Fluid dynamics (& climate) for "Physics majors"?

Peter Read
University of Oxford
UK

"Every physicist should know some fluid dynamics, and every university Physics department should include the subject In its core curriculum"

T. E. Faber
Fluid Dynamics for Physicists
CUP (1995)

HOWEVER - hardly any UK universities actually do it!

Background

- Introducing fluid flow and GFD to undergraduates in **PHYSICS?**
  - **Engaging at a quantitative level (with maths!)**
  - ***And* enthusing them!**
- Fluid flow and Climate as topics in the **mainstream Physics course**.....?
  - Oxford's "experiment" in putting fluid flow & climate physics into the mainstream (compulsory) elements of the undergraduate Physics course
  - **Why....?**
  - **How....?**

Why?

- Fluid flow is close to everyday experience
  - Unlike quantum mechanics or relativity!
- Relevance to many applications of Physics
  - Engineering
  - Astrophysics
  - Plasmas
  - Biophysics
    - respiration, circulation, motility……
  - Atmospheres and oceans
    - Environment and climate
  - Planetary interiors……
- Role of Nonlinearity…!!!
  - Instability, chaos, turbulence etc…..

How...?

- Lectures in 3rd year [~130 students]
  - Fluid flow
    - General introduction to fluid flow and simple applications
    - Draws on mainstream mathematical concepts
  - Climate Physics
    - Radiation, energy balance & simple models of climate change
    - Draws on mainstream topics e.g. in thermal & statistical physics…
- Practical experiments in 3rd year
  - Rolling programme during the year…..
  - Pairs of students - 2 day experimental investigations
- Optional specialist lectures in 4th year [~30 students]
  - GFD
  - Climate
  - Atmospheric chemistry
  - Remote sounding
- Research projects [4th year]
  - Open-ended investigation using research-level apparatus

3rd year fluid flow course

- Applications of fluid flow in astrophysics, engineering, biology, weather & climate, oceanography, geophysics….
- Basic equations & conservation laws
- Simple models of flow flows
  - Poiseuille flow
  - Reynolds' experiment & instabilities
  - Couette flow & instabilities [Taylor vortices]
- Vorticity and its physical interpretation
- Inviscid, irrotational flows
  - Principles of aircraft flight
- Surface water waves
  - Nonlinear waves, solitons and KdV equation
- Very viscous flows
  - Stokes flow around sphere
  - Reversibility and microbe motility
- Elementary rotating flows
  - Taylor columns
  - Ekman layers

New…

Demos?

•Taylor-Couette

•Magnus effect

•Surface waves?

•Taylor's dye expt

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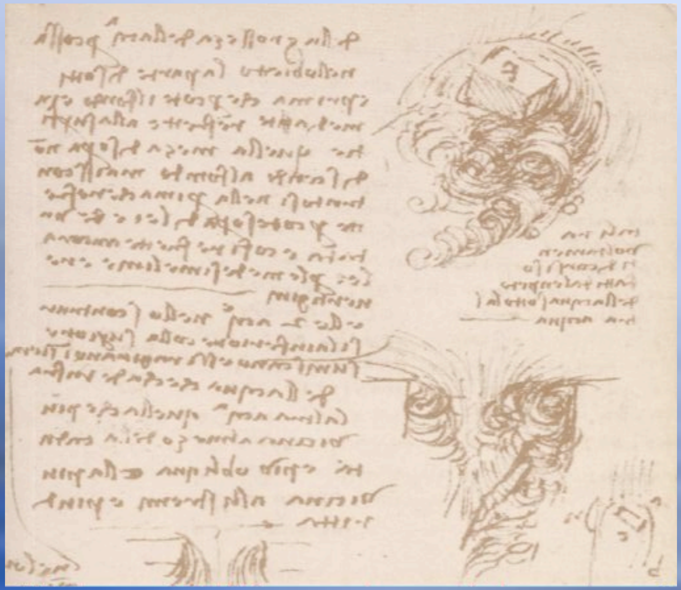
How to illustrate these topics?

- Images
- Movies
- Numerical model simulations
- Physical demonstrations
  - [still being developed - inspiration welcome...!]
- QUANTITATIVE example problems....

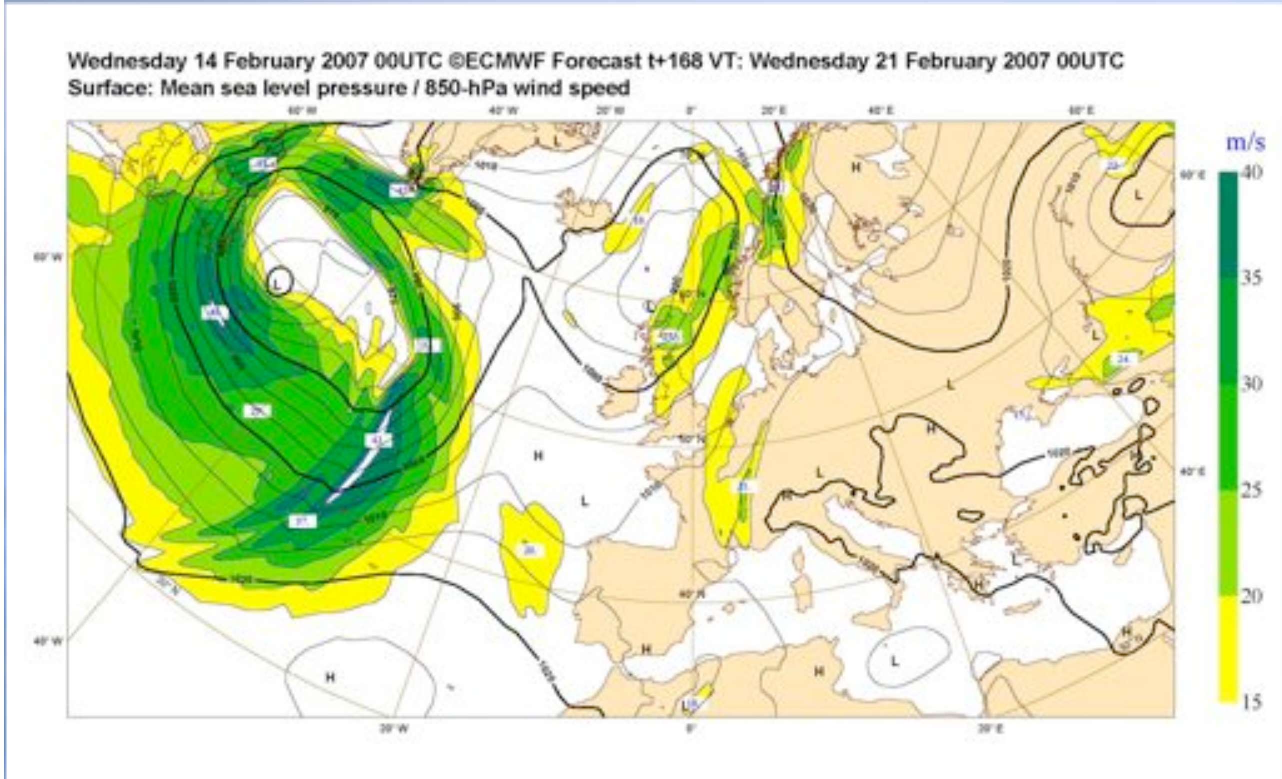
BUT

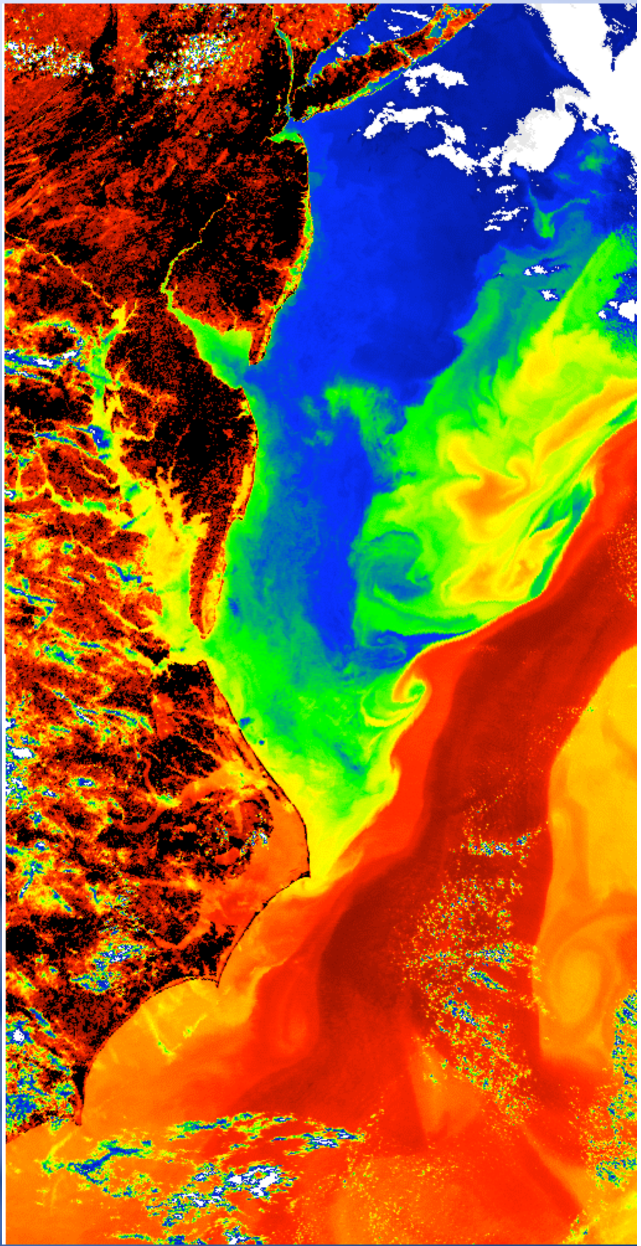
- Shortage of time.....
- Large numbers (> 100 students)

Natural water flows

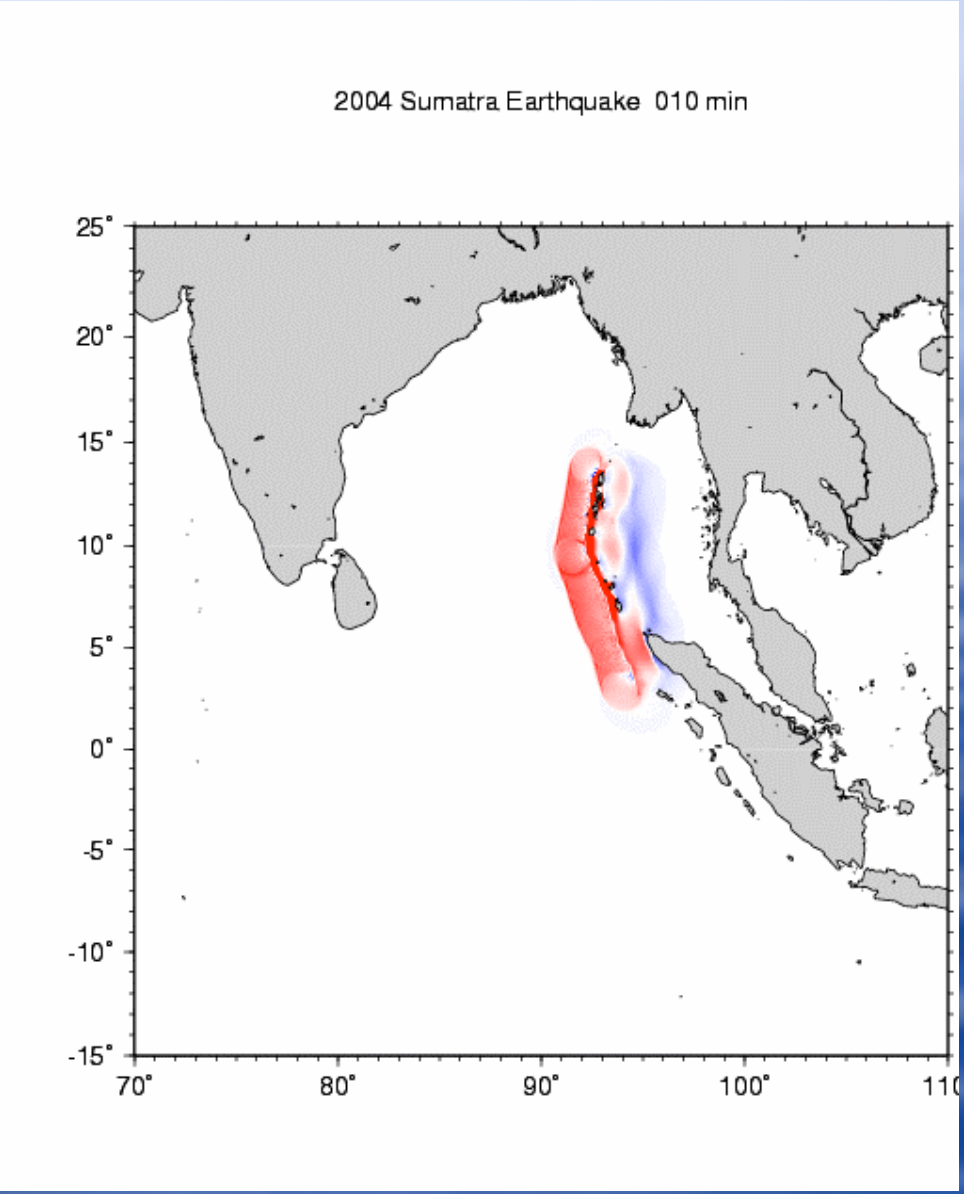


Weather & Ocean eddies





Asian Tsunami



Severn Bore

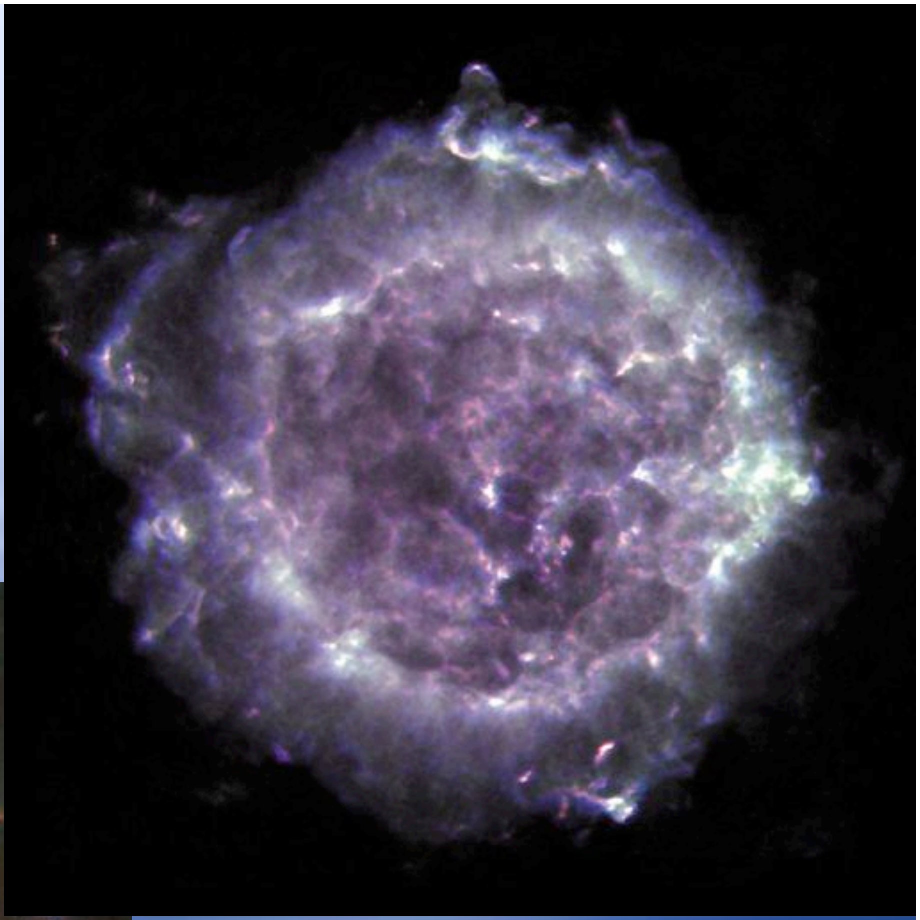
[Exploregloucestershire.co.uk]

Jupiter's Great Red Spot… and other atmospheric motions

(NASA)

Astrophysical fluid flows

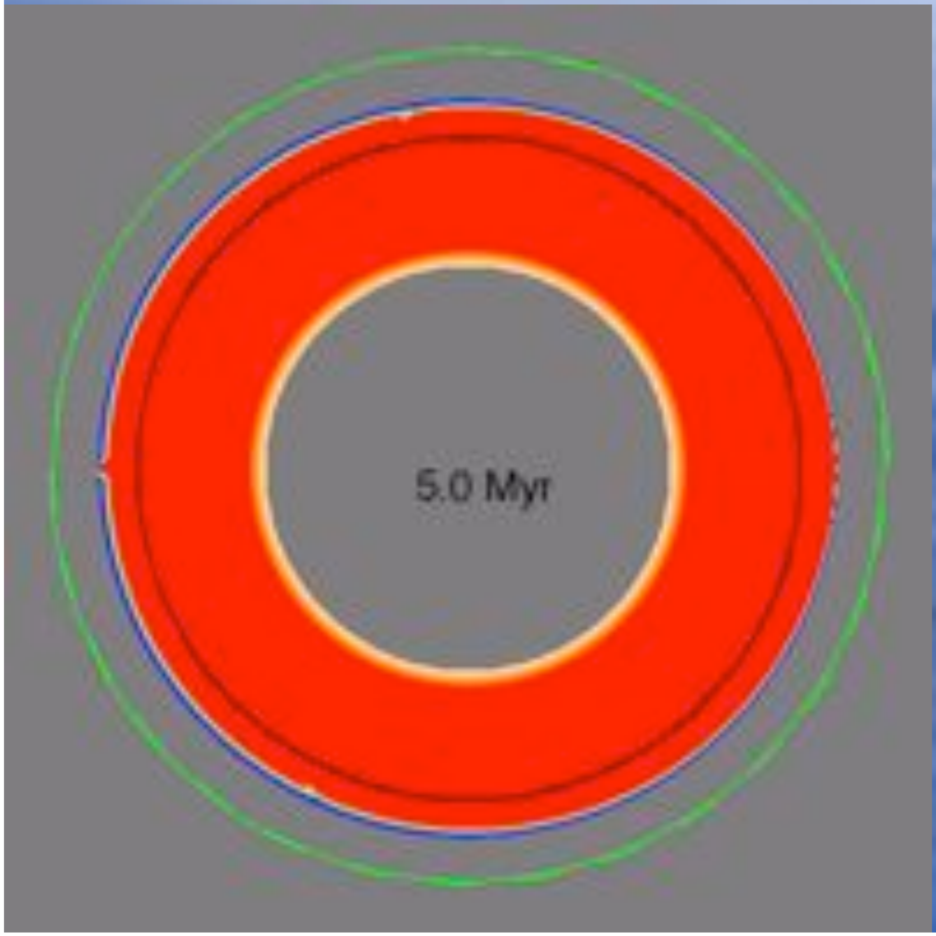
Supernova remnant in LMC - Hubble Space Telescope

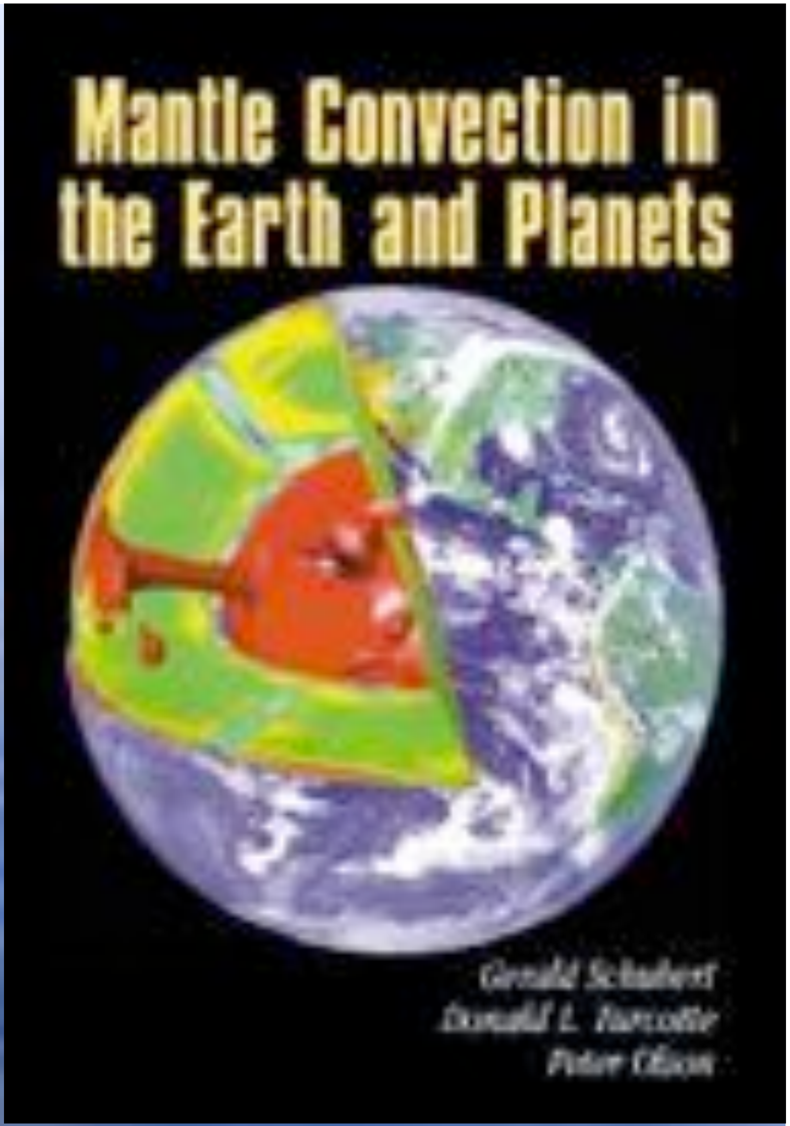


Supernova remnant Cassiopeia A -radio image by the Very Large Array (VLA)

Aerodynamics

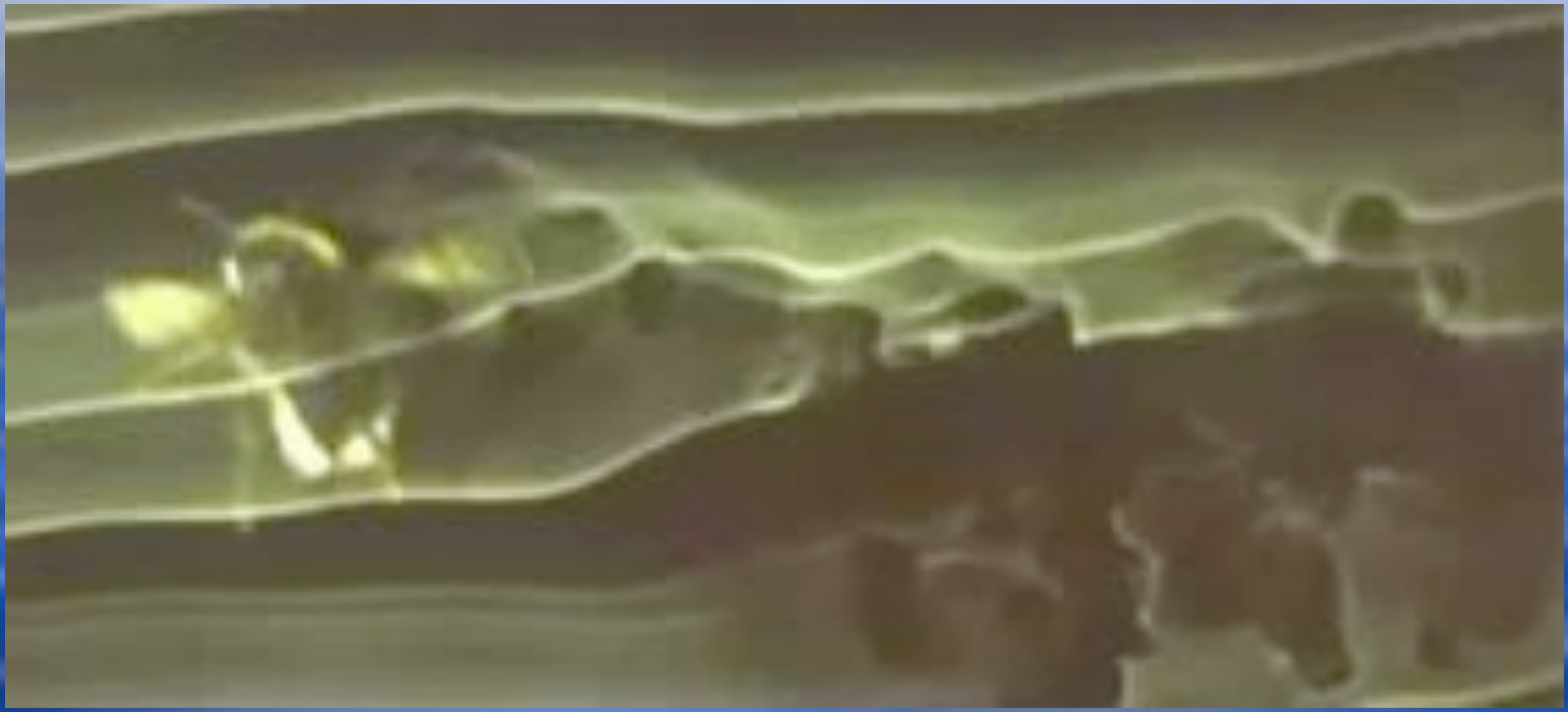
Fluid motions deep inside the Earth





Credit: Zhong, S., and Gurnis, M., Caltech 1994

Flight of the bumble-bee



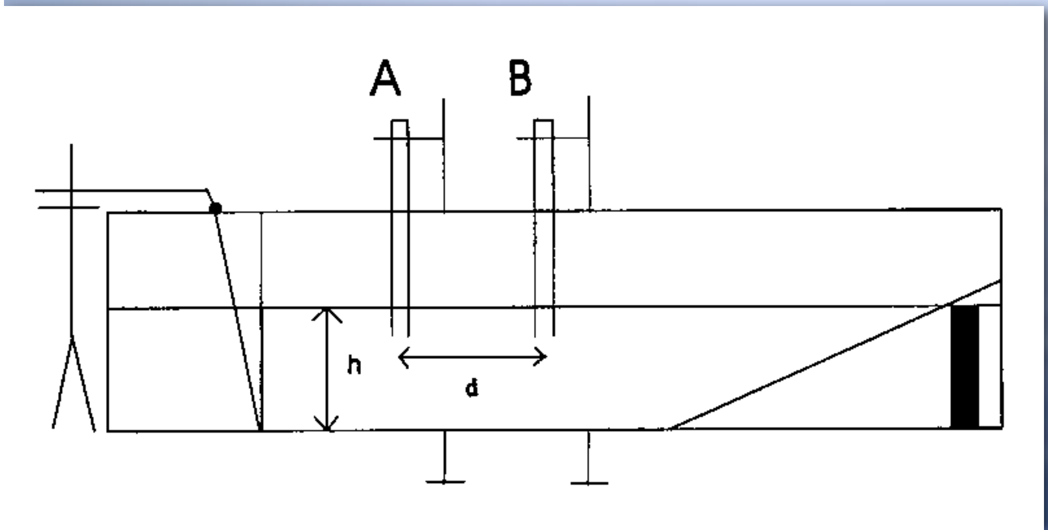
(Adrian Thomas, Zoology Department, Oxford University)

Low Re flows - time reversibility

Practical laboratory experiments [3rd year]

- Hands-on experience of phenomena and measurement techniques
- QUANTITATIVE study of physical processes
- Course includes both atmospheric physics and fluid flow experiments
  - Surface water waves
  - Differentially heated rotating annulus
  - Others……? [ideas welcome!]

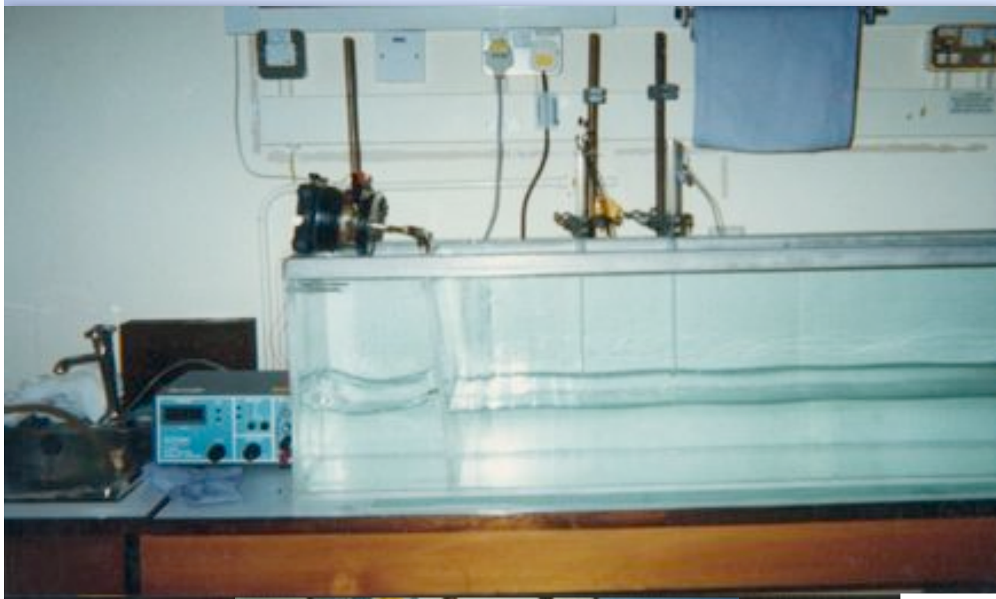
Surface water waves

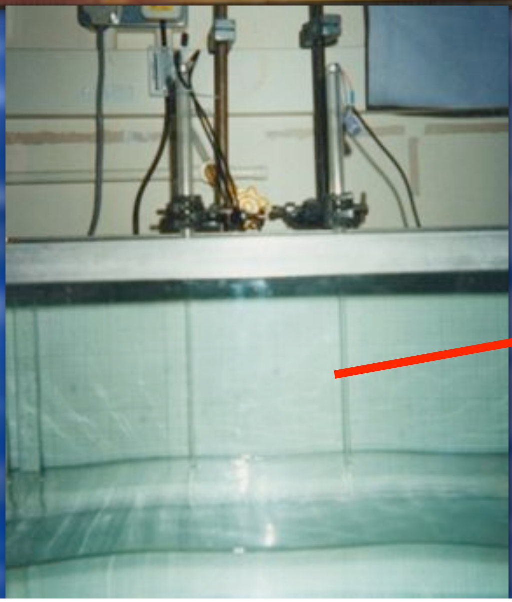


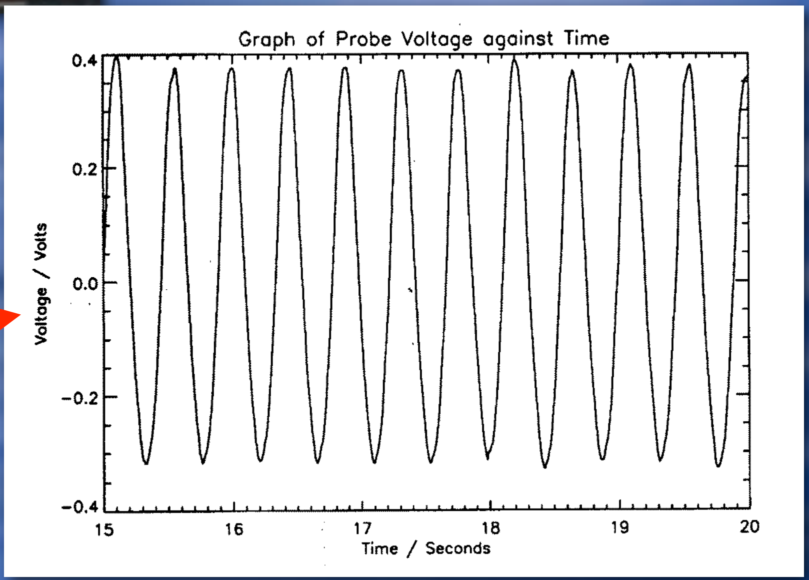
- Long rectangular channel (~2 m)
- 20 cm deep
- Hinged, oscillatory wave-maker at one end
- Sloping ‘beach’ at far end
- Measurements?
  - Pressure probes
  - Particle-tracking visualisations

Pressure sensors (electret microphones)
In sealed tubes used to sense
displacement of water surface

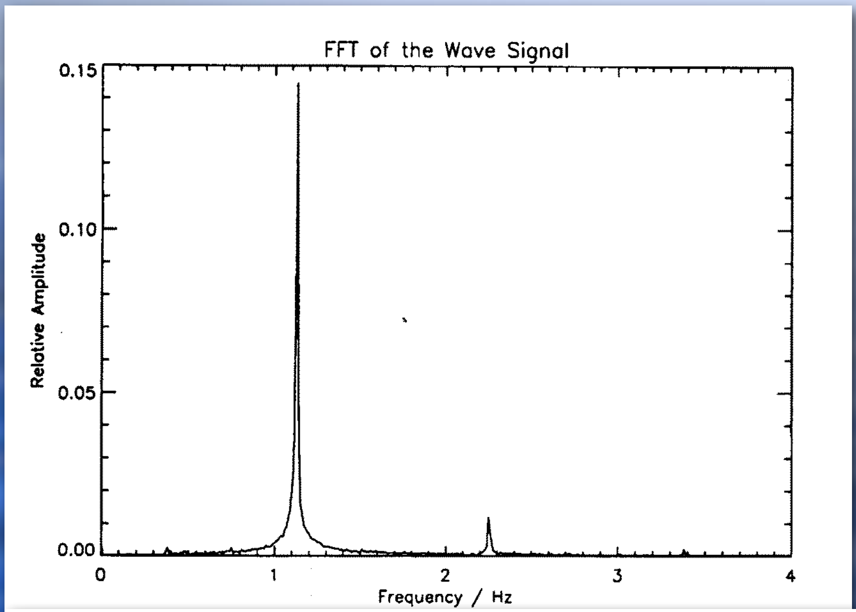
Surface water waves

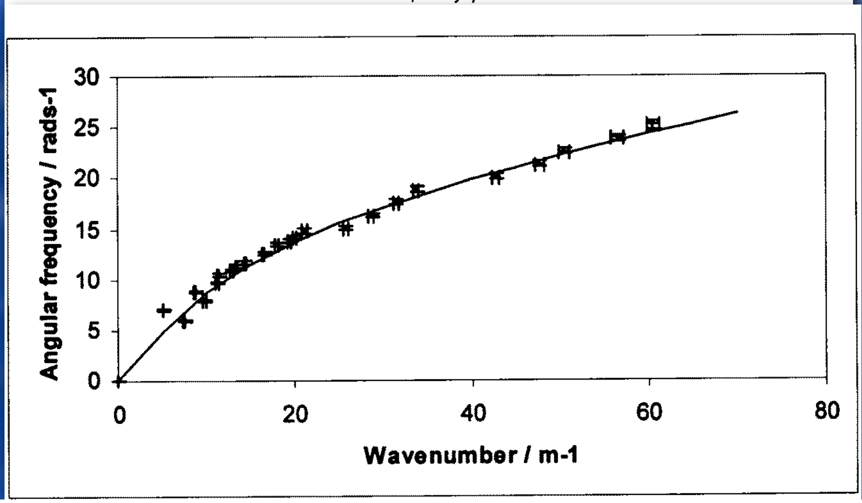






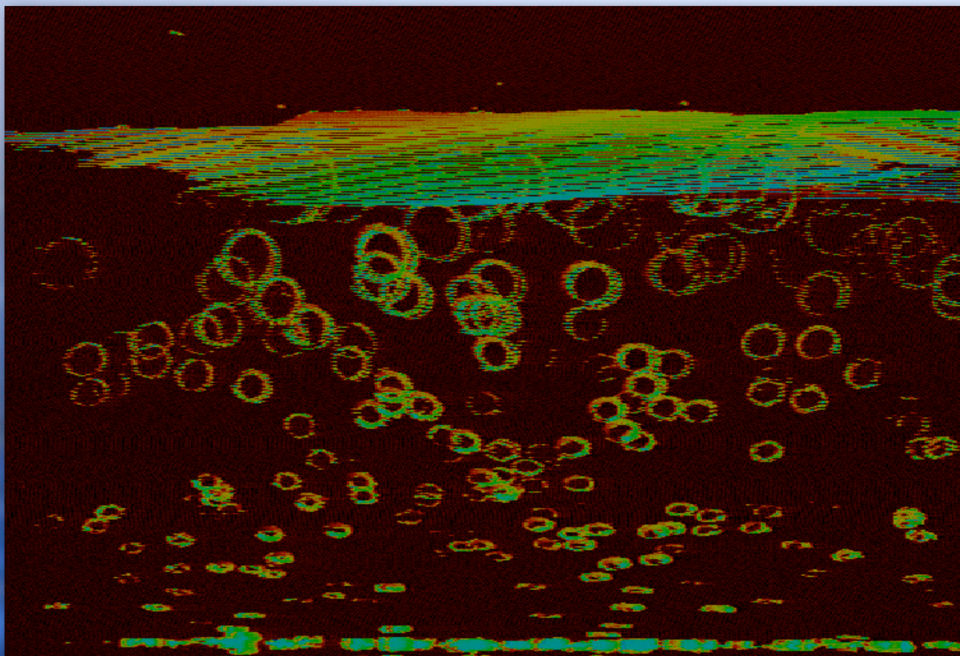
Surface water waves

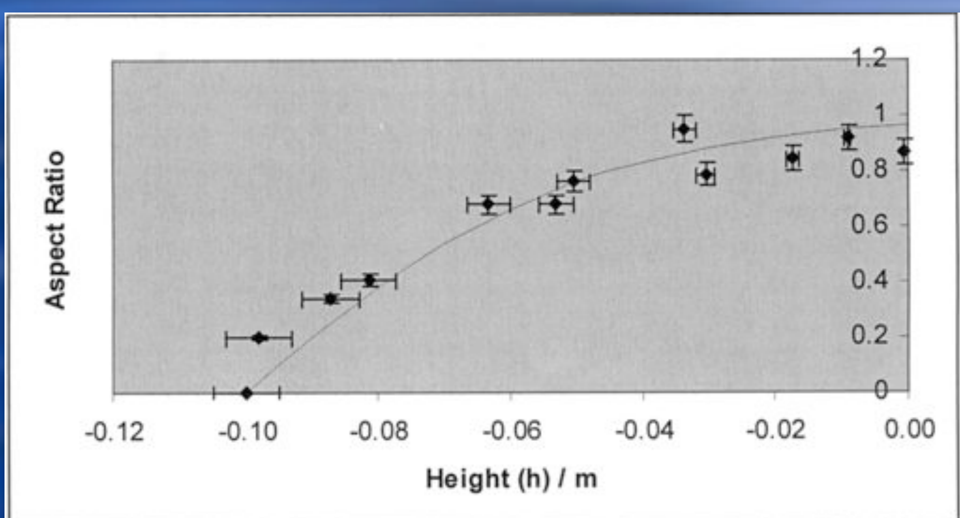




- Dual pressure probes allow measurement of frequency & wavelength
- Dispersion relation of waves in finite-depth tank

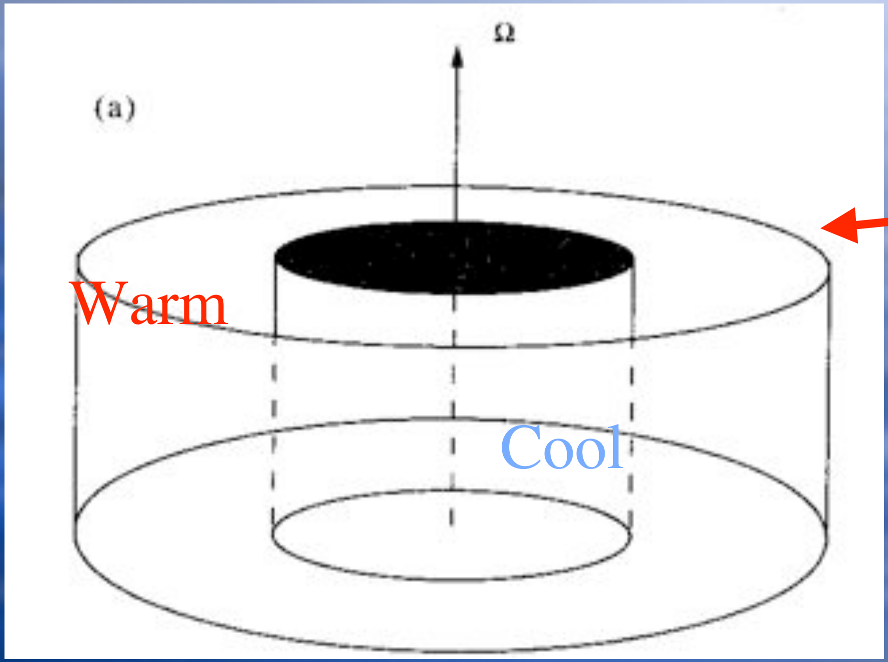
Surface water waves

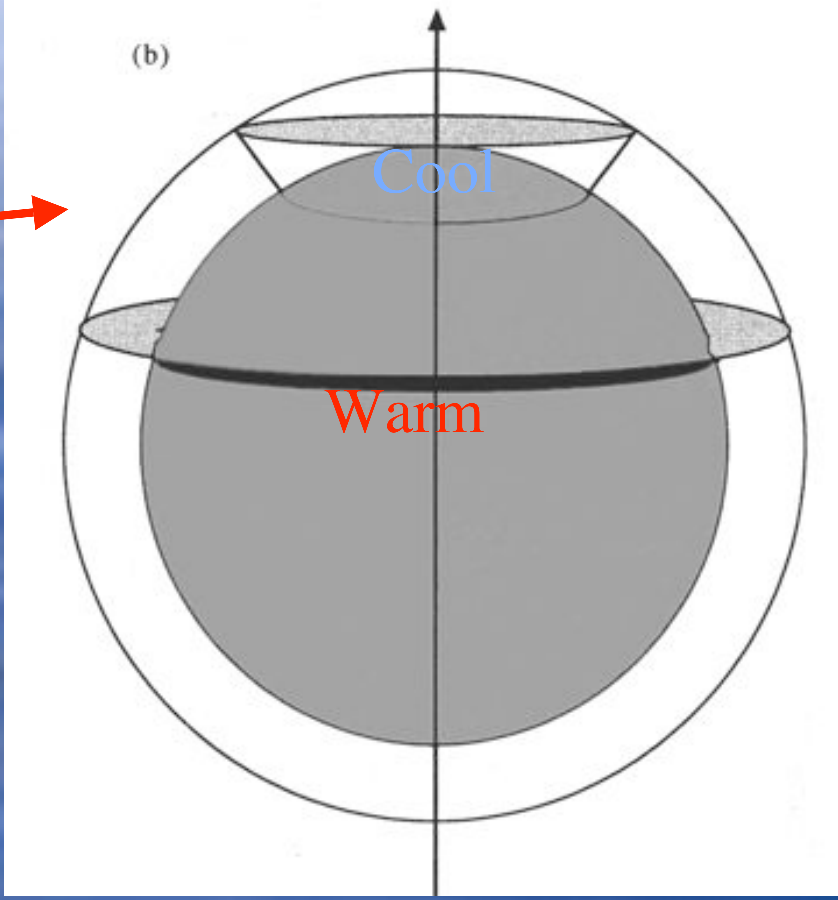




- Tracer particle visualisation
  - Vertical light sheet
  - Video camera
  - Particle tracking software (e.g. Digimage, Digiflow…)
- Measure elliptical trajectories
- Stokes drift/wave-mean flow interactions…..?

Differentially-heated rotating annulus: a laboratory "model" of a global planetary atmosphere

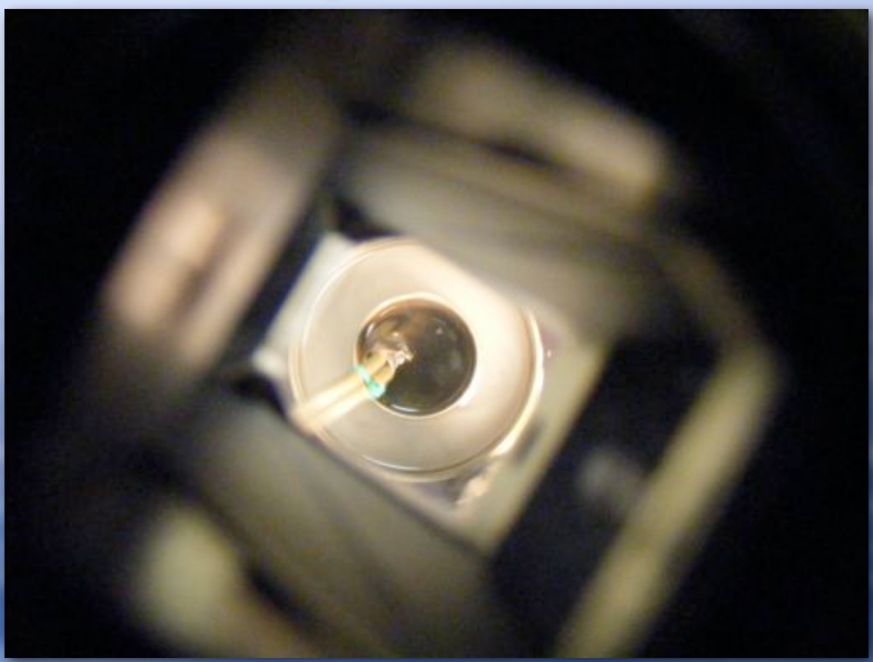




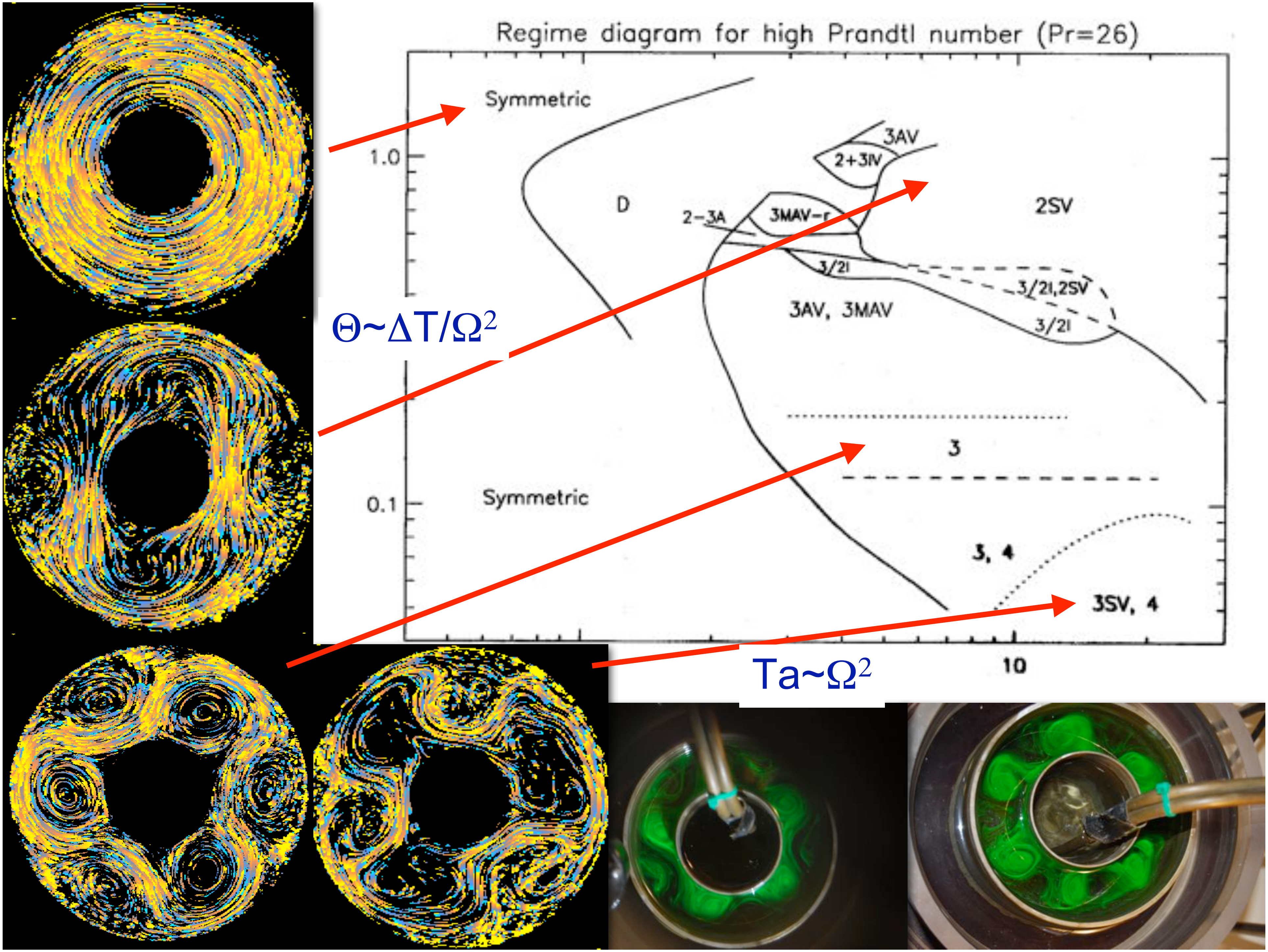
Rotating annulus experiment

- Rotating cylindrical tank
- Heated outer bath
- Cold water circulated in inner bath

Rotating annulus experiment

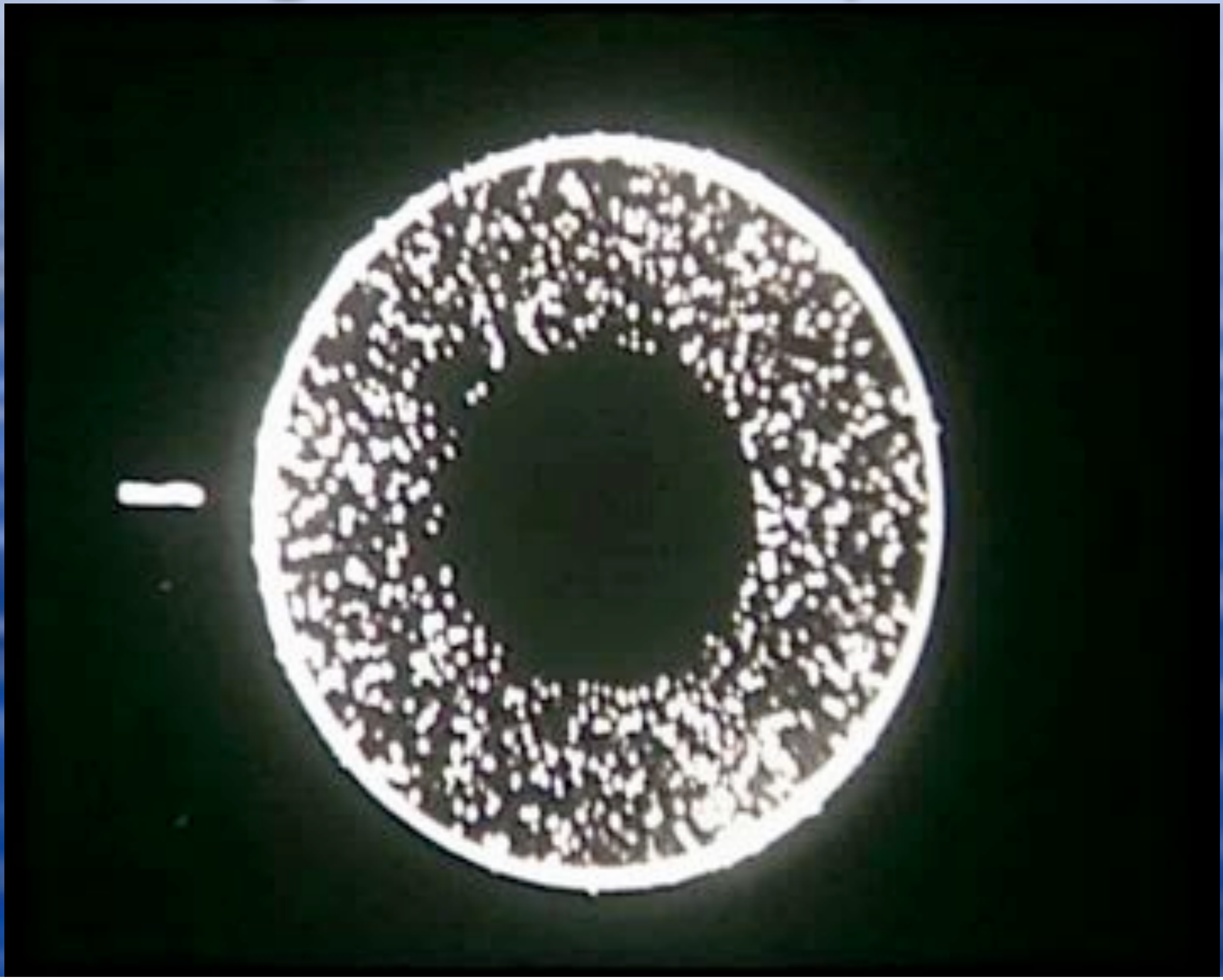


- 'Mearlmaid' or 'Kalliroscope' visualisation
- 'Rotoscope' to observe in rotating frame
  - Rotating Dove prism
  - Rotate synchronously with tank
- Or video camera....?
  - Particle tracking under dev.

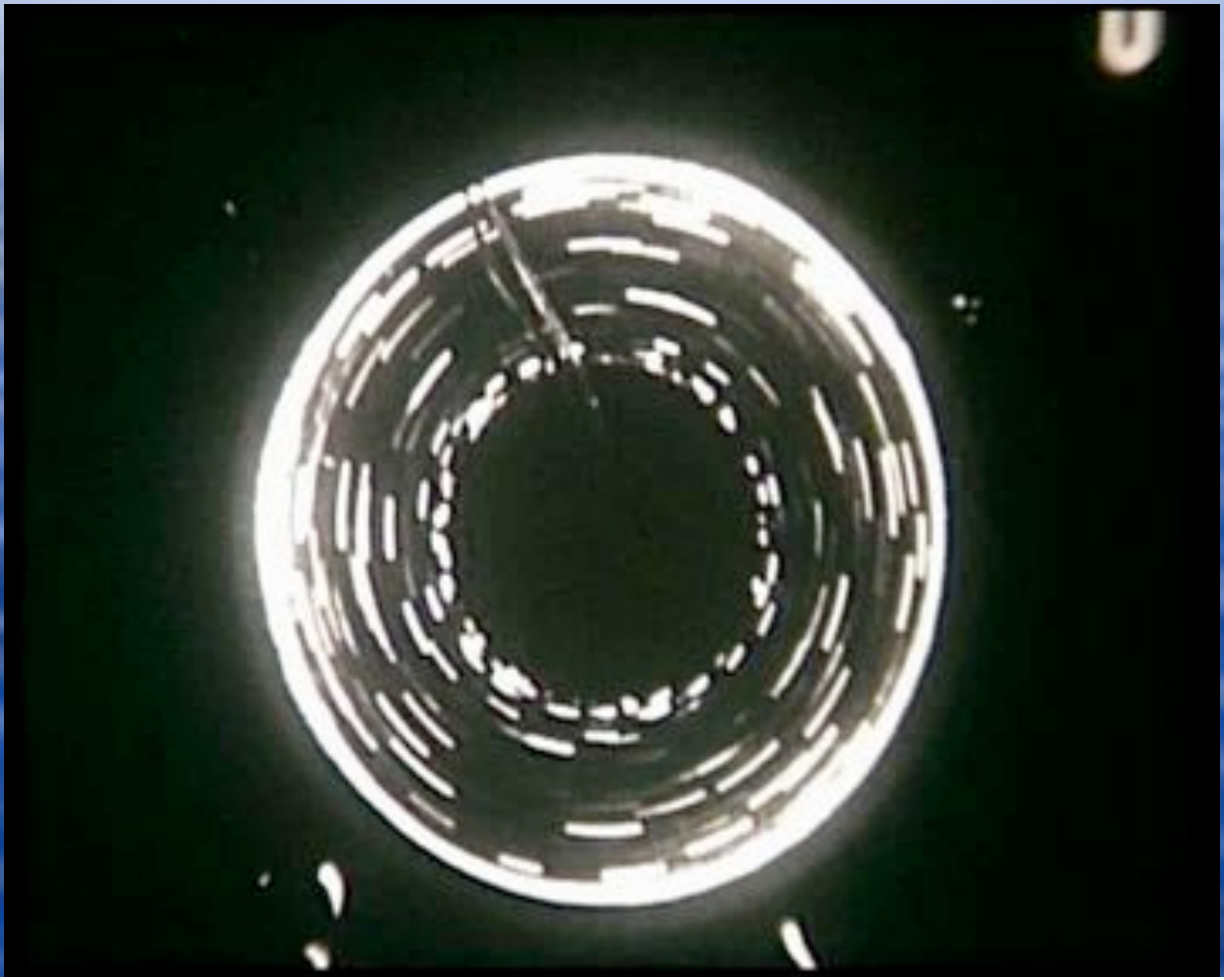


Regime diagram for high Prandtl number (Pr=26)
Symmetric
1.0
3AV
2+3IV
D
2SV
2-3A
3MAV-r
3/2I
3/2I,2SV
3AV, 3MAV
3/2I
3
0.1
Symmetric
3, 4
3SV, 4
10
Θ~ΔT/Ω²
Ta~Ω²

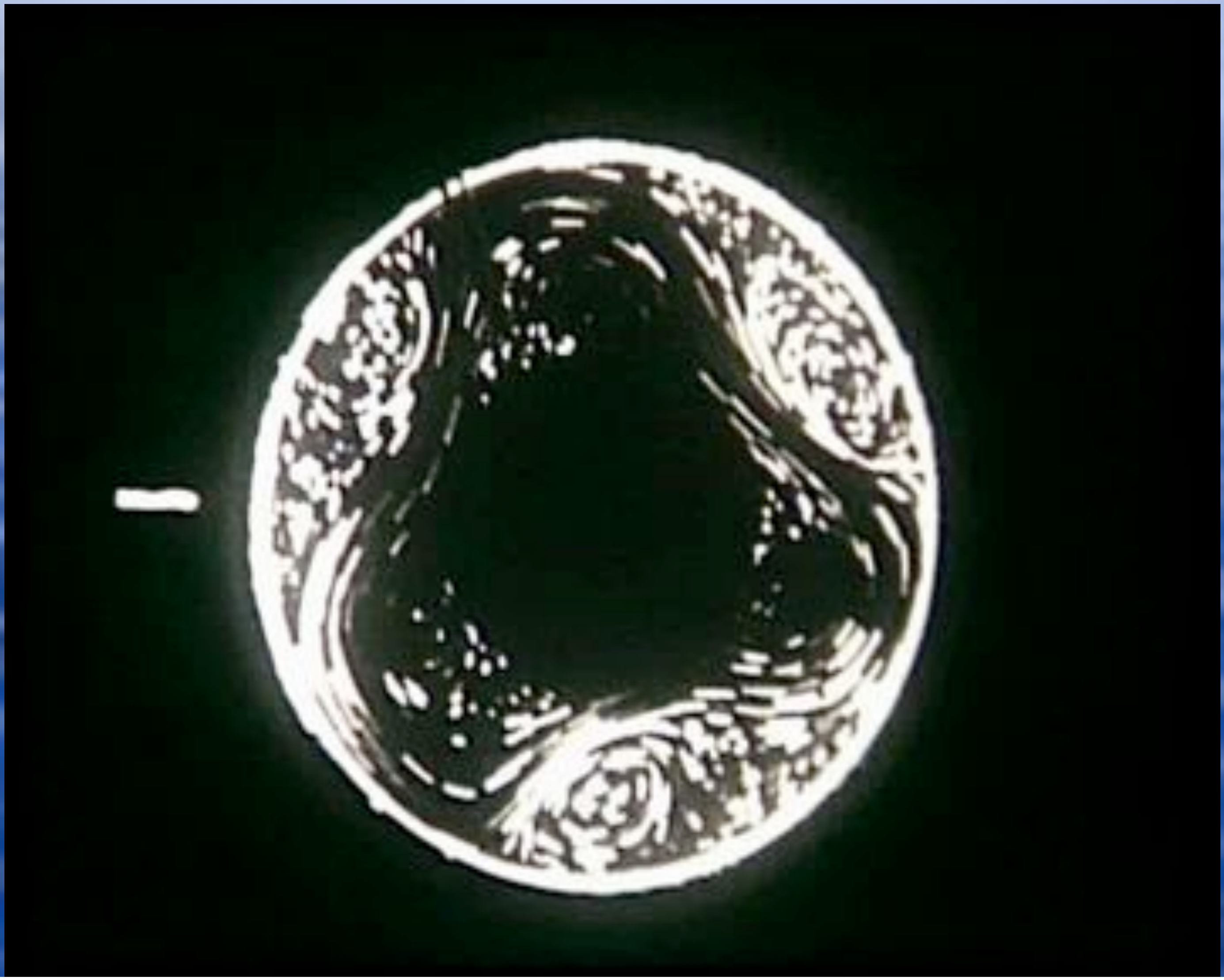
Rotating annulus experiment



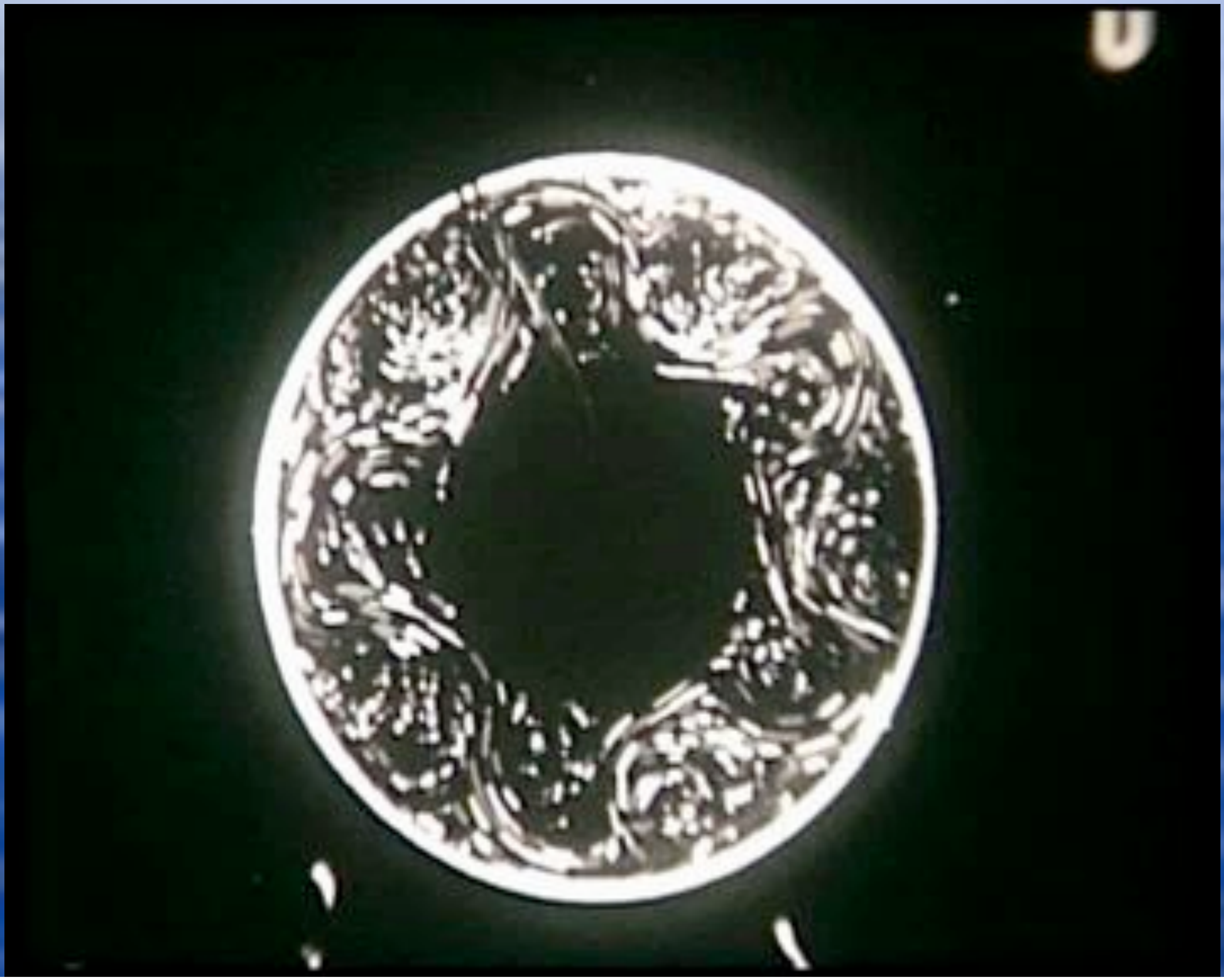
Rotating annulus experiment



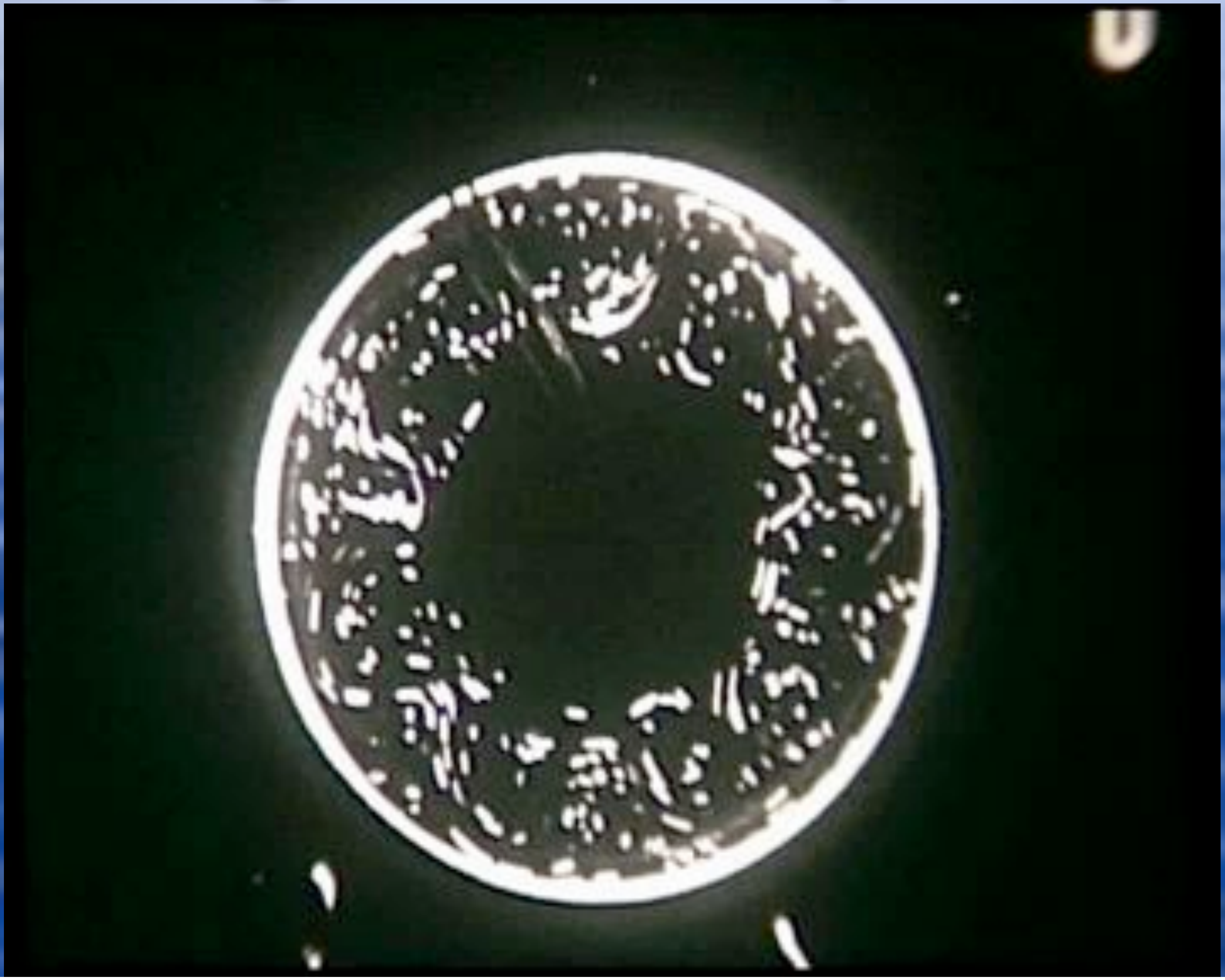
Rotating annulus experiment



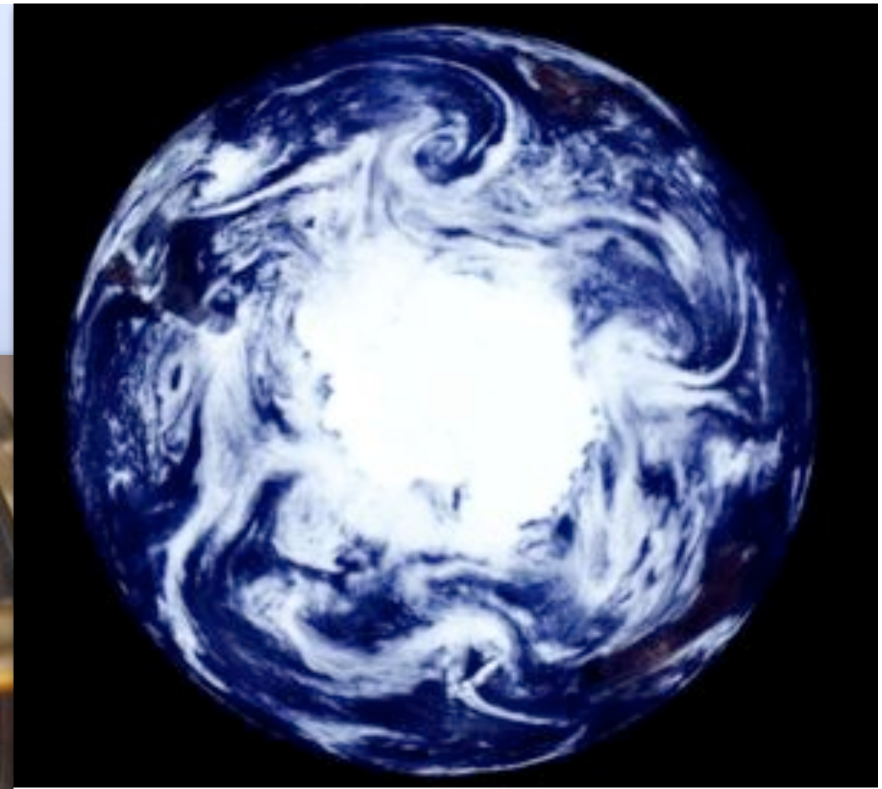
Rotating annulus experiment

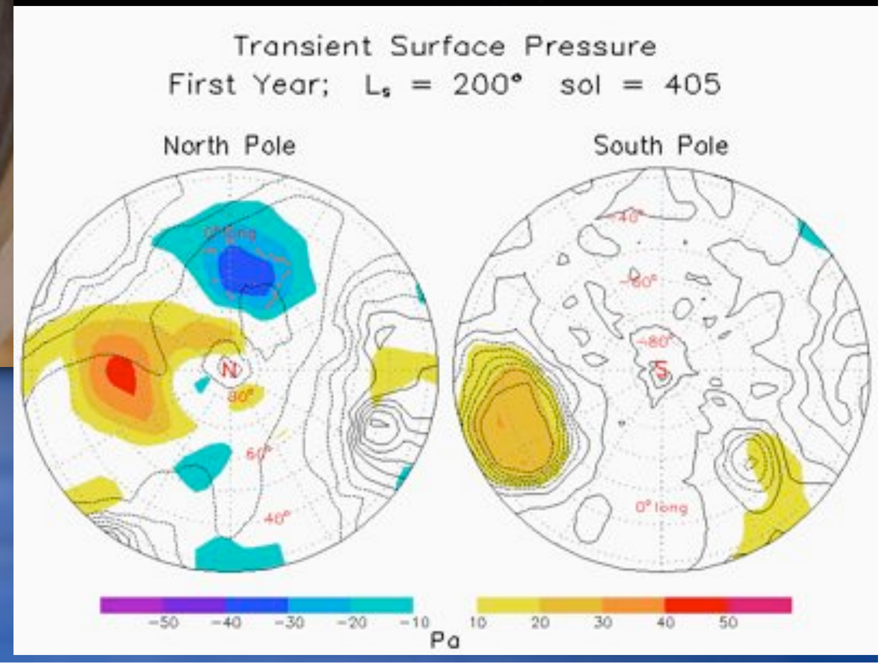


Rotating annulus experiment



Analogy with the Earth & Mars



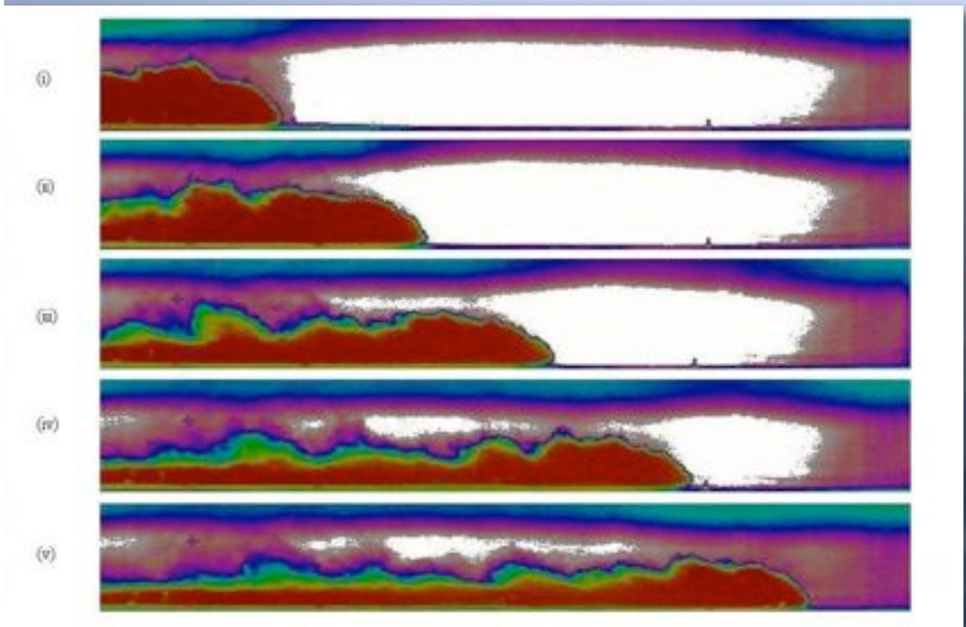


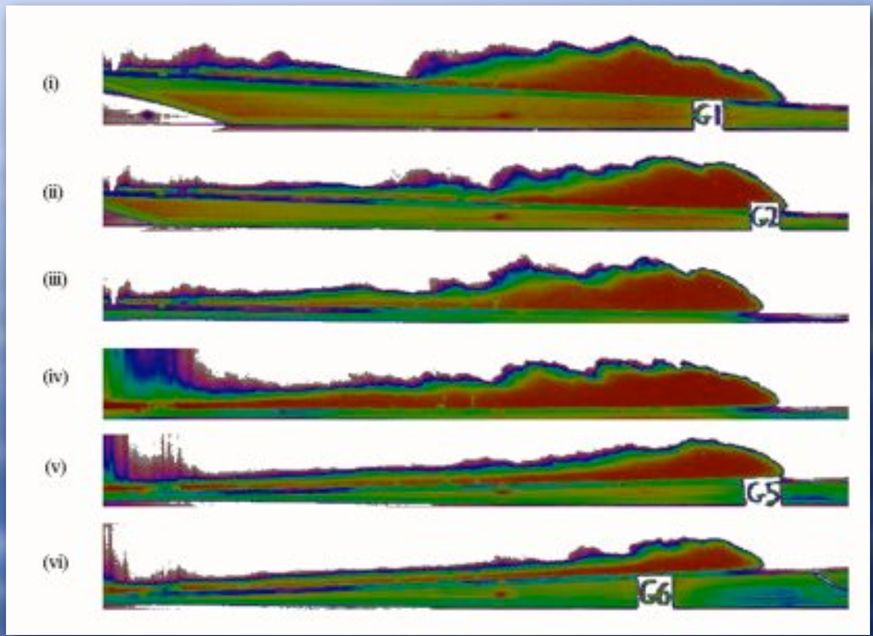
- GFD Lab

4th year Research Projects Examples:

- Rotating annulus studies
  - 2-layer baroclinic-gravity wave interactions
    - See Paul Williams' presentation
  - Dispersive waves and wave packets on β-plane
- Density fronts and density currents
- Barotropic instabilities
  - Shear layers and jets
  - Momentum transport
  - Polygonal waves.....

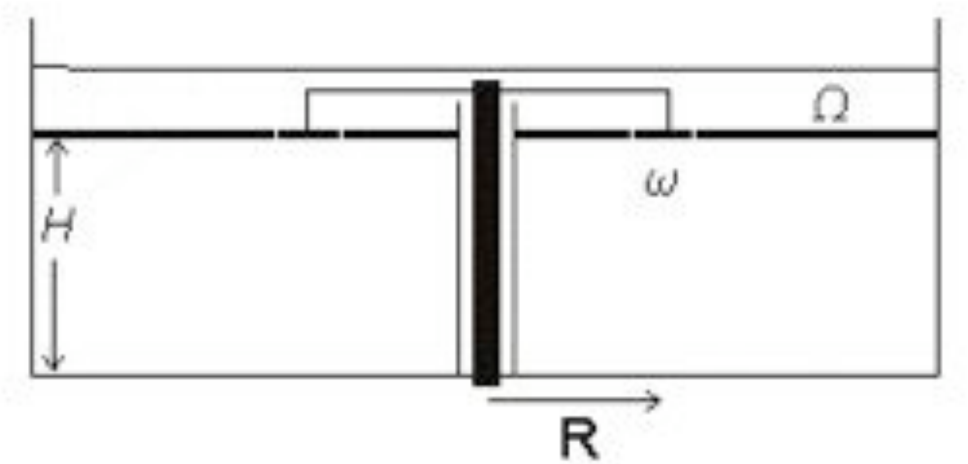
Density currents



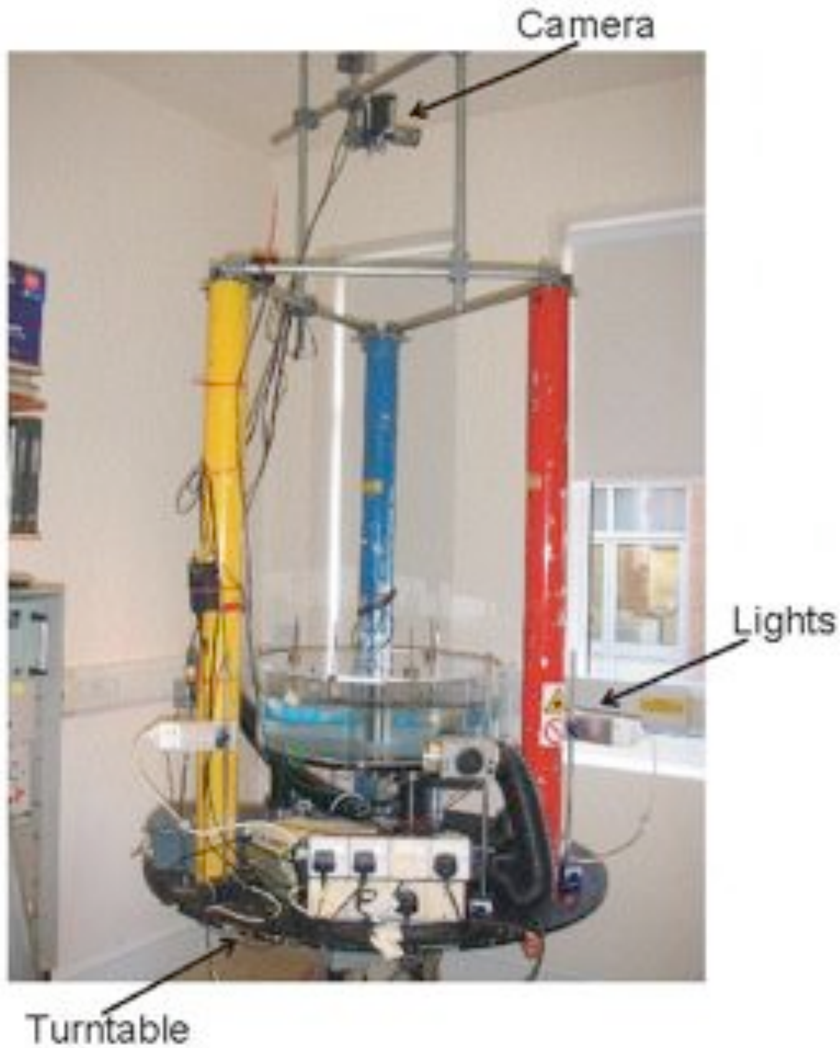


- Lock-release flow of dense (salty) water into fresh
- Visualisation of front
  - Propagation speed
  - Instabilities
  - Interactions with sloping boundaries…..

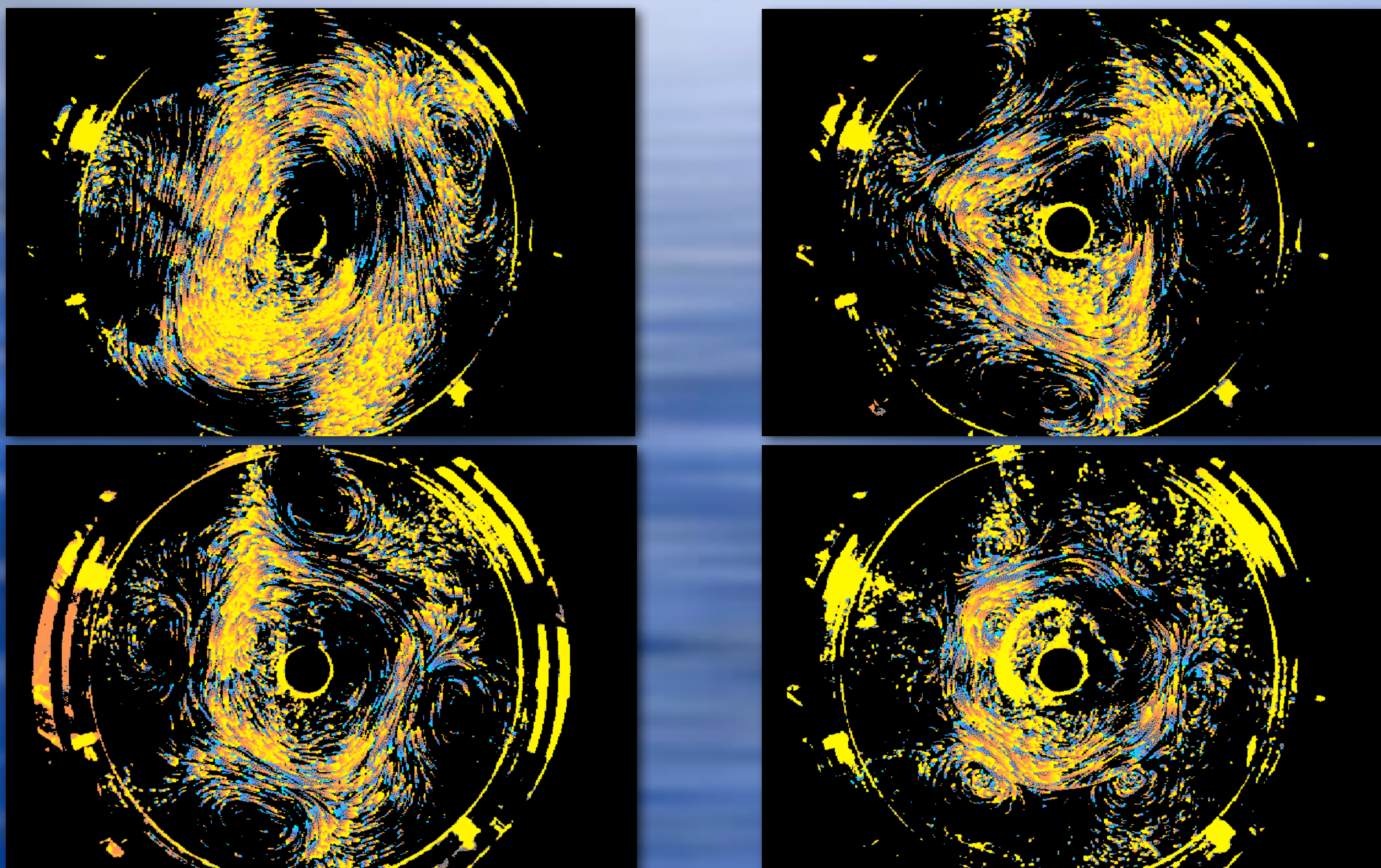
Barotropically unstable polygonal jets



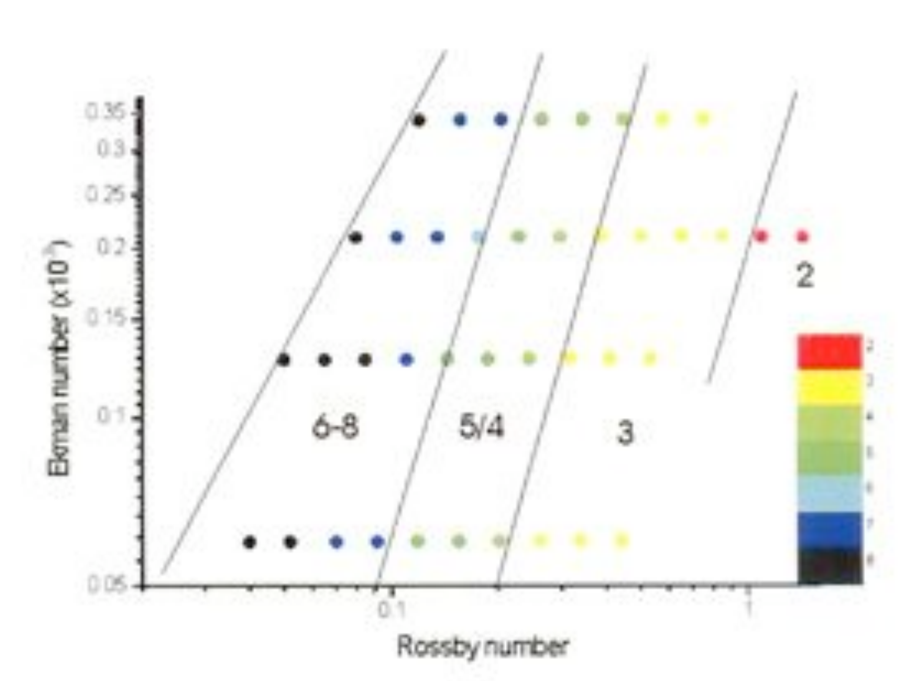
- Cylindrical tank rotates at angular velocity Ω
- Rigid lid in contact with the working fluid
- Annular ring in the lid or radius *R* differentially rotates at angular velocity ω

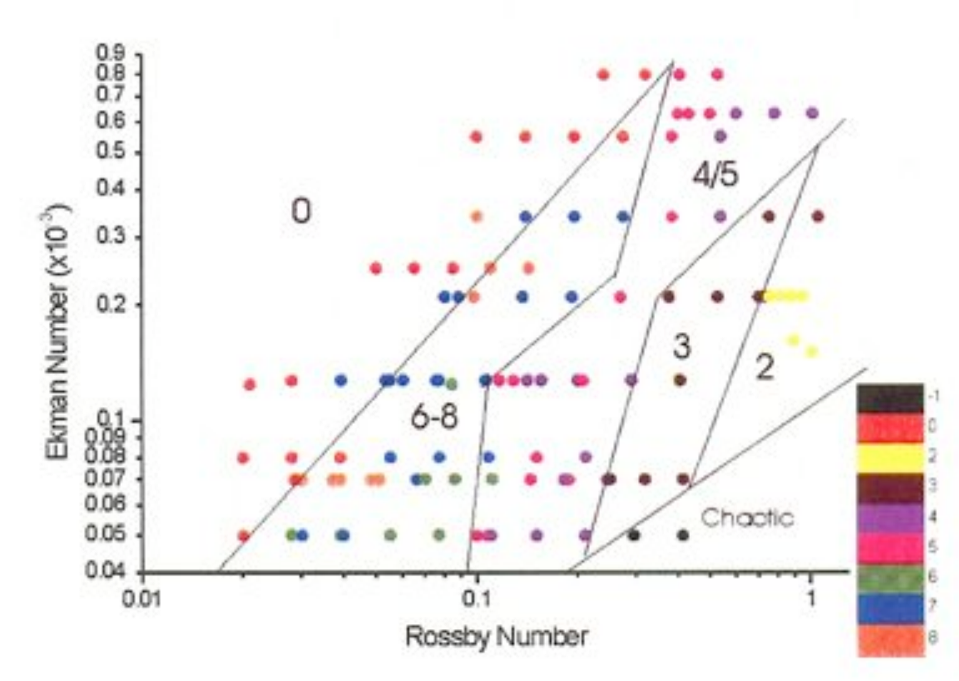


Various polygonal flows as fn of |Ro|



Regime diagrams

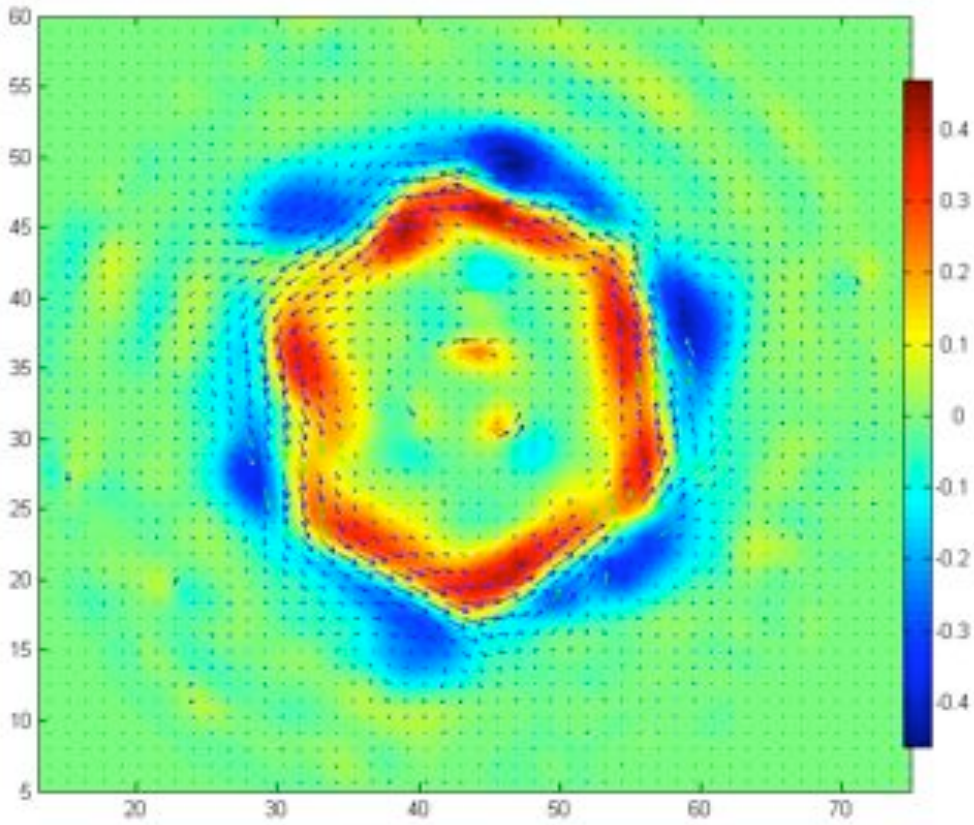




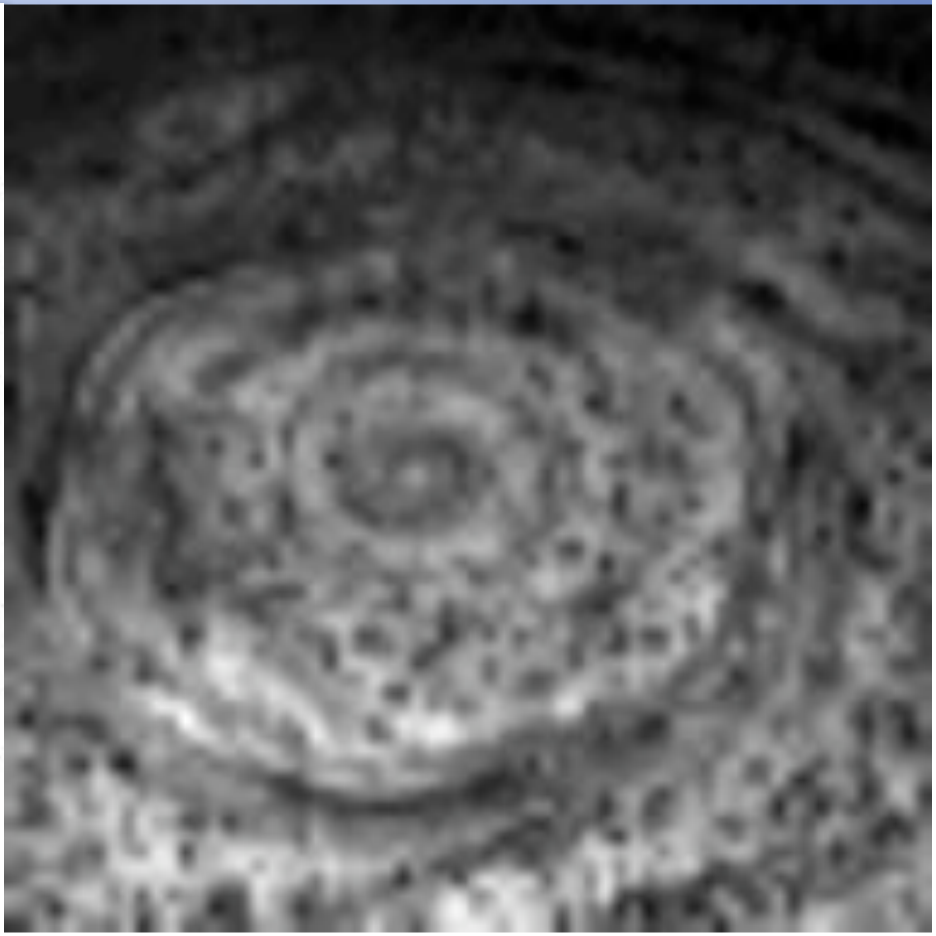
- Ro -ve +ve
- Equilibrated wavenumber depends *primarily* on Ro - not E

Equilibrated Hexagons

GFD Laboratory

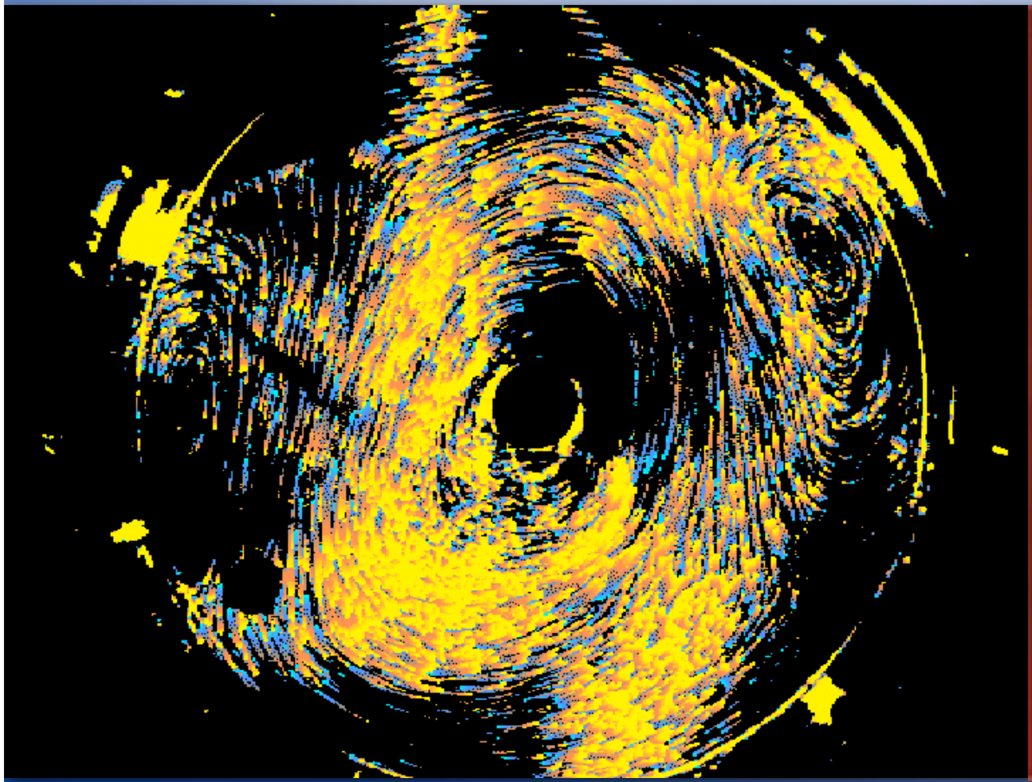


Saturn (Cassini)

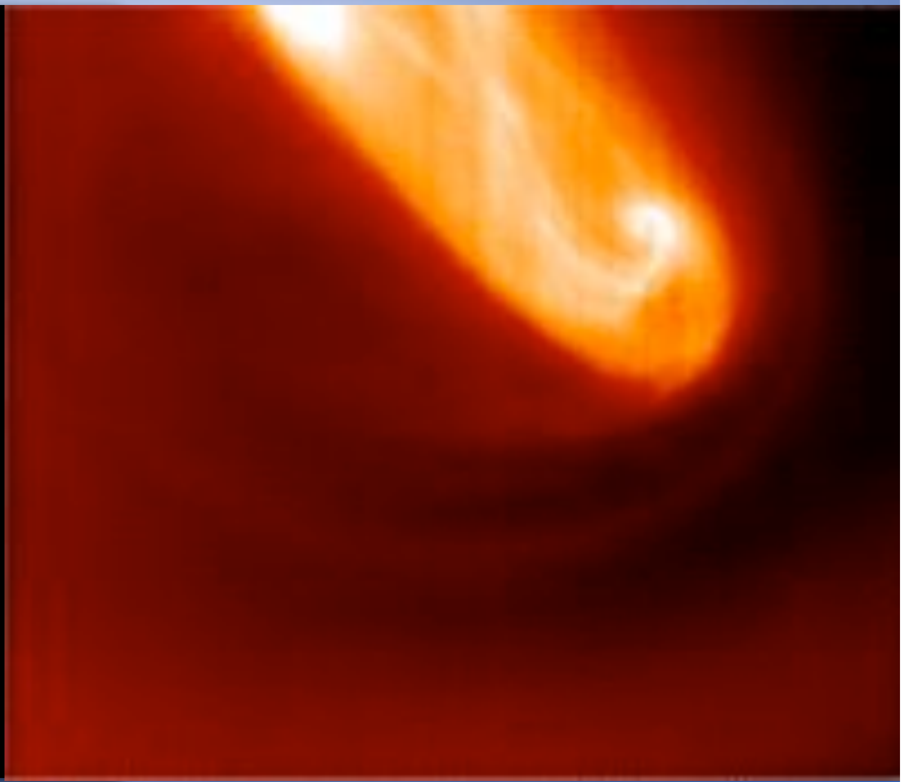


Equilibrated Dipole

GFD Laboratory



Venus (South Pole)



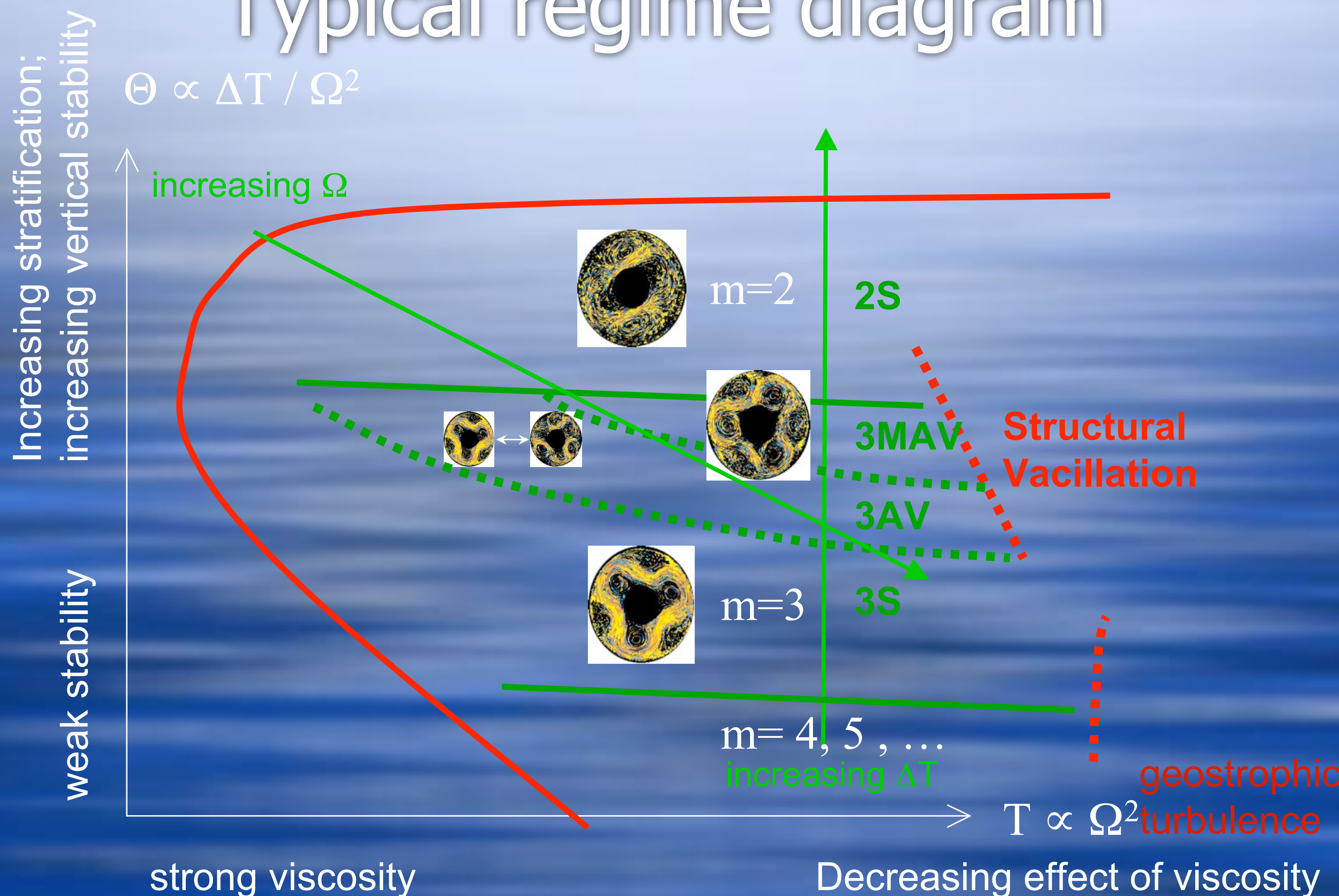
VIRTIS (Venus Express)

See http://www.atm.ox.ac.uk/rotatingfluids/

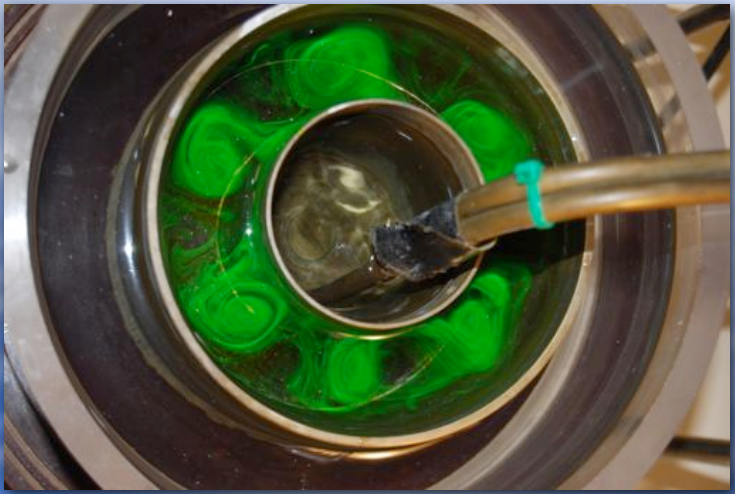
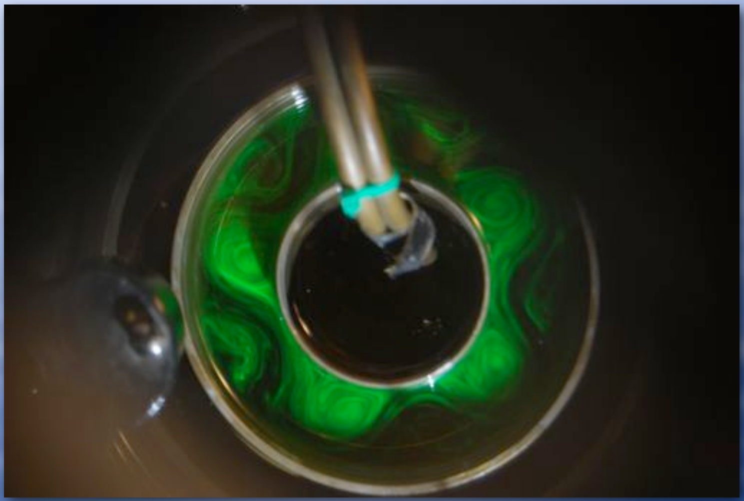
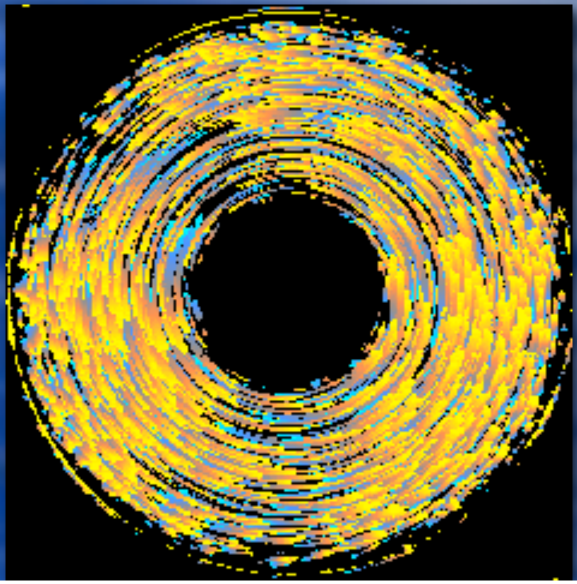
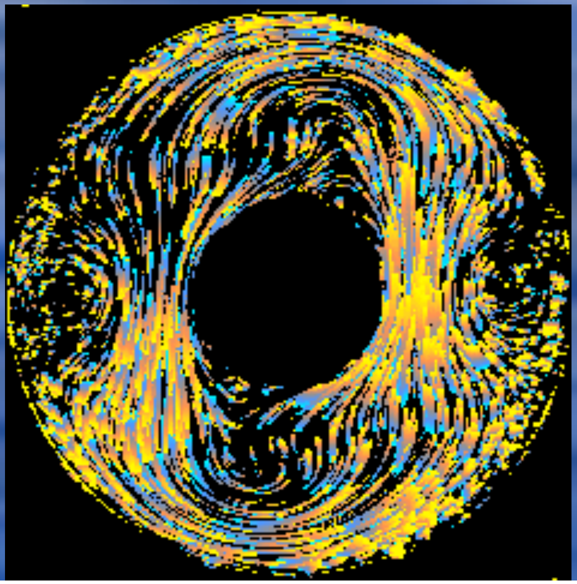
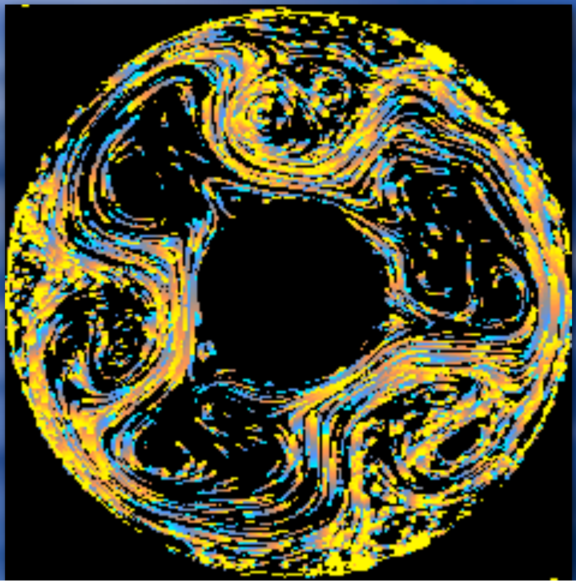
Conclusions

- Fluid dynamics offers much scope to train and excite young Physicists
  - "modern" and relevant!
  - Intellectually and technically challenging
  - ***Can be FUN….!***
- Rare opportunity to include discussion of ***nonlinear*** phenomena
- Lecture demonstrations and practical experiments
  - Scope for much more development……
  - QUANTITATIVE wherever possible……
  - Problem of large audiences?
  - Rich area for open-ended investigations
  - Projects contribute to research publications

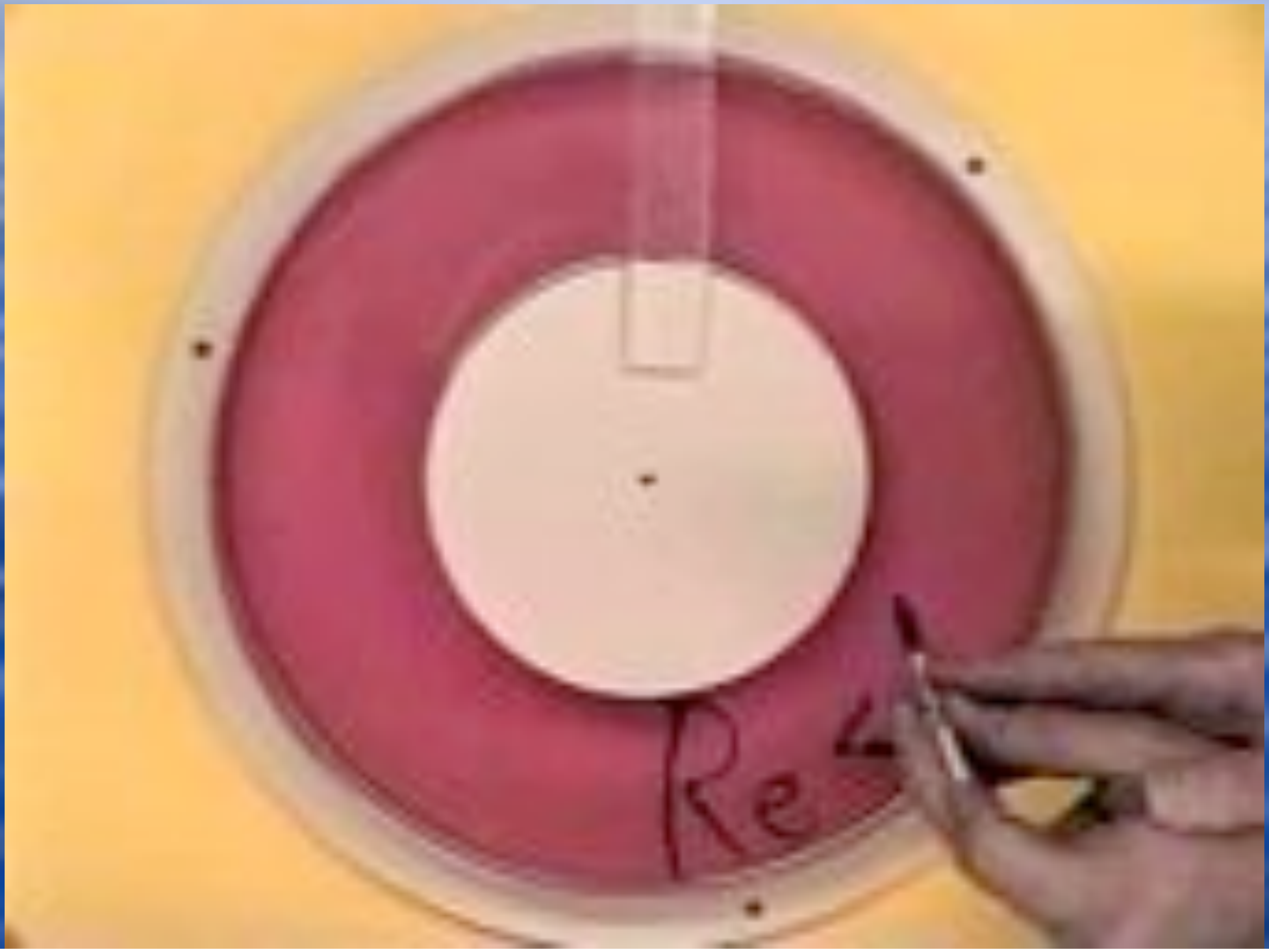
Typical regime diagram



Rotating annulus experiment

Low Re flows - time reversibility



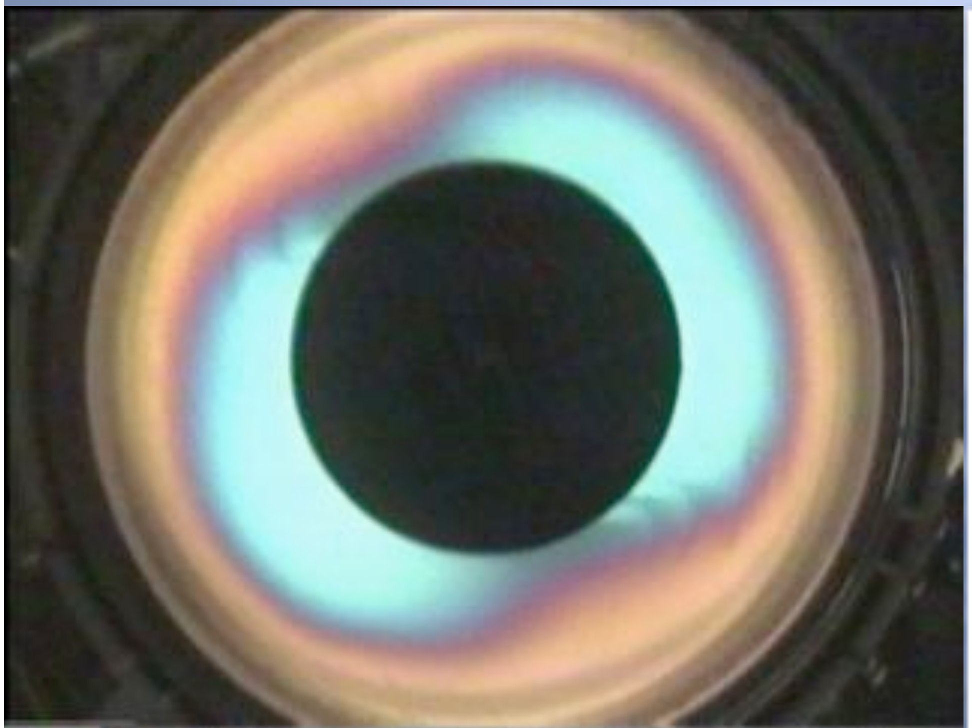
3rd year Climate Physics course

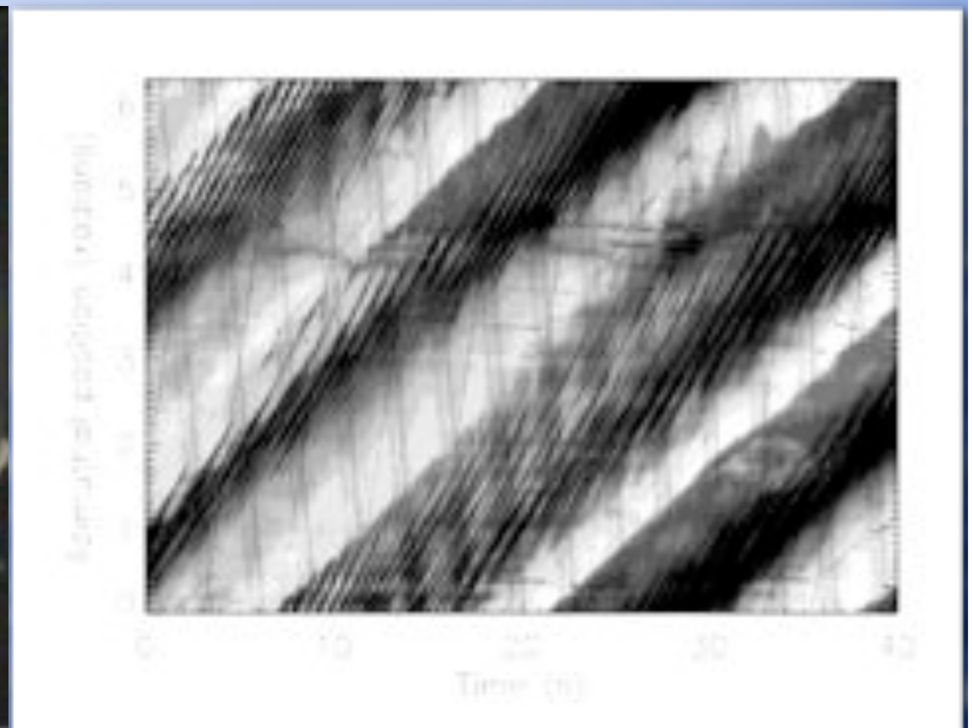
- Composition and structure of the atmosphere
- Hydrostatic balance
- Adiabatic lapse rate & potential temperature
  - Convective stability
- Water vapour
  - Condensation and cloud formation
- Oceanic structure and circulation
  - Oceanic equation of state
- Radiative transfer
  - Solar radiation
  - Black body radiation & Kirchoff's laws
- Instruments for remote sensing of climate variables
- Climate sensitivity and feedback mechanisms
  - Energy balance models
  - Greenhouse effect
- External forcing of climate
- Mechanisms of sudden climate change
  - Multiple climate equilibria

4th year Atmosphere/Oceans course: GFD

- Geostrophic & hydrostatic balance
- Shallow water equations
  - Inertio-gravity waves
  - Vorticity & potential vorticity
- Quasi-geostrophic theory
  - Rossby waves
  - Baroclinic instability
- Oceanic structure and circulation
  - Ekman pumping
  - Stommel model
  - Western boundary currents
  - Equatorial Kelvin waves
- Weather forecasting & predictability
- Climate & climate variability
  - Atmosphere-ocean coupling in tropics
  - THC & palaeoclimates
- Planetary fluid dynamics
  - Mars - seasonal cycles, topographic circulations, tides & transient waves
  - Slowly rotating planets - Titan and Venus - Hadley circulations, super-rotation
  - Giant planets - multiple jets, stable eddies, geostrophic turbulence…..

Baroclinic-gravity wave interactions





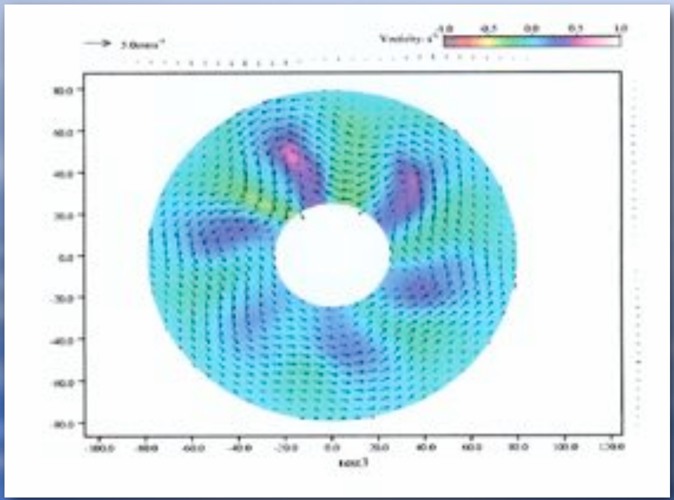
- 2-layer stratified annulus with differentially-rotating lid
- Coexistence of baroclinic and short wavelength gravity waves

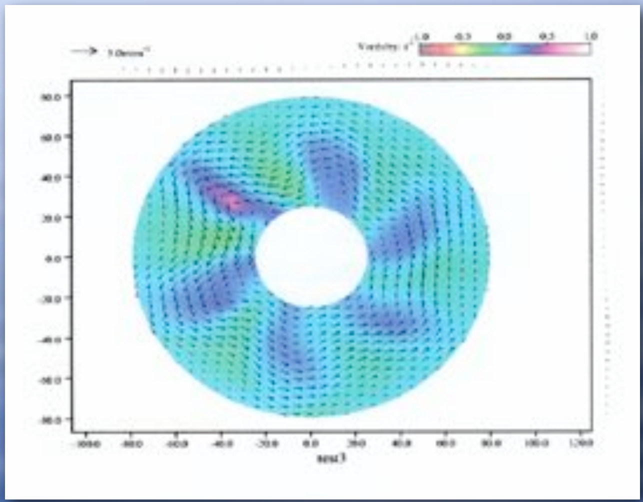
Fluid flow in industry

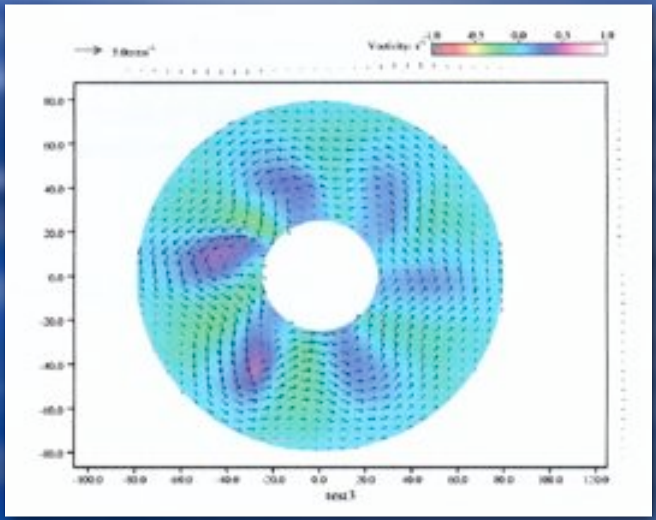
 

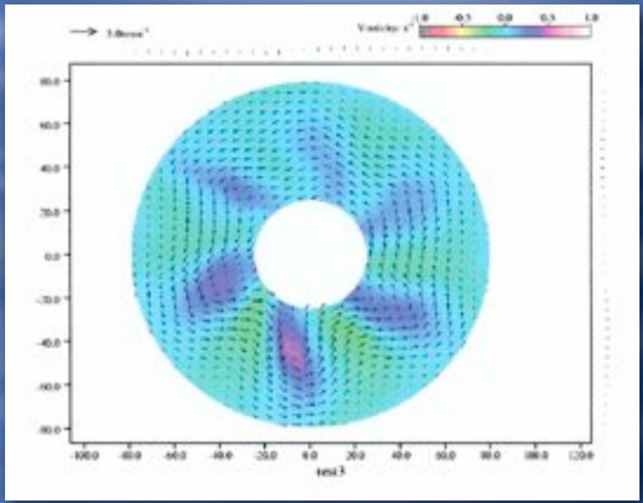
Image credits: Greenpeace

Baroclinic wave packets









Volcanoes

(From 'Hawaii's Volcanoes, by Scott Rowland)