

Stratified Inclined Duct

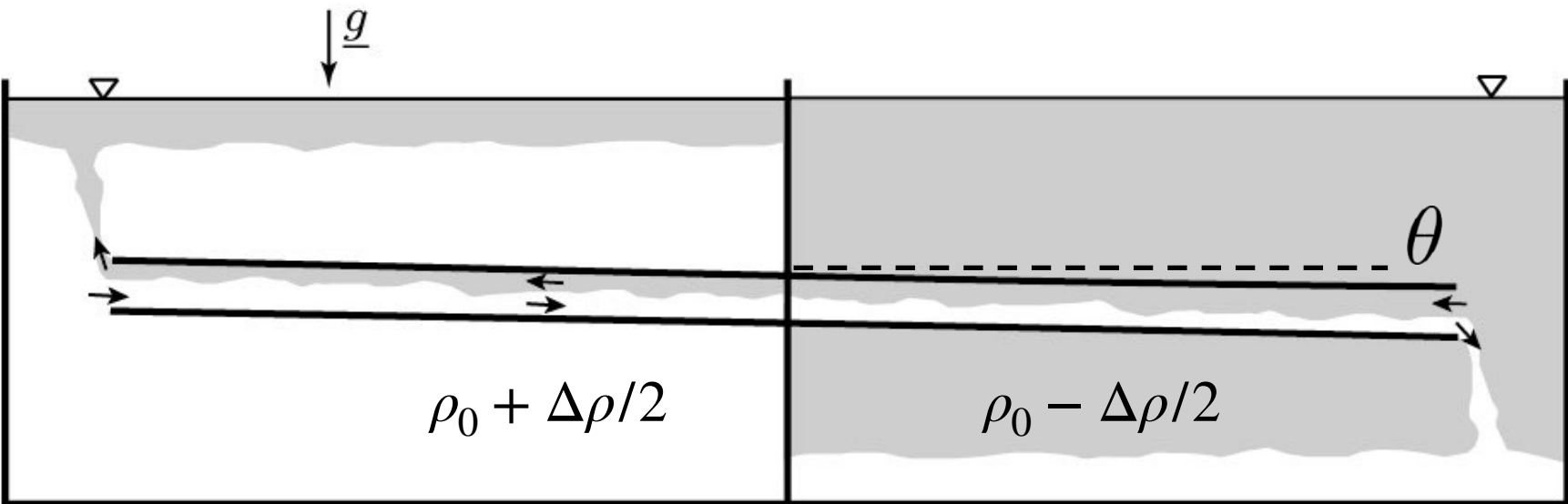
Adrien Lefauve
et al.:
Jamie Partridge
Qi Zhou
Stuart Dalziel
Colm Caulfield
Paul Linden
Xianyang Jiang

What is it all about?

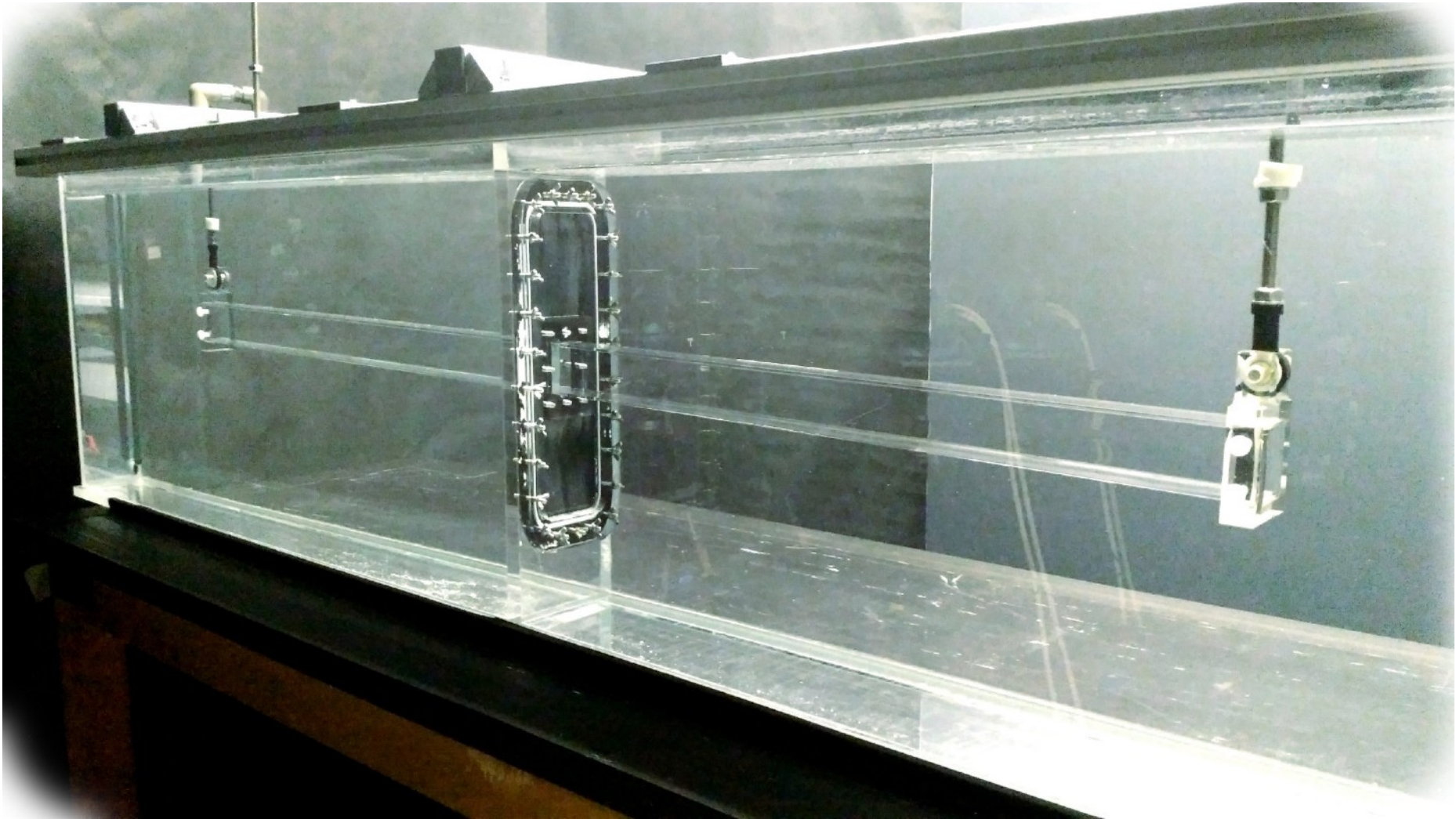
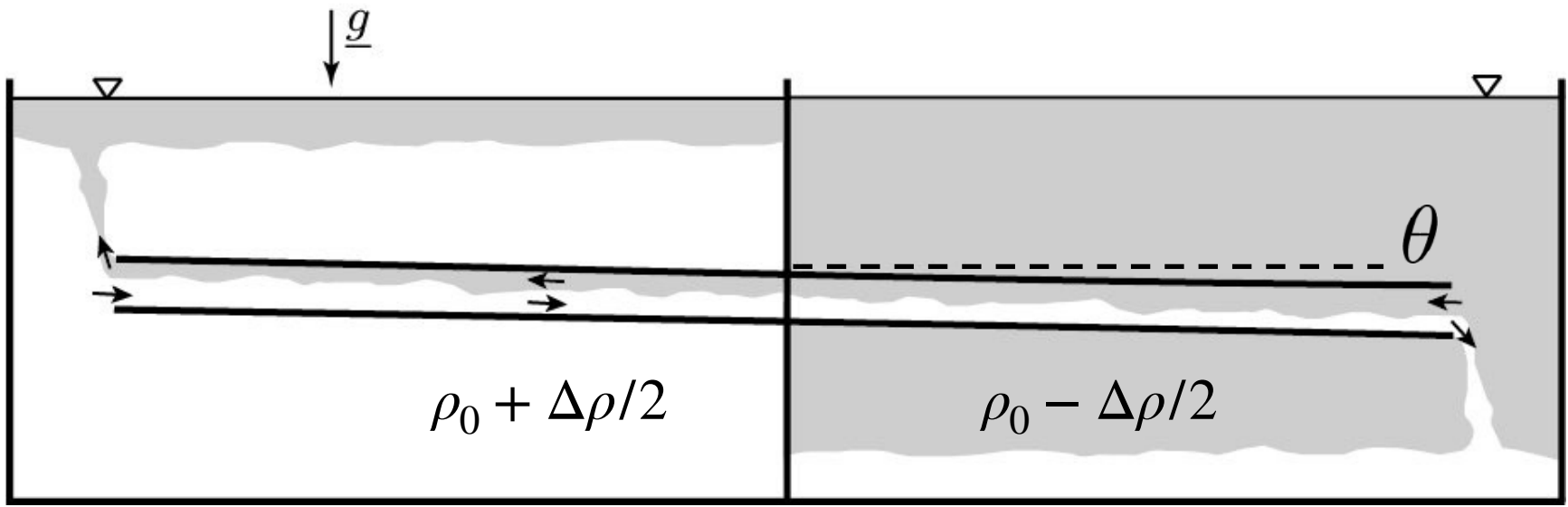
GKB lab lunch

12 June 2021

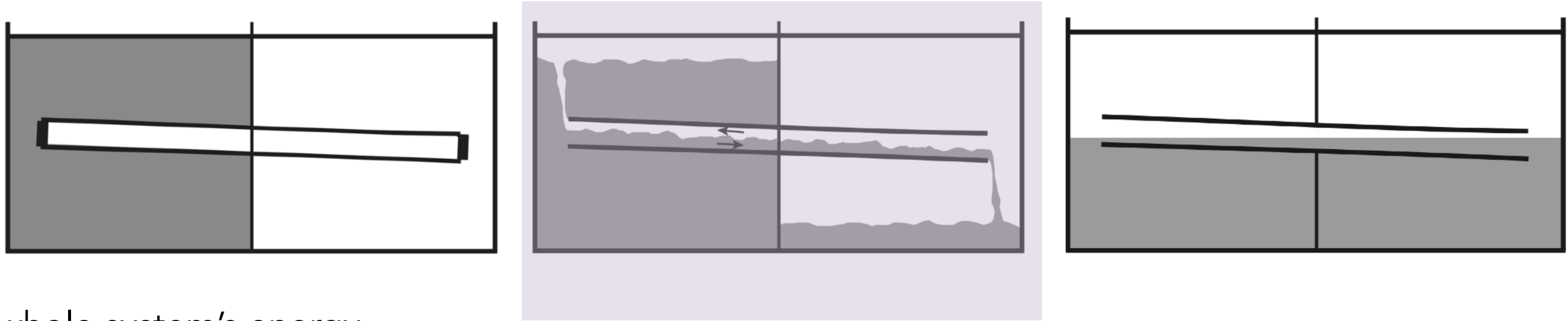
The Stratified Inclined Duct (SID)



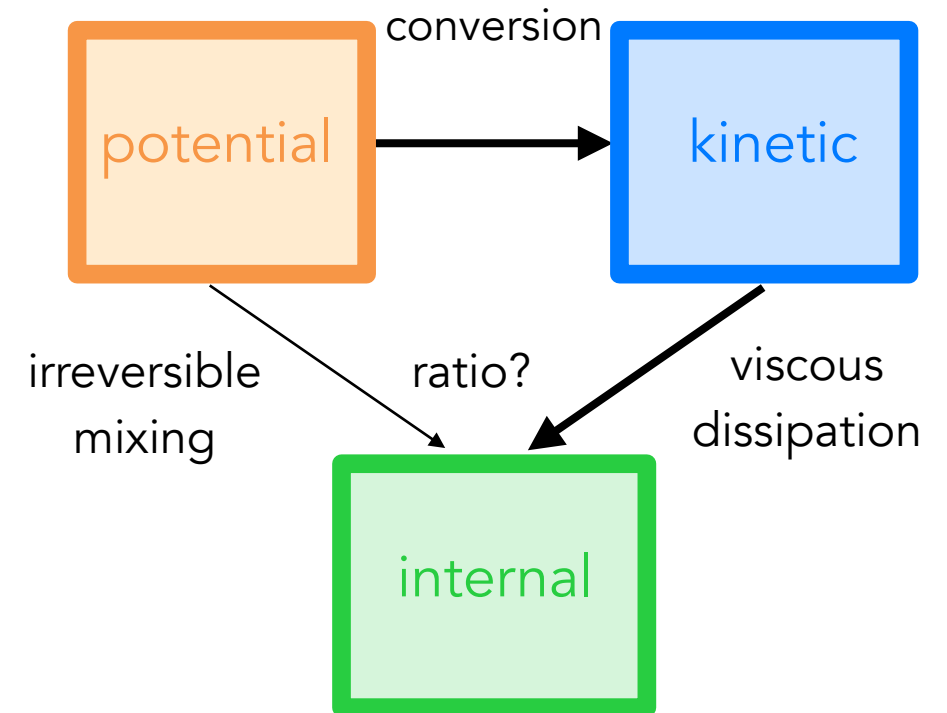
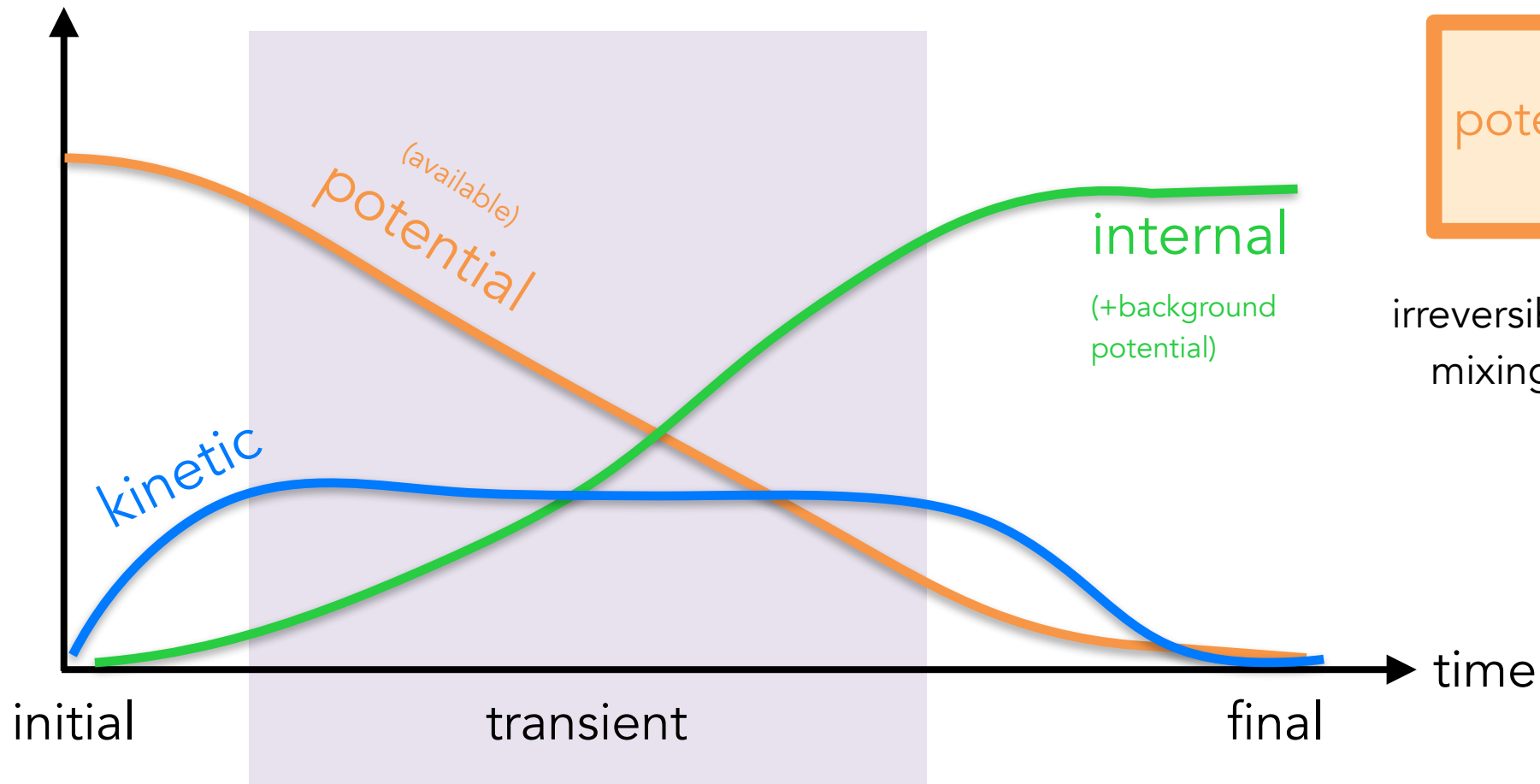
The Stratified Inclined Duct (SID)



The physics



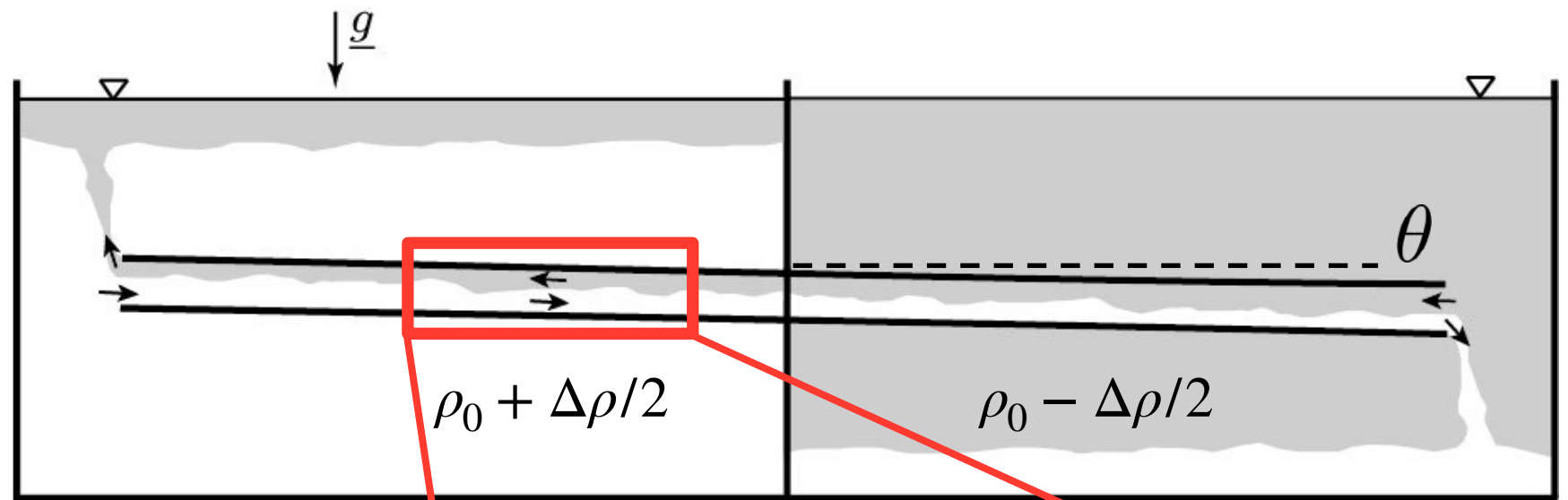
whole system's energy



Focus: "temporary steady state"

Goal: Study **mixing** in a **simple** but **realistic stratified shear flow**

The mathematics



Isolate the flow inside the duct

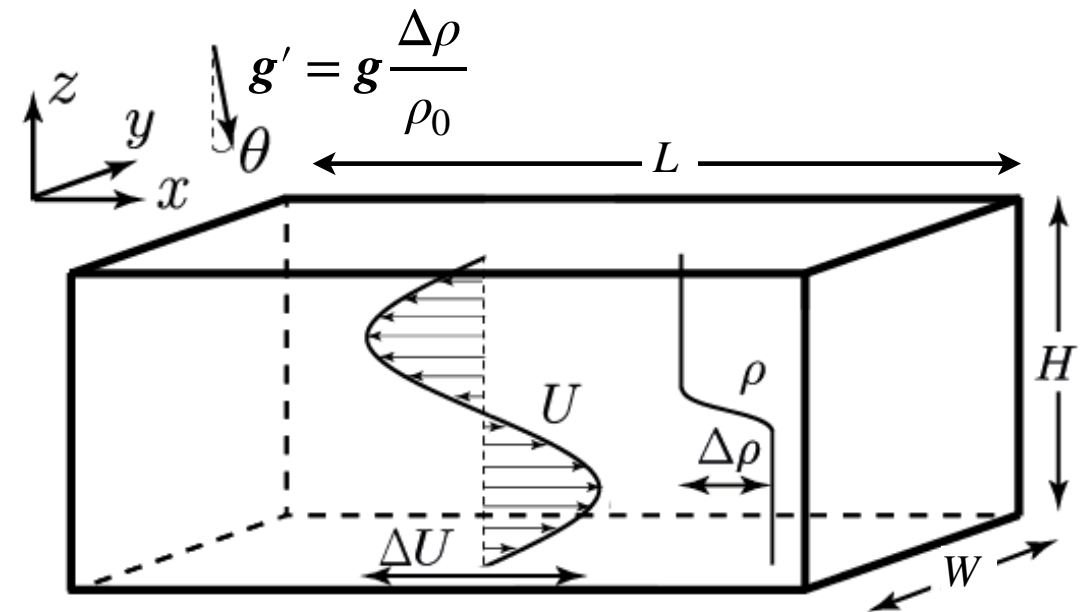
$$\nabla \cdot \mathbf{u} = 0$$

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

$\propto \frac{g'H}{(\Delta U)^2}$ stratification/shear tilt
inertia/viscosity

$$\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho = \frac{1}{Re Pr} \nabla^2 \rho \quad \propto \frac{\Delta U H}{\nu}$$

diffusion ratio
 $= \frac{\nu}{\kappa}$

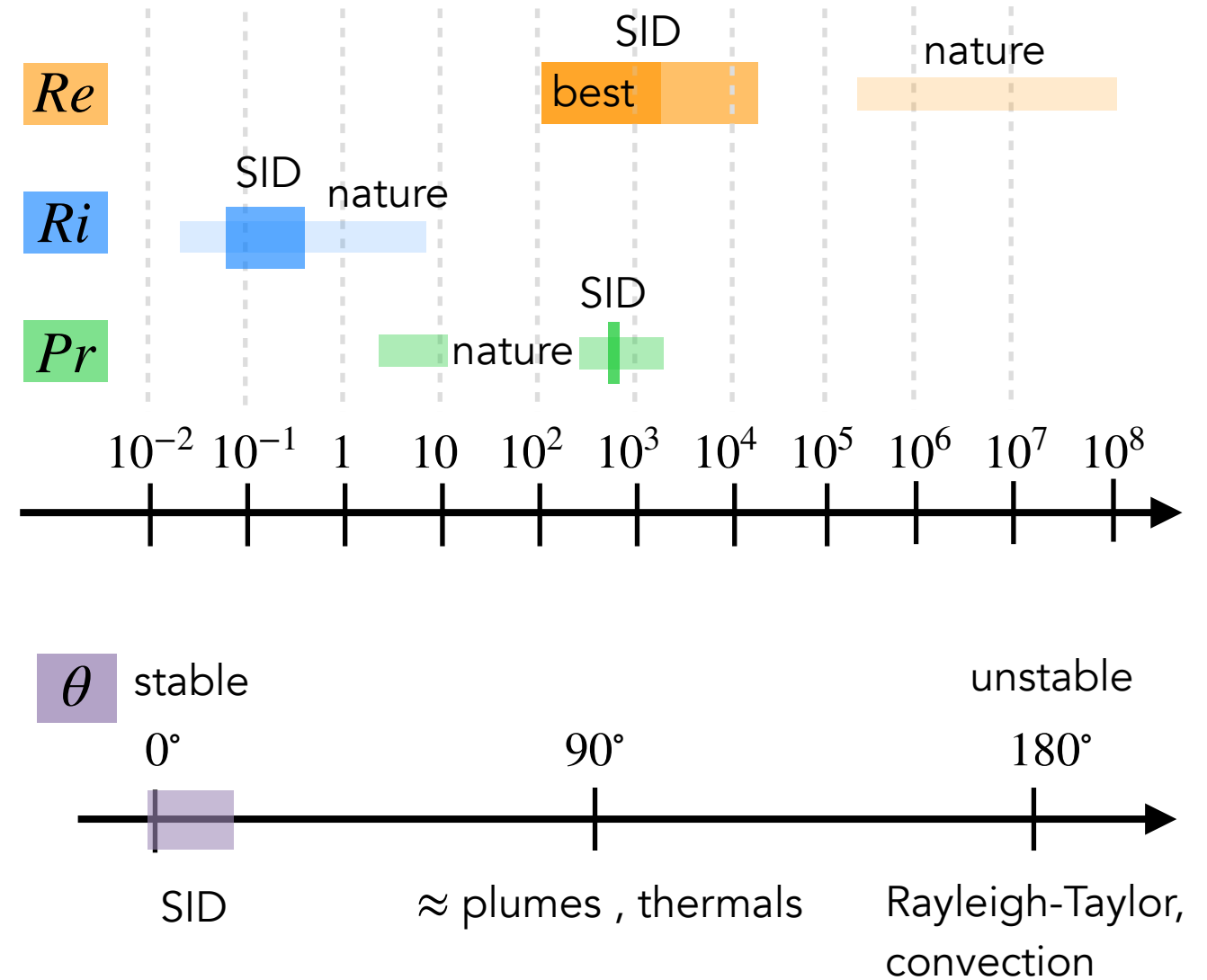


Parameters of SID

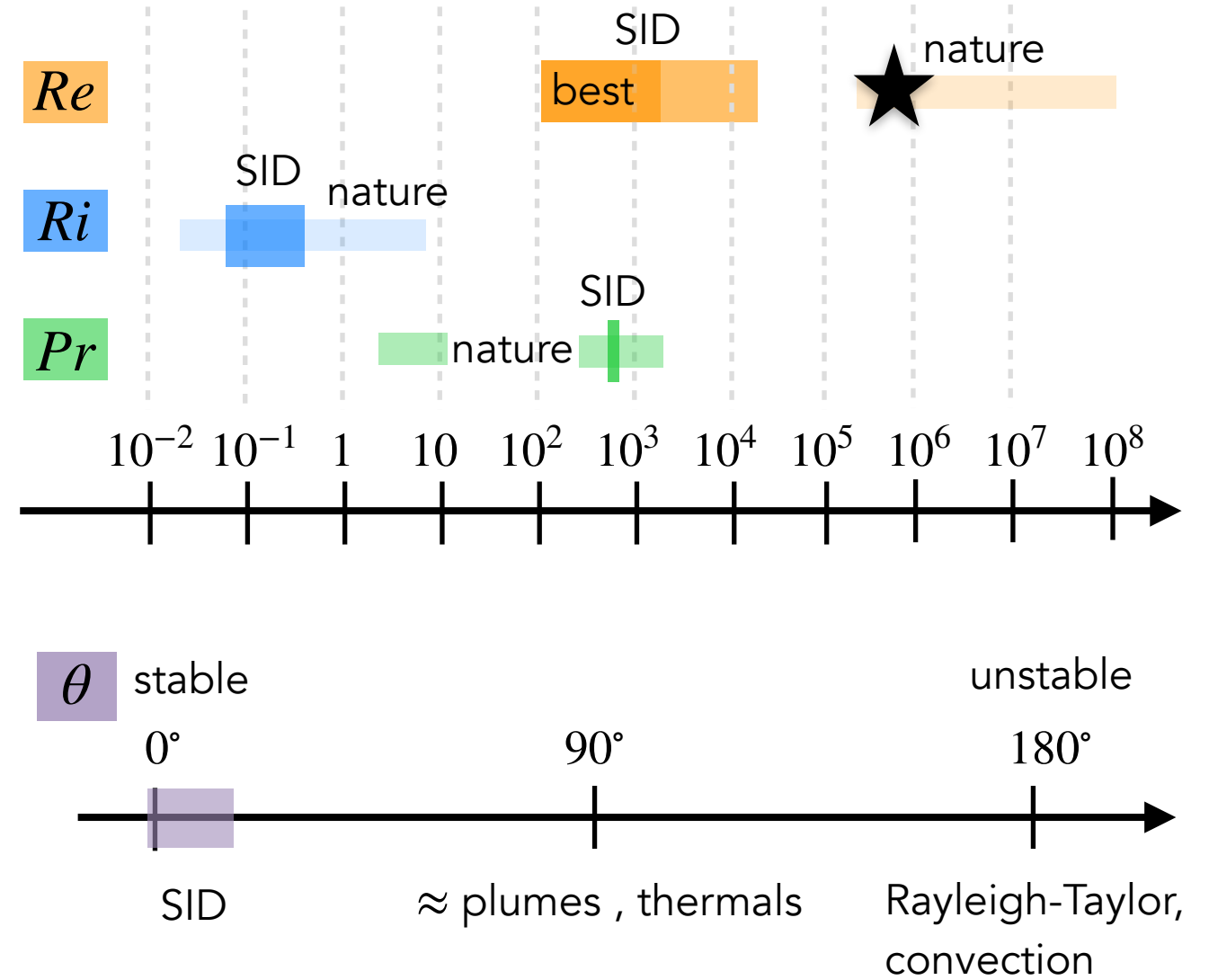
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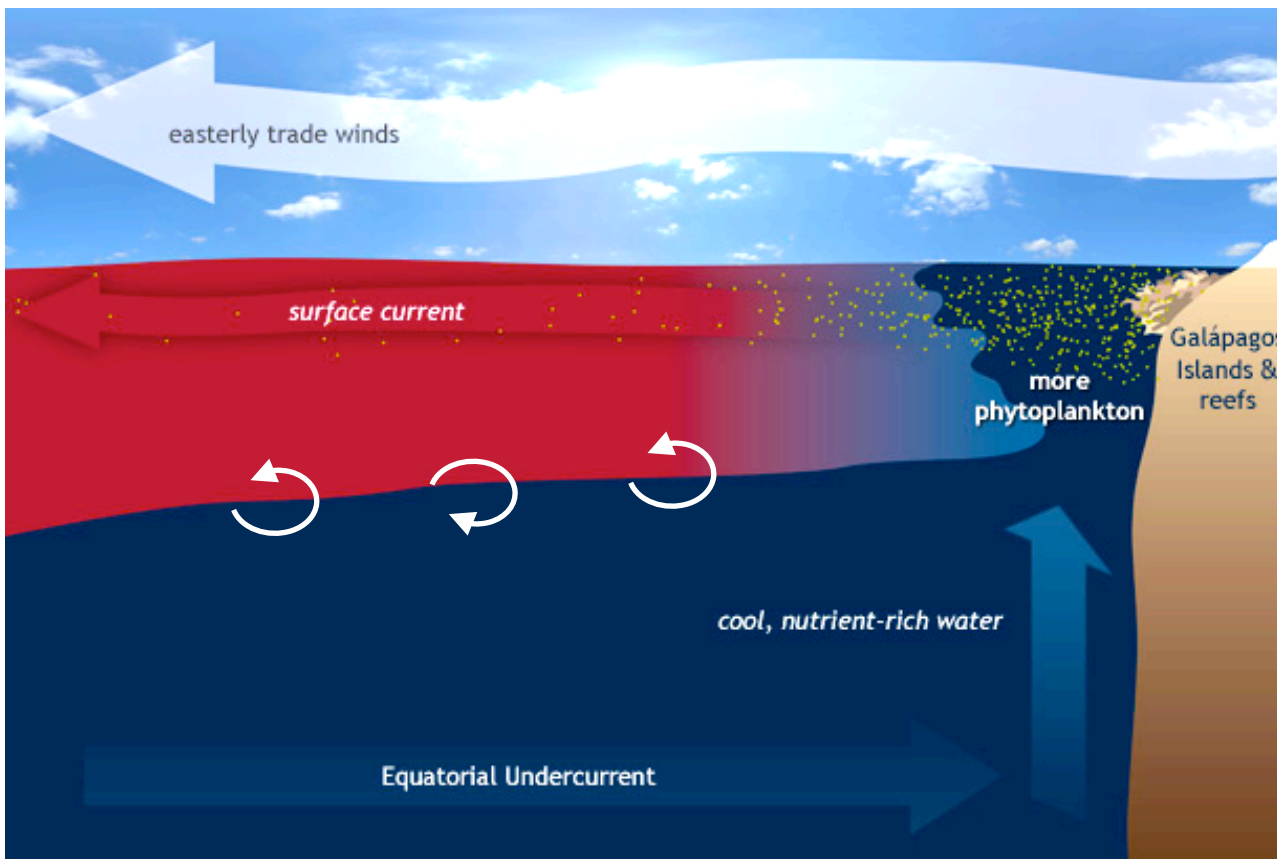
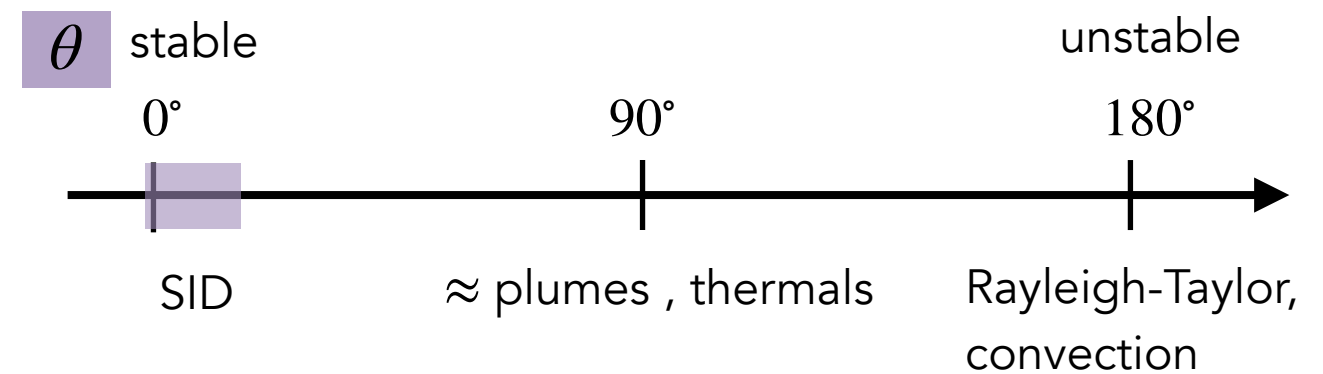
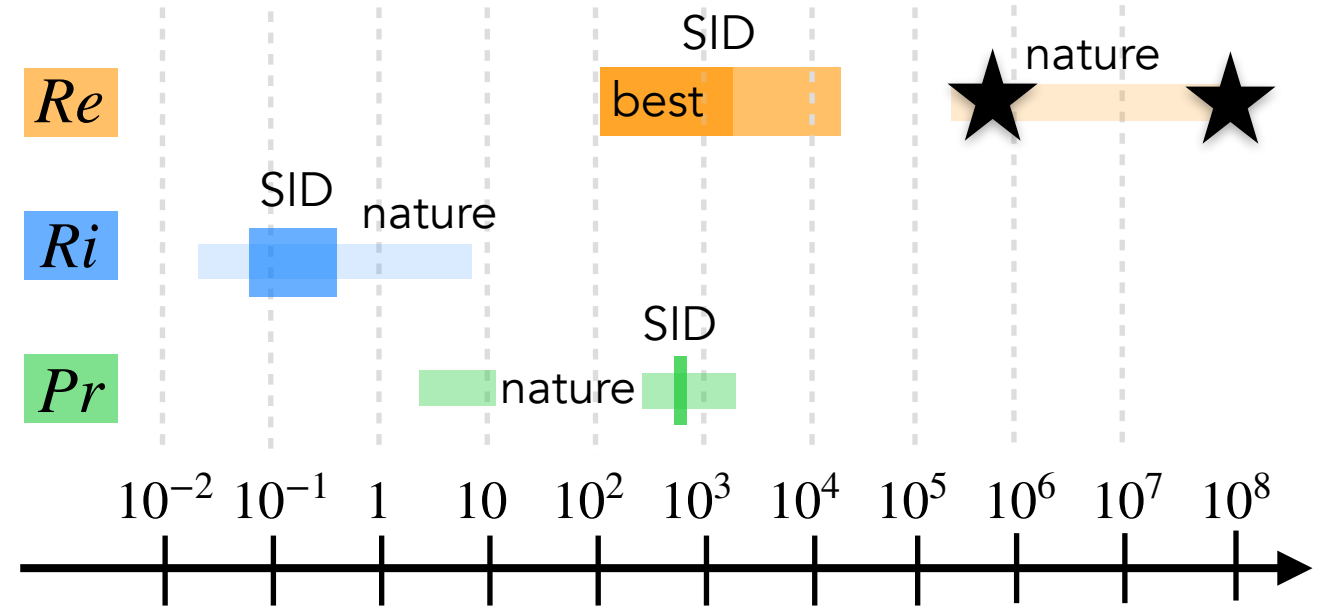
$$\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho = \frac{1}{Re Pr} \nabla^2 \rho$$



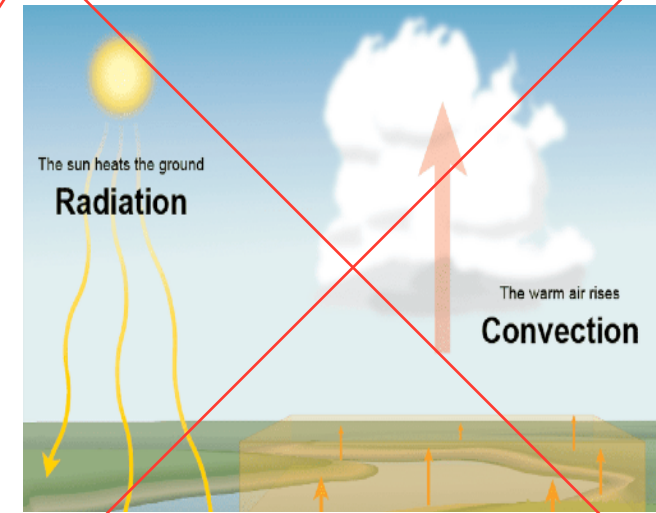
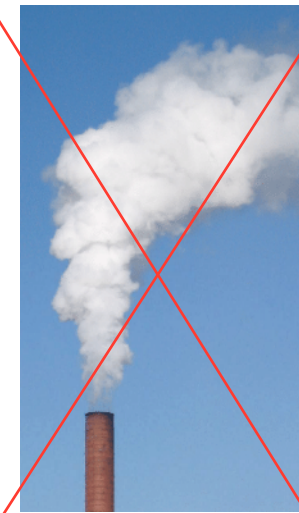
Parameters of SID



Parameters of SID



~~No external forcing:
 tides
 solar radiation
 rain
 wind
 internal waves
 ...~~



Parameters of SID

$$\nabla \cdot \mathbf{u} = 0$$

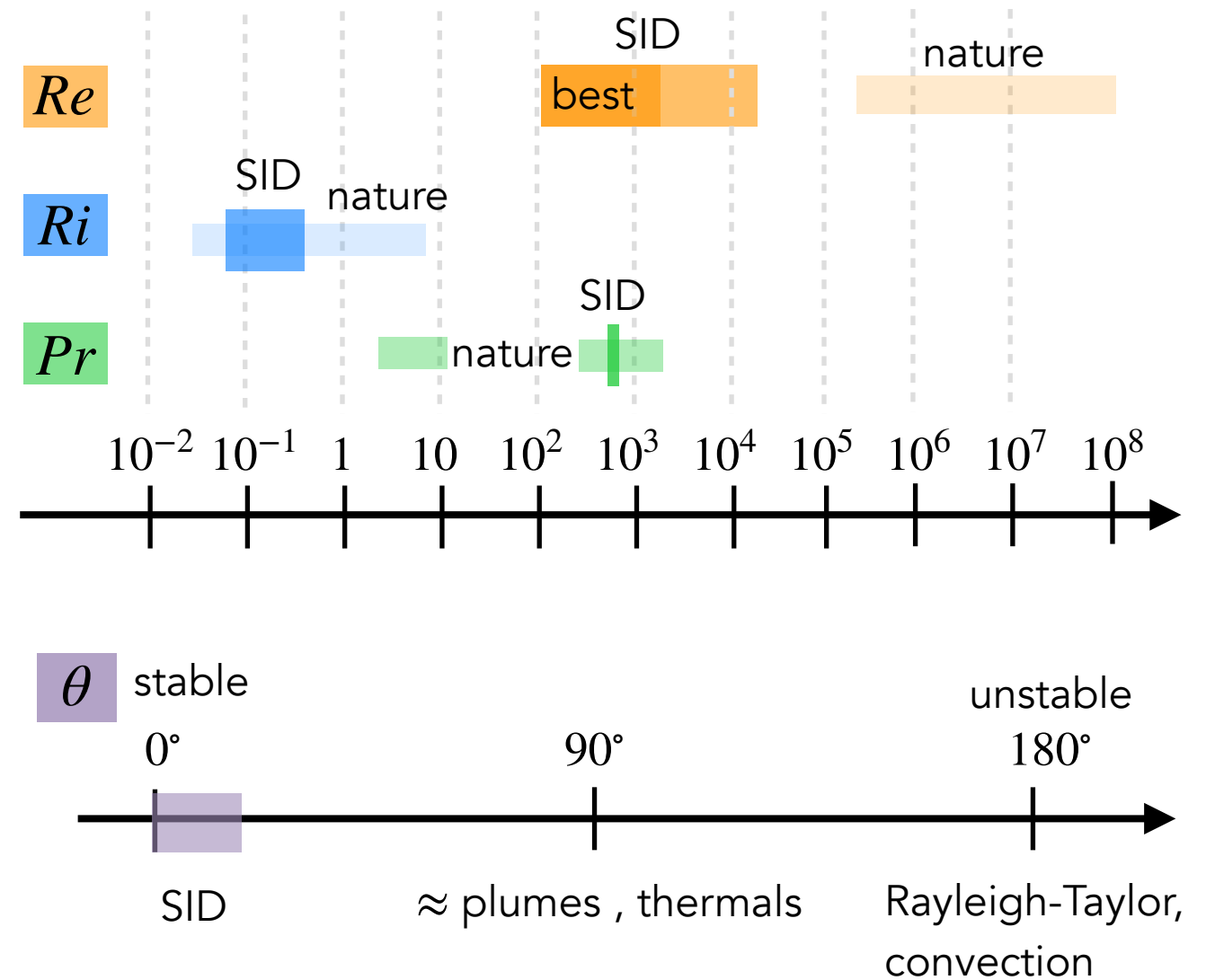
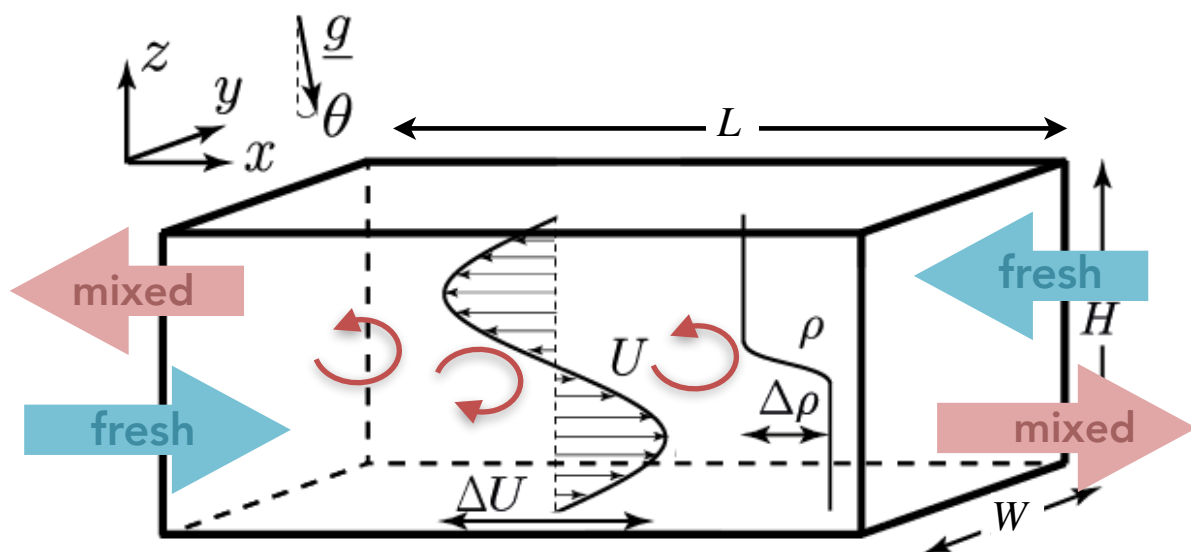
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$$\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho = \frac{1}{Re Pr} \nabla^2 \rho$$

+ initial conditions

+ boundary conditions

Trivial for whole system
but **tricky** for duct section



y, z : no slip for \mathbf{u} , no flux for ρ

Parameters of SID

$$\nabla \cdot \mathbf{u} = 0$$

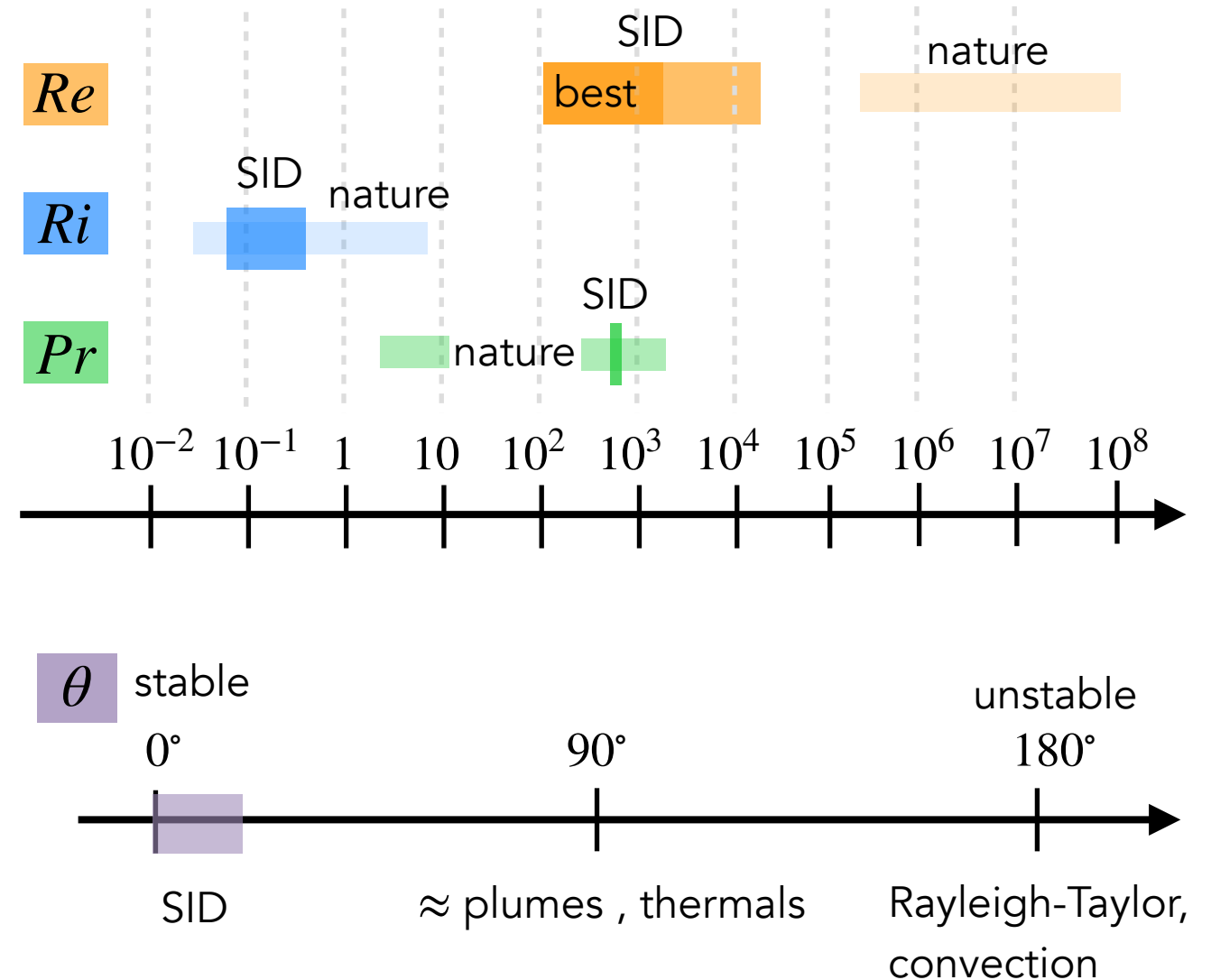
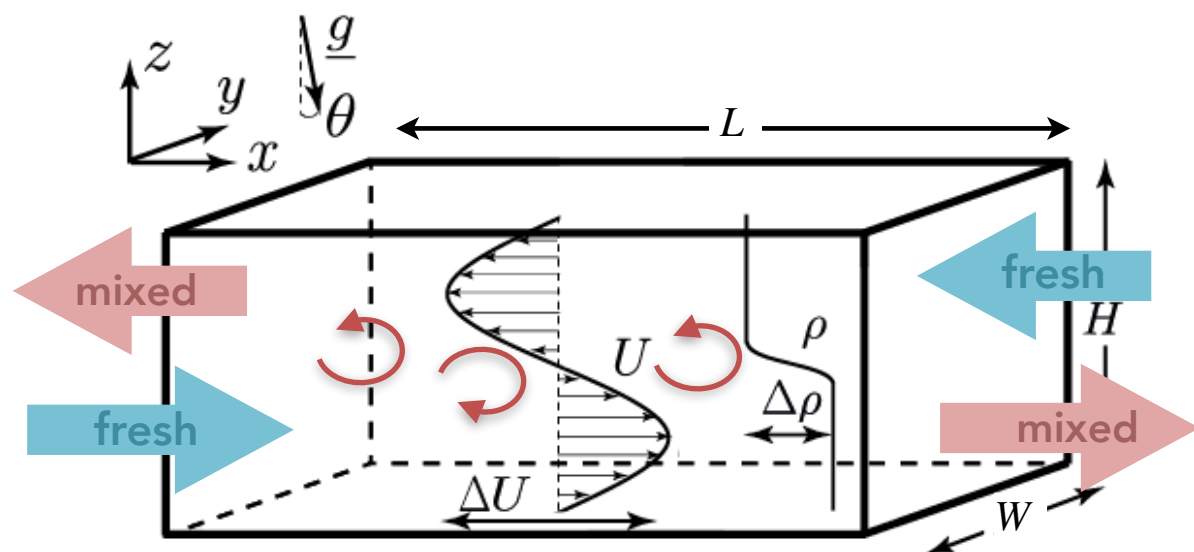
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Trivial for whole system
but **tricky** for duct section



y, z : no slip for \mathbf{u} , no flux for ρ

x : non-periodic

- in-flow of "fresh" fluid
- out-flow of "mixed" fluid
- mean flow $U(y, z)$ feeding turbulence

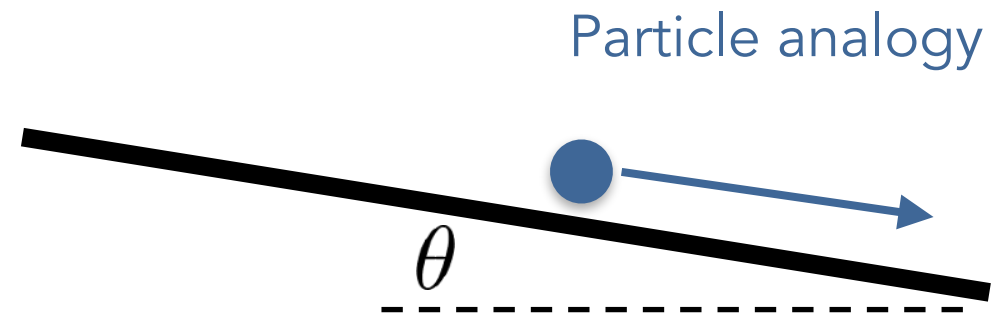
1. The first discoveries
2. New measurements

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3. Flow energetics

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2. New measurements
3. Flow energetics
4. The future

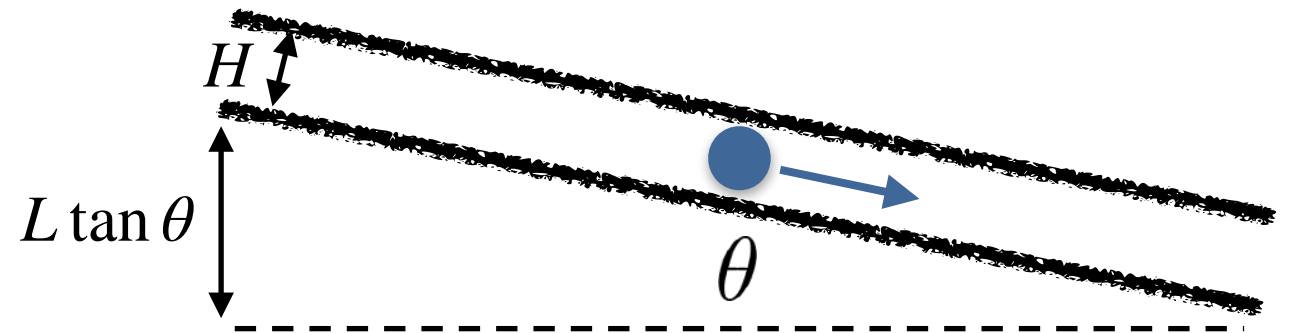
1. The typical flow velocity is $U \sim \sqrt{g'H}$
 $KE \sim g'H$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \frac{1}{Re} \nabla^2 u + \rho g' \sin \theta$$



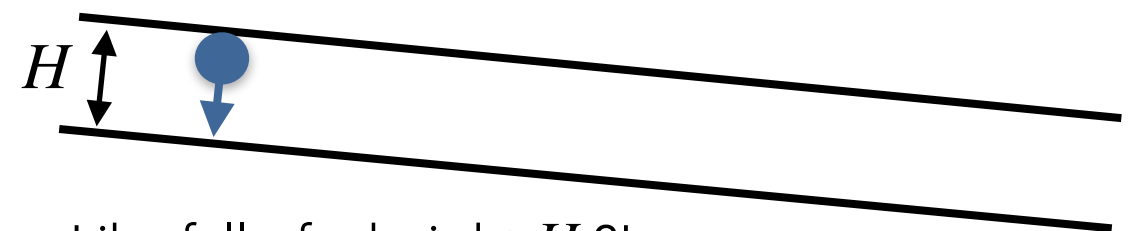
NOT a free fall (infinite duct \Leftrightarrow periodic BCs)

X $KE \sim (g' \sin \theta t)^2$



NOT a fall of a height $L \tan \theta$ balanced by

X viscous friction: $KE \sim g' L \tan \theta Re$



Like fall of a height H ?!

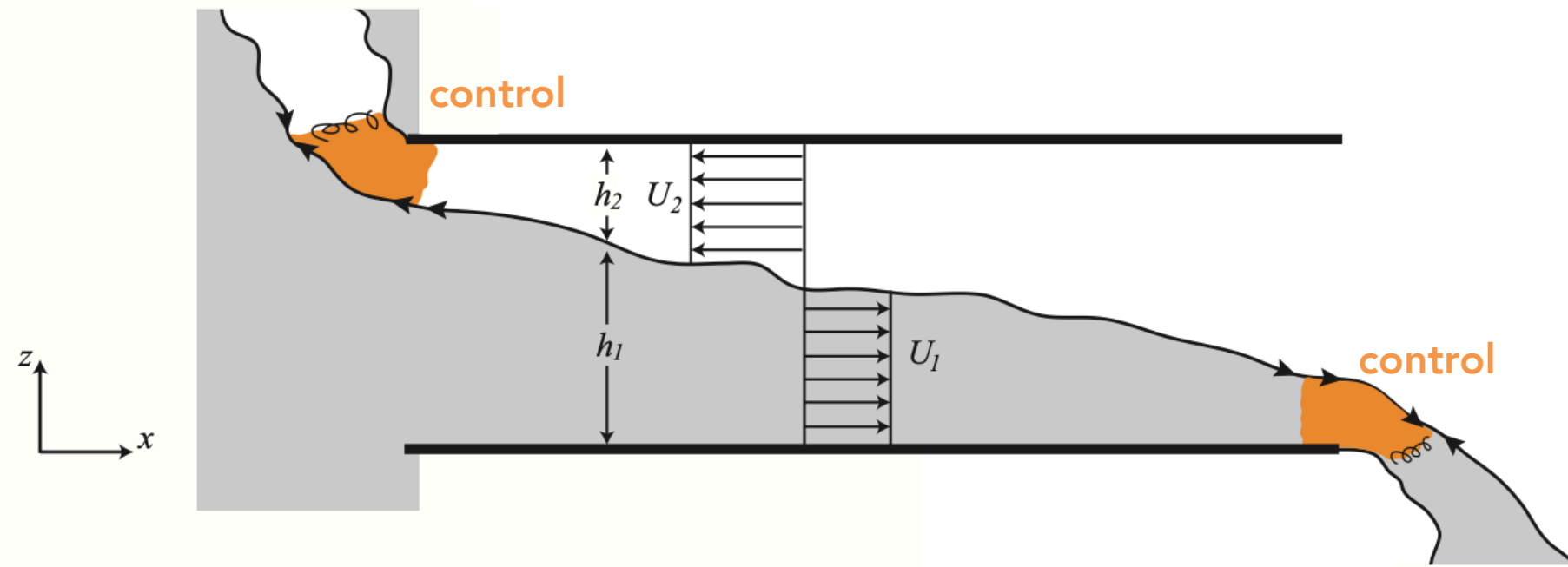
✓ $KE \sim g'H$

independent of tilt θ and viscosity Re !

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \frac{1}{Re} \nabla^2 u + \rho g' \sin \theta$$

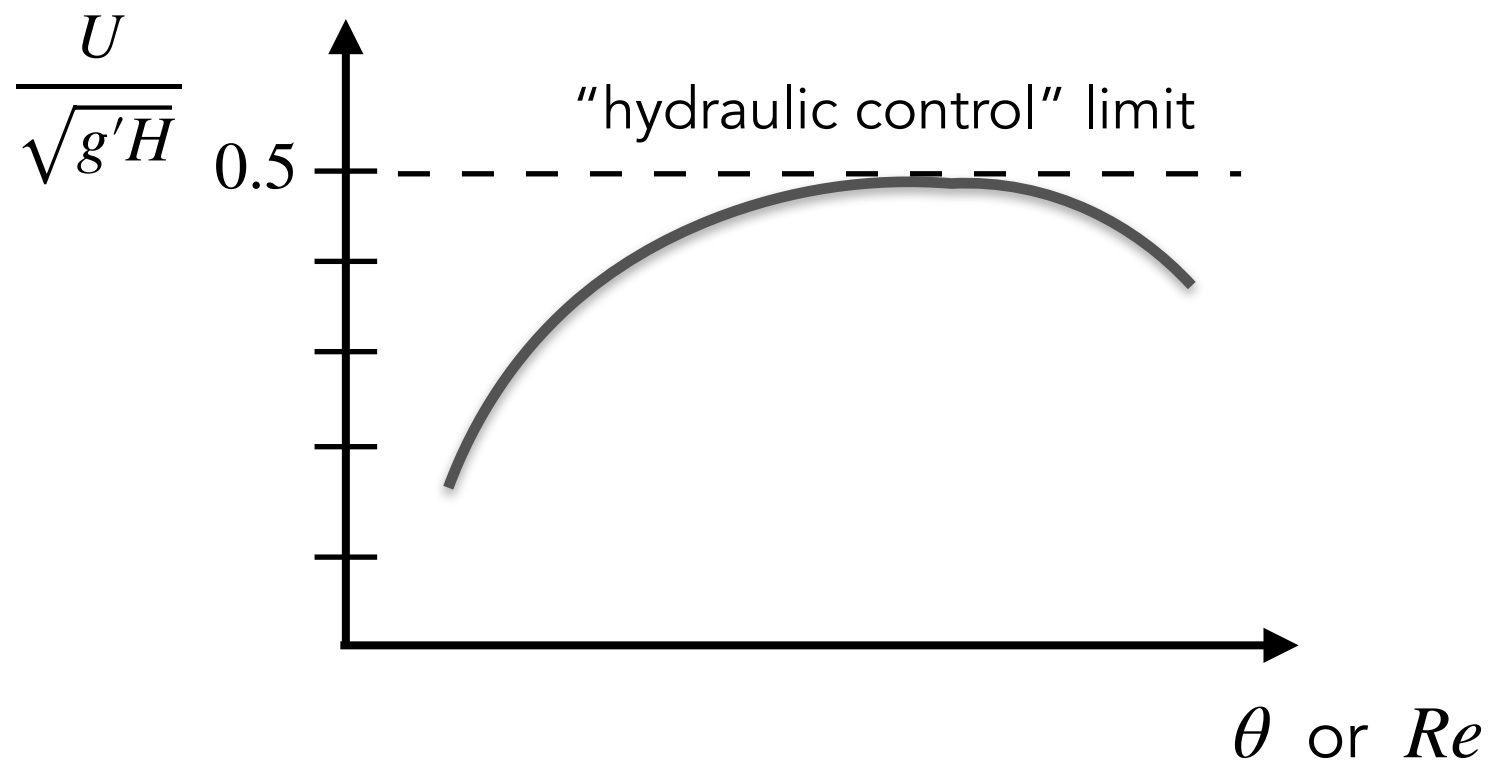
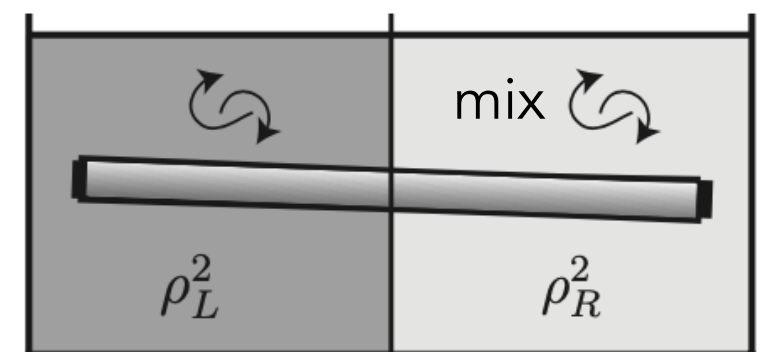
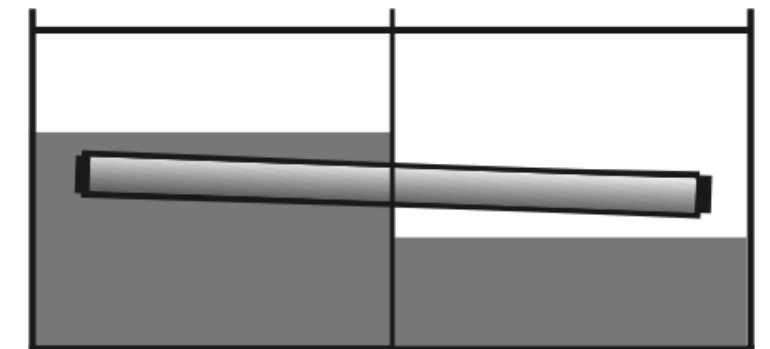
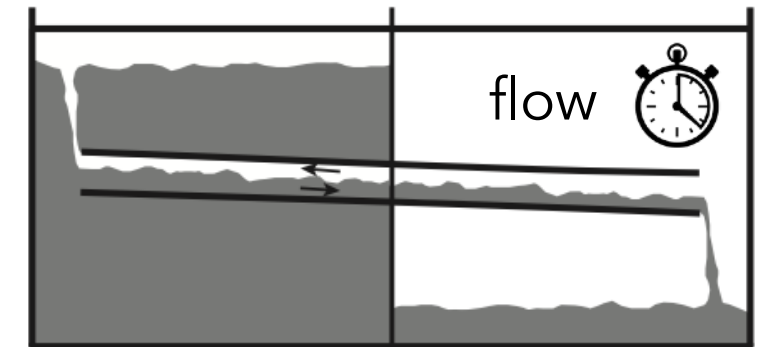
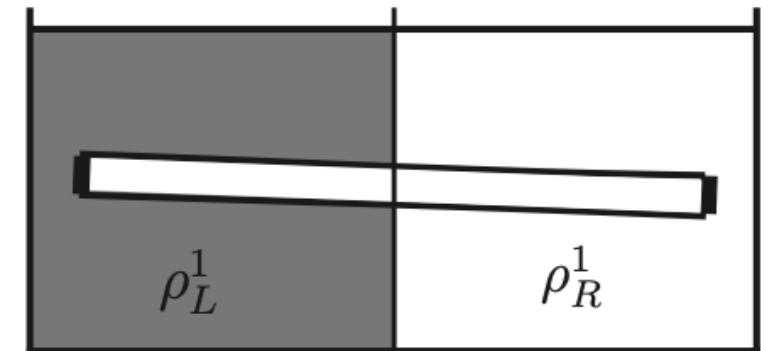
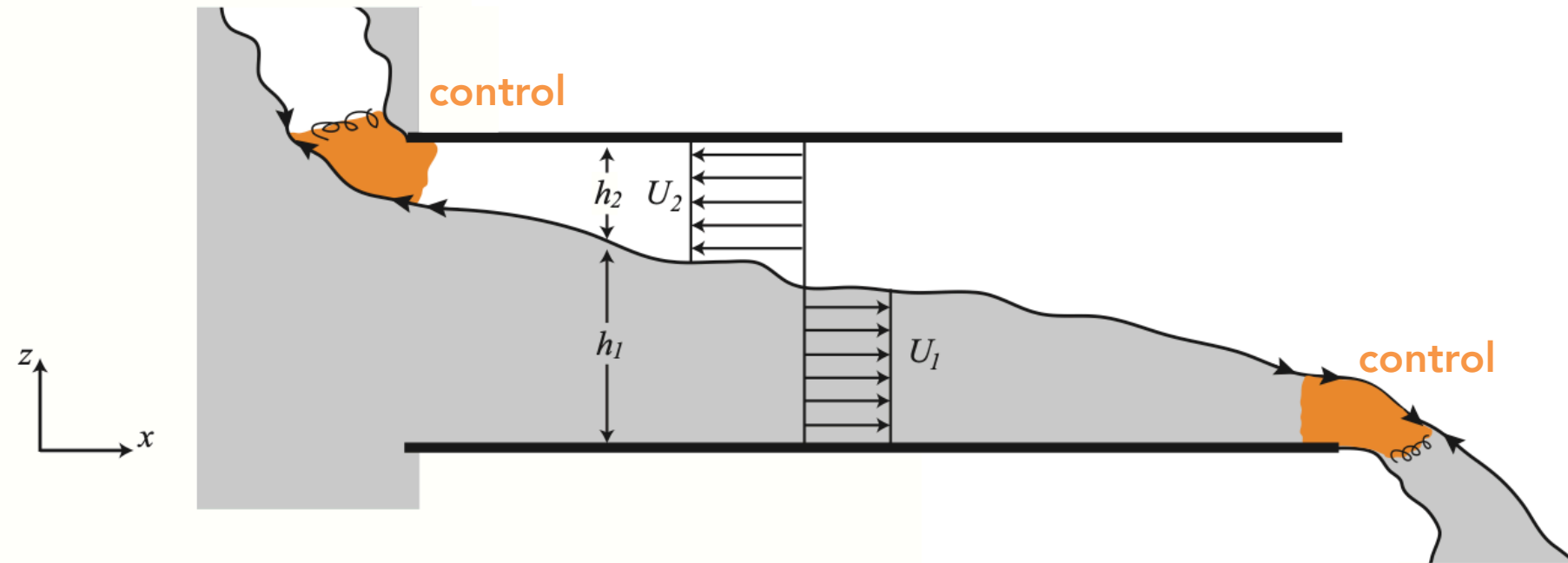
"hydraulic control"

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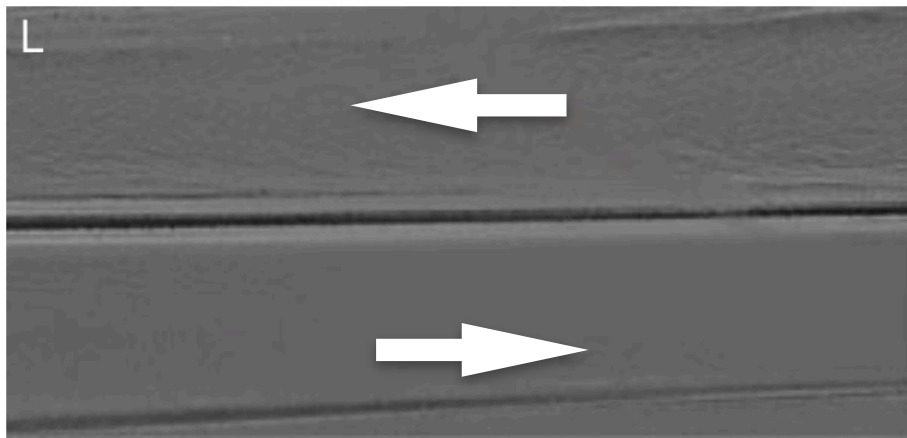
salt flux measurements



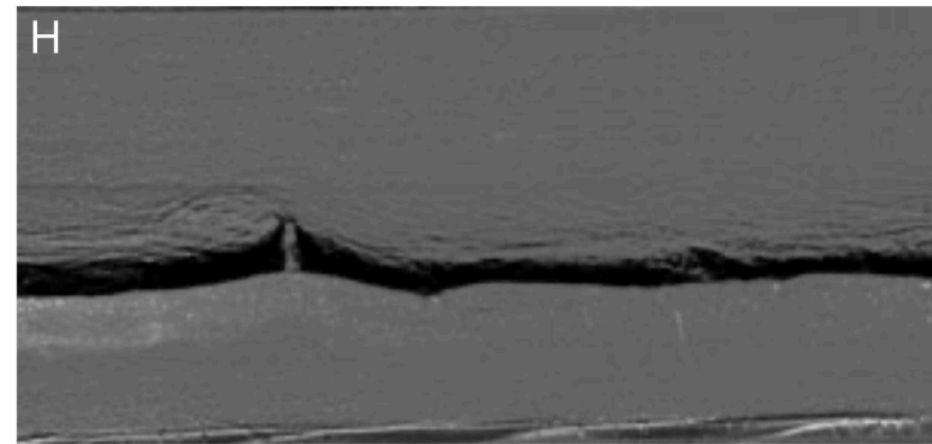
2. There are four qualitative flow regimes

Shadowgraphs

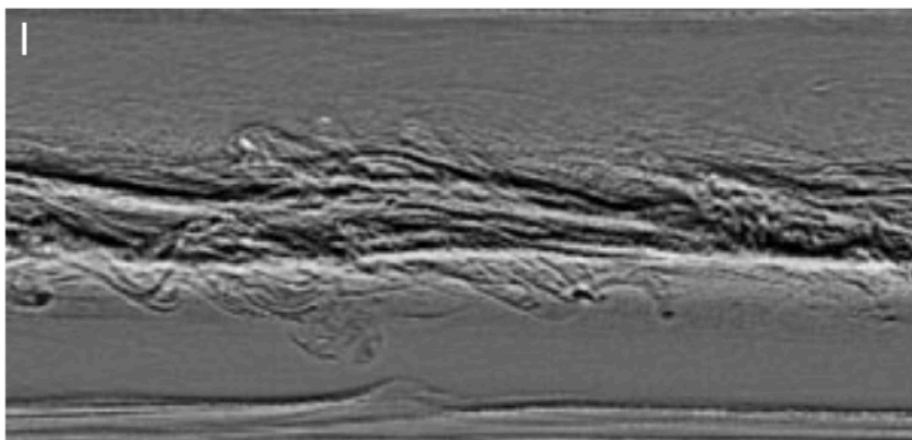
L: Laminar



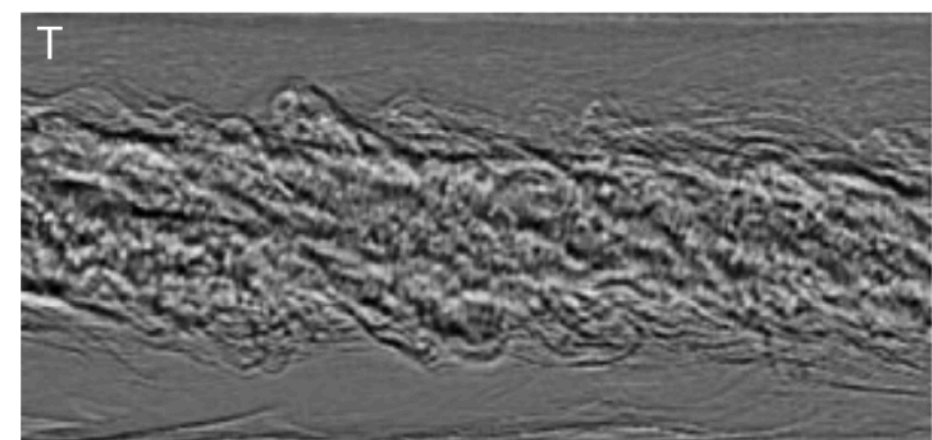
H: Holmboe waves



I: Intermittent



T: Turbulent

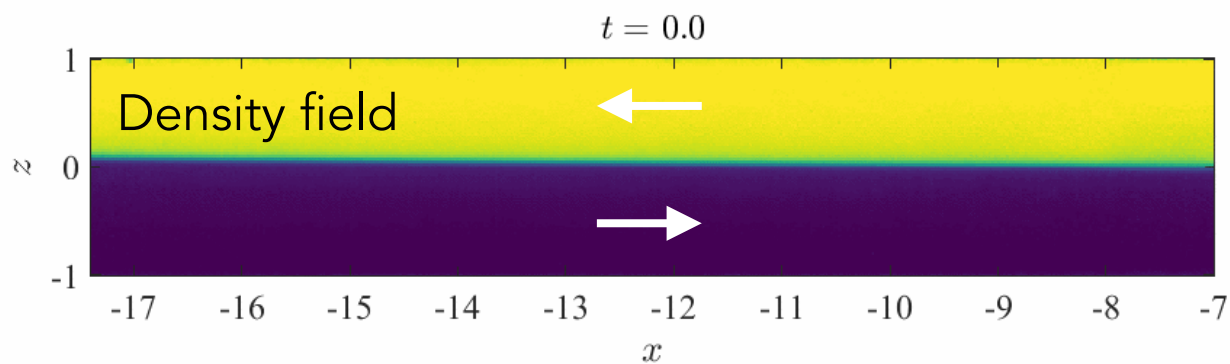


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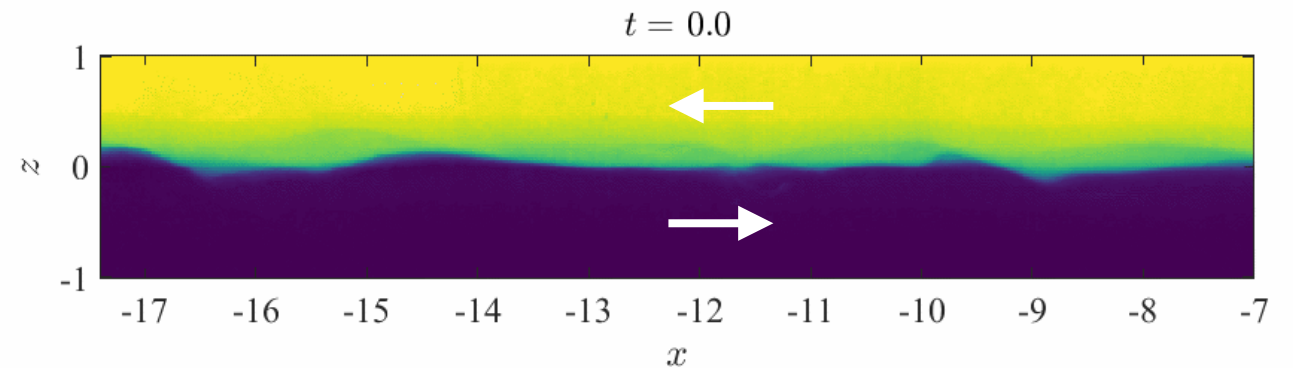
Shadowgraphs

Laser Induced Fluorescence (LIF)

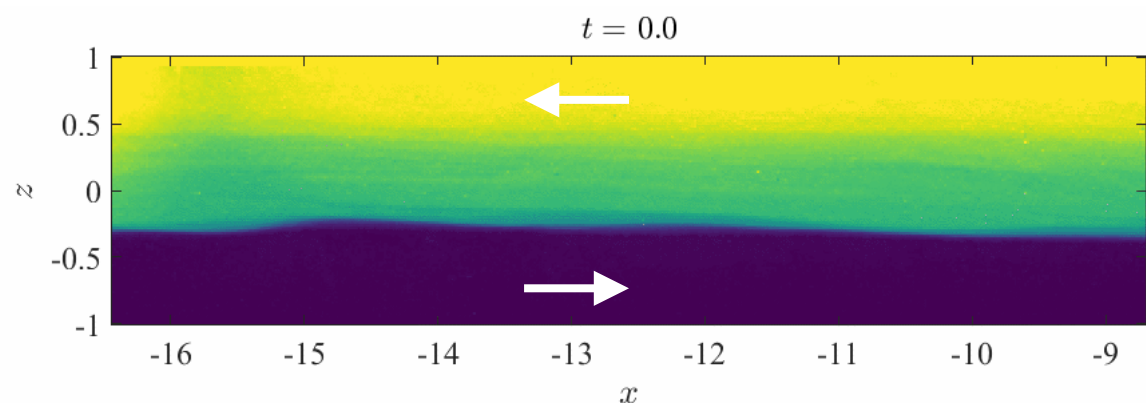
L: Laminar



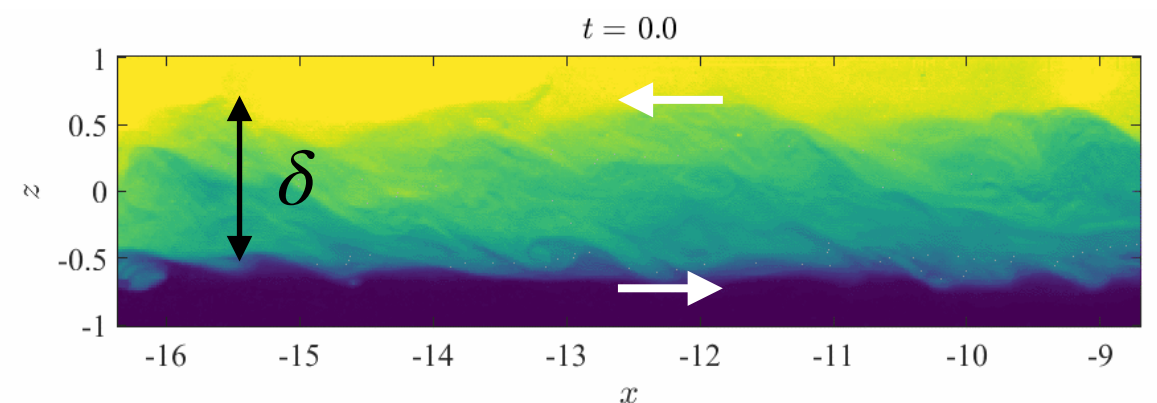
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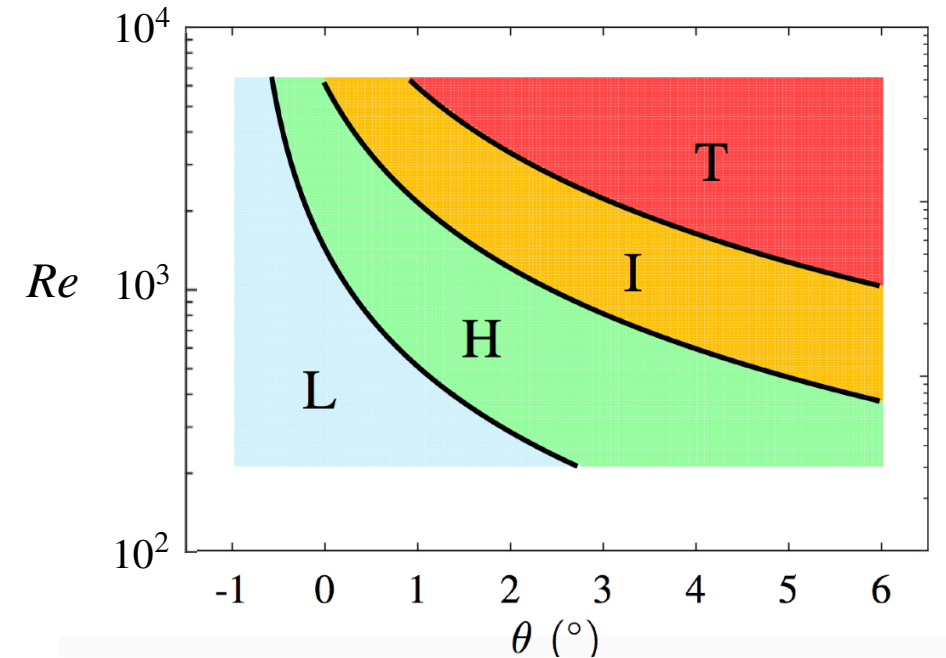
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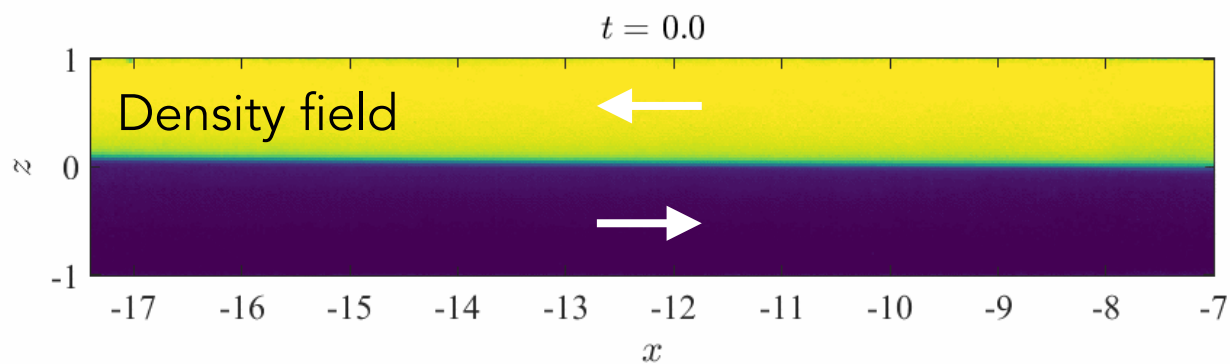
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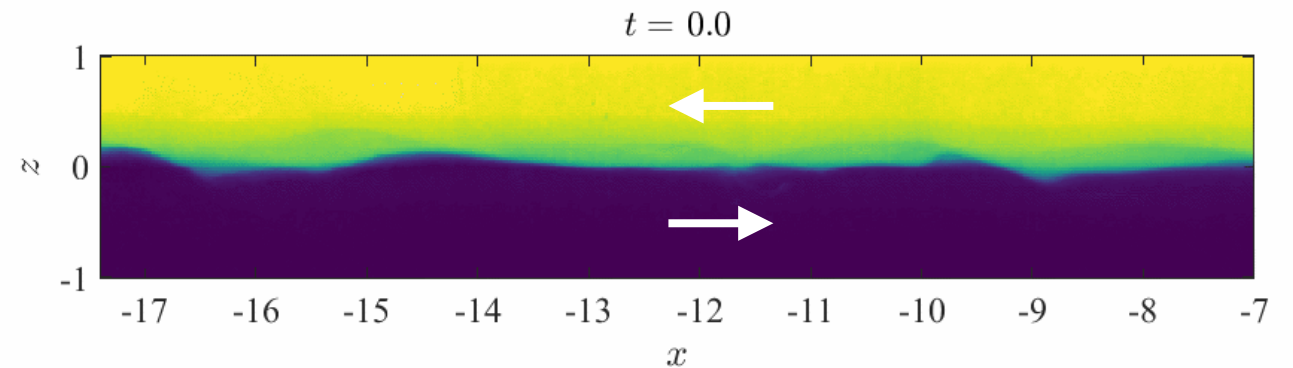
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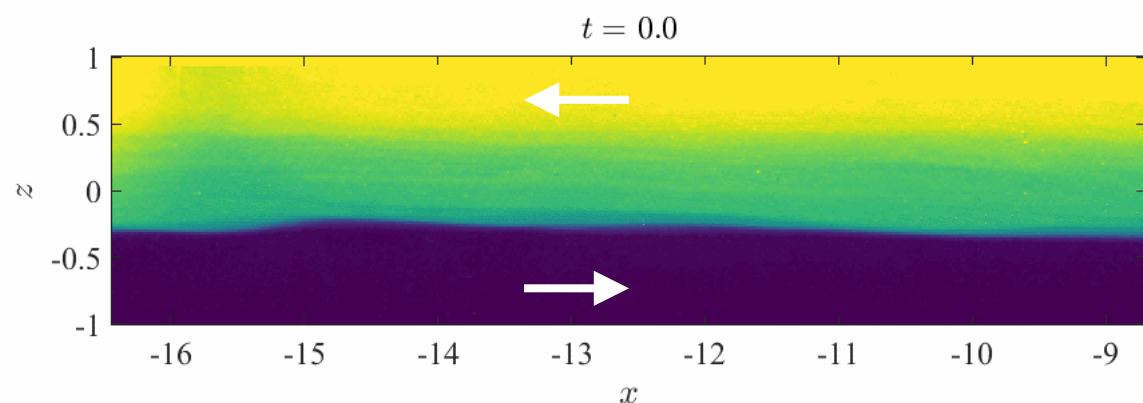
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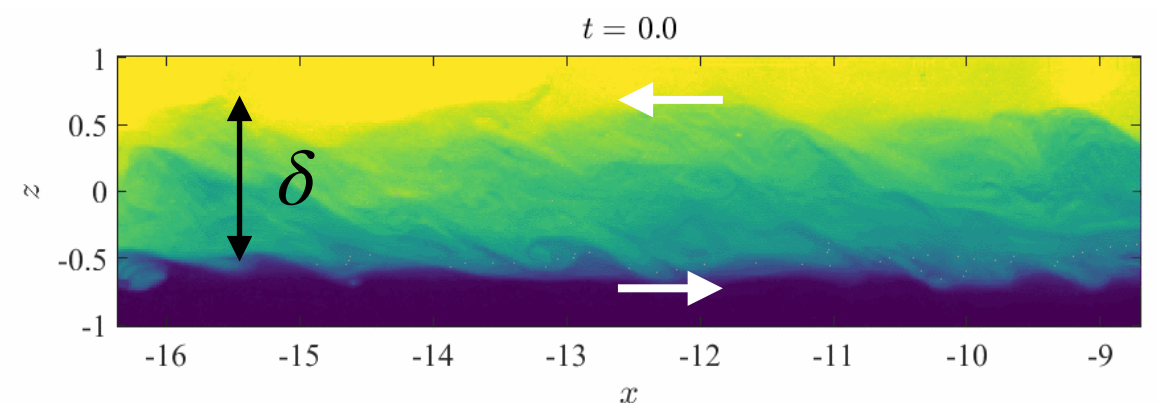
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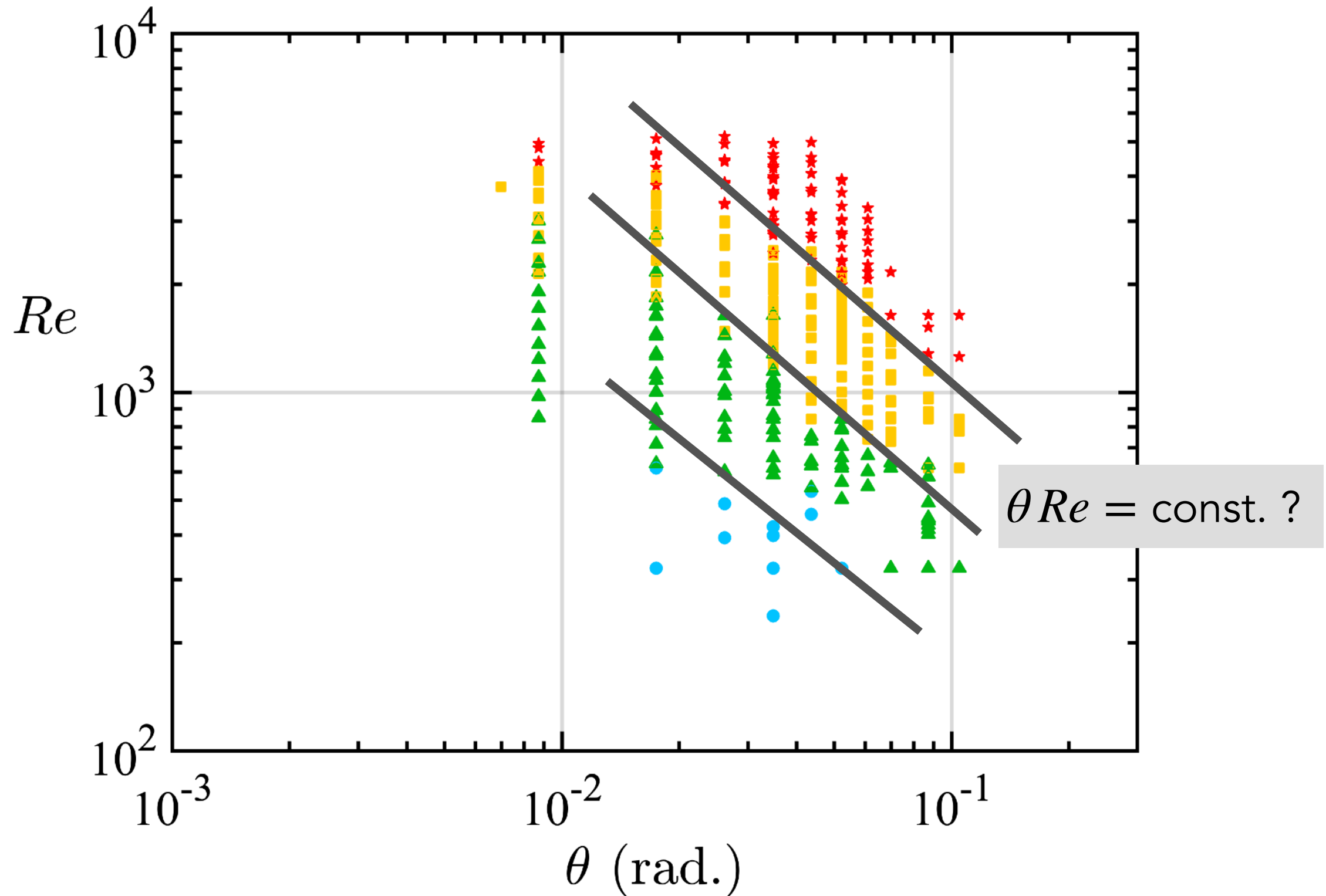
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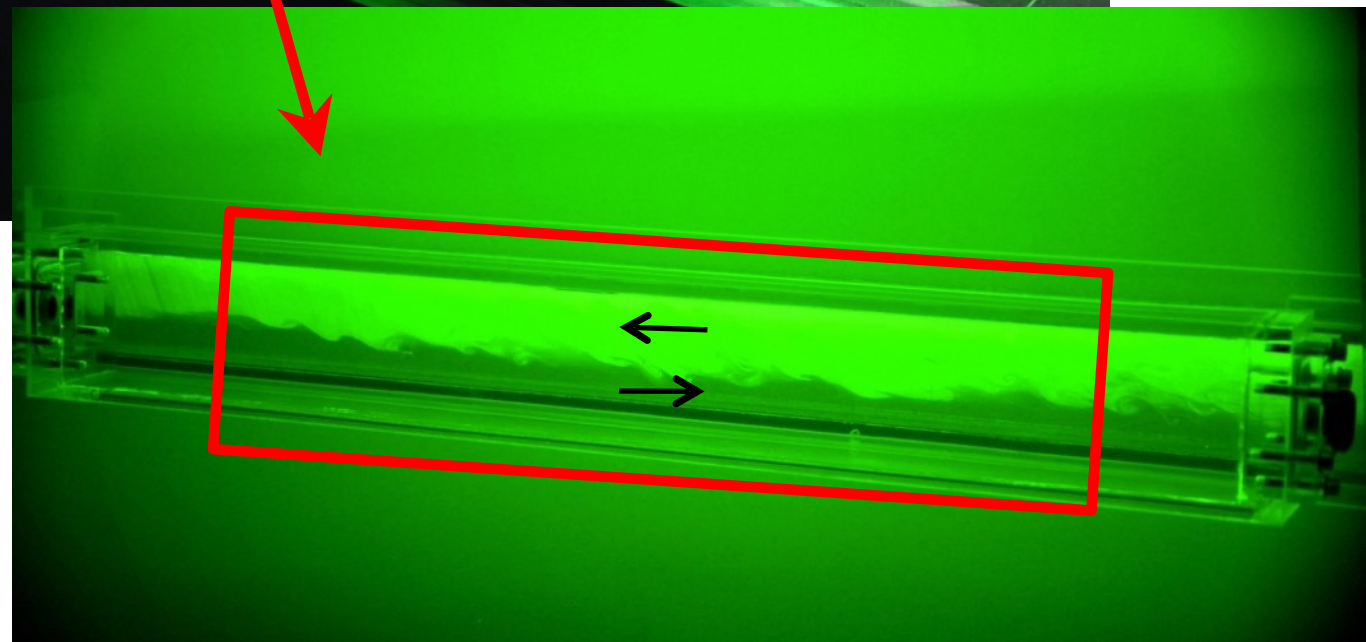
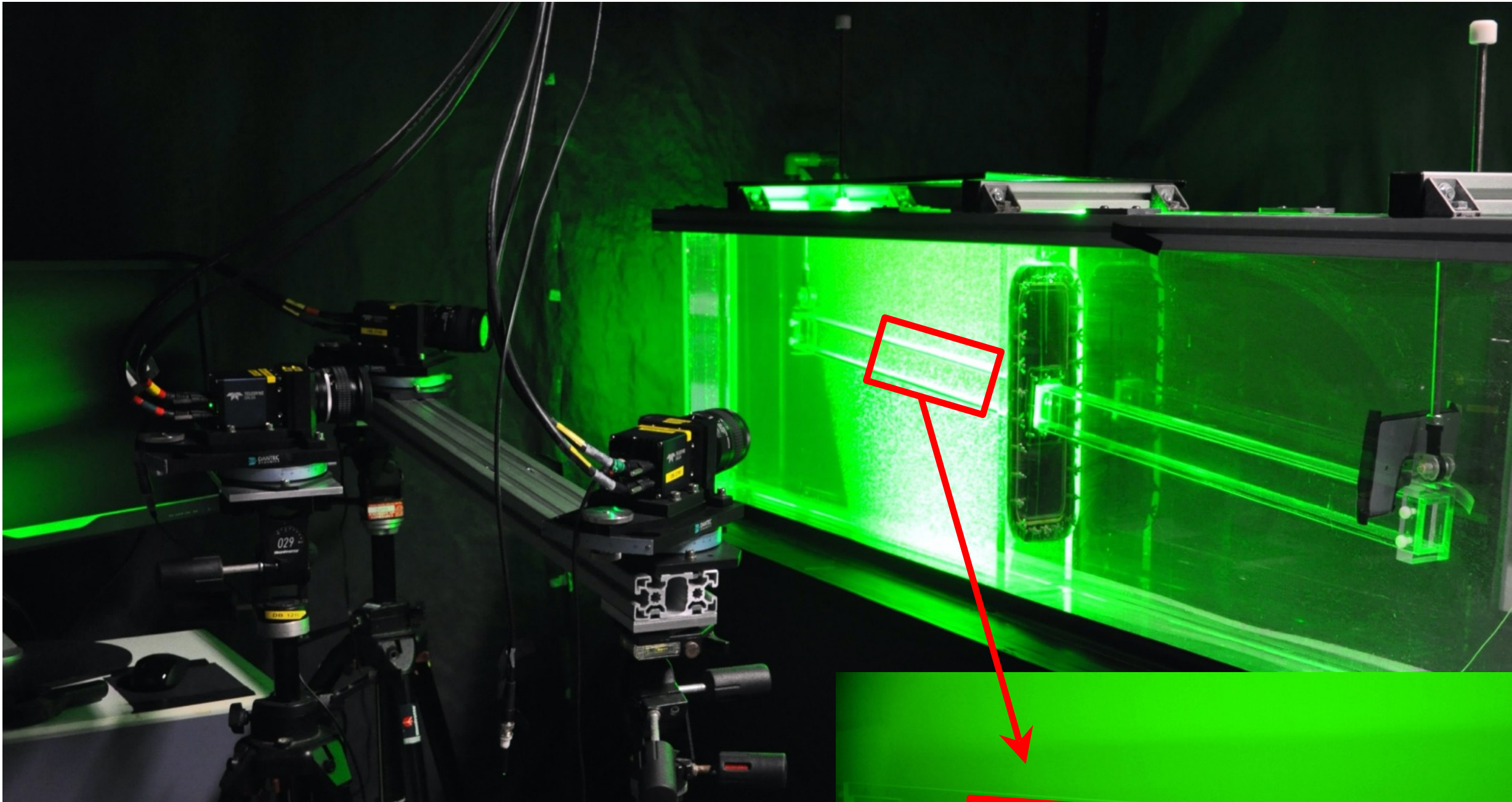
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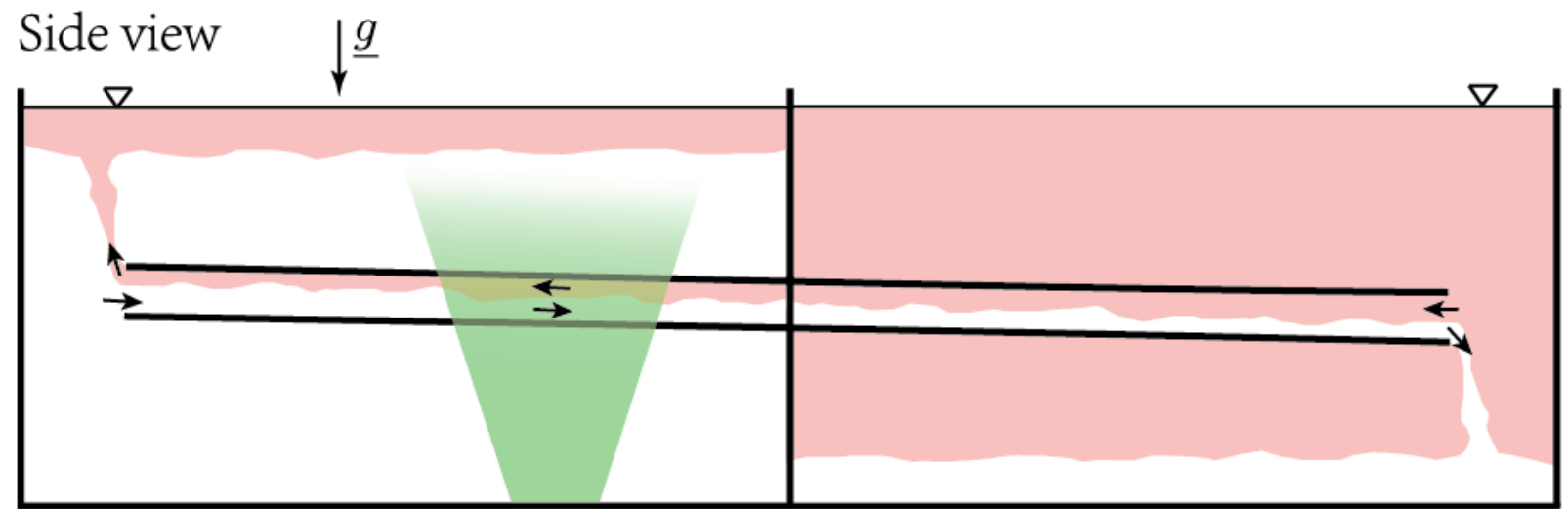
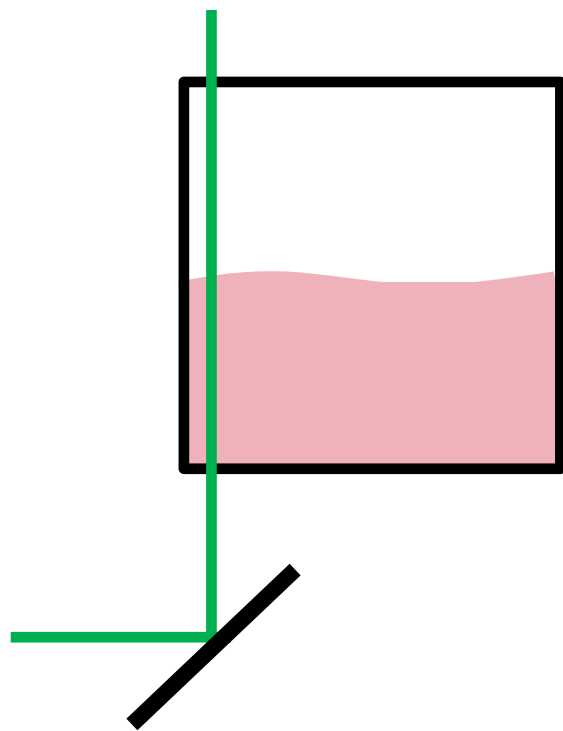


New measurements



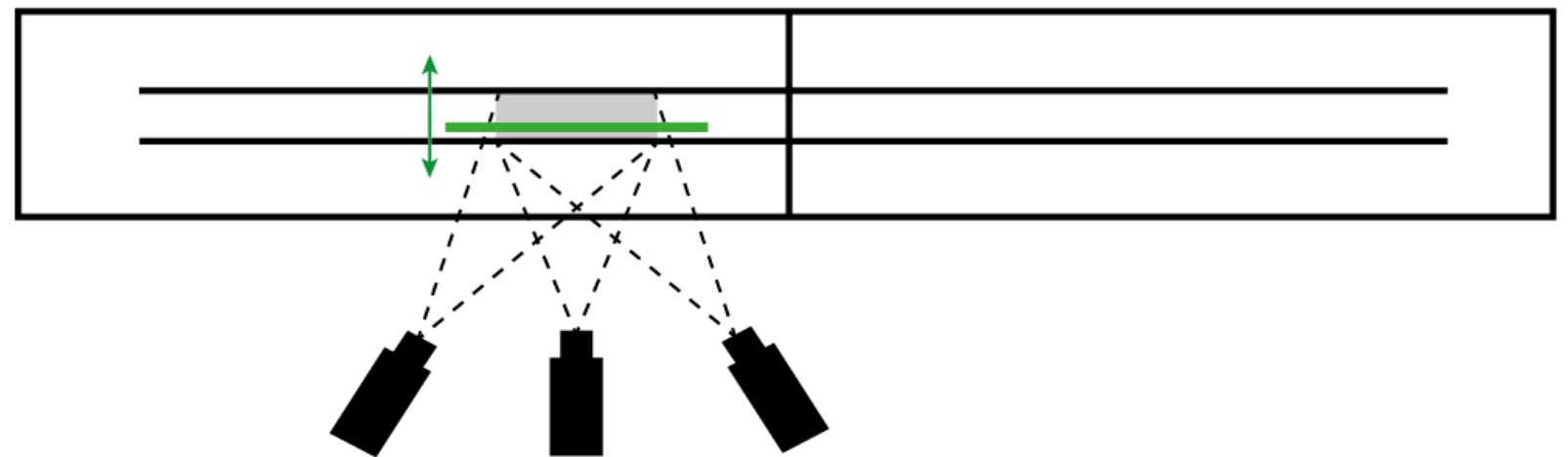
New measurements

Obtain u, v, w and ρ
in x, y, z, t !



pulsed laser
fast scanning system

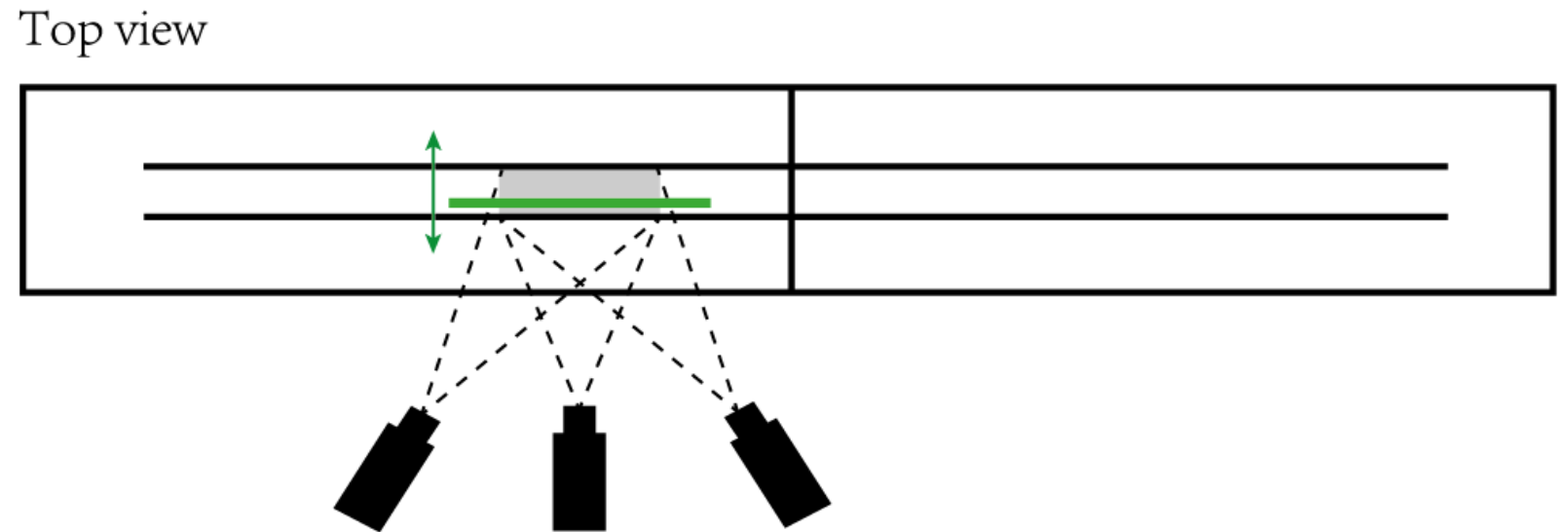
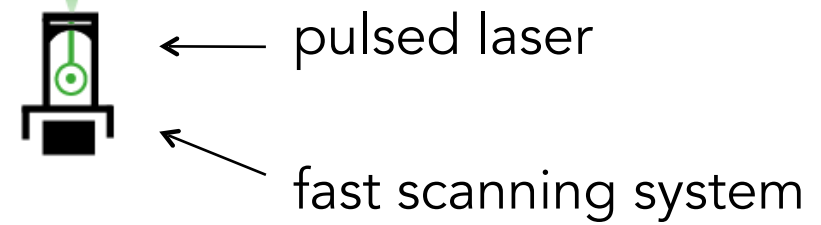
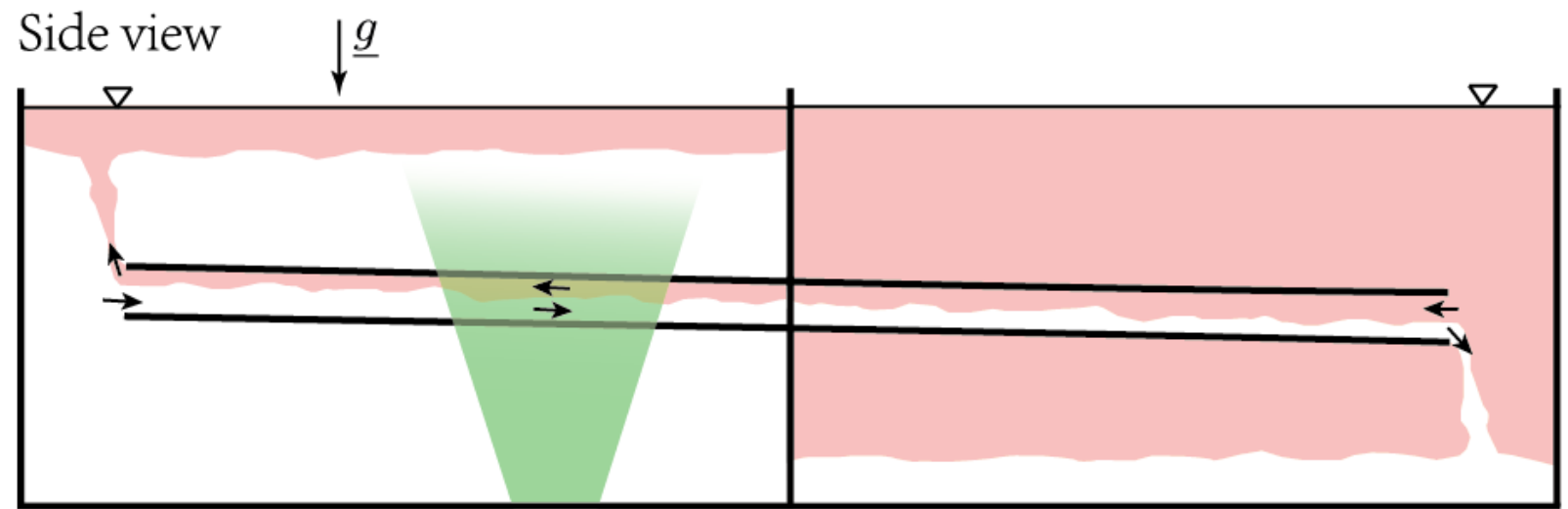
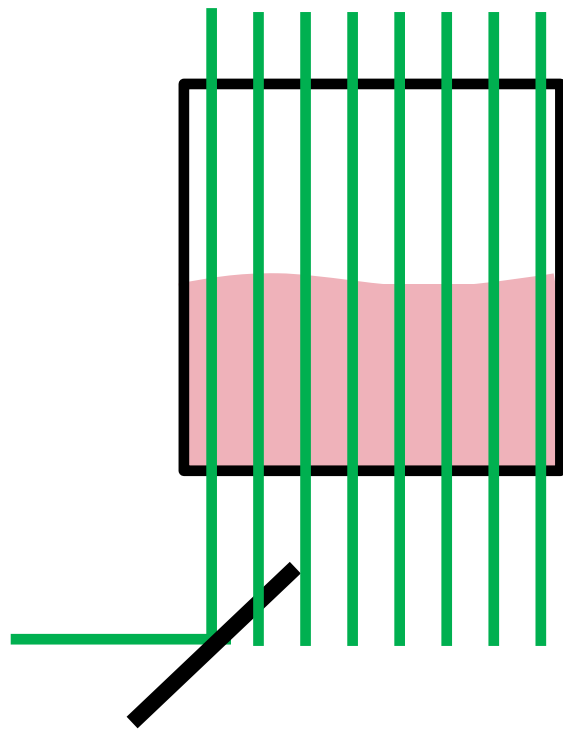
Top view



3 x 8 Mpx cameras @ 200 fps

New measurements

Obtain u, v, w and ρ
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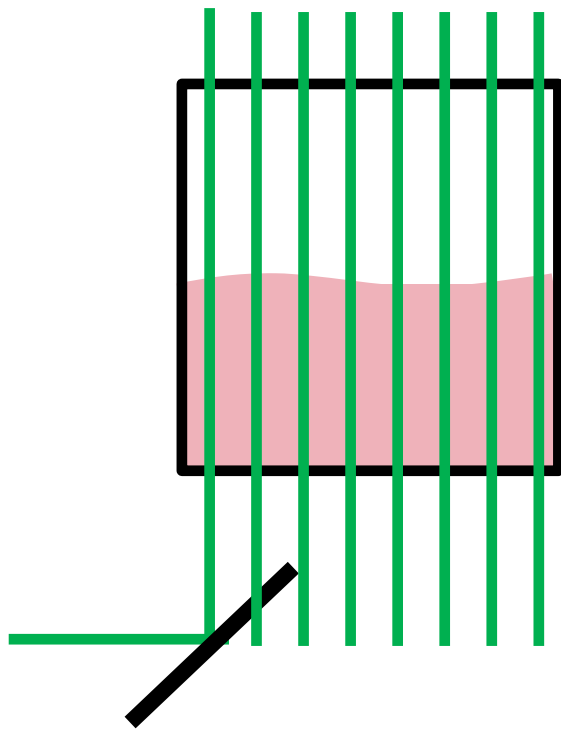
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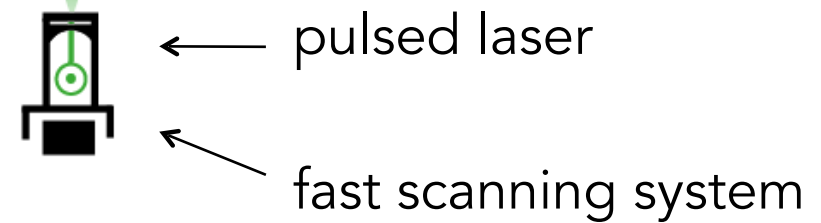
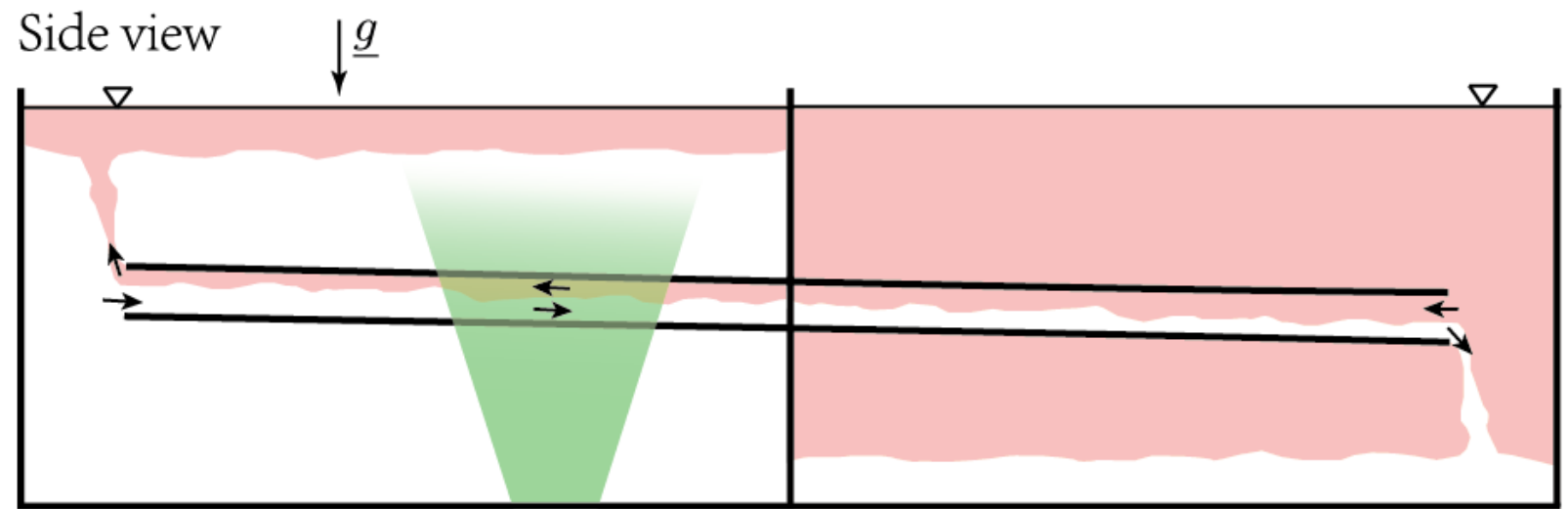
Obtain u, v, w and ρ
in x, y, z, t !

Resolution

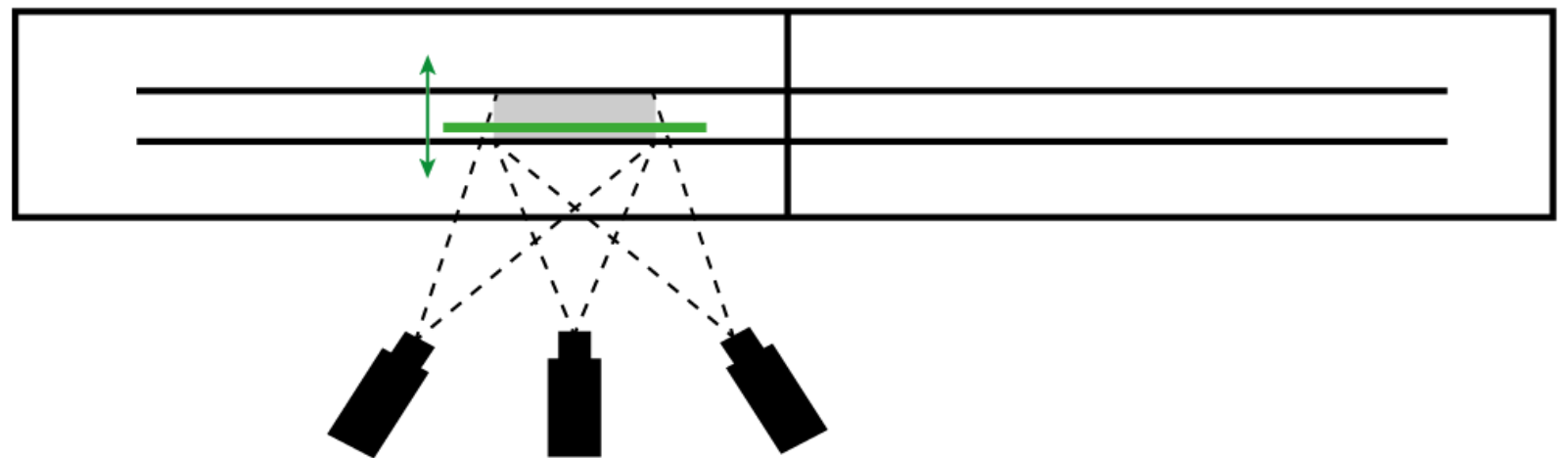
400 x 30 x 80 x 300
 x y z t



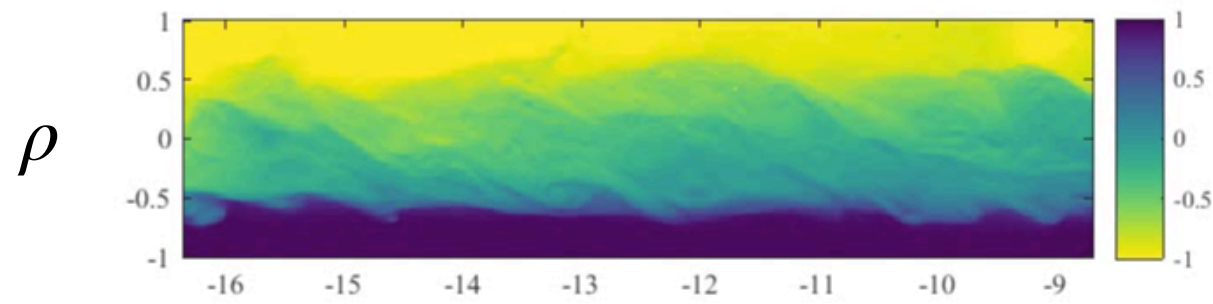
16 data sets in θ, Re plane
each: ~150 GB of raw data
~2 GB once processed



Top view



3 x 8 Mpx cameras @ 200 fps

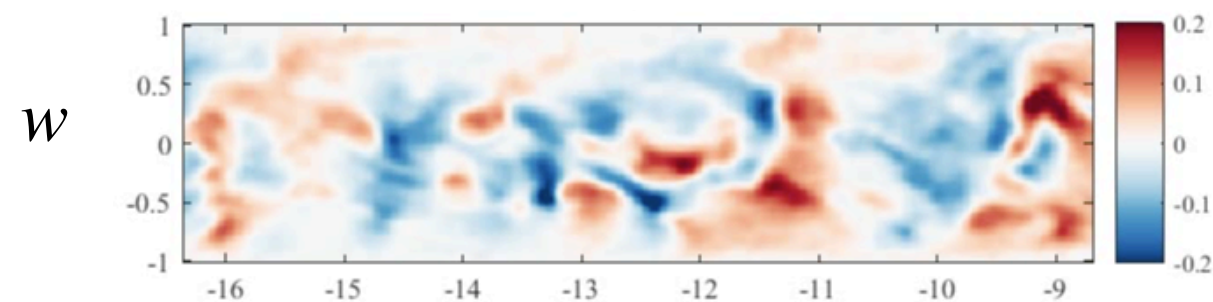
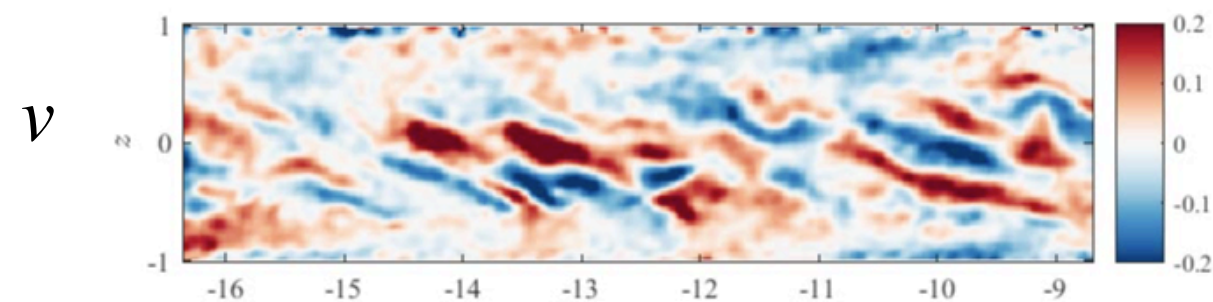
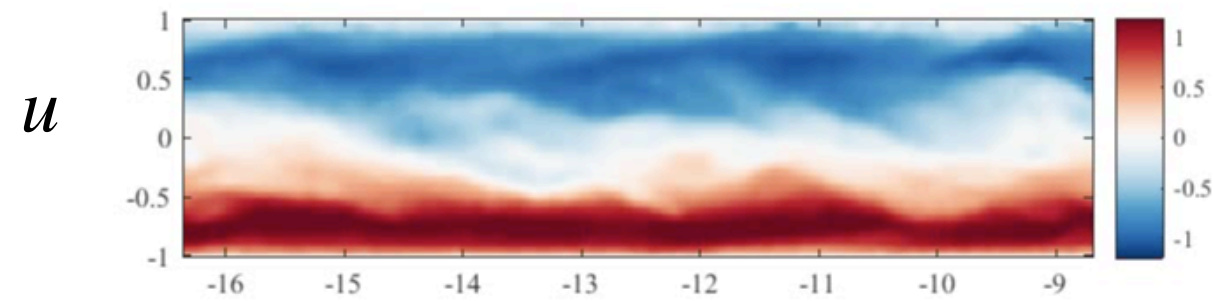
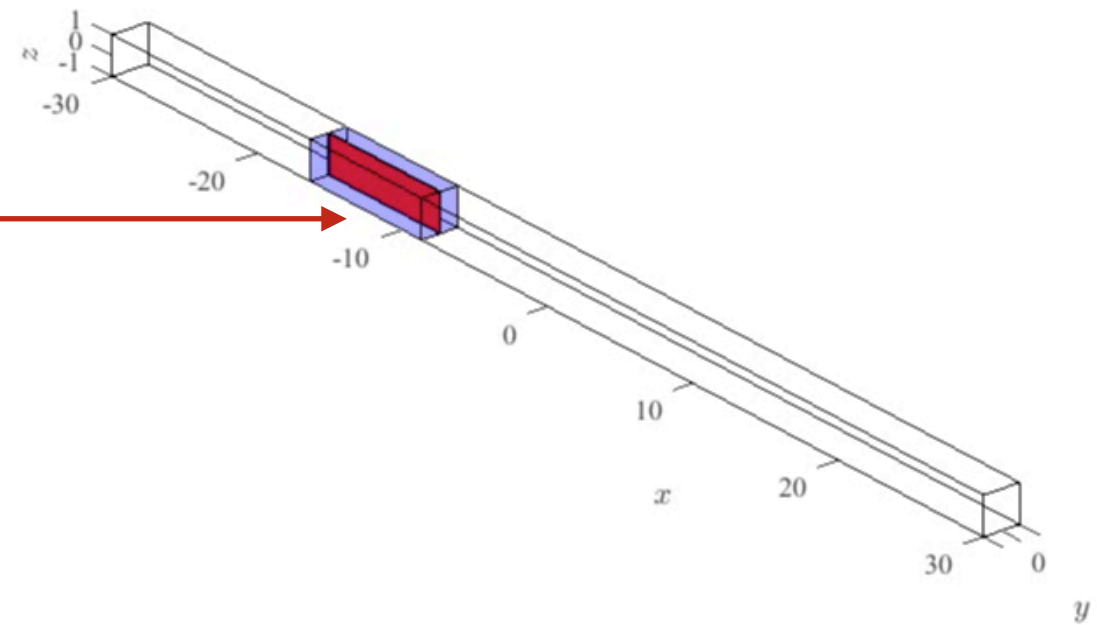


$\theta = 6^\circ \quad Re = 1255$

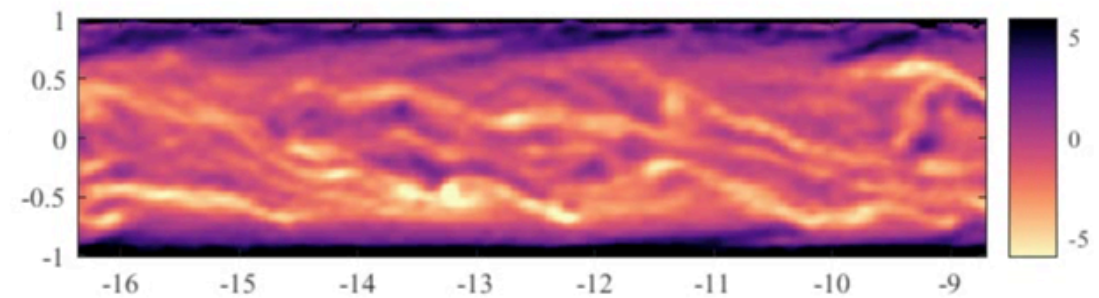
$y = 0.03$

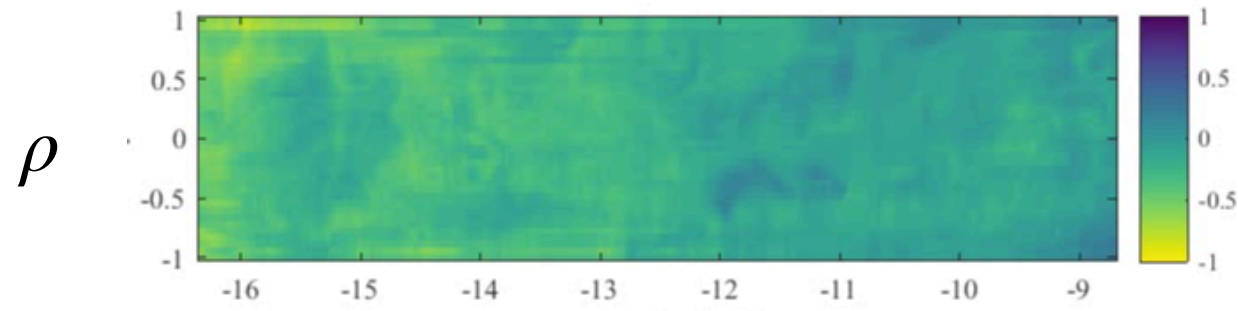
Scan: $t = 0.00$

Vertical plane



Vorticity ω_y



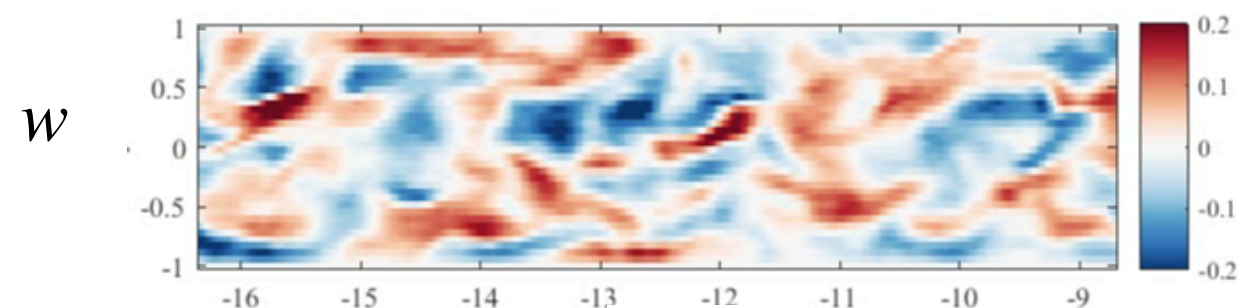
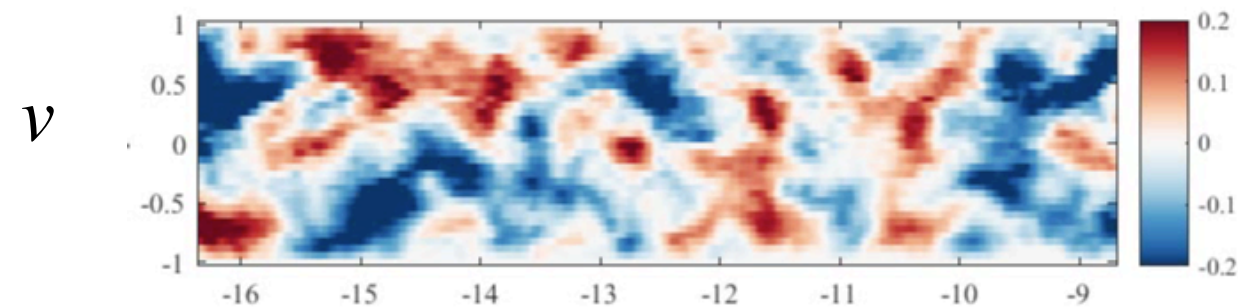
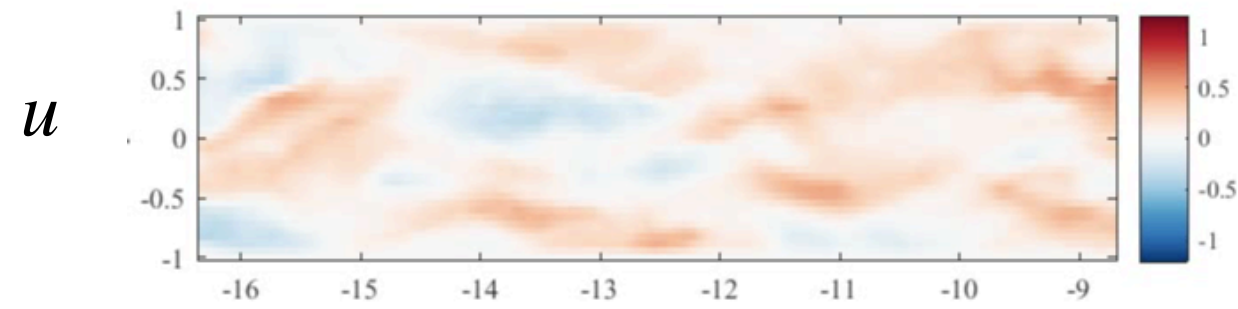
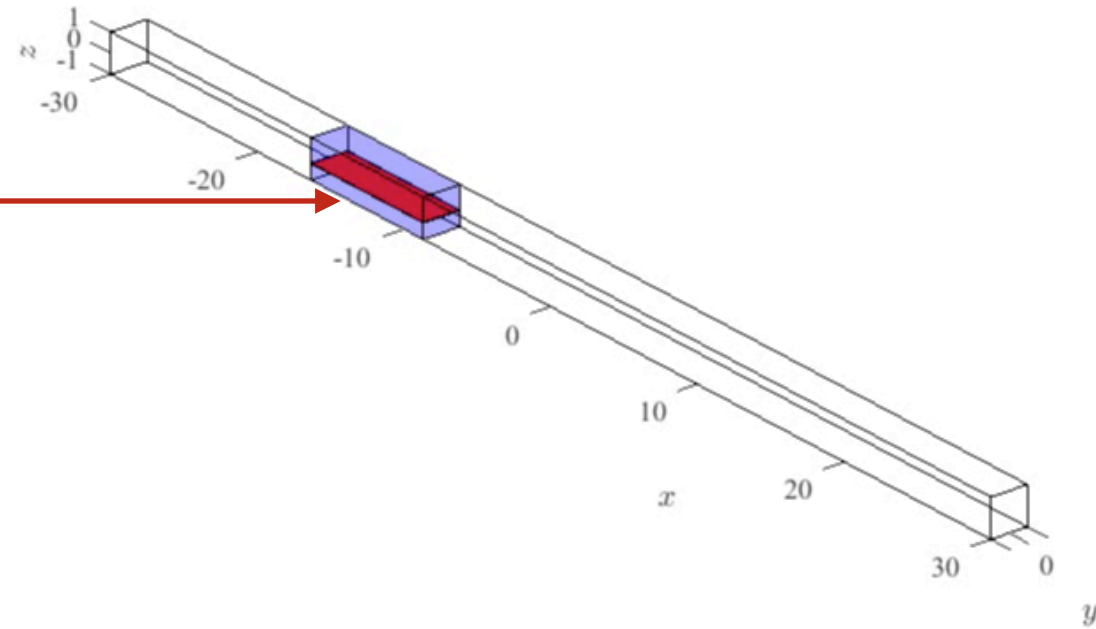


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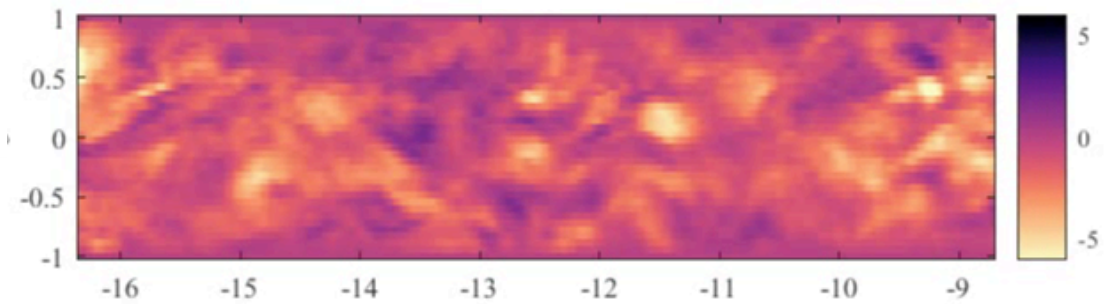
$z = -0.21$

Scan: $t = 0.00$

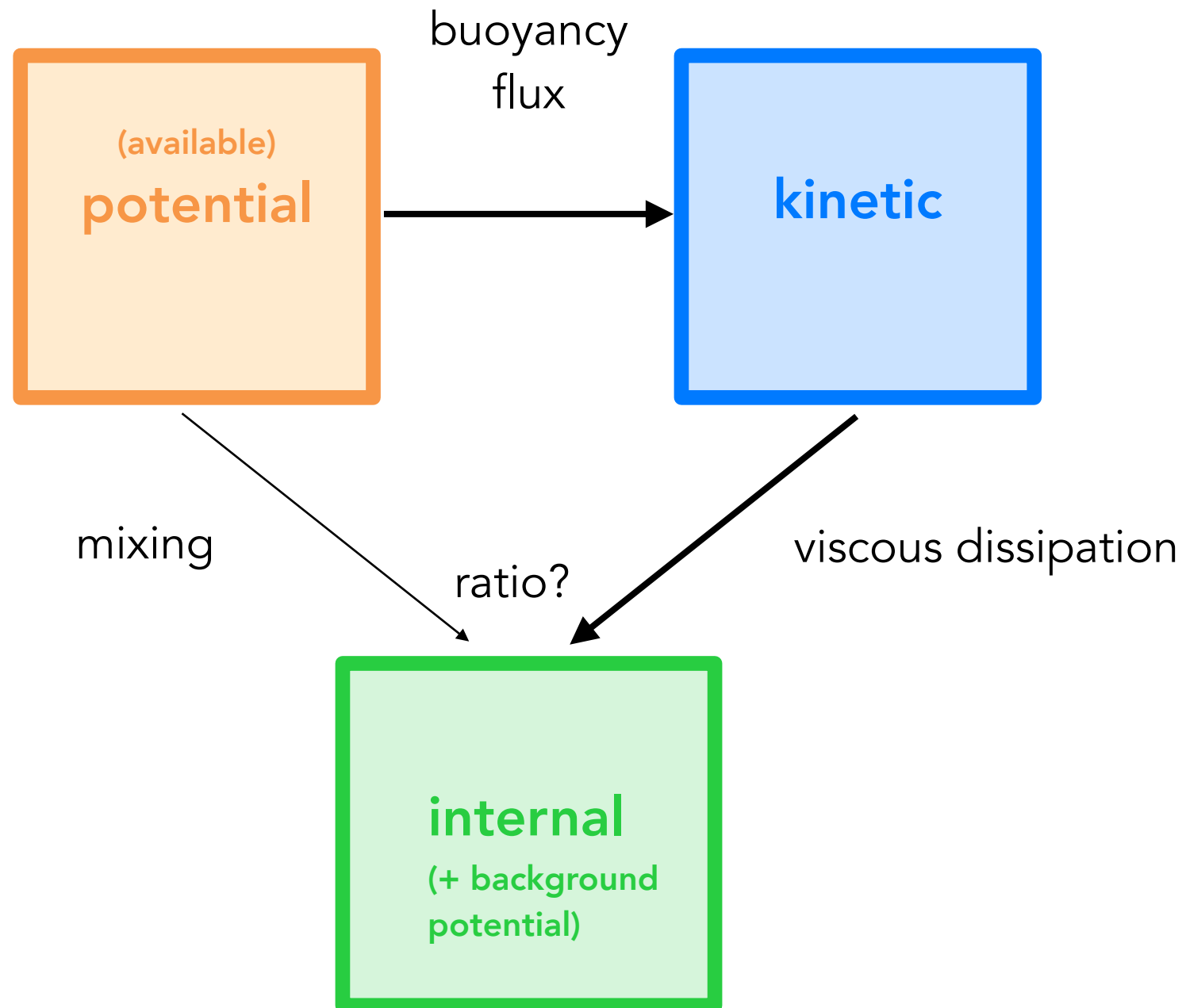
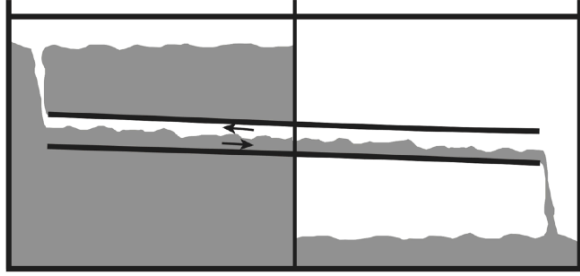
Horizontal plane



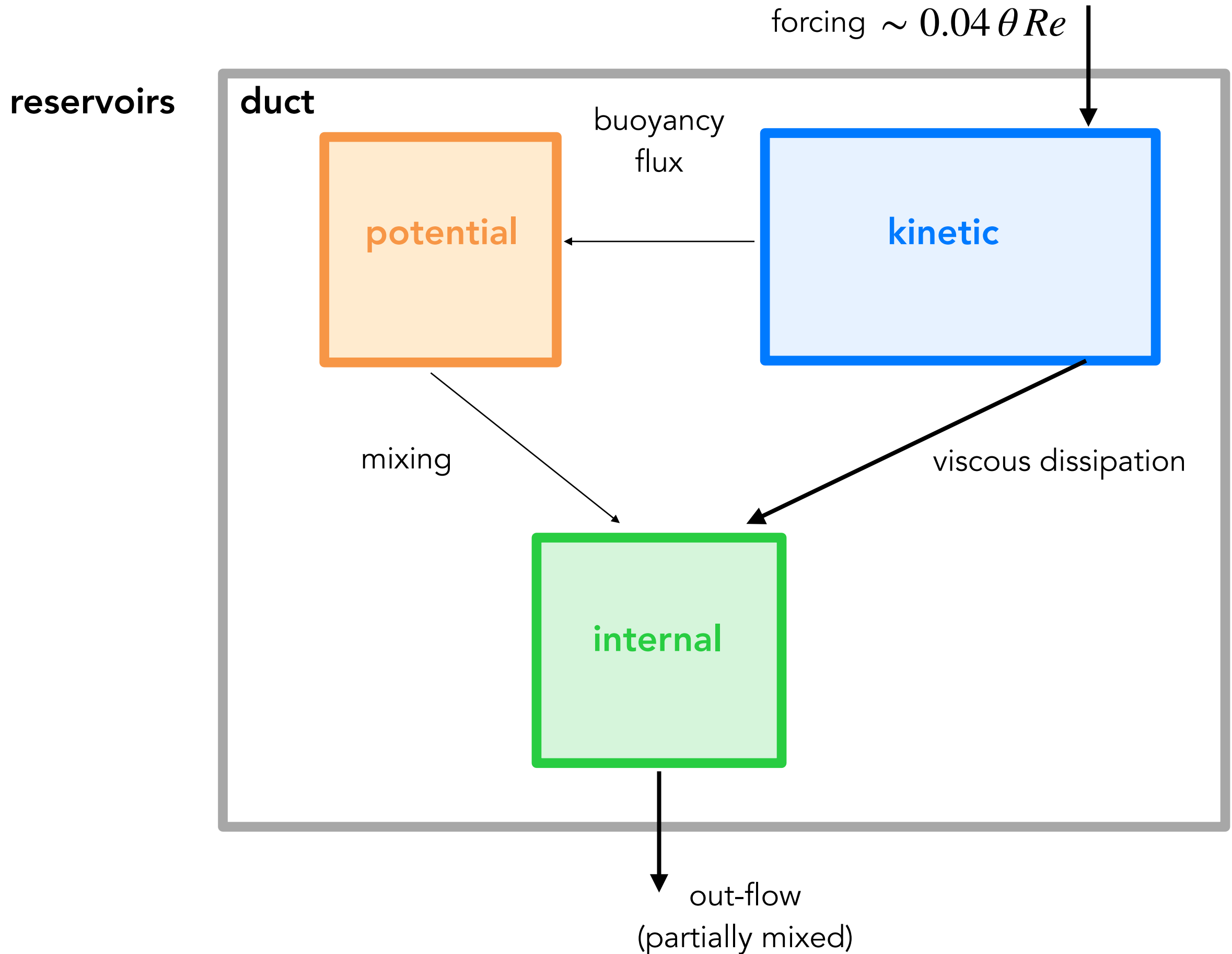
Vorticity ω_y



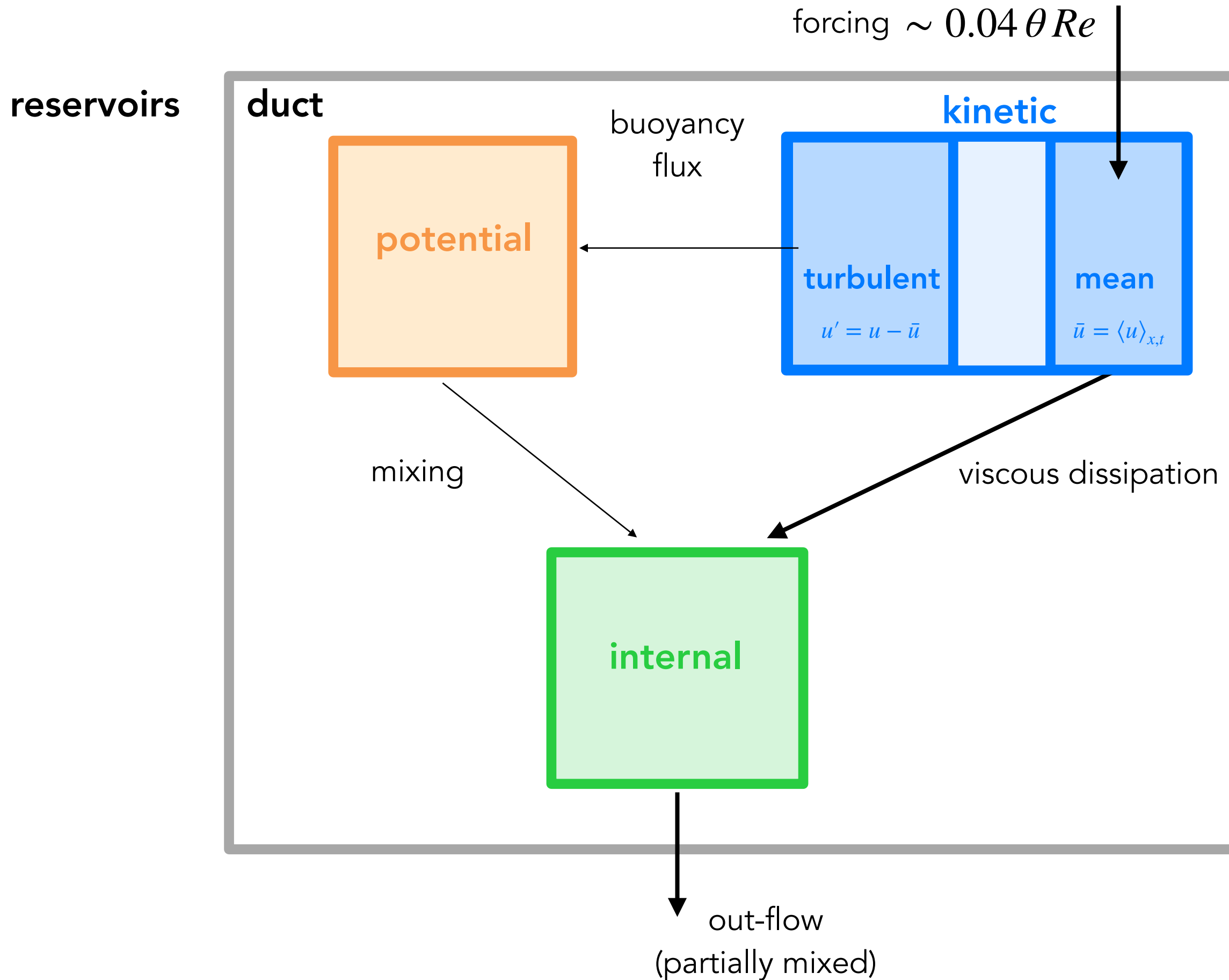
Flow energetics



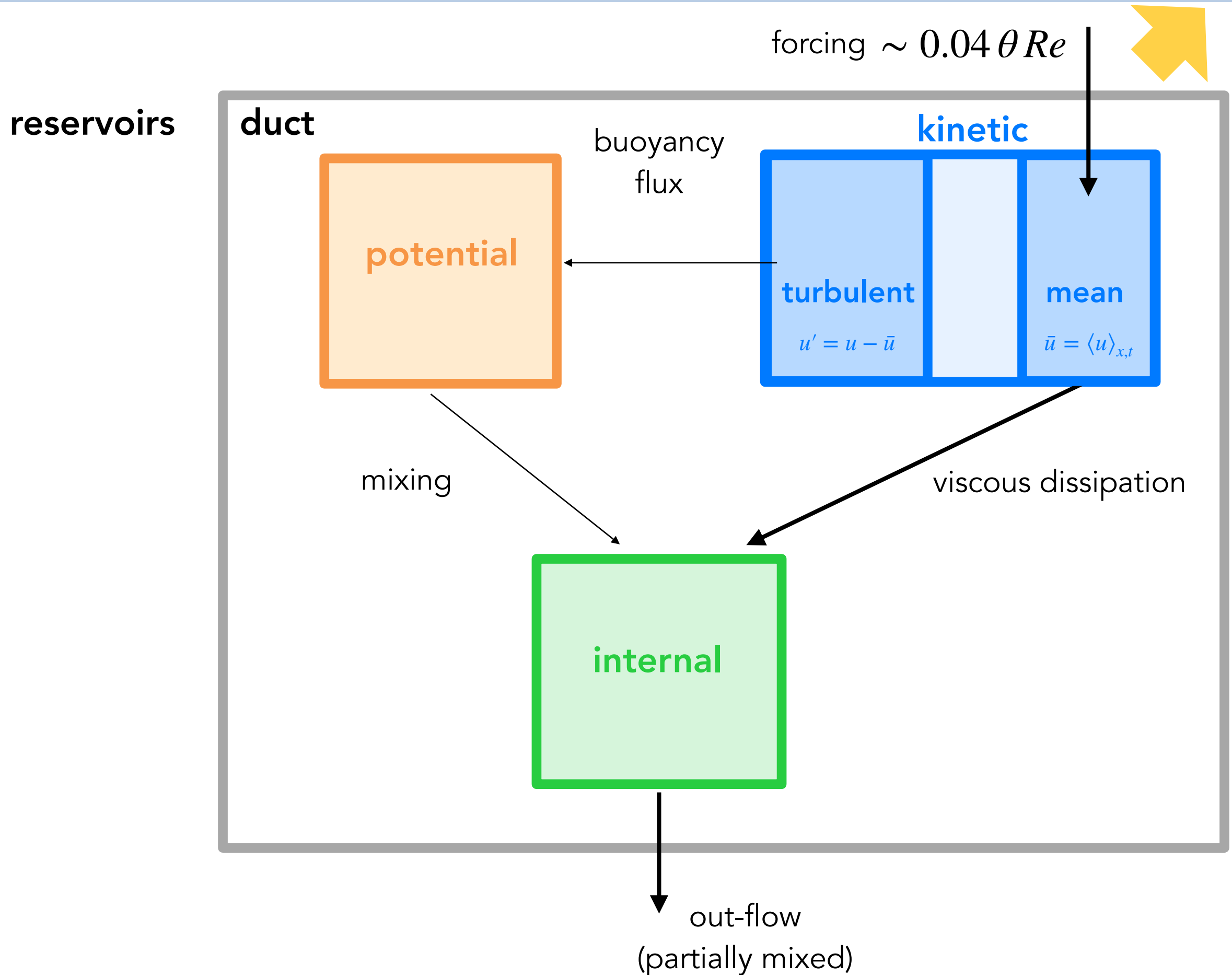
Flow energetics



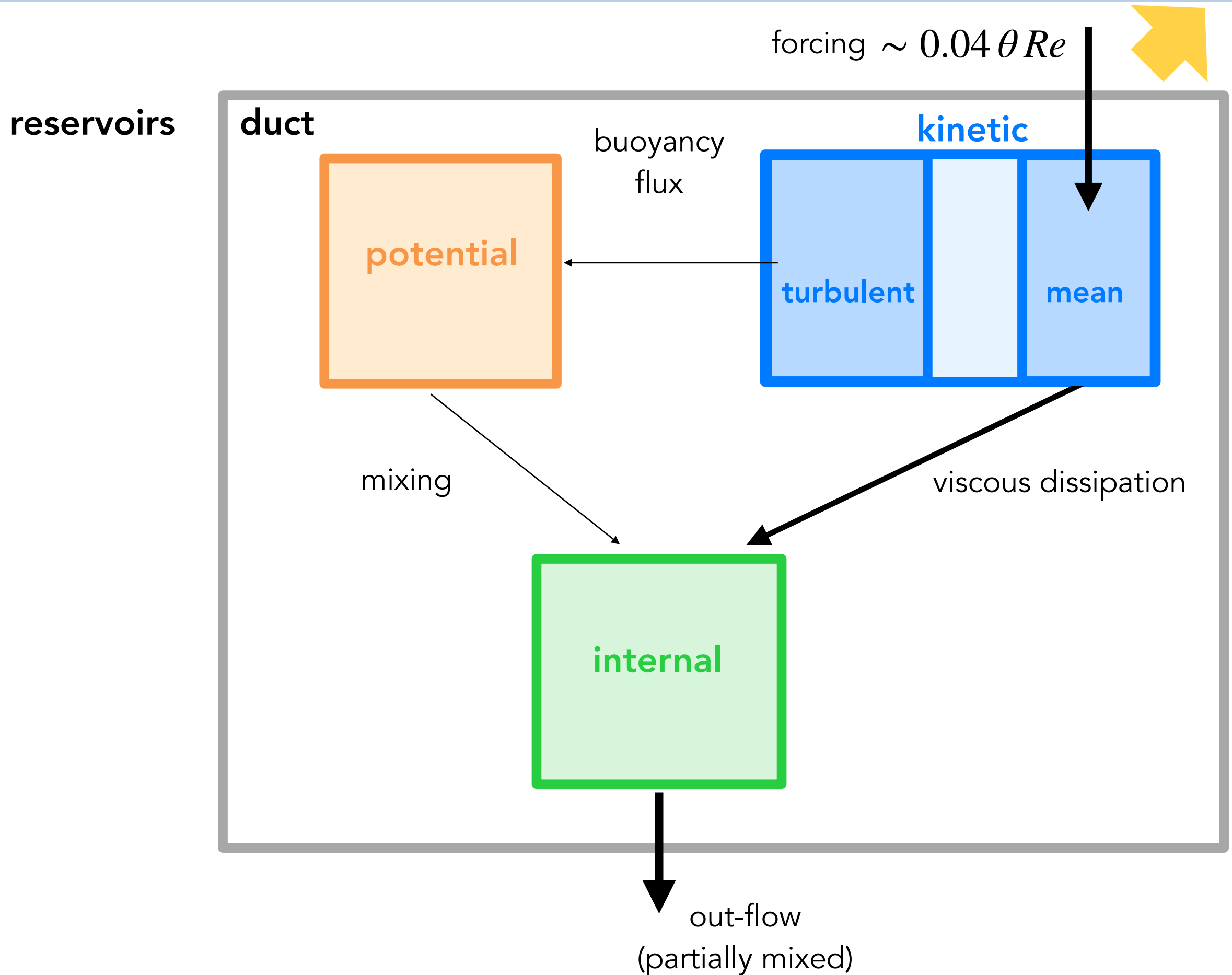
Flow energetics

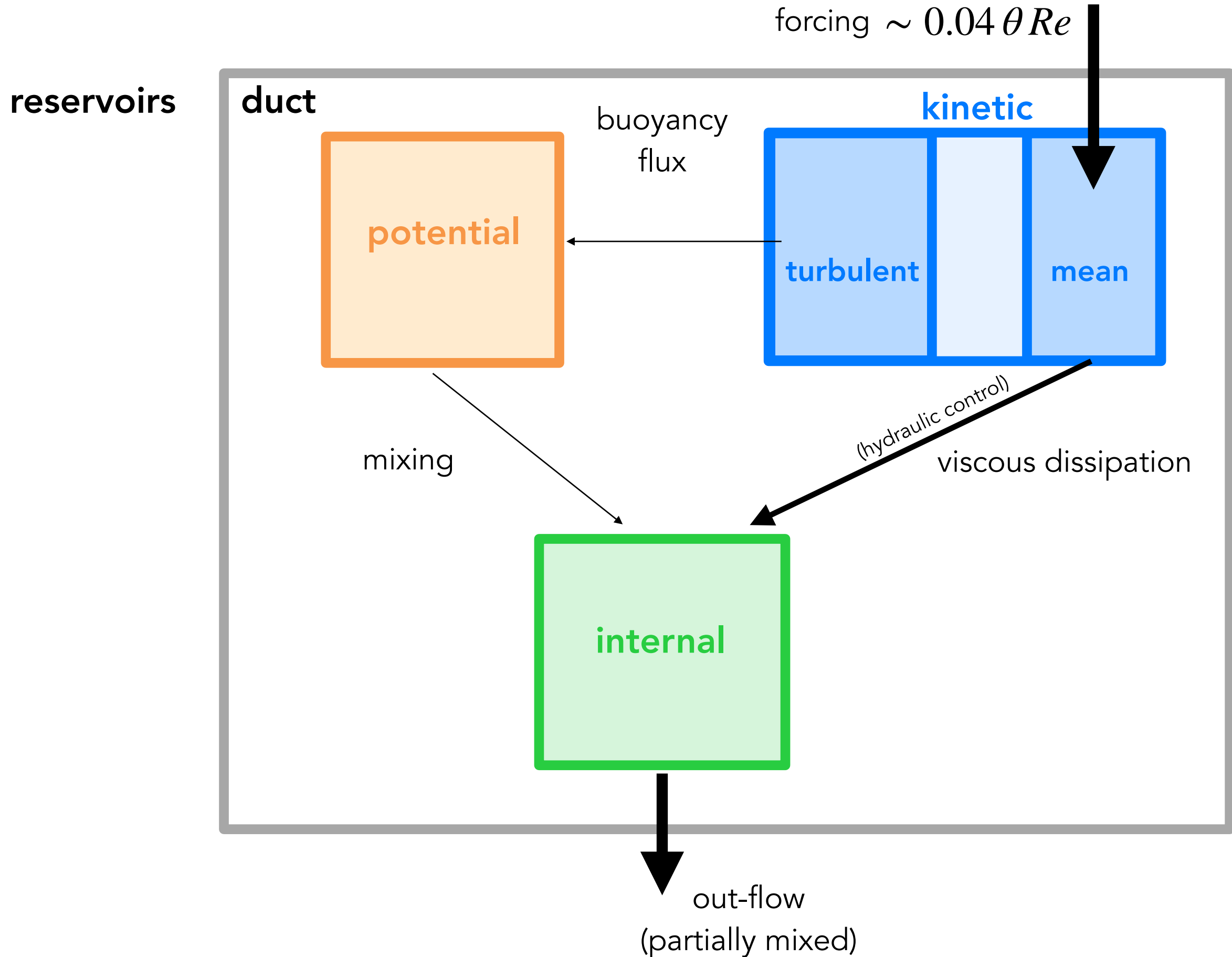


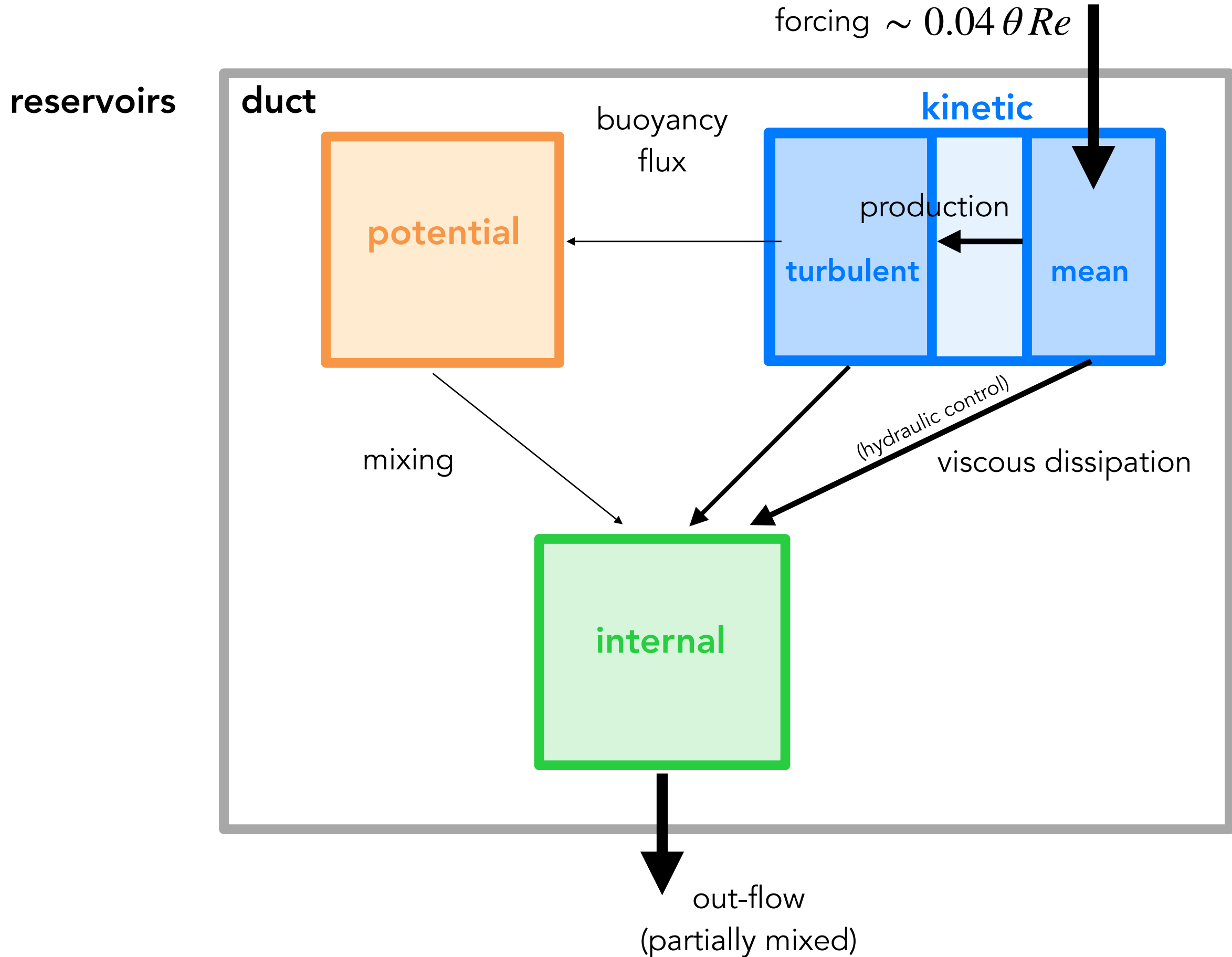
Flow energetics

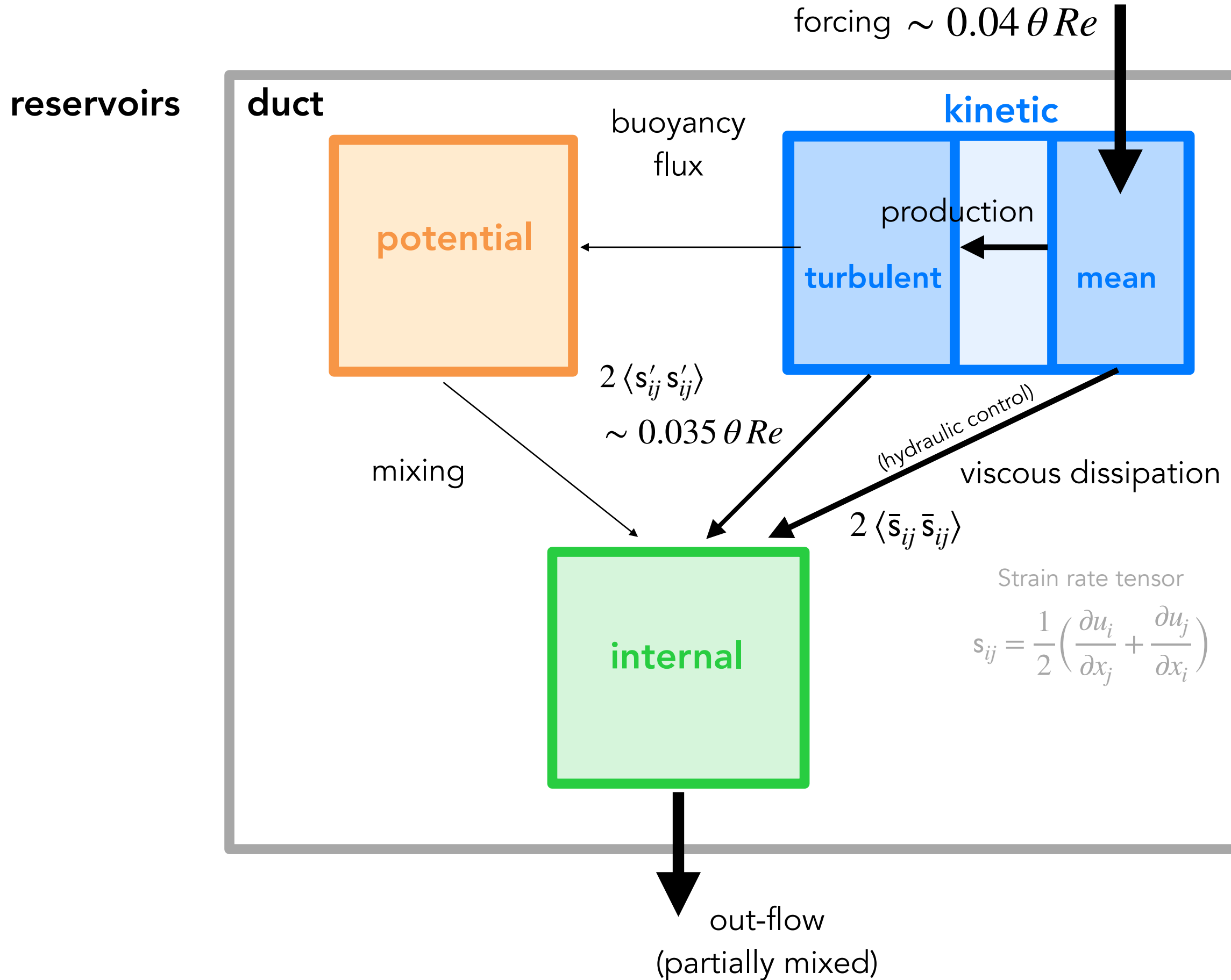


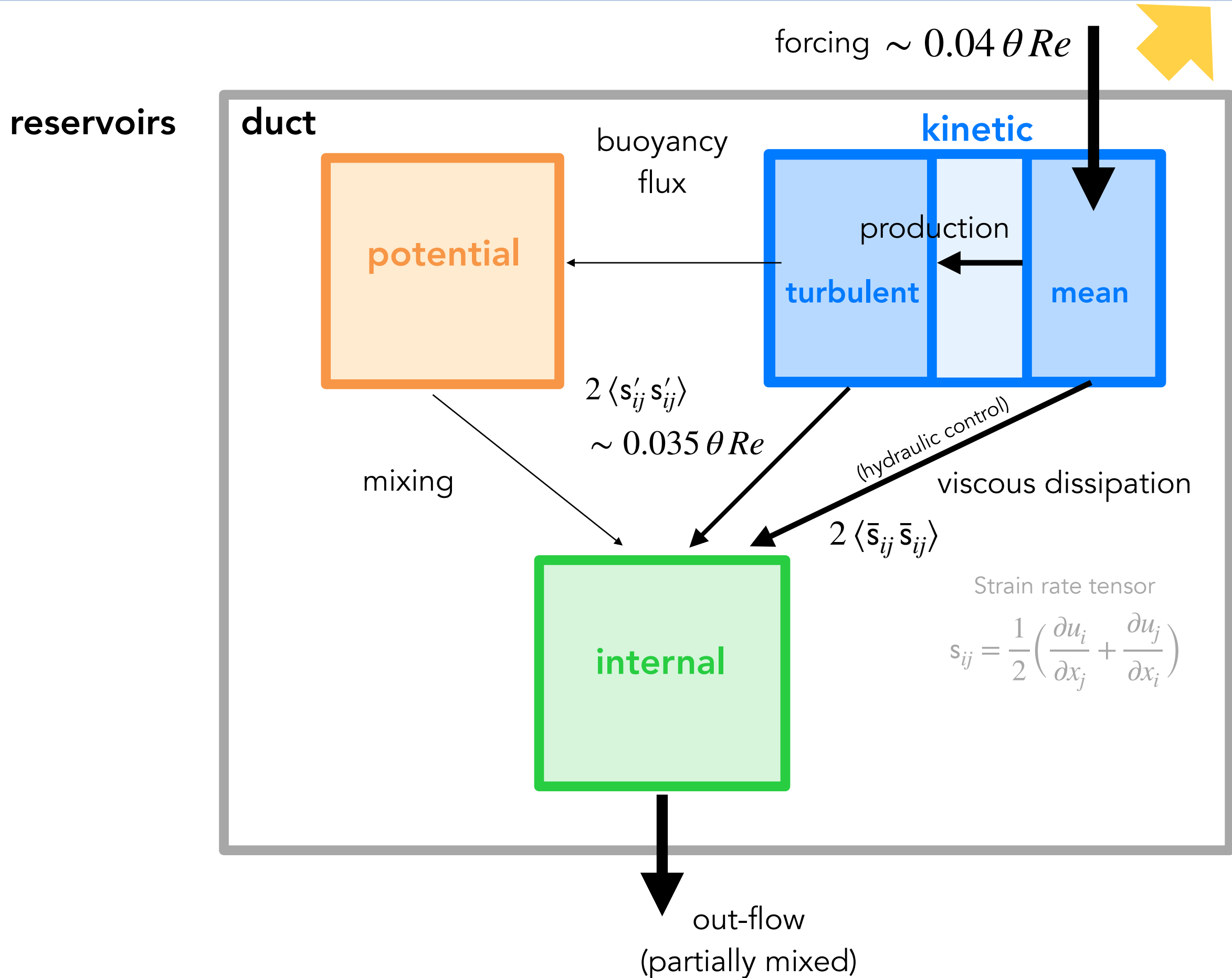
Flow energetics

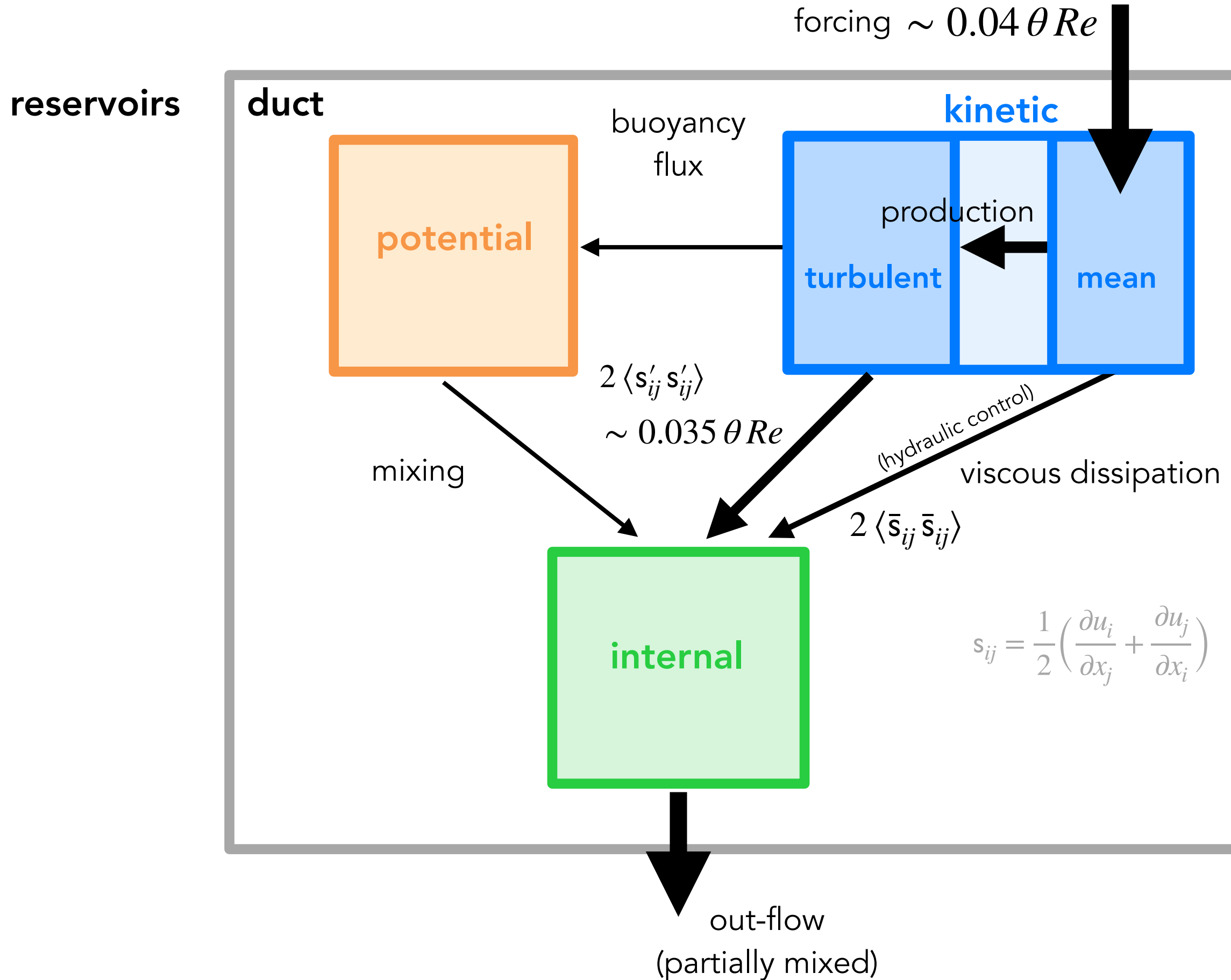


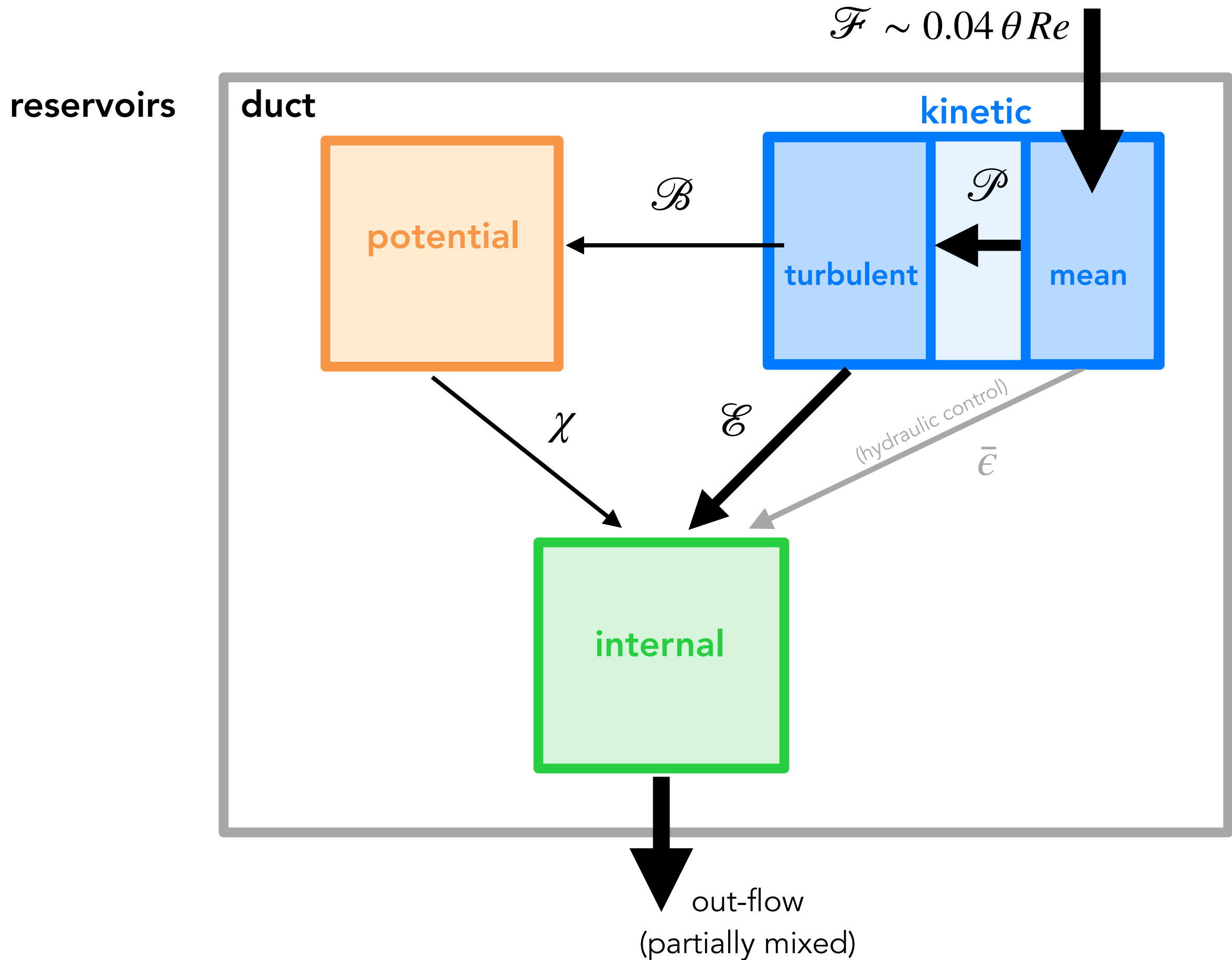


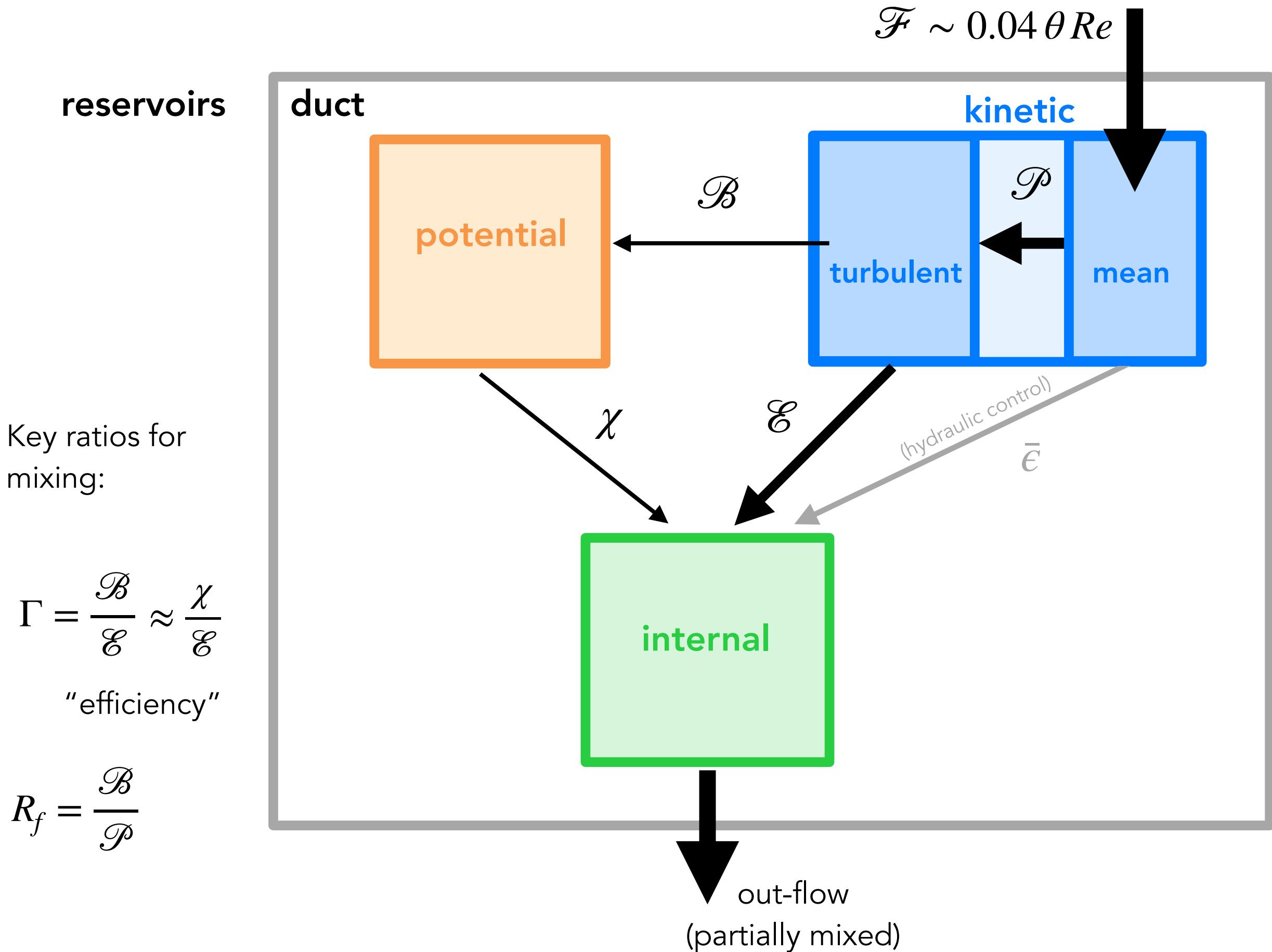


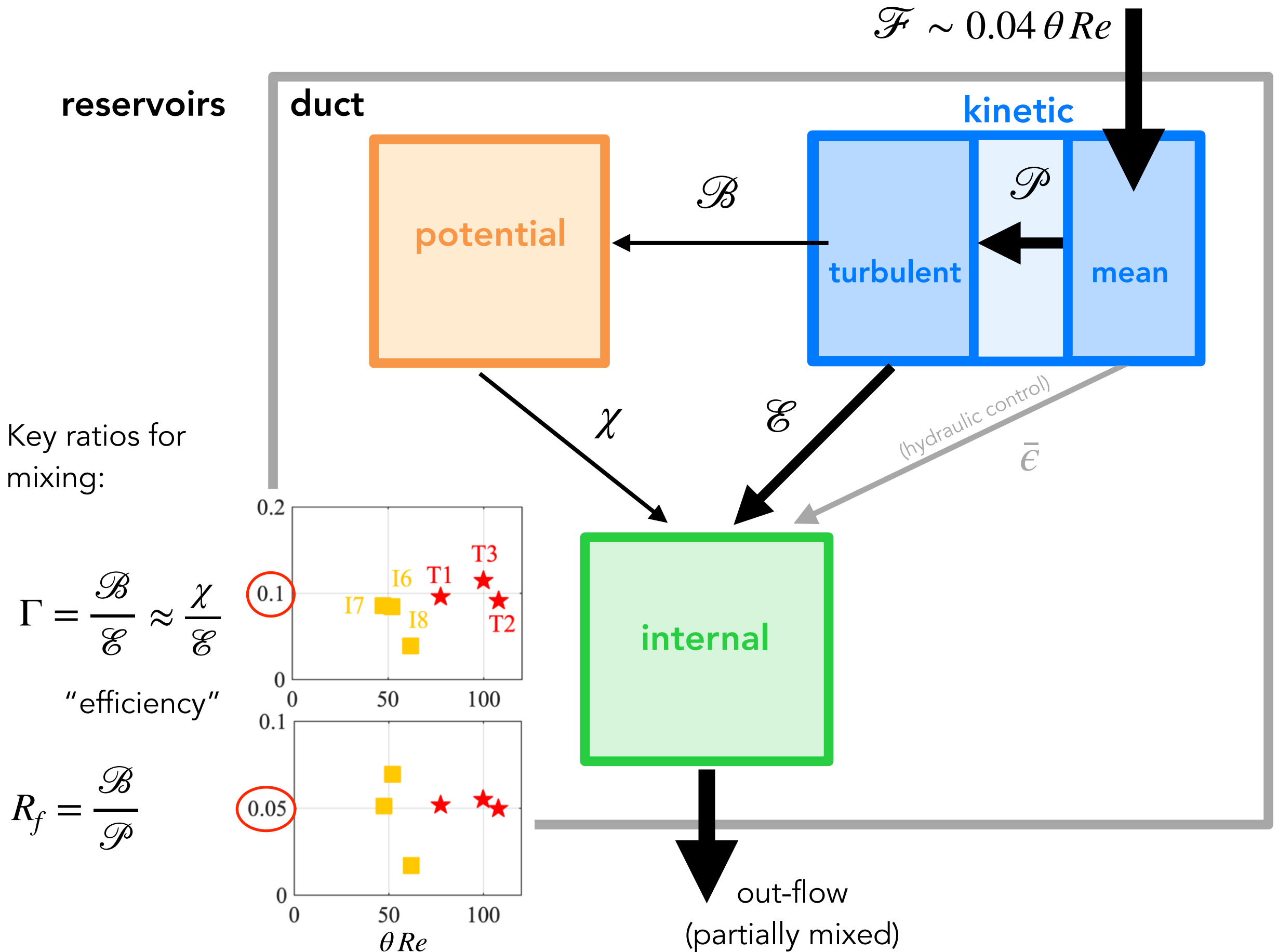






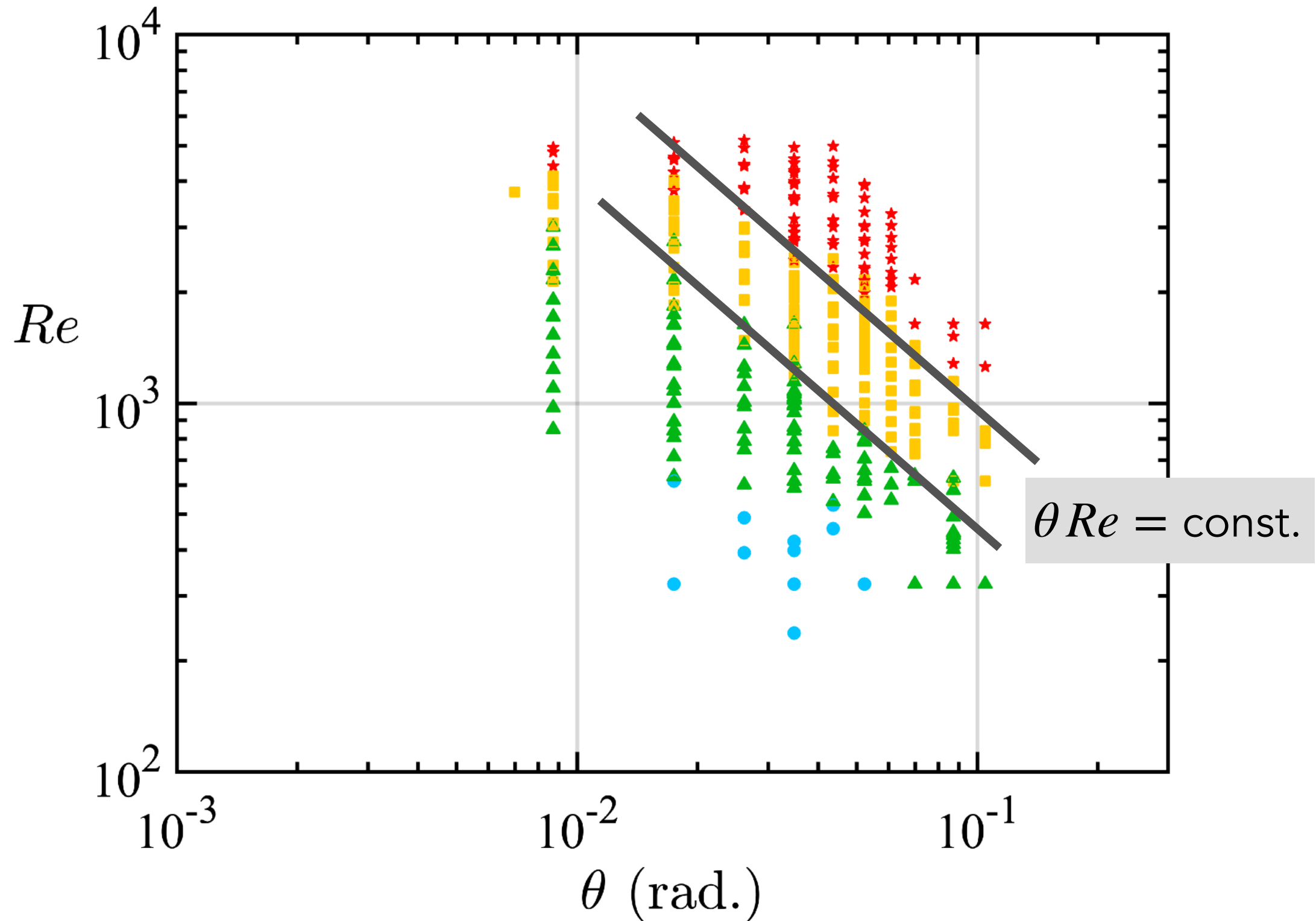






Flow regimes and $\langle s'_{ij} s'_{ij} \rangle \sim \theta Re$

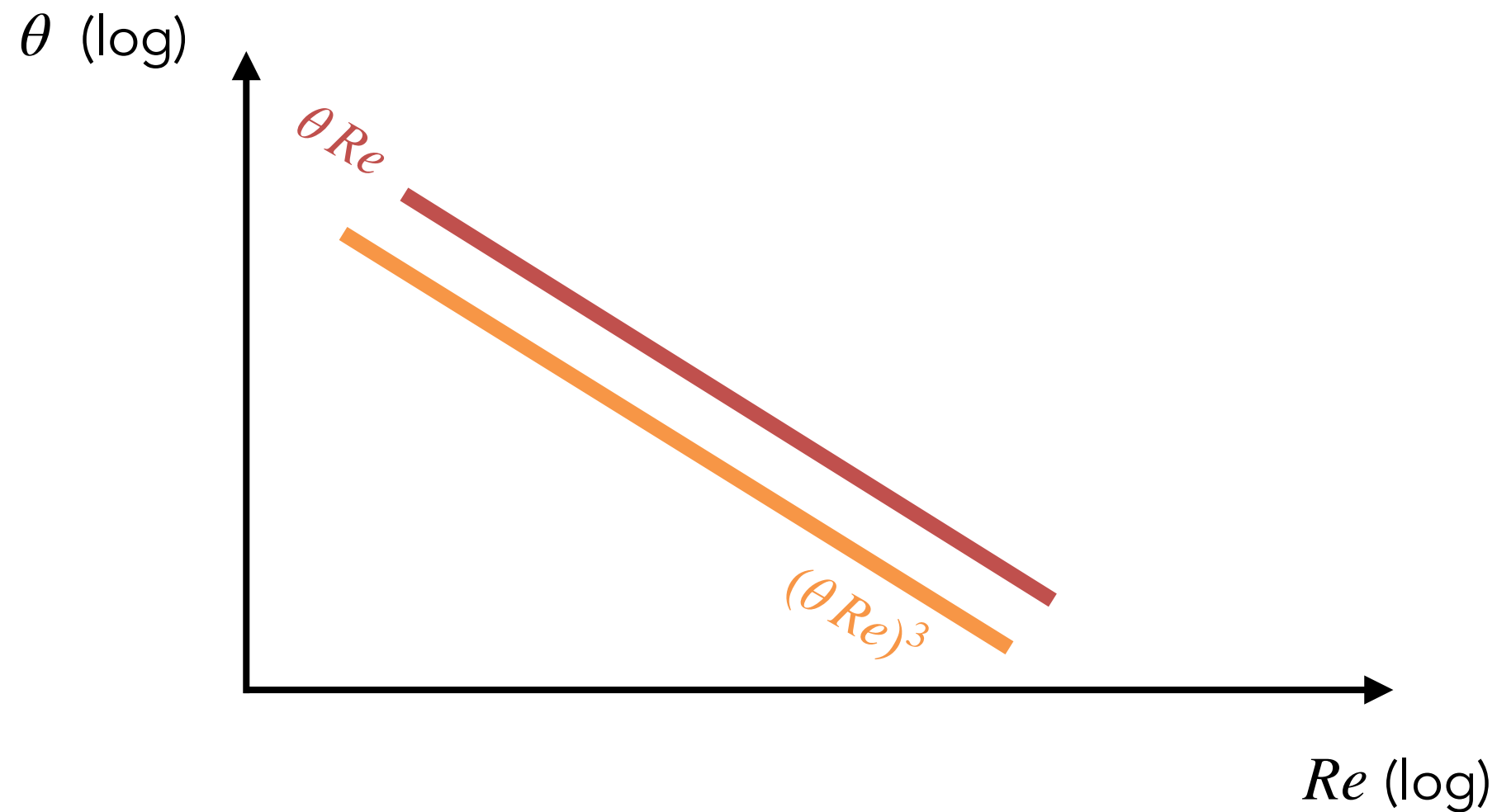
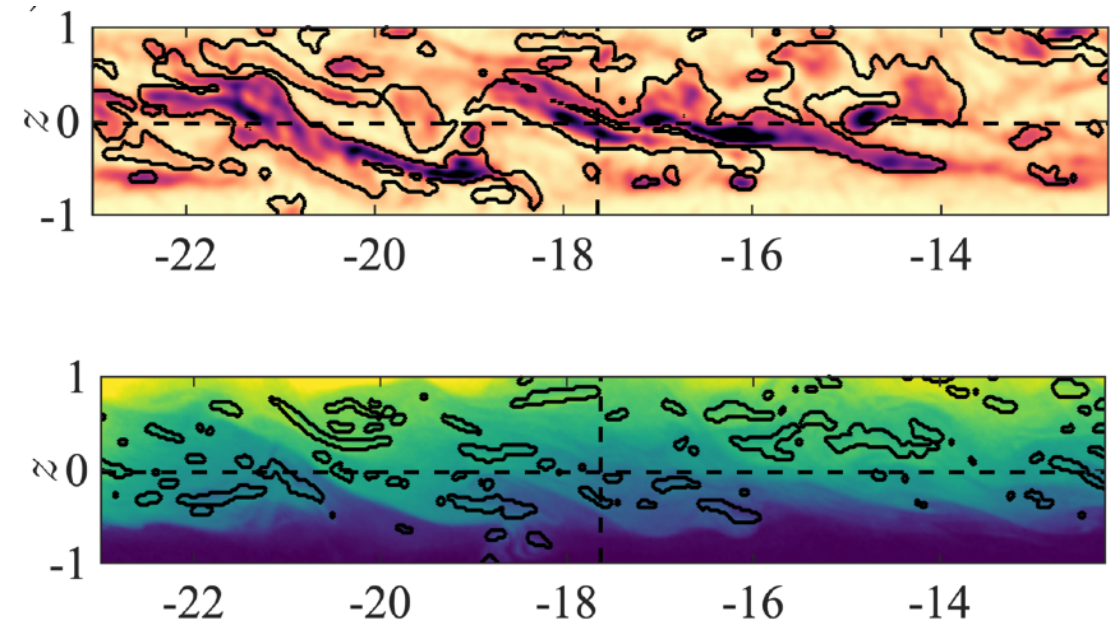
Flow regimes and $\langle s'_{ij} s'_{ij} \rangle \sim \theta Re$



Flow regimes and $\langle s'_{ij} s'_{ij} \rangle \sim \theta Re$

Enstrophy fraction (% of volume where $|\omega'|^2 > 2$)

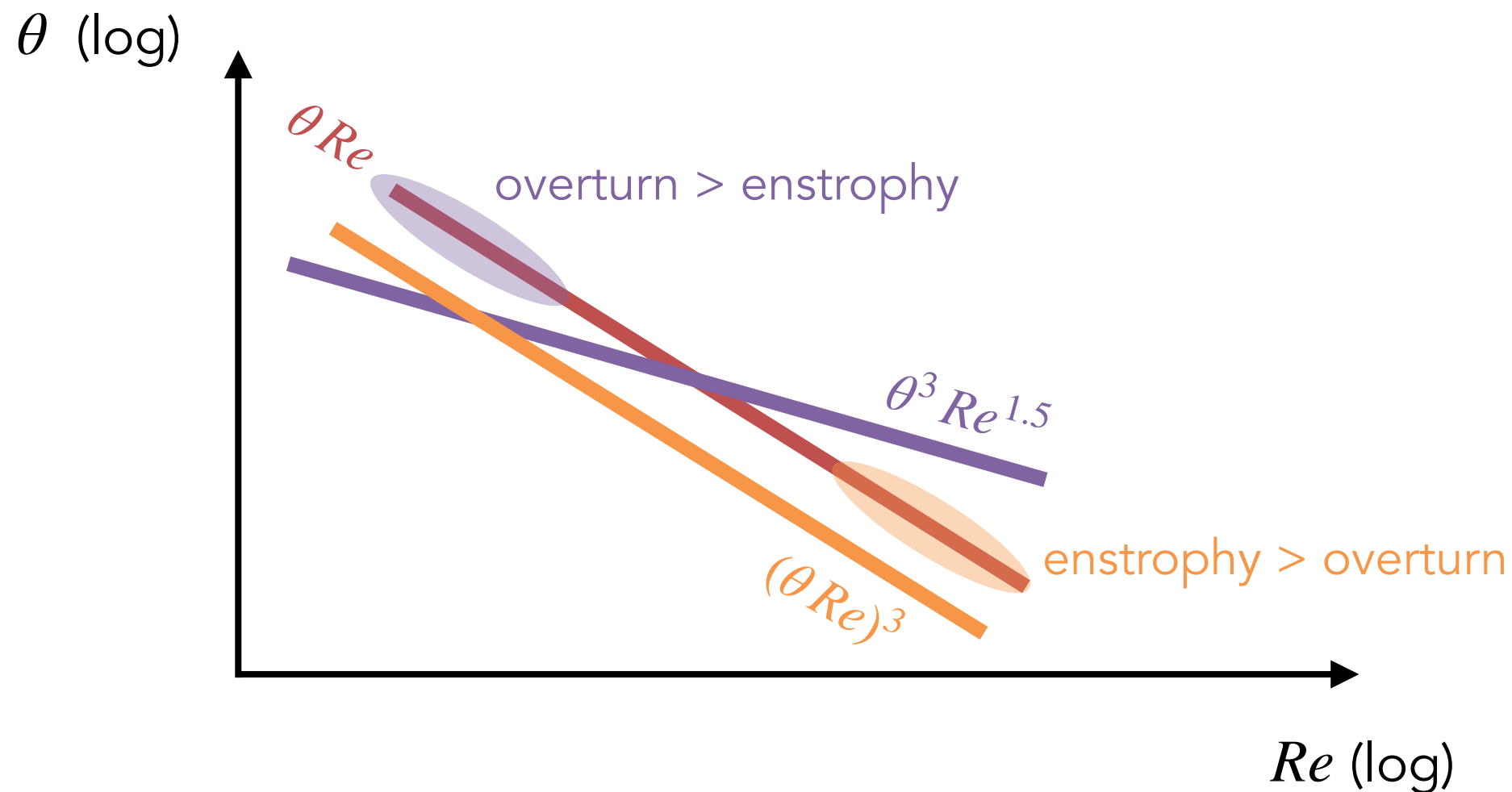
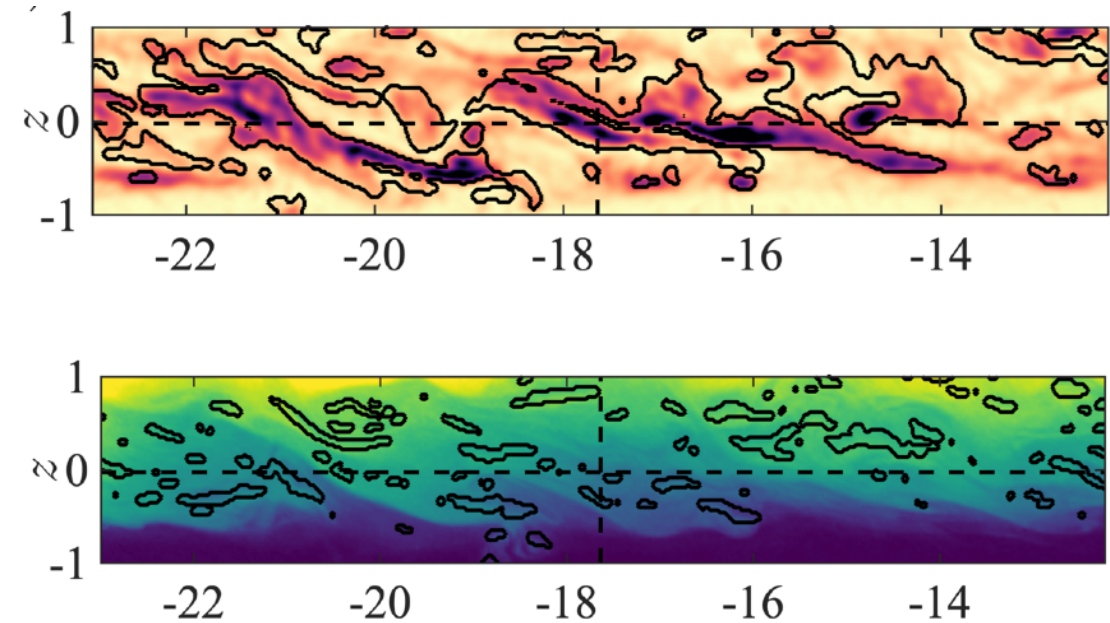
Overturn fraction (% of volume where $\partial_z \rho > 0$)



Flow regimes and $\langle s'_{ij} s'_{ij} \rangle \sim \theta Re$

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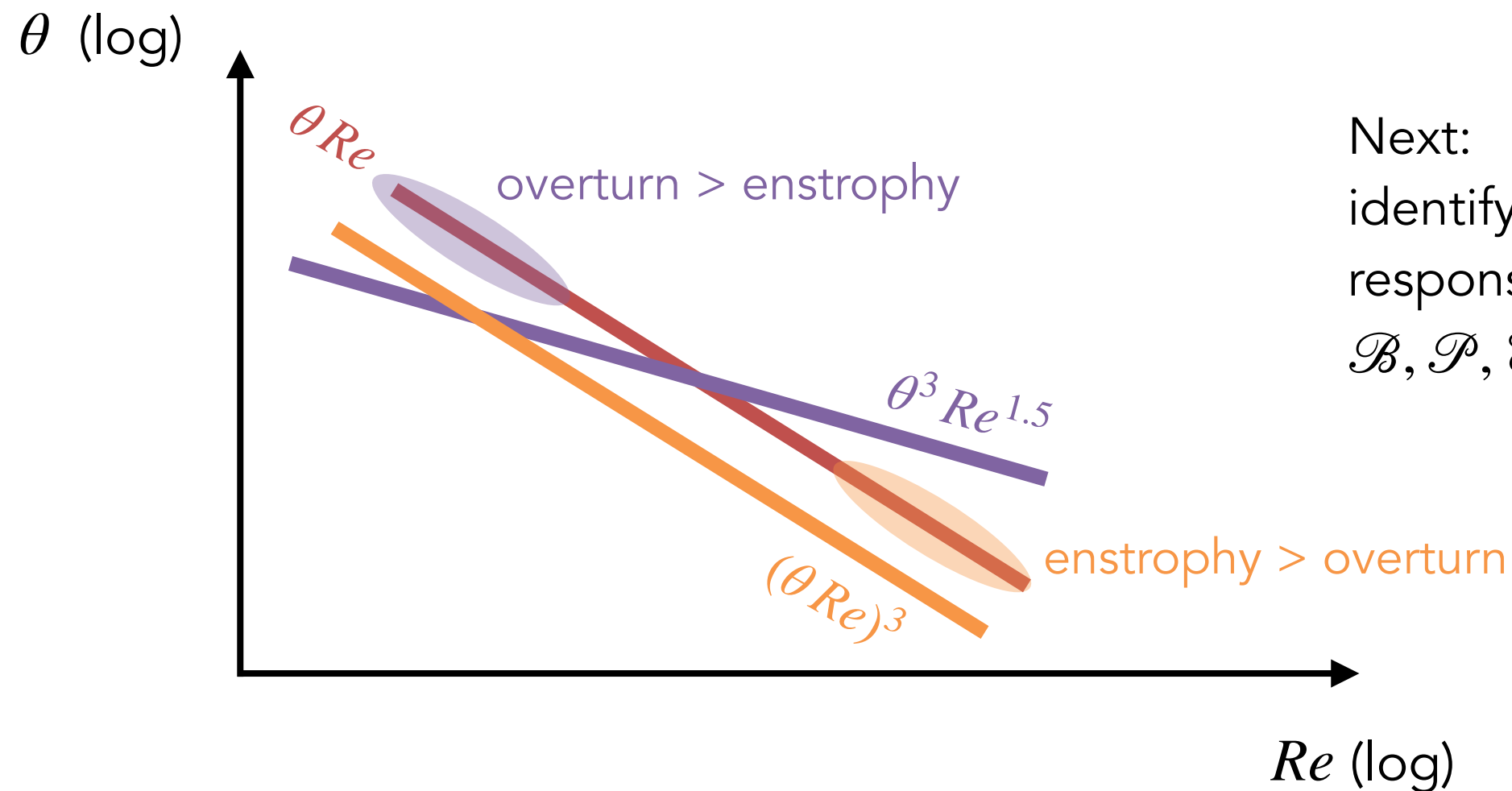
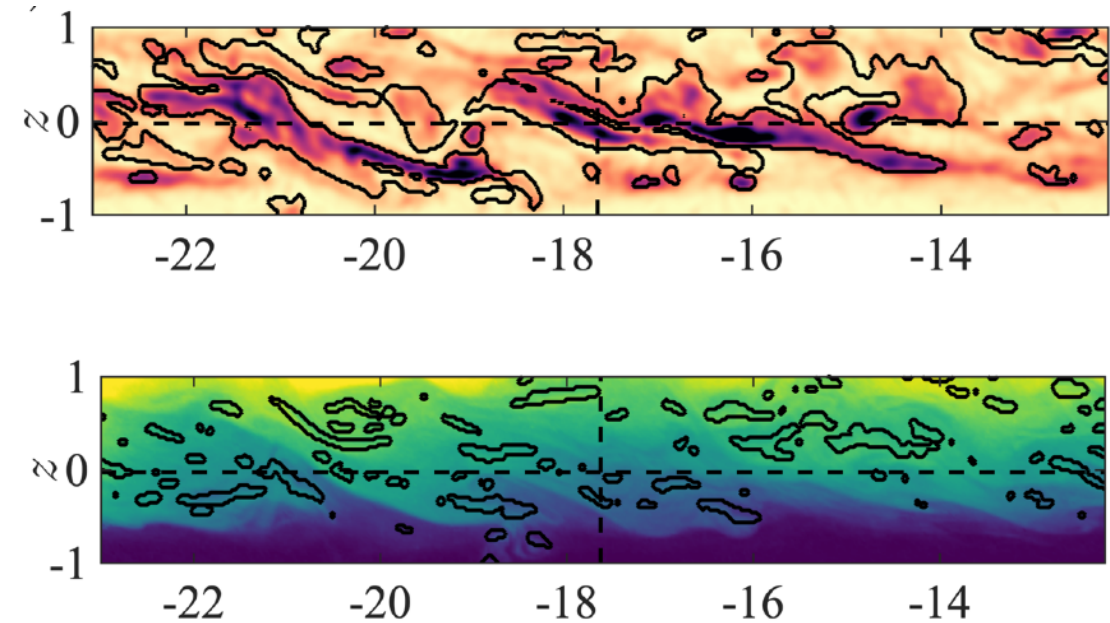
Overturn fraction (% of volume where $\partial_z \rho > 0$)



Flow regimes and $\langle s'_{ij} s'_{ij} \rangle \sim \theta Re$

Enstrophy fraction (% of volume where $|\omega'|^2 > 2$)

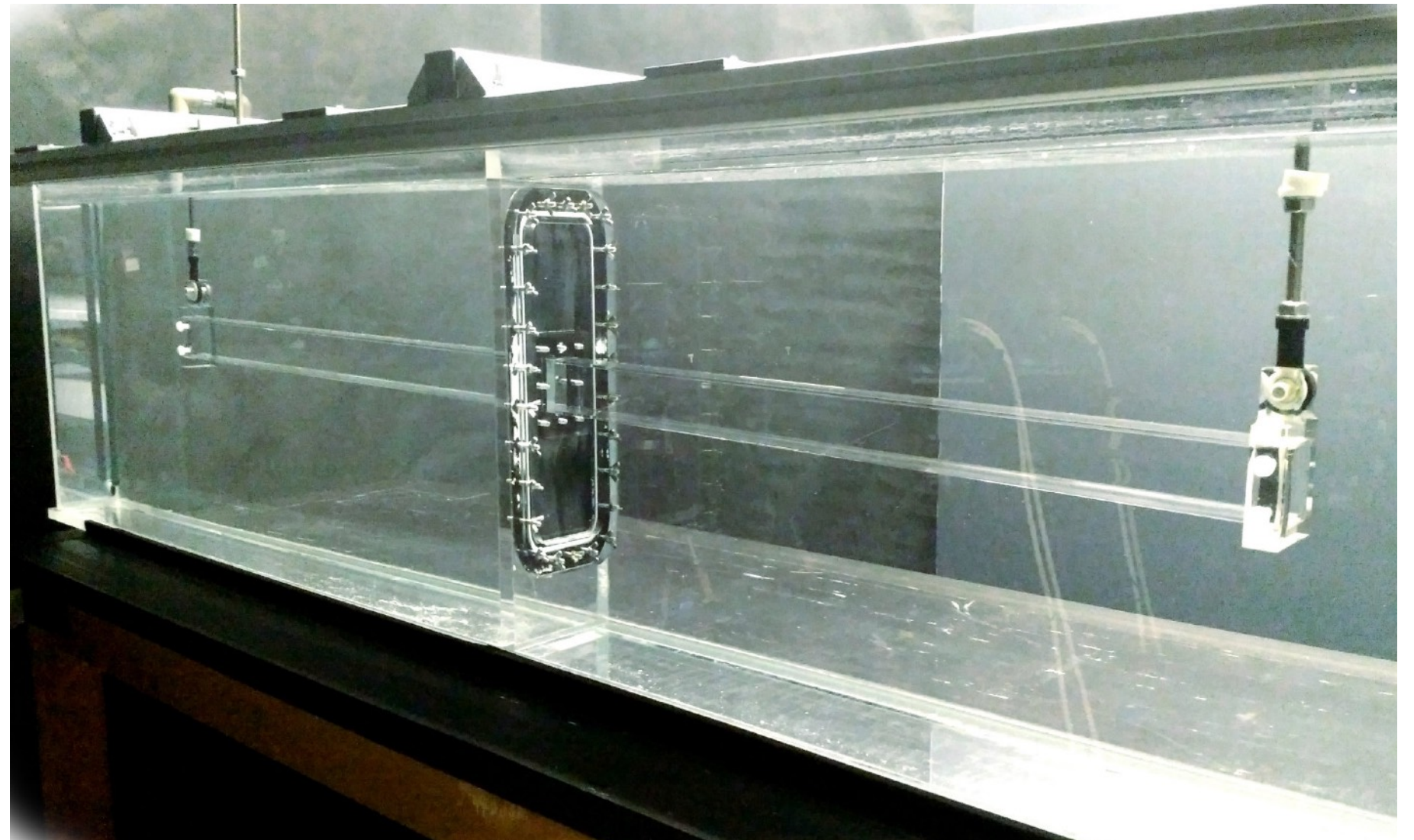
Overturn fraction (% of volume where $\partial_z \rho > 0$)



Next:
identify **flow structures**
responsible for
 $\mathcal{B}, \mathcal{P}, \mathcal{E}, \chi \dots$

The future

A new setup



The future

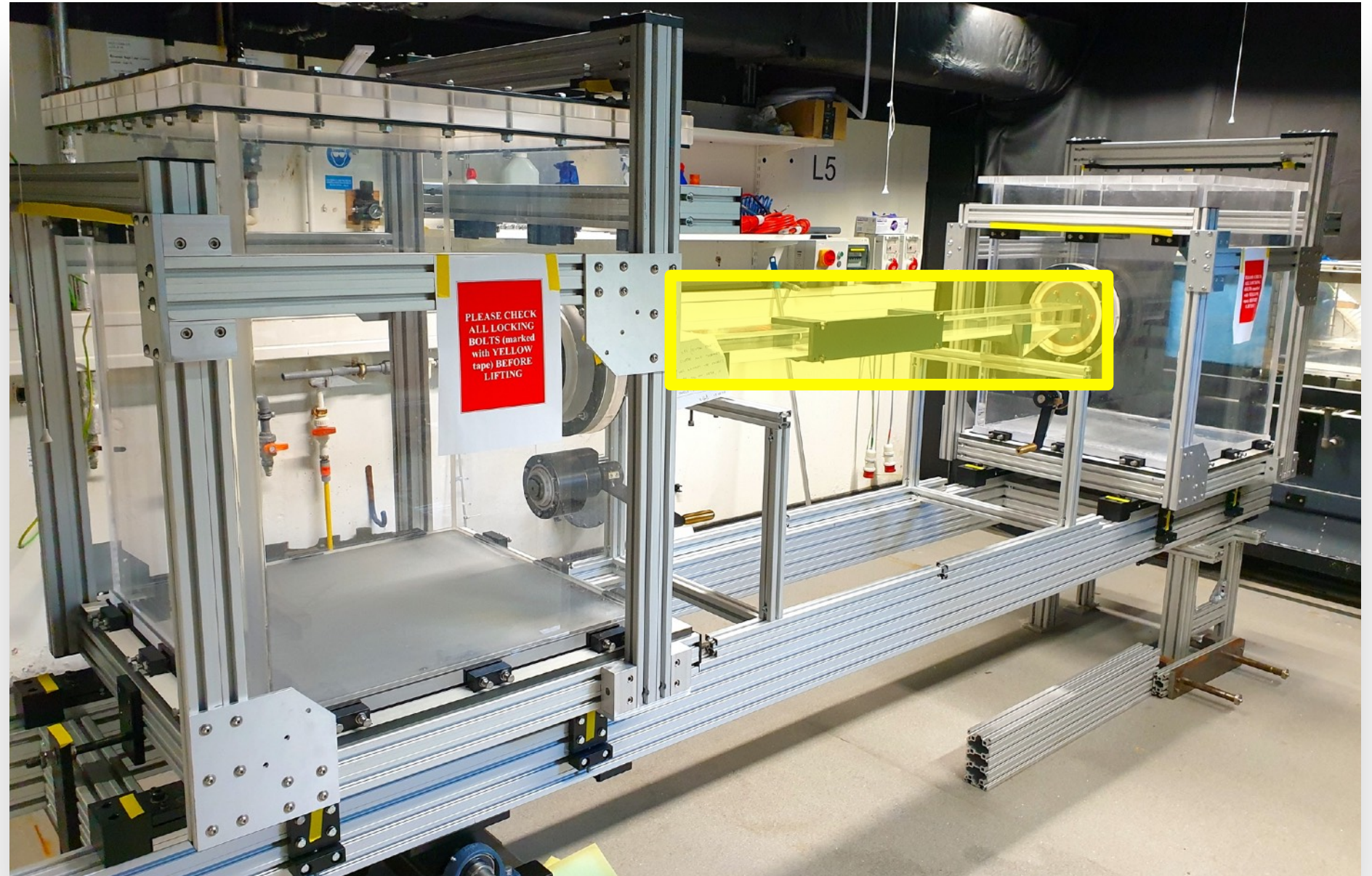
A new setup



The future

A new setup

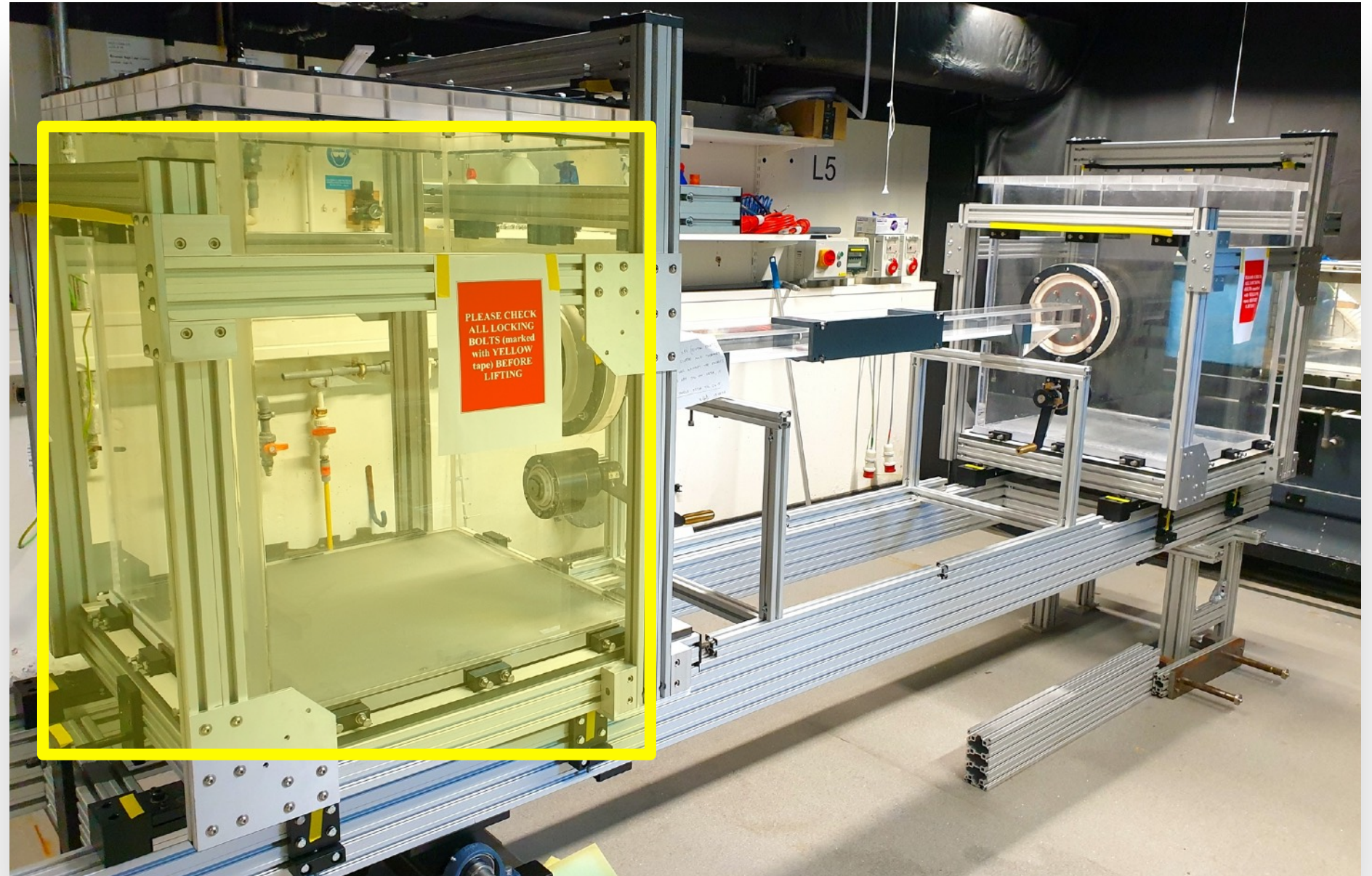
- Clearer optics (duct in air)
- Longer run times
- No free surfaces
- Adjust tilt during experiment



The future

A new setup

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The future

A new setup

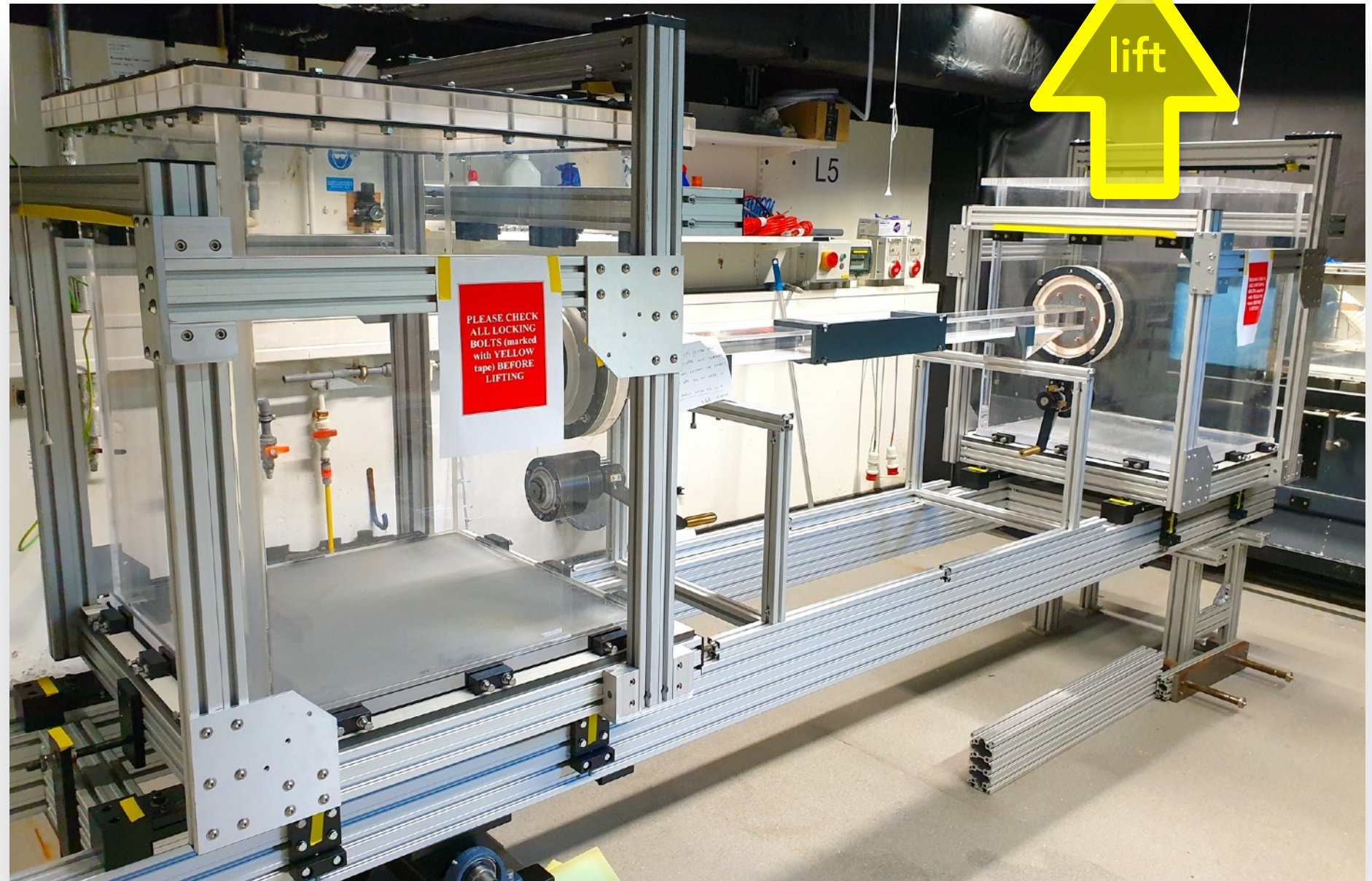
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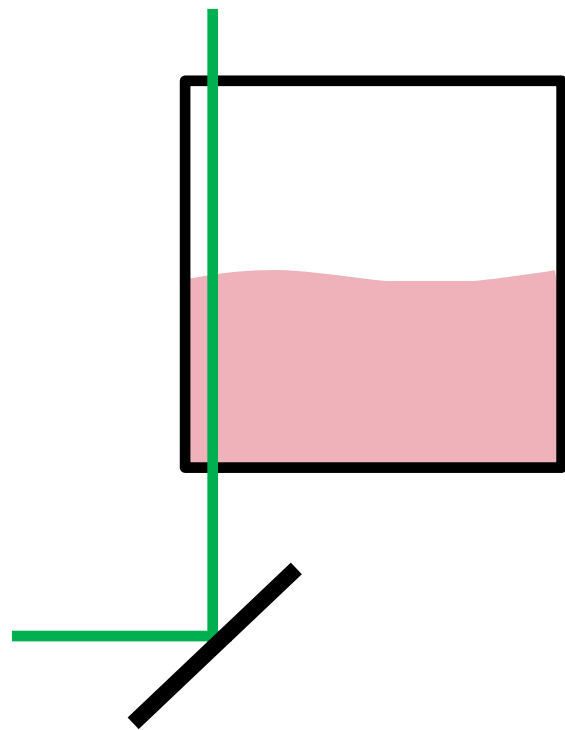
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Faster laser, cameras



100 planes / s

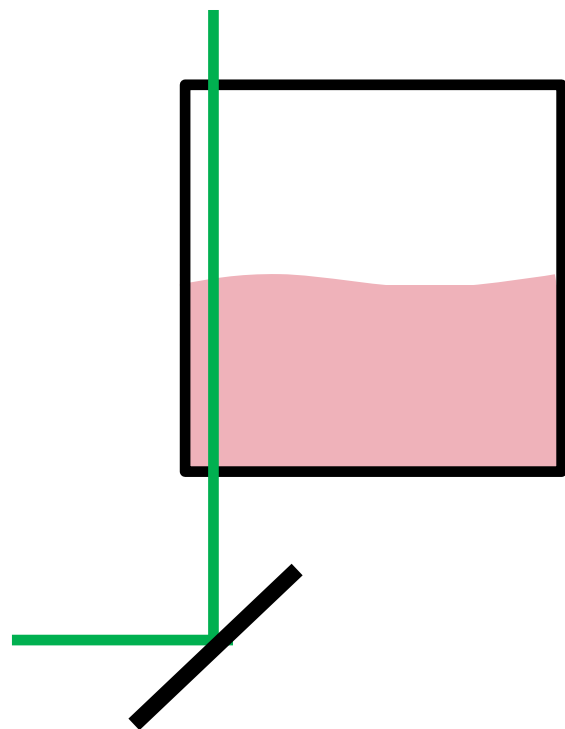
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100 planes / s

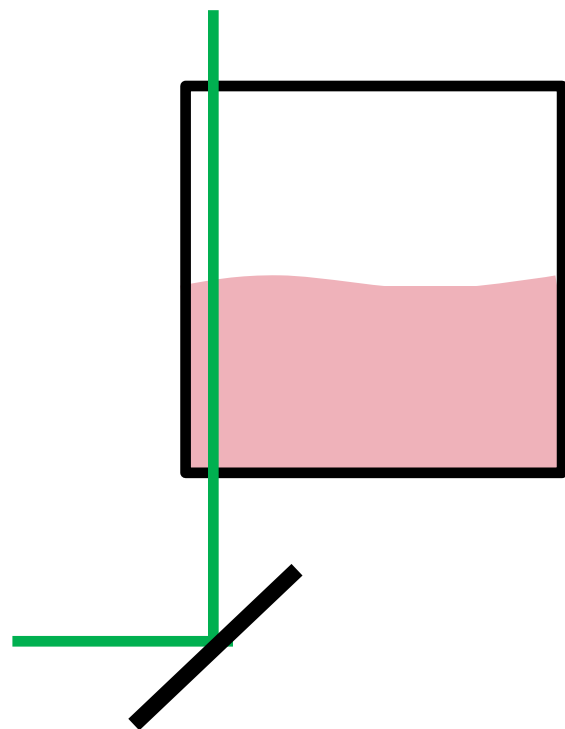
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Faster laser, cameras



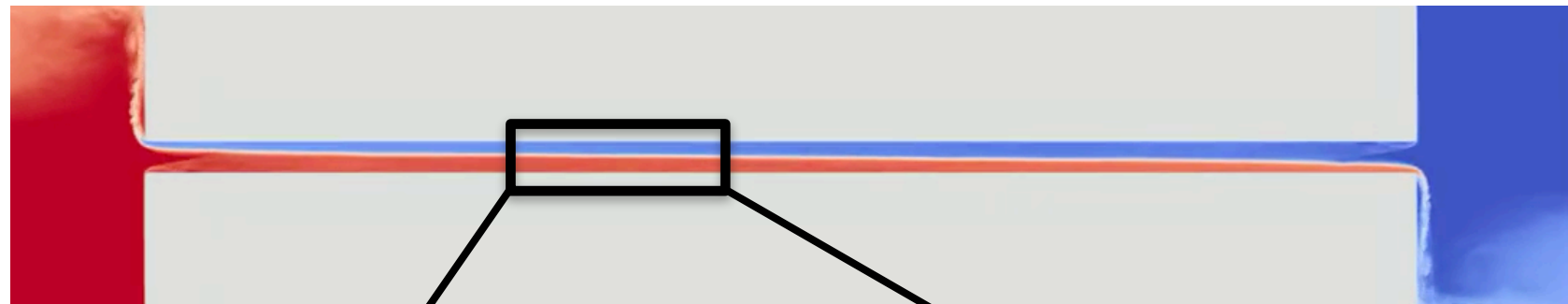
1000 planes / s

- More instantaneous volume reconstruction
- Higher spatial and temporal resolution

The future

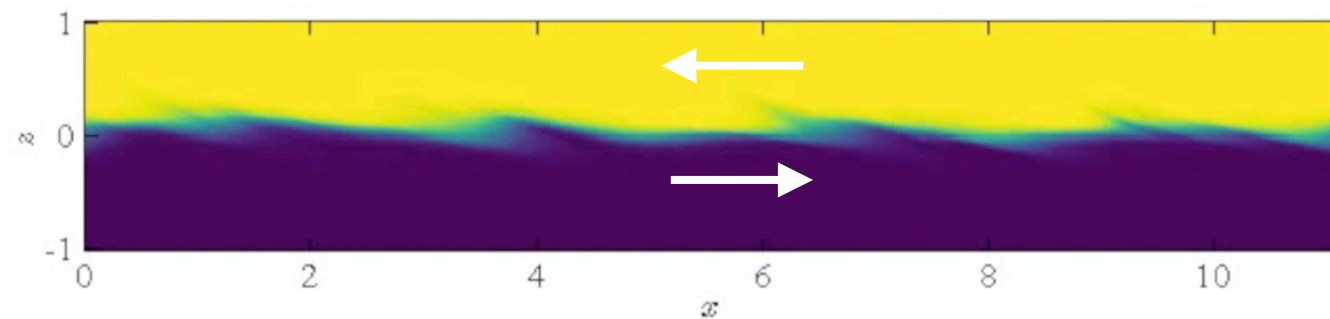
Numerical simulations

Lower resolution,
full geometry
("easy" BCs)



Credit:
Ricardo Frantz
(Code: Xcompact3D)

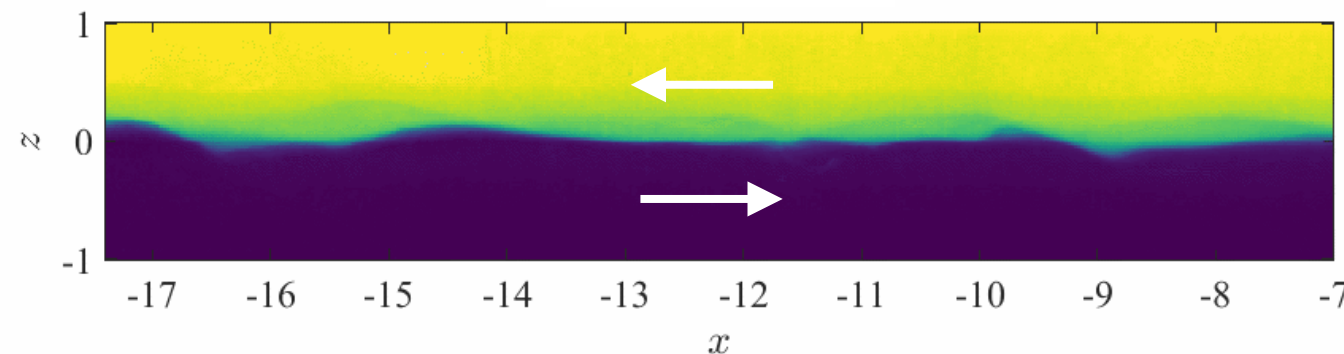
Higher resolution,
duct sub-section
("hard" BCs)



Credit:
Qi Zhou (Code: Diablo)

Experiments

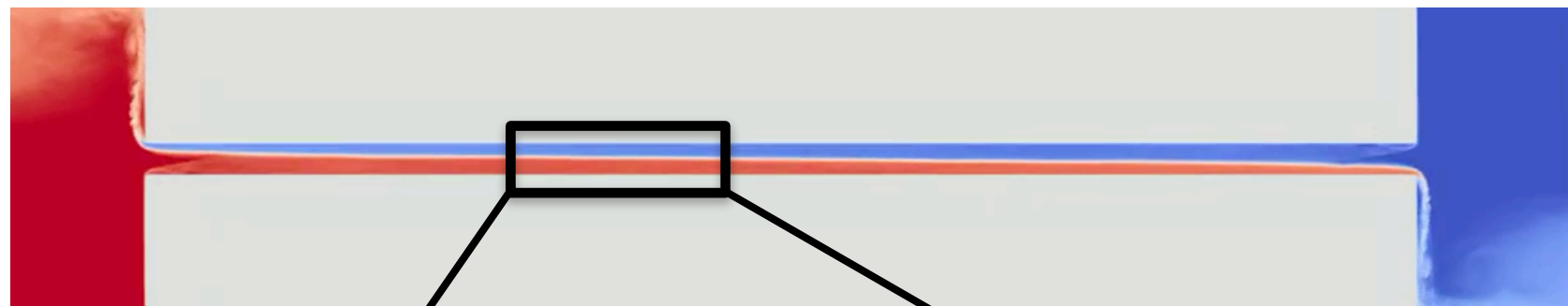
"Real" flow but errors
"Low" resolution



The future

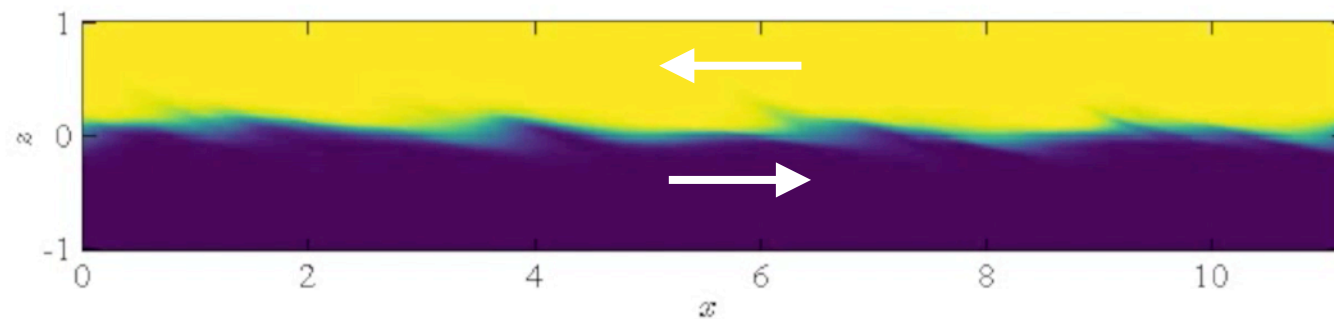
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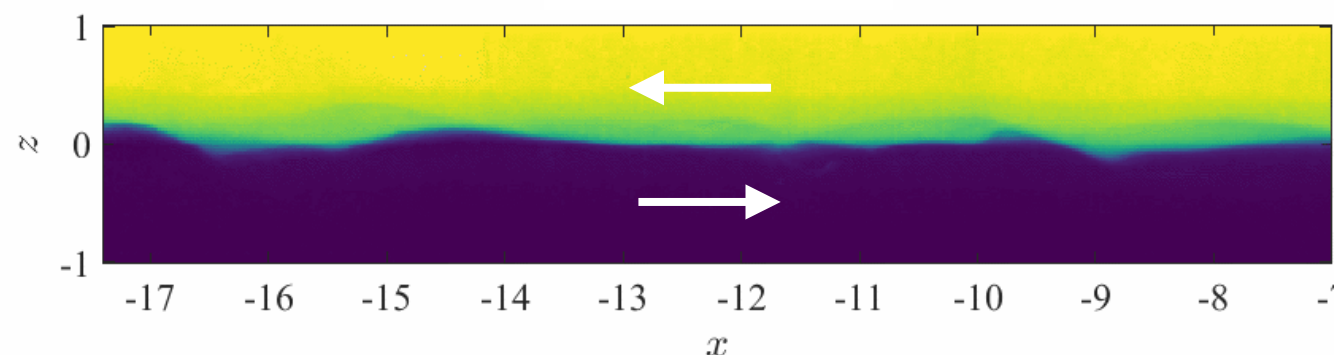
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Experiments

"Real" flow but errors
"Low" resolution



data
assimilation

The future

