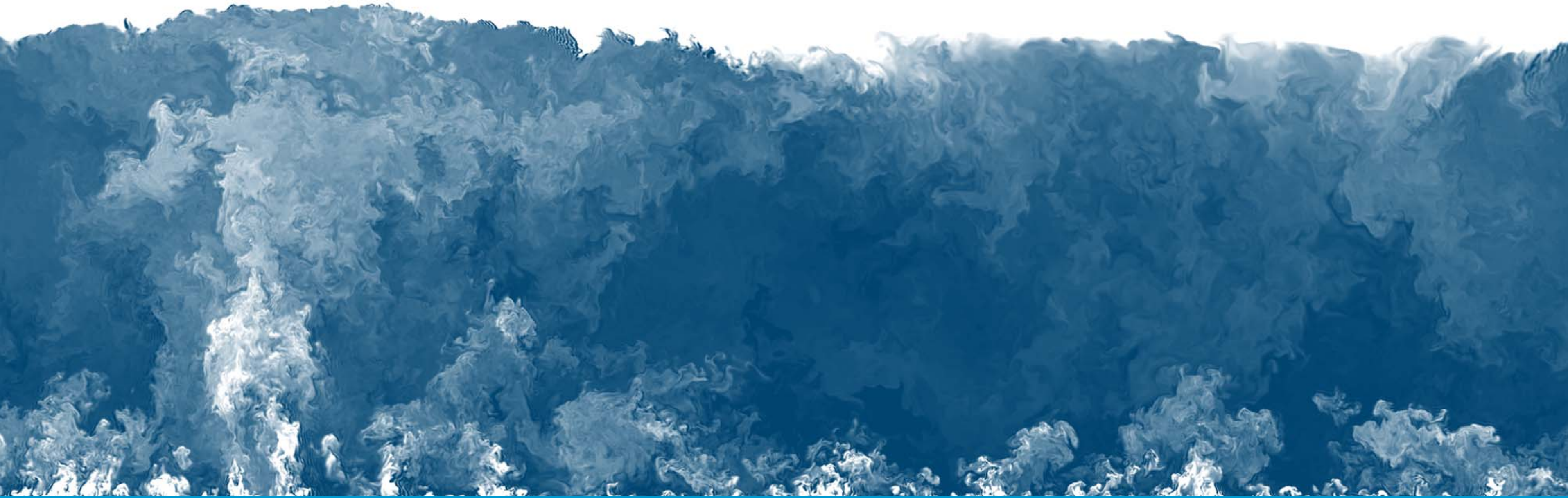
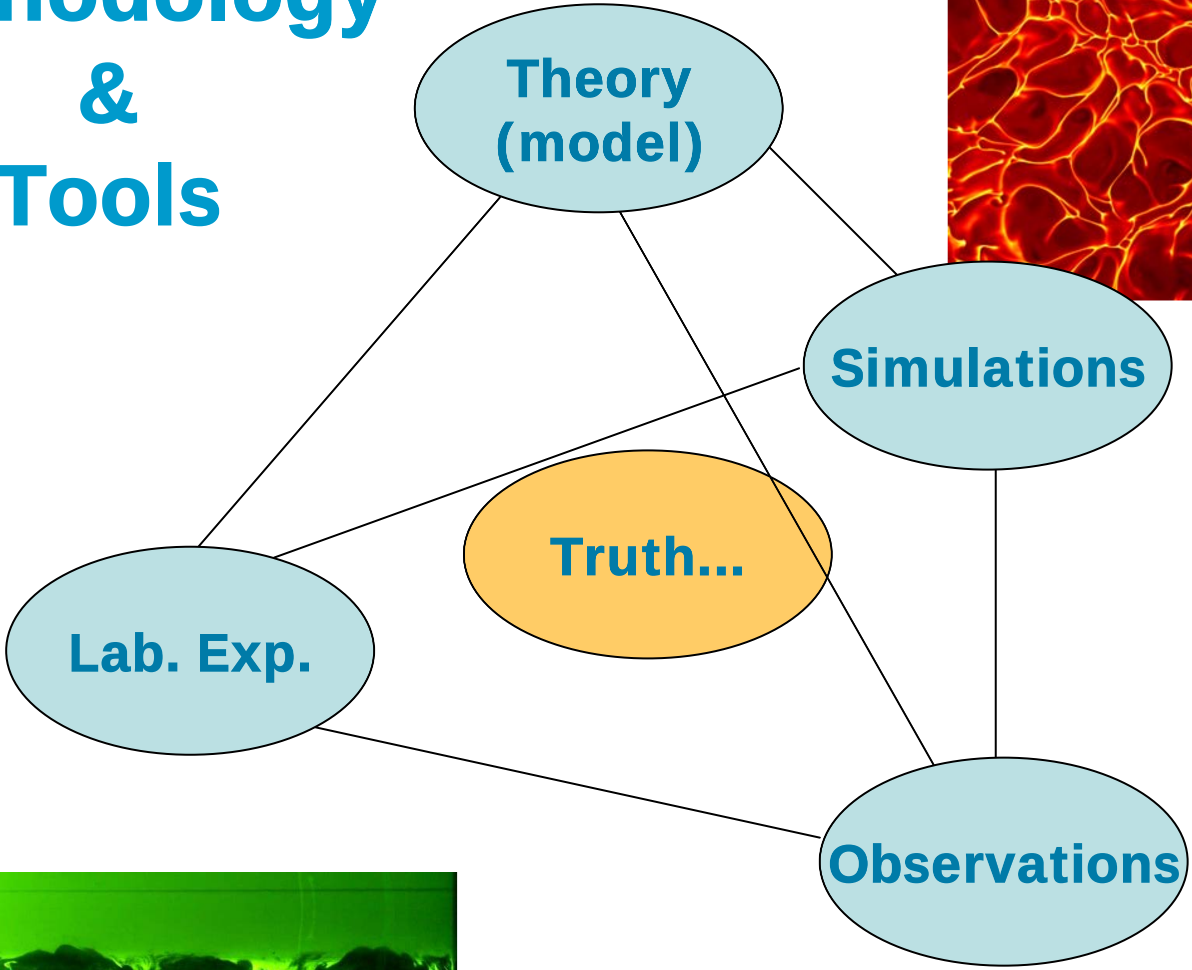
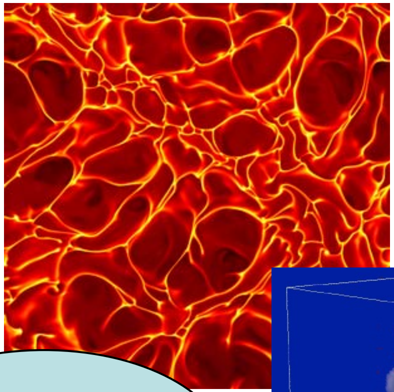
Modeling, Validation and Physics of Turbulent Flows: opportunities offered by petascale Direct Simulation

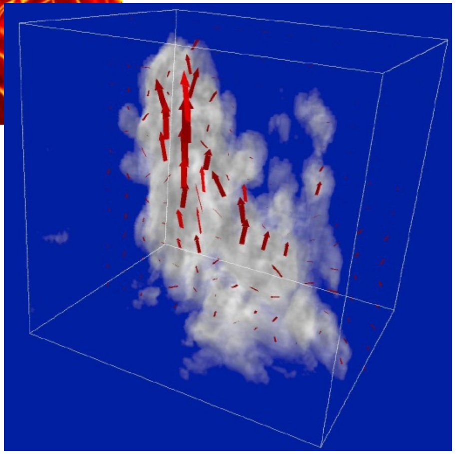


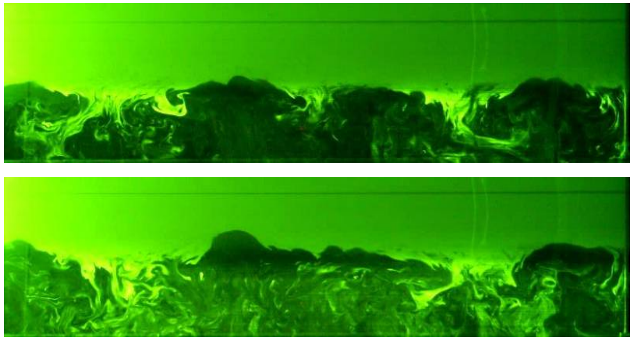
Harm Jonker (Multi-Scale Physics, Delft, Netherlands)
Peter Sullivan & Ned Patton (National Center for Atmospheric Research, USA)
Maarten van Reeuwijk (Imperial College, UK), Jerome Schalkwijk (Delft)

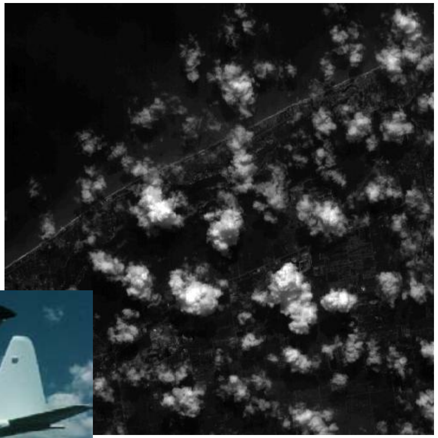
Methodology & Tools



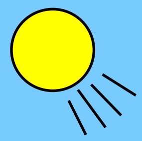


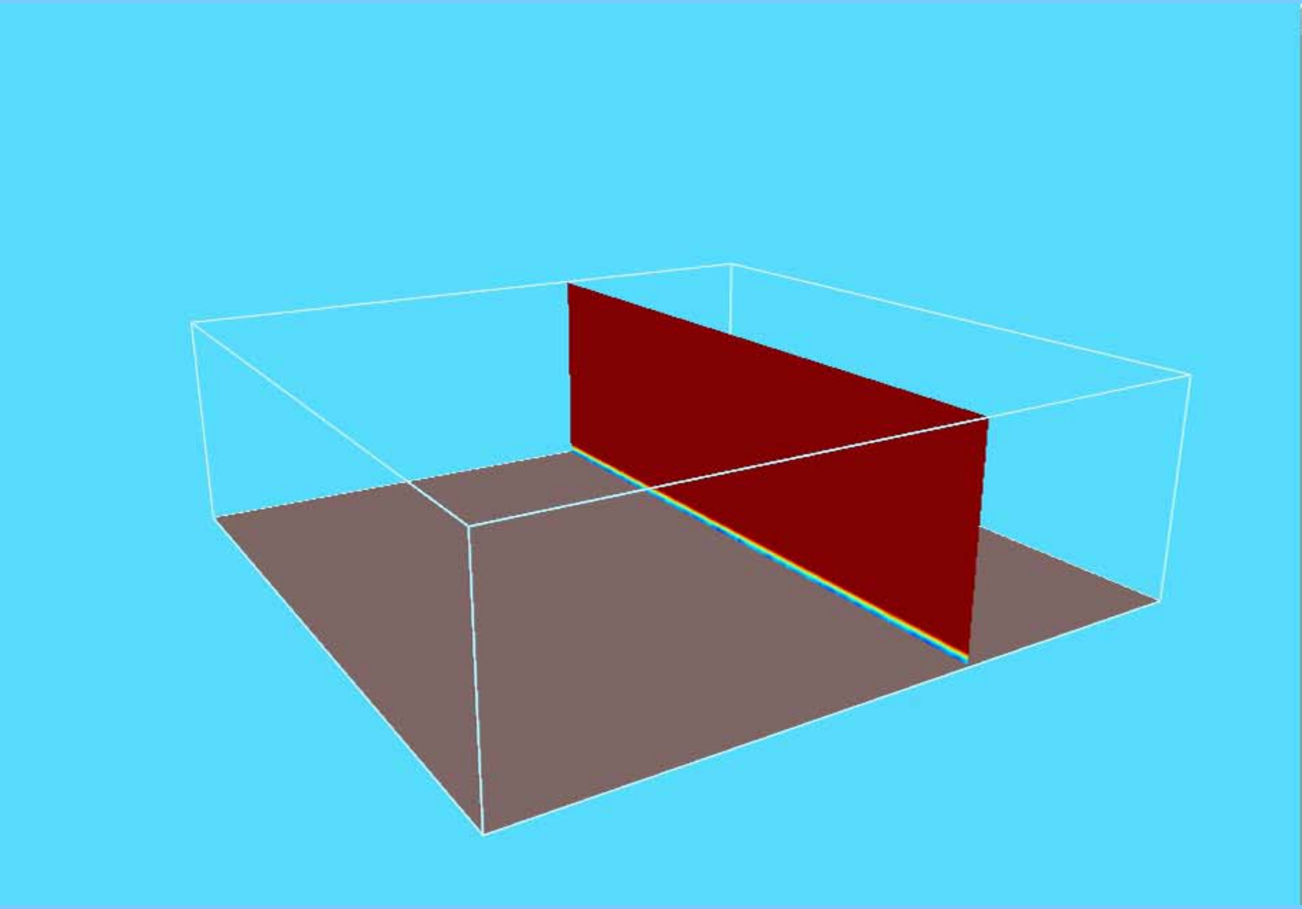


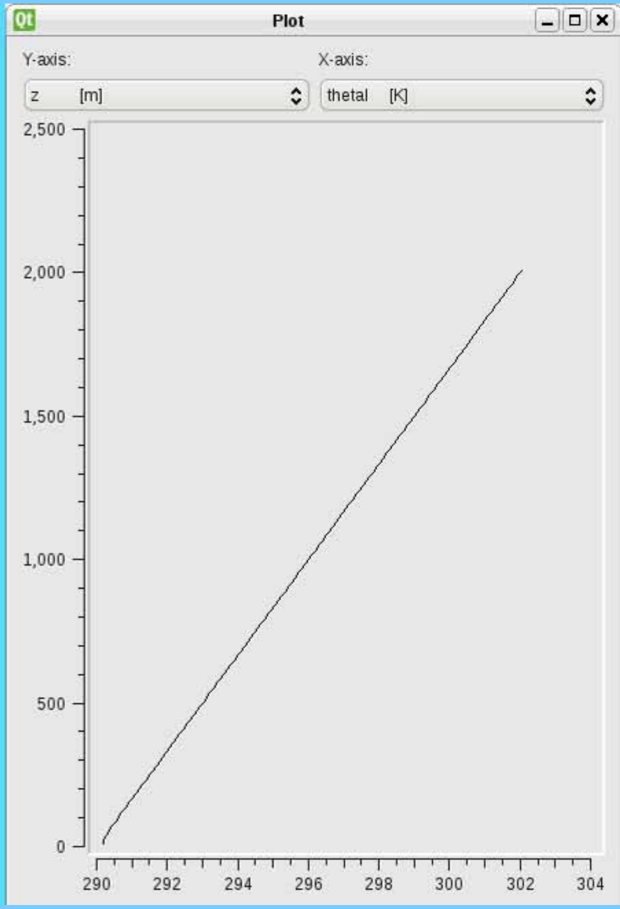




Burgers – conference 2000





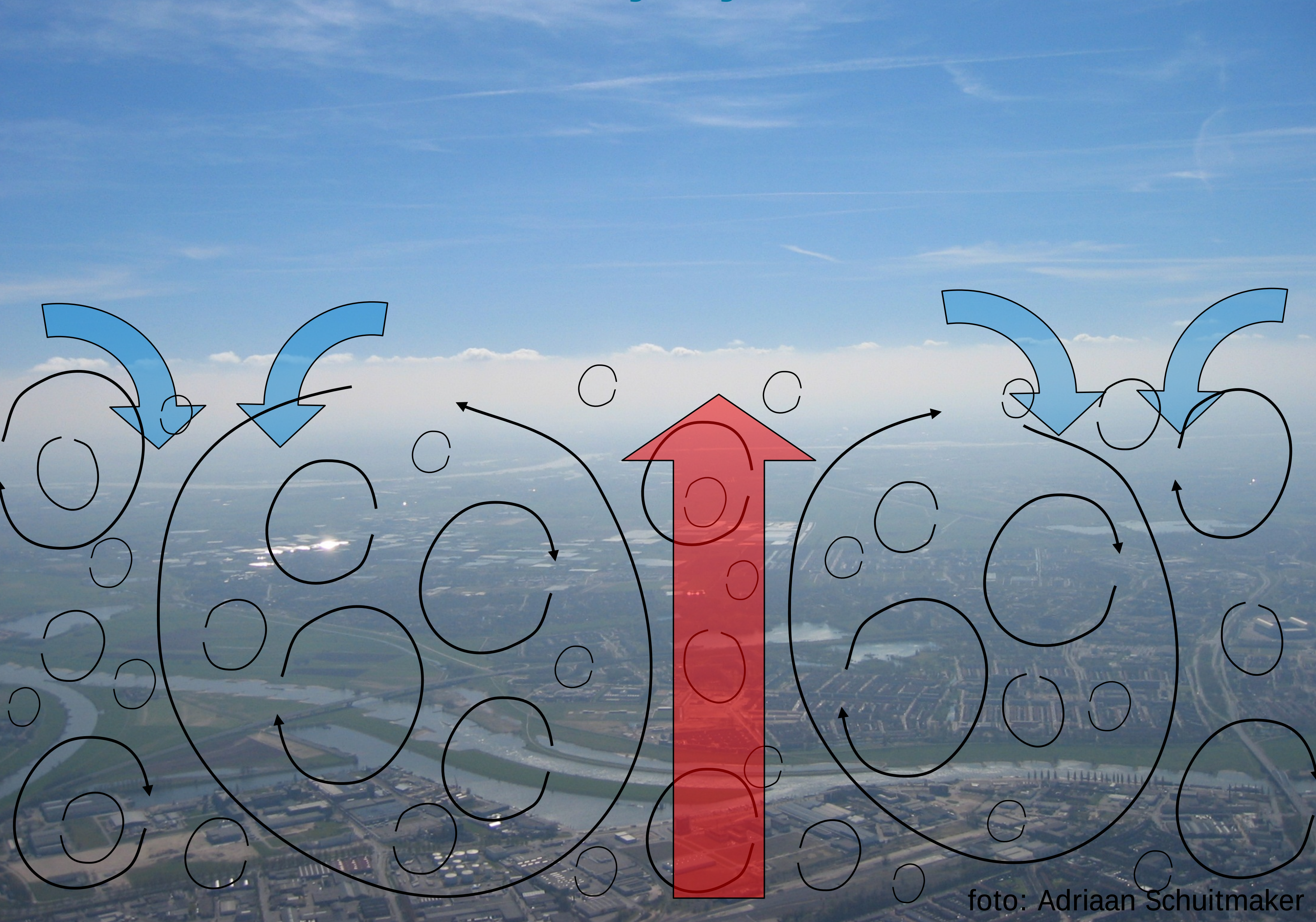


$\theta \rightarrow$

Large Eddy Simulation (GPU)

courtesy Jerome Schalkwijk

The convective boundary layer ...



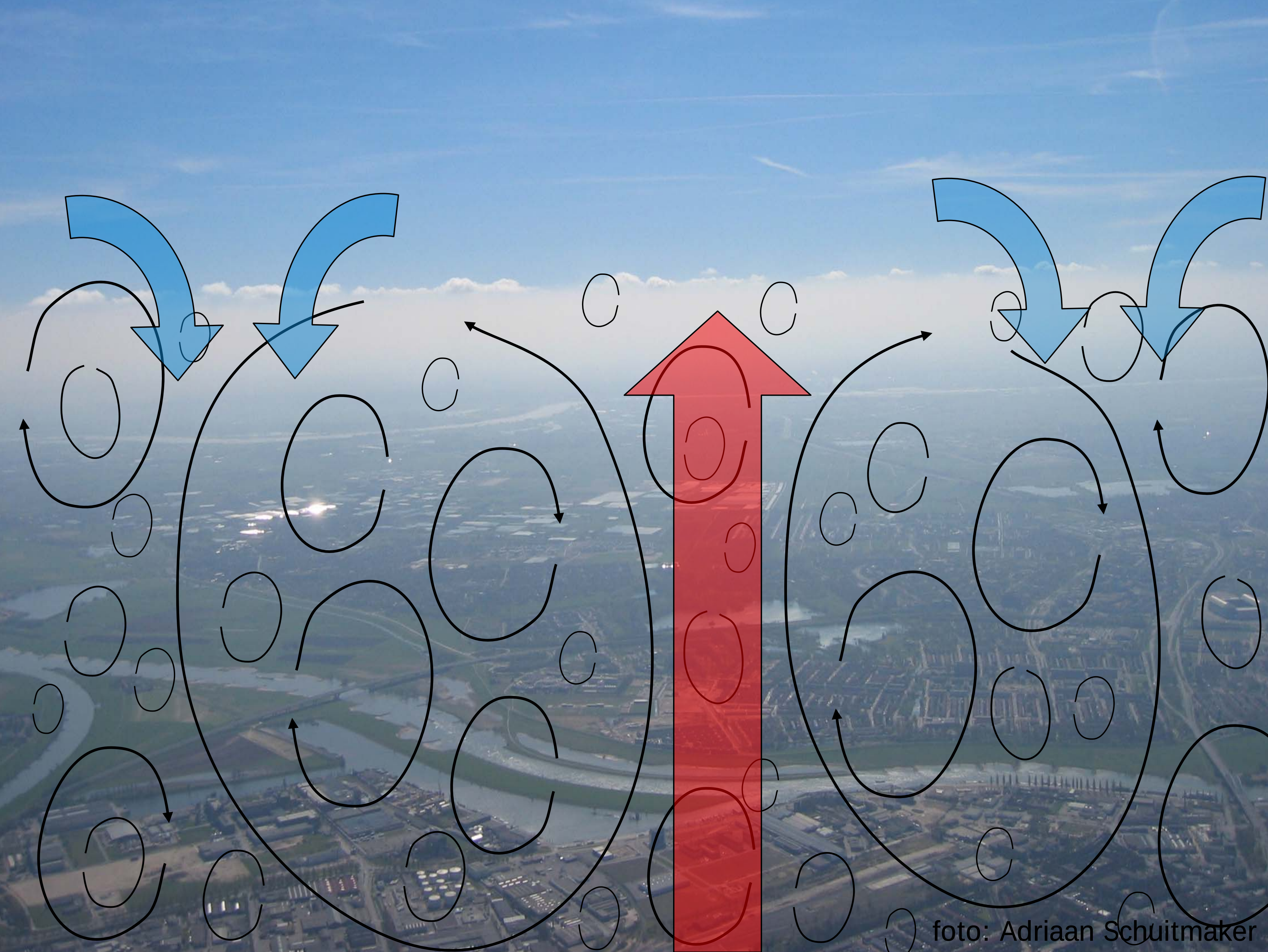
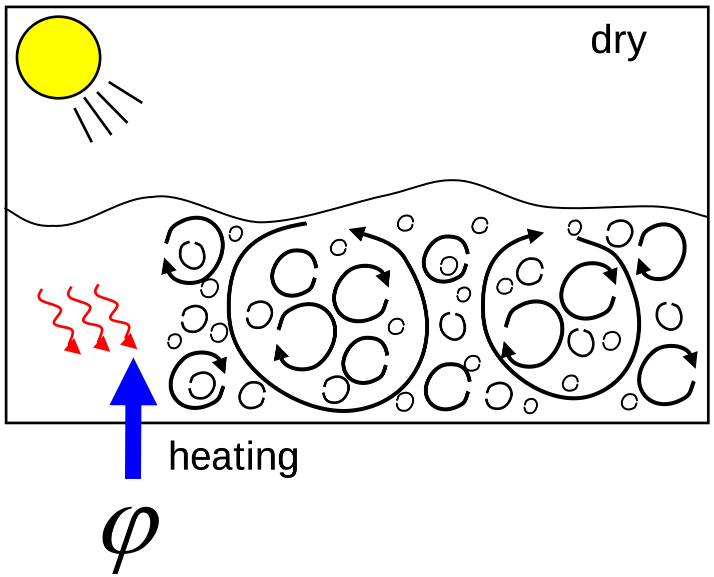
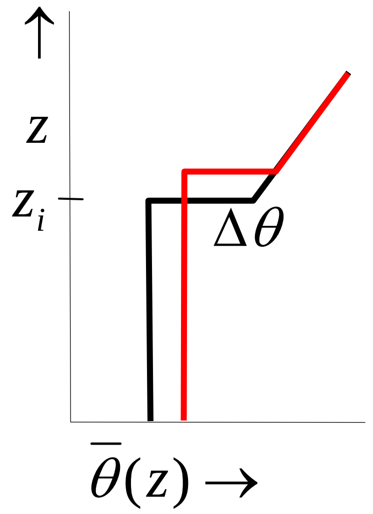


foto: Adriaan Schuitmaker





growth-rate: $$\boxed{w_e = \frac{dz_i}{dt}}$$ **'law'**

$$w_* = \left(\frac{g}{\theta_0} \varphi z_i \right)^{1/3}, \quad \mathrm{Ri} = \frac{g}{\theta_0} \frac{\Delta\theta \, z_i}{w_*^2}$$

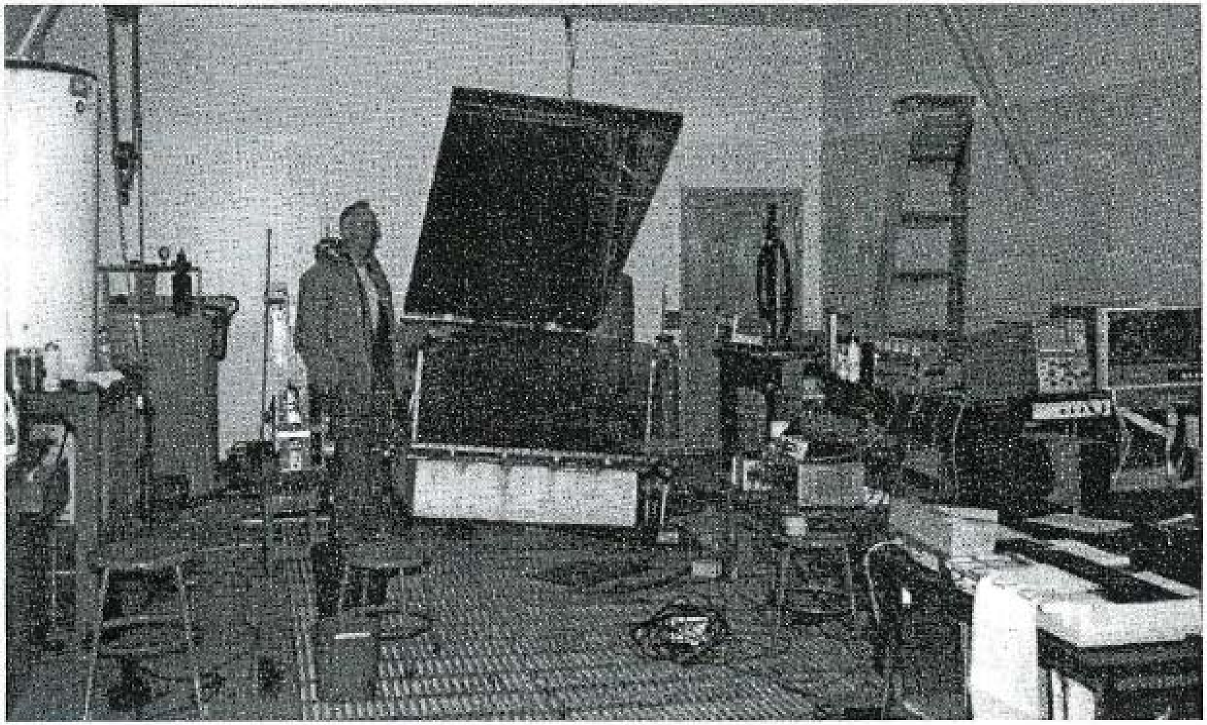
$$\frac{w_e}{w_*} = A Ri^{-1}$$

$$A = 0.2$$

Water Tank: Deardorff, Willis and Stockton, JFM 1980

Laboratory Experiments
(thermal convection tank)

Deardorff et al. water tank model of shear-free CBL (1960-80s)



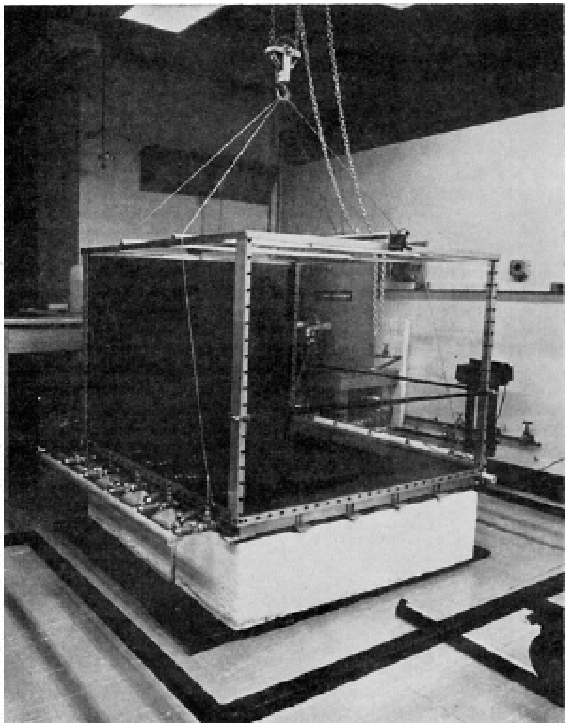


Figure 7.10 Tank used by Deardorff (pictured above) and Willis in their laboratory experiments. (Deardorff and Willis.)

From Sorbjan, Z., 1989: *Structure of the Atmospheric Boundary Layer*, Prentice Hall, 317 pp.

courtesy E. Fedorovich

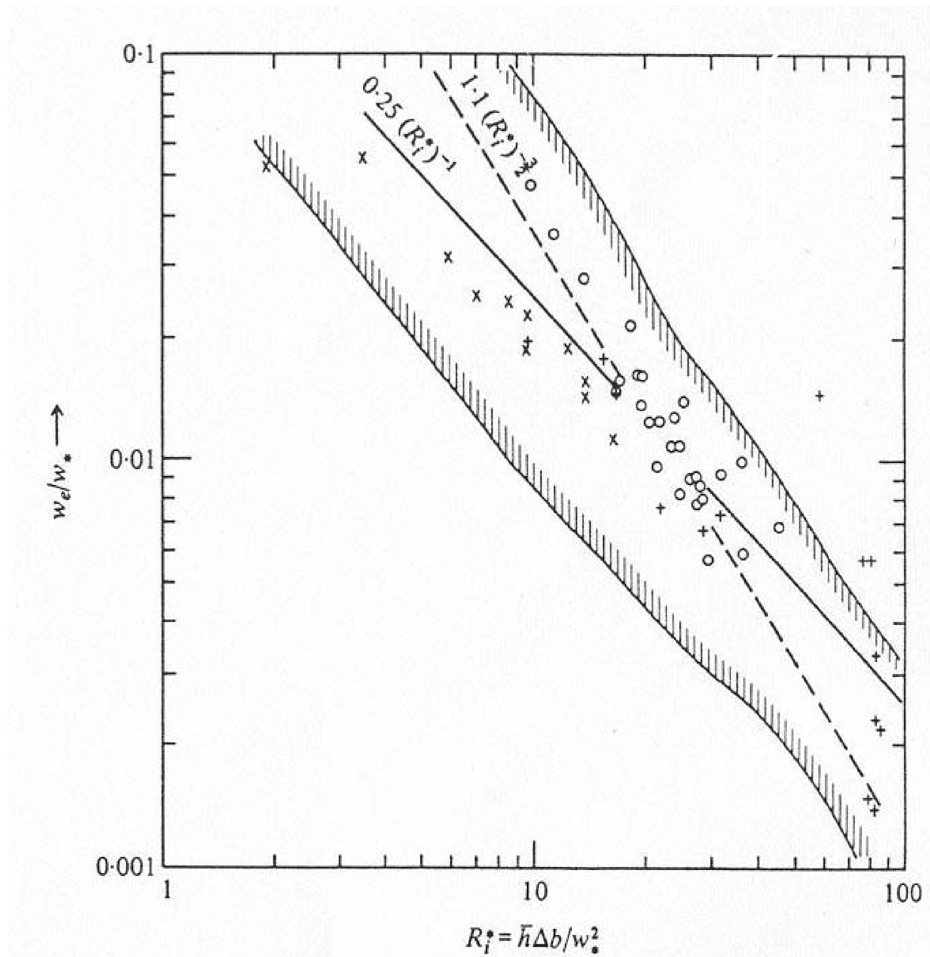
Laboratory Experiments (thermal convection tank)

Entrainment rate

$$w_e = \frac{dz_i}{dt}$$

$$\uparrow$$

$$\frac{w_e}{w_*}$$



$$Ri \rightarrow$$

$$\frac{w_e}{w_*} = A Ri^{-1}$$

$$A = 0.25$$

Deardorff, Willis and Stockton, JFM 1980



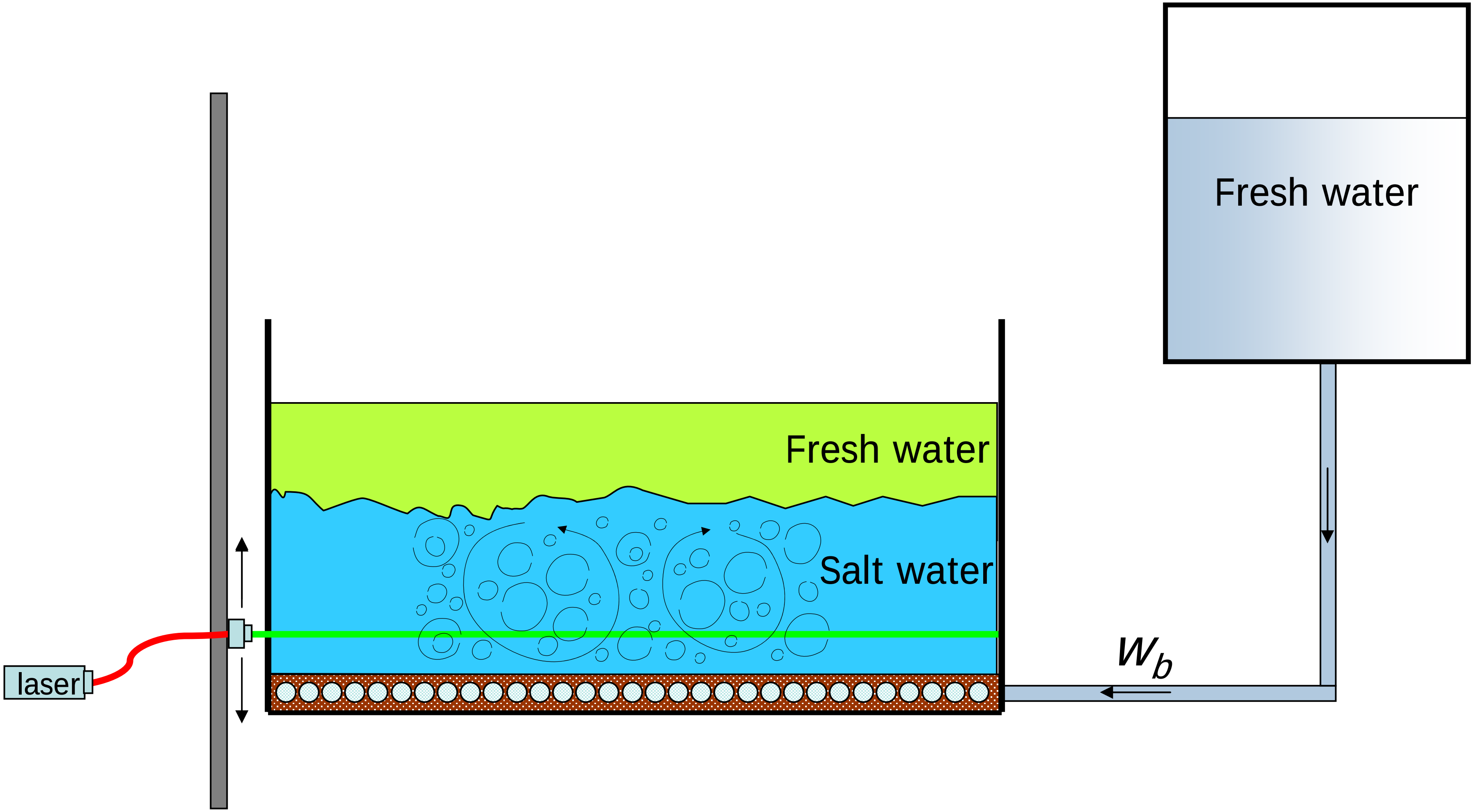


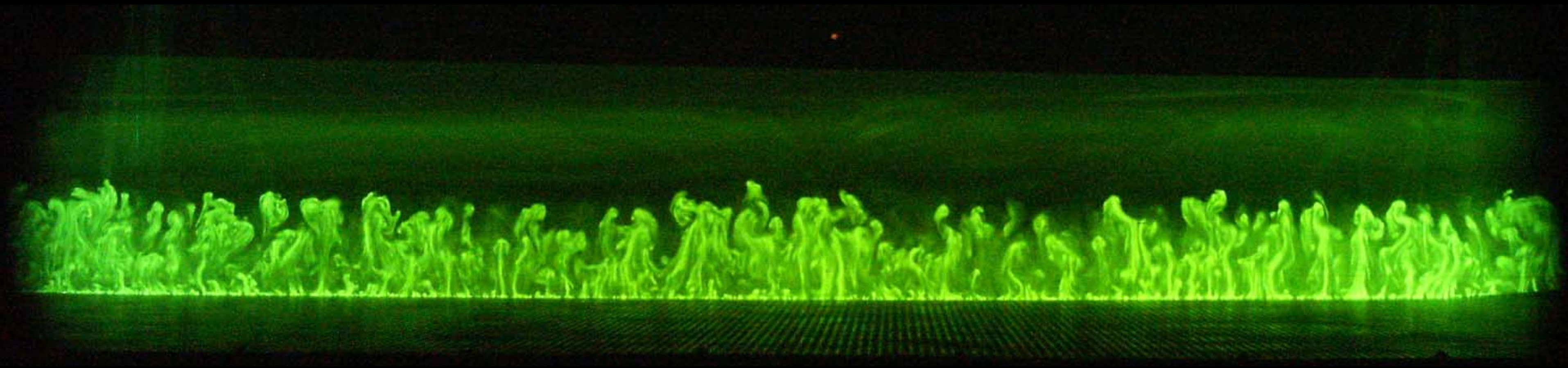




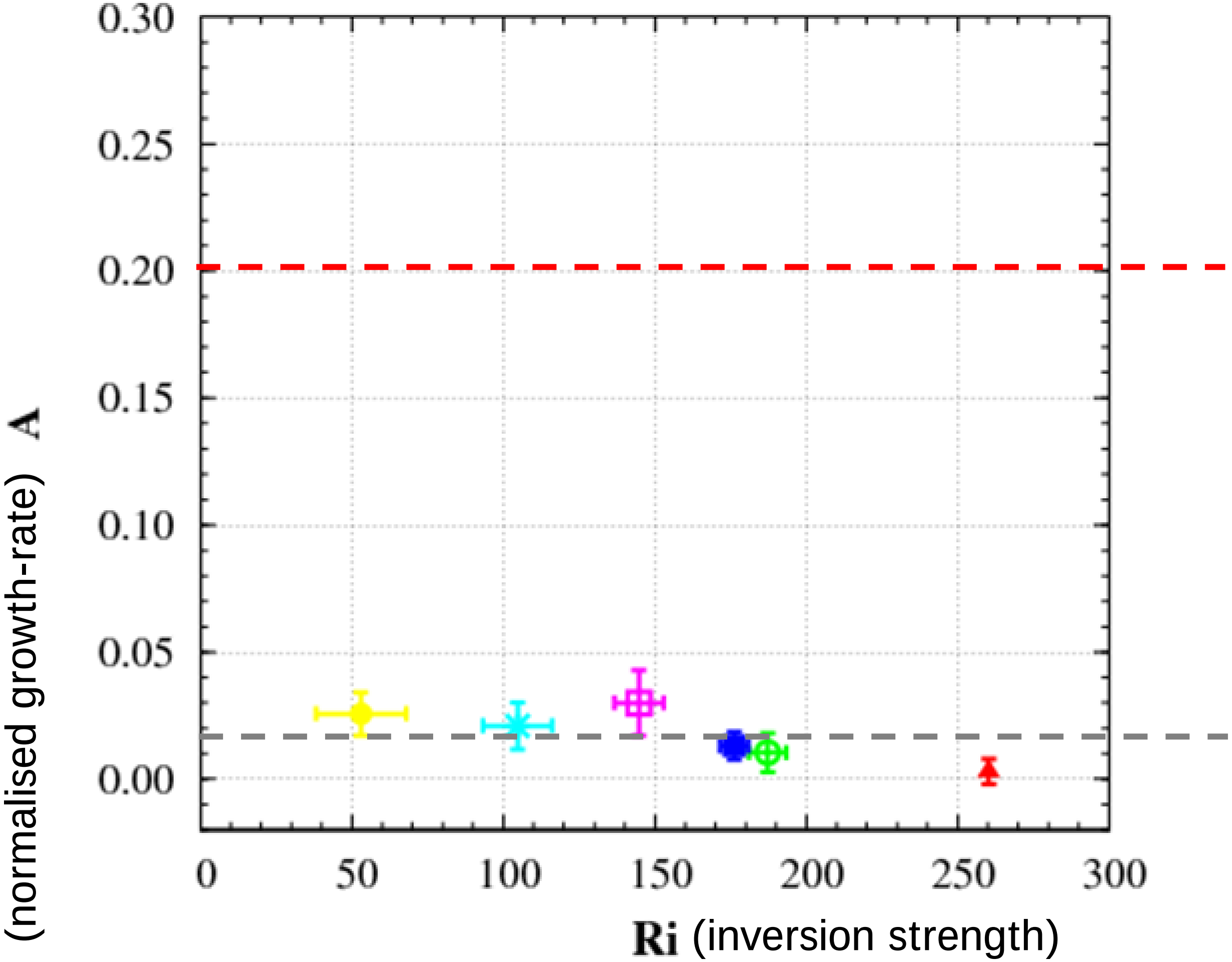


Experimental setup





experimental results



$A \approx 0.2$

$A \approx 0.02$

1970-1980

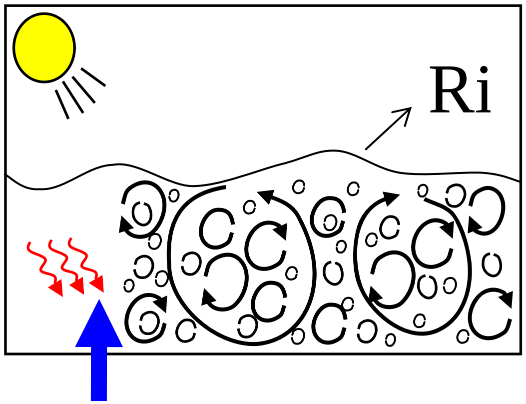
J. Deardorff

factor 10 ??

Controversy ...

J.S. Turner

Governing equations



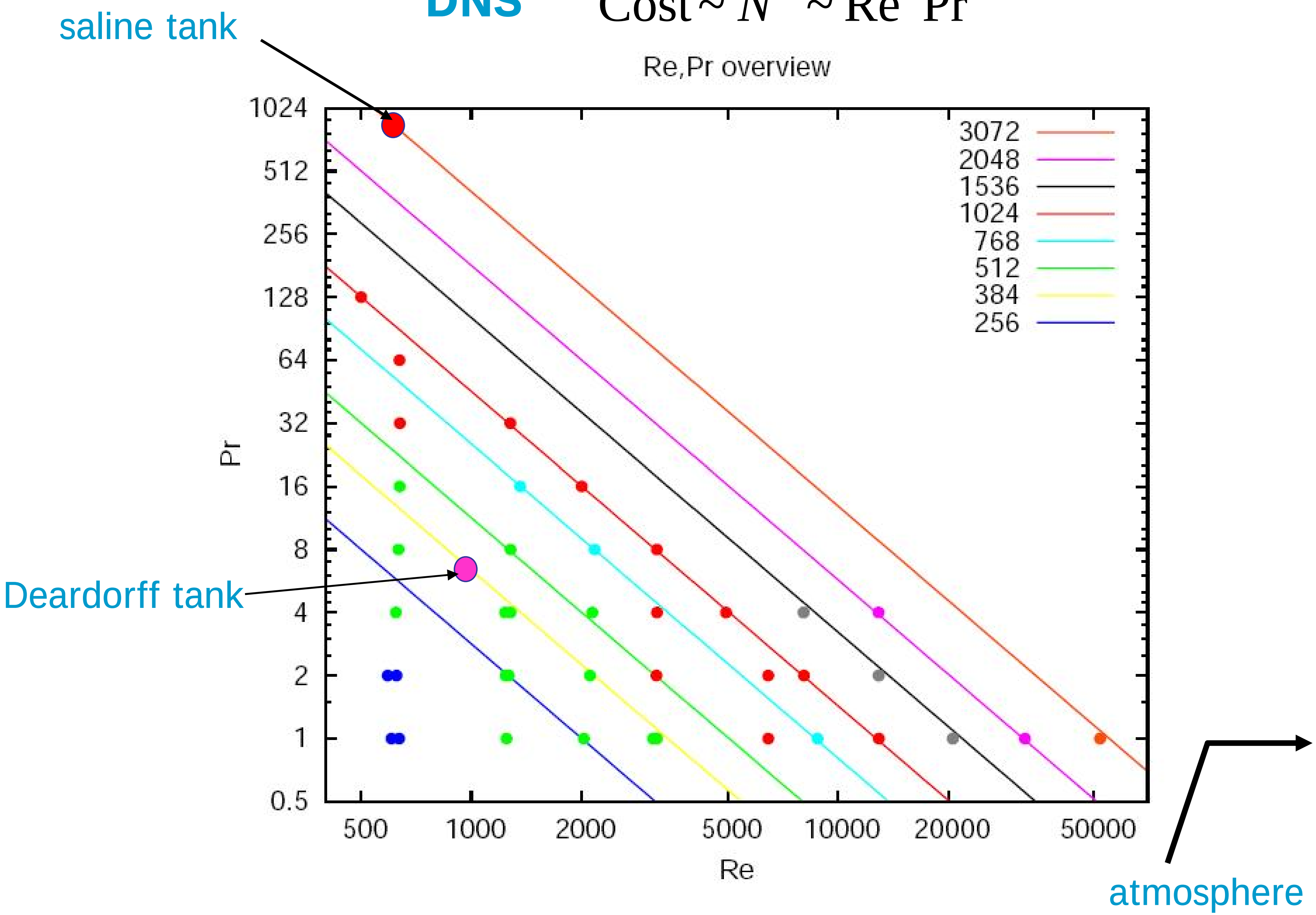
range: ~1km to ~1mm

$$\frac{\partial u_i}{\partial t}+\frac{\partial u_j u_i}{\partial x_j}=\boxed{\frac{1}{\mathrm{Re}}\frac{\partial^2 u_i}{\partial x_j^2}}-\frac{\partial p}{\partial x_i}+\theta\delta_{i3}$$

$$\frac{\partial \theta}{\partial t}+\frac{\partial u_j \theta}{\partial x_j}=\boxed{\frac{1}{\mathrm{RePr}}\frac{\partial^2 \theta}{\partial x_j^2}}$$

		atmosphere	tank (heat)	tank (salt)
Reynolds number	$\mathrm{Re}=\frac{w_* z_i}{\nu}$	$\mathrm{Re}=10^8$	$\mathrm{Re}=10^3$	$\mathrm{Re}=10^3$
Prandtl number	$\mathrm{Pr}=\frac{\nu}{\kappa}$	$\mathrm{Pr}=1$	$\mathrm{Pr}=10$	$\mathrm{Pr}=10^3$
Peclet number	$\mathrm{Pe}=\mathrm{RePr}$	$\mathrm{Pe}=10^8$	$\mathrm{Pe}=10^4$	$\mathrm{Pe}=10^6$

DNS $\text{Cost} \sim N^4 \sim \text{Re}^3\,\text{Pr}^2$



Distributed European Infrastructure for Supercomputing Applications

DEISA resource allocation: 2M cpu-hr

Site	*Architecture*	*cores used*	Grid
SARA	IBM Power 6	1024	1024 x 1024 x 768
CINECA	IBM BCX/5120	2048	2048 x 2048 x 1024
LRZ	SGI Altix 4700	3072	1536 x 1536 x 768
Juelich	Bluegene	32,768	3072 x 3072 x 1536

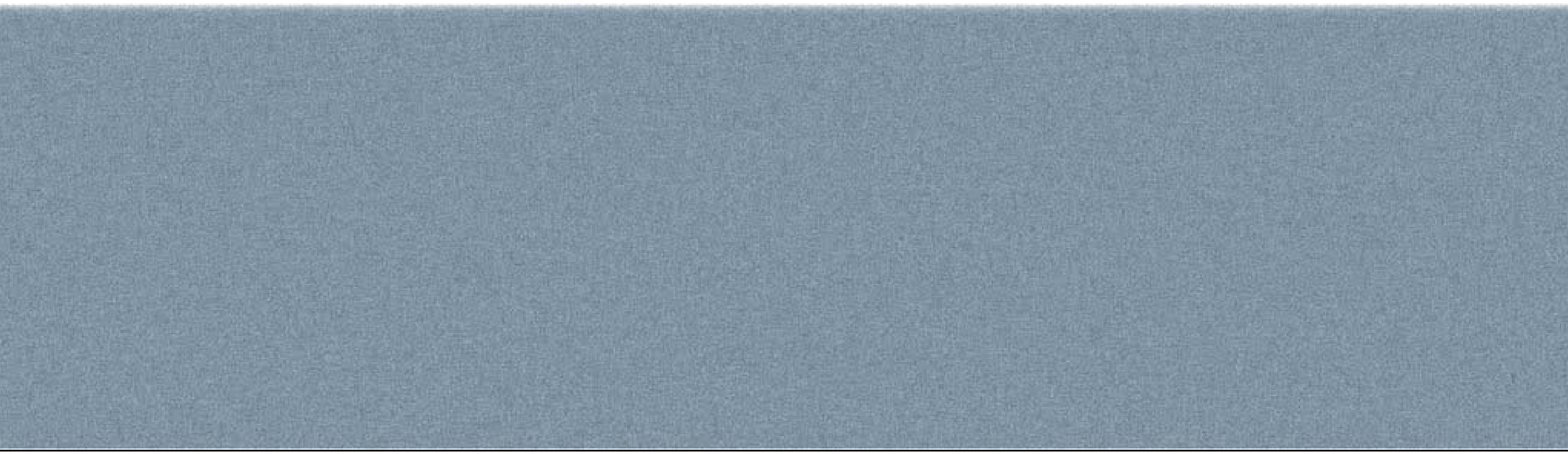
(CINECA)

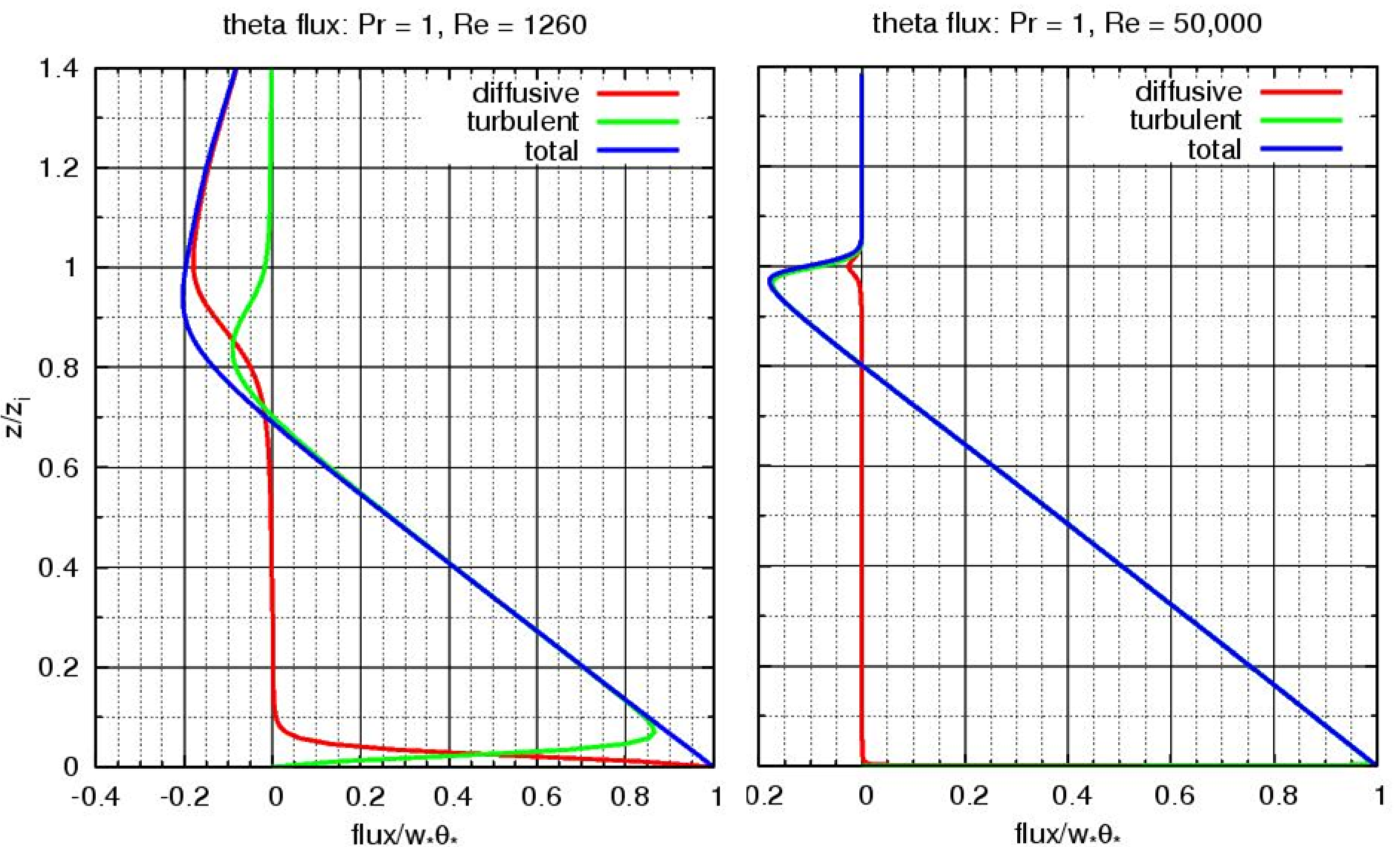
$$N_x = N_y = 2048, \quad N_z = 1024, \quad p = 2048$$

$$L_x = L_y = 3072m, \quad L_z = 1280m$$

$$\mathrm{Re} = 30{,}000 \quad \mathrm{Pr} = 1$$

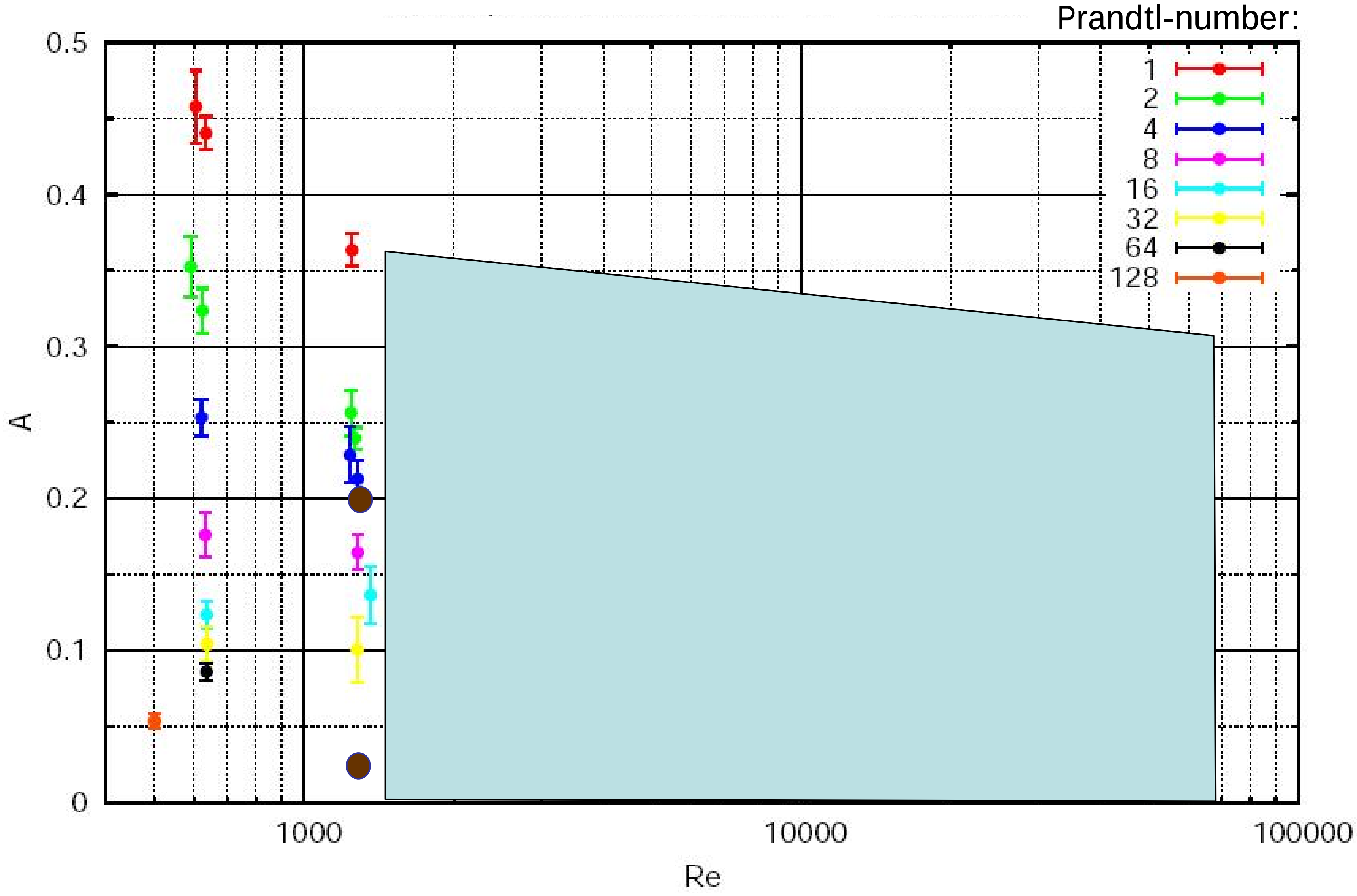
(potential) Temperature animation



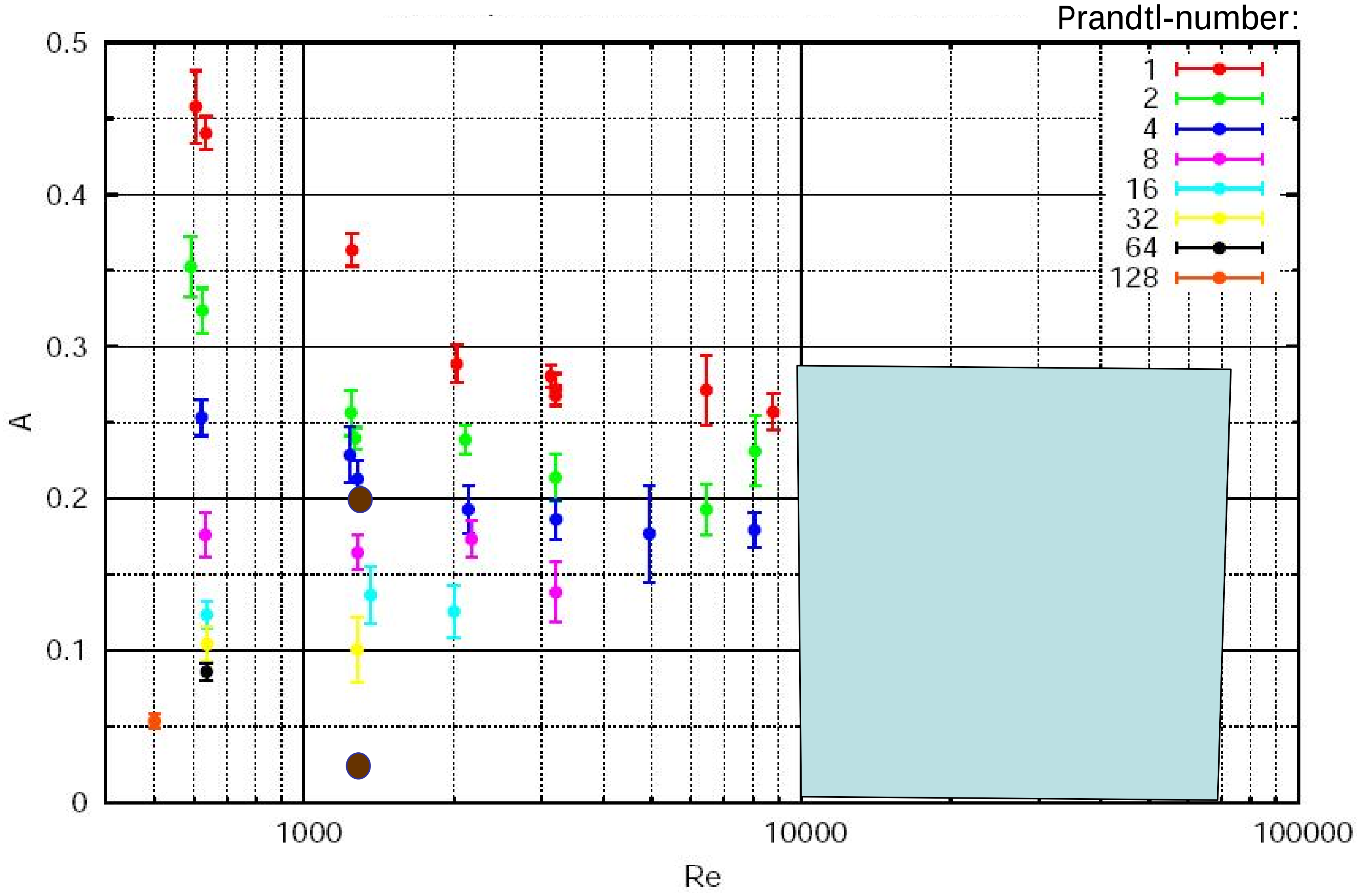


theta flux: Pr = 1, Re = 1260
theta flux: Pr = 1, Re = 50,000
diffusive
turbulent
total
z/z_i
flux/w*θ*
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

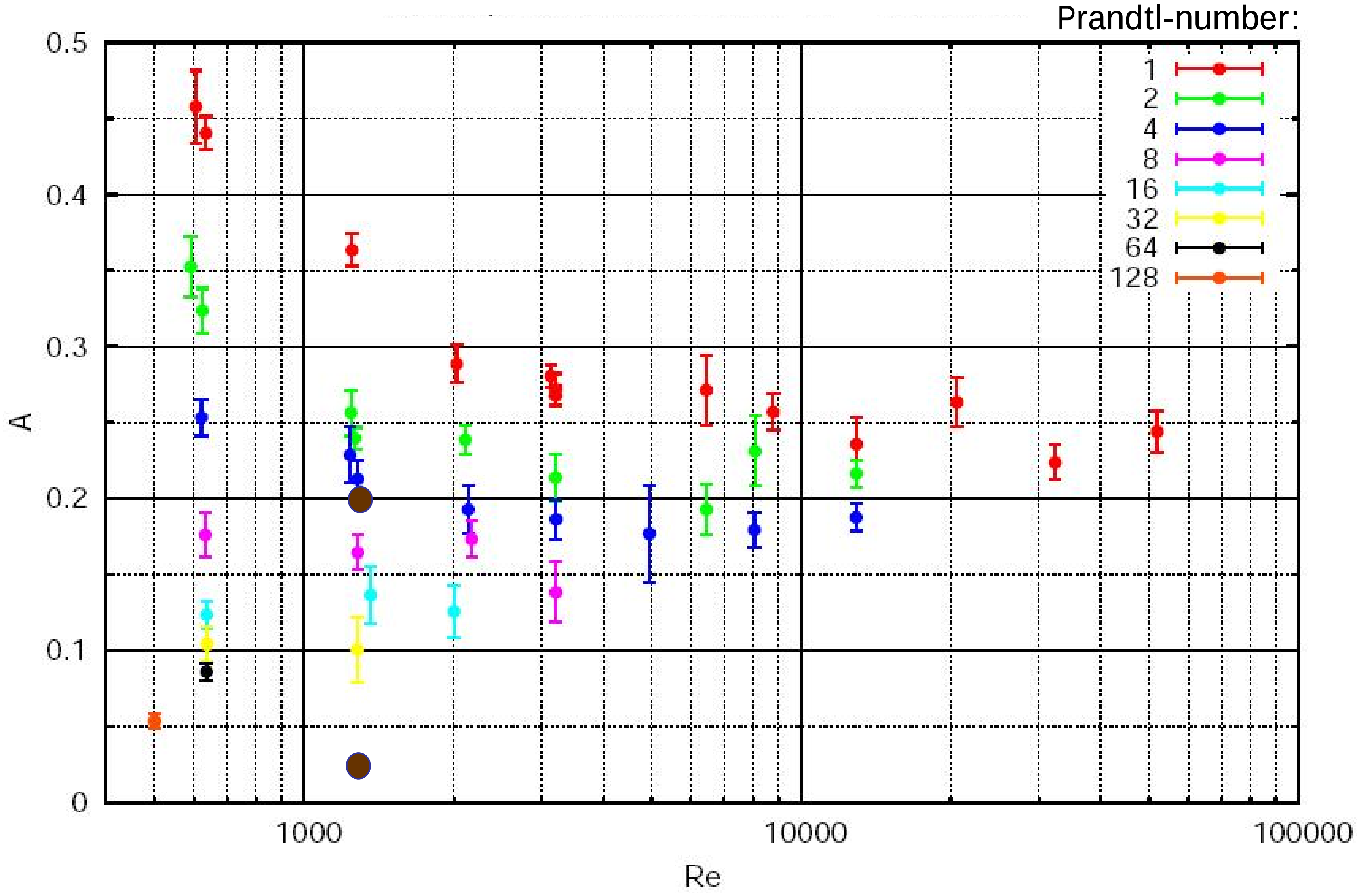
The importance of large computations



The importance of large computations

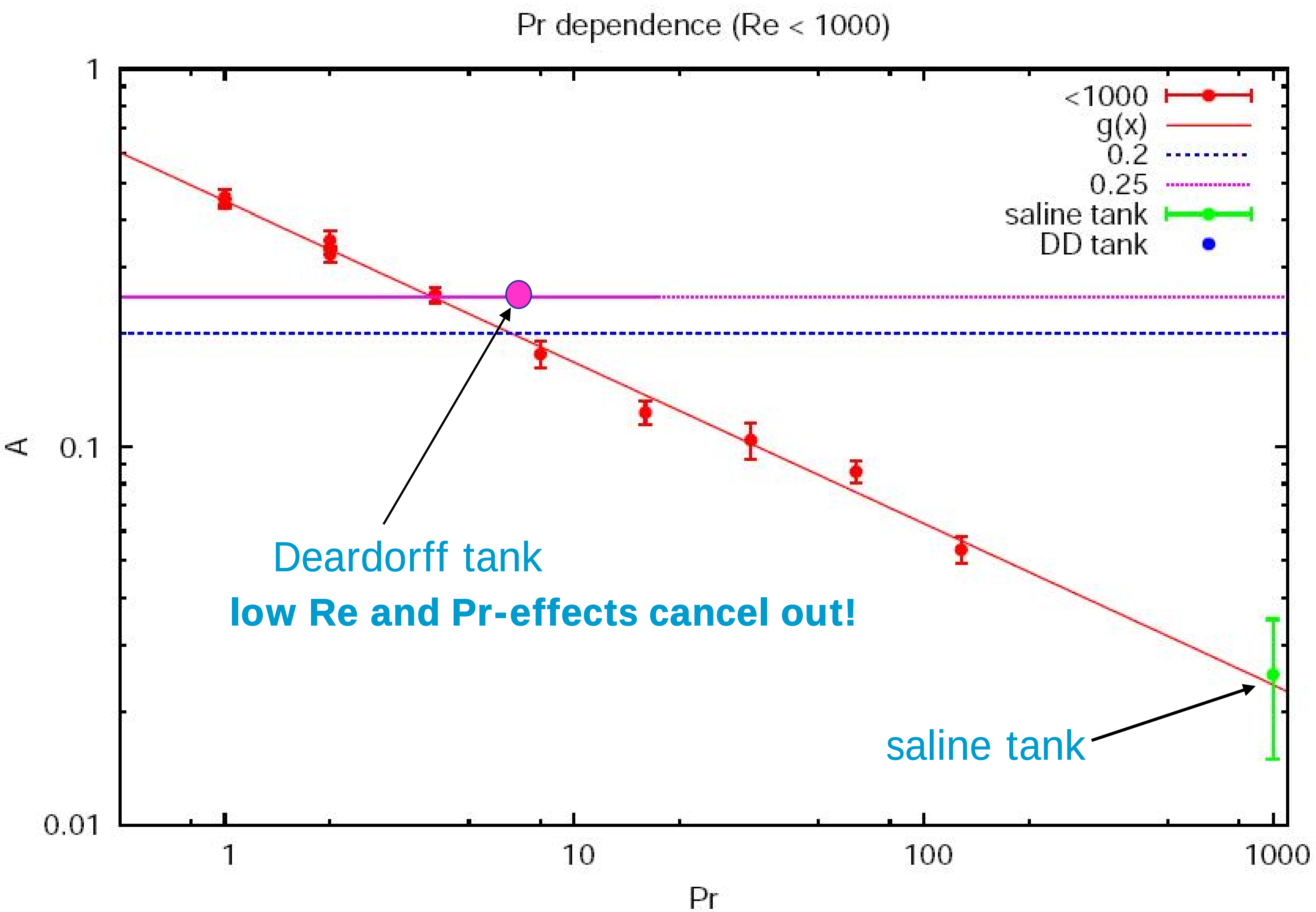


The importance of large computations

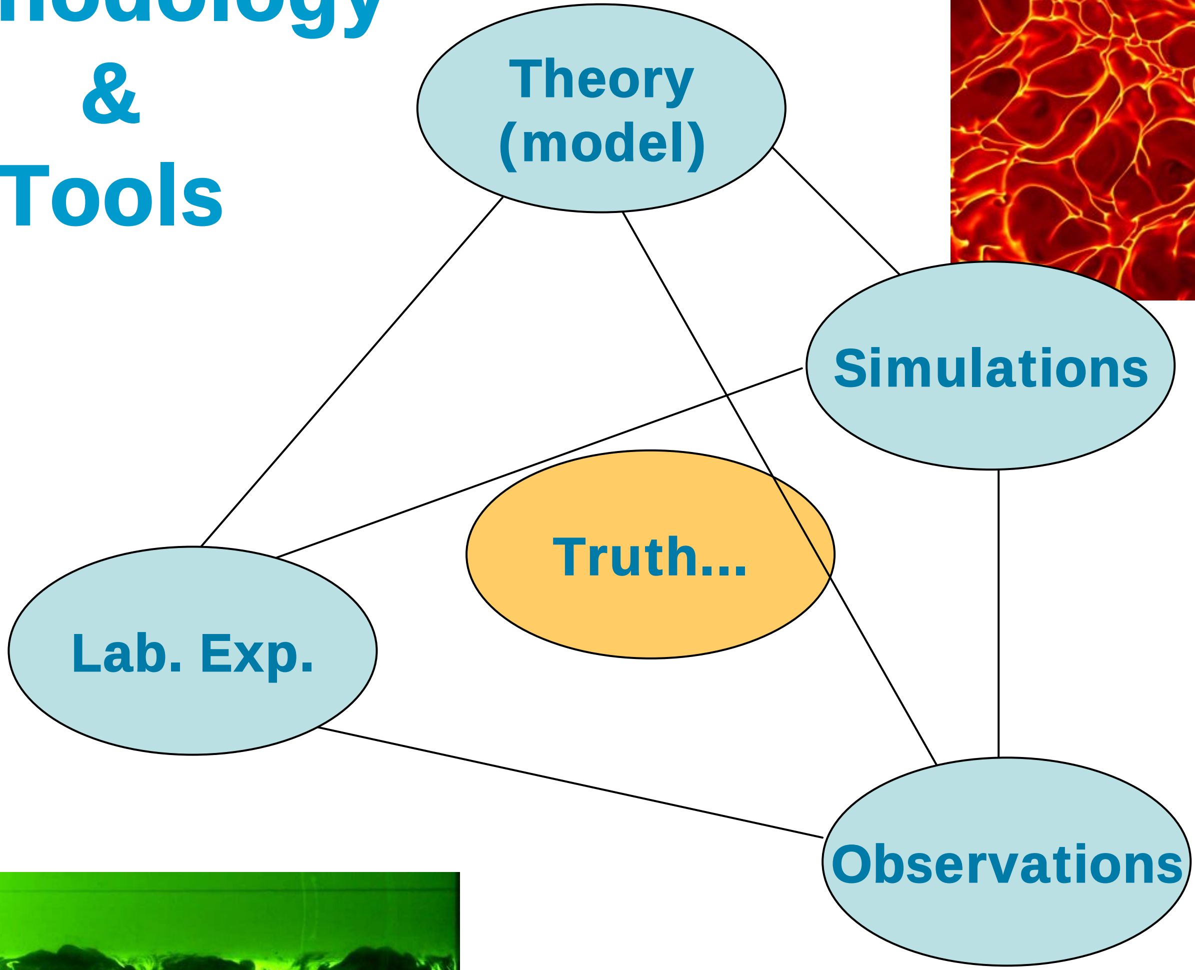


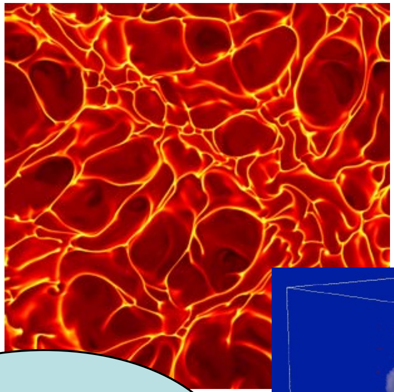
Re number must be really large before fluid-properties can be neglected

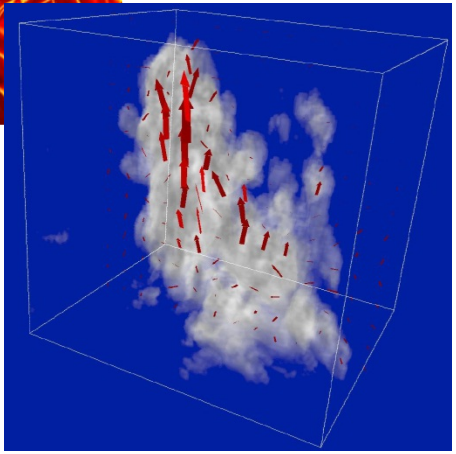
Fortuity or talent?

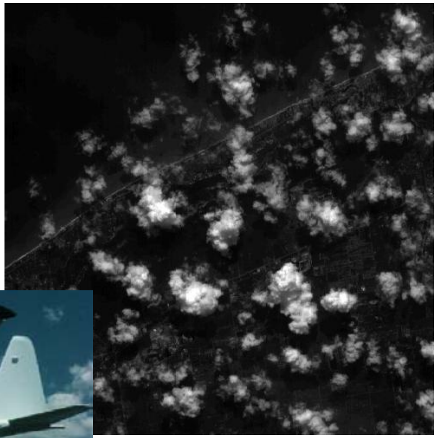


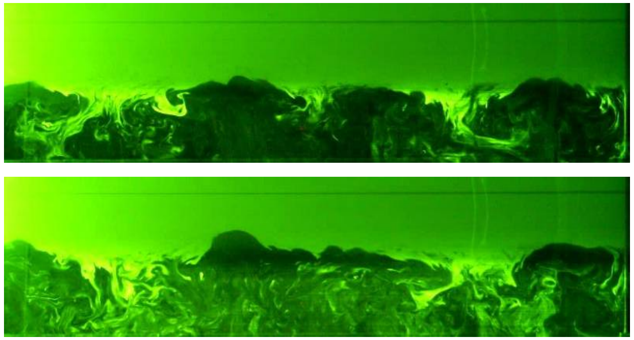
Methodology & Tools











Direct Simulation vs Understanding Turbulence

- DNS has now the ability to form the computational analog of laboratory experiments

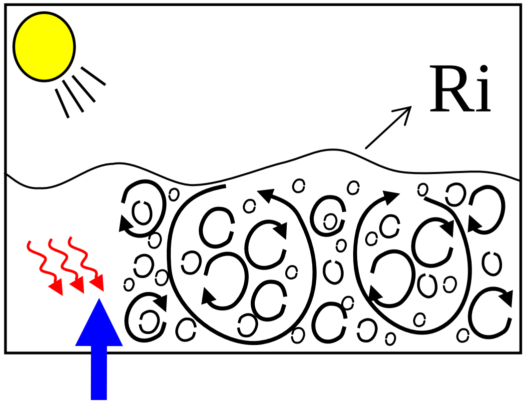
- ‘interesting’ Reynolds numbers can be reached

- yields no immediate understanding

- ideal research tool (interactive)

- my impression: there seem a lack of hypotheses

Governing equations DNS



$$\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \theta \delta_{i3}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial u_j \theta}{\partial x_j} = \frac{1}{\mathrm{RePr}} \frac{\partial^2 \theta}{\partial x_j^2}$$

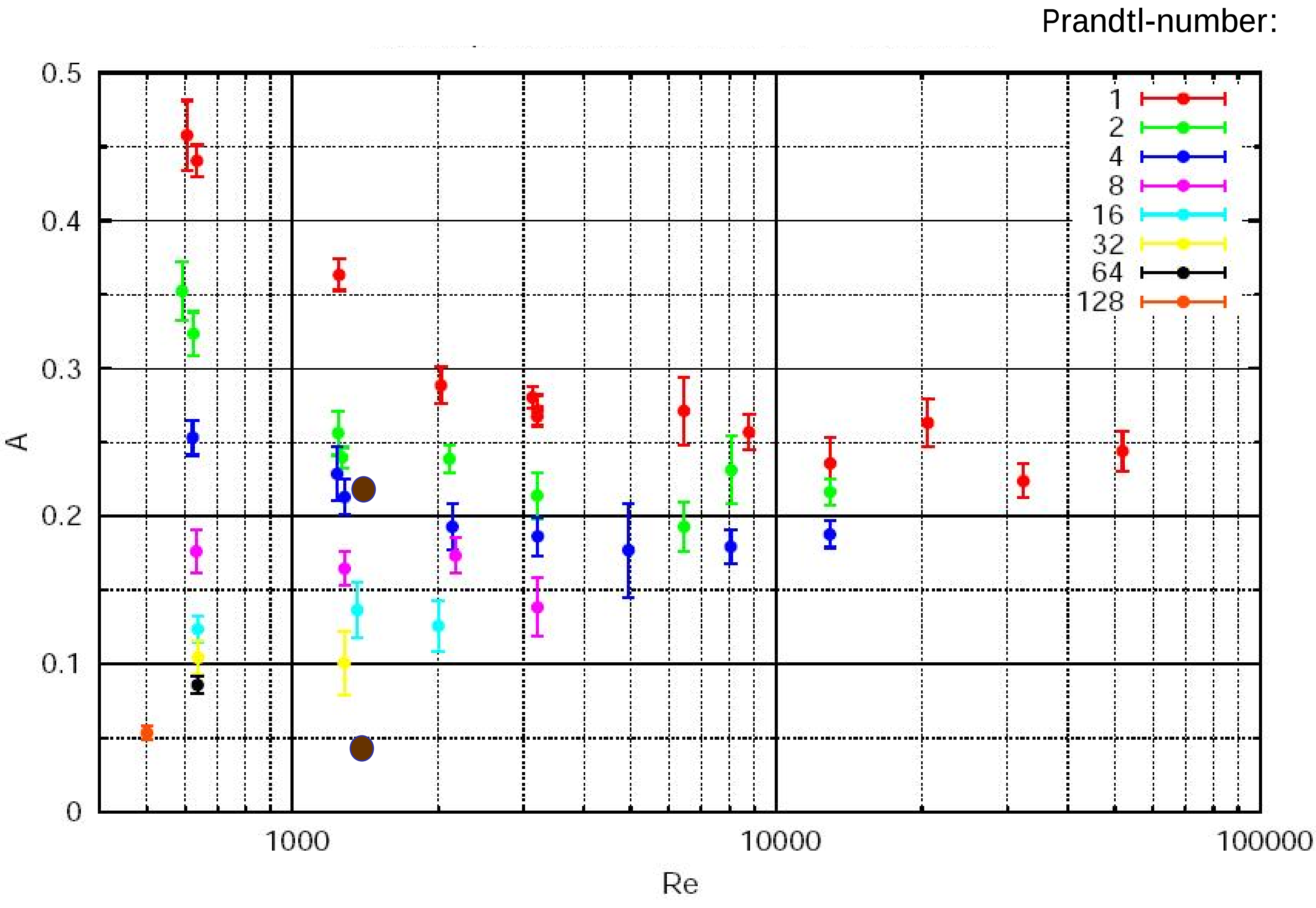
Compare to a Reynolds-stress turbulence model

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u}_j \overline{u}_i}{\partial x_j} = \cdots$$

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\partial \overline{u}_j \overline{\theta}}{\partial x_j} = \cdots$$

wouldn't fit!

The Pr influence at large Reynolds numbers



Large Reynolds/Peclet limits

$$\frac{w_e}{w_*} = f(\mathrm{Ri}, \mathrm{Re}, \mathrm{Pr})$$

or

$$\frac{w_e}{w_*} = f(\mathrm{Ri}, \mathrm{Re}, \mathrm{Pe})$$

$$\mathrm{Re} \to \infty \qquad (\mathrm{Pe} \to \infty)$$

$$\Downarrow \qquad\qquad \Downarrow$$

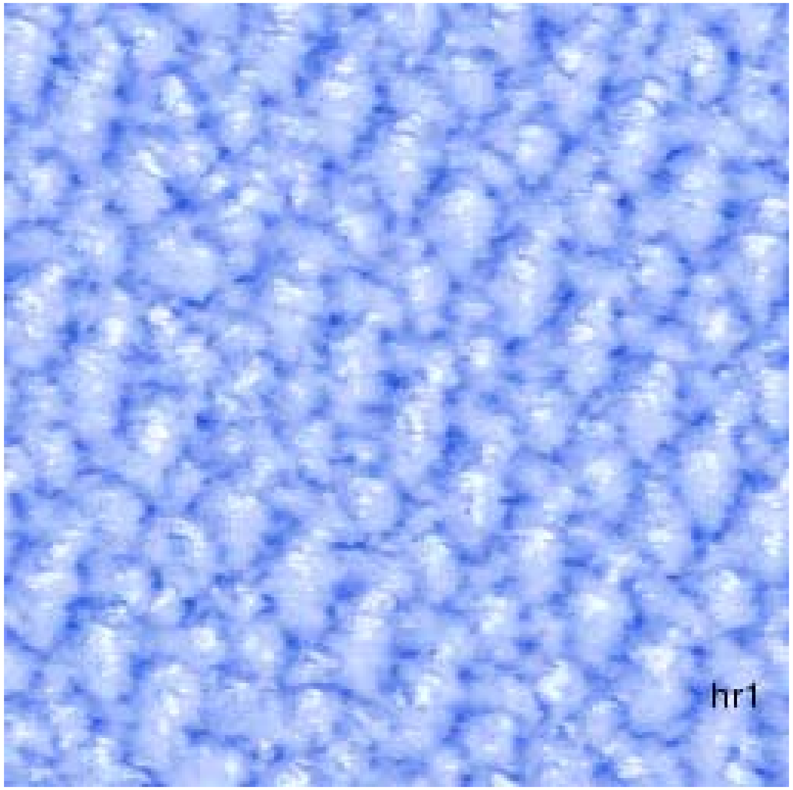
$$\frac{w_e}{w_*} = f(\mathrm{Ri}, \mathrm{Pr})$$

$$\frac{w_e}{w_*} = f(\mathrm{Ri})$$

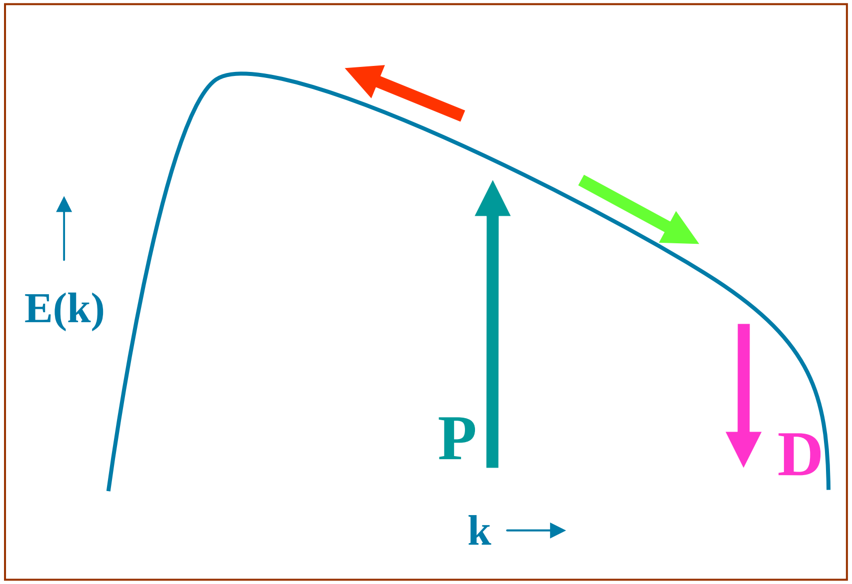
LES of Stratocumulus

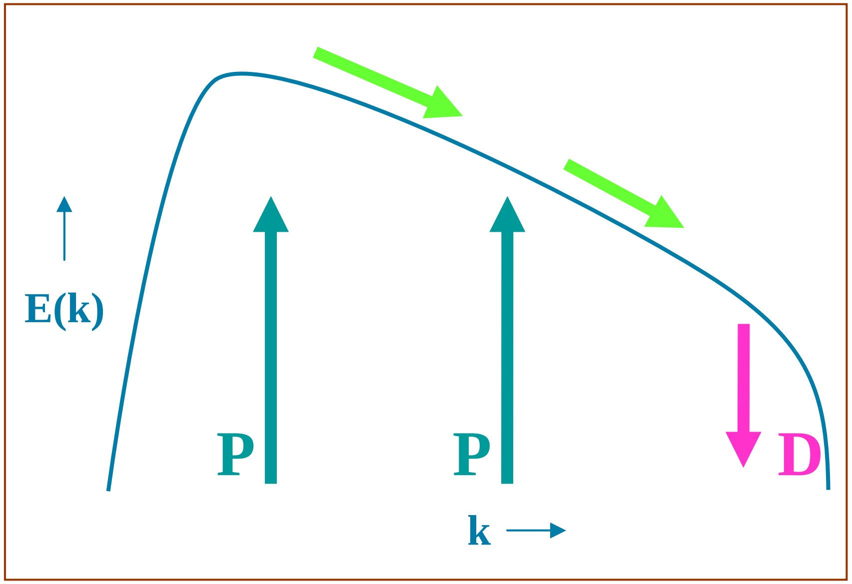
L = 25.6km Dx = Dy = 100m

t = 1…16hr, liquid water path



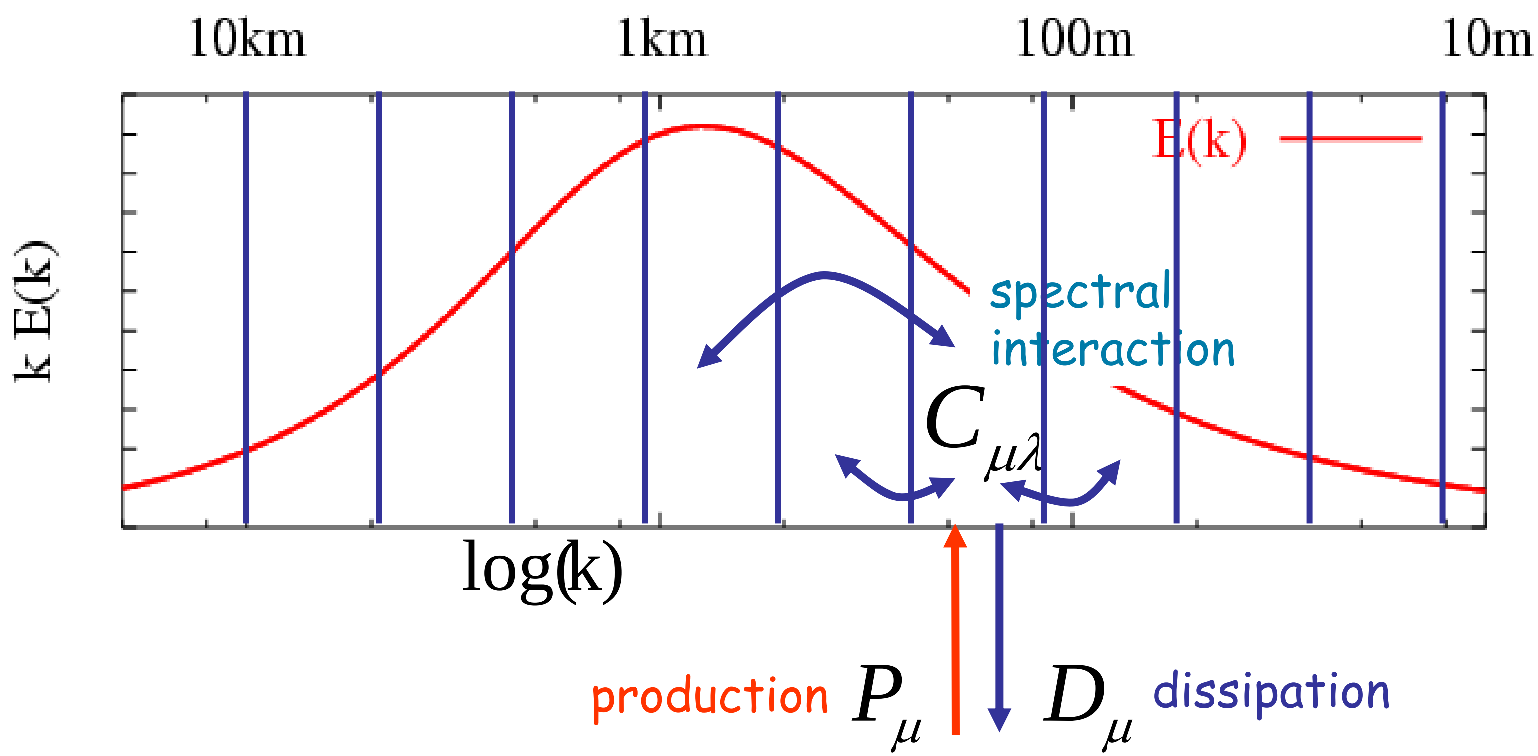
Inverse Cascade?





2-D or not 2-D: that's the question

Spectral variance budget

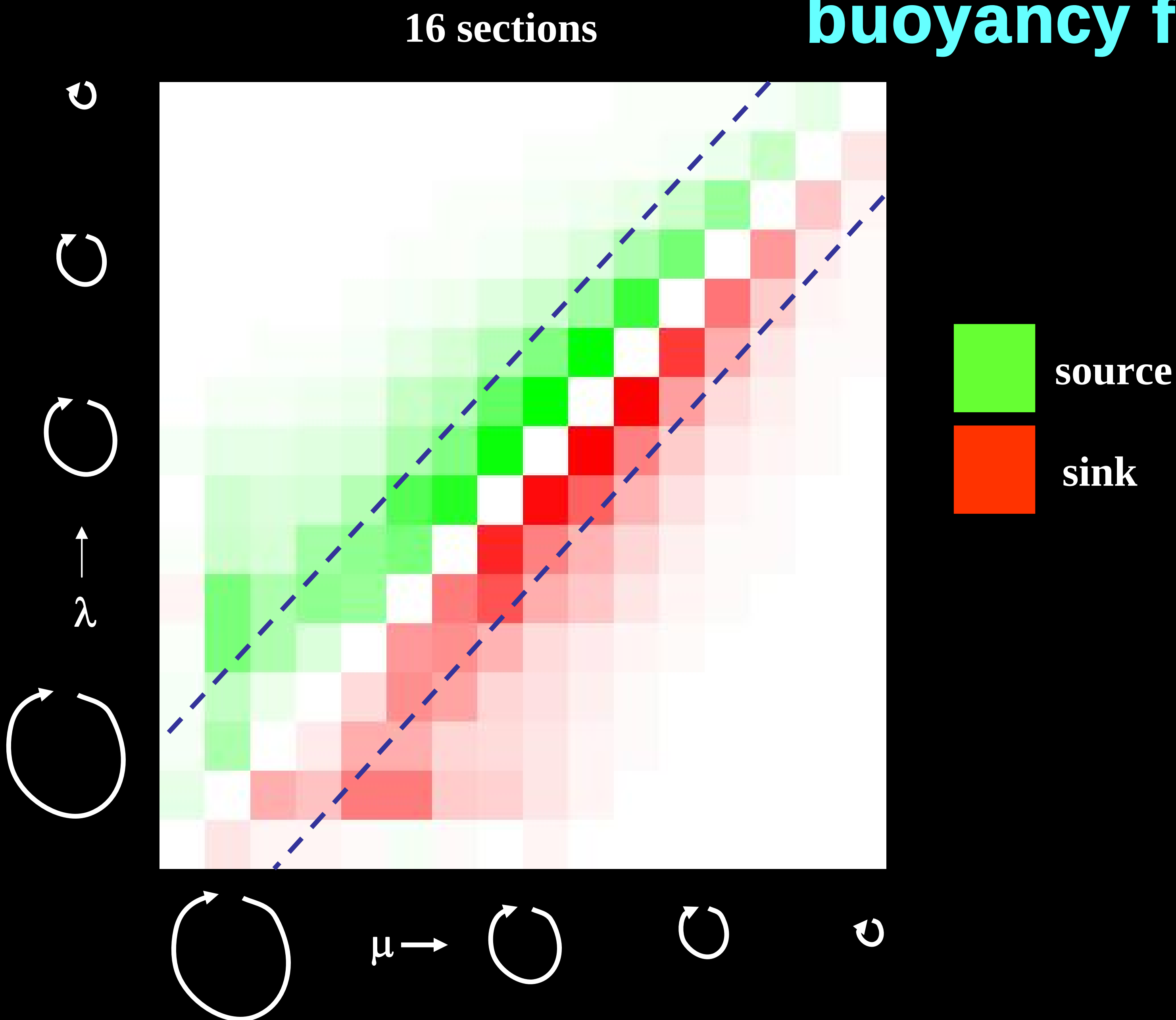


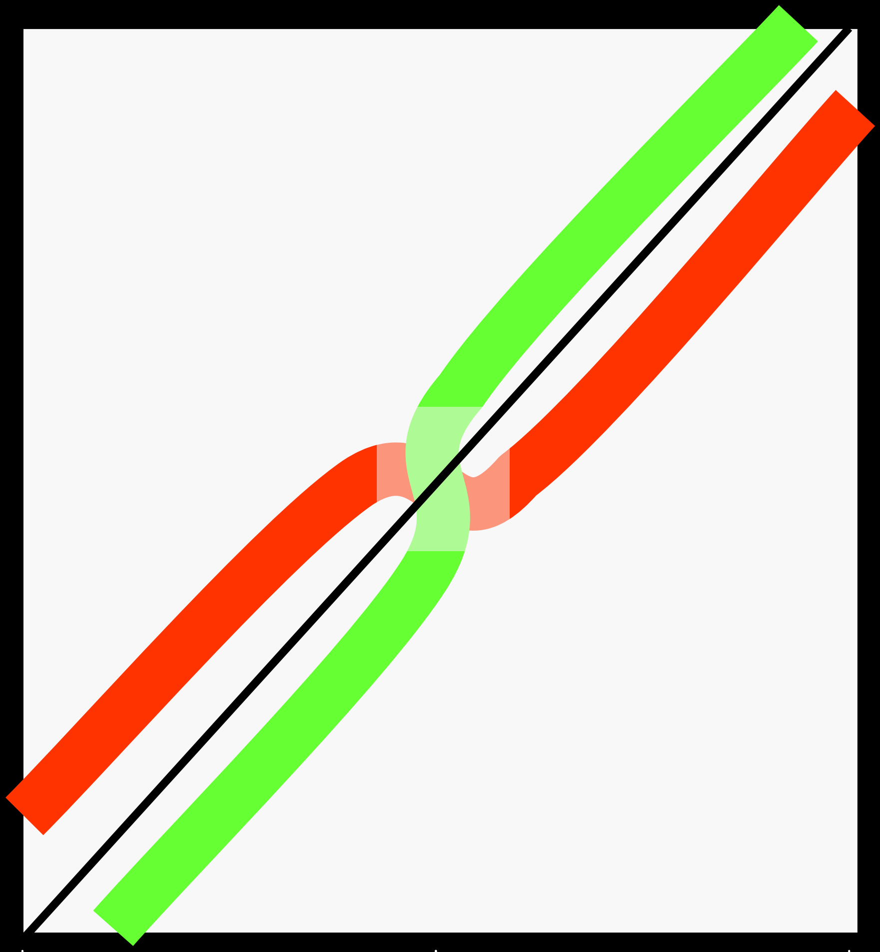
$$c = \bar{c} + c_1 + c_2 + \ldots\ldots + c_n \longrightarrow \frac{d}{dt}\overline{c_\mu^2} = P_\mu - D_\mu + \sum_\lambda C_{\mu\lambda}$$

scale by scale variance budget

Scale Interaction Matrix $C_{\mu\lambda}$

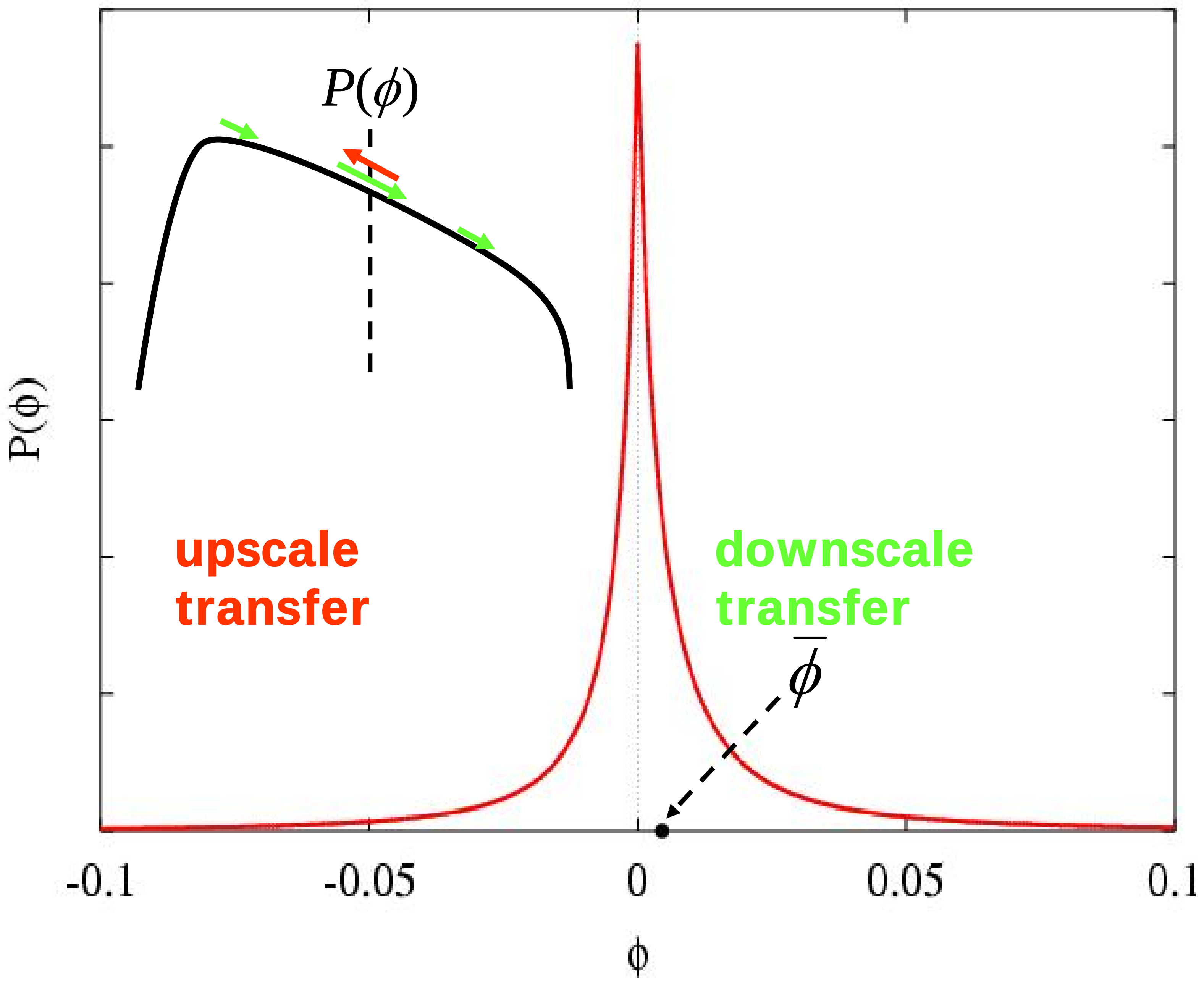
buoyancy field





2D
upscale cascade

3D
downscale cascade



$P(\phi)$
upscale
transfer
downscale
transfer
$\bar{\phi}$
P(φ)
-0.1
-0.05
0
0.05
0.1
φ

Concluding remarks

- ‘Why modeling works’ - does it really work?

- Direct Simulation will soon become the ideal research tool for turbulence (direct interaction)

- Are we capable of defining the most pressing hypotheses in turbulence?