Energy dissipation caused by boundary layer instability at vanishing viscosity

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GDR Turbulence 2018
Université Nice Sophia Antipolis
October 17th 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

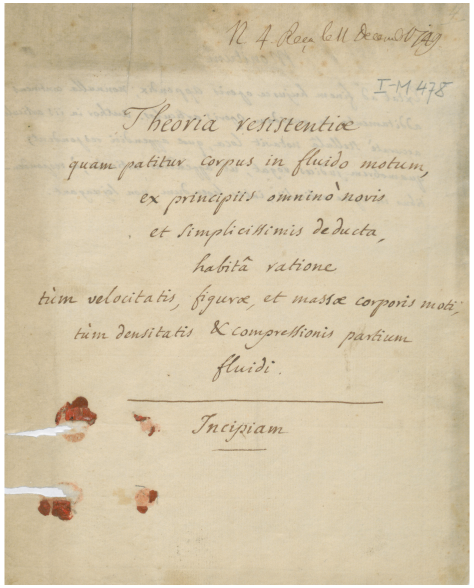
Leonhard Euler
(1707-1783)

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

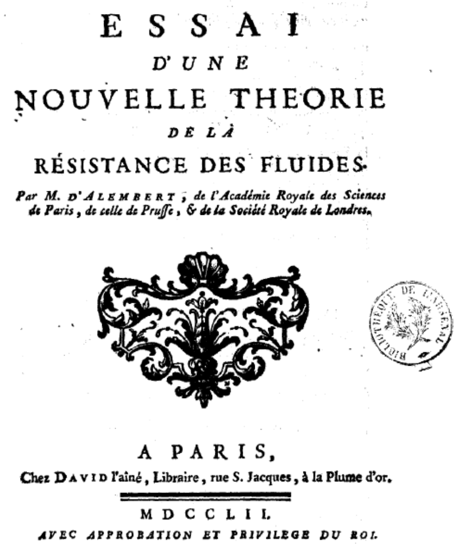


N. 4 Reçu le 11 Decemb 1749

I-M 478

Theoria resistentiæ
quam patitur corpus in fluido motum,
ex principiis omninò novis
et simplicissimis deducta,
habitâ ratione
tùm velocitatis, figuræ, et massæ corporis moti,
tùm 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

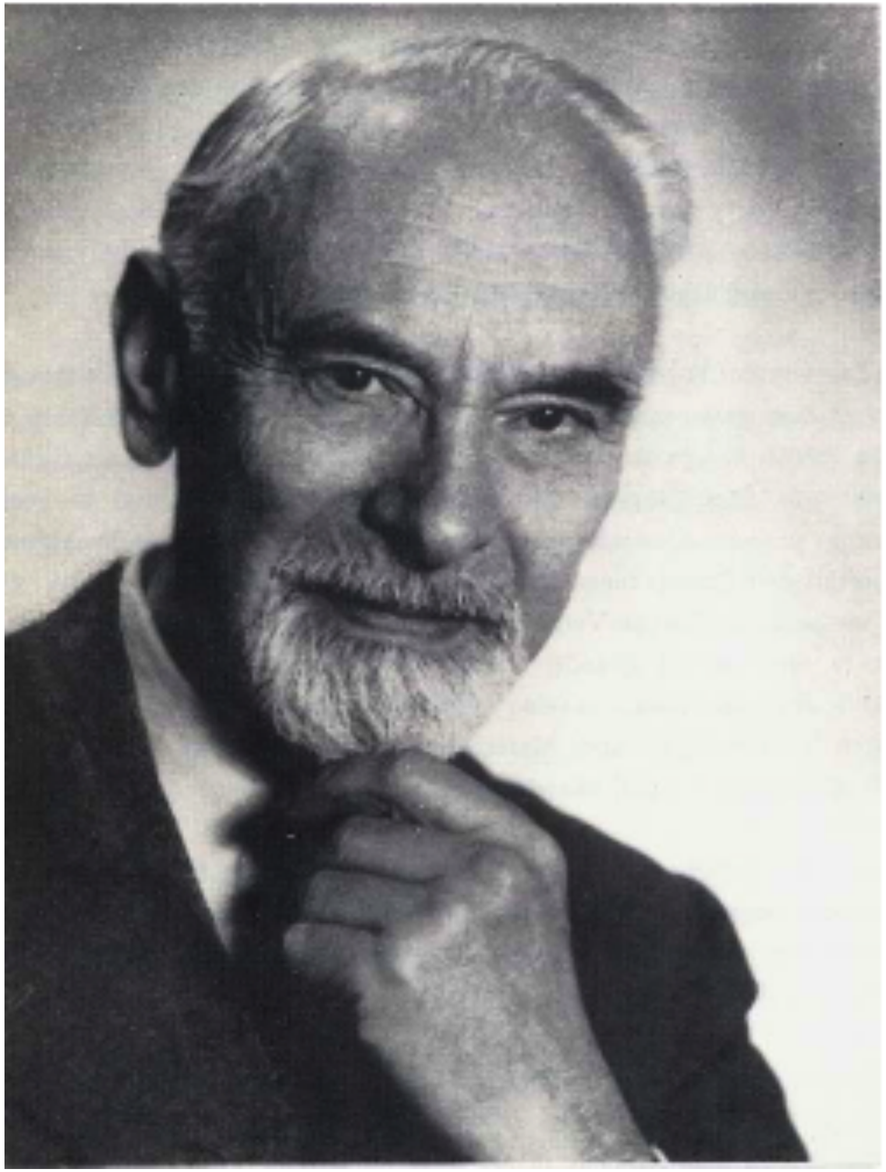
> *’It seems to me that the theory, developed in all possible rigor, gives, at least in several cases, a strictly vanishing resistance, a singular paradox which I leave to future geometers to elucidate.’*

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

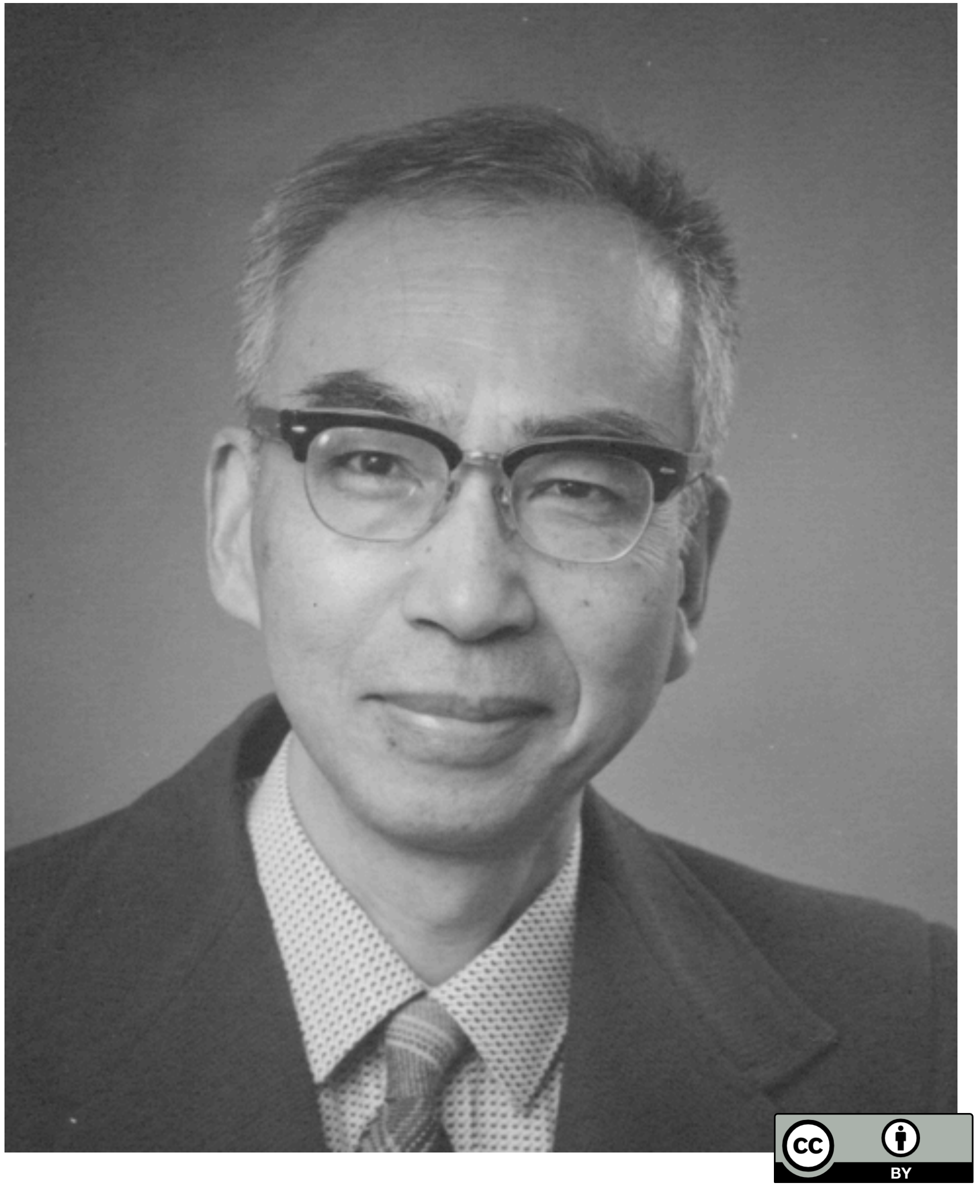
Adhémar Jean-Claude
Barré de Saint-Venant
(1797-1886)

George Stokes
(1819-1903)

Ludwig Prandtl
(1875-1953)

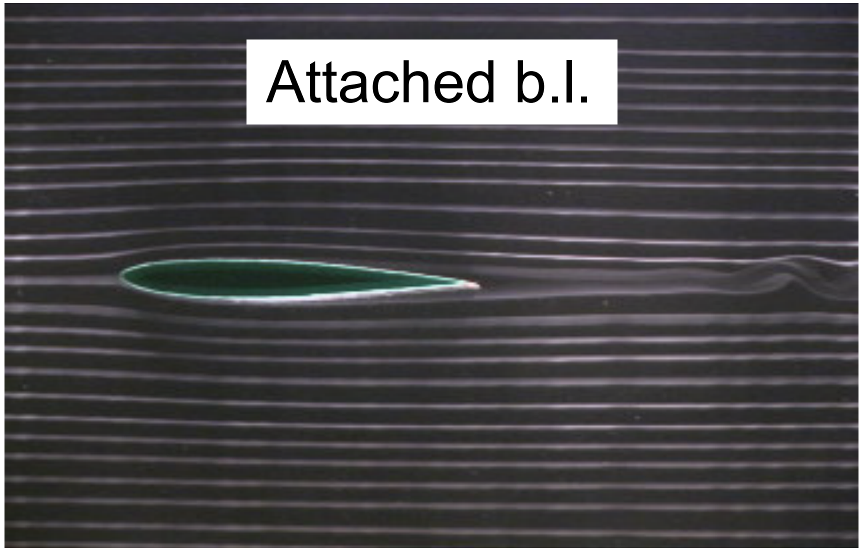


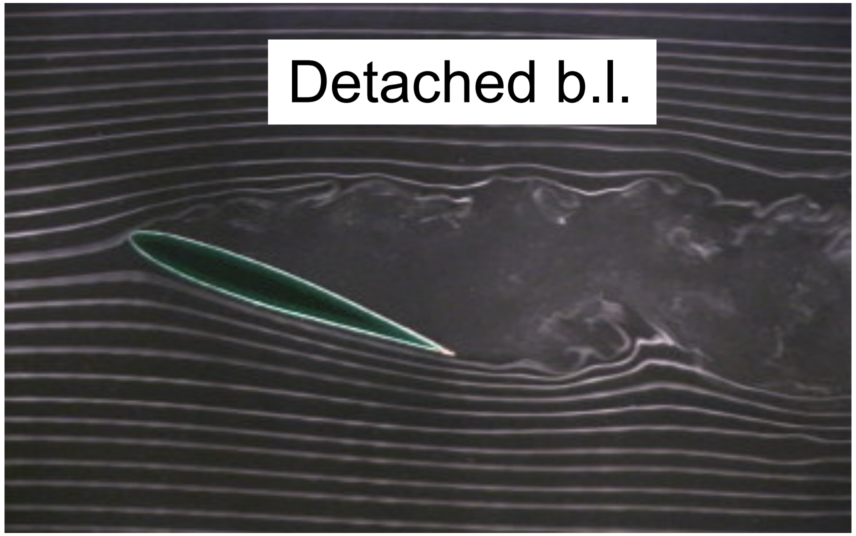
Toshio Kato
(1917-1999)



1904: Prandtl’s boundary layer theory

- Prandtl (1904) proposed to use Euler equation far from walls and Navier-Stokes equation in boundary layers attached to walls.
- He predicted that the thickness of the boundary layers attached to walls scales as $Re^{-1/2}$,
- Prandtl’s theory does not apply if the boundary layers detach.


Attached b.l.


Detached b.l.

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

What is the inviscid limit of Navier-Stokes?

Navier-Stokes equations with no-slip boundary conditions:

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

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

Same initial conditions ———— ?

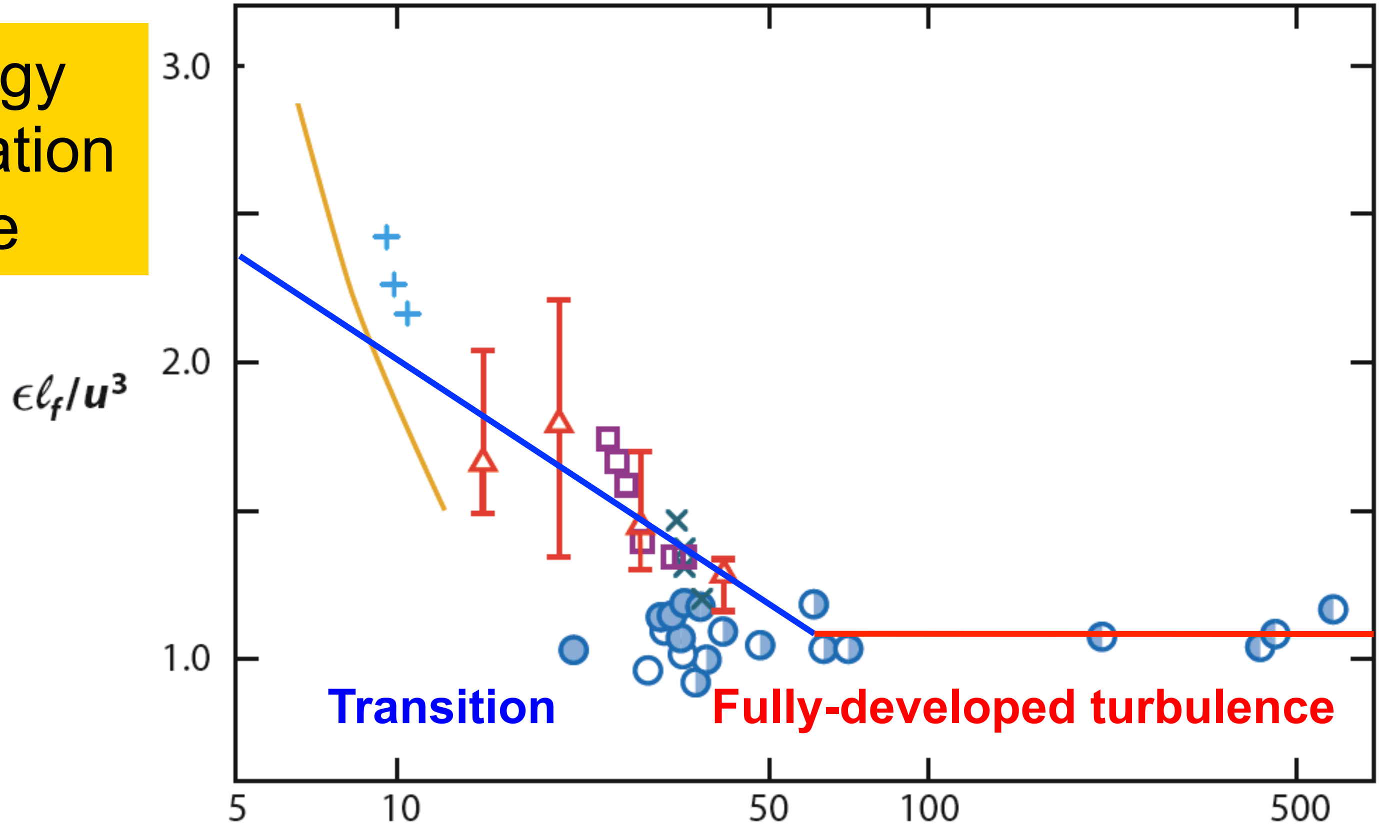
Euler equations with slip boundary conditions:

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

Laboratory experiments

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

Energy dissipation rate

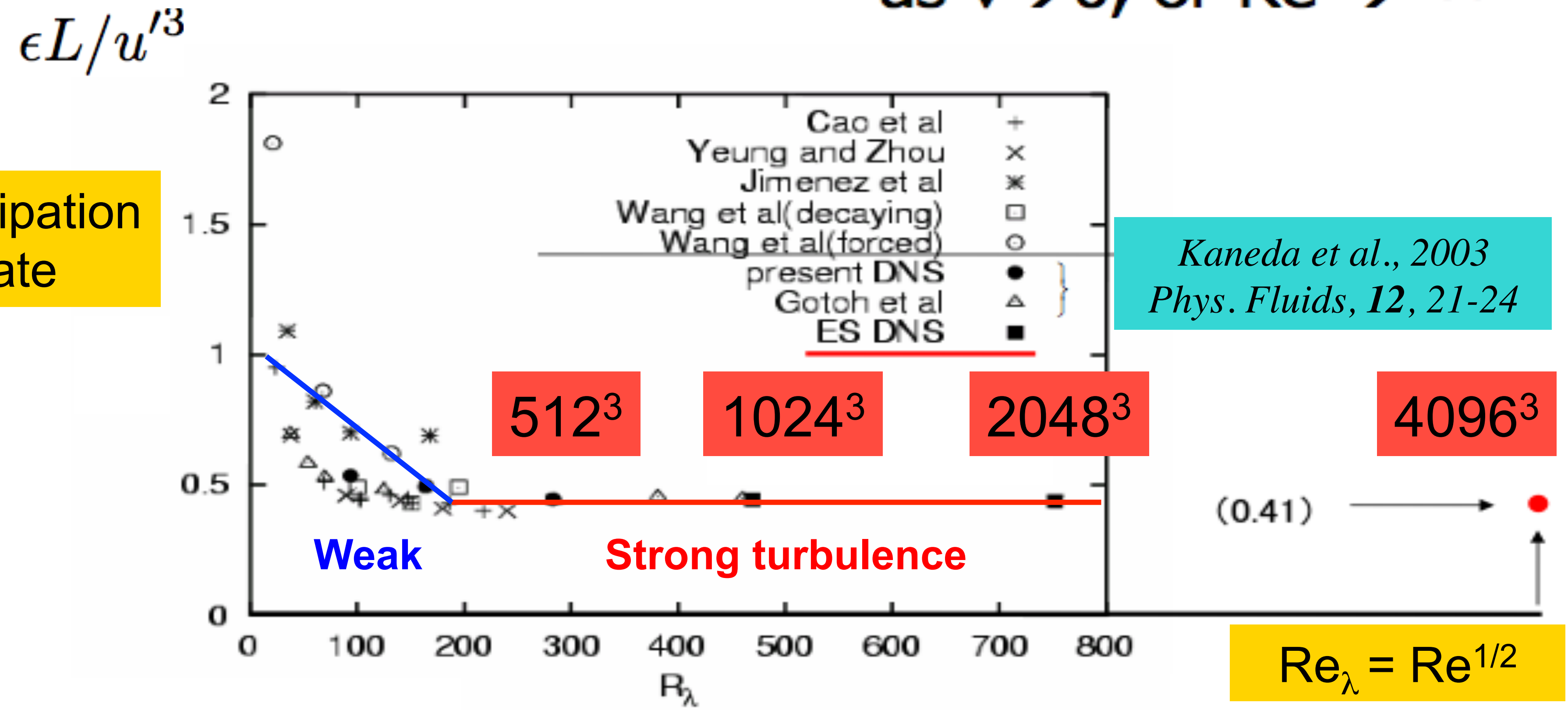


$Re_\lambda = Re^{1/2}$

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

Numerical experiments

Normalized energy dissipation → ?
as $\nu \to 0$, or $Re \to \infty$



Dissipation rate

Kaneda et al., 2003
Phys. Fluids, **12**, 21-24

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

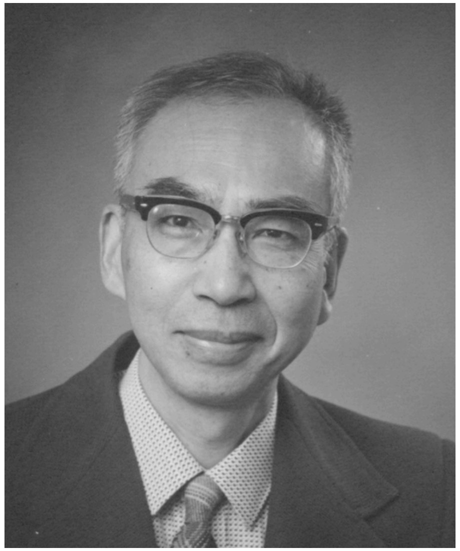
Both laboratory and numerical experiments
show that the dissipation rate of turbulent flows
becomes independent of the fluid viscosity for large *Re*

1984: Kato’s theorem

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

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

$$\nu \to 0$$



Toshio Kato (1917-1999)

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

and, if and only if,
this happens in a boundary layer
whose thickness scales as Re^{-1}

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

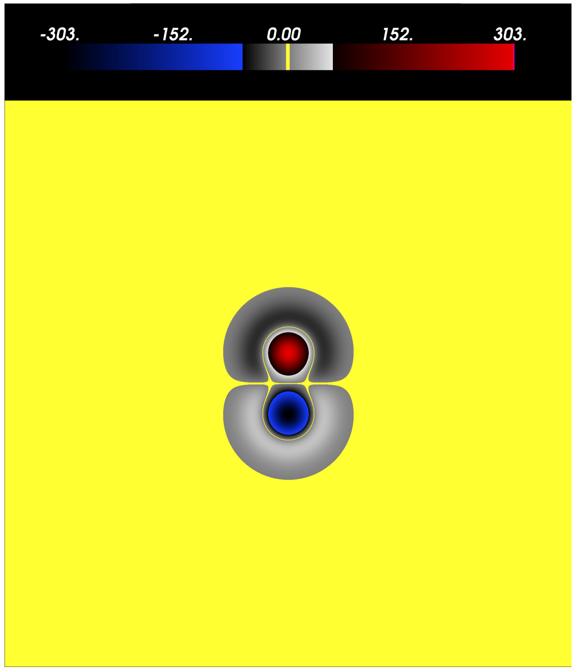
$$\downarrow$$

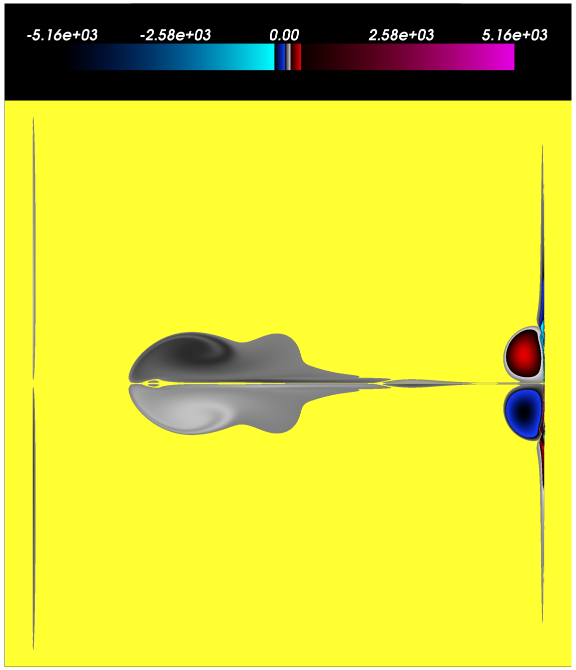
$$\boxed{\delta x \propto \mathrm{Re}^{-1}}$$

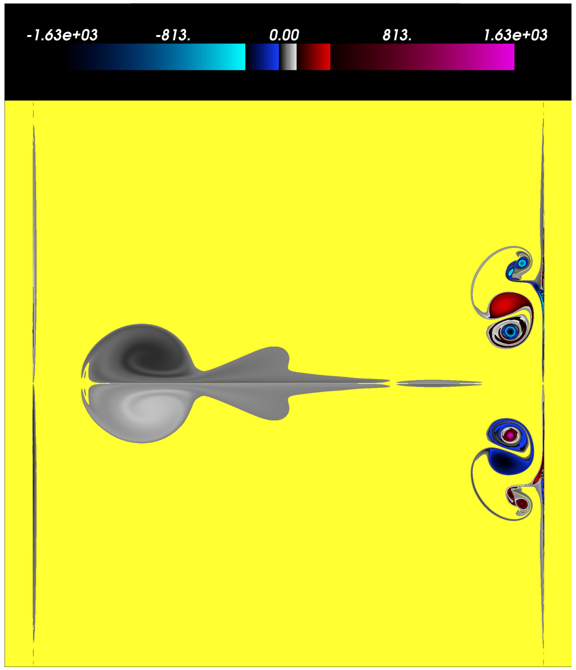
This requires using
smaller resolution
to compute high
Reynolds flows
than predicted by
Prandtl’s theory

Dipole crashing onto a wall in 2D

DNS
Resolution
$N=8192^2$





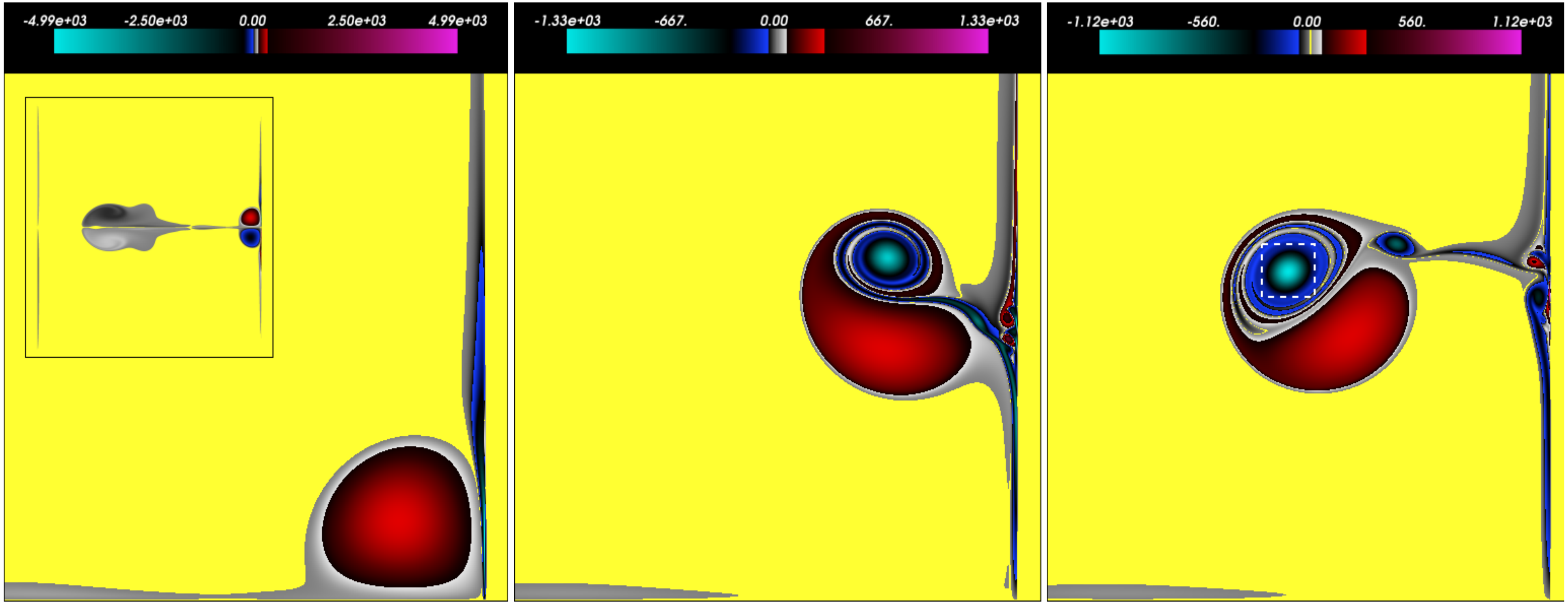


Zoom when boundary layers detach

Resolution
$N=16384^2$

Navier-Stokes equations
with volume penalization
integrated using Fourier

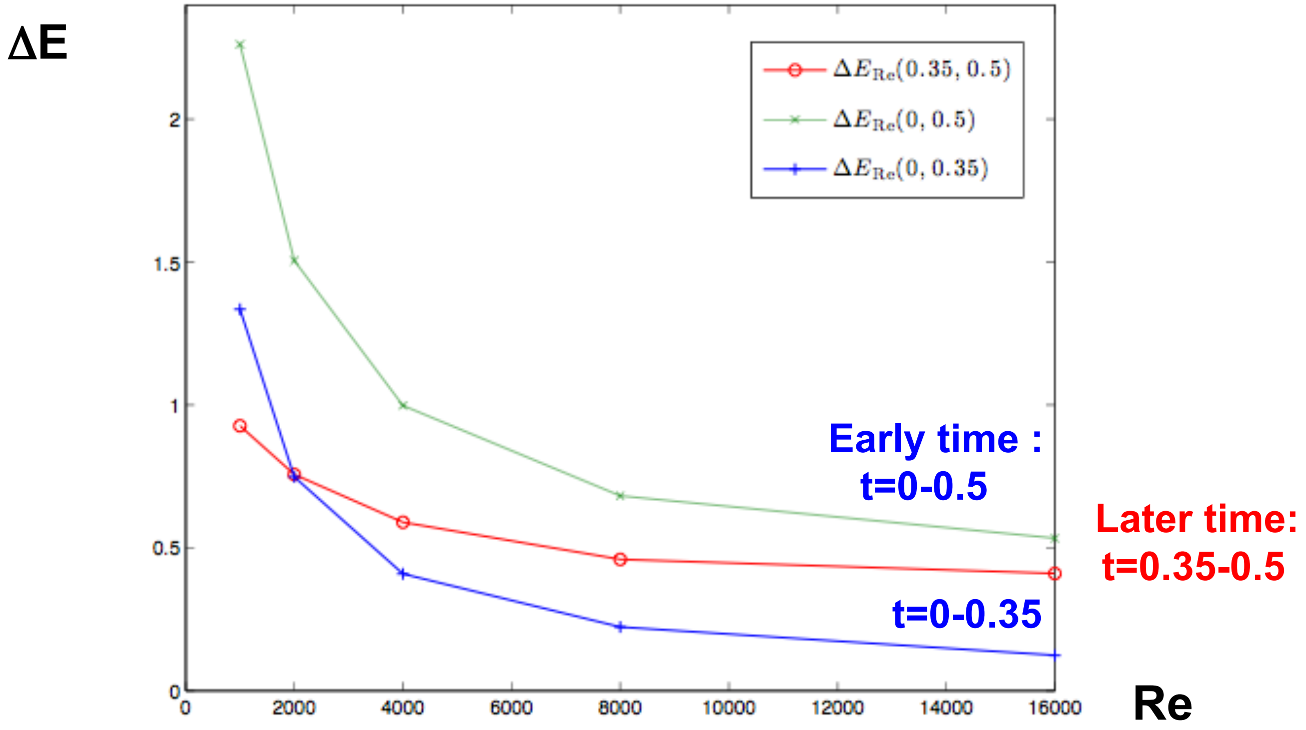
Nguyen van yen, M. F.
and Schneider,
PRL, ***106****(18), 2011*



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

Energy dissipation

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



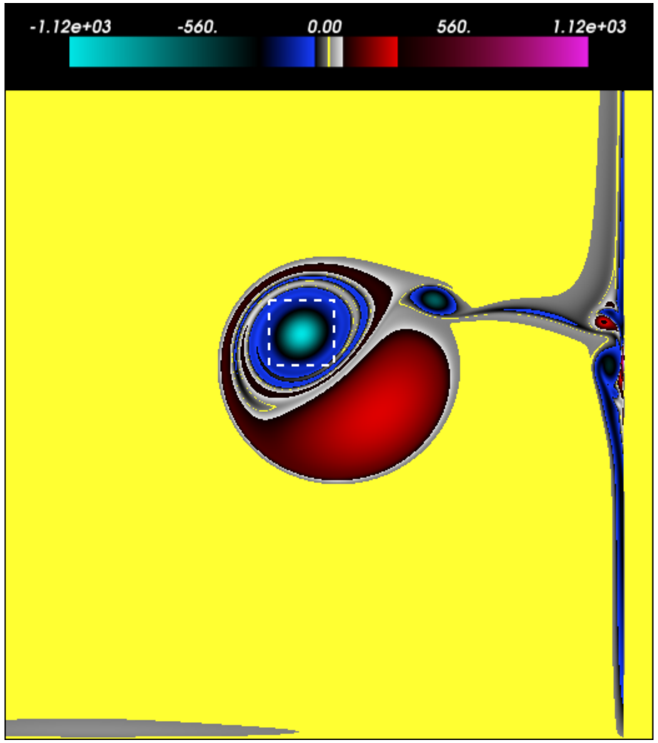
Early time :
t=0-0.5

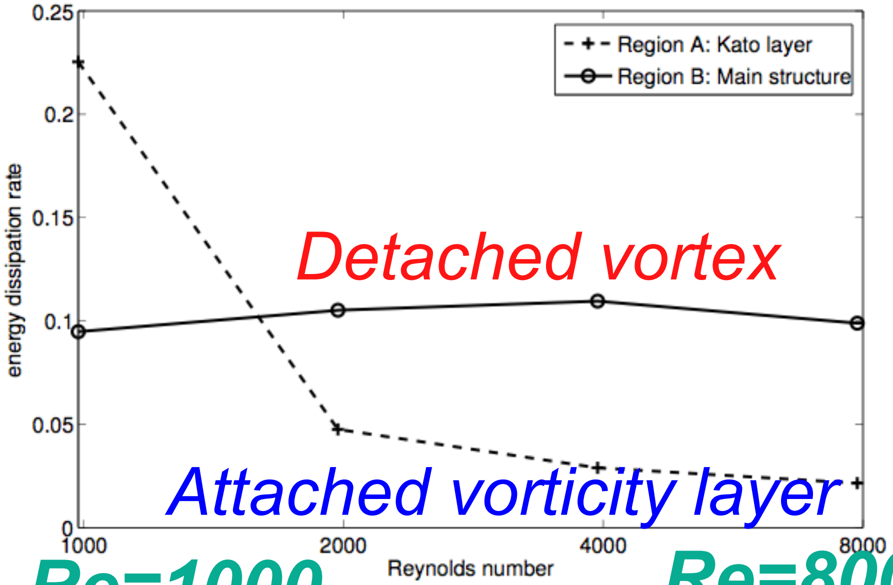
t=0-0.35

Later time:
t=0.35-0.5

Production of dissipative structures

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





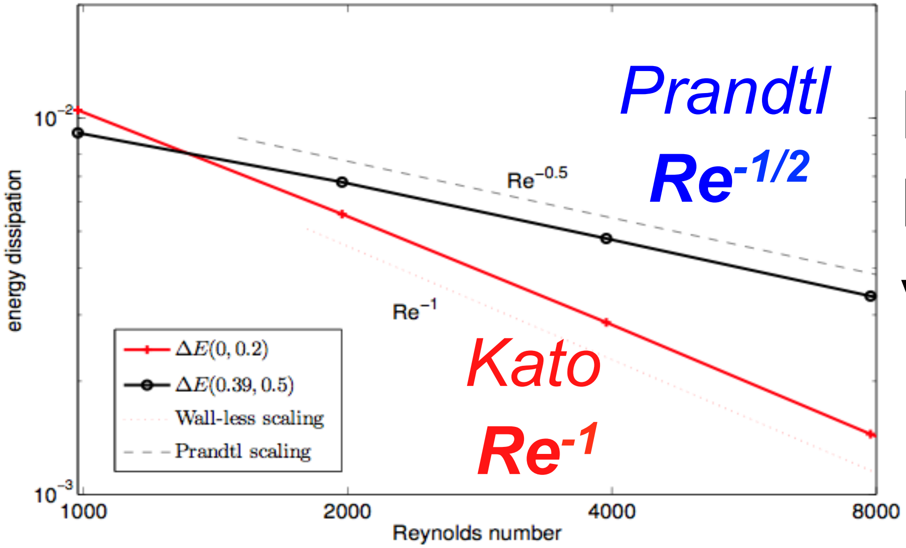
Detached vortex

Attached vorticity layer

Re=1000

Re=8000

Energy dissipation rate *(-2ν Z)* versus *Re*



Prandtl

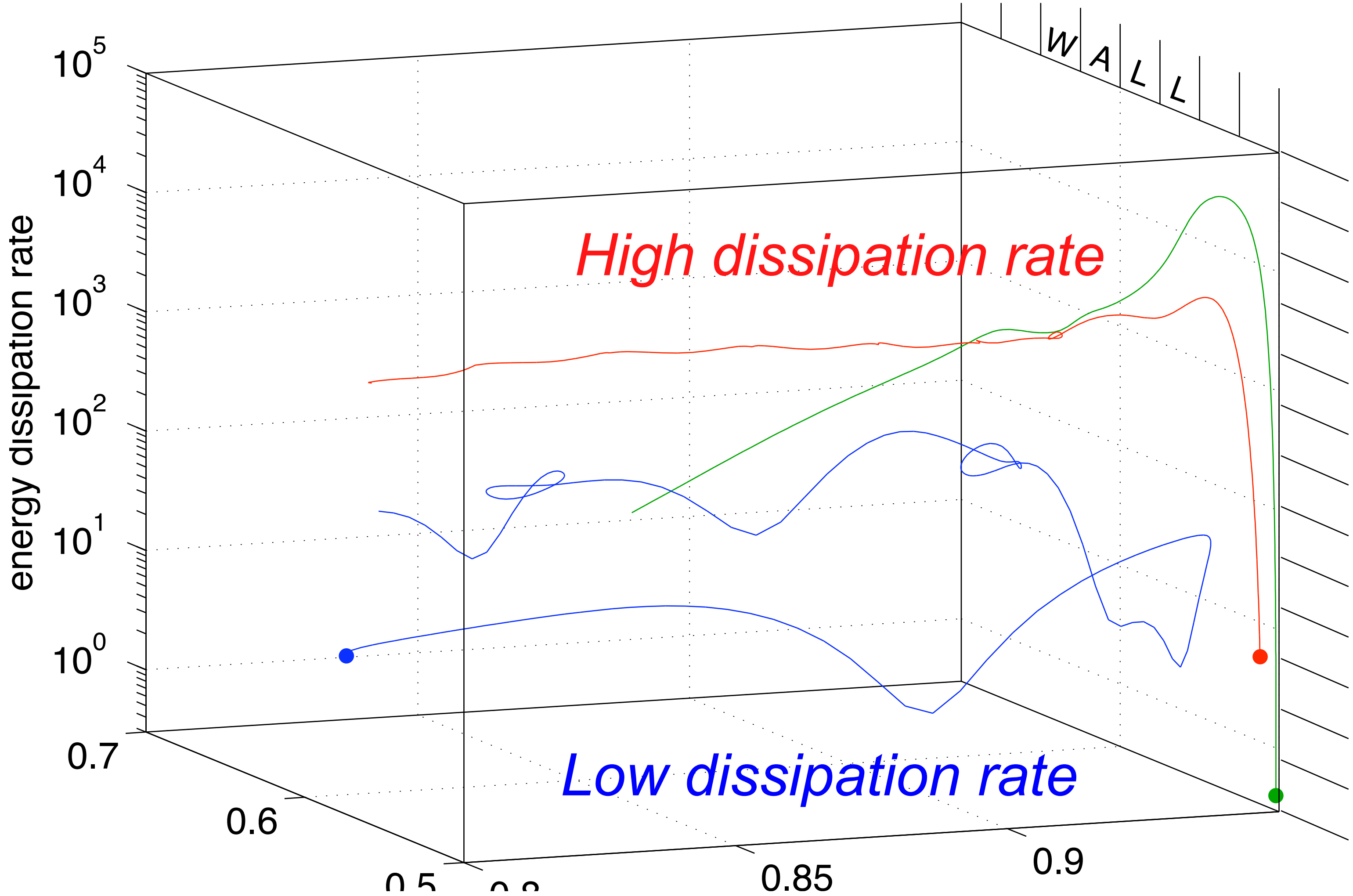
Re$^{-1/2}$

Kato

Re^{-1}

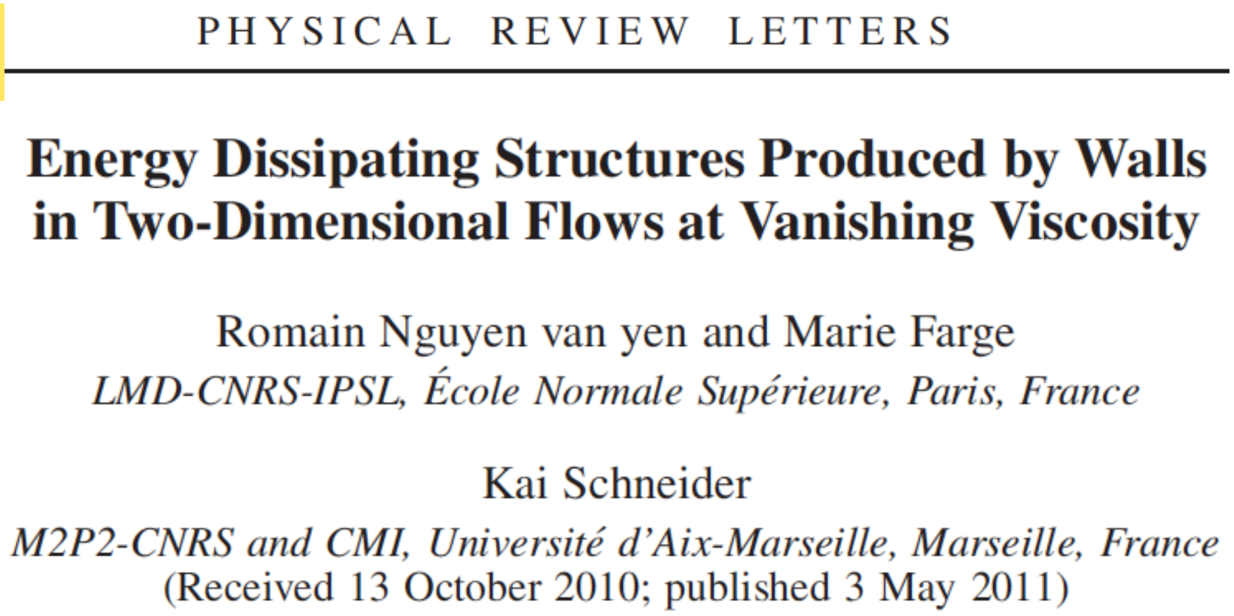
Energy Dissipation versus *Re*

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

Romain Nguyen van yen and Marie Farge
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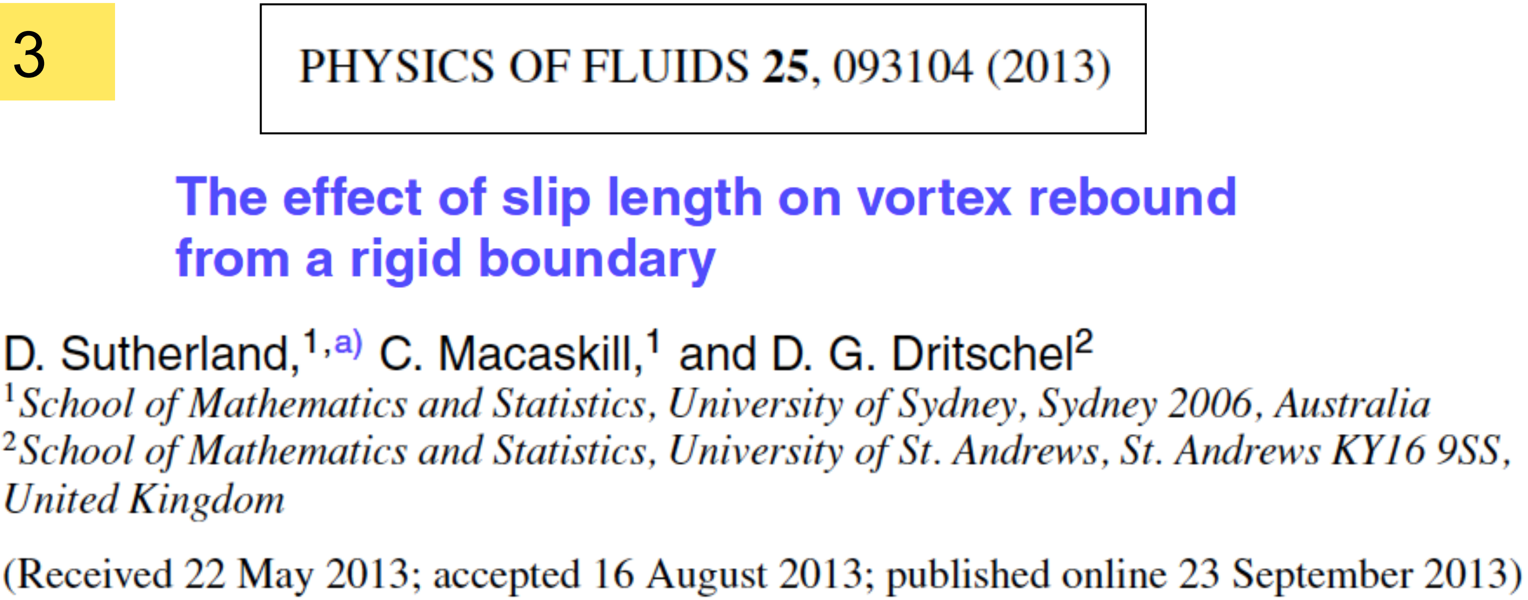
(Received 13 October 2010; published 3 May 2011)

2013



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

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

D. Sutherland,[1,a] C. Macaskill,[1] and D. G. Dritschel[2]
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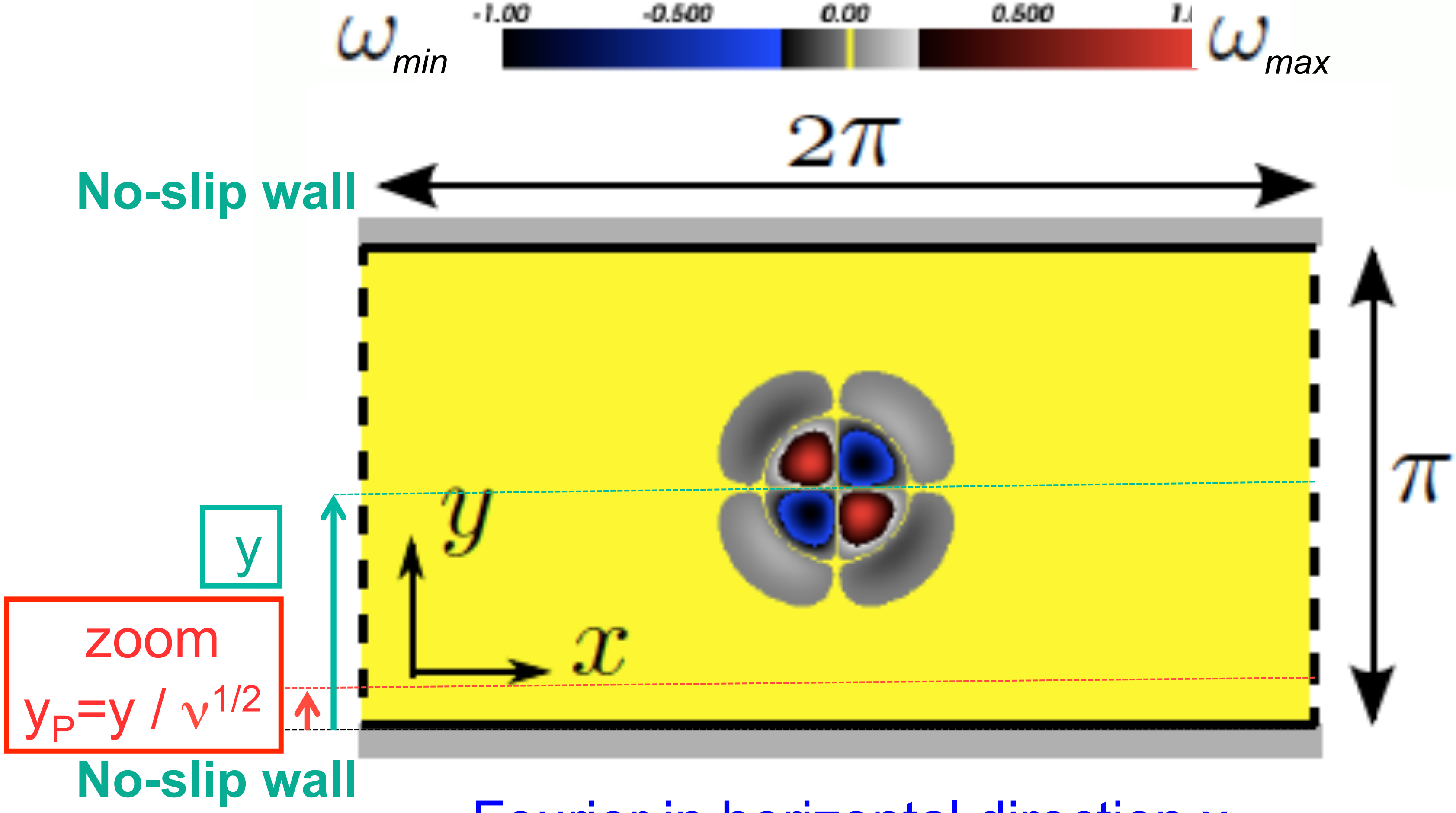
(Received 22 May 2013; accepted 16 August 2013; published online 23 September 2013)

Comparison Navier-Stokes and Euler-Prandtl



Fourier in horizontal direction x

5th order compact finite differences in y

3rd order Runge-Kutta in time

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 : $y_P = y / \nu^{1/2}$

$$\boxed{\begin{aligned}
&\partial_t \omega_P + \mathbf{\nabla}.(\mathbf{u}_P \omega_P) = \partial^2_{y_P}\omega_P \\
&\omega_P(x, y_P, 0) = 0 \\
&\psi_P(x, y_P, t) = \int_0^{y_P} \mathrm{d}y'_P \int_0^{y'_P} \mathrm{d}y''_P \omega_P(x, y''_P, t) \\
&\partial_{y_P}\omega_P(x,0,t) = -\partial_x p_E(x,0,t),
\end{aligned}}$$

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

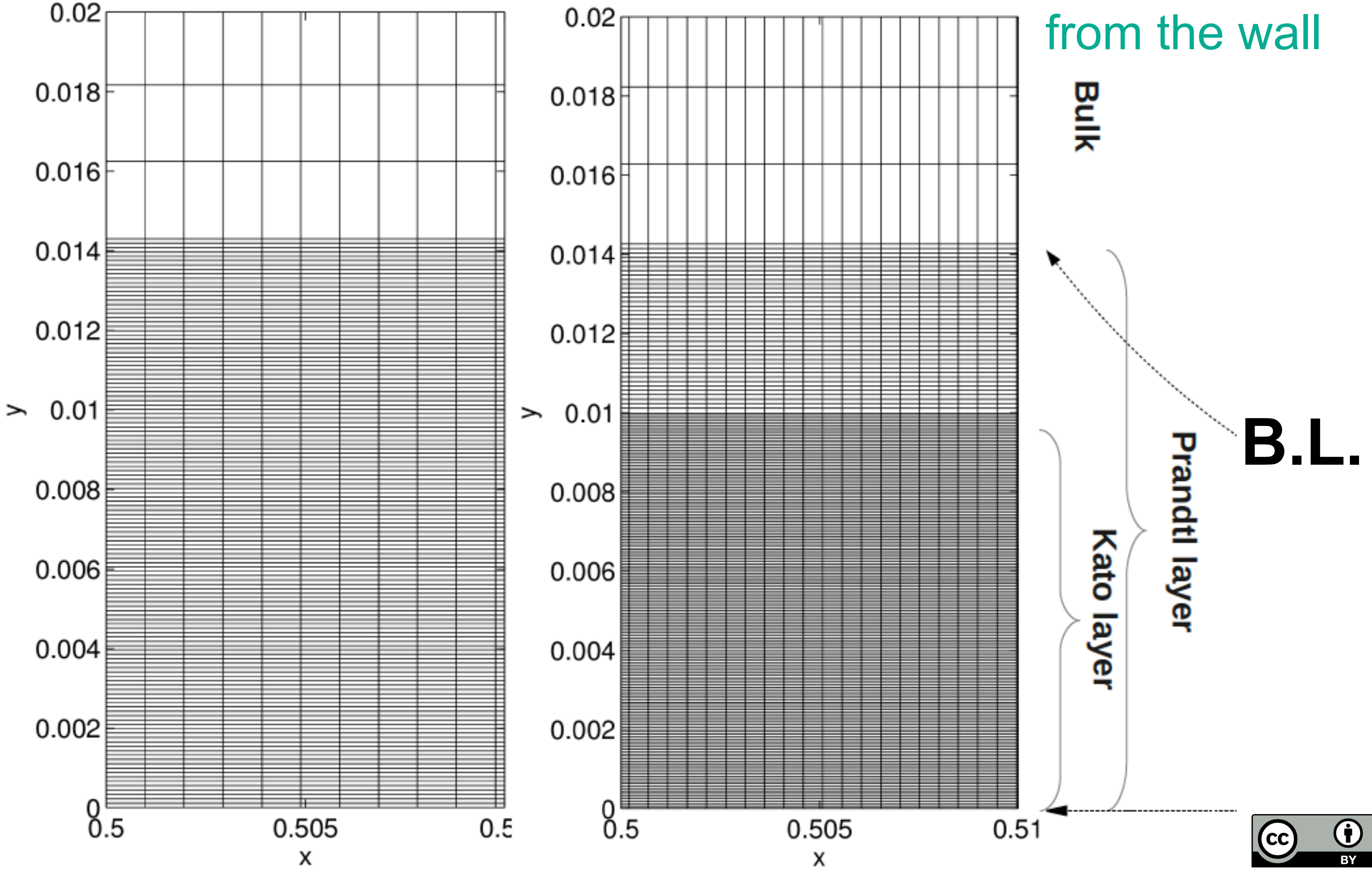
- Second order finite differences in x and y.
- Second order semi-implicit Runge-Kutta in t.
- Neumann boundary condition at y=0 when inverting.

Computational grid

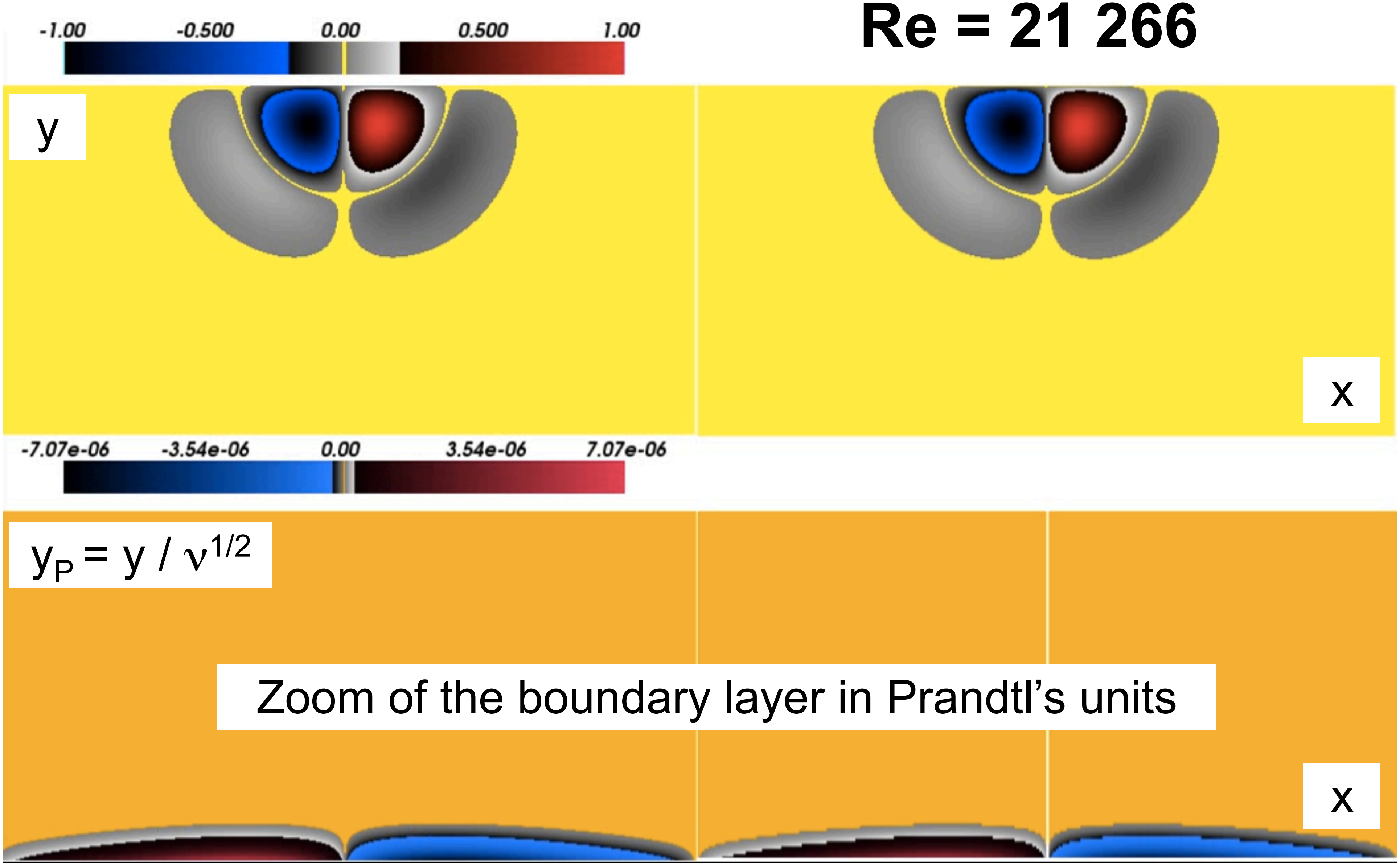
Before t=54

After t=54

when B.L. detachs from the wall



Re = 21 266



Zoom of the boundary layer in Prandtl's units

Euler and Prandtl **Navier-Stokes**

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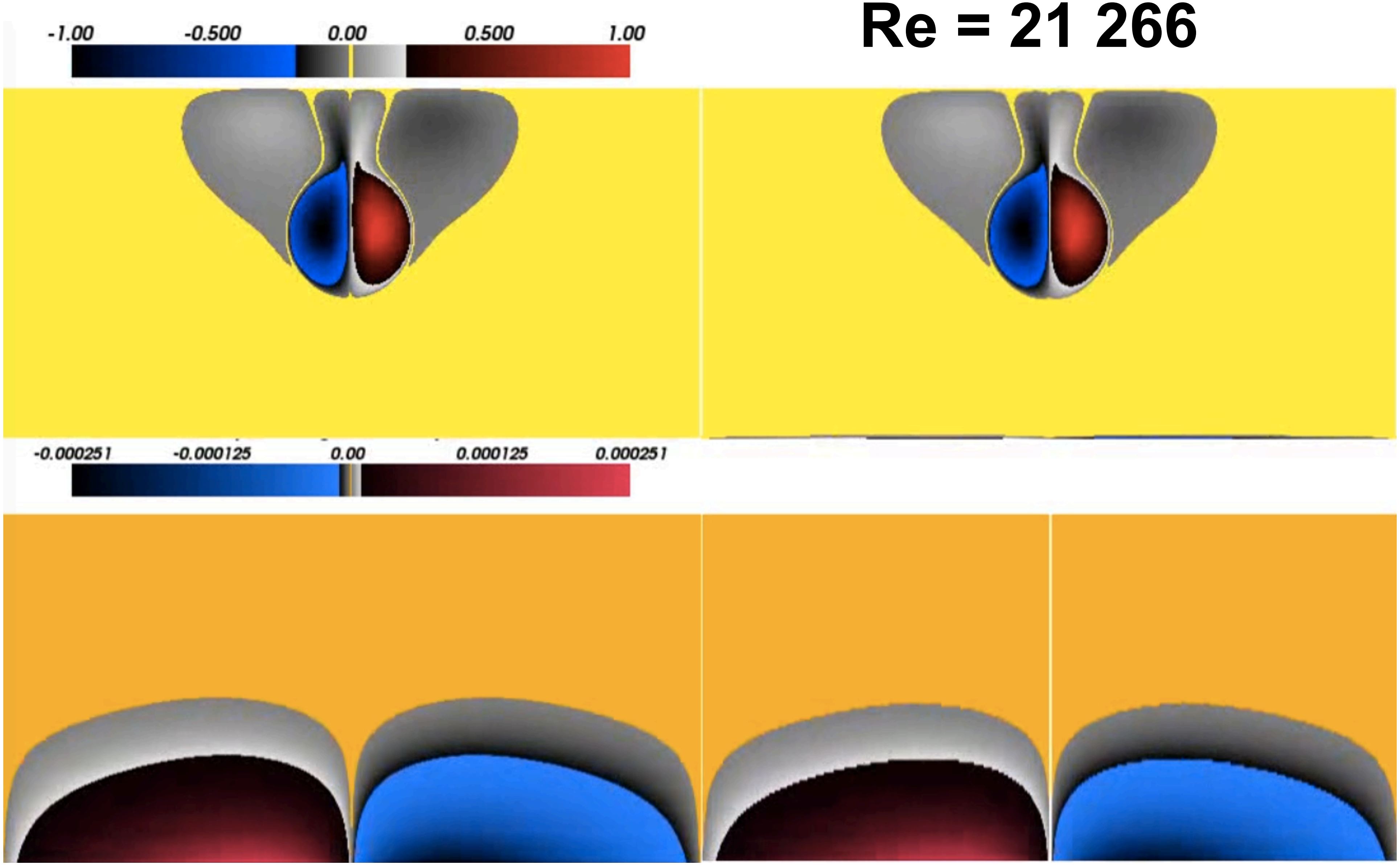

Euler and Prandtl

Navier-Stokes

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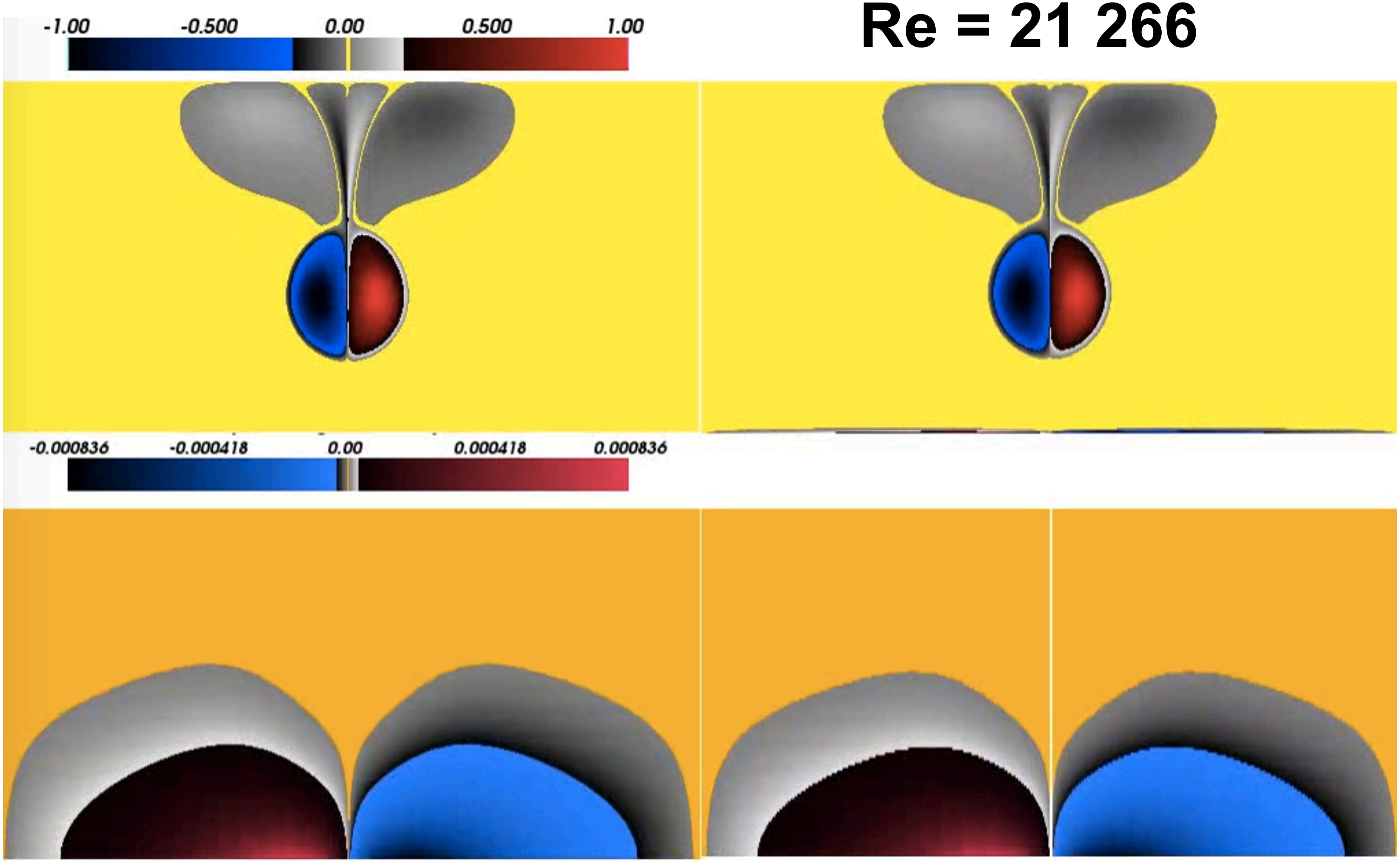

Euler and Prandtl

Navier-Stokes

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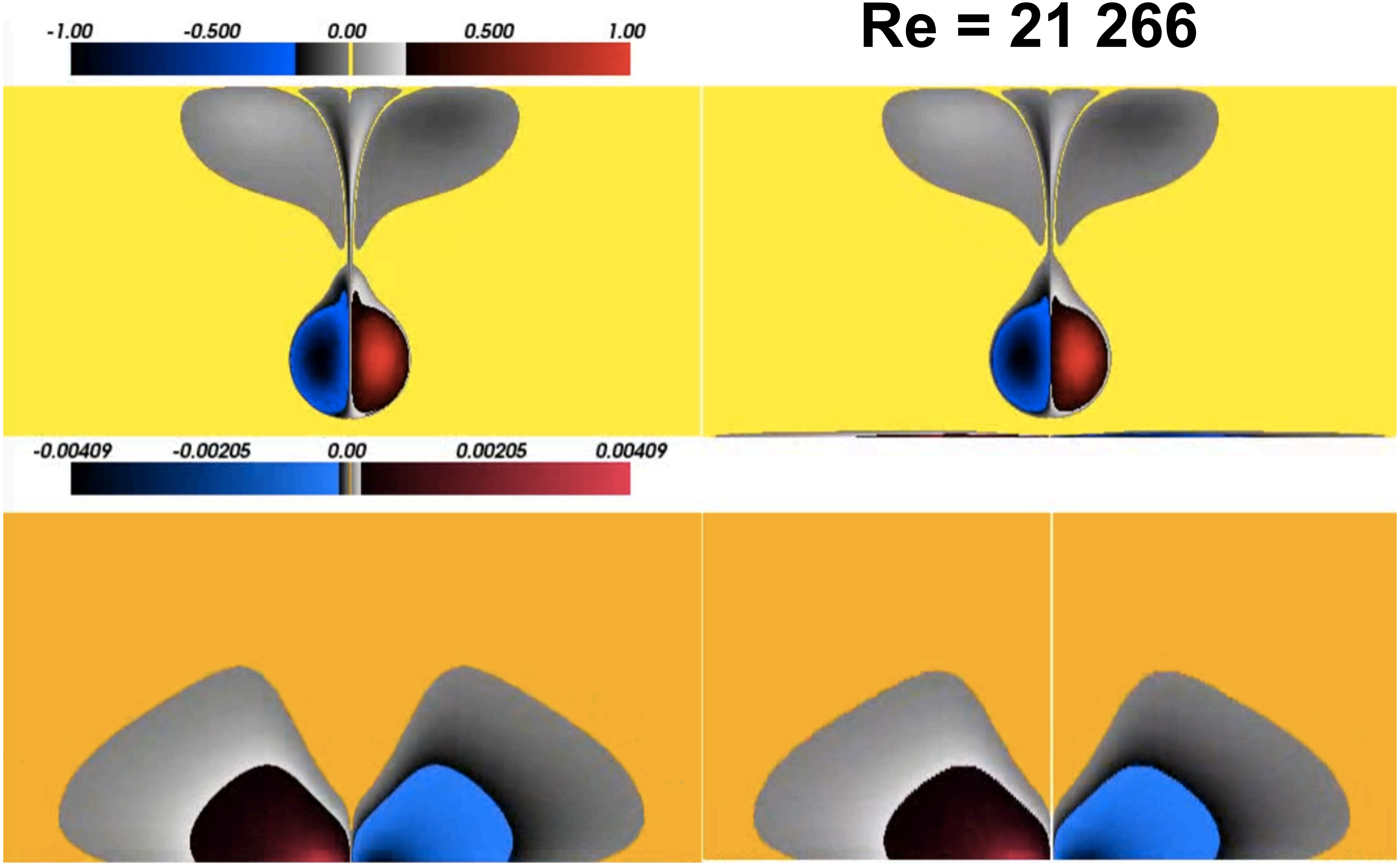

Euler and Prandtl

Navier-Stokes

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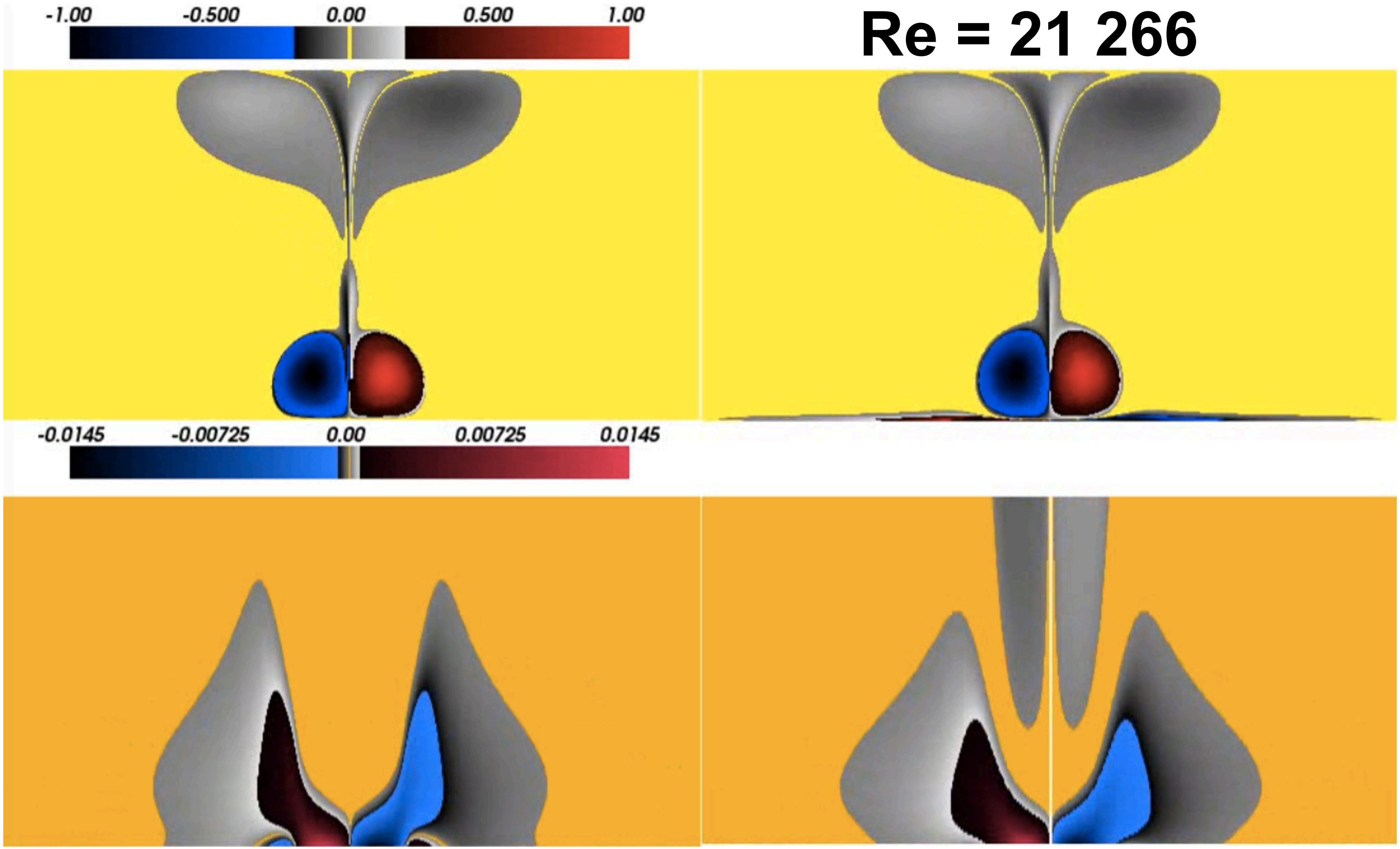

Euler and Prandtl

Navier-Stokes

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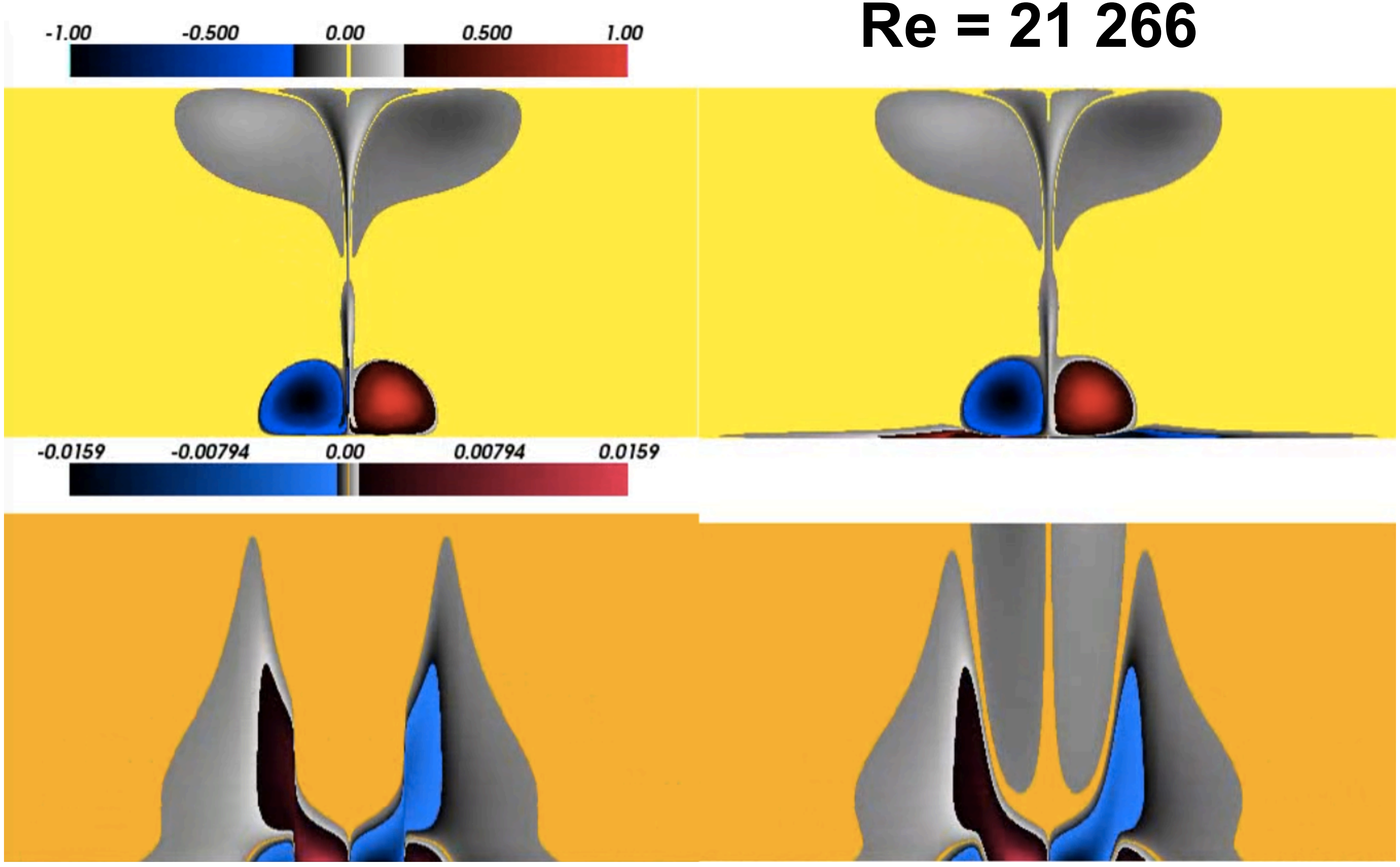

Euler and Prandtl **Navier-Stokes**

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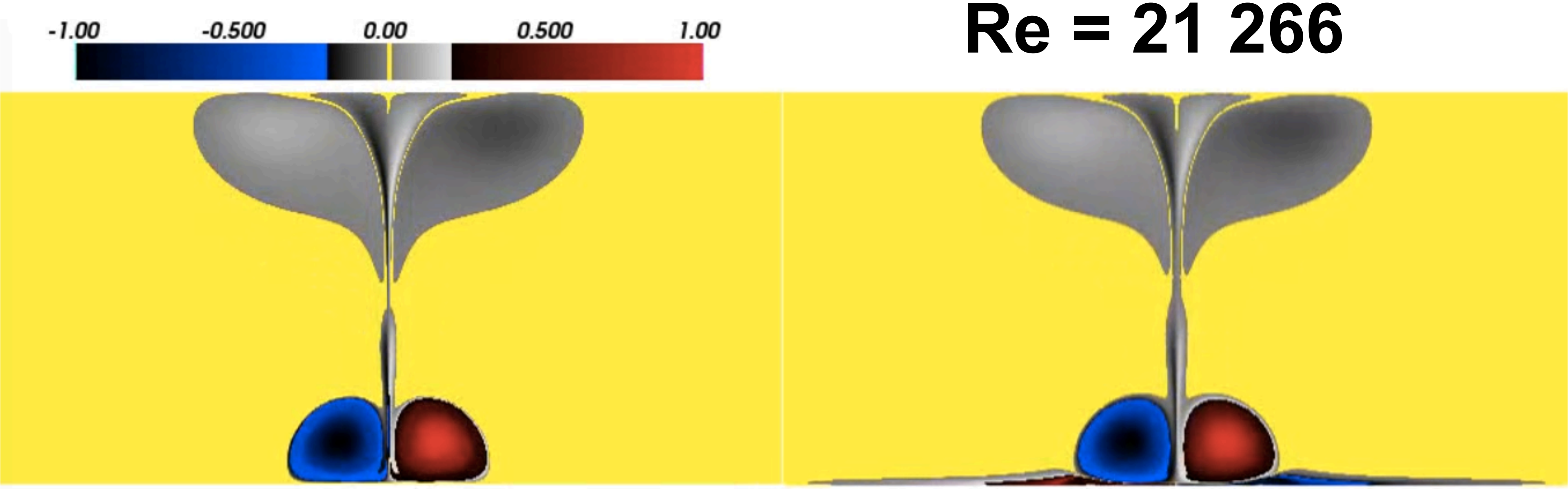
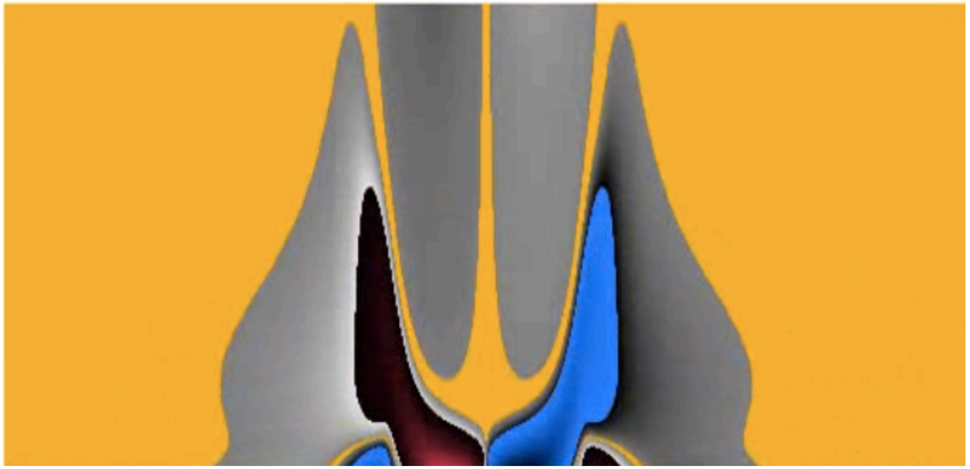




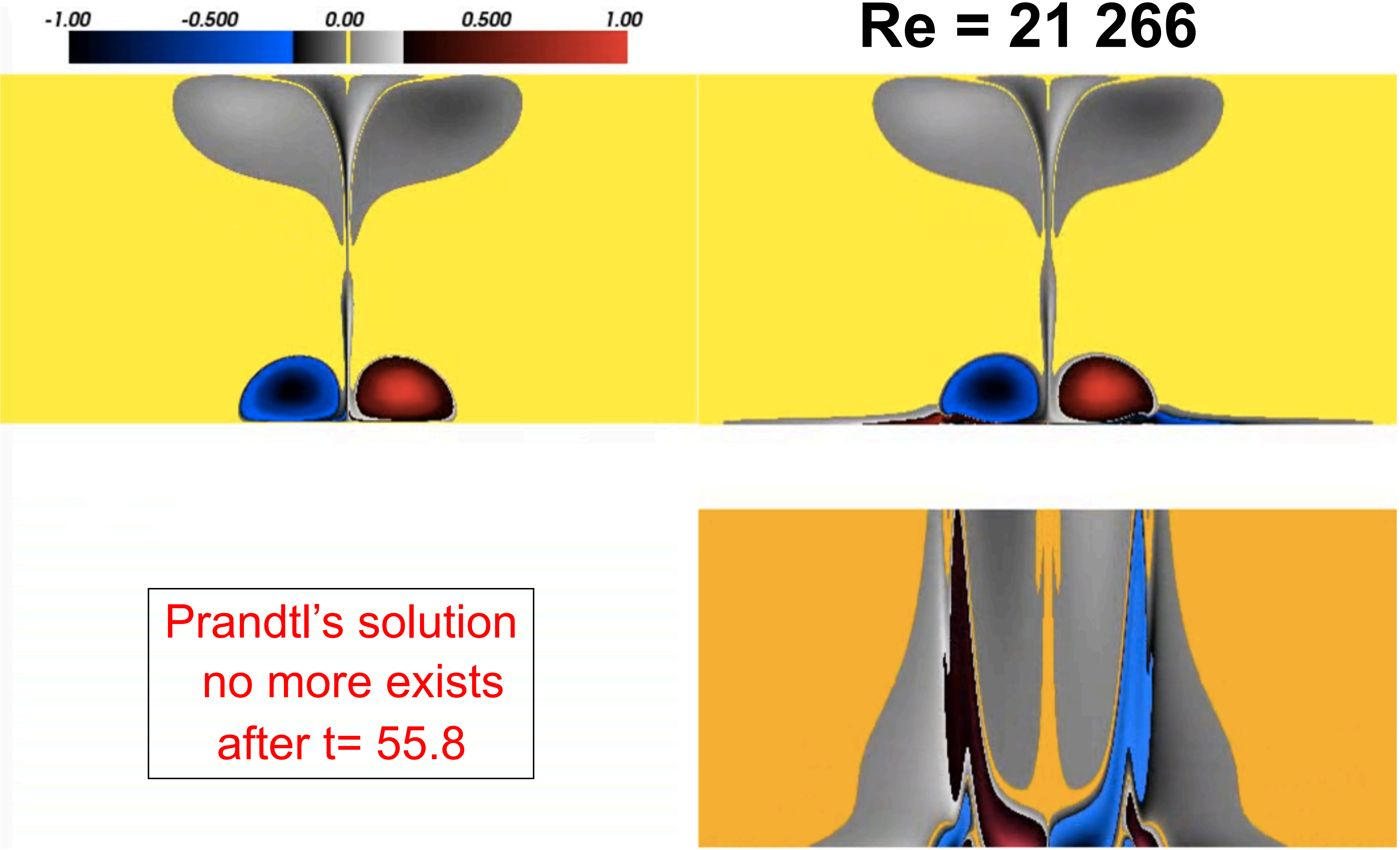
Prandtl’s solution
becomes singular
at t= 55.8

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

Euler

Navier-Stokes

Re = 21 266



Prandtl's solution
no more exists
after t= 55.8

Euler

Navier-Stokes

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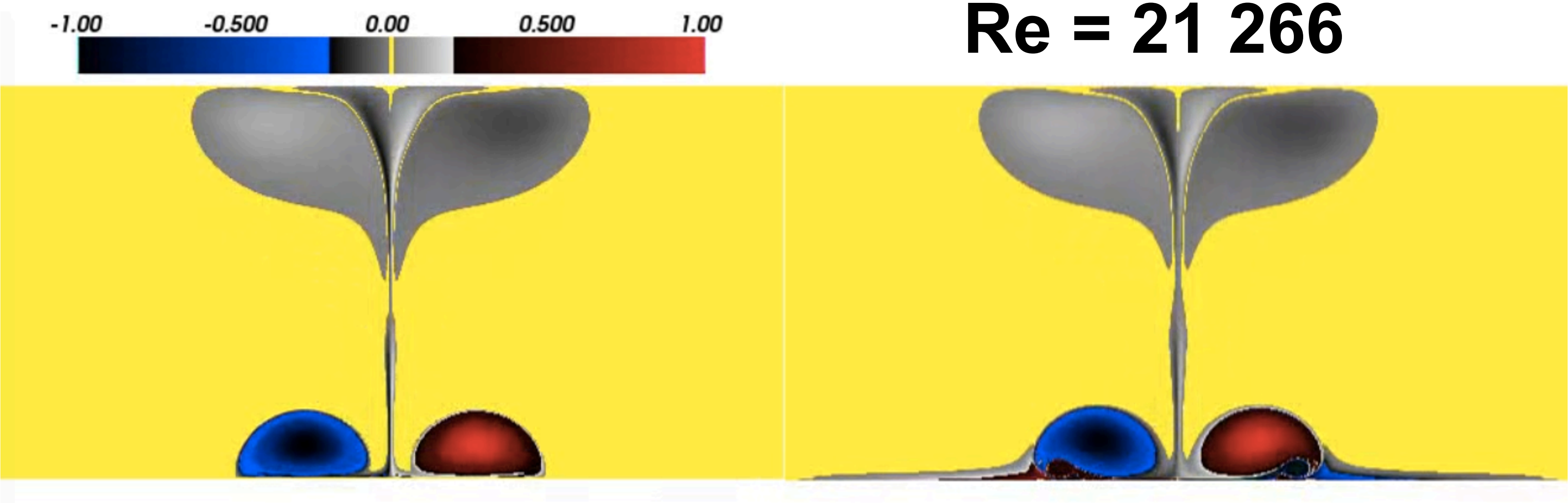

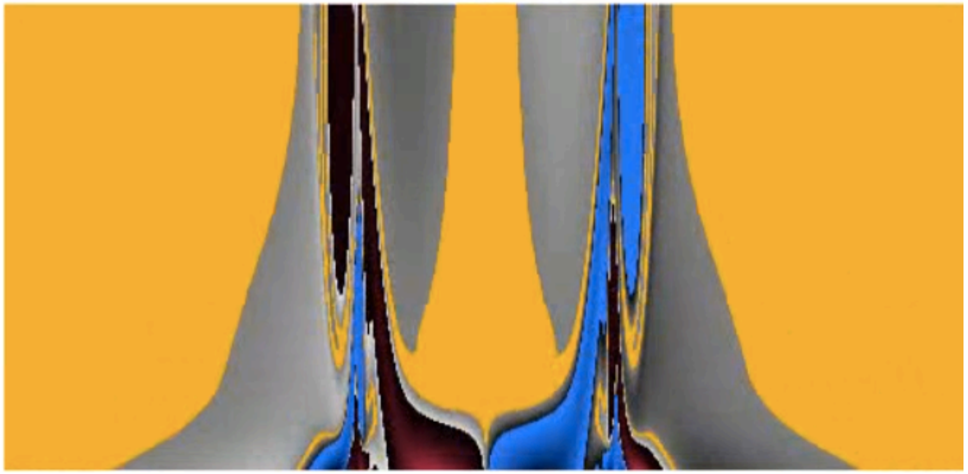

Prandtl's solution
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Euler

Navier-Stokes

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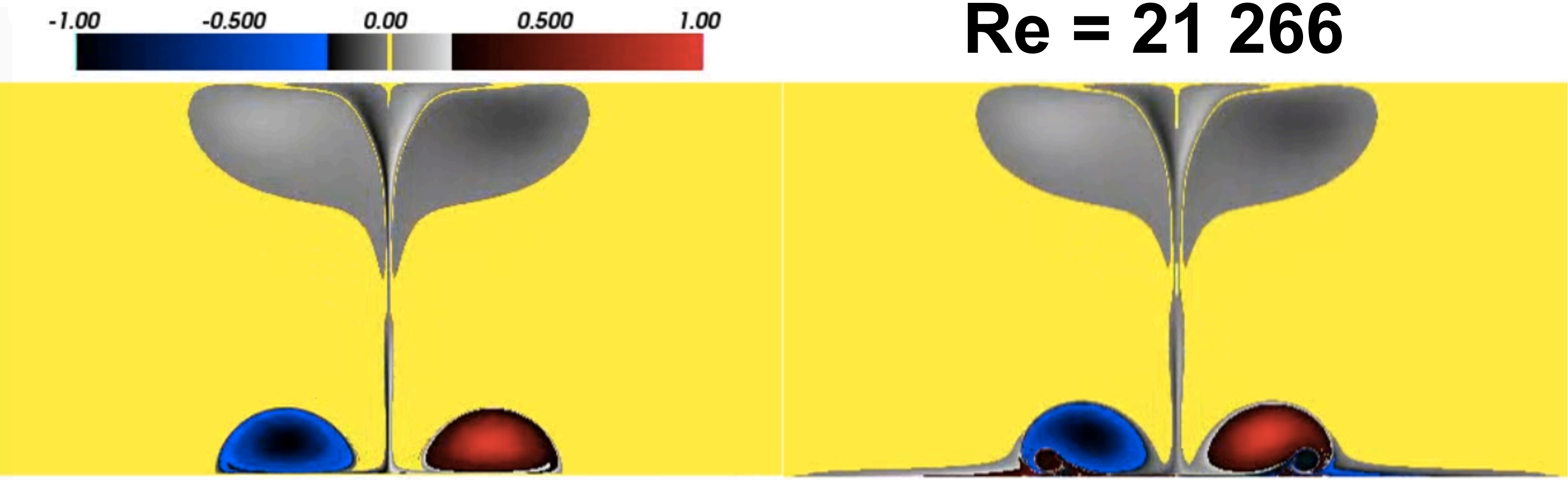

Prandtl's solution
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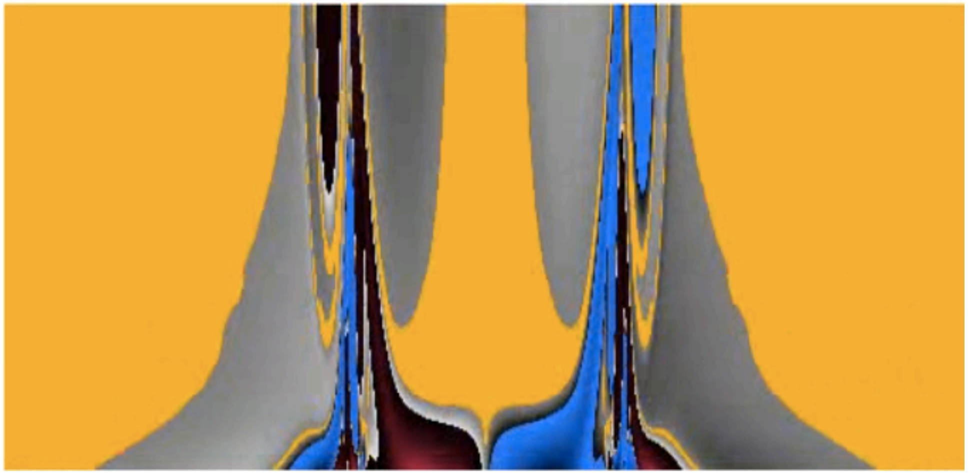

Euler

Navier-Stokes

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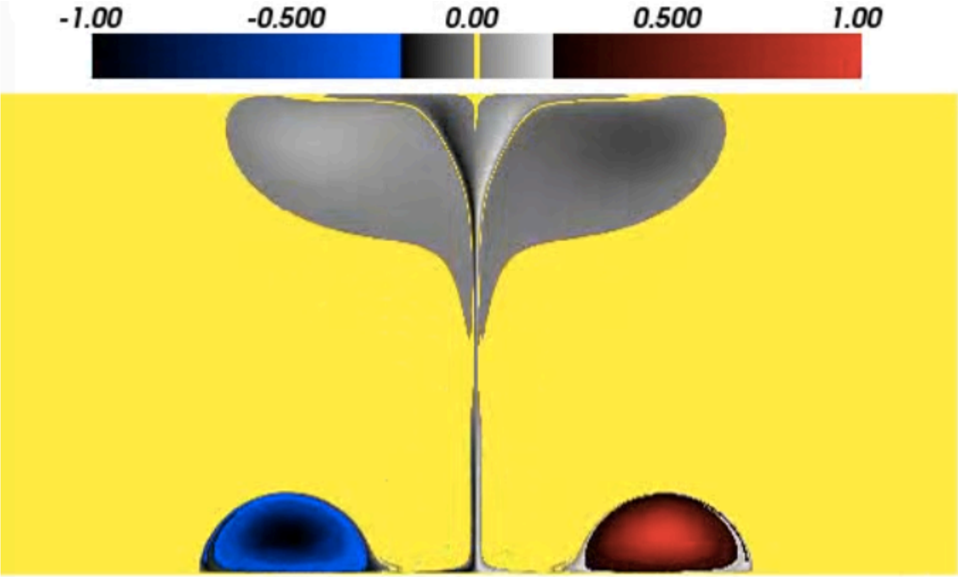

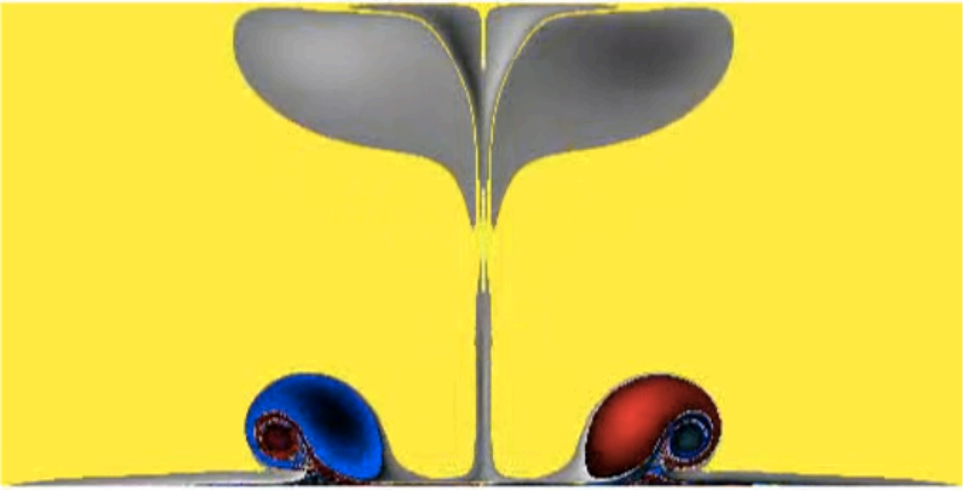

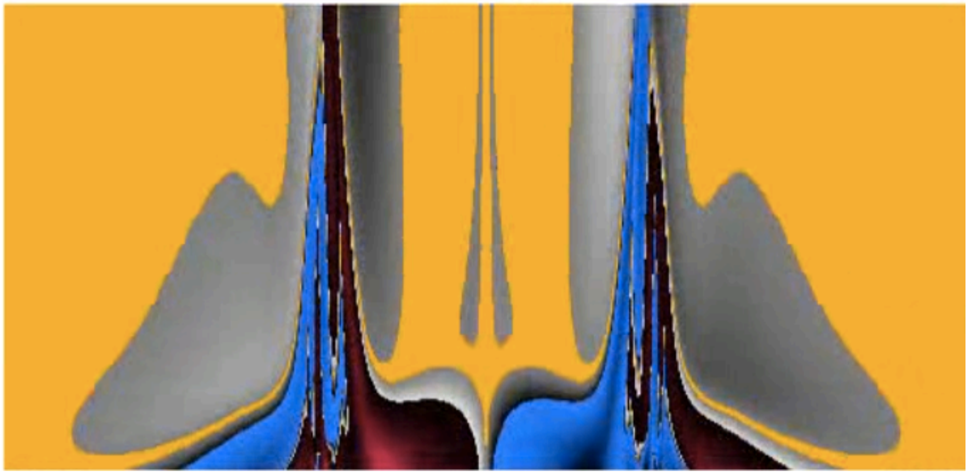

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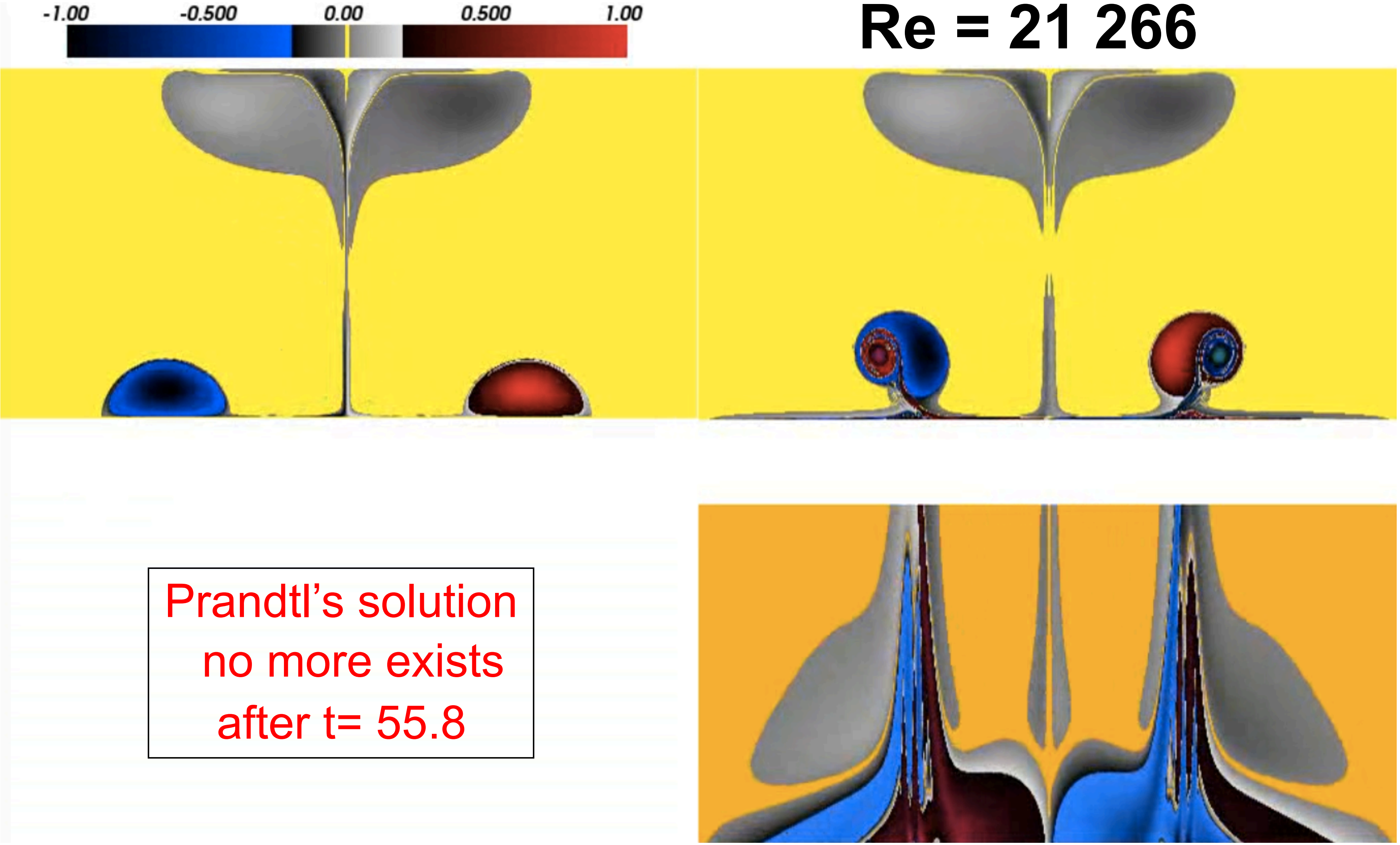

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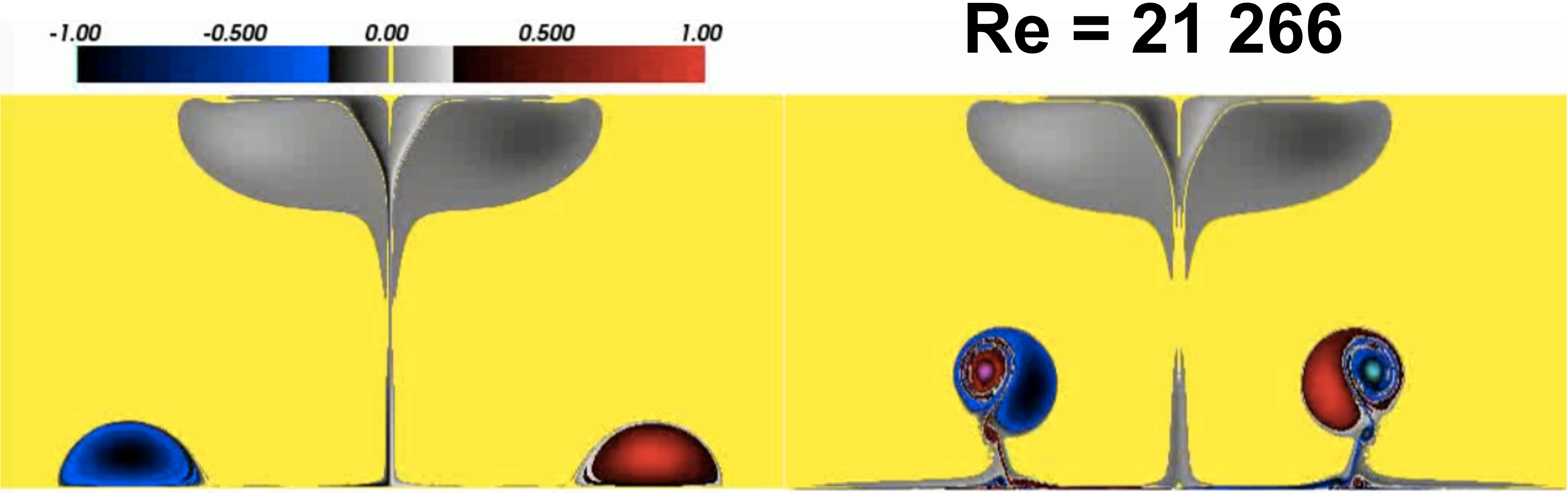

Prandtl’s solution
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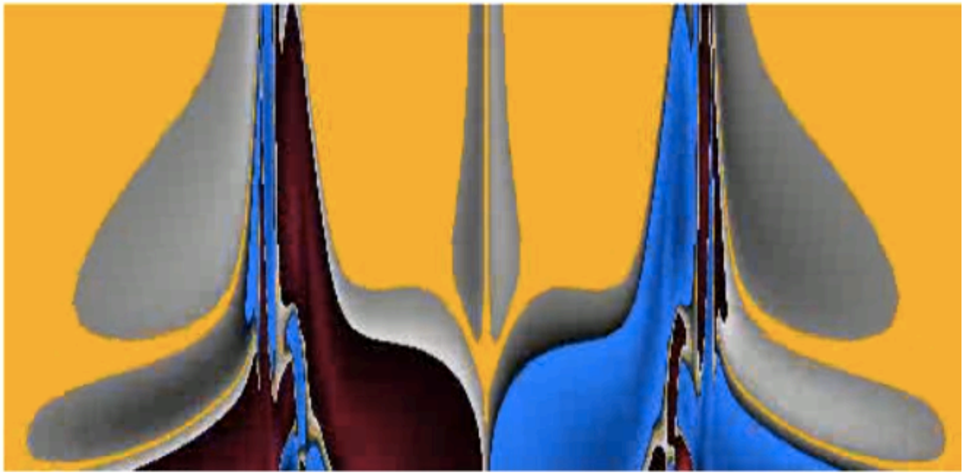

Euler

Navier-Stokes

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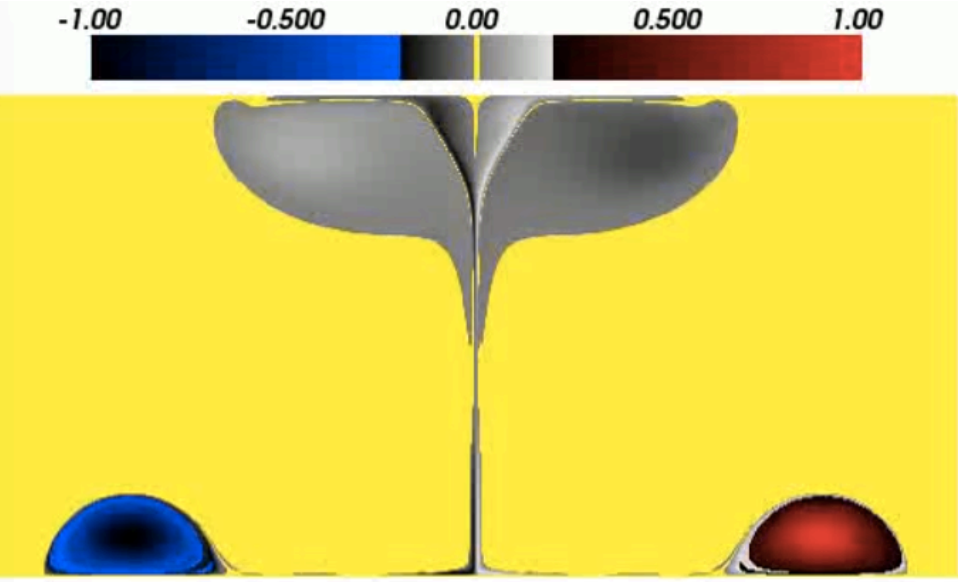

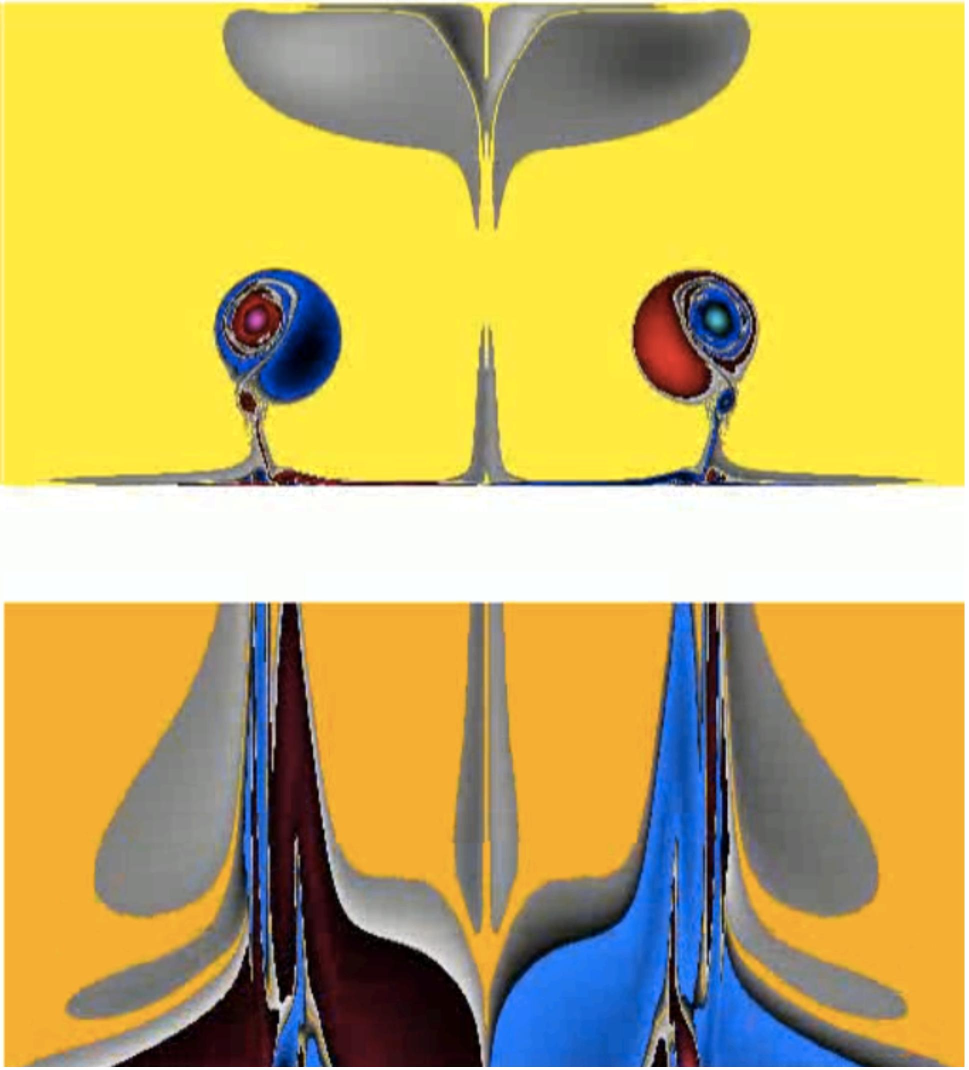

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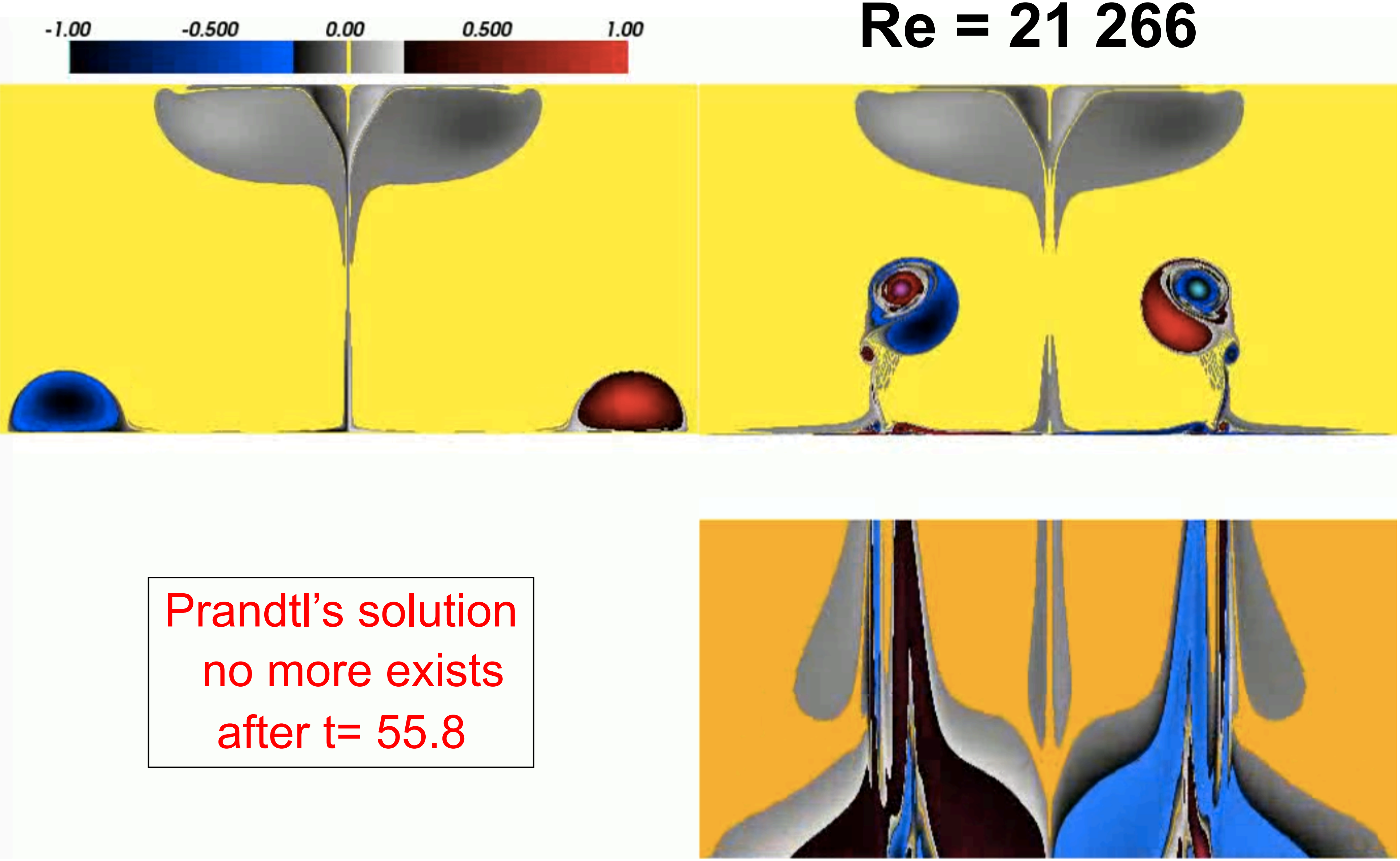

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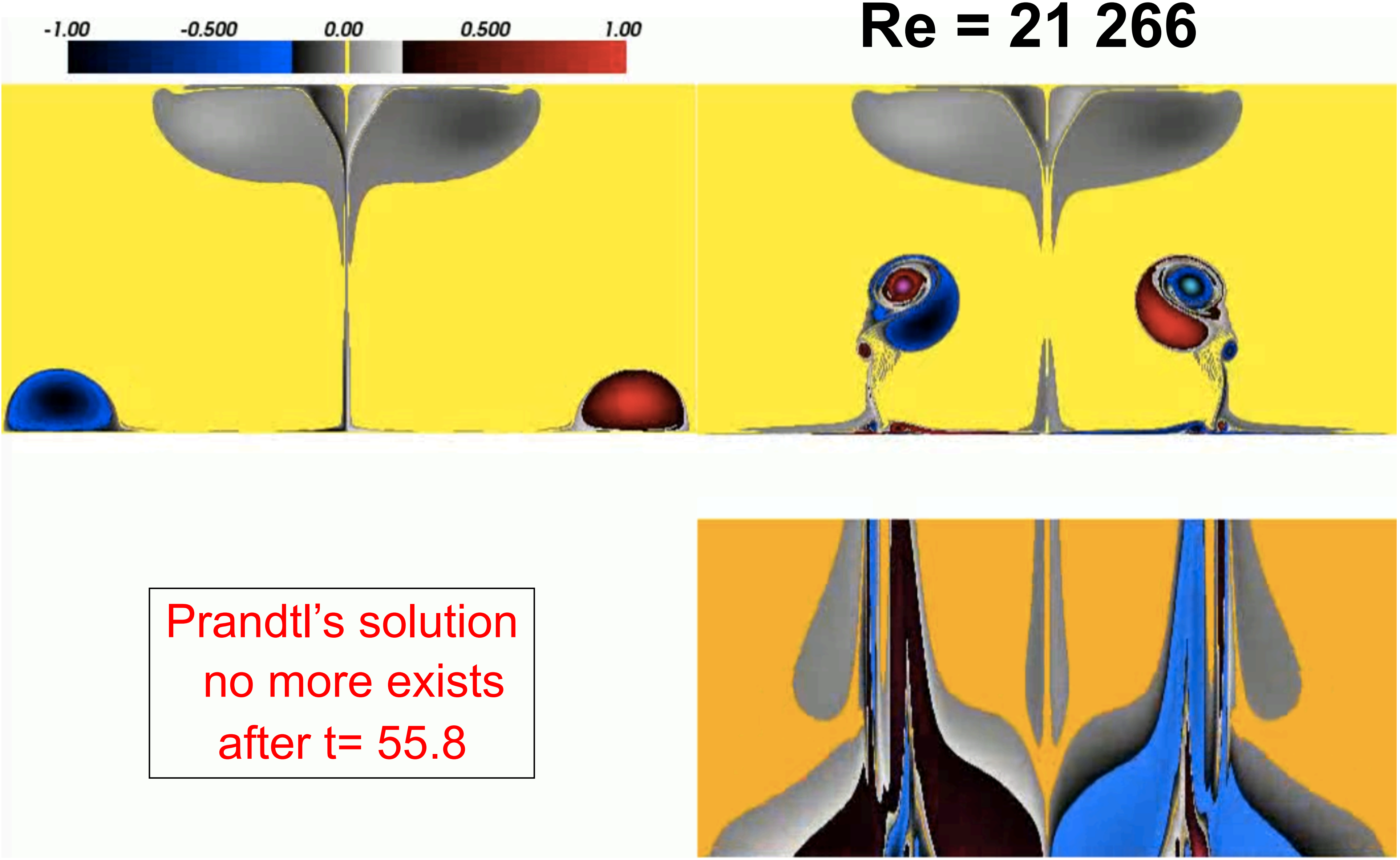


Prandtl's solution
no more exists
after t= 55.8

Euler

Navier-Stokes

Prandtl's singularity

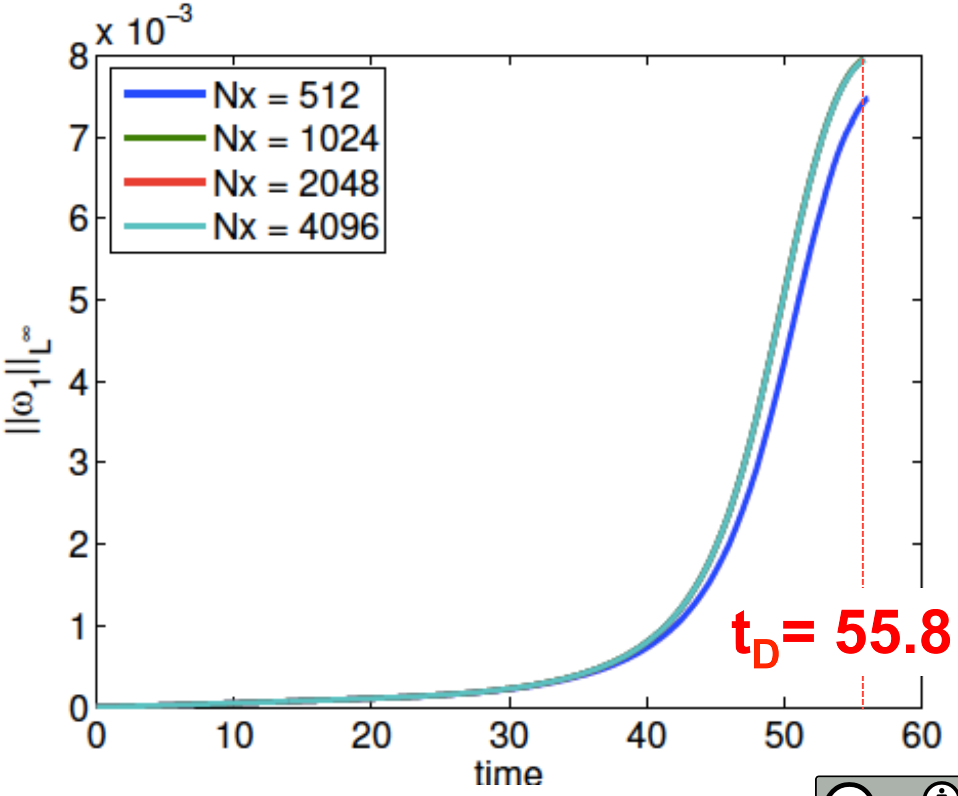
Prandtl equation has well-known finite time singularity

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

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

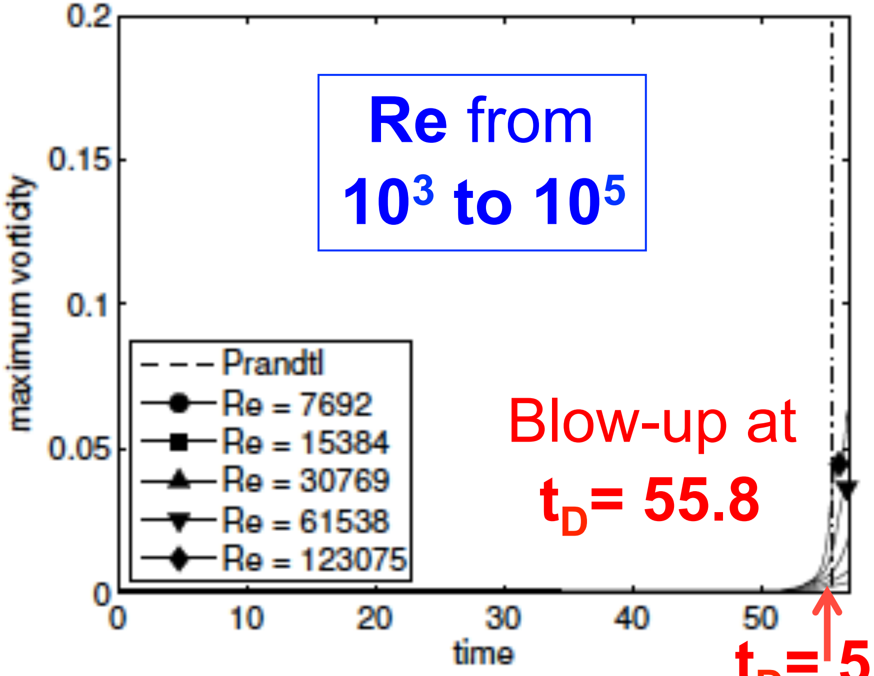
This is observed in our computations as expected,

$\boxed{\text{for } t \to t_D \simeq 55.8}$



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 $[0, t_D]$.

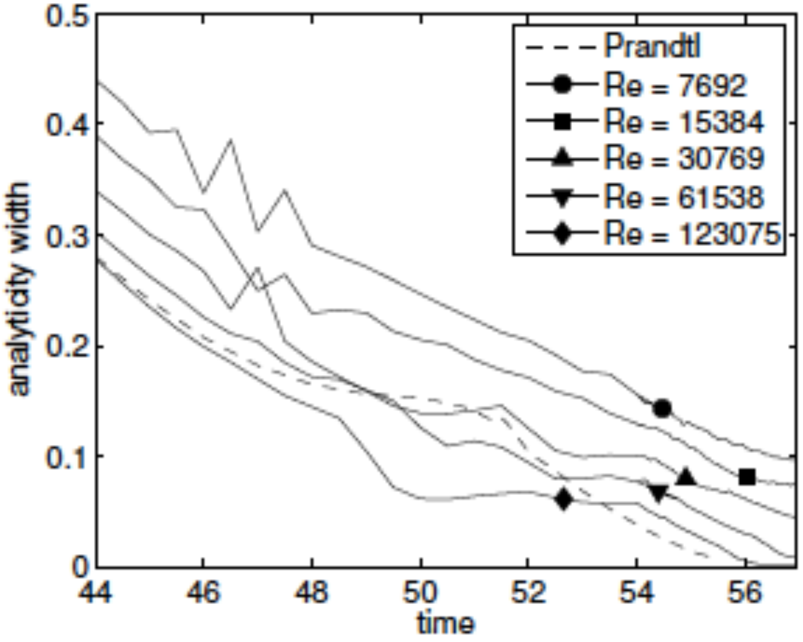


Re from 10^3 to 10^5

Blow-up at **t_D= 55.8**

t_D= 55.8

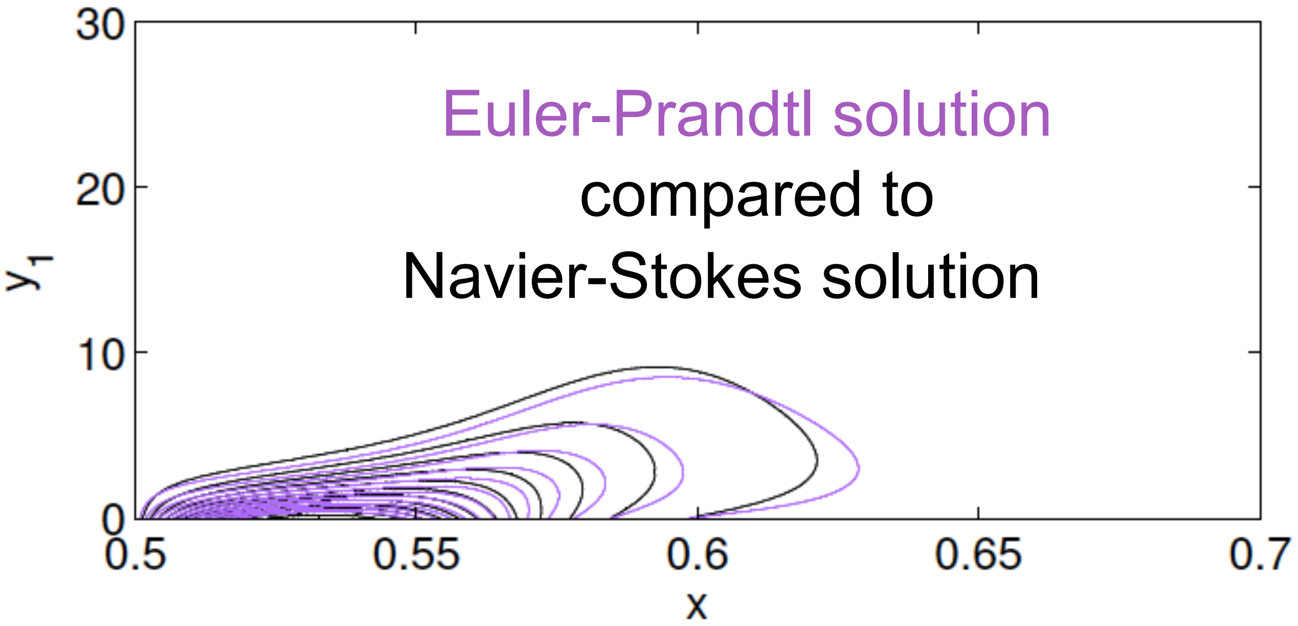
Evolution of vorticity max



Evolution of analyticity strip

Show convergence!

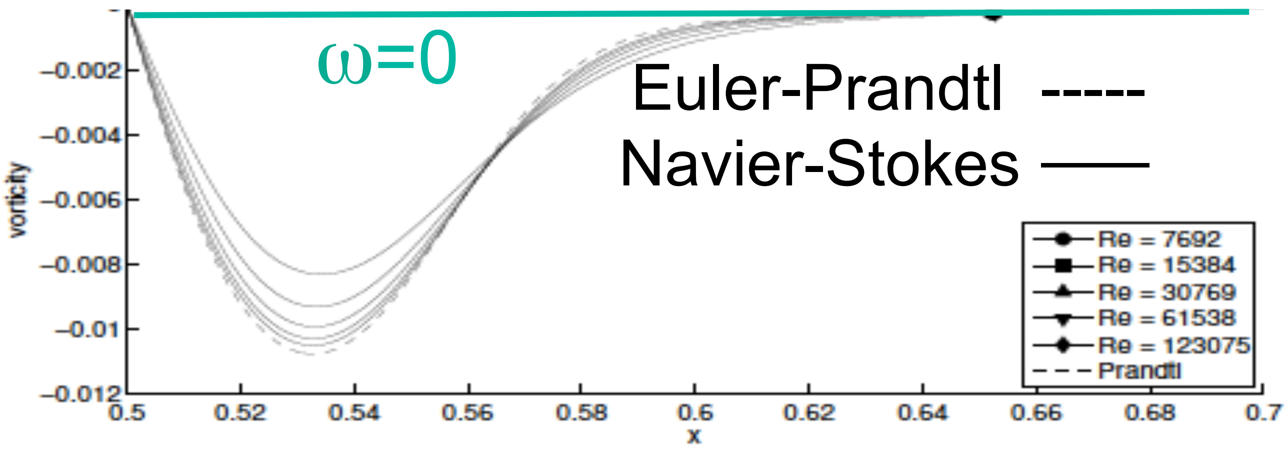
Vorticity along the wall at $t=50 < t_D$



Euler-Prandtl solution

compared to

Navier-Stokes solution

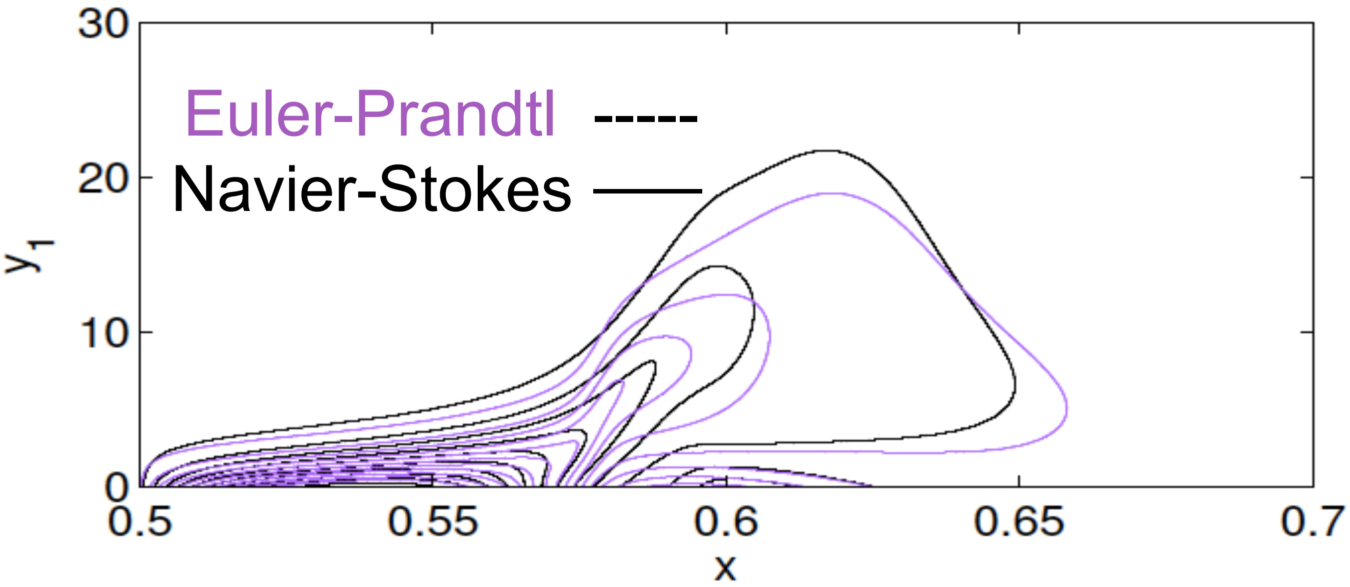


$\omega=0$

Euler-Prandtl -----

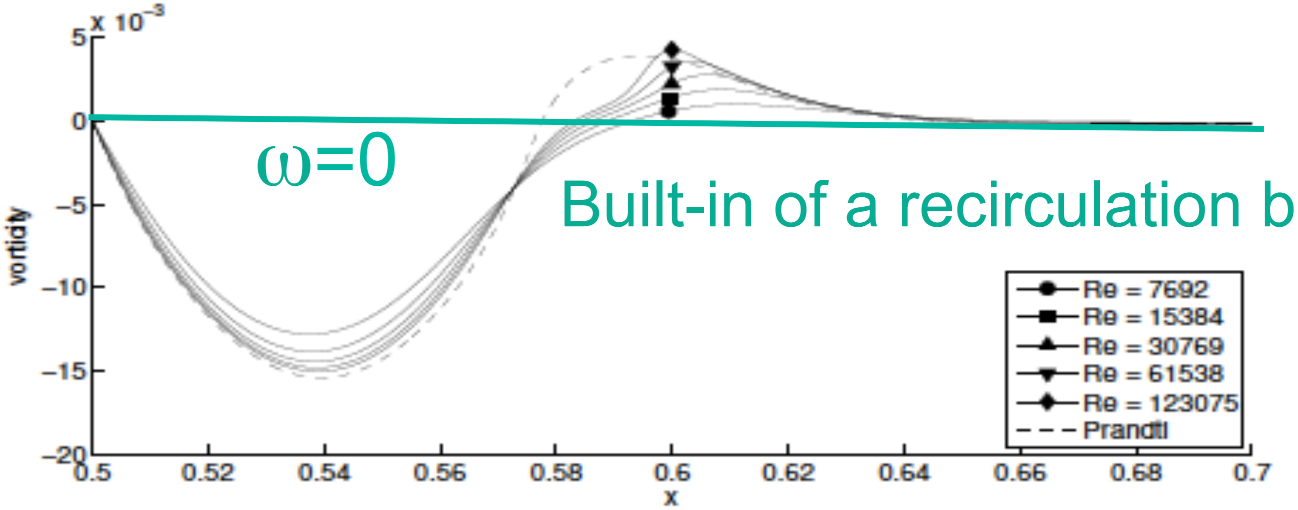
Navier-Stokes ——

Vorticity along the wall at t=54 < t_D



Euler-Prandtl -----

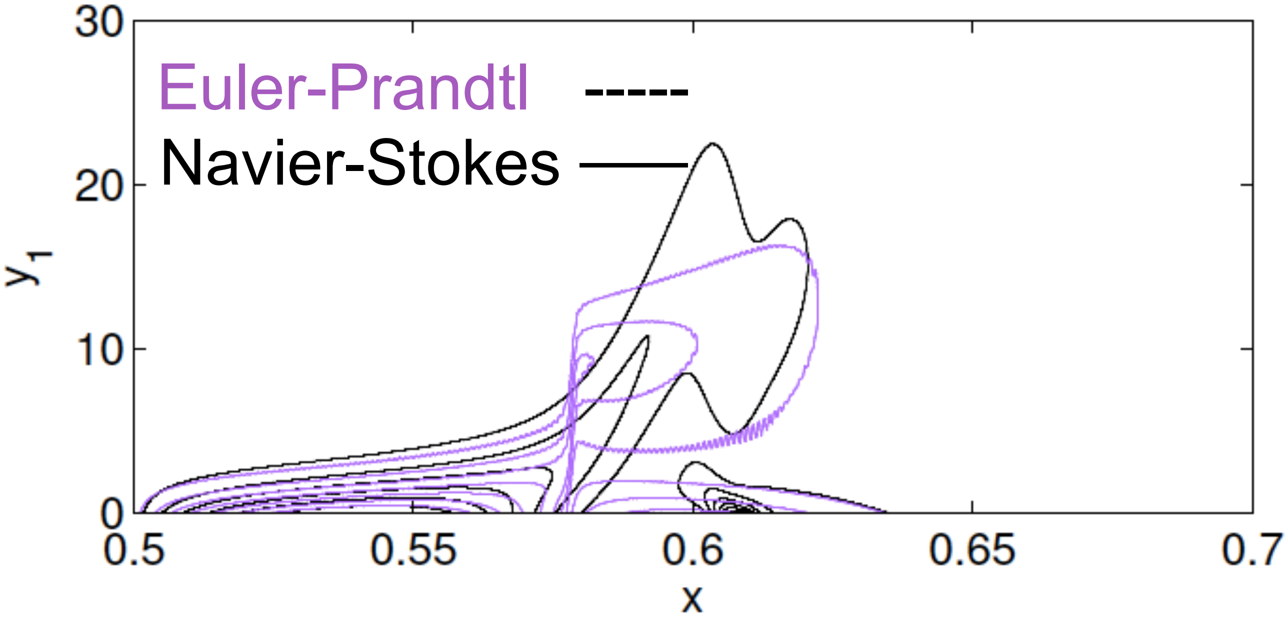
Navier-Stokes ——

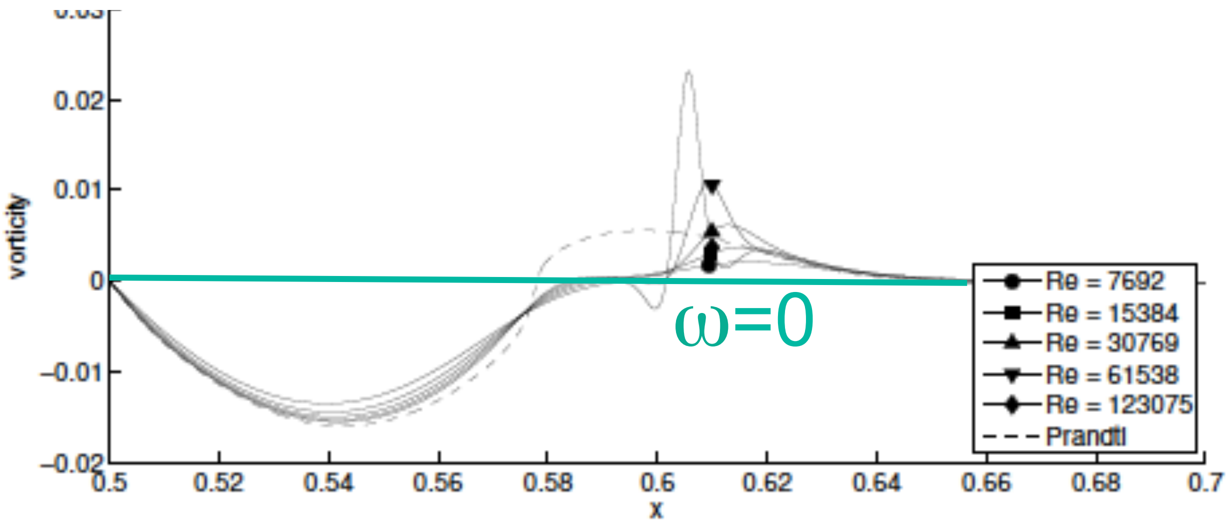


$\omega=0$

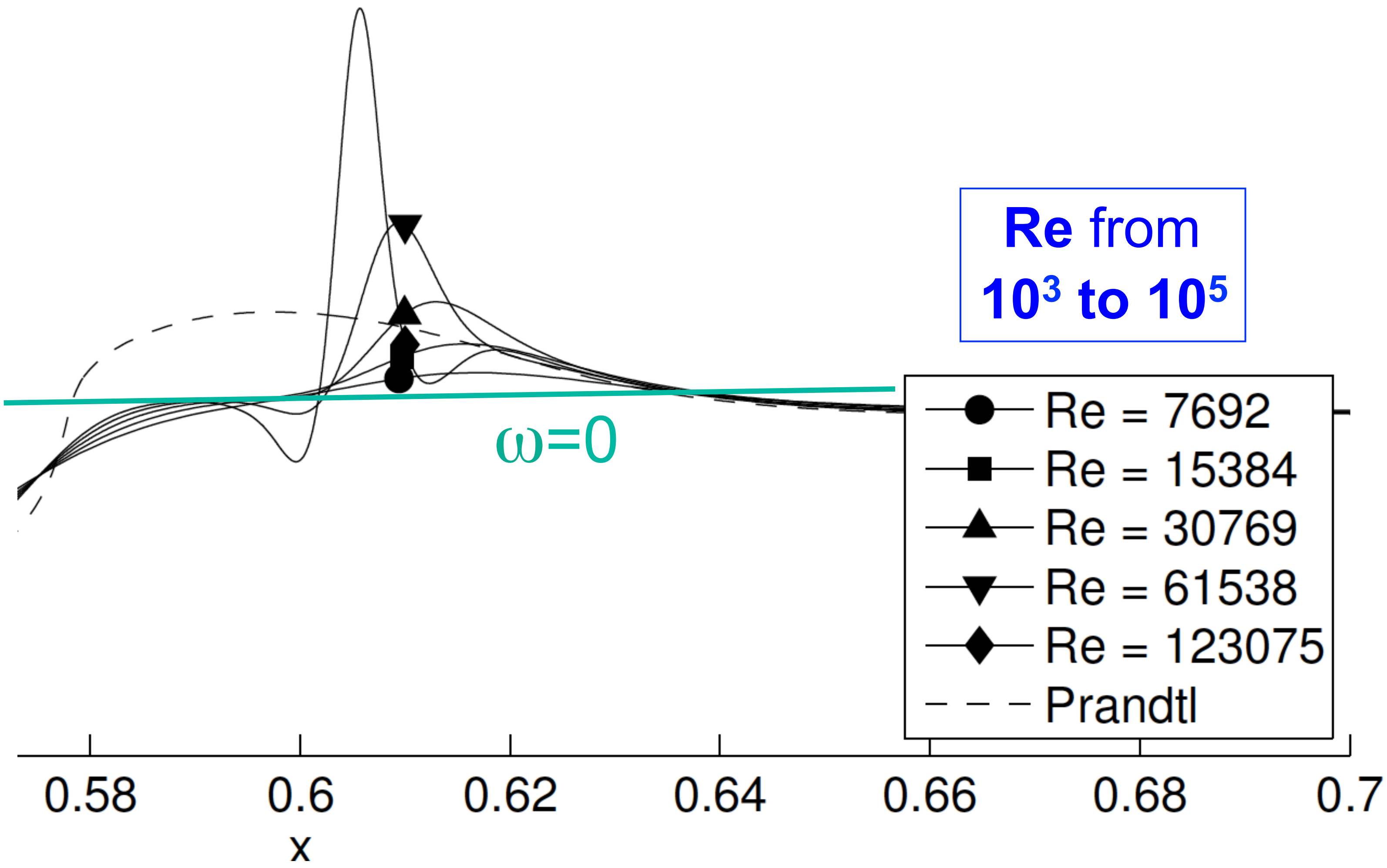
Built-in of a recirculation bubble

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





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

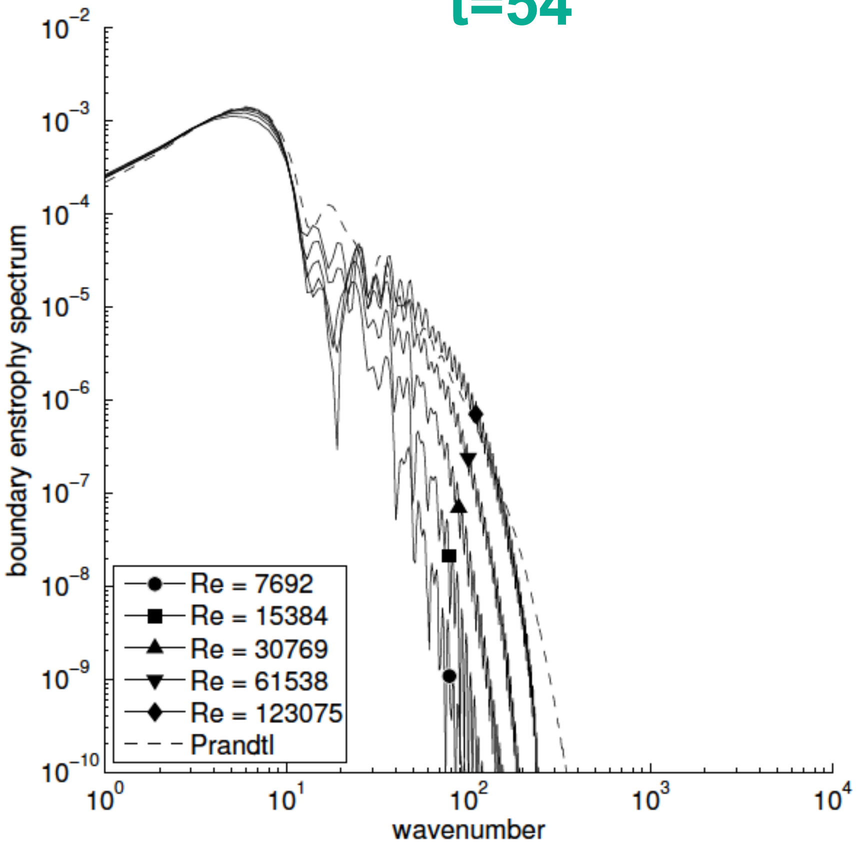


Re from

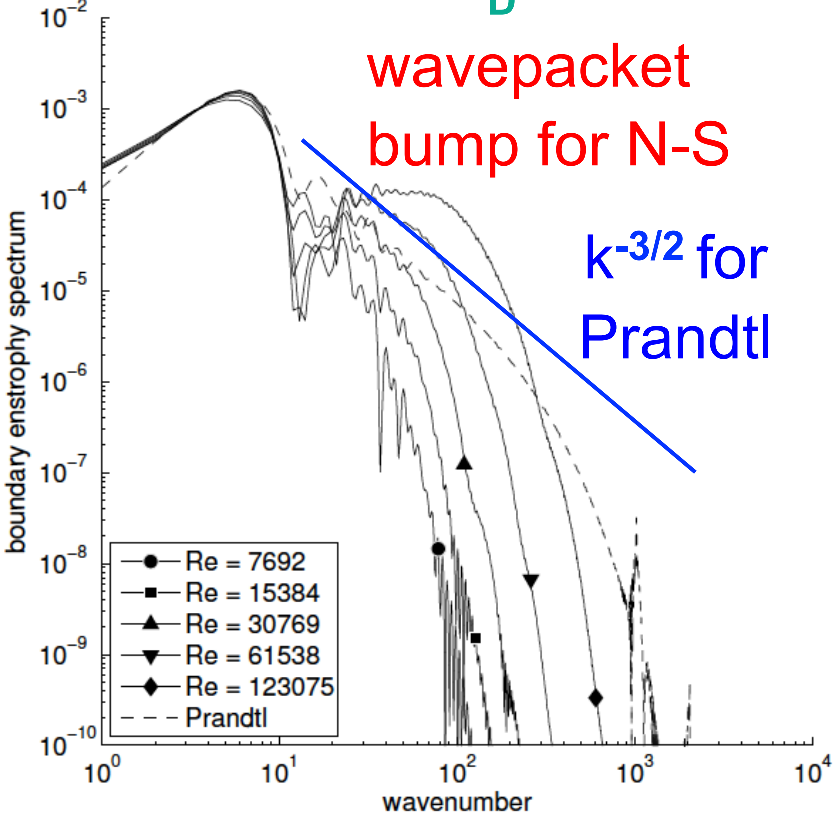
10^3 to 10^5

Spectrum of the boundary vorticity

$t=54$



$t=55.3 < t_D = 55.8$

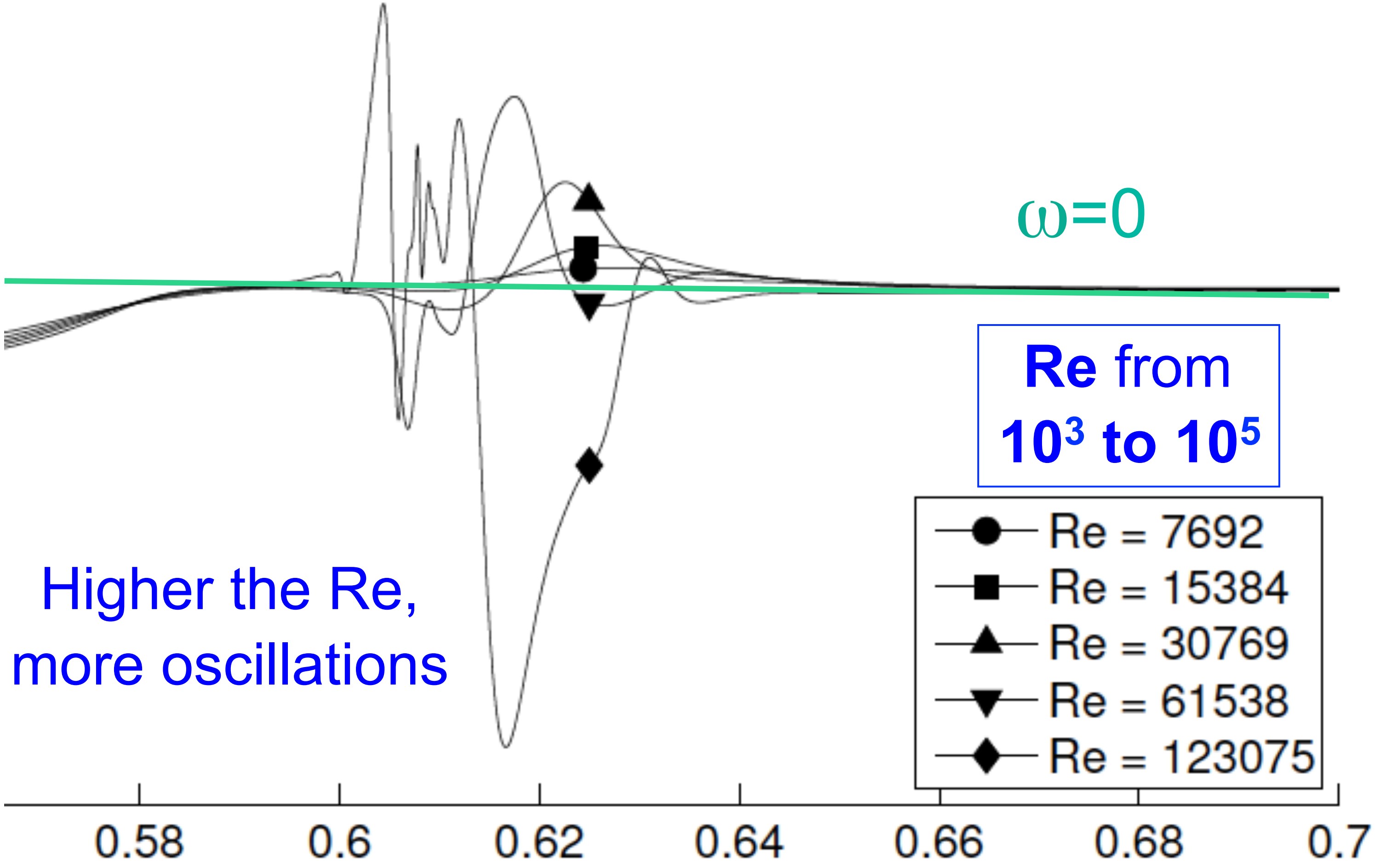

wavepacket bump for N-S

$k^{-3/2}$ for Prandtl

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=57.5 > t_D

Production of a wavepacket of vorticity
when and where boundary layer detaches

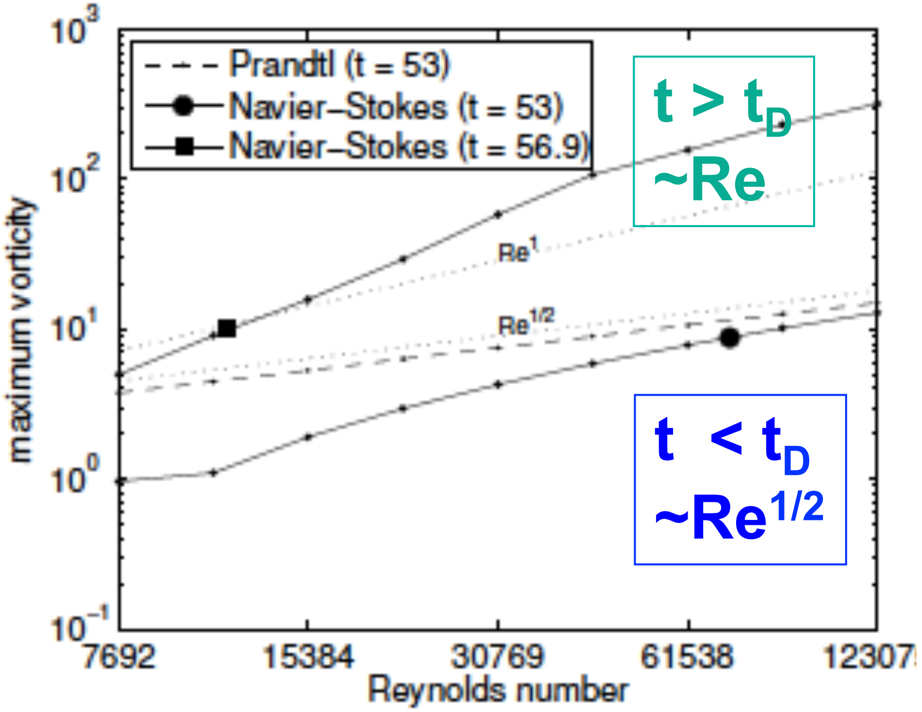


Re from
10^3 to 10^5

Higher the Re,
more oscillations

Scaling from Re=7692 to 123075

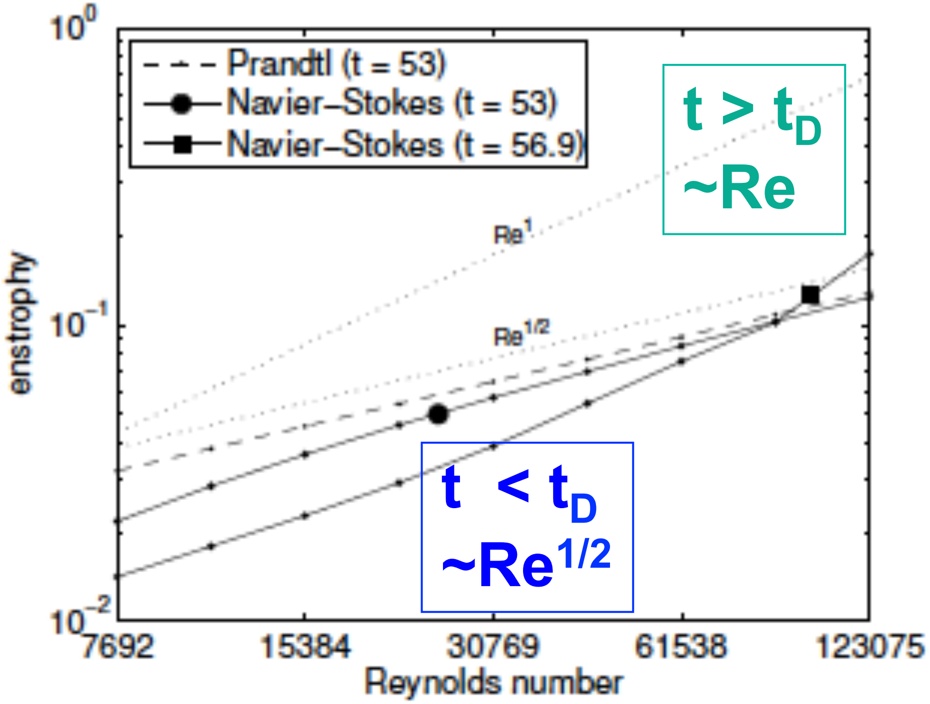
Vorticity max



$t > t_D$
~Re

$t < t_D$
~Re$^{1/2}$

Enstrophy



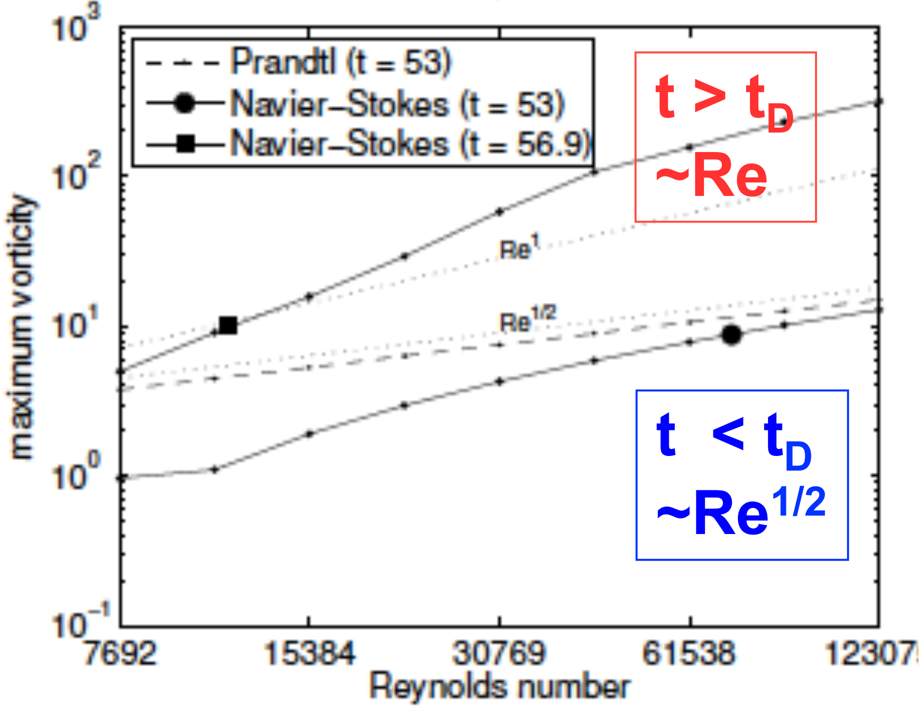
$t > t_D$
~Re

$t < t_D$
~Re$^{1/2}$

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

Scaling from Re = 7692 to 123075

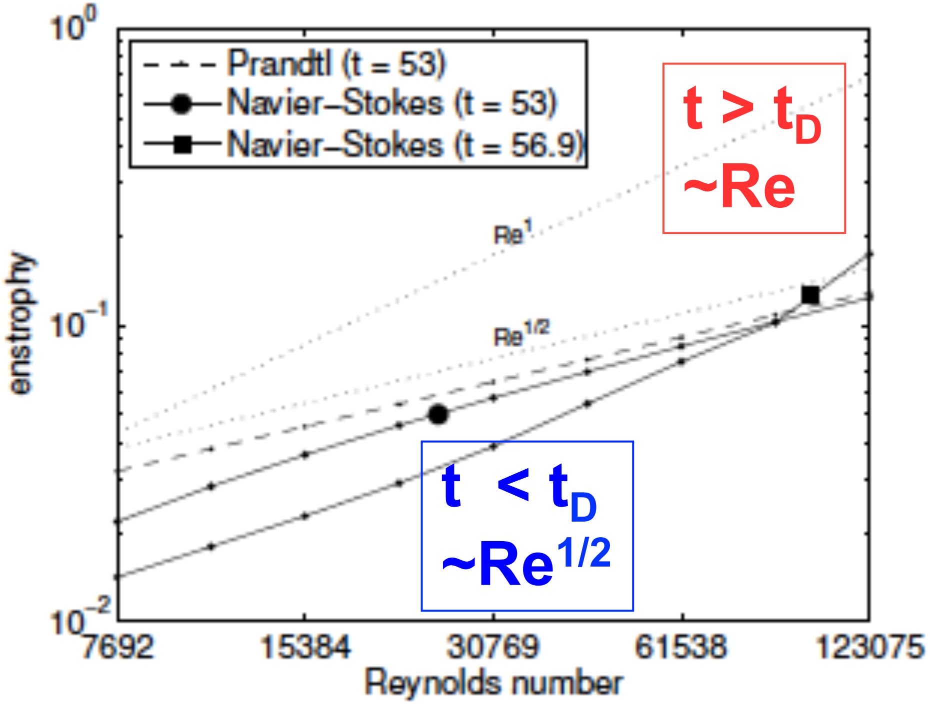
Vorticity max



$t > t_D$
$\sim Re$

$t < t_D$
$\sim Re^{1/2}$

Enstrophy



$t > t_D$
$\sim Re$

$t < t_D$
$\sim Re^{1/2}$

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

Nguyen van yen, M. F.
and Schneider,
Phys. Rev. Lett., ***106****(18), 2011*

Nguyen van yen, Waidmann, Klein,
M. F. and Schneider,
J. Fluid Mech., 849, 676-717, 2018

Relation to the von Karman wall 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

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

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

Attached / detached boundary layer

- The Prandtl solution becomes singular at t_D when BL detaches.
- The Navier-Stokes solution converges uniformly to the Euler solution before the boundary layer remains attached and ceases to converge after the boundary layer 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 where Prandtl's solution becomes singular. It apprears not on the wall but near le wall.

Nguyen van yen, Waidmann, Klein,
M. F. and Schneider,
J. Fluid Mech., 849, 676-717, 2018

Interpretation of the von Karman wall law

- 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 wall law of von Karman.

Nguyen van yen, Waidmann, Klein,
M. F. and Schneider,
J. Fluid Mech., 849, 676-717, 2018

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,
Acta Mathematica, ***63***

C. de Lellis and L. Székzlyhidi, 2010
Archives Rational Mechanics and Analysis,
195*(1), 221-260*

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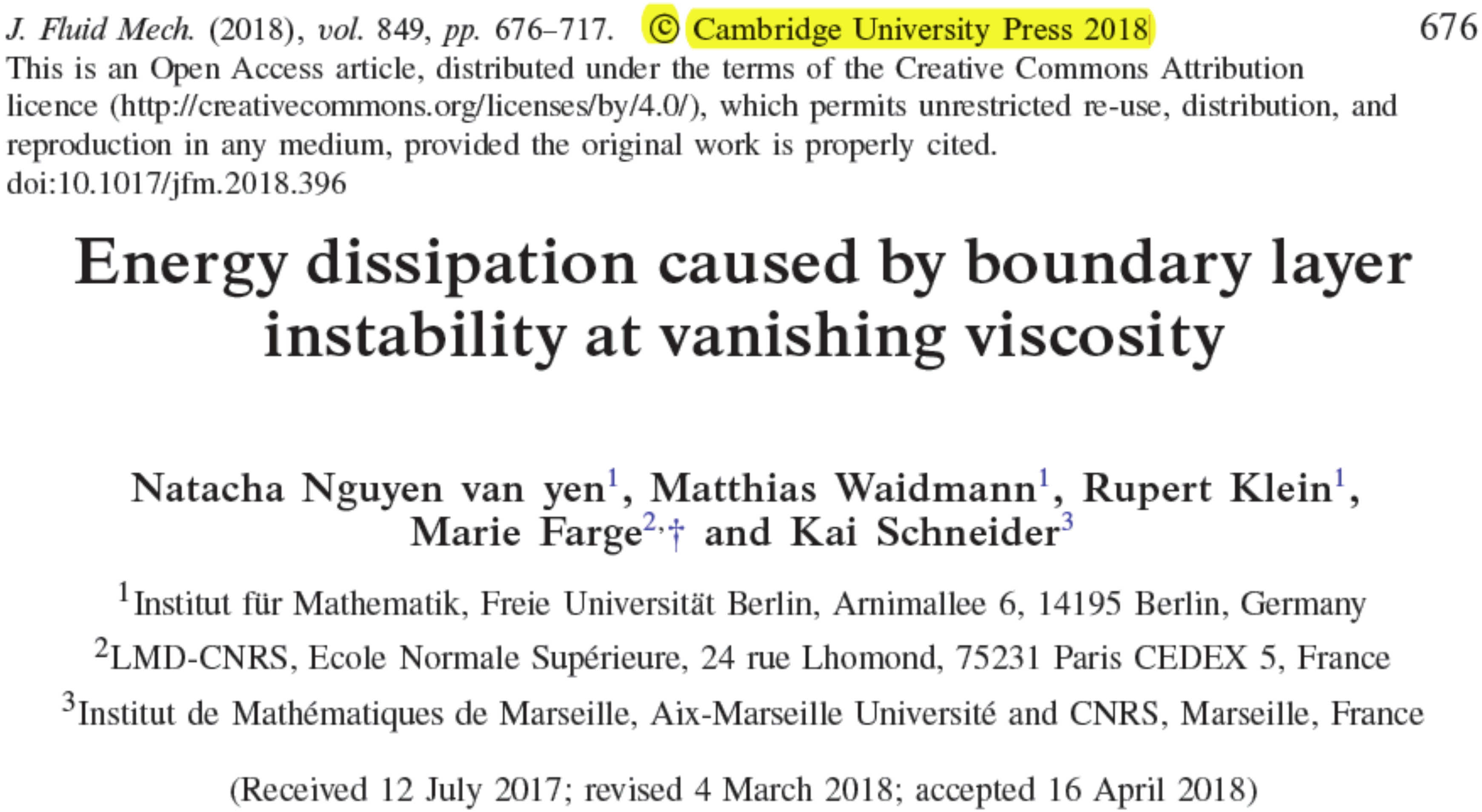

J. Fluid Mech. (2018), *vol.* 849, *pp.* 676–717.

doi:10.1017/jfm.2018.396

Energy dissipation caused by boundary layer instability at vanishing viscosity

Natacha Nguyen van yen[1], **Matthias Waidmann**[1], **Rupert Klein**[1],
Marie Farge[2,†] **and Kai Schneider**[3]

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[2]LMD-CNRS, Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris CEDEX 5, France
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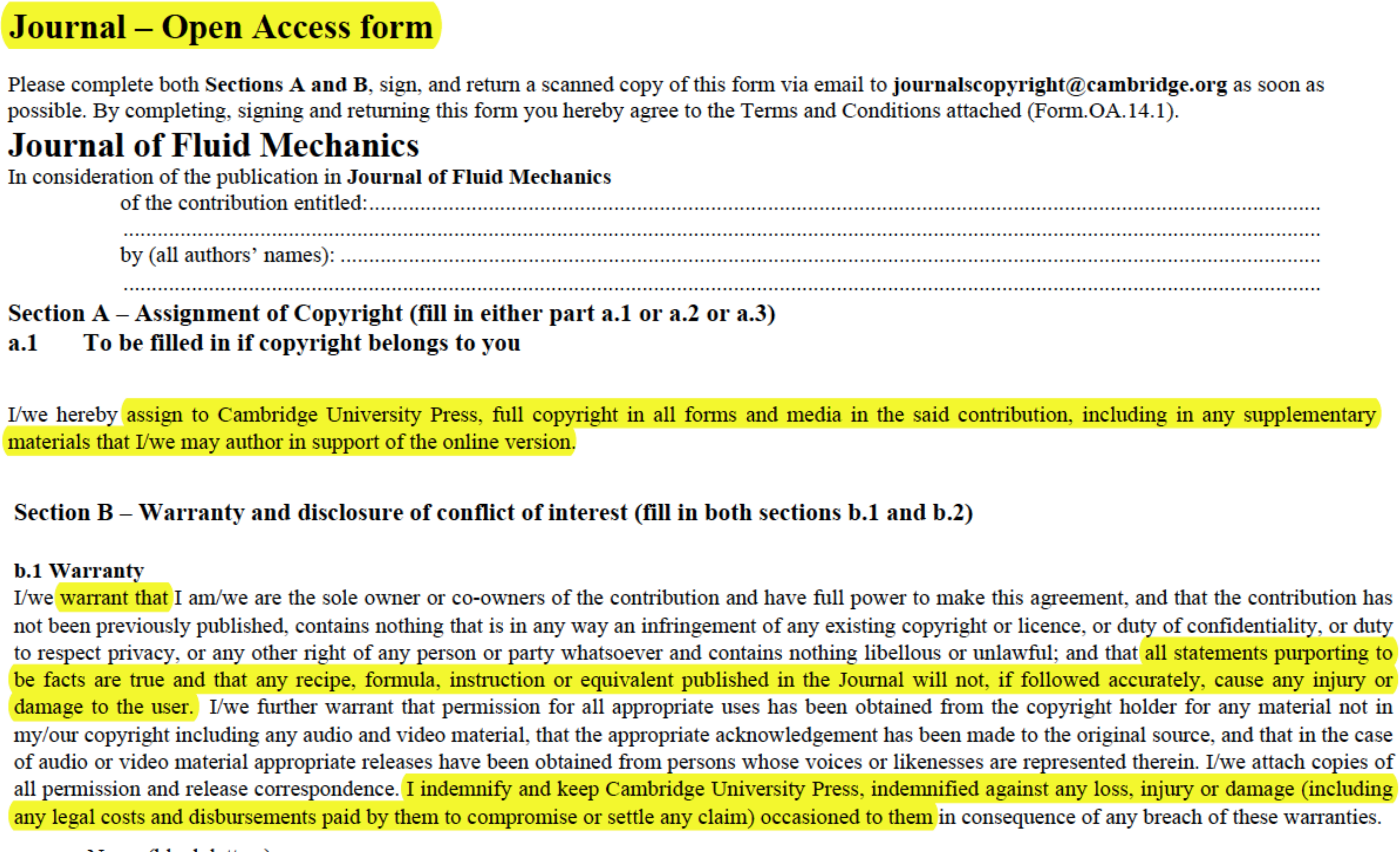

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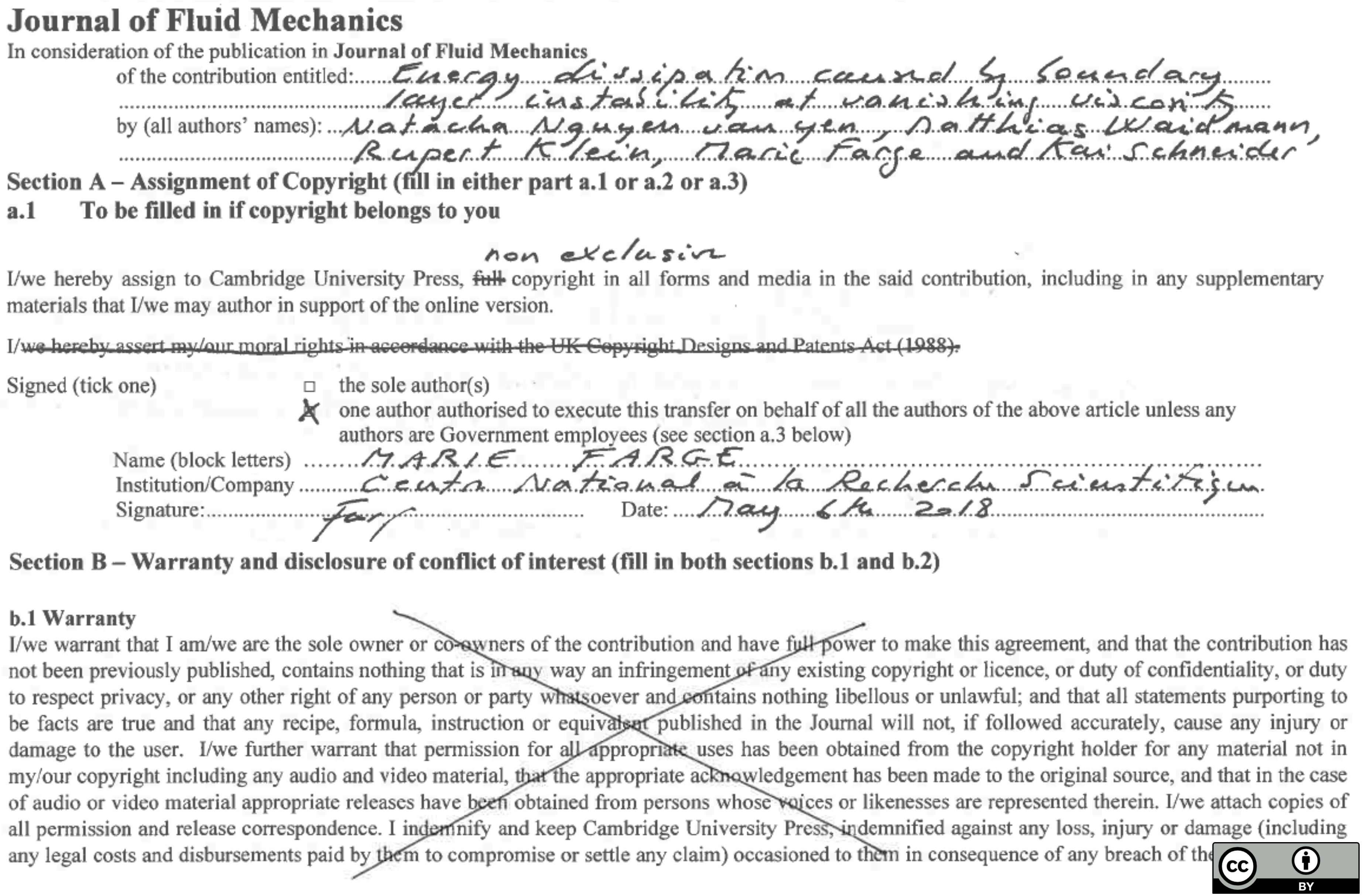

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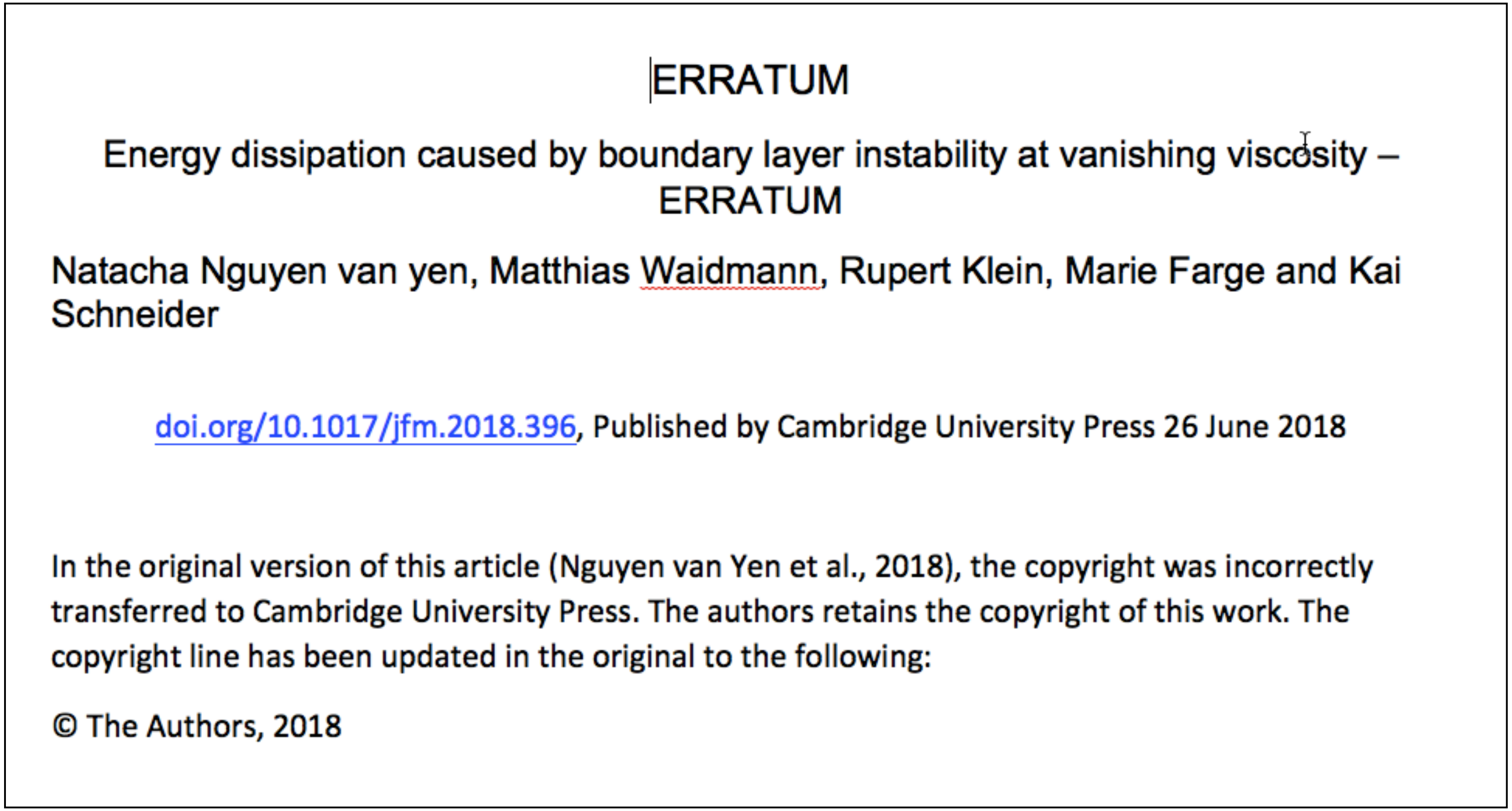

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Energy dissipation caused by boundary layer instability at vanishing viscosity – ERRATUM

Natacha Nguyen van yen, Matthias Waidmann, Rupert Klein, Marie Farge and Kai Schneider

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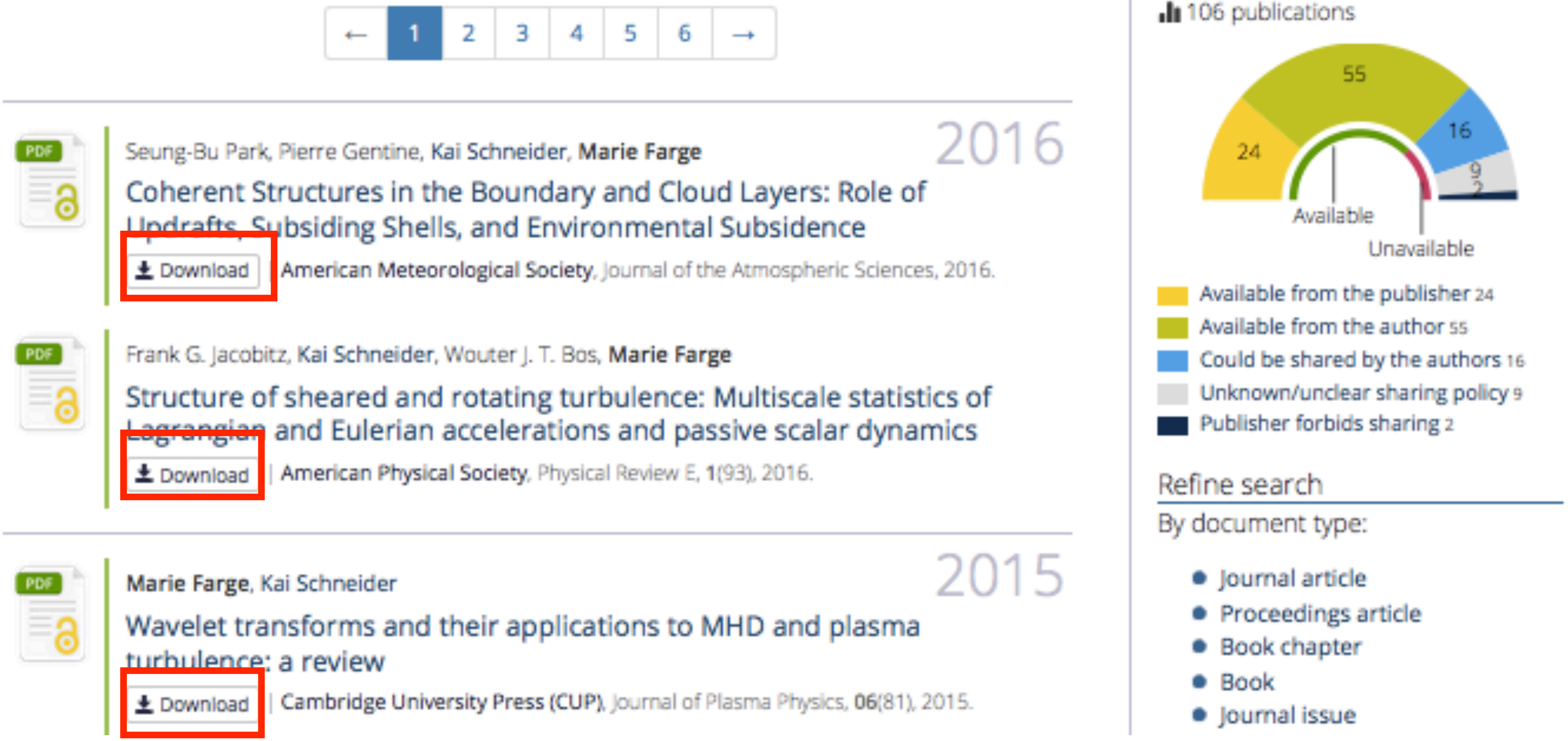

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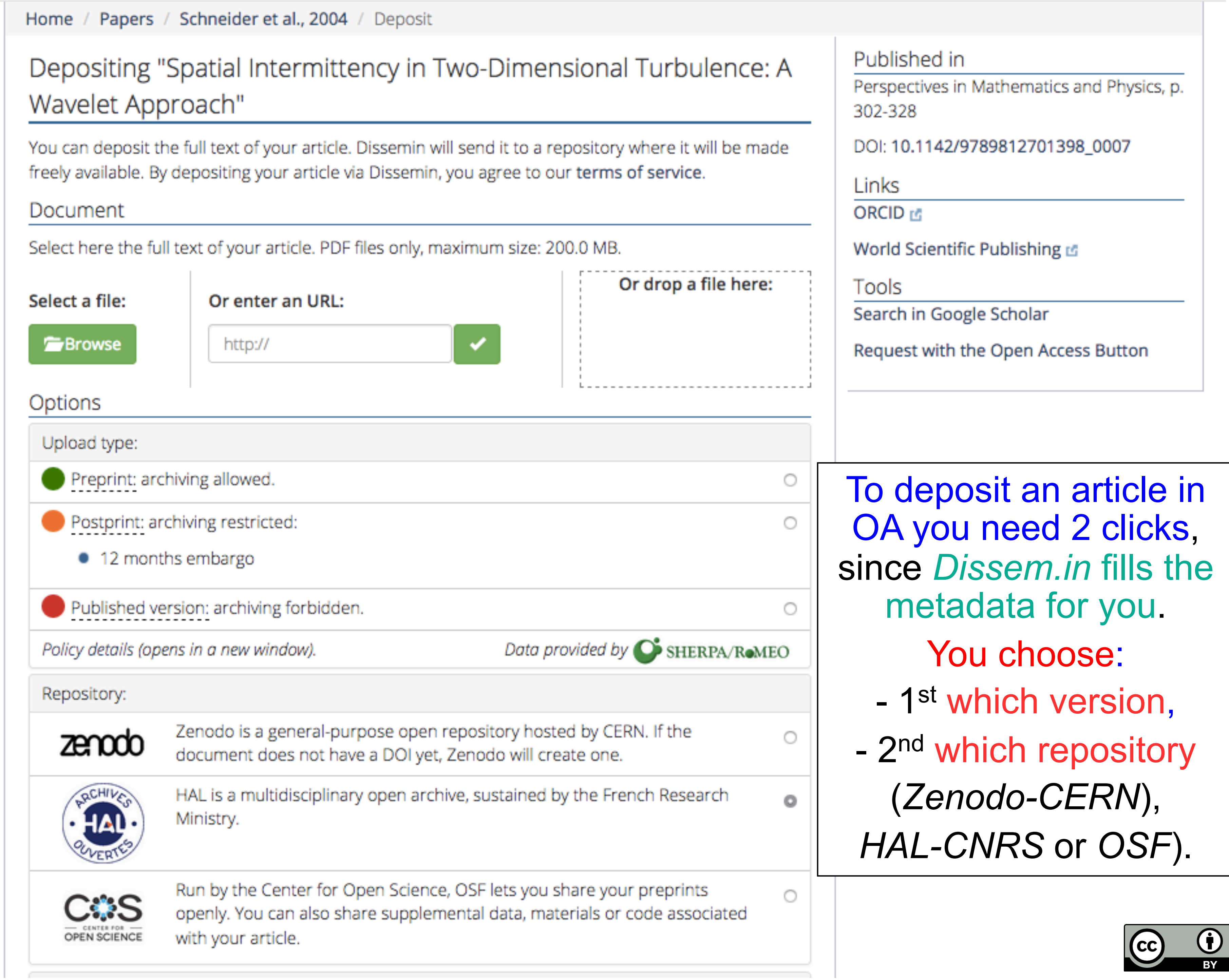

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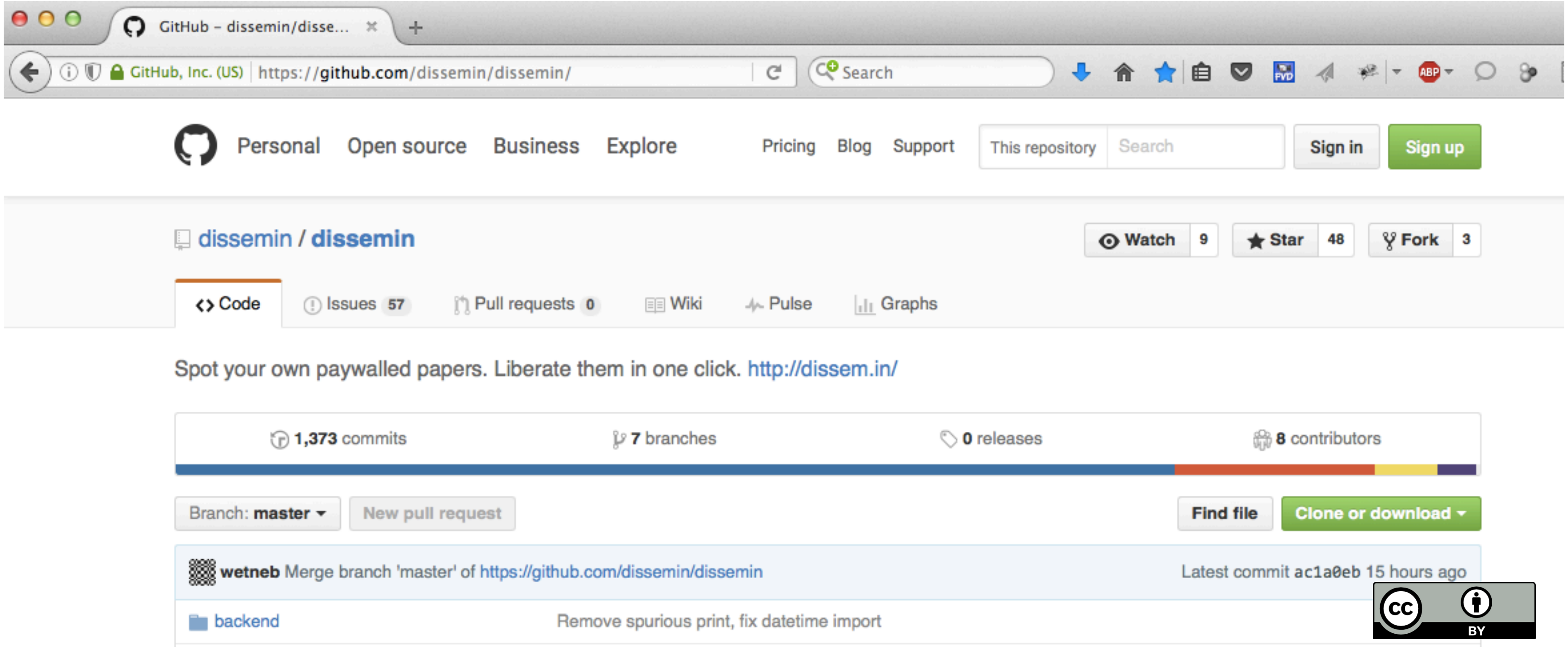

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