Energy dissipation caused by boundary layer instability at vanishing viscosity

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Journées Kolmogorov d'Evry 2018
Université d'Evry-Val-d'Essone
September 26th 2018

1750: Euler's problem

On 16 May 1748 Euler, president of the Prussian Academy of Sciences, read the problem he proposed for the Prize of Mathematics to be given in 1750 :

'Deduce from new principles, as simple as possible,
a theory to explain the resistance
exerted on a body moving in a fluid,
as a function of the body's velocity, shape and mass,
and of the fluid's density and compressibility'.

Six mathematicians, including d'Alembert, sent a manuscript, but Euler was not satisfied with them and decided to postpone the prize to 1752.

Grimberg, *D'Alembert et les équations aux dérivées partielles en hydrodynamique, Thèse de Doctorat, Université de Paris VII, 1998*

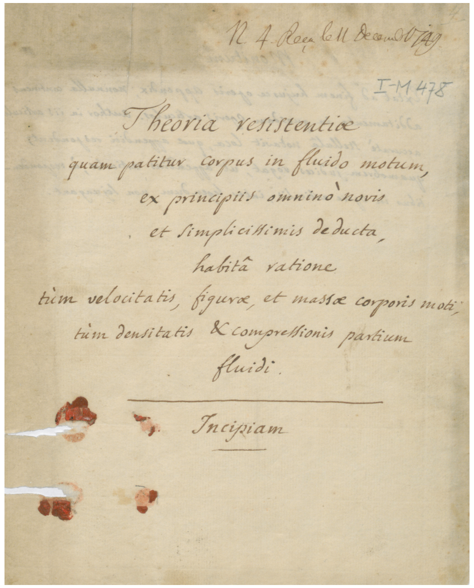
Leonhard Euler
(1707-1783)

Jean Le Rond d'Alembert
(1717-1783)

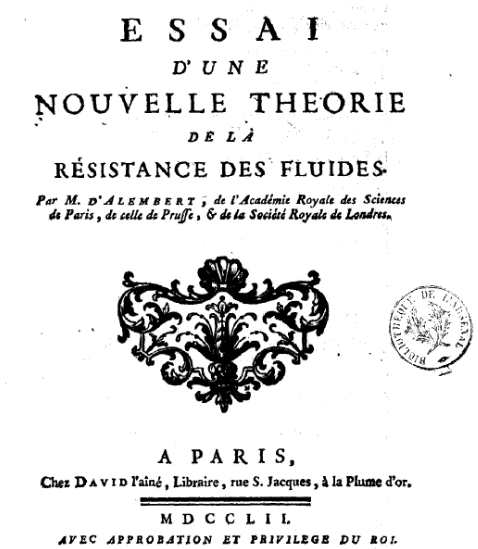
1752: d'Alembert's paradox

D'Alembert was upset and took back his manuscript of 1749, translated it into French and published it in 1752.

1749


Theoria resistentiæ
quam patitur corpus in fluido motum,
ex principiis omnino novis
et simplicissimis deducta,
habita ratione
tum velocitatis, figuræ, et massæ corporis moti,
tum densitatis & compressionis partium
fluidi.

Incipiam


ESSAI
D'UNE
NOUVELLE THEORIE
DE LA
RÉSISTANCE DES FLUIDES.
Par M. D'ALEMBERT, de l'Académie Royale des Sciences de Paris, de celle de Prusse, & de la Société Royale de Londres.

A PARIS,
Chez DAVID l'aîné, Libraire, rue S. Jacques, à la Plume d'or.
MDCCLII.
AVEC APPROBATION ET PRIVILEGE DU ROI.

1752

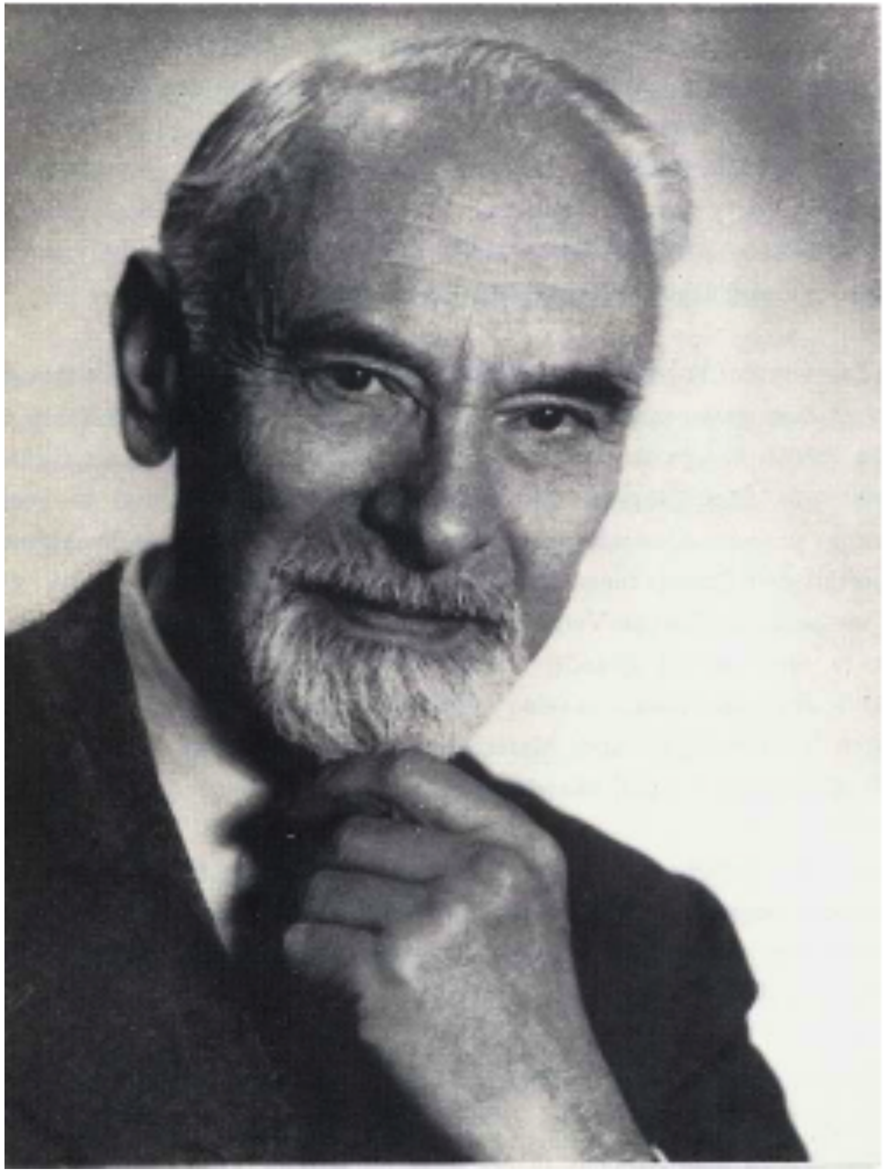
'It seems to me that the theory, developed in all possible rigor, gives, at least in several cases, a strictly vanishing resistance, a singular paradox which I leave to future geometers to elucidate.'

https://gallica.bnf.fr/ark:/12148/bpt6k206036b

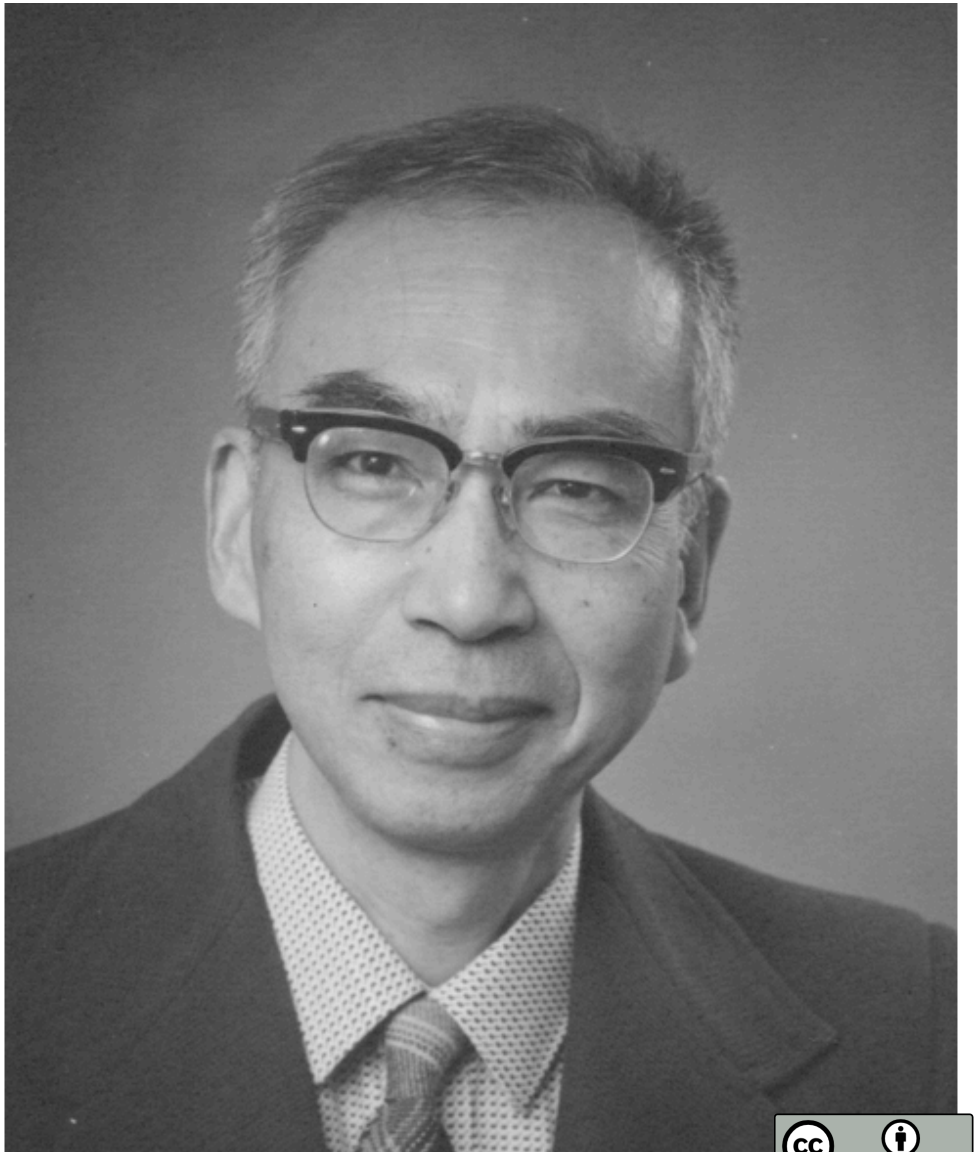
Adhémar Jean-Claude Barré de Saint-Venant (1797-1886)

George Stokes (1819-1903)

Ludwig Prandtl
(1875-1953)

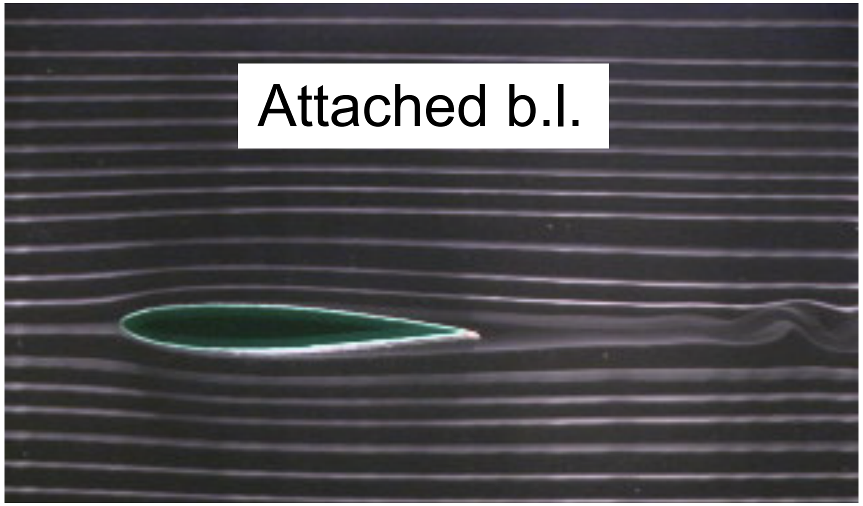


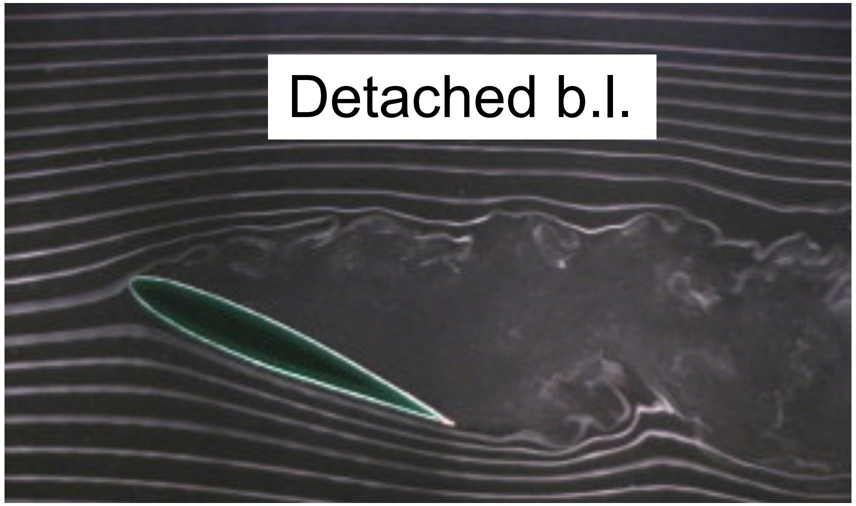
Toshio Kato
(1917-1999)



1904: Prandtl's boundary layer theory

- Prandtl (1904) predicted that the thickness of the boundary layer in contact with a solid body *(left)* scales as $Re^{-1/2}$,
  the inverse square root of the Reynolds number *Re*,
- But Prandtl's theory does not apply for separated flow regions where the boundary layer detaches from the solid body *(right)*.





Prandtl, Über Flüssigkeitsbewegung bei sehr kleiner Reibung, Proceedings of the 3rd ICM in Heidelberg, 484-491, 1904

What is the inviscid limit of Navier-Stokes?

Navier-Stokes equations with
no-slip boundary conditions:

$$\begin{cases} \partial_t \mathbf{u} + (\mathbf{u} \cdot \boldsymbol{\nabla})\mathbf{u} = -\boldsymbol{\nabla} p + \frac{1}{\mathrm{Re}} \boldsymbol{\nabla}^2 \mathbf{u} \\ \boldsymbol{\nabla} \cdot \mathbf{u} = 0 \\ \mathbf{u}_{|\partial\Omega} = \mathbf{0}, \qquad \mathbf{u}(0, \cdot) = \mathbf{v} \end{cases} \longrightarrow \mathbf{u}_{\mathrm{Re}}(t, \mathbf{x}) \quad \text{for } \nu \to 0,\ \mathrm{Re} \to +\infty$$

$\mathrm{Re} = VL\nu^{-1}$ the Reynolds number

Same initial conditions

?

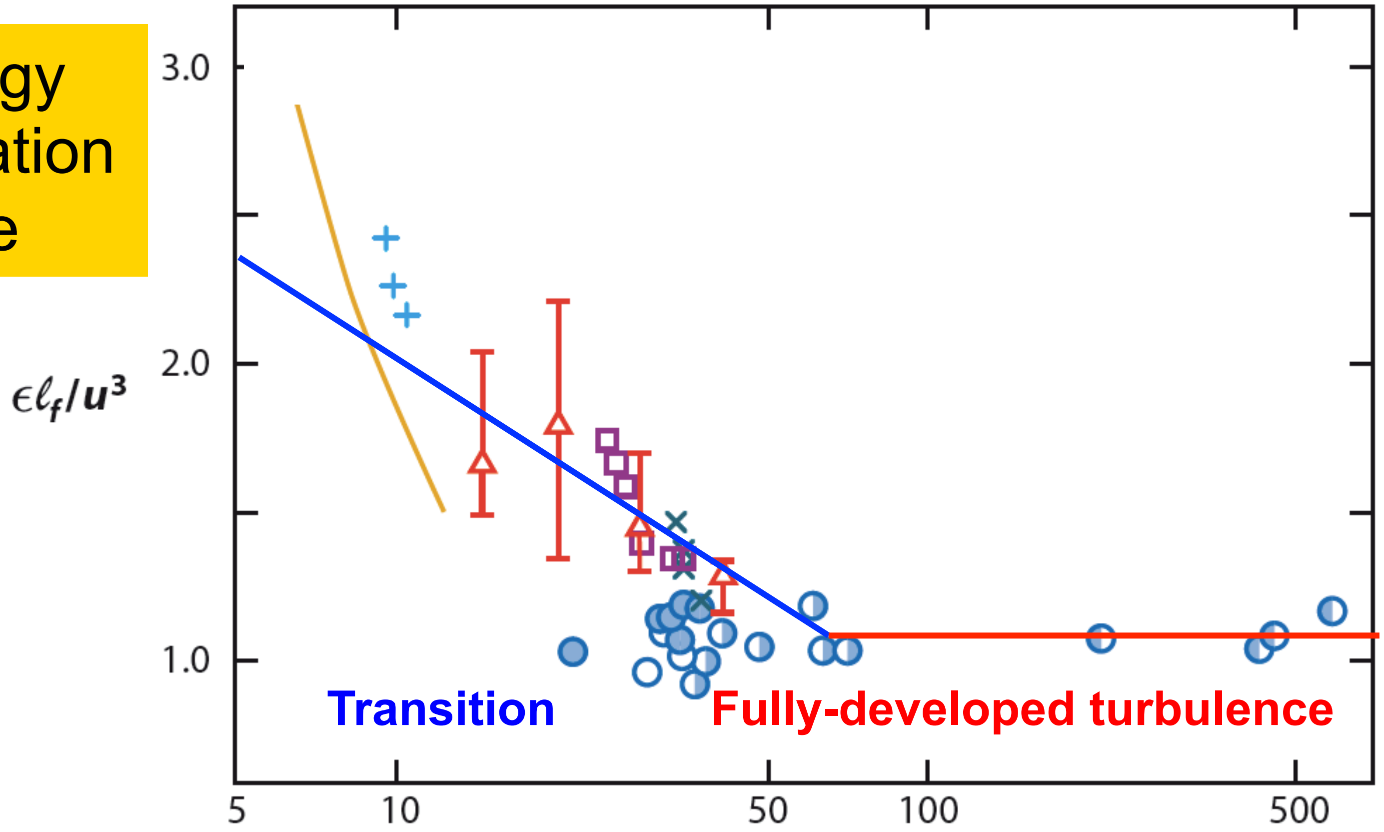
Euler equations with
slip boundary conditions:

$$\begin{cases} \partial_t \mathbf{u} + (\mathbf{u} \cdot \boldsymbol{\nabla})\mathbf{u} = -\boldsymbol{\nabla} p \\ \boldsymbol{\nabla} \cdot \mathbf{u} = 0 \\ \mathbf{u}_{|\partial\Omega} \cdot \mathbf{n} = \mathbf{0}, \qquad \mathbf{u}(0, \cdot) = \mathbf{v} \end{cases} \longrightarrow \mathbf{u}(t, \mathbf{x}) \quad \text{for } \nu = 0,\ \mathrm{Re} = +\infty$$

Laboratory experiments

Vassilicos, Ann. Rev. Fluid Mech., ***47***, *2015*

Energy dissipation rate

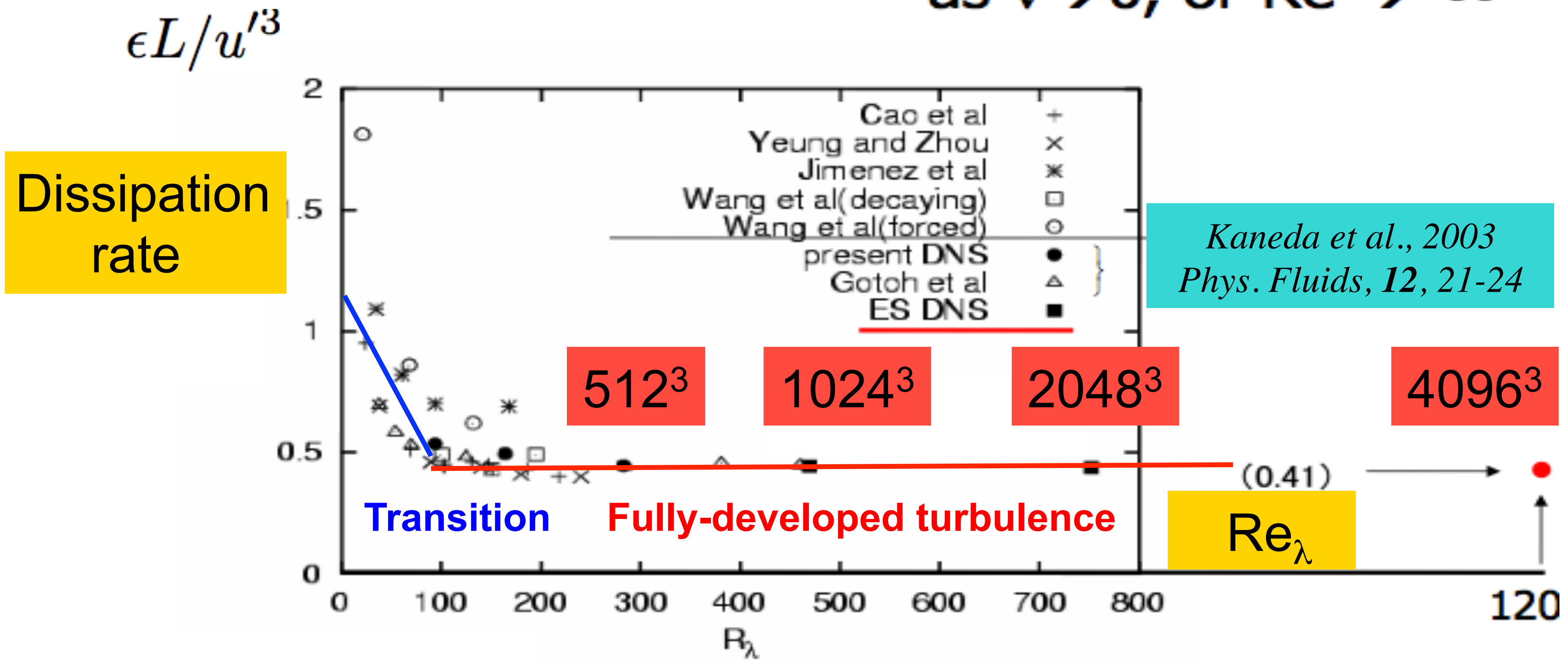


$Re_\lambda = Re^{1/2}$

For $\nu \rightarrow 0$ or $\mathrm{Re} \rightarrow +\infty$
energy dissipation does not vanish
but becomes constant

Numerical experiments

Normalized energy dissipation → ?
as ν→0, or Re → ∞



Both laboratory and numerical experiments
show that the dissipation rate of turbulent flows
becomes independent of the fluid viscosity for large *Re*

1984: Kato's theorem

Navier-Stokes solution converges towards the Euler solution,
if and only if, energy dissipation vanishes

$$\Delta E_{\mathrm{Re}}(0,T) = \mathrm{Re}^{-1} \int_0^T \mathrm{d}t \int_\Omega \mathrm{d}\mathbf{x} \left|\nabla \mathbf{u}(t,\mathbf{x})\right|^2 \underset{\substack{\mathrm{Re}\to\infty \\ \nu \to 0}}{\longrightarrow} 0,$$

and, if and only if, this happens in a boundary layer of
thickness inversely proportional to the Reynolds number *Re*

Kato, 1984, Remarks on zero viscosity limit for non stationary Navier-Stokes flows with boundary, MSRI Berkeley

~~$\delta x \propto \mathrm{Re}^{-\frac{1}{2}}$~~

$$\delta x \propto \mathrm{Re}^{-1}$$

This requires using smaller resolution to compute high Reynolds flows than predicted by Prandtl's theory

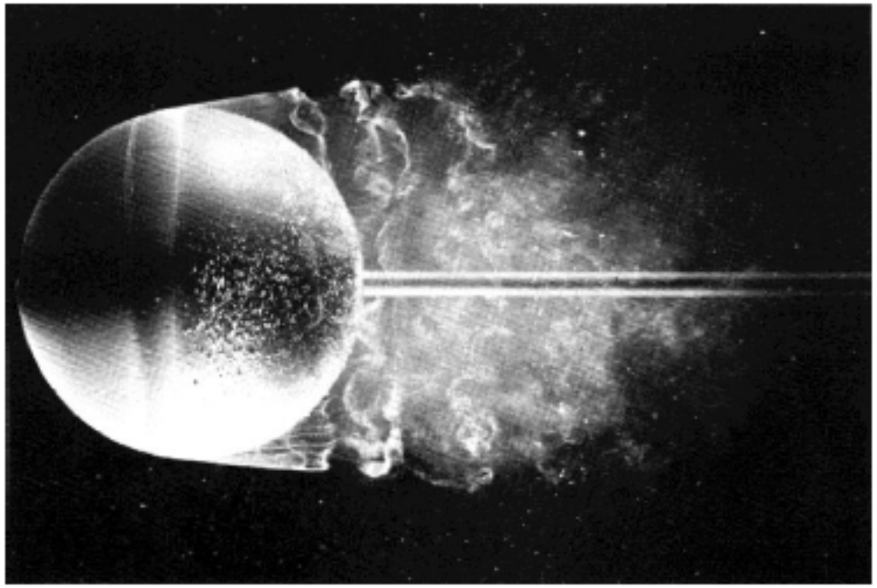
Dissipation of energy in the inviscid limit

- In an incompressible flow ($\rho = 1$)

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\int \frac{\mathbf{u}^2}{2} = -\nu \int \omega^2 = -2\nu Z$$

- To dissipate energy, vorticity needs to be created and/or amplified, in such a way that $Z \sim \nu^{-1}$.

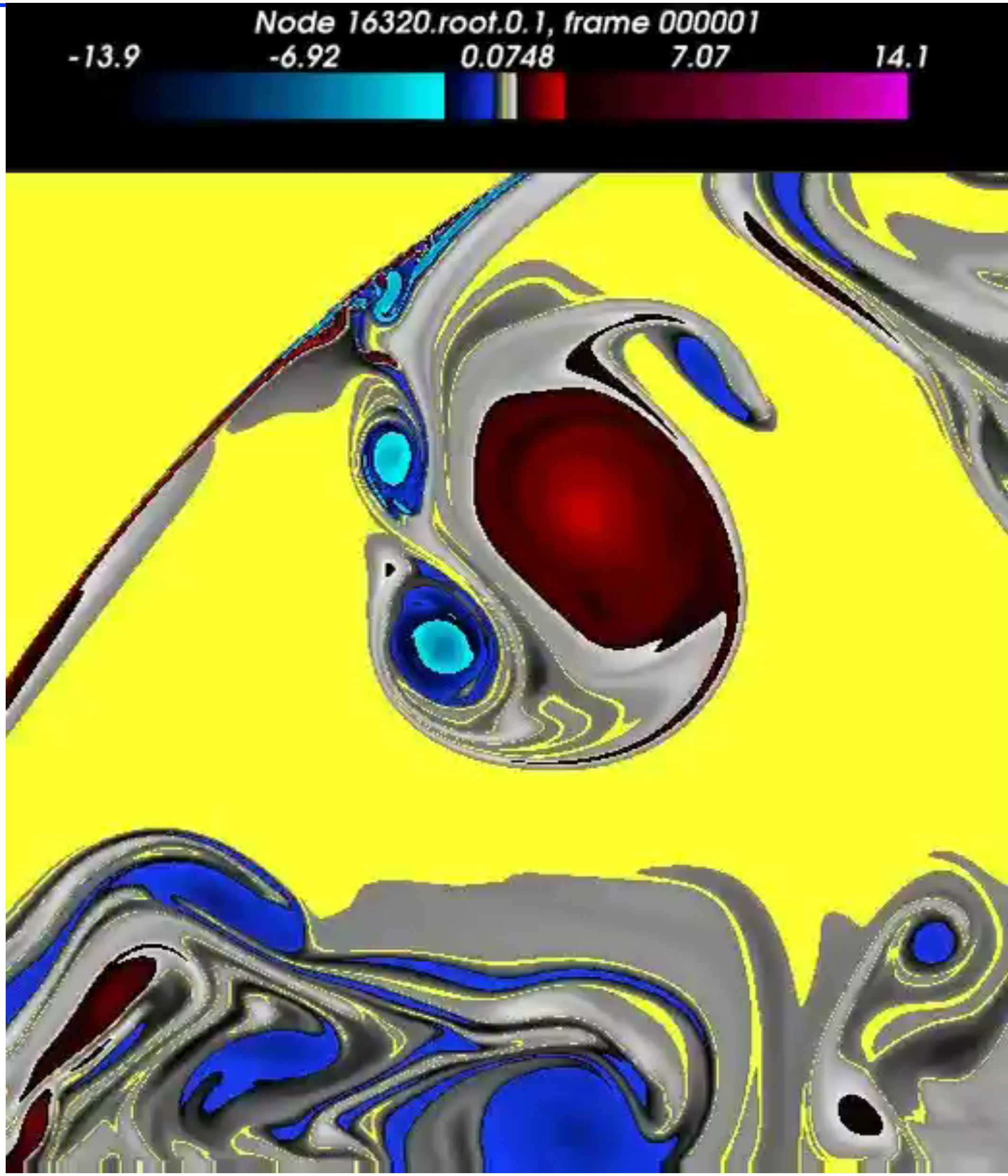
Possible vorticity distributions:
$\omega \sim \nu^{-1/2}$ over $O(1)$ area,
$\omega \sim \nu^{-1}$ over $O(\nu)$ area.



with E energy, Z enstrophy,
ν fluid kinematic viscosity,
ω flow vorticity.

2D Flow inside a cylinder

Resolution
$N=8192^2$

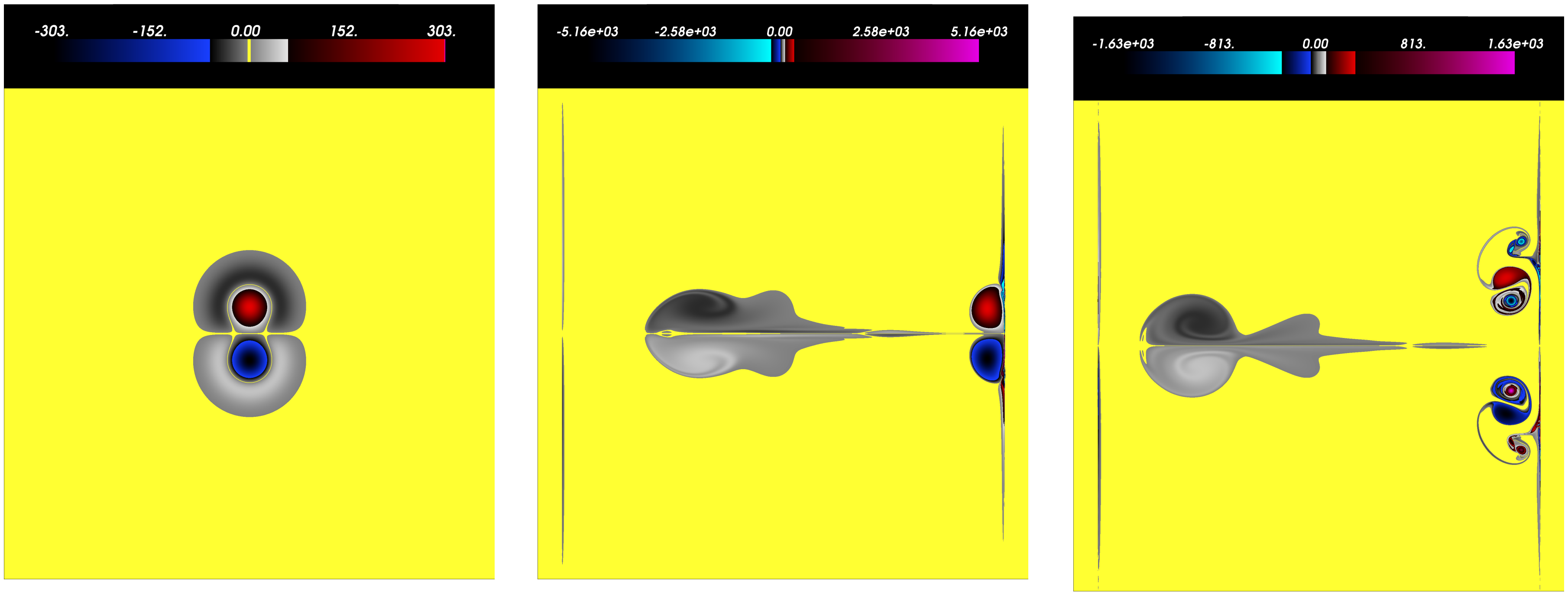


Navier-Stokes equations with volume penalization integrated using Fourier

K. Schneider and M. F., Phys. Rev. Lett., ***95****, 244502 (2005)*

Dipole crashing onto a plane wall

DNS
Resolution
$N=8192^2$

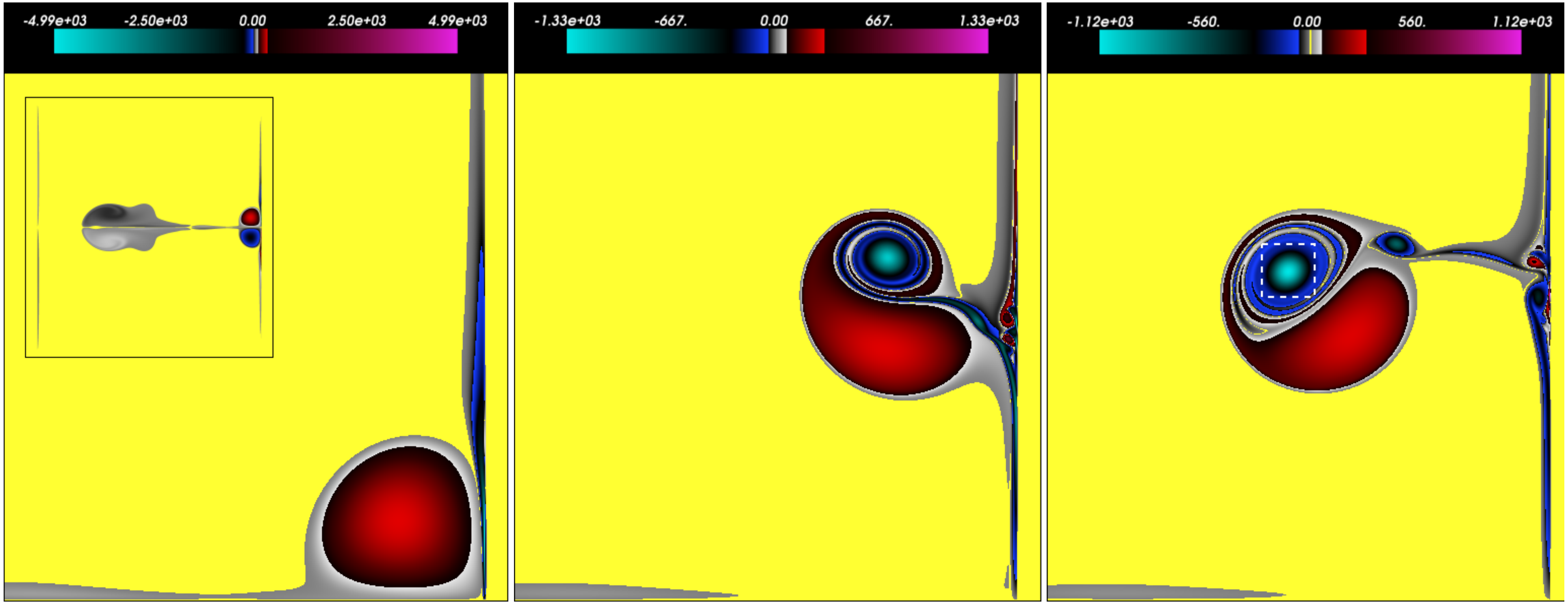


Dipole crashing onto a wall in 2D

Resolution
$N=16384^2$

Navier-Stokes equations with volume penalization integrated using Fourier

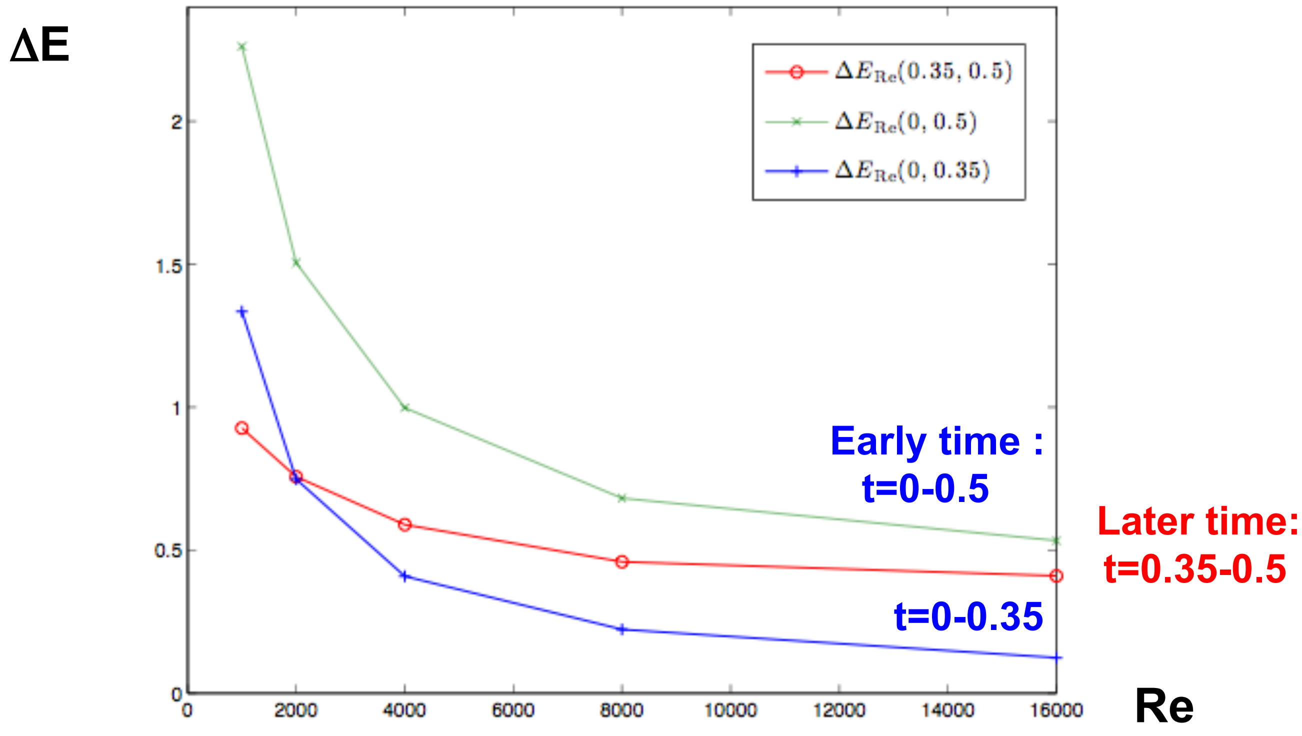
*Nguyen van yen, M. F. and Schneider, PRL, **106**(18), 2011*



t=0.3 *t=0.4* *t=0.5*

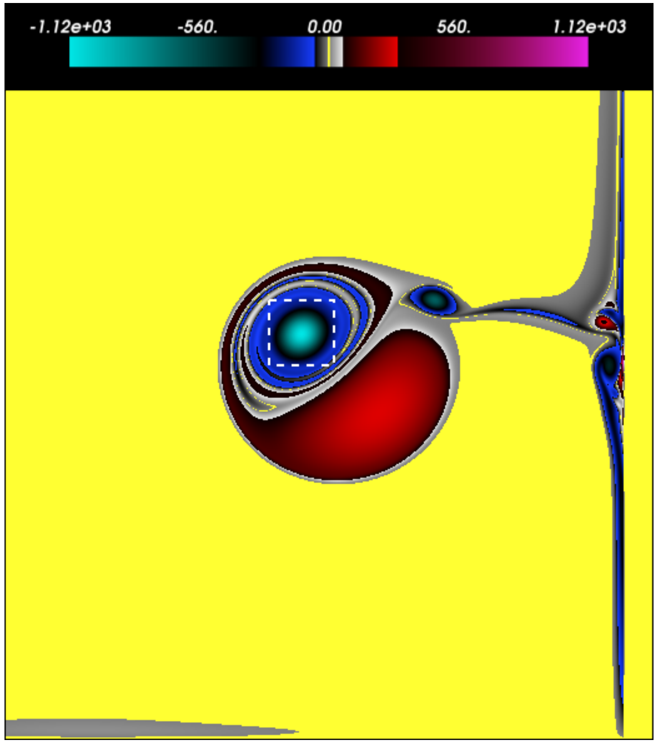
Energy dissipation

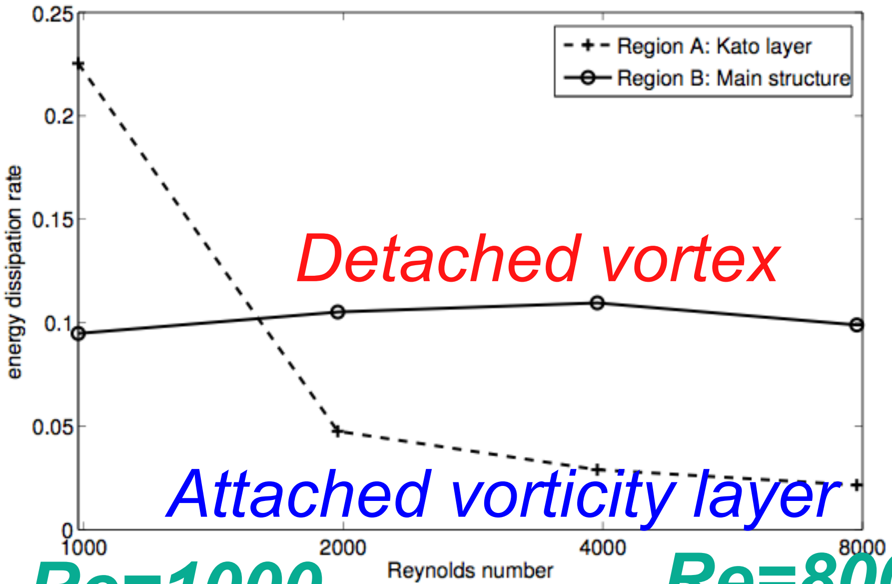
Energy dissipated
when the dipole crashes onto the wall
at increasing Reynolds numbers



Production of dissipative structures

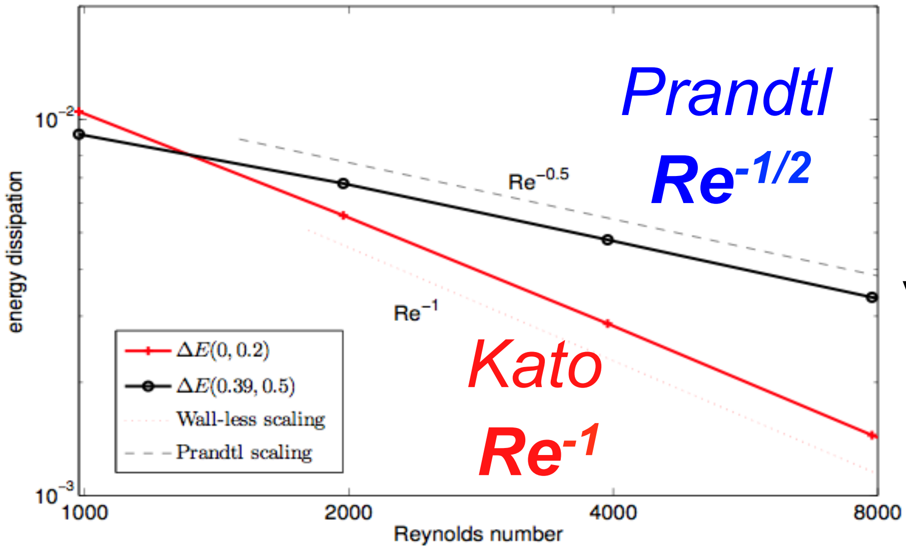
*Nguyen van yen, M. F. and Schneider, PRL, **106**(18), 2011*





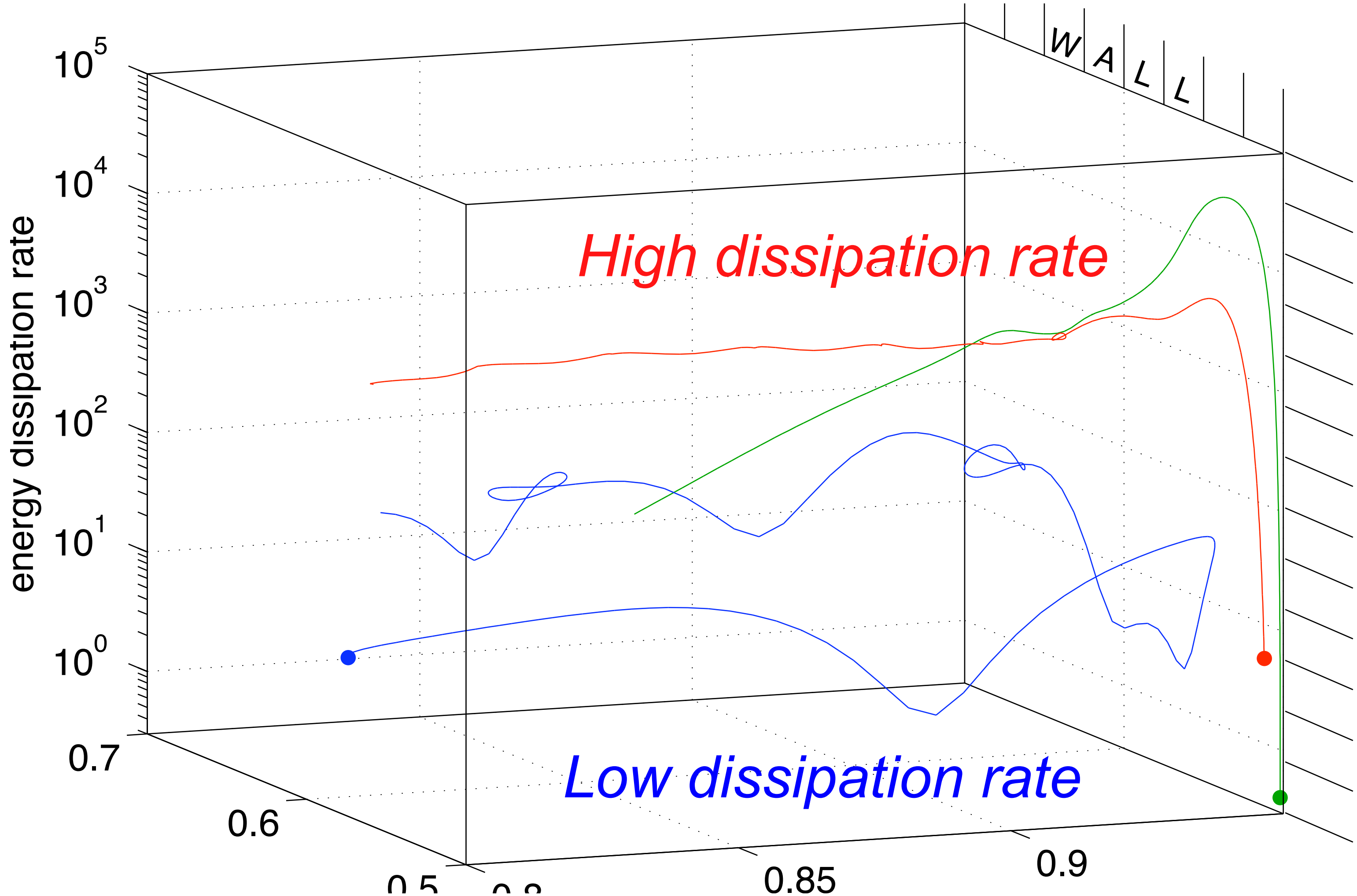
Re=1000 Re=8000

Energy dissipation rate $(-2\nu Z)$ versus Re



Energy Dissipation versus Re

Production of dissipative structures



*R. Nguyen van yen, M. F. and K. Schneider, PRL, **106**(18)*

2011

PHYSICAL REVIEW LETTERS

Energy Dissipating Structures Produced by Walls in Two-Dimensional Flows at Vanishing Viscosity

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(Received 13 October 2010; published 3 May 2011)

2013

PHYSICS OF FLUIDS **25**, 093104 (2013)

The effect of slip length on vortex rebound from a rigid boundary

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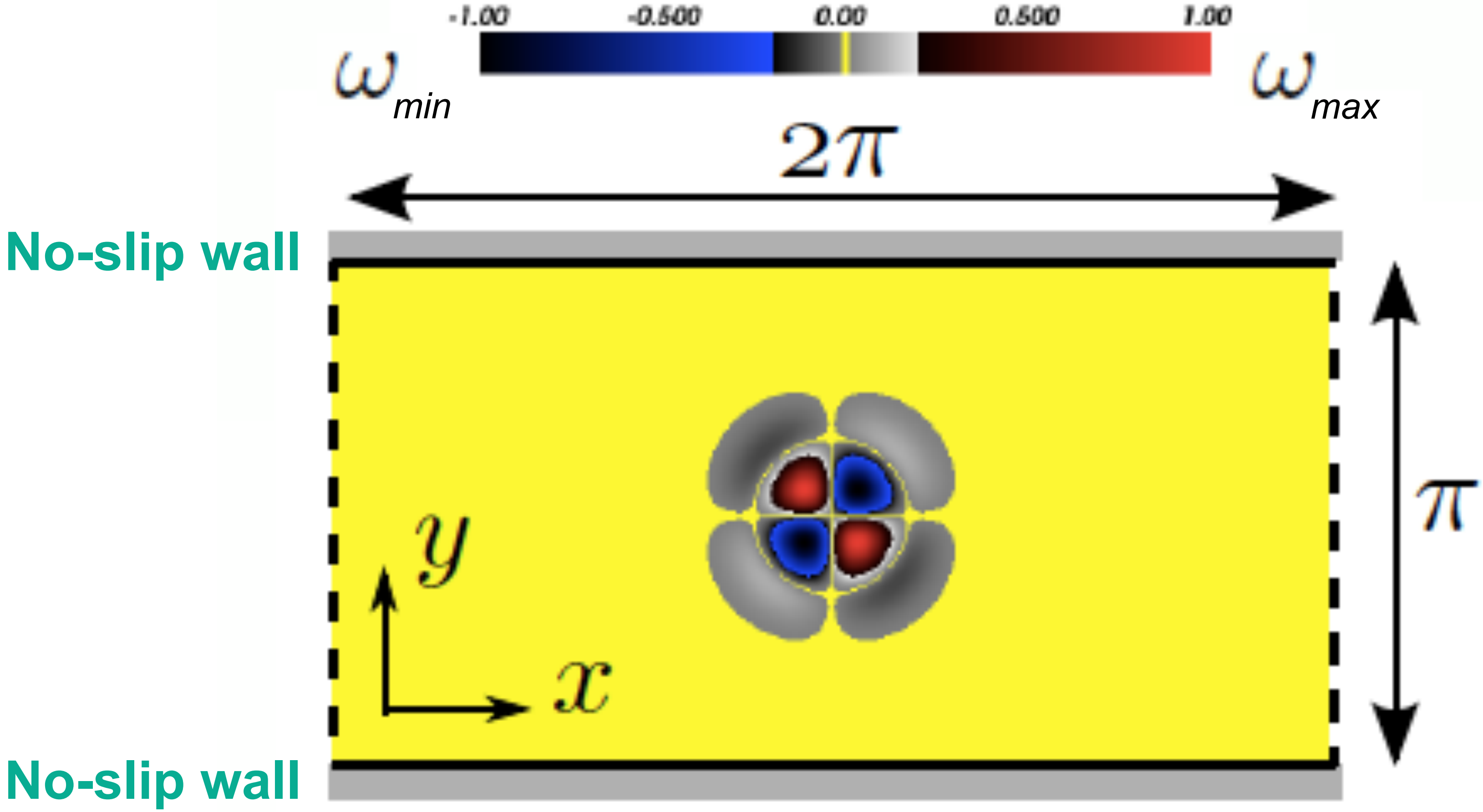
(Received 22 May 2013; accepted 16 August 2013; published online 23 September 2013)

Comparison Navier-Stokes and Euler-Prandtl

Initial vorticity field: vortex quadrupole



$$\psi_i(x,y) = Axy \exp\left(-\frac{(x-x_0)^2 + (y-y_0)^2}{2s^2}\right)$$

Prandtl equation coupled to Euler

Ansatz for the vorticity field as $\mathrm{Re} \to \infty$:

$$\omega(x,y) = \omega_E(x,y) + \nu^{-1/2}\omega_P(x,\nu^{-1/2}y) + \omega_R(x,y)$$

Prandtl's variable : $y_P = y / \nu^{1/2}$

$$\partial_t \omega_P + \boldsymbol{\nabla}.(\mathbf{u}_P \omega_P) = \partial^2_{y_P} \omega_P$$

$$\omega_P(x, y_P, 0) = 0$$

$$\psi_P(x, y_P, t) = \int_0^{y_P} \mathrm{d}y'_P \int_0^{y'_P} \mathrm{d}y''_P \omega_P(x, y''_P, t)$$

$$\partial_{y_P} \omega_P(x, 0, t) = -\partial_x p_E(x, 0, t),$$

where p_E is the pressure calculated from ω_E which is the vorticity given by Euler equation

Comparison Navier-Stokes and Euler-Prandtl

Navier-Stokes solver

- Fourier in x and compact finite differences of 5th order with non-uniform grid in y.
- Third order Runge-Kutta in t.
- Periodic in x and no-slip boundary conditions in y.

Euler solver

- Fourier with hyperdissipation in x and y.
- Third order Runge-Kutta in t.
- Mirror-symmetry around y=0 to impose boundary conditions.

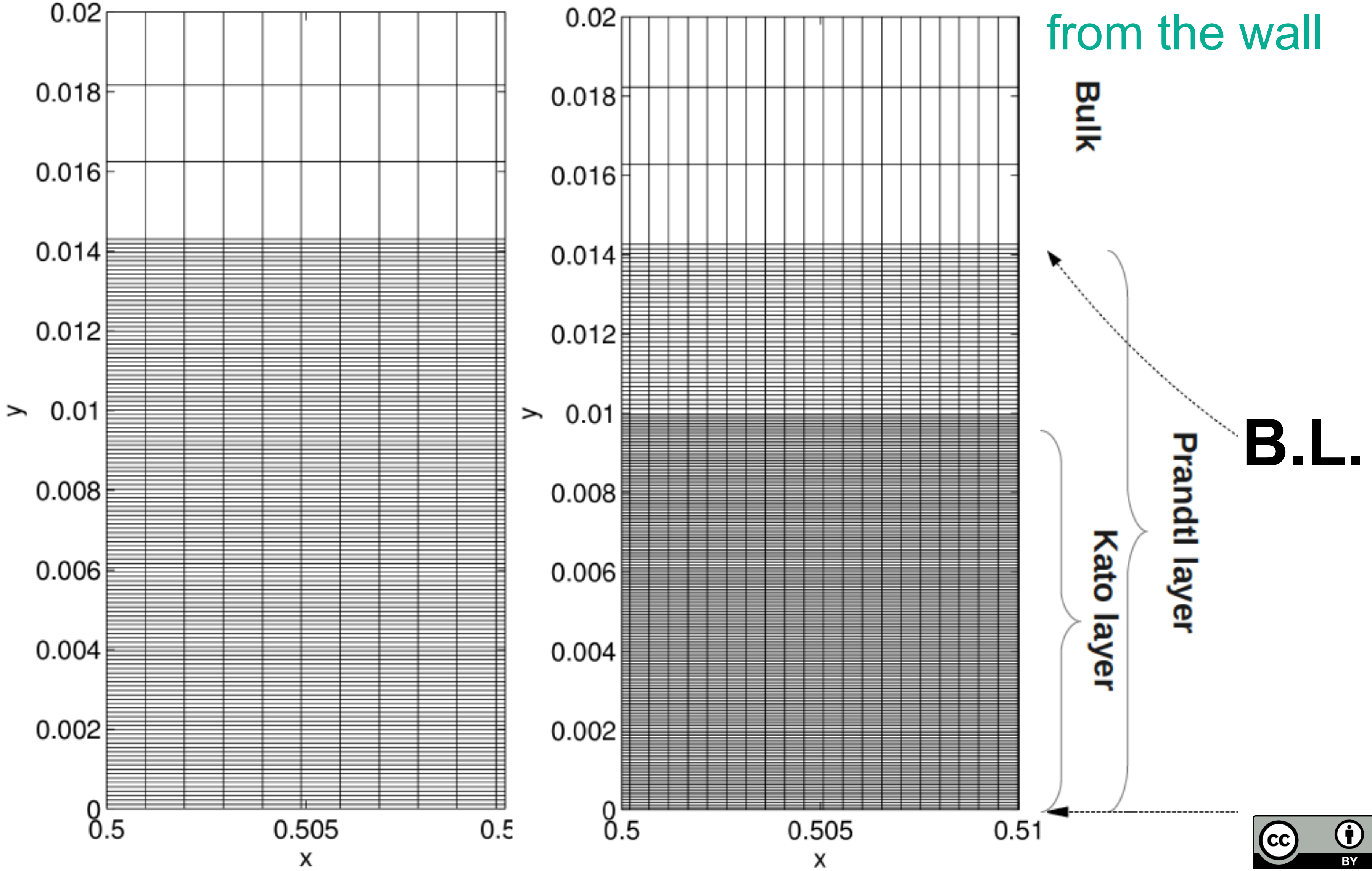
Prandtl solver

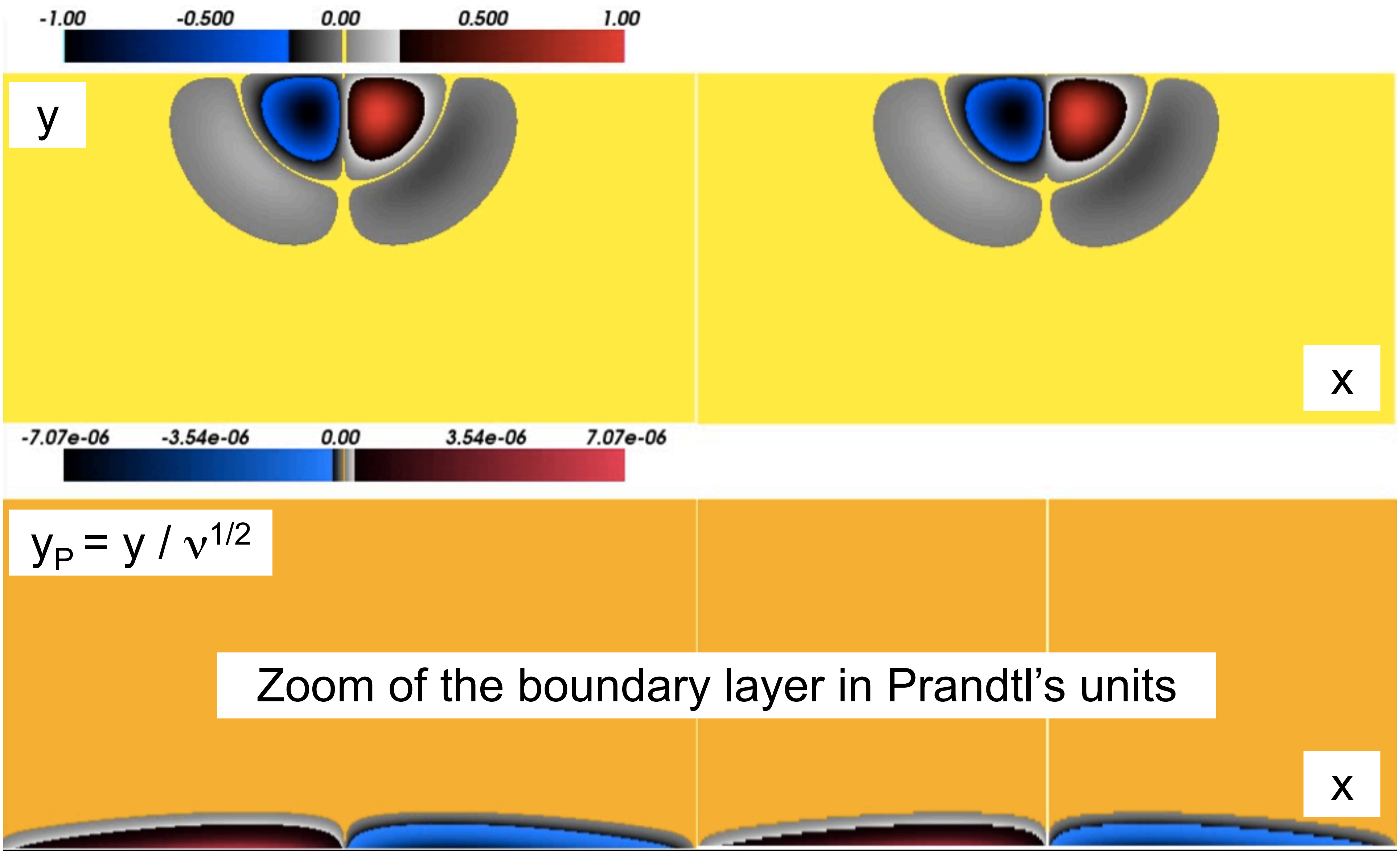
- Second order finite differences in x and y.
- Second order semi-implicit Runge-Kutta in t.
- Neumann boundary condition at y=0 when inverting.

Computational grid

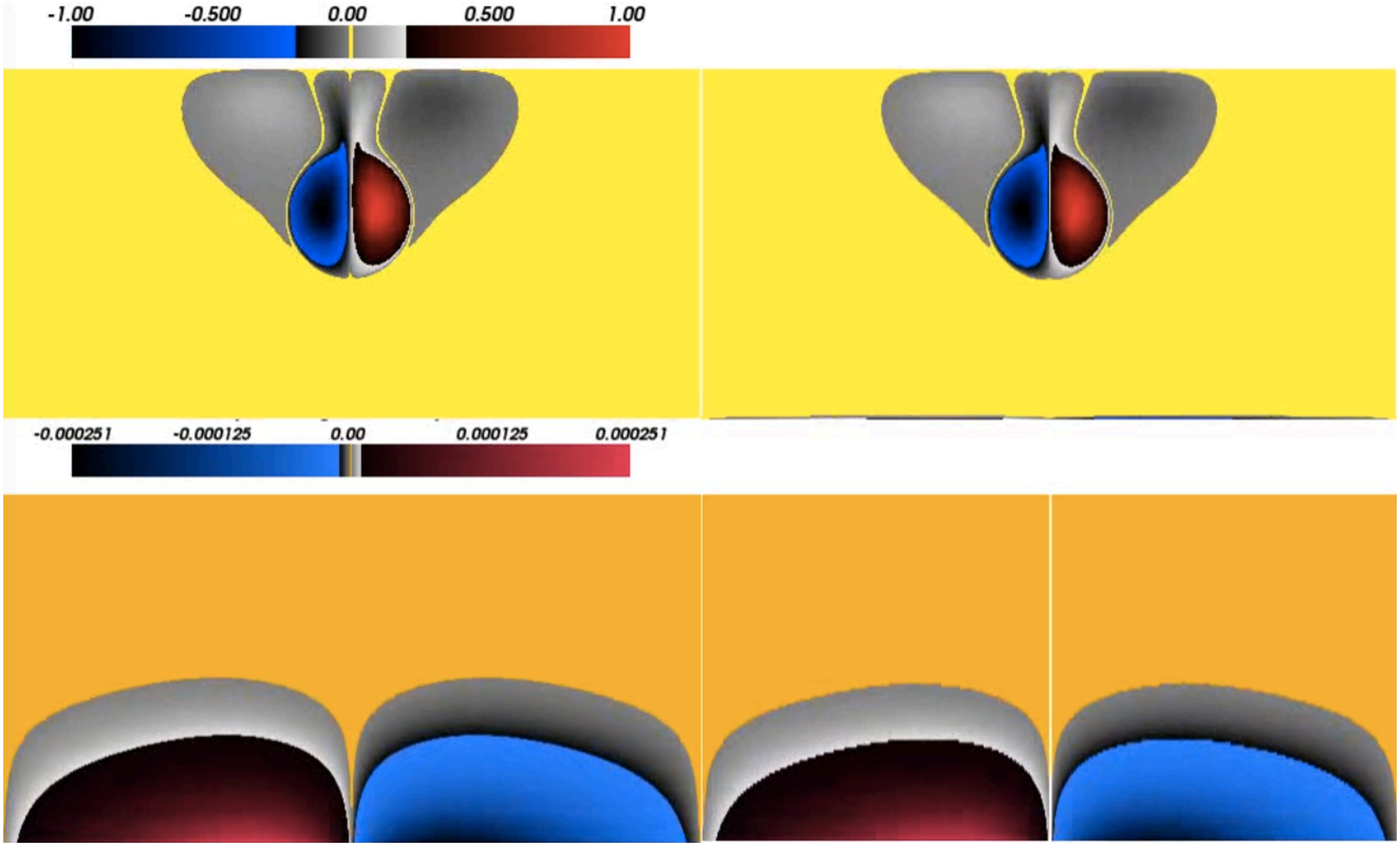
Before t=54

After t=54 when B.L. detachs from the wall



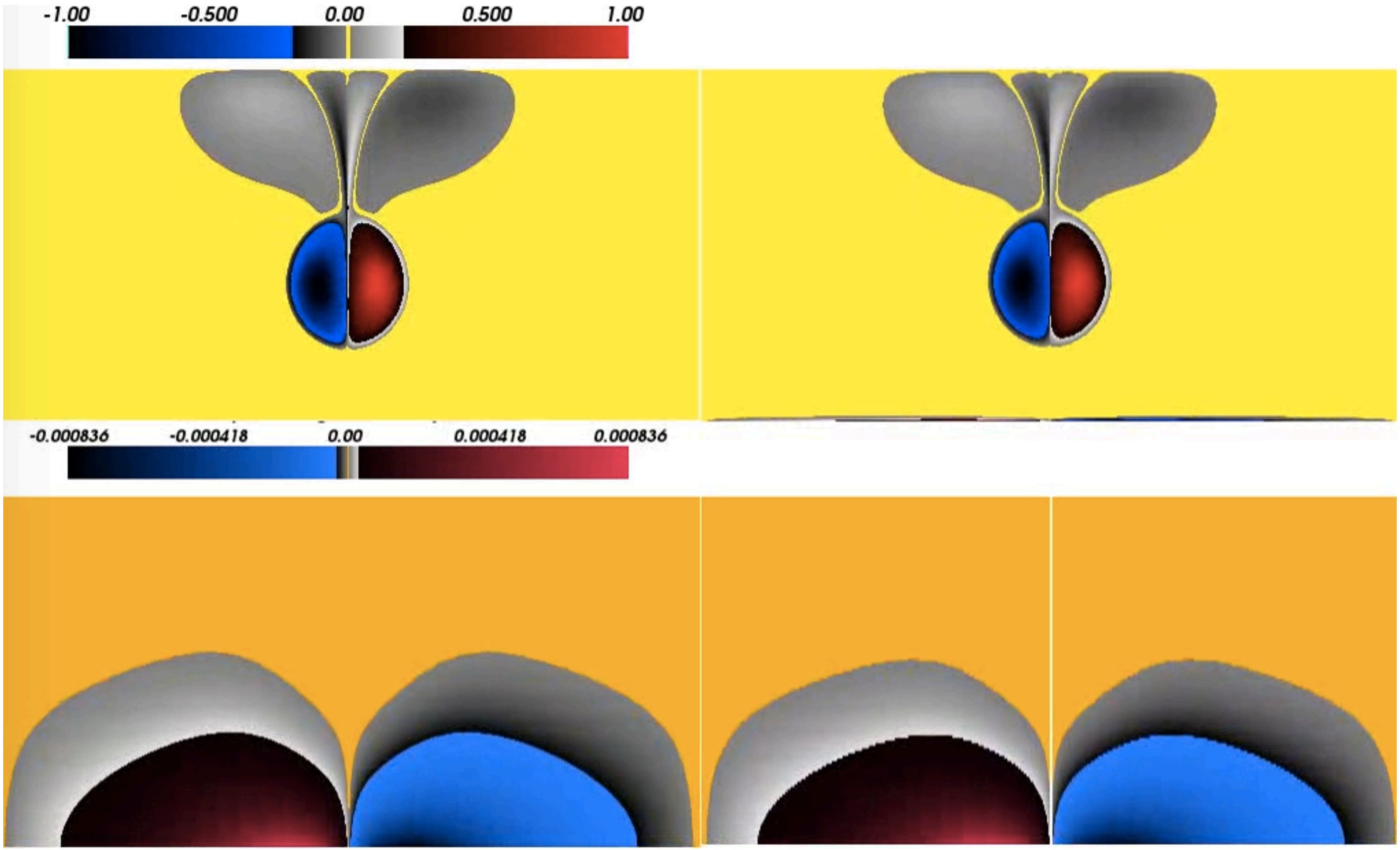


Euler and Prandtl **Navier-Stokes**

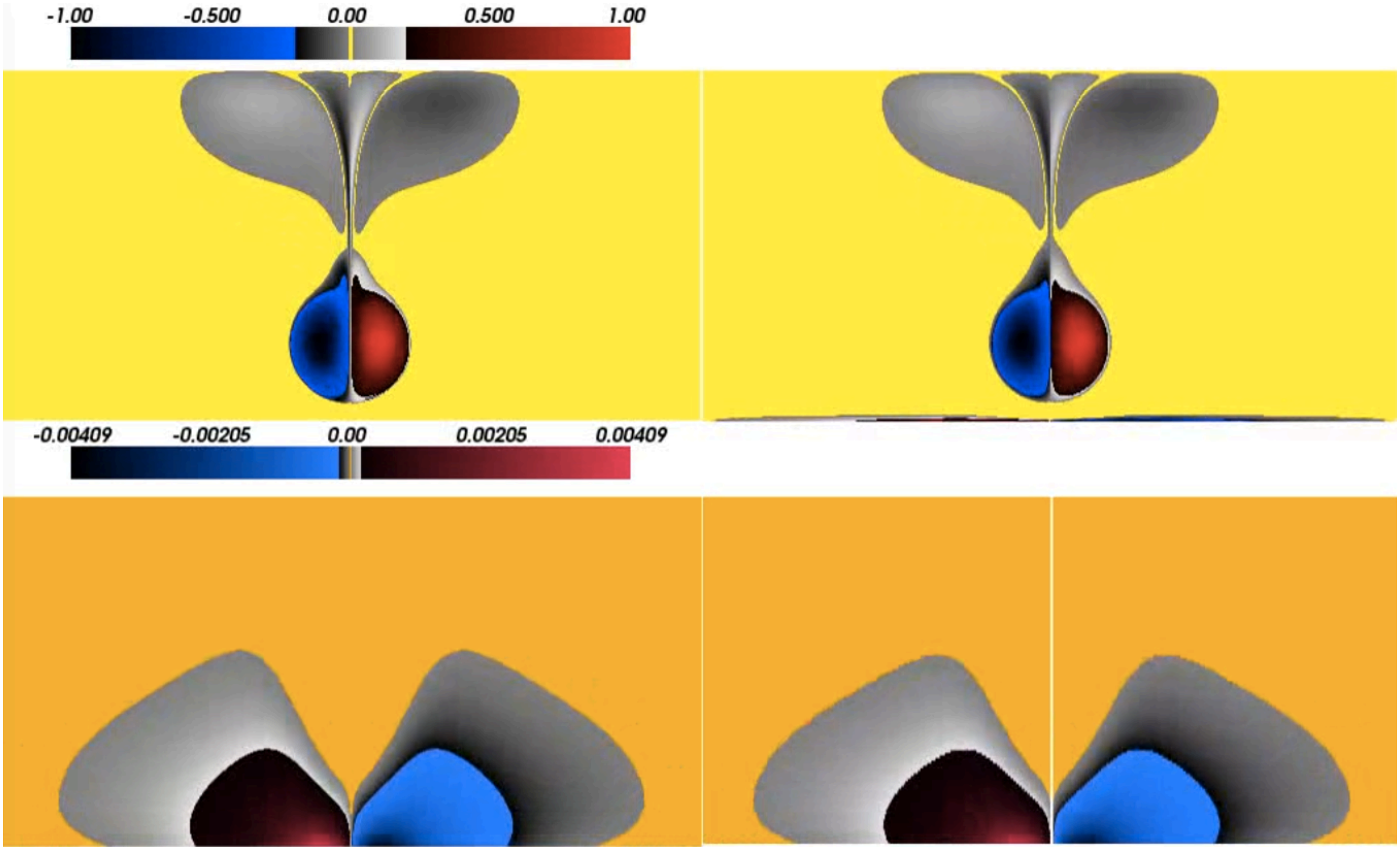


Euler and Prandtl

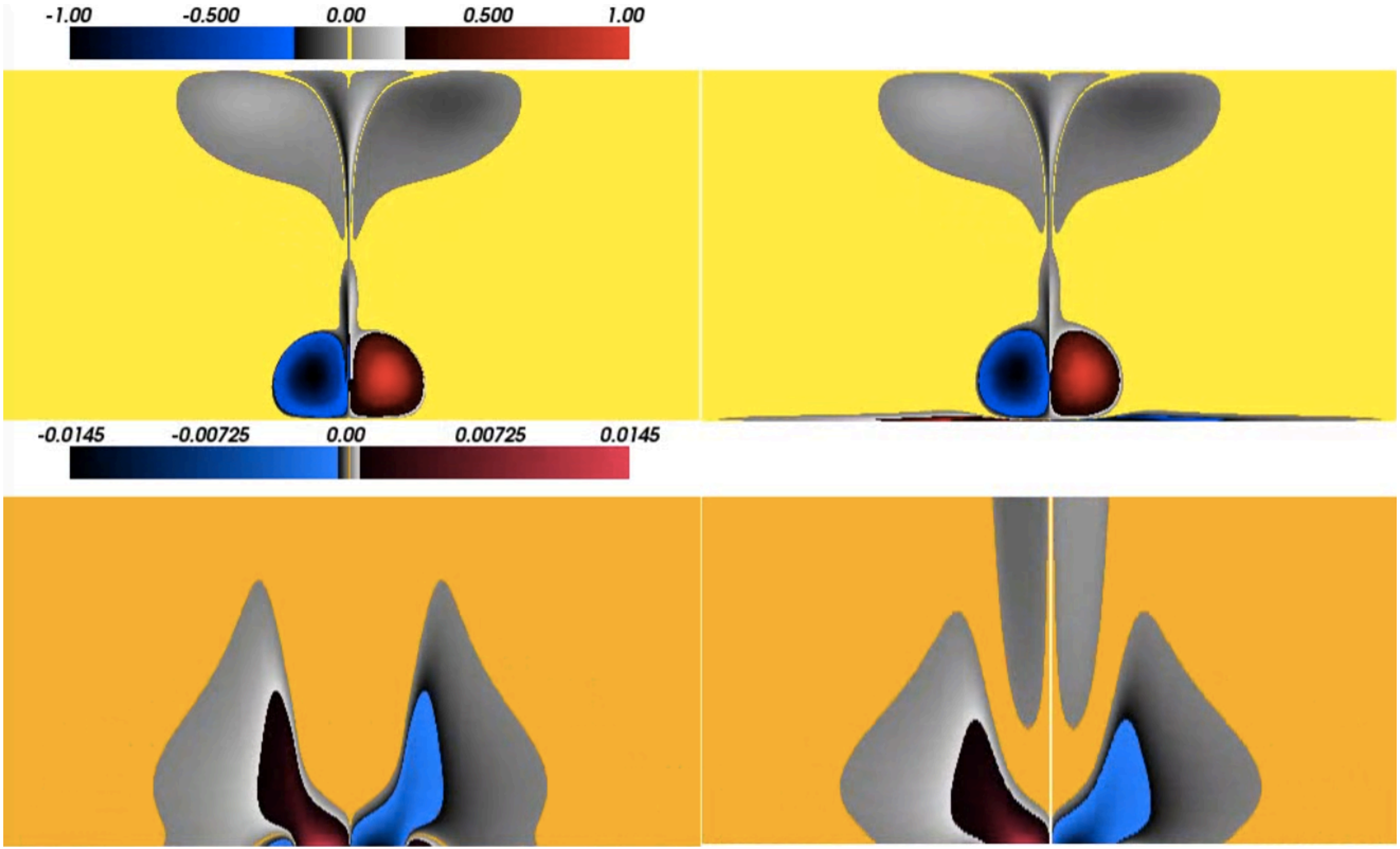
Navier-Stokes



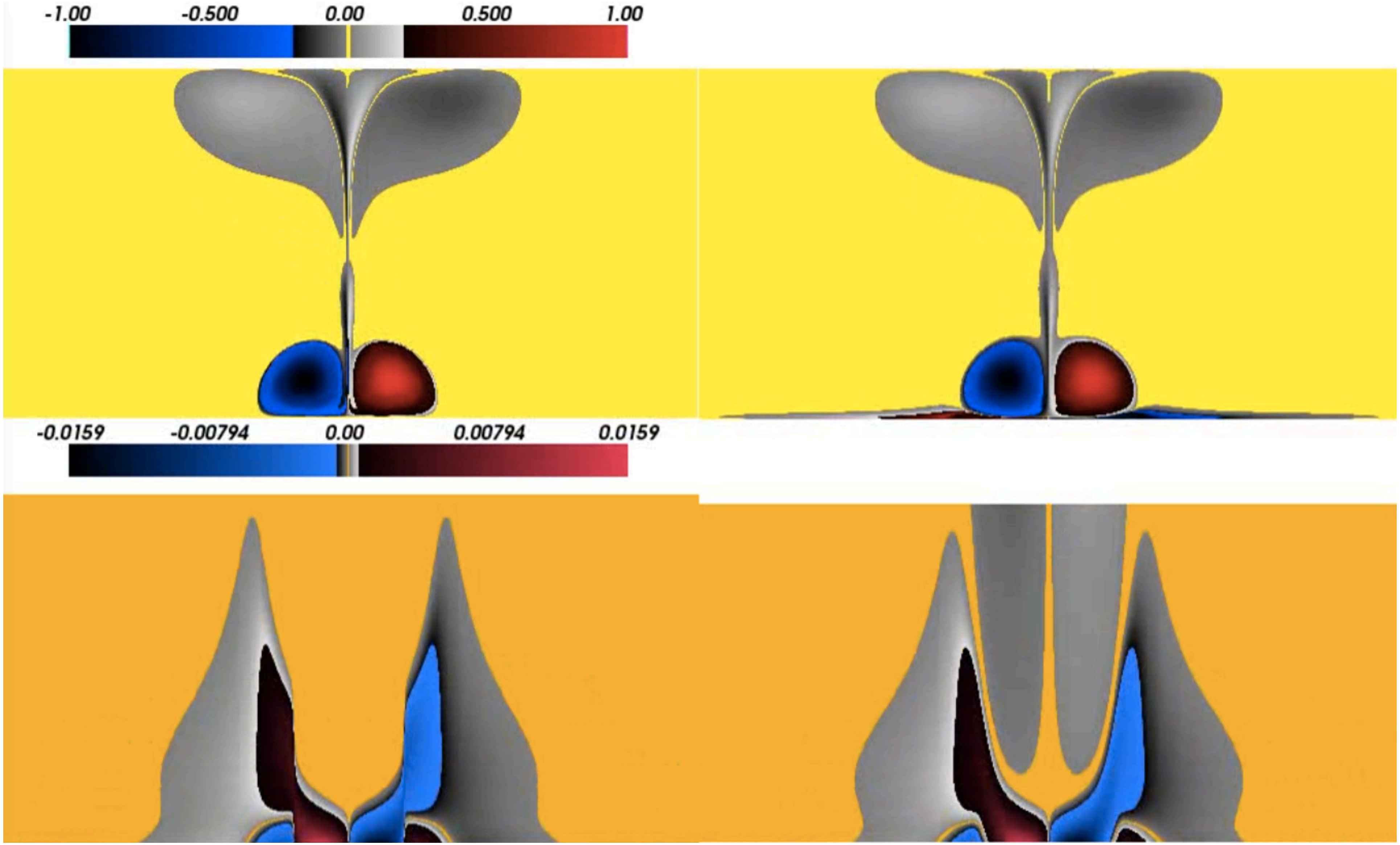
Euler and Prandtl **Navier-Stokes**



Euler and Prandtl **Navier-Stokes**

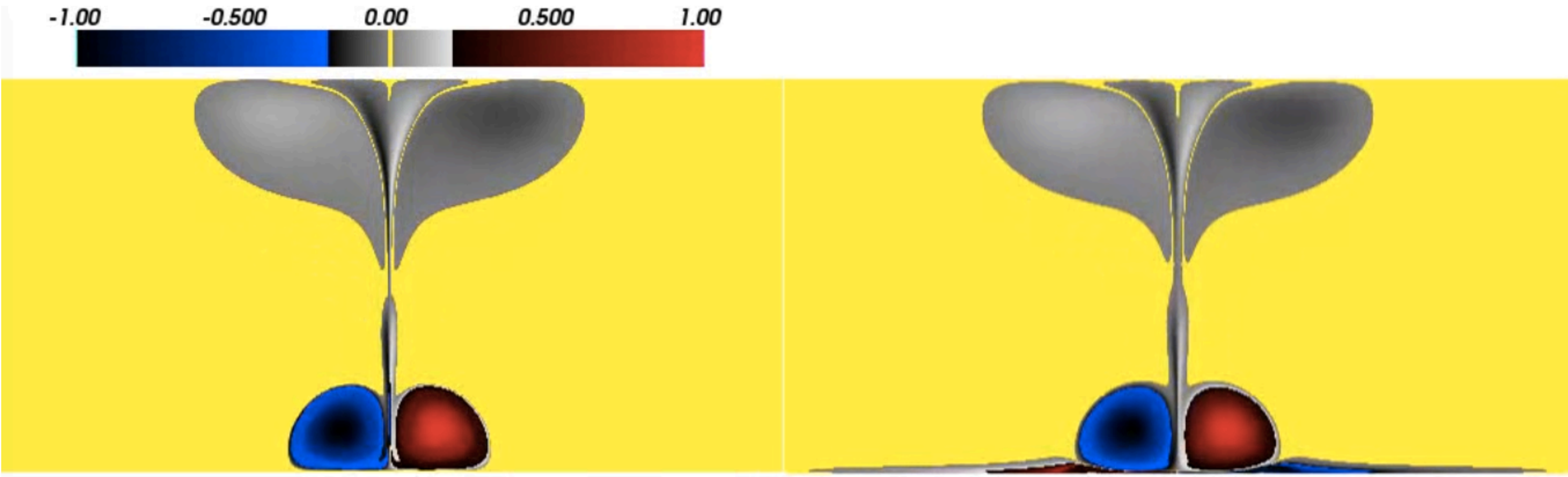


Euler and Prandtl Navier-Stokes

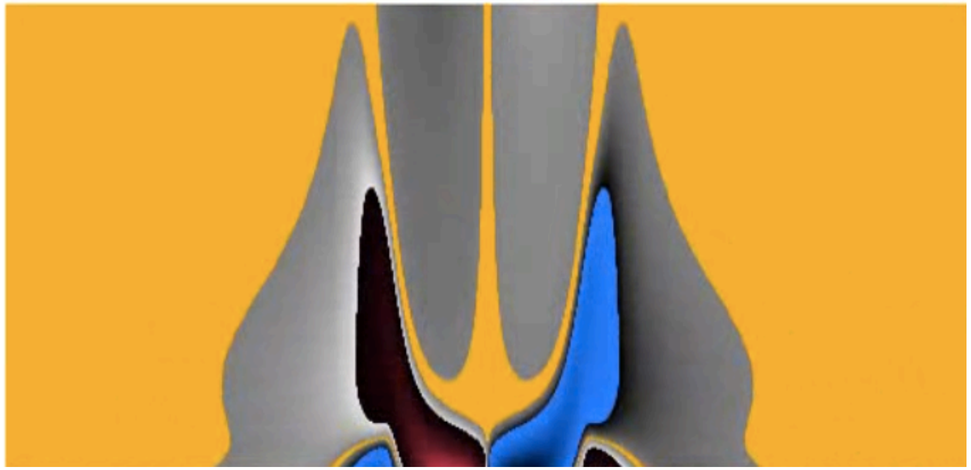


Euler and Prandtl

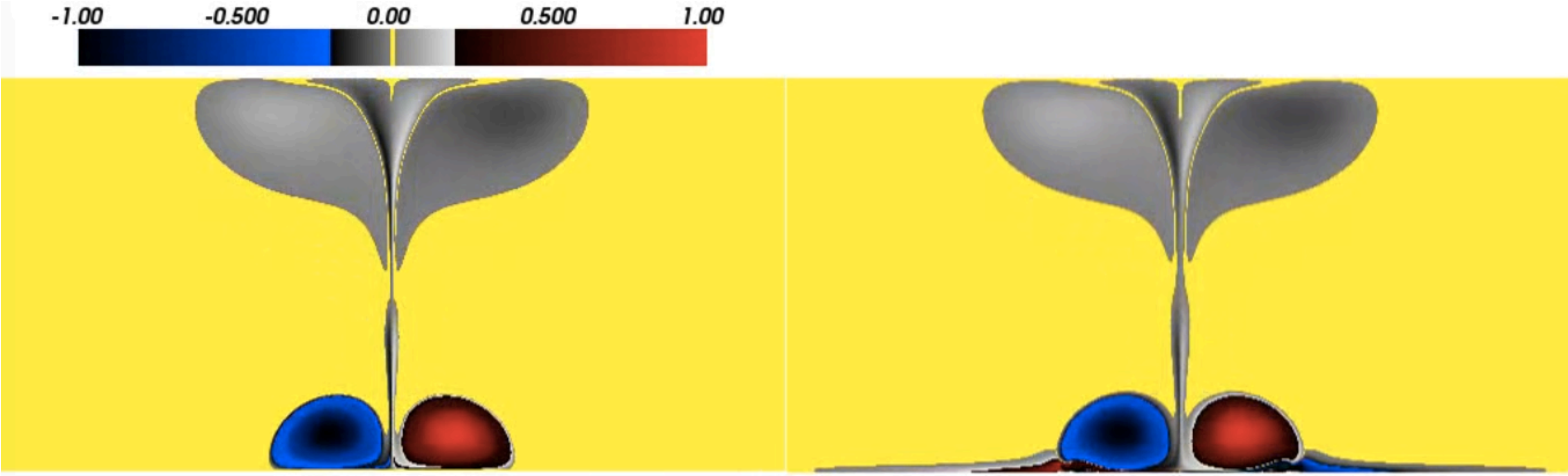
Navier-Stokes



Prandtl's solution
no more exists
after t= 55.8



Euler **Navier-Stokes**



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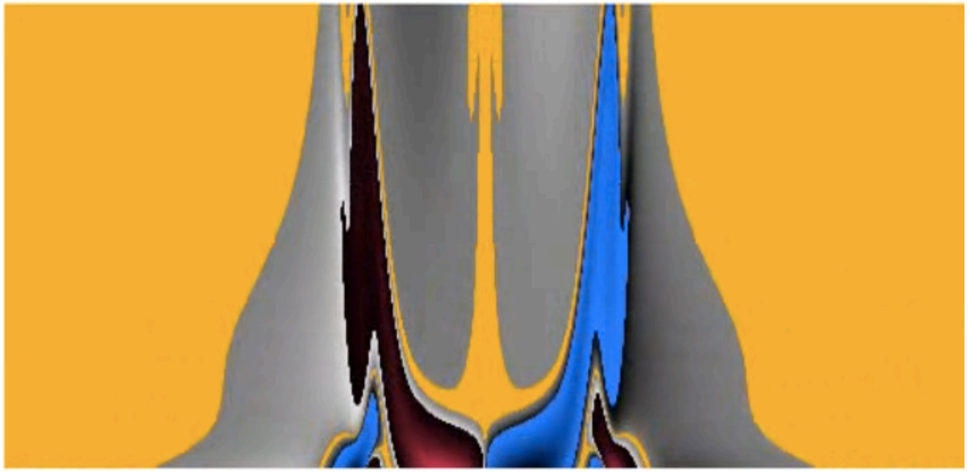
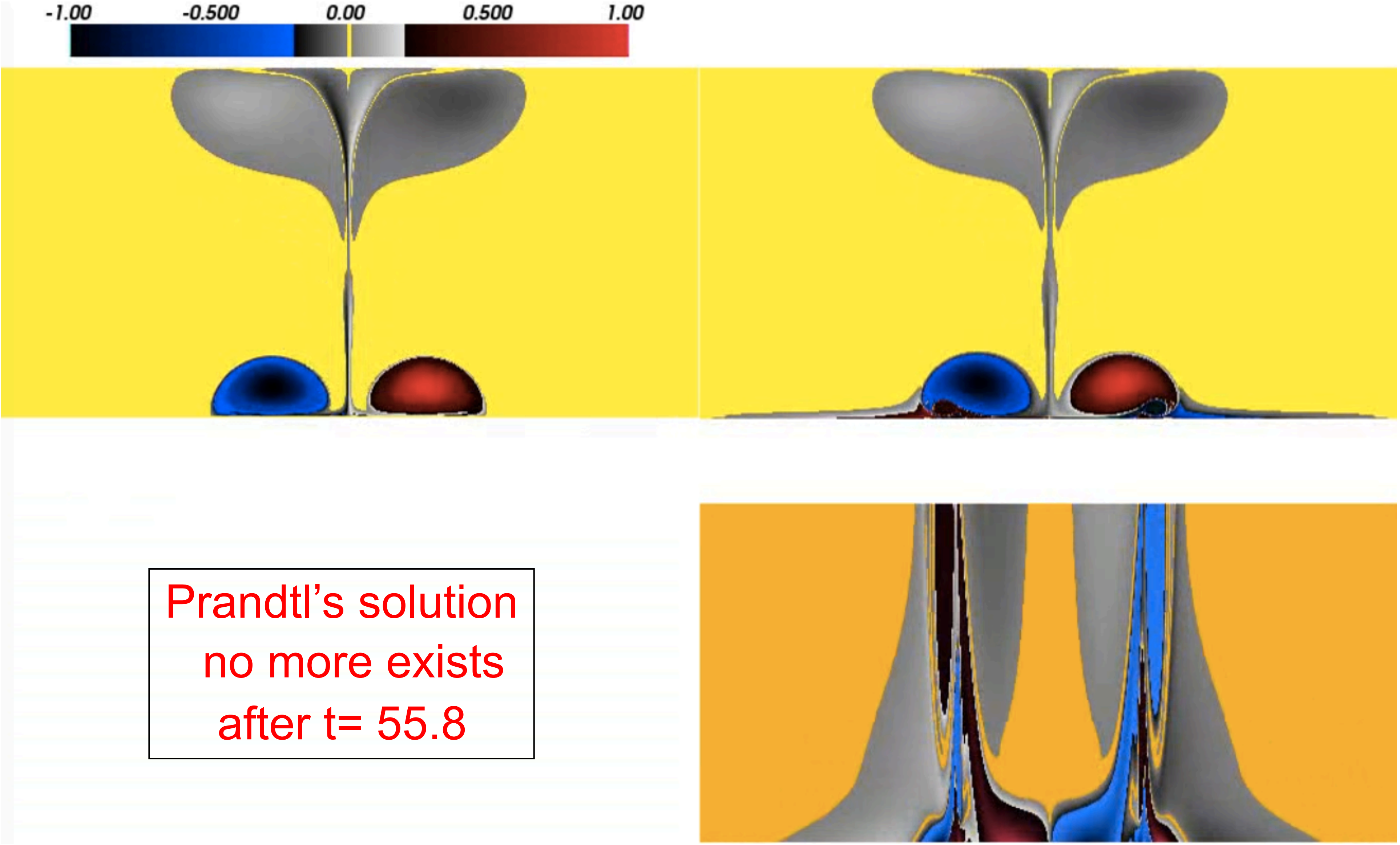


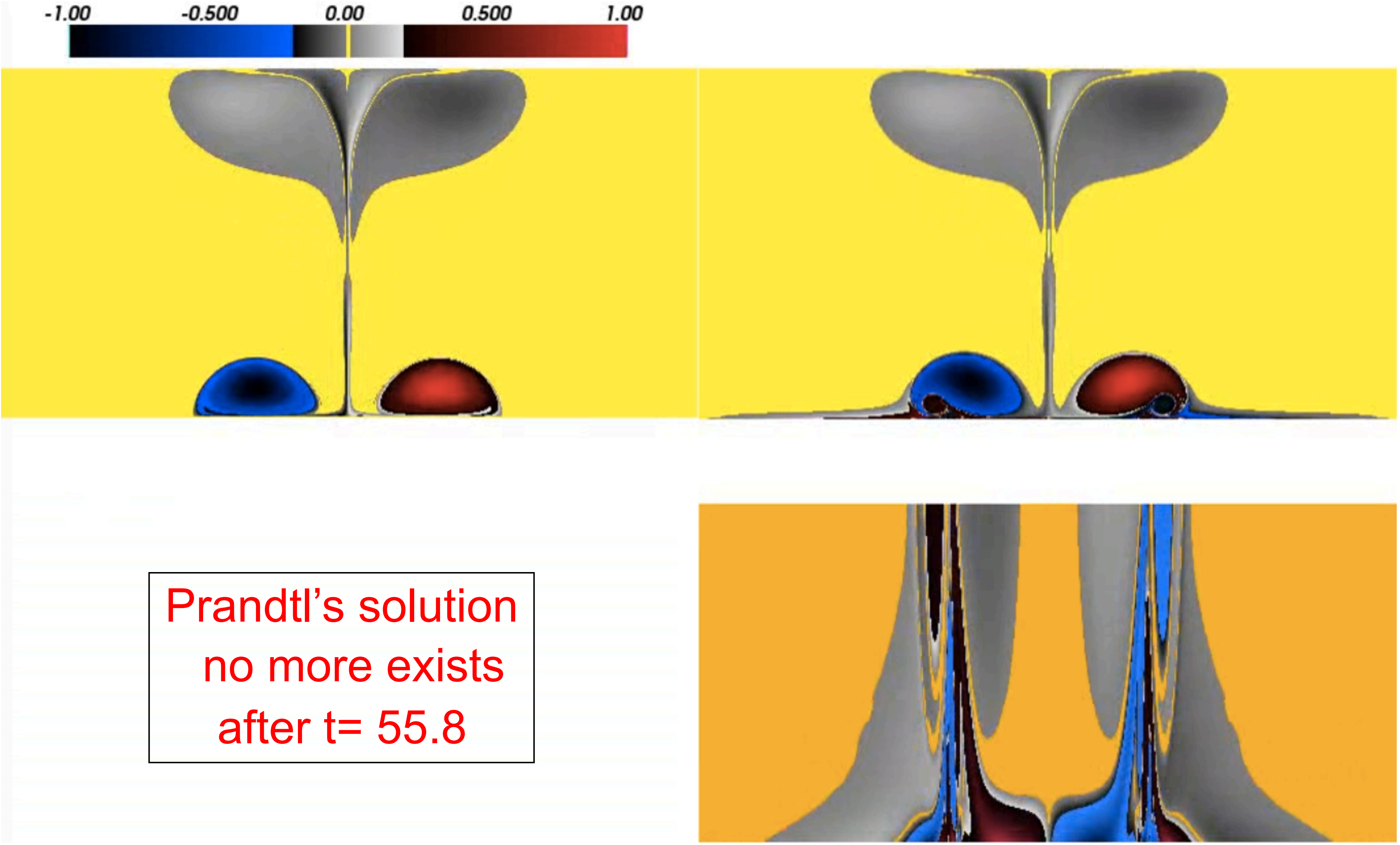
Euler

Navier-Stokes



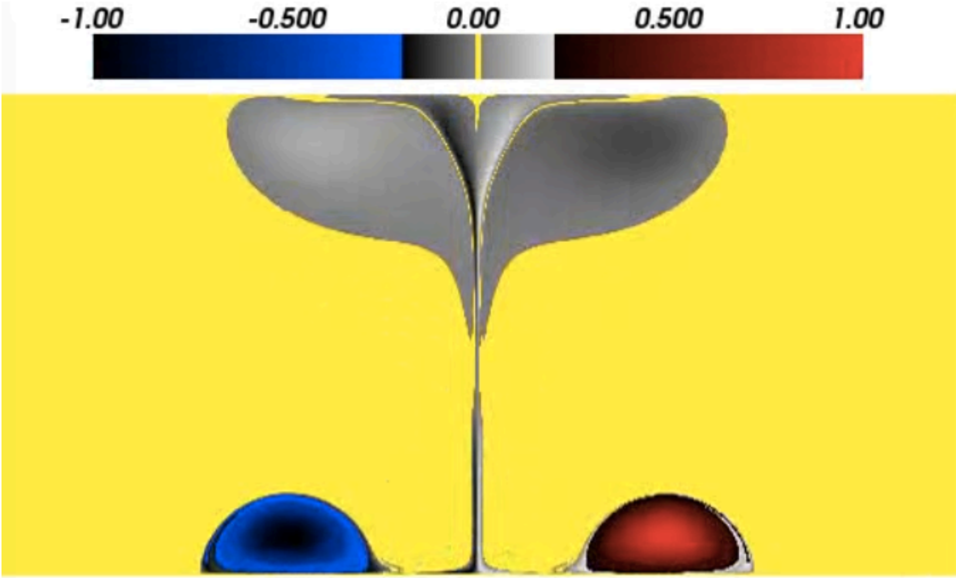
Euler

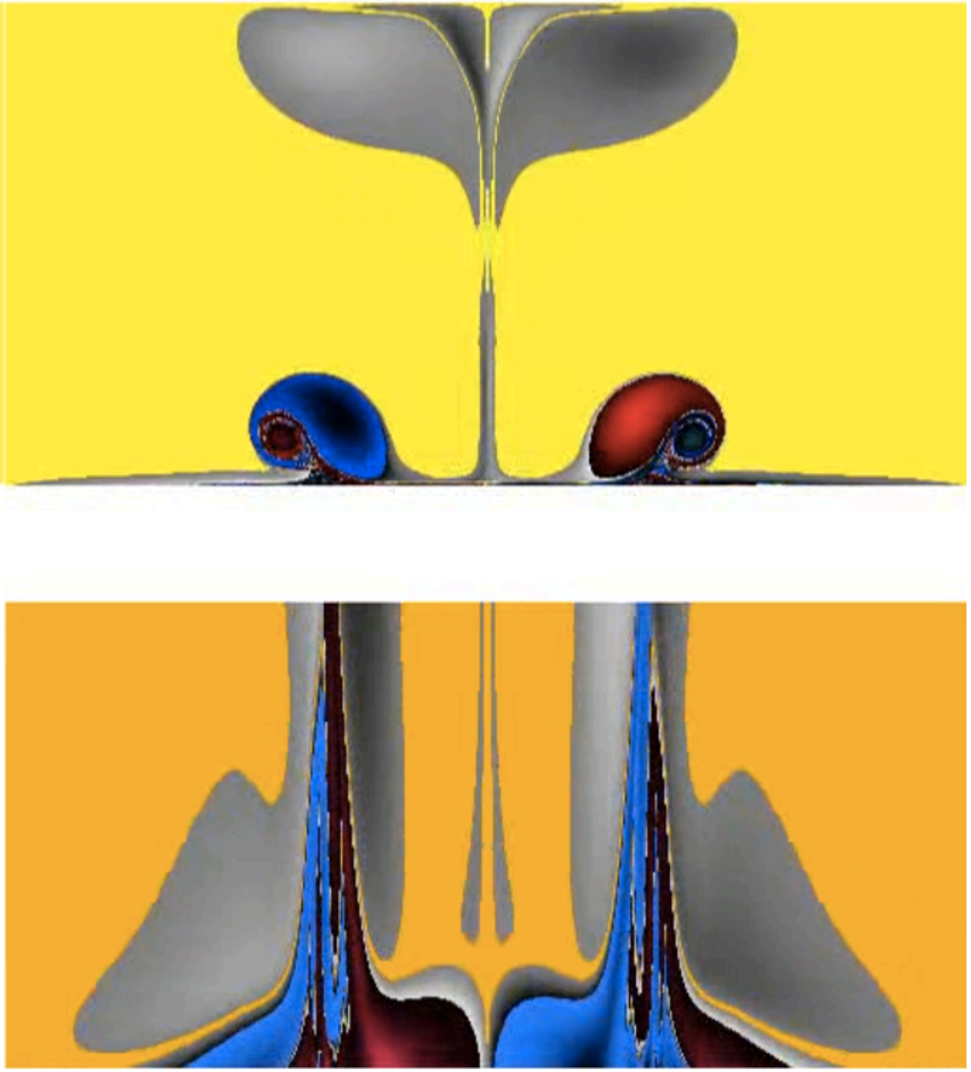
Navier-Stokes



Euler

Navier-Stokes





Prandtl's solution
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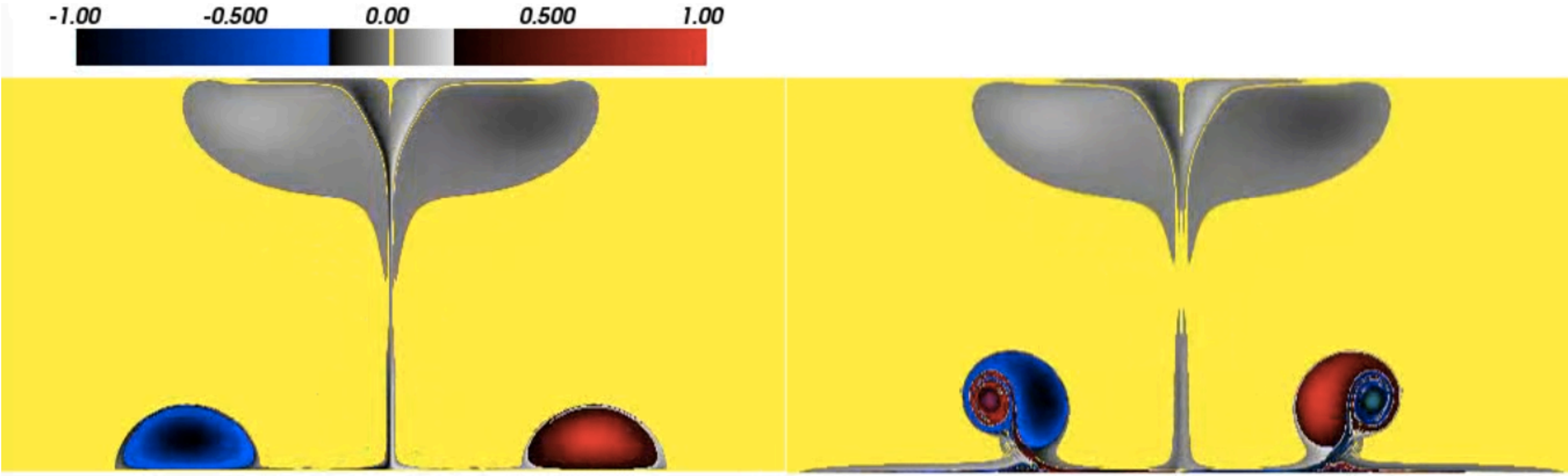

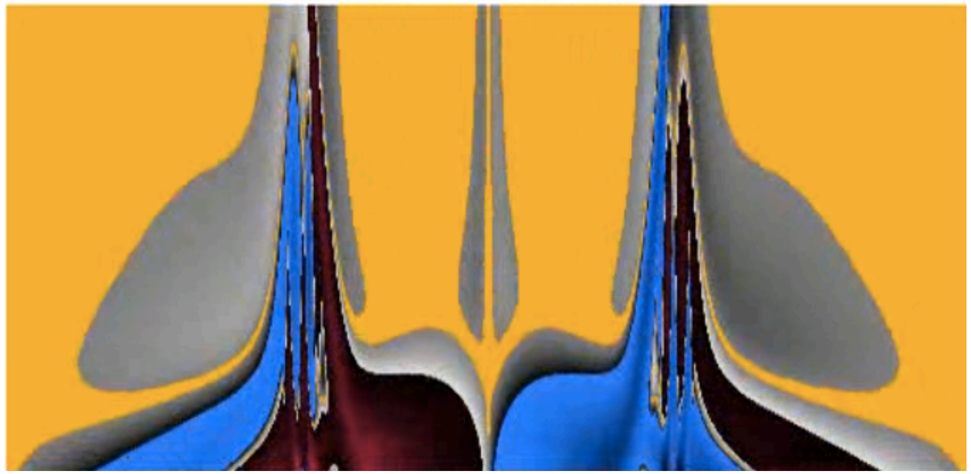

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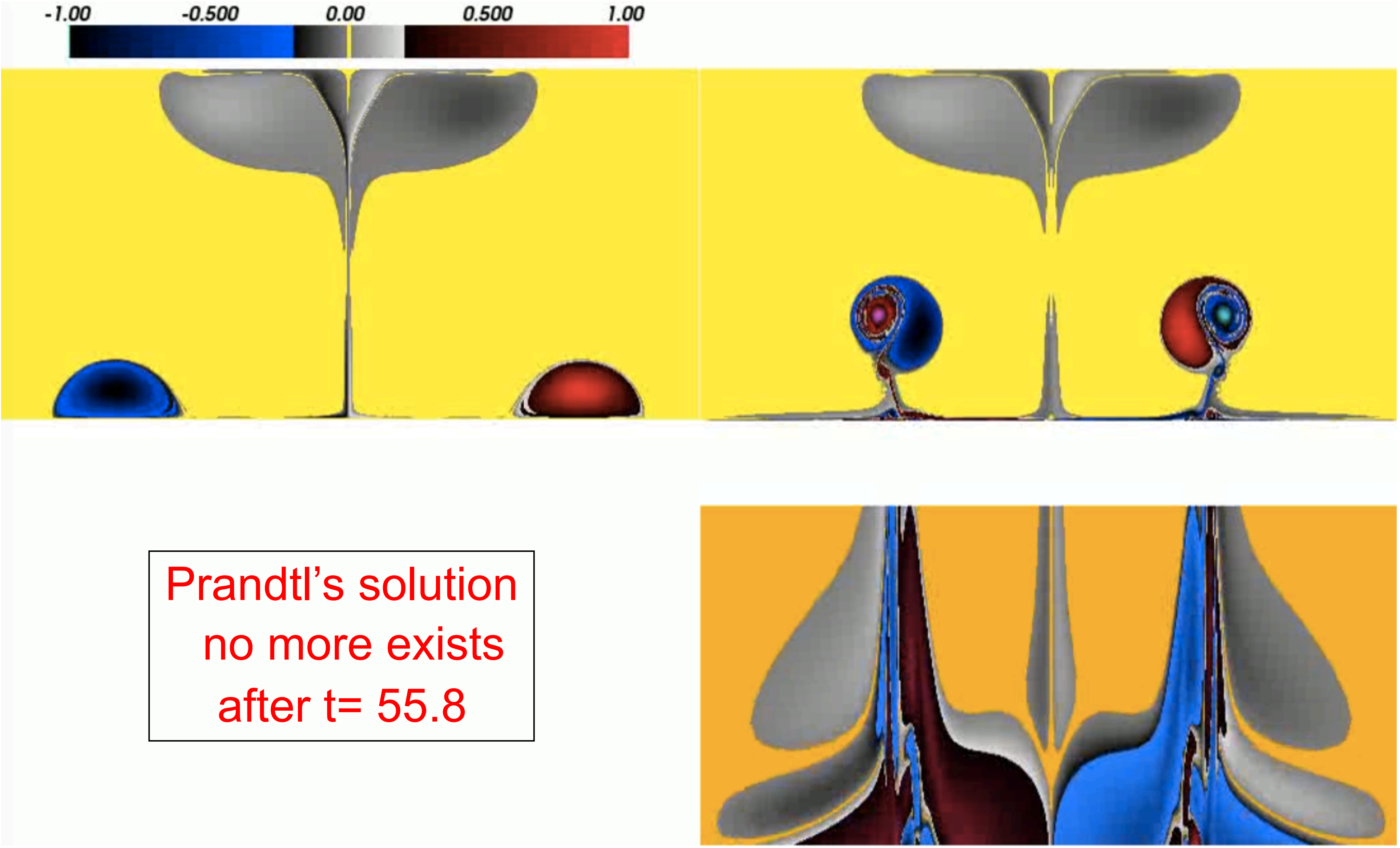
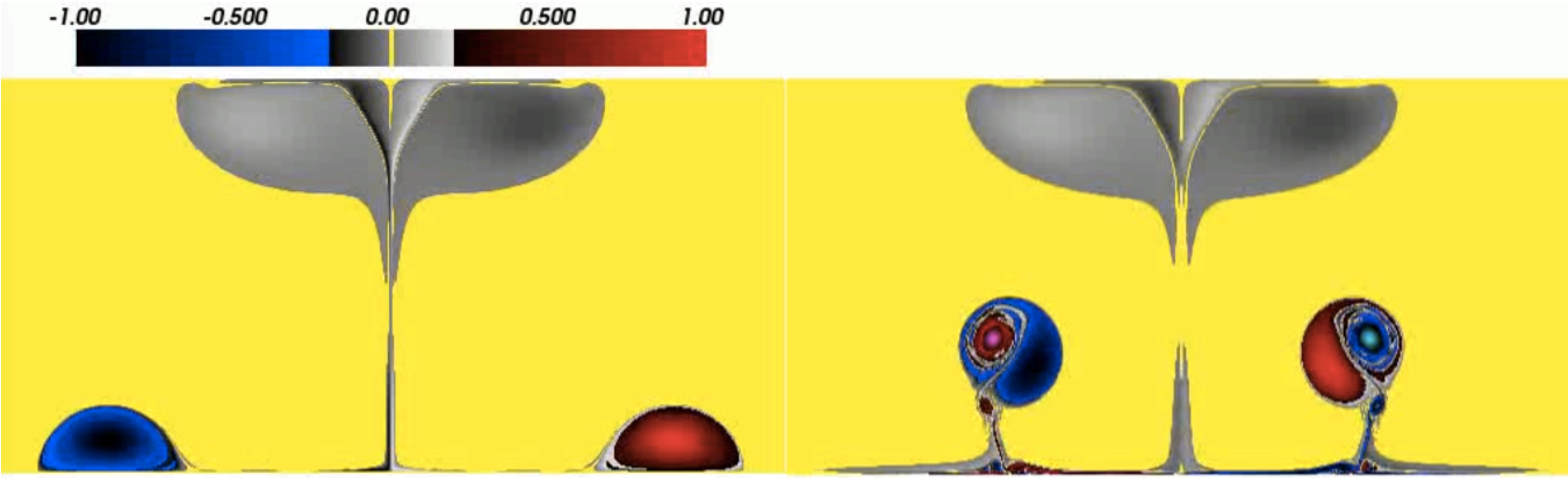
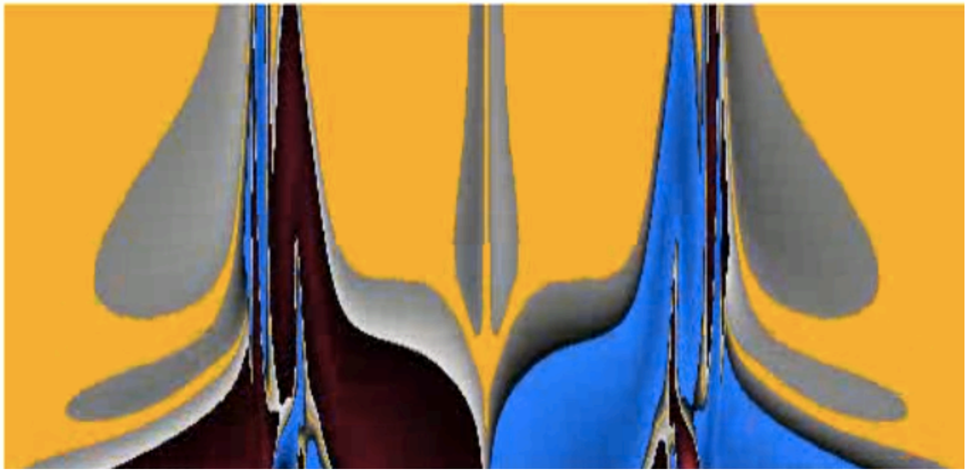


Euler

Navier-Stokes





Prandtl's solution
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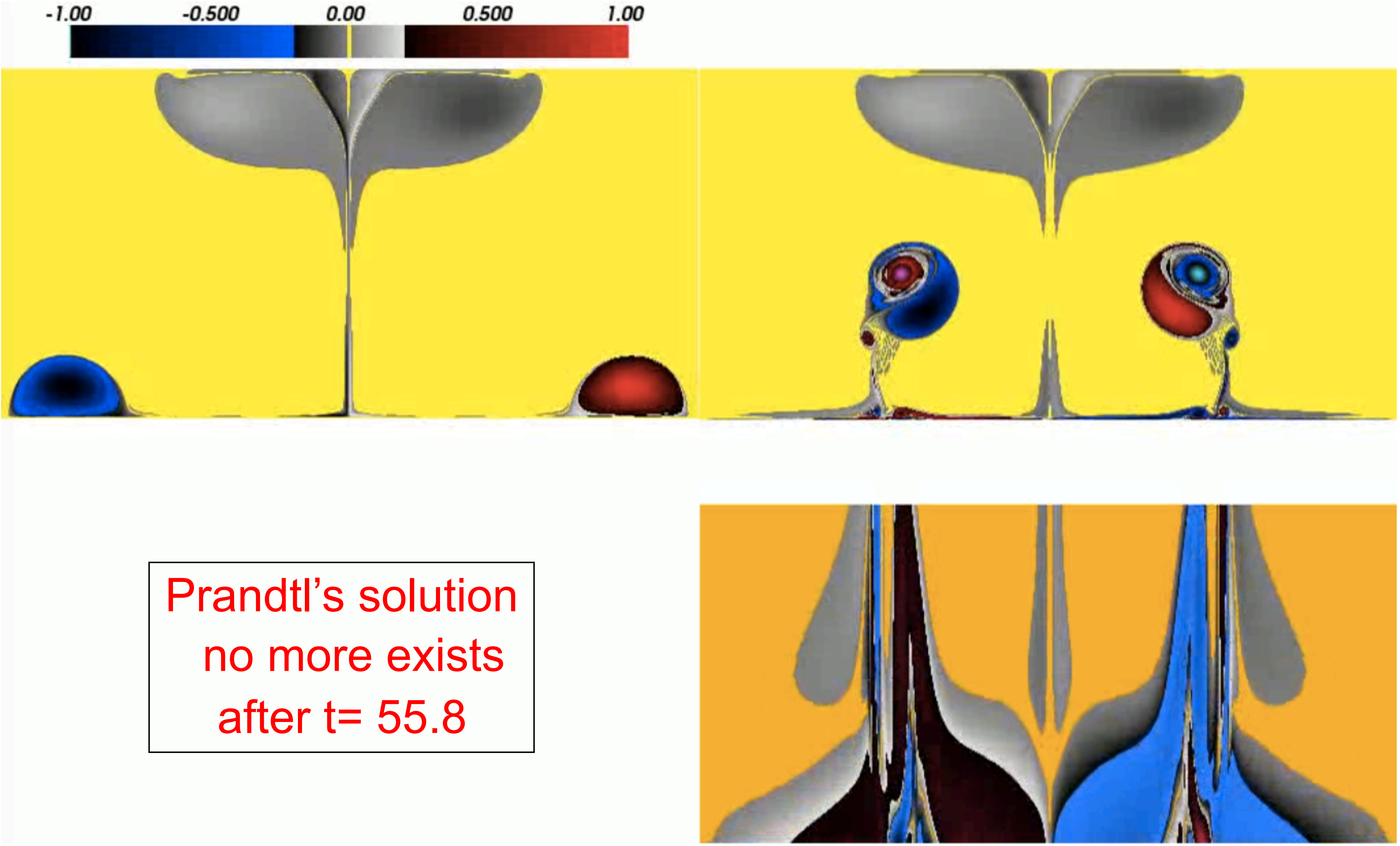
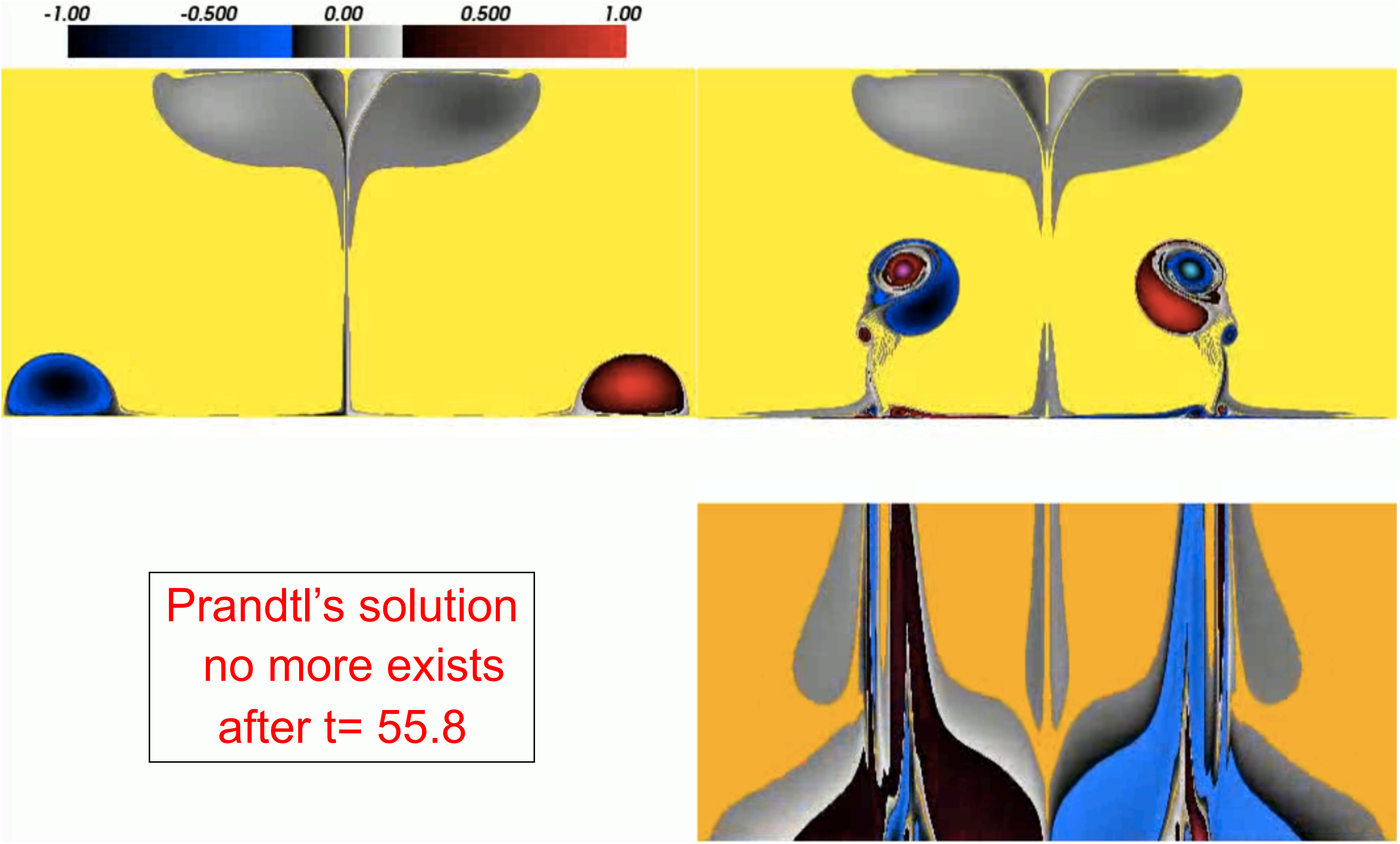
Euler

Navier-Stokes



Euler **Navier-Stokes**



Euler **Navier-Stokes**

Prandtl's singularity

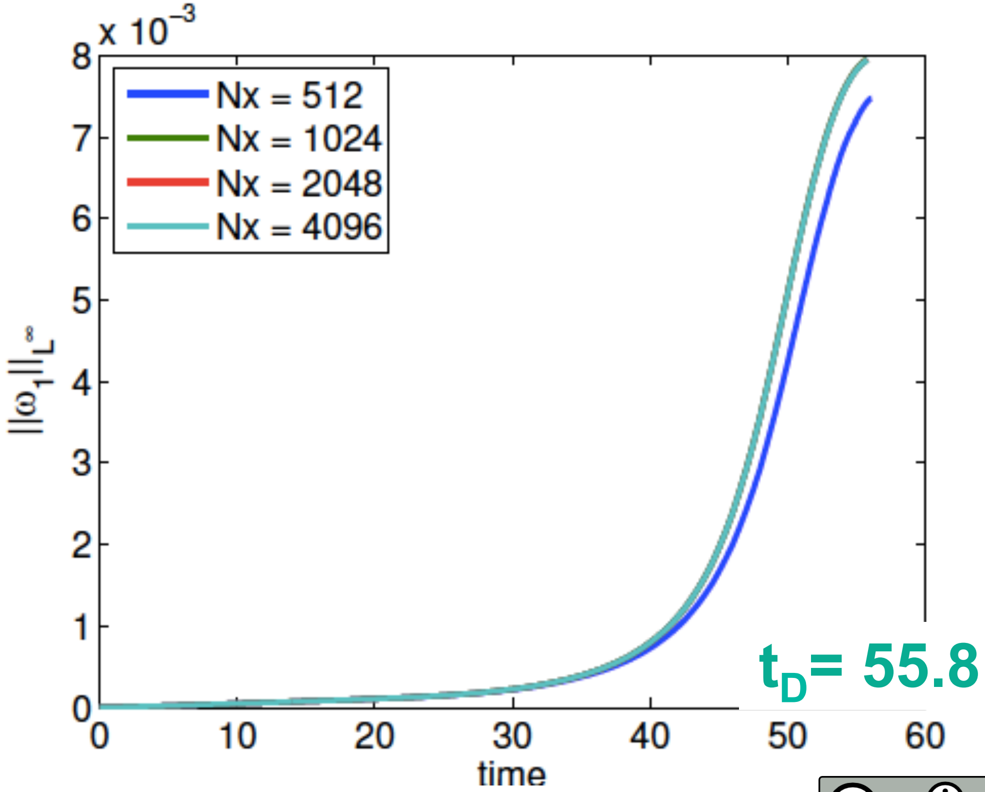
Prandtl equation has well-known finite time singularity

- $|\partial_x \omega_1|$ and $u_{1,y}$ blows up,
- ω_1 remains bounded.

L. L. van Dommelen and S. F. Shen., 1980
*J. Comp. Phys., **38**(2)*

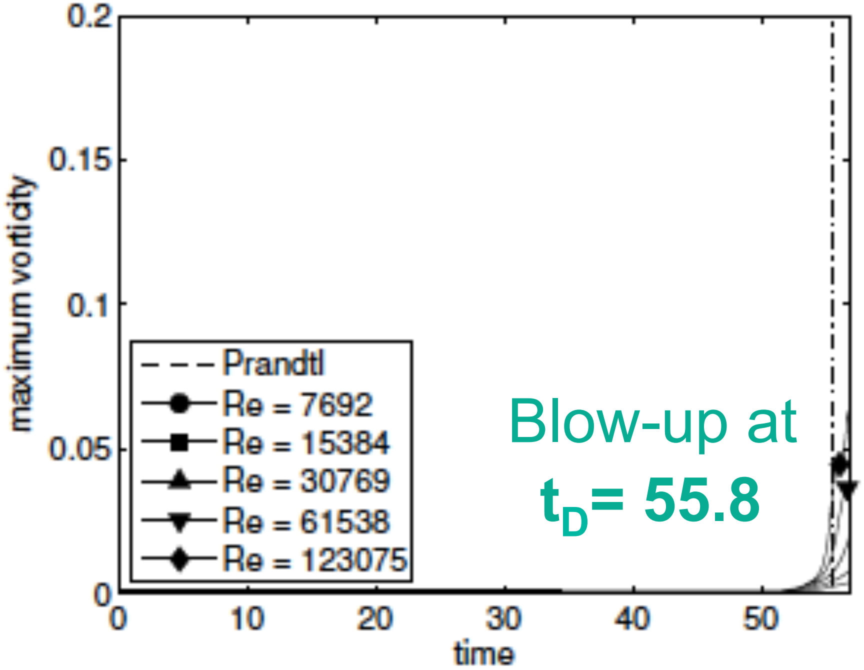
This is observed in our computations as expected,

for $t \to t_D \simeq 55.8$

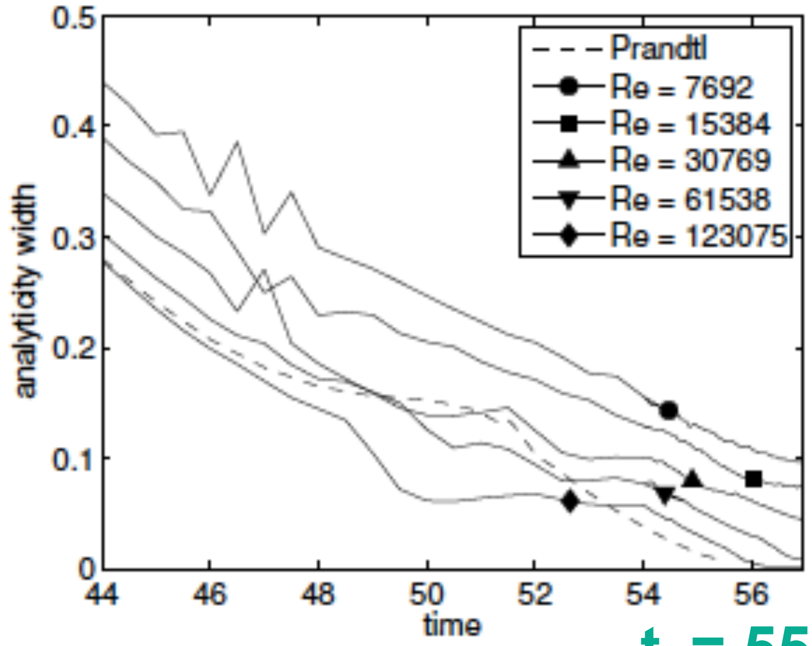


Prandtl solution's blow-up at t_D=55.8

According to Kato's theorem, and since ω_1 remains bounded uniformly until t_D, we expect that $\mathbf{u}_\nu \xrightarrow[\nu \to 0]{L^2} \mathbf{u}_0$ uniformly on $[0, t_D]$.



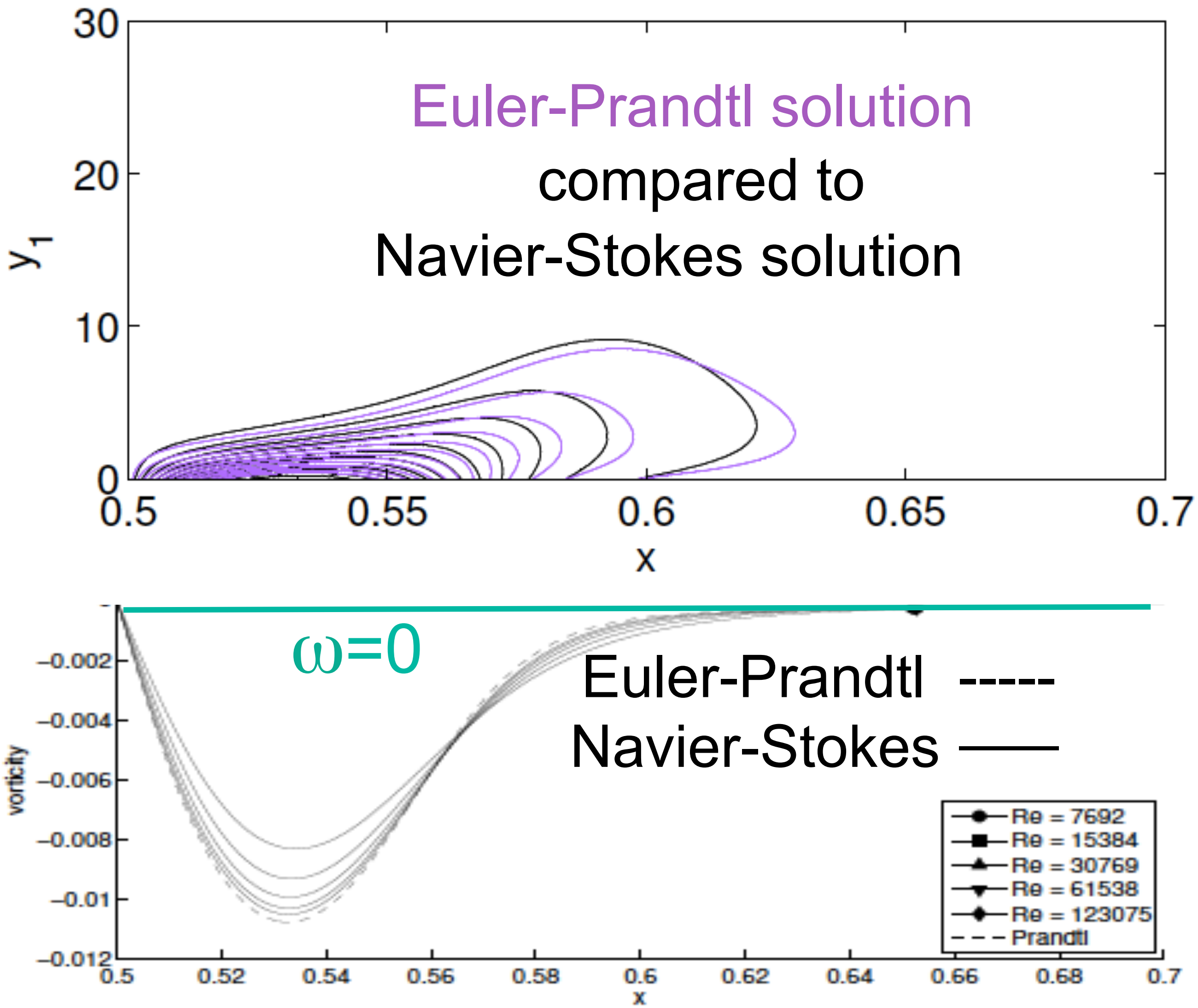
Evolution of vorticity max



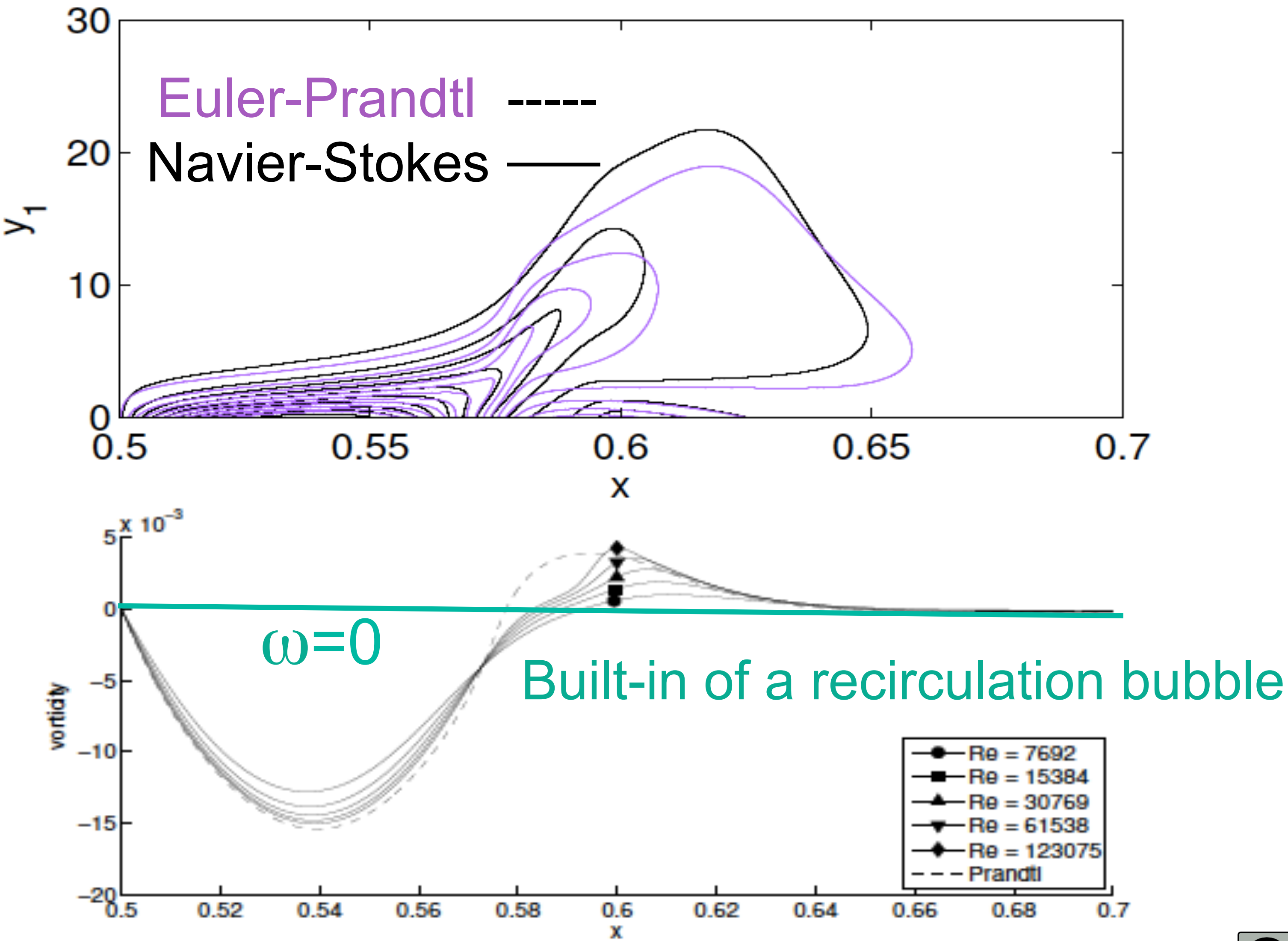
Evolution of analyticity strip

Show convergence!

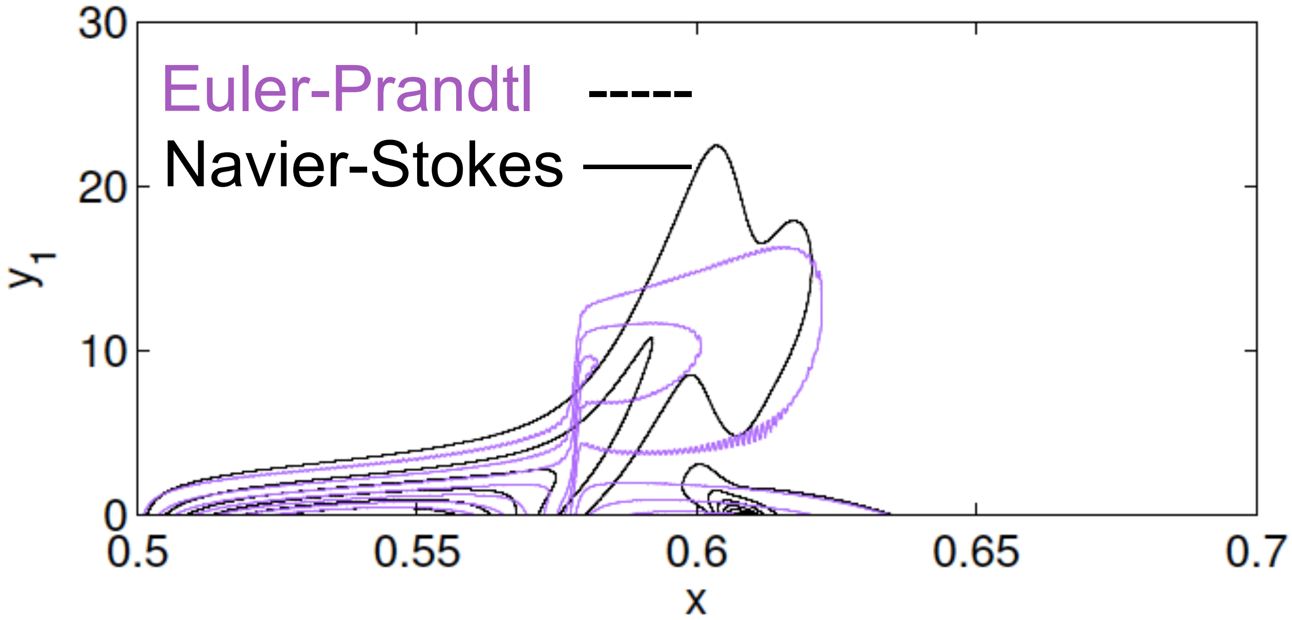
Vorticity along the wall at $t=50 < t_D$

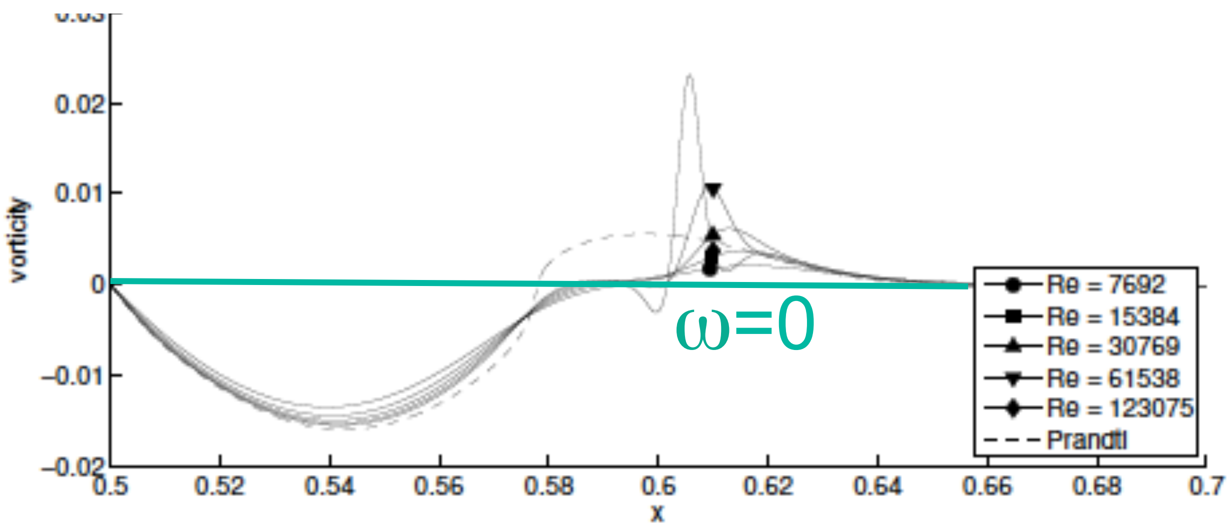


Vorticity along the wall at $t=54 < t_D$

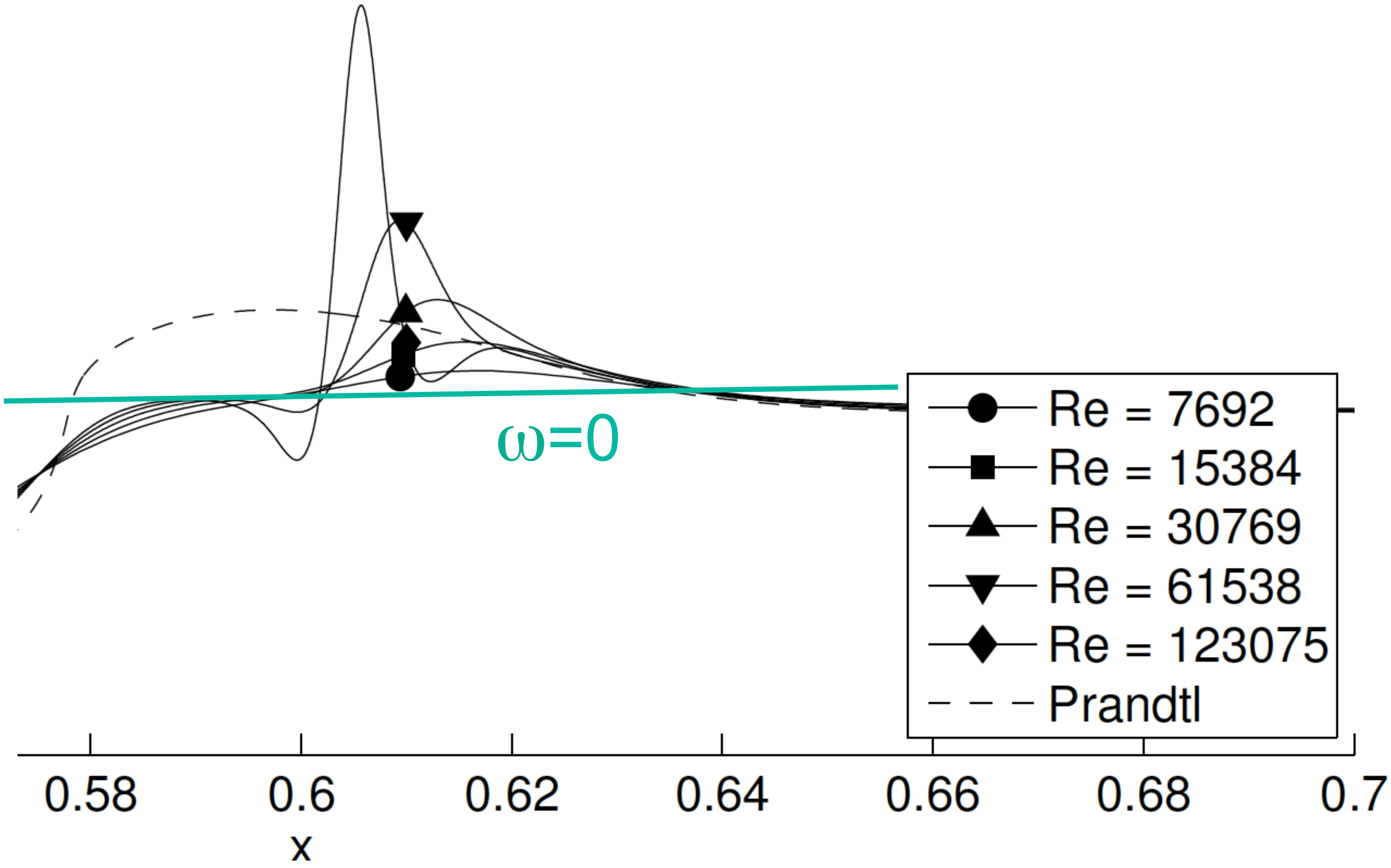


Vorticity along the wall at $t=55 < t_D$

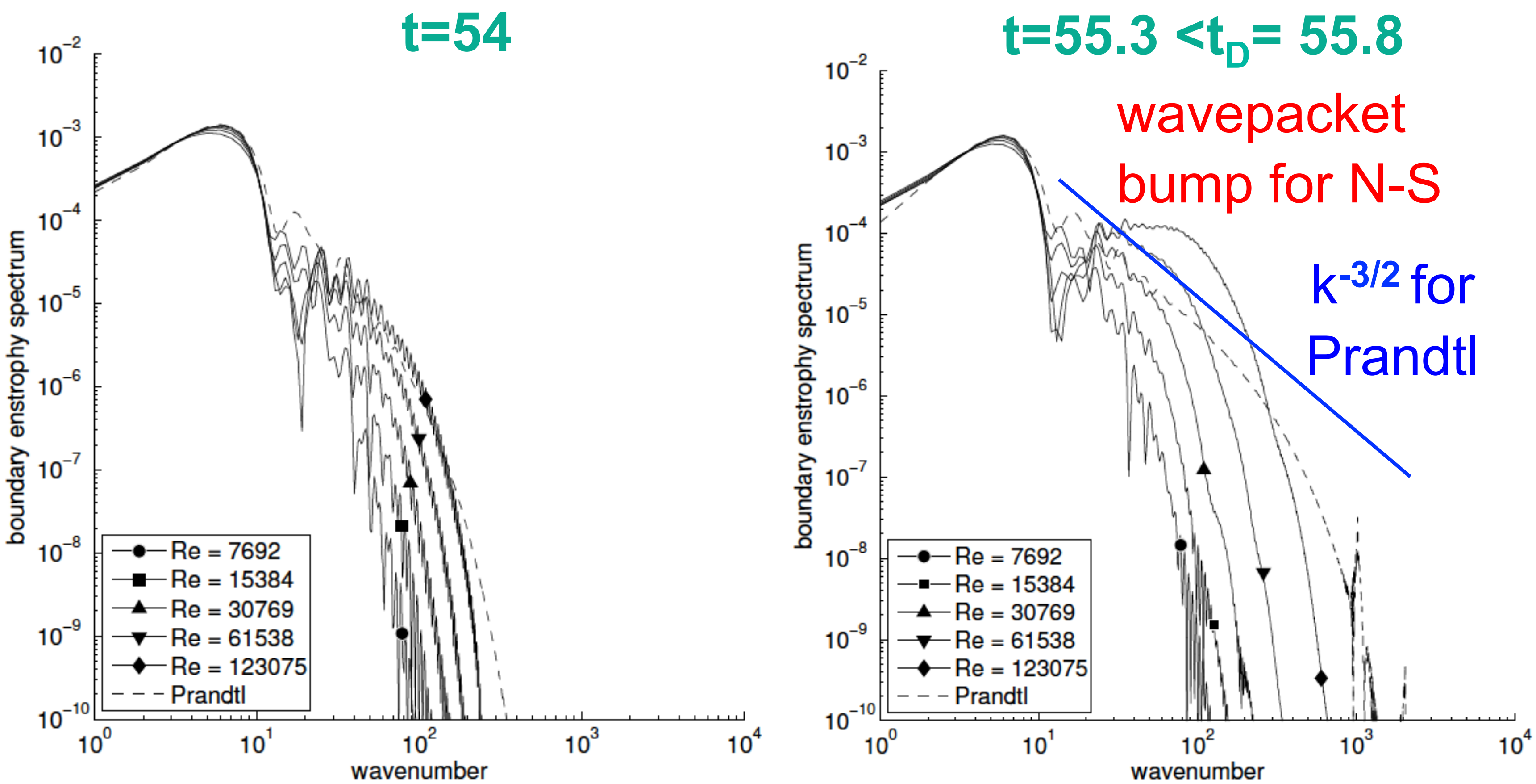




Vorticity along the wall at $t=55.3 < t_D$

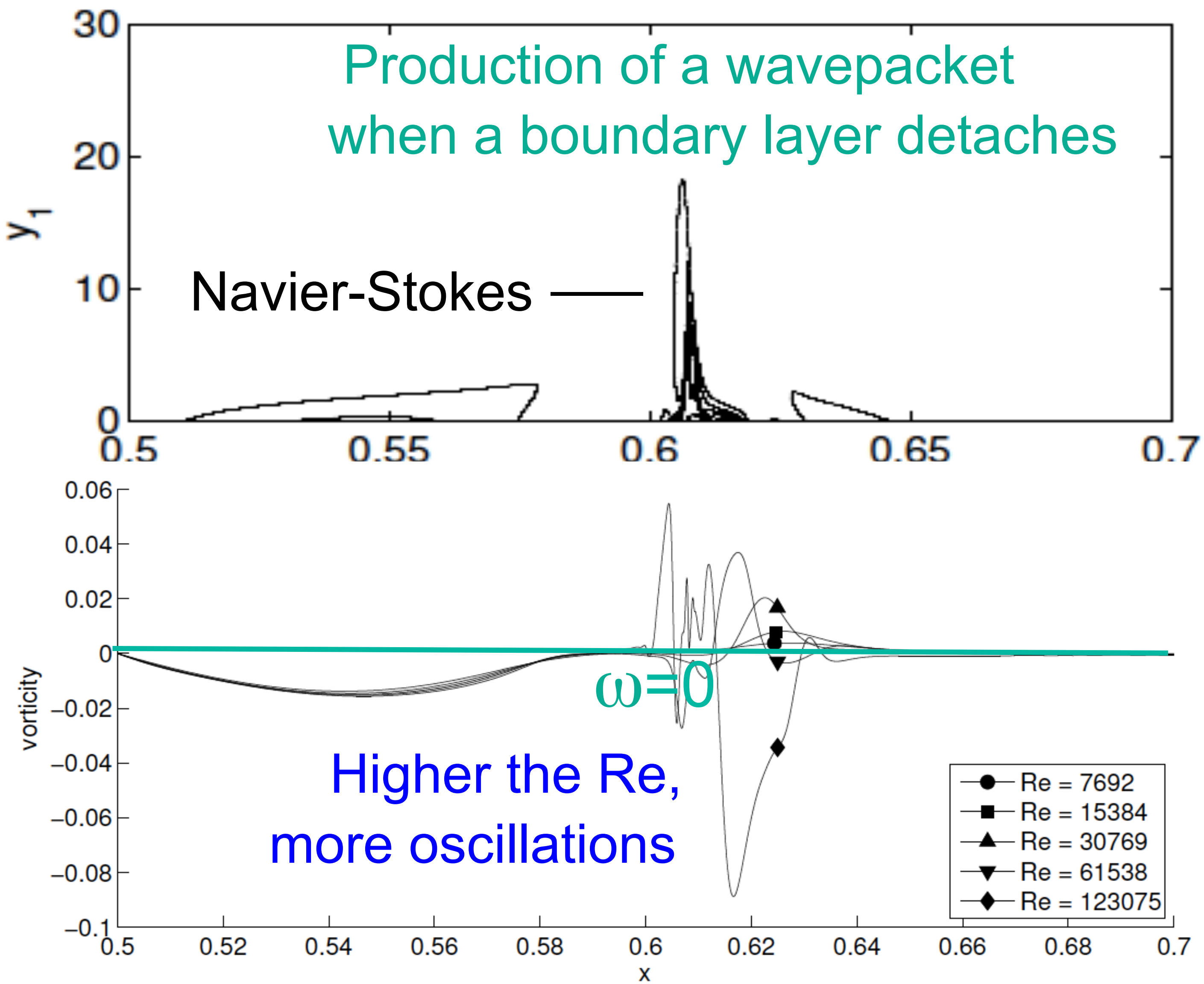


Spectrum of the boundary vorticity

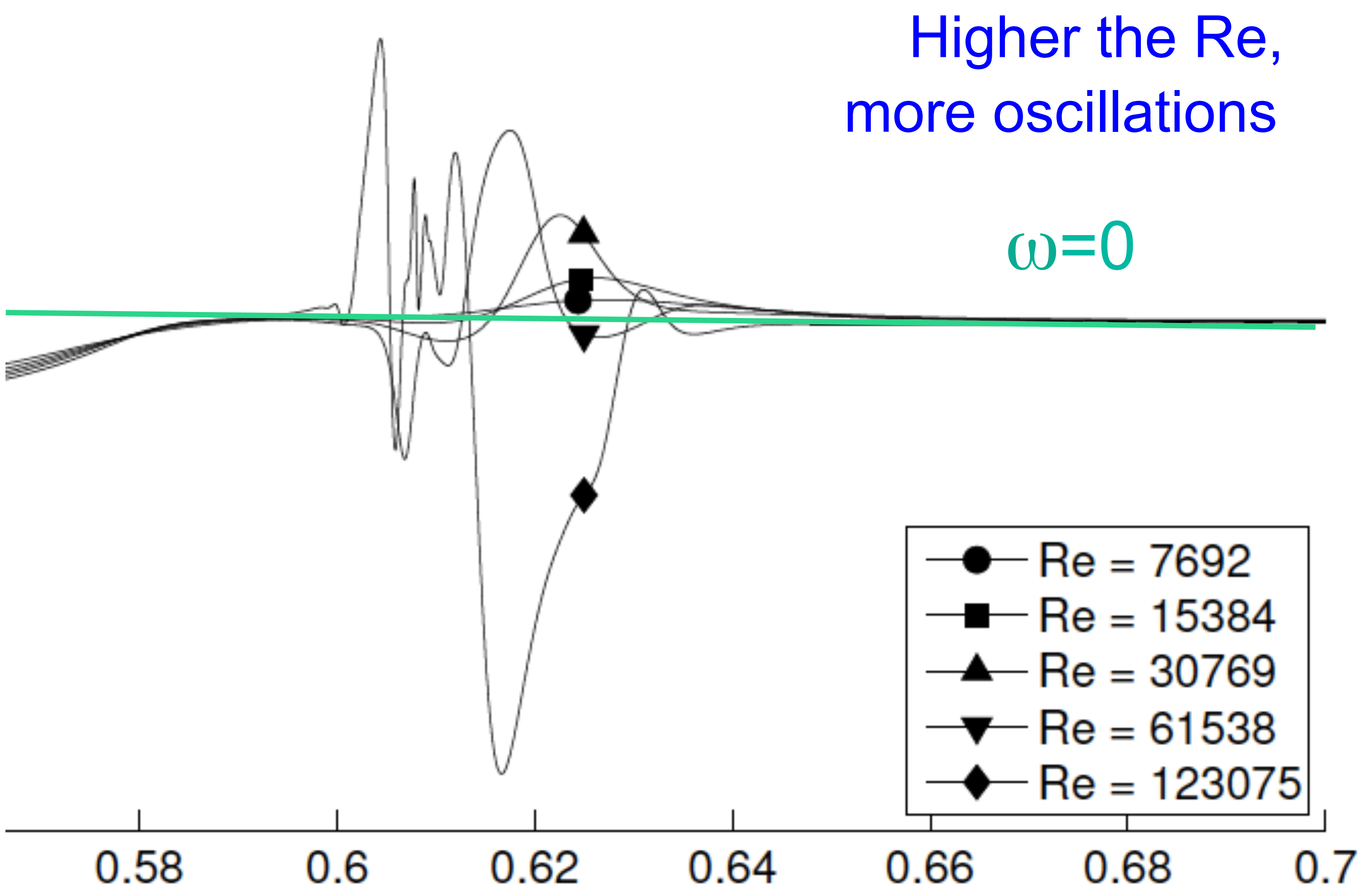


The Prandtl's solution behaves as $k^{-3/2}$ for large k, consistent with the build-up of a jump singularity of vorticity along the wall, while Navier-Stokes develops a bump which spreads in k with Re.

Vorticity along the wall at t=57 > t_D

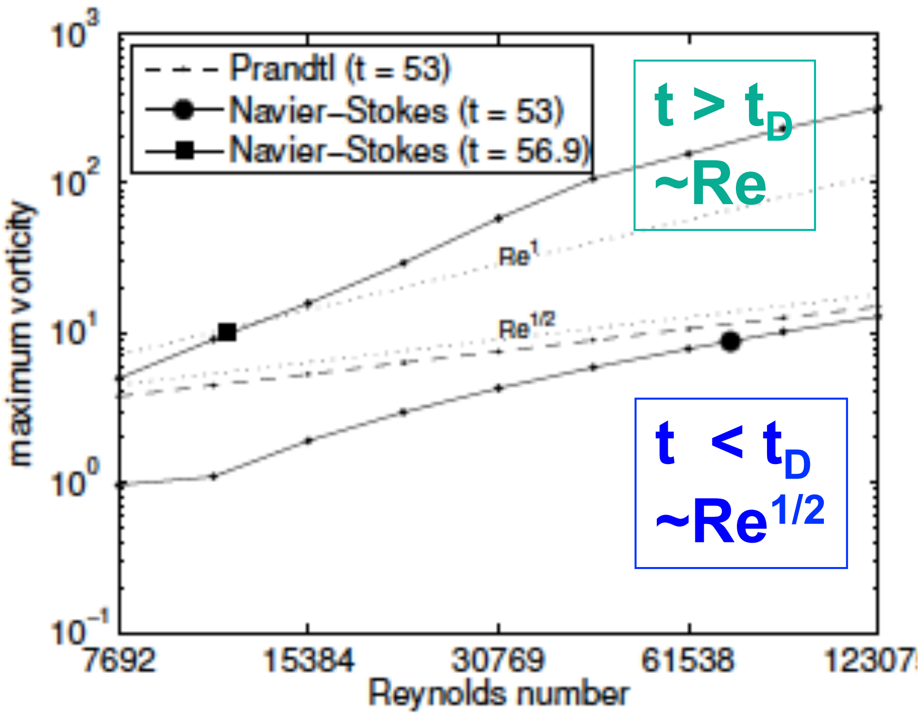


Vorticity along the wall at t=57.5 > t_D

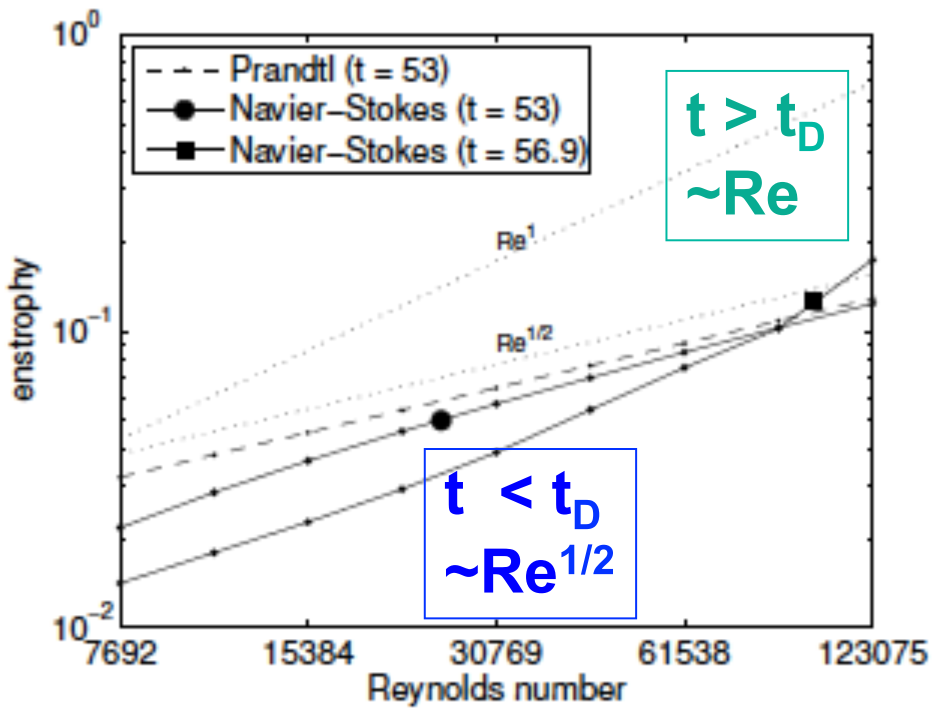


Scaling from Re=7692 to 123075

Vorticity max



Enstrophy



We observe Prandtl's scaling in $Re^{1/2}$ before $t_D \sim 55.8$ and Kato's scaling in Re after.

What about the von Karman log law?

In turbulent boundary layers the mean velocity profile satisfies

$$\langle U(y) \rangle \simeq \frac{U_\tau}{K_{\text{karman}}} \log\left(\frac{yU_\tau}{\nu}\right)$$

the so called 'log law', where

$$U_\tau = \sqrt{\nu \left\langle \frac{\mathrm{d}U}{\mathrm{d}y}\bigg|_{y=0} \right\rangle}$$

is the friction velocity.

This shows that the bulk velocity and U_τ have the same scaling with Re. This can be seen as a statistical signature of a boundary layer thickness Re^{-1}, which is consistent in some sense with the existence of a Kato layer.

T. von Karman, Uber laminare und turbulente Reibung. Z. ang. Math. Mech. 1 (4), 233{252,, 1921

Conclusions

- The Prandtl solution becomes singular at t_D when BL detaches.

- The Navier-Stokes solution converges uniformly to the Euler solution before BL detaches, and ceases to converge after BL detaches.

- The detached BL has spatial scales as fine as Re^{-1}, whic are produced in different directions and not only parallel to the wall, while the attached BL is parallel to the wall and scales as $Re^{-1/2}$.

- The maximal vorticity of Navier-Stokes solution does not appear at the same location of the Prandtl singularity. This contradicts the picture of BL detachment seen as a local process coinciding with Prandtl singularity.

Conclusions

- The velocity gradient du/dy at the wall scales like Re, which can be seen as the statistical signature of the existence of a boundary layer of thickness Re in the neighborhood of the wall.

- Hence, the log-law, which is obtained from experimental results, is consistent with the existence of a Kato layer. This connection can be made in a phenomenological way without invoking the Kolmogorov scale and cascade.

- Our results may help in investigating rigorous foundations to the phenomenological theory of von Karman.

Open questions

Numerical results suggest that a new asymptotic description of the flow beyond the breakdown of the Prandtl regime is possible.
Studying it might help to answer the following questions:

- Would Navier-Stokes solution looses smoothness after t_D?
- Would it converges to a weak singular dissipative solution of Euler's equation analog to dissipative shocks in Burgers solution?
- How can such a weak solution be approximated numerically?

This might lead to a new resolution of d'Alembert's paradox in terms of the production of weak singular dissipative structures due to the interaction of fully-developed turbulent flows with walls.

J. Leray, 1934
Sur le mouvement d'un fluide visqueux,
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J. Fluid Mech. (2018), *vol.* 849, *pp.* 676–717.

doi:10.1017/jfm.2018.396

Energy dissipation caused by boundary layer instability at vanishing viscosity

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(Received 12 July 2017; revised 4 March 2018; accepted 16 April 2018)

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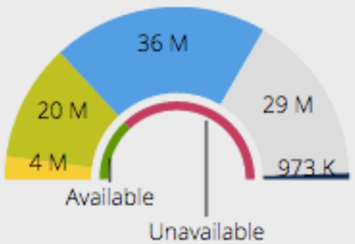

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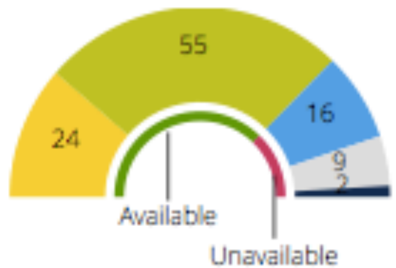

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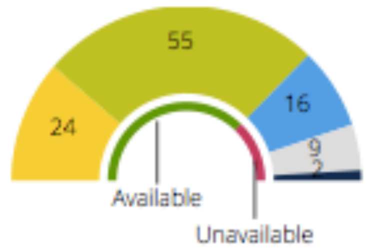

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