WE'VE OUTGROWN THE WIND TUNNEL

An industrial perspective on high Reynolds number aerodynamics

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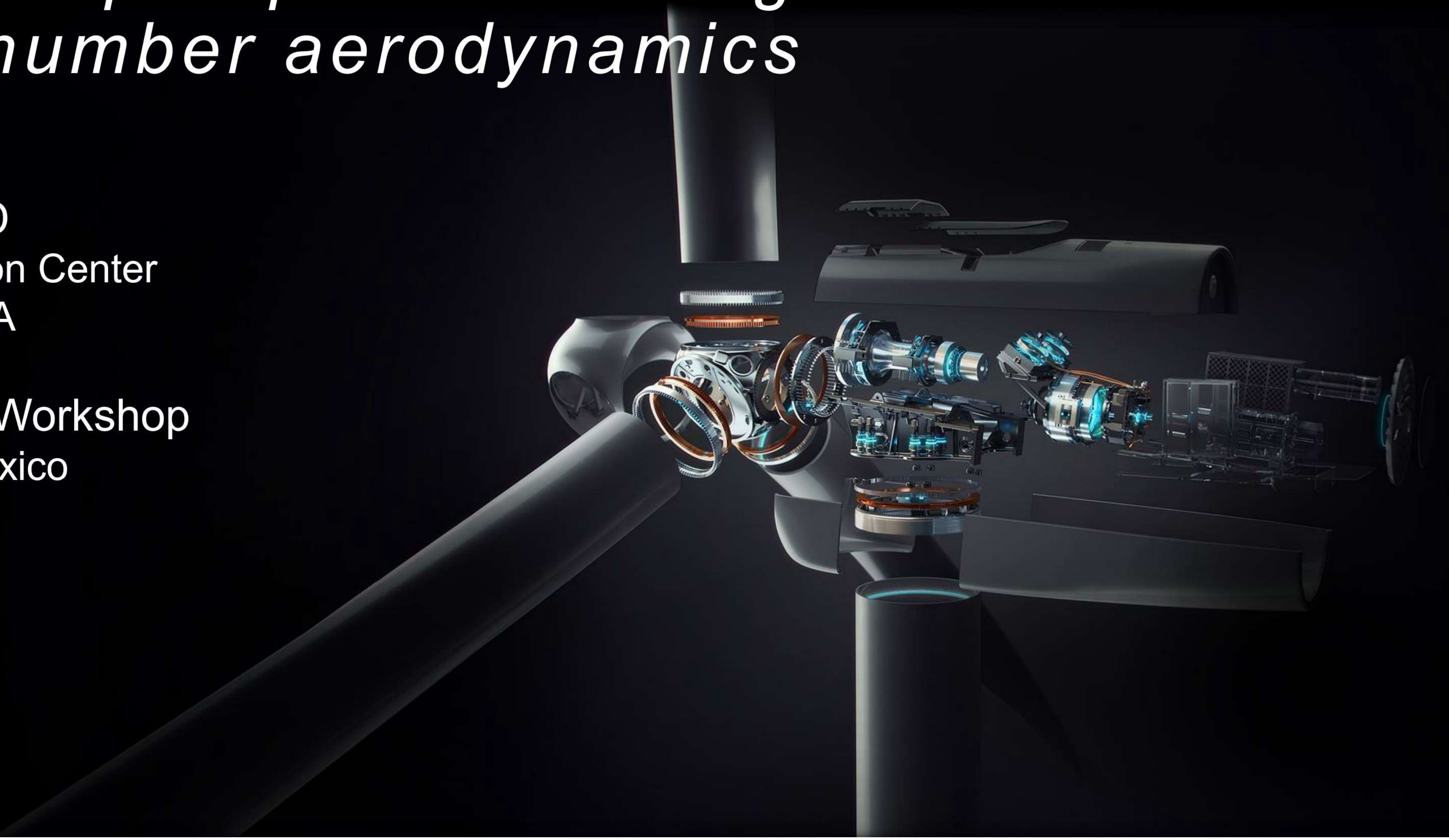
Albuquerque, New Mexico



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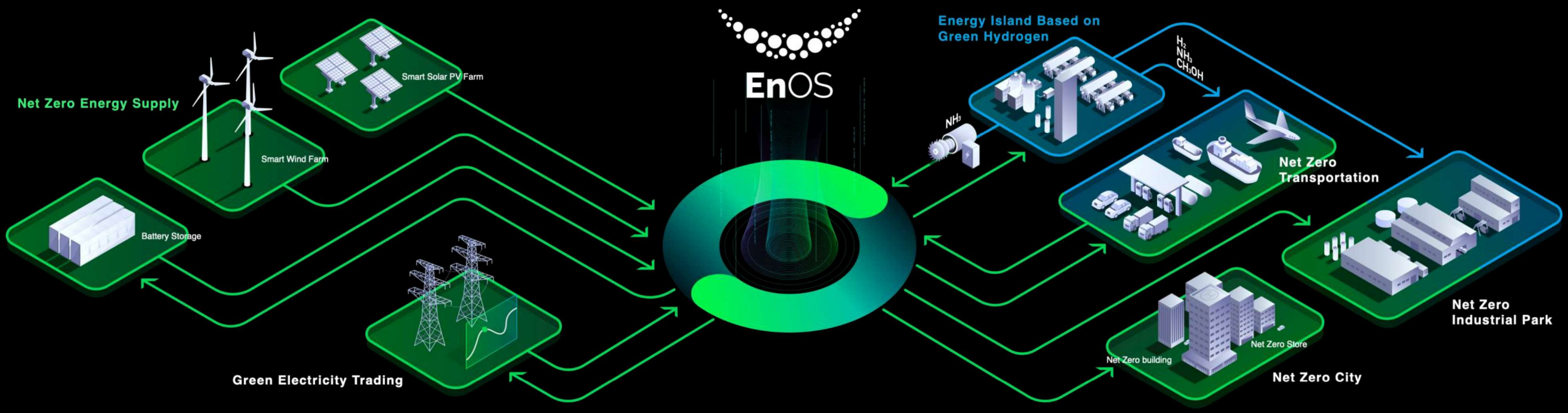
"We don't sell high-Reynolds number aerodynamics."

--Eddie Mayda, 2024

Envision Energy ***does*** sell wind turbines with large blades that experience high Reynolds numbers.

We can't let the unknowns of high Reynolds number aerodynamics stop us.

Envision is a leader in achieving a Global Net Zero Transition



20+ R&D and operation centers

50+ Manufacture bases

50%+ International talents

Innovation Center

Global Innovation
CenterSilkeborg, Denmark

Global Gearbox Innovation Center
Dortmund, Germany

Global Drivetrain Innovation Center
Dortmund, Germany

Global Engineering Center of Excellence
Hamburg, Germany

Global Blade Innovation Center
Colorado, US

Global Green Hydrogen Innovation Center
Boston, US

Solar Innovation Center
San Jose, US

Envision Racing
London, UK

Envision-Hongshan Carbon-Neutral Fund
Wuxi, China

China R&D & Operation HQ
Shanghai, China

Operation Center

Bahia Blanca, Argentina
Paris, France
California, USA
London, UK
Santiago, Chile
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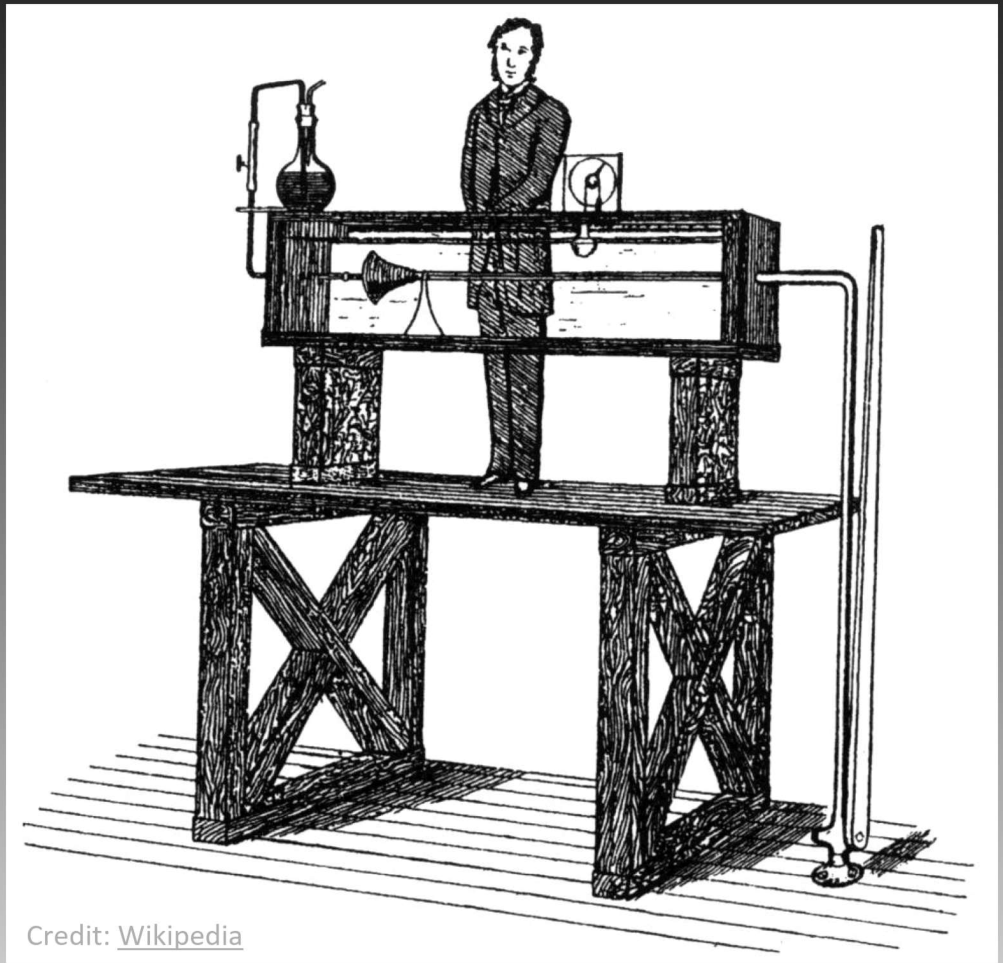
Bangalore, India
Jakarta, Indonesia
Mexico City, Mexico

Let’s talk Reynolds Number



Osborn Reynolds' experiment on fluid dynamics in pipes circa 1883

$$Re_c = \frac{\rho V c}{\mu} \approx 3 \times 10^6$$

is *relatively* easy to achieve in a wind tunnel

Outline

- Industry trends
- Why is Reynolds number important?
- Airfoil design
- How have we “outgrown” the wind tunnel?
- High-Re polars for use in turbine simulations

Industry trends

$$Re_c = \frac{\rho V c}{\mu}$$

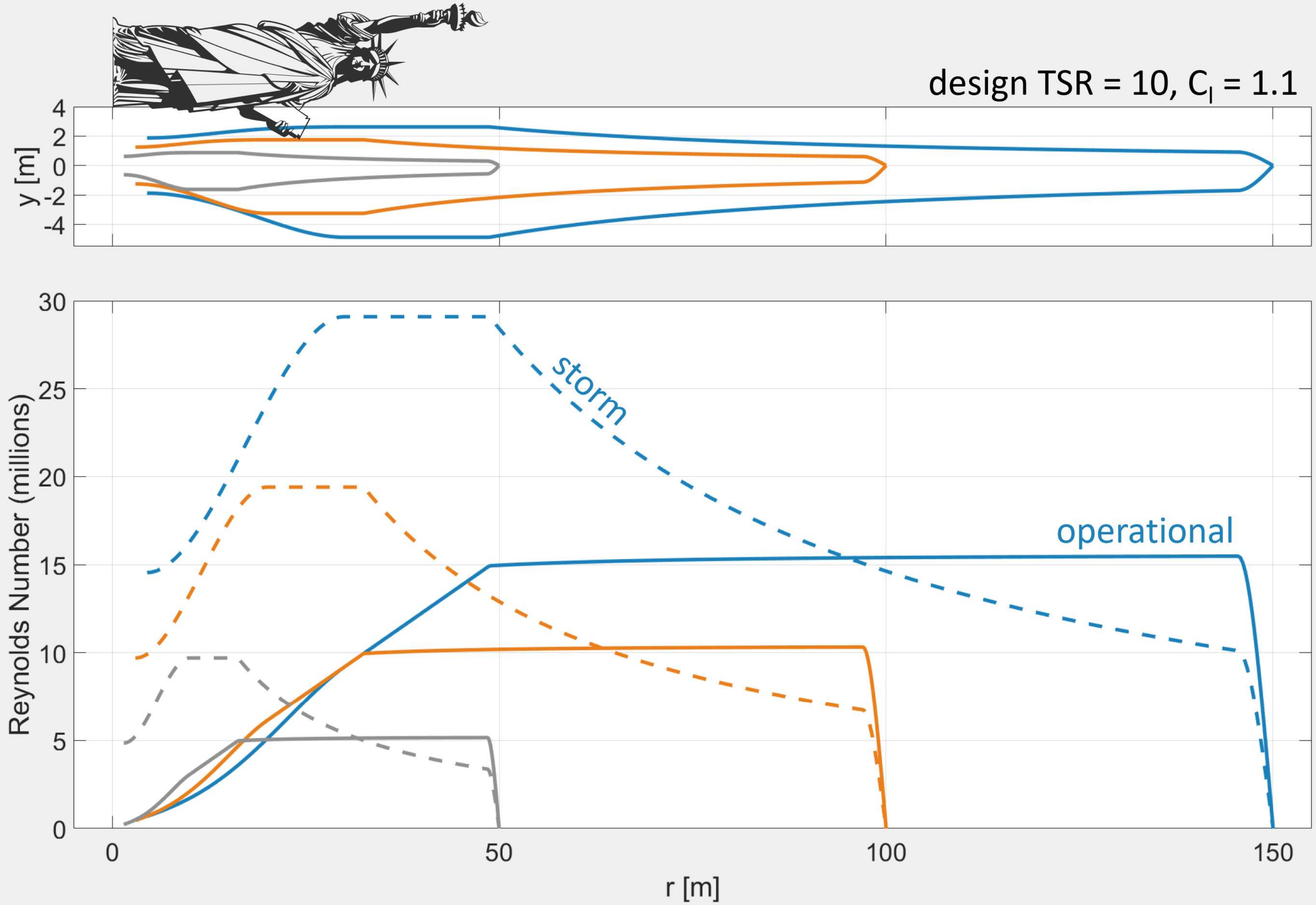
Geometry

↑ Rotor diameter

↑ Chord length (BEM)

Local wind speed

- Operational tip speed ~90 m/s
- Storm ~57 m/s

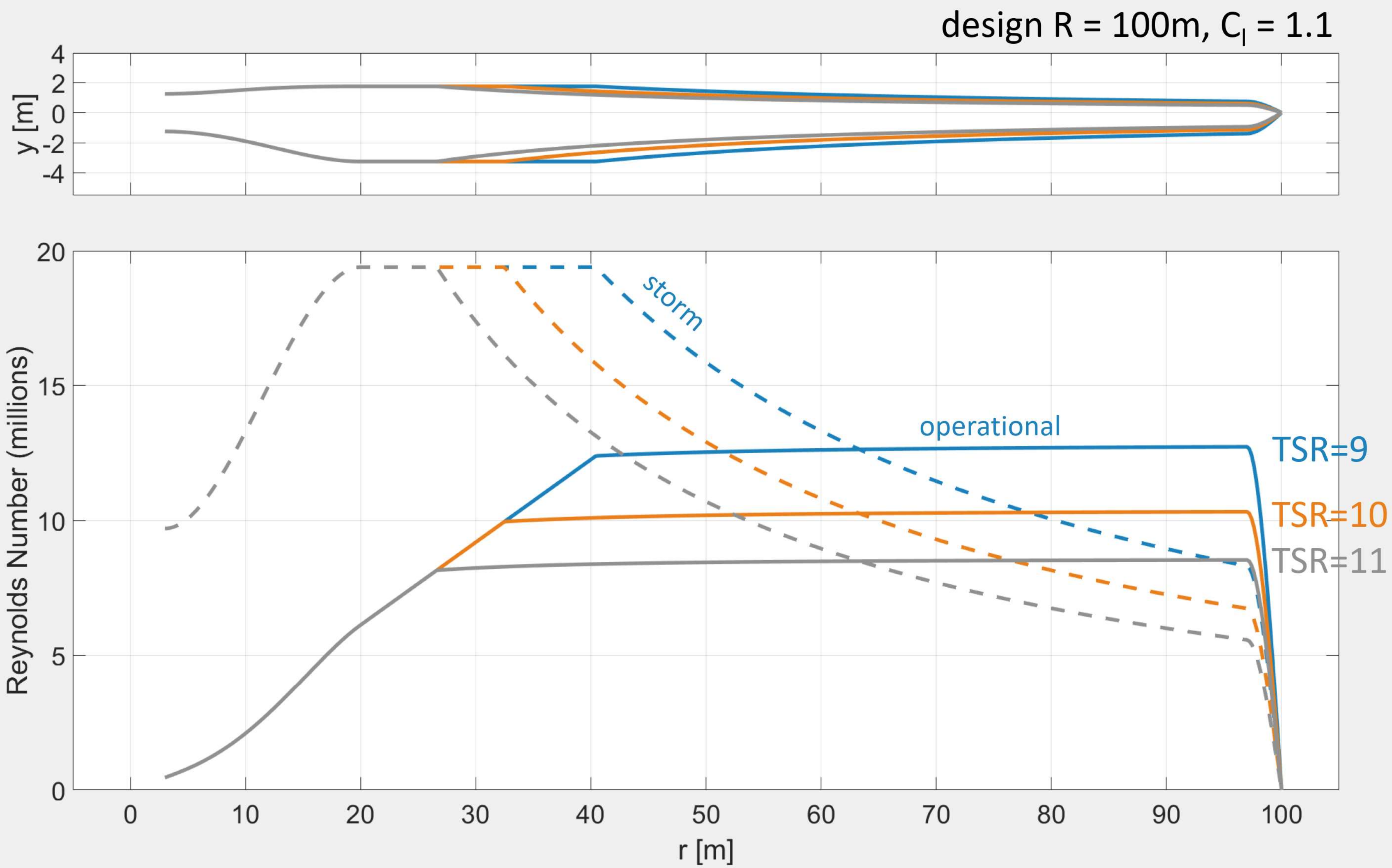


Industry trends

$$Re_c = \frac{\rho V c}{\mu}$$

Geometry

- Design trends
  - ↑ Higher TSR
  - ↓ Low induction
- Lead to
  - ↓ Reduced chord length



Why is Reynolds number important?

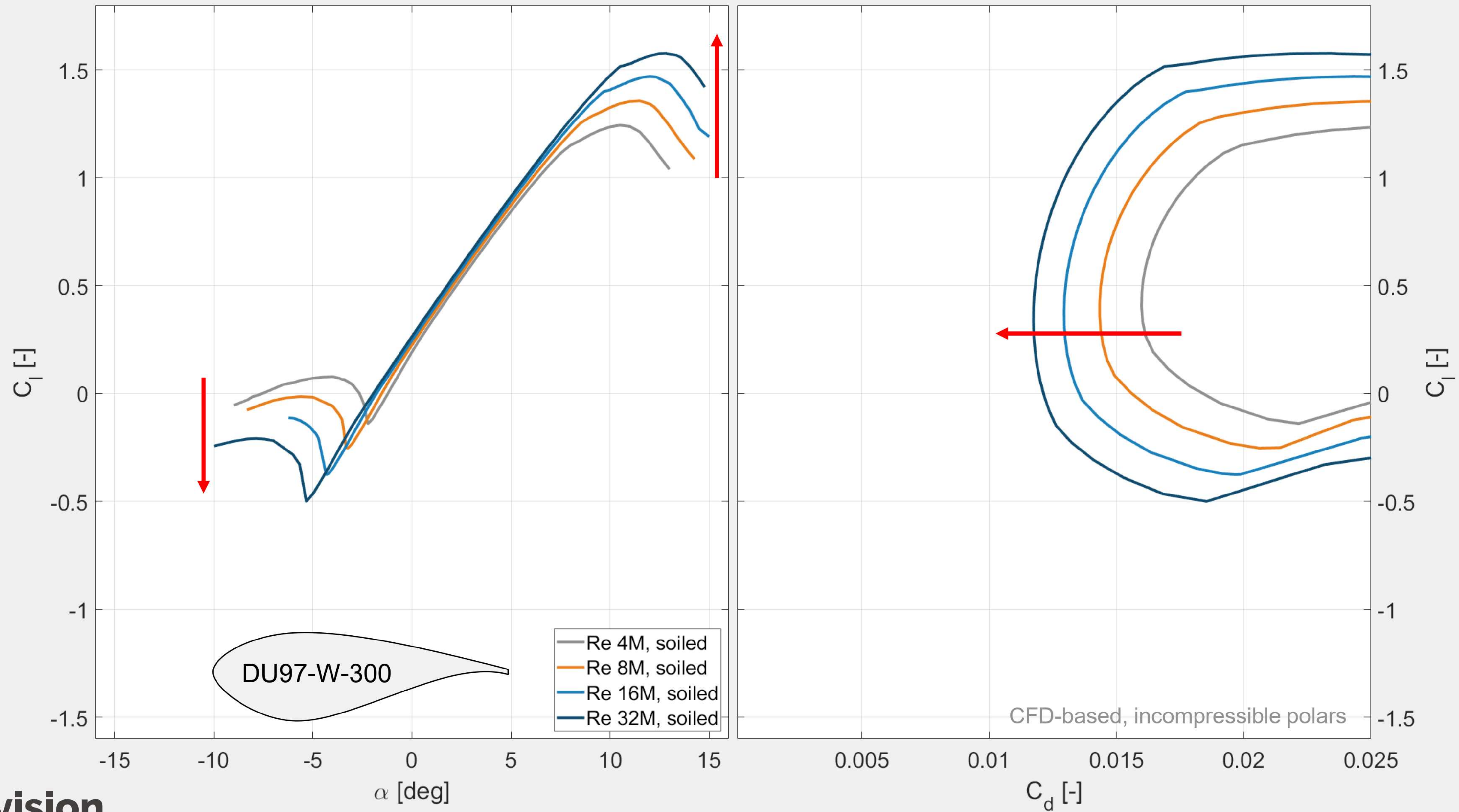
Power Production
- Reduced C_d → higher L/D
- Reduced lift sensitivity to leading-edge roughness
- Harder to achieve laminar flow

Turbine Loads
- Variation of maximum/minimum C_l
- Unsteady aerodynamics

Airfoil Design
- Utilize the benefits (L/D and sensitivity to roughness)
- Address the challenges (laminar flow and max/min lift)

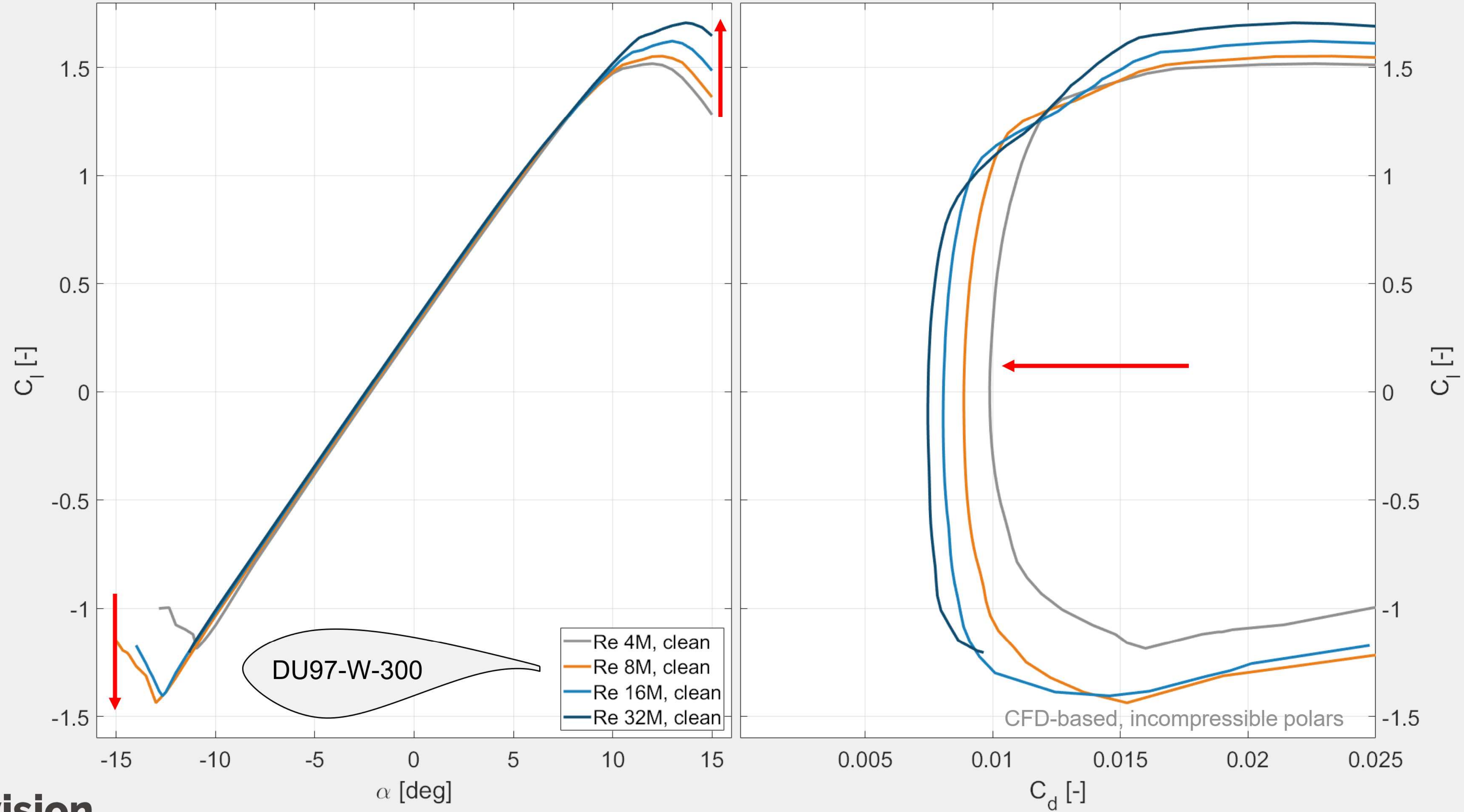
Reynolds effects

Reduced C_d, Variability of Max/Min C_l (Rough LE)



Reynolds effects

Reduced C_d, Variability of max/min C_l (Clean)



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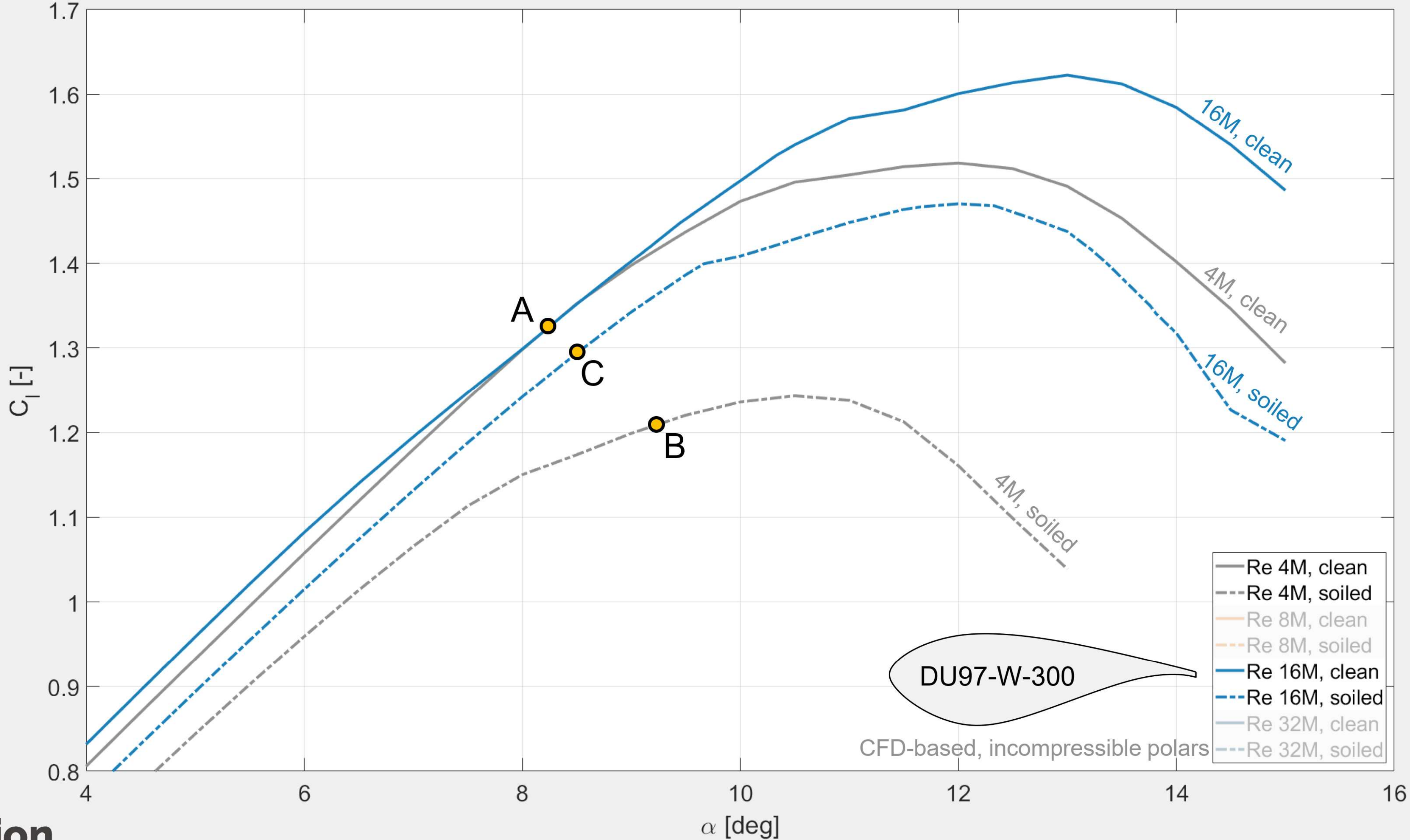
Reynolds effects

Reduced lift sensitivity to leading-edge roughness



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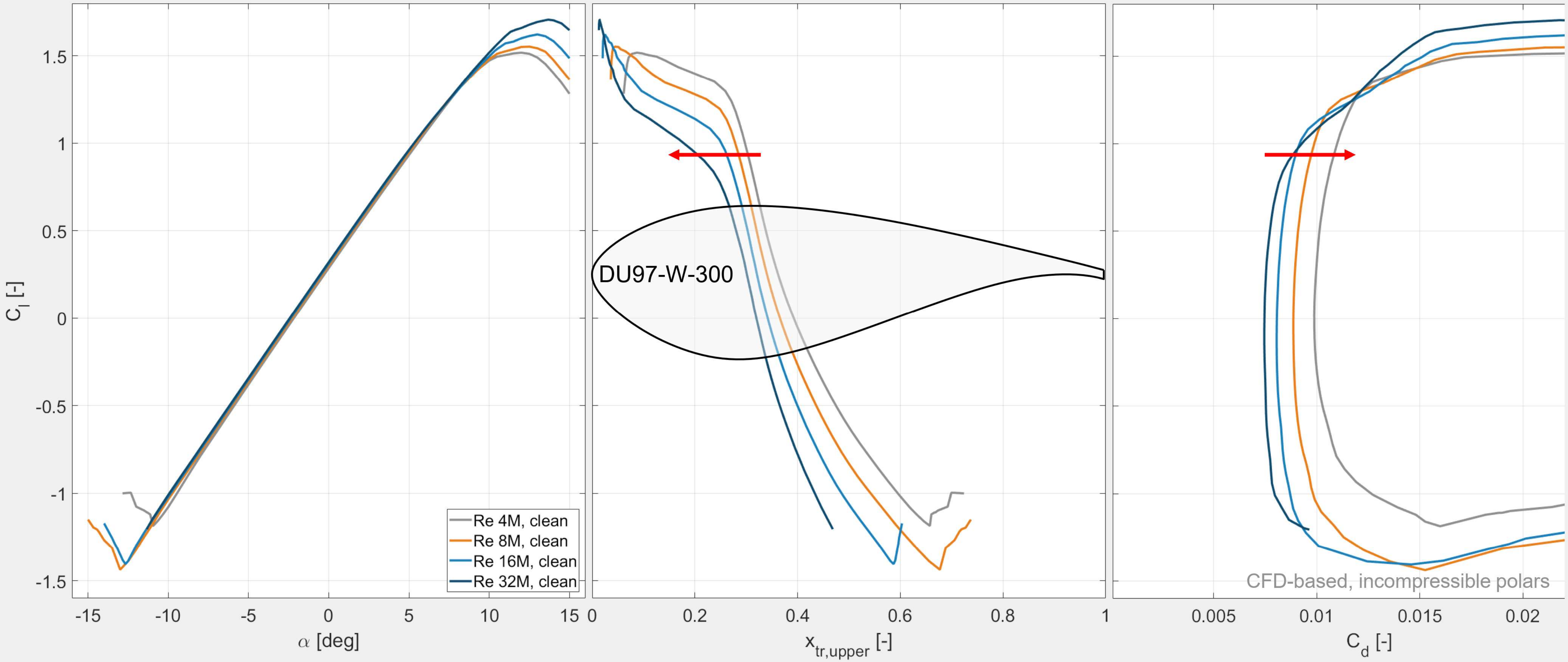
Reynolds effects

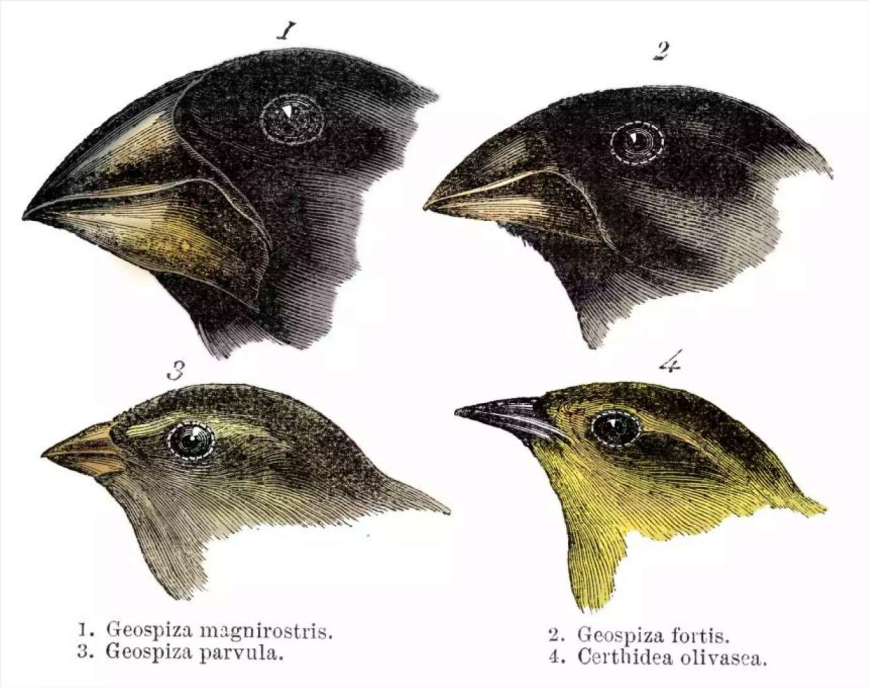
Harder to achieve laminar flow



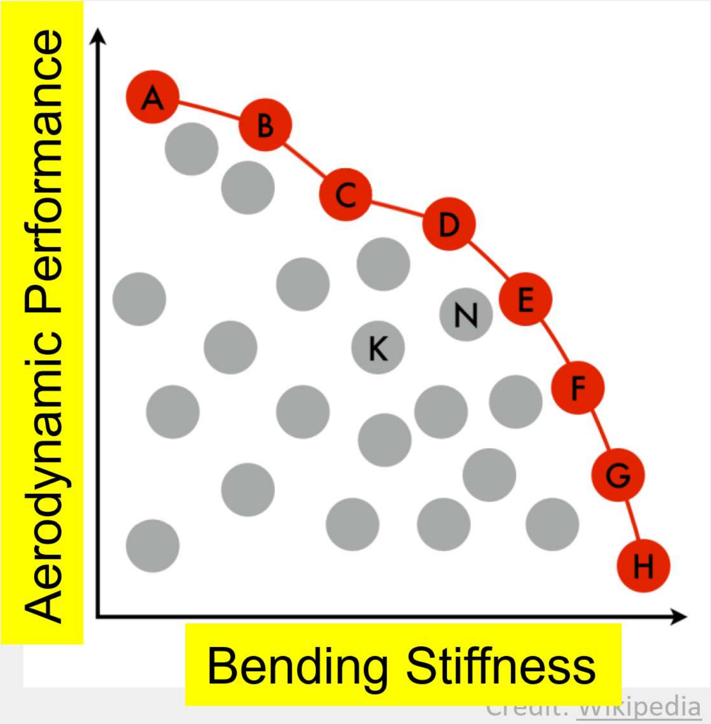
Airfoil Design

Genetic algorithm optimization

- It may be slow… but it's robust
- And airfoil design is a multi-objective problem



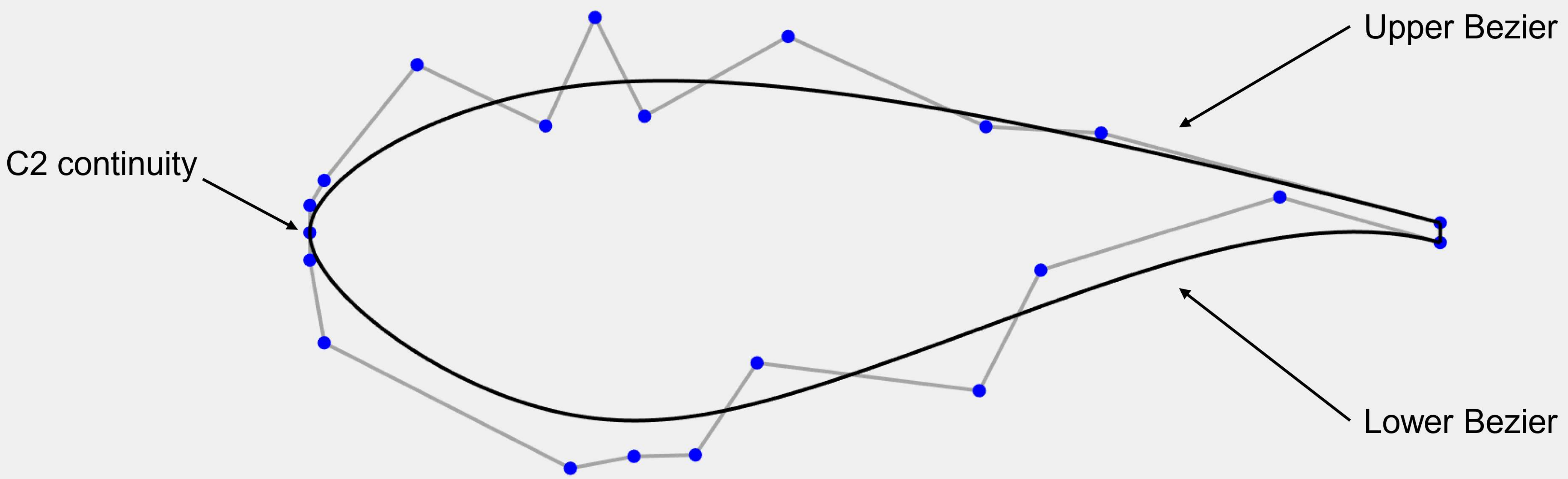
Credit: ThoughtCo.



Credit: Wikipedia

Airfoil Design

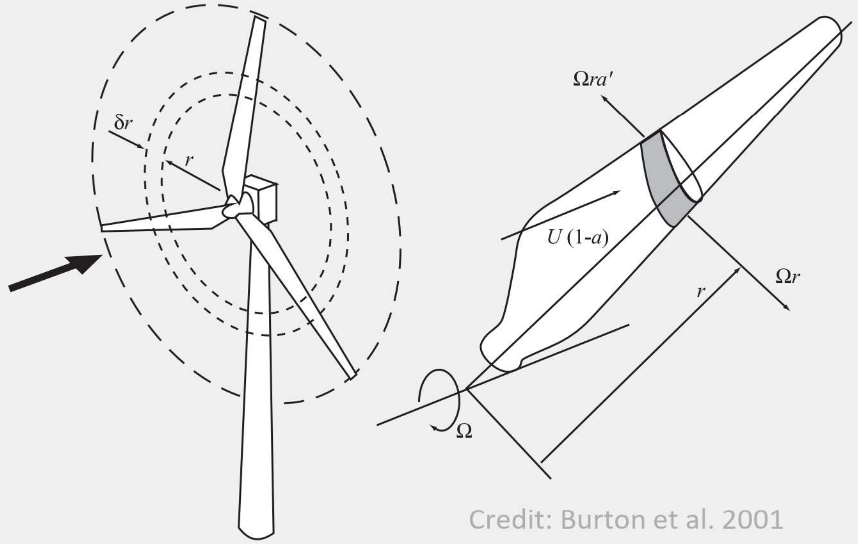
Geometric DNA



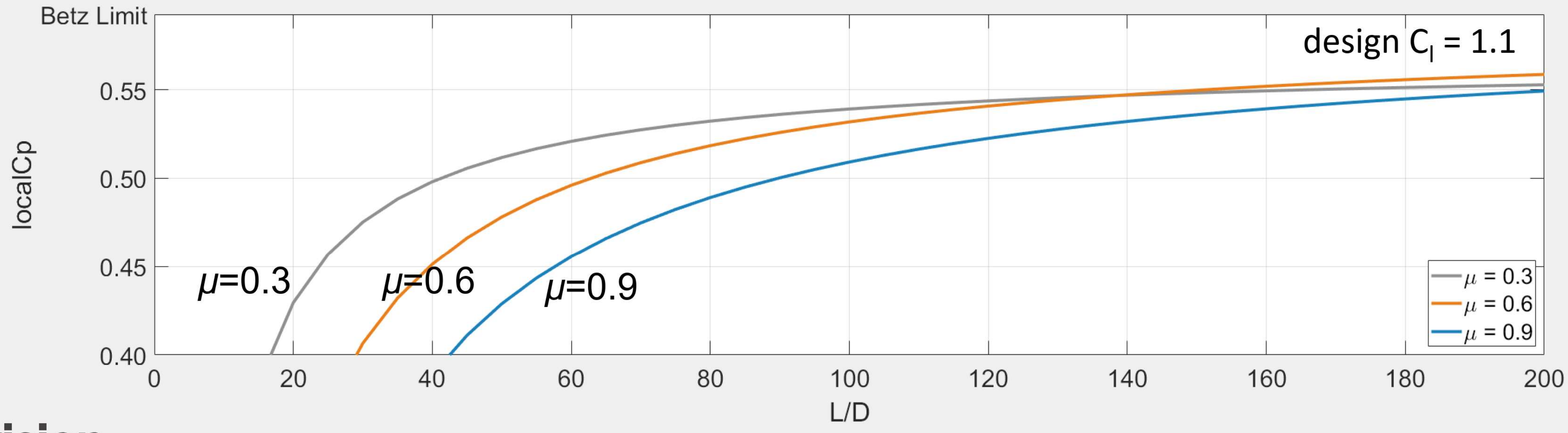
Airfoil Design

BEM-based performance metric

- Xfoil with inhouse modifications
- Clean (e^N transition) and turbulent cases
- Consider multiple Reynolds numbers
- AeroDyn simulations with turbulent wind



Credit: Burton et al. 2001



Airfoil Design

New Airfoils = New Technology

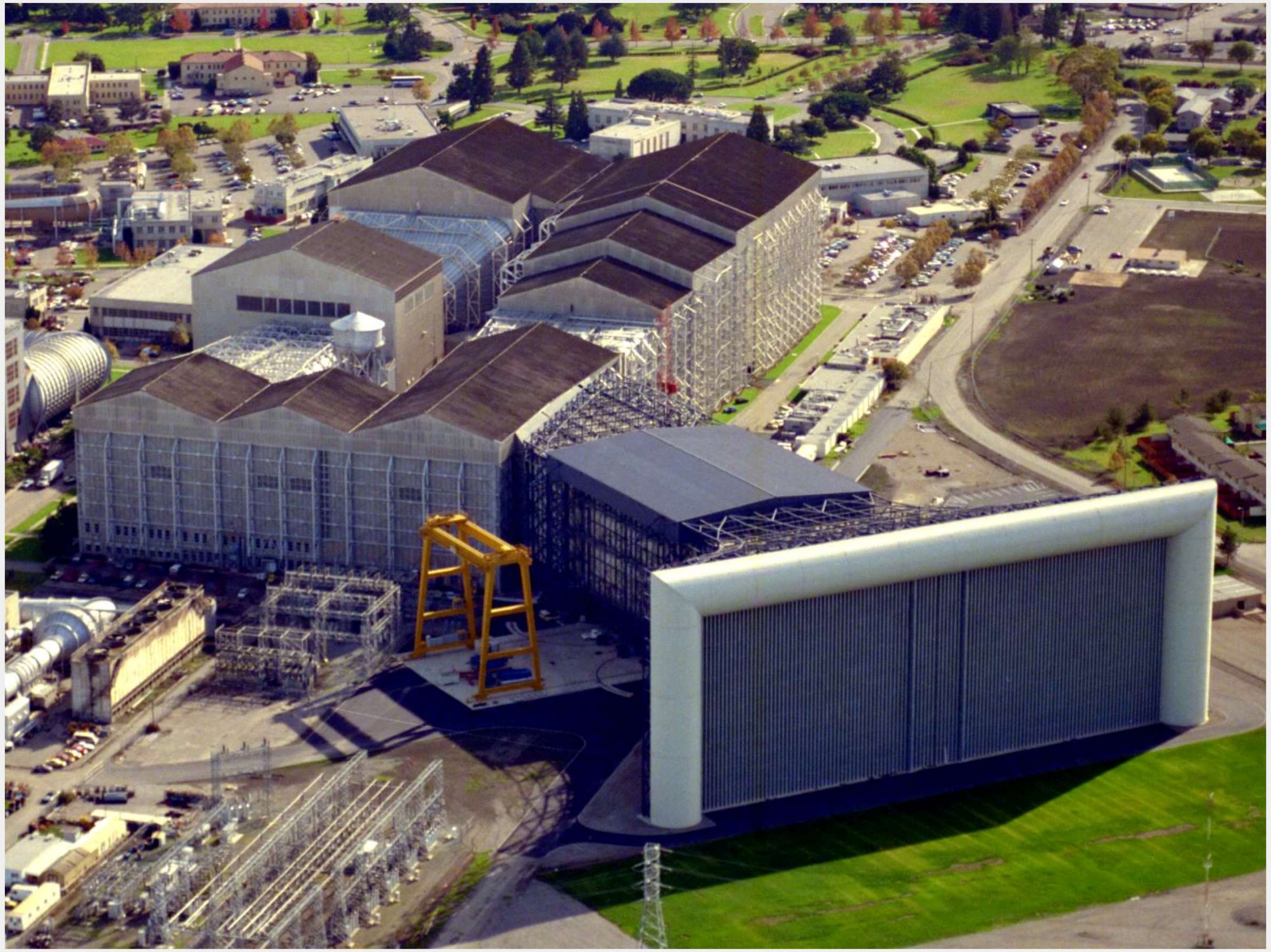
↓

New Technology requires Derisking

↓

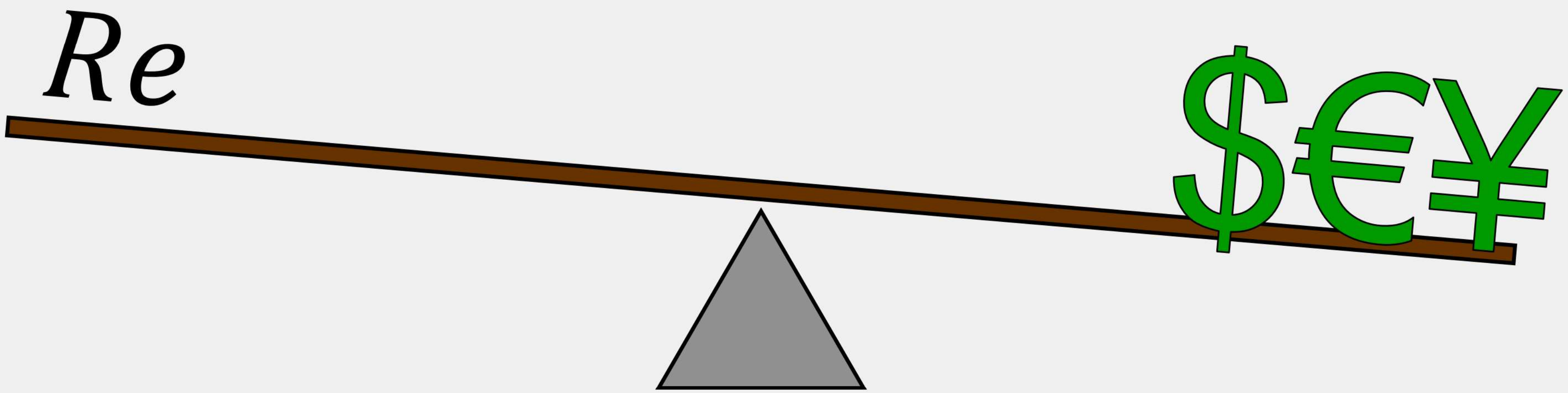
Wind Tunnel Validation

How have we "outgrown" the wind tunnel?



Credit: NASA

How have we "outgrown" the wind tunnel?



"There ain't no such thing as a free lunch"

↓

And the wind industry's pockets are not as deep as those of defense contractors or national space programs

↓

We test at the highest possible Reynolds number that we can afford

Pursuing higher wind tunnel Reynolds numbers

Wind speed

$$Re_c = \frac{\rho V c}{\mu}$$

"Simple"… more wind!

- $ More power, bigger fan(s)
- $ More cooling
- $ Stronger model mount
- ? Compressibility effects

Pursuing higher wind tunnel Reynolds numbers

Model chord length

$$Re_c = \frac{\rho V c}{\mu}$$

Seems simple…

- More chord!
  - $ Bigger model
  - $ Bigger test section
  - $ Stronger model mount
  - ? Blockage effects
  - ? Aspect ratio effects

Pursuing higher wind tunnel Reynolds numbers

Air density (and viscosity)

$$Re_c = \frac{\rho V c}{\mu}$$

Getting exotic… more density!

- $ Pressurized flow path
- $ Smaller, specialized model
- $ Longer cycle time
- ? Model add-ons (VGs in particular)

Credit: DLR

How do we process our wind tunnel data?

Reynolds number transformation

Credit: openclipart.org

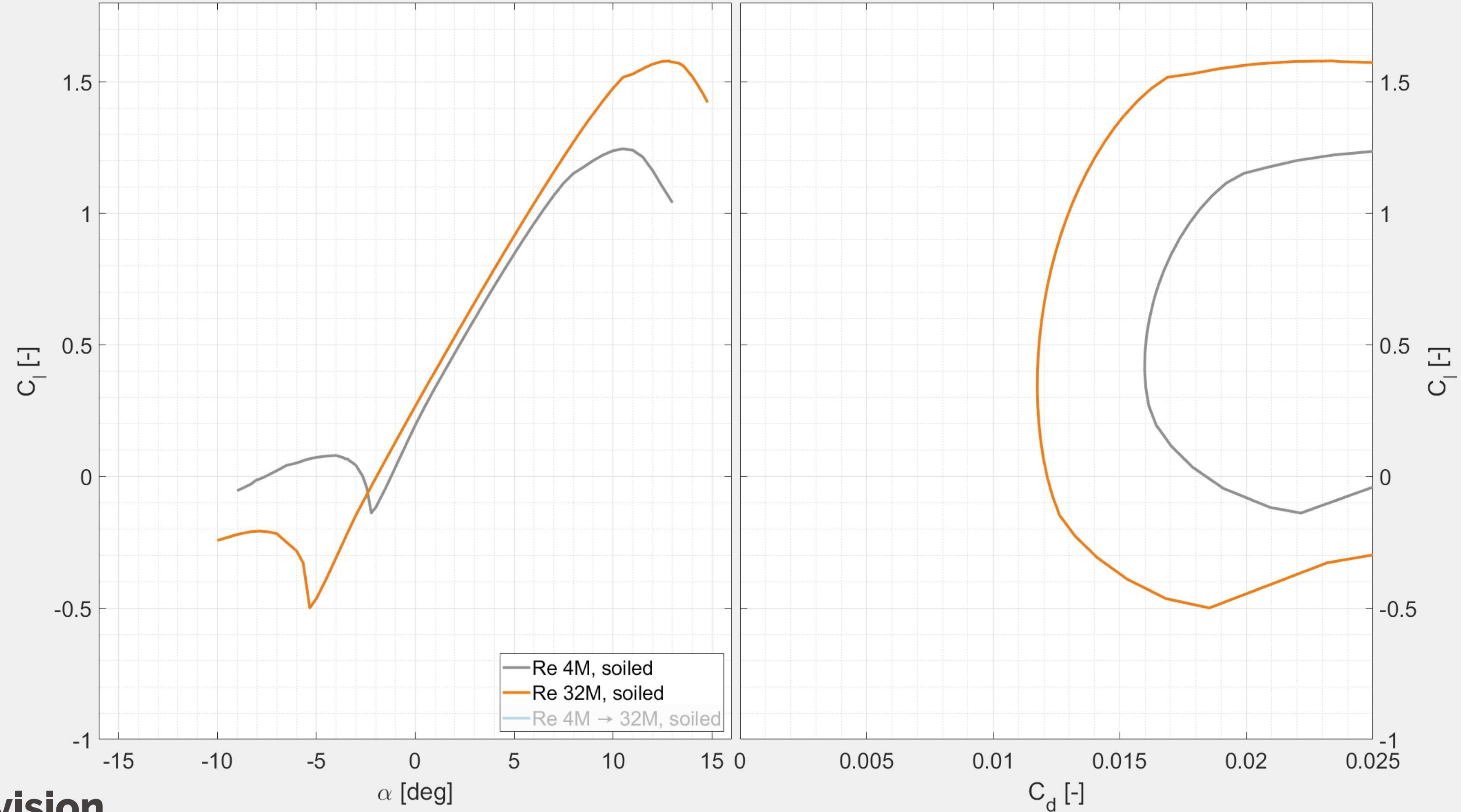
Assume self-similar polar shapes

1. Create CFD polars at wind tunnel *Re* and higher target *Re*
   - Expose trends in C_d, max/min C_l, etc.
   - Use a trusted transition model: e^N!
2. Determine scale and offset coefficients to mimic CFD trends
3. Apply tuned linear transform to wind tunnel data

$$\tilde{\alpha} = A_1 \alpha + A_0$$
$$\tilde{C}_l = L_1 C_l + L_0$$
$$\tilde{C}_d = D_1 C_d + D_0$$
$$\tilde{C}_m = M_1 C_m + M_0$$

How do we process our wind tunnel data?

Reynolds number transformation



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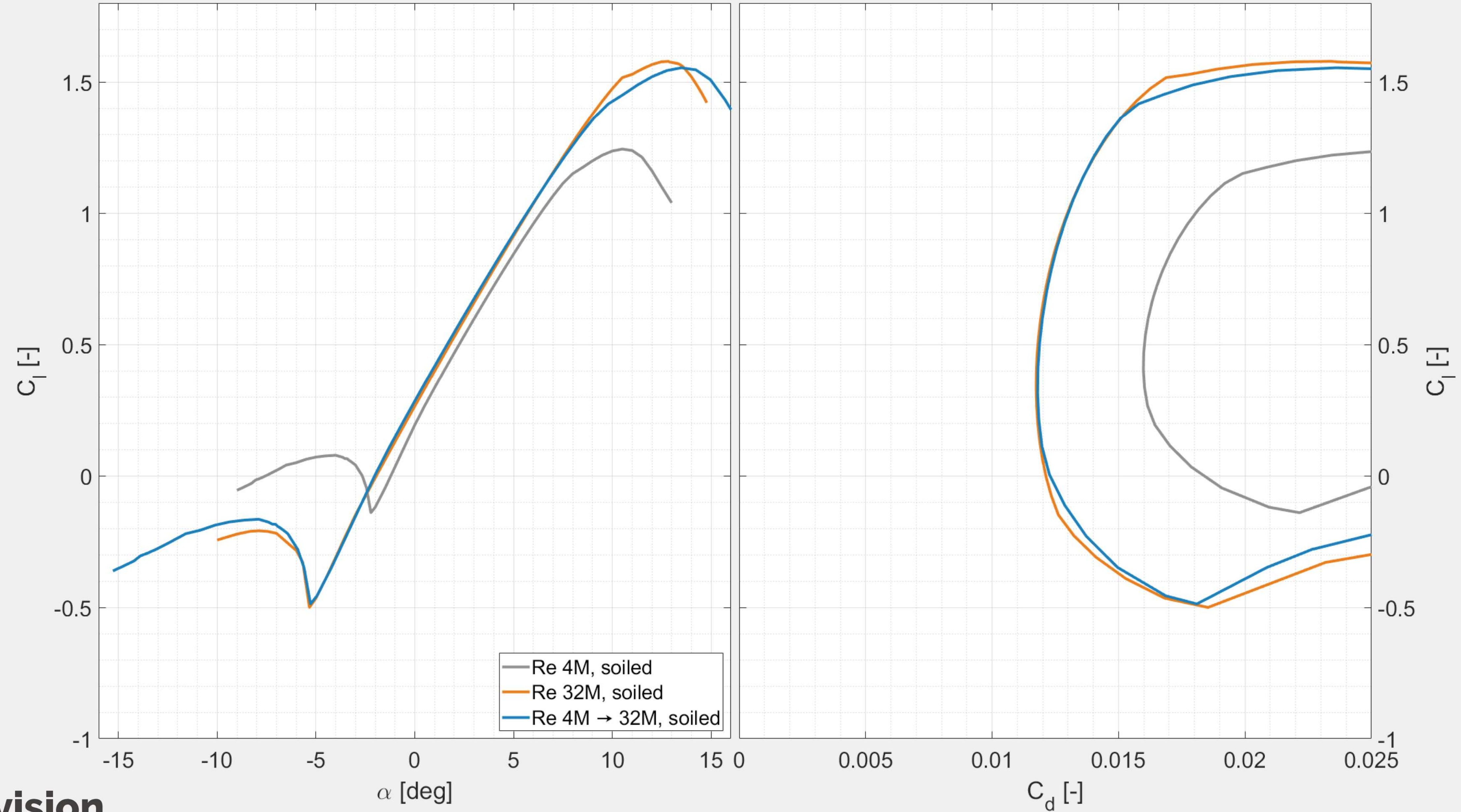
Reynolds number transformation



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Wrap-up

- High Reynolds numbers are driven by unrelenting rotor growth
- Airfoil design to provide competitive edge
- Validate new designs in the wind tunnel
  - Highest Re possible given real-world constraints
- Create airfoil polars at relevant Reynolds numbers
  - Wind Tunnel + CFD + Transformations


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Thank you!