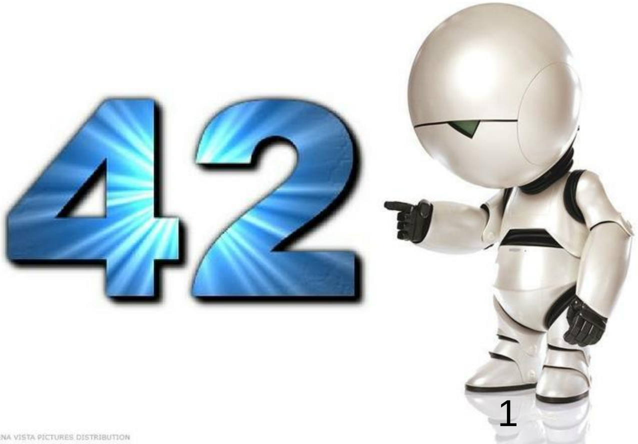
Zonal Jets

Editors: Boris Galperin and Peter Read

CUP [due to appear 2015?]

The answer to life, the Universe and everything?



04 BUENA VISTA PICTURES DISTRIBUTION

Multiple zonal jet formation in rotating, thermally-driven convection on a topographic β-plane

Peter Read
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+T. Jacoby, L.P.H.T. Rogberg, R. D. Wordsworth, Y.H. Yamazaki, K. Miki-Yamazaki, R.M.B. Young, J. Sommeria, H. Didelle, S.Viboud & B. Galperin

Motivation

- Phenomenology of anisotropic large-scale turbulence and "jets" in geophysical and planetary fluids
  - in oceans cf in gas giant planet atmospheres,
- Questions:
  - (i) Why are jets prominent on gas giant planets but weak in the oceans?
  - (ii) energetics and energy flow (esp. on gas giants)?
    - large apparent $C(K_E, K_Z)$ conversion rates?
    - Relationship to more general (upscale?) energy cascades?
    - Local or non-local?
  - (iii) Potential Vorticity and configuration of zonal jets?
    - PV mixing ('Phillips effect')
    - PV staircases?
  - (iv) Passive tracer transport and mixing?
    - Zonation and transport barriers?

2D turbulence with rotation & sphericity

Cascade becomes anisotropic at a scale where Rossby waves become important

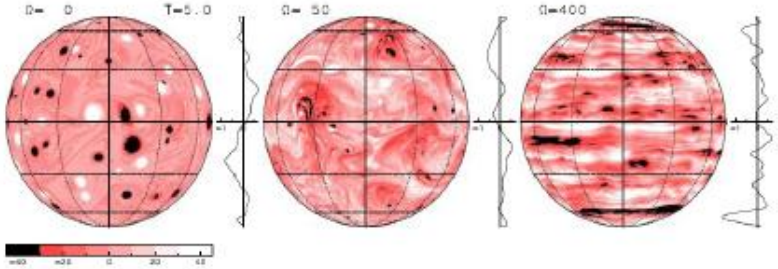
L_b » $\sqrt[5]{e/b^3}$; where t_{RW} » L/U

- $L < L_\beta$; Nonlinear effects dominate
- $L > L_\beta$; β–effect dominates

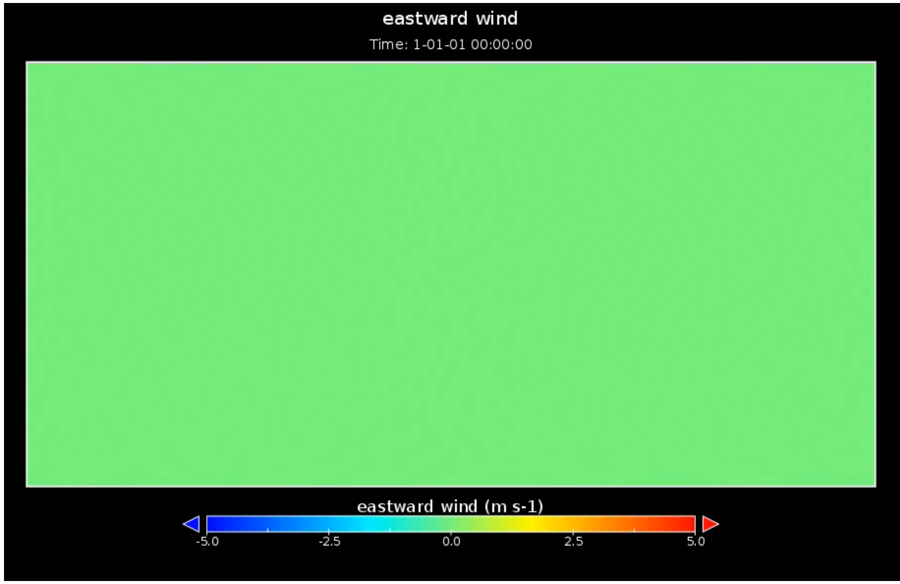
[Vallis & Maltrud 1993]

Kinetic energy removed at largest scales e.g. by bottom friction

$L^3\ L_{Rh} = \sqrt{2U_{rms}/b}$; Rhines scale



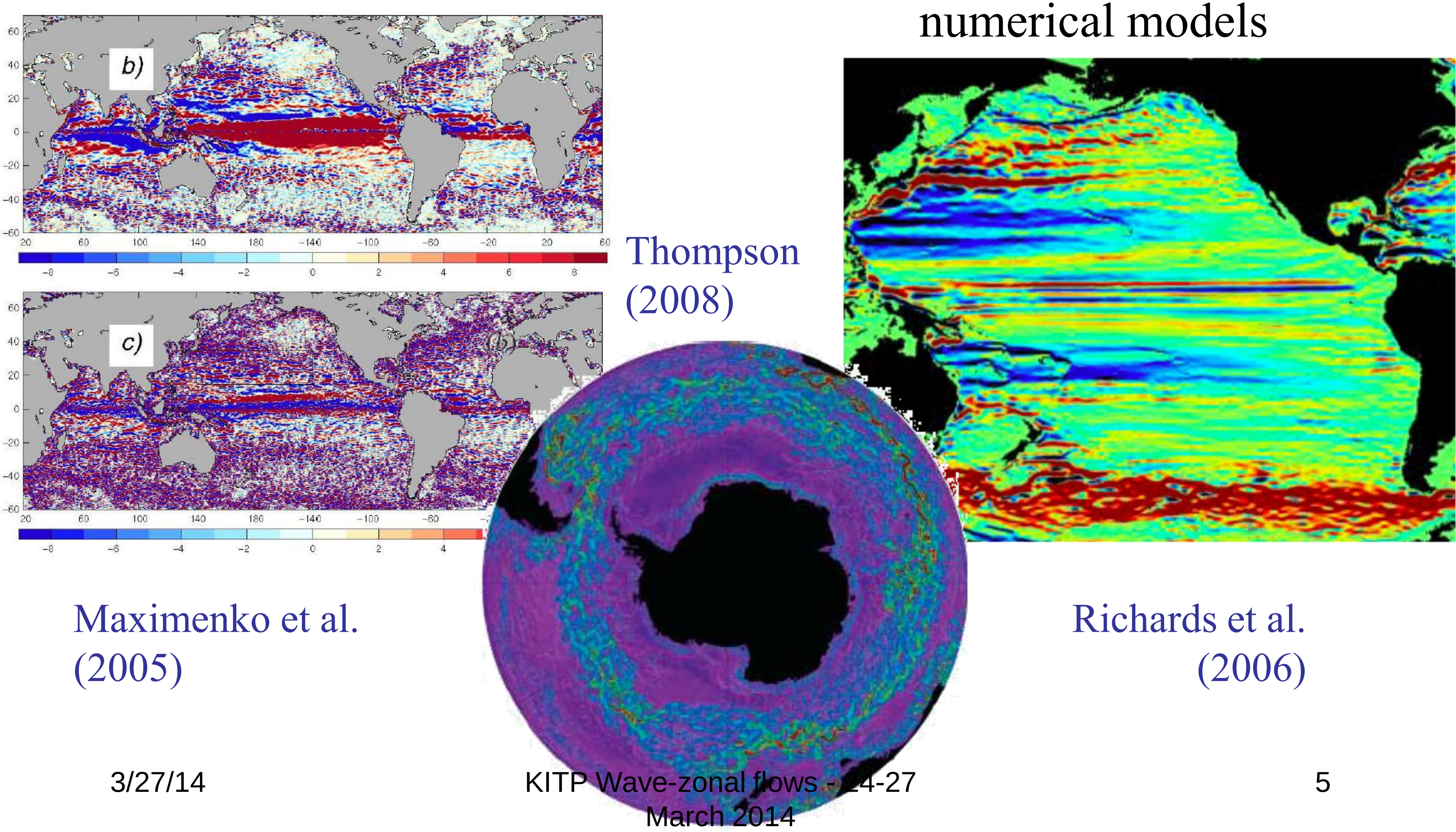
[Yoden et al., 1999]



Wang & Read (2014 – in preparation)

`Zonation' in the Ocean

Pacific Ocean in observations & eddy-permitting numerical models

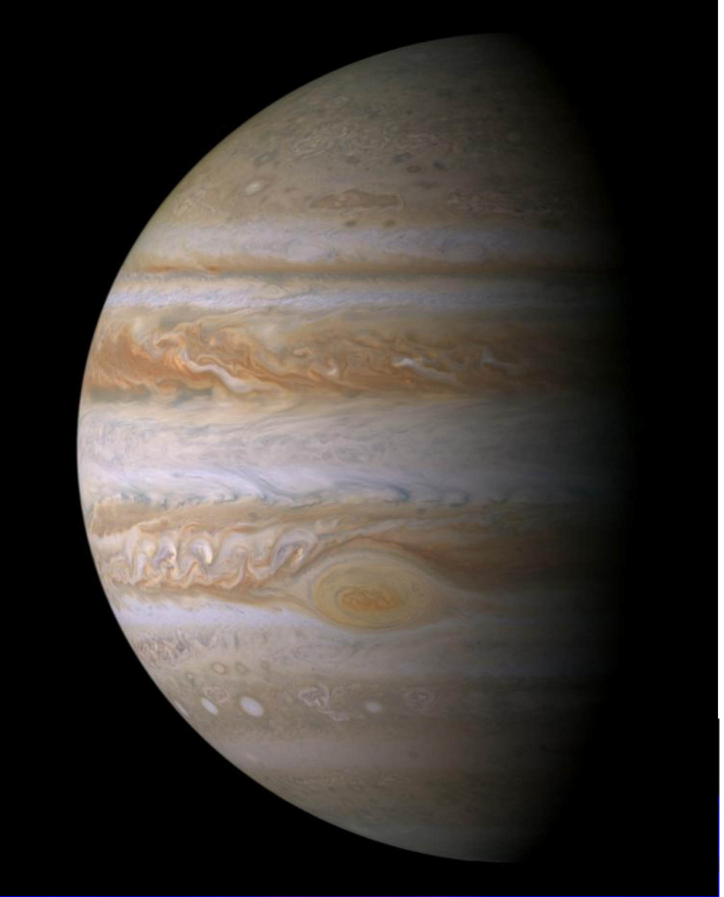


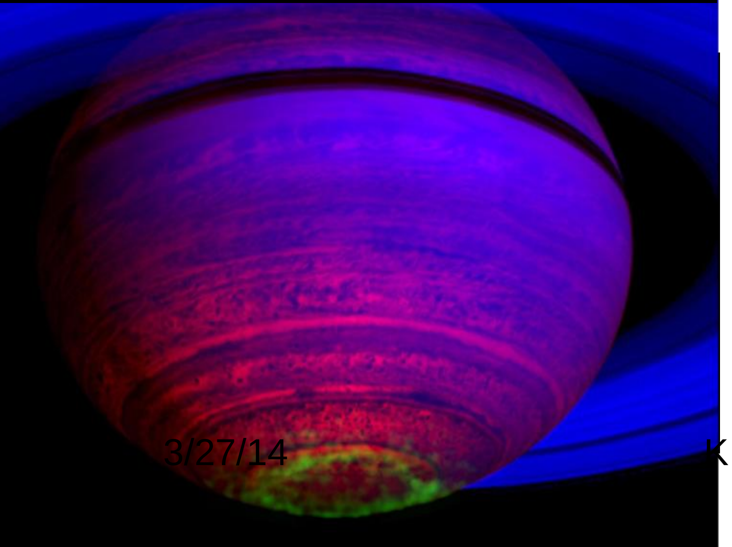
Thompson (2008)

Maximenko et al. (2005)

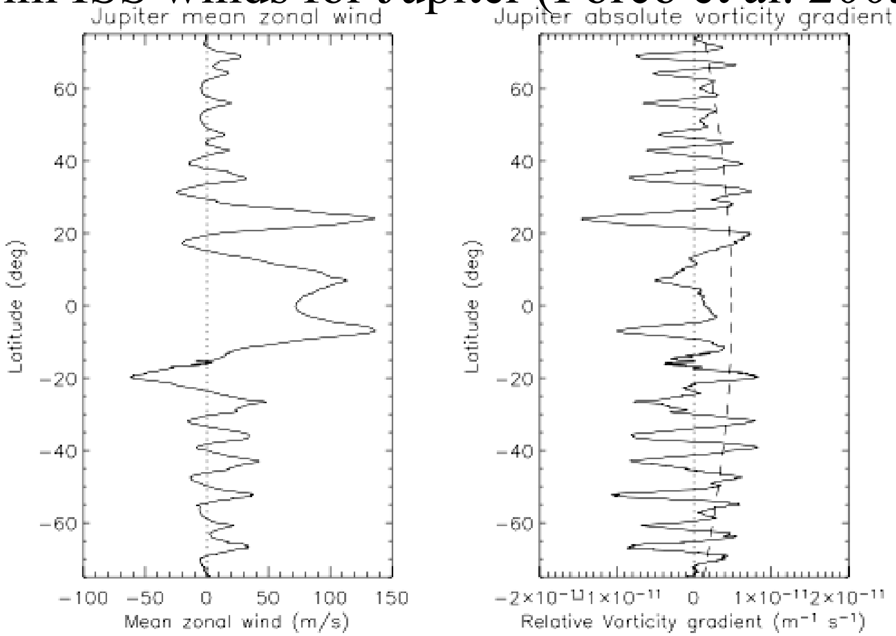
Richards et al. (2006)

Planetary Zonal Jets





Cassini ISS winds for Jupiter (Porco et al. 2003)

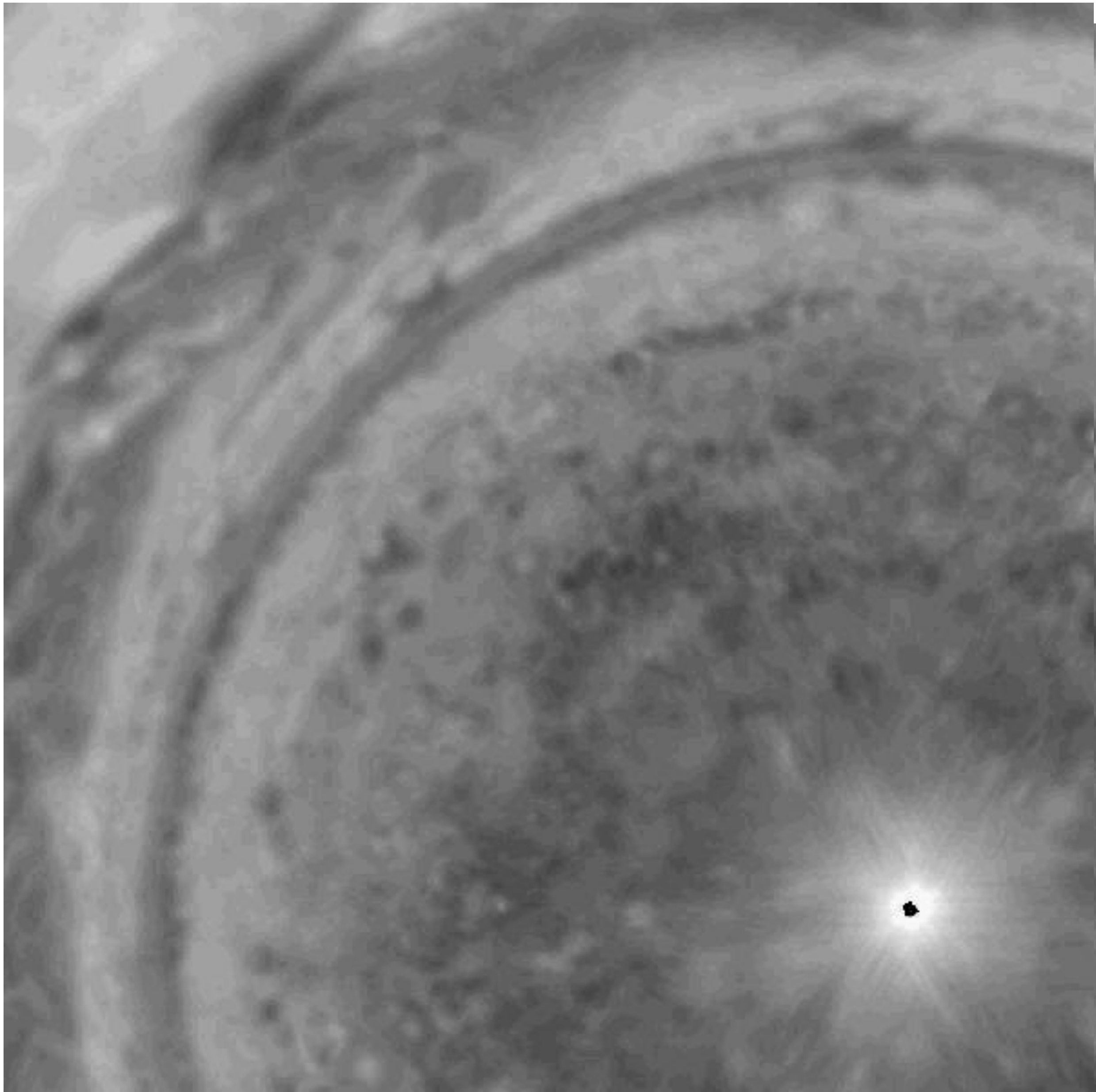


- Robust, long-lived and ~rectilinear?
- $q_y = \beta - u_{yy} < 0$ in easterly jets
- Jets maintained by horizontal eddy momentum fluxes (Reynolds stresses)?
  - $C(K_E,K_Z) \sim 3\text{-}12 \times 10^{-5}$ W kg^{-1} [??]

Zonal jets on Jupiter (Cassini)

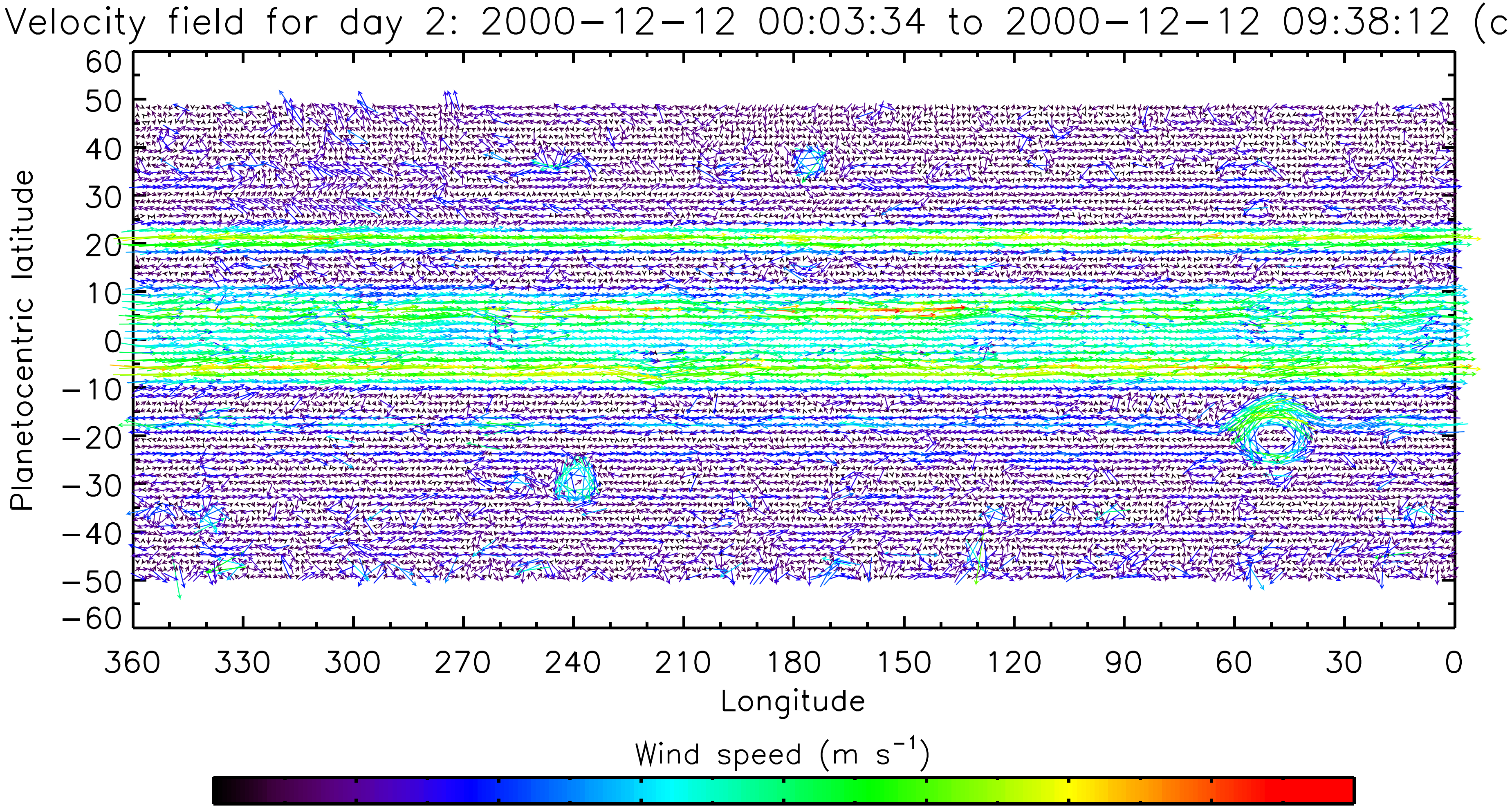
- Unique series of Jupiter images from the Cassini fly-by in December 2000

- Closest approach has resolution ~0.05 deg/px



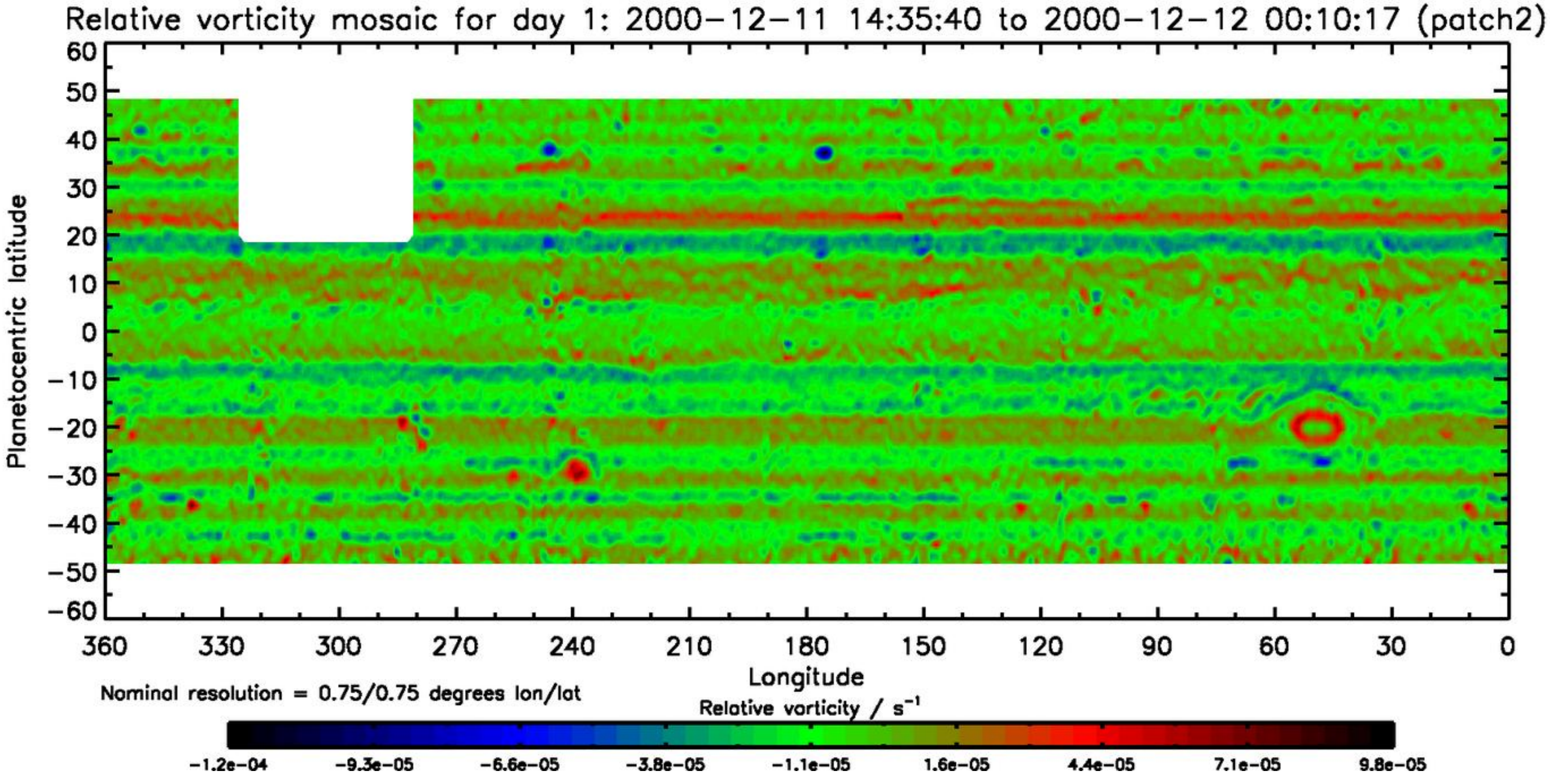
Credits:
Ashwin Vasavada
Cassini Orbiter
Imaging Team
(2001)

Velocity fields



Jupiter: relative vorticity

(Cassini ISS images - Galperin et al 2014)



Spectrally local vs nonlocal interactions?

- Decompose 2D KE spectrum *E(k$_x$,k$_y$)dk$_x$ dk$_y$* into
  - zonal mean

$$E_Z(n)dn = E(k_x = 0, k_y)dk_y;\ n = [k_x^2 + k_y^2]^{1/2}$$

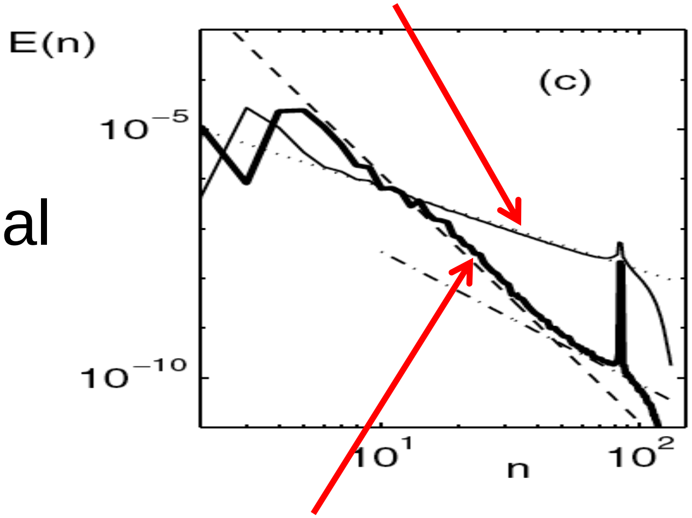
  - and directionally-averaged non-zonal (residual) components

$$E_R(n)dn = \left[\int_0^{2\pi} E(k_x \neq 0, k_y)\, n\, d\phi\right] dn:$$

such that

$$\int_0^\infty \int_0^\infty E(k_x, k_y)\, dk_x\, dk_y = \int_0^\infty [E_Z(n) + E_R(n)]\, dn$$

For ideal 'zonostrophic flow' - $E_R \sim n^{-5/3}$
[spectrally-local, isotropic inverse cascade]



$E_Z \sim n^{-5}$
[non-local "cascade"]
e.g. Sukoriansky et al. (2002) PRL….

Jupiter's kinetic energy spectrum

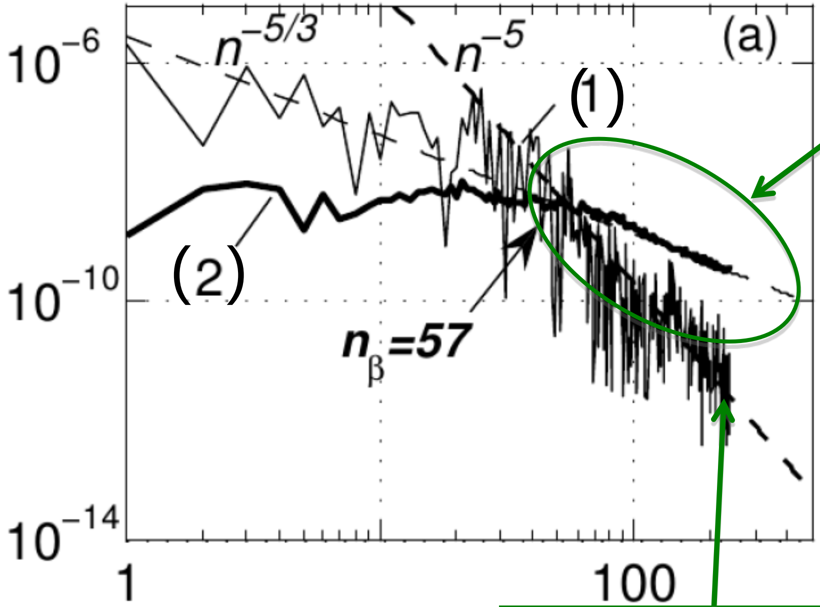
Zonostrophy index $R_\beta = L_R/L_\beta \, H \, 5$

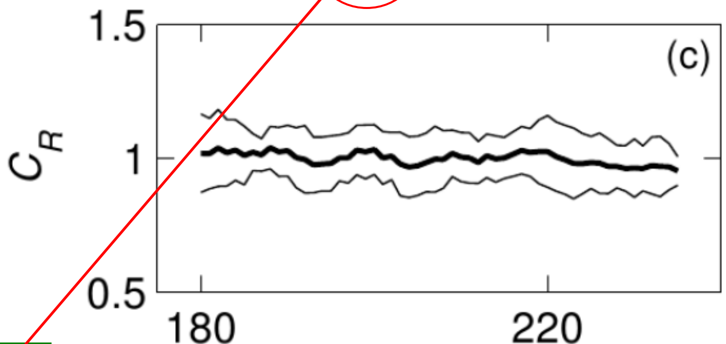
Shallowing slope (~ $n^{-5/3}$?)

- Upscale cascade?

$$E_Z = C_Z b^2 (n/a)^{-5} \qquad (1)$$

$$E_R = C_R e^{2/3} (n/a)^{-5/3} \qquad (2)$$





~n^{-5} -> non-local energy transfers

Thin: Zonal spectrum

Thick: Residual (eddy) spectrum

Compensated residual spectrum with $\pm\sigma$ error bars

e» 0.5 - 1´ 10^{-5} W kg^{-1}

See Galperin et al. (2014)

How to realise in Laboratory Experiments?

- Experimental requirements
  - Horizontal scale $L > L_{Rh} \sim \pi(2U_{rms}/\beta)^{1/2}$
  - Reynolds number $UL/\nu > 10^3$
  - Ekman number $(\nu/fD^2) \leq 10^{-5}$
  - Suitable forcing on a small scale (<< L)

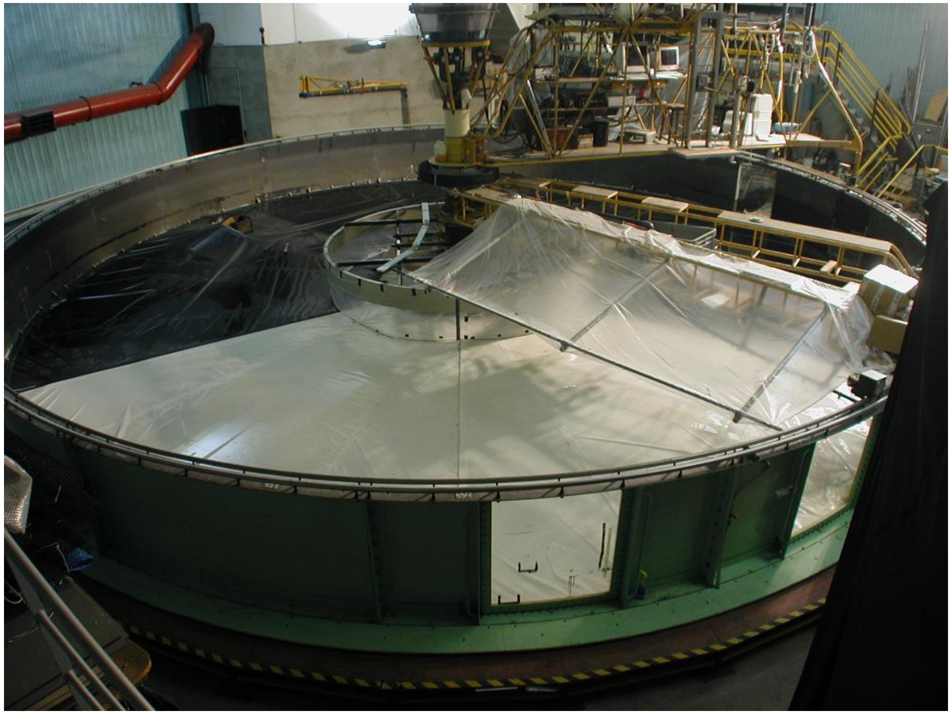
    \- preferably not fixed in space…
  - Rapid rotation (small Rossby number)

$$\Downarrow$$

LARGE-SCALE EXPERIMENT

(GRENOBLE 13 m dia. Rotating table)

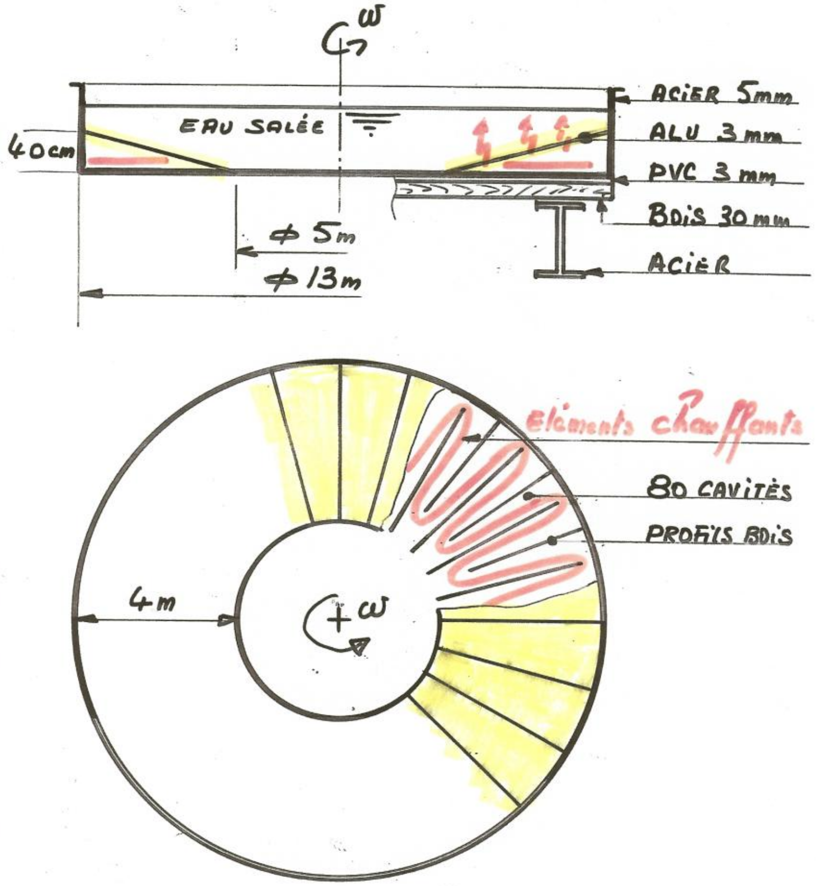
Experimental configuration 1: Salt-driven convection



- Overhead salt-water spray system
- Nozzles mounted on rotating, radial arm
- Spacing/orientation designed to supply uniform buoyancy flux
- Rotation, density and flow rate (buoyancy flux) controlled

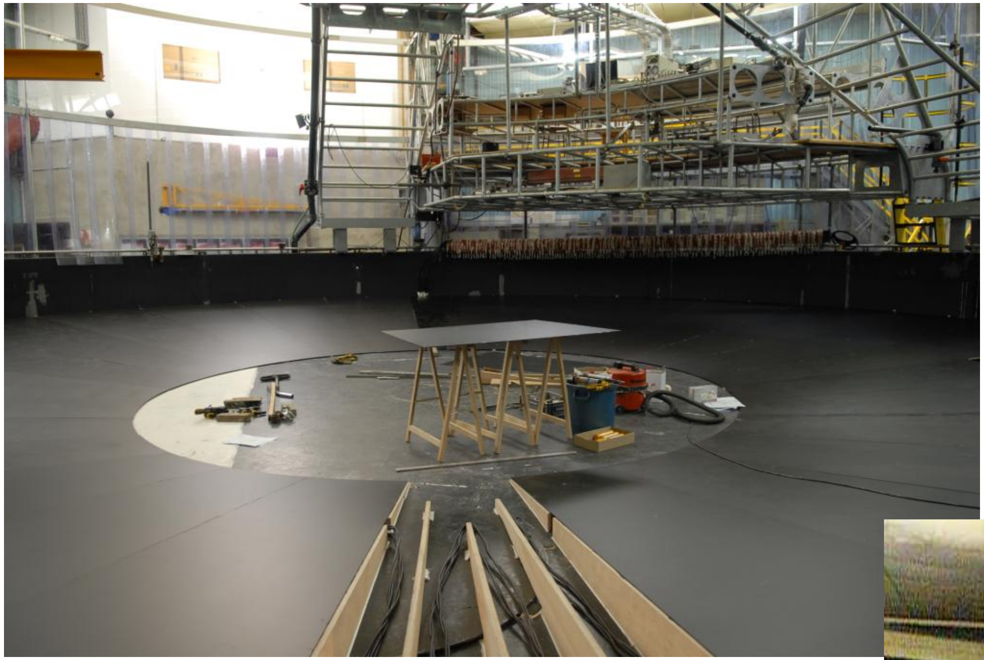
Experimental configuration 2: THERMALLY-forced convection

- Coriolis Platform, Grenoble (France)
- ~3km of heating cable layed beneath hollow sloping bottom
- Smooth, rigid sloping bottom of segmented Al plates
- Upward slope with *r* at approx. 6°

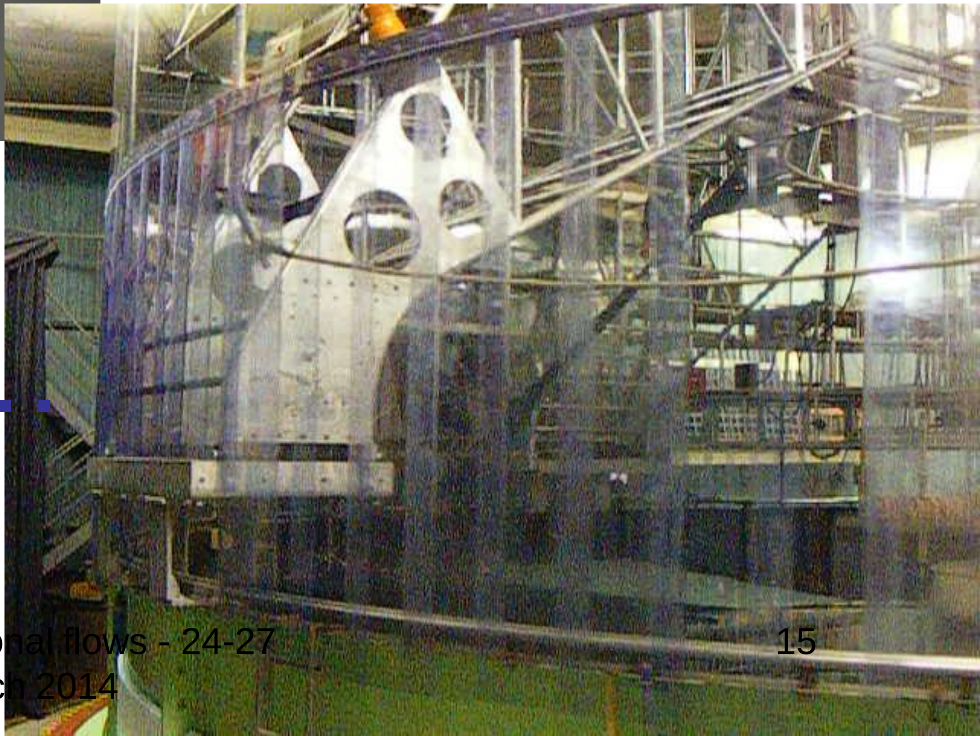


EXPERIENCE de CONVECTION FORCEE (P. Read).
LEGI. Coriolis 05.07

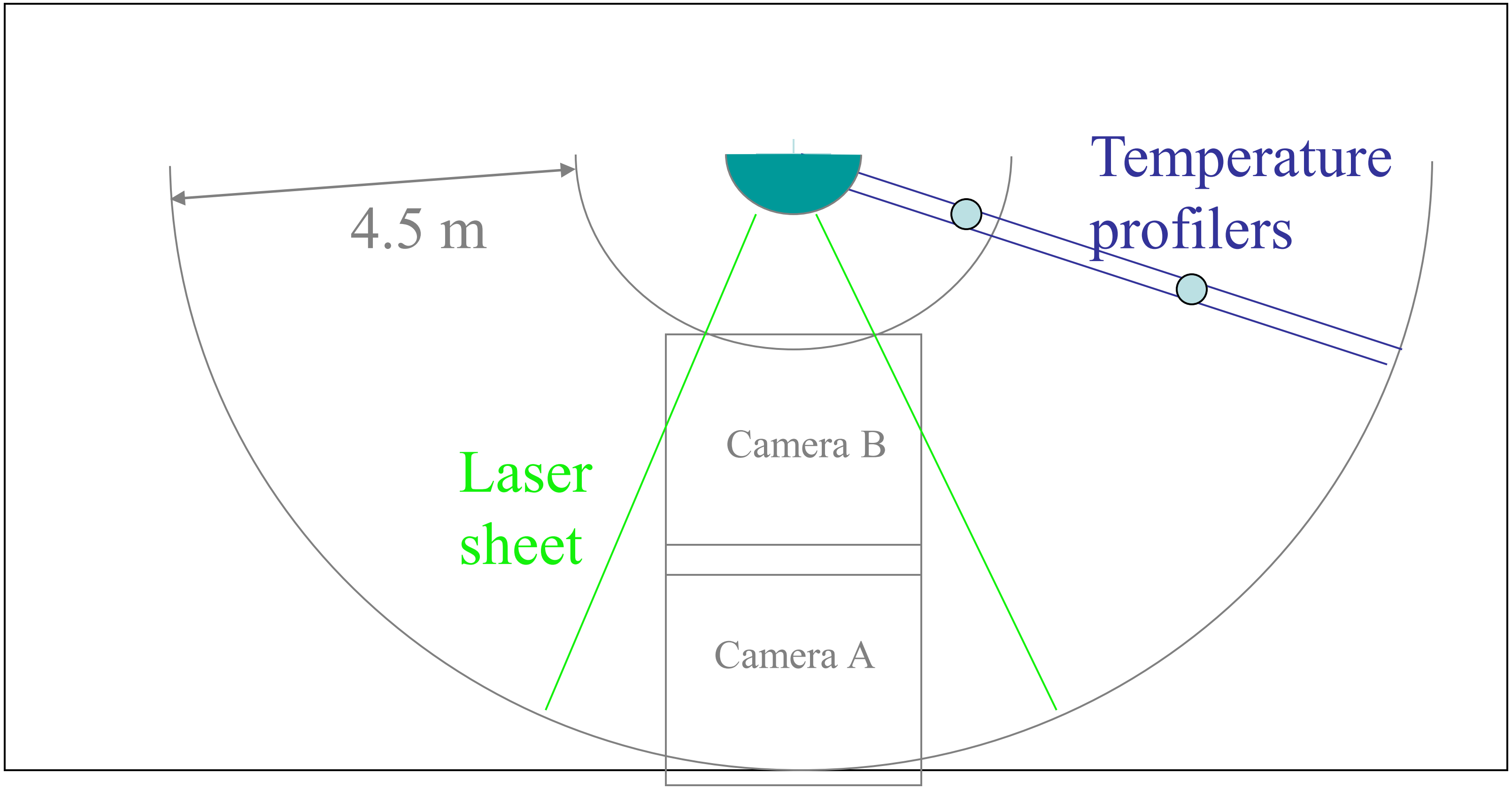
Upward-sloping bottom



Experiment running…

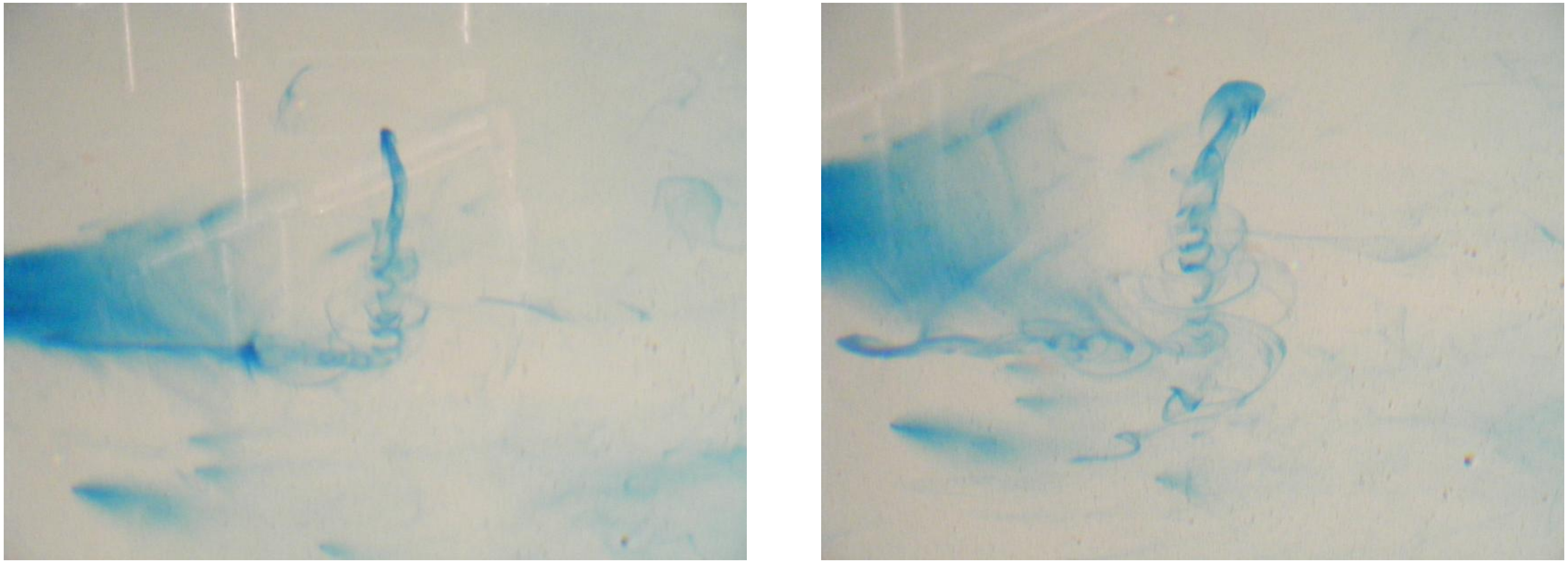


Measurement configuration



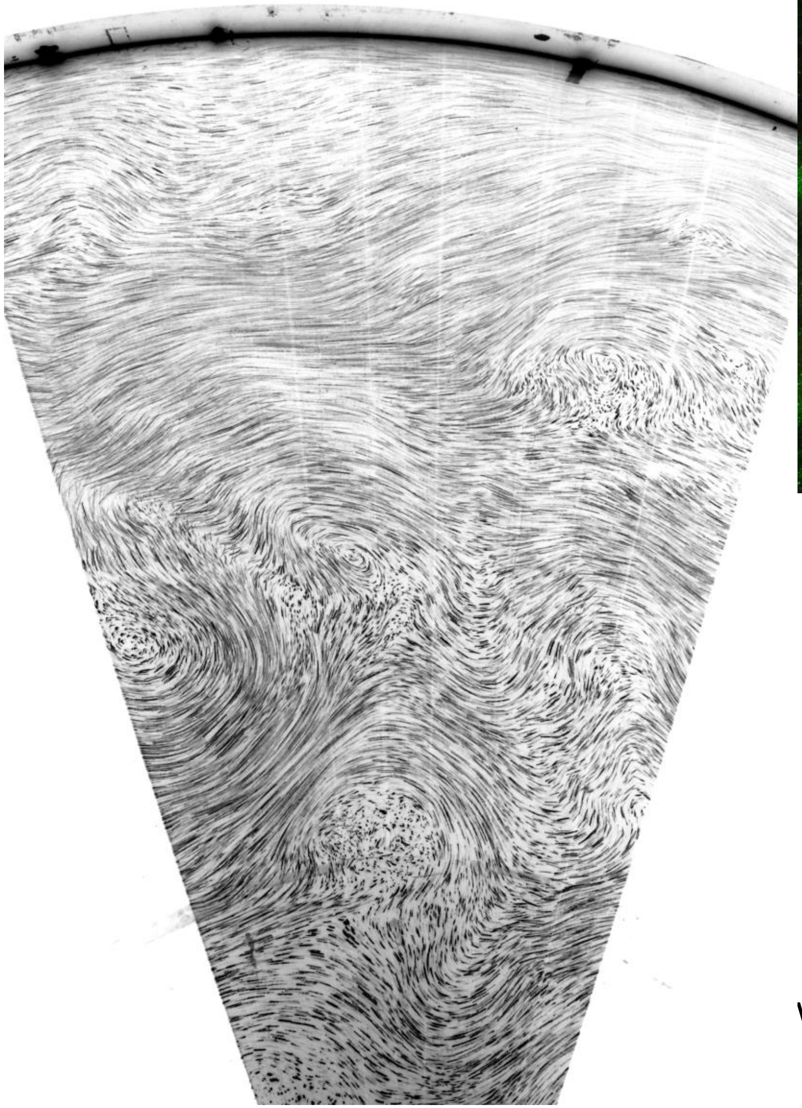
BUT views ~7% only of total area! – *keyhole diagnostics*

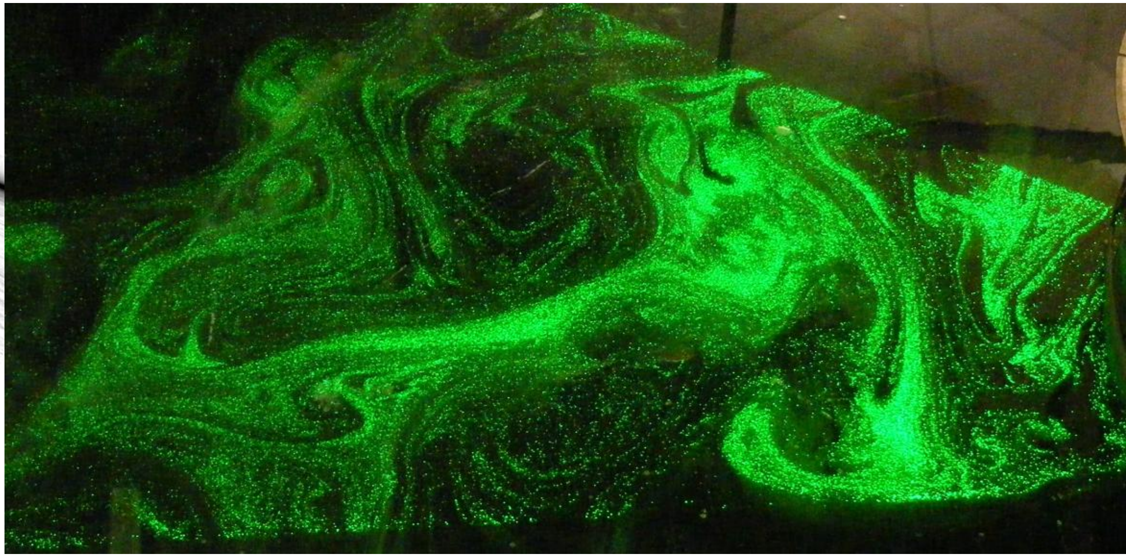
Small-scale convection?



- 11 kW of heating => $F_B \sim 5.8 \times 10^{-8}\ \mathrm{m^2\ s^{-3}}$
- Intermittent convective plumes form compact, intense cyclonic vortices
  - Around 5-50 cm diameter
  - Consistent with $l_{rot} \sim (Ro^*)^{1/2} h$; $Ro^* = (F_B/f^3h^2)^{1/2} \sim 10^{-3}\text{-}10^{-2}$ [Fernando et al. 1991]

Flow visualisation in laser sheet





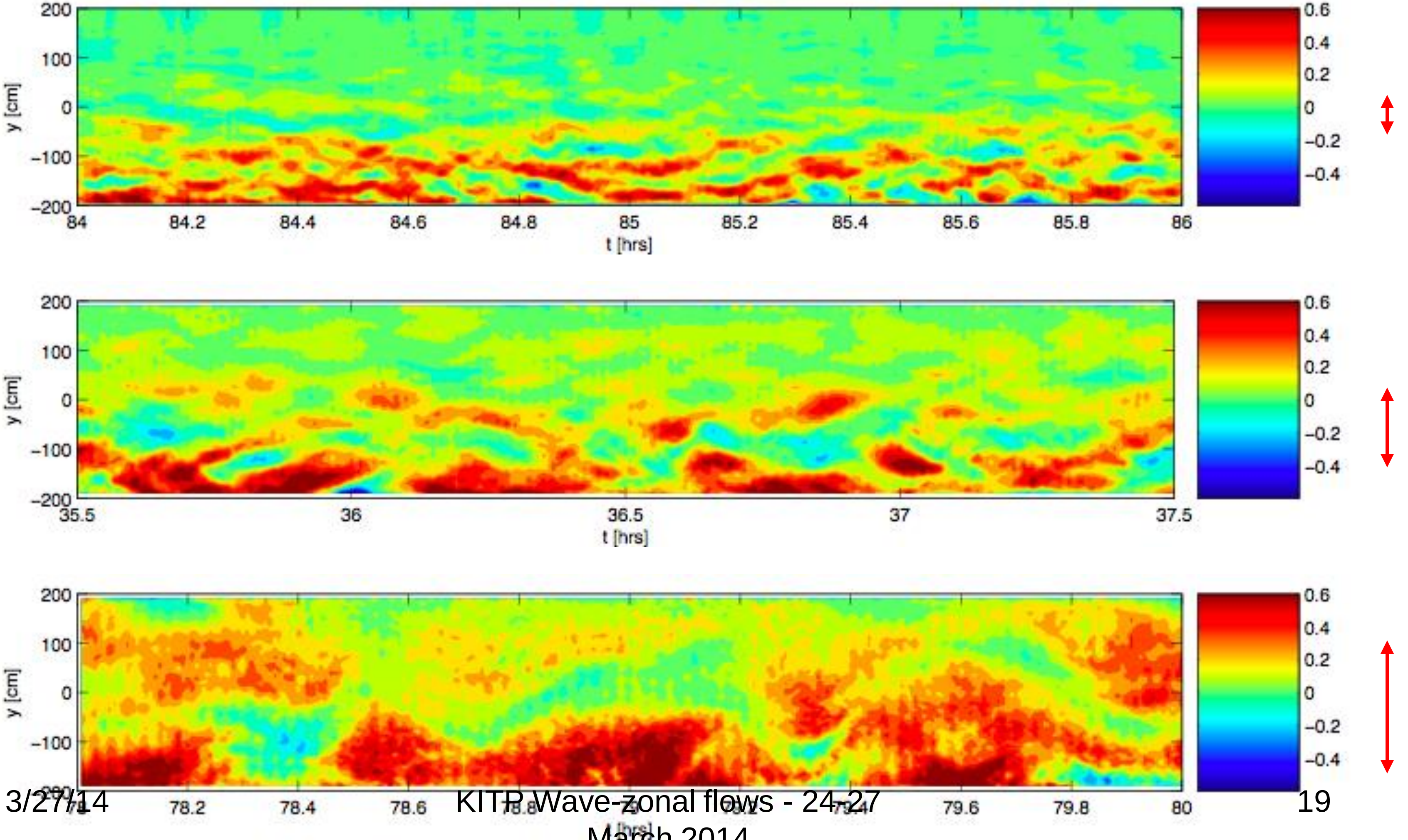
- Neutrally buoyant particles
  - Measure horizontal velocity using PIV/CIV
- Jets & vortices
- Baroclinic instabilities?

Radial scale of Azimuthal mean jets

Azimuthal mean azimuthal (zonal) velocity

$\beta L^2/(2u_{rms})$

L_{Rh}



580

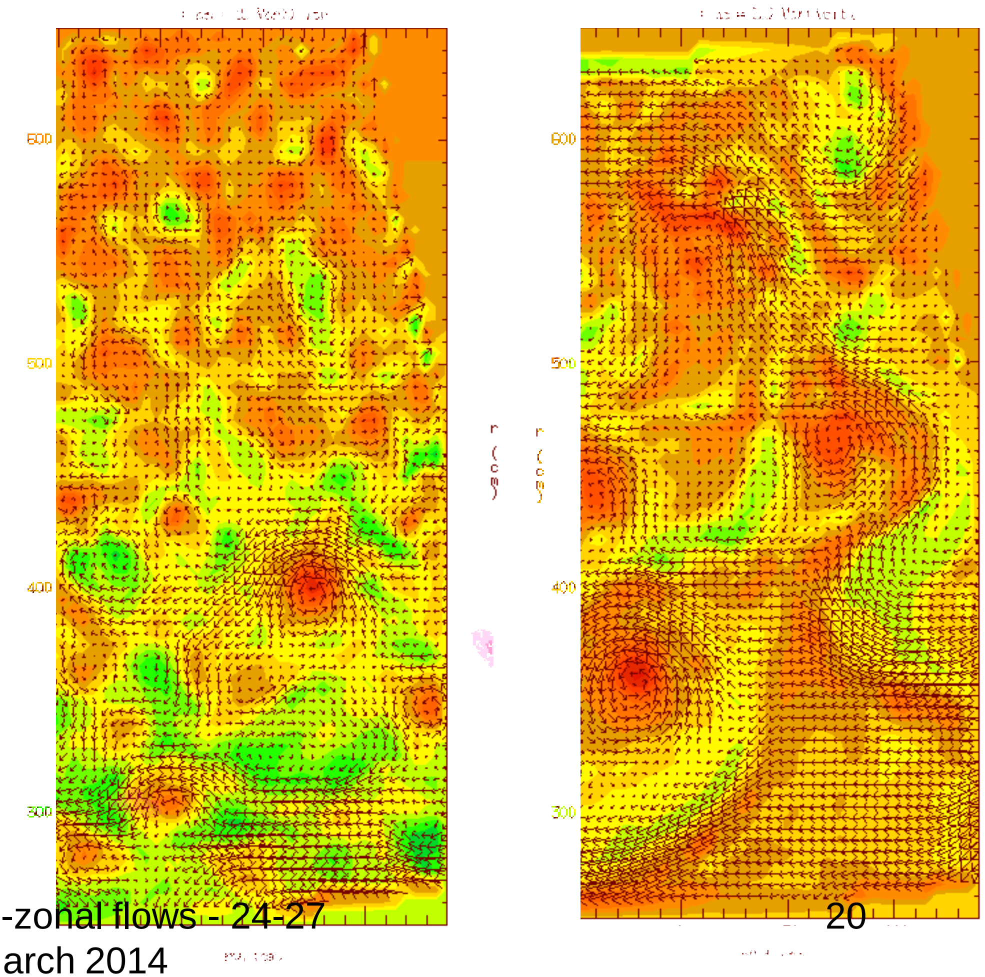
180

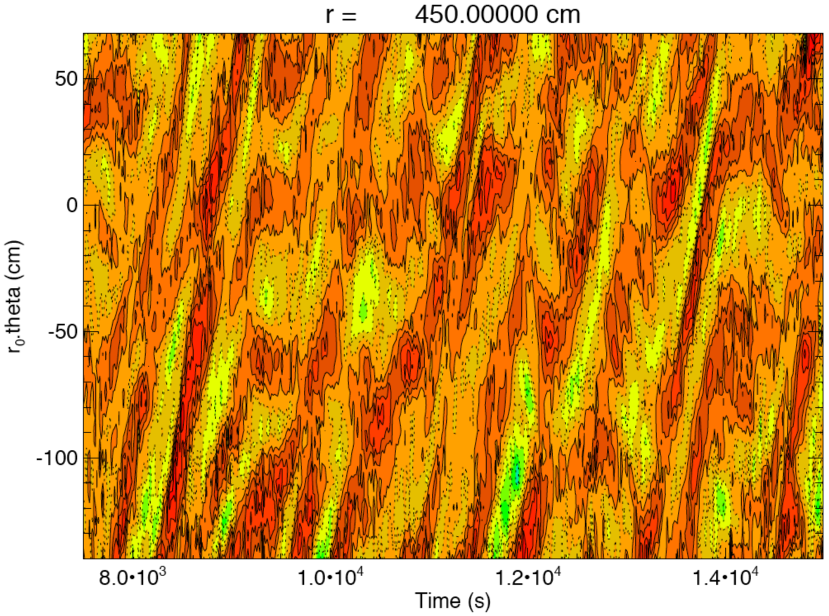
42

(SW) Potential Vorticity fields

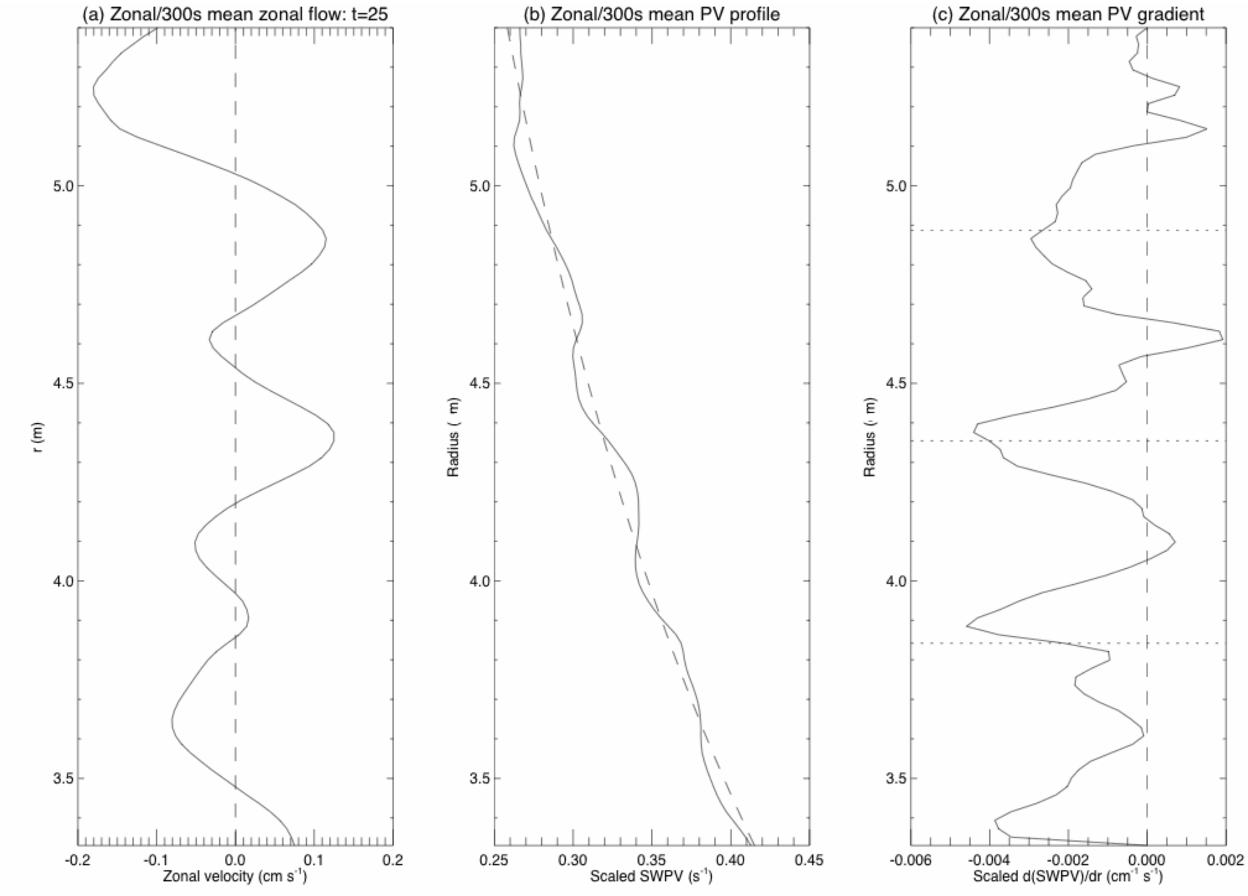
E =	$5\text{x}10^{-6}$	$2\text{x}10^{-5}$
$\beta L^2/(2u_{rms})$ =	395	91

- $q = (\zeta + 2\Omega)/h(r)$
- Complex vortex dynamics & waves
- 'Eastward' propagation of discrete vortices





Potential Vorticity “Staircases”:



Laboratory

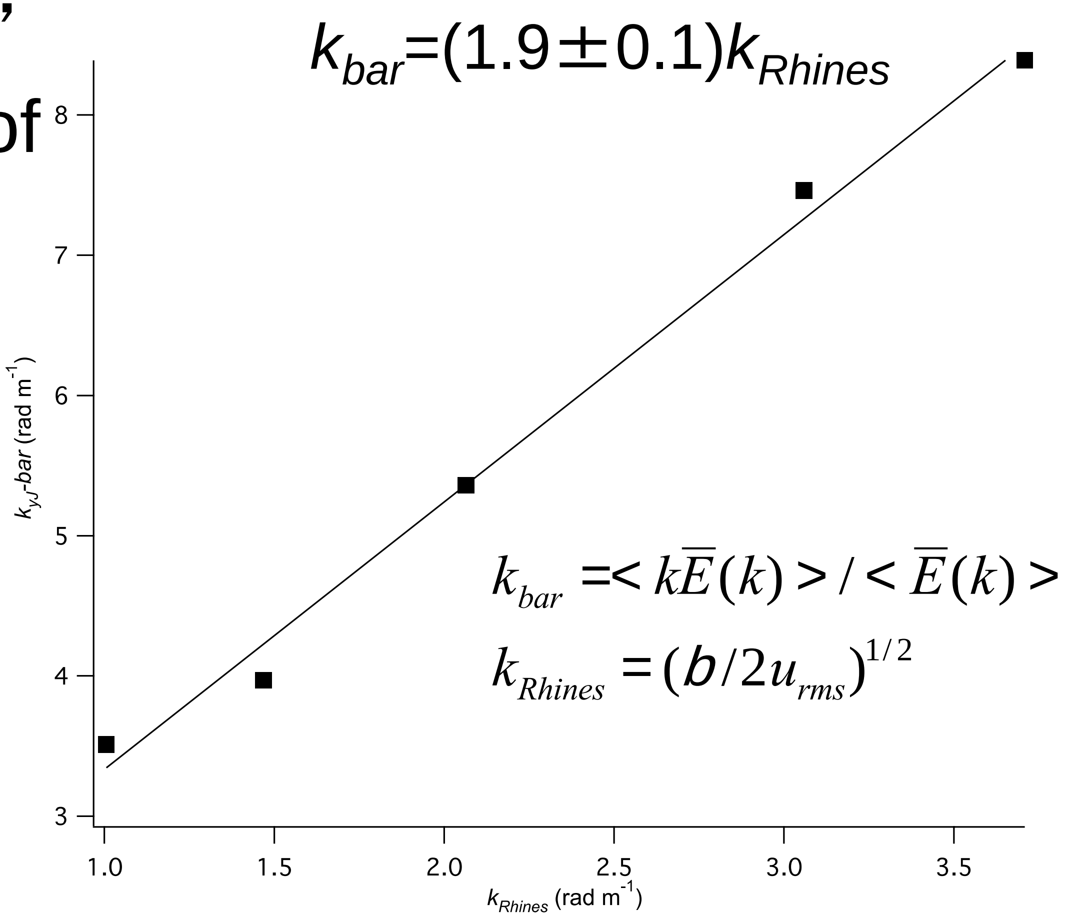
- Band-wise PV homogenisation in retrograde jets
- PV gradient still shows sustained reversals…..instability or forcing?

Scaling of jet separation

- Determine ‘centroid’ radial wavenumber of jets (k_{bar})
- ‘Pre-whiten’ zonal flow

$$\hat{u}(r) = (\bar{u} - <\bar{u}>)\left(\frac{r}{r_0}\right)^3$$

- FFT to get E(k)
- Find k_{bar} vs k_{Rhines}

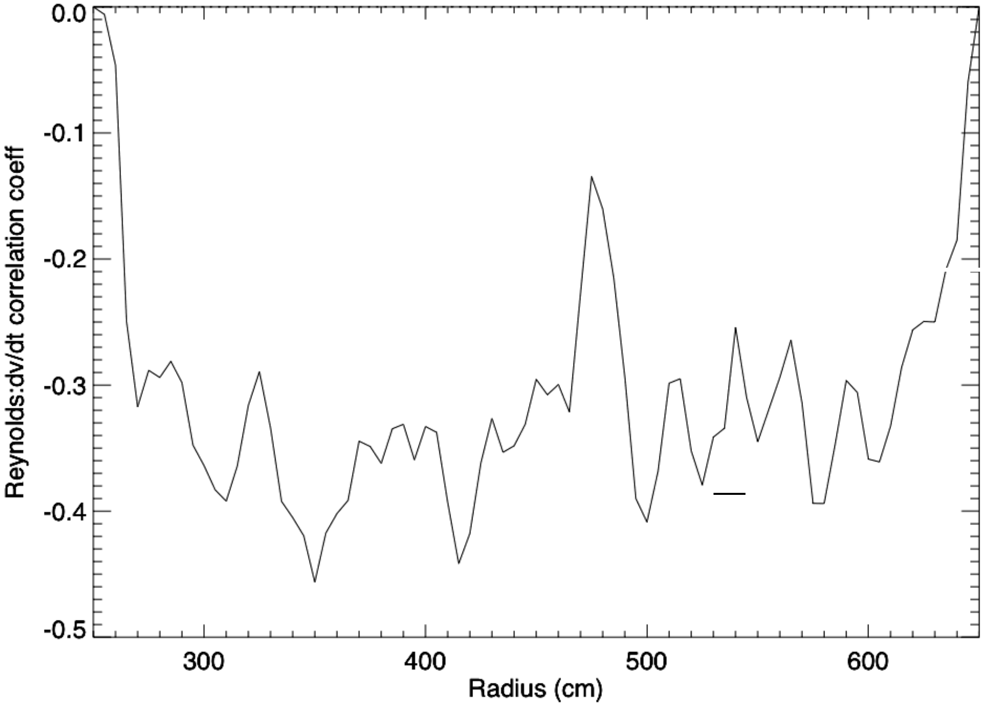


$k_{bar} = (1.9 \pm 0.1) k_{Rhines}$

$$k_{bar} = < k\bar{E}(k) > / < \bar{E}(k) >$$

$$k_{Rhines} = (b/2u_{rms})^{1/2}$$

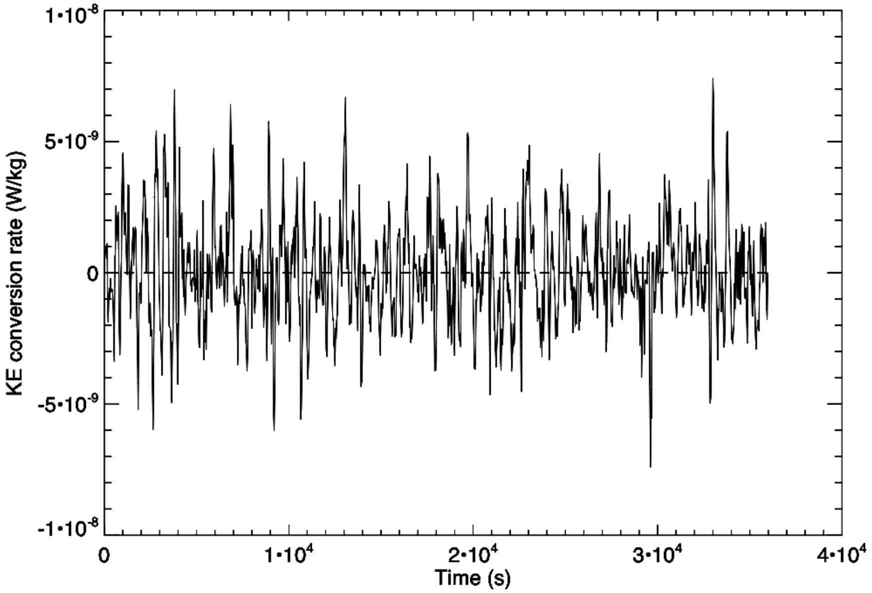
Eddy-zonal flow interactions:
non-local spectral energy transfer?

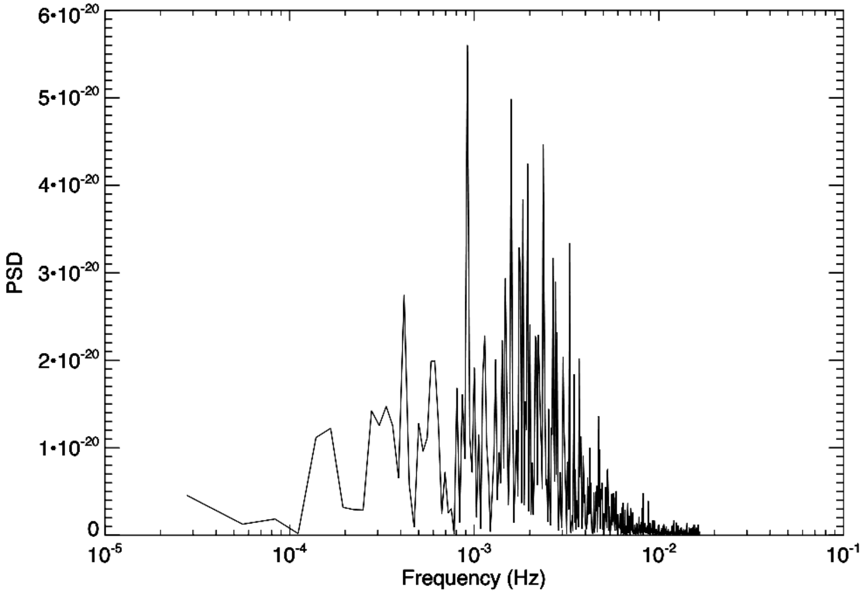


- Separately compute $1/r\,\partial(r\overline{u'v'})/\partial r$ and $\partial\bar{u}/\partial t$
- Correlate in time
- Significant anti-correlation (C ~ -0.4) ***across all radii***:
  - Systematic KE conversion from eddies->mean flow

Eddy-zonal flow interactions:

non-local spectral energy transfer?



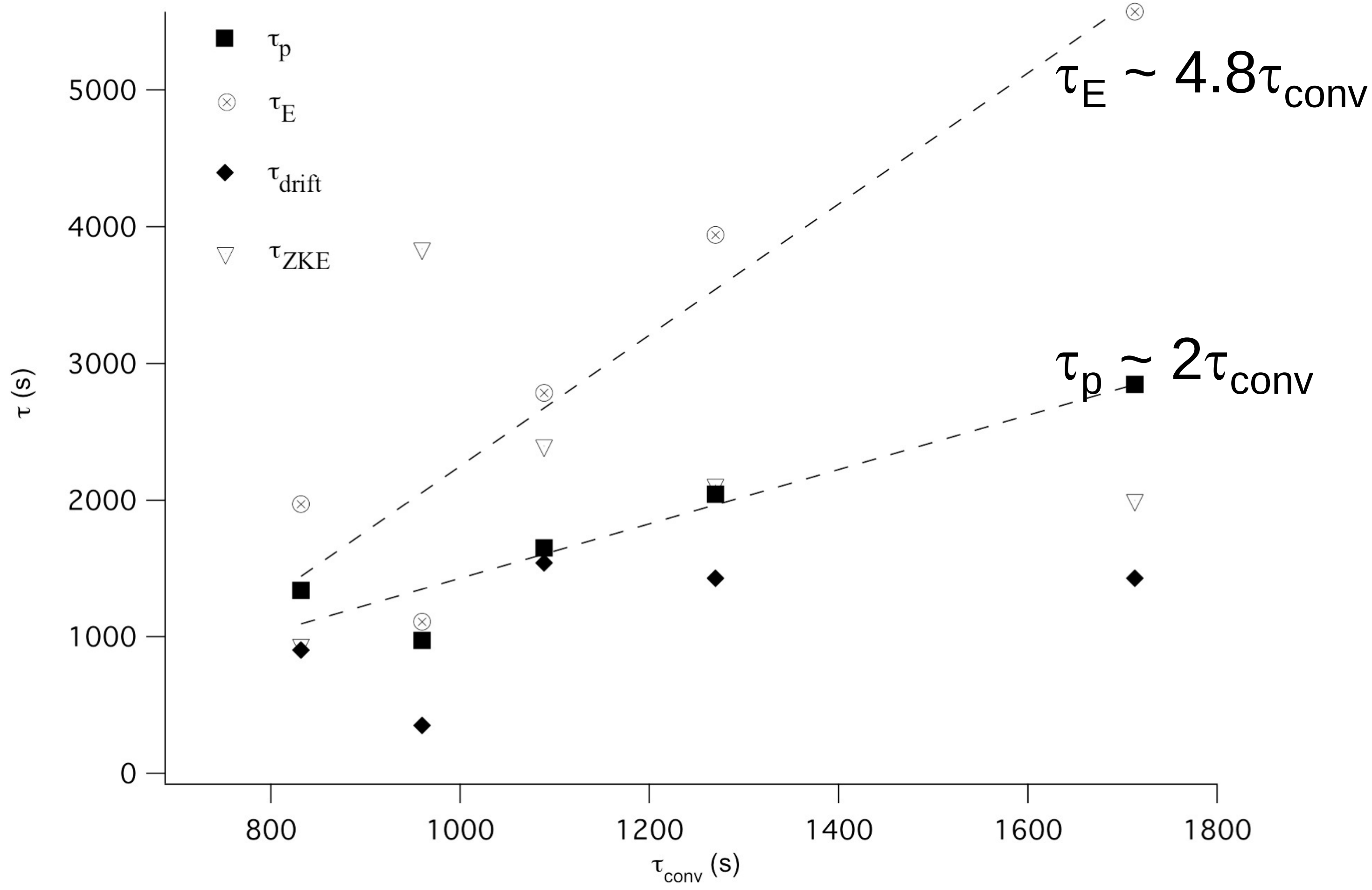


- Compute $C(K_E,K_Z)$ as a function of time -- Strongly **variable** [including its sign]
- Systematic KE conversion from eddies -> zonal mean flow [averaged in time]
  - Mean conversion rate ~ 0.5-5 x 10^{-10} W/kg (~ 0.1-1% of F_B)
  - **Instantaneous conversion rate ~10-50 times bigger**
- Hint of a characteristic timescale/period O(10^3 s)?
  - Cyclic decay/instability of zonal jets?

$$t_p = 1/\sqrt{4u_{rms}b} \approx 1900\ \text{s; or}$$

$$t_E = H/\sqrt{rN} \approx 2000\ \text{s}$$

τ_{conv} vs timescales?

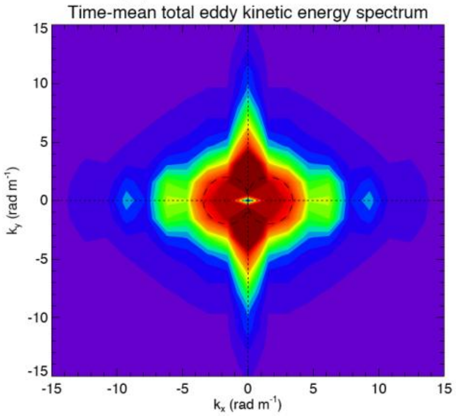


$\tau_E \sim 4.8\tau_{conv}$

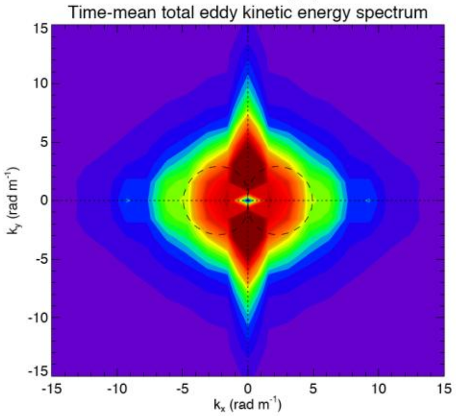
$\tau_p \sim 2\tau_{conv}$

43

(a)



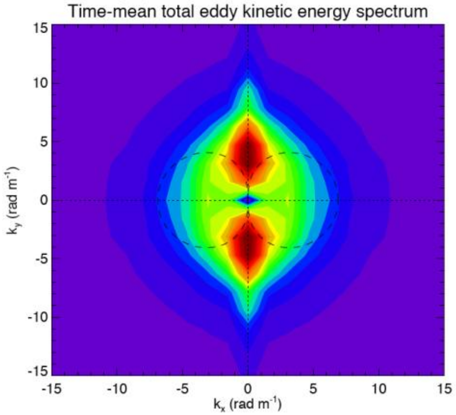
(b)



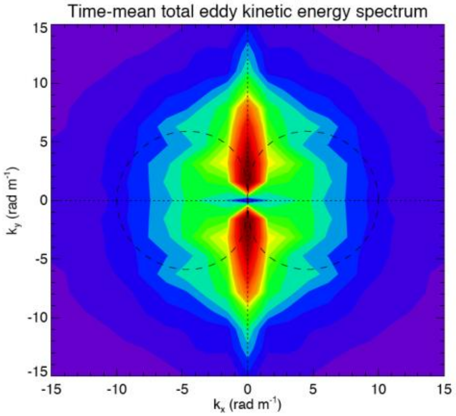
91

180

(c)



(d)

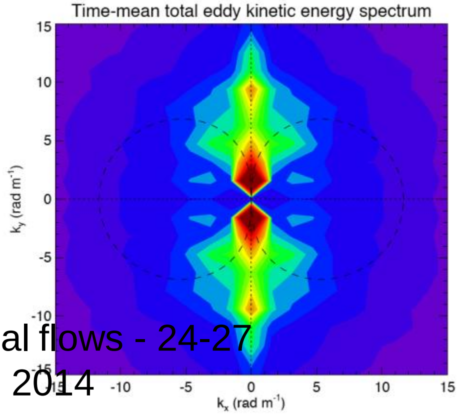


395

KE spectra

$$\frac{bL^2}{U_{rms}} = 581$$

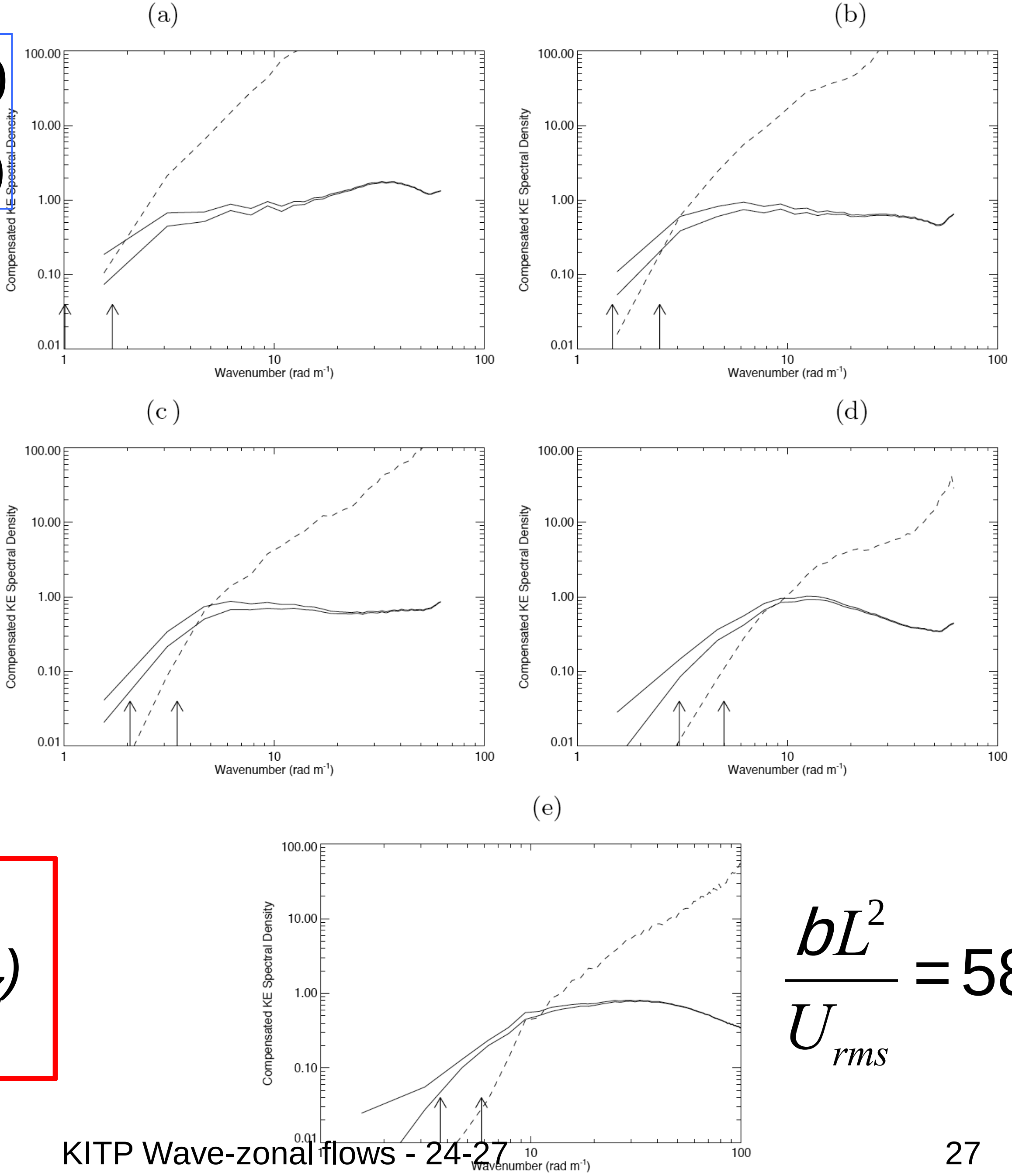
(e)



$$E_Z = C_Z b^2 (n/a)^{-5} \qquad (1)$$

$$E_R = C_R \varepsilon^{2/3} (n/a)^{-5/3} \qquad (2)$$

43



91

KE spectra *(compensated)*

180

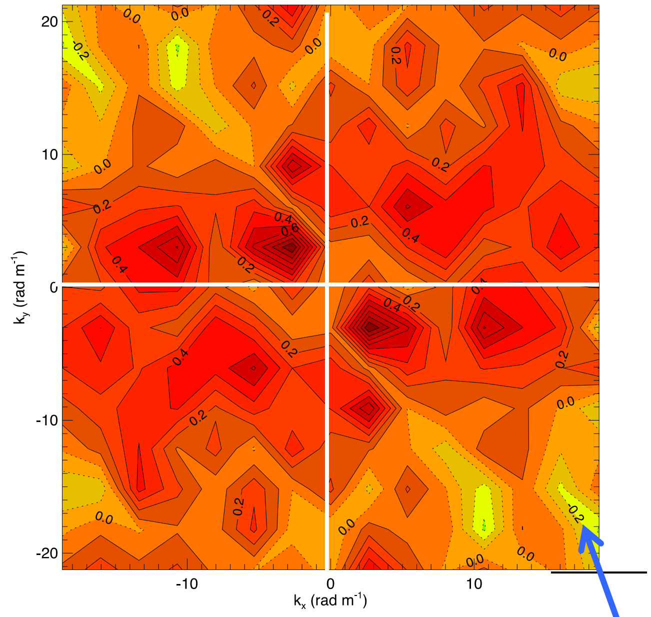
395

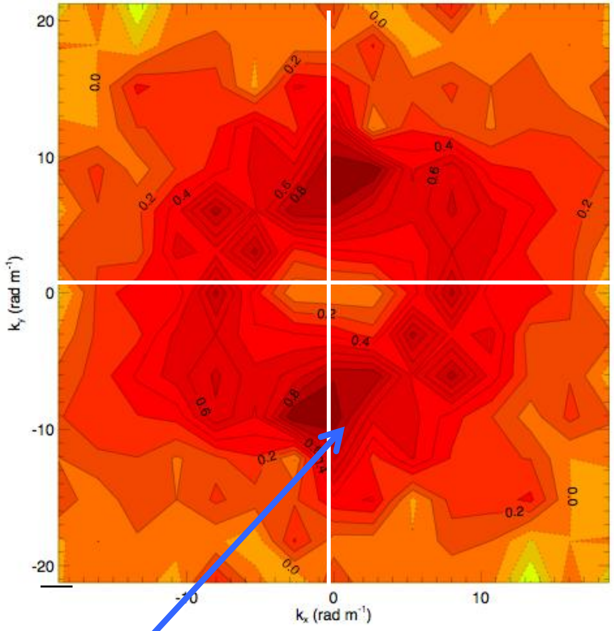
ε ~ 5 x 10^{-10} W kg^{-1}
= 0.2-1 x $C(K_E,K_Z)$
≈ 1% x F_B

$$\frac{bL^2}{U_{rms}} = 581$$

Eddy-zonal flow interactions:

non-local spectral energy transfer?





- Spectral energy transfer function
  - ☐ $T_\Omega = 2\pi k \,\mathrm{Re} \int_{\mathbf{p+q=k}} \mathbf{dpdq/(}2\pi)^2\, \mathbf{p{\times}q}/p^2 <\zeta(\mathbf{p},t)\zeta(\mathbf{q},t)\zeta(\mathbf{-k},t)>;\ (p,q)>|k_{max}|$
  - – Peaks on k_y axis with β-effect – ***NON-LOCAL transfer***
  - – ***No such peak without*** β-effect

Zonostrophy & tracer transport?

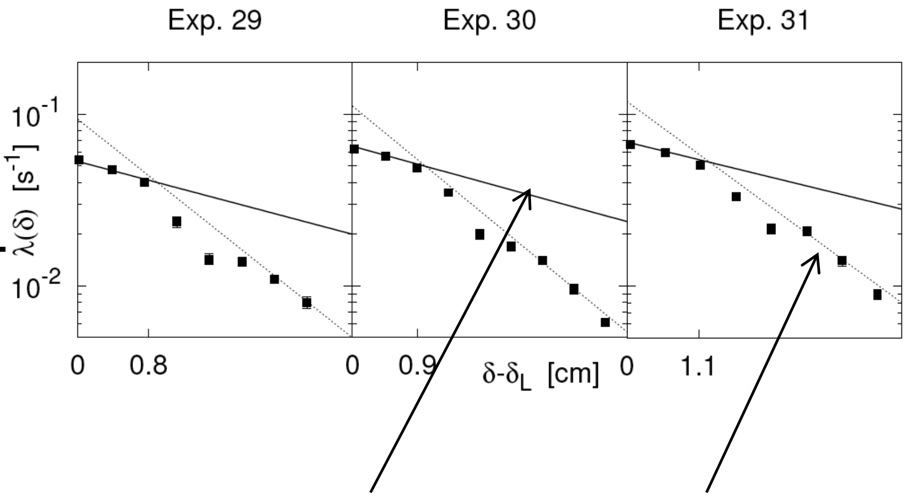
- Turbulence becomes anisotropic for $L > L_\beta$
- Tracer diffusivity (e.g. obtained from FSLEs) scale-dependent (Richardson law) for $L < L_\beta$ ($k > k_\beta$)

$$D_y = C_D e^{1/3} k^{-4/3}$$

- For $L > L_\beta$, however, D_y becomes scale-independent (Taylor law)

$$D_y = C_D^+ e^{1/3} k_b^{-4/3} = C_D^* e^{3/5} b^{-4/5}$$

FSLEs vs scale



Richardson law Taylor law

(Laboratory experiments by Stefani Espa In Rome:

- *Galperin et al. 2014 submitted)*

- Break in gradient at ~$2L_\beta$

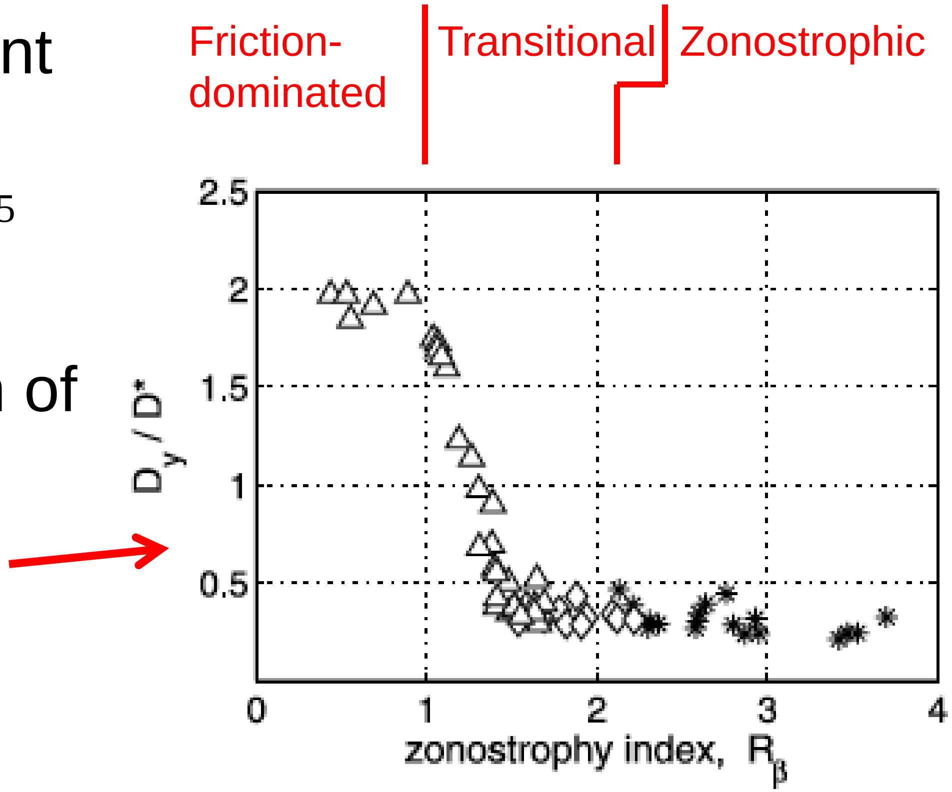
Zonostrophy & tracer transport?

- For $L > L_\beta$, however, D_y becomes scale-independent (Taylor law)

$$D_y = C_D^+ \epsilon^{1/3} k_\beta^{-4/3} = C_D^* \epsilon^{3/5} \beta^{-4/5}$$

- Large scale (Taylor) diffusivity a strong function of R_β
    - Much weaker in transitional/zonostrophic regimes

$$D_y \approx 0.3 \epsilon^{3/5} \beta^{-4/5}$$



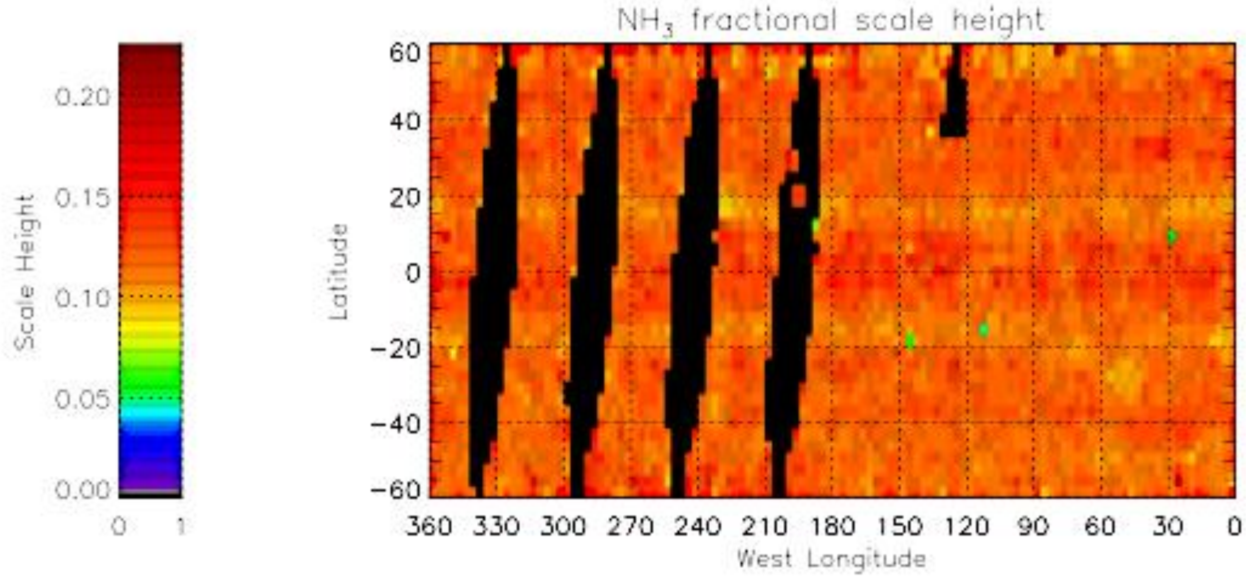
Sukoriansky et al. GRL (2009)

- Uses barotropic vorticity equn on a sphere

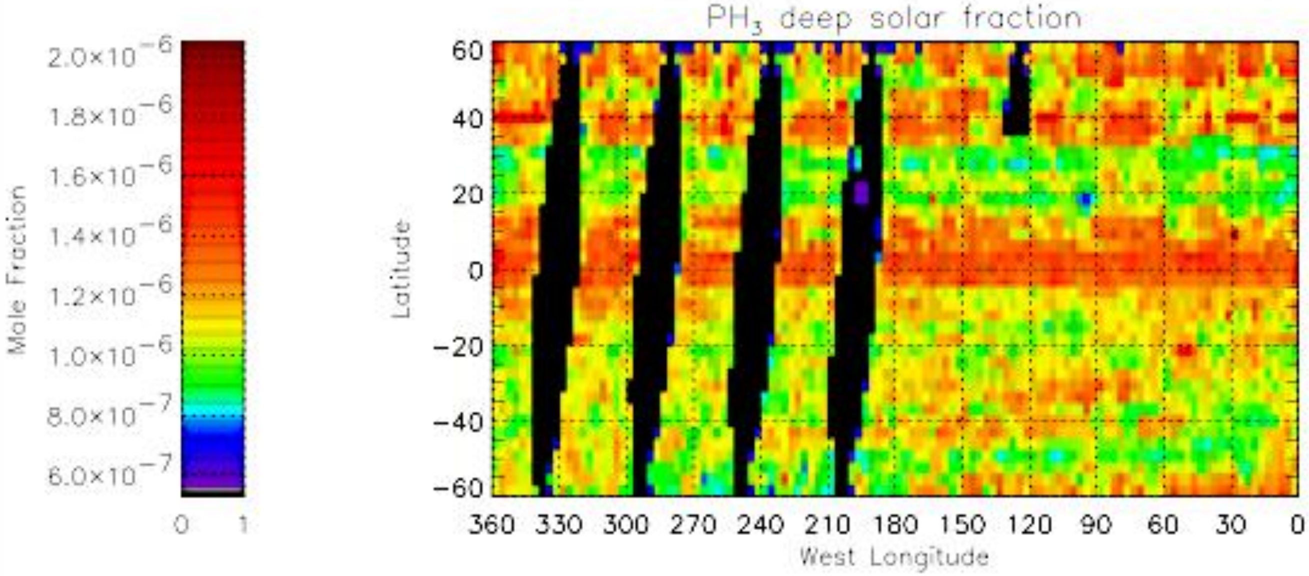
    - Consistent with spread of debris on Jupiter from comet Shoemaker-Levy?
    - Jet-scale meridional barriers…?

Belts & Zones as transport barriers?

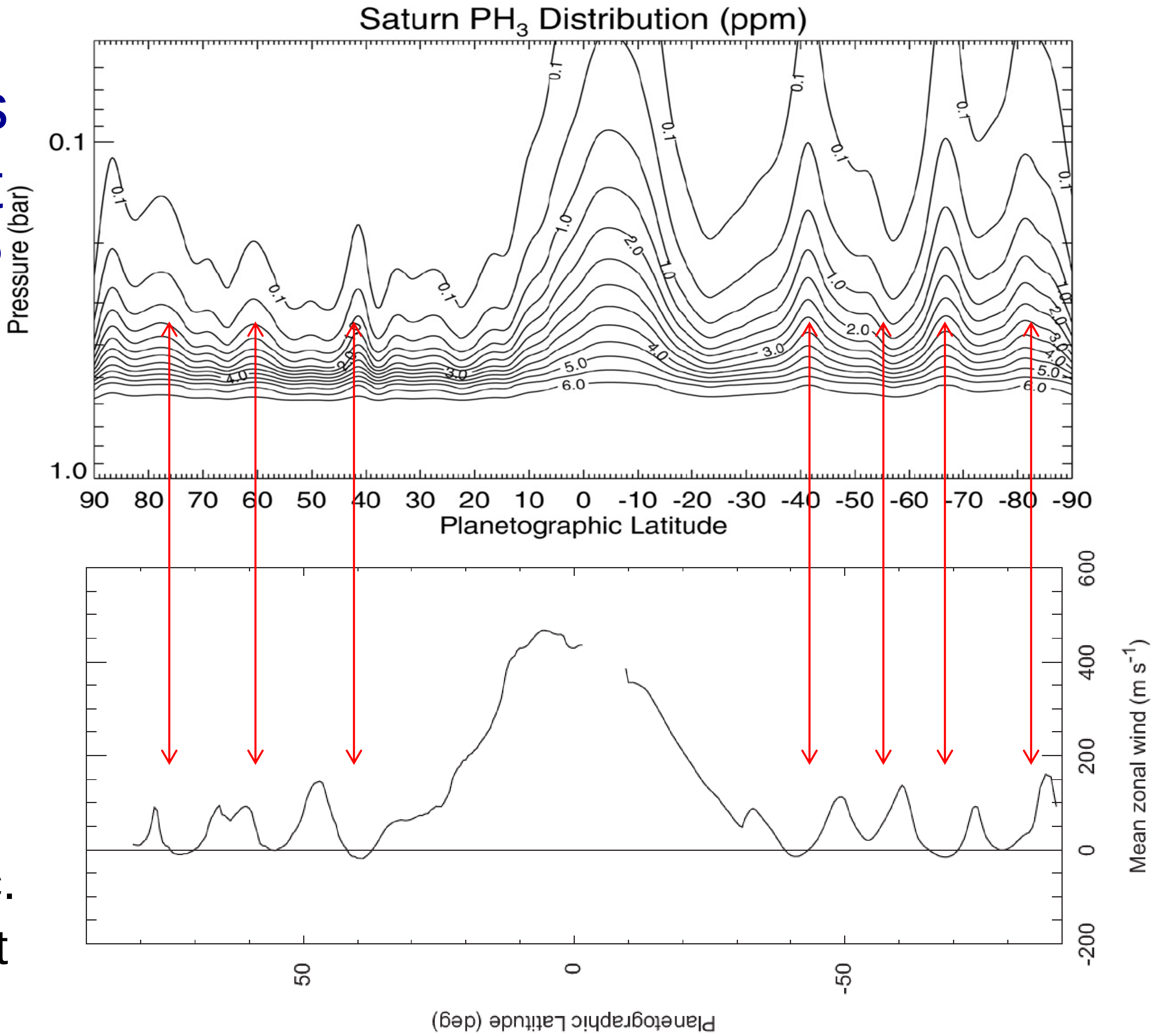
- Zones regions of enhanced NH_3 & PH_3 (from deep levels)
- Belts regions of weaker tracer conc.
  - (Irwin et al. 2004)



Jupiter (Cassini CIRS)



Belts & Zones as transport barriers?



- Zones regions of enhanced NH_3 & PH_3 (from deep levels)
- Belts regions of weaker tracer conc.
- (Fletcher et al. 2009)

Laboratory Experiments: the challenge of producing zonostrophic conditions?

- Experimental requirements
  - Horizontal scale L > $L_{Rh} \sim \pi(2u_{rms}/\beta)^{1/2}$ i.e. $\beta L^2 / u_{rms} \geq 100$
  - AND Zonostrophy parameter $k_\beta(\sim[\beta^3/\varepsilon]^{1/5})/k_R$

$$R_\beta = \frac{k_\beta}{k_{Rh}} \approx \left[\beta u_{rms} \tau_E^2\right]^{1/10} = [\beta^*.Ro^2.E^{-1}]^{1/10} \geq 2$$

Approximating $\varepsilon \sim u^2_{rms}/(2\tau_E)$

  - Translates to

$$\left[\frac{u_{rms} H \tan\theta}{\nu}\right] \geq 10^3 \text{ AND } \frac{\beta L^2}{u_{rms}} \geq 100$$

  - Or $\boxed{\dfrac{\nu}{\Omega L^2 \tan^2\theta} << 10^{-5} \text{ setting } \dfrac{\beta L^2}{u_{rms}} = 100}$

Zonostrophic expts?

	Coriolis (Grenoble)	New Coriolis (Grenoble)	10Hz (Oxford)	100Hz (Grenoble)	Torino	Cryo He
ν x 1e-6 ($m^2\ s^{-1}$)	1	1	1	1	1	0.02
Ω (rad/s)	0.18	0.5	60	600	2	3
L (m)	4.5	6	0.3	0.25	2.5	1.0
Θ (°)	6	10	30	45	10	25
Ek_Z	2.48E-05	1.65E-06	5.55E-07	2.66E-08	1.78E-06	3.07E-08
Ξ	1.701	2.230	2.488	3.370	2.1	3.323

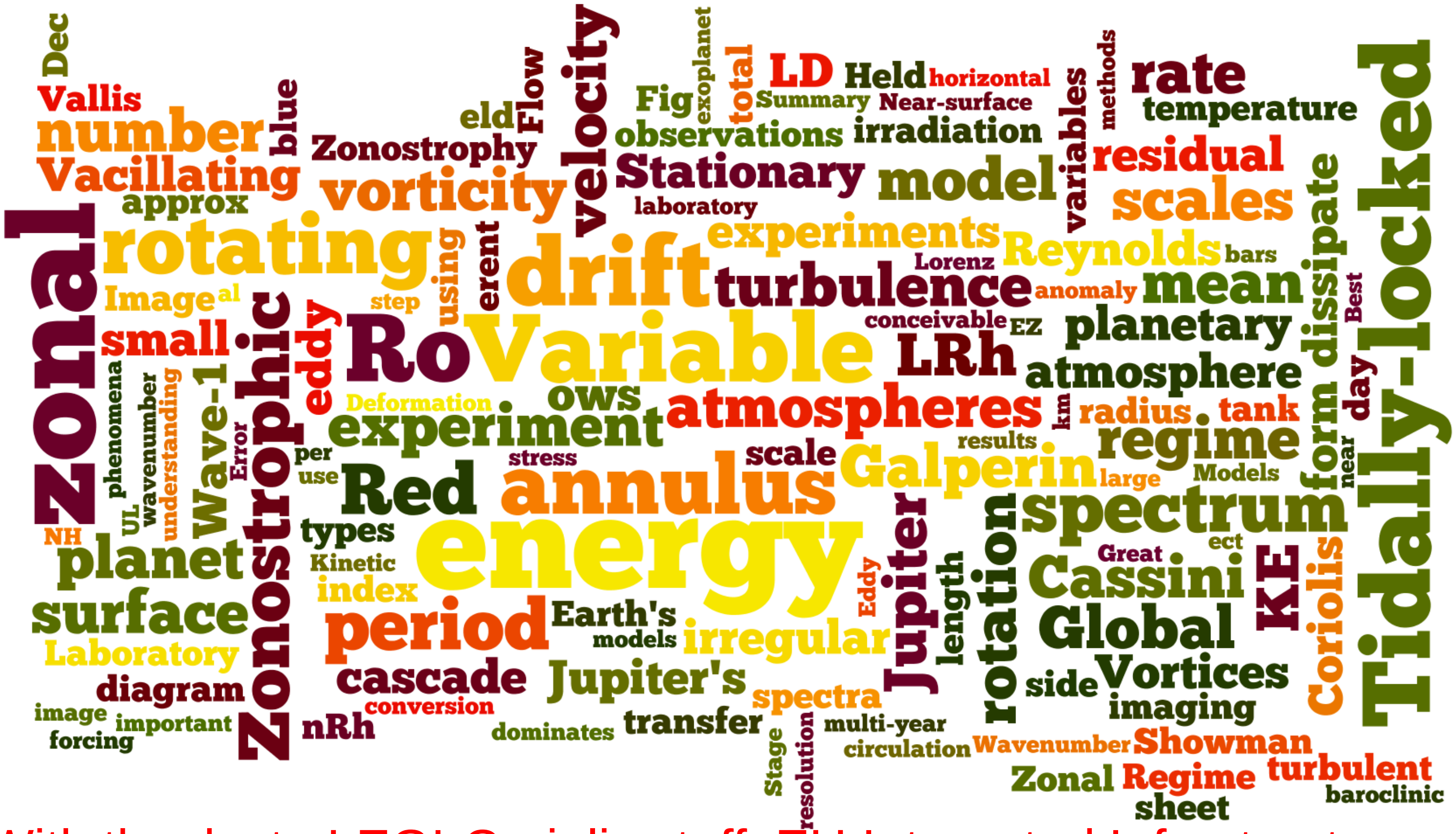
$$R_\beta \approx (\beta U_{rms} \tau_E^2)^{1/10};\ \text{but } U_{rms}^2 \propto \frac{F_B}{H}\ \text{ so } R_\beta \propto \left(\frac{[F_B H]^{1/2}\tan\theta}{\nu}\right)^{1/10}$$

Larger R_β ⇒ deeper tank, steeper slope and/or stronger forcing(!!)

Conclusions

- Multiple-jet formation by nonlinear eddy-zonal flow processes in forced-dissipative geostrophic turbulence
  - Shows clear Rhines scaling in jet separation
  - Eddy->zonal flow energy exchanges dominate
  - Vorticity dynamics and jet stability?
    - Determines strength of jets?
    - Jets meander unless $R_\beta \,\square\, k_\beta/k_{Rhines} \,\square\, 2$
  - Mixing and transport barriers?
    - Reduced lateral dispersion in ~zonostrophic flow?
- We have [real experimental/observational] data!
  - Lab experiments [PIV velocities…]
  - Jupiter cloud winds, PV….

Thanks for your attention!



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