How can numerical simulations contribute?

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Supercomputing

- More and more organized on European scale (Petaflop Project Pace)

- DEep Computing Initiative within DEISA
  → 2 turbulence projects (2006/2007)
- Resolution of the most intensive gradients in turbulence at R_λ~100 on a 2048^3
- 800,000 CPUh on 512 CPUs (1.9Tbyte RAM)
- 1 velocity snapshot = 68 Gbyte
- Quasi-Lagrangian analysis in 51^3 around 100 Lagrangian tracers (700 Gbytes)
- UNICORE platform for Grid computing
- Parallel NetCDF for I/O

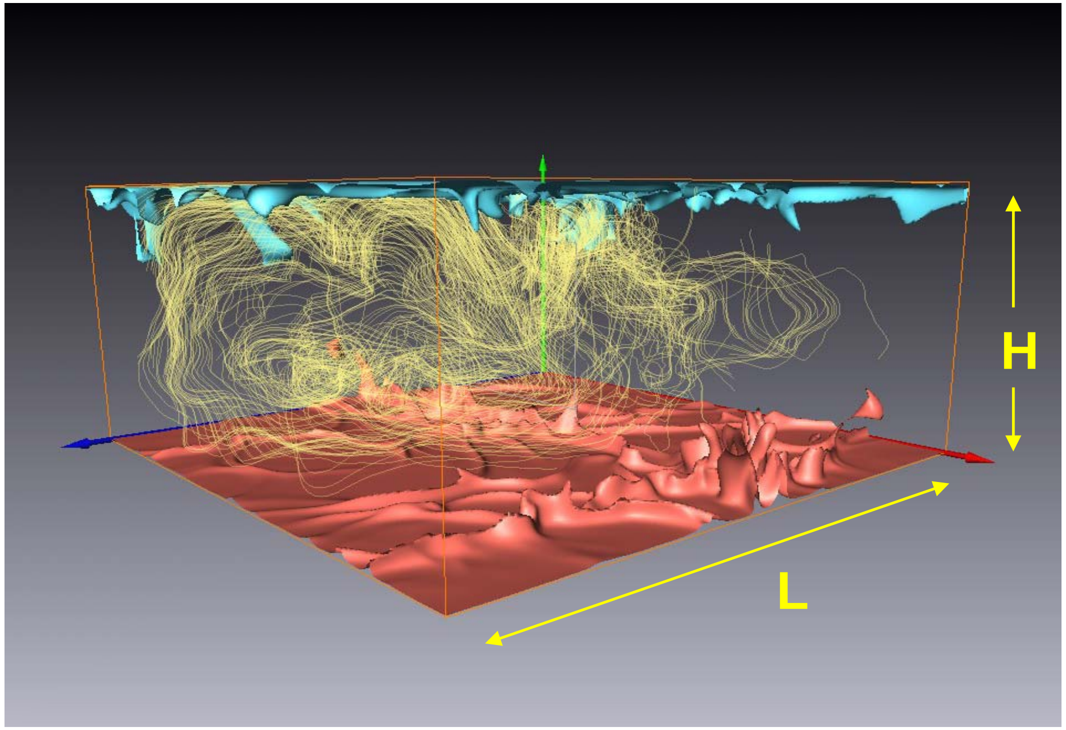
Distributed European Infrastructure for Supercomputing Applications

Case 1: Cartesian Cell

<u>Geometry and Parameters</u>

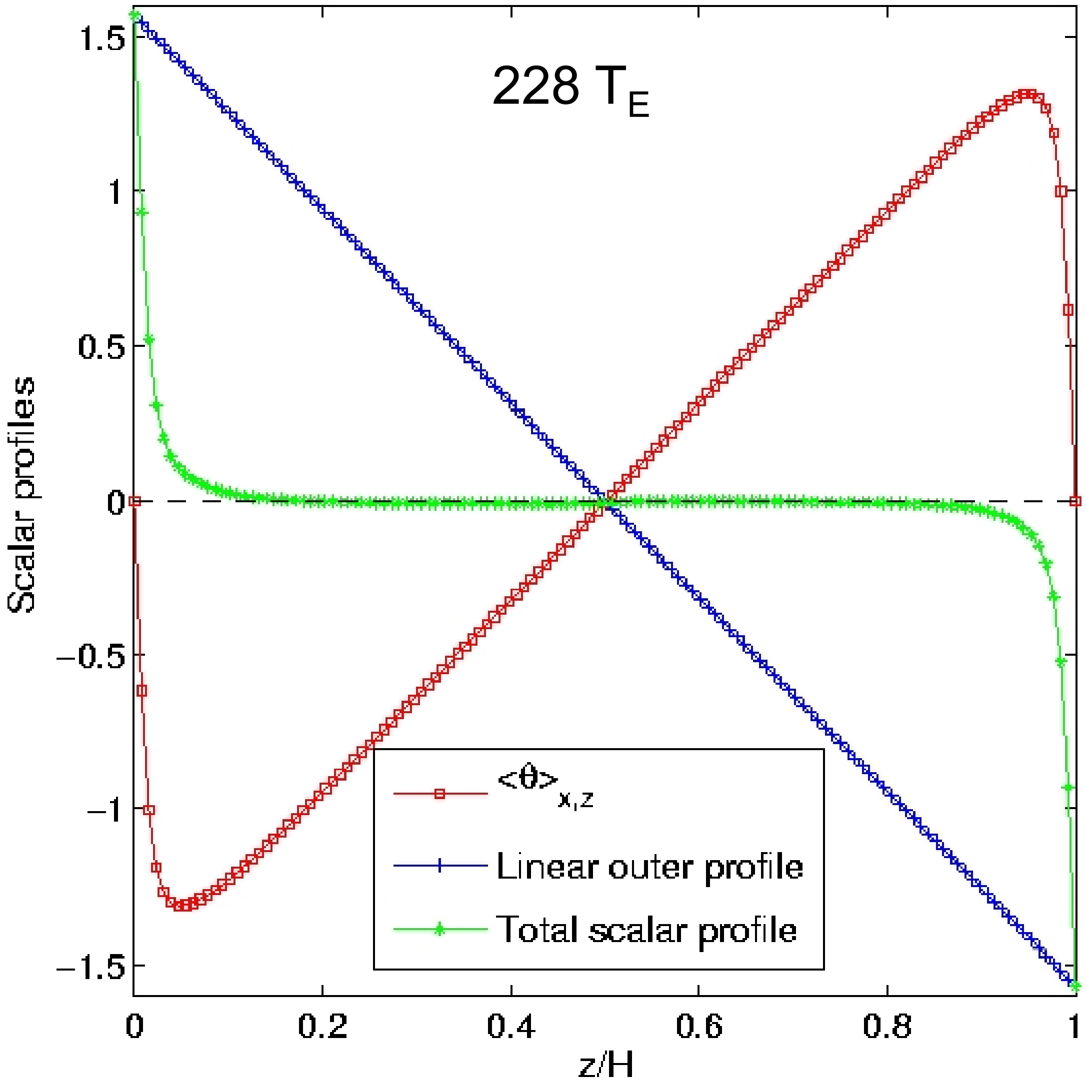
- Cartesian geometry (x,y,z)
- $Ra=10^7–10^9$
- Pr=0.7 (later Pr > 1)
- Aspect ratio: Γ=L/H=2-32

- Free-slip boundaries in z
- Equidistant grid
- Periodic side walls



Temperature Profile

$$N_x \times N_y \times N_z = 256 \times 256 \times 129$$



Pr=0.7
Ra=1.1×10^7
Γ=2

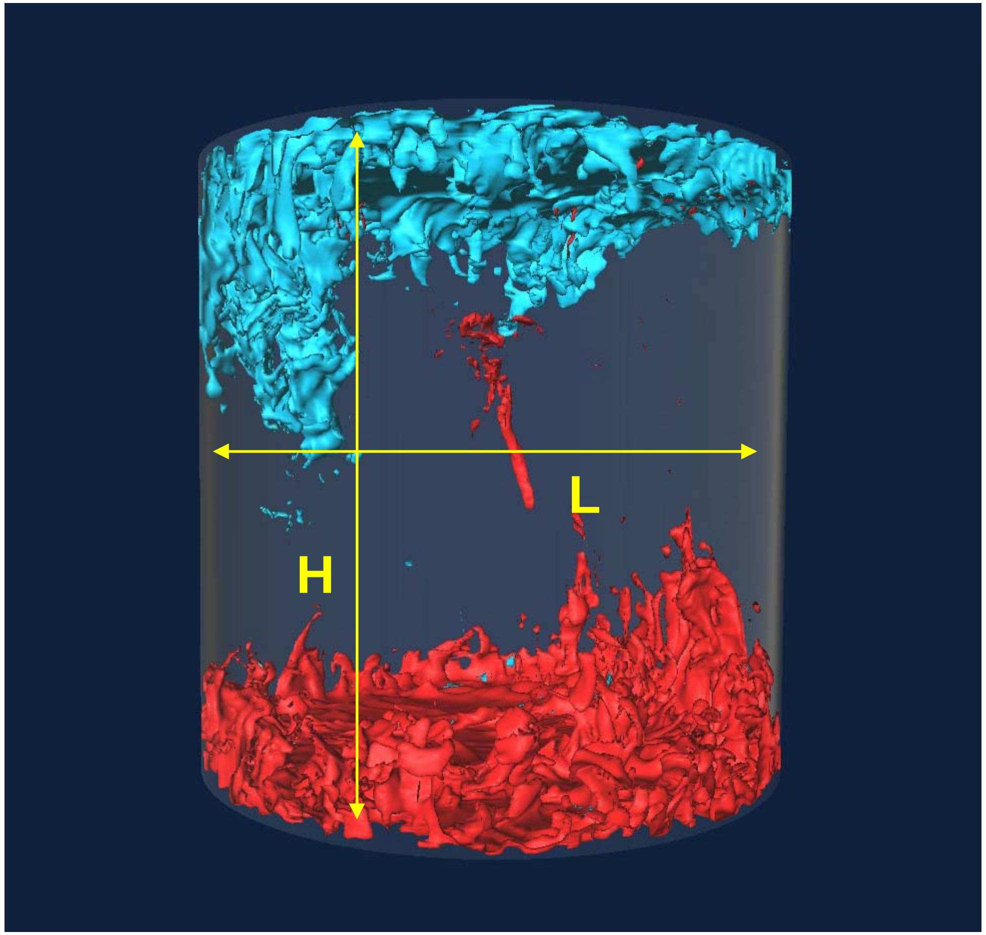
R_λ=80
Nu=27.85 $\pm$ 0.56

$$\delta_T = \frac{H}{2Nu} = 3\Delta$$

$$\frac{\eta_K}{\Delta} \approx 1$$

Case 2: Cylindrical Cell

(Verzicco & Orlandi, JCP 1996)



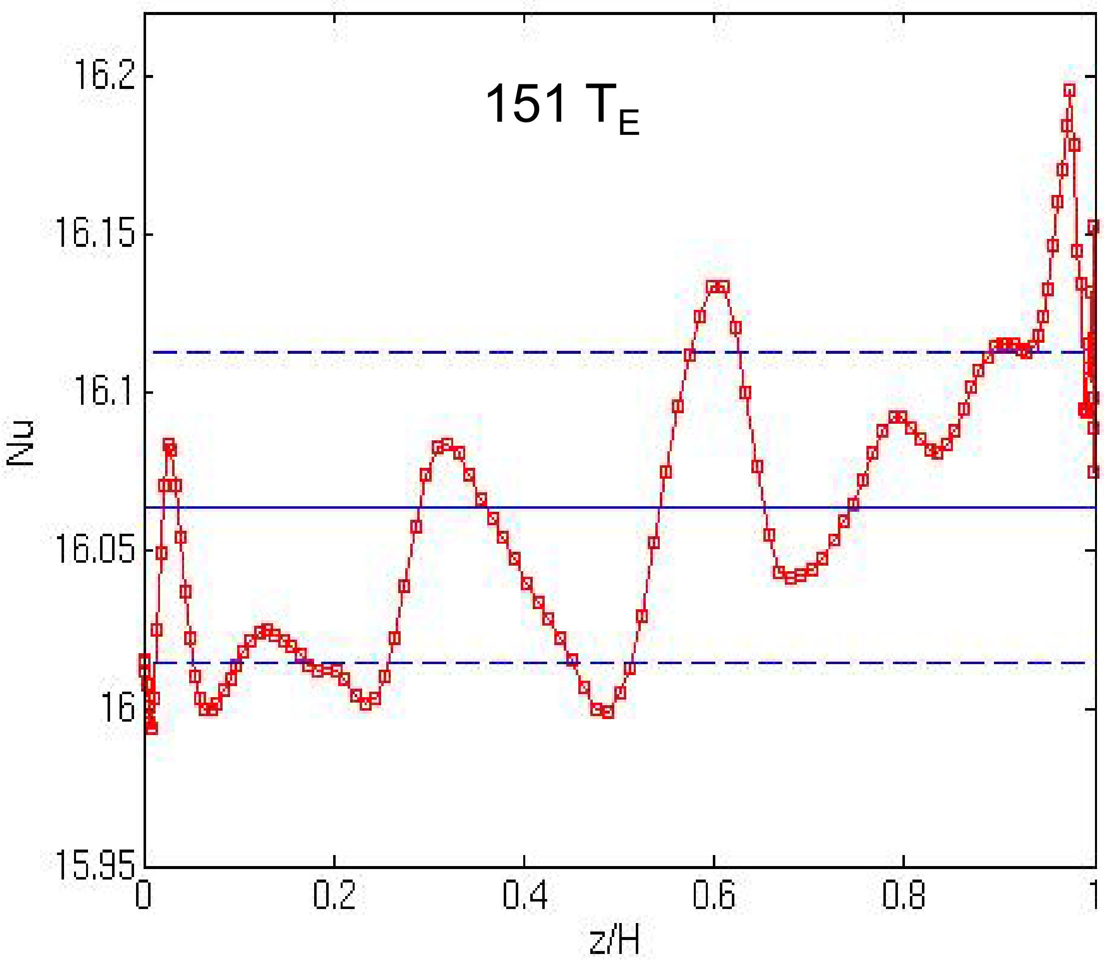
Geometry and Parameters

- Cylindrical geometry (r,θ,z)
- Ra=10^{7}–10^{12}
- Pr=0.7 (later Pr > 1)
- Aspect ratio: Γ=L/H=1, 3, 5

- No-slip boundaries for flow
- Non-equidistant grid
- Temperature fixed at bottom/top
- Adiabatic side walls

Nusselt Number Convergence

$$N_\theta \times N_r \times N_z = 257\times165\times128$$



Pr=0.7

Ra=10^7

Γ=3

$R_\lambda=(Ra/Pr)^{1/4}\sim100$

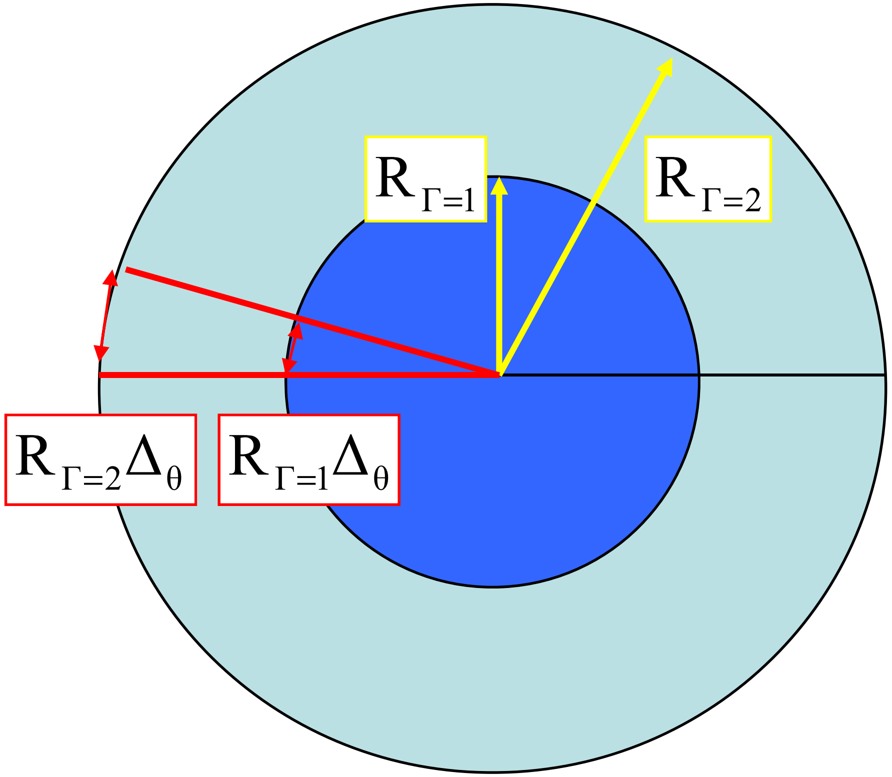
Nu=16.06 ± 0.05

$$\delta_T = \frac{H}{2\,Nu} \approx 0.03$$

$$\frac{\eta_K}{\tilde{\Delta}} \geq \frac{3}{4}$$

$$\tilde{\Delta} = \sqrt[3]{\max(\Delta_r) R\Delta_\theta \max(\Delta_z)}$$

Towards Large Γ



Example:

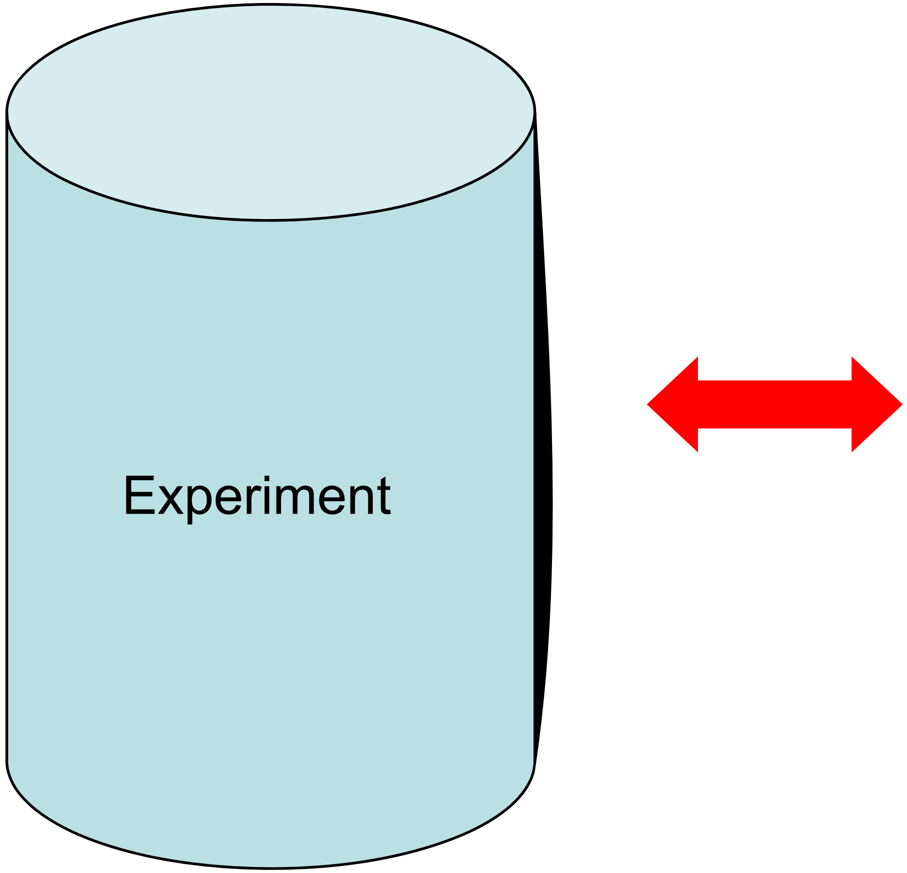
Sustain resolution & Double Γ

$$\tilde{\Delta}_{\Gamma=2} = \sqrt[3]{\max(\Delta_r)\,\underbrace{\Gamma R_{\Gamma=1}}_{R_{\Gamma=2}}\,\underbrace{\frac{\Delta_\theta}{\Gamma}}_{\Delta_{\theta,\Gamma=2}}\,\max(\Delta_z)}$$

$$\tilde{\Delta}_{\Gamma=2} = \tilde{\Delta}_{\Gamma=1} \rightarrow \Gamma N_\theta \times \Gamma N_r \times N_z$$

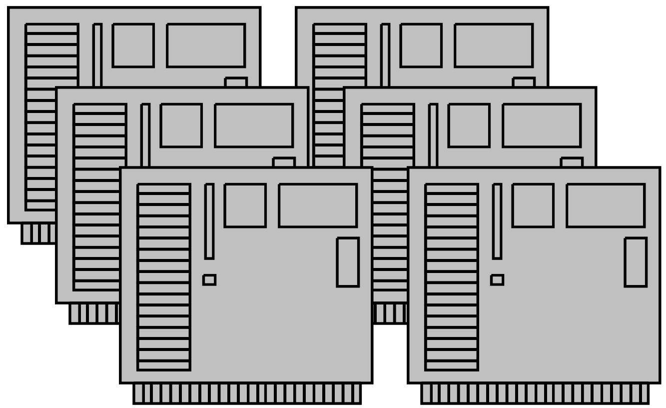
Number of lateral grid points grows with Γ^2 if the strong resolution constraints are sustained!

Contributions (I)



Direct participation

Parallel data processing
Database for later use



Indirect participation

Associated suprcomputing projects on classical/quantum turbulence

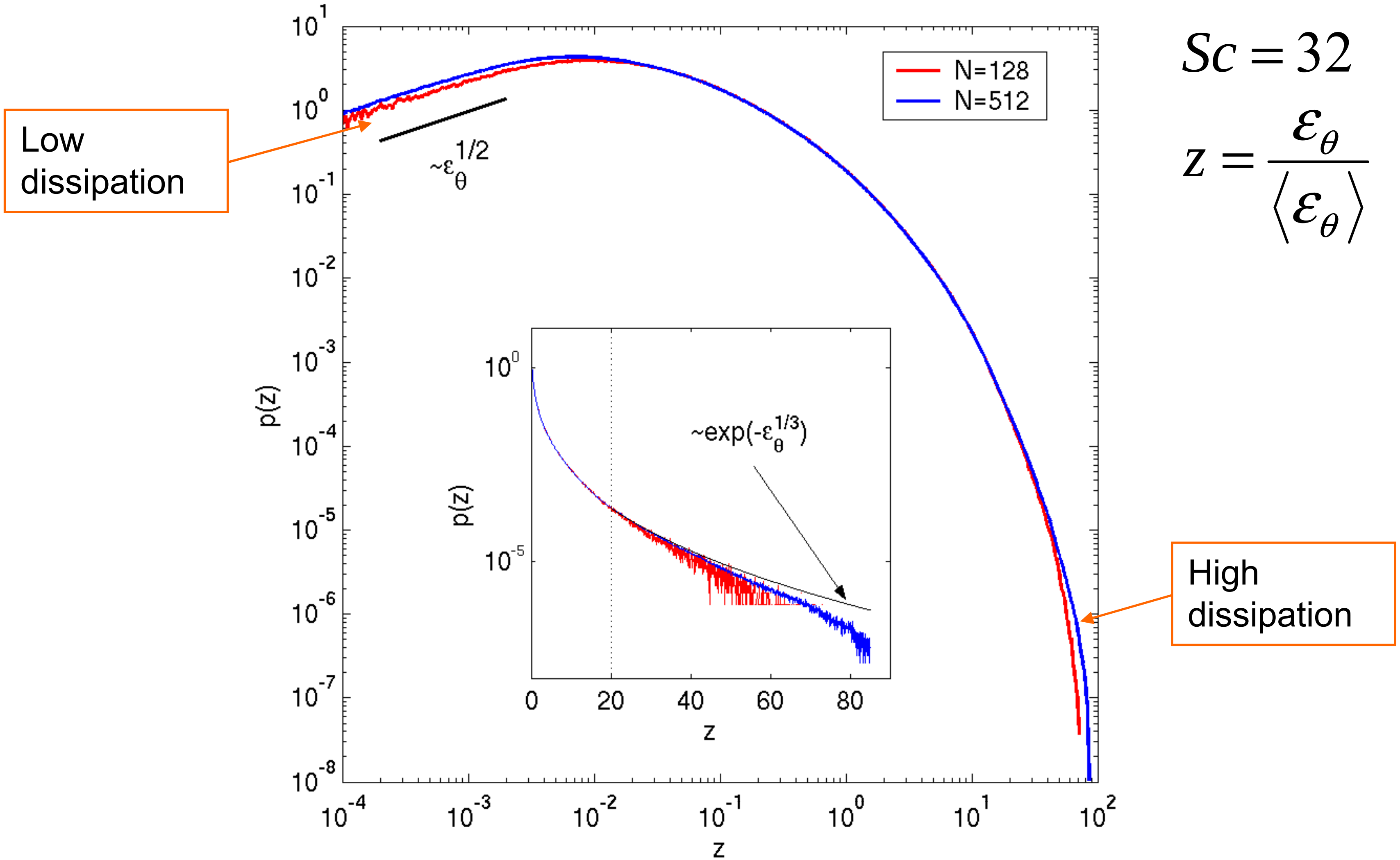
Contributions (II)

- Resolution of high-Ra boundary layers
- Transition from laminar to turbulent boundary layer at $Ra>10^{11}$
- What are the differences to „classical“ boundary layers?
- Detailed Lagrangian study of breakdown of wind for aspect ratios $\Gamma>1$
- Ultimate regime of convection?

- M. Emran (Ilmenau)
  R. Verzicco (Bari)

Resolution in High-Sc Mixing

(Schumacher, Sreenivasan & Yeung, JFM 2005)



$$Sc = 32$$

$$z = \frac{\varepsilon_\theta}{\langle \varepsilon_\theta \rangle}$$

Resolution Criterion

(Grötzbach, JCP 1983; Schumacher, Sreenivasan & Yeung, JFM 2005)

- Maximum wavenumber (or finest scale) resolved $k_{max} \approx \pi/\Delta$
- Resolution constraint for $Pr \leq 1$

$$\boxed{k_{max}\eta_K \geq \alpha} \quad (\alpha > 1)$$

Recent experiences from pseudospectral DNS: $\alpha > 3$

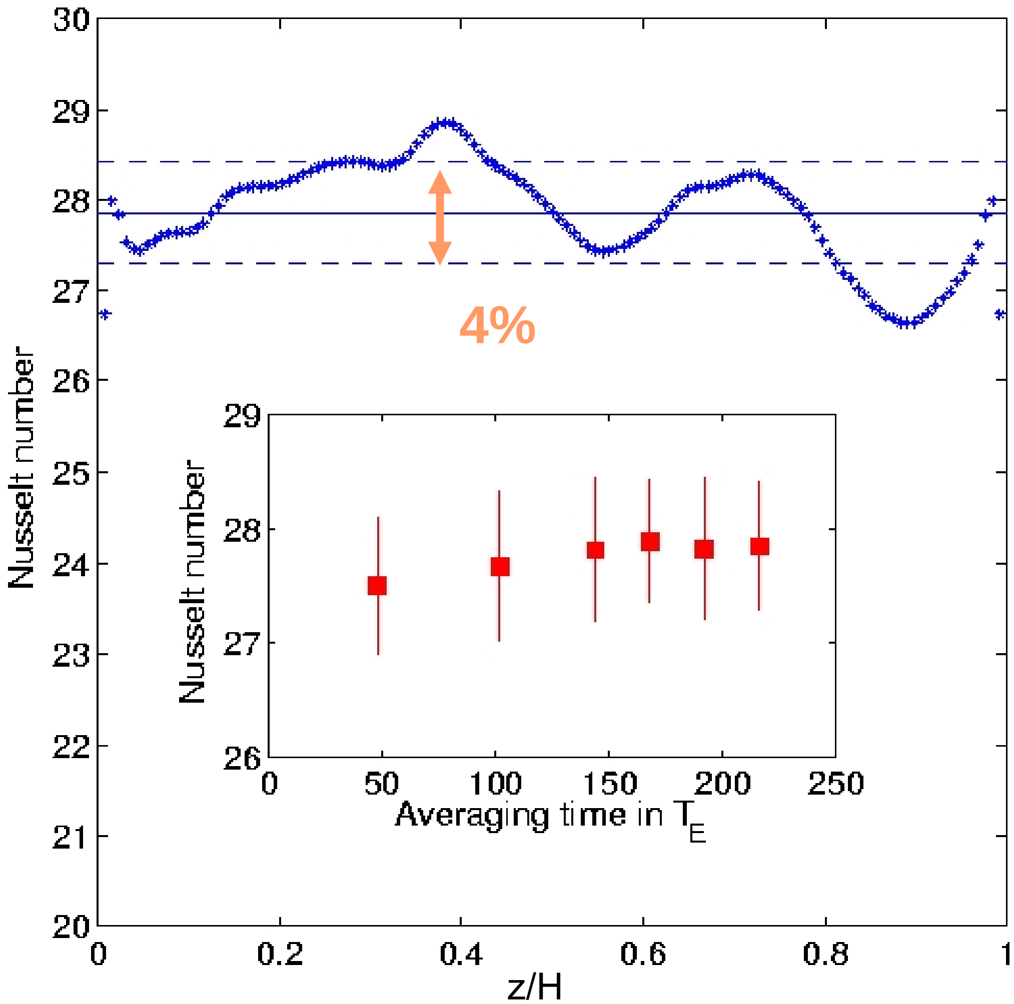
- Kolmogorov length

$$\eta_K = \frac{\nu^{3/4}}{\langle \varepsilon \rangle^{1/4}} = H\left(\frac{Pr^2}{Nu\,Ra}\right)^{1/4}$$

- Grid spacing

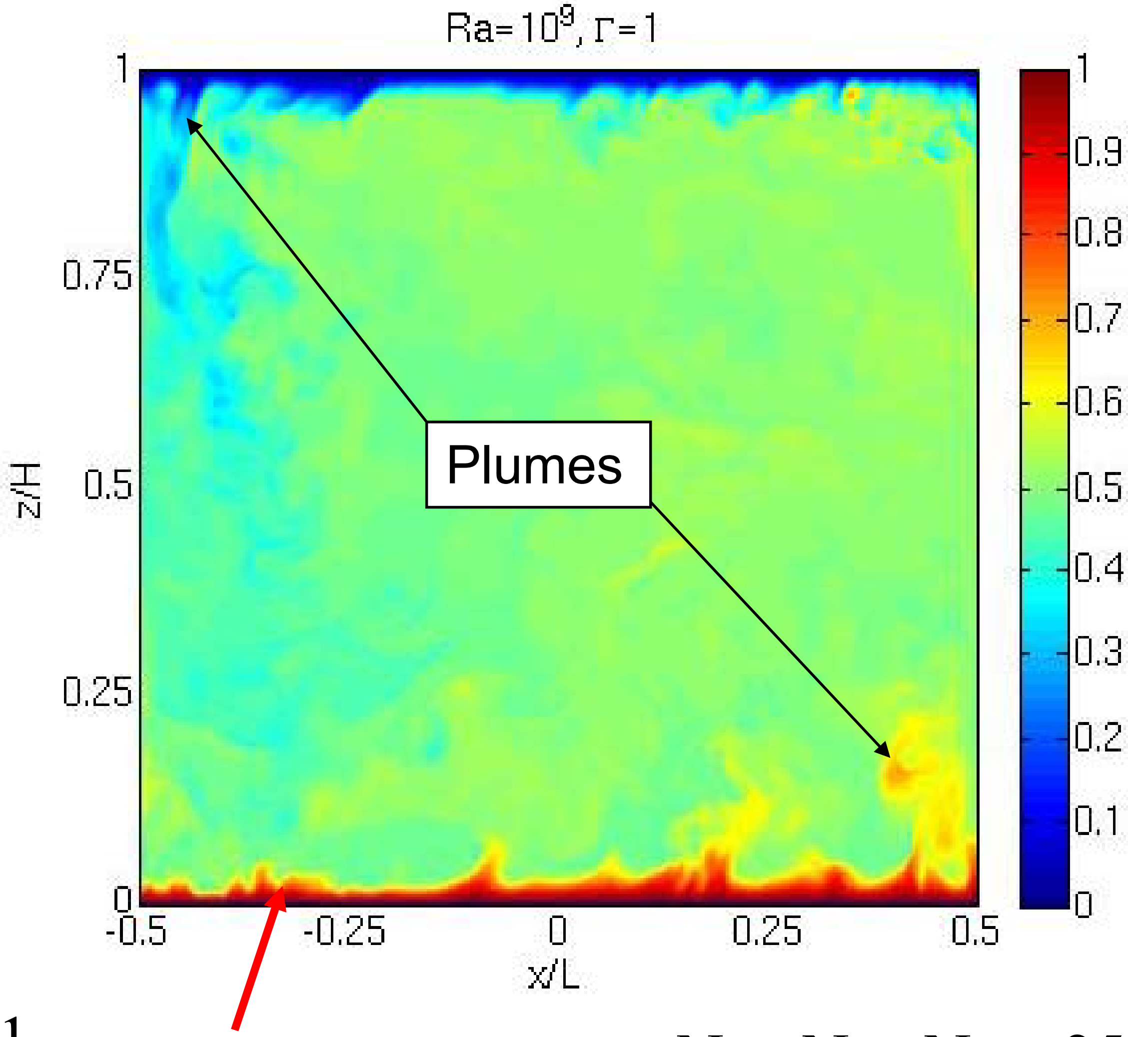
$$\boxed{\Delta \leq \frac{H\pi}{\alpha}\left(\frac{Pr^2}{Nu\,Ra}\right)^{1/4}} \quad \text{or} \quad \frac{\eta_K}{\Delta} \geq \frac{\alpha}{\pi}$$

Nusselt Number Convergence



Very slow convergence !

Temperature Field (Pr=0.7)



$$\frac{\eta_K}{\widetilde{\Delta}} \geq \frac{3}{4}$$

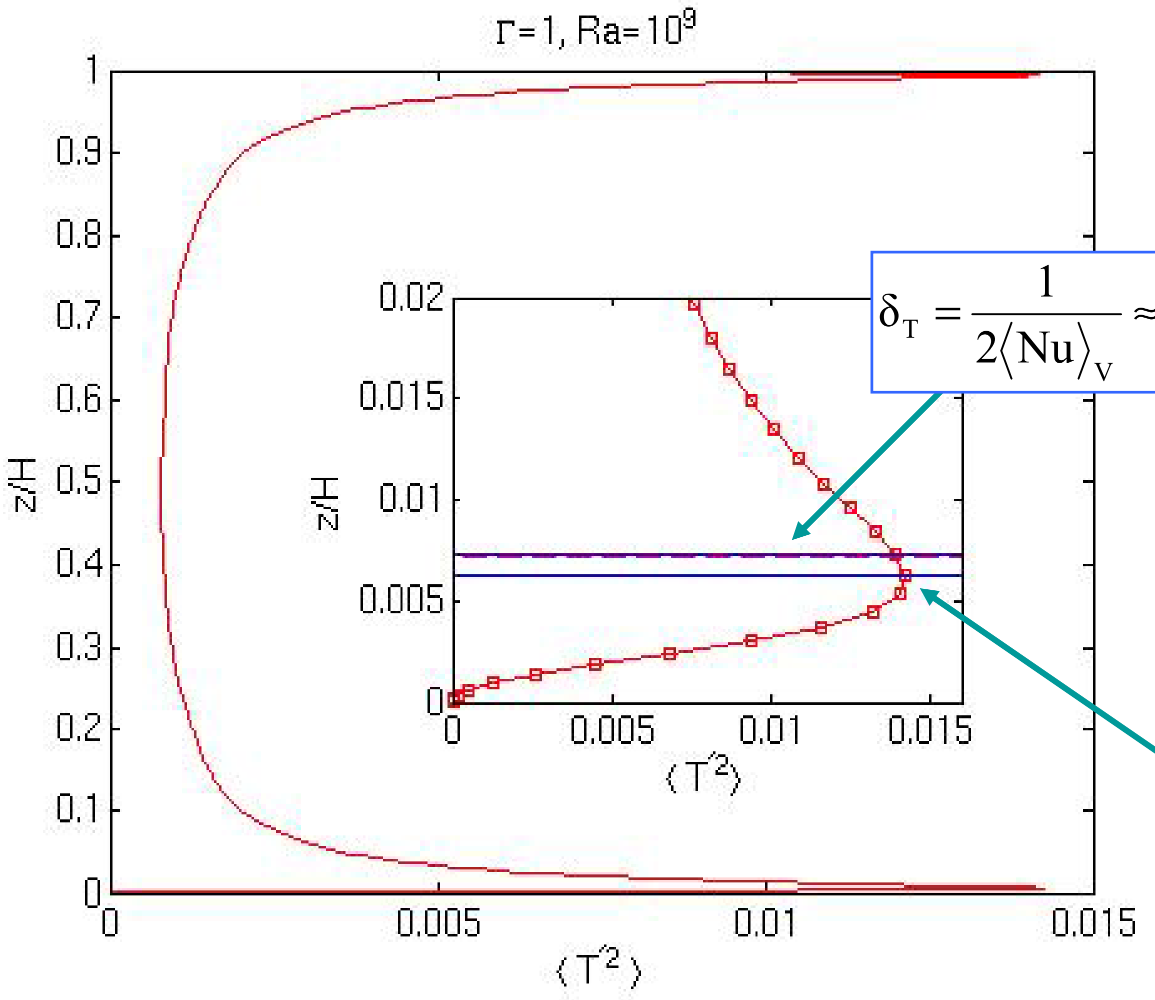
$$\delta_T = \frac{1}{2\,Nu} \approx 0.0077$$

$$N_\theta \times N_r \times N_z = 257 \times 193 \times 257$$

$$\widetilde{\Delta} = \sqrt[3]{\max(\Delta_r) R \Delta_\theta \max(\Delta_z)}$$

Temperature Fluctuation Profile

257 grid points



$$\delta_T = \frac{1}{2\langle Nu \rangle_V} \approx \frac{1}{2Nu_{top}} \approx \frac{1}{2Nu_{bottom}}$$

Maximum

Thermal boundary layer is resolved with 13 grid cells

Boundary layer thickness deviates from peak mean square by 17.5%