Jupiter's Great Red Spot, Saturn's Polar Hexagon, and Monterey Bay:
Insights from Laboratory Experiments

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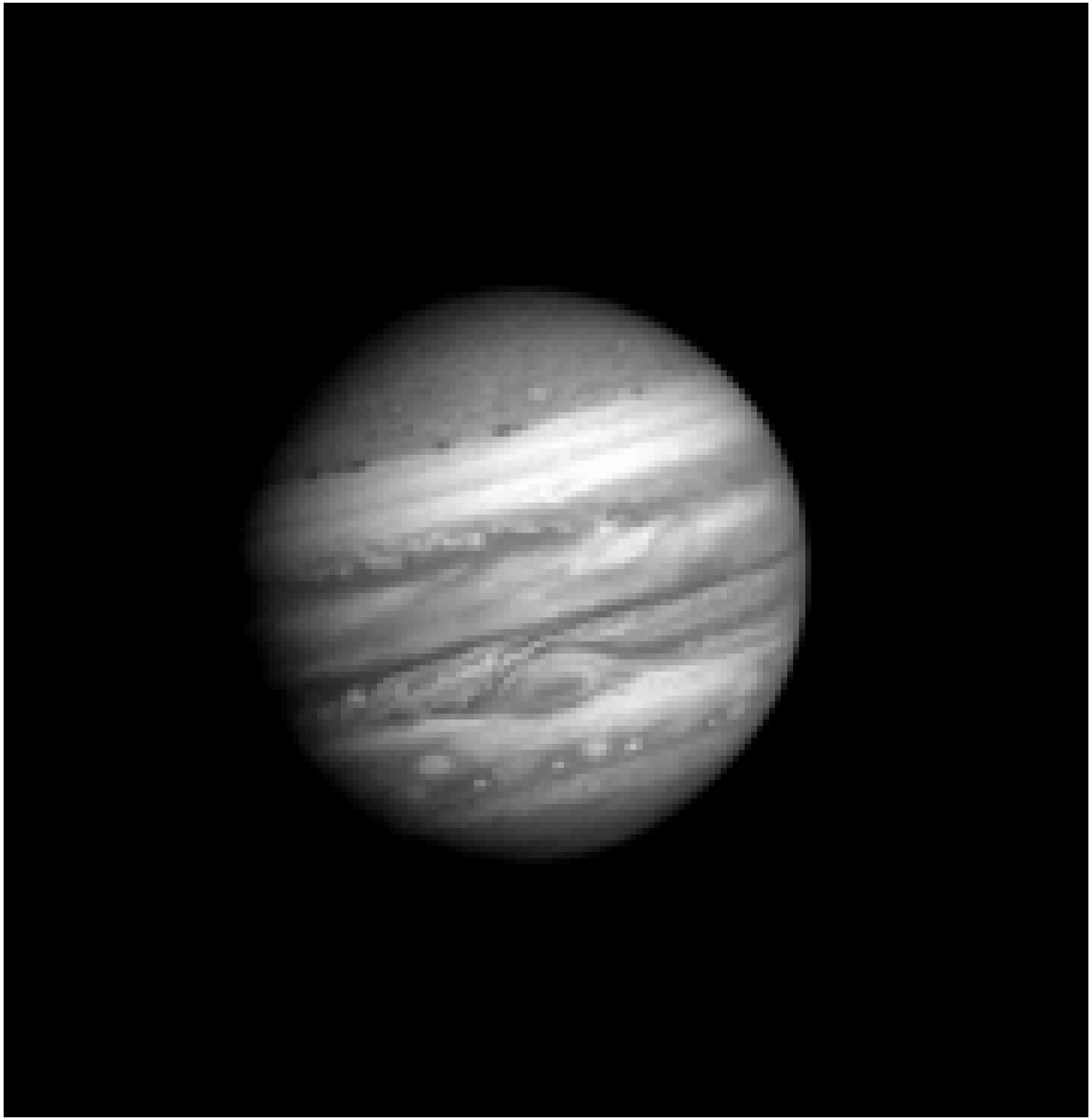
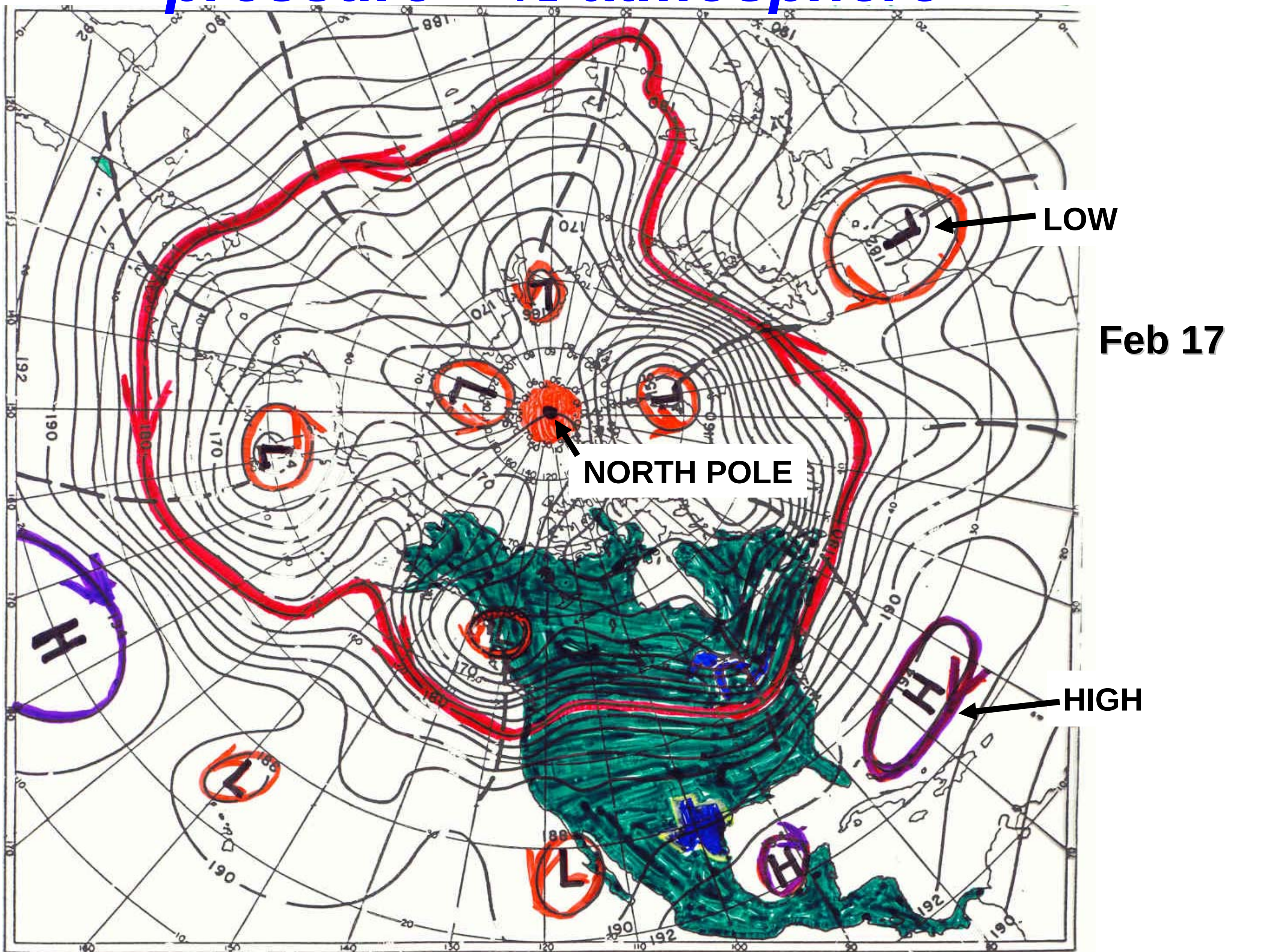
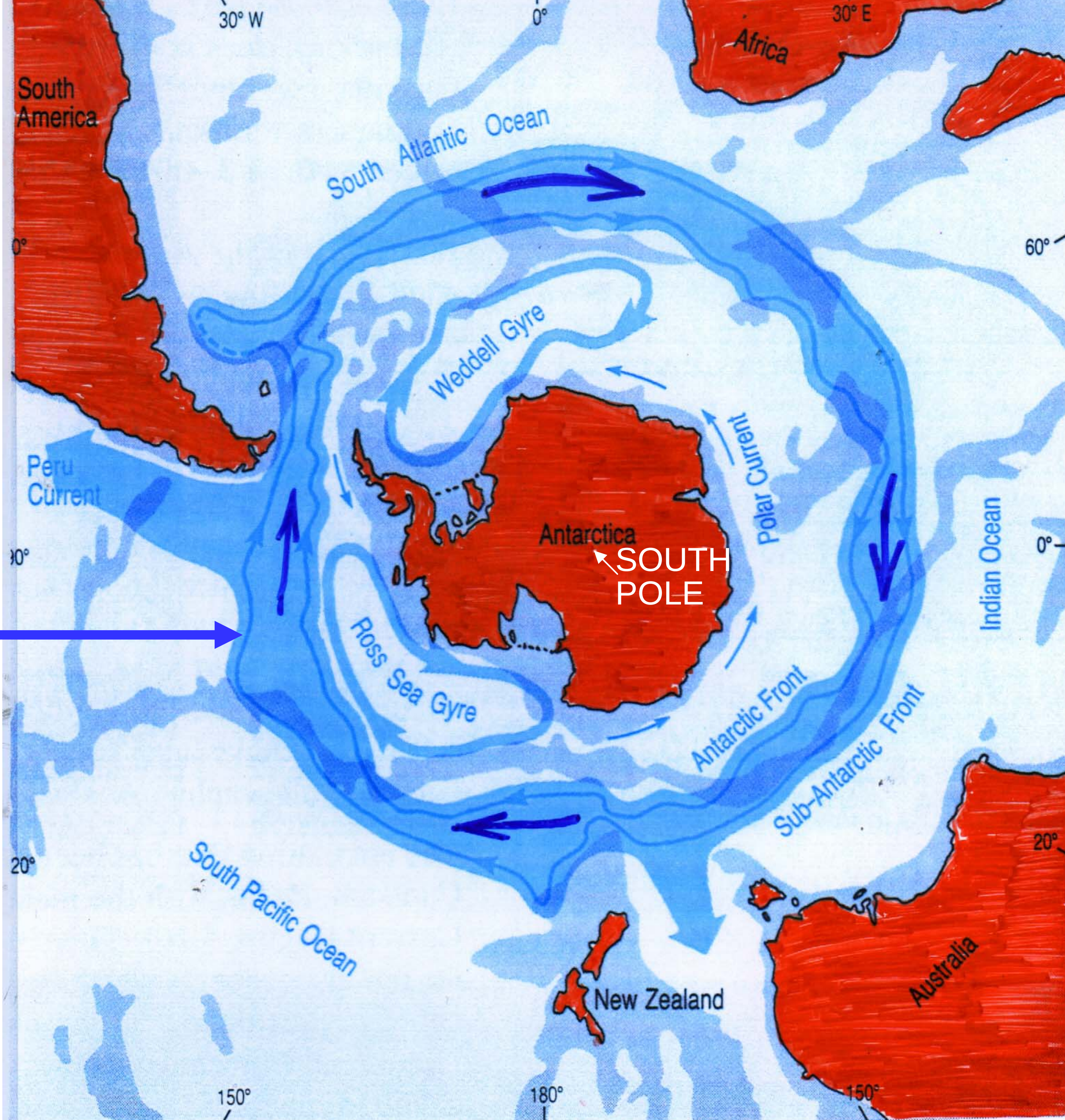
Jupiter: from Voyager I spacecraft



Weather map: fluid direction at altitude where pressure = ½ atmosphere



Antarctic circumpolar current



Atmosphere and oceans **contain long-lived**

- ***jets***
  - Gulf Stream, Jet Stream,
    Antarctic Circumpolar Current, …

- ***eddys***
  - Jupiter’s Great Red Spot,
    high and low pressure systems, hurricanes, …

On earth:

Measure velocity of fluid in ocean with respect to earth rather than with respect to the “fixed stars”

Then an earthbound observer interprets the motion in terms of an additional force, the

Coriolis force

Direction of the Coriolis force

- Let $\boldsymbol{\Omega}$ be the angular velocity vector for the earth
  ($\boldsymbol{\Omega}$ direction: with right thumb parallel to a line from the south to north pole, right fingers point in the earth's rotation)

- Let $\boldsymbol{u}$ be the fluid velocity at a point on the earth's surface
- Then Coriolis force = $2(fluid\ density)\vec{u}\times\vec{\Omega}$

where the direction of the Coriolis force is given by the right-hand rule (rotate $\boldsymbol{u}$ into $\boldsymbol{\Omega}$)

Question: does a hurricane rotate clockwise or counter-clockwise?

Compare: *Coriolis effect* to *inertial effect*

$$Rossby\ no. = \frac{inertial\ effect}{Coriolis\ effect} = \frac{fluid\ velocity}{4\pi \times (rotation\ rate) \times size}$$

In atmosphere and oceans:

velocity ~ 2 m/sec

earth rotation rate = 1 revolution/day

size ≥ 200,000 m (≅120 miles)

Rossby number ~ 0.1

Does water swirl down a bath tub drain in the clockwise *or* the counter-clockwise direction?

- In a bath tub

  velocity of water ~ 0.05 m/sec

  rotation rate of earth = 1 revolution/day ≅ 10^{-5} rev/sec

  size of bath tub eddy ~ 0.02 m

- So the Rossby number is

$$\frac{velocity = 0.05\ m/s}{4\pi \times (rotation\ rate = 10^{-5}\ rev/s) \times (size = 0.02\ m)} \sim 50000$$

Conclusion: **Coriolis force is completely negligible!**

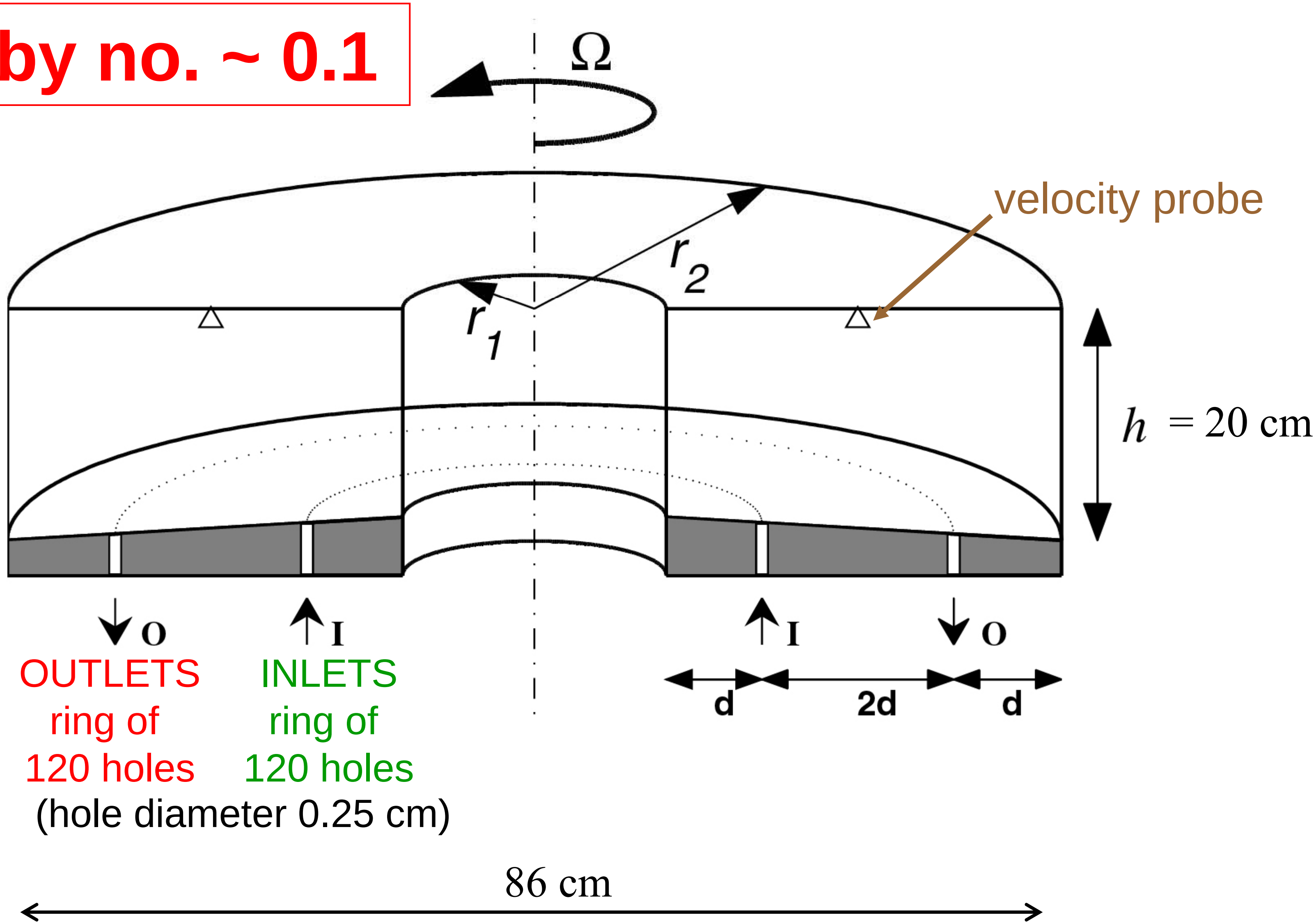
Oceanic flow experiments in the laboratory

$$\text{Rossby no.} = \frac{\textit{inertial effect}}{\textit{Coriolis effect}} = \frac{\textit{fluid velocity}}{4\pi \times (\textit{rotation rate}) \times \textit{length}}$$

- In the laboratory we can make
  Rossby number ~ 0.1, as in oceans
    - velocity ~ 0.2 m/sec
    - tank rotation rate = 1 revolution/sec
    - size ~ 0.2 m

Oceanic-type flow in the laboratory

Rossby no. ~ 0.1

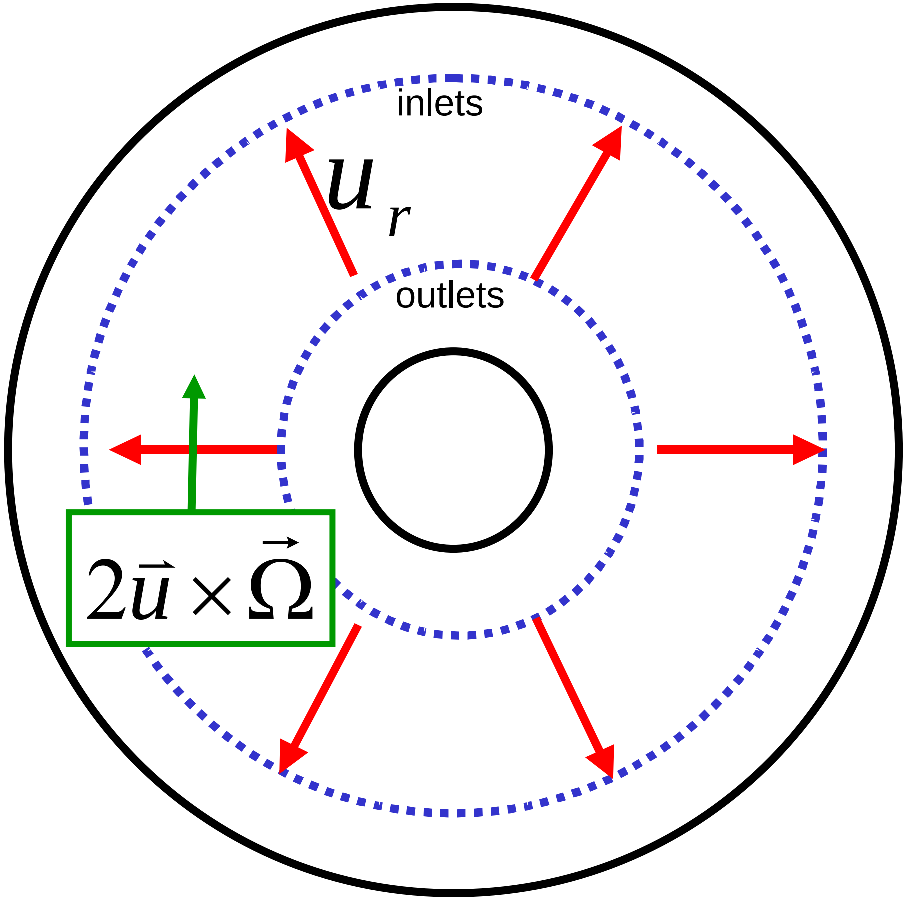


β-effect: sloping bottom mimics earth's variation of Coriolis force with latitude

fluid: water

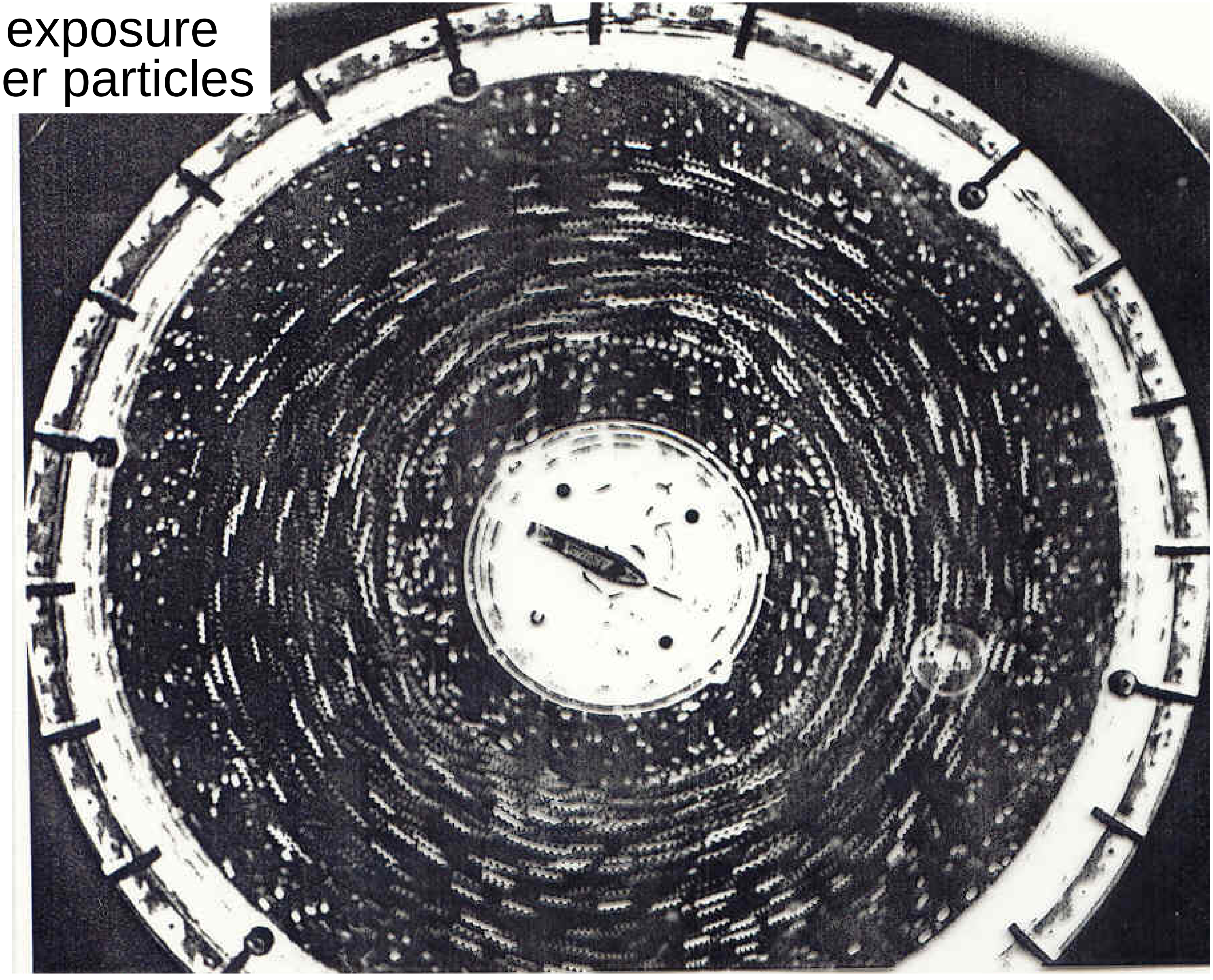
Weak pumping produces strong jet stream

Pump outward:
counter-rotating jet

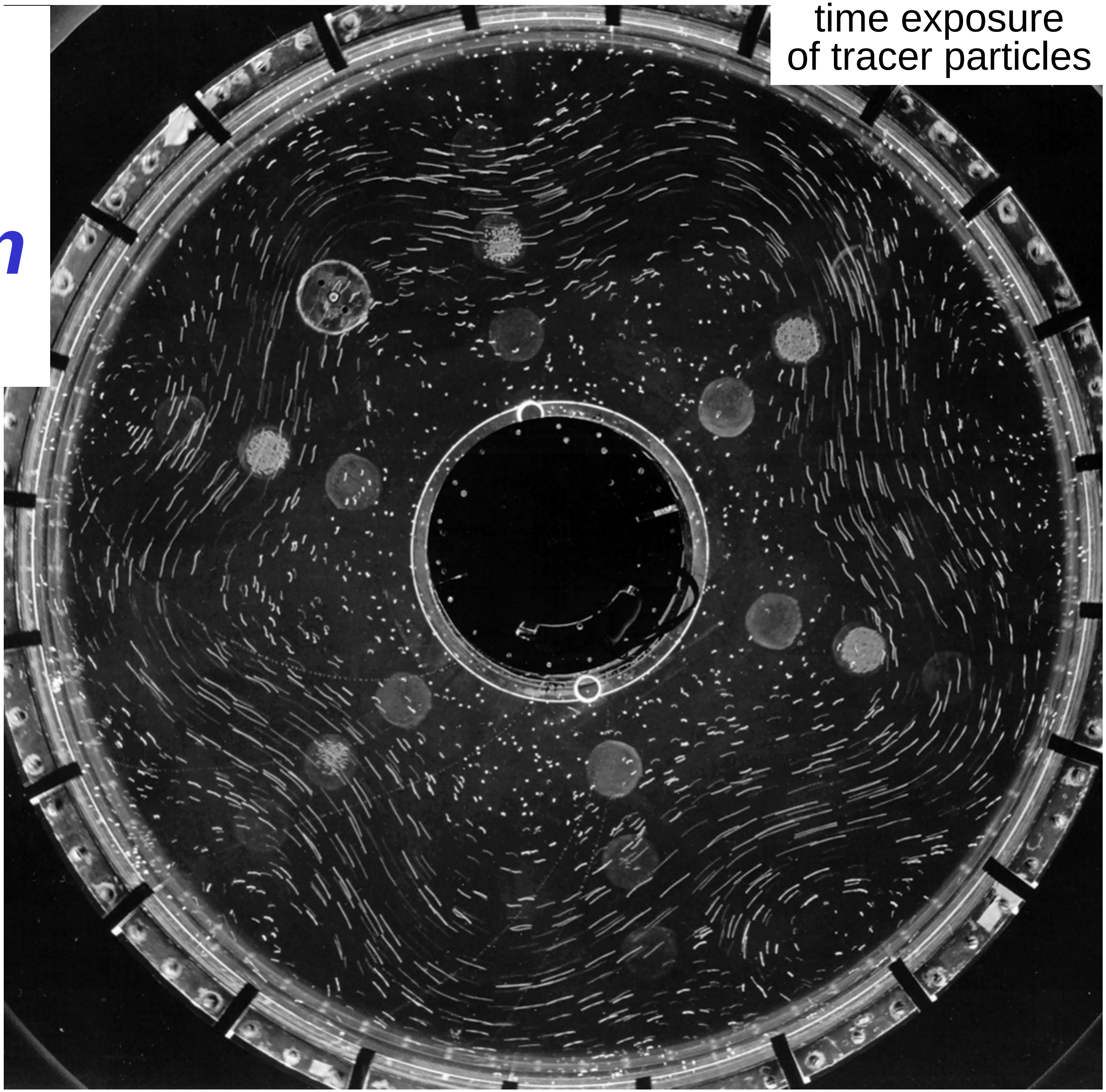


Low pumping: circular jet

time exposure
of tracer particles



Pump faster: waves form on the jet

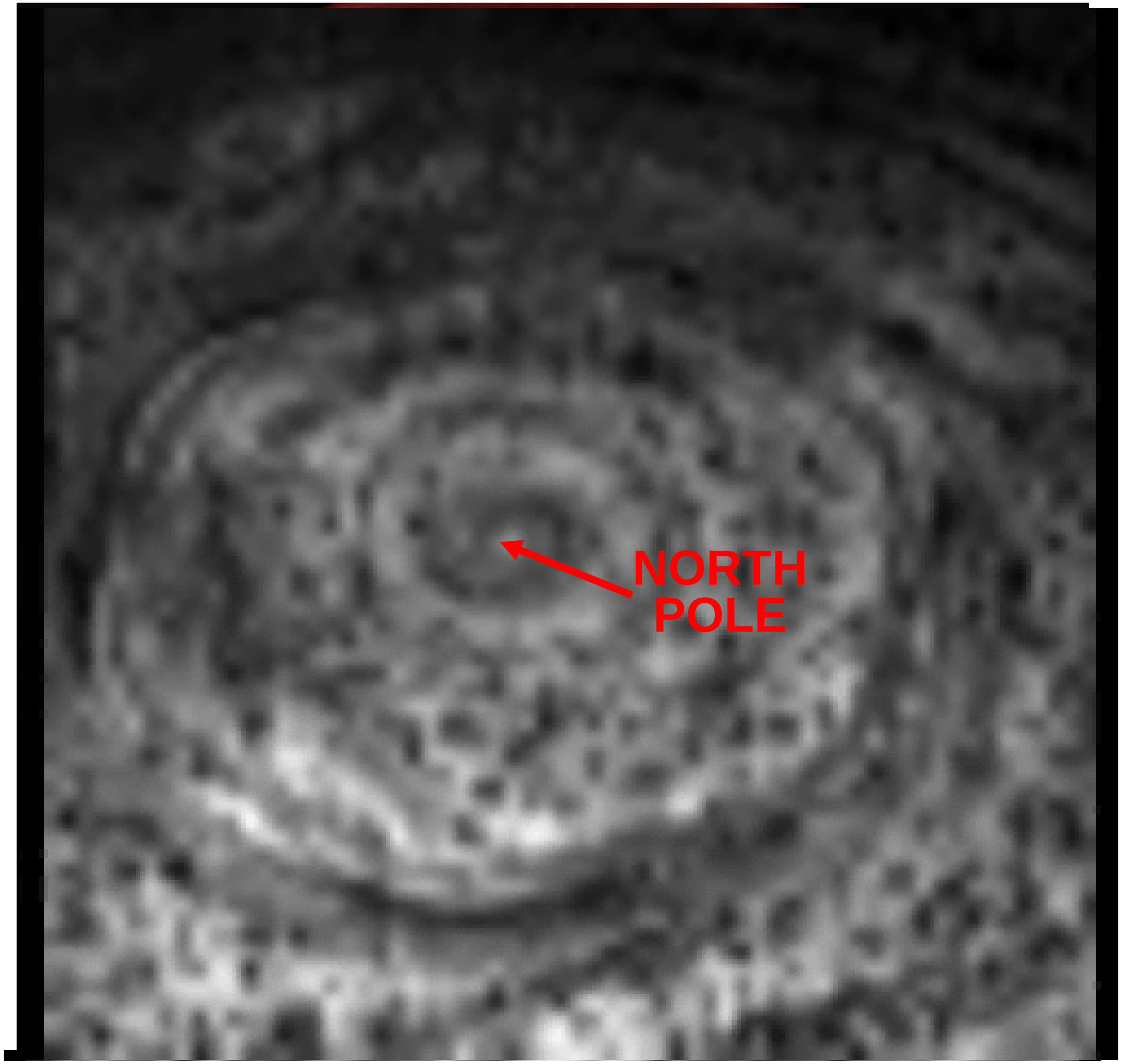


time exposure of tracer particles

Number of waves depends on on pumping and rotation frequency

29 OCTOBER 2006: ***NASA's Casini spacecraft reveals***
"bizarre 6-sided feature encircling the north pole of Saturn"

http://saturn.jpl.nasa.gov/home/index.cfm



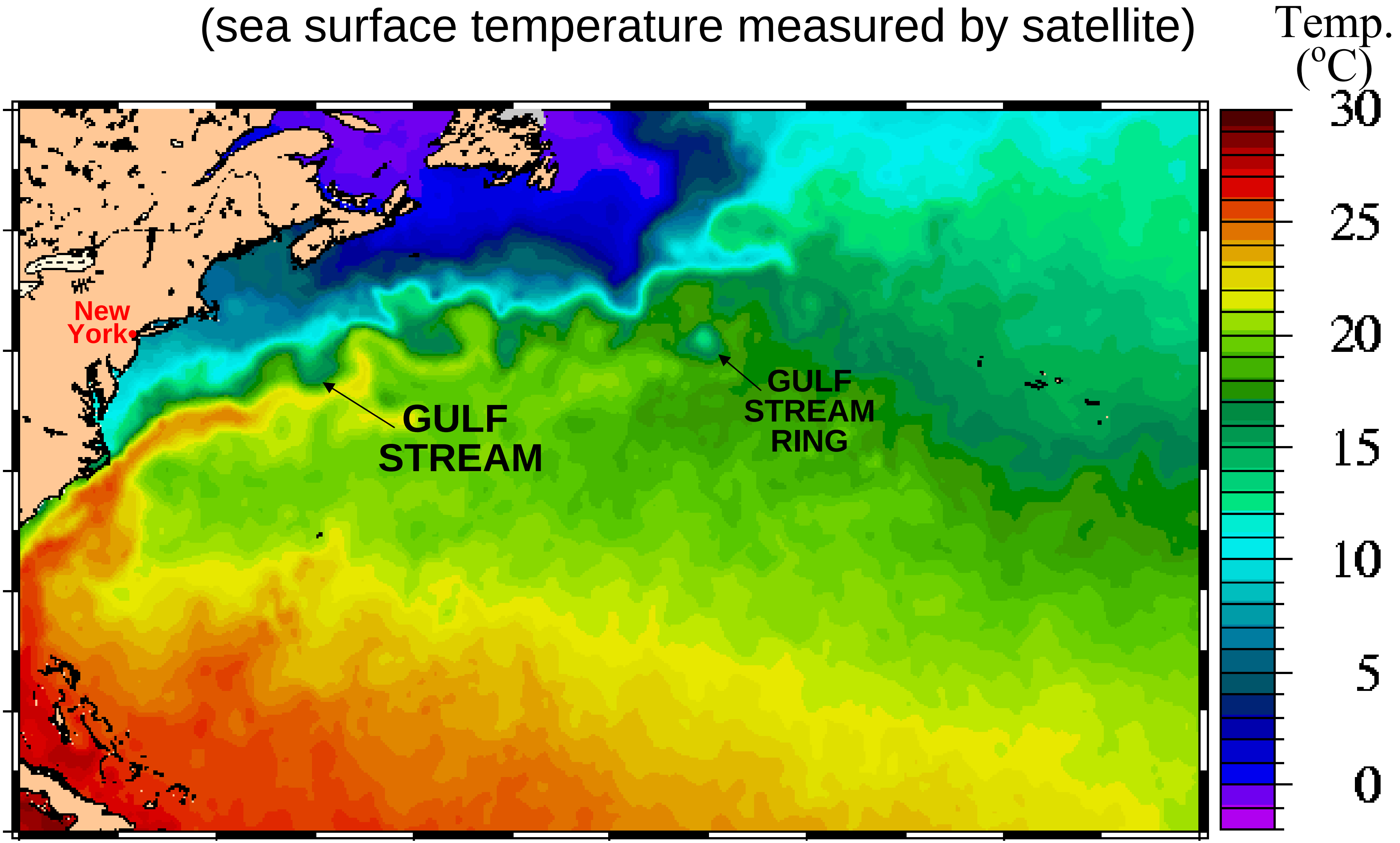
Each side
13,800 km

Period
10h 39min 24s

Latitude
78^{o} North

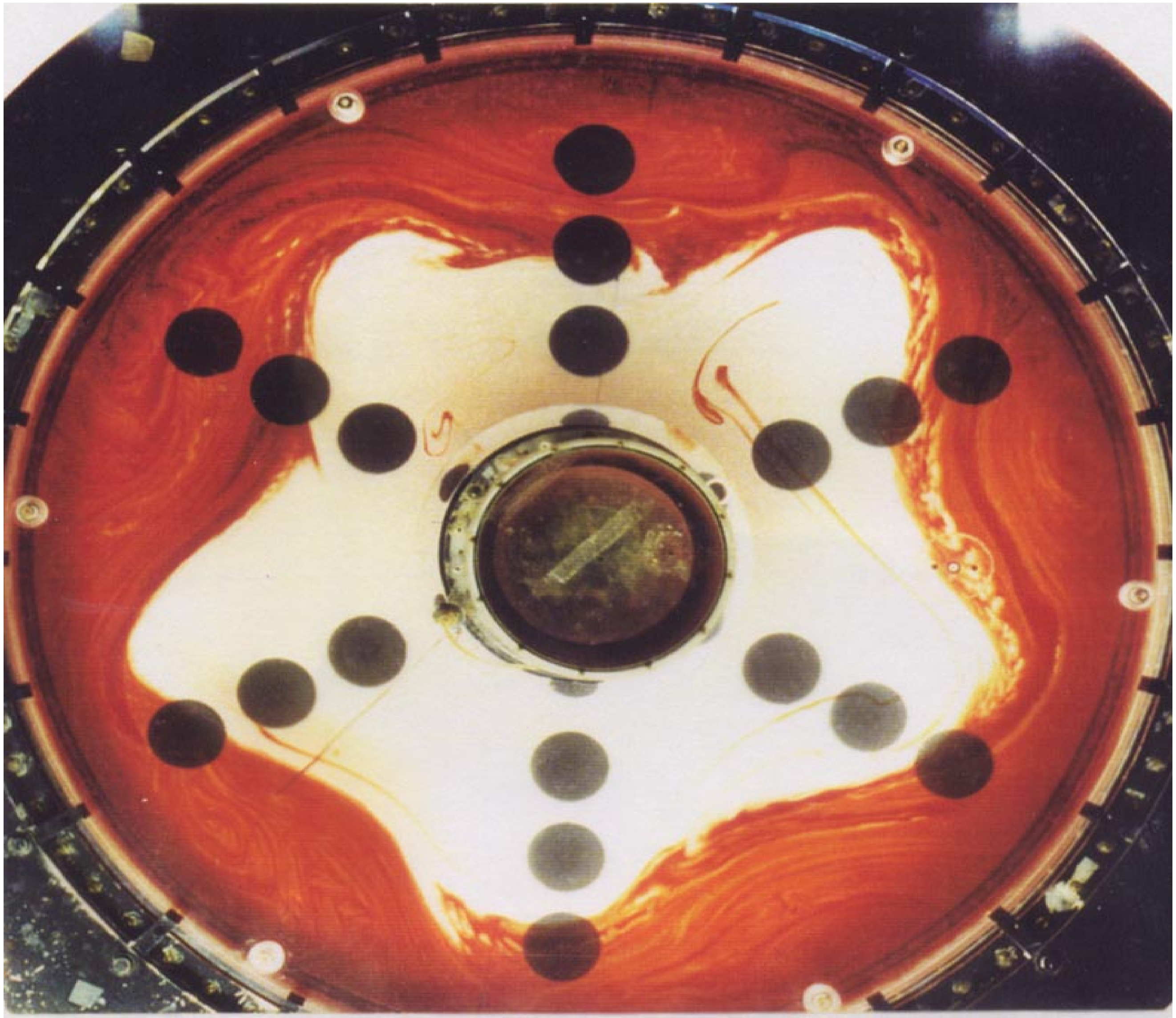
Jets are barriers:
cold water doesn't cross the Gulf Stream

(sea surface temperature measured by satellite)



Jets are barriers

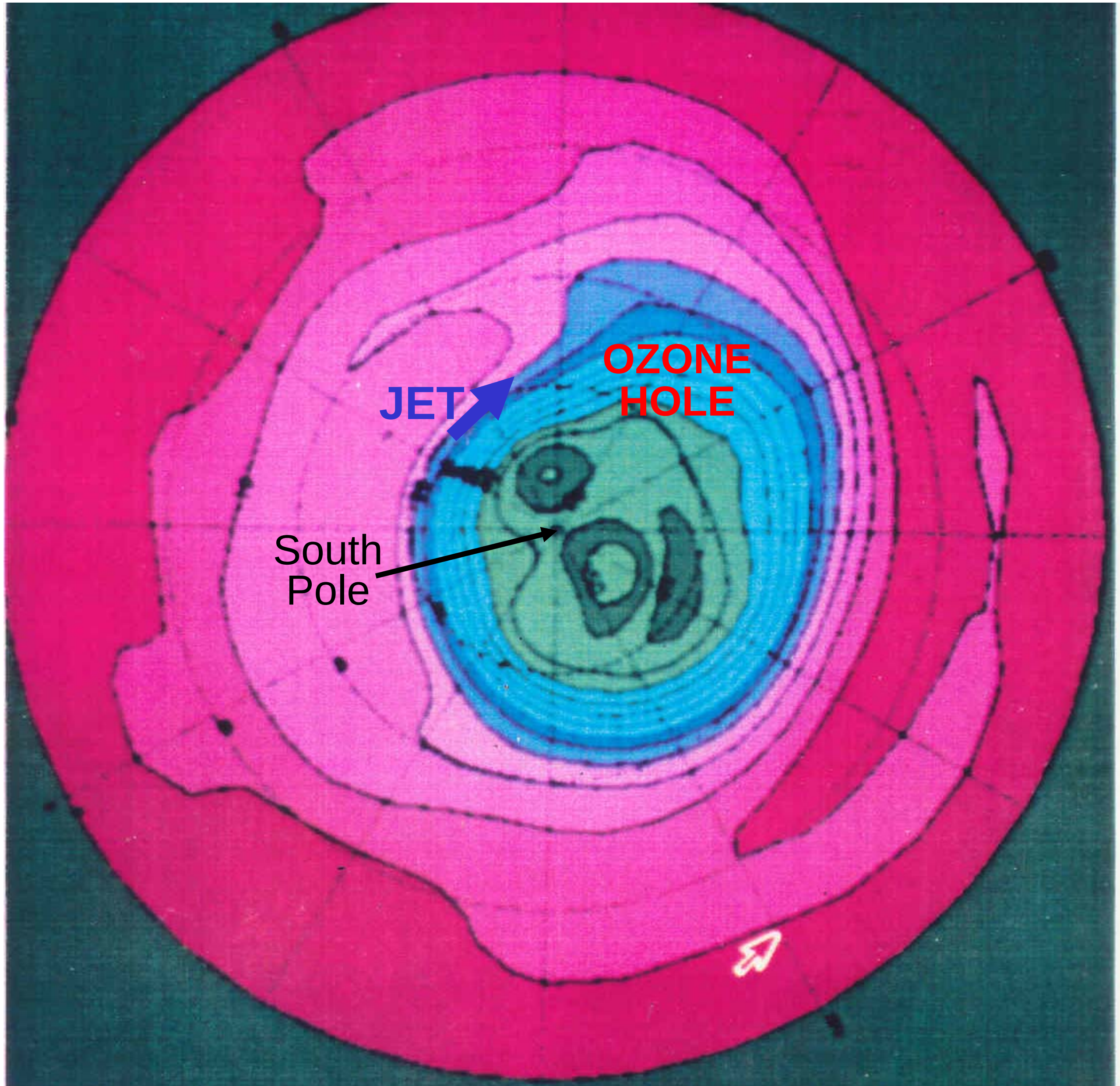
Example: inject dye near outer edge of tank



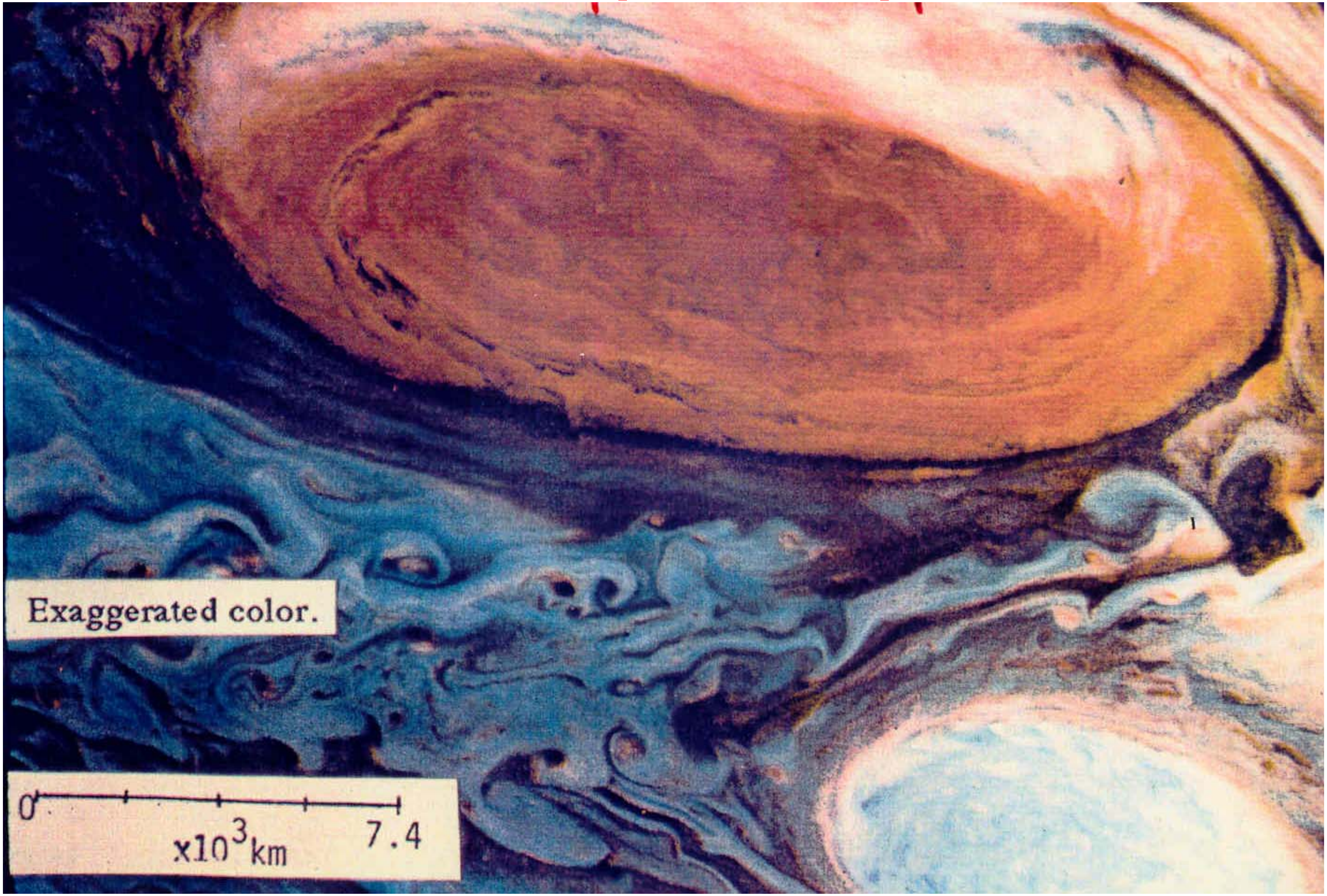
A jet in the atmosphere above the South Pole is a barrier to the flow of ozone into Ozone Hole

Red: *high* ozone concentration

Blue: *low* ozone concentration



Great Red Spot of Jupiter



Voyager 2 photo (1979)

First report of a large spot on Jupiter

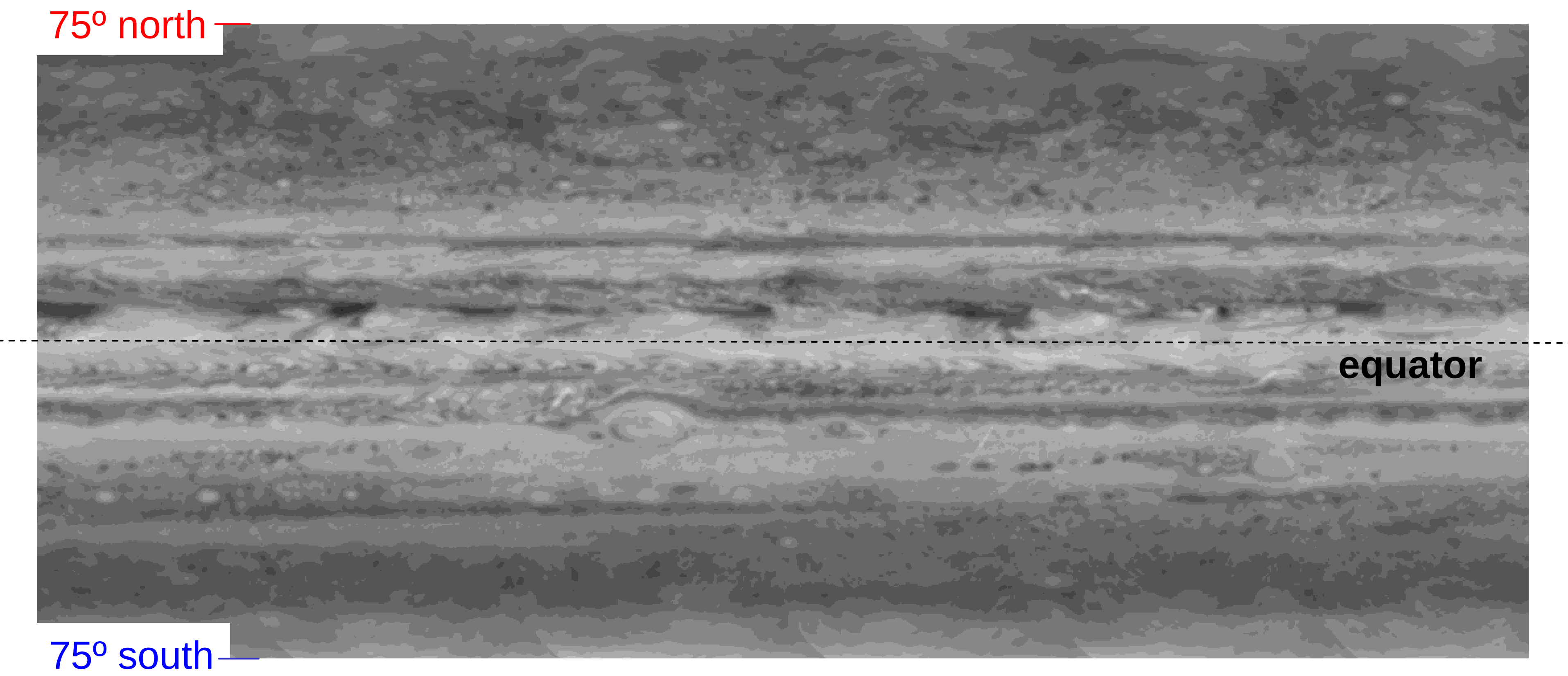
PHILOSOPHICAL
TRANSACTIONS:
GIVING SOME
ACCOMPT
OF THE PRESENT
Undertakings, Studies, and Labours
OF THE
INGENIOUS
IN MANY
CONSIDERABLE PARTS
OF THE
WORLD

Vol I.
For *Anno* 1665, and 1666.

A Spot in one of the Belts of Jupiter

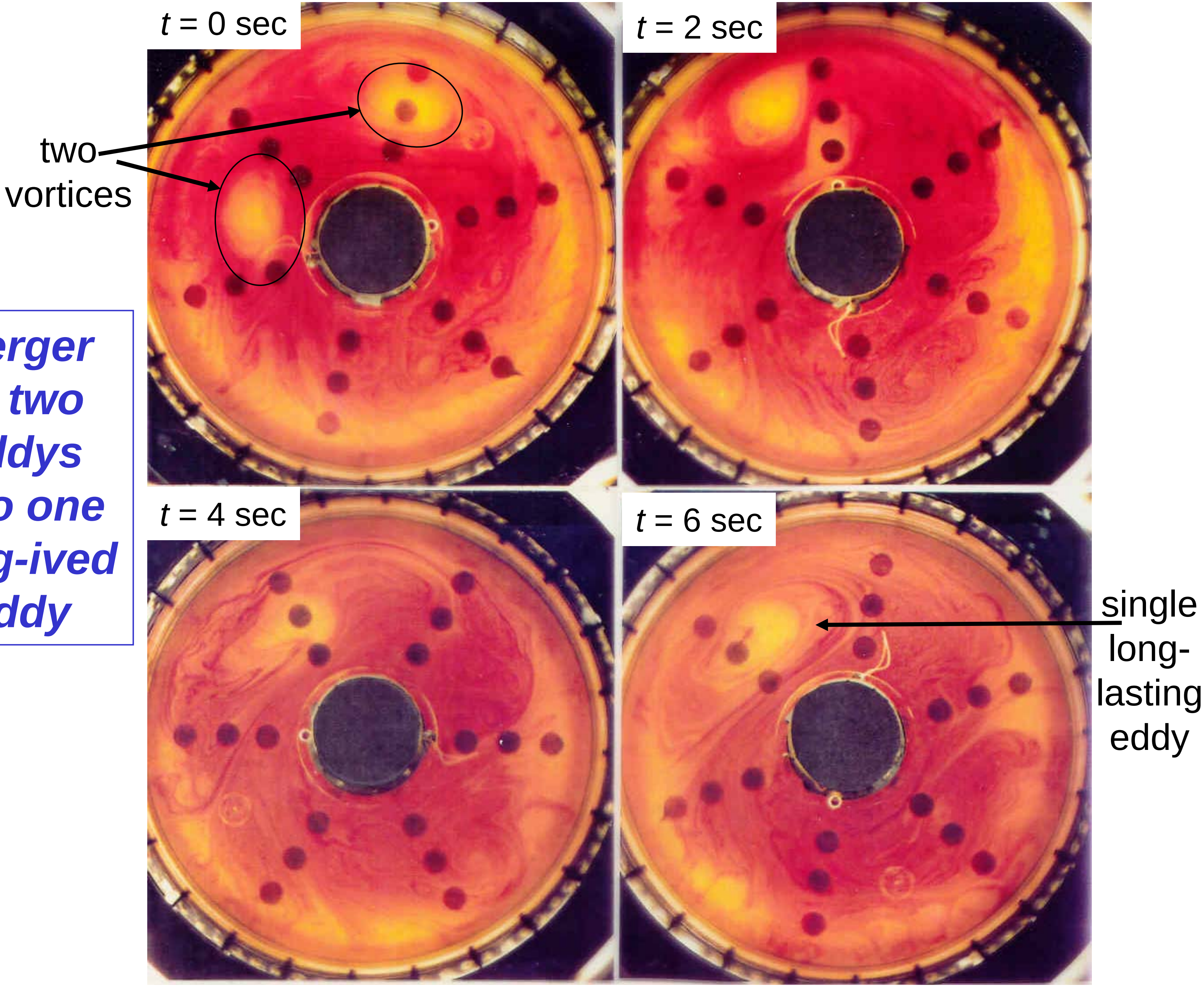
The Ingenious Mr. *Hook* did, ſome moneths ſince, intimate to a friend of his, that he had, with an excellent twelve foot Teleſcope, obſerved, ſome days before, he than ſpoke of it, (*videl.* on the ninth of *May*, 1664. about 9 of the clock at night) a ſmall Spot in the biggeſt of the 3 obſcurer *Belts* of *Jupiter*, and that, obſerving it from time to time, he found, that within 2 hours after, the ſaid Spot had moved from Eaſt to Weſt, about half the length of the Diameter of *Jupiter*.

Great Red Spot and eastward & westward jets on Jupiter



photos from Cassini spacecraft

Merger of two eddys into one long-ived eddy



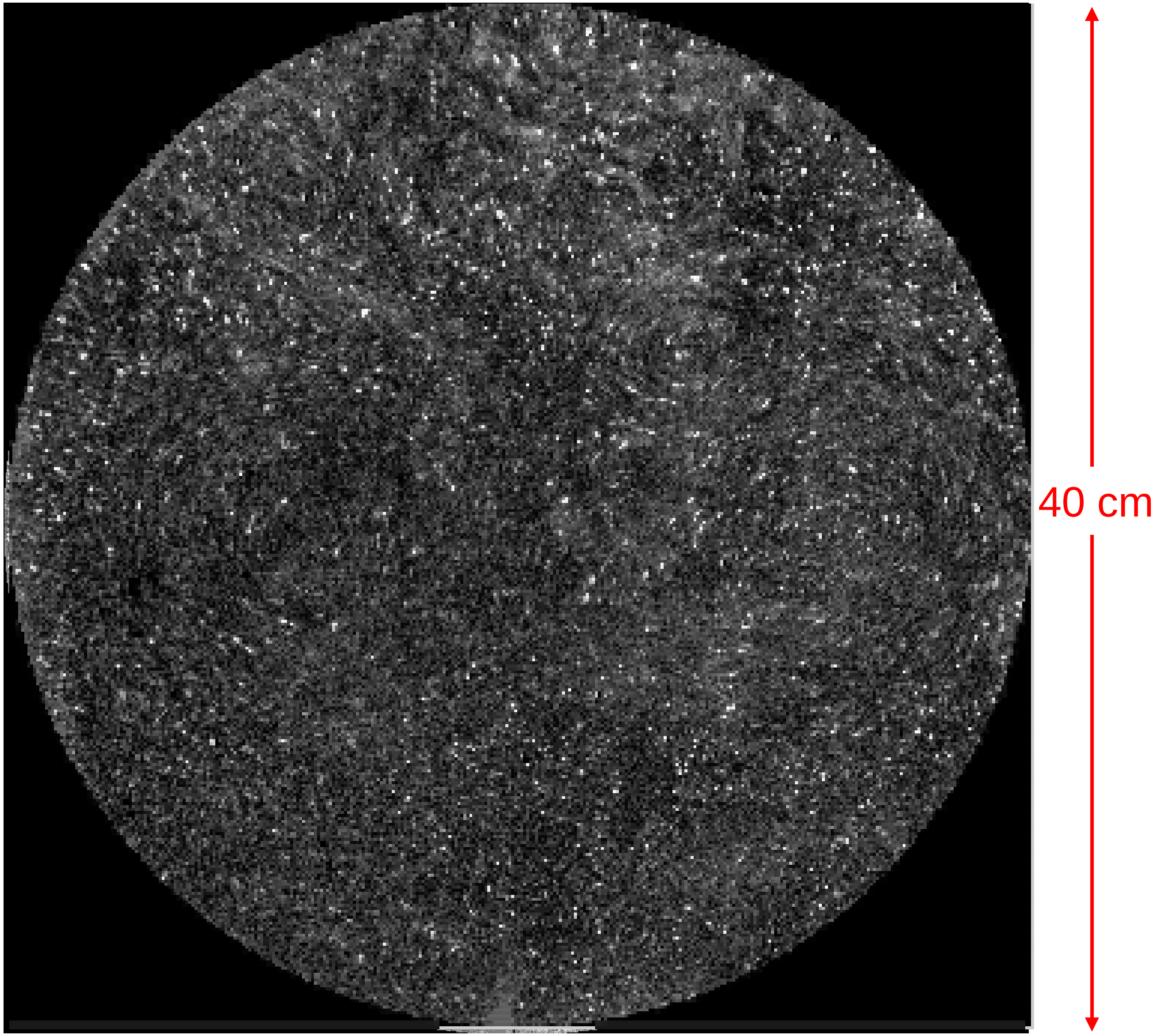
UT laboratory experiment reveals conditions in which a long-lived large eddy like Jupiter's Great Red Spot can spontaneously form

- strong Coriolis force
- turbulent flow
- average velocity varies strongly with latitude
- Coriolis force varies with latitude

Structures in turbulent flow

in a rotating tank

Fluid depth 48 cm.
Horizontal laser sheet 8 cm below top.



Lyapunov Exponent characterizes rate of separation of nearby particles

Aleksandr Lyapunov
1857-1918

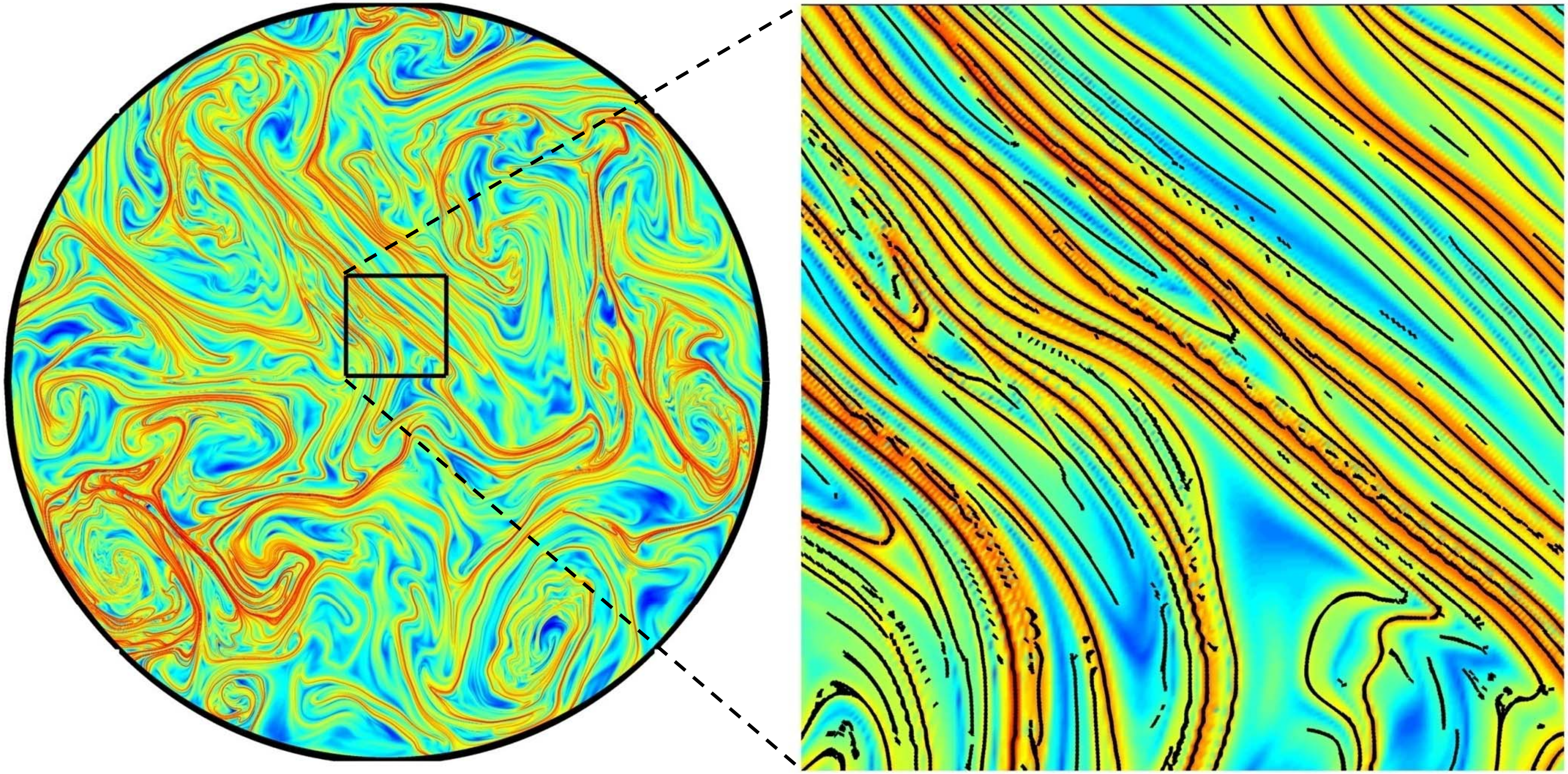
Consider two points with infinitesimal separation $\delta\vec{r}(t=0)$

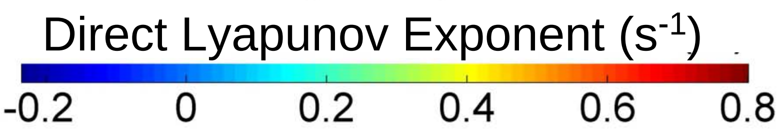
Then the largest Lyapunov exponent is

$$\lambda = \lim_{t\to\infty} \frac{1}{t}\left(\log \frac{\delta\vec{r}(t)}{\delta\vec{r}(0)} \right)$$

For physical systems: Wolf, Swift, Swinney, Vastano: *Physica D* **16** (1985)

Direct Lyapunov Exponent field



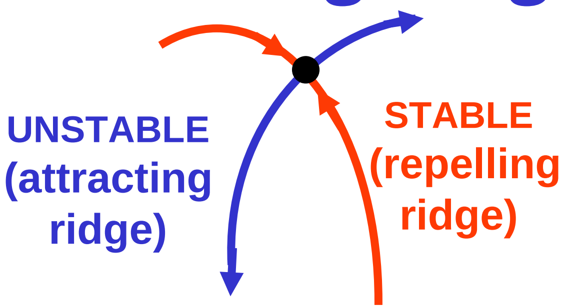


Black lines are maximizing curves (***ridges***) of the DLE field

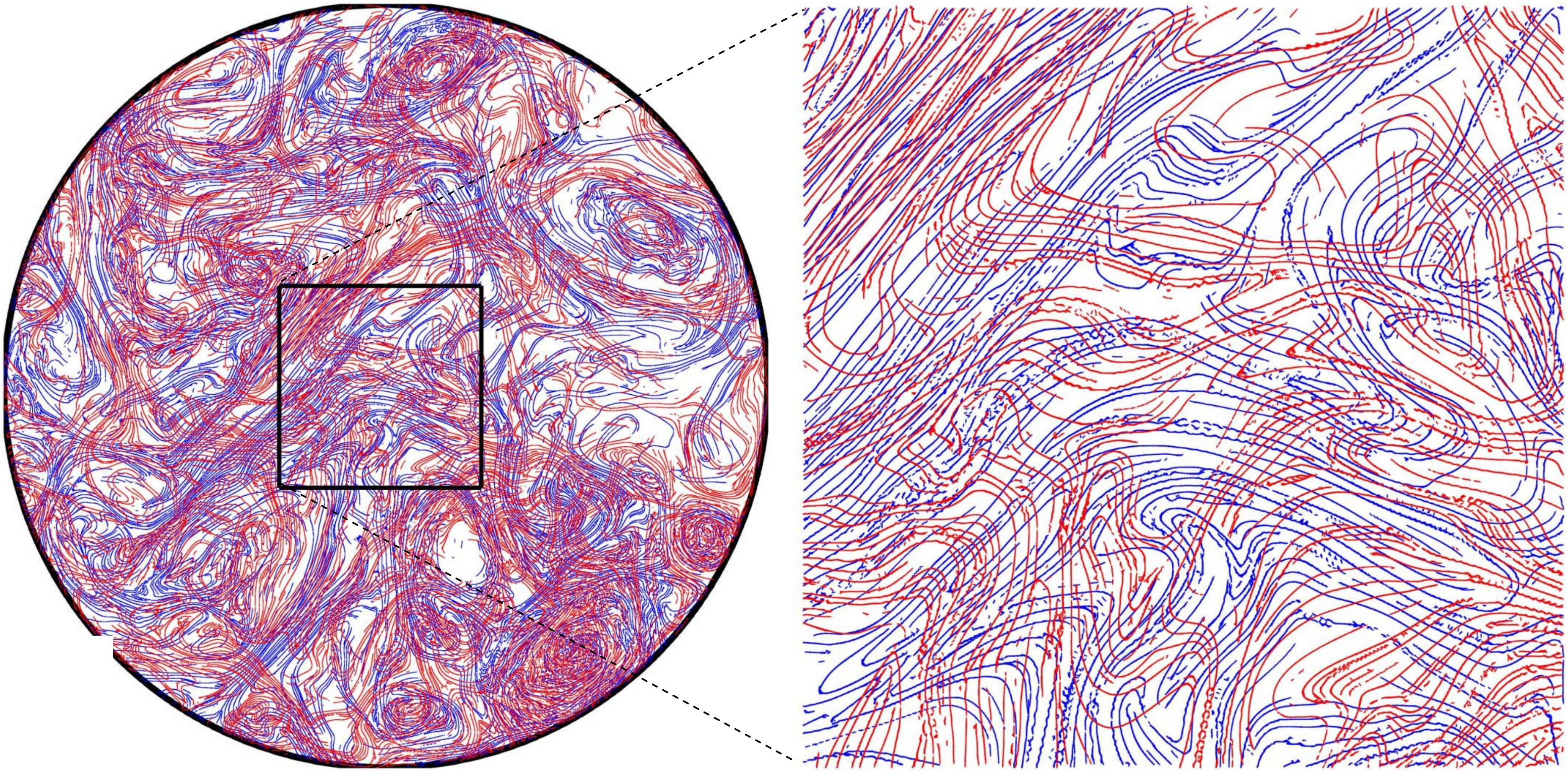
Maximizing curves (ridges) are transport barriers

→ **Transport across a ridge is negligible**

The Lagrangian Skeleton of Turbulence



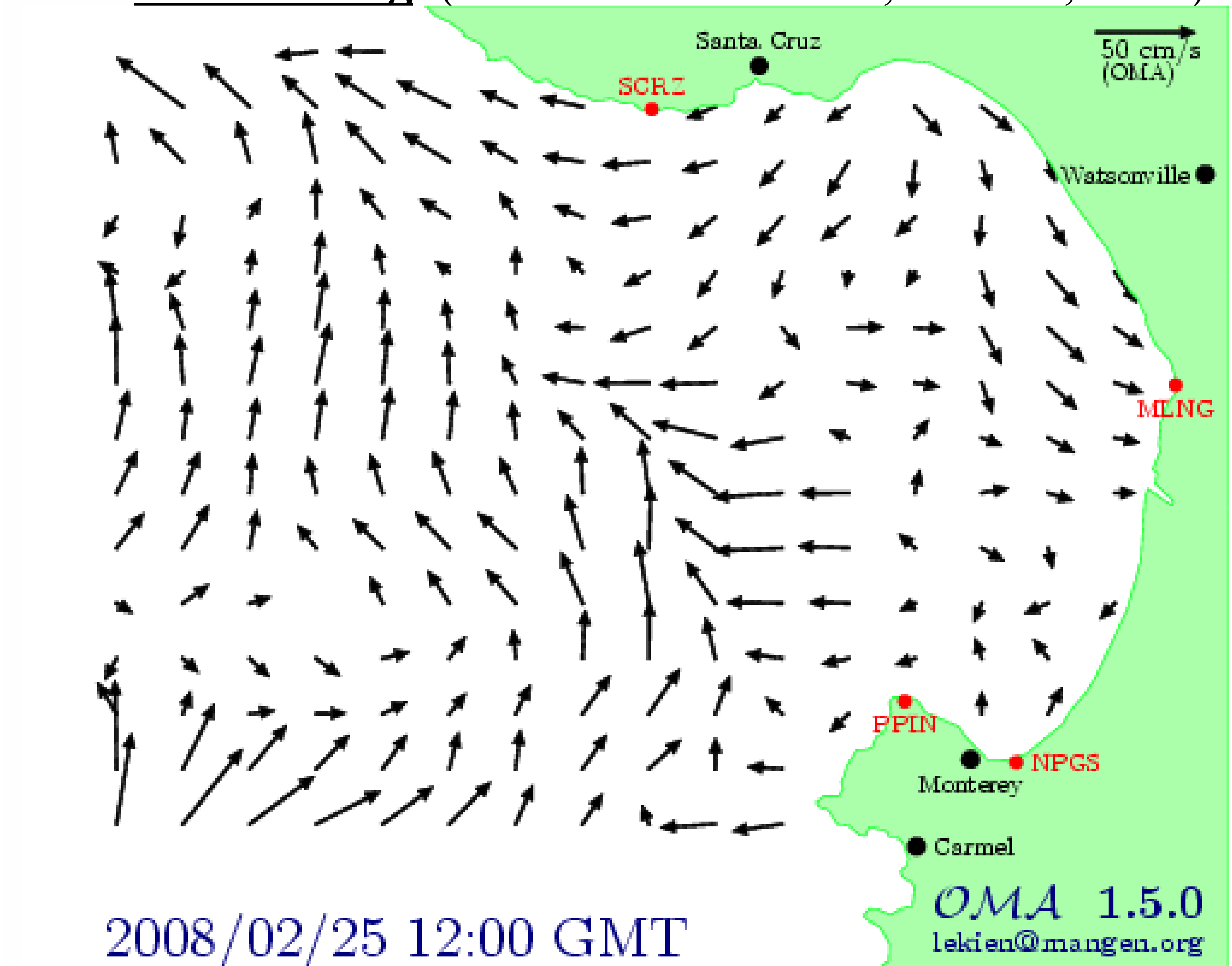
U. Texas experiment (2007)



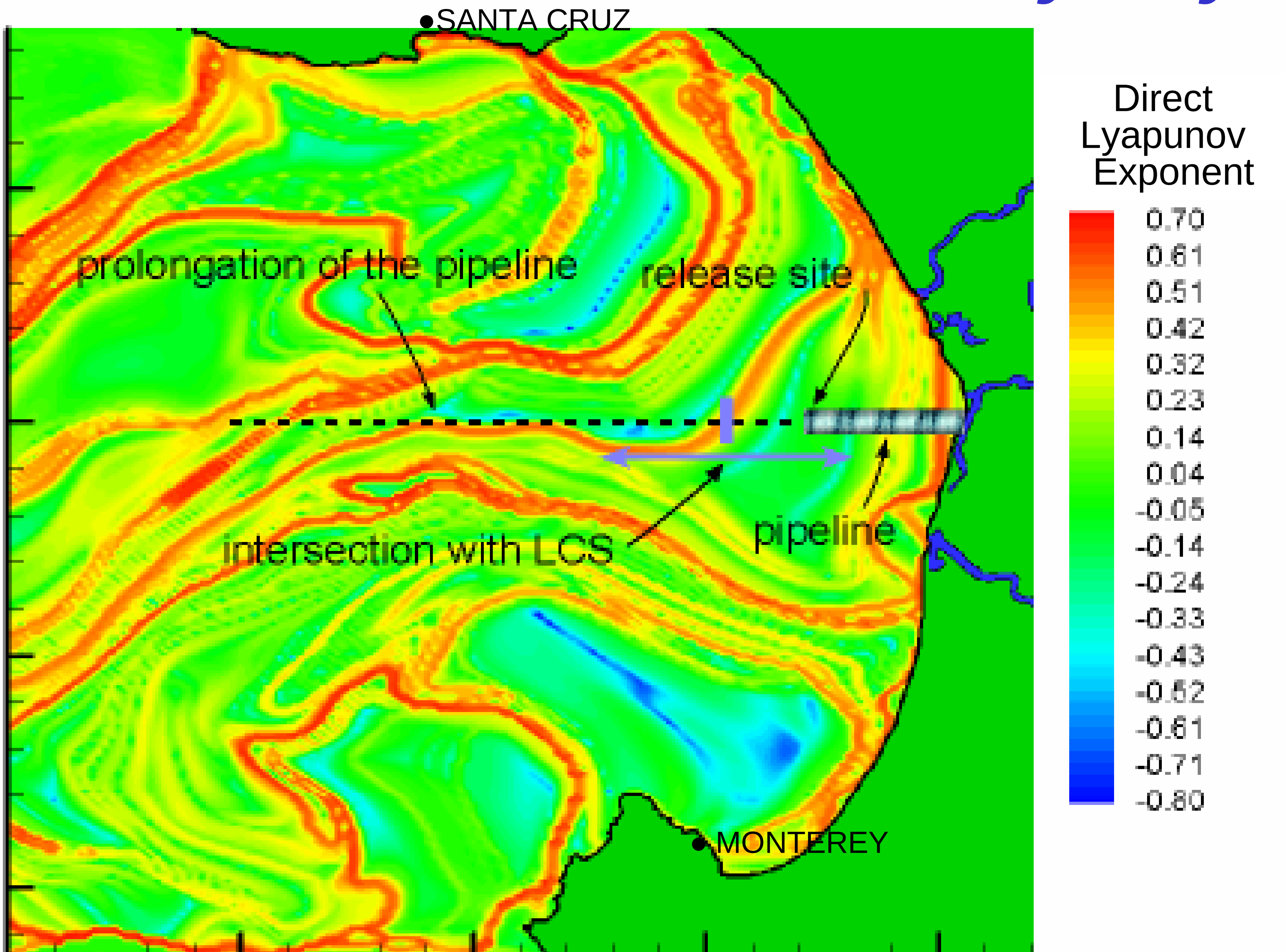
Real time velocities in Monterey Bay

using surface radar

ManGen.org (Lekien and Couliette, Caltech, 2008)



Pollution control in Monterey Bay



Future applications

of Lyapunov methods

- Compute transport in ocean eddys, hurricanes, …
- Calculate friction (drag) in flow past cars, trucks, trains, planes, ducks, …

This work is only now becoming possible through

- *velocity field time series data*
- *large scale parallel computing*

-- for example, UT Ranger

***To understand dynamics of atmosphere and oceans* (to predict climate)**

NEED:

- field observations
- laboratory experiments
- computations

Oceanic and Atmospheric Flows

- ***Coriolis force*** $(-2\Omega \times \boldsymbol{u})$

  makes atmospheric and oceanic flows different

- long-lived ***jets and eddys***

  example: highs, lows, jet stream, Gulf Stream

- jets can have ***waves***

  example: Saturn's Polar Hexagon

- ***Lyapunov methods***: determine pollutant and nutrient transport

  --- **example: Monterey Bay**