2019. 10/16 - 19.   Physics at the equator: from lab to the stars @ Lyon, France.

Rossby Waves and Rotationally-Influenced Convective Modes in the Solar Convection Simulations

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Background of the Study

Importance of Solar Rossby Waves

- Large-scale ($l \lesssim 120$) convection in the Sun is still poorly understood.
- Equatorial Rossby waves have recently been detected on the solar surface (Fig.1) [Löptien et al., 2018, Nature Astron.]
- They contribute a significant fraction of the large-scale velocity power.

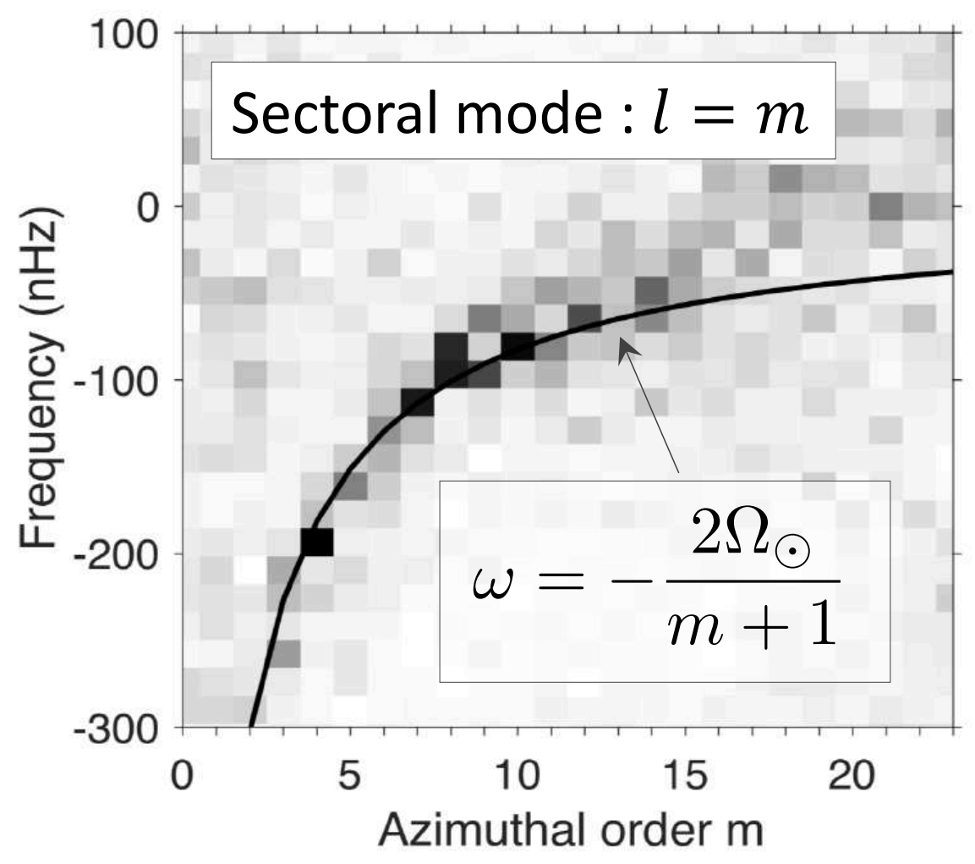

Fig 1: Power Spectrum of radial vorticity

Thermal Rossby Wave (Columnar Convection)

- Thermal Rossby waves originate from the conservation law of potential vorticity $(\nabla\times\vec{v} + 2\vec{\Omega}_\odot)/\rho \approx$ const. and propagate in a prograde direction.
- Often attributed to an equatorial acceleration of the differential rotation.
- Reported many times in simulations but NOT found in observations so far.

Methods

Numerical Simulation

- Rotating convection with solar-like stratification from $0.71R_\odot$ to $0.96\ R_\odot$.
- Solar rotation rate $\Omega_\odot/2\pi = 431$nHz is used but the luminosity is decreased by 20 to achieve a solar-like differential rotation (Fig.2)

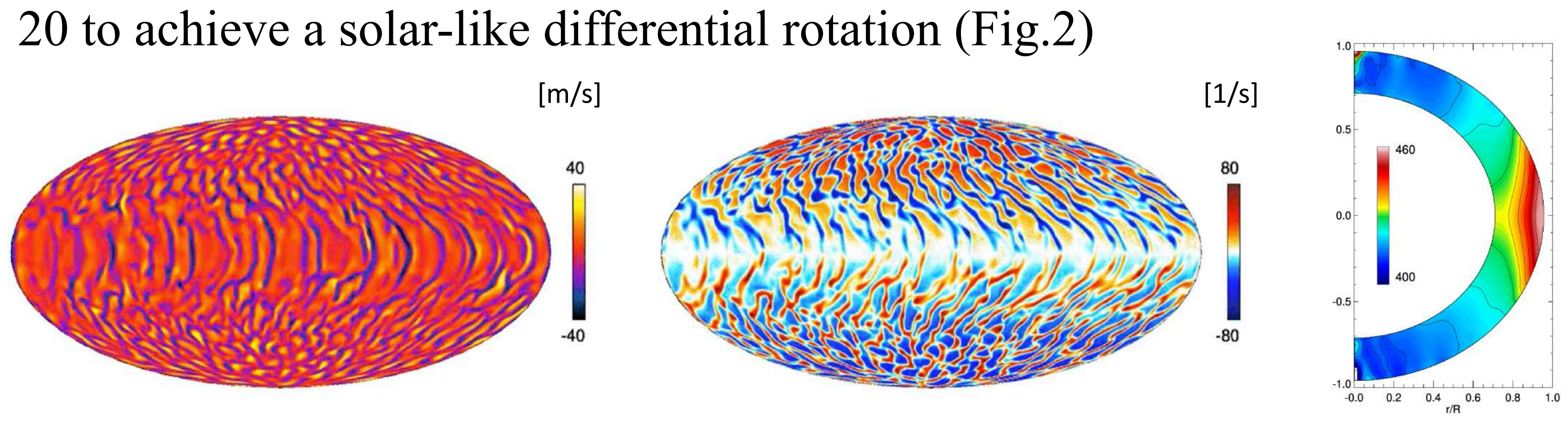

Fig 2: Snapshots of (Left) radial velocity and (Center) radial vorticity at r/R$_\odot$=0.95. (Right) Differential rotation.

Data analysis

- Total 15-year data with the time cadence of about 4.7 days is analyzed.
- Perform SVD on the power spectrum $P_m(r,\omega)$ to extract the eigenfunctions.

Results I : Equatorial Rossby Wave

Power Spectrum & Eigenfunctions

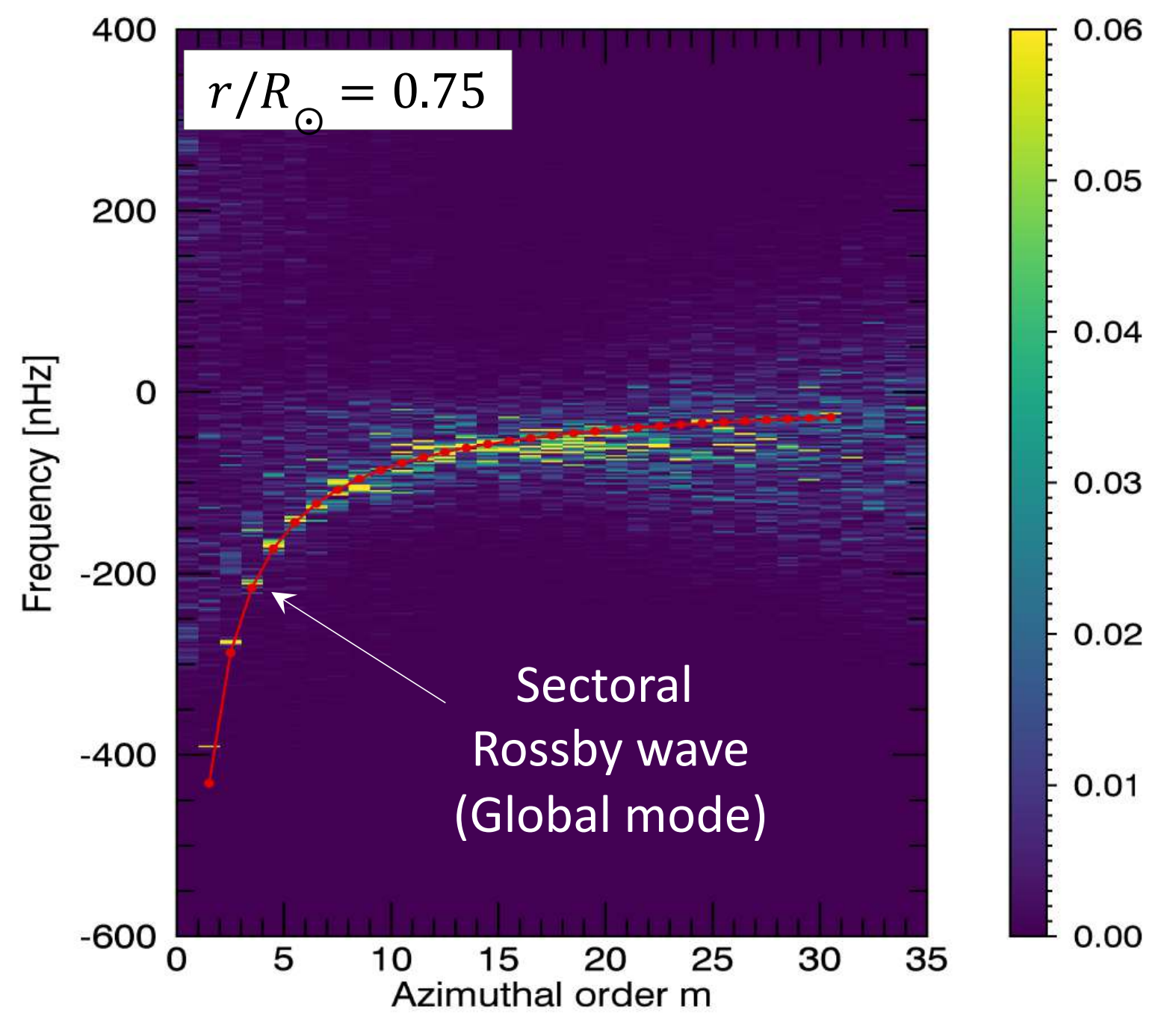

Fig 3: Power spectrum of v_θ (symmetric).

- A well-defined power ridge can be seen on the sectoral mode ($l = m$) Rossby wave dispersion relation.
- In our simulation, the sectoral mode Rossby wave exists globally in radius only for $m < m_c \approx 4$.
- Eigenfunctions of this mode agree well with the linear theory for $m \lesssim m_c$
- The motion is mostly toroidal and the mode is in a geostrophic balance.

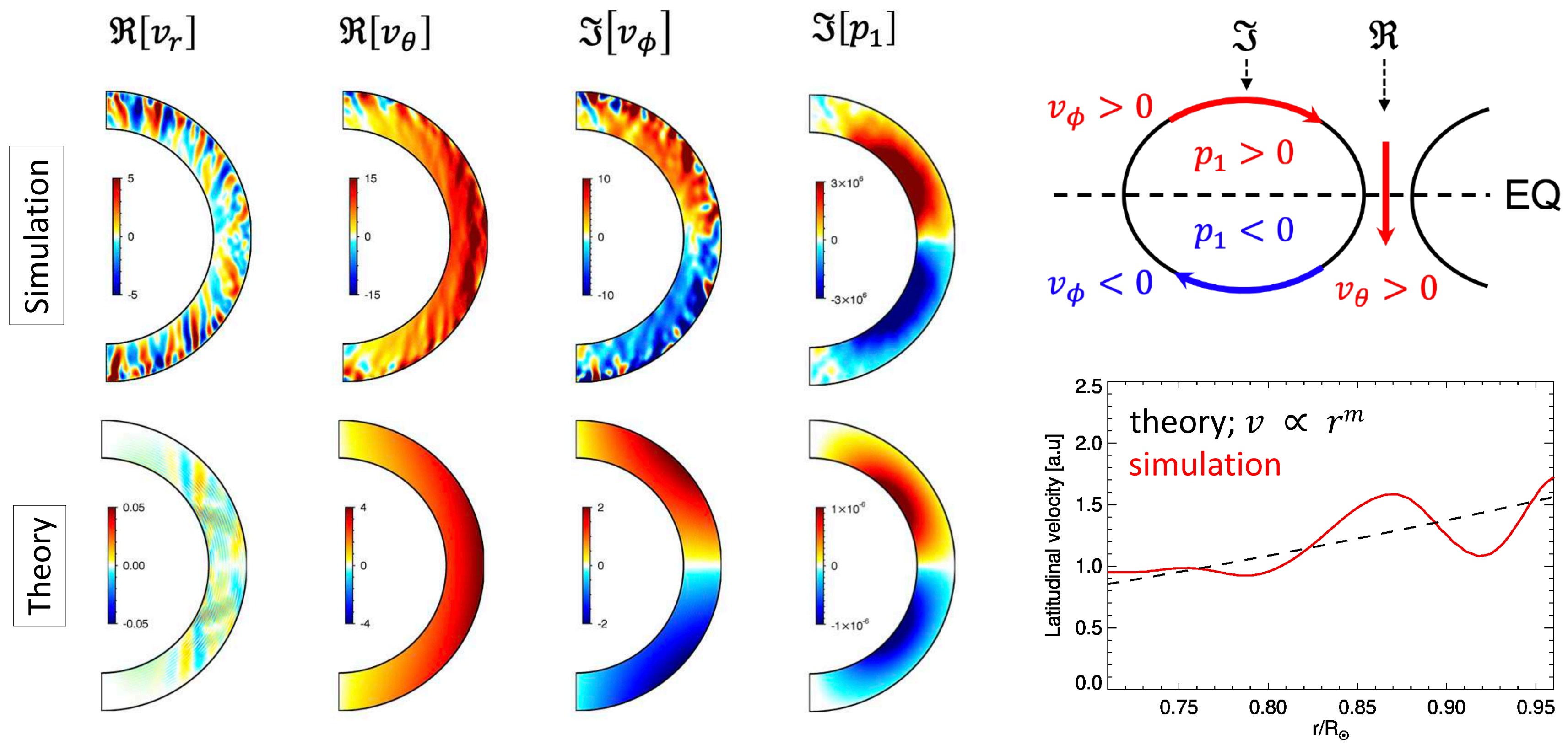

Fig 4: Eigenfunctions of the equatorial Rossby waves for m = 2 case (Right) $v_\theta(r)$ at the equator.

Results II : Convective Modes

Power Spectra : Prograde & Retrograde Modes

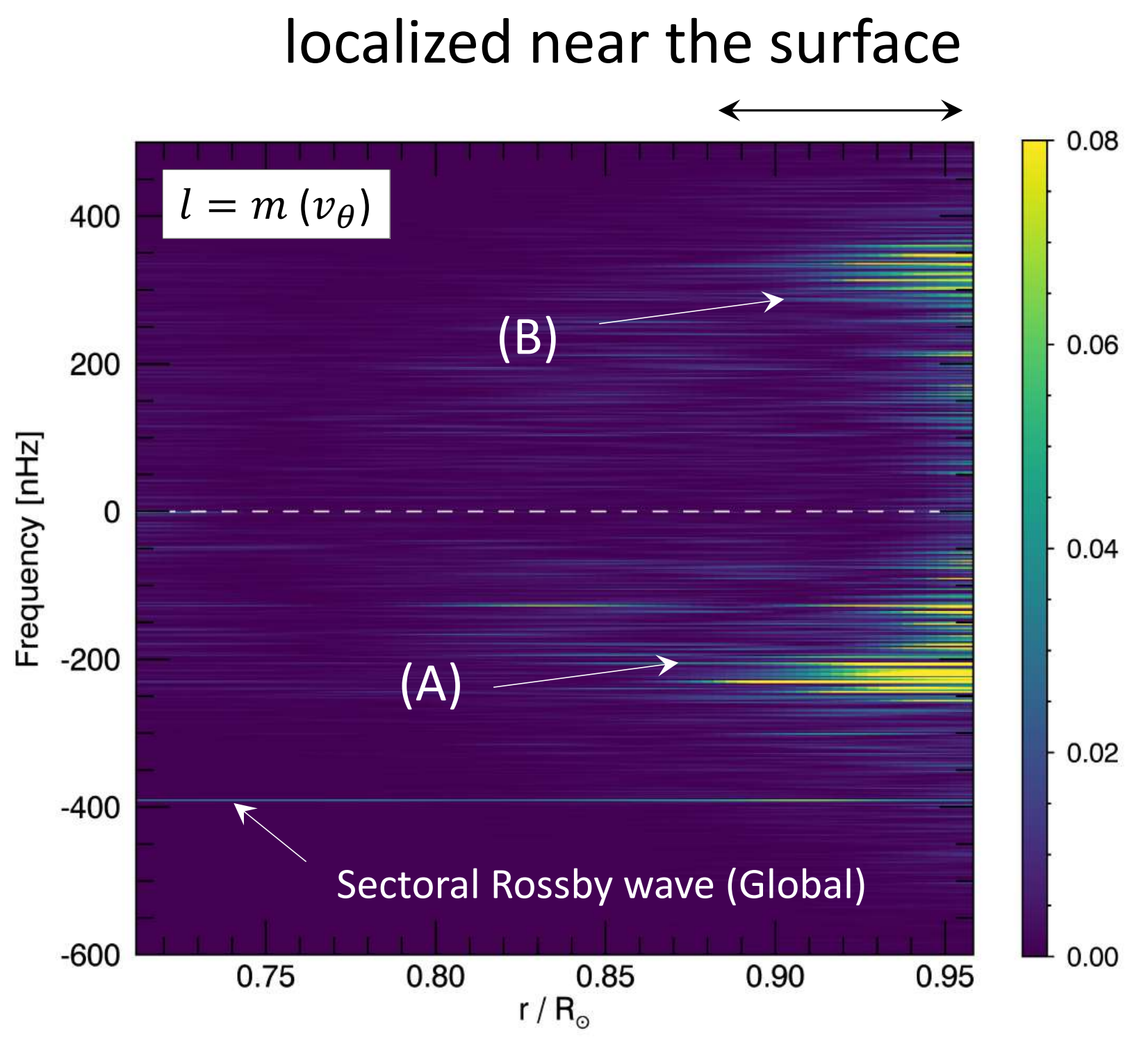

Fig 5: $l = m$ Power Spectrum of v_θ at $m = 1$

- We also find two distinct modes that are mostly localized near the surface

$$\text{in} \left\{ \begin{array}{l} l = m \text{ spectrum of } v_\theta \\ l = m+1 \text{ spectrum of } \nabla\cdot\vec{v}_h \end{array} \right.$$

(A) Retrograde mode: $\omega < 0$
(B) Prograde mode: $\omega > 0$

- These two modes form a continuous power ridge across $m = 0$ (Fig.6)

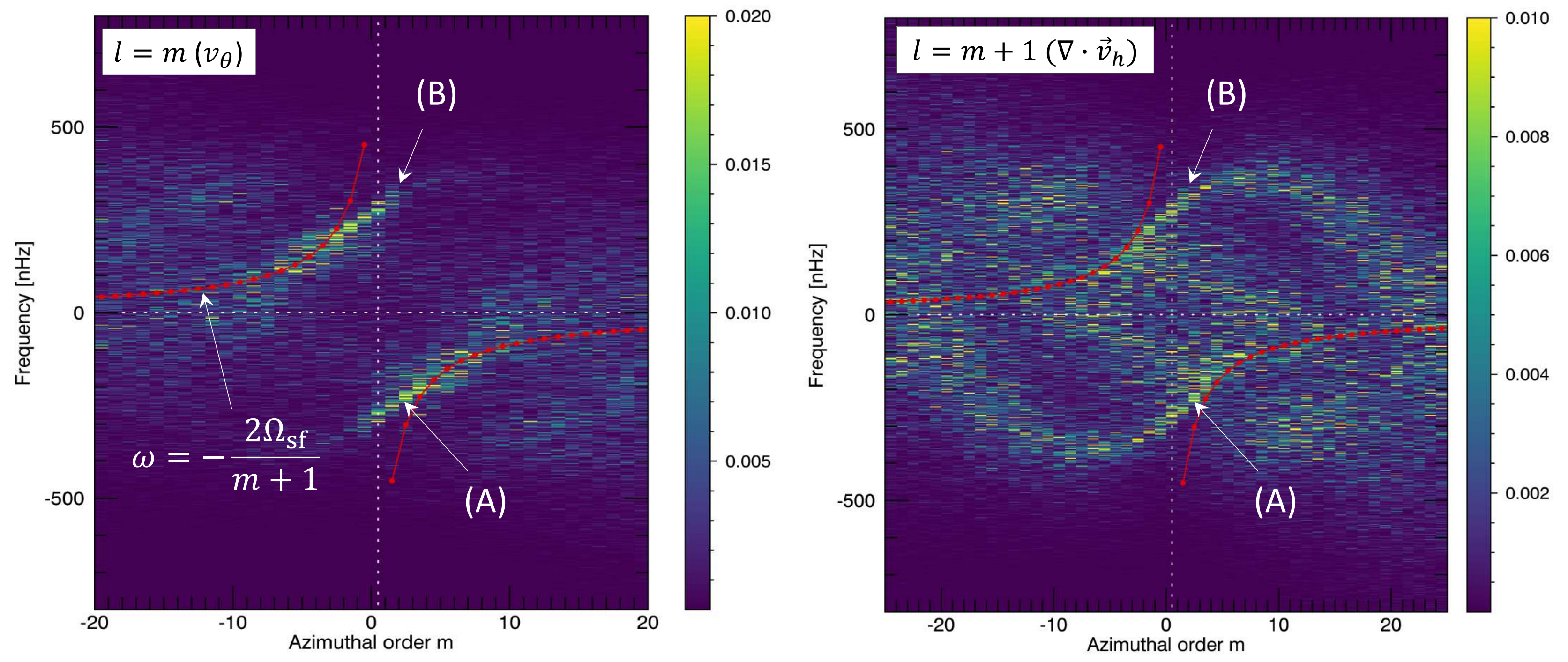

Fig 6: (Left) $l = m$ power spectrum of v_θ and (Right) $l = m$+1 power spectrum of $\nabla\cdot\vec{v}_h$ near the surface

(A) Retrograde Mode

Retrograde propagating mode has a nature of equatorial Rossby waves with the radial node $n = 1$ mode. The motion is more toroidal than radial.

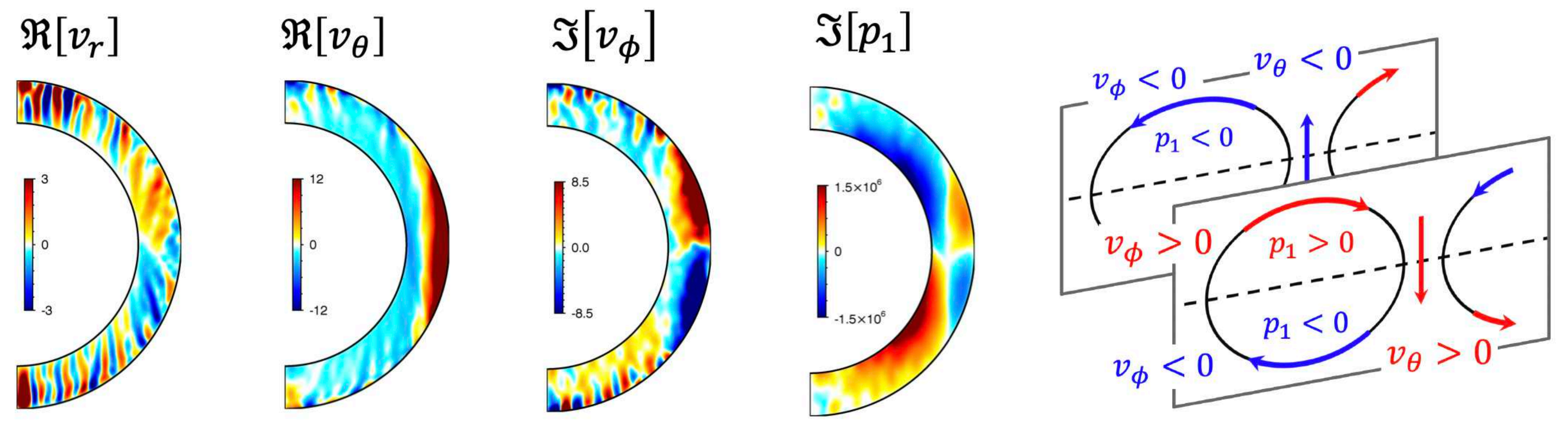

Fig 7: (Left) Eigenfunction of retrograde propagating mode at $m = 2$ and (Left) schematic picture of this mode

(B) Prograde Mode

Prograde propagating mode has a nature of anti-symmetric ($l = m + 1$) thermal Rossby waves. Vortical motion in z-direction is prominent.

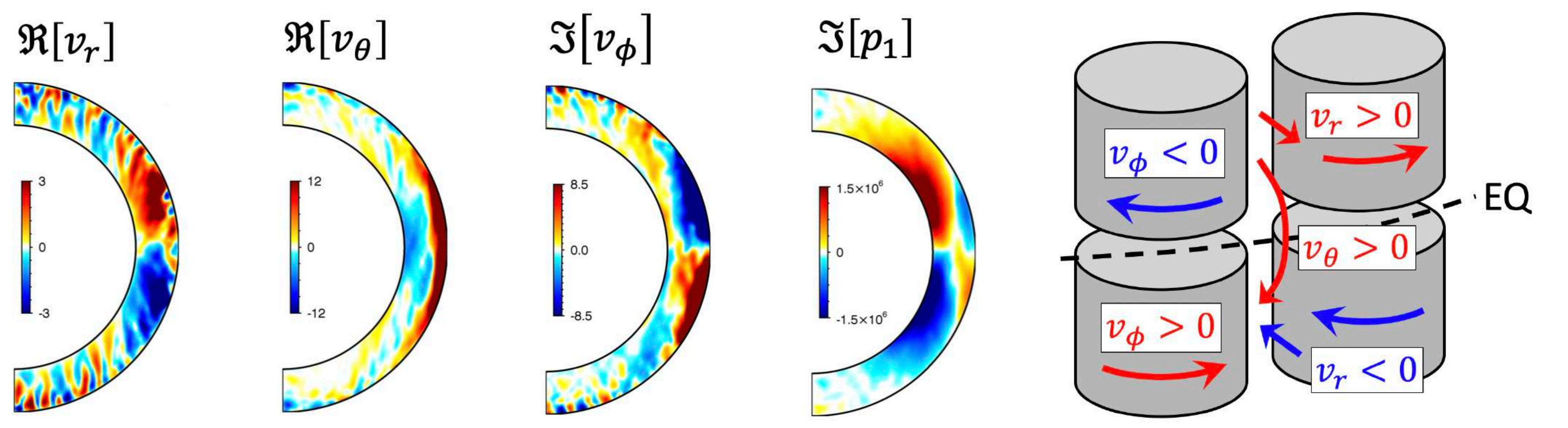

Fig 8: (Left) Eigenfunction of prograde propagating mode at $m = 2$ and (Left) schematic picture of this mode

Summary & Discussion

- A mode-by-mode analysis of multiple Rossby waves is reported.
- A mixed-mode with both equatorial Rossby wave nature and anti-symmetric thermal Rossby wave nature is found in our simulation.
- These modes are thought to be convectively-driven.
- These convective modes might be understood as an equatorially-trapped Poincaré convection mode [Zhang., 1994, Simitev and Busse., 2003]
- Effects of differential rotation and stratification?
- Any implications for the angular momentum transport in the Sun?
- Linear analysis is ongoing to address the above issues.