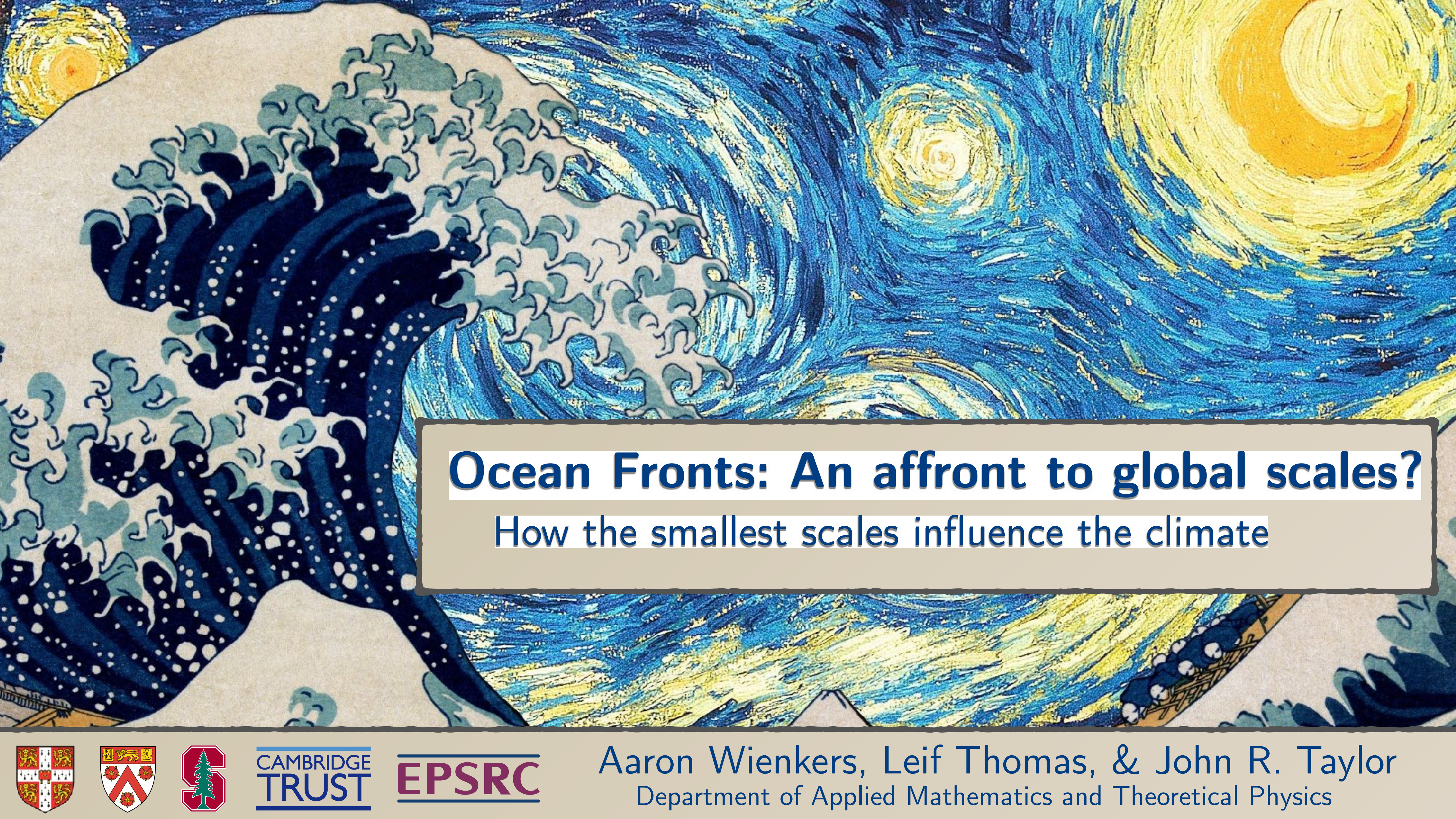
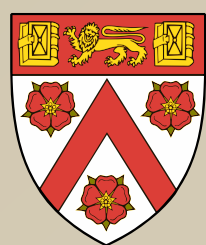




Ocean Fronts: An affront to global scales?

How the smallest scales influence the climate

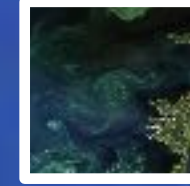


Aaron Wienkers, Leif Thomas, & John R. Taylor
Department of Applied Mathematics and Theoretical Physics

Global Scales



Mesoscales



Mesoscales

NASA/USGS

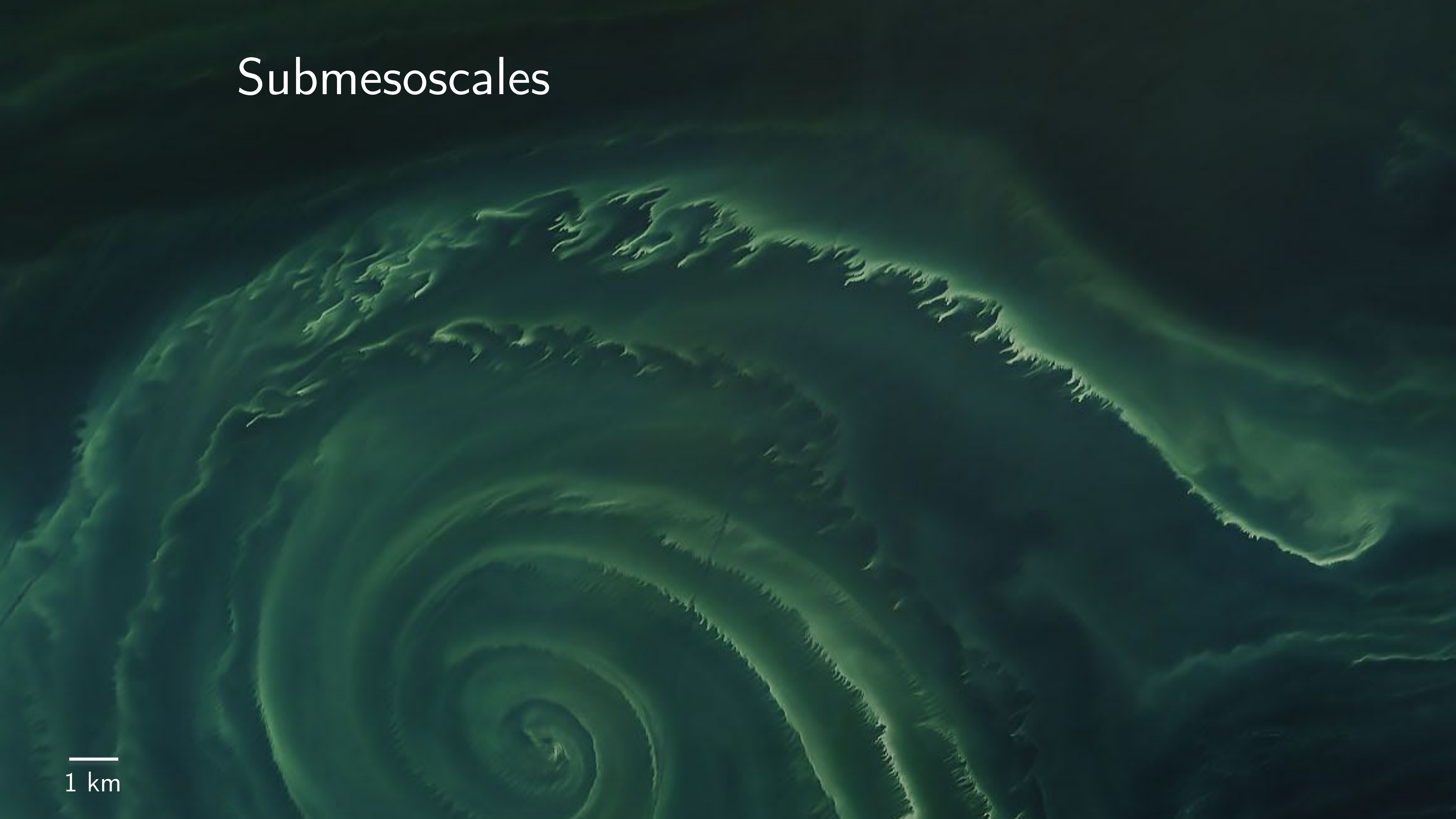
Ship

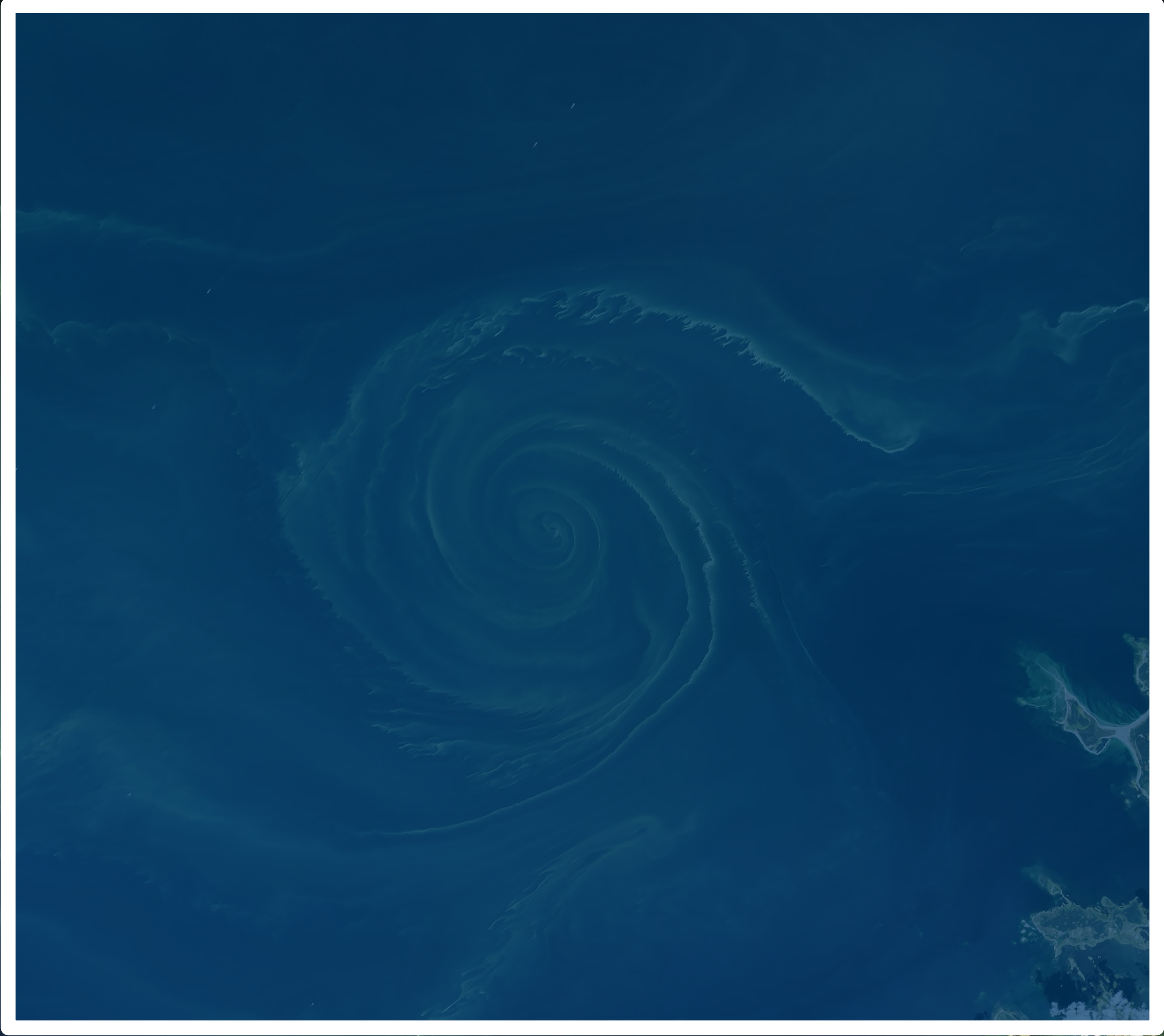


10 km



Submesoscales

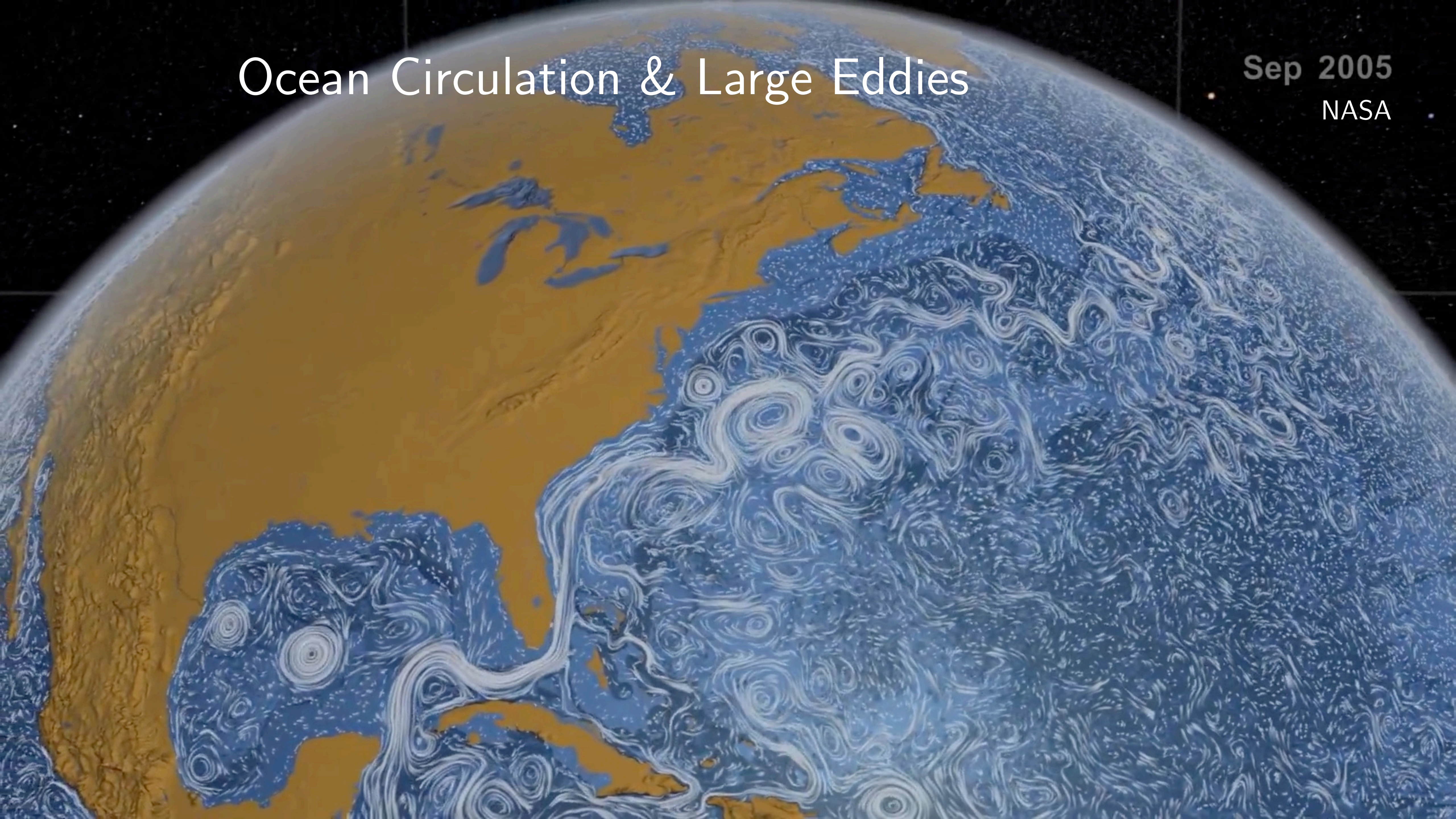




10 km

Ocean Circulation & Large Eddies

Sep 2005
NASA



Challenge in Geophysical Fluid Dynamics

Monet (1892)

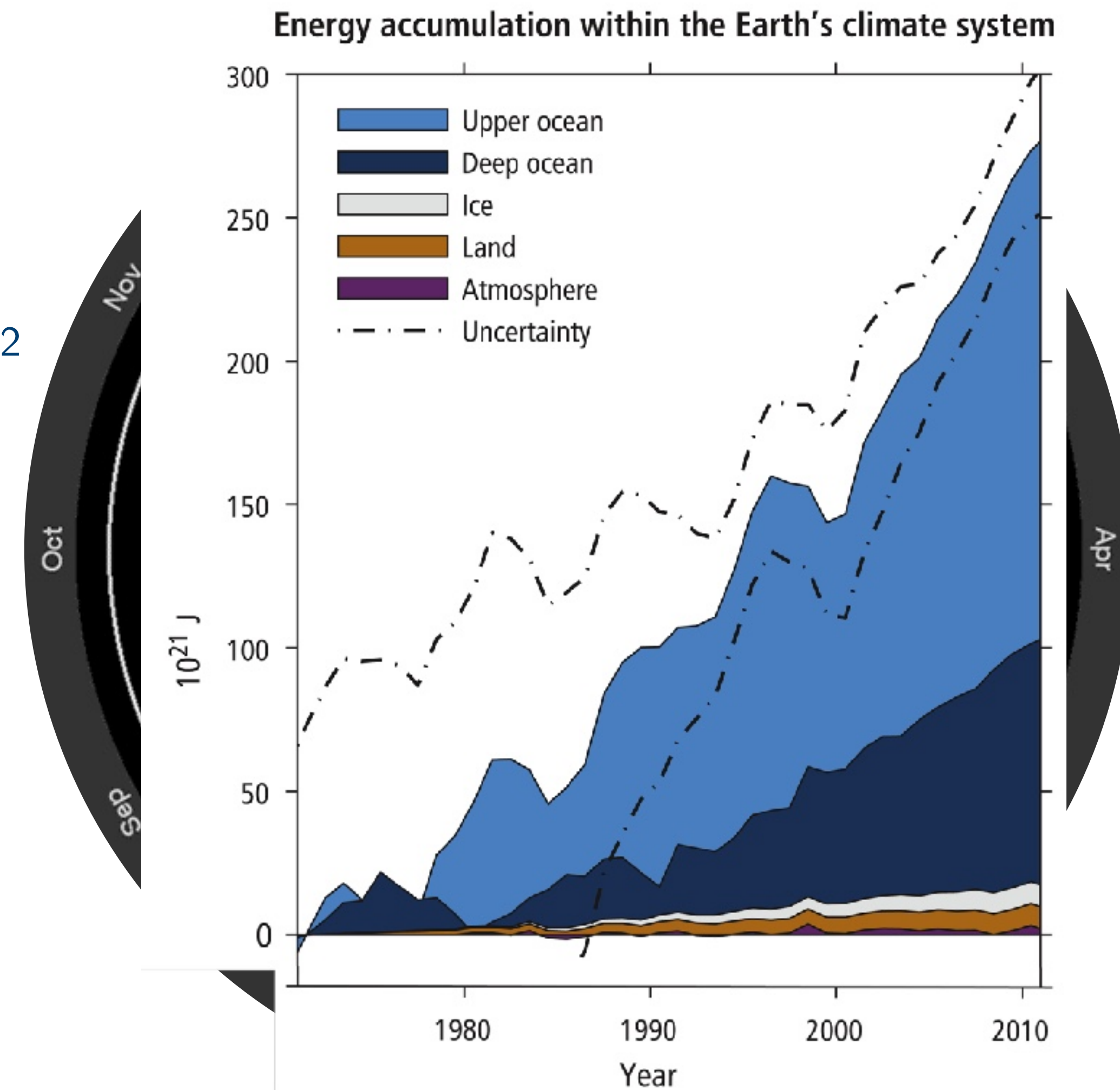
- Dynamic range of motions is $\sim 10^8$
 - $\therefore$ Capturing every scale is prohibitively expensive
- Under-resolved scales are still important!
 - In climate & weather models and storm tracking
- Need to see the Forest *and* the Trees



Can Fluid Dynamics Save the Planet?

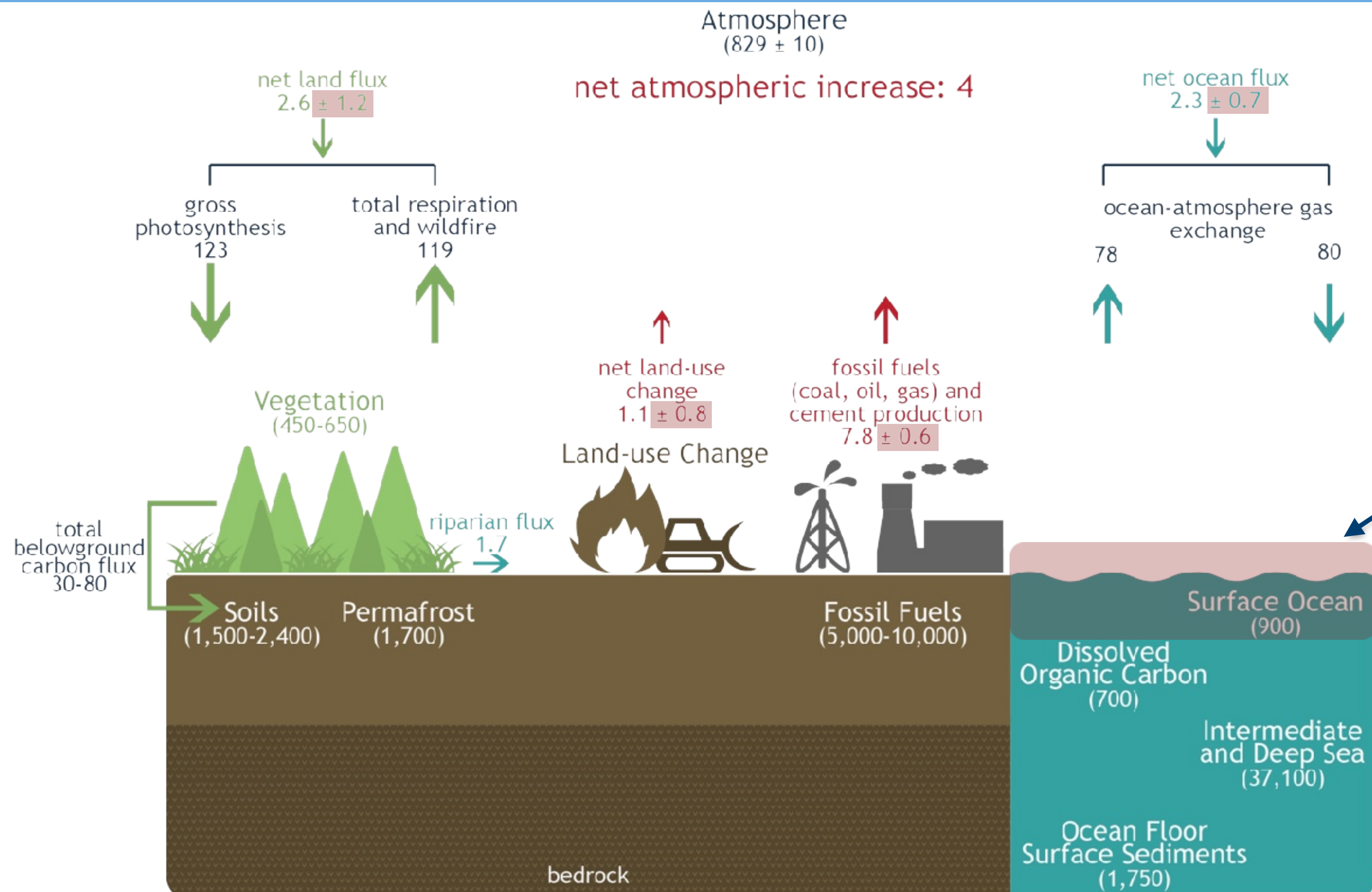
HARVARD (2017)

- Ocean has taken **93%** of heat generated since the industrial revolution, and **30%** of anthropogenic CO₂
 - Will this uptake stop?
 - How does the ocean and atmosphere warming feedback on these processes?
 - Is there a catastrophic tipping point?



Carbon Fluxes

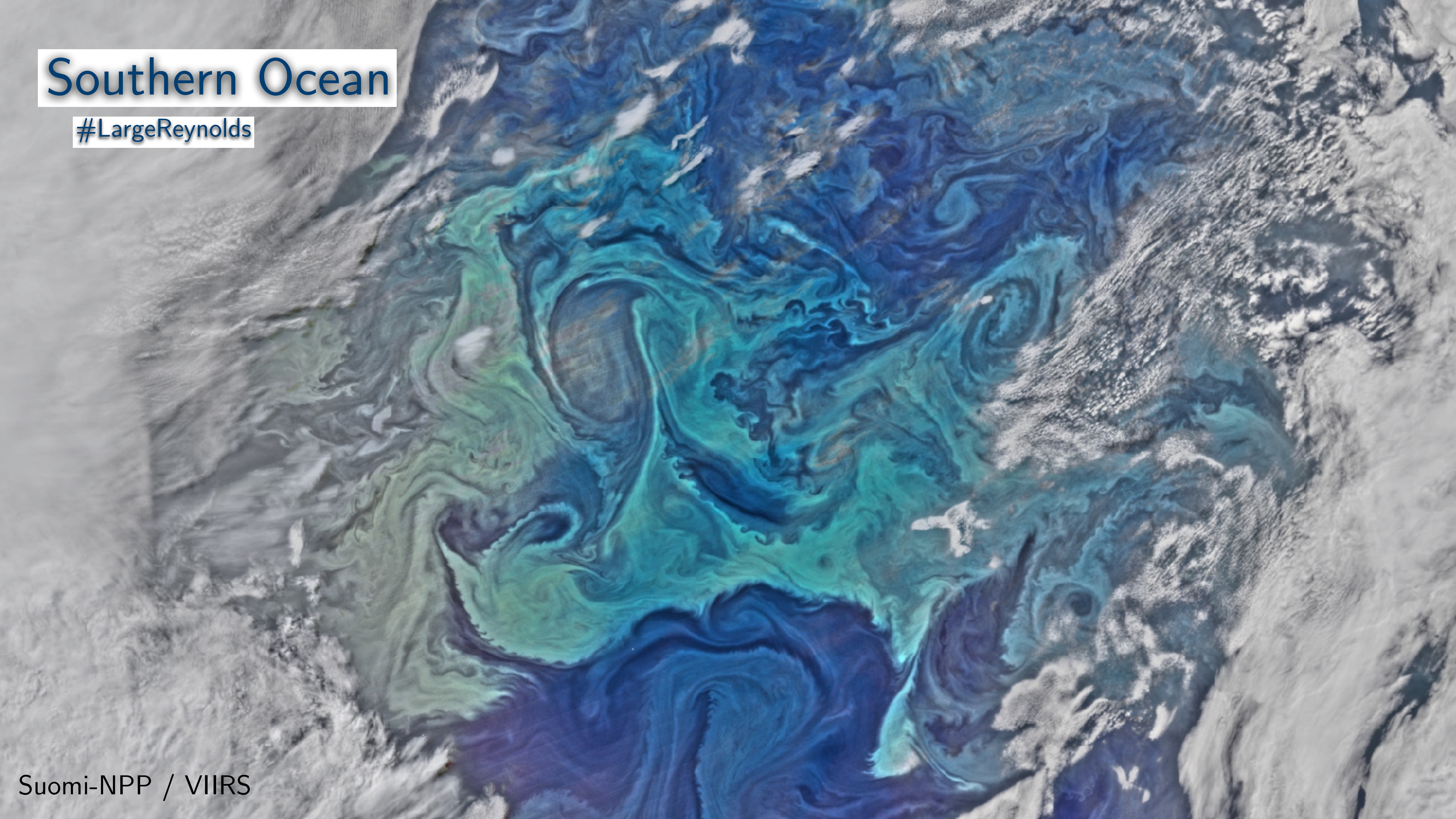
Kayler, et al. (2017)



Submesoscales
important here!

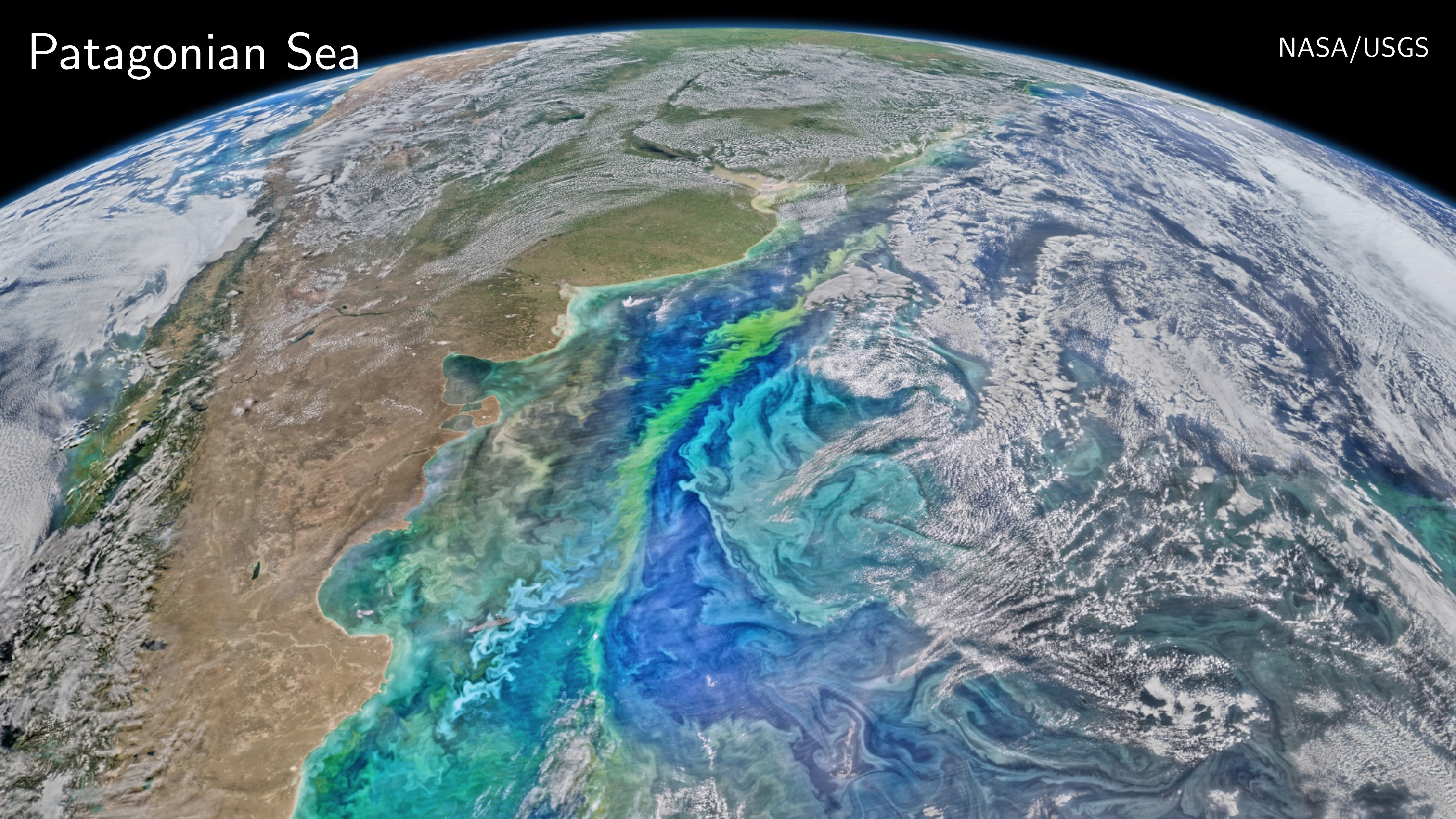
Southern Ocean

#LargeReynolds



Patagonian Sea

NASA/USGS





van Gogh (1889)

Force Balance in the Submesoscales (1-10 km)

$$\frac{D\mathbf{u}}{Dt} = \underbrace{\frac{\nabla p}{\rho_0}}_{\text{Pressure}} - \underbrace{2\boldsymbol{\Omega} \times \mathbf{u}}_{\text{Rotation}} + \underbrace{\nu \nabla^2 \mathbf{u}}_{\text{Viscosity}} - \underbrace{g \frac{\rho}{\rho_0} \hat{\mathbf{k}}}_{\text{Buoyancy}}$$

$\mathcal{O}(1)$ $\mathcal{O}(1)$ $\mathcal{O}(1)$

FUN!

Fronts: The Gulf Stream

$$M^2 \equiv -g\partial_x \rho / \rho_0$$

f : Coriolis Parameter

$$M^2 / f^2 \approx 40$$

Cold

Front A region with a large horizontal density gradient, $\partial_x \rho = -M^2 \rho_0 / g$, typically balanced by a *perpendicular* current.

Warm

Fronts: River Outflow into the Gulf of Mexico

Fresh

Salty

$$M^2 \equiv -g\partial_x \rho / \rho_0$$

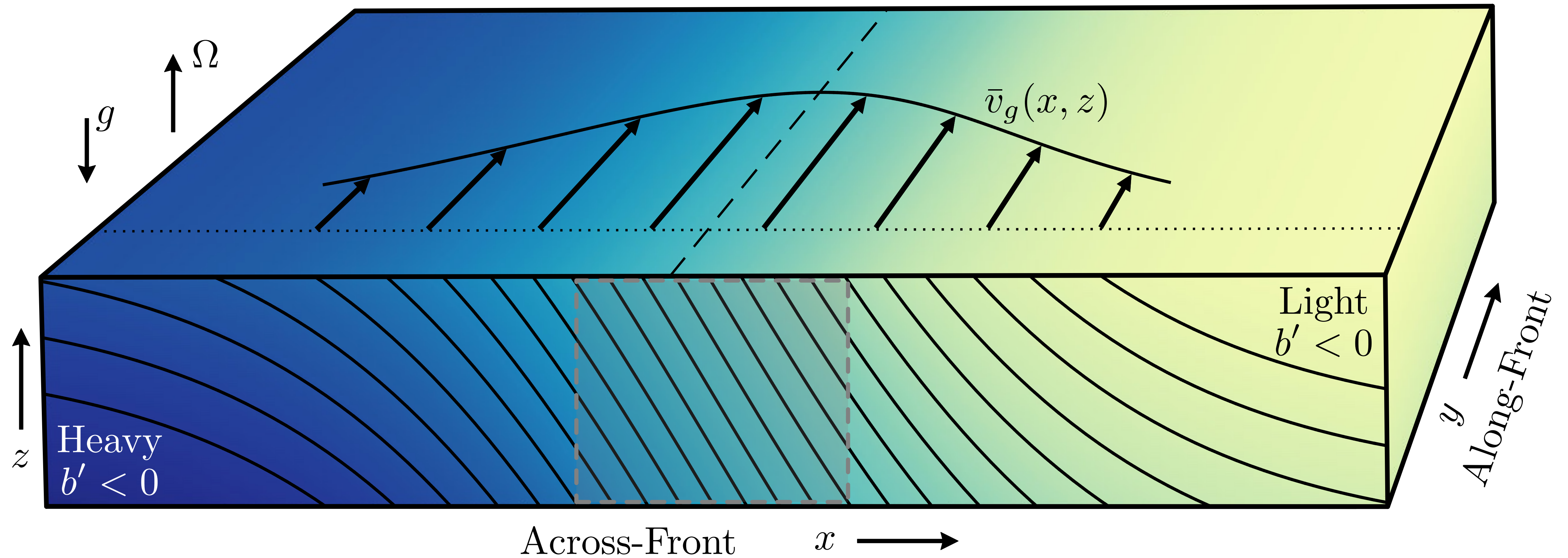
f : Coriolis Parameter

$$M^2 / f^2 \approx 500$$

Dynamics within a Front

What happens in a front (doesn't necessarily) stay within a front

Structure of a Front



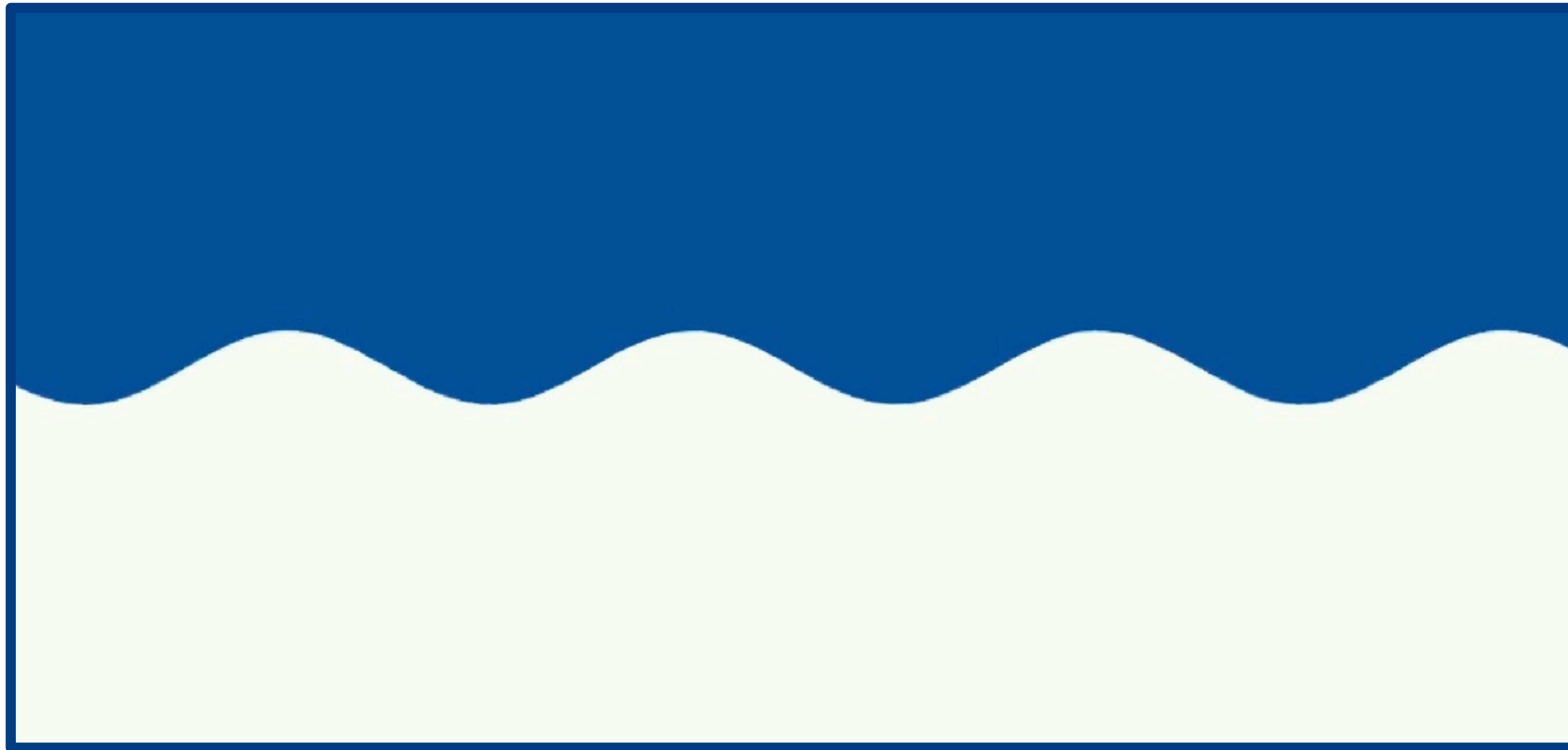
Internal Gravity Oscillations

Copley (1754)



$$\omega = \sqrt{-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}} = \sqrt{N^2}$$

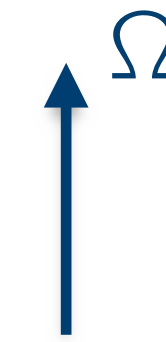
Convective (Rayleigh-Taylor) Instability



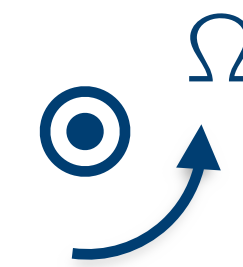
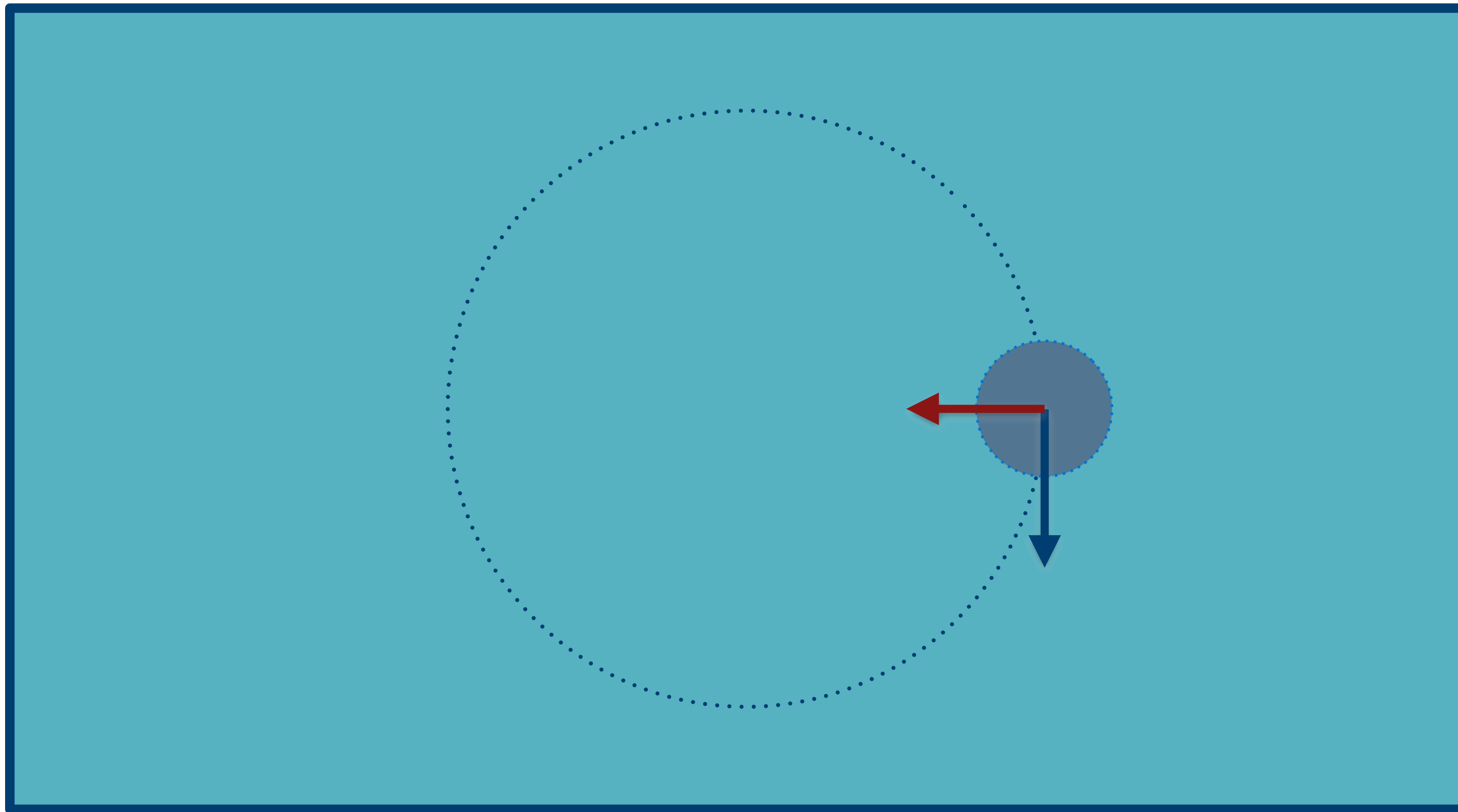
$$\omega = \sqrt{-\frac{g}{\rho_0} \frac{\partial \rho}{\partial z}} = \sqrt{N^2}$$

Inertial Oscillations

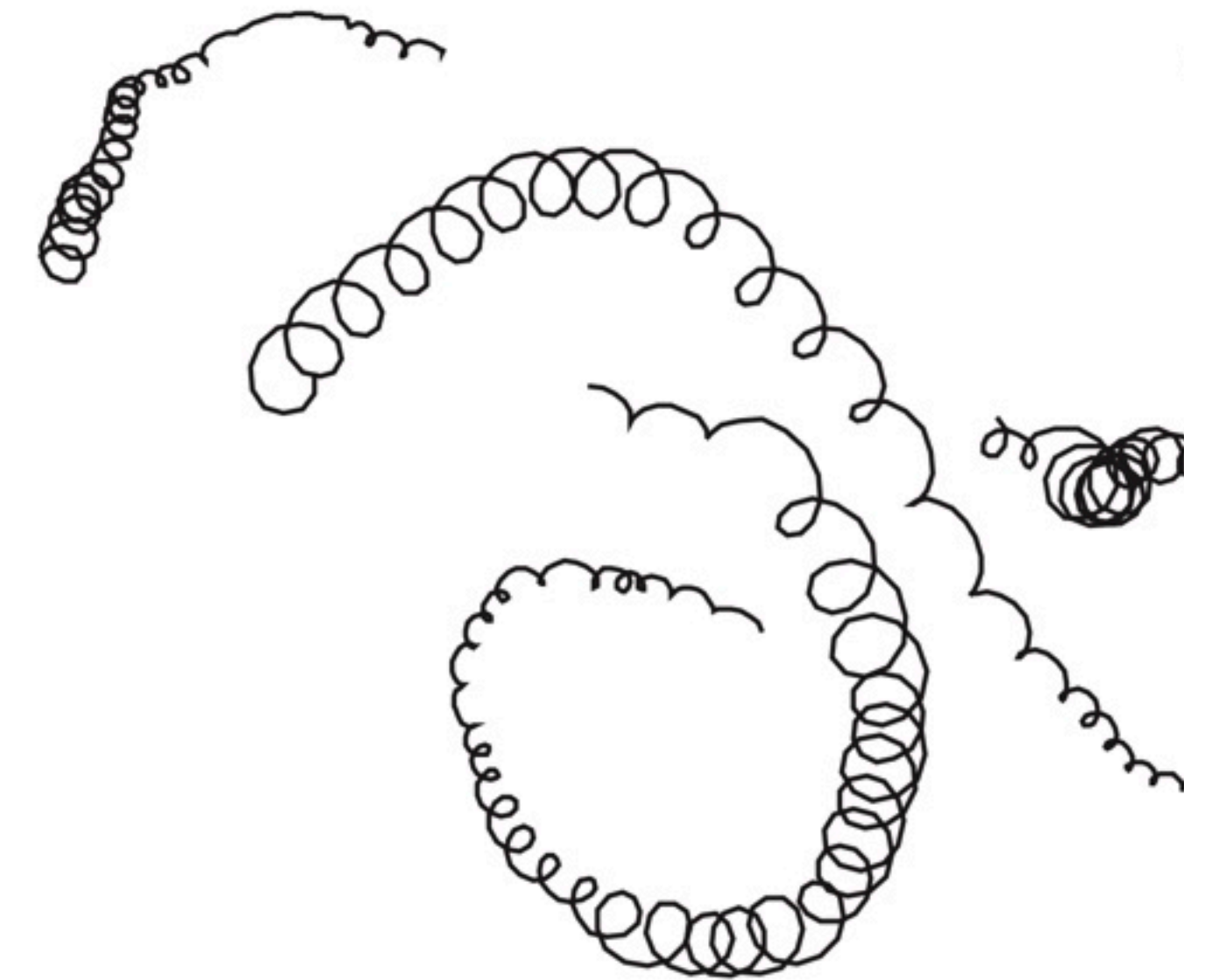
Copley (1754)



Inertial Oscillations



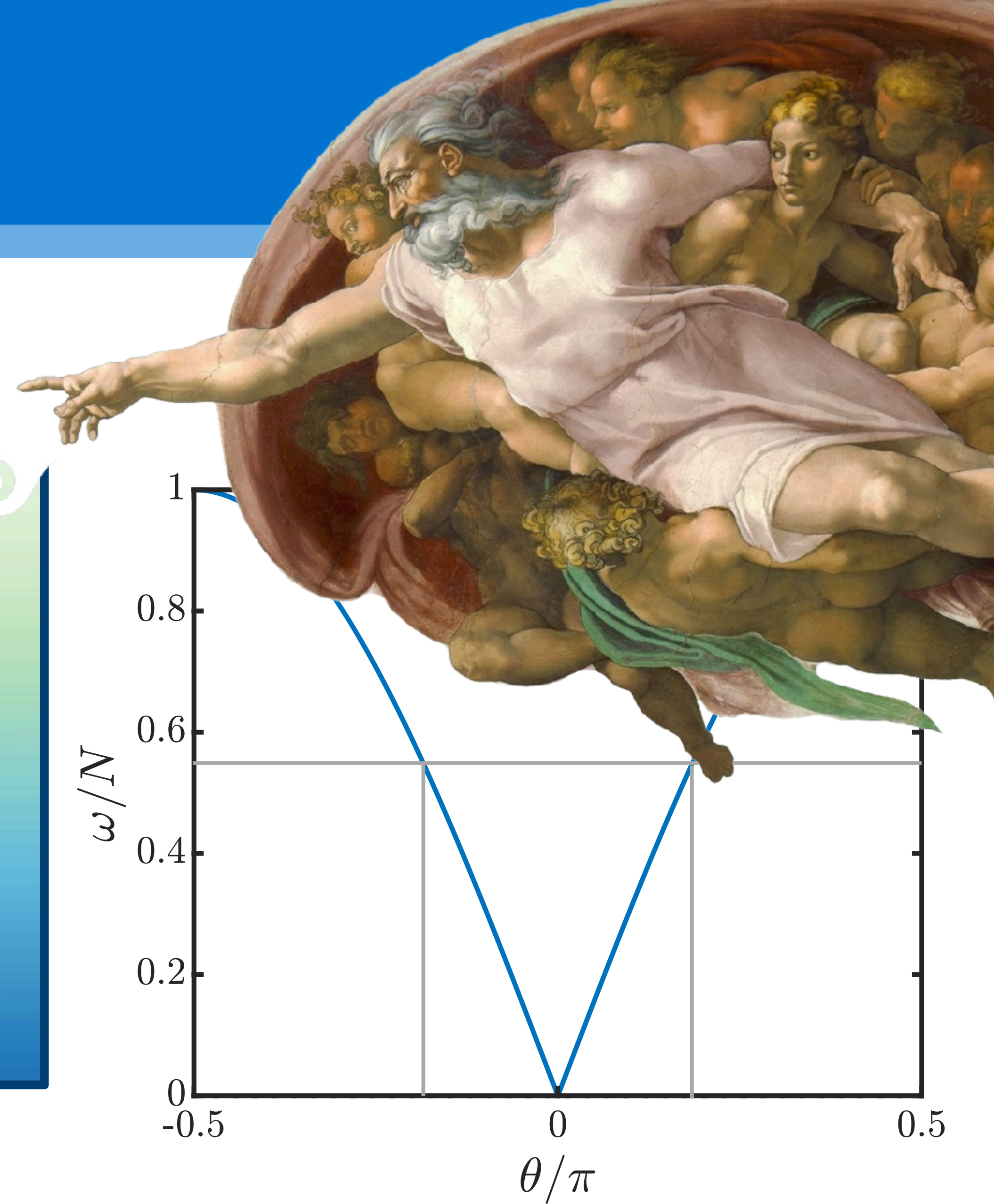
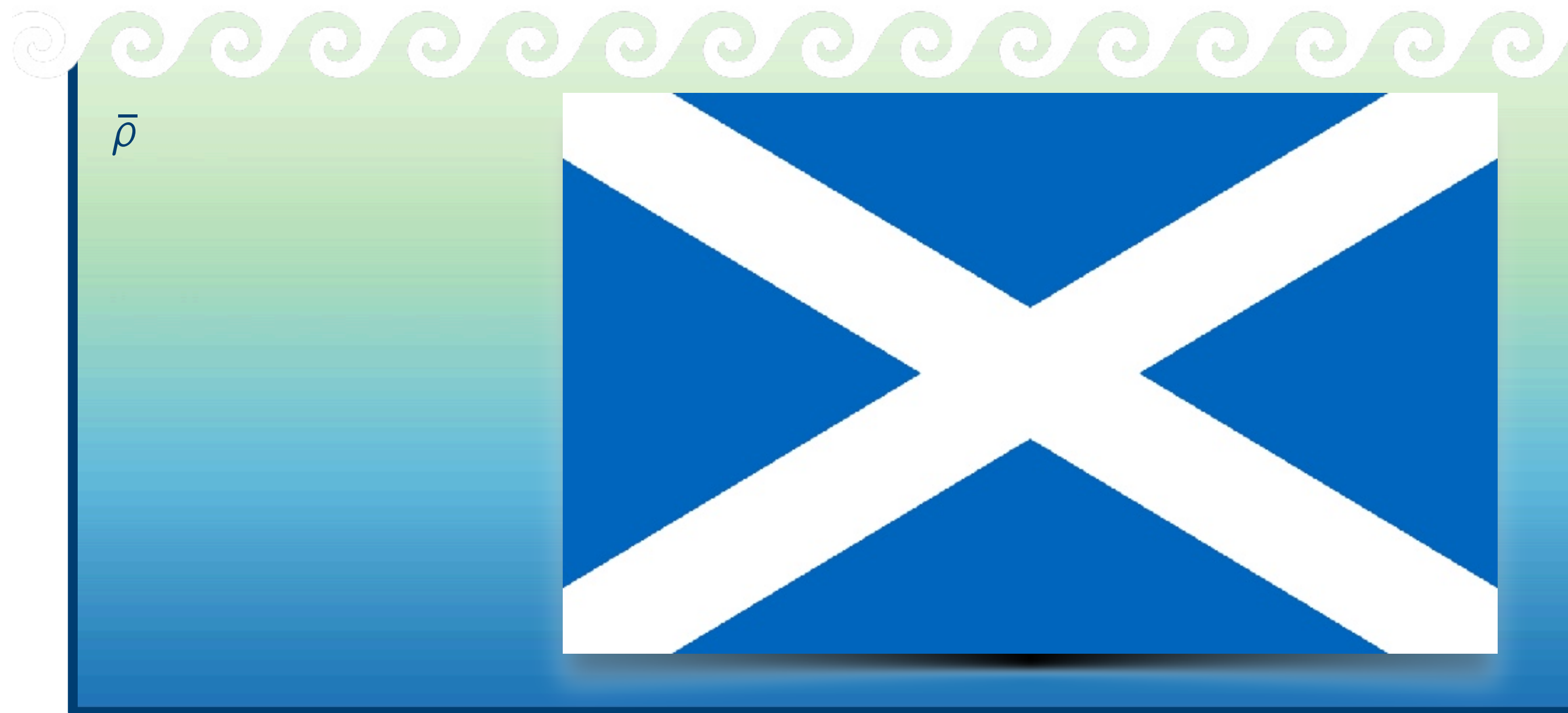
$$\omega = 2\Omega \sin \varphi = f$$



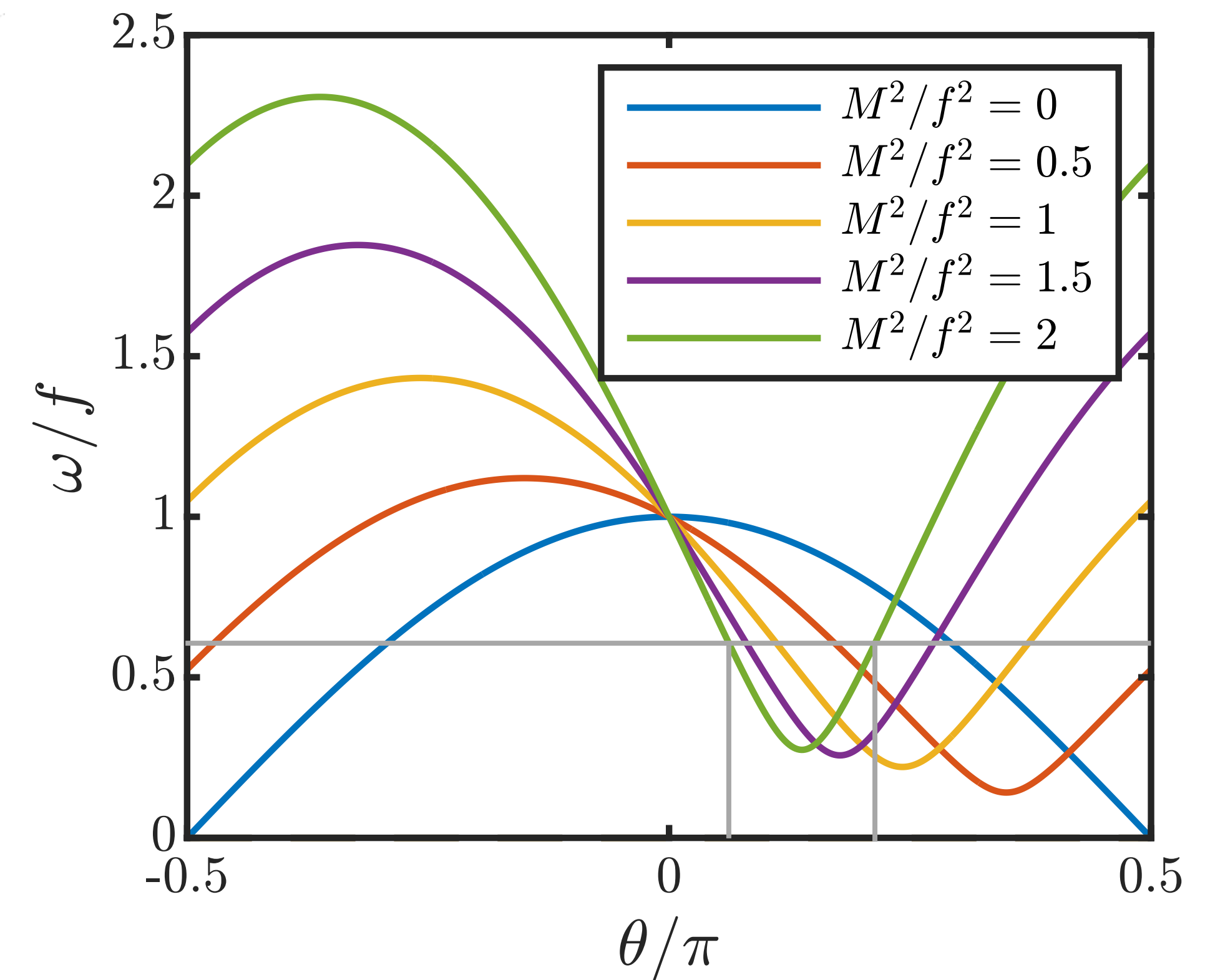
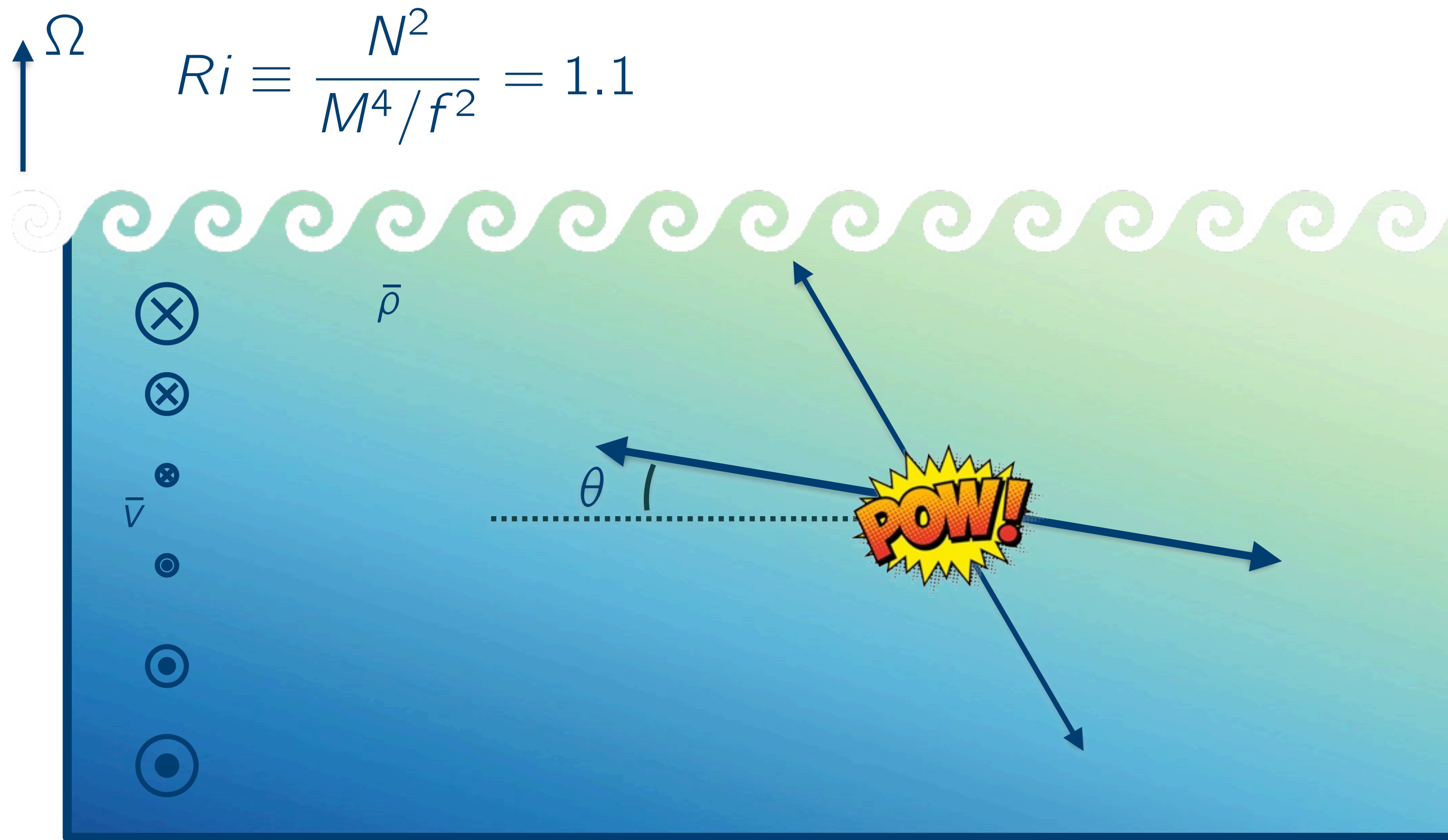
100 km

Linear (Small) Perturbations

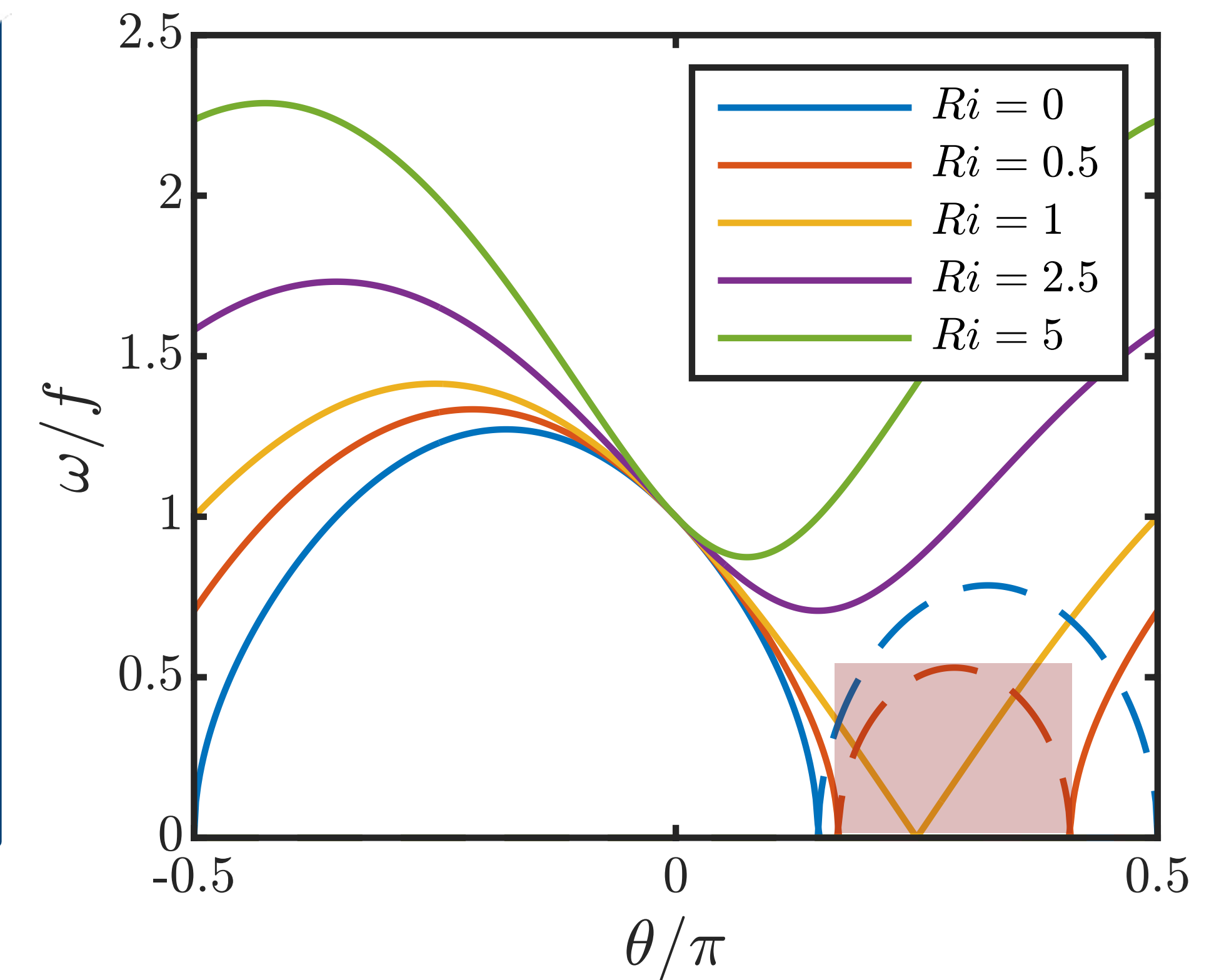
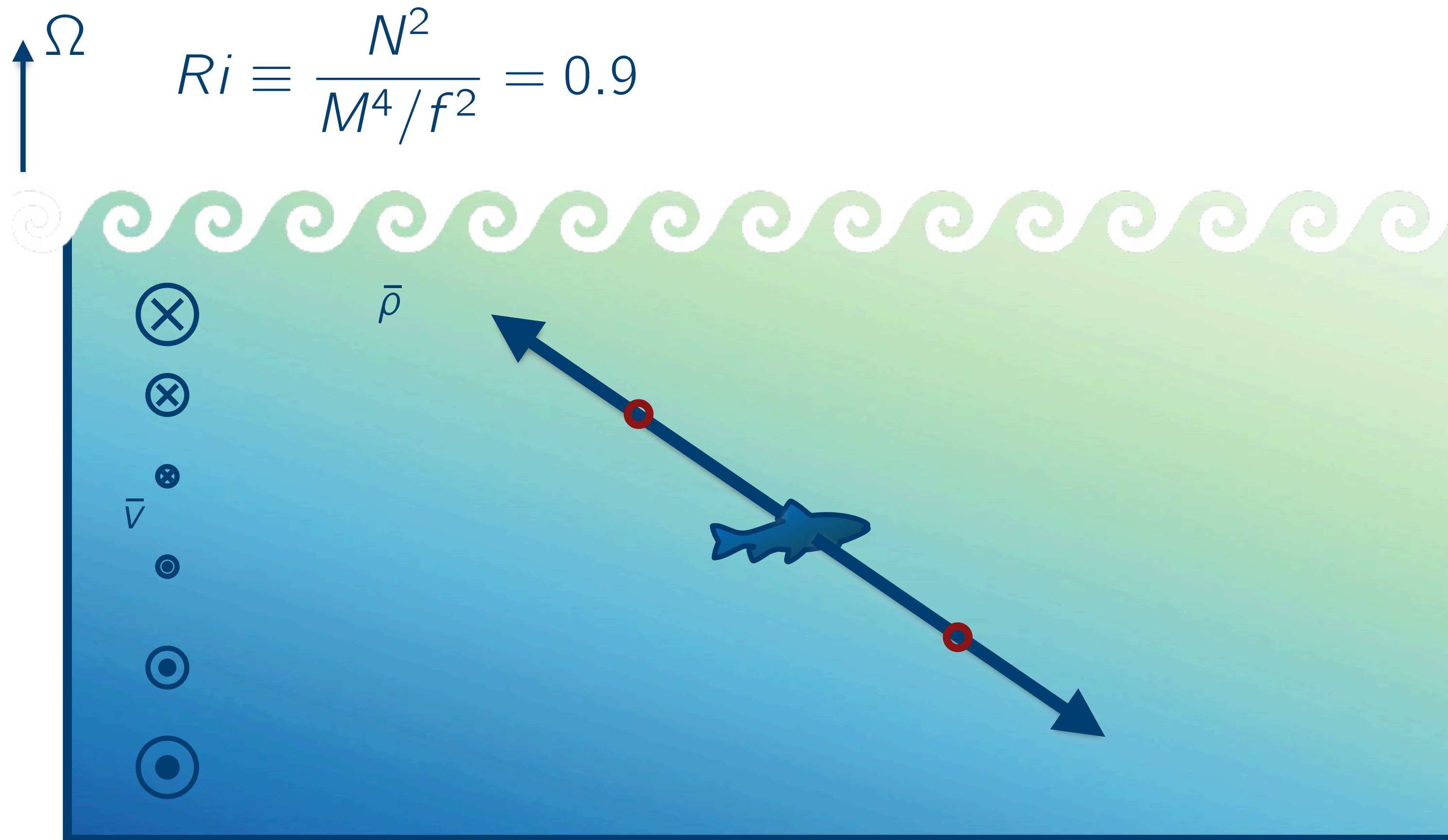
Michelangelo (1512)



Inertia-Gravity Waves



Inertia-Gravity Waves → Symmetric Instability (SI)

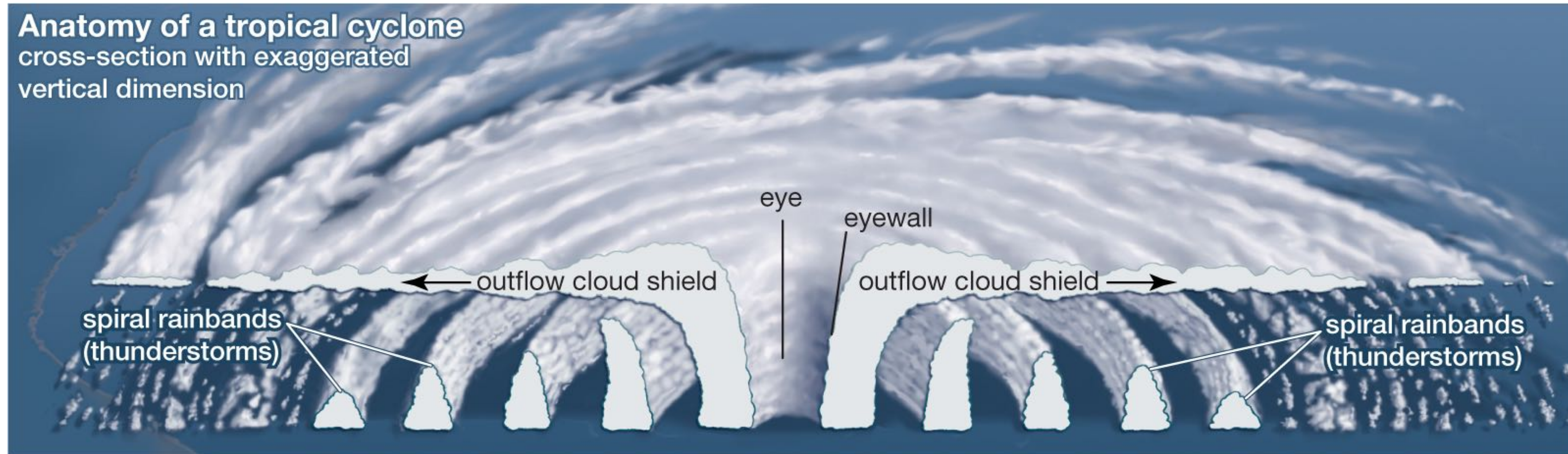


Atmospheric Waves

Internal Waves

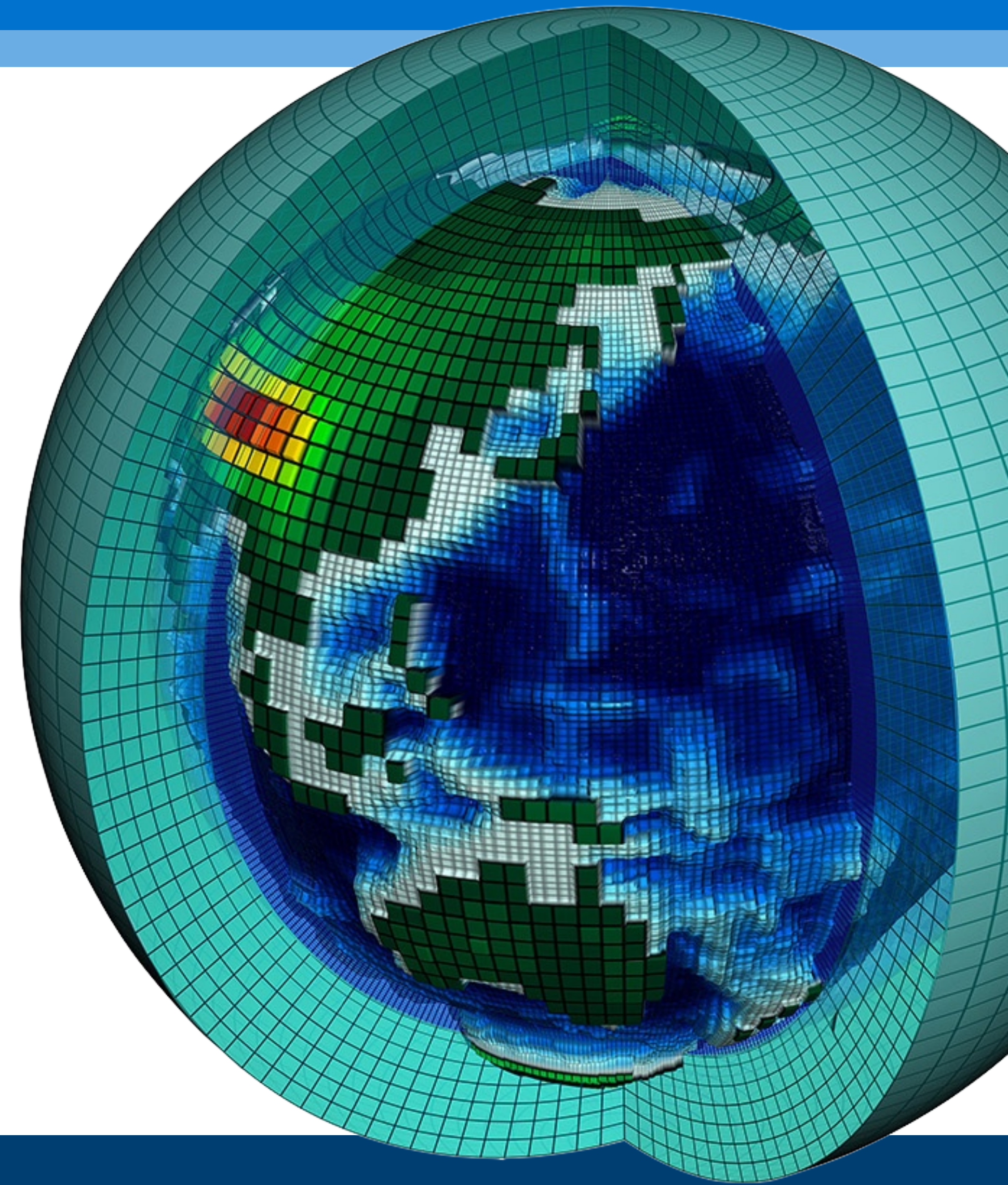
Symmetric Instability Observations

Zehnder (2019)



So...why is this important?

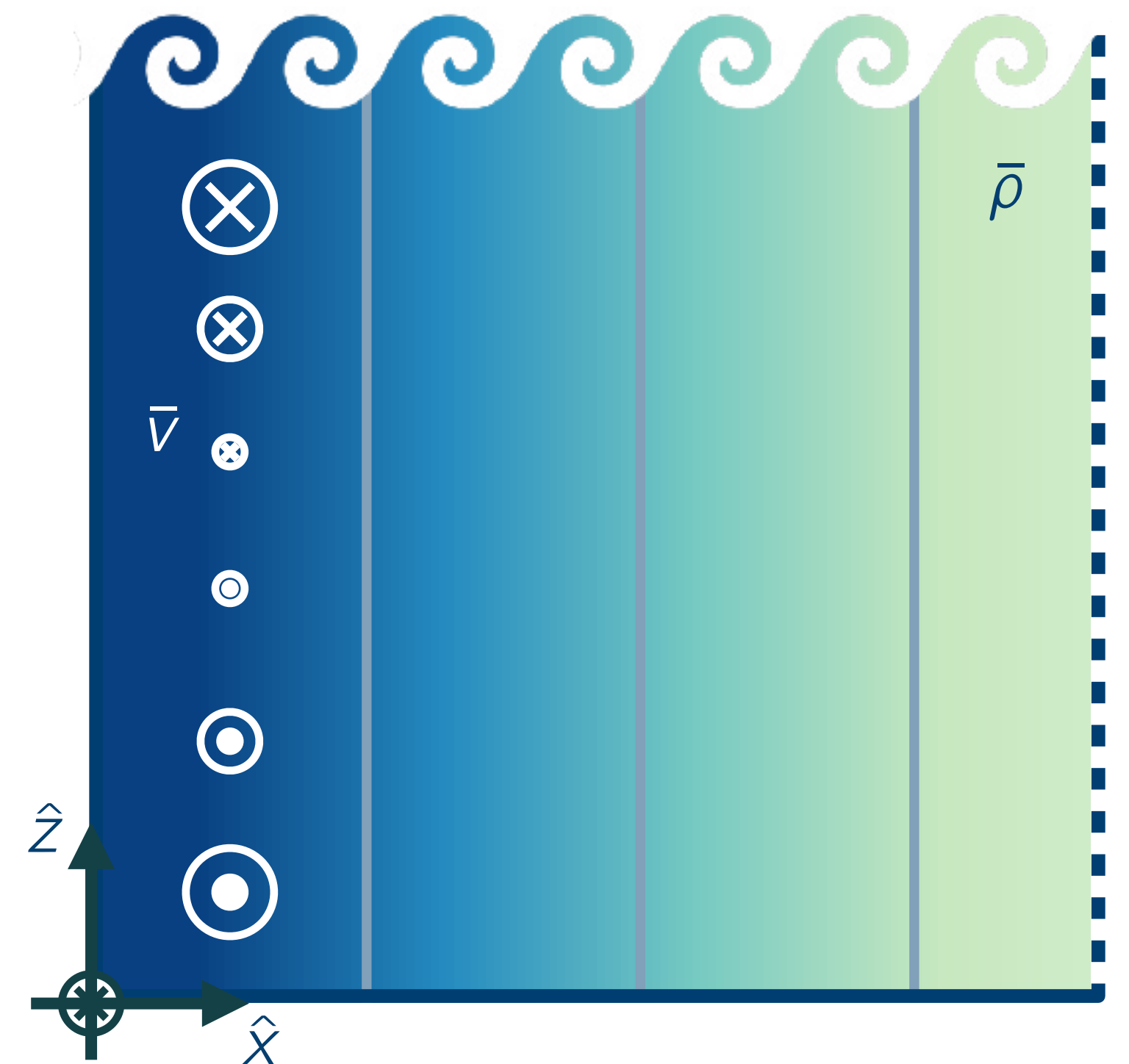
- Modelling the entire ocean/atmosphere is **impossible**
- Back to the Forest and the Trees:
 - Should get away from empirically “tuning” models
 - *Physically* model backscatter (towards large scales) and eddy damping (to small scales)



Nonlinear Effects

Equilibration of an SI-Unstable Front

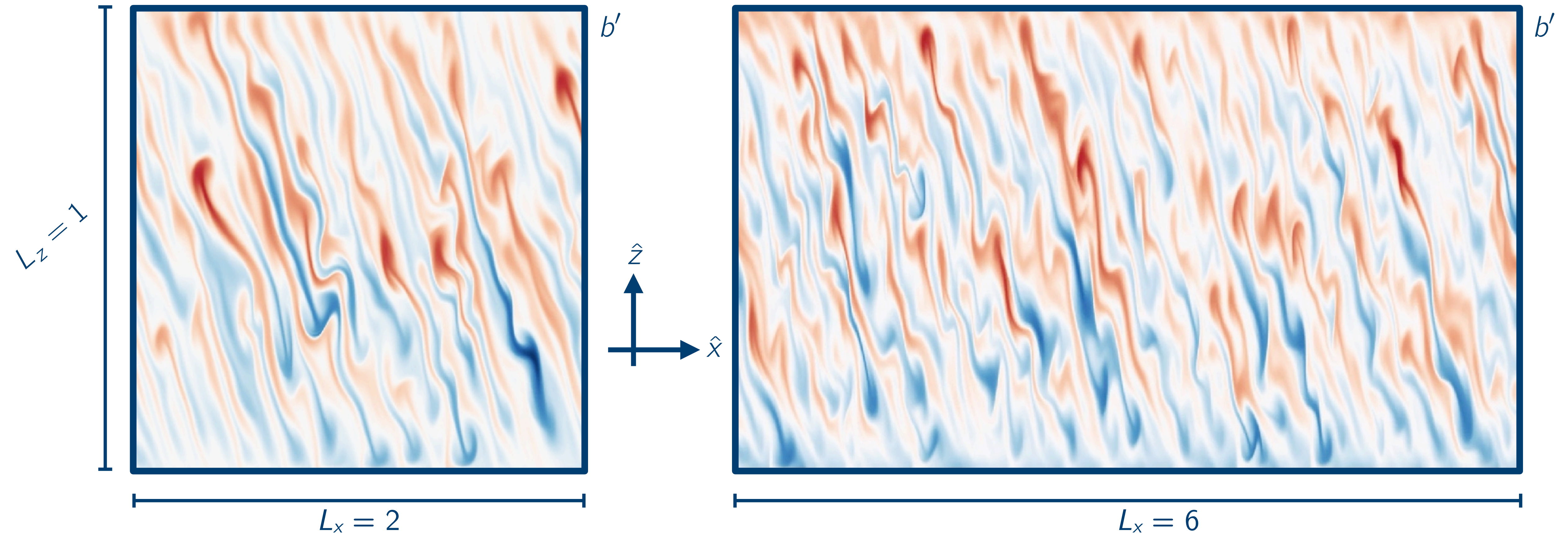
- 2D pseudo-spectral / finite difference simulations
 - Initial condition in Geostrophic Balance
- Focus on a “vertical” front
- SI prompts large oscillations and enhances mixing



Equilibration of Frontal Regions

$$M^2/f^2 = 1$$

$$M^2/f^2 = 10$$



Summary

Brooklyn Museum (12)

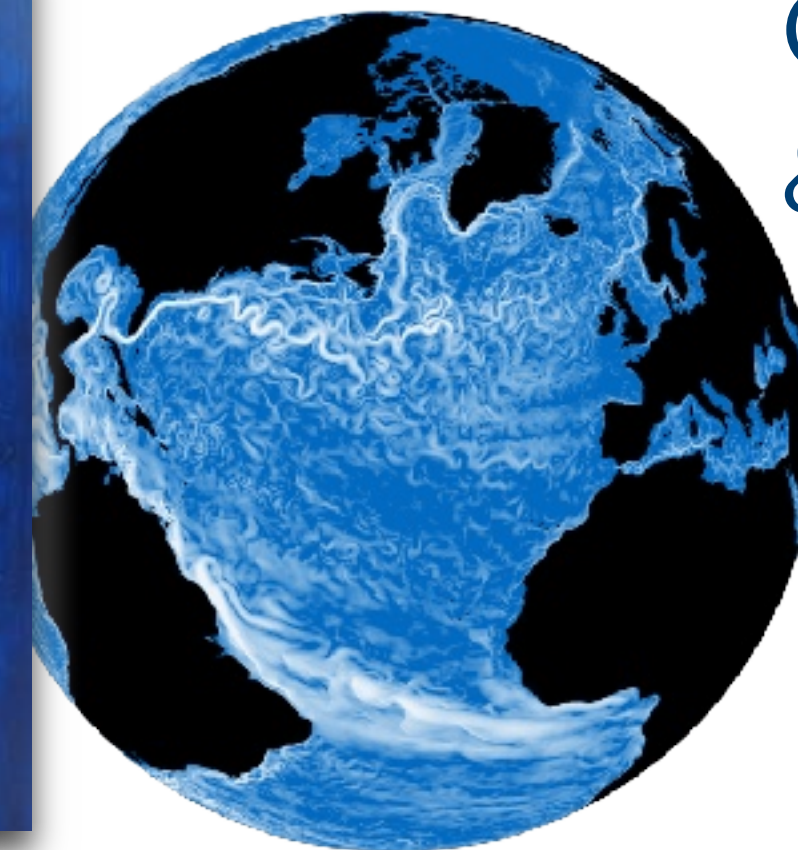
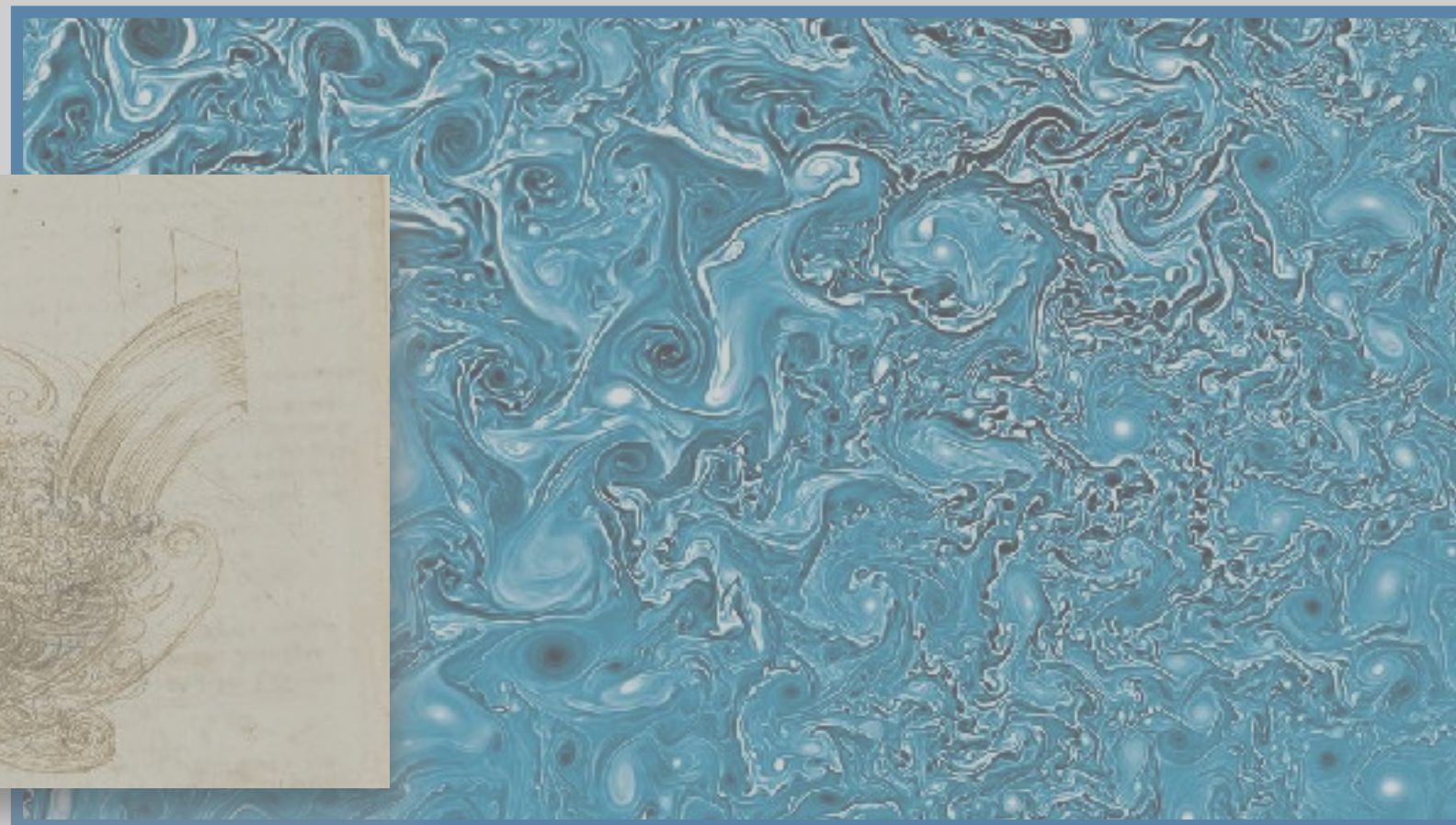
Waves & Eddies



Symmetric Instability

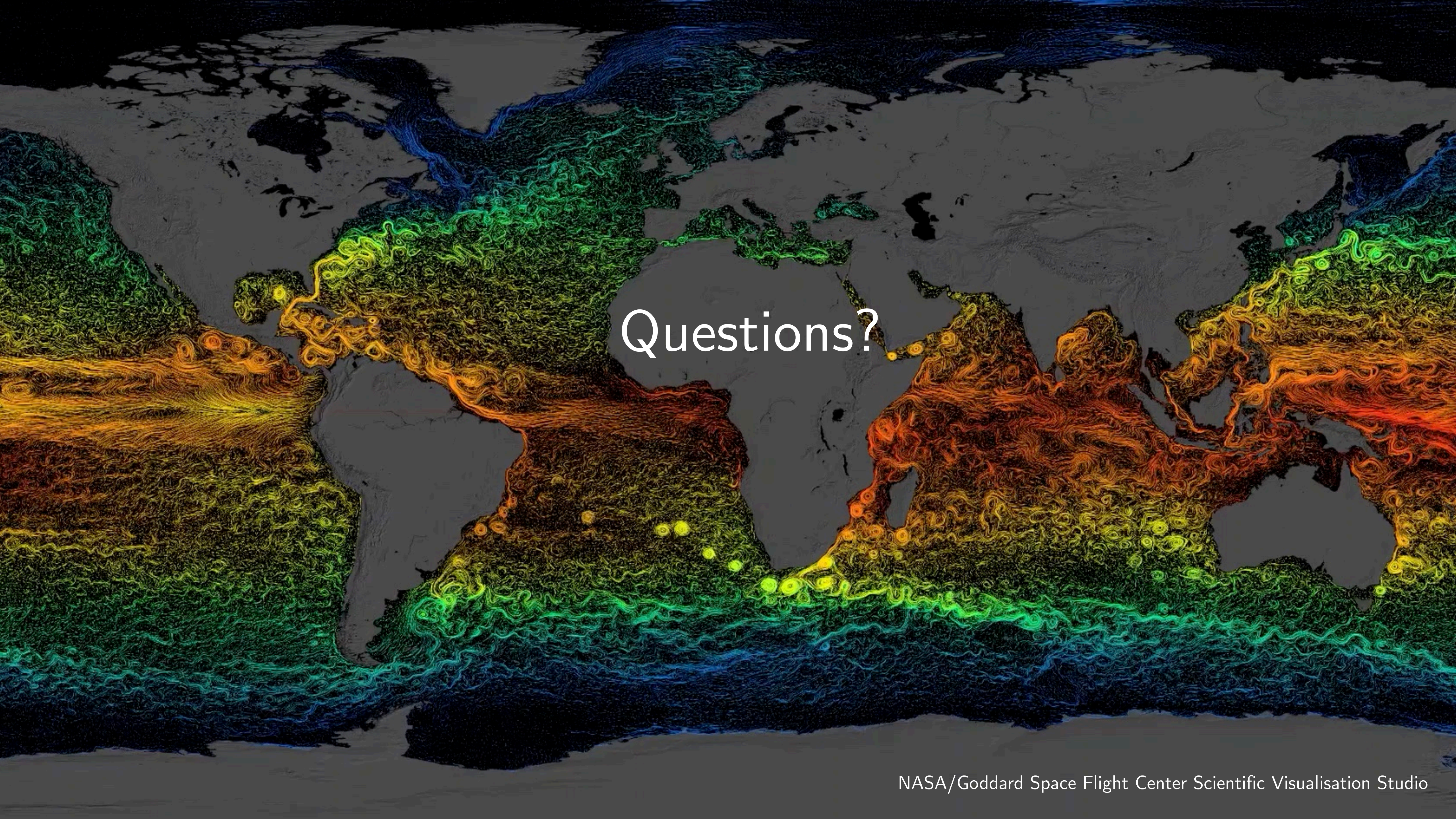


Turbulence



Ocean Circulation & The Circle of Life



A global map visualization of magnetic field lines, likely from a heliographic projection. The lines are color-coded, with blue and green at the poles and transitioning through yellow and orange to red at the equator. The lines show a complex, swirling pattern, particularly concentrated around the equatorial region. The word "Questions?" is centered in white text over the Atlantic Ocean.

Questions?