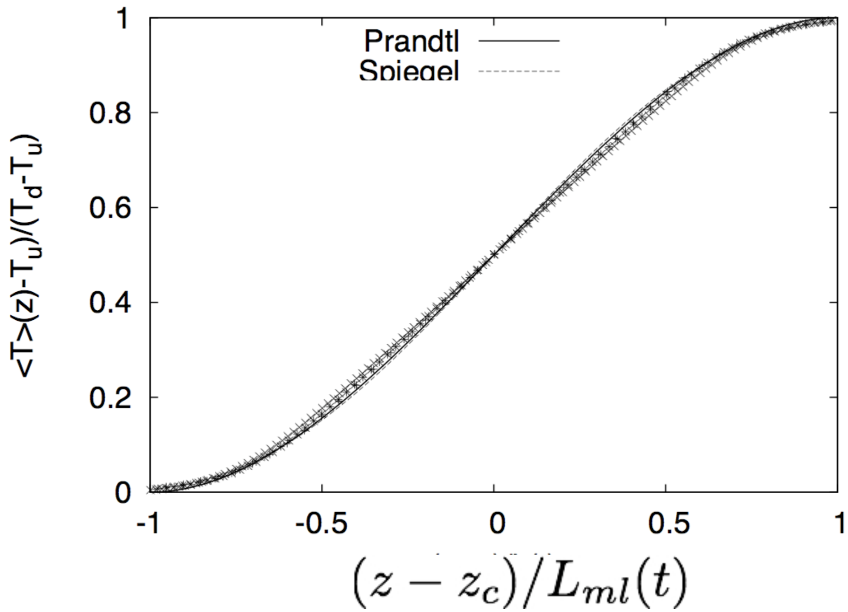
$$\partial_t \bar{T} + \partial_z \overline{v_z \theta} = \kappa \partial_{zz} \bar{T} \qquad \phi = \partial_z \bar{T} \qquad t' = (L_{ml}(t))^{\alpha}$$

$$\partial_{t'} \phi = \partial_z (\phi^n \partial_z \phi)$$

$$\xi = \frac{z}{L_{ml}(t)} \qquad \phi(\xi) = [\frac{n}{2(2+n)}(1-\xi^2)]^{1/n}$$

n=1 (Prandtl) [Boffetta, DeLillo & Musacchio PRL 2010]
n=1/2 (Spiegel)





NON NEGLIGABLE ADIABATIC GRAD.

$$\overline{v_z\theta} = -K(z,t)\partial_z\bar{T}$$

$$\partial_t \bar{T} + \partial_z \overline{v_z \theta} = \kappa \partial_{zz} \bar{T}$$

$$\begin{cases} \frac{1}{2}\partial_t \overline{\theta^2} + \partial_z \overline{\theta^2 w} = \beta(z)\overline{\theta w} - \epsilon_\theta + \kappa \partial_z \overline{\theta \partial_z \theta} \\ \frac{1}{2}\partial_t \overline{v^2} + \partial_z [\overline{v^2 w} + \overline{wP}] = g\overline{\theta w} - \epsilon_\nu + \nu \partial_z \overline{w \partial_z w} \\ \partial_t \overline{\theta w} + \partial_z [\overline{\theta w^2} + \overline{\theta P}] = g\overline{\theta^2} + \beta(z)\overline{w^2} + \partial_z [\nu \overline{\theta \partial_z w} + \kappa \overline{w \partial_z \theta}] - \epsilon_{\theta,w} \end{cases}$$

$$\boxed{\beta(z) = \partial_z \bar{T} - \gamma}$$

$$\begin{cases} \frac{1}{2}\partial_t \overline{\theta^2} + \partial_z \overline{\theta^2 w} = \beta(z)\overline{\theta w} - \epsilon_\theta \\ \frac{1}{2}\partial_t \overline{v^2} + \partial_z [\overline{v^2 w} + \overline{wP}] = g\overline{\theta w} - \epsilon_\nu \\ \partial_t \overline{\theta w} + \partial_z [\overline{\theta w^2} + \overline{\theta P}] = g\overline{\theta^2} + \beta(z)\overline{w^2} - \epsilon_{\theta,w} \end{cases}$$

$$\begin{cases} \partial_z \overline{\theta^2 w} = -D_\theta(t)\partial_z \partial_z \overline{\theta^2} \\ \partial_z \overline{(v^2 + P)w} = -D_v(t)\partial_z \partial_z \overline{v^2} \\ \partial_z [\overline{\theta w^2} + \overline{\theta P}] = -D_{\theta,w}(t)\partial_z \partial_z \overline{w\theta} \end{cases}$$

$$D_\theta(t) = \alpha_\theta\ L_{ml}(t)\dot{L}_{ml}(t)$$

$$D_v(t) = \alpha_v\ L_{ml}(t)\dot{L}_{ml}(t)$$

$$D_{\theta,w}(t) = \alpha_{\theta,w}\ L_{ml}(t)\dot{L}_{ml}(t)$$

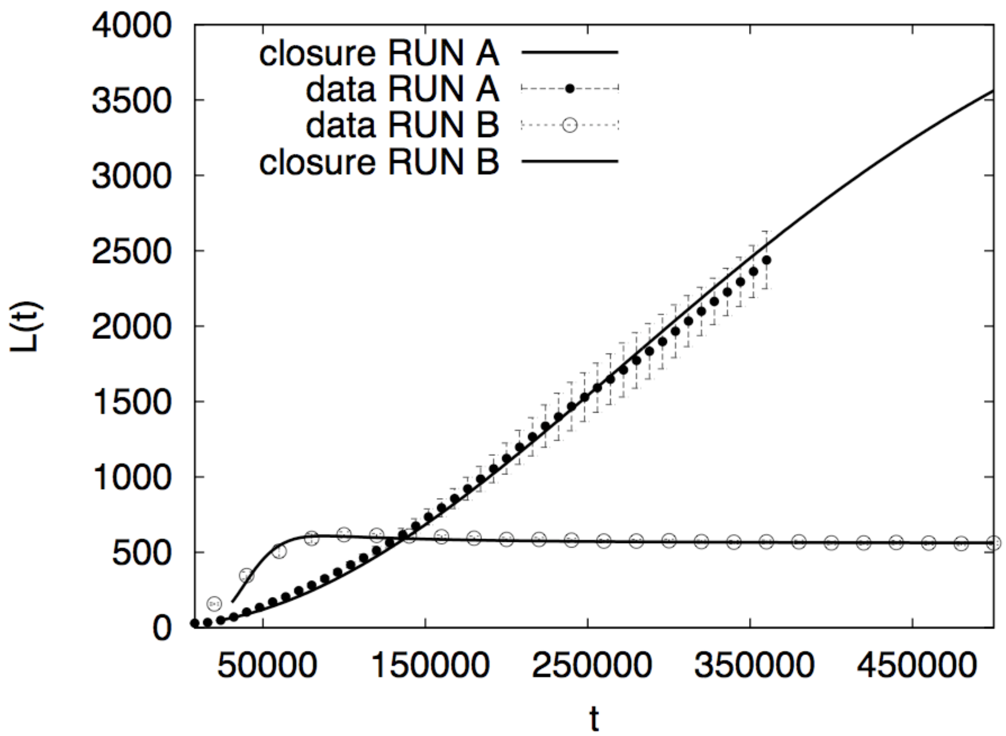
$$\epsilon_\theta(t) = \beta_\theta \frac{\overline{\theta^2(t)}\sqrt{\overline{w^2(t)}}}{L_{ml}(t)}$$

$$\epsilon_v(t) = \beta_v \frac{\overline{w^2(t)}\sqrt{\overline{w^2(t)}}}{L_{ml}(t)}$$

$$\epsilon_{\theta,v}(t) = \beta_{\theta,v} \frac{\overline{w\theta}\sqrt{\overline{w^2(t)}}}{L_{ml}(t)}$$

RUN A: $\gamma = 1.6e^{-5}$ $L_{ad} \sim 6000$ small stratification

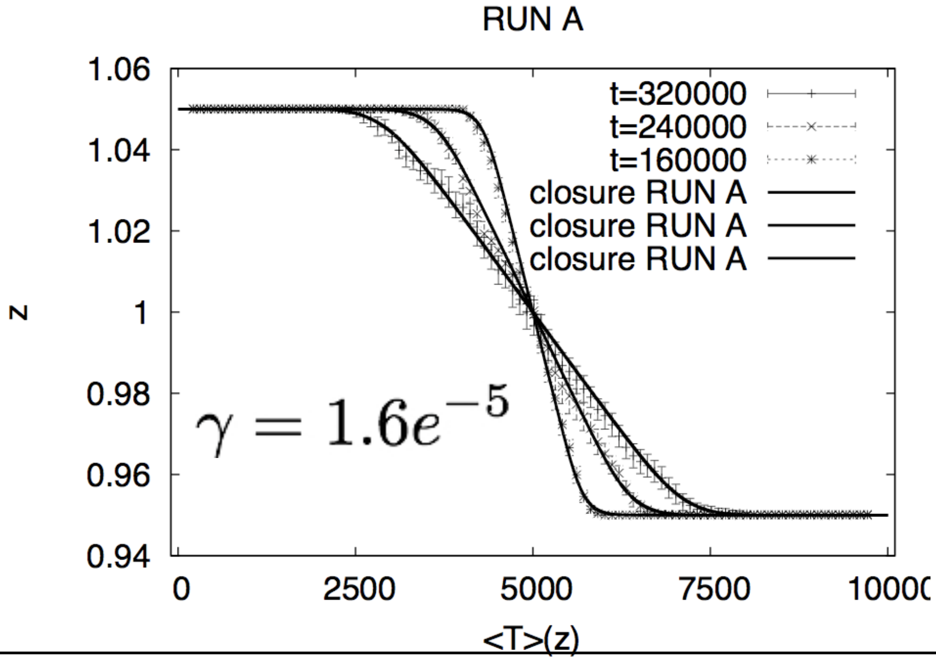
RUN B: $\gamma = 1.6e^{-4}$ $L_{ad} \sim 600$ large stratification



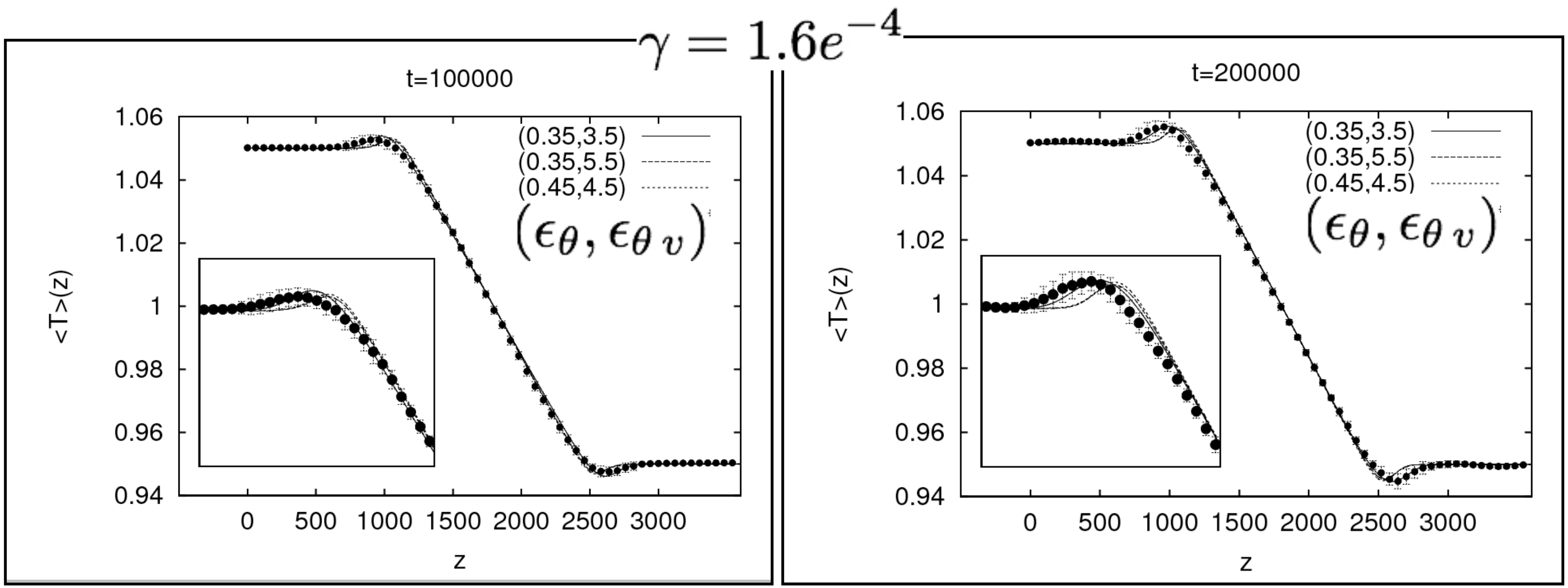
$$L(t) = \frac{1}{L_x} \int dx dz \, \chi \left[\frac{T(x,z) - T_u}{T_d - T_u} \right].$$

$$\begin{cases} \chi[\xi] = 2\xi; & 0 \le \xi \le 1/2 \\ \chi[\xi] = 2\,(1-\xi); & 1/2 \le \xi \le 1 \end{cases}$$

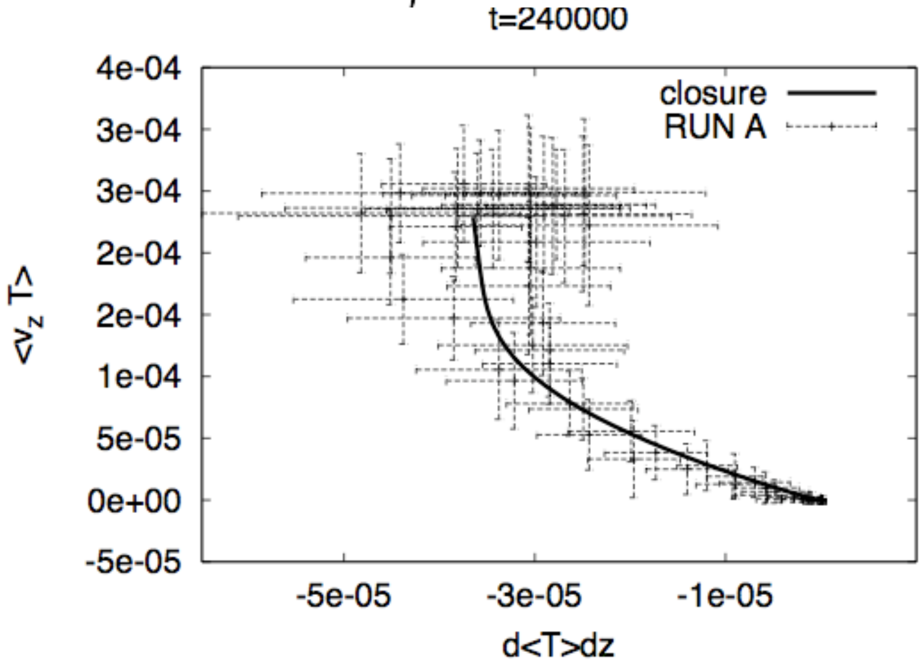
small stratification

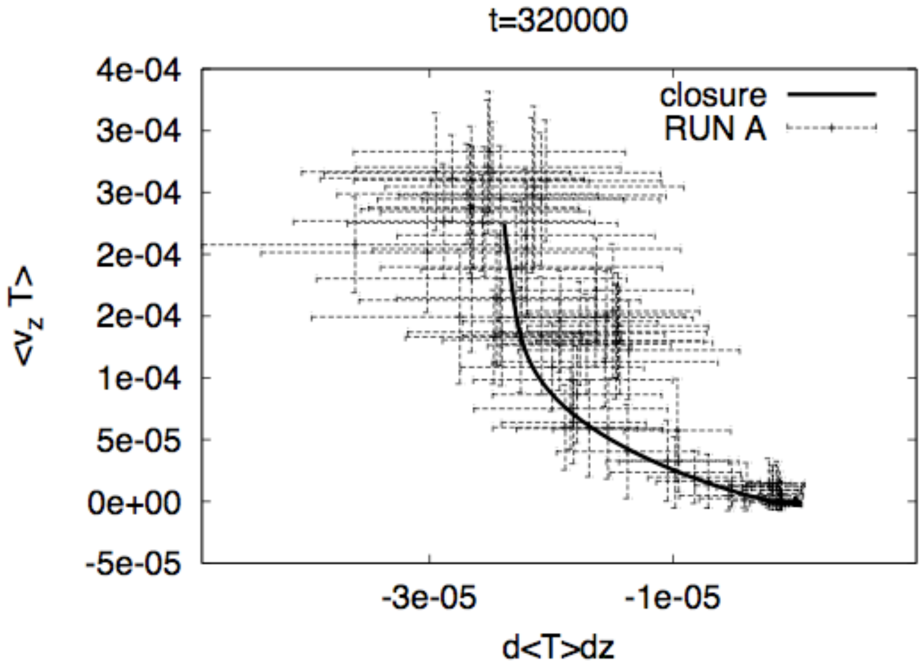


large stratification



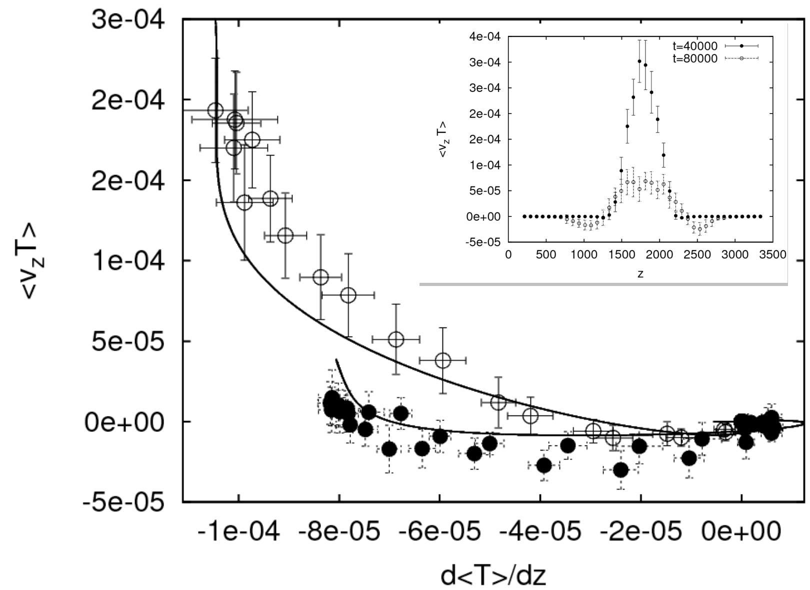
$$\gamma = 1.6e^{-5}$$





$$\overline{v_z \theta} = -K(z,t)\partial_z \bar{T}$$

$$\gamma = 1.6e-4$$



$$K(z,t) = L_{ml}(t)V(t) \sim (L_{ml}(t))^{3/2}$$
$$K(z,t) = (L_{ml}(t))^{5/2}\partial_z \bar{T}$$
$$K(z,t) = (L_{ml}(t))^{2}(\partial_z \bar{T})^{1/2}\partial_z \bar{T}$$

Rayleigh Taylor systems in 2d:

-) Incompressible unstratified at large Reynolds
-) Compressible unstratified at "moderate" Reynolds
-) Incompressible stratified at large Reynolds
-) Incompressbile unstratified + reaction at large Reynolds

Turbulent mixing with chemical reactions

$$\partial_t \phi + u_j \partial_j \phi = \kappa \Delta \phi + \frac{1}{\tau_R} R(\phi)$$

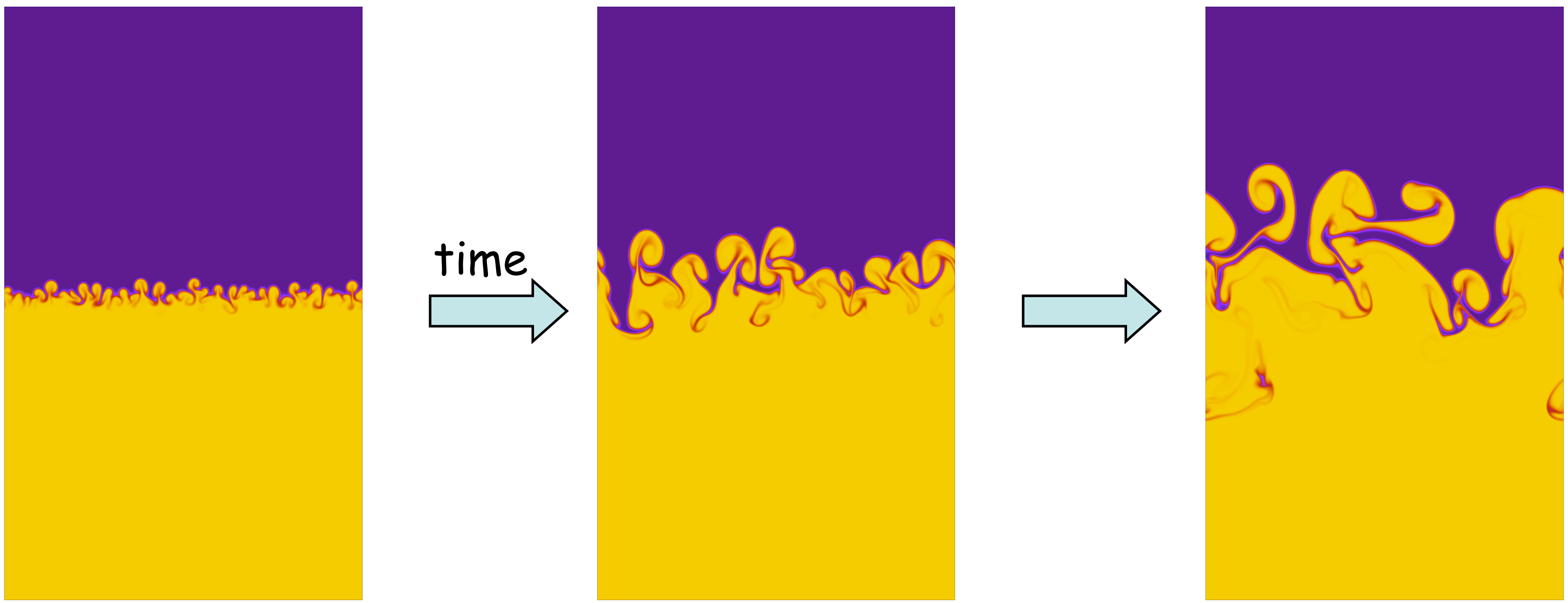
Advection-diffusion-reaction equation
Fisher-Kolmogorov-Petrovskii-Piskunov equation

$$R(\phi) = \alpha \phi (1 - \phi)$$

$$V_f = \sqrt{\kappa \tau_R}$$

Control parameter: $Da = \frac{\tau_{\text{turb}}}{\tau_R}$ (Damköhler number)

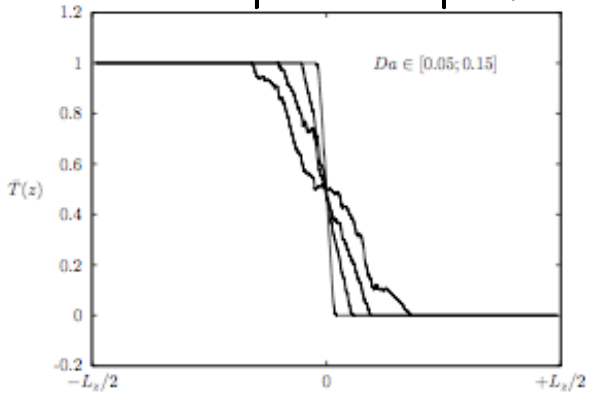
Since in RT τ_{turb} grows in time ⇒ $Da = Da(t)$



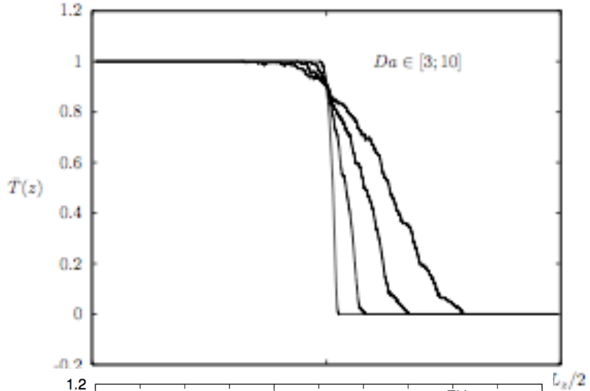
Reaction front evolution

In our setup the advected field is temperature (as in, e.g., turbulent combustion)

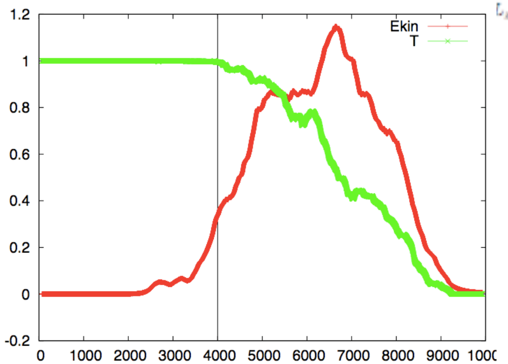
Mean temperature profiles



slow reaction

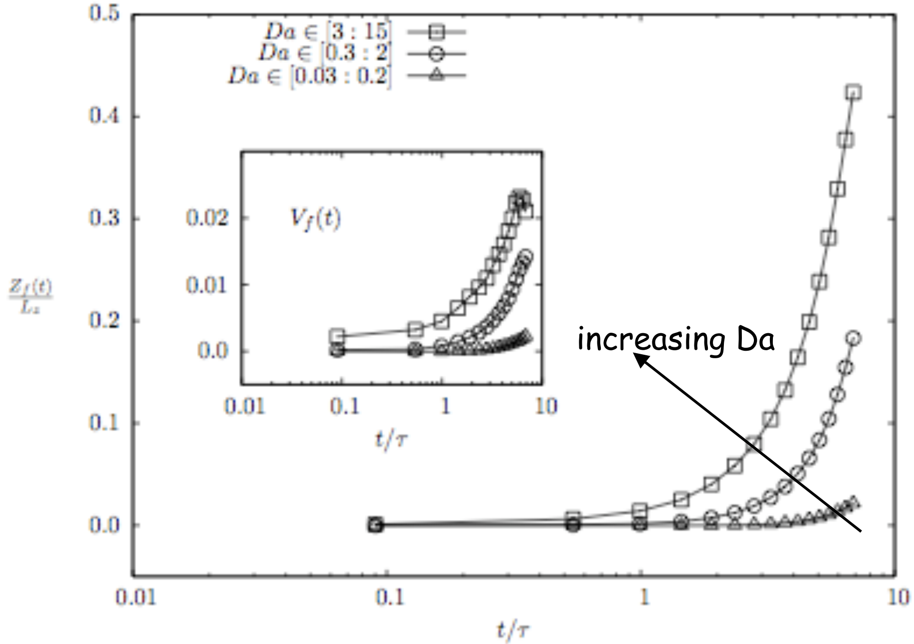


fast reaction



Reaction front coordinate

$$Z_f(t) = \int_{-L_z/2}^{+L_z/2} \overline{T}(z,t)dz$$

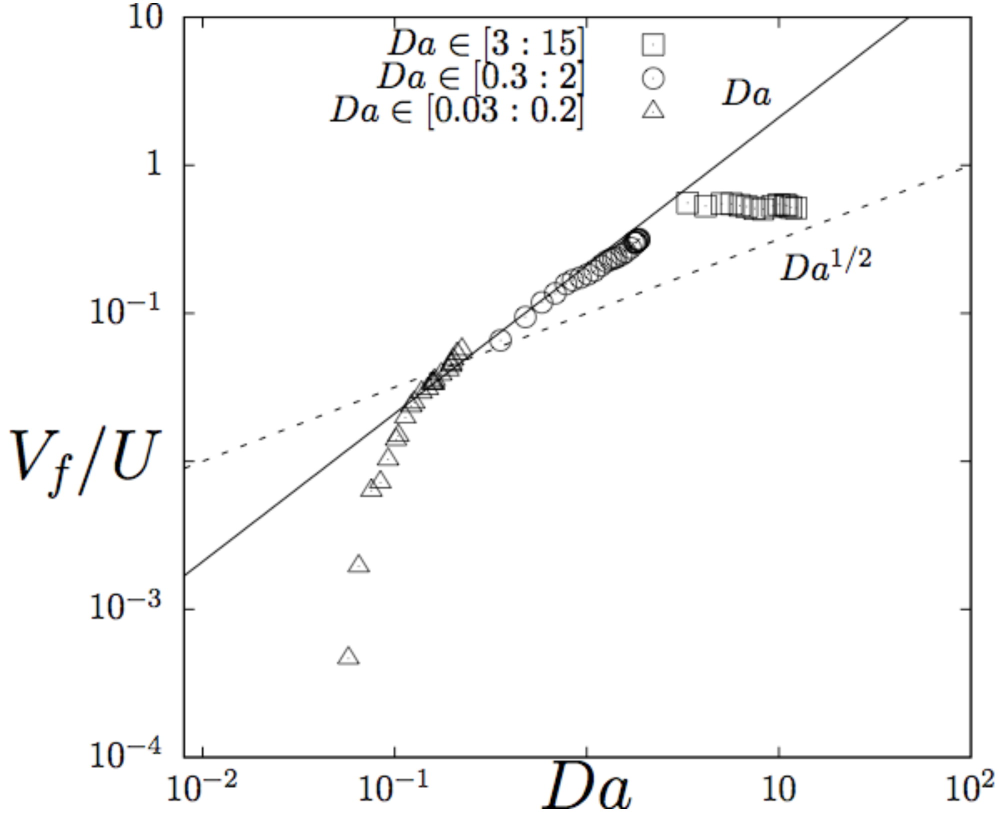


Speed front vs Damköhler

Front speed $$V_f(t) \equiv \partial_t Z_f(t) = \frac{1}{\tau_R}\langle T(1-T)\rangle$$

$$V_f(t) = \frac{1}{\tau_R}[\overline{T}(1-\overline{T}) - \overline{\theta^2}] \propto \frac{L(t)}{\tau_R} = U(t)Da(t) \qquad \frac{V_f(t)}{U(t)} \sim Da$$

(vs $Da^{1/2}$ for pre-mixed combustion) → Non-stationarity of RT turbulence...!



(L. B. F. Mantovani, M. Sbragaglia et al, **Europhys. Lett.**, in press (2011))

$$S_T^{(p)}(R,t) \equiv \langle|\delta_R T|^p\rangle \sim \left(\frac{R}{L(t)}\right)^{2/3},$$

J. Fluid Mech. (2009), *vol.* 633, *pp.* 1–16. © 2009 Cambridge University Press 1
doi:10.1017/S0022112009007666 Printed in the United Kingdom

Reactive Rayleigh–Taylor turbulence

M. CHERTKOV[1], V. LEBEDEV[1,2] AND N. VLADIMIROVA[1,3,4]†

$$F_T^{(p)}(R,t) = \frac{\langle|\delta_R T|^p\rangle}{\langle|\delta_R T|^{p/2}\rangle^2} \sim R^{-2/3} L(t)^{2/3}$$

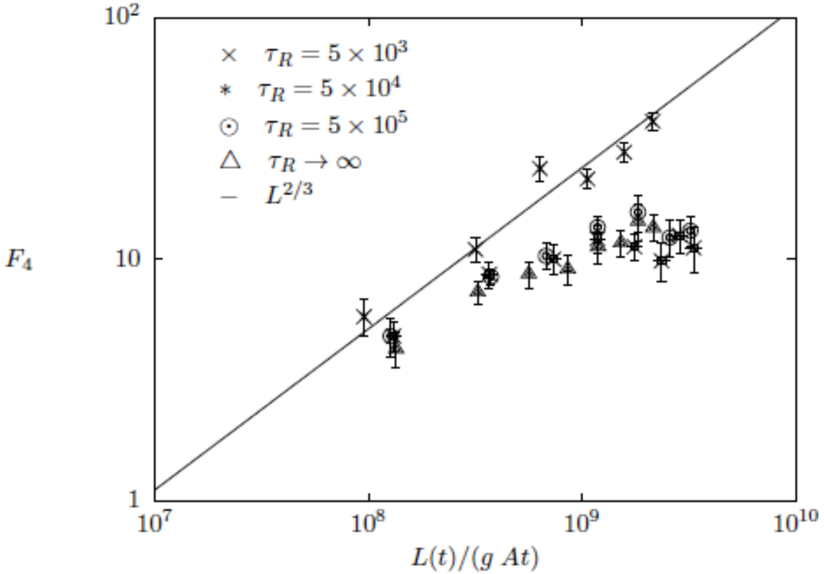
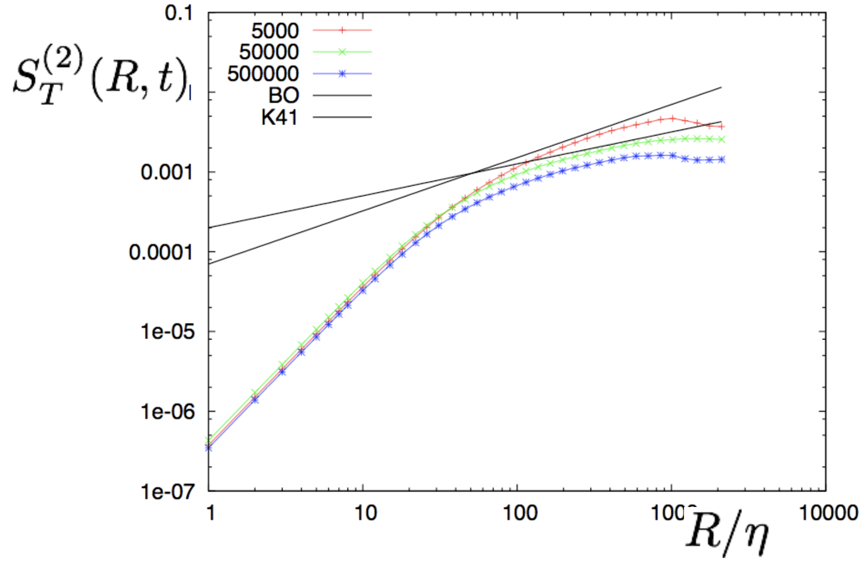


Fig. 6: The 4-th order flatness F_4 for the three runs and for the non-reacting RT ($\tau_R \to \infty$). Data from run A ($Da \gg 1$) agree well, within error bars, with the prediction given by equation (14) $F_4 \sim L^{2/3}$.



- LBM -> good agreement with NSE eqs over 4 decades of scales
- 2d RT: BOLGIANO scaling (if Batchelor parametrisation used)
- Temperature: high intermittency
- Velocity: low intermittency (if any!)
- Stratification: arrest & overshoot: problems for simple positive-defined Prandtl mixing length theory.
- RT + flames: asymmetry in the front propagation, tendency toward a K41 scaling.

-Lattice Boltzmann Methods for thermal flows: continuum limit and applications to compressible Rayleigh-Taylor systems. A. Scagliarini, L. B, M. Sbragaglia, K. Sugiyama, and F. Toschi, PoF (2010)

-High Resolution study of Rayleigh-Taylor turbulence: small scales statistics. L. B, F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PoF (2010)

-Second order closure for stratified convection: bulk region and overshooting: L.B., F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, PRE (2011)

-Reactive RT systems: front propagation and non-stationarity; L.B. F. Mantovani, M. Sbragaglia, A. Scagliarini, F. Toschi & R. Tripiccione, EPL (2011)