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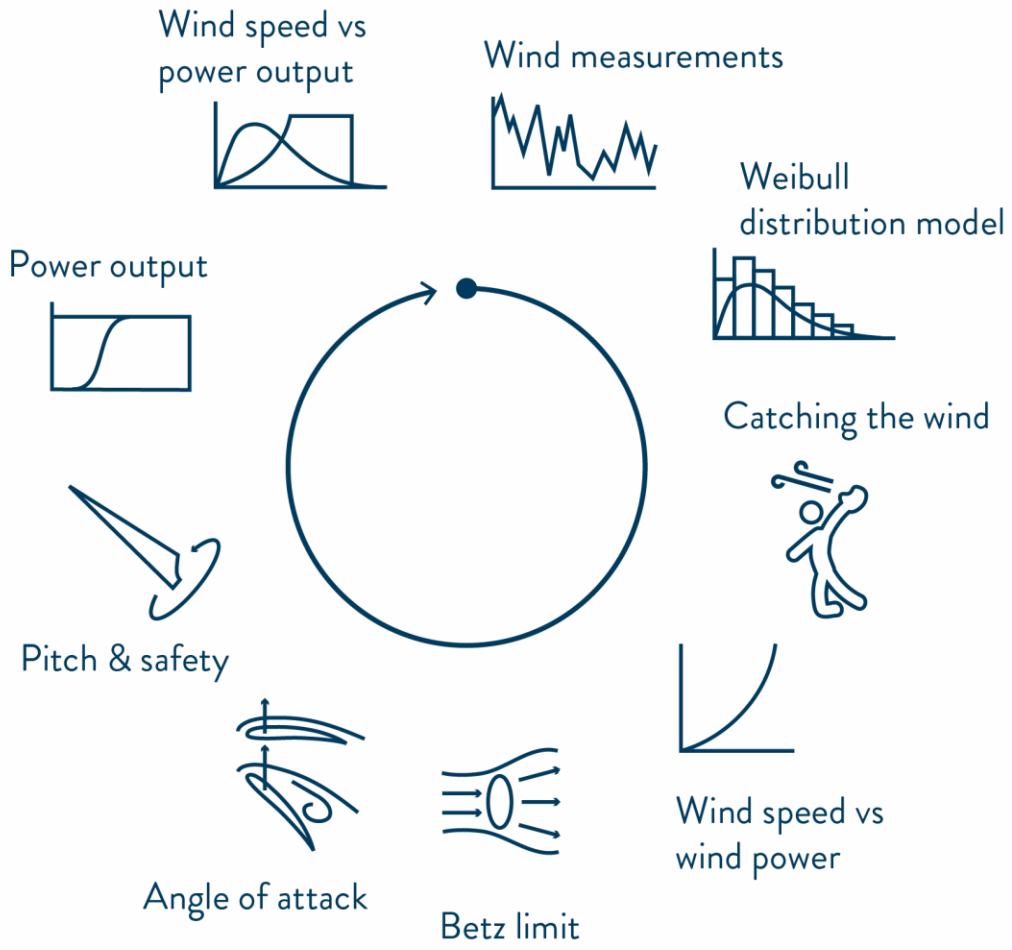
Wind to power



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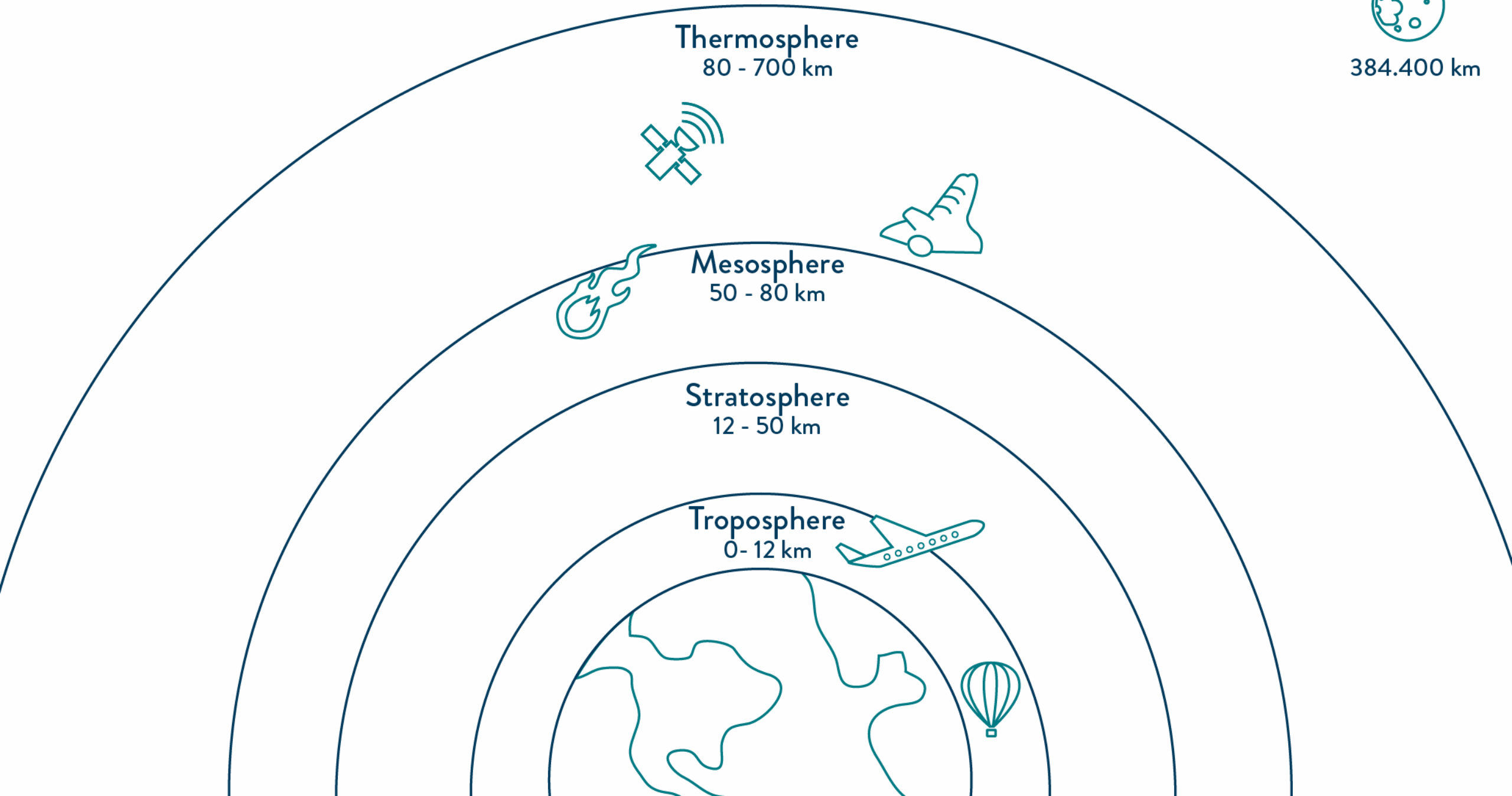
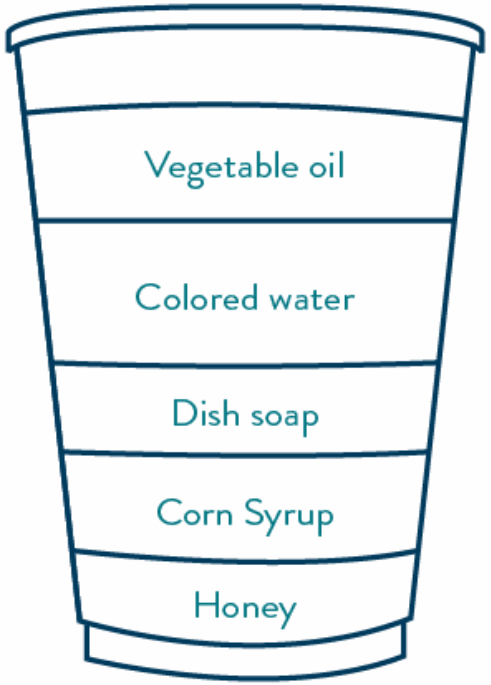
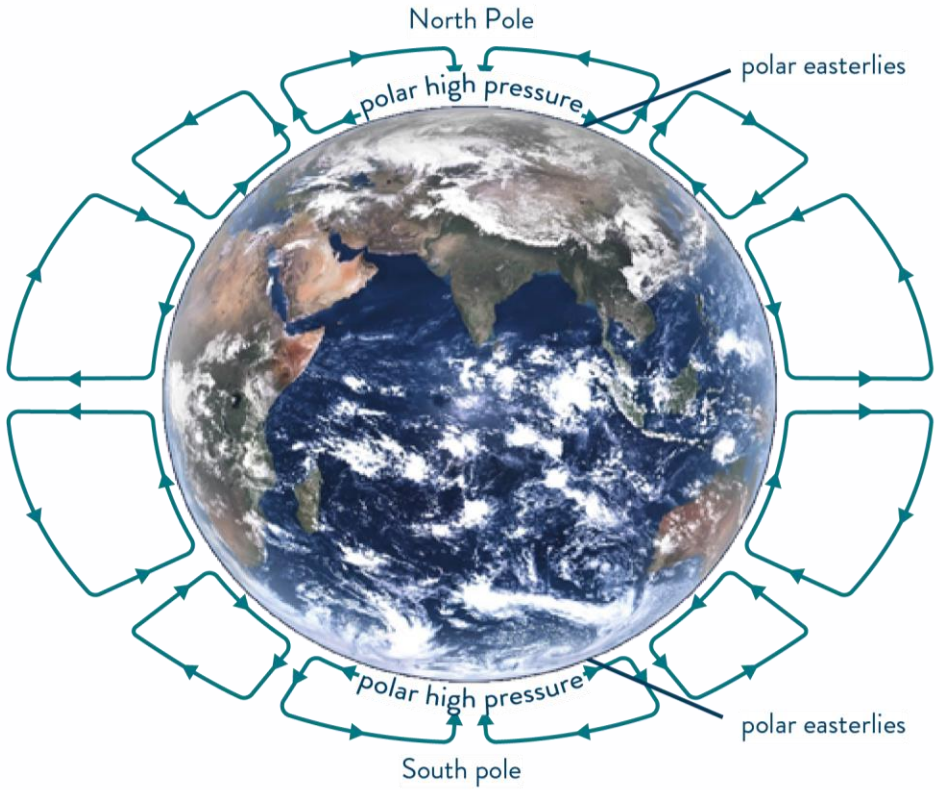

Thermosphere
80 - 700 km
Mesosphere
50 - 80 km
Stratosphere
12 - 50 km
Troposphere
0- 12 km
384.400 km

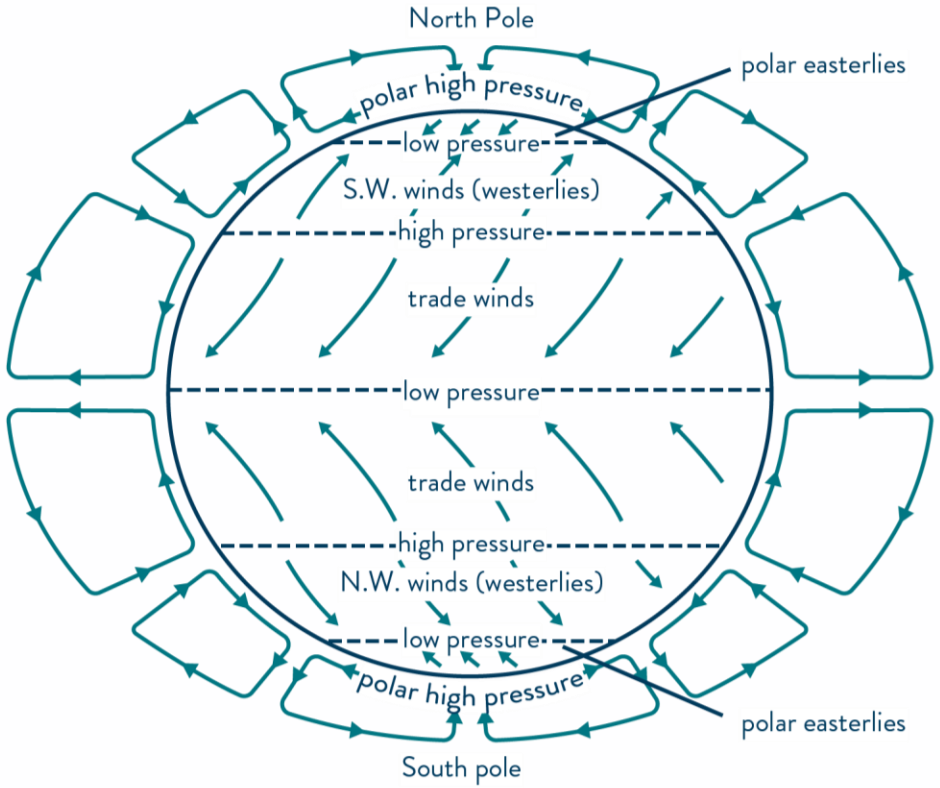
Effects of pressure and density



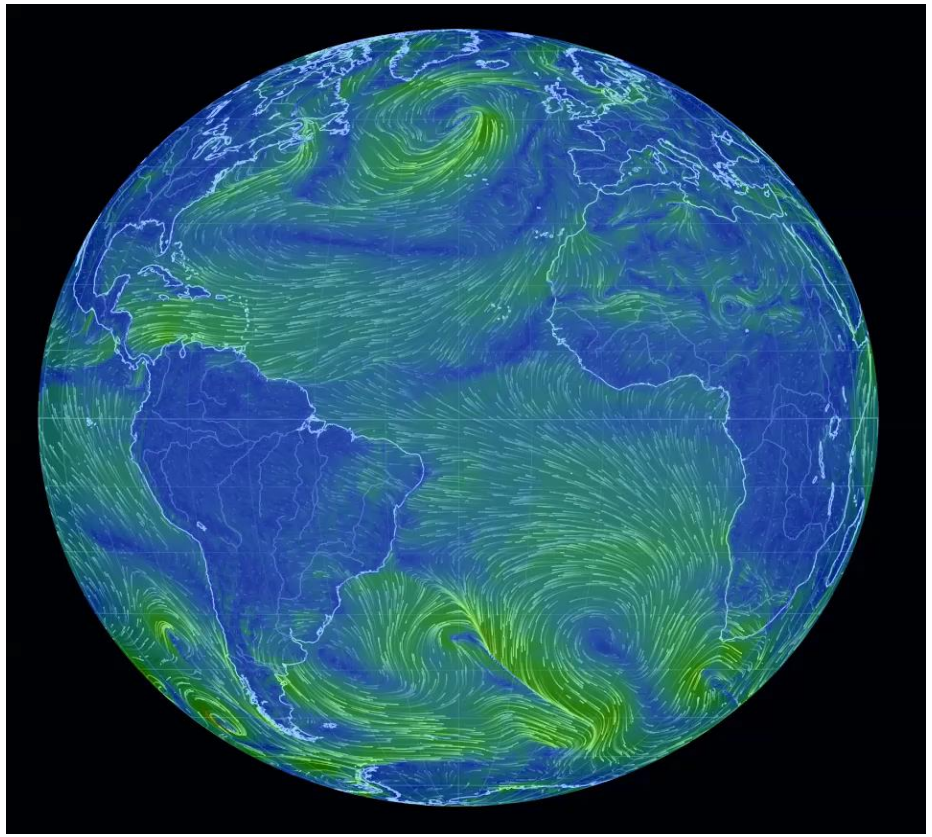
Origin of wind (in the troposhere)

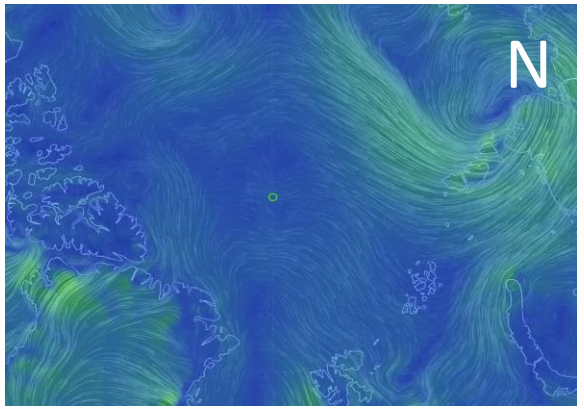


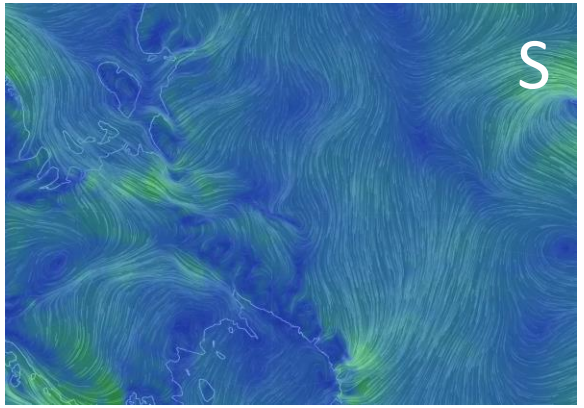
Origin of wind (in the troposhere)



Global winds





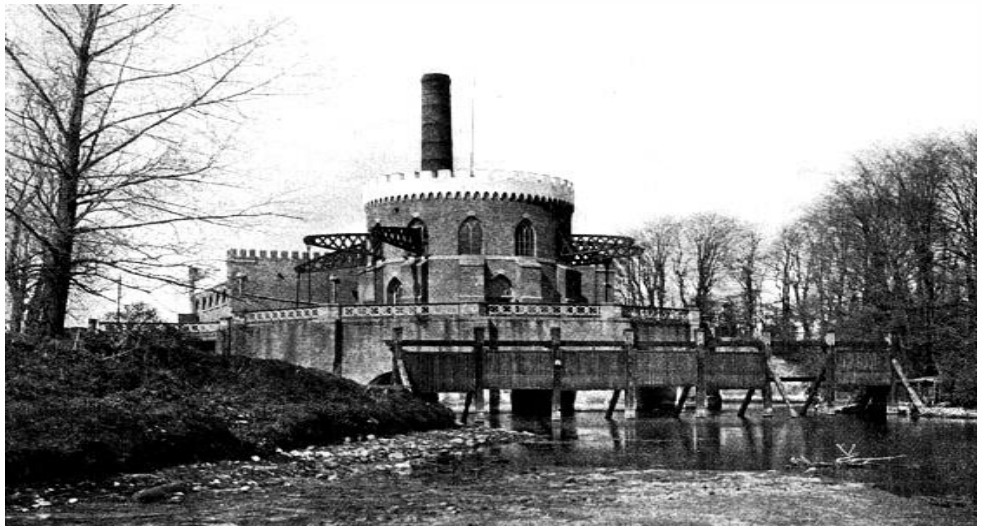


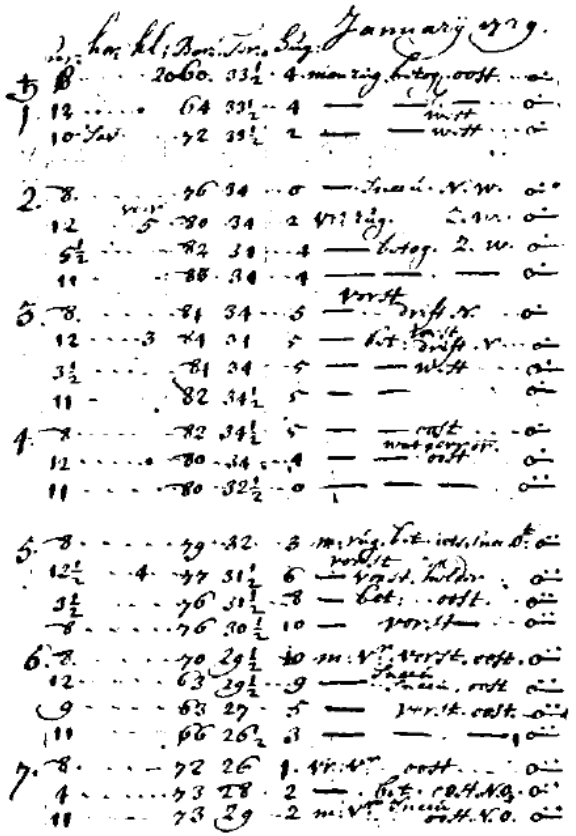
https://earth.nullschool.net/

Measuring wind

To predict wind, we need to study wind behaviour!

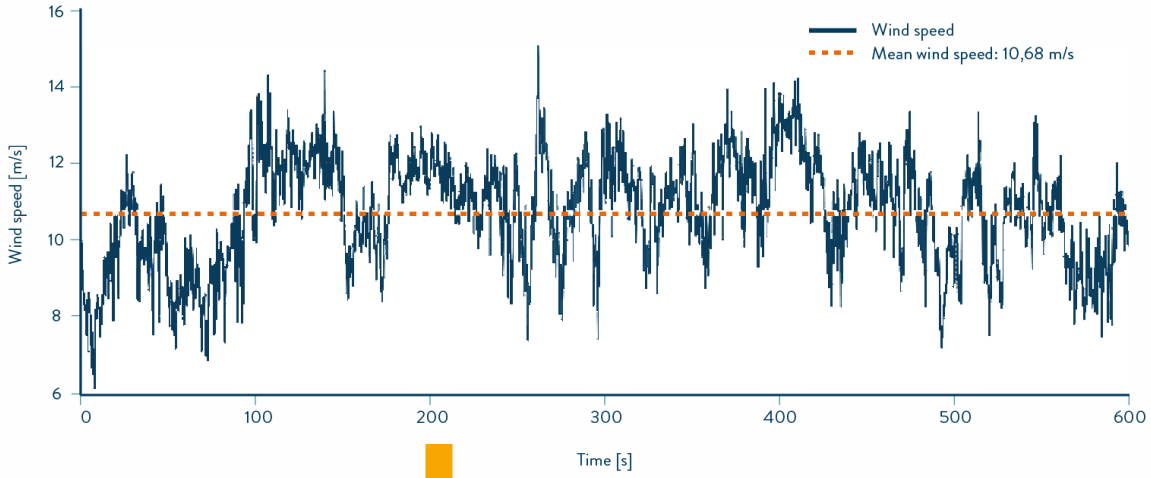
- Wind measurements
- Nicolaus Cruquius (1678 – 1754)





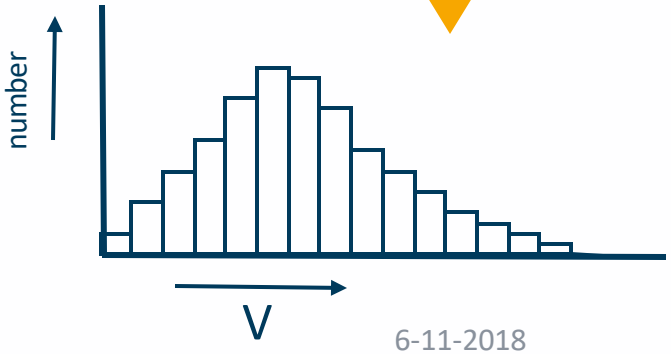
Measuring wind

Processing wind data

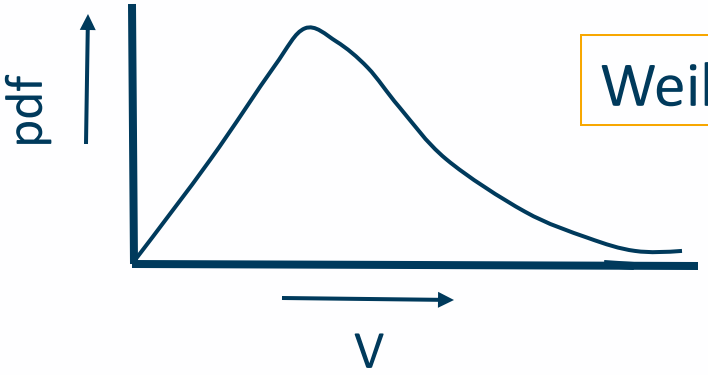


10-min average

histogram



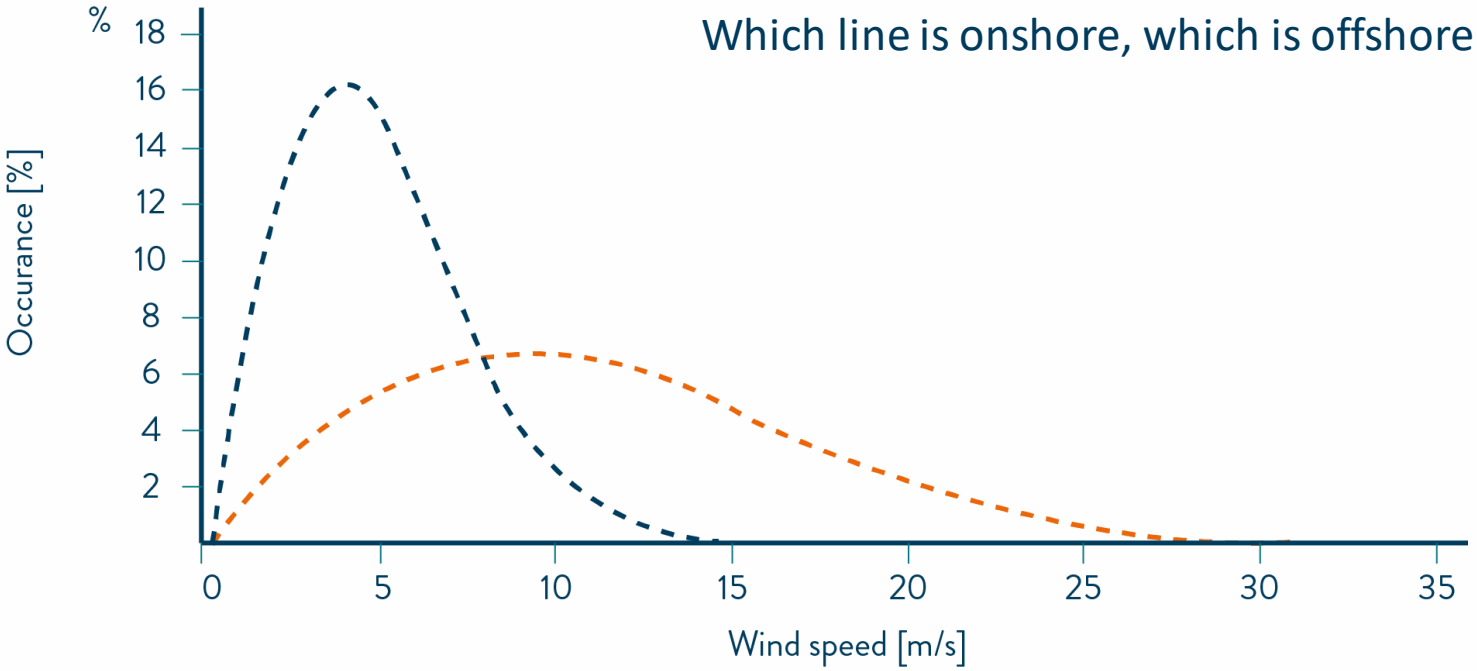
probability density function



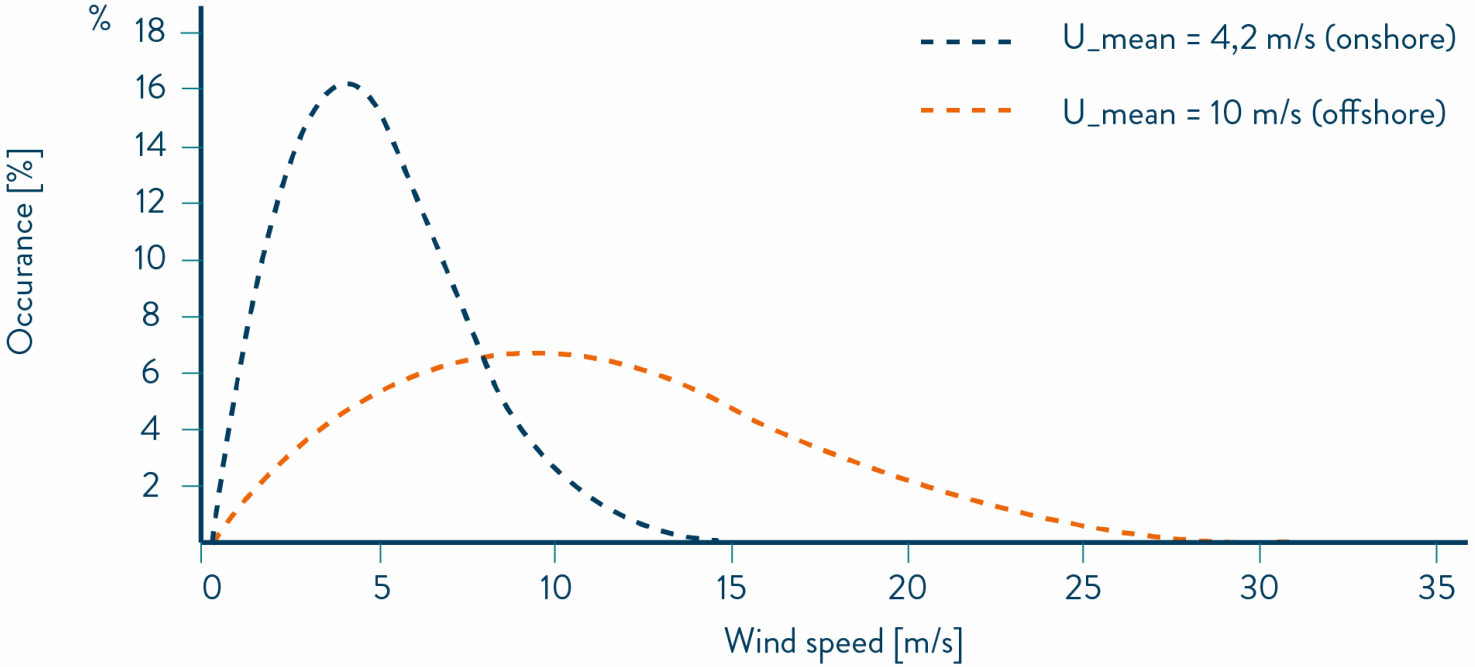
Weibull

Onshore wind vs offshore wind

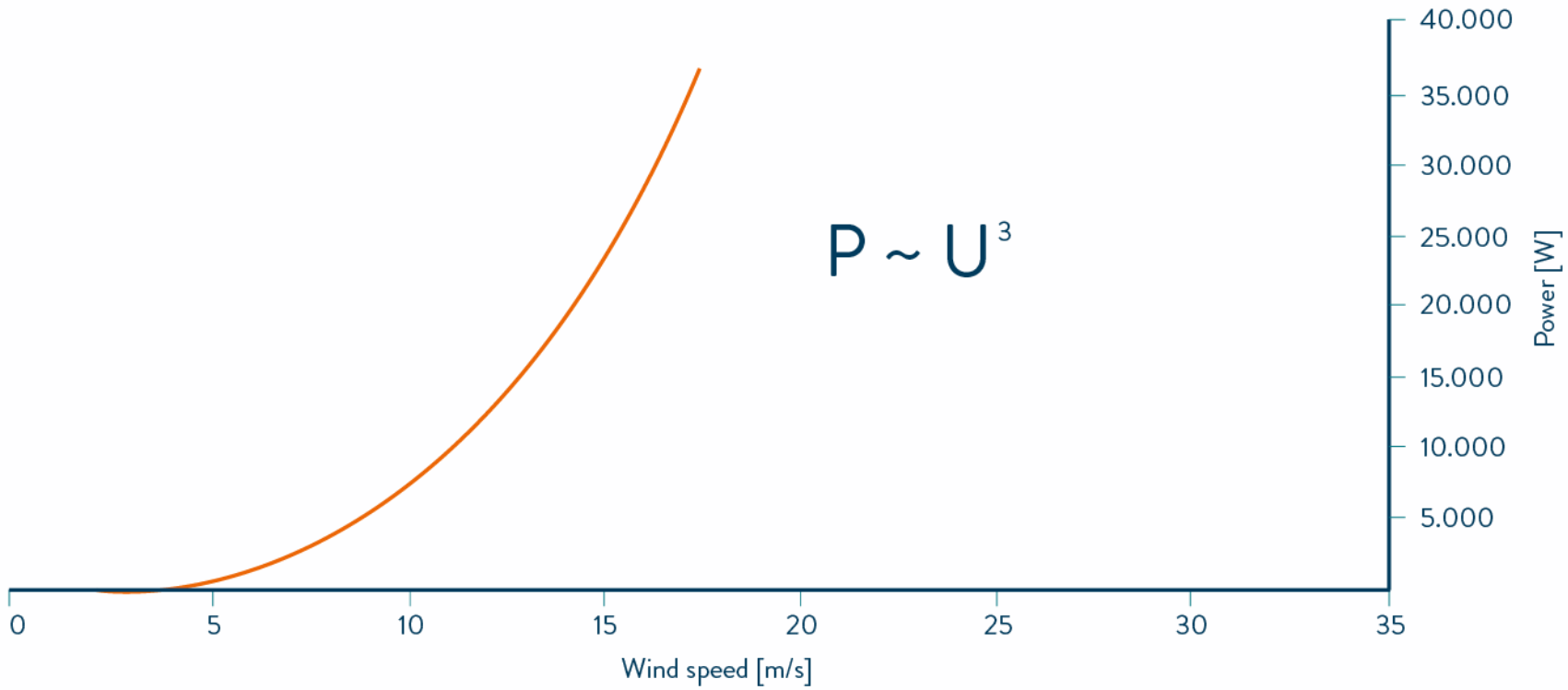
Which line is onshore, which is offshore?



Onshore wind vs offshore wind



Wind speed to wind power

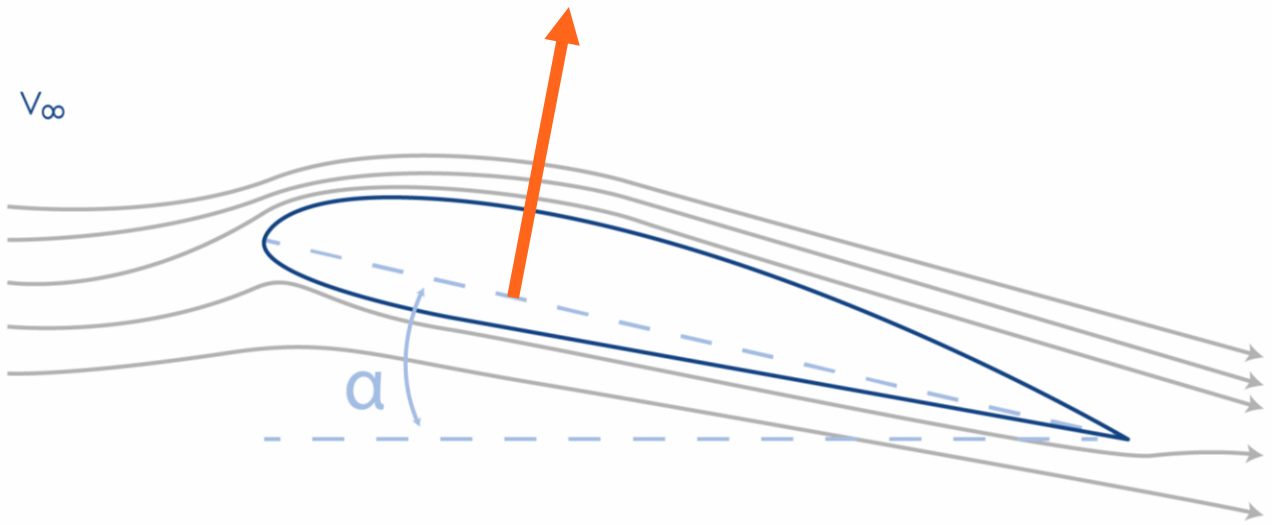


How to catch the wind

Drag turbine

Lift turbine

Aerodynamic lift



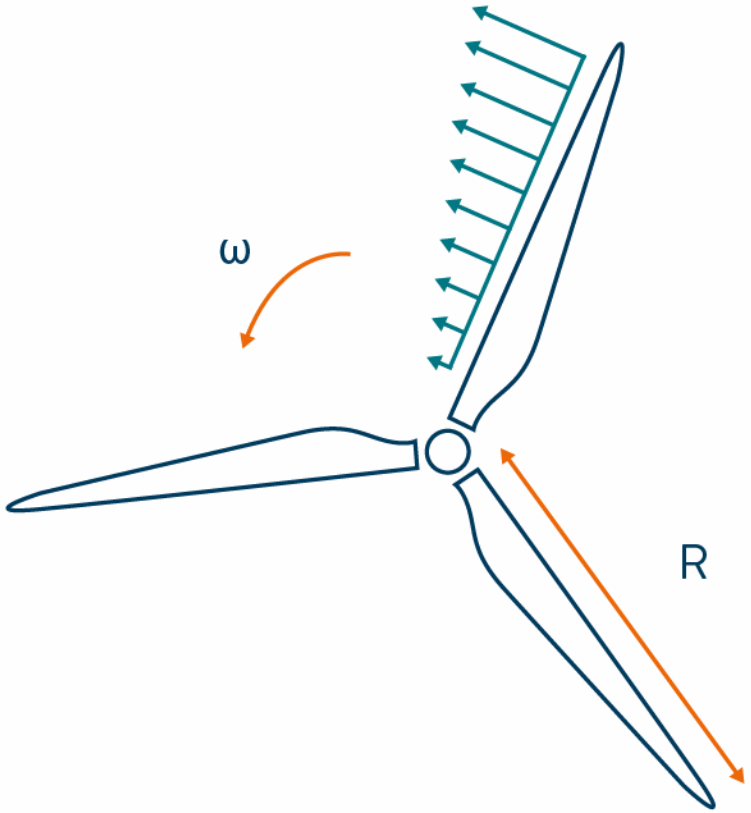
α = Angle of attack

Chord = line between landing edge and tailing edge

Velocity variation

$$v_{tip} = \omega R$$

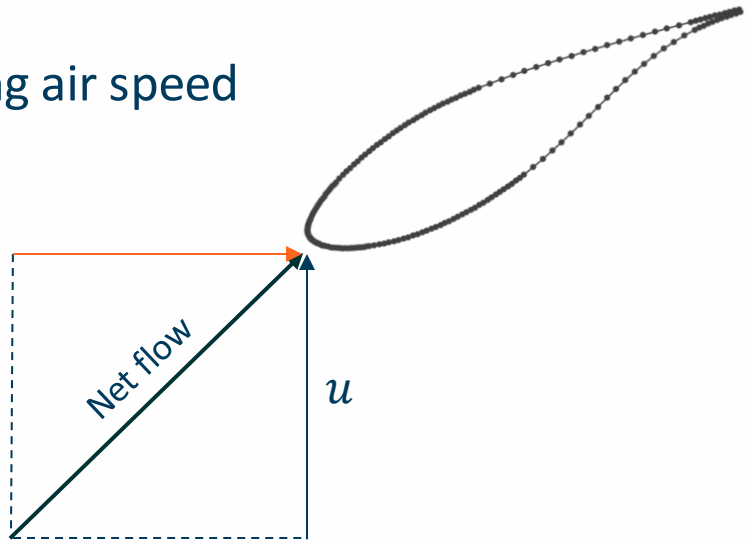
Max tip speed?



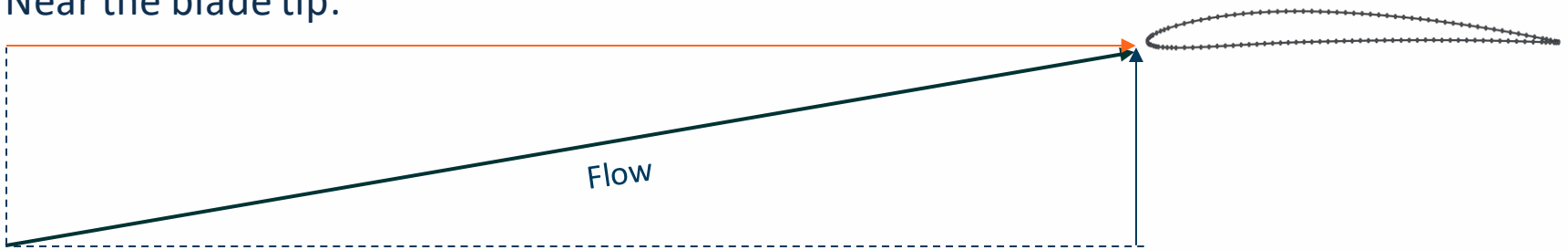
Velocity triangle

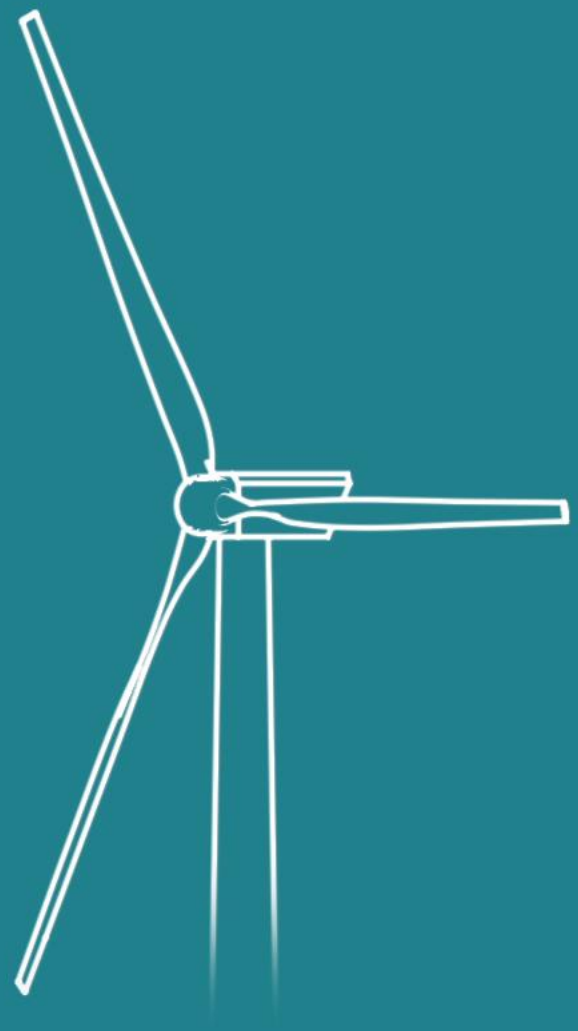
- Optimal angle of attack vs angle of incoming air speed

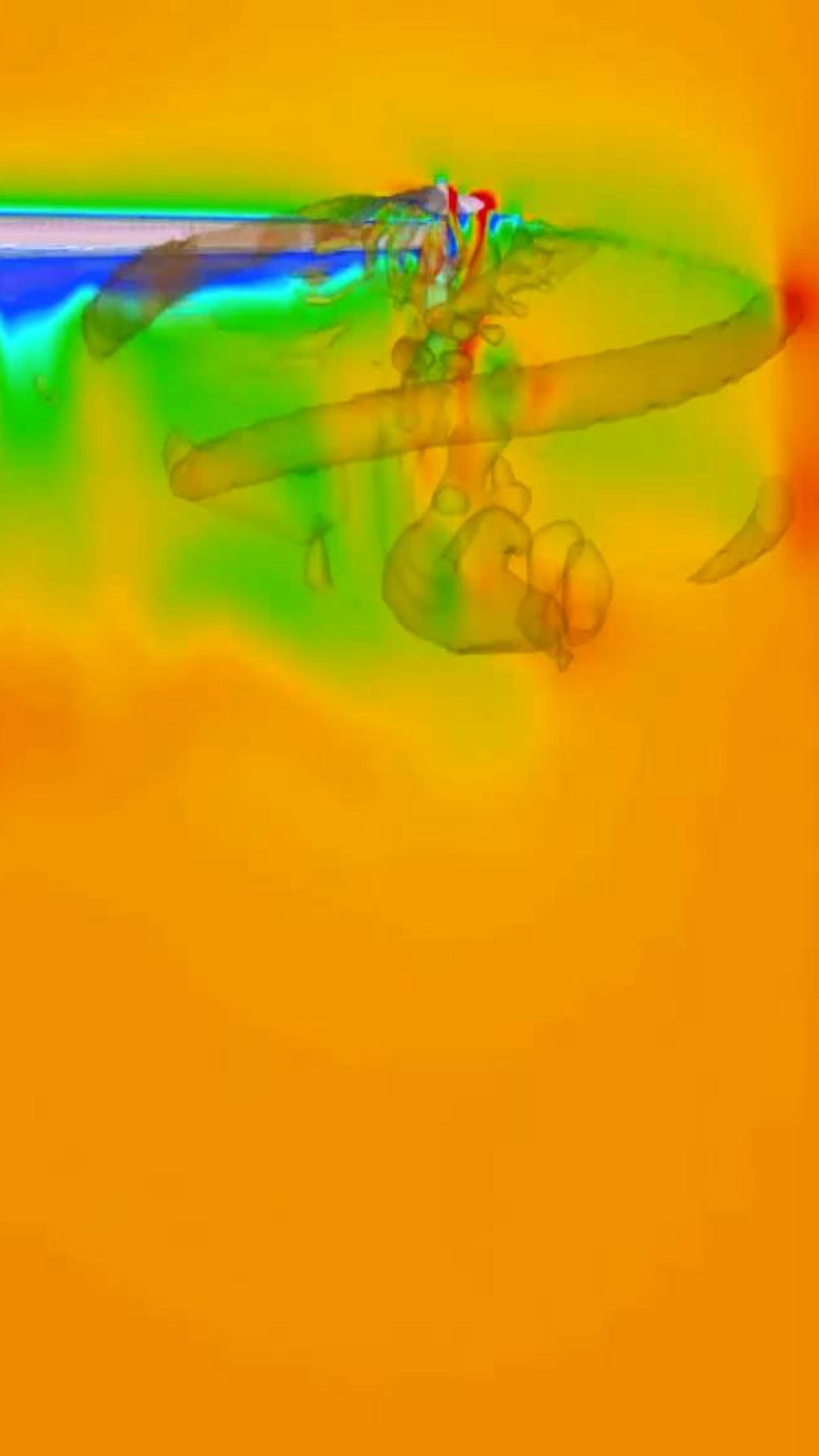
Near the blade root:



Near the blade tip:







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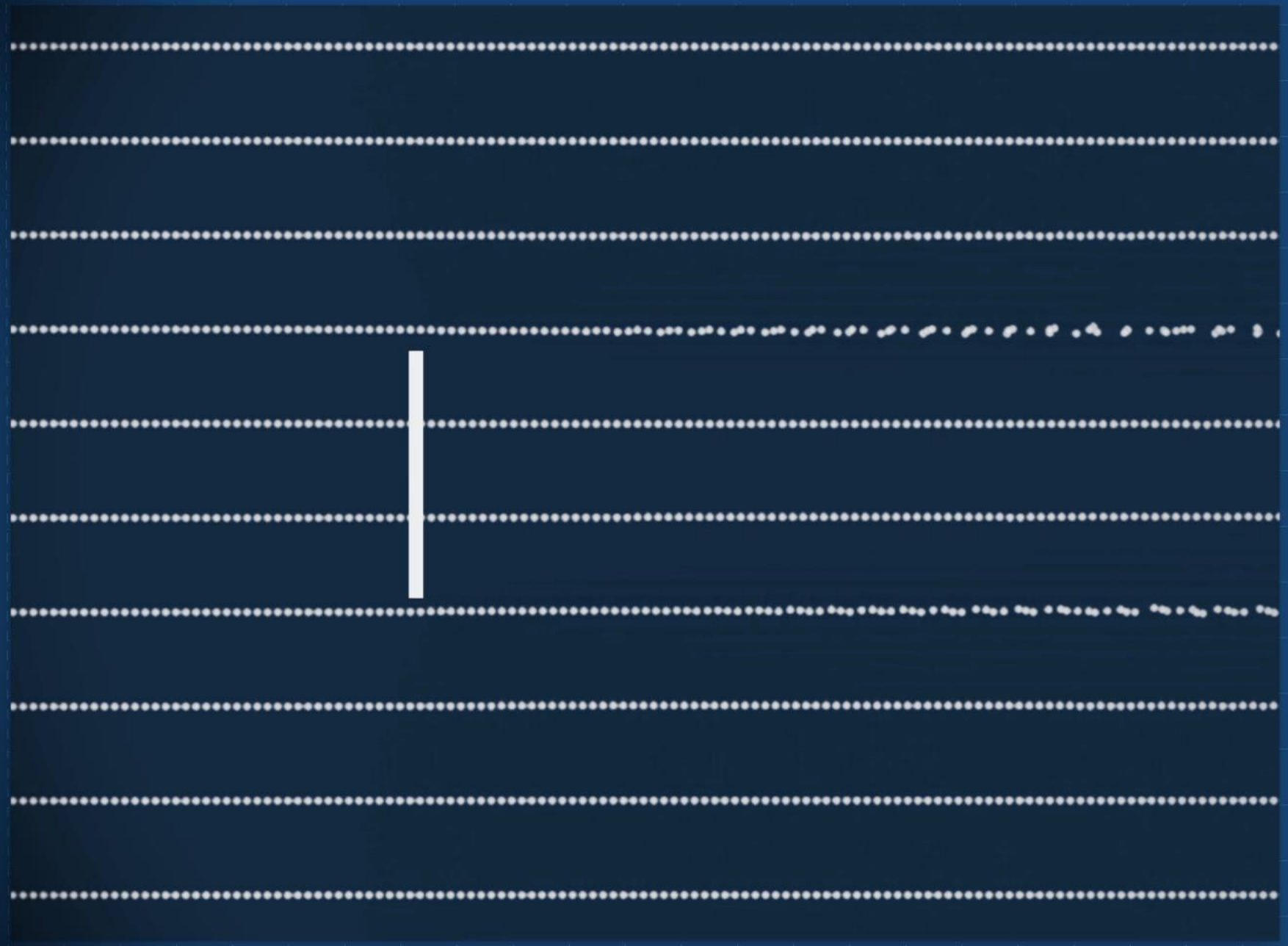

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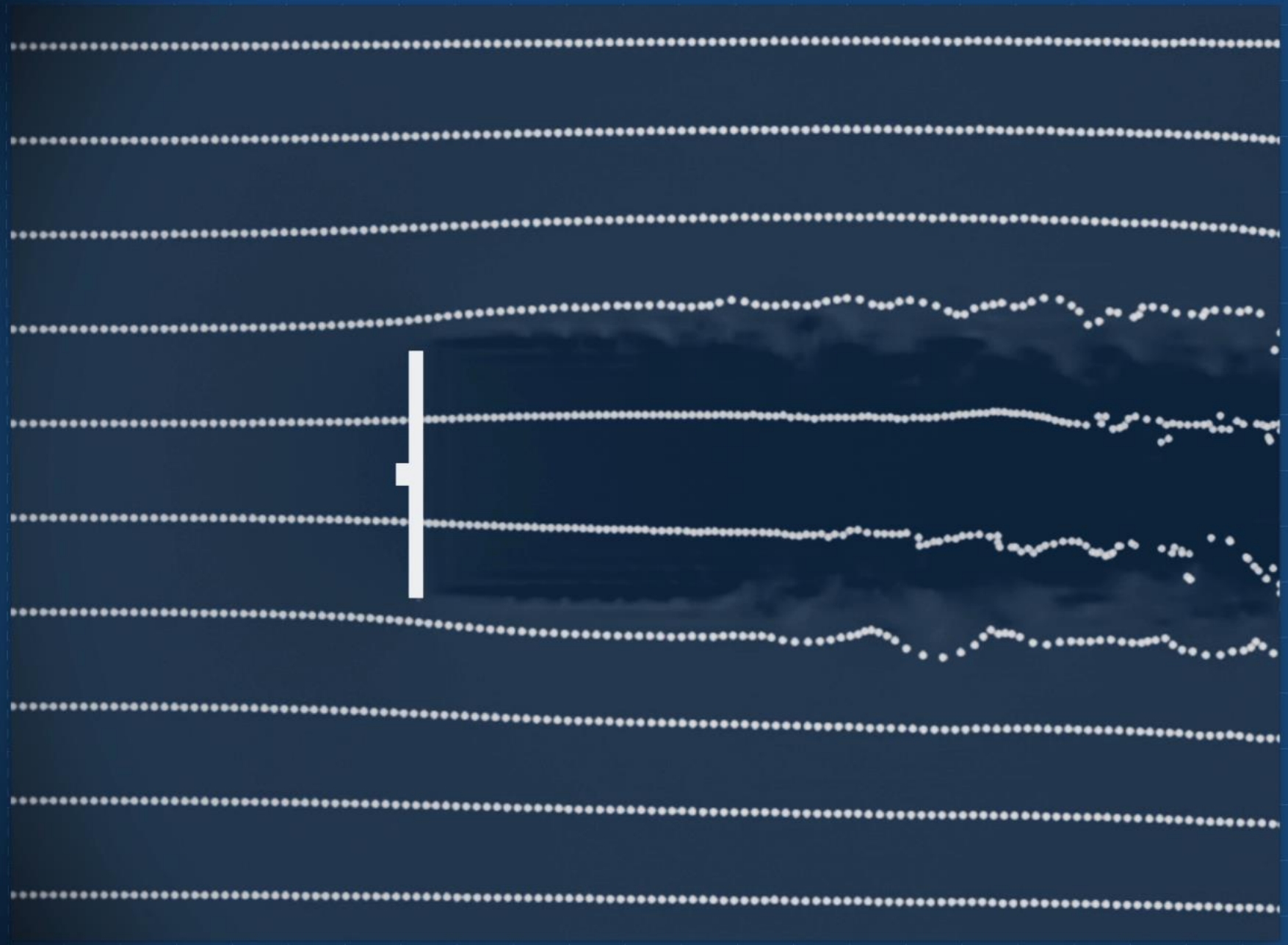

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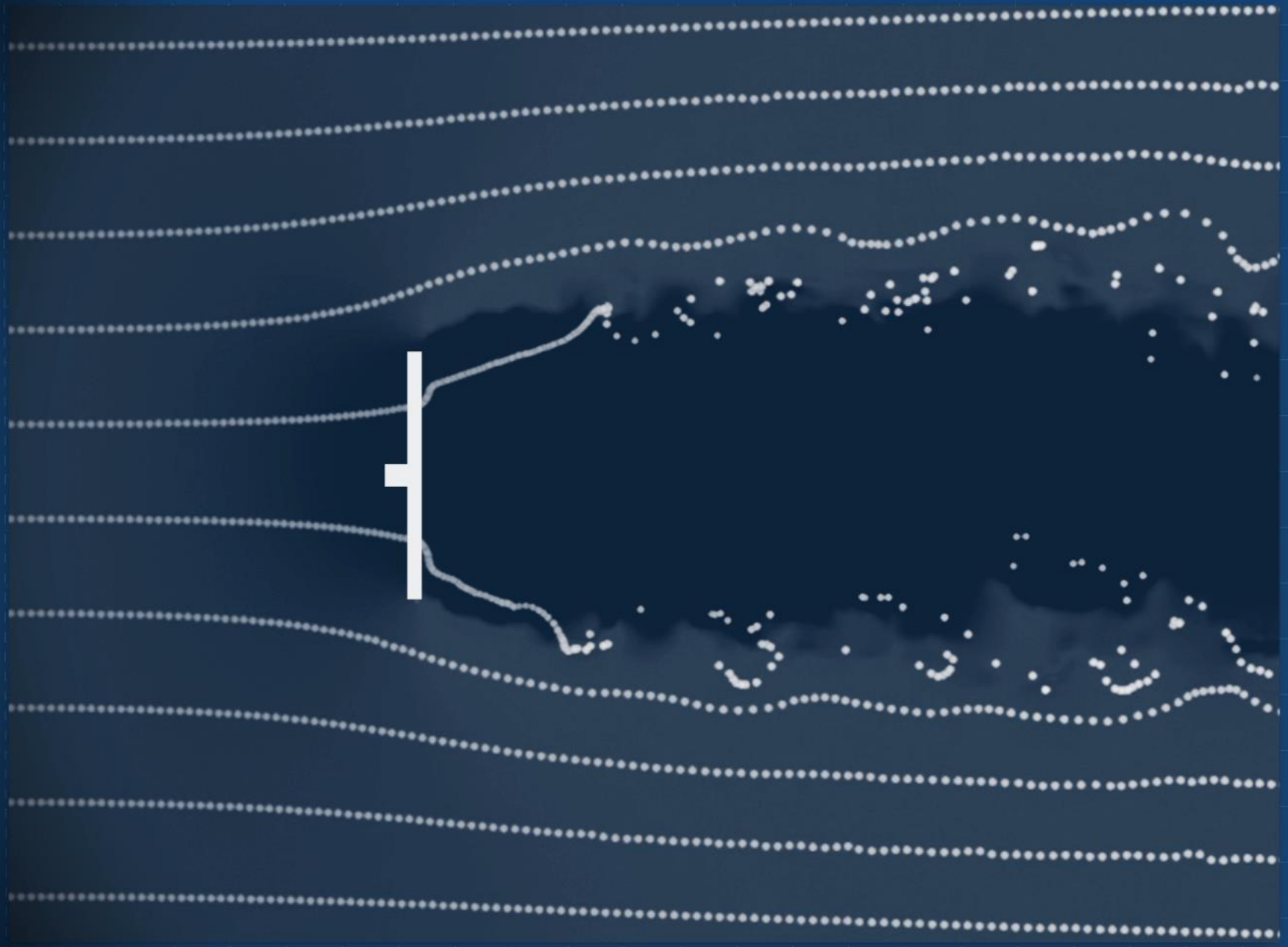

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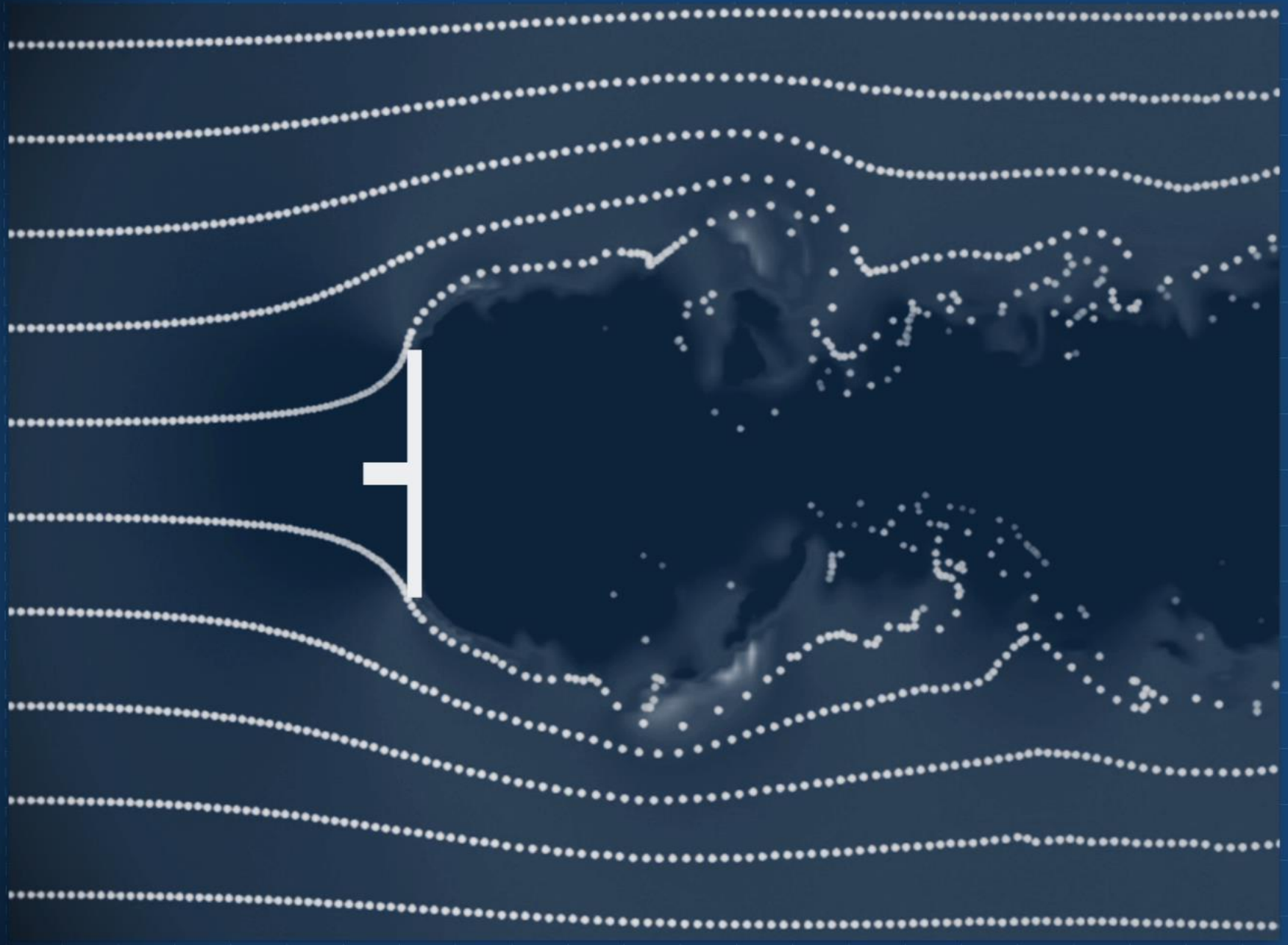

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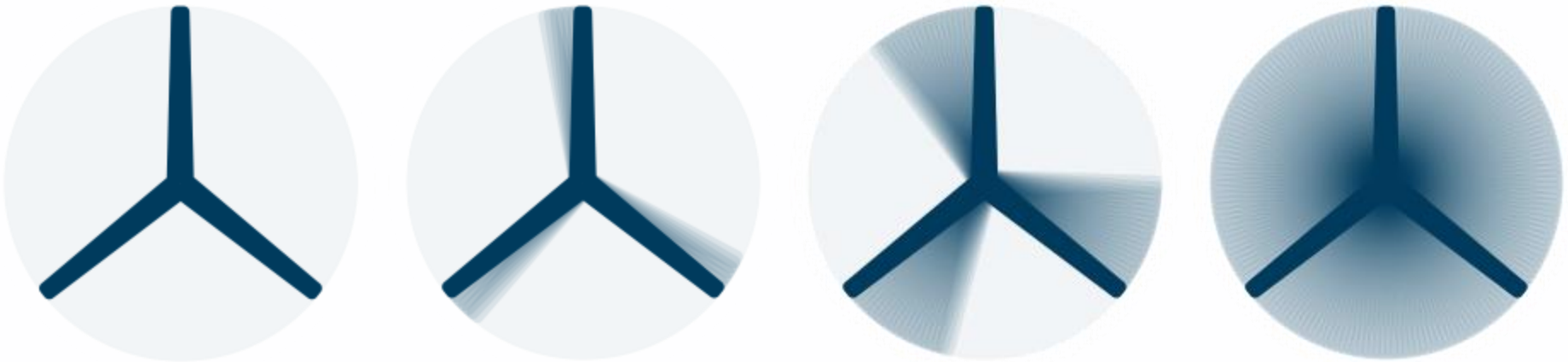
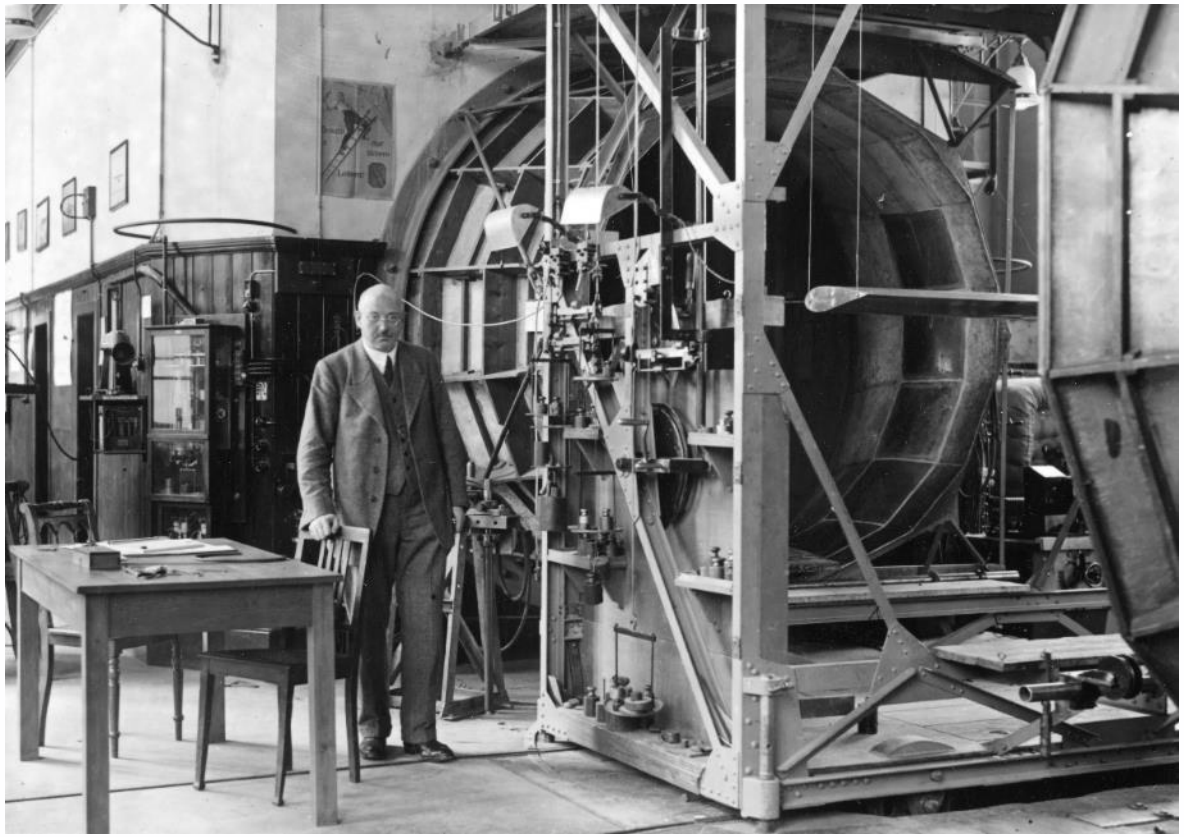
Finding the optimum operating point



Betz limit



$$C_P = \frac{P_{rotor}}{P_{wind}}$$

Momentum Theorem

Three basic equations:

1. The continuity equation: mass flow = *rho_i*A_i**u_i = *rho_d*A_d*u_d = rho_w*A_w*u_w*
2. Conservation of momentum: *F = mass flow* x *velocity difference* → *dp * A_d = rho*A_d*u_d* x *(u_i – u_w) = rho*A_i*u_i* x *(u_i – u_w)*
3. Bernoulli's equation for dynamic pressure *p_tot = p_static + 0.5*rho*v^2*

Key assumption: air is incompressible → rho = constant

Solution:

*dp = (p2-p1) = 0.5*rho*(u_i ^2– u_w^2) = rho*u_d* x *(u_i – u_w)* → *u_d = 0.5*(u_i + u_w)*

Trick: *u_d = u_i * (1-a)* → *u_w = u_i * (1-2a)*

here: *a* = induction factor, value between 0 and 1

Cp = *Power rotor/Power wind* = *Force disc * velocity at disc / 0.5*rho*A_d*u_i^3*

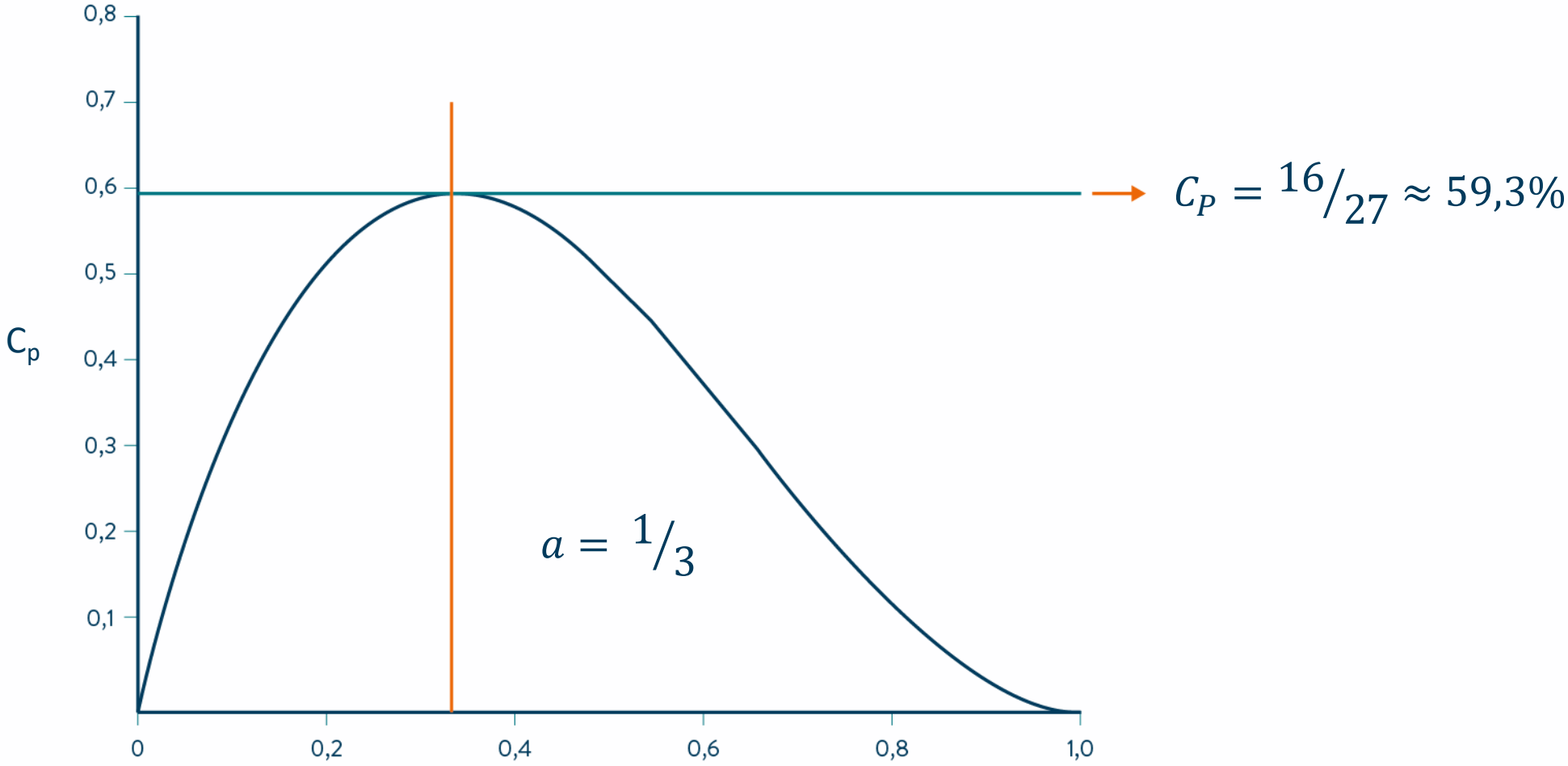
= *rho*u_d* x *(u_i – u_w) *A_d*vd* / 0.5*rho*A_d*u_i^3

= *2*u_d^2* x *(u_i – u_w)* / u_i^3

Apply trick → = *4a*(1-a)^2*

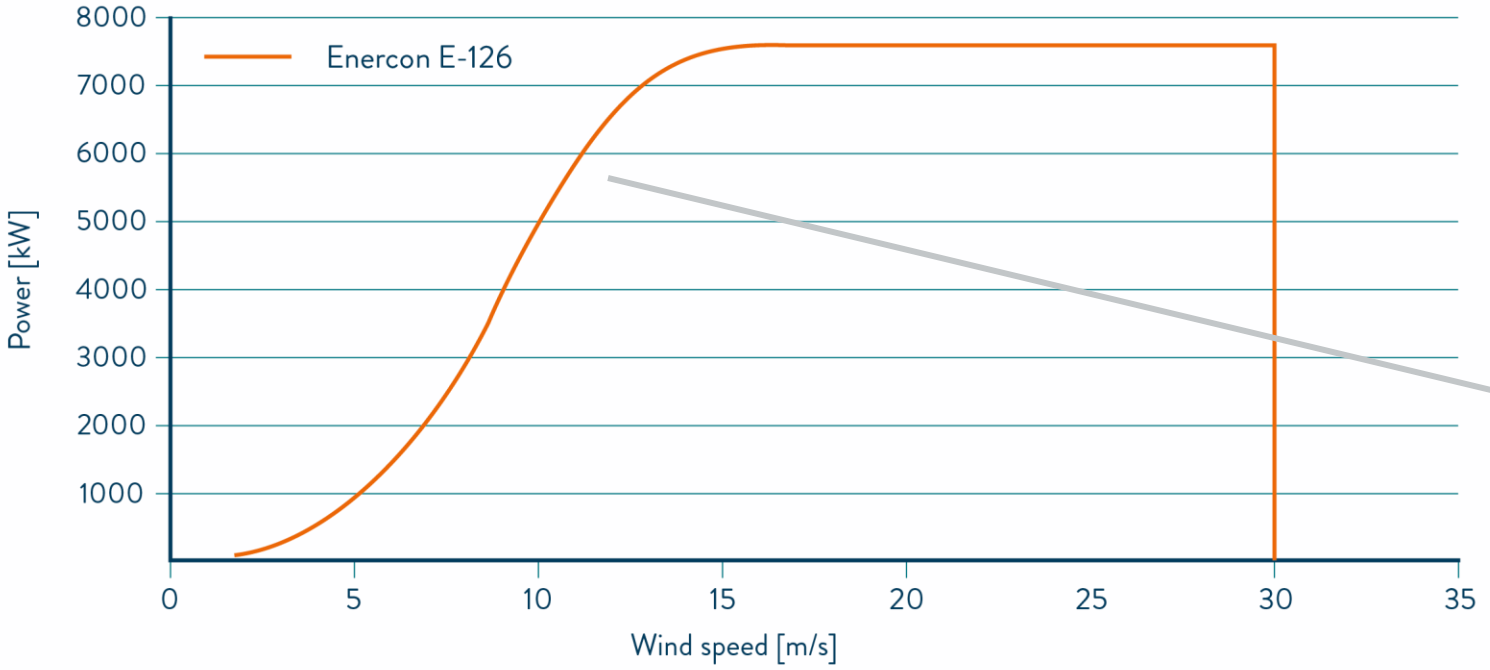
When is *Cp* greatest?

Betz limit – max. power coefficient



$C_P = {}^{16}/_{27} \approx 59{,}3\%$

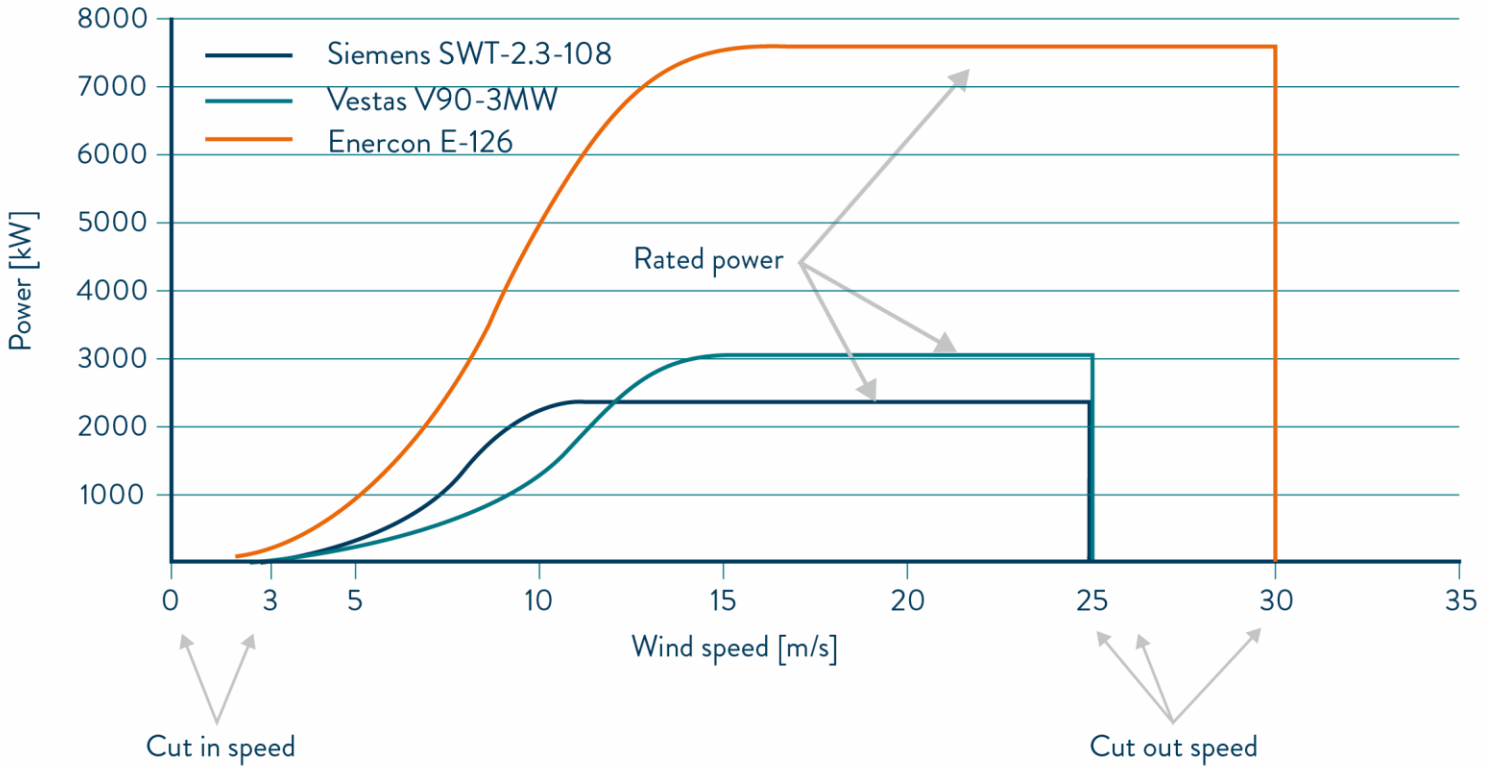
Power curve



$$P = C_P \frac{1}{2} \rho U_\infty^3 \pi R^2$$

Pitch control

Power curve



Siemens

Vestas

Enercon

Wind turbine disaster

- Hornslet wind farm Denmark, February 22, 2008
- Vestas Nordtank NKT 600-180/4
- Faulty braking system
- > 5 times allowed rpm
- Blade fracture causes imbalance

Safety: cut out speed

Safety: cut out speed

Safety: cut out speed

Safety: cut out speed

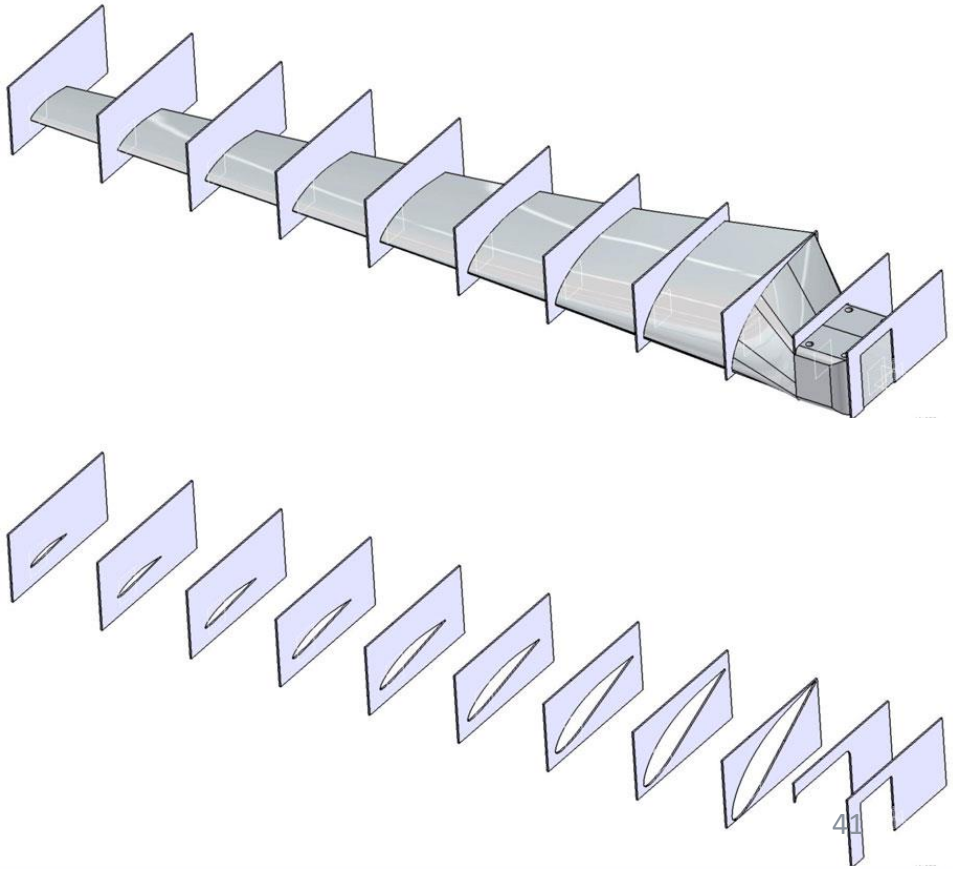
Safety: cut out speed

Safety: cut out speed

The movie

Design considerations

1. Airfoil shape
2. Blade twist
3. Number of blades vs rotation speed



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