IXth ISSF Cambridge, 29th August 2022

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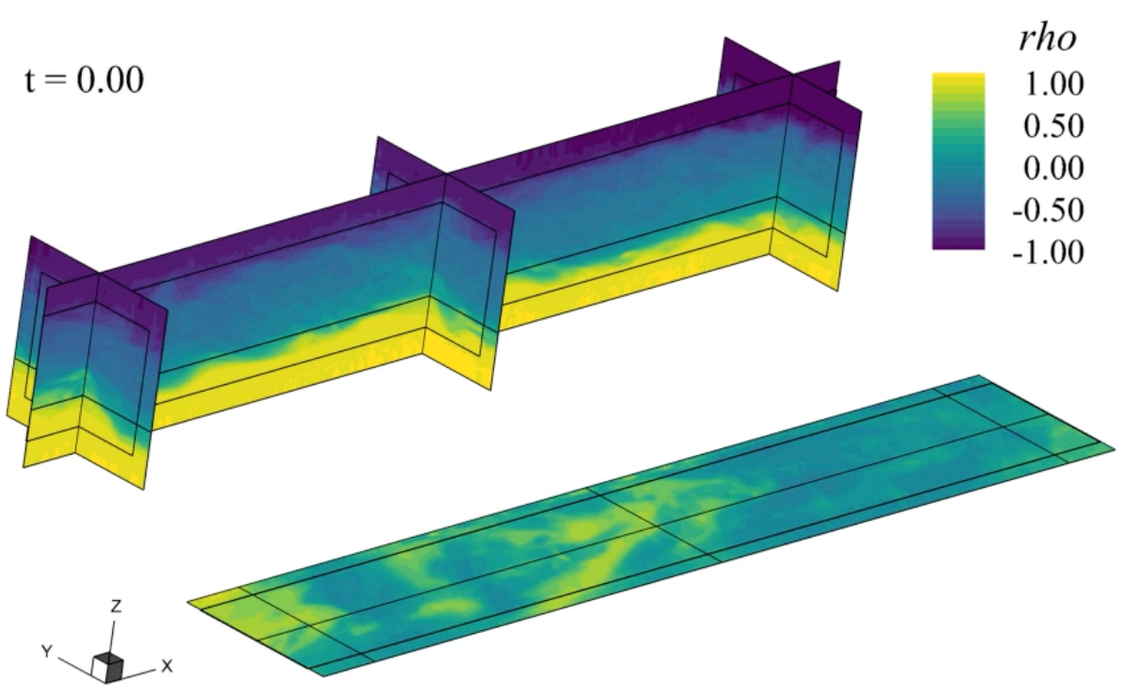
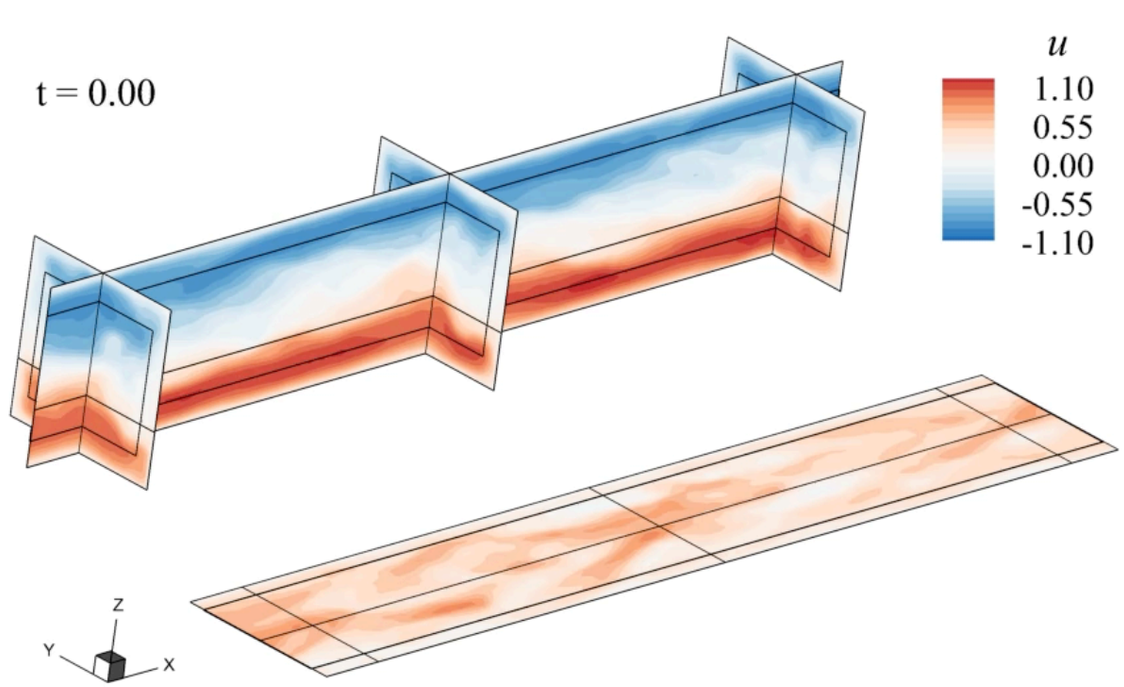
Experimental properties of continuously-forced, shear-driven, stratified turbulence

Adrien Lefauve, Paul Linden, Stuart Dalziel + “The STAMP team”





Funding: EPSRC Engineering and Physical Sciences Research Council

The Leverhulme Trust

erc European Research Council

Experimental measurements

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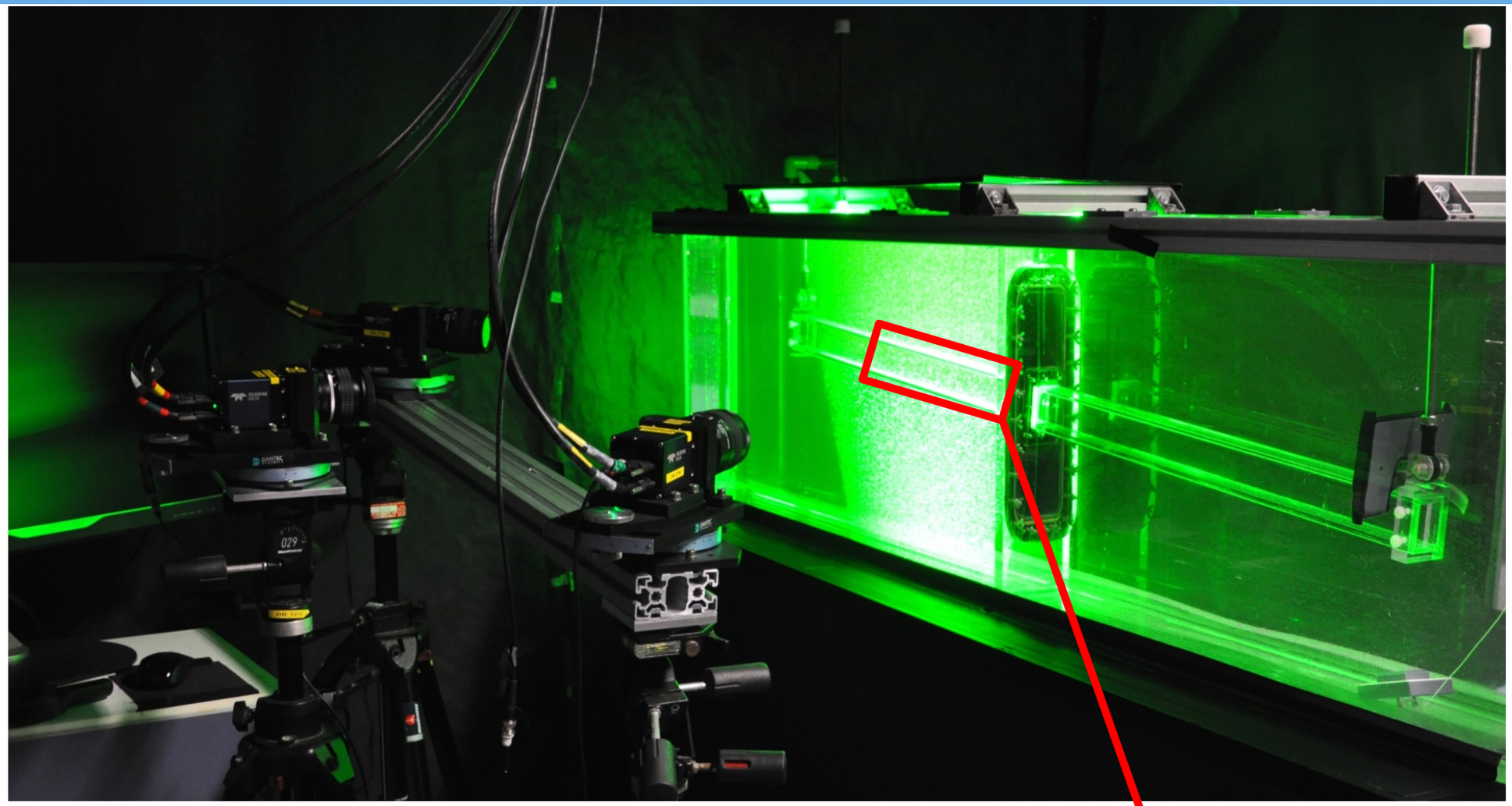
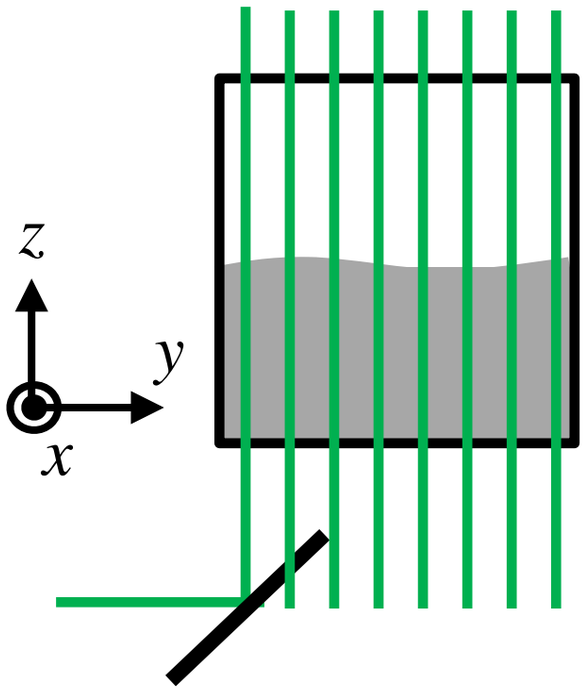
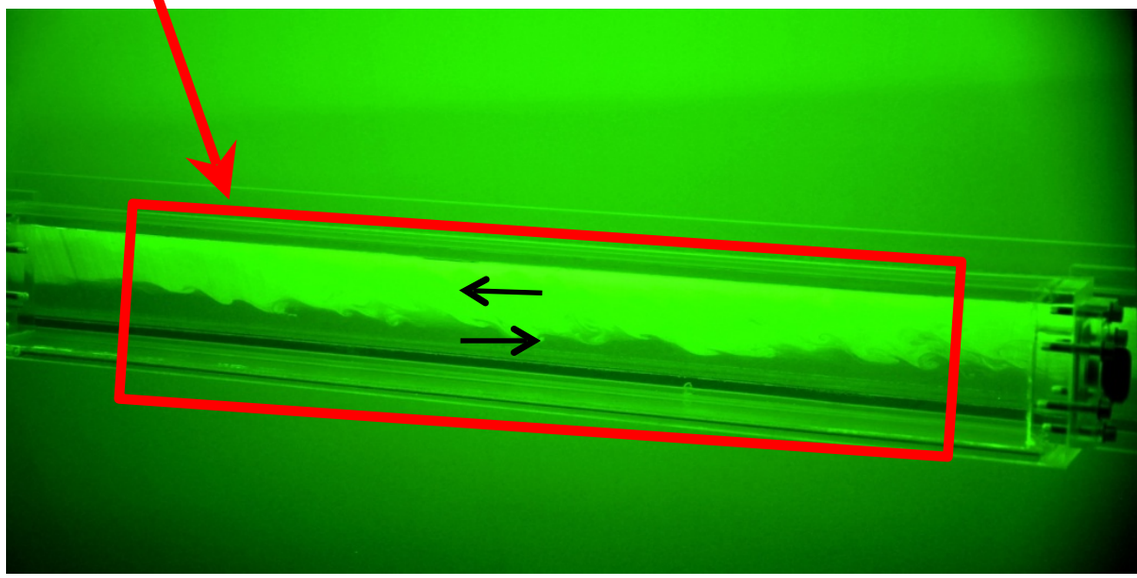
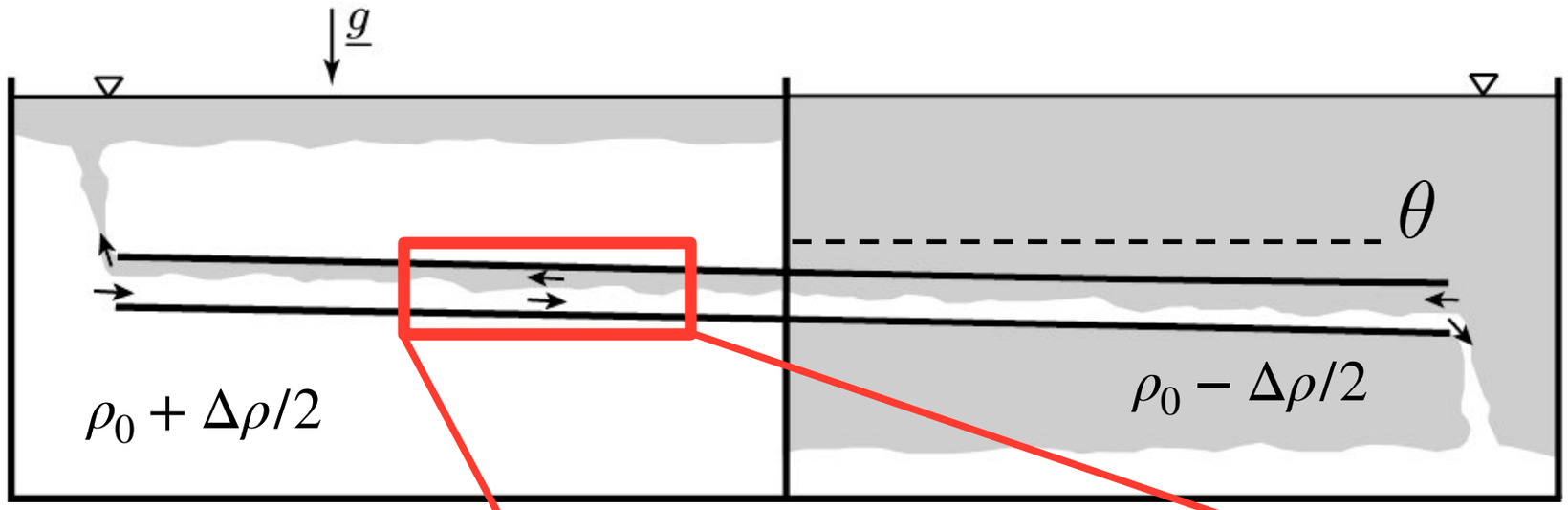




u, v, w and ρ data
at vector resolution
400 x 30 x 100 x 300
in x y z t



Flow parameters in SID



Isolate the flow inside the duct

Richardson number

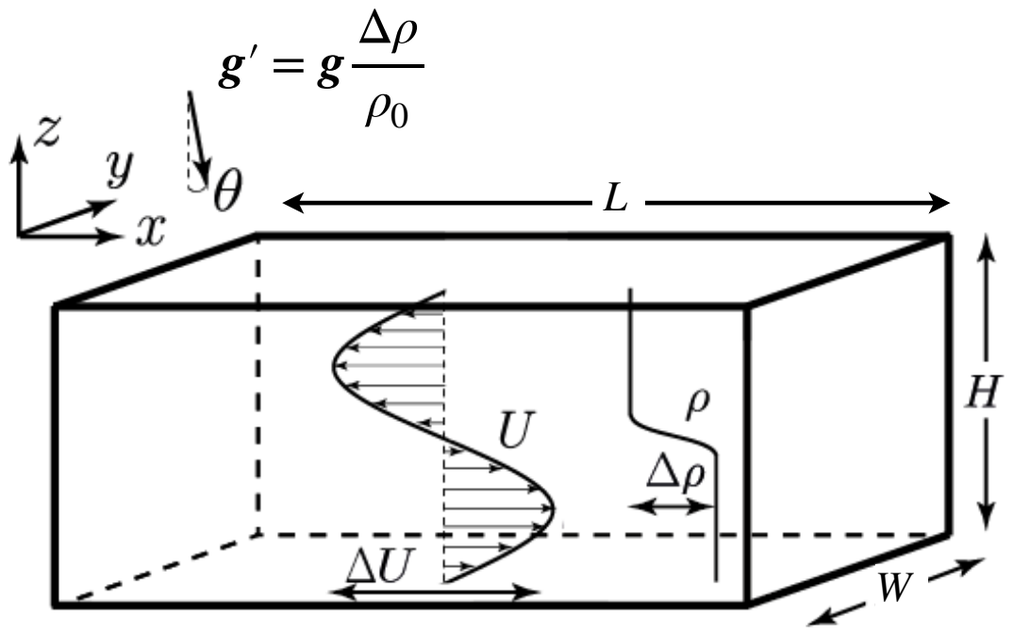
$$\sim \frac{g'H}{(\Delta U)^2} \approx 0.1 - 0.5$$

Tilt angle

Momentum:

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u}\cdot\nabla\boldsymbol{u} = -\nabla p + \frac{1}{Re}\nabla^2\boldsymbol{u} + Ri\,\rho \begin{pmatrix} \sin\theta \\ 0 \\ -\cos\theta \end{pmatrix}$$

Reynolds number $\sim \dfrac{\Delta U\, H}{\nu}$



Mass:

$$\frac{\partial \rho}{\partial t} + \boldsymbol{u}\cdot\nabla\rho = \frac{1}{Re\,Pr}\nabla^2\rho$$

Prandtl/Schmidt number $= \dfrac{\nu}{\kappa} \approx 700$

Data sets: 16 experiments

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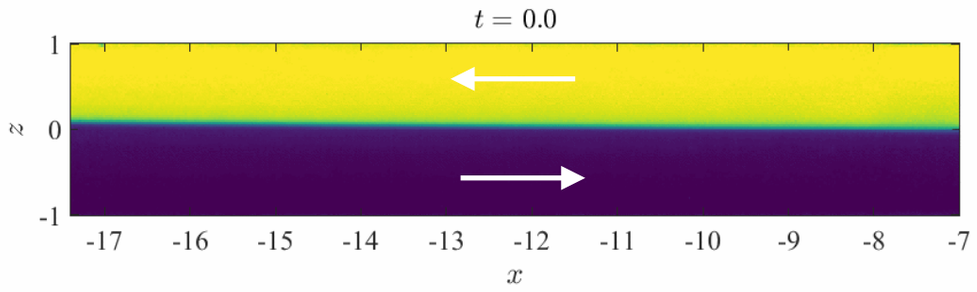
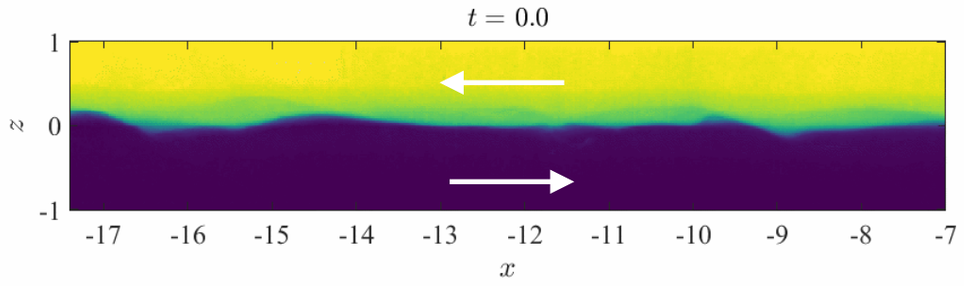
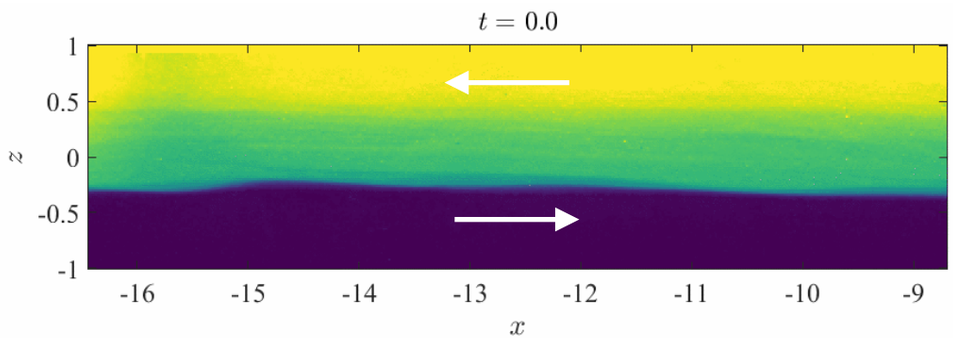
Laminar flow



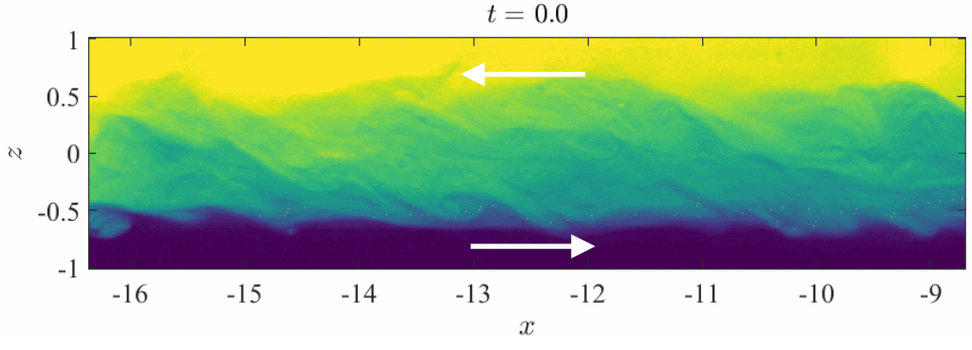
Holmboe waves

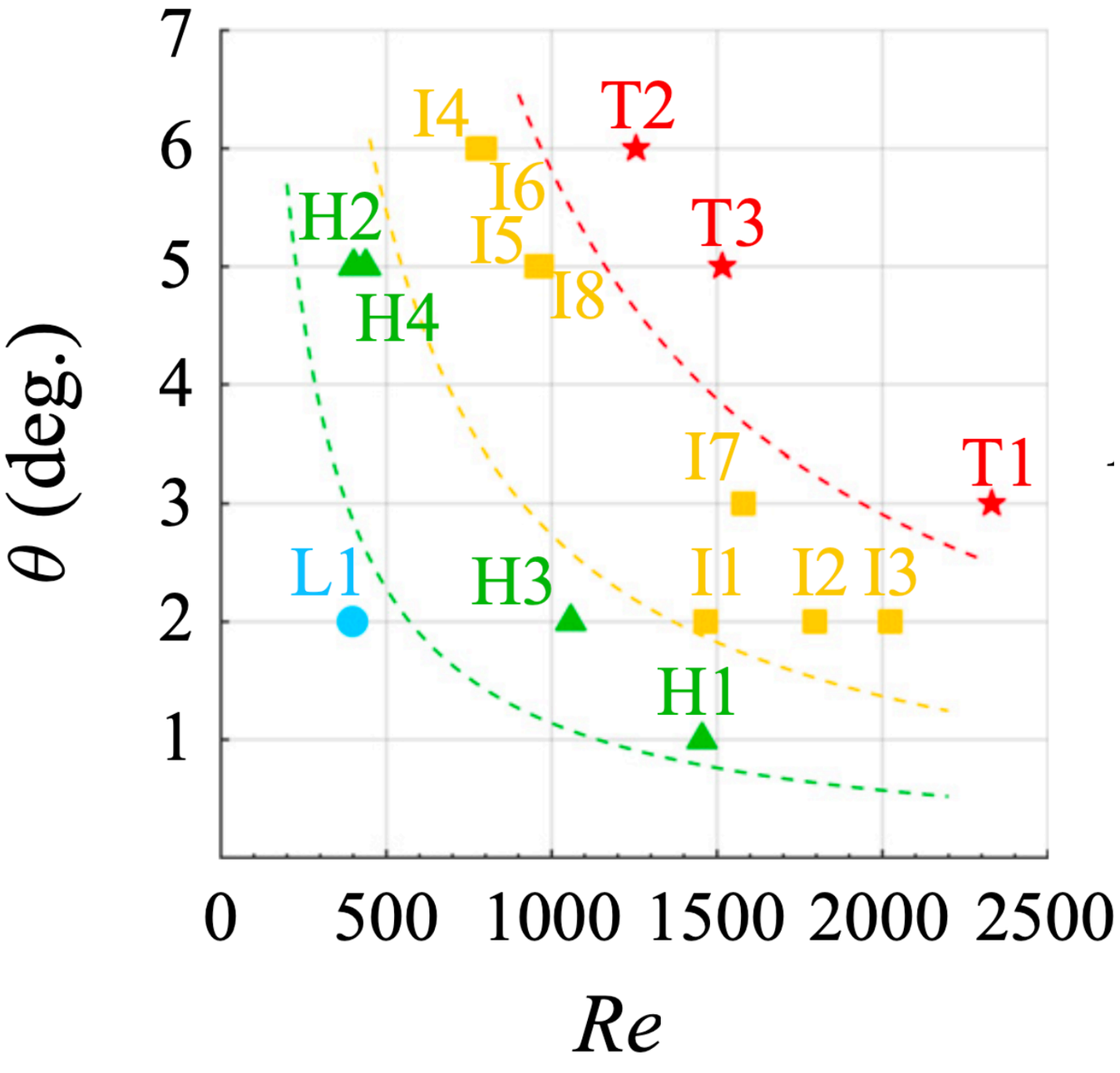


Intermittent turbulence



Turbulence





“Shear-layer” cropping and rescaling

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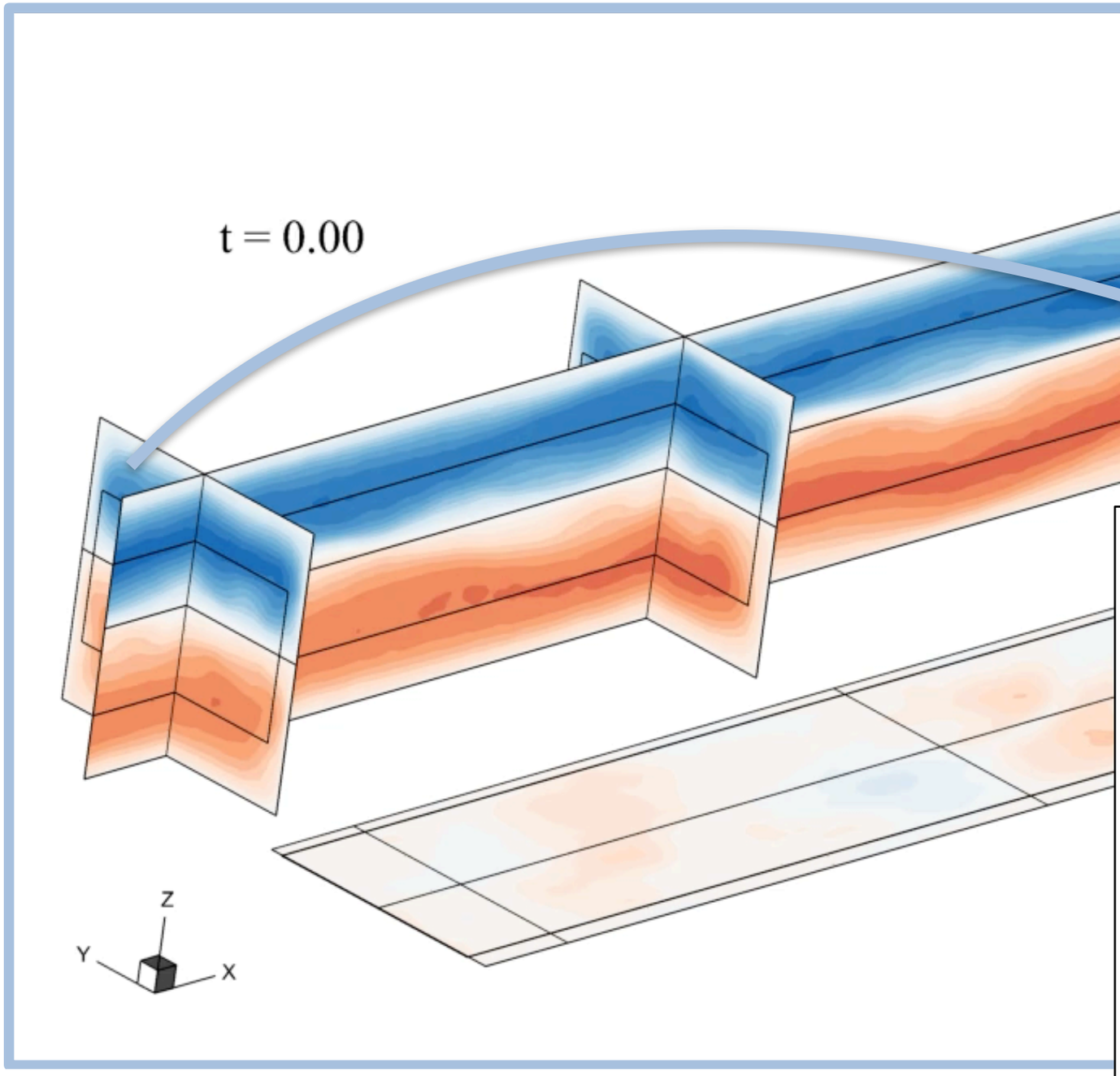

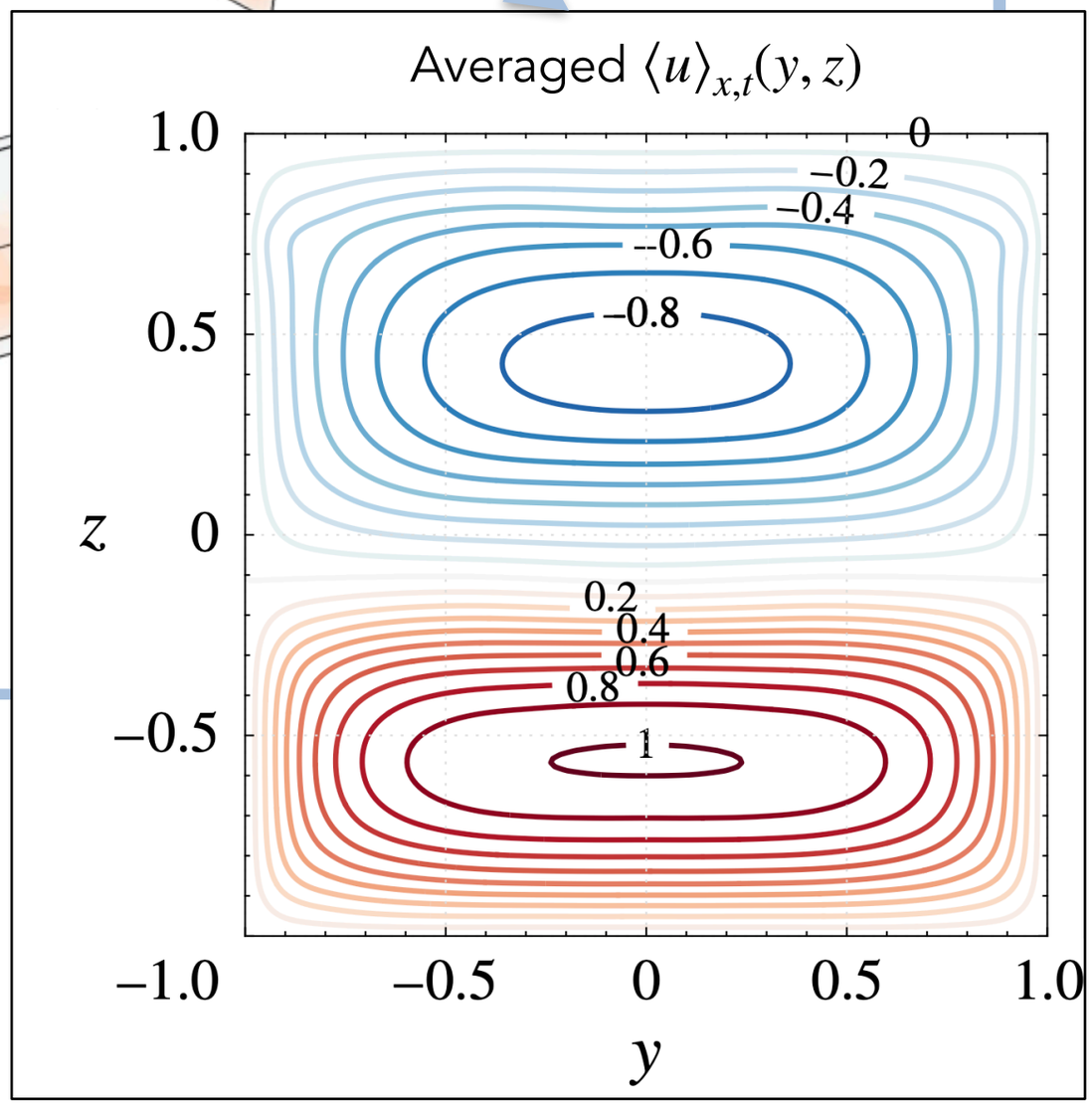

Data repository: [doi.org/10.17863/CAM.75370](doi.org/10.17863/CAM.75370)

Online movies: alefauve.com/datasetsmovies

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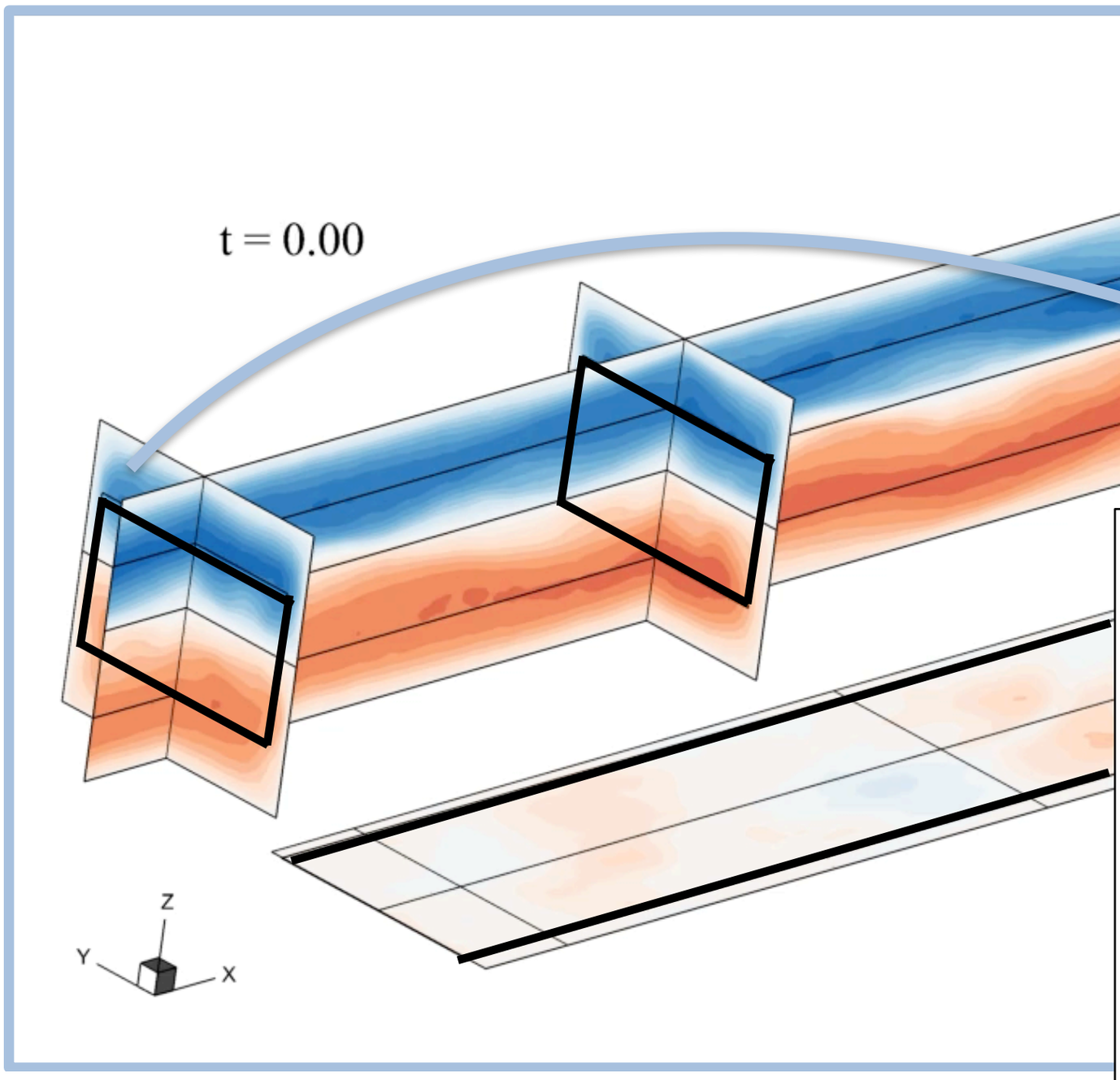

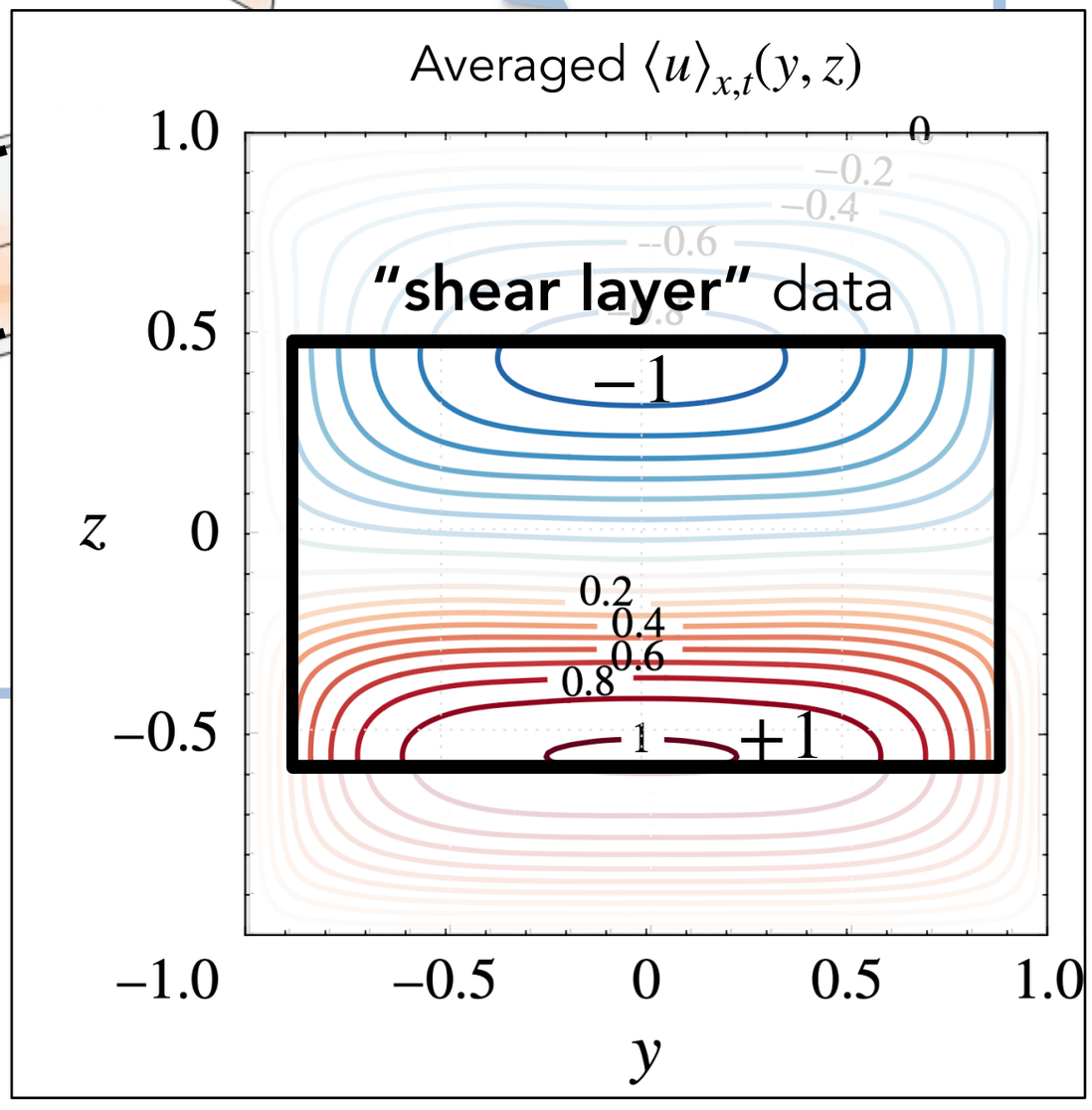

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Ri_g and "self-organisation"

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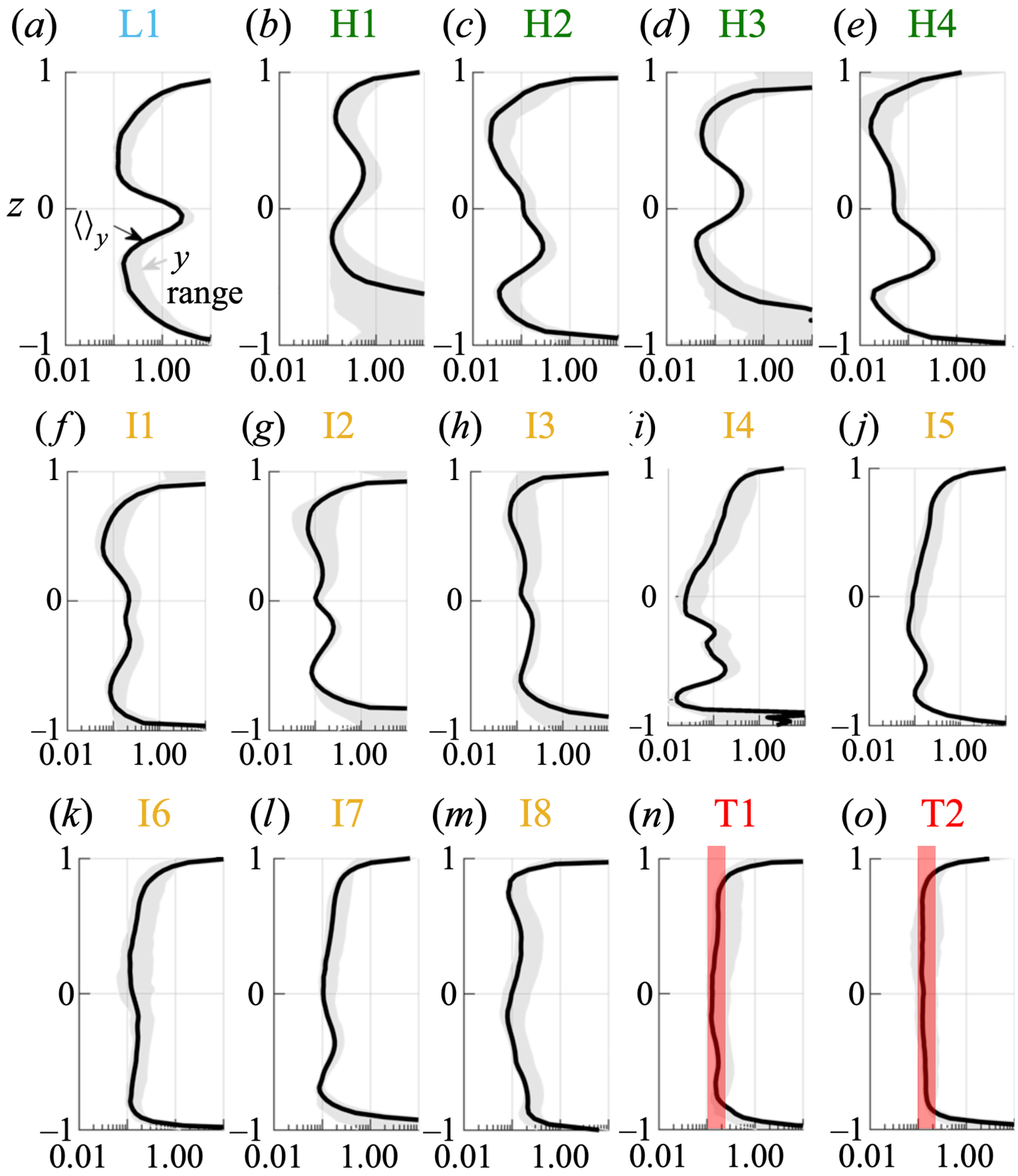

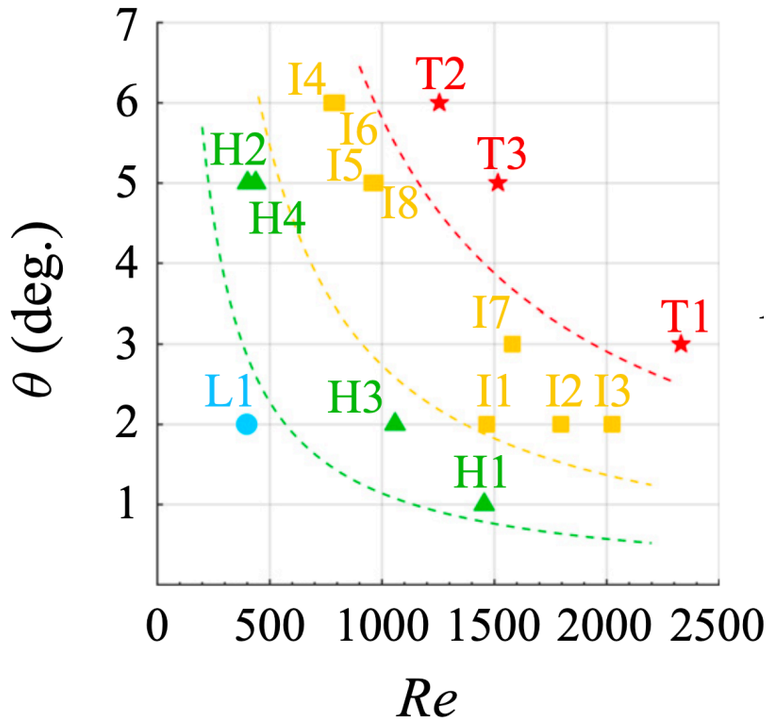

Gradient Richardson number:

$$Ri_g = -\frac{\partial_z \bar{\rho}}{(\partial_z \bar{u})^2}$$

Ri_g and "self-organisation"

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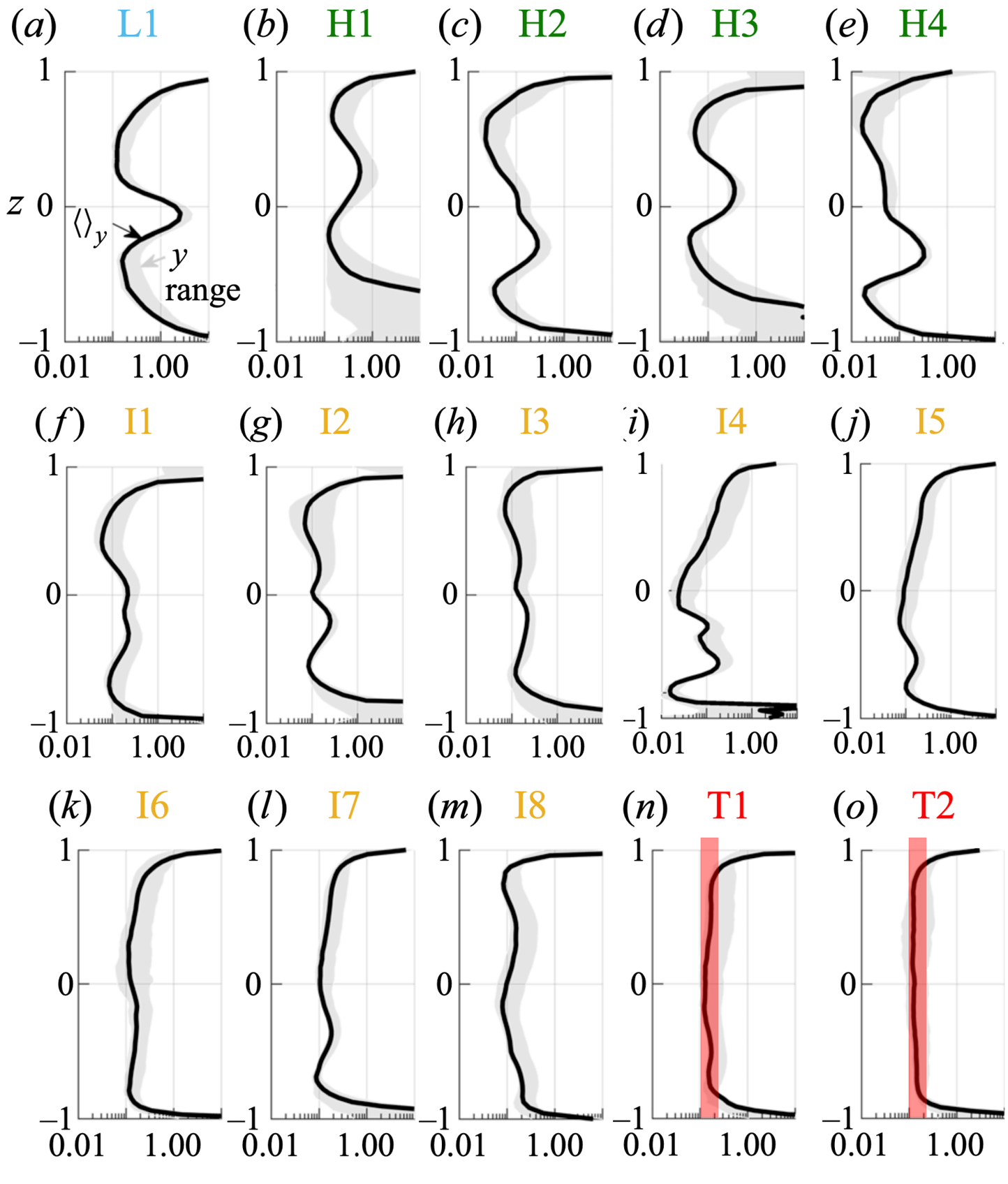
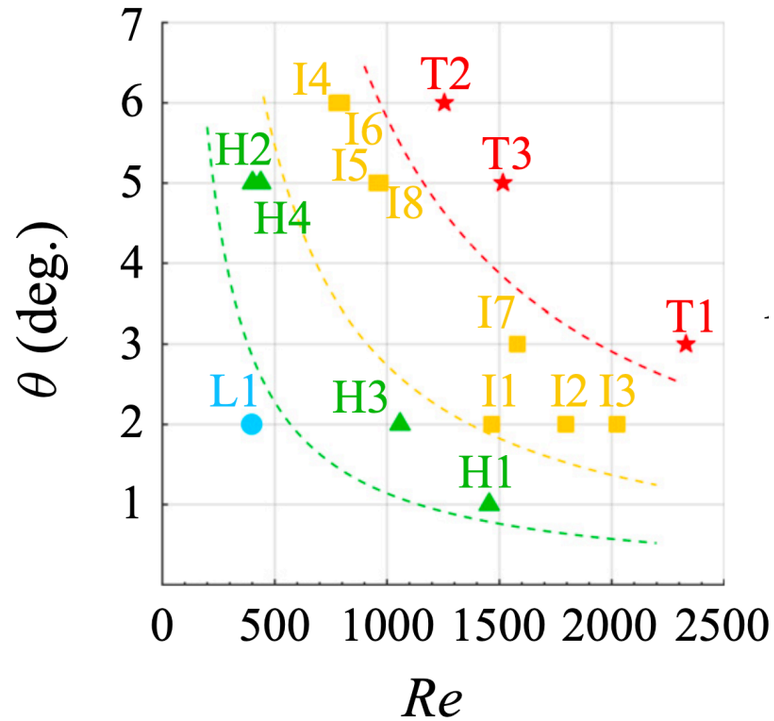
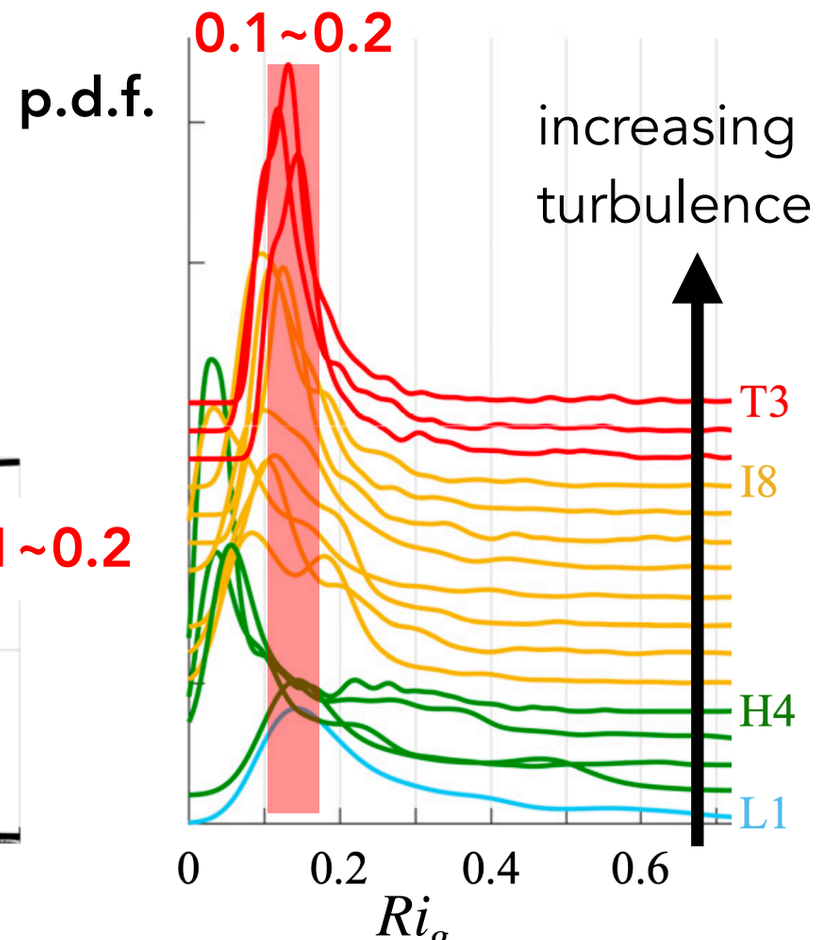






Turbulent components

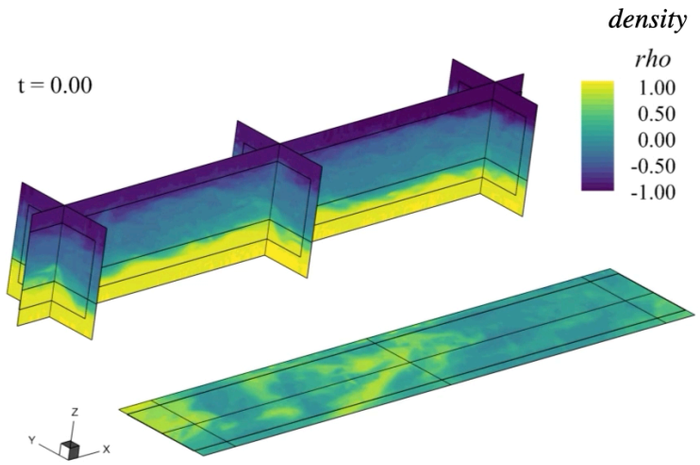
Dataset

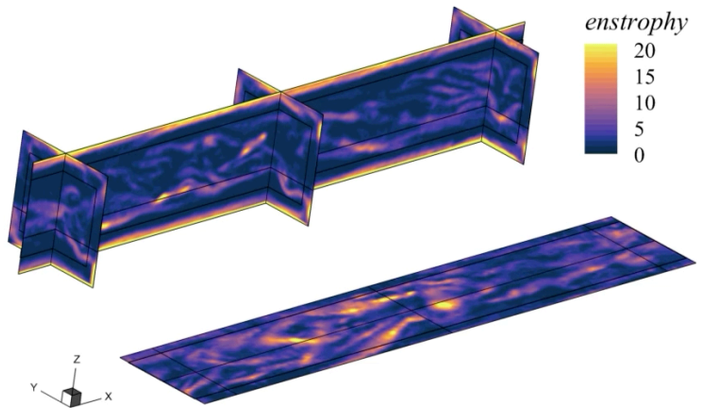
T3

$\theta = 5^{\circ}$

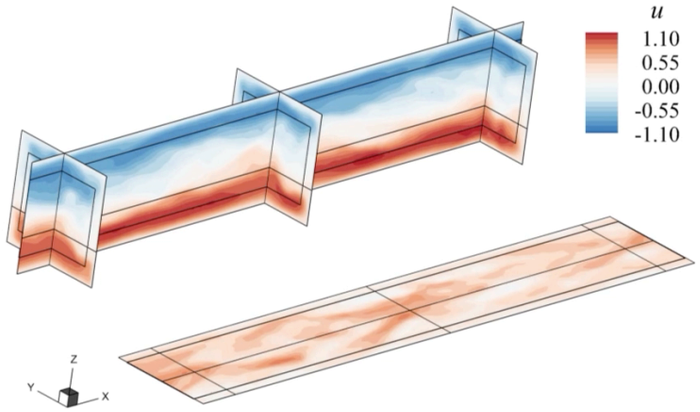
$Re^{s} = 1145$

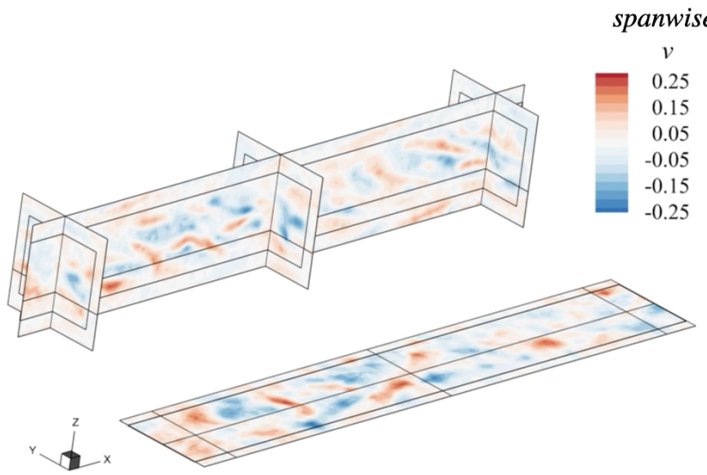
$Ri_{b}^{s} = 0.147$

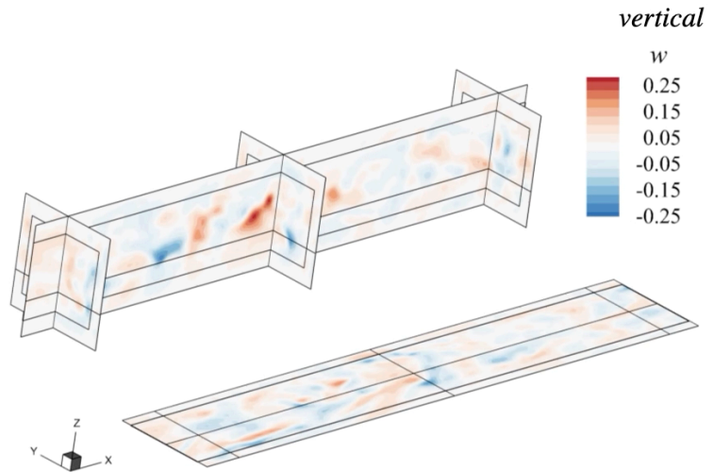




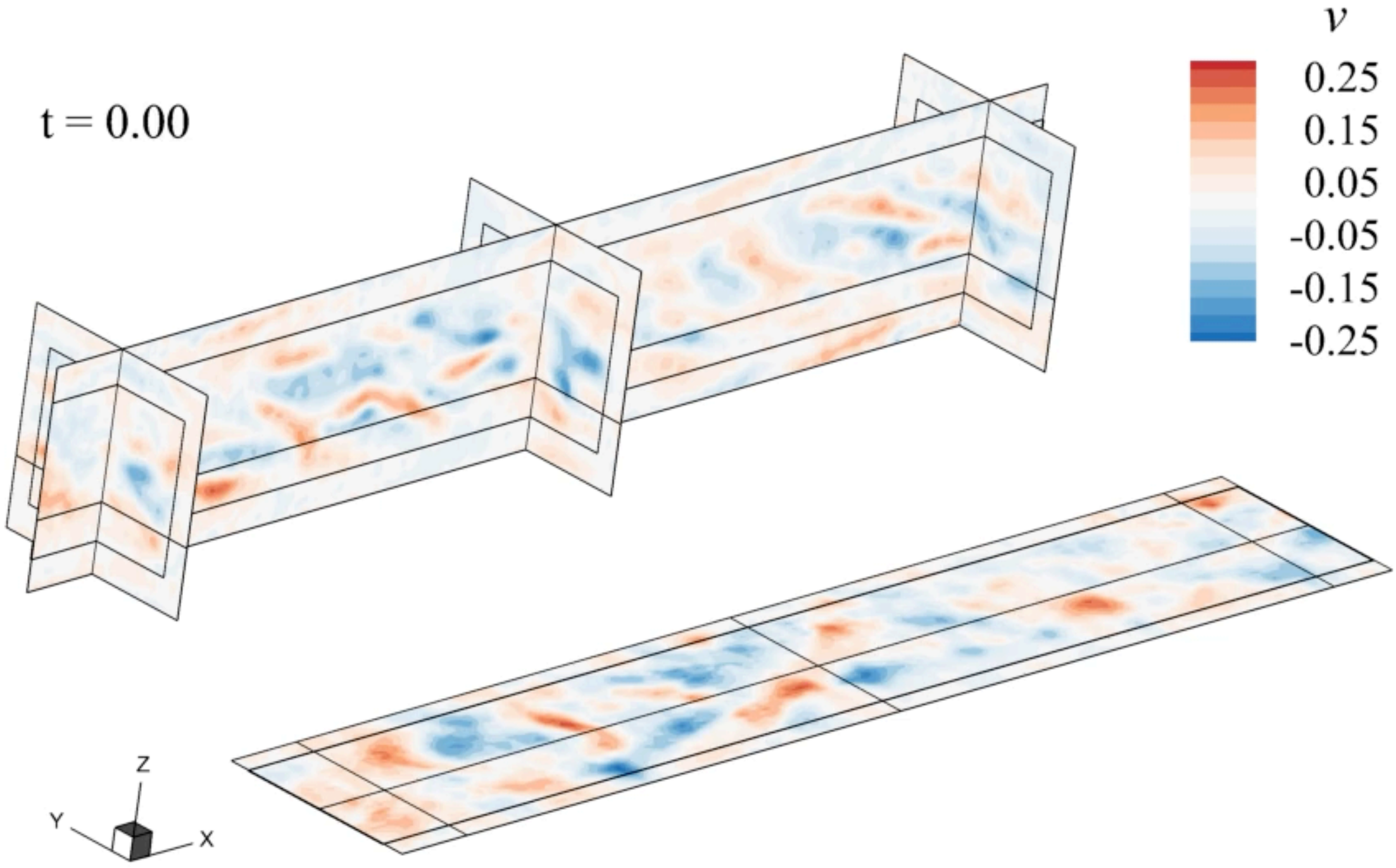
velocity $\mathbf{u} = (u, v, w)$





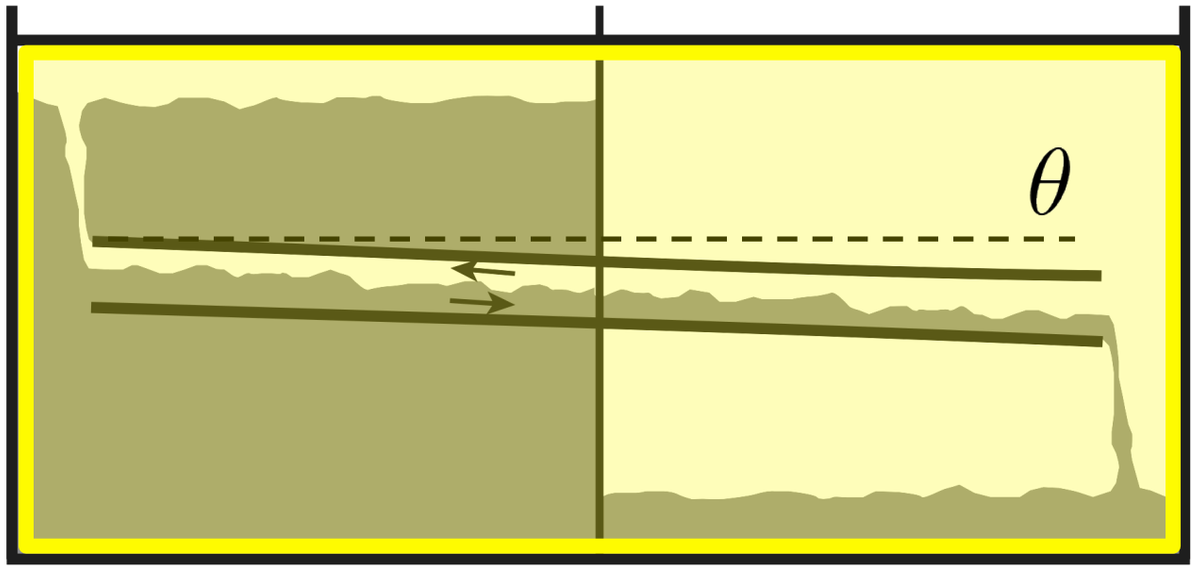


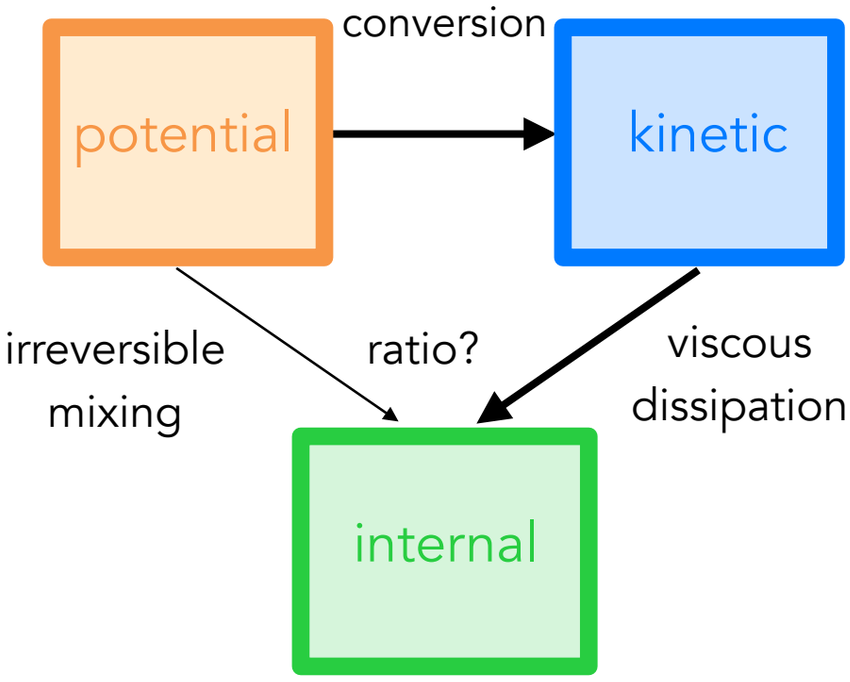
Turbulent components

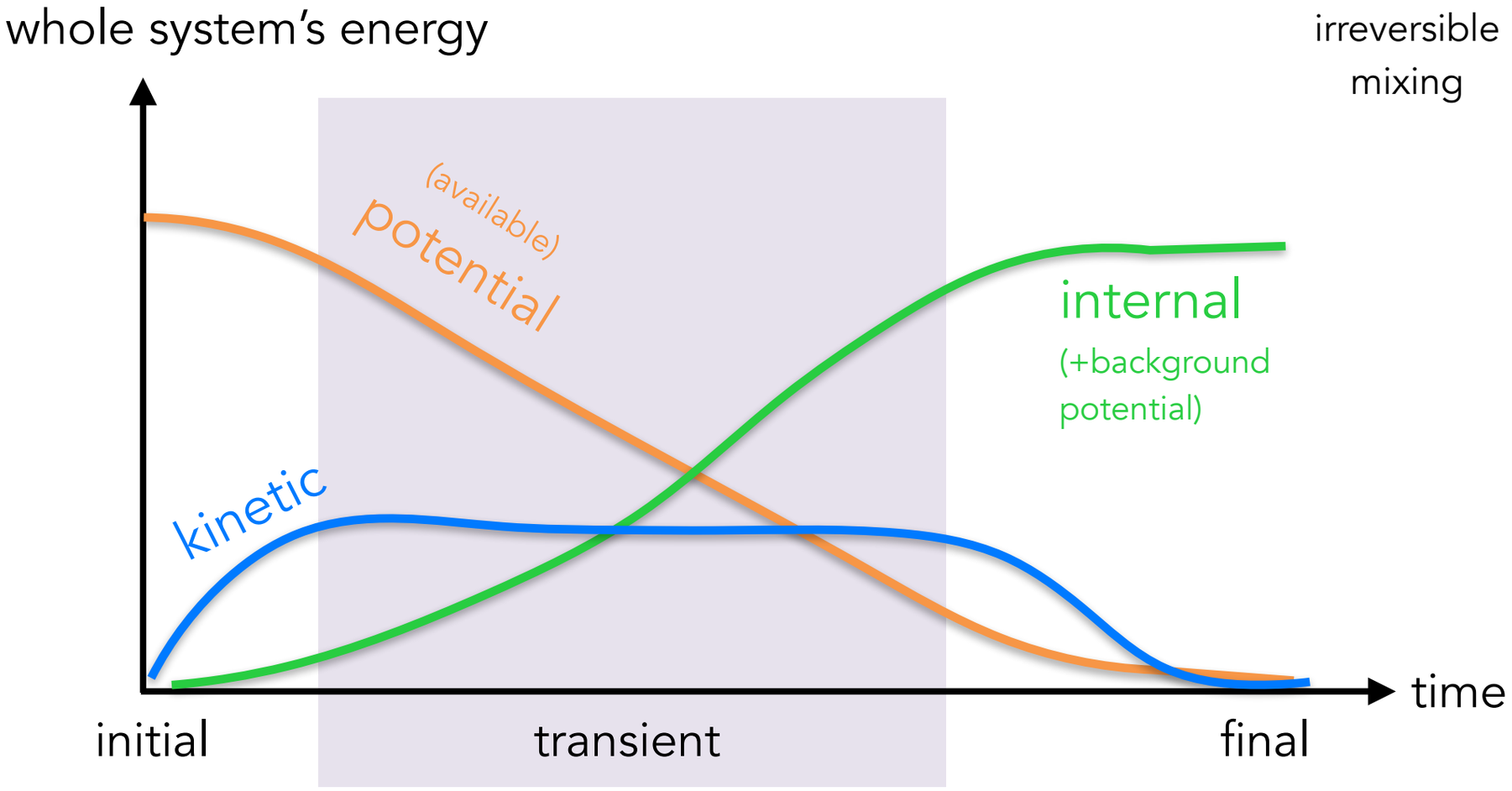


Note: incompressibility enforced by "projecting" data on $\nabla \cdot \mathbf{u} = 0$

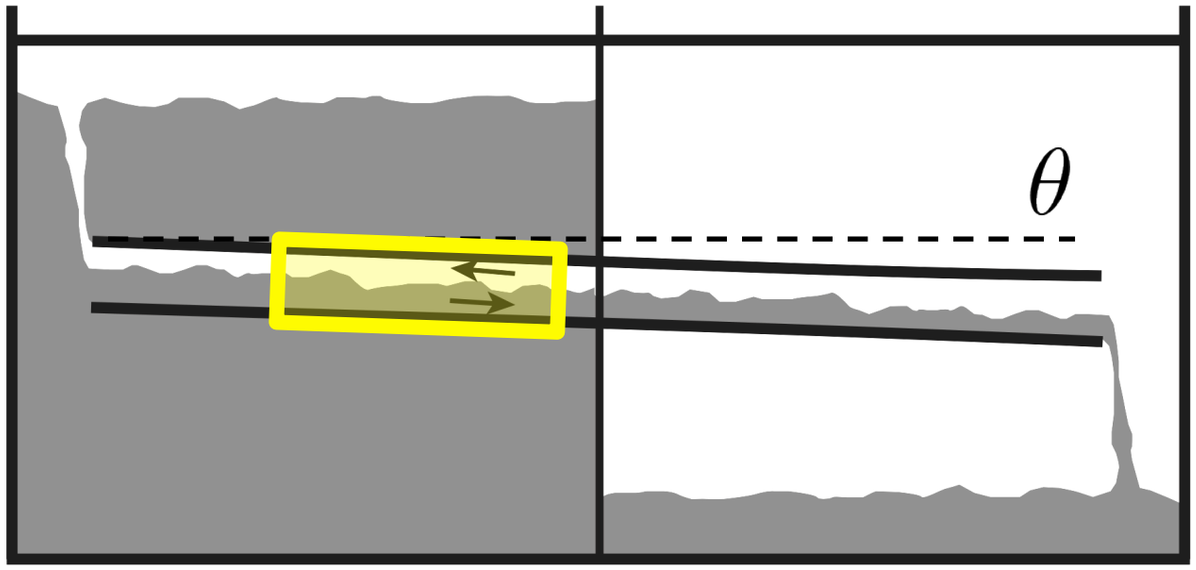
Energetics: overview

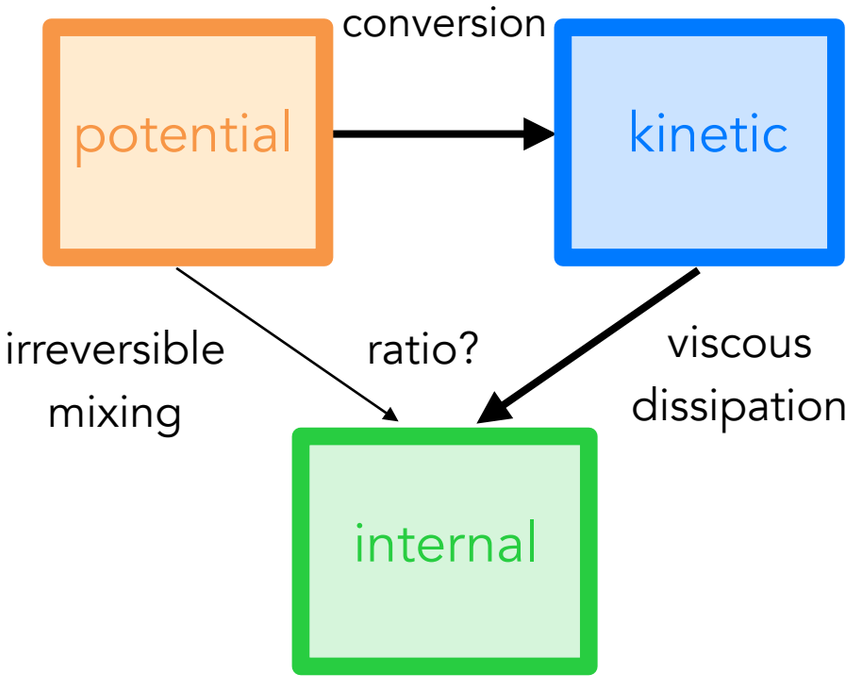


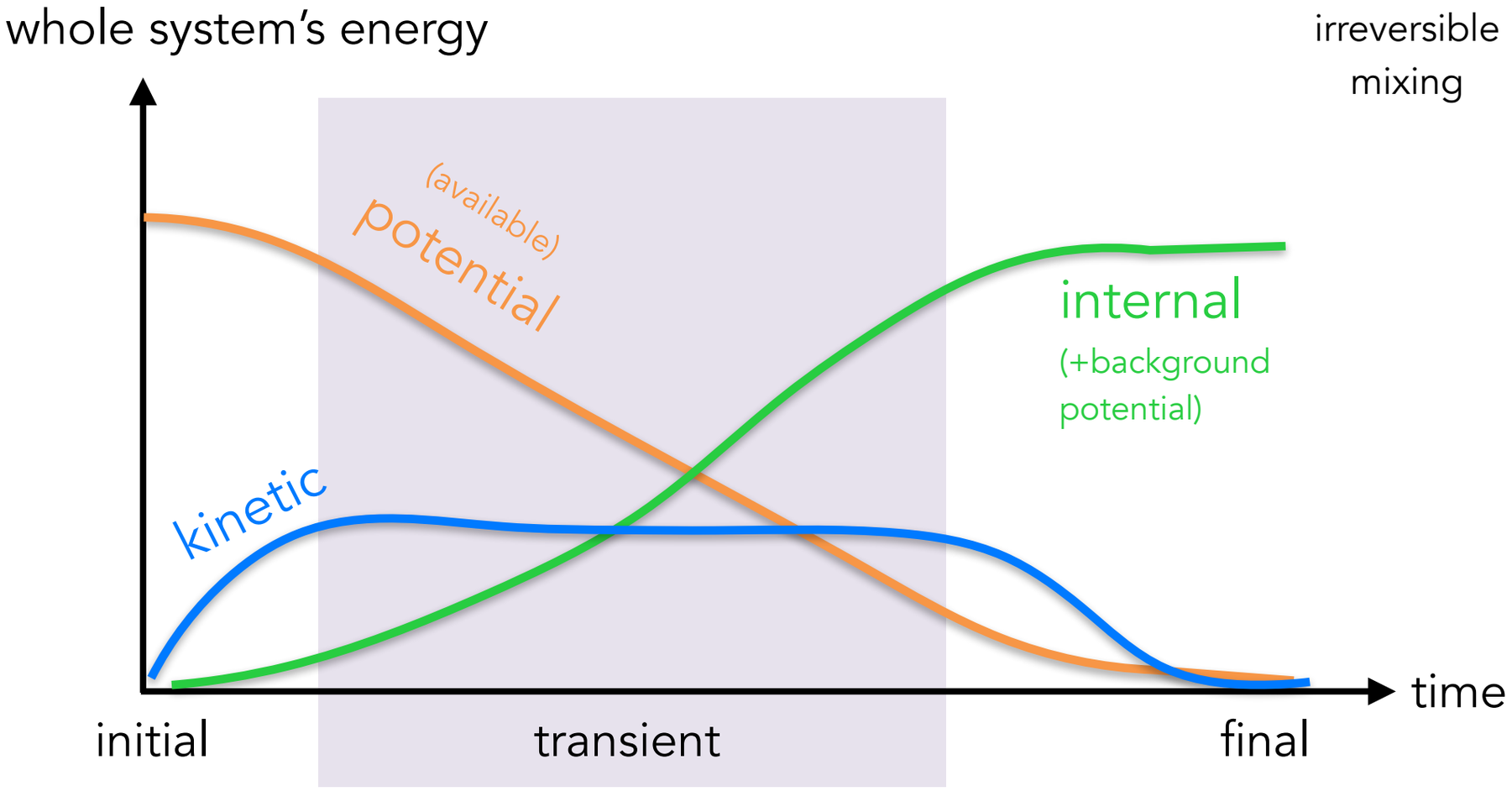




Energetics: overview







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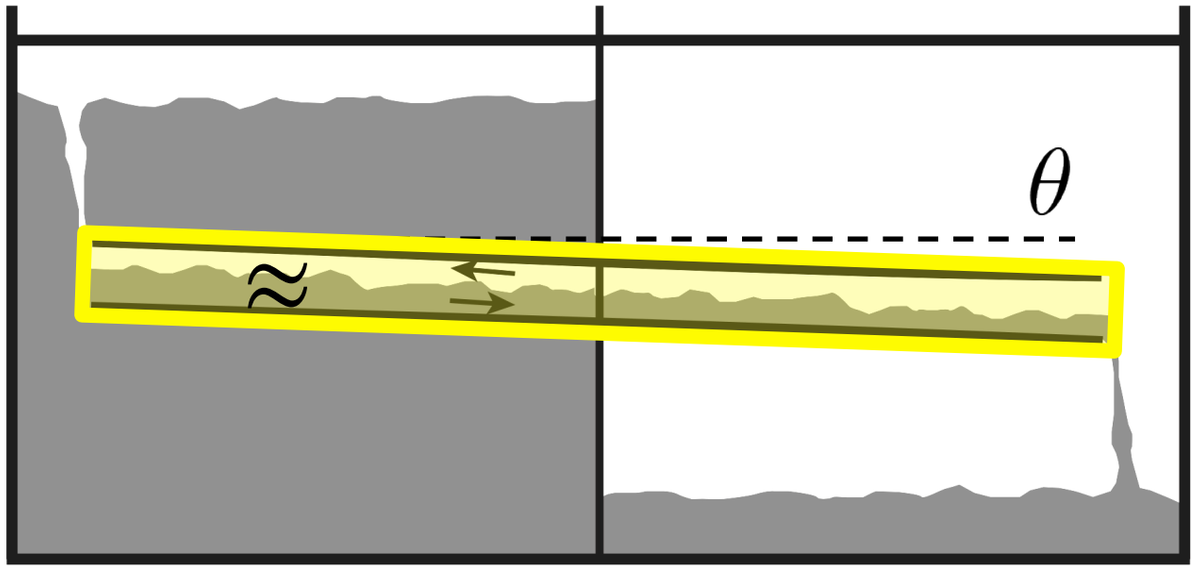
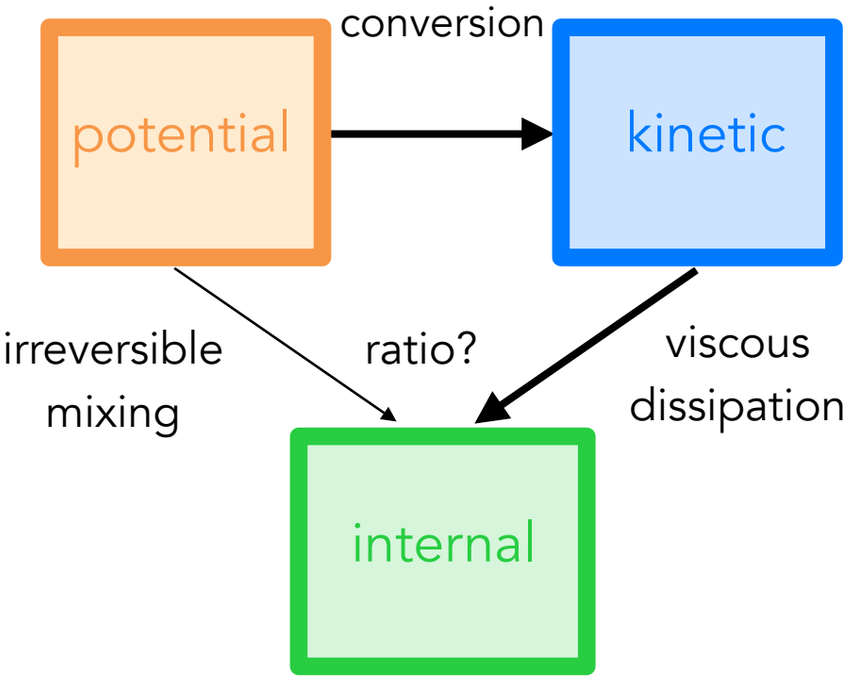
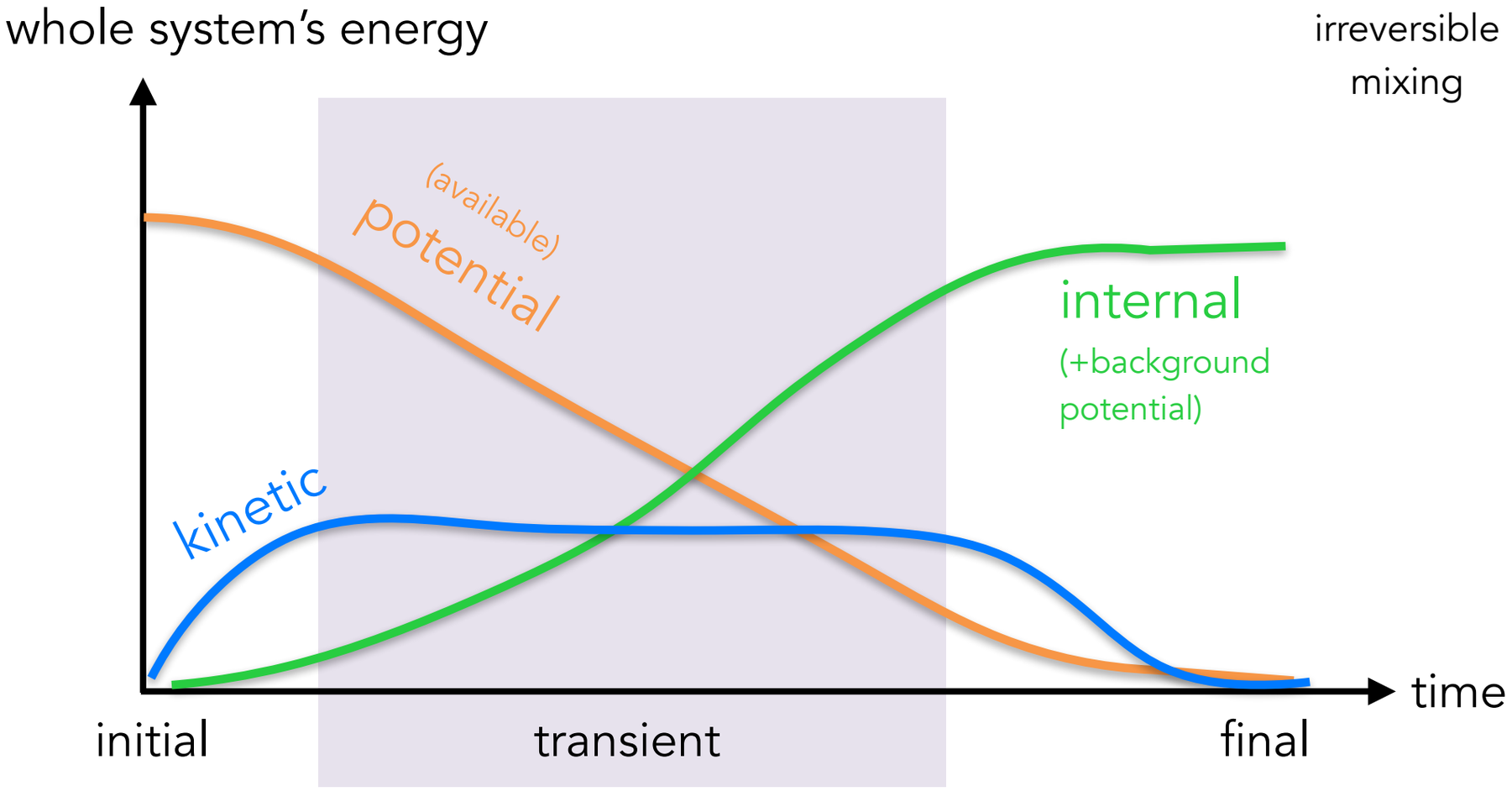
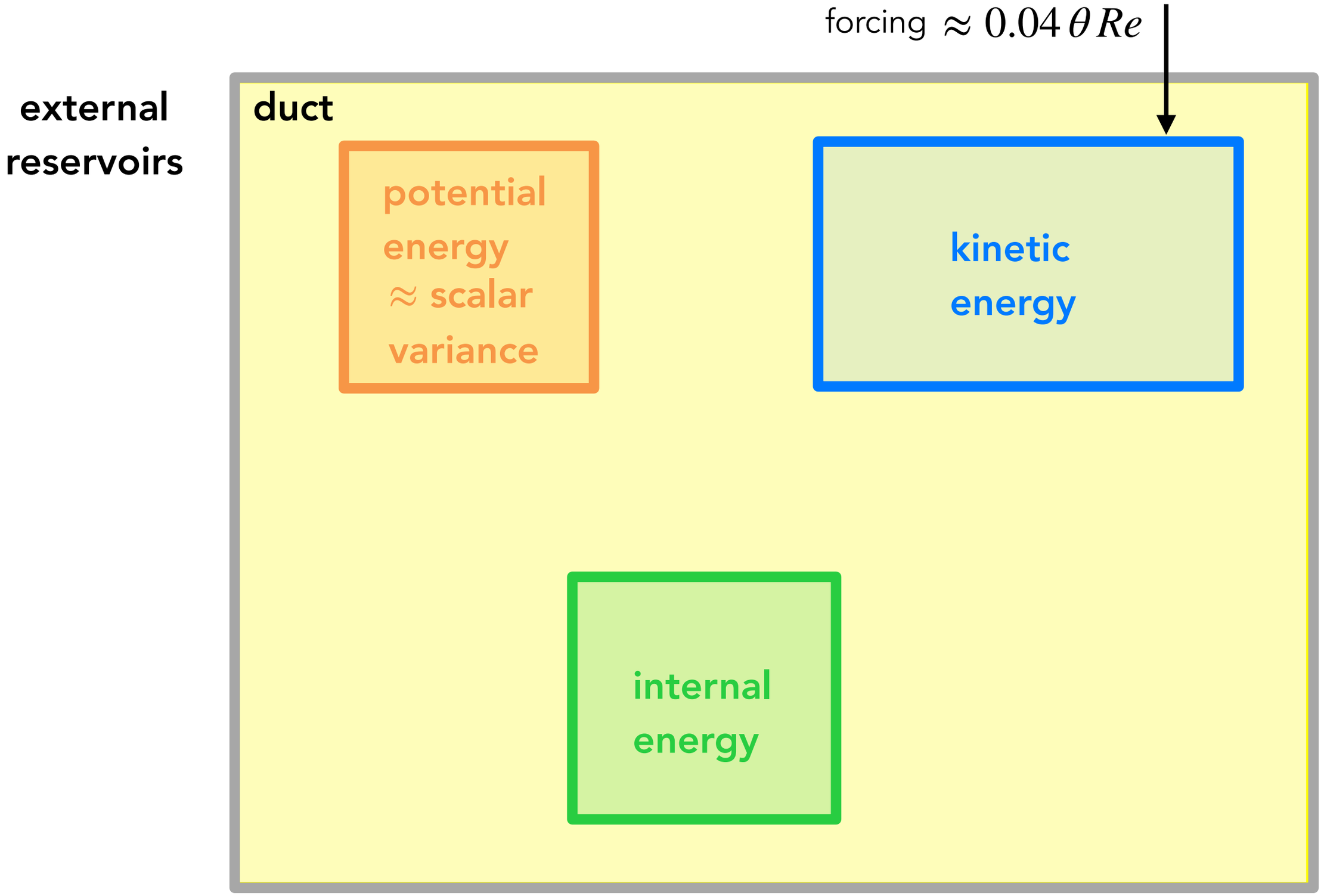






Energetics: basics



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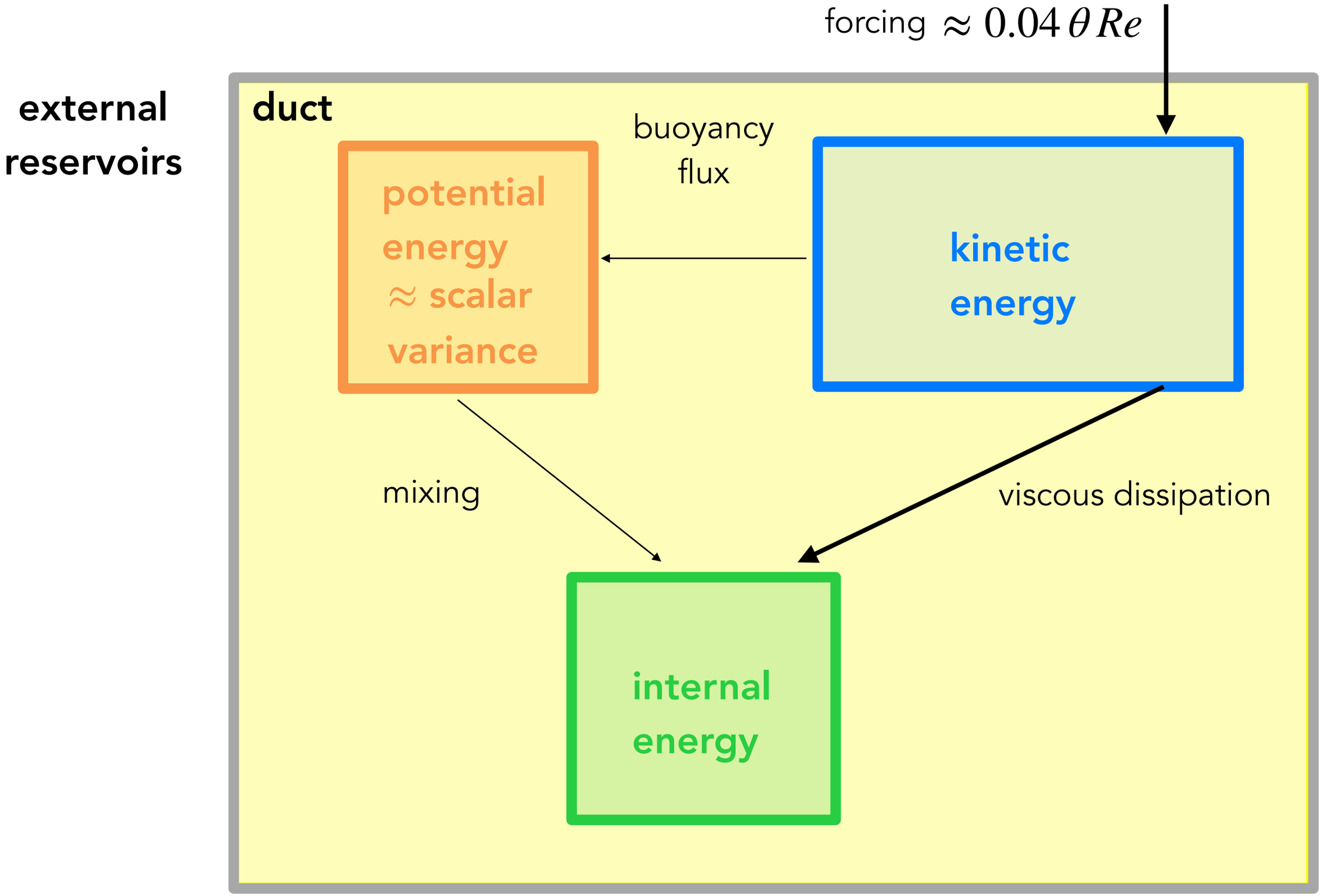
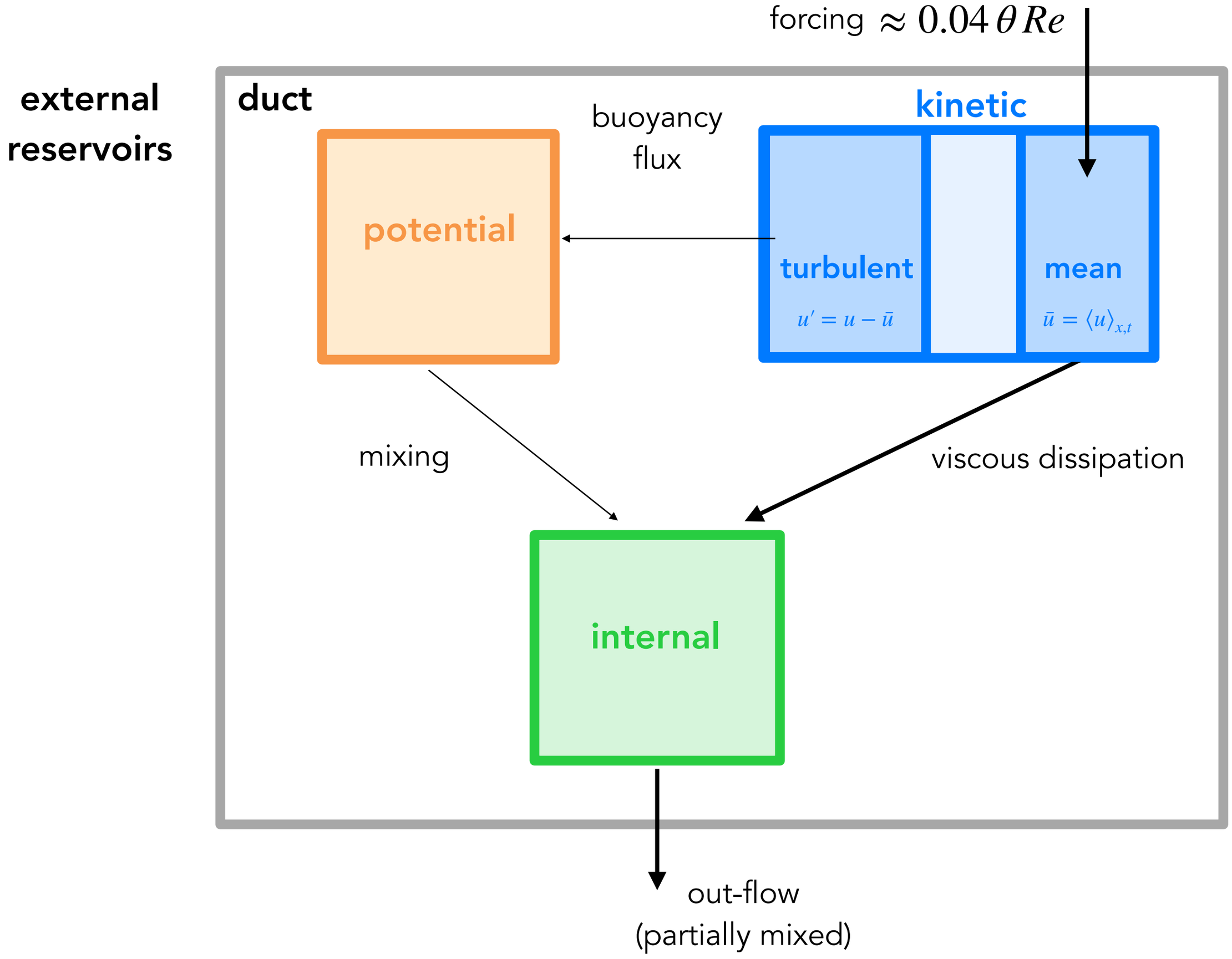
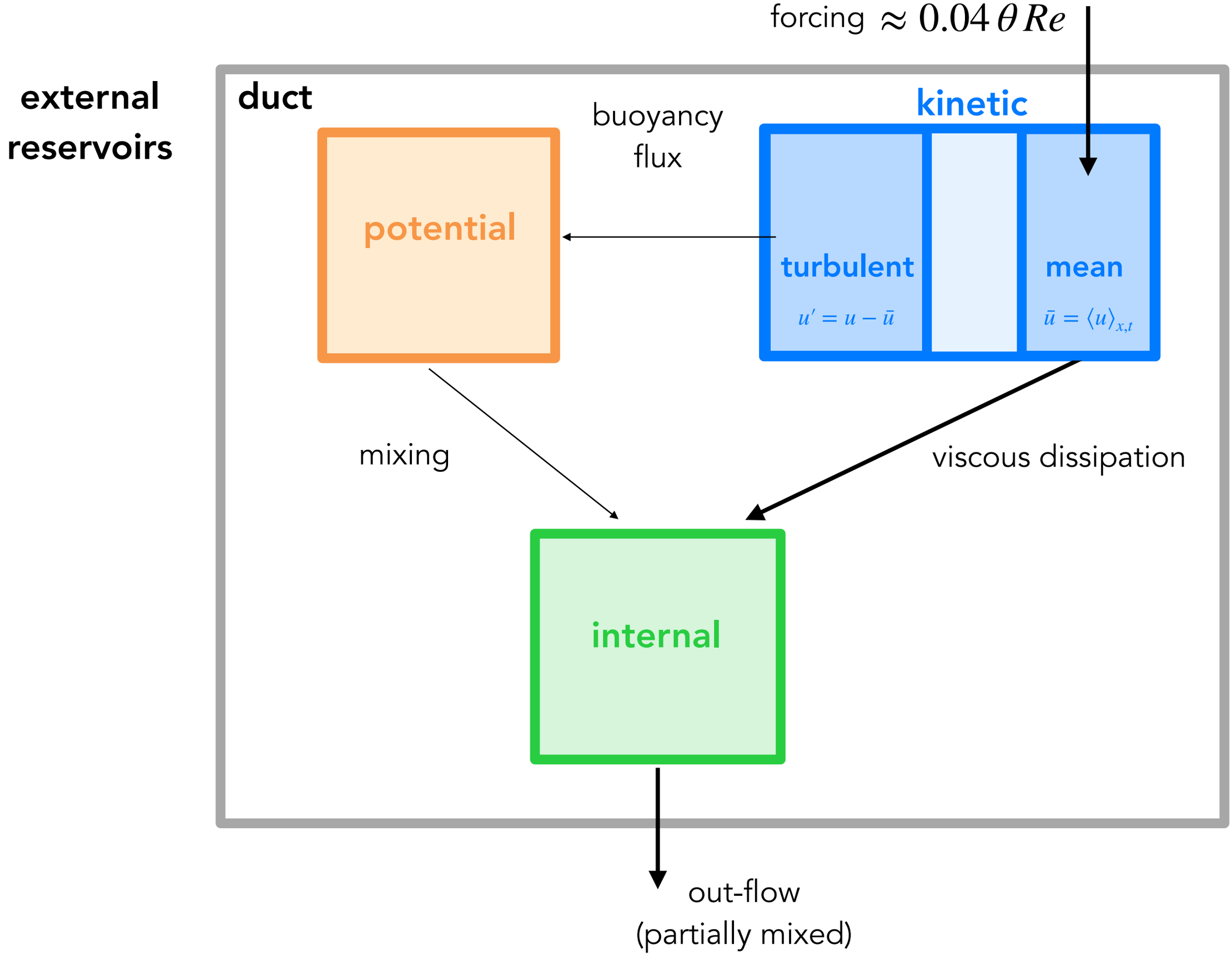


Energetics: mean and turbulent KE



Energetics: increase forcing



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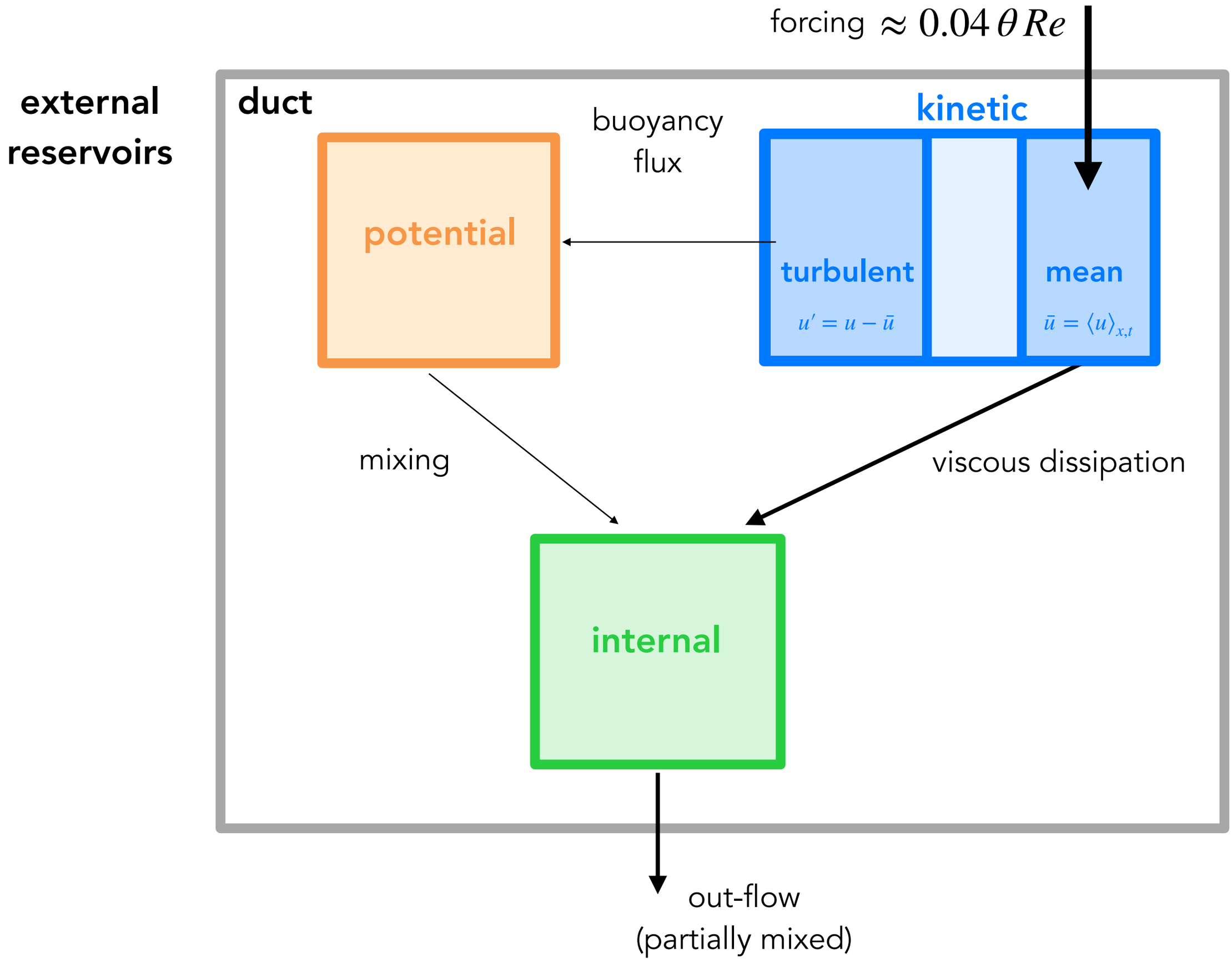

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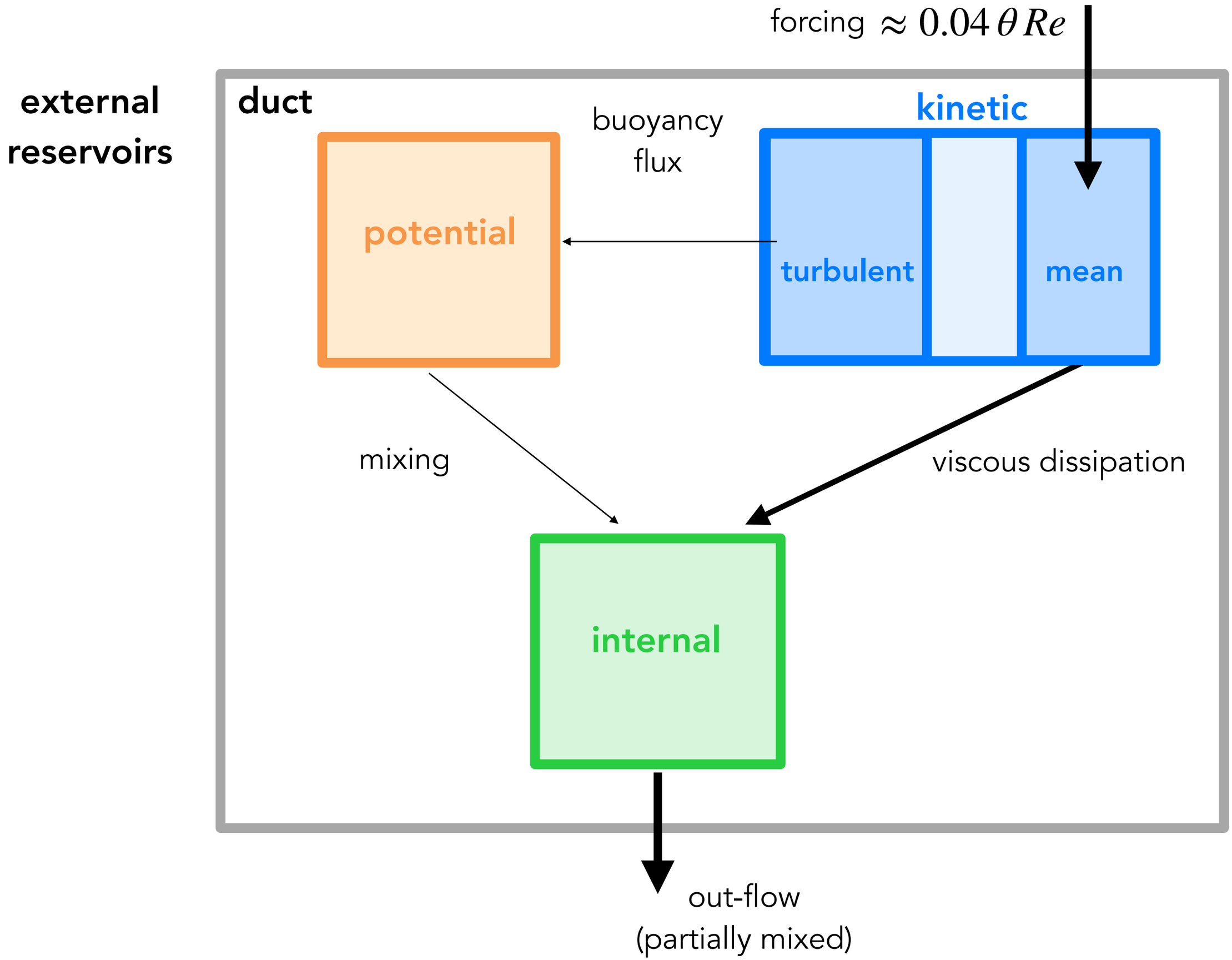

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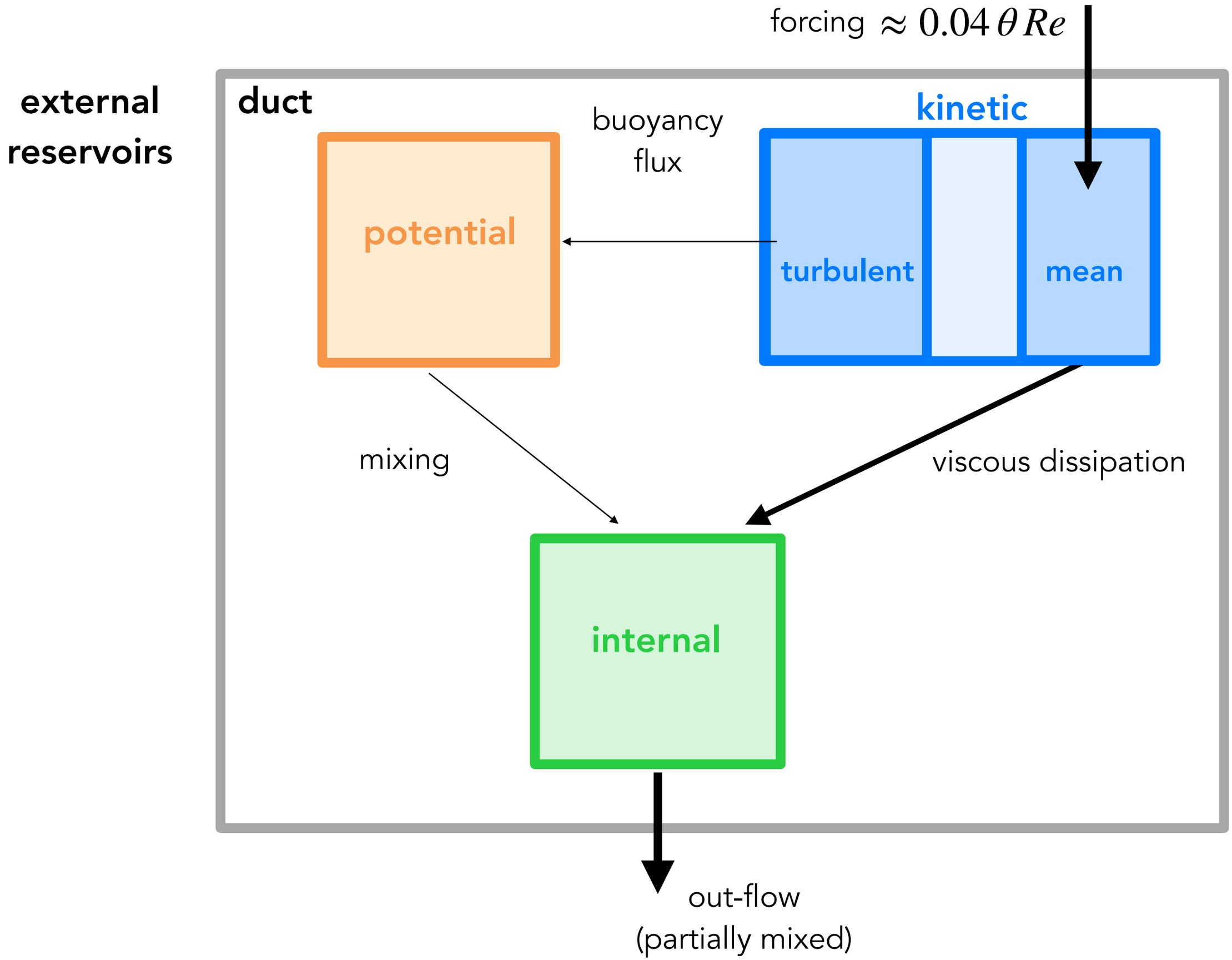

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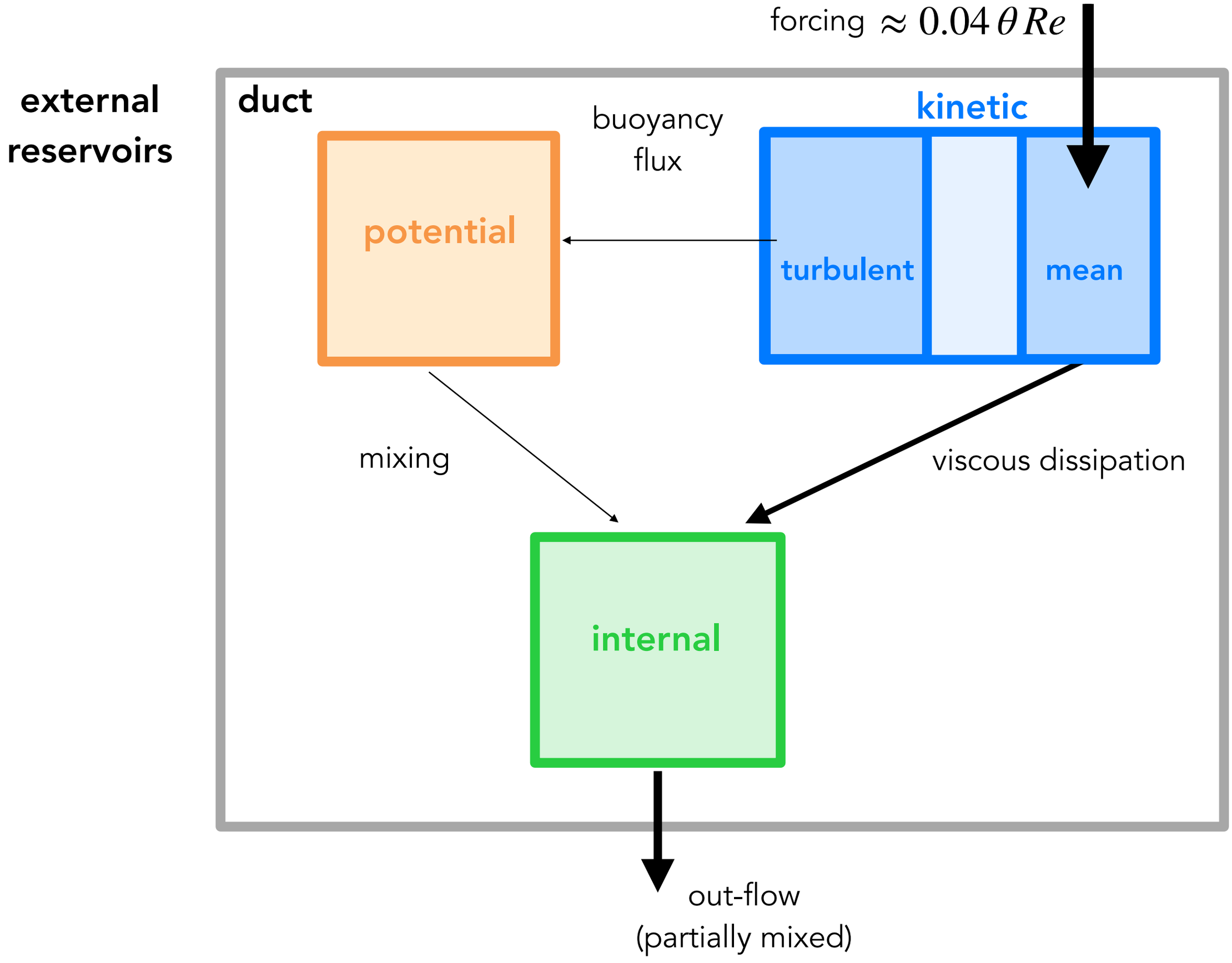
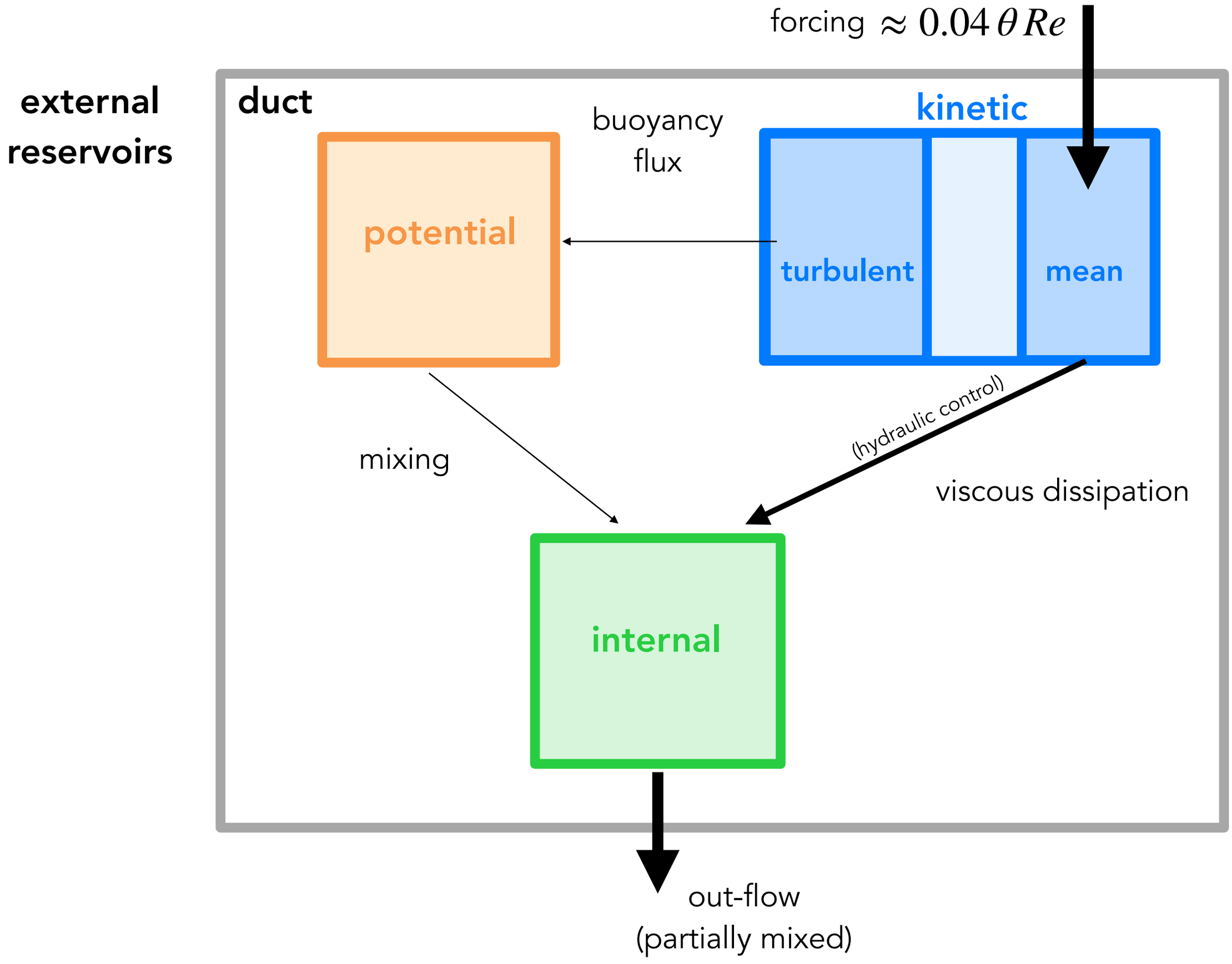
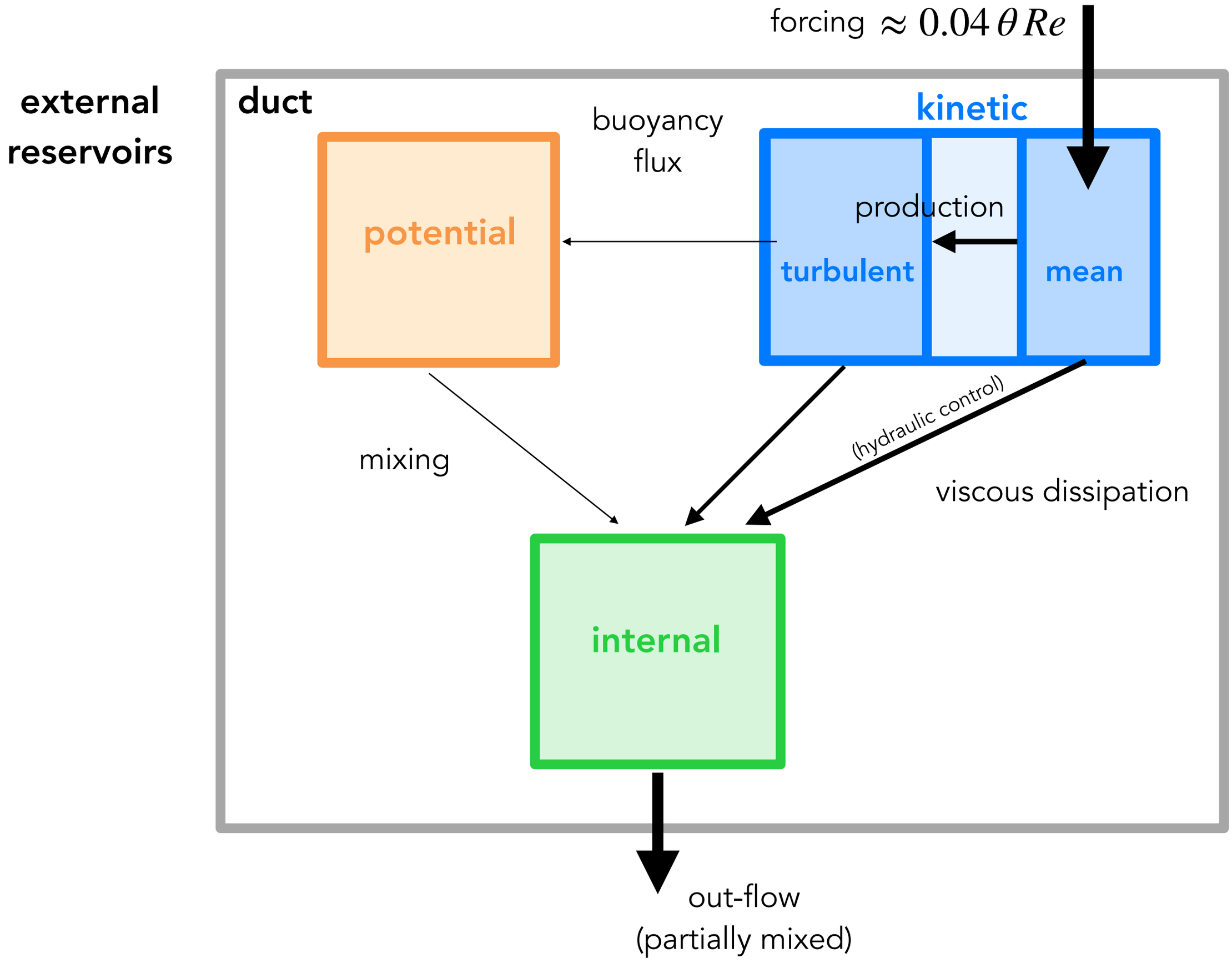


Energetics: towards turbulence



Energetics: towards turbulence



Energetics: towards turbulence

forcing $\approx 0.04\,\theta\,Re$

external reservoirs

duct

potential

buoyancy flux

kinetic

production

turbulent

mean

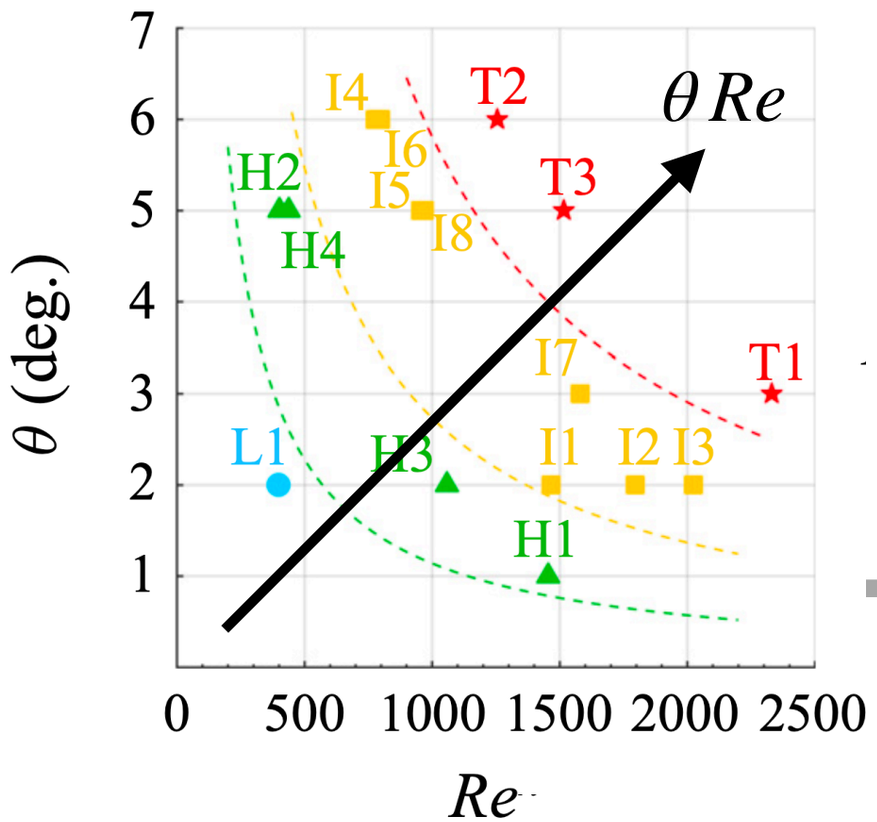
mixing

(hydraulic control)

viscous dissipation

internal

out-flow (partially mixed)



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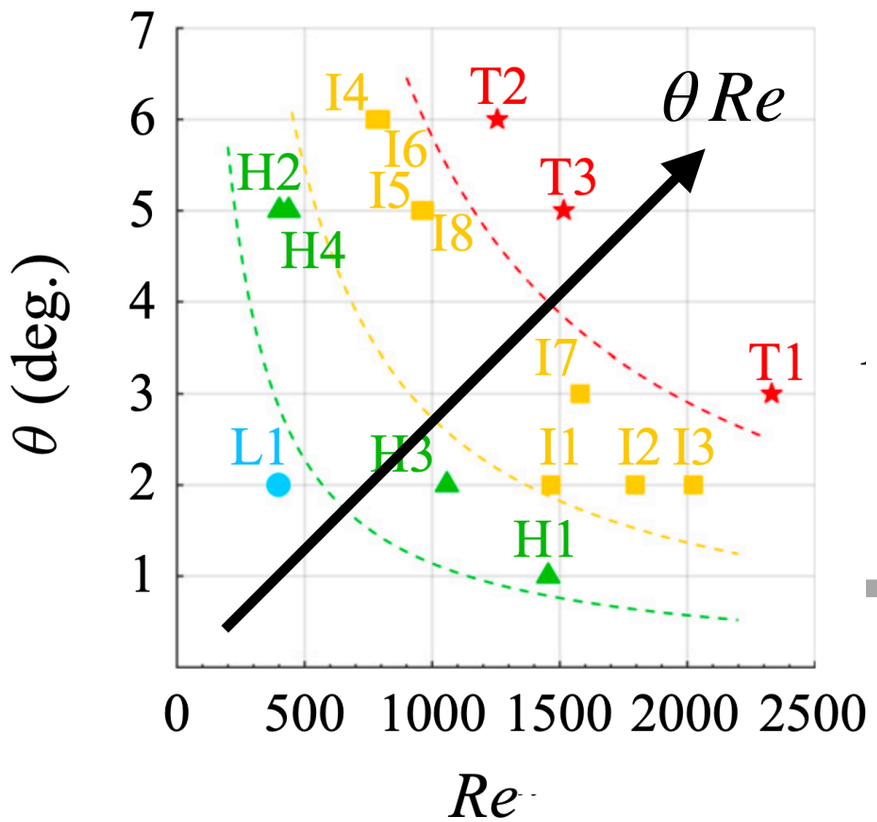

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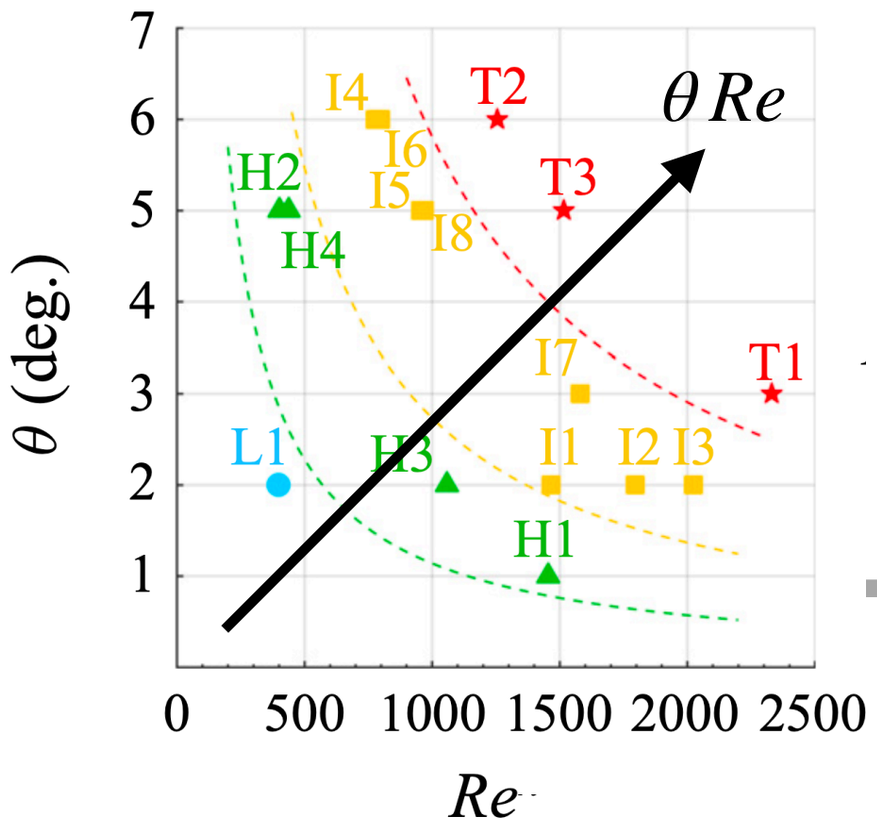


Energetics: turbulence

external reservoirs

duct

forcing $\approx 0.04\,\theta\,Re$

kinetic

potential

turbulent

mean

$\mathscr{B}$

$\mathscr{P}$

$\mathscr{E}$

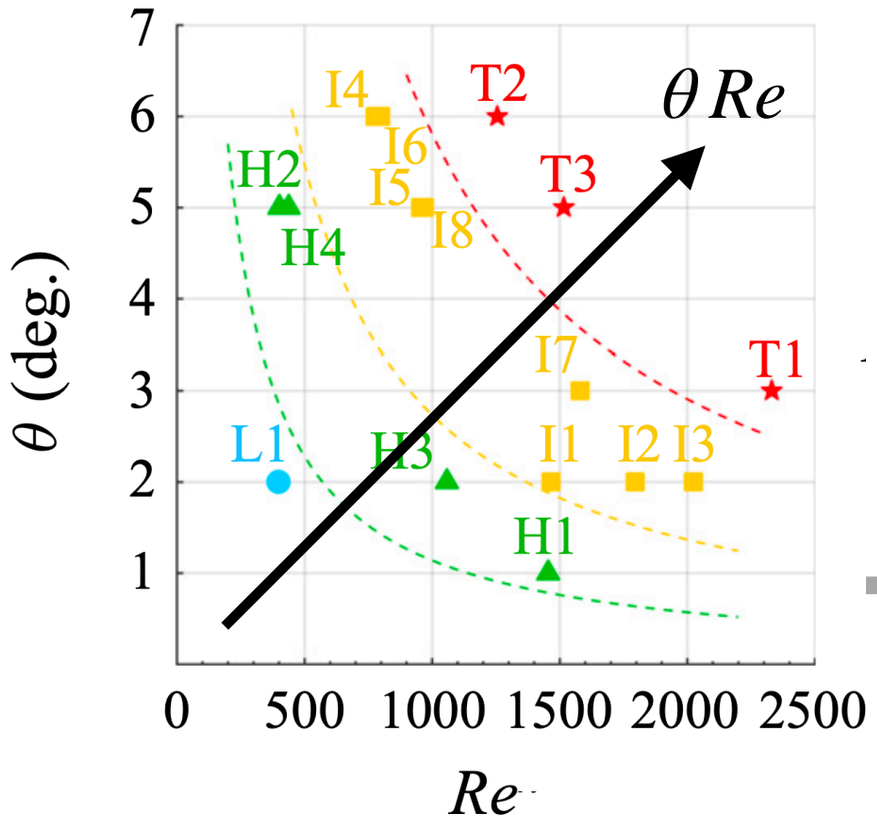
χ

(hydraulic control)

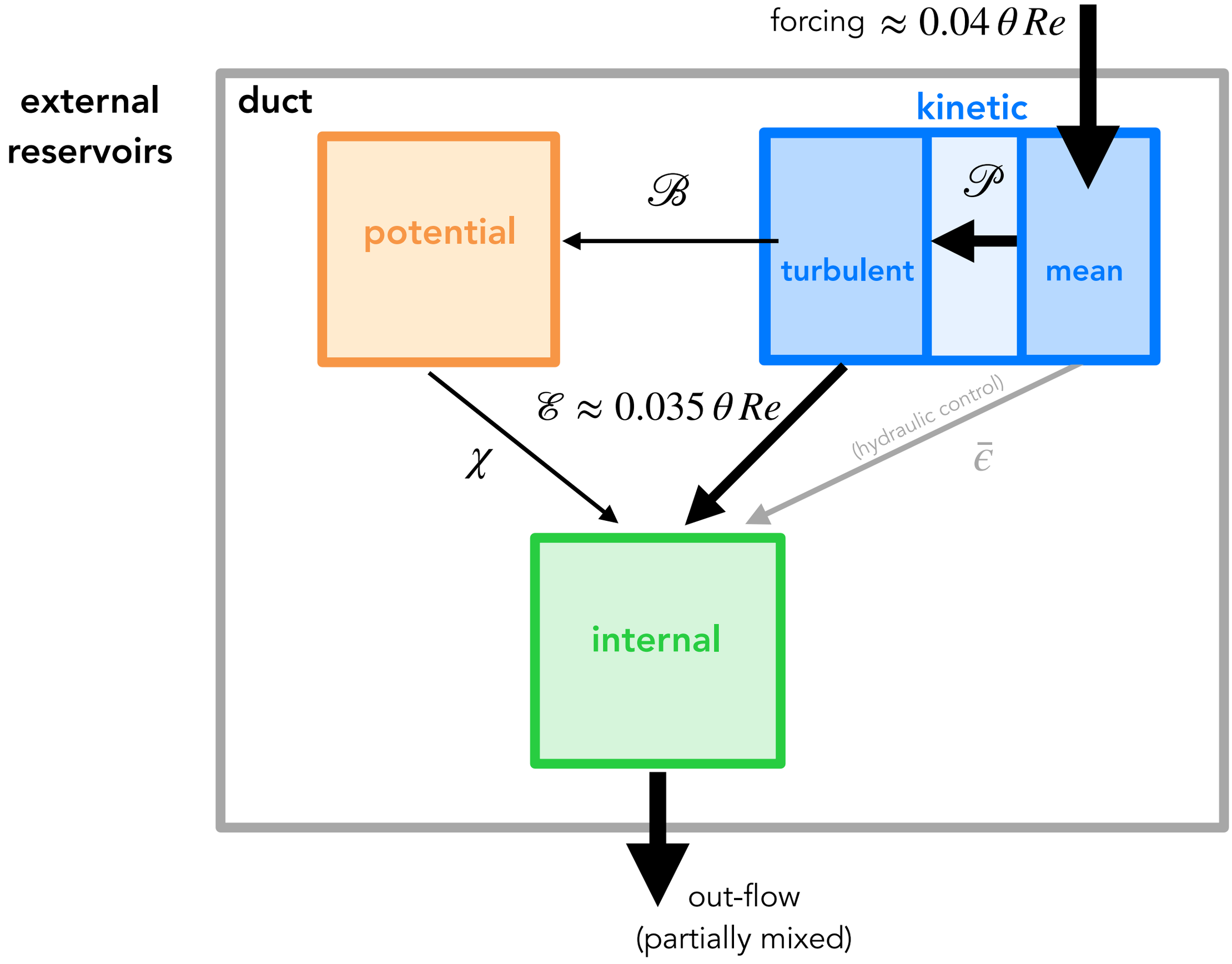
$\bar{\epsilon}$

internal

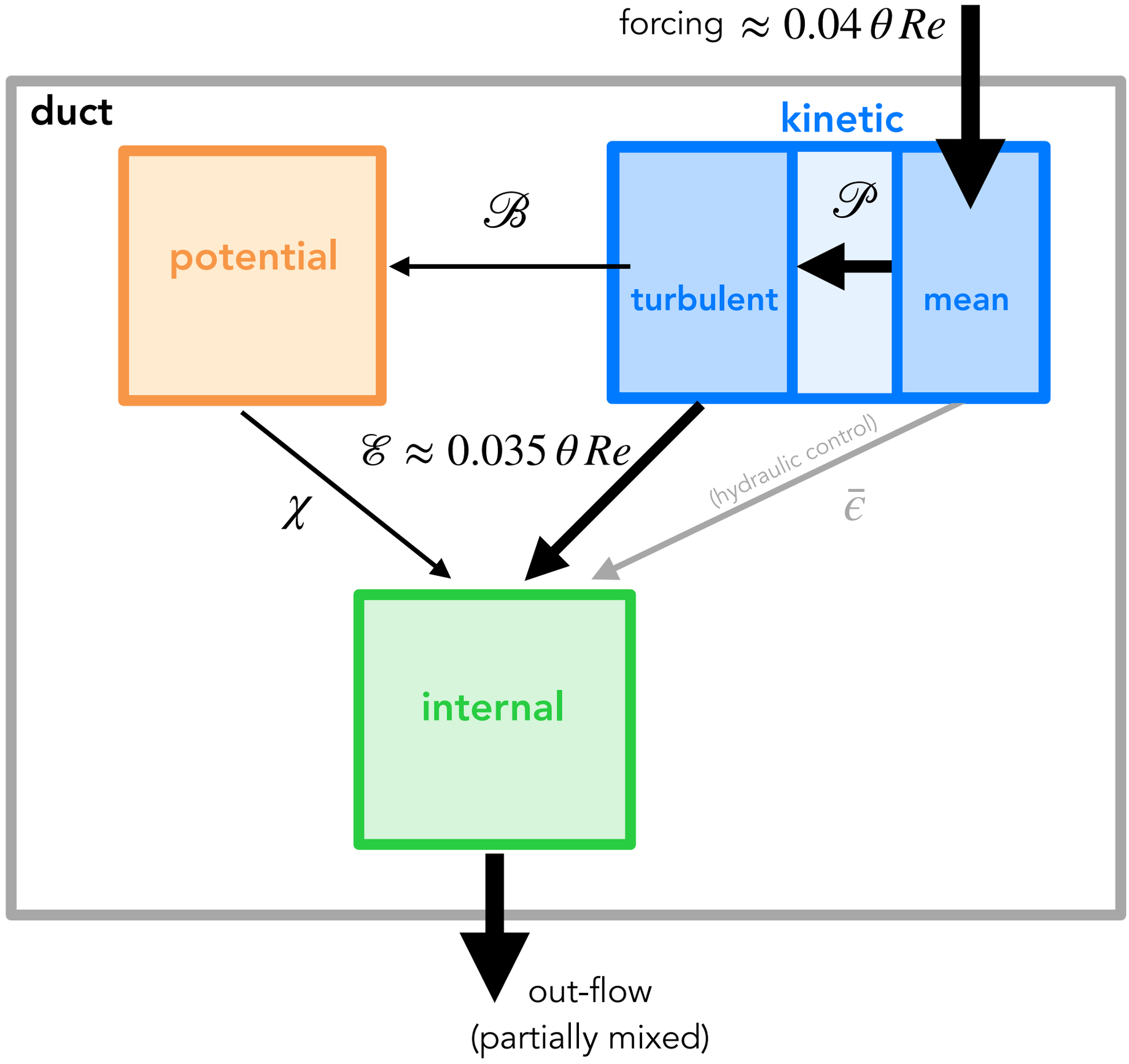
out-flow
(partially mixed)



Energetics: turbulence



Energetics: asymptotic turbulence



Key flux ratios for "mixing"

$$\Gamma = \frac{\mathscr{B}}{\mathscr{E}} \approx \frac{\chi}{\mathscr{E}}$$

$$R_f = \frac{\mathscr{B}}{\mathscr{P}}$$

Energetics: asymptotic turbulence

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external reservoirs

forcing $\approx 0.04\,\theta\,Re$

duct

kinetic

potential

$\mathscr{B}$

$\mathscr{P}$

turbulent

mean

$\mathscr{E} \approx 0.035\,\theta\,Re$

(hydraulic control)

χ

$\bar{\epsilon}$

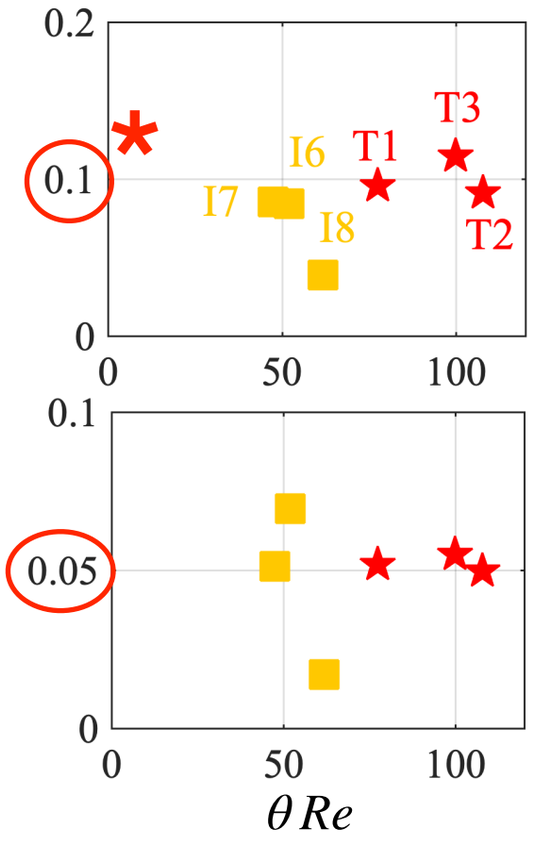
internal

out-flow
(partially mixed)

Key flux ratios for "mixing"

$$\Gamma = \frac{\mathscr{B}}{\mathscr{E}} \approx \frac{\chi}{\mathscr{E}}$$

$$R_f = \frac{\mathscr{B}}{\mathscr{P}}$$



Energetics: asymptotic turbulence

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external reservoirs

forcing $\approx 0.04\,\theta\,Re$

duct

kinetic

potential

$\mathscr{B}$

$\mathscr{P}$

turbulent

mean

$\mathscr{E} \approx 0.035\,\theta\,Re$

χ

(hydraulic control)

$\bar{\epsilon}$

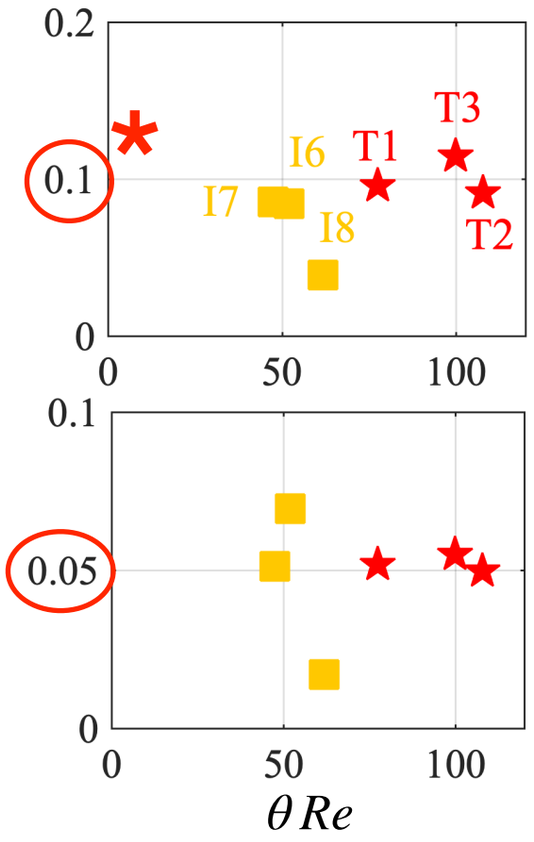
internal

out-flow
(partially mixed)

Key flux ratios for "mixing"

$$\Gamma = \frac{\mathscr{B}}{\mathscr{E}^*} \approx \frac{\chi}{\mathscr{E}}$$

$$R_f = \frac{\mathscr{B}}{\mathscr{P}}$$



To find out more…

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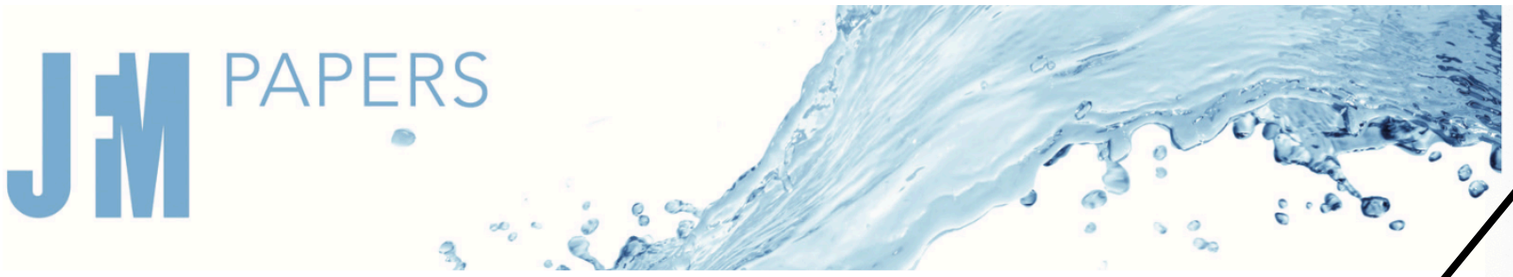
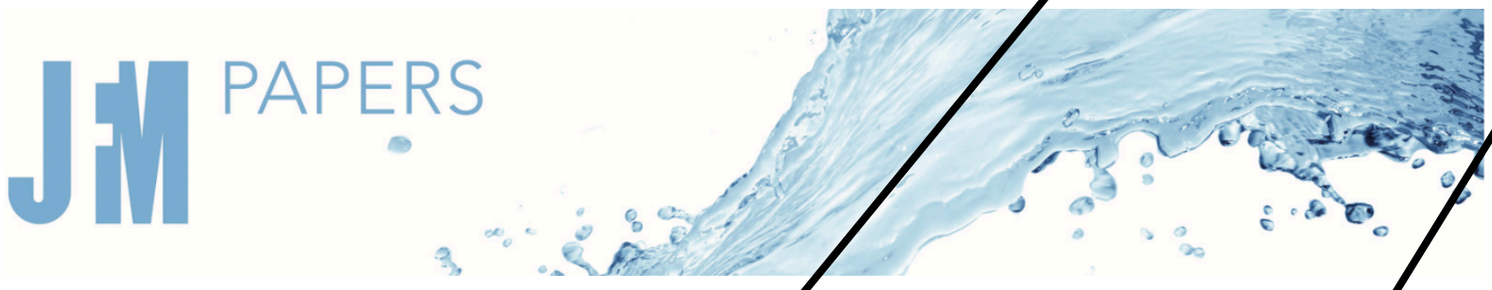
Lefauve & Linden (2022) JFM, **937**, A34 & A35



Experimental properties of continuously forced, shear-driven, stratified turbulence. Part 1. Mean flows, self-organisation, turbulent fractions



Experimental properties of continuously forced, shear-driven, stratified turbulence. Part 2. Energetics, anisotropy, parameterisation

Tested dissipation surrogates:

$$\langle \mathcal{E} \rangle \approx \begin{cases} \dfrac{15}{Re^s} \langle (\partial_{x_i} u_i')^2 \rangle \\ \dfrac{15}{2Re^s} \langle (\partial_{x_i} u_j')^2 \rangle, \quad i \neq j \\ -\dfrac{30}{Re^s} \langle \partial_{x_i} u_j' \partial_{x_j} u_i' \rangle, \quad i \neq j \end{cases}$$

Tested flux-gradient models:

eddy diffusivity?

$$\overline{u'w'} = \nu_T \, \partial_z \bar{u}$$

$$= L_m^2 \, (\partial_z \bar{u})^2$$

mixing length?

$$\overline{w'\rho'} = \kappa_T \, \partial_z \bar{\rho}$$

$$= L_\rho^2 \, \partial_z \bar{u} \, \partial_z \bar{\rho}$$

Turbulent Prandtl $Pr_T = \dfrac{\nu_T}{\kappa_T} \approx 3$