# DIRECT FEM-SIMULATION (DFS) OF TURBULENT (BLUFF BODY) FLOW

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# INTRO: WE BELONG TO A TRADITION:

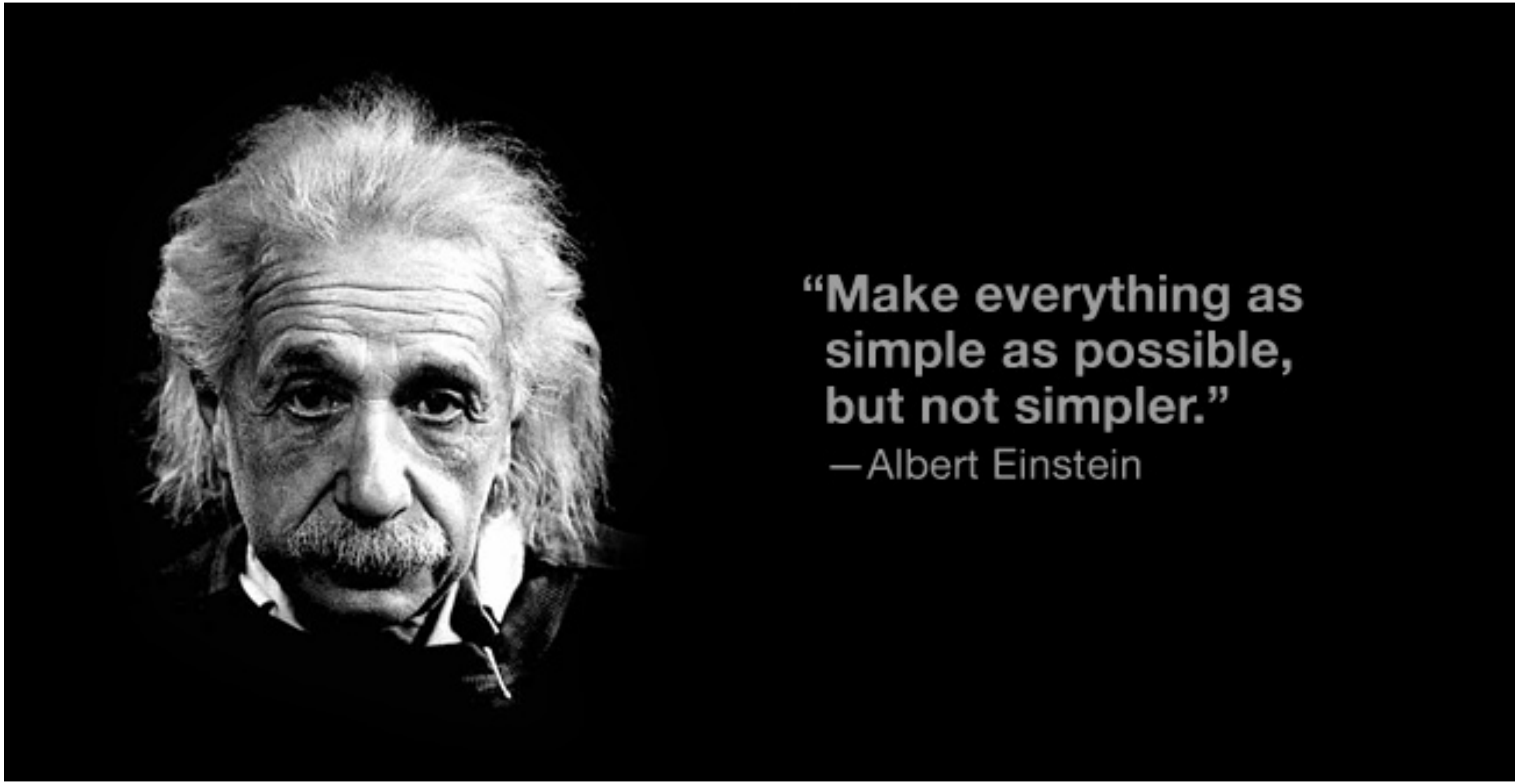
- MATHEMATICS
- MATHEMATICAL PHYSICS: PDEs
- CONSTRUCTIVE MATHEMATICS: COMPUTE
- FINITE ELEMENT MATHEMATICS
- AUTOMATED MATHEMATICAL SIMULATION

- EULER – D’ALEMBERT – NAVIER-STOKES – COURANT – LIONS - - -

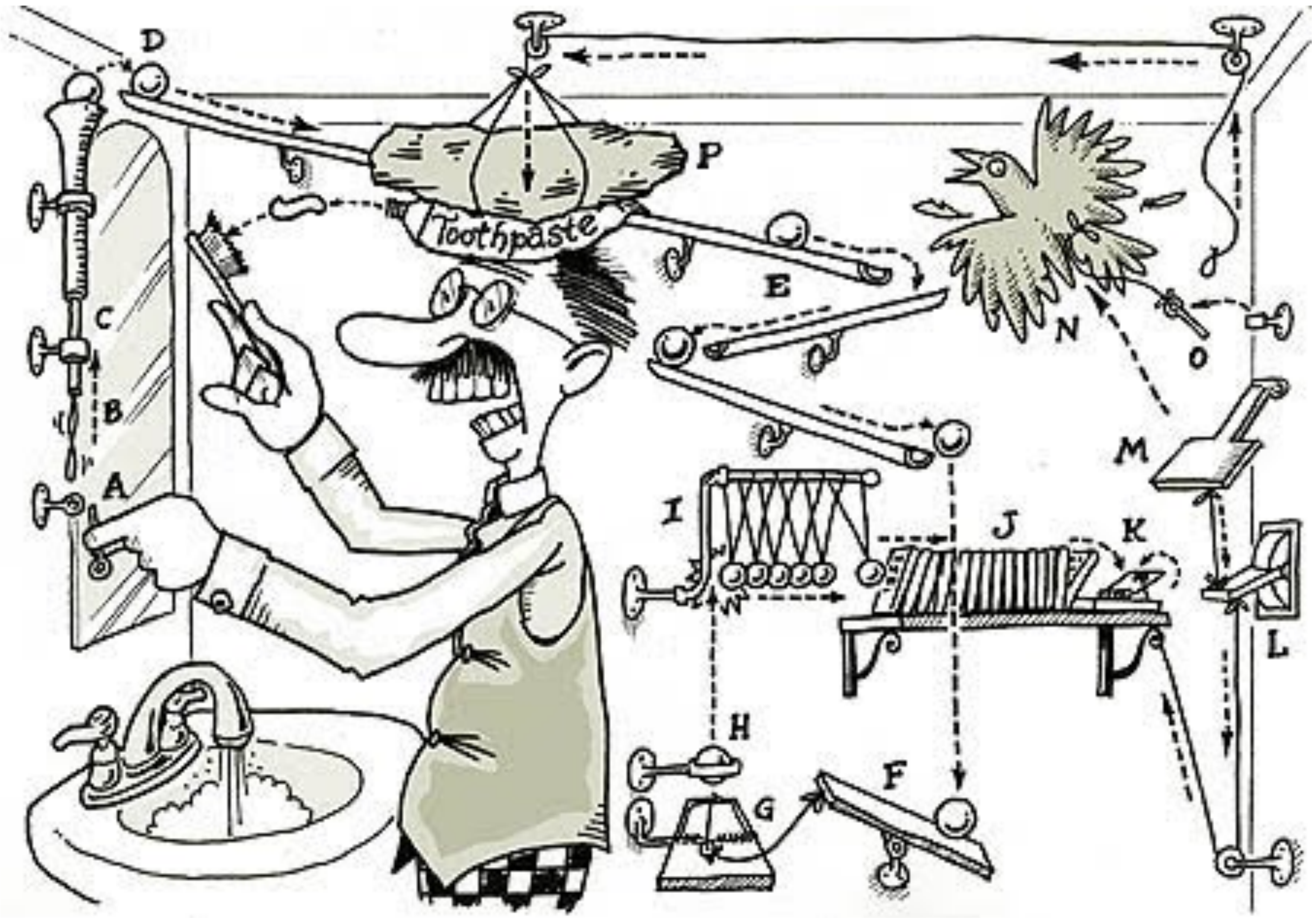
# HAMMING: PURPOSE OF COMPUTING:

- INSIGHT - UNDERSTANDING
- NOT NUMBERS

# PLAN: MAKE FLUID MECH AS SIMPLE AS POSSIBLE (ASAP) BUT NOT SIMPLER



# THIS IS OCKHAM’S RAZOR



# FLUID MECH ASAP

# AS SIMPLE AS POSSIBLE BUT NOT SIMPLER

- COMPUTABLE

- UNDERSTANDABLE

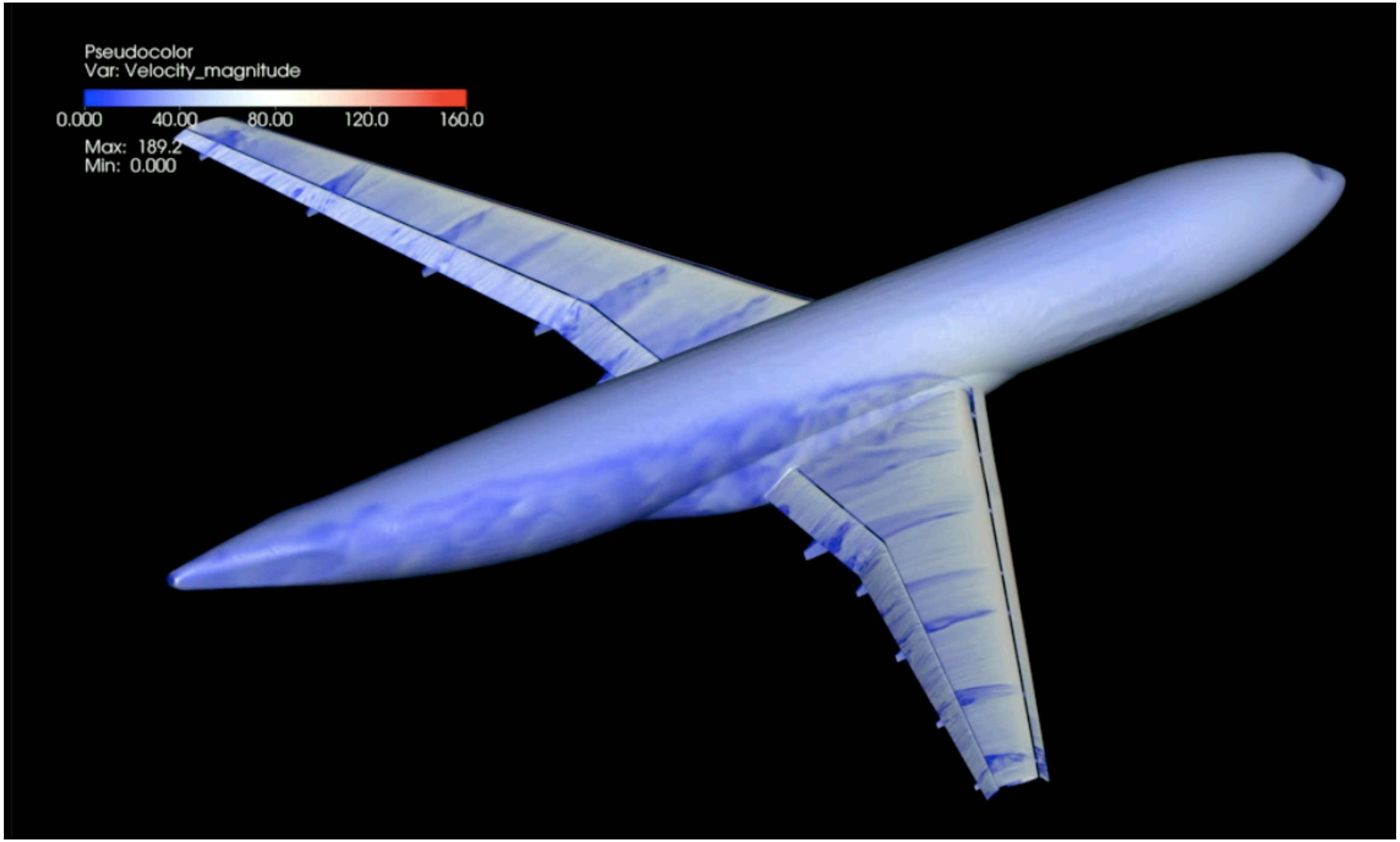
# DFS: DIRECT FEM-SIMULATION

- NAVIER/STOKES (INCOMPRESSIBLE)
- HIGH REYNOLDS – SMALL VISCOSITY
- SMALL SKIN FRICTION:
- SLIP BOUNDARY CONDITION

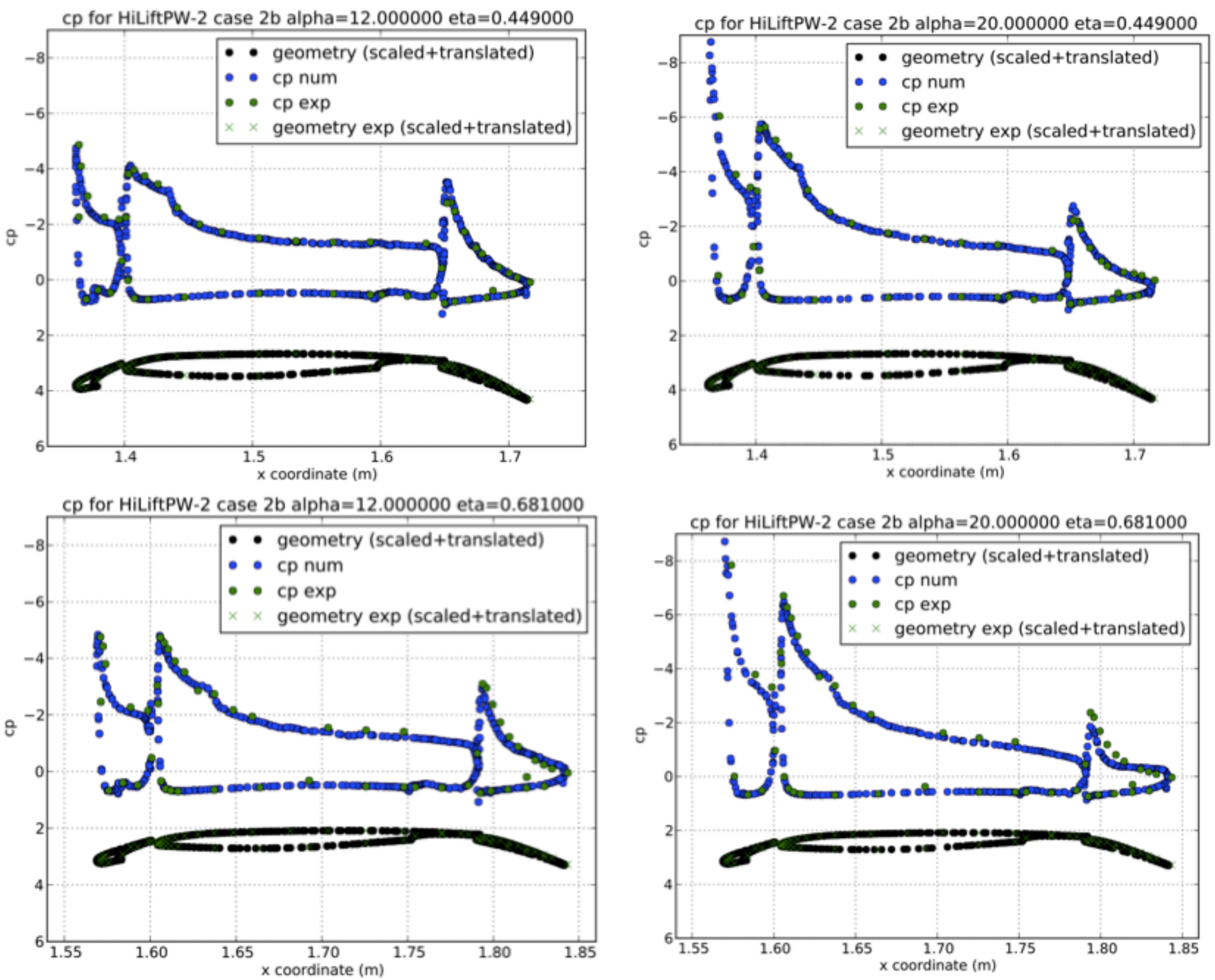
- RESIDUAL STABILIZED GALERKIN G2
- ADAPTIVE
- DUALITY BASED OUTPUT ERROR CONTROL
- NO TURBULENCE MODEL BEYOND RES STAB

# COMPUTABLE: 3 MILLION POINTS:

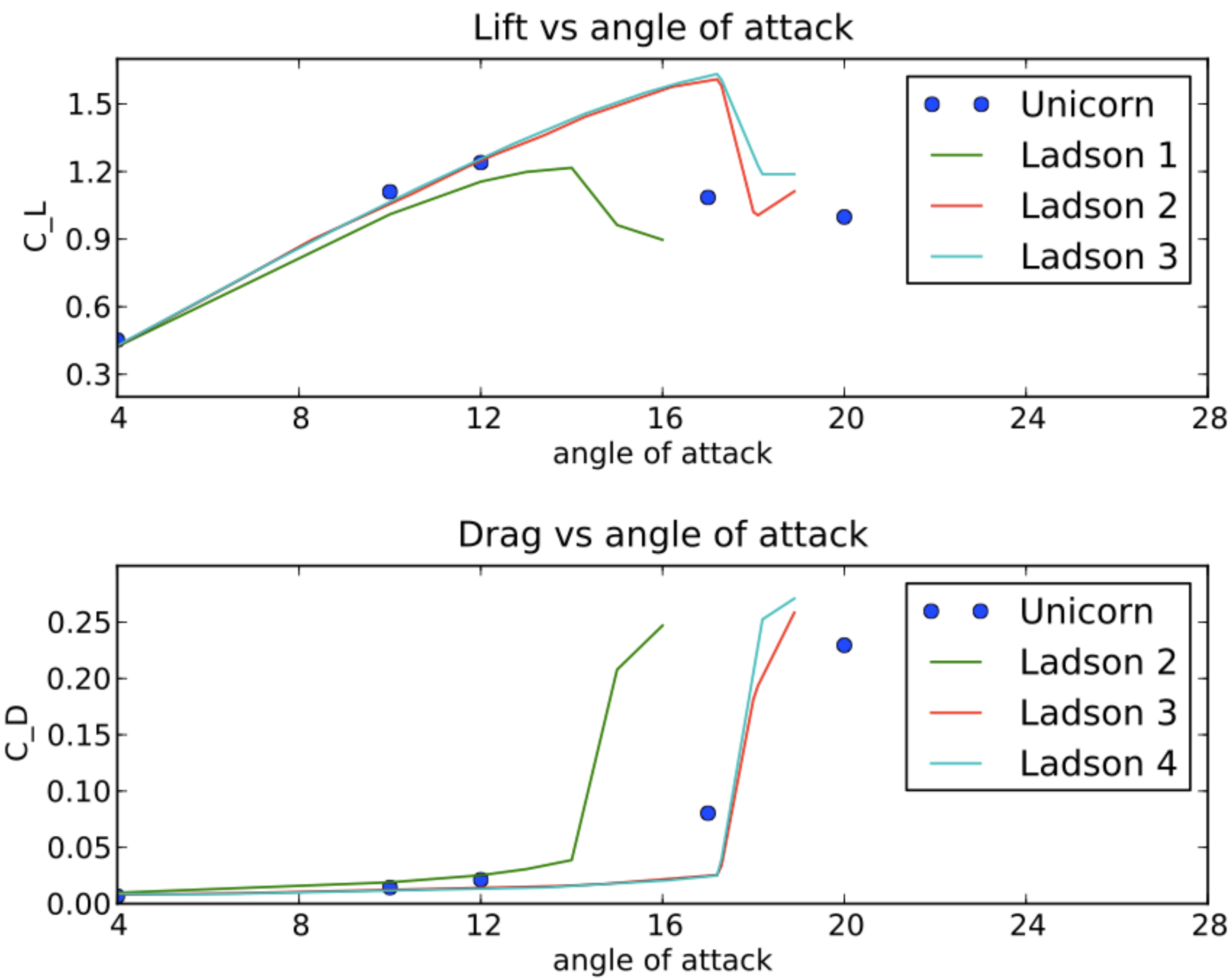
# FIRST SIMULATION OF FULL AIRPLANE



# PRESSURE DISTRIBUTION:
# COMPUTATION = OBSERVATION



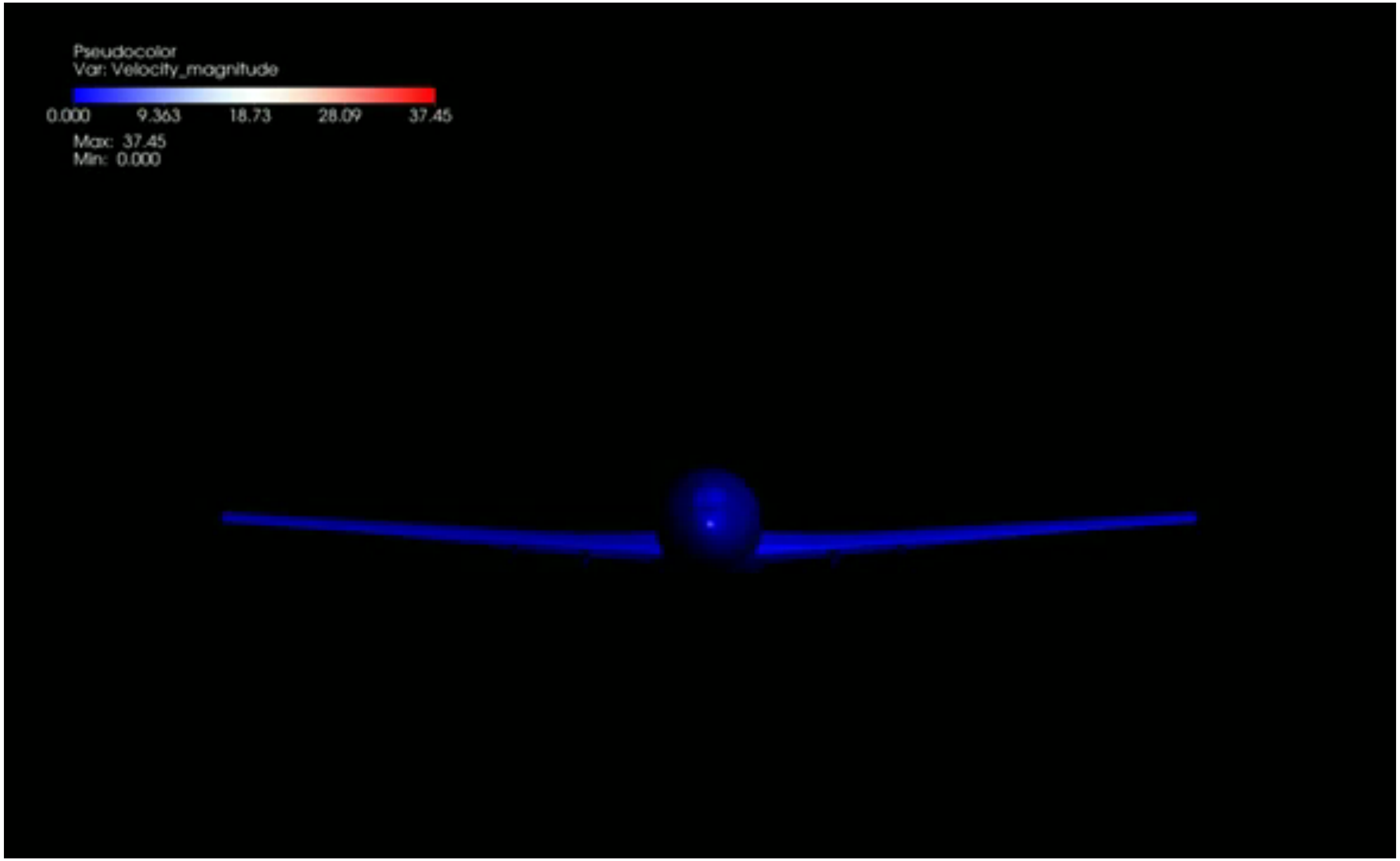
# LIFT + DRAG NACA0012:
# COMPUTATION = OBSERVATION



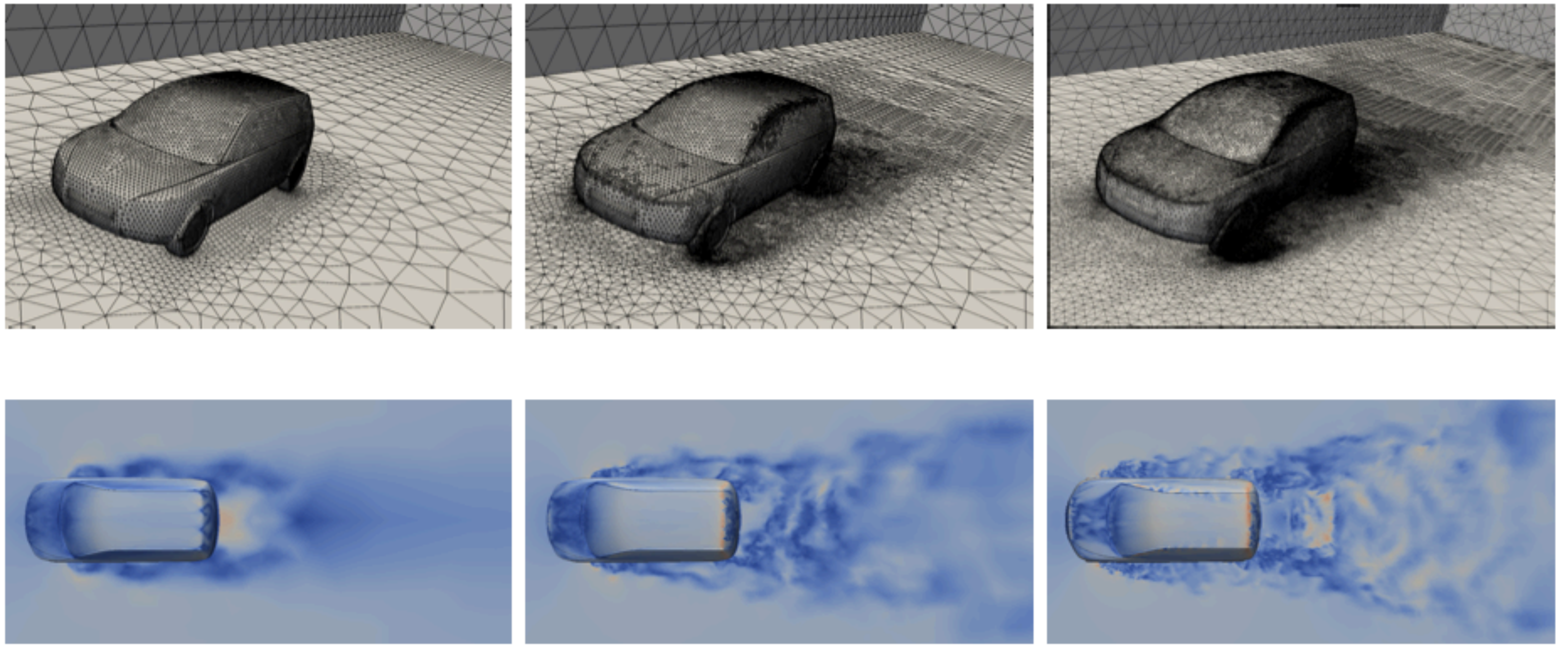

[J.Jansson/J.Hoffman/N.Jansson, 2011]

# LOOK AT MOVIE CTL WEB PAGE

## 2nd HIGHLIFT AIAA June 22-23



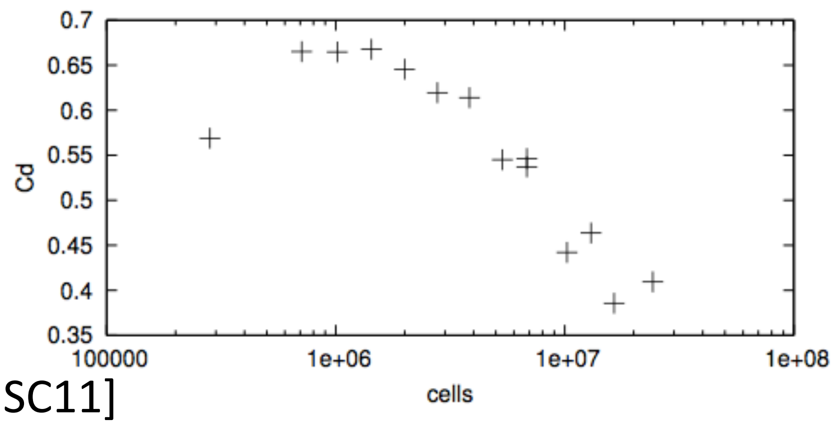
# COMPUTABLE: DRAG OF CAR



[Geometric model from of Volvo Cars]

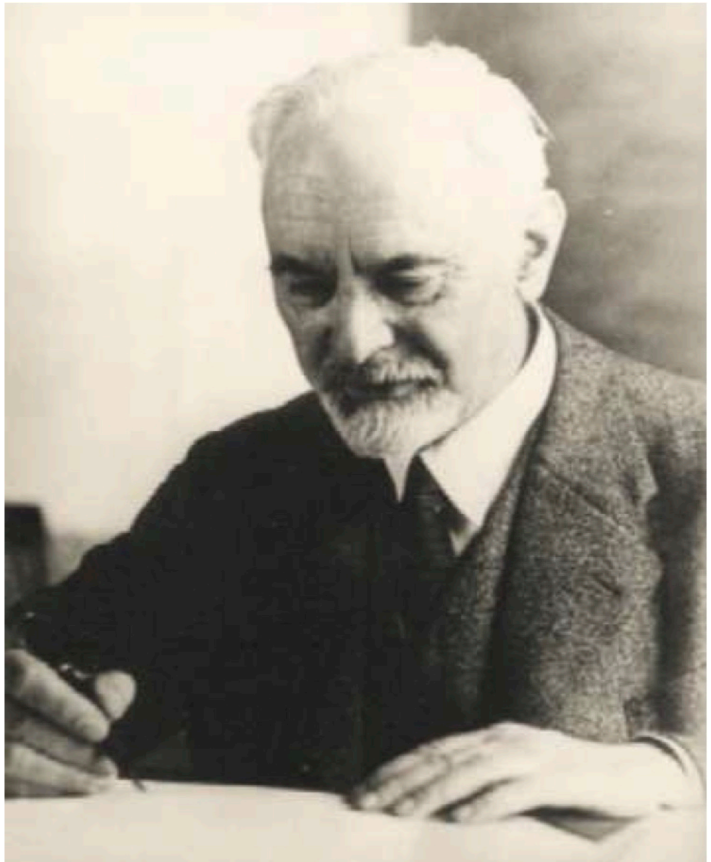
## Aerodynamic drag

- Refine w.r.t error in drag
- Reference value $C_D = 0.359$




[N.Jansson/J.Hoffman/M.Nazarov Supercomputing SC11]

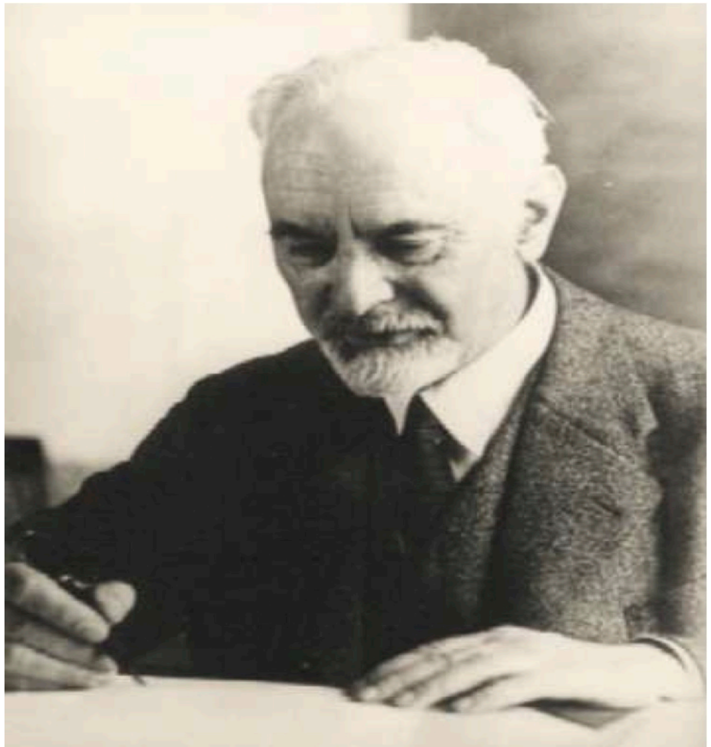
# PRANDTL: BUT THIS IS IMPOSSIBLE!



# DRAG FROM BOUNDARY LAYER:

NO BOUNDARY LAYER WITH SLIP

YOU HAVE TO USE NO-SLIP!!



# MOIN + KIM: YES! THIS IS IMPOSSIBLE!

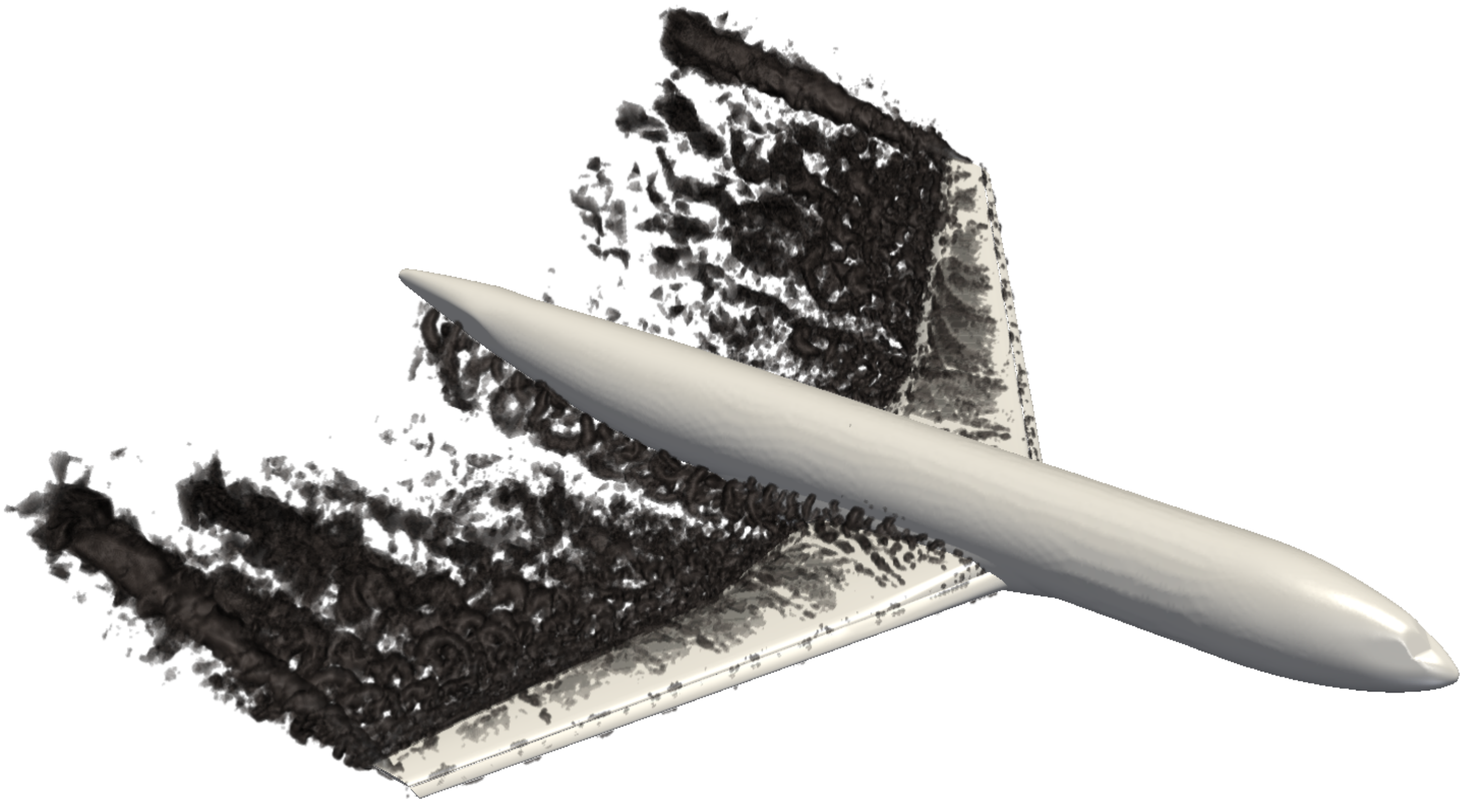
- 10^16 MESH POINTS NEEDED
- TO RESOLVE BOUNDARY LAYER
- PRANDTL: HAVE TO RESOLVE BOUNDARY LAYER

- WORK: 10^32 = 10^20 X TODAYS CAPACITY

- MOORE'S LAW = WAIT 120 YEARS AT LEAST!

- NS: NOT COMPUTABLE

# TURBULENT BLUFF BODY FLOW:
# UNDERSTANDABLE =
# POTENTIAL FLOW MODIFIED BY
# 3D ROTATIONAL SLIP SEPARATION

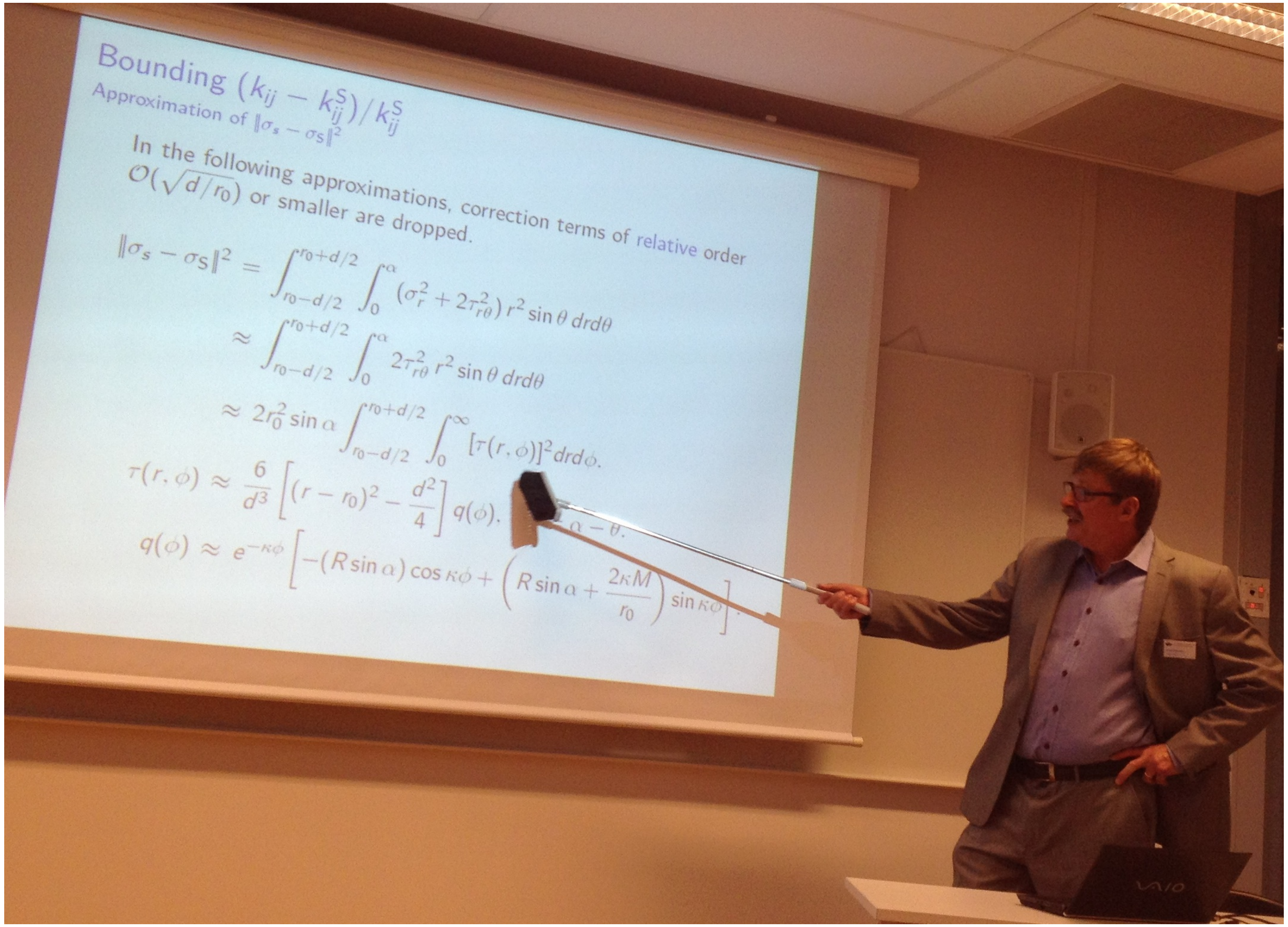


# BUT THIS IS IMPOSSIBLE!

- TURBULENT FLOW IS NOT UNDERSTOOD
- TURBULENT FLOW CANNOT BE UNDERSTOOD
- TURBULENT WILL NEVER BE UNDERSTOOD

# CALCULUS: AS DIFFICULT AS POSSIBLE

# CALCULUS IS AN ART



# SOLID MECHANICS: TOO SIMPLE

# NITSCHE: FEM UNDERSTANDABLE!

# (AND THIS IS FUN!)

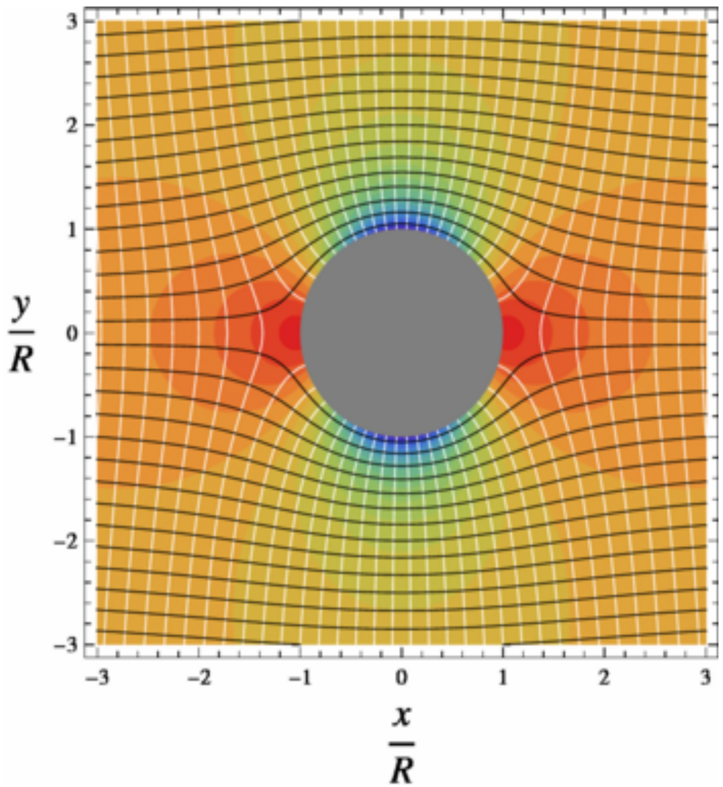
# EULER 1750: FLUID MECHANICS:
# SIMPLE: POTENTIAL FLOW


**Everything that the theory of fluids contains is embodied in the two equations I have formulated. It is not the laws of mechanics that we lack in order to pursue this research, only the analysis which has not been sufficiently developed for this purpose.**

# D'ALEMBERT 1752: TOO SIMPLE POTENTIAL FLOW: ZERO DRAG

**It seems to me that the theory (potential flow), 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.**

# POTENTIAL FLOW: NS/SLIP
# ZERO DRAG



# BIRKHOFF 1950: FM IS A MESS

NO REASON TO BELIEVE THAT ANY POTENTIAL FLOW IS STABLE

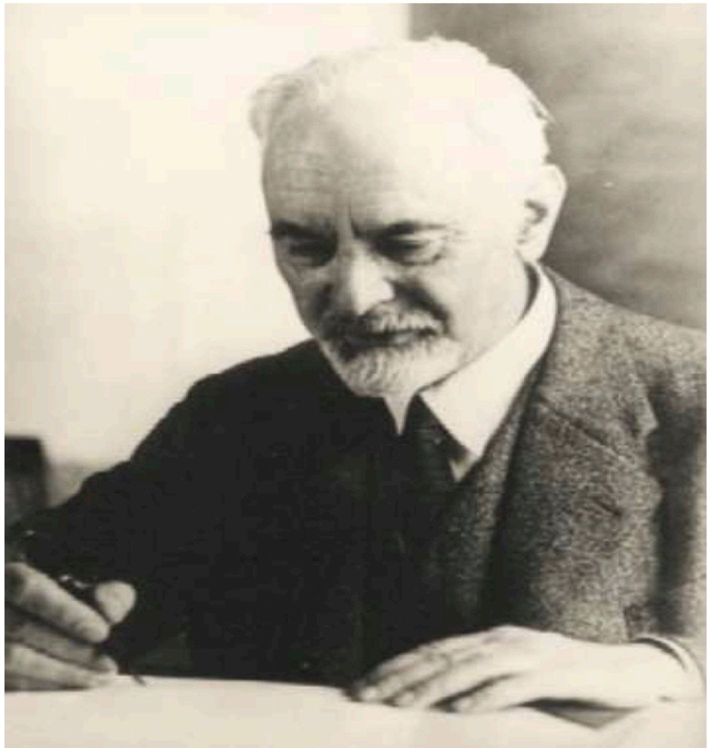
# HINSHELWOOD 1956: FM IS A MESS


**D'Alembert's paradox separated fluid mechanics from its start into theoretical fluid mechanics explaining phenomena which cannot be observed and practical fluid mechanics or hydraulics observing phenomena which cannot be explained.**

FATHER OF MODERN FLUID MECH:

NOT COMPUTABLE+UNDERSTANDABLE

MODERN FM: A MESS

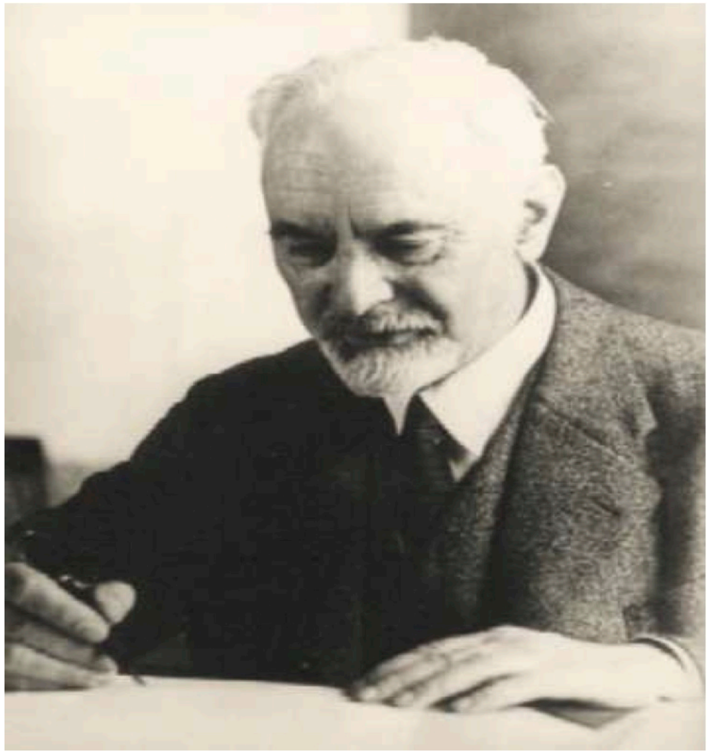


# FM NOT A MESS: FM MADE ASAP: COMPUTE + UNDERSTAND TODAY

# 256 YEARS TO RESOLVE D'ALEMBERTS PARADOX 1752 - 2008

- HOFFMAN-JOHNSON 2008 JMFM
- BIRKHOFF WAS RIGHT 1950!

# DRAG FROM BOUNDARY LAYER:
# UNPHYSICAL UNMATHEMATICAL:
# PRANDTL WAS WRONG: A MESS



# SOCIOLOGY OF MODERN FLUID MECH:

- COMPUTABLE + UNDERSTANDABLE:
- MAKES FLUIDS COMMUNITY ANGRY:
- HAVE TO DO SOMETHING

- NOT COMPUTABLE + UNDERSTANDABLE:
- IS APPLAUDED BY FLUIDS COMMUNITY:
- OK TO DO NOTHING

# TO SHOW PRANDTL WAS WRONG:

- HERESY
- NOT ALLOWED
- MUST BE STOPPED

# SECRET OF FLIGHT

- NEW THEORY OF FLIGHT JMFM 2013!?
- OLD THEORY OF FLIGHT WRONG
- AIAA REJECTS NEW THEORY

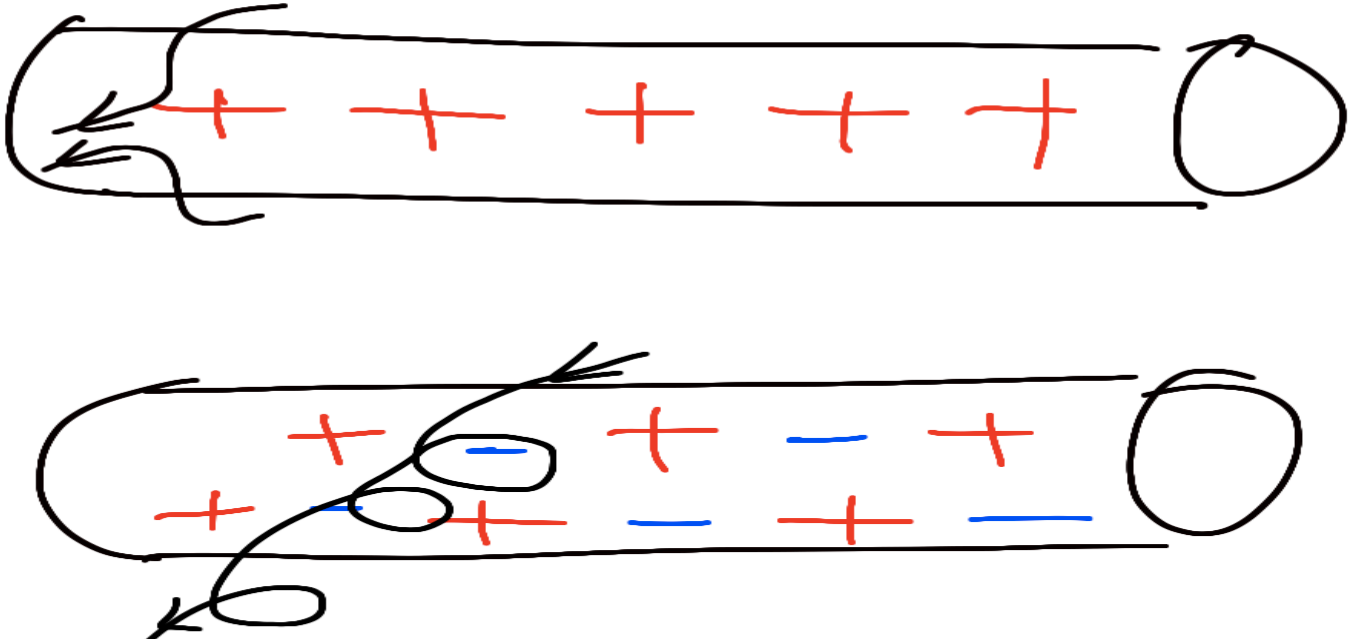
# HJ RESOLUTION 2008:

POTENTIAL FLOW NOT OBSERVED BECAUSE:

- UNSTABLE
- UNSTABLE AT SEPARATION
- IRROTATIONAL 2D SLIP SEPARATION

UNSTABLE HIGH PRESSURE REPLACED BY STABLE OSCILLATING PRESSURE

PRESSURE ENERGY INTO KINETIC ROTATIONAL ENERGY BY BERNOULLI



# PRANDTL 1904 RESOLUTION:

POTENTIAL FLOW NOT OBSERVED BECAUSE

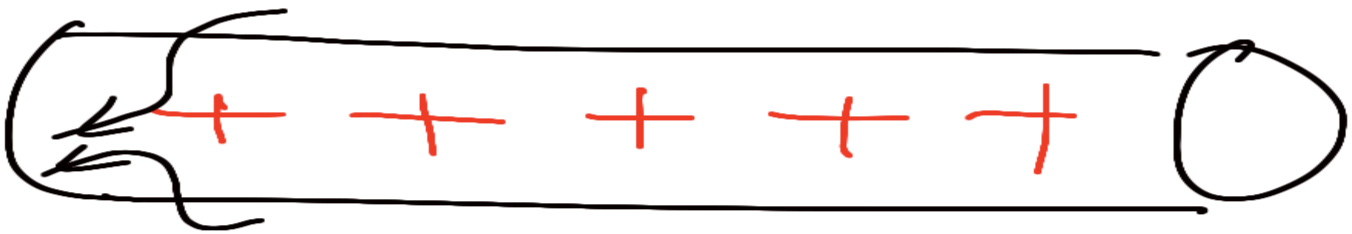
- SLIP
- NO BOUNDARY LAYER
- ALL FLOWS HAVE TO OBEY NO-SLIP!

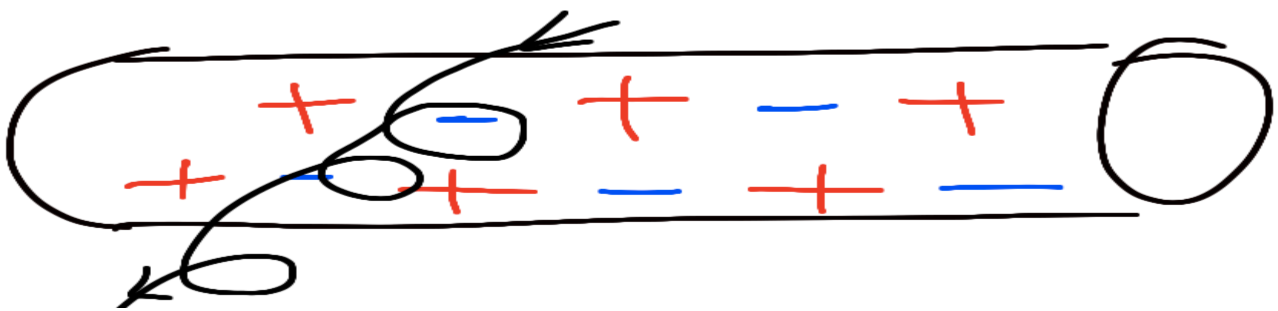
# HJ RESOLUTION 2008

- POTENTIAL FLOW MODIFIED BY
- ROTATIONAL 3D SLIP SEPARATION
- STABLE PHYSICAL

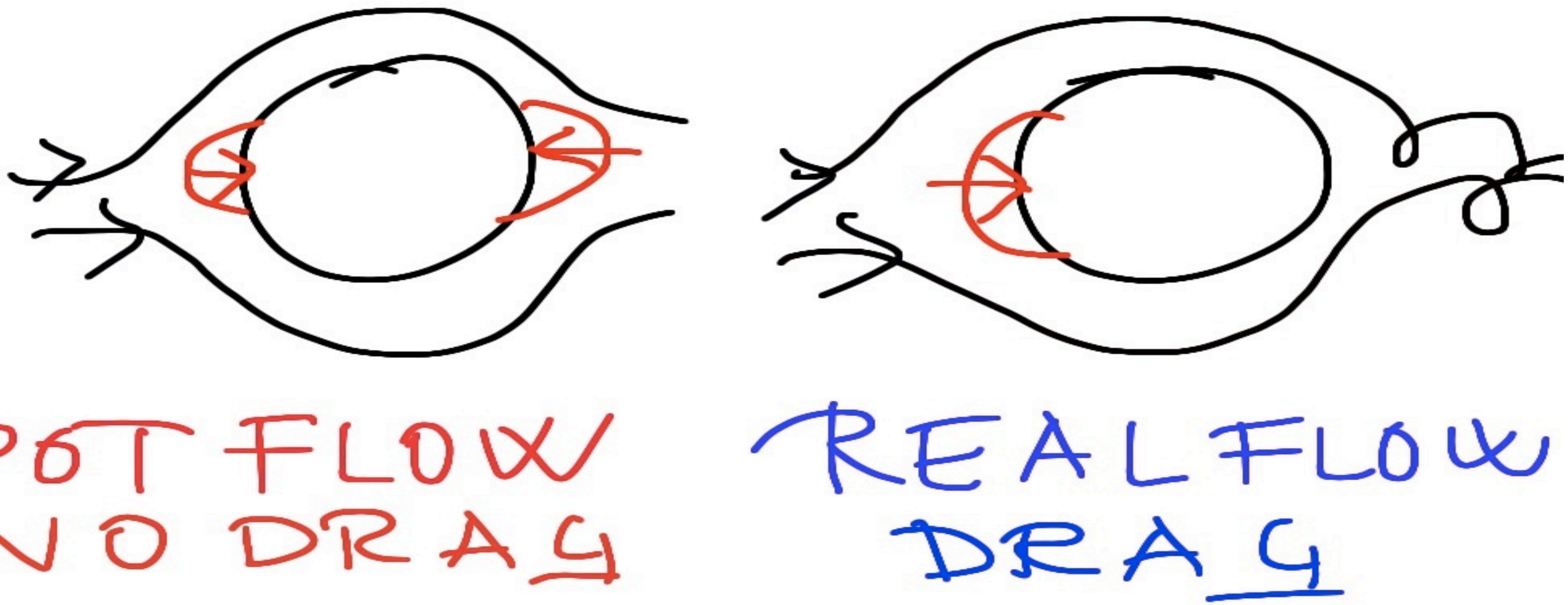
- EULER’S DREAM COME TRUE

UNSTABLE HIGH PRESSURE REPLACED BY STABLE OSCILLATING PRESSURE PRESSURE ENERGY INTO KINETIC ROTATIONAL ENERGY BY BERNOULLI



# RESOLUTION D'ALEMBERT'S PARADOX: ROTATIONAL SLIP SEPARATION WITHOUT PRESSURE RISE GIVES DRAG



# BLUFF BODY FLOW:
# 90% OF FLUID MECHANICS:
# FORCES ON BODY

EXTERIOR FLOW:

- AIRPLANE, CAR, BOAT…

INTERIOR FLOW:

- ENGINE, HEART…

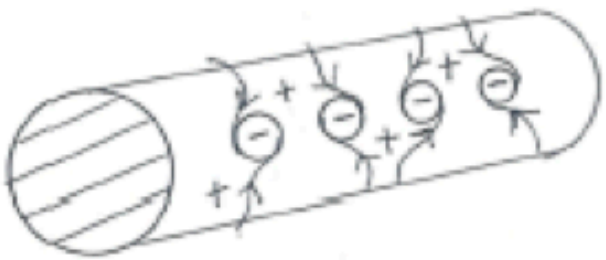
BLUFF BODY FLOW

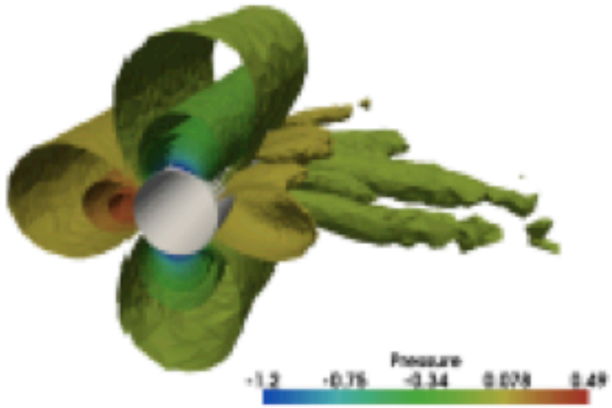
= POTENTIAL FLOW

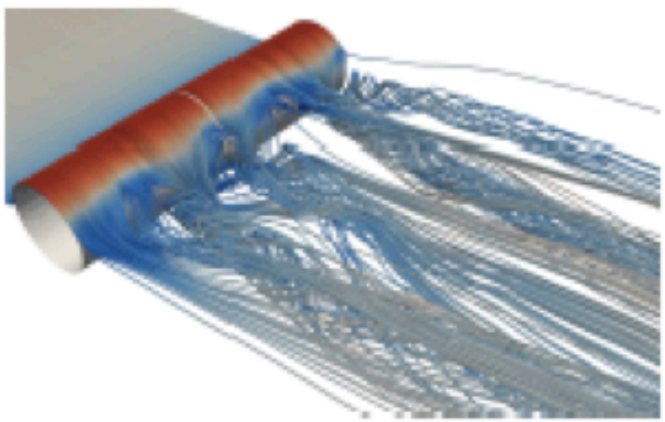
+ 3D ROTATIONAL SLIP SEPARATION

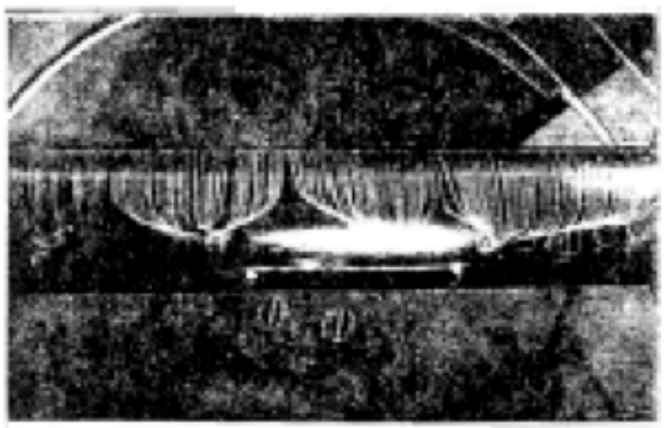
- COMPUTABLE
- UNDERSTANDABLE

# REAL FLOW: ROTATIONAL SLIP SEP:
# NO HIGH PRESSURE AT SEP: DRAG

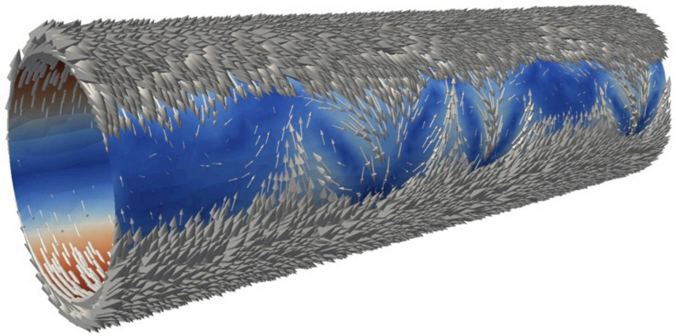






# Linear stability analysis

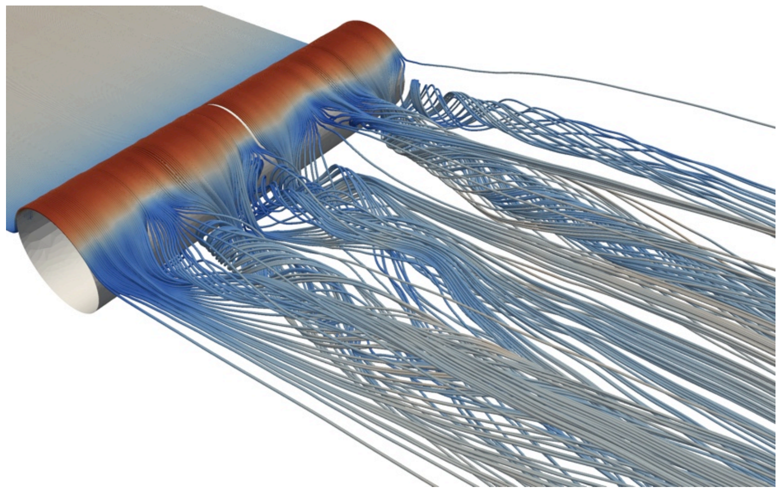


- Linearized equations:

$\partial \phi/\partial t + (u\cdot\nabla)\phi + (\phi\cdot\nabla)u + \nabla\theta = 0, \ \nabla\cdot\phi=0$

- Vorticity equations:

$\partial \omega/\partial t + (u\cdot\nabla)\omega - (\omega\cdot\nabla)u = 0, \ \omega=\nabla\times u$



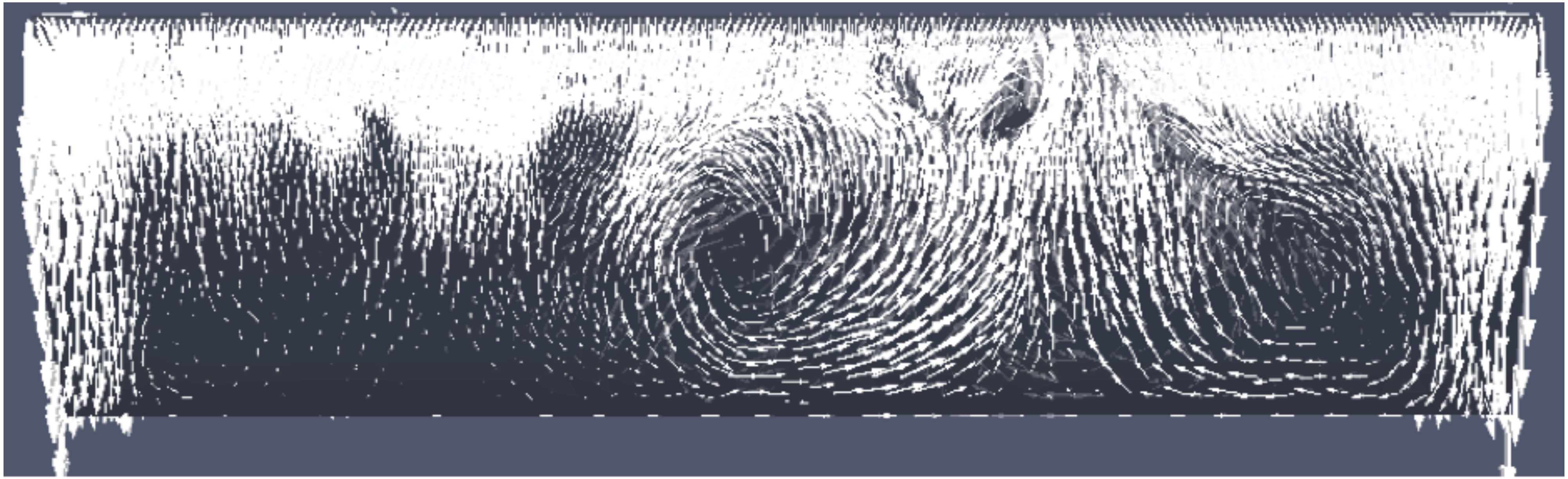
- Key for stability: solution gradient $\nabla u$
- At separation: $\nabla u$ = [2 0 0; 0 -2 0; 0 0 0]

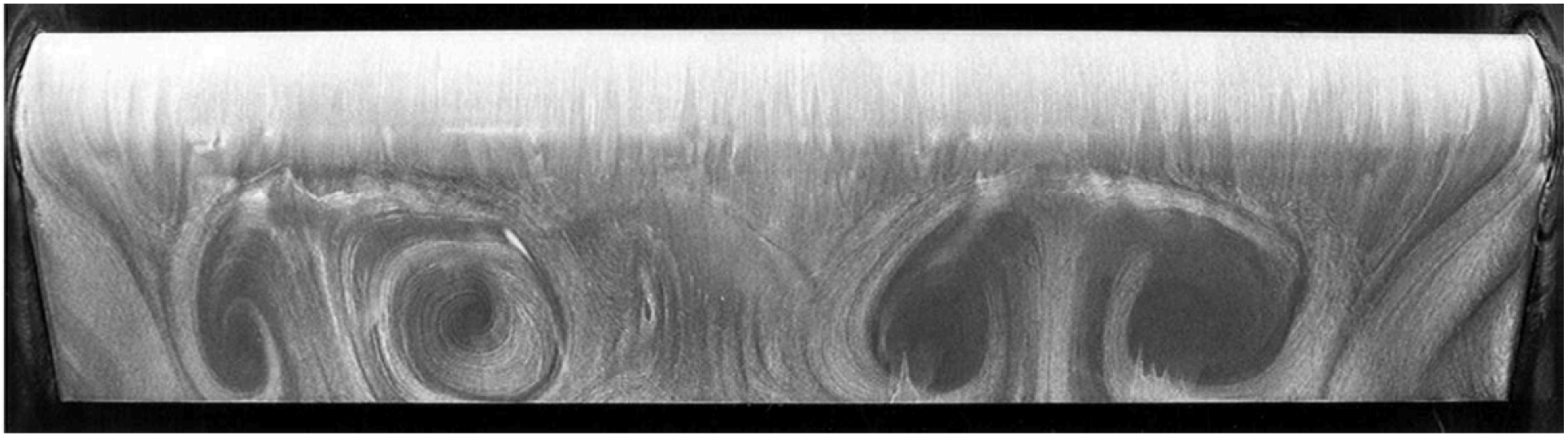
Potential solution is exponentially unstable at separation:

1. $\partial \phi_2/\partial t + (u\cdot\nabla)\phi_2 + \partial \iota/\partial_2 = 2\phi_2$ (exponential growth of $\phi_2$)
2. $\partial \omega_1/\partial t + (u\cdot\nabla)\omega_1 = 2\omega_1$ (exponential growth of $\omega_1$)

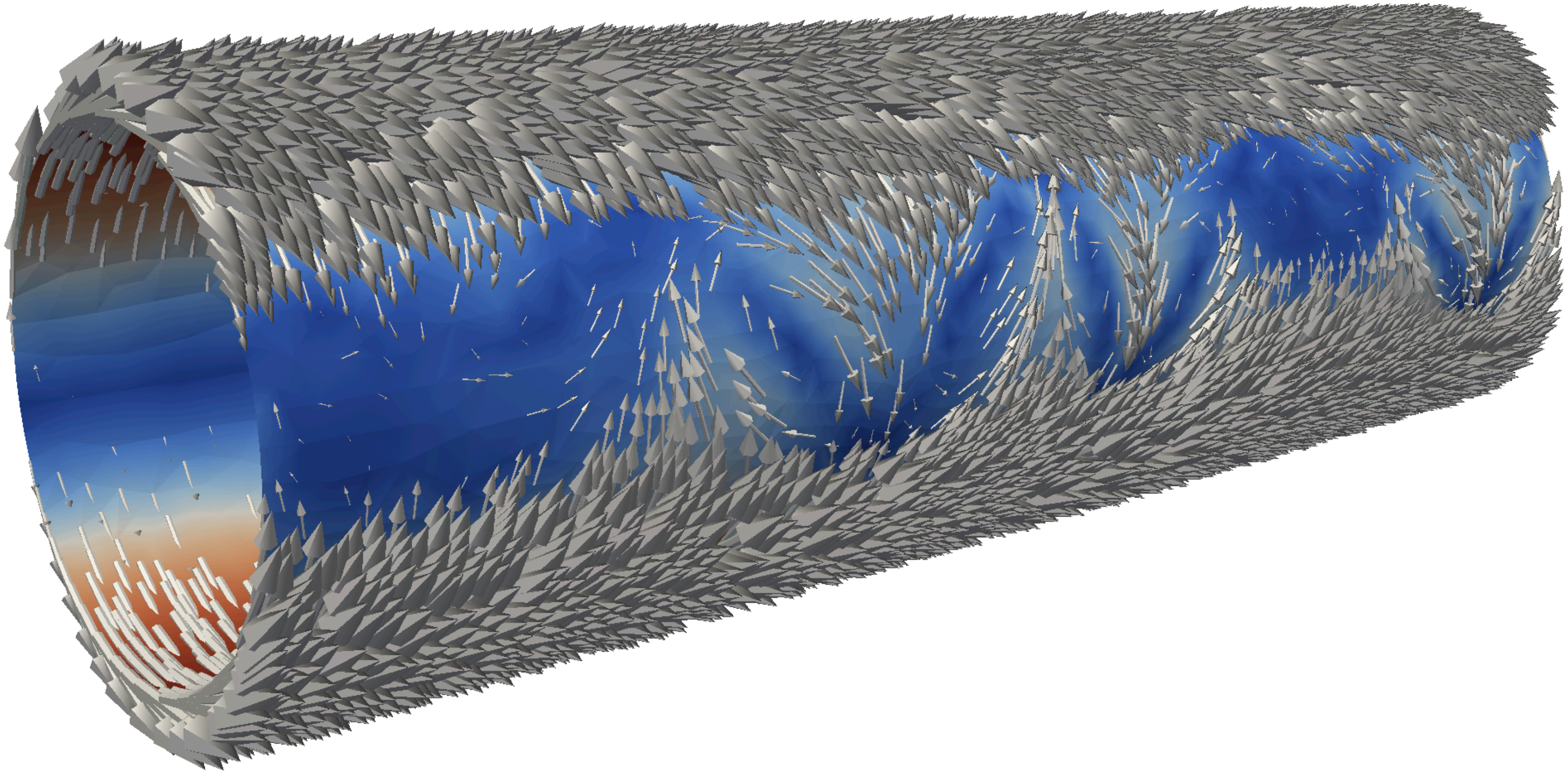
[J.Hoffman/C.Johnson, Springer 07, BIT 08, JMFM 08]

# ROTATIONAL SLIP SEPARATION: COMPUTATION VS EXPERIMENT

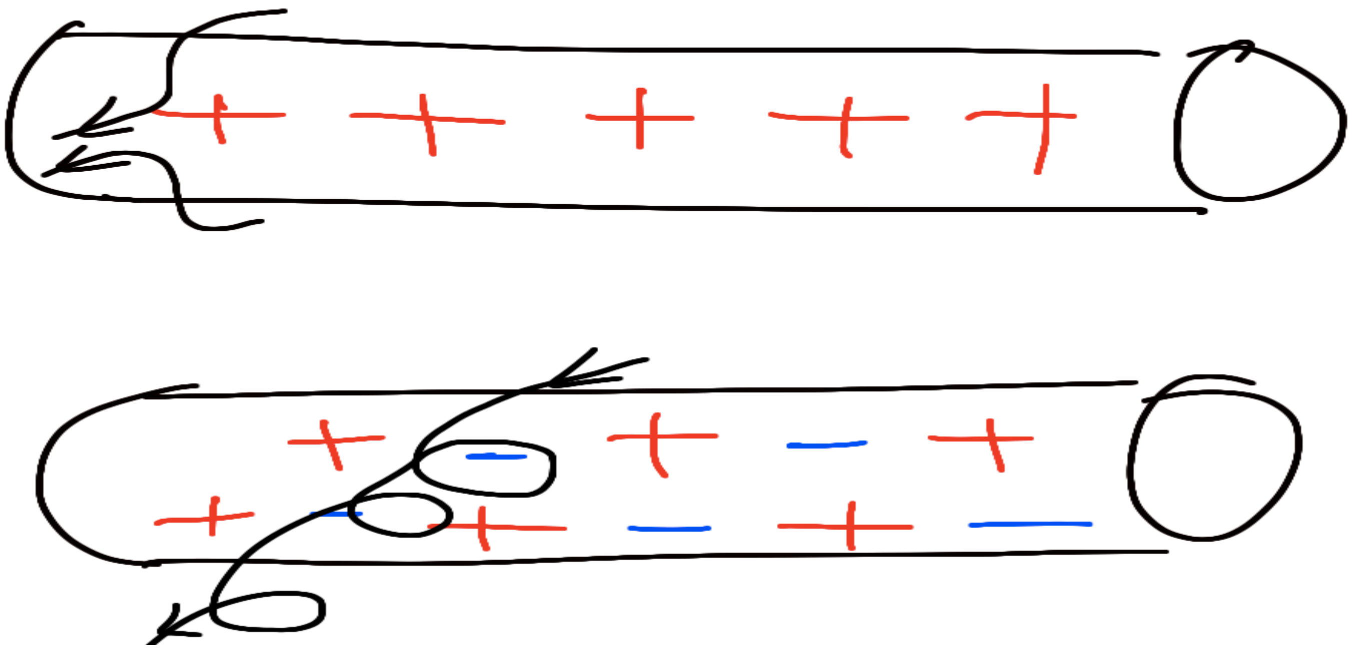




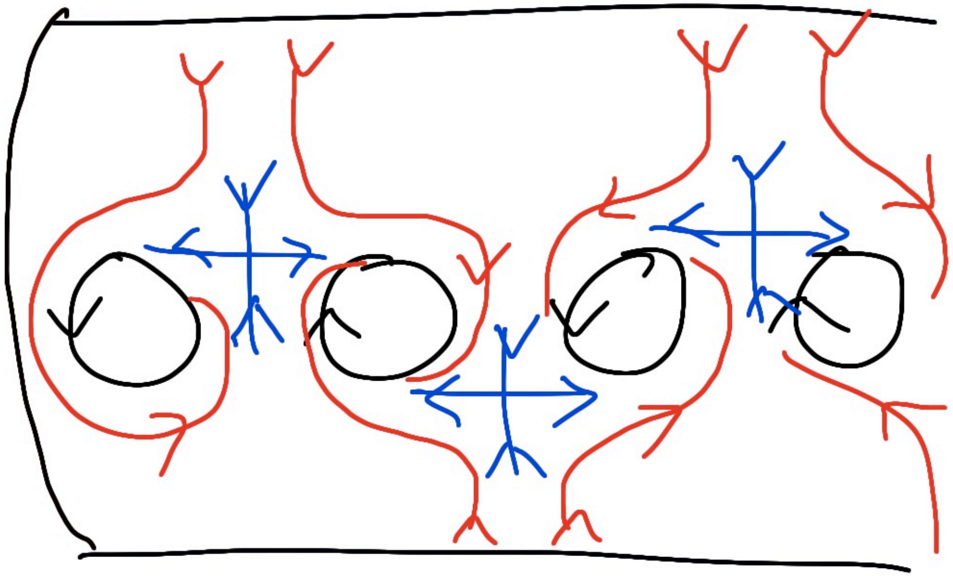
# OPPOSING FLOW: RETARDATION



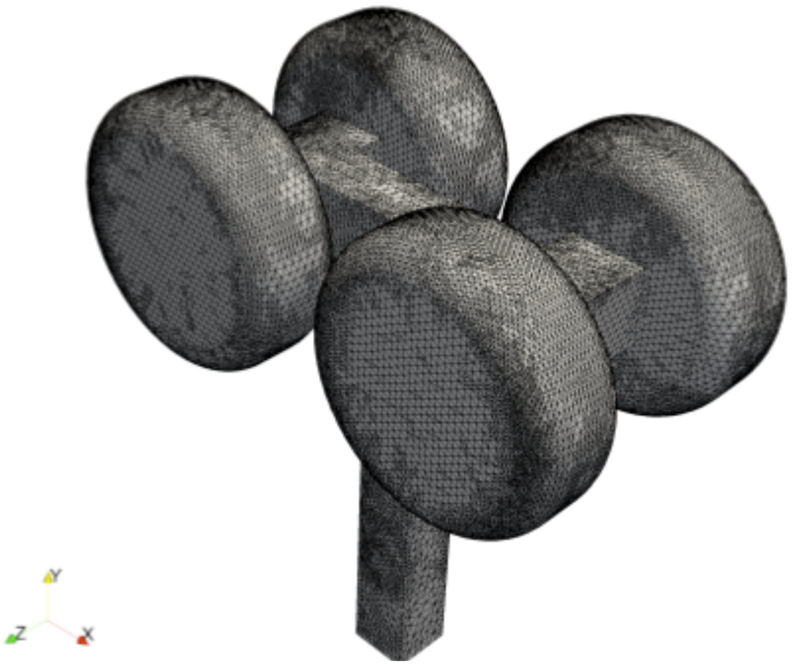
UNSTABLE HIGH PRESSURE REPLACED BY STABLE OSCILLATING PRESSURE PRESSURE ENERGY INTO KINETIC ROTATIONAL ENERGY BY BERNOULLI

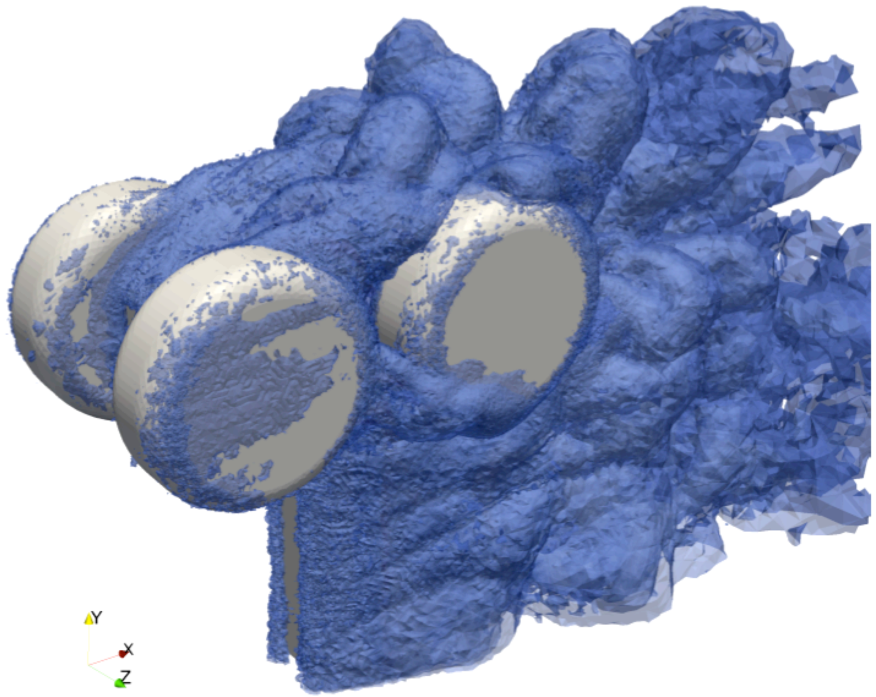


# POT FLOW SEP REPLACED BY
# 3D ROTATIONAL SLIP SEPARATION



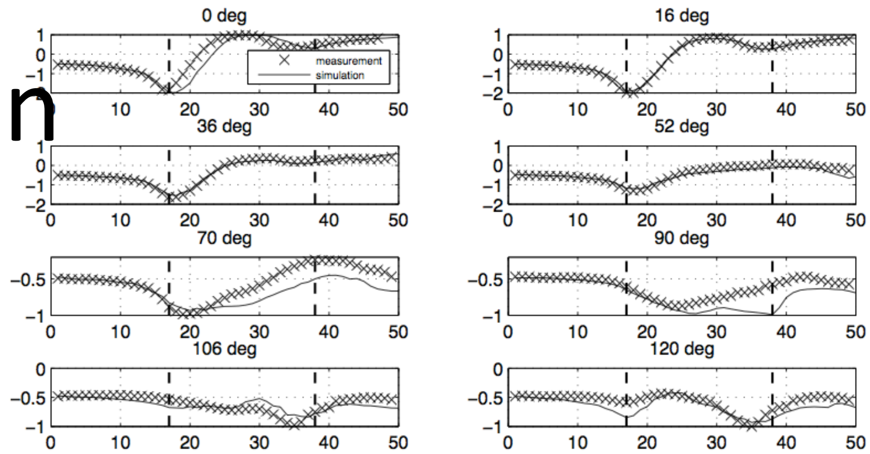
# LANDING GEAR

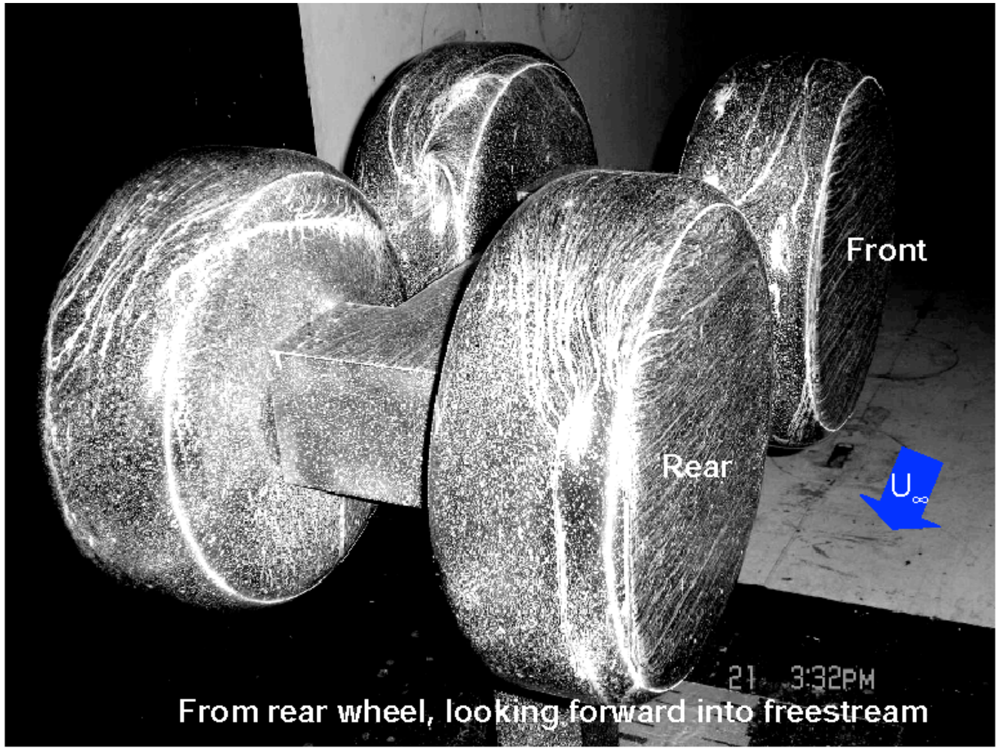


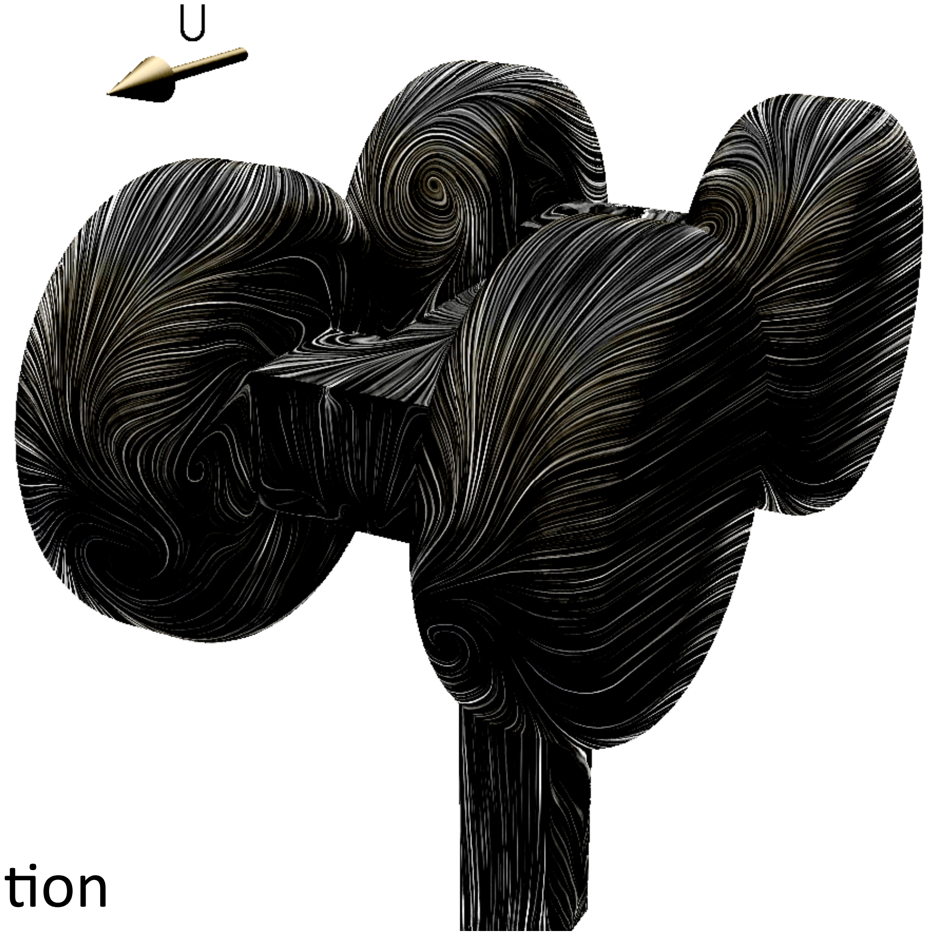



# 3D ROTATIONAL SLIP SEPARATION

# Experiment/Simulation
# - surface pressures
# - oil film visualization

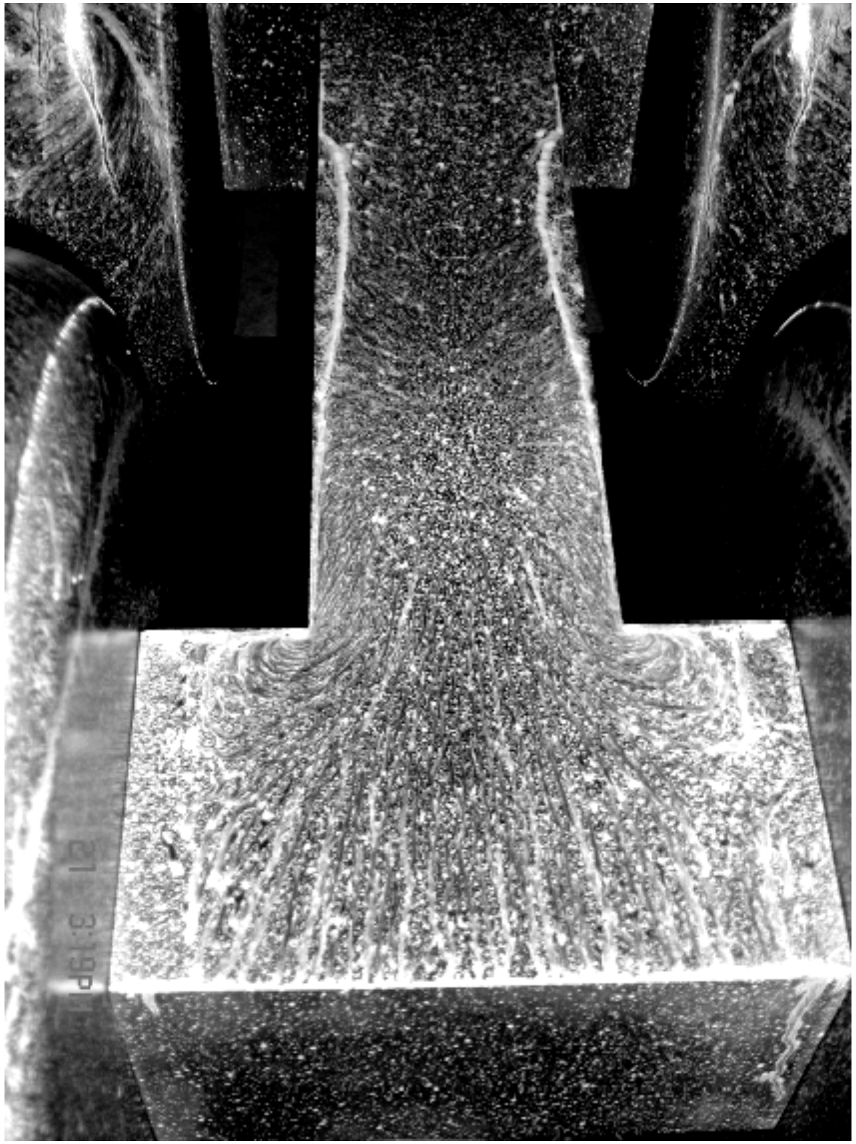


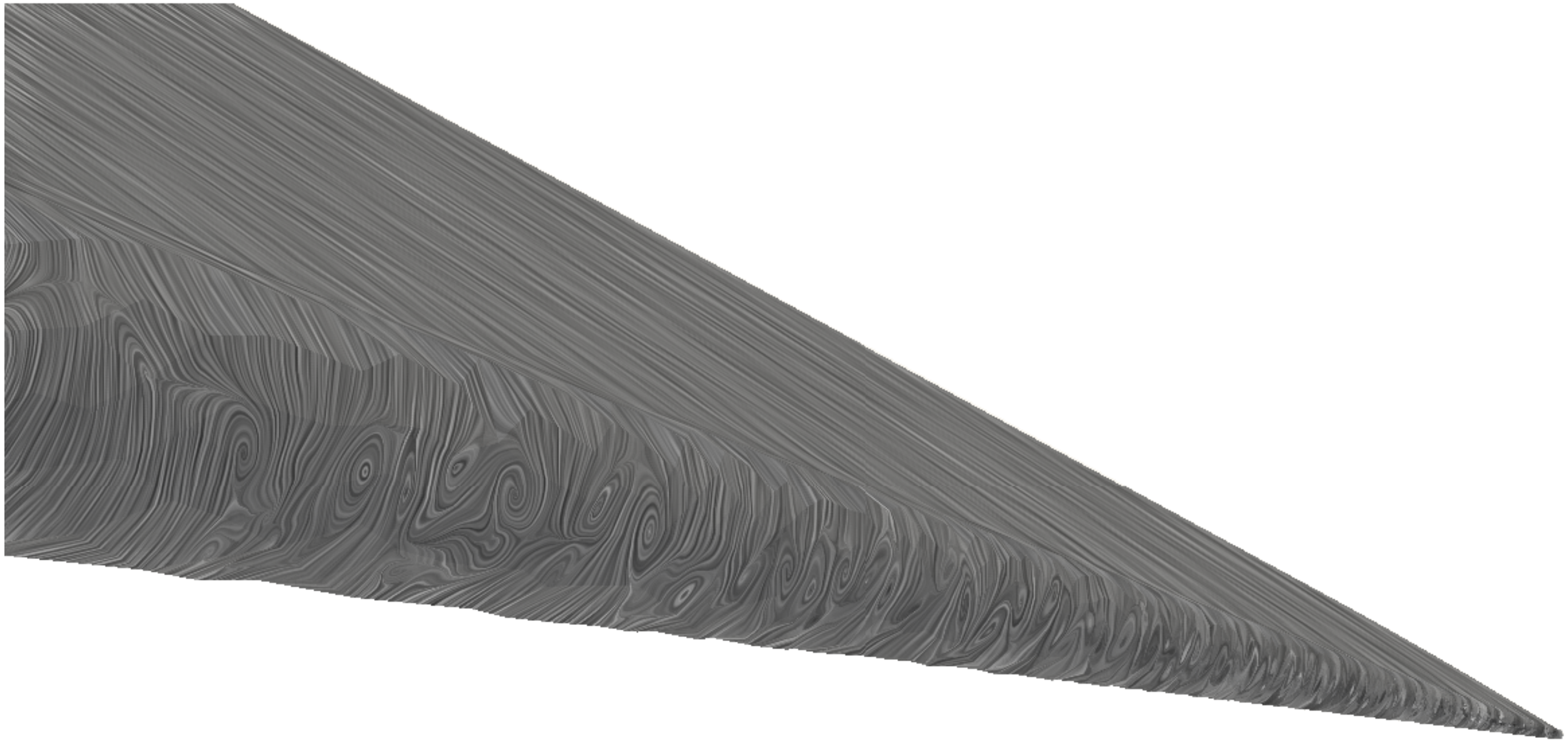




Surface flow separation patterns
No boundary layer - inviscid separation

# Experiment vs Simulation oil film visualization



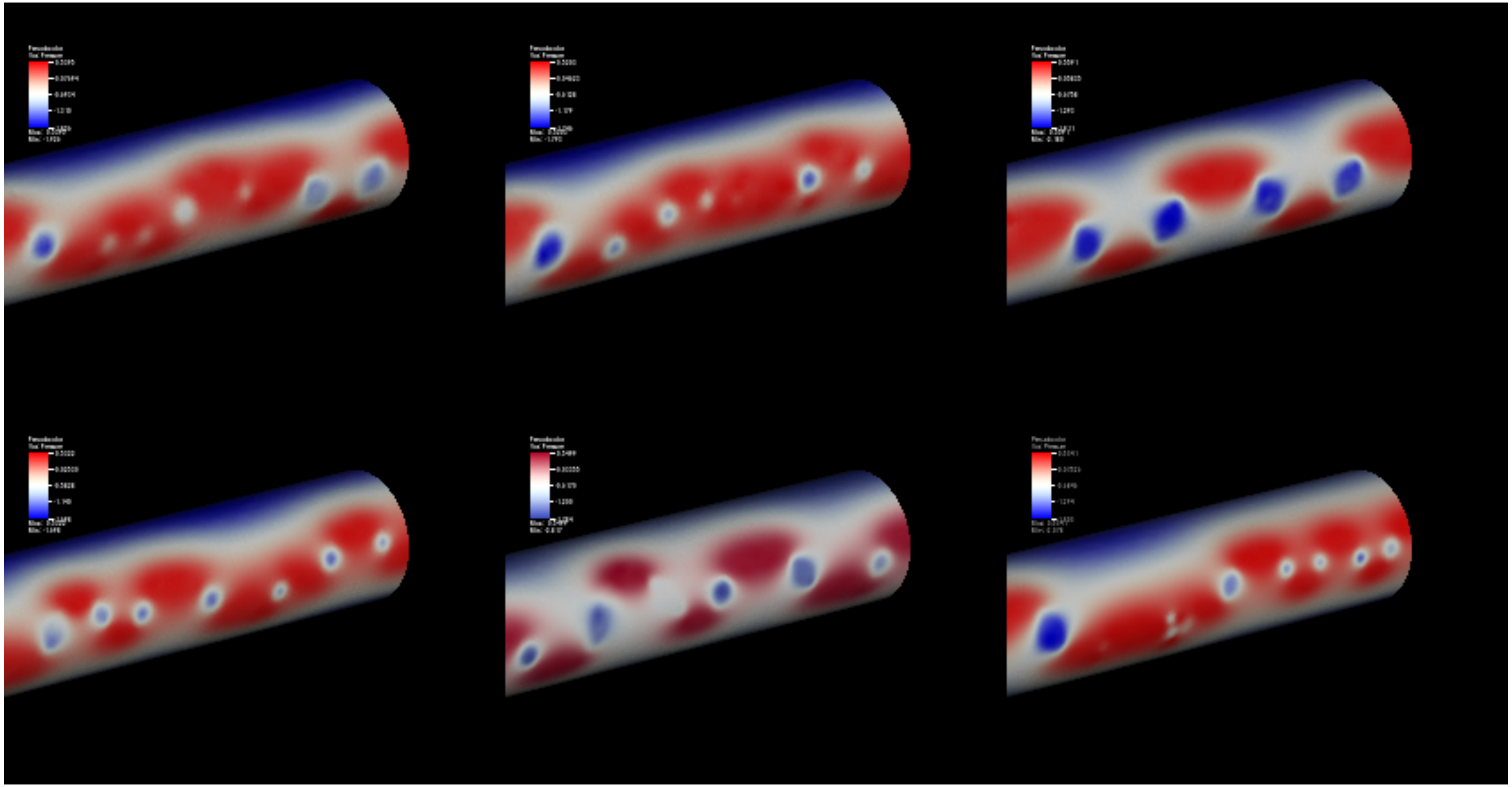
# OILFILM FLOW: TRAILING EDGE
# AOA = 4



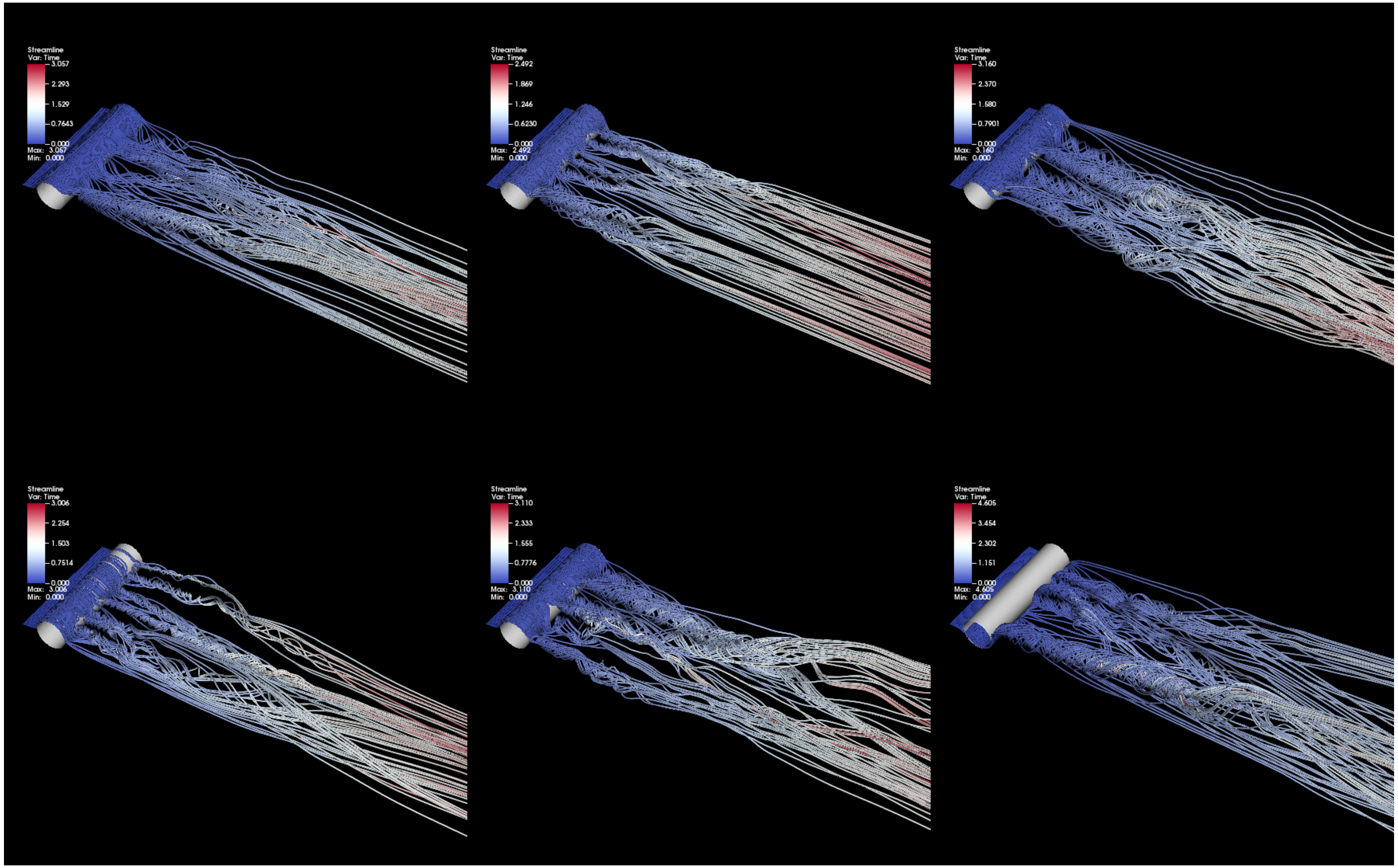
# EFFECT OF

- INCREASING RE?
- DECREASING VISC?
- DECREASING MESH SIZE?

# SURFACE PRESSURE: DRAG: CONST.



# TURBULENT WAKE GETS LONGER



# SWEEP GETS LONGER

# REAL FLOW:
# POTENTIAL FLOW +
# 3D ROTATIONAL SLIP SEPARATION:

- COMPUTABLE
- UNDERSTANDABLE

# 3D ROTATIONAL SLIP SEPARATION
# = ELEGANT SEPARATION

- LARGE SCALE STRUCTURE: COMPUTABLE
- MINIMIZE OPPOSING FLOW INSTABILITY
- ELIMINATE HIGH PRESSURE SEPARATION

- KUTTA CONDITION AT TRAILING EDGE
- SMOOTH ELEGANT SEPARATION
- SECRET OF FLIGHT = ELEGANT SEPARATION

# DRAG AND LIFT OF BLUFF BODY COMPUTABLE + UNDERSTANDABLE

- NEAR FIELD: RESOLVABLE

- FAR FIELD WAKE: NOT RESOLVABLE
- NO INFLUENCE ON SURFACE PRESSURE:
- DRAG + LIFT

# DRAG AND LIFT OF BLUFF BODY COMPUTABLE + UNDERSTANDABLE

- UNDER MESH REFINEMENT:

- TOTAL TURBULENT DISSIPATION: CONSTANT
- DRAG - SURFACE PRESSURE: CONSTANT

- LOCAL TURB DISSIPATION DECREASES
- SWEEP GETS LONGER

# DRAG QUEEN

# SLIP = SKIN FRICTION = 0

- SLIP
- FORCE BOUNDARY CONDITION
- NEUMANN CONDITION

- FORCE KNOWN: SKIN FRICTION = SMALL

- WE BREAK THE DICTATE BY PRANDTL TO USE NO-SLIP: HERESY!

OBSERVE SMALL SKIN FRICTION:

USE SLIP:

DISCOVER: NO BOUNDARY LAYERS

- OBSERVATION
- NOT HYPOTHESIS

# WE DO NOT SAY THAT THERE ARE NO BOUNDARY LAYERS

- WE SIMPLY DON'T TALK ABOUT THEM!
- OCKHAMS RAZOR: WE DON'T NEED THEM

- WE DO NOT SPEAK ABOUT GHOSTS
- WE DO NOT SAY THAT THEY DO NOT EXIST
- WE DON'T NEED THEM

# DFS BLUFF BODY FLOW POSSIBLE:
# REAL FLIGHT SIMULATOR POSSIBLE

# REAL NS SAILING SIMULATOR

# SOME REFERENCES 2013


- J.Hoffman, J.Jansson, R.Vilela de Abreu, C.Degirmenci, N.Jansson, K.Müller, M.Nazarov and J.Hiromi Spühler, Unicorn: parallel adaptive finite element simulation of turbulent flow and fluid-structure interaction for deforming domains and complex geometry, Computer and Fluids, Vol.80, pp.310-319, 2013.
- R.Vilela de Abreu, J.Hoffman and N.Jansson, Towards the development of adaptive finite element methods for aeroacoustics, submitted
- J.Jansson, J.Hoffman and N.Jansson, Simulation of 3d unsteady incompressible flow past a NACA 0012 wing section, submitted
- J.Hoffman, J.Jansson and C.Johnson, New Theory of Flight, submitted
- J.Jansson, N.C.Degirmenci and J.Hoffman, Framework for adaptive fluid-structure interaction with industrial applications, Int. J. Materials Engineering Innovation, in press.
- M.Nazarov and J.Hoffman, Residual based artificial viscosity for simulation of turbulent compressible flow using adaptive finite element methods, Int. J. Num. Methods Fluids, Vol.71(3), pp.339-357, 2013.

# CJ ON LINE

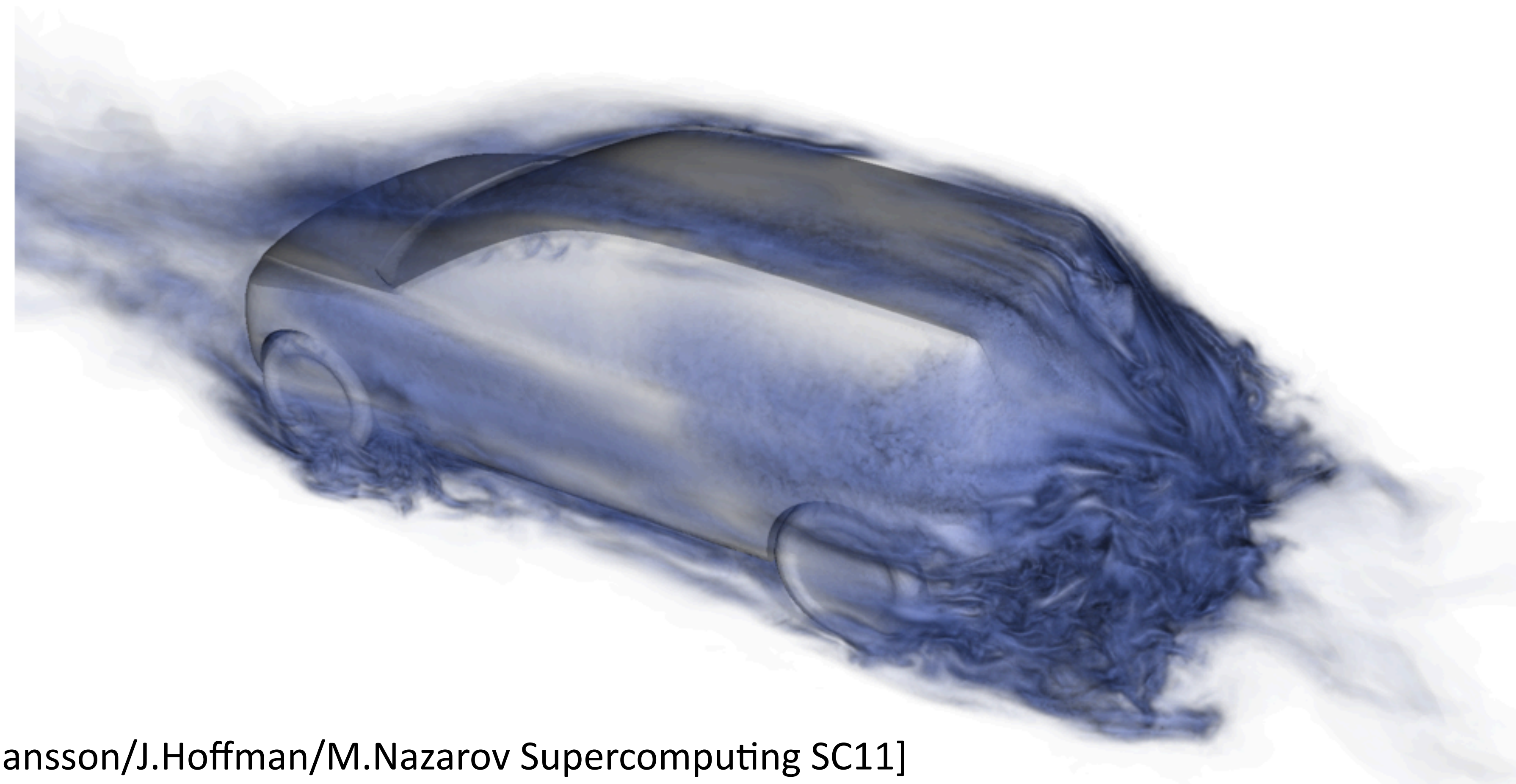
- http://claesjohnson.blogspot.se

- MATHEMATICAL SIMULATION TECHNOLOGY
- WORLD AS COMPUTATION
- SECRET OF FLIGHT
- COMPUTATIONAL BLACKBODY RADIATION
- BOOKS

# DUAL SOLUTION: SENSITIVITY

## Dual solution

The solution charaterize sensitivty in the output (drag)



[N.Jansson/J.Hoffman/M.Nazarov Supercomputing SC11]

# DUAL SOLUTION: SENSITIVITY