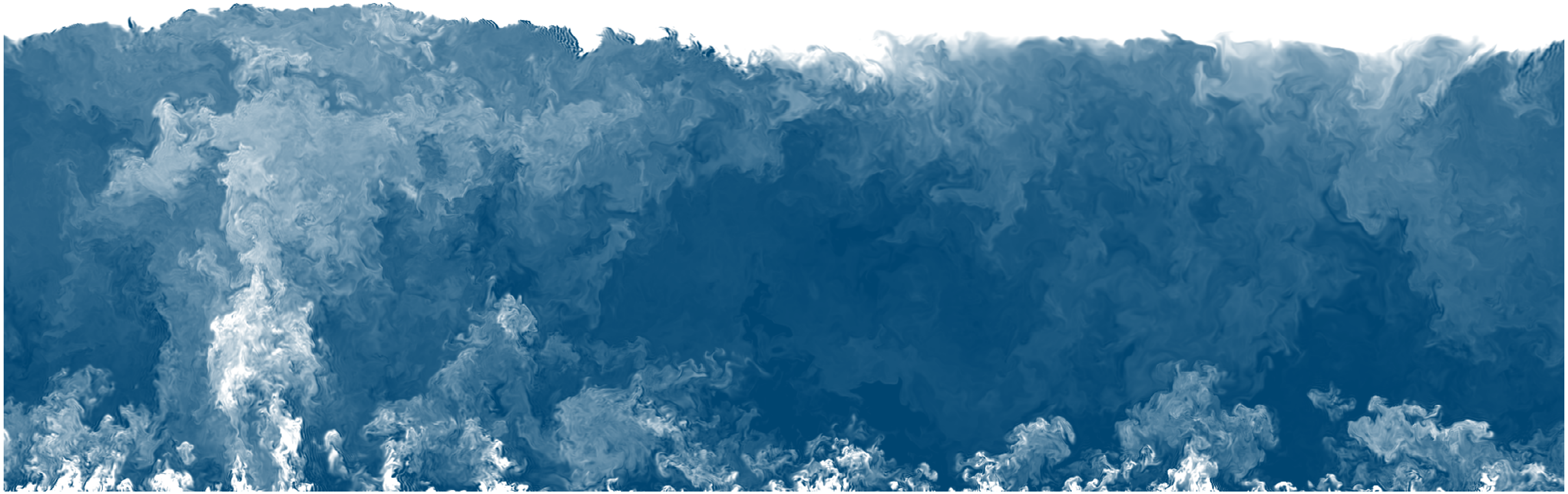
PINNACLE: Pinning down the growth-rate law of Atmospheric Convective Boundary Layers



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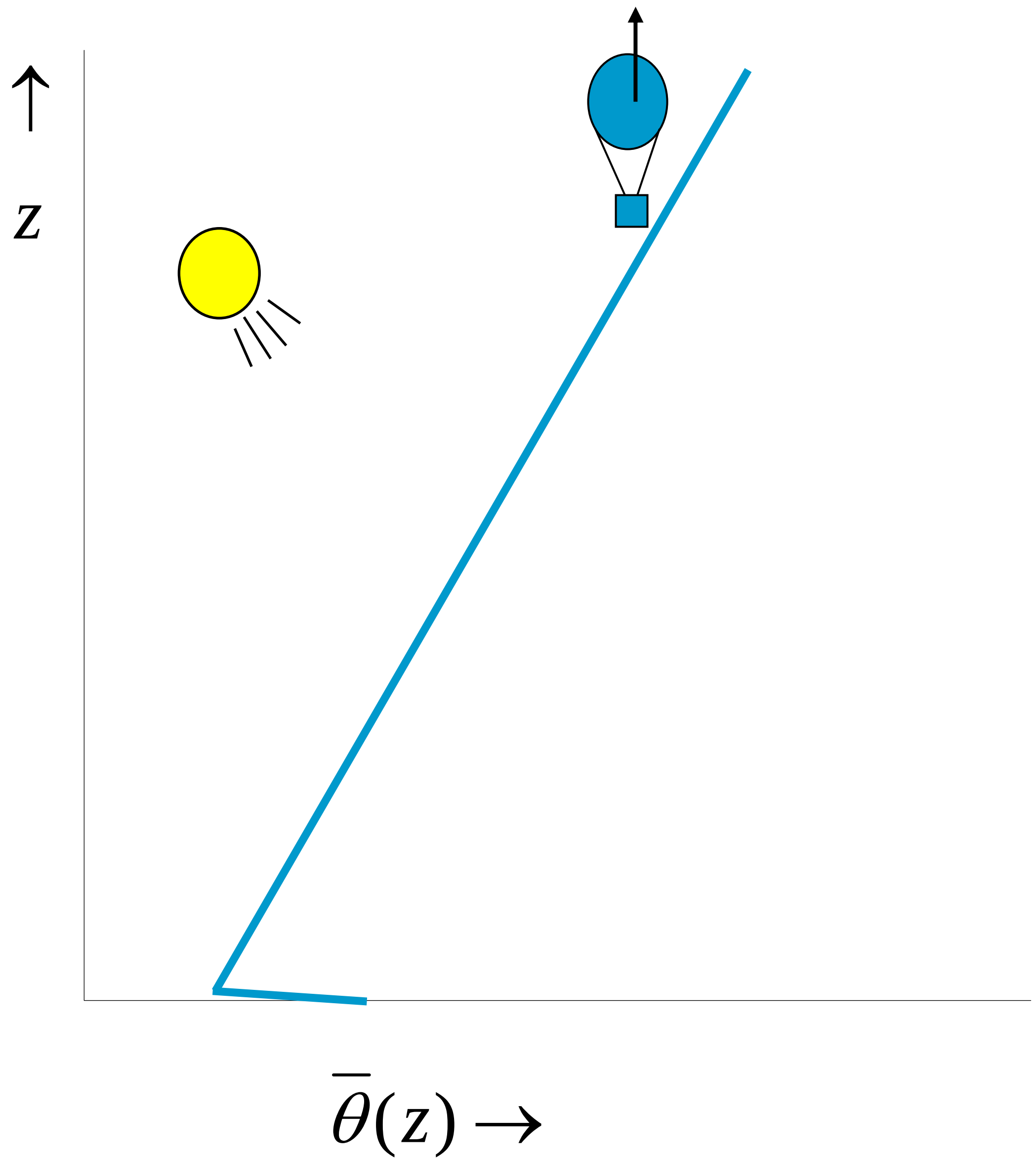
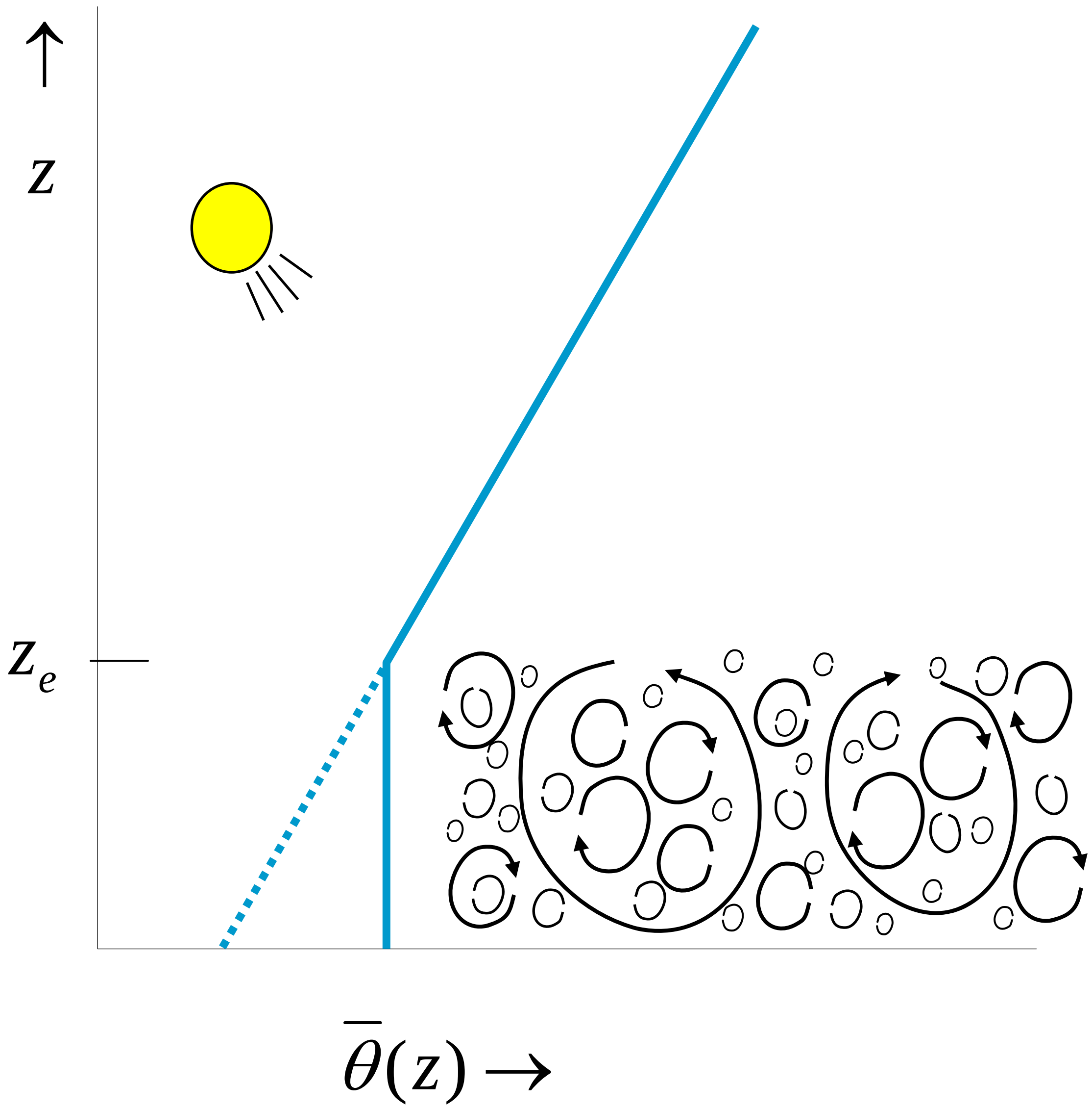
Peter Sullivan & Ned Patton (National Center for Atmospheric Research, USA)

DEISA: Distributed European Infrastructure for Supercomputing Applications

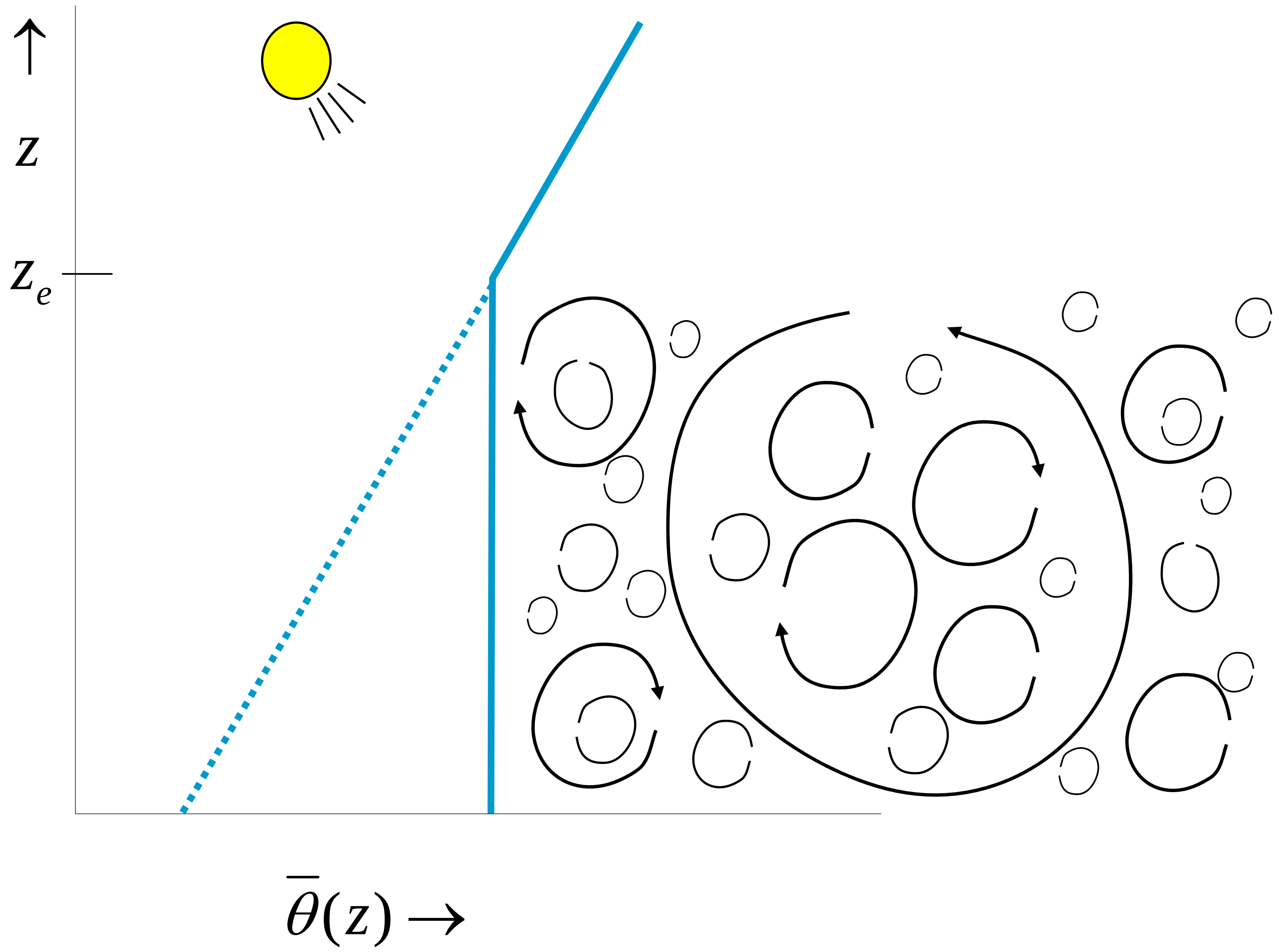
Multi-Scale Physics Faculty of Applied Sciences TU Delft



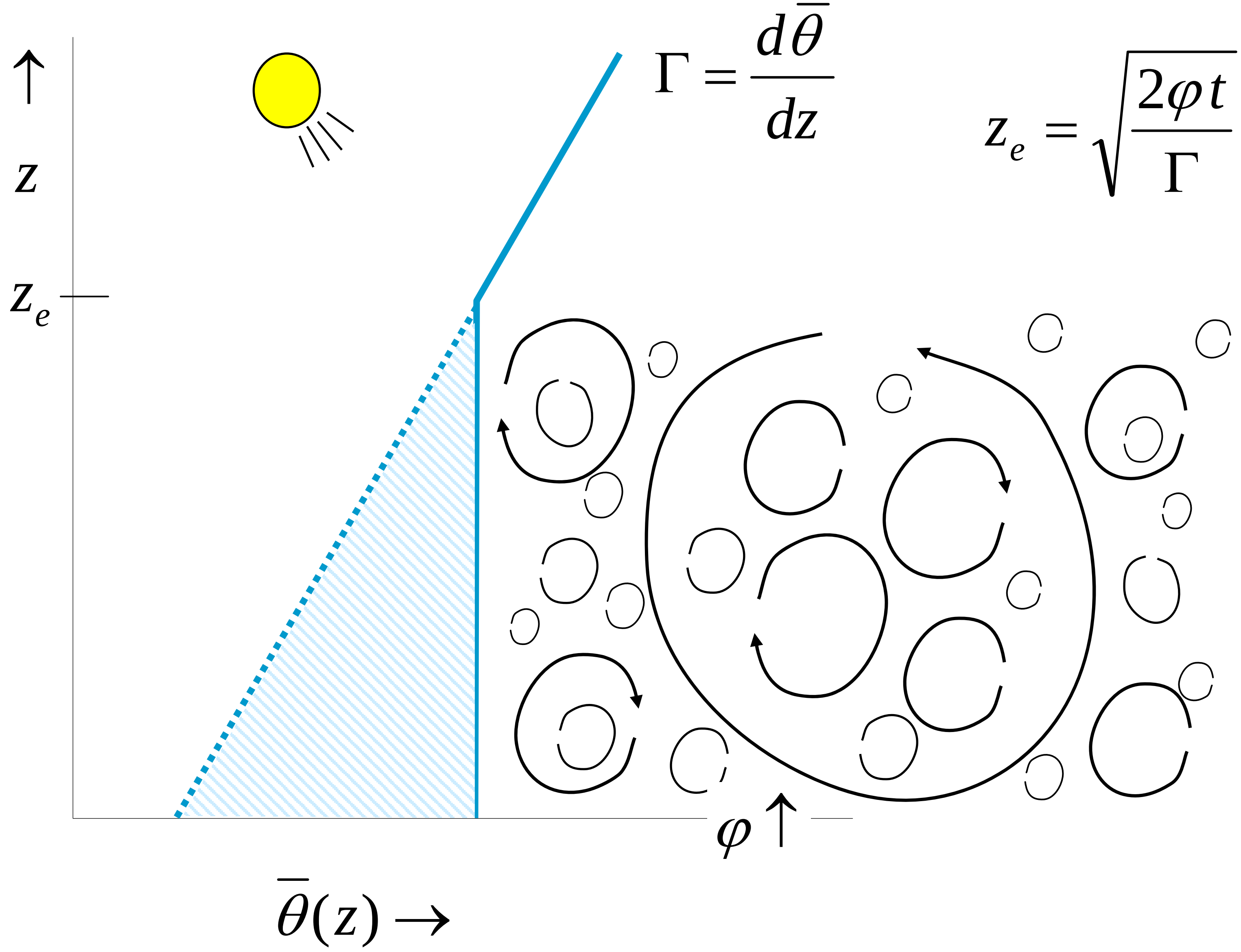
z
$\overline{\theta}(z) \rightarrow$



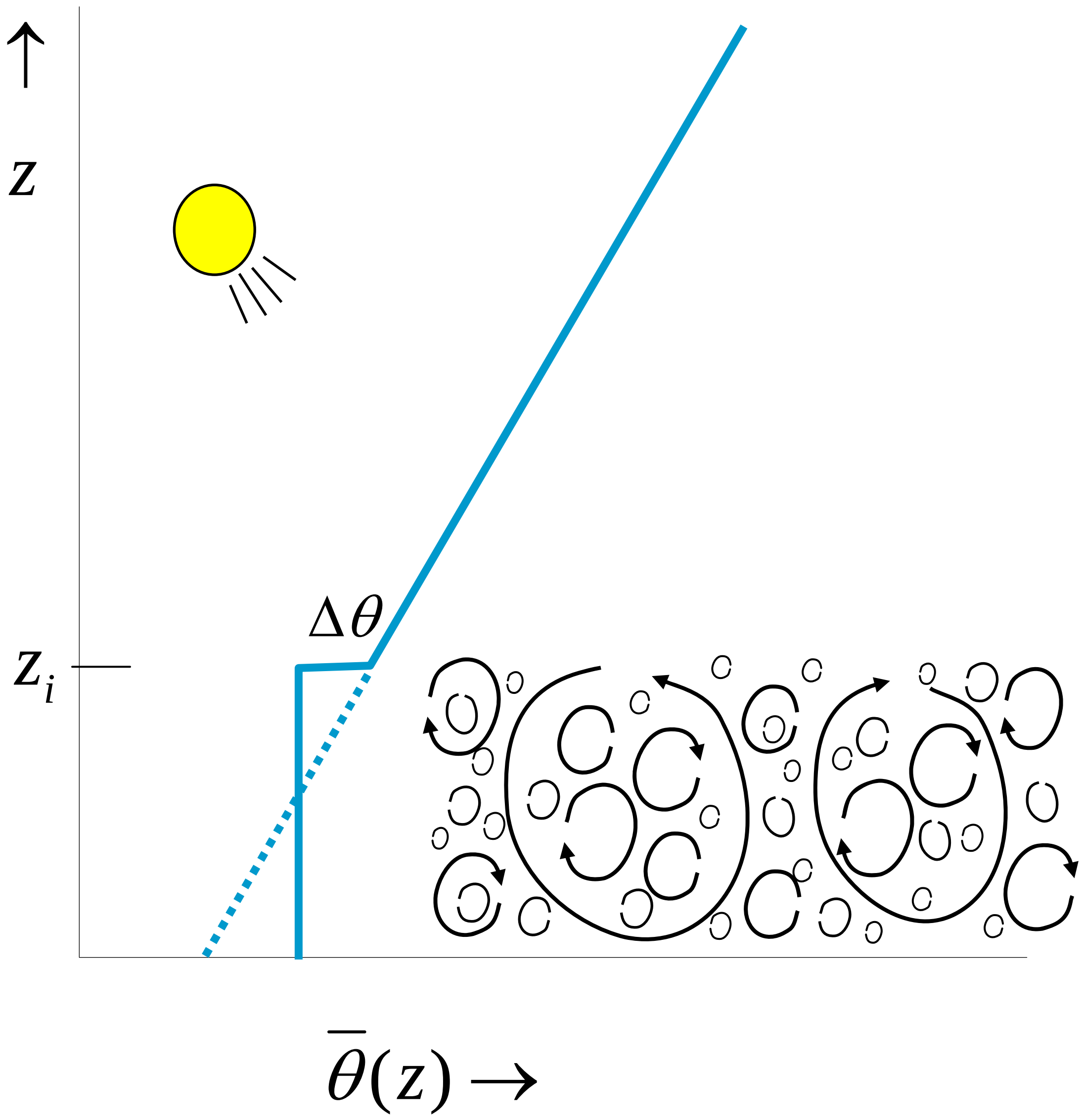
z
z_e
$\overline{\theta}(z) \rightarrow$



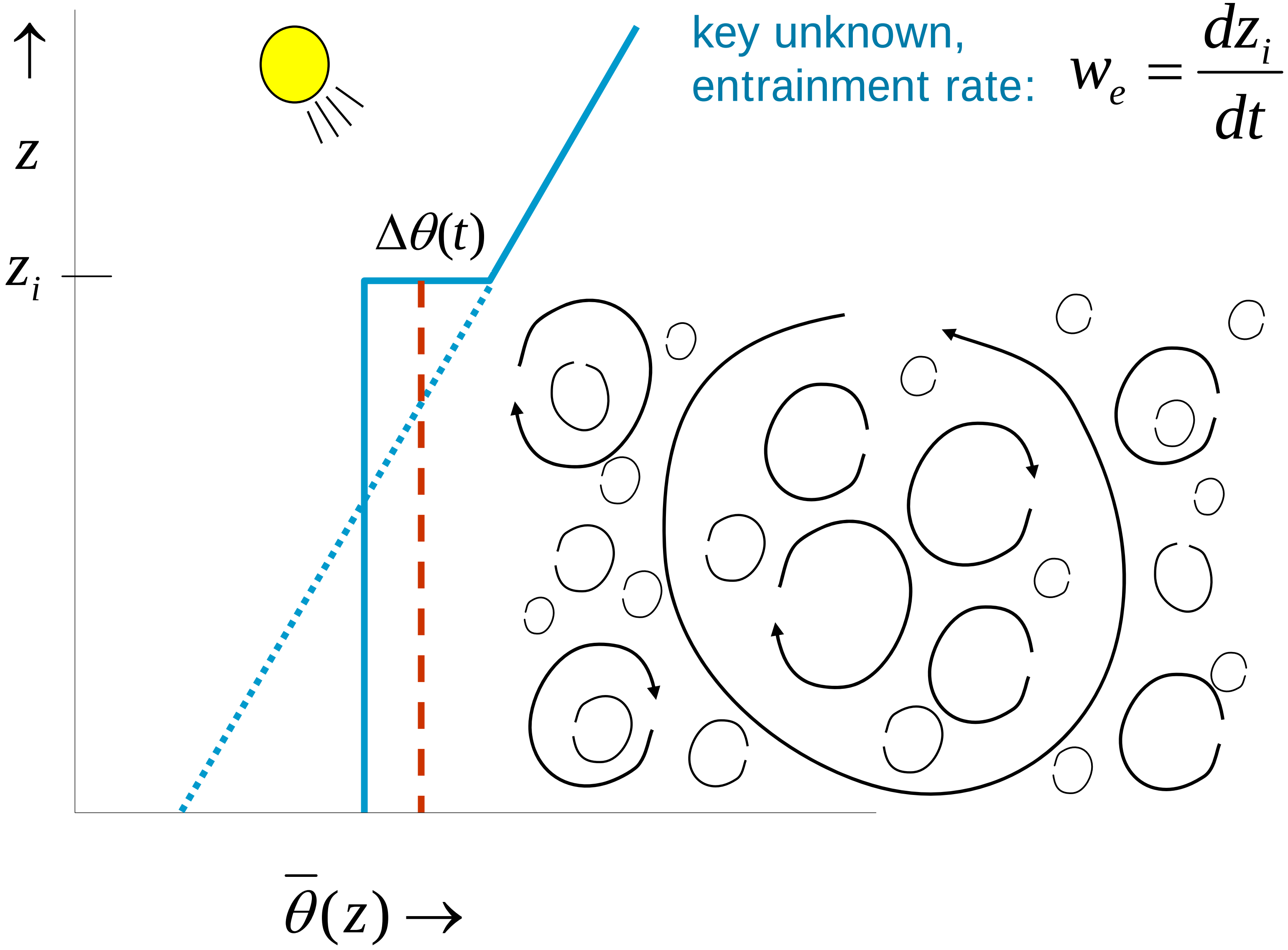
z
z_e
$\overline{\theta}(z) \rightarrow$



$\Gamma = \frac{d\overline{\theta}}{dz}$
$z_e = \sqrt{\frac{2\varphi t}{\Gamma}}$
z
z_e
φ
$\overline{\theta}(z) \rightarrow$



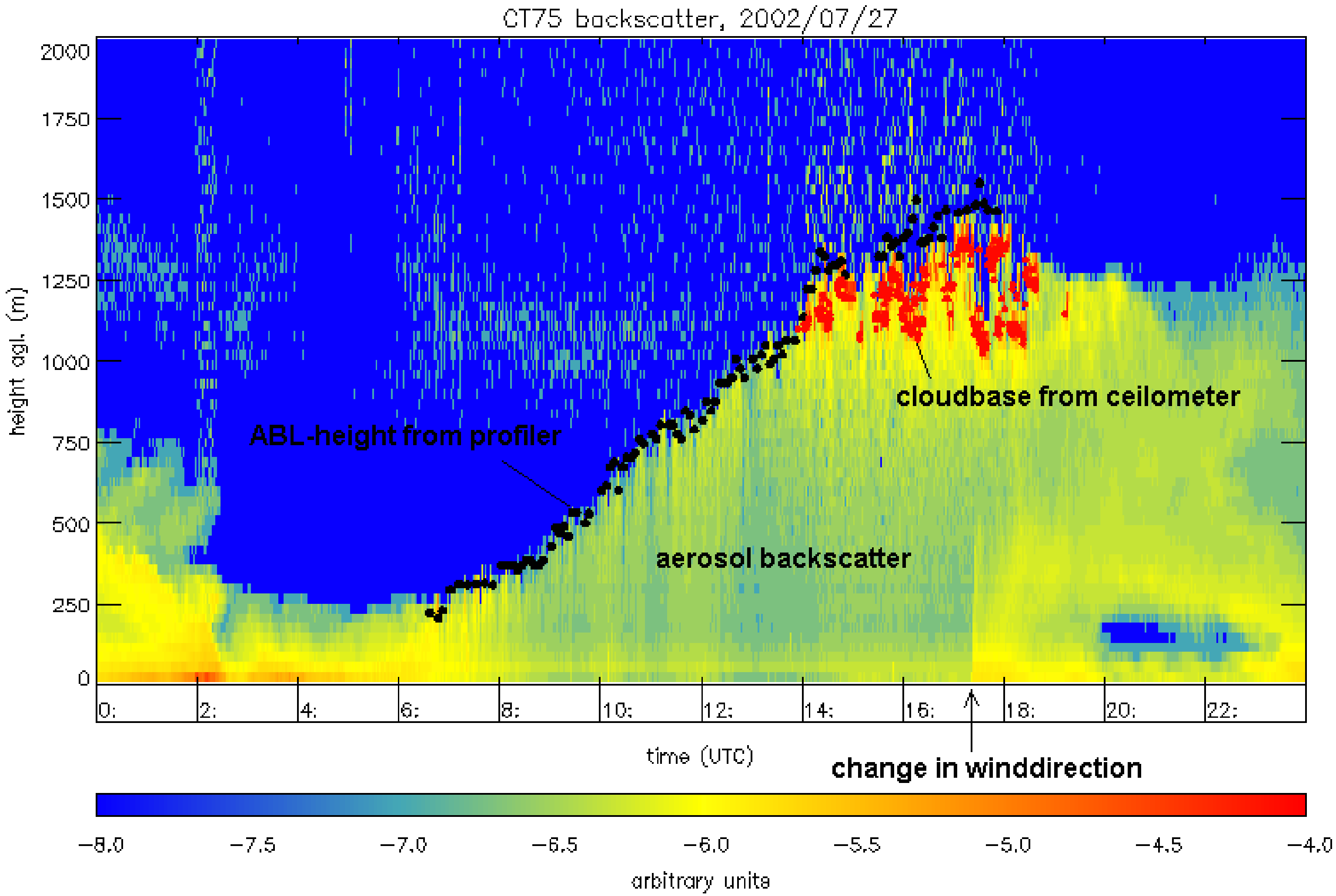
z
$\Delta\theta$
z_i
$\overline{\theta}(z) \rightarrow$



z
z_i
$\Delta\theta(t)$
key unknown,
entrainment rate: $w_e = \frac{dz_i}{dt}$
$\overline{\theta}(z) \rightarrow$

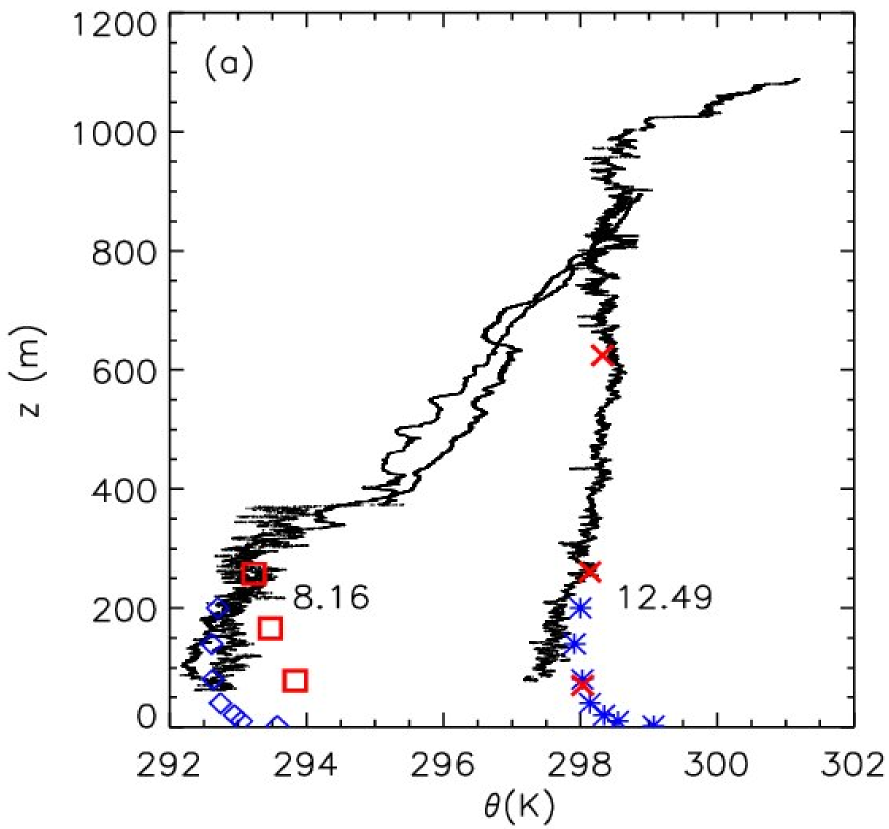

courtesy Adriaan Schuitmaker

Evolution of the boundary layer

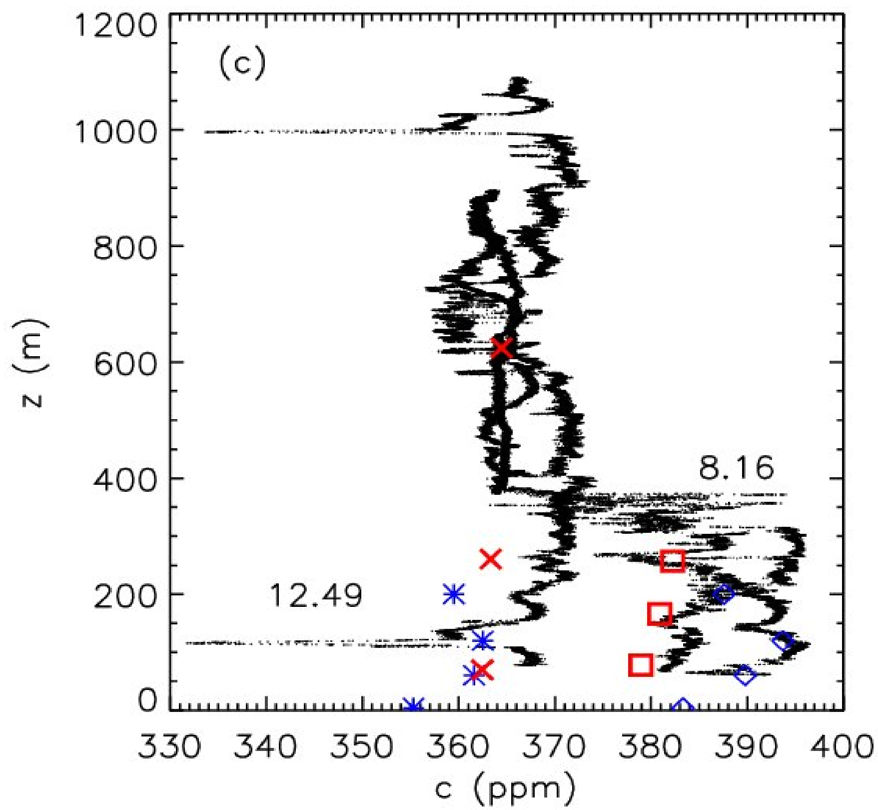


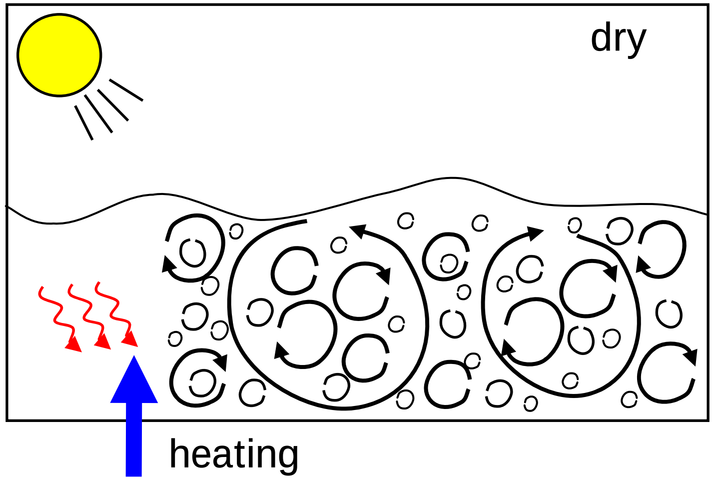
Vertical profiles

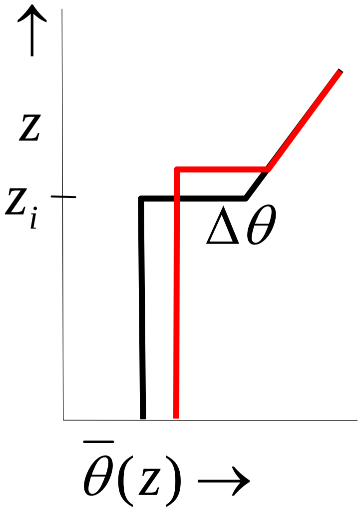
Potential temperature



Carbon dioxide







growth-rate:

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

Weather, Climate, Air Quality Models

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

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

$$A = 0.25$$

Water Tank: Deardorff, Willis and Stockton, JFM 1980

Atmospheric Observations / Field experiments

- the real thing!

- incomplete information (3D,t)
- as is (no control)
- reproducibility
- parameter studies impossible

Numerical Simulation: LES (RANS, ...)

- complete information
- excellent control (forcings, b-conditions)
- reproducibility
- parameter studies!

- not real
- lack of critical tests

Laboratory Experiments (convection tank)

- reasonable amount of information
- reasonable control (forcings, b-conditions)
- reasonable reproducibility
- parameter studies possible
- it is real
- viscous effects play a role

Direct Numerical Simulation

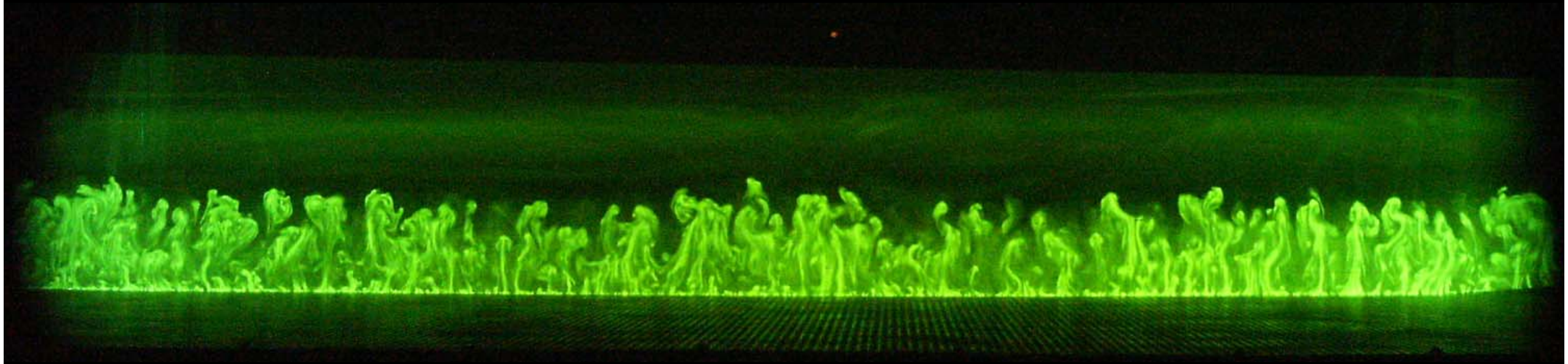


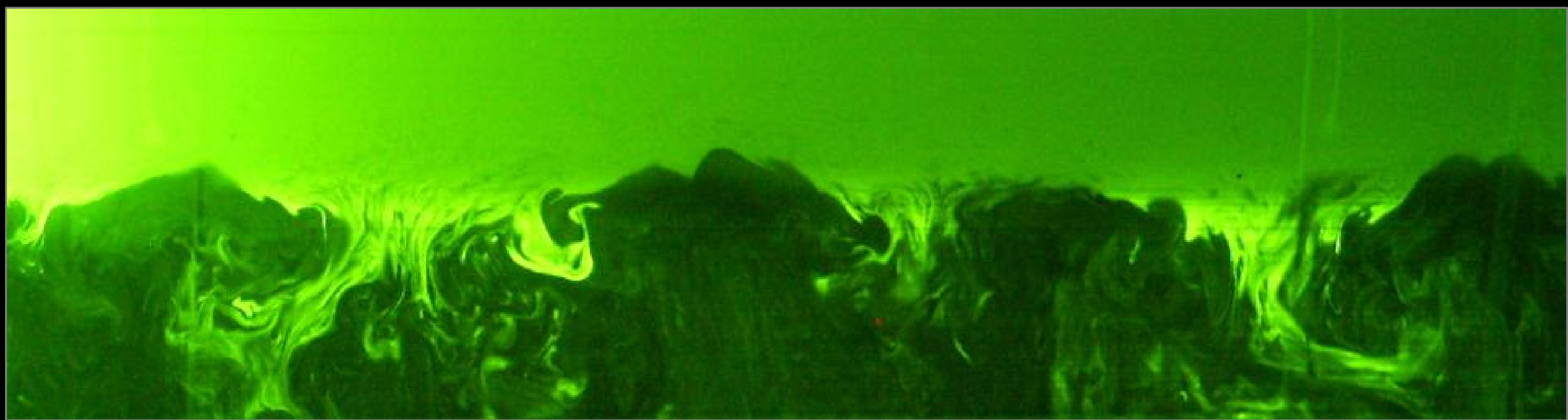










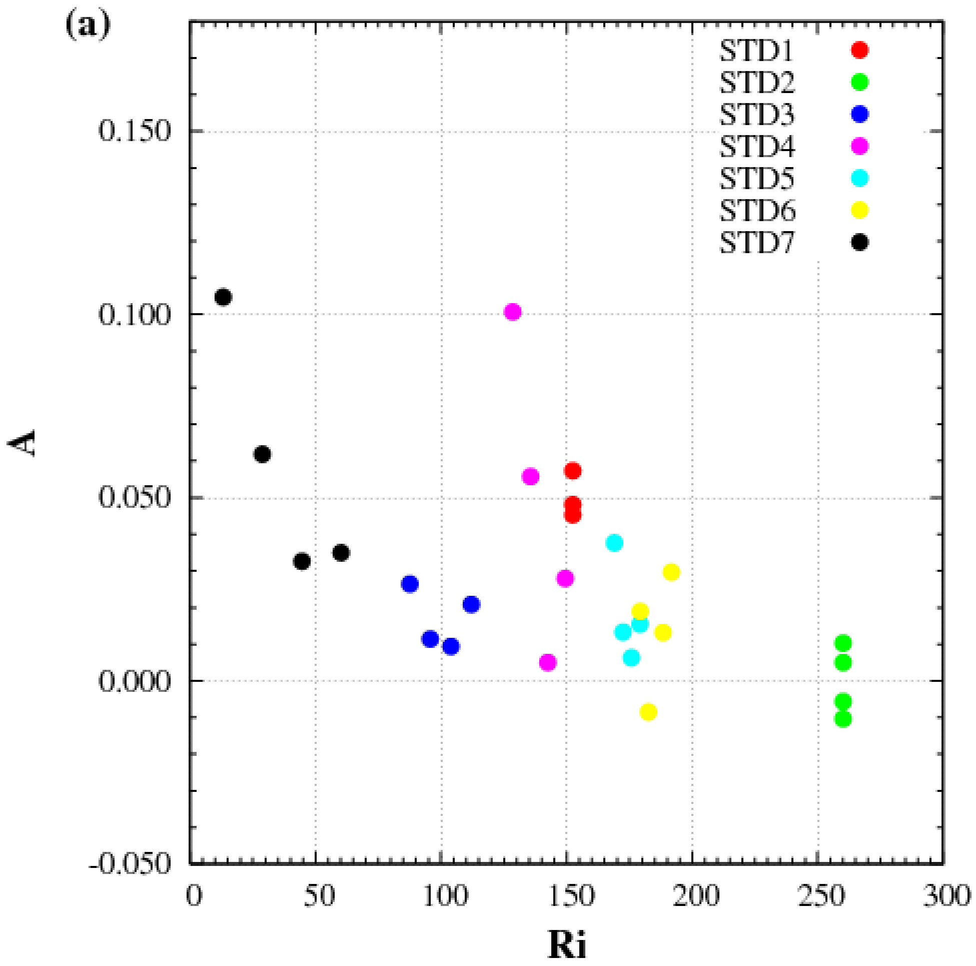


Saline Convection Tank

$$A = \frac{w_e}{w_*} Ri$$

$$A \approx 0.02$$

see also Kantha, 1980



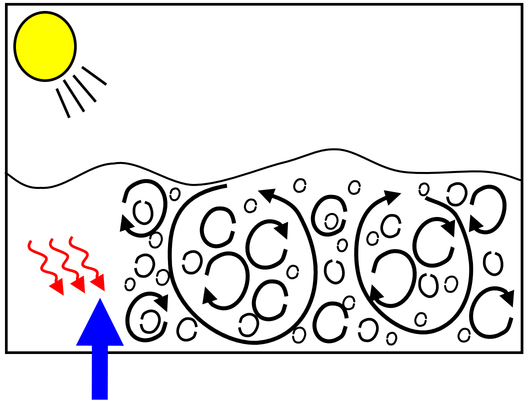
A=0.25, tank: Deardorff, Willis and Stockton, JFM 1980

Controversy

Fernando, 1991, Annu. Rev. Fluid Mech:

In this area of research, perhaps no other specific topic
has been more controversial than the entrainment law.
[...],
and it is surprising that the experiments performed
by different investigators, [..], have reported entrainment
rates sometimes differing by a factor of five.

Governing equations

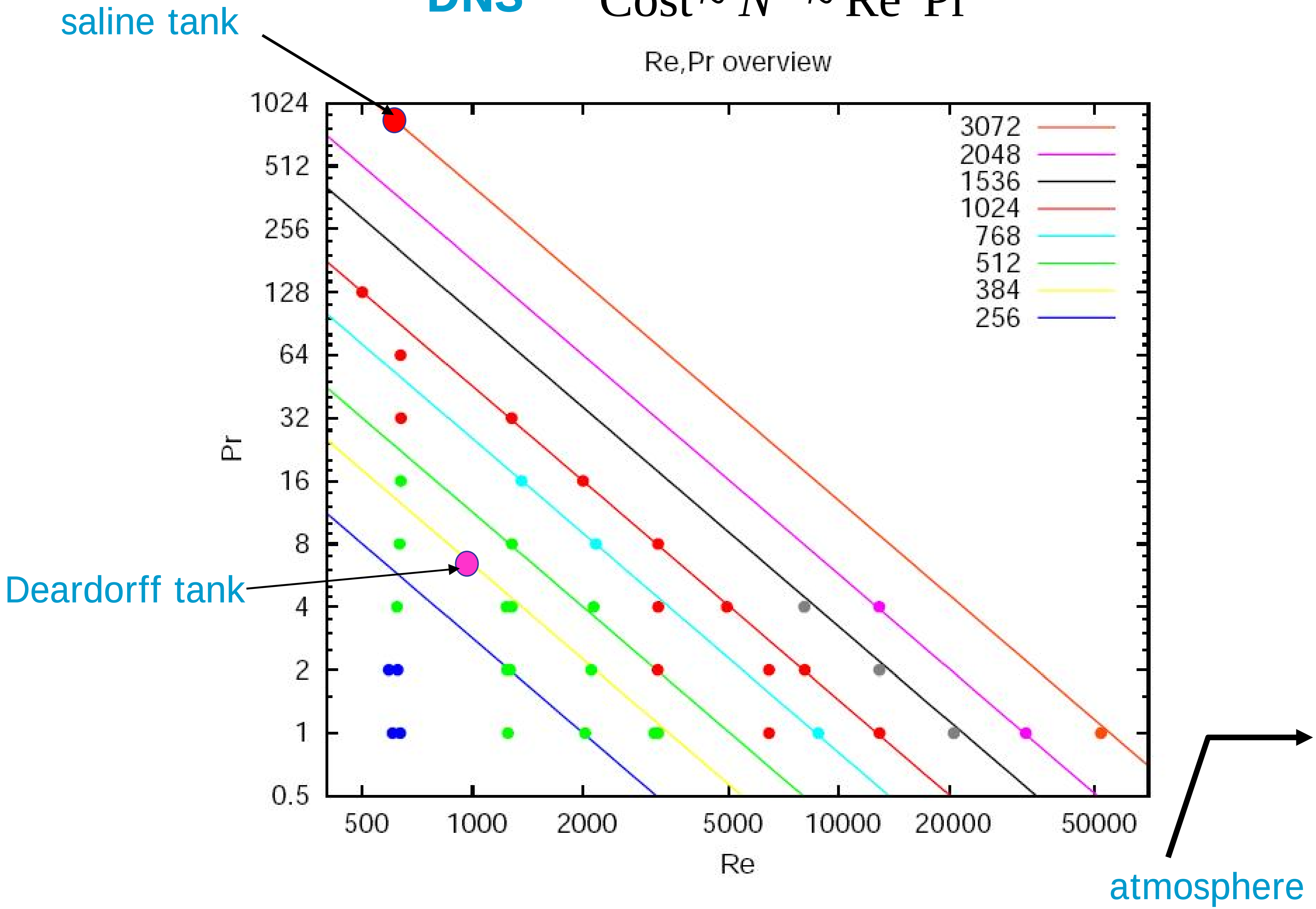


$$\frac{\partial u_i}{\partial t} + \frac{\partial u_j u_i}{\partial x_j} = \frac{1}{\mathrm{Re}} \frac{\partial^2 u_i}{\partial x_j^2} - \frac{\partial p}{\partial x_i} + \theta \delta_{i3}$$

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

		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	$\mathrm{Pr} = \frac{\nu}{\kappa}$	$\mathrm{Pr}=1$	$\mathrm{Pr}=10$	$\mathrm{Pr}=1000$

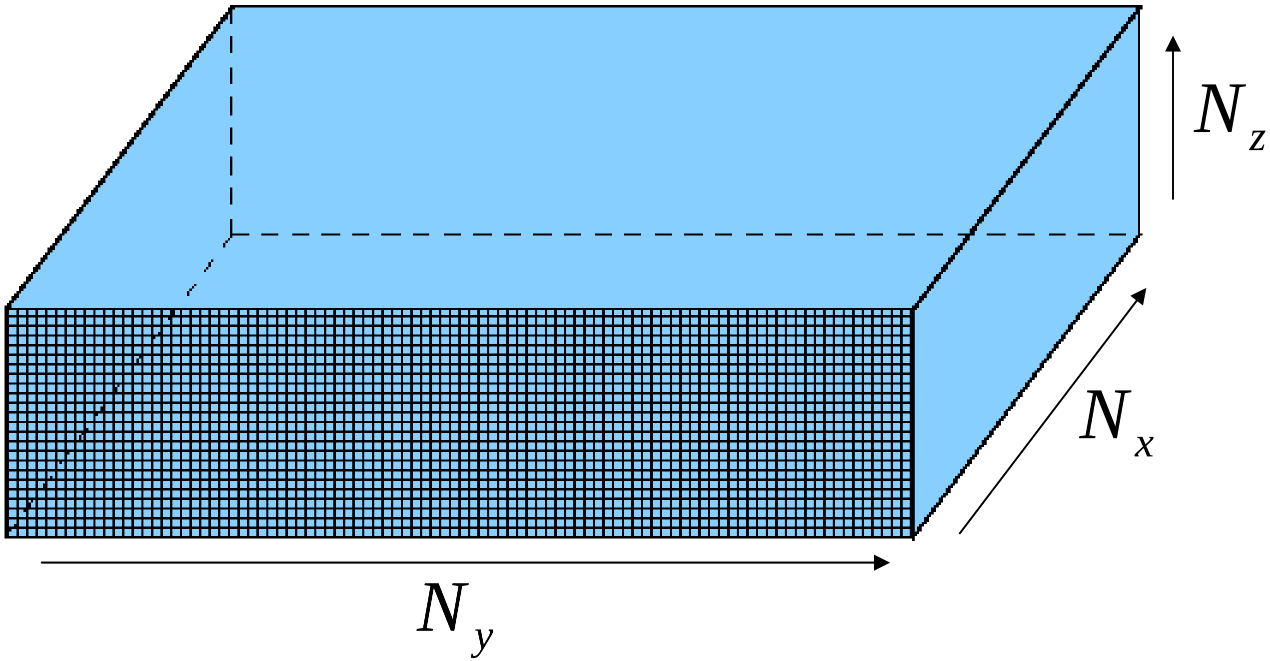
DNS $\text{Cost} \sim N^4 \sim \text{Re}^3\,\text{Pr}^2$



CODE: Sparkle

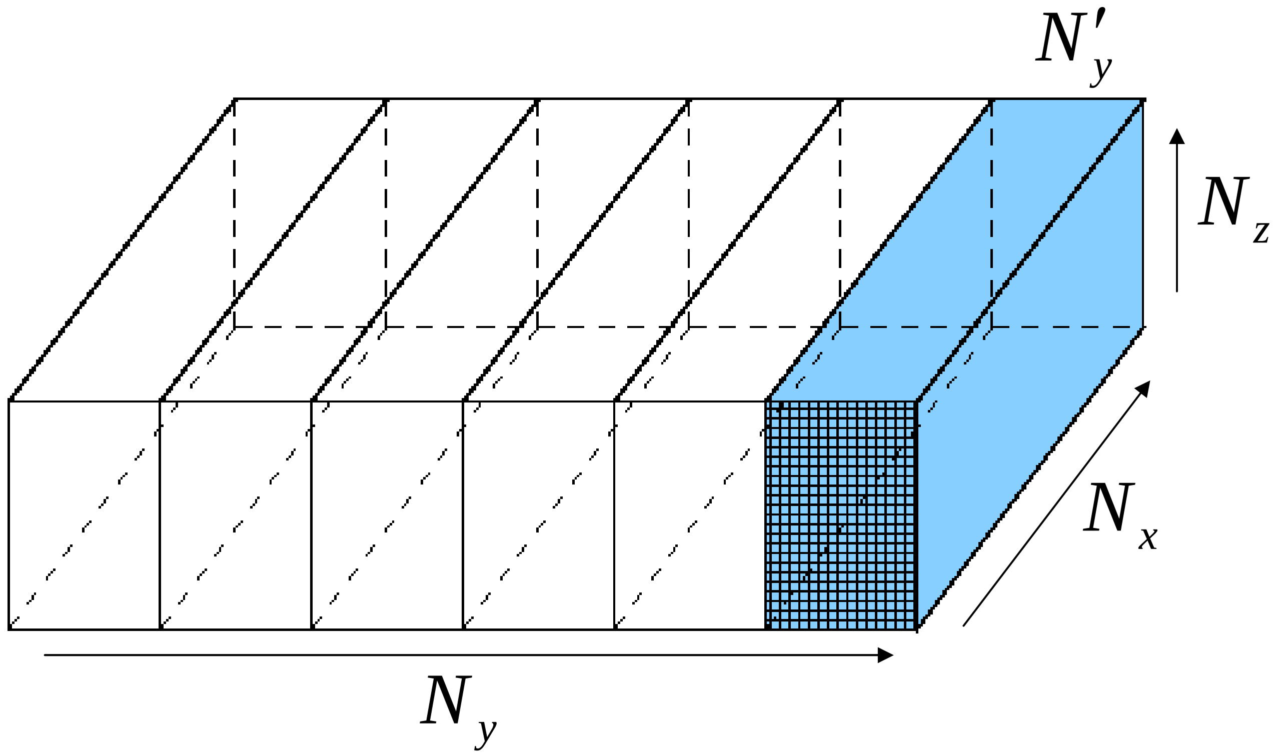
- Fortran 90
- MPI
- concise and simple
- Spatial discretisation: Central difference (2^{nd} order)
- Time integration: Adams-Bashforth (2^{nd} order)
- vertical: walls (free/no-slip, prescribed temperature/flux)
- Lateral periodic boundary conditions
- Poisson equations for pressure: FFTs in lateral directions, tridiagonal in vertical.

Computational Load $C = N_x N_y N_z N_t$



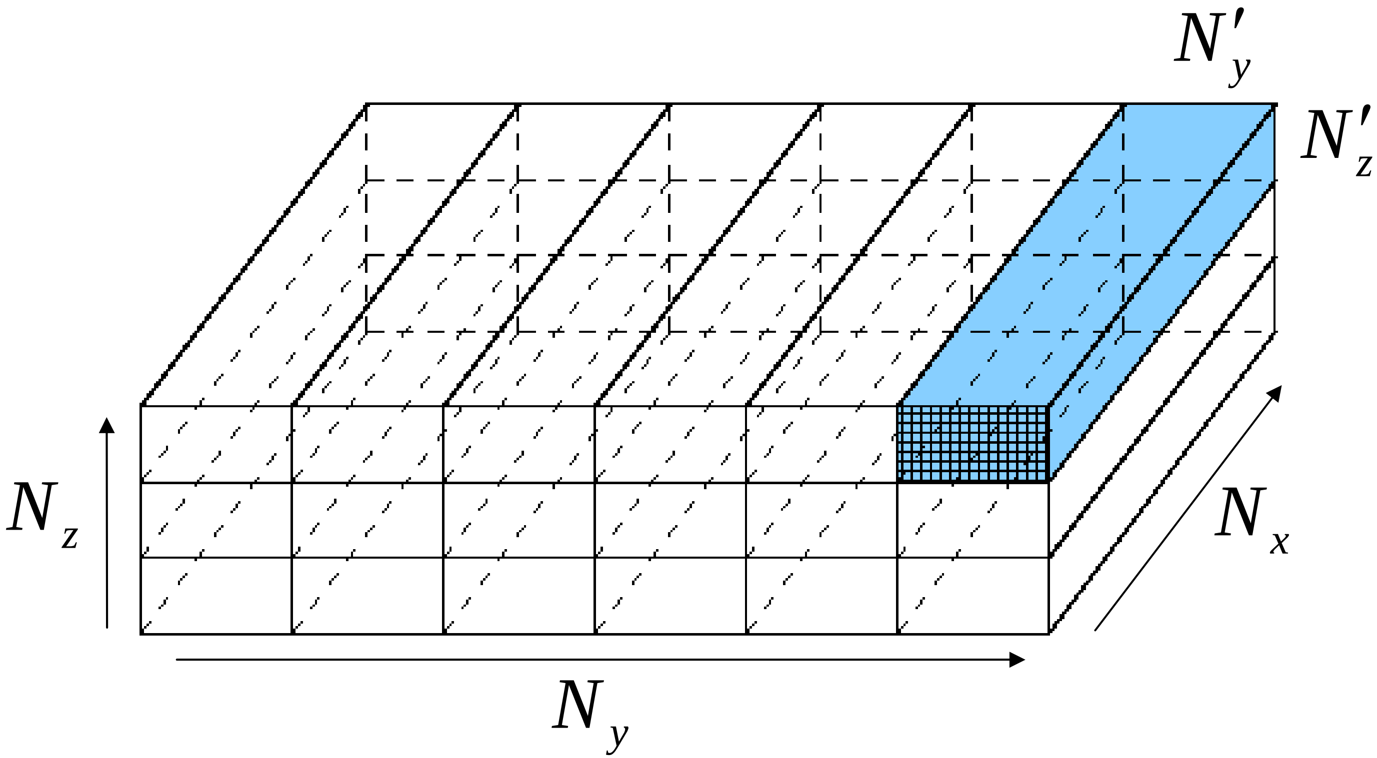
Domain decomposition

$$N'_y = \frac{N_y}{p}$$



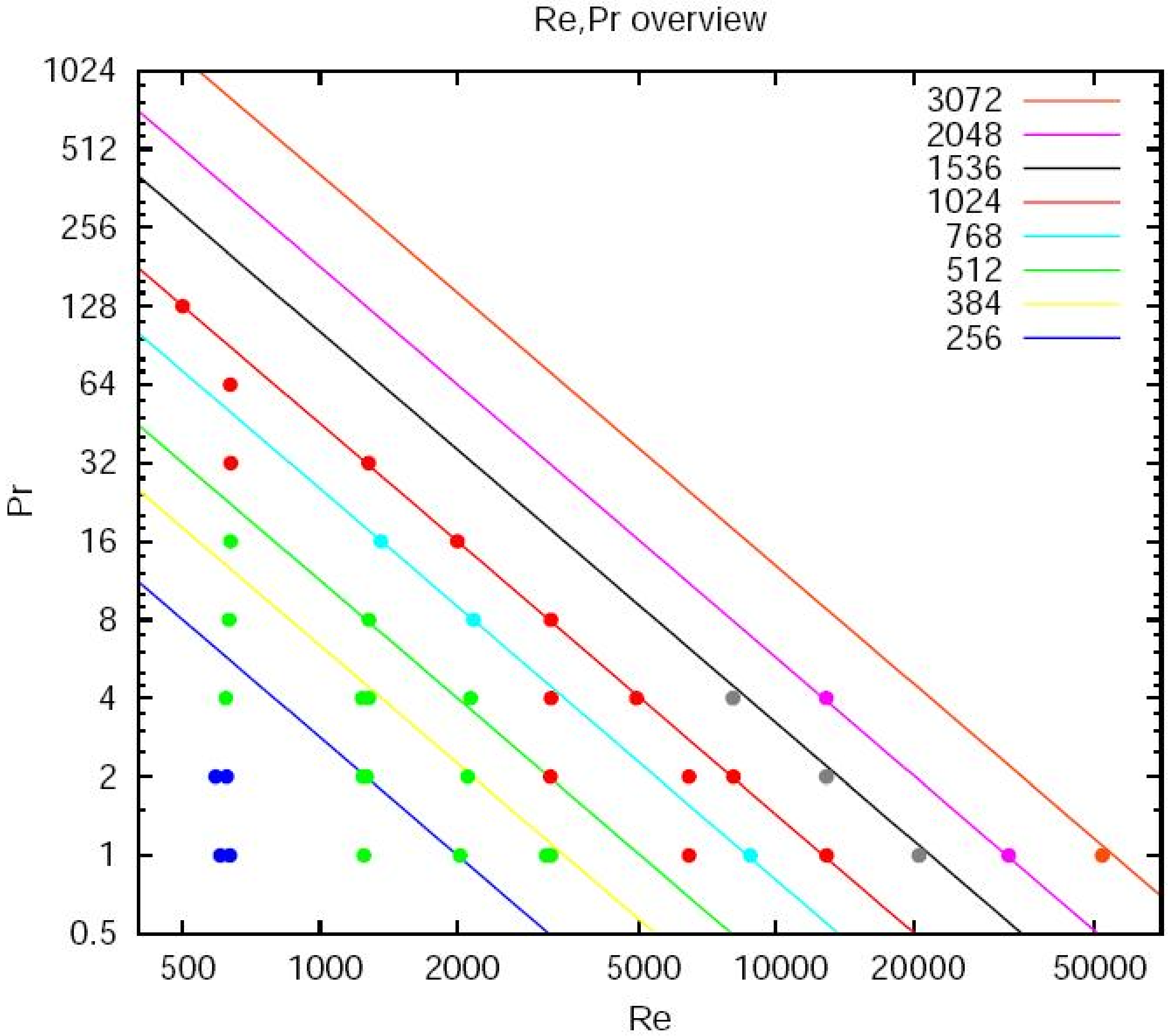
speedup $$\frac{C}{C' + O} \sim \frac{N_x N_y N_z}{N_x N'_y N_z + \alpha N_x N_z} \sim \frac{p}{1 + \alpha\, p / N_y} \qquad N >> p \ldots$$

2D domain decomposition
(define communicators in y and z)



speedup $$\frac{C}{C'+O} \sim \frac{N^3}{N^3/p + \alpha N^2/\sqrt{p}} = \frac{p}{1+\alpha\sqrt{p}/N} \qquad N >> \sqrt{p}$$

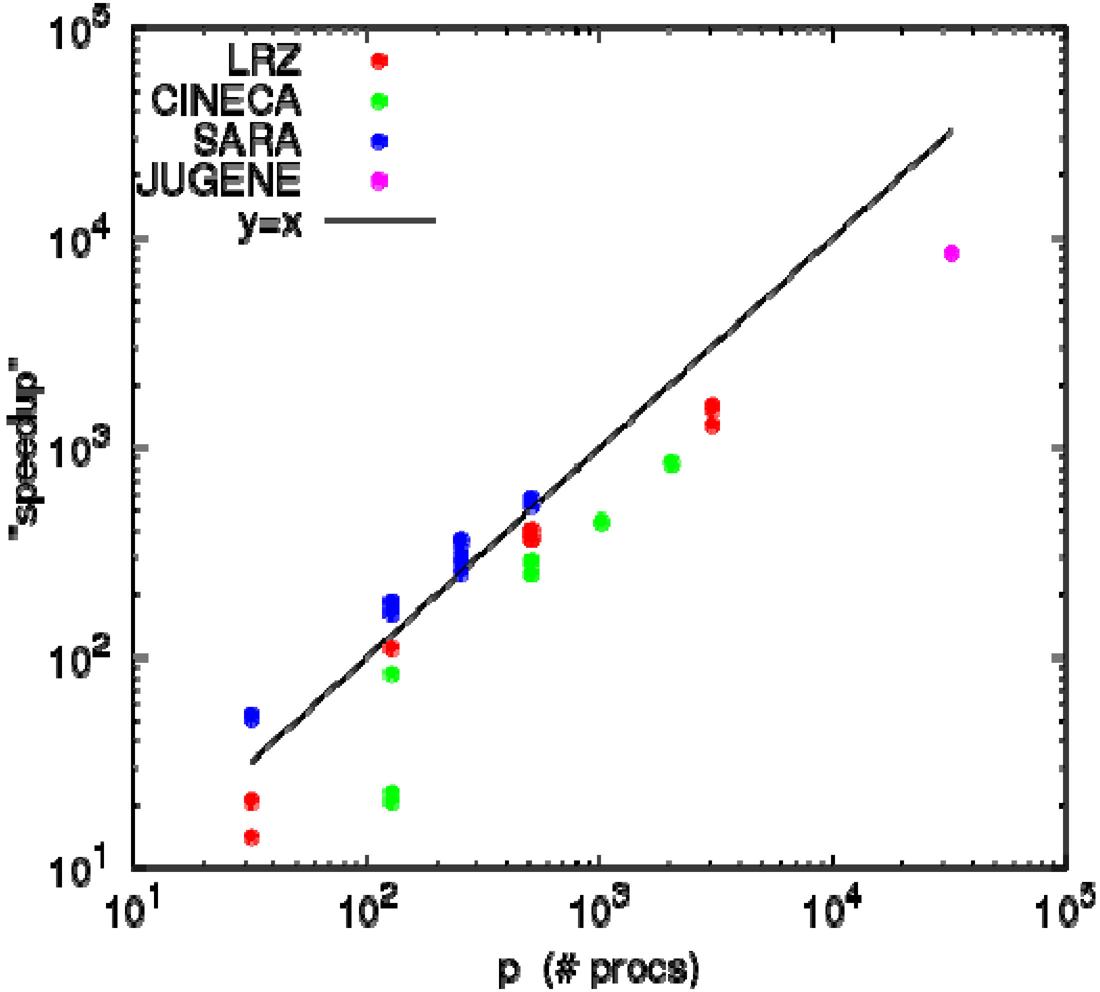
DNS $\text{Cost} \sim N^4 \sim \text{Re}^3\,\text{Pr}^2$



DEISA resource allocation: 1.9M cpu-hr

Site	*Architecture*	*Max nr 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

speedup



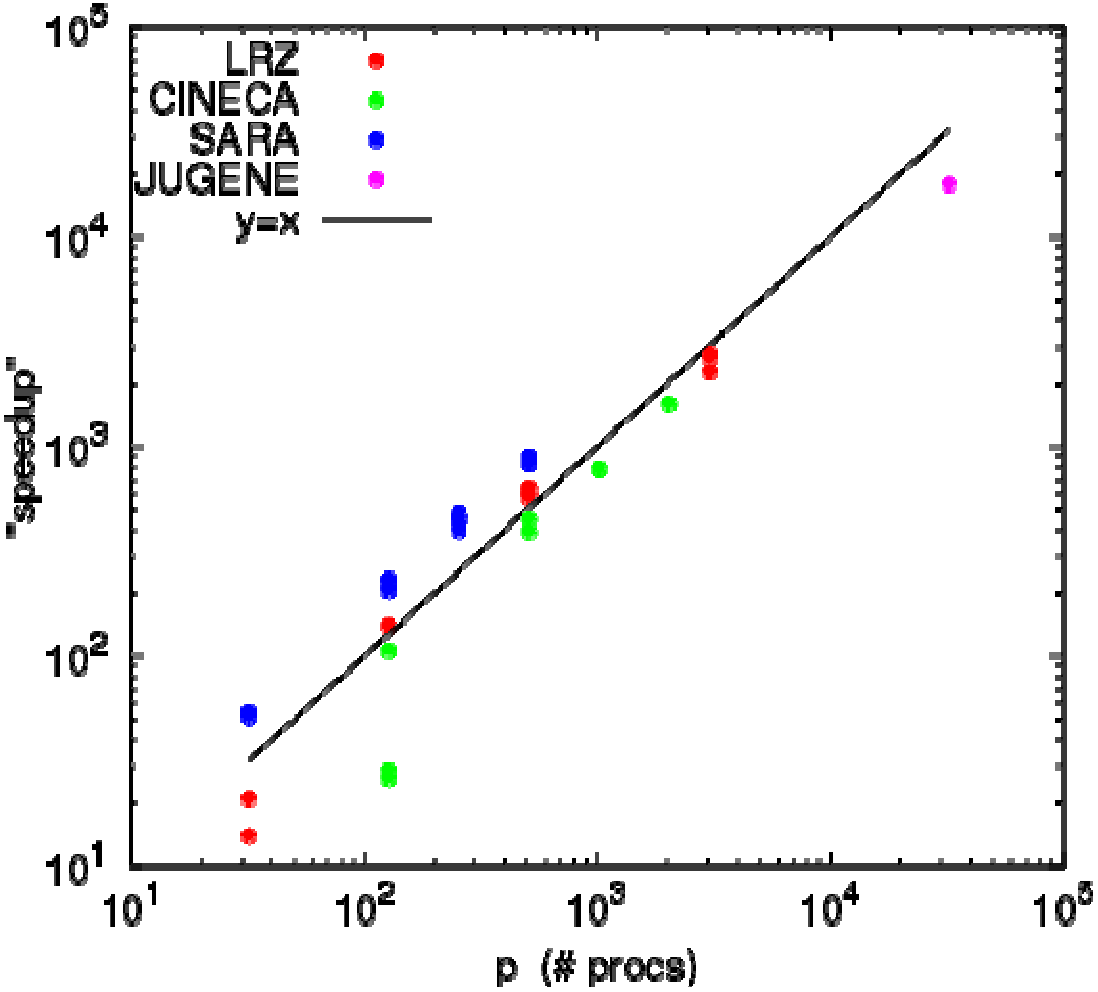
$$S_p = \frac{C_1}{C_p} = \frac{C_1}{\text{WallClock}}$$

$$C_1 = ?$$

$$C_1 \approx \alpha\, N_x N_y N_z N_t$$

$$\alpha = 10^{-6}$$

speedup



$$S_p = \frac{C_1}{C_p} = \frac{C_1}{\text{WallClock}}$$

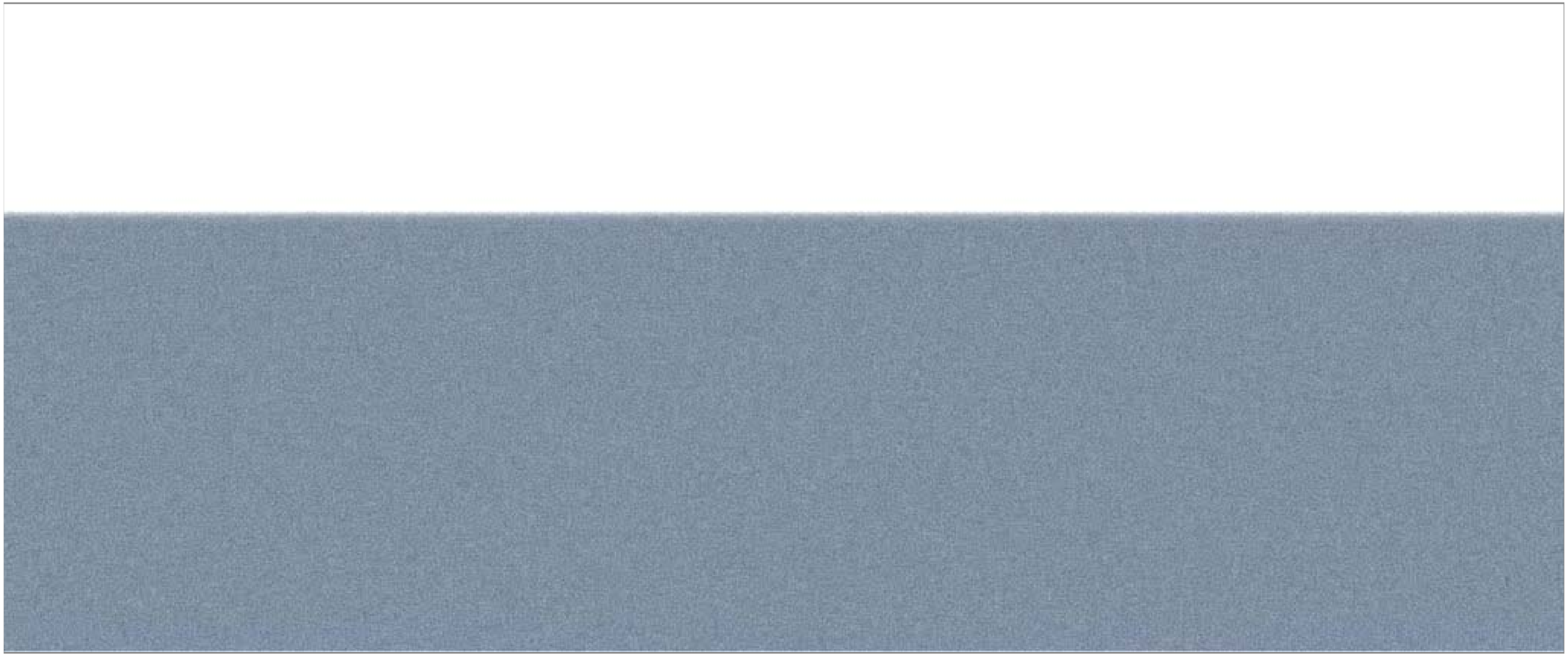
theoretical scaling FFT's in x and y: $C_1 \approx \alpha\, N_x \log(N_x) N_y \log(N_y) N_z N_t$

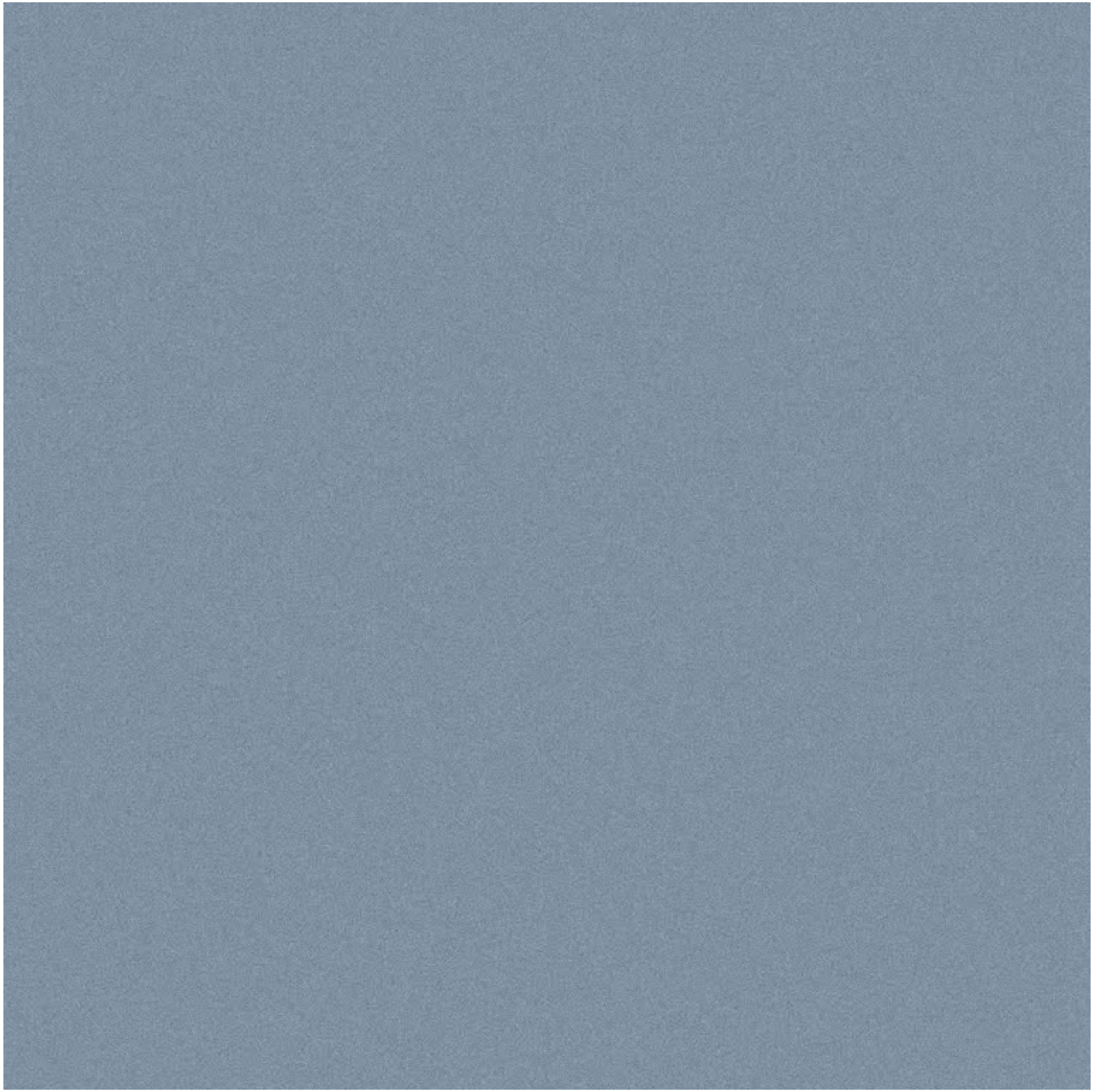
$$N_x = N_y = 2048, \quad N_z = 1024, \quad p = 2048$$

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

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

(potential) Temperature animation





(CINECA)

horizontal slice

$z = 0.04 z_i$

$N_x = N_y = 2048$

$L_x = L_y = 3072m$

$\mathrm{Re} = 30{,}000$

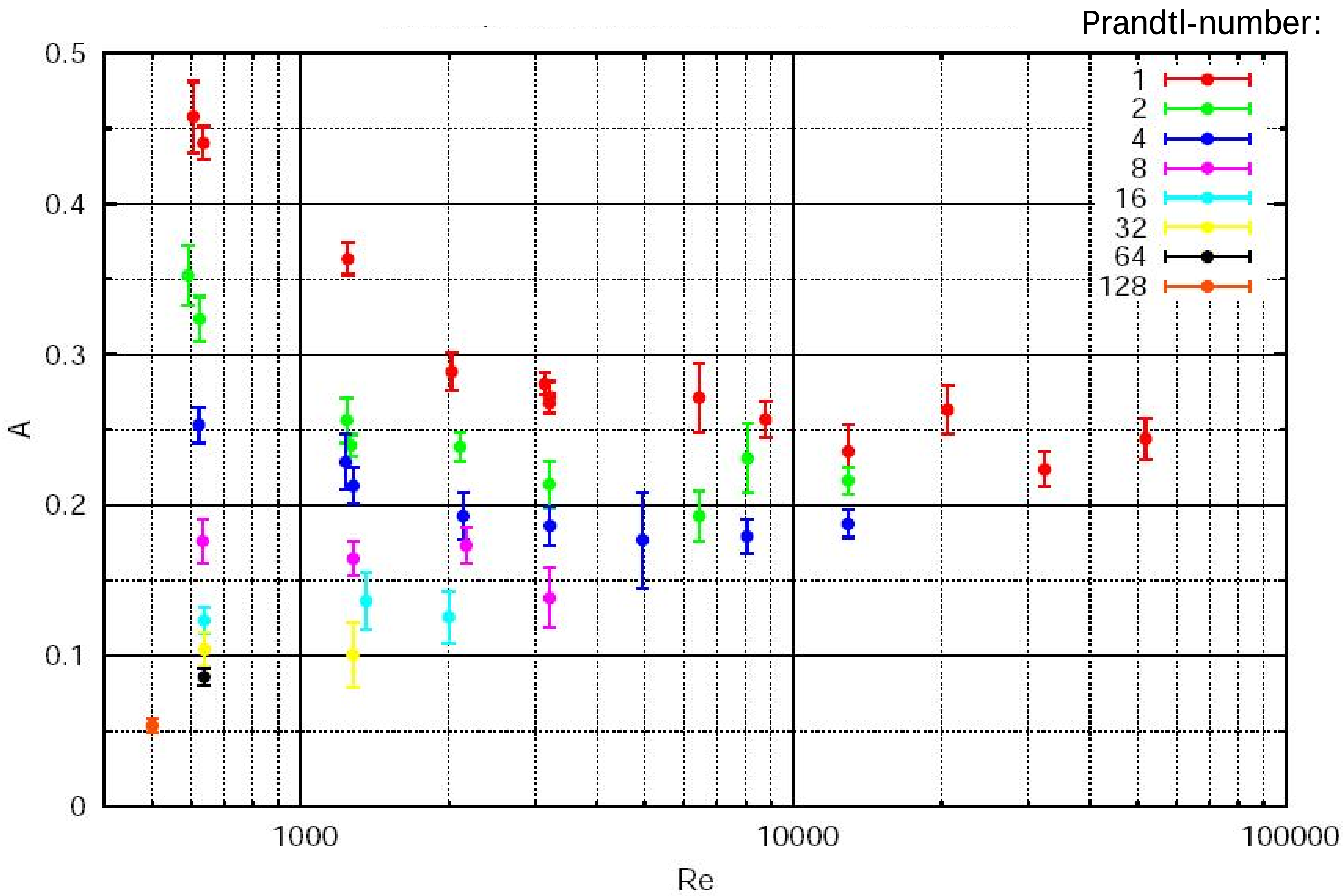
$\mathrm{Pr} = 1$

Bottle necks

- debug queue for huge runs
- storage (scratch/home/archive & data-movement)
- cpu-failure and MPI deadlock

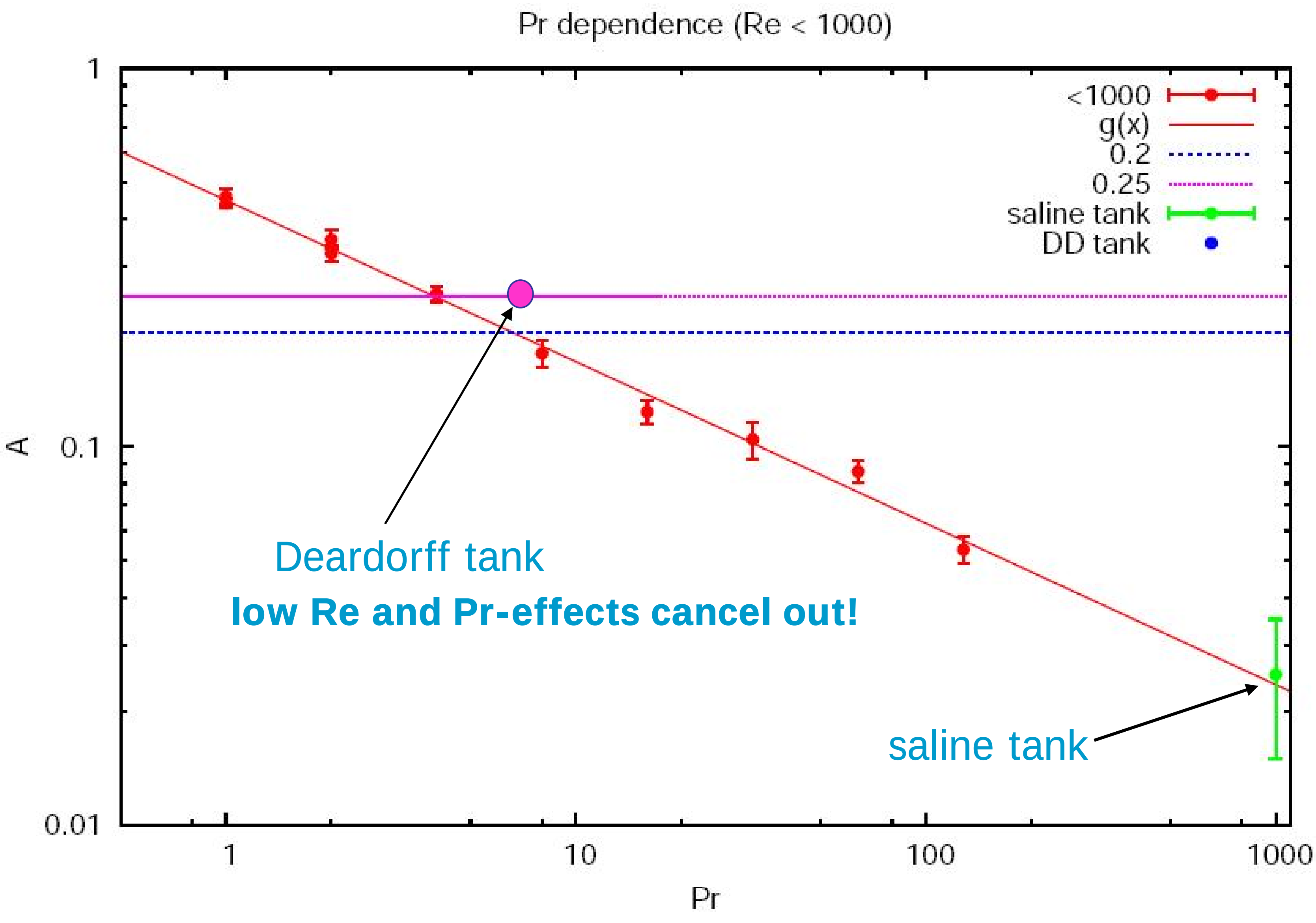
  (sanity-check: non-blocking send/recv to neighbor cpus)

The importance of large computations



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

Fortuity or talent?



Thanks! SARA: Wim Rijks, Walter Lioen; CINECA, LRZ, FZJ (various people)

Conclusion

DEISA-DNS (PINNACLE) study shows that:

- Laboratory Experiments on Entrainment have been influenced too much by molecular processes (Re, Pr)

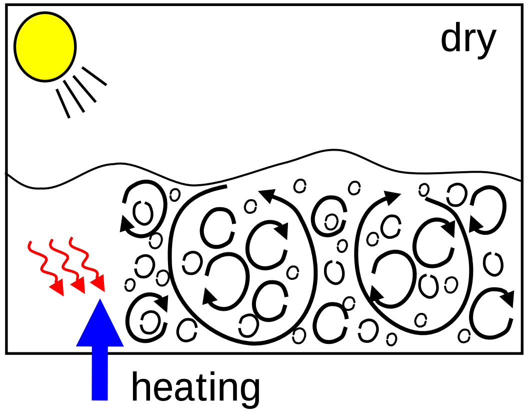
- the PINNACLE project did indeed pin down the <u>growth-rate law for atmospheric convection</u>:

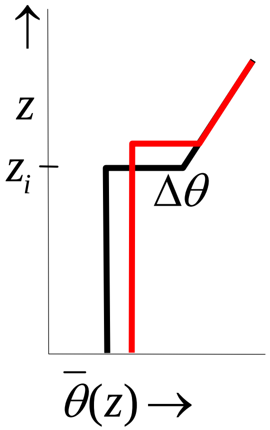
$$w_e = w_* \frac{A}{Ri}, \quad A = 0.25$$

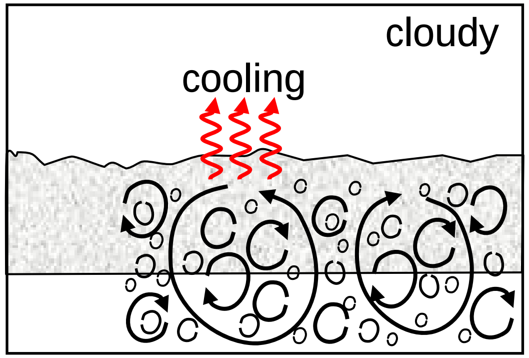
- a new era starts with DNS "ideal experiments"

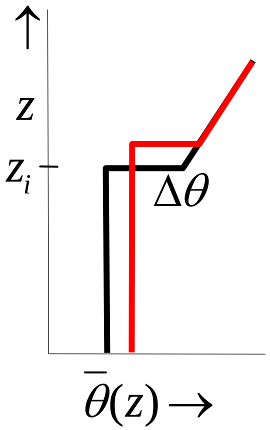
Distributed
European
Infrastructure for
Supercomputing
Applications

outlook


dry
heating


z
z_i
$\Delta\theta$
$\overline{\theta}(z) \rightarrow$


cloudy
cooling


z
z_i
$\Delta\theta$
$\overline{\theta}(z) \rightarrow$