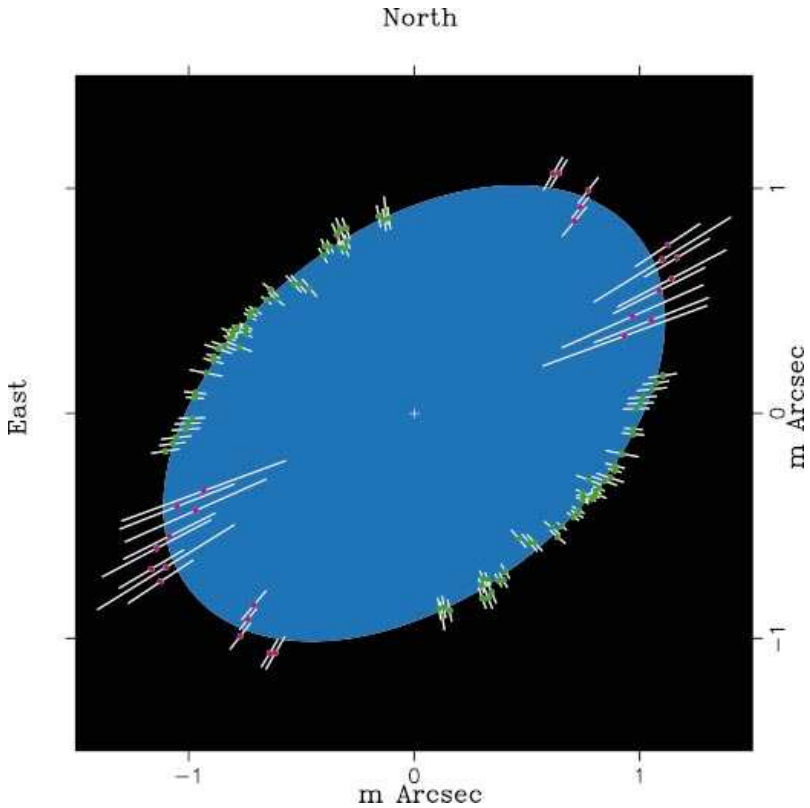
Modelling rapidly rotating stars

Daniel Reese

August 21, 2007

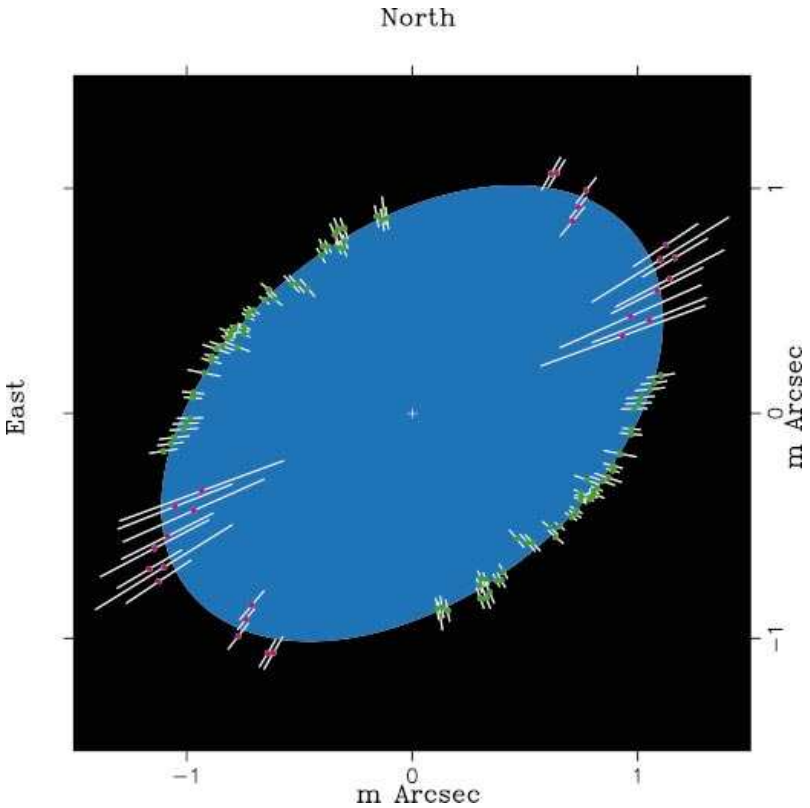
HELAS II, Göttingen
Helioseismology, Asteroseismology and MHD Connections

Introduction

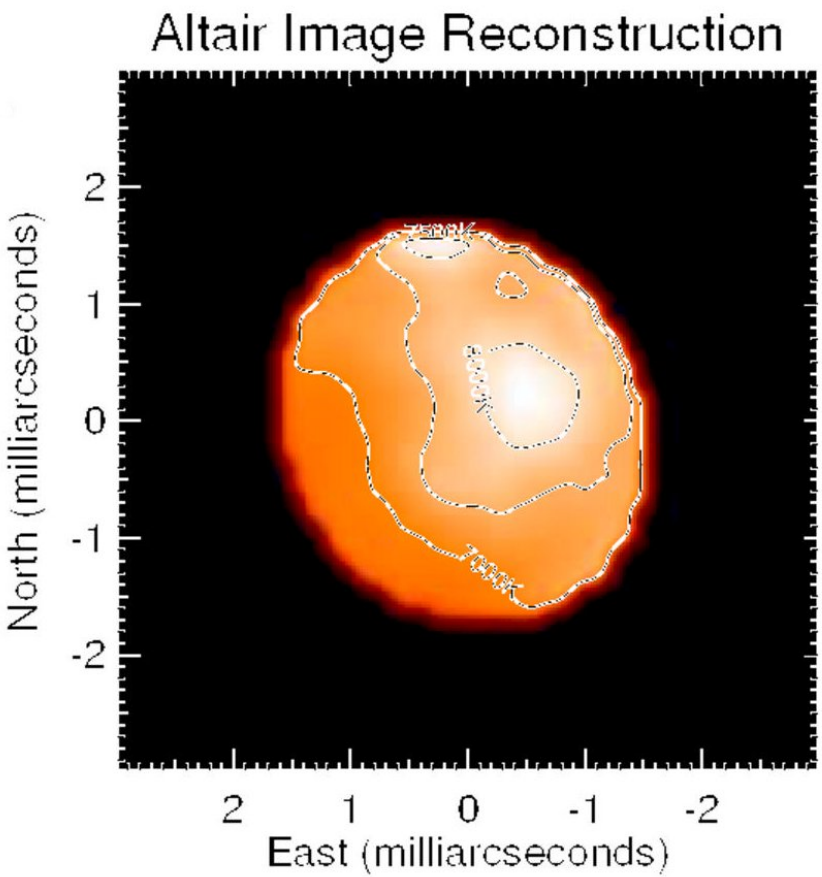


Achernar
(Domiciano de Souza et al., 2003)

Introduction

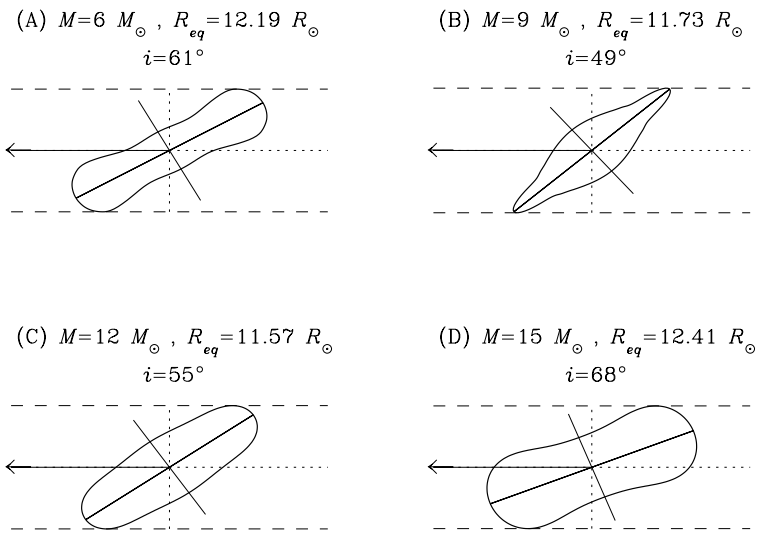


Achernar
(Domiciano de Souza et al., 2003)



Altair
(Monnier et al., 2007)

- this has caught the attention of those doing stellar models:



Models for Achernar
(Jackson et al., 2004)

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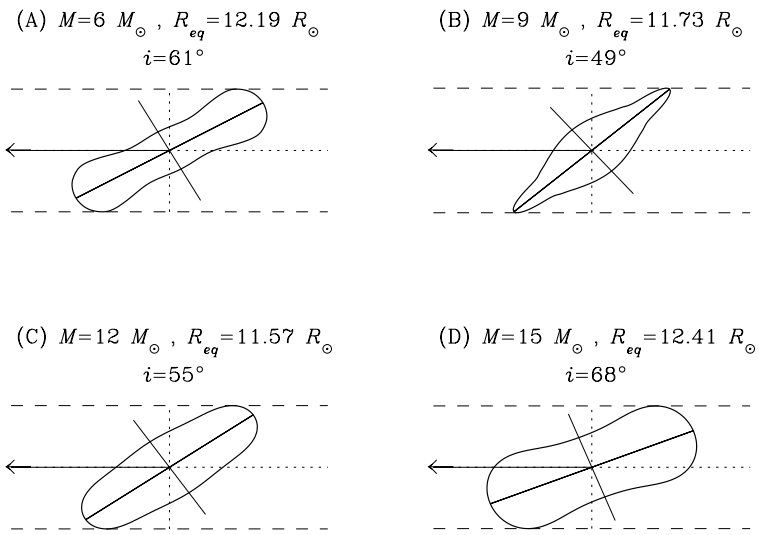


Models for Achernar
(Jackson et al., 2004)

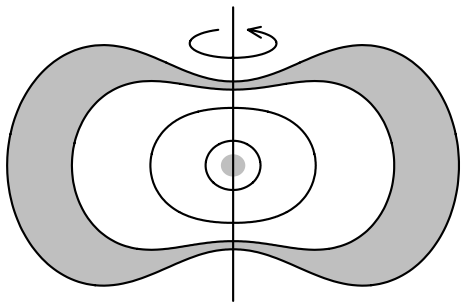
What is involved when making models of such stars?

Outline

Physical phenomena

Physical phenomena

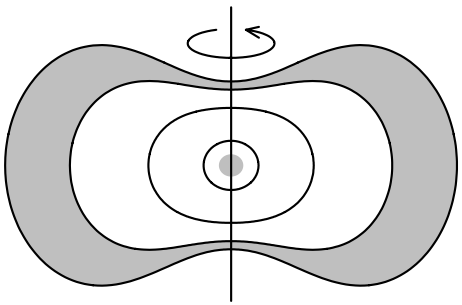
- centrifugal deformation



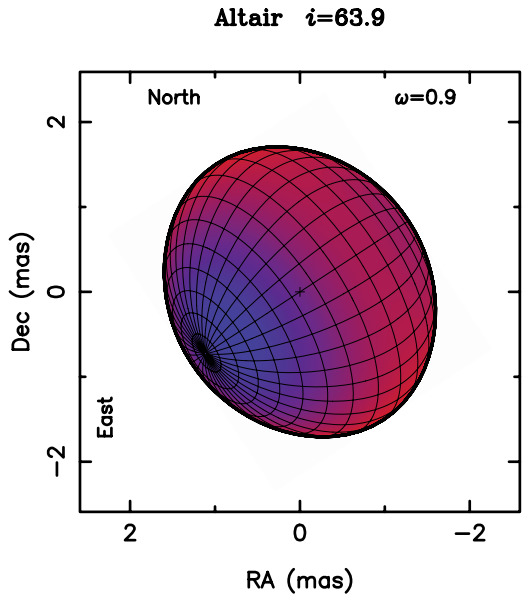
(MacGregor et al., 2007)

Physical phenomena

- centrifugal deformation
- gravitational darkening



(MacGregor et al., 2007)



(Peterson et al., 2006)

Physical phenomena

- centrifugal deformation
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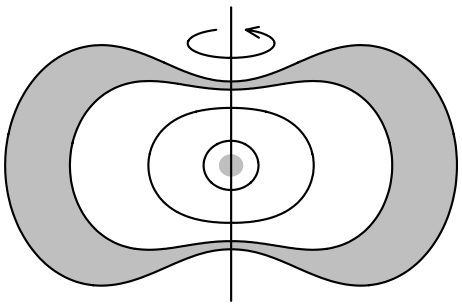
- baroclinicity



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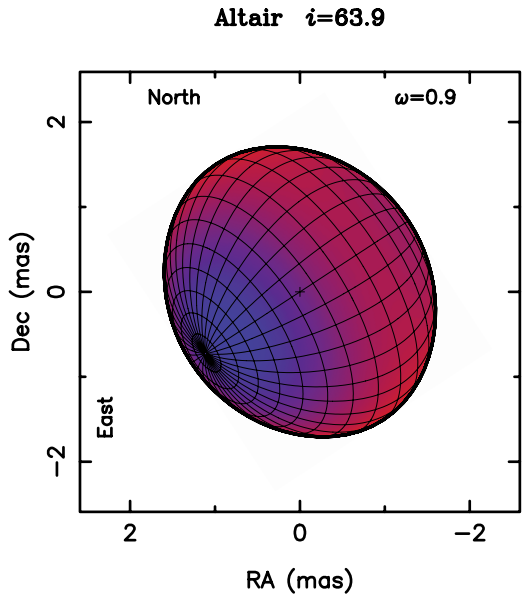
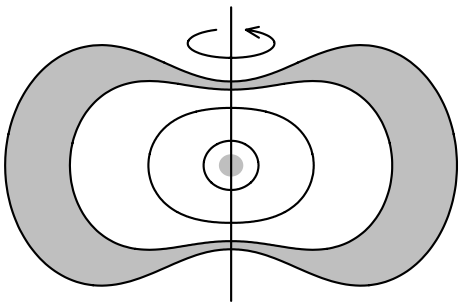


(Peterson et al., 2006)

Physical phenomena

- centrifugal deformation
- gravitational darkening
- baroclinicity
  - differential rotation
  - meridional circulation



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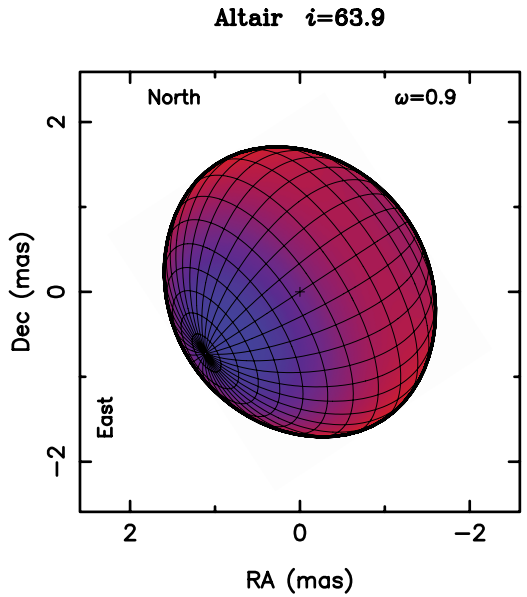

(Peterson et al., 2006)

Physical phenomena

- centrifugal deformation
- gravitational darkening
- baroclinicity
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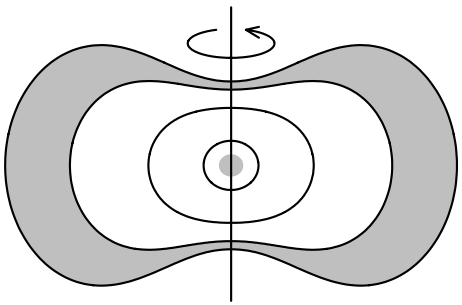
  - meridional circulation
- transport processes



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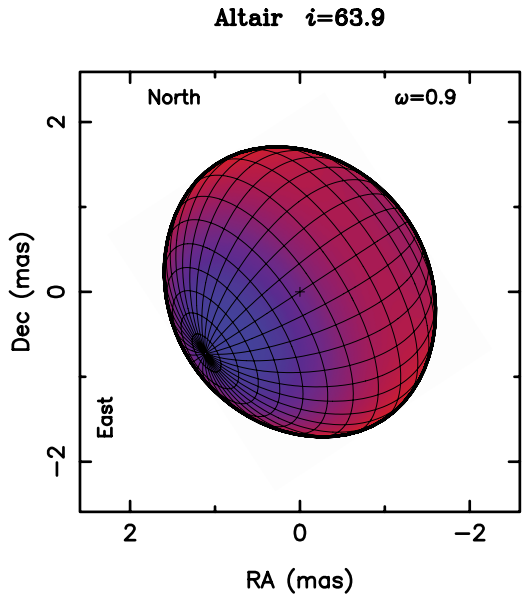
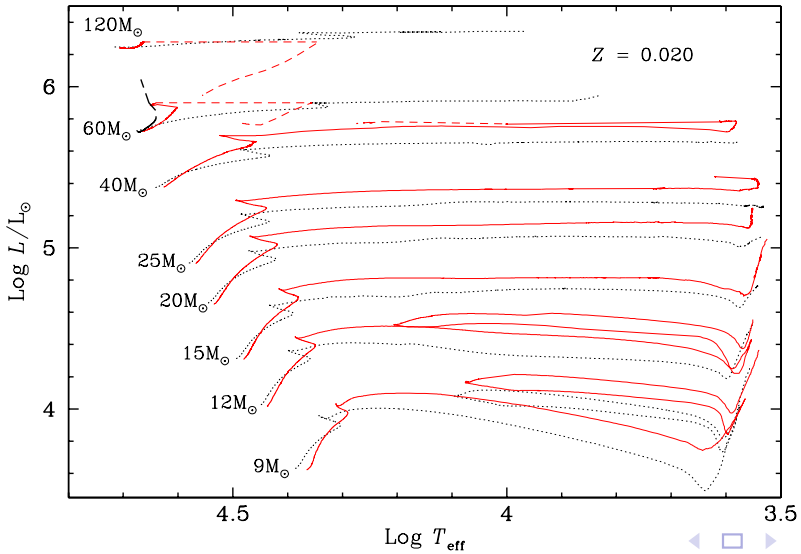


(Peterson et al., 2006)

Recent models

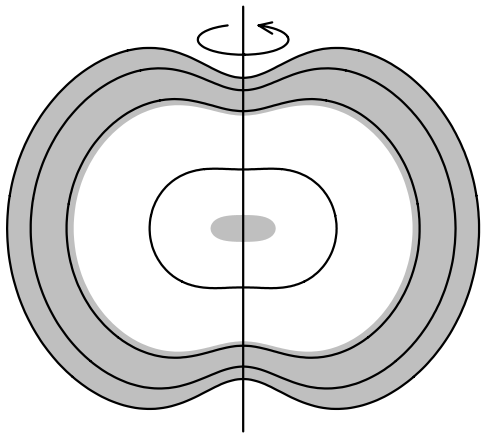
Meynet & Maeder (2000), and other papers

- shellular rotation profile, $\Omega(r)$ *(see Zahn, 1992)*
- 1D formalisme
- stellar evolution
- transport processes (chemical elements and angular momentum)



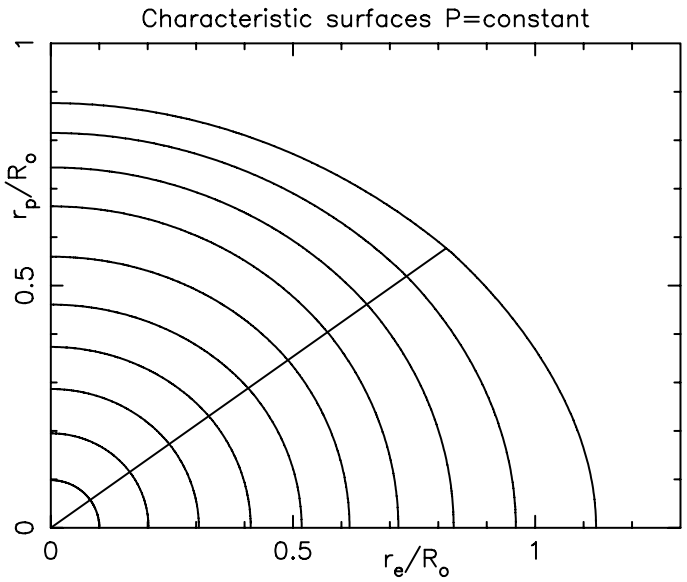
Jackson et al. (2004, 2005), MacGregor et al. (2007)

- barotropic models
- conservative rotation profile: $\Omega(s)$
- attempt to describe Achernar



(MacGregor et al., 2007)

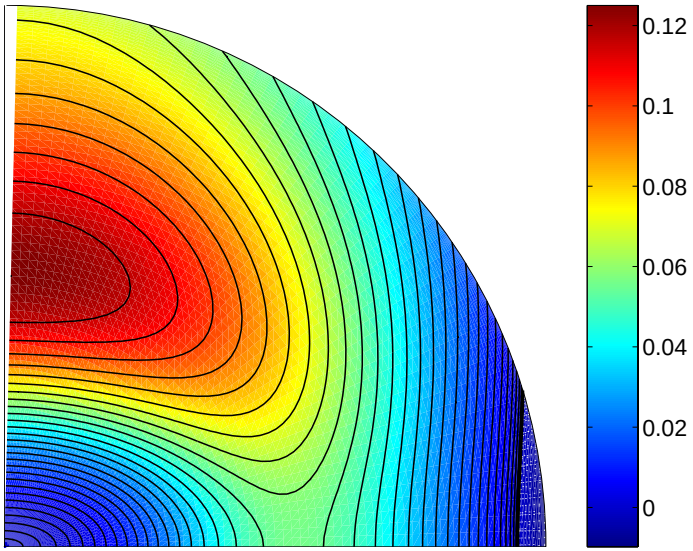
- Roxburgh (2004)
  - barotropic uniformly rotating model
- Roxburgh (2006)
  - transforms 1D models into 2D models
  - arbitrary 2D rotation profile
  - thermal equilibrium not solved



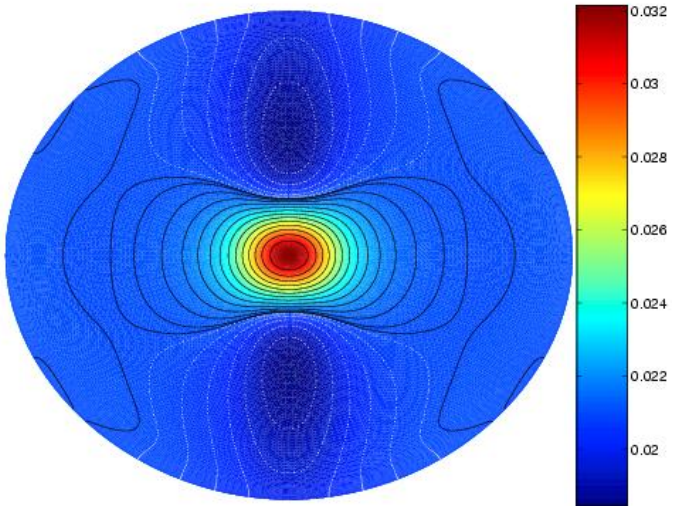
(Roxburgh, 2006)

The ESTER project

- Rieutord (2006)
  - boussinesq model with baroclinic flows
- Espinosa & Rieutord (2007)
  - compressible baroclinic model in spherical container



(Espinosa & Rieutord, 2007)



(Courtesy of M. Rieutord)

Pulsation modes

- many uncertainties remain in models
  - need for observational constraints

Pulsation modes

- many uncertainties remain in models
  - need for observational constraints
- difficulties
  - pulsation modes are not given by a single spherical harmonic: this is a 2D eigenvalue problem
  - unfamiliar mode geometry and frequency spectrum

The frequency spectrum

- Inadequacy of perturbative methods at rapid rotation rates

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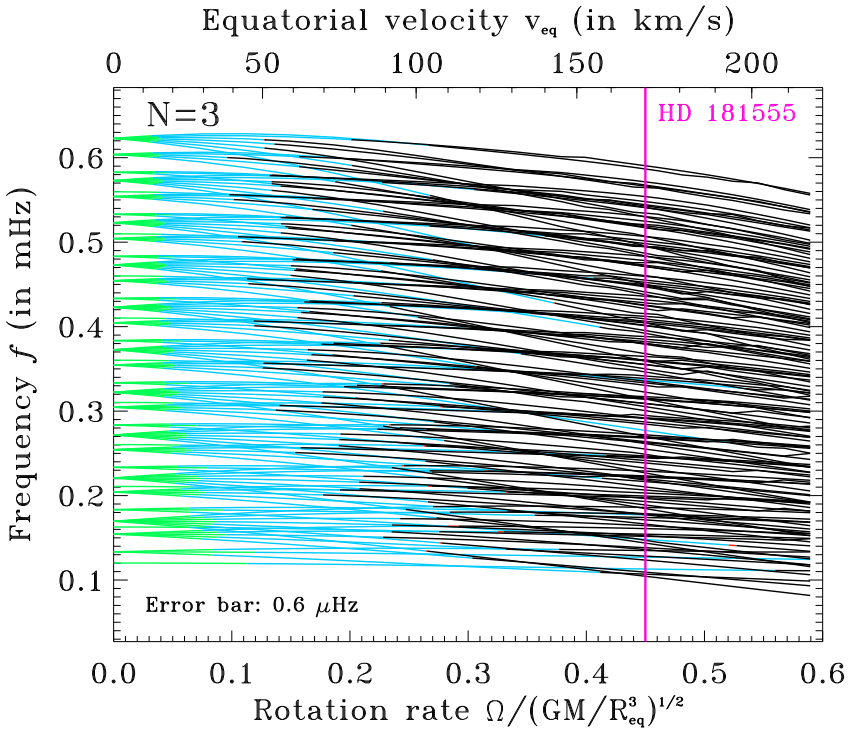

(Reese et al., 2006)

The frequency spectrum

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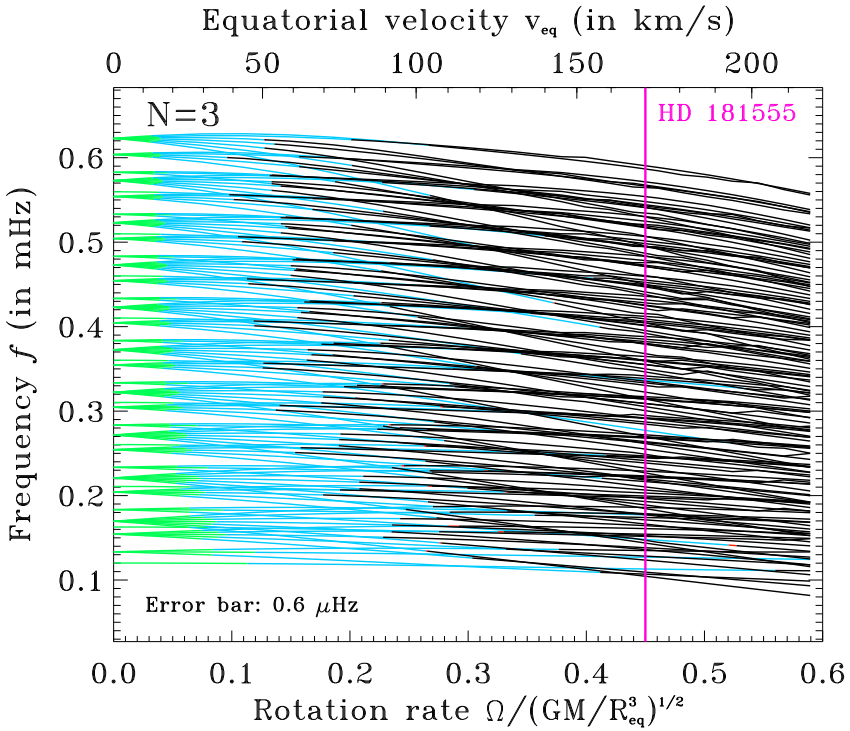
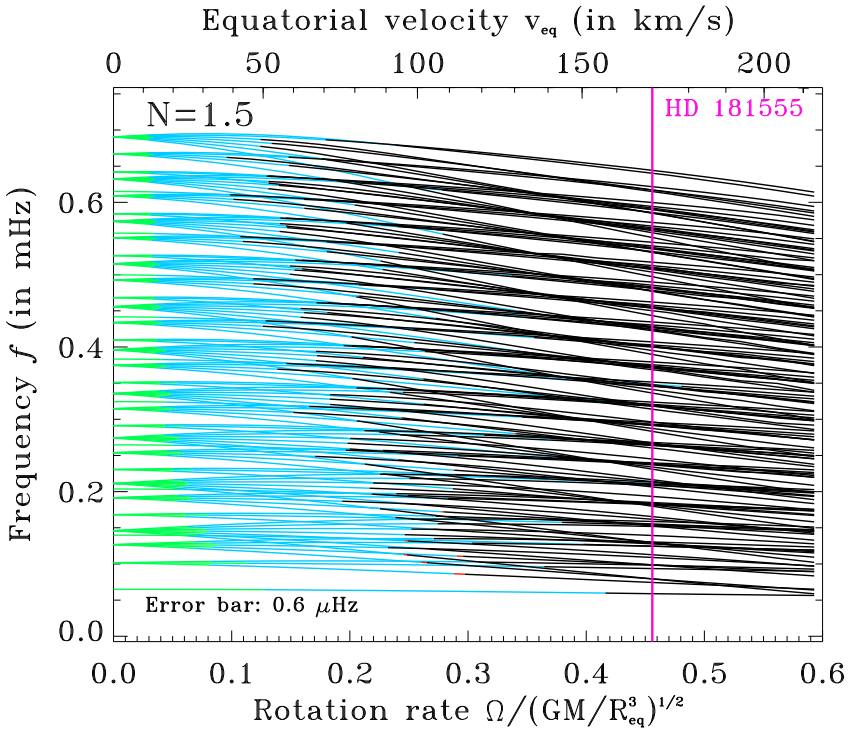
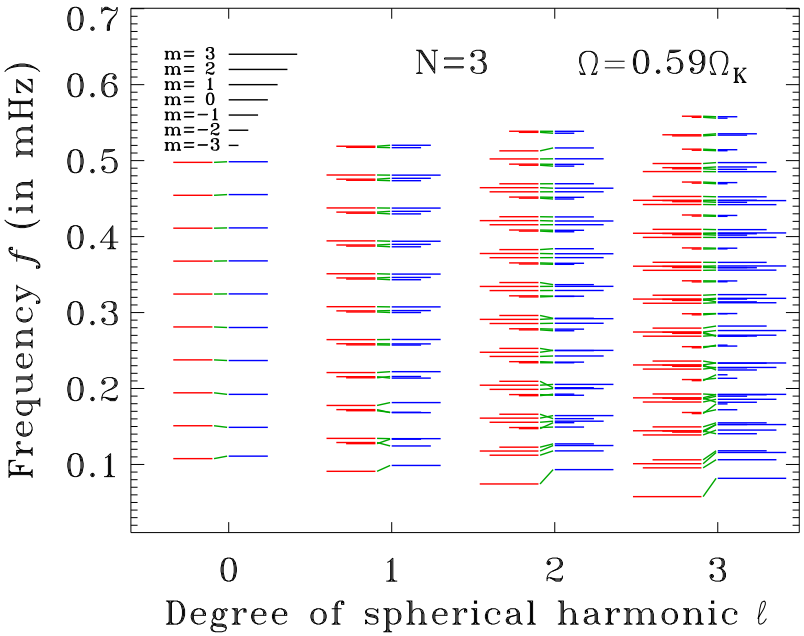
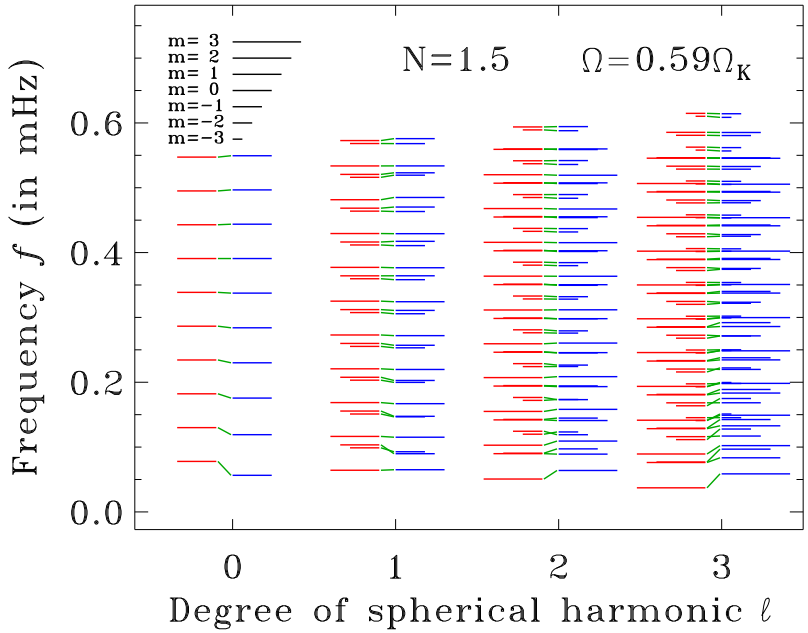




(Reese et al., 2006)

A new frequency organisation

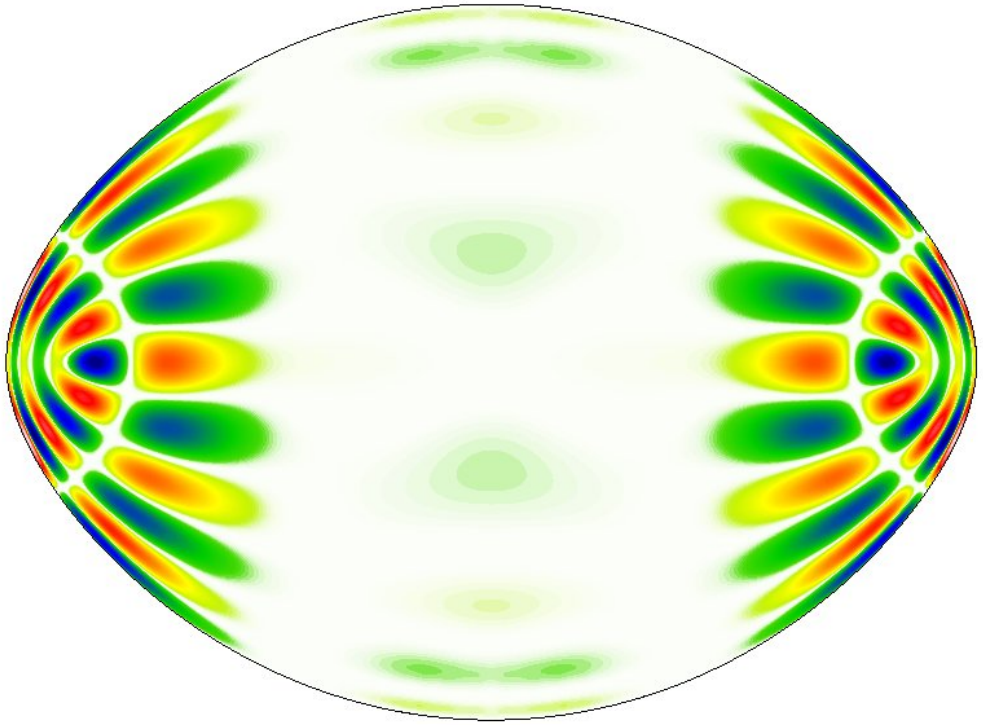




(Lignieres et al., 2006, Reese et al., in preparation)

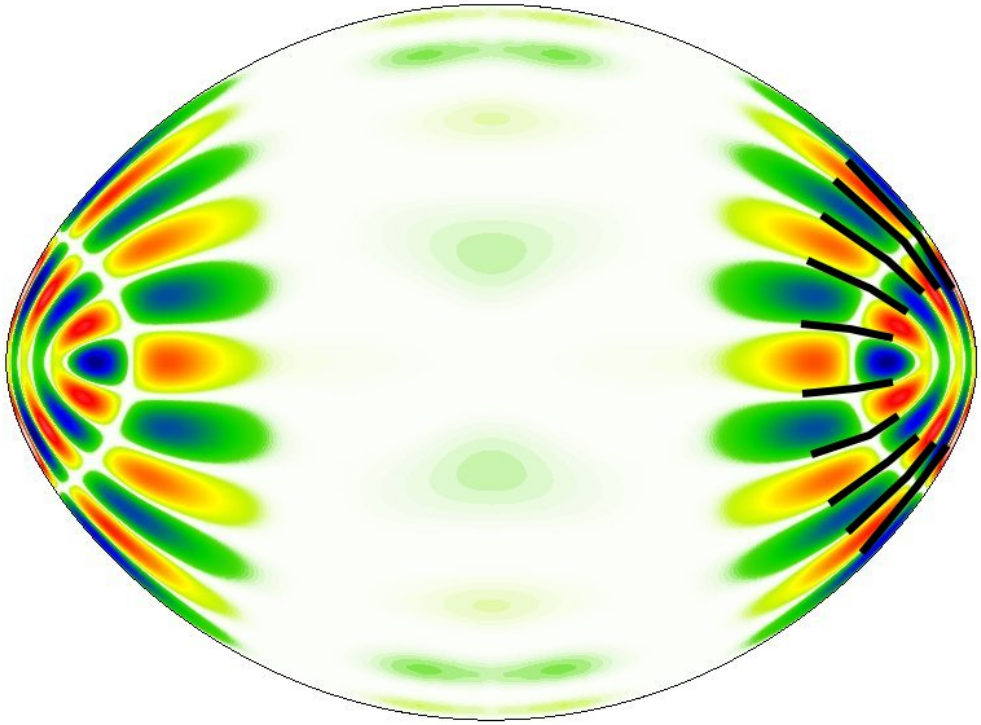
$$\omega_{n,\ell,m} = n\Delta_n + \ell\Delta_\ell + |m|\Delta_m + \alpha^{\pm}$$

Mode geometry



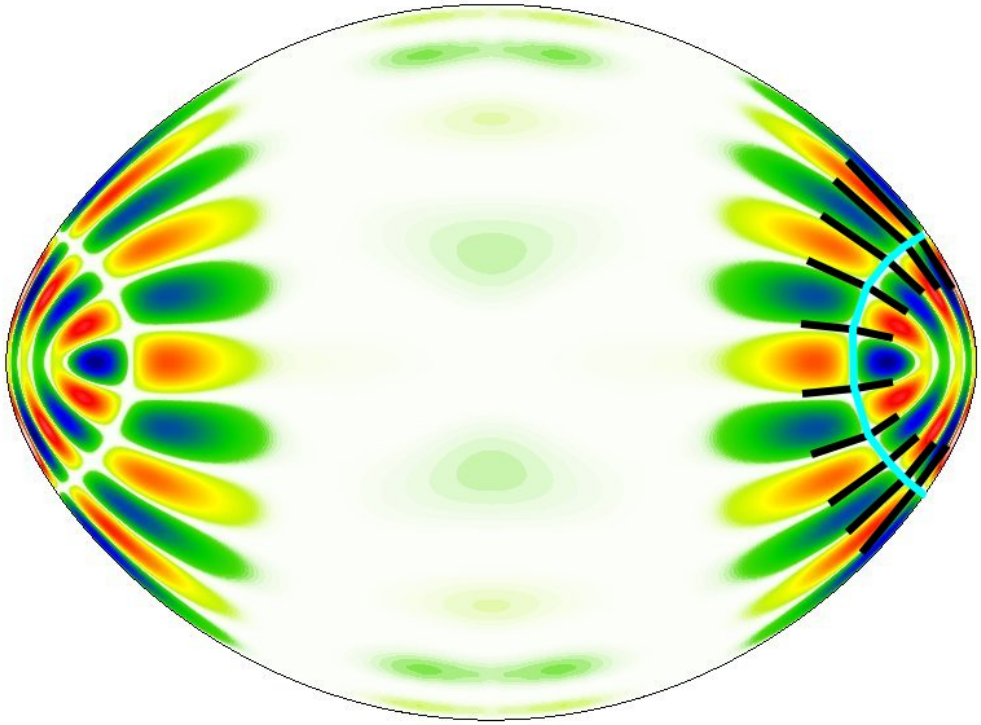
- mode energy concentrated around equatorial region

Mode geometry

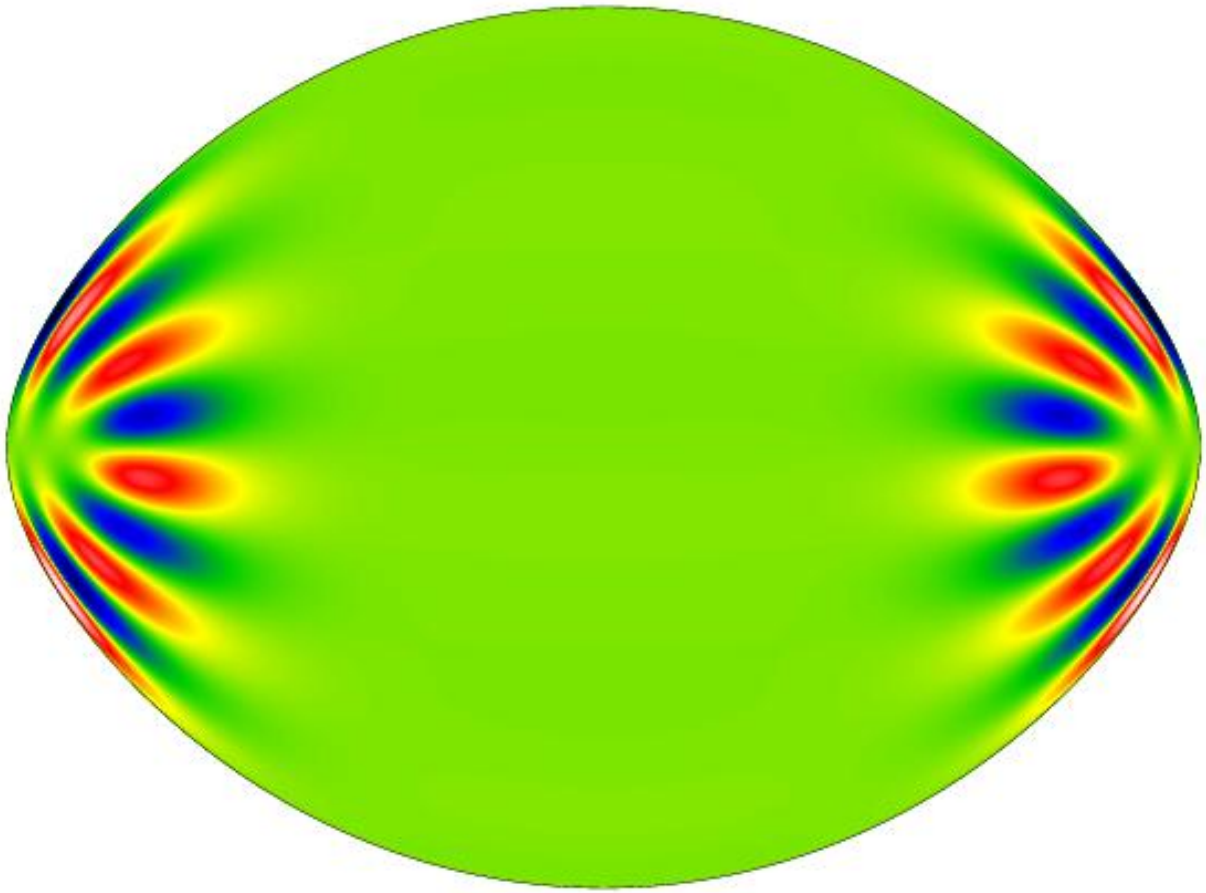


- mode energy concentrated around equatorial region
- there are 10 "radial" nodes ($\tilde{n} = 10$)

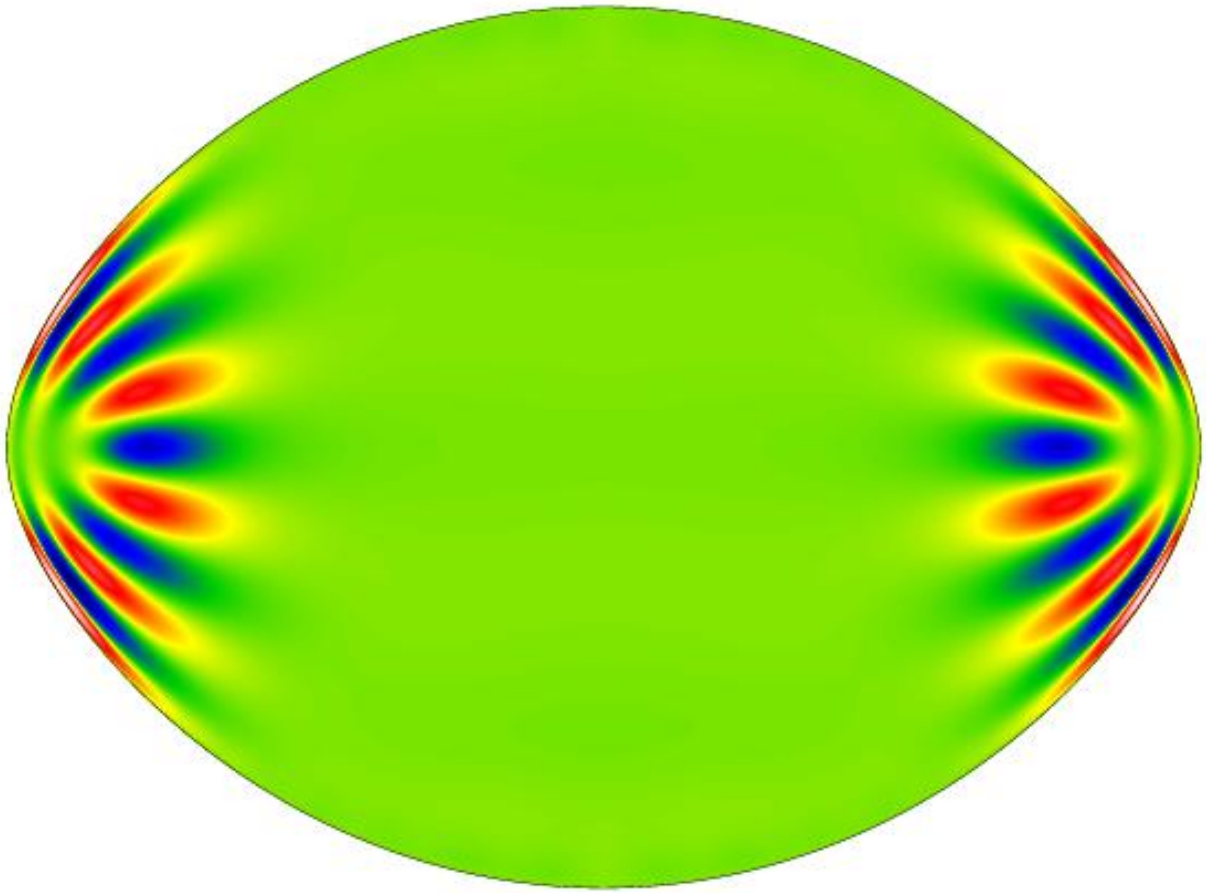
Mode geometry



- mode energy concentrated around equatorial region
- there are 10 "radial" nodes ($\tilde{n} = 10$)
- there is 1 "latitudinal" node ($\tilde{\ell} = 1$)



$$\tilde{n} = \quad 9, \quad \tilde{\ell} = 0$$



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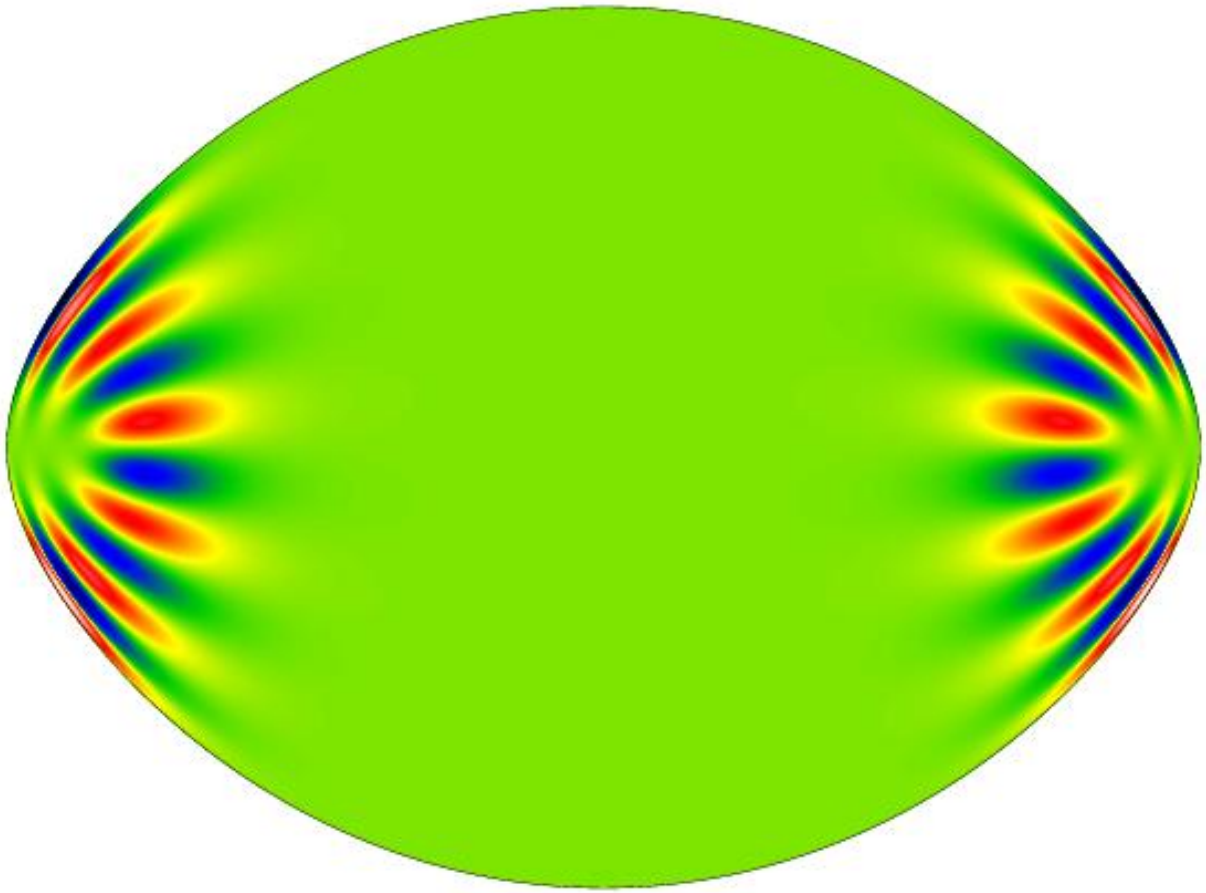
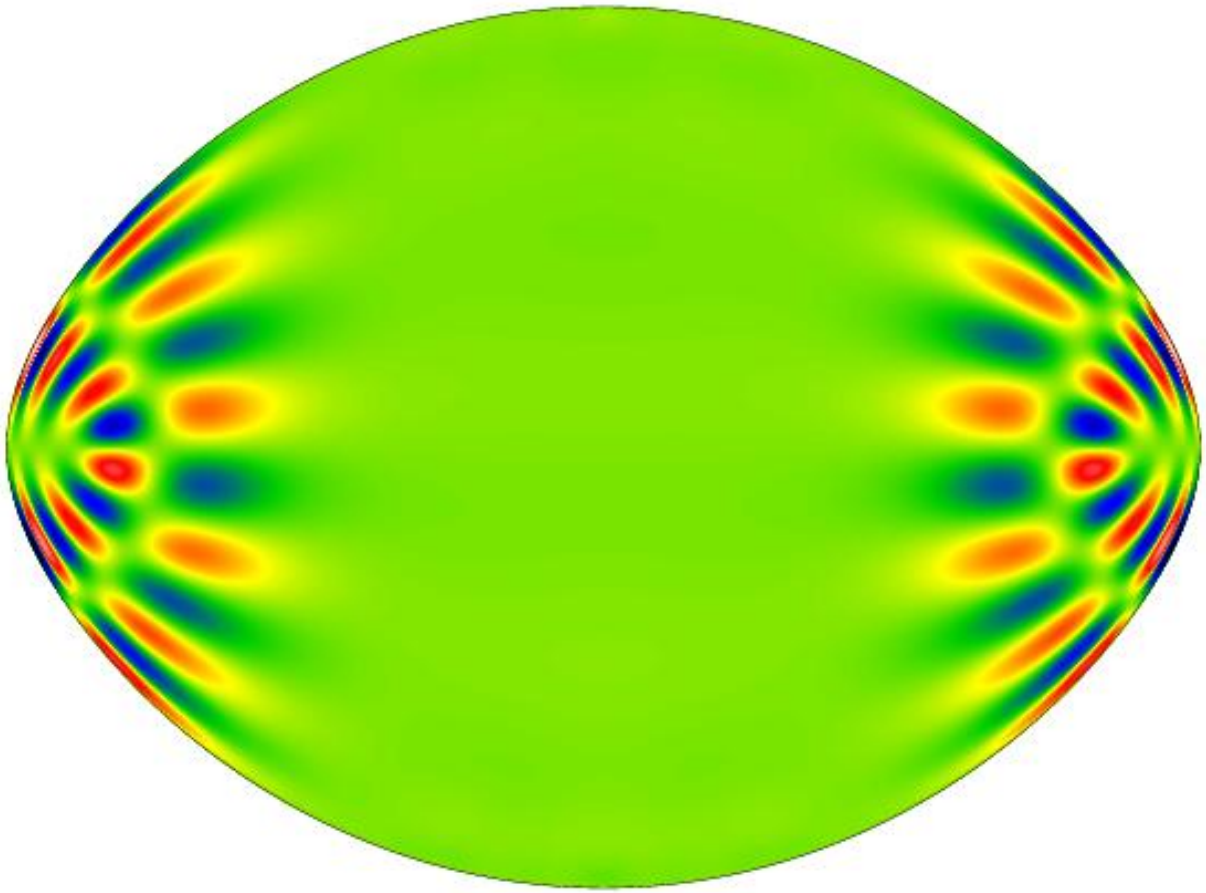
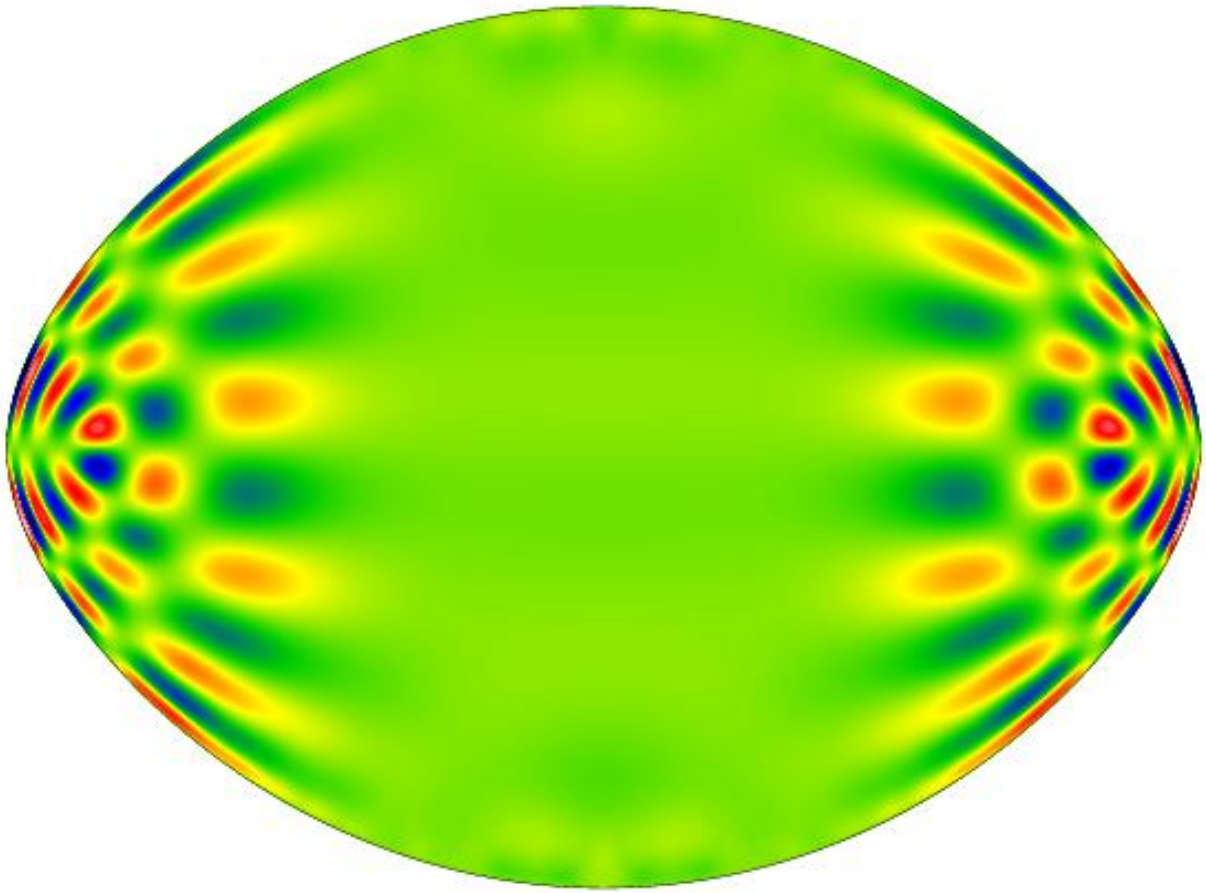


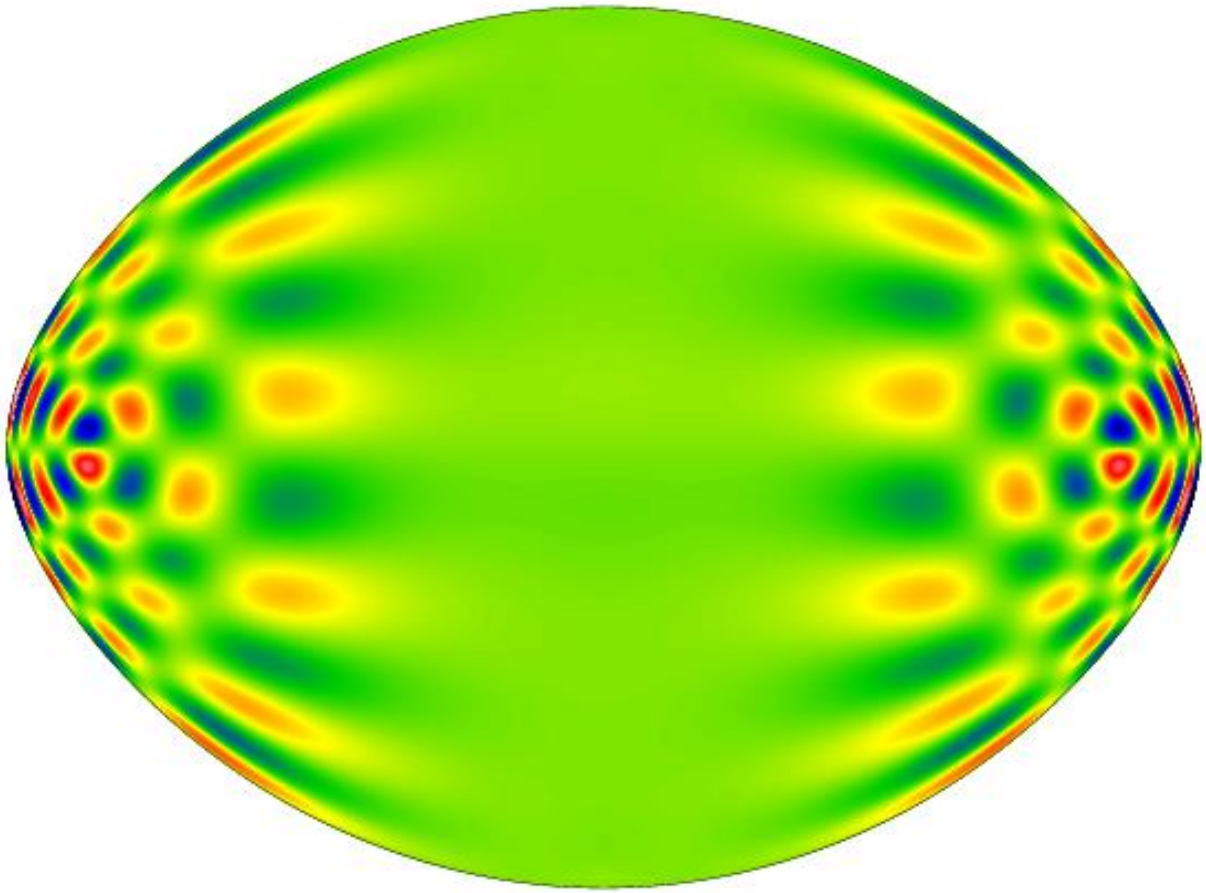
$$\tilde{n} = 11, \quad \tilde{\ell} = 0$$



$$\tilde{n} = 11, \quad \tilde{\ell} = 1$$

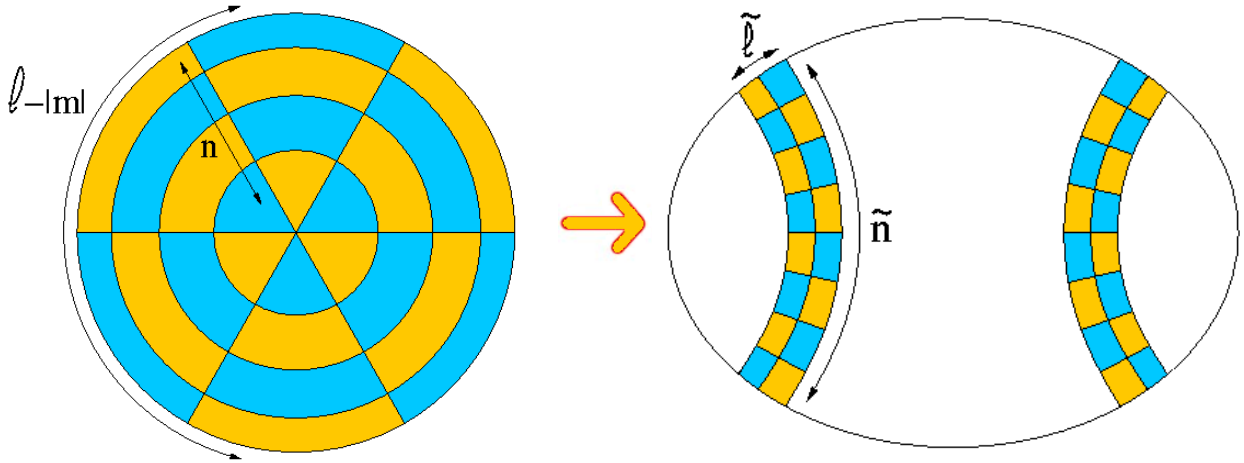


$$\tilde{n} = 11, \quad \tilde{\ell} = 2$$



$$\tilde{n} = 11, \quad \tilde{\ell} = 3$$

Question: what is the link between this mode geometry and the geometry of modes in non-rotating stars?



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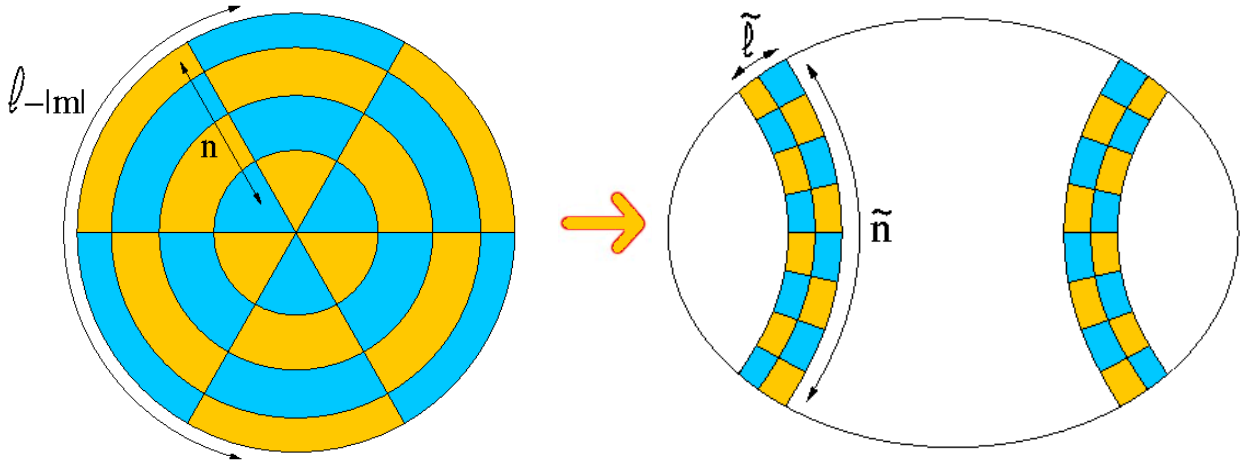
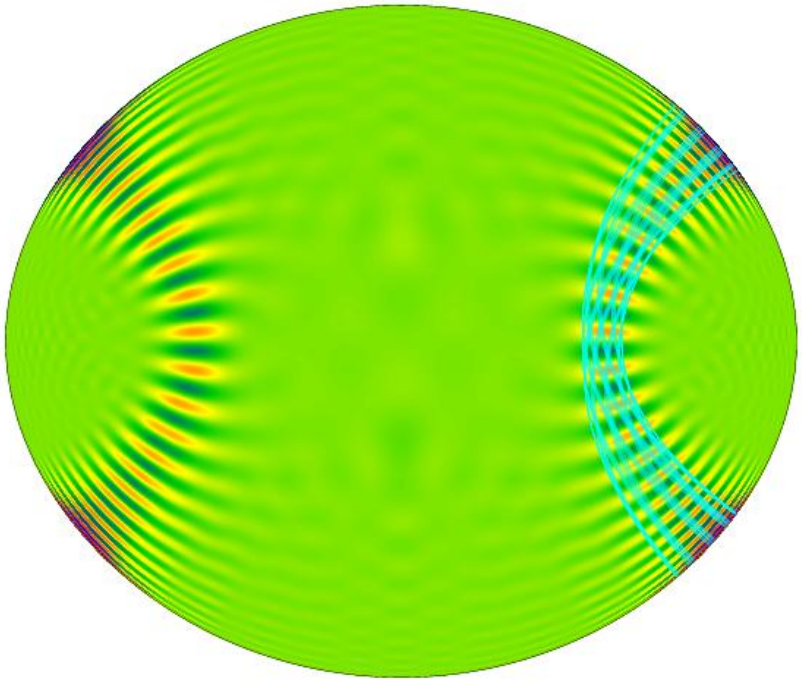


$$\begin{aligned} \tilde{n} &= 2n + \varepsilon, \\ \tilde{\ell} &= \frac{\ell - |m| - \varepsilon}{2}, \\ \varepsilon &\equiv \ell + m \ [2] \end{aligned}$$

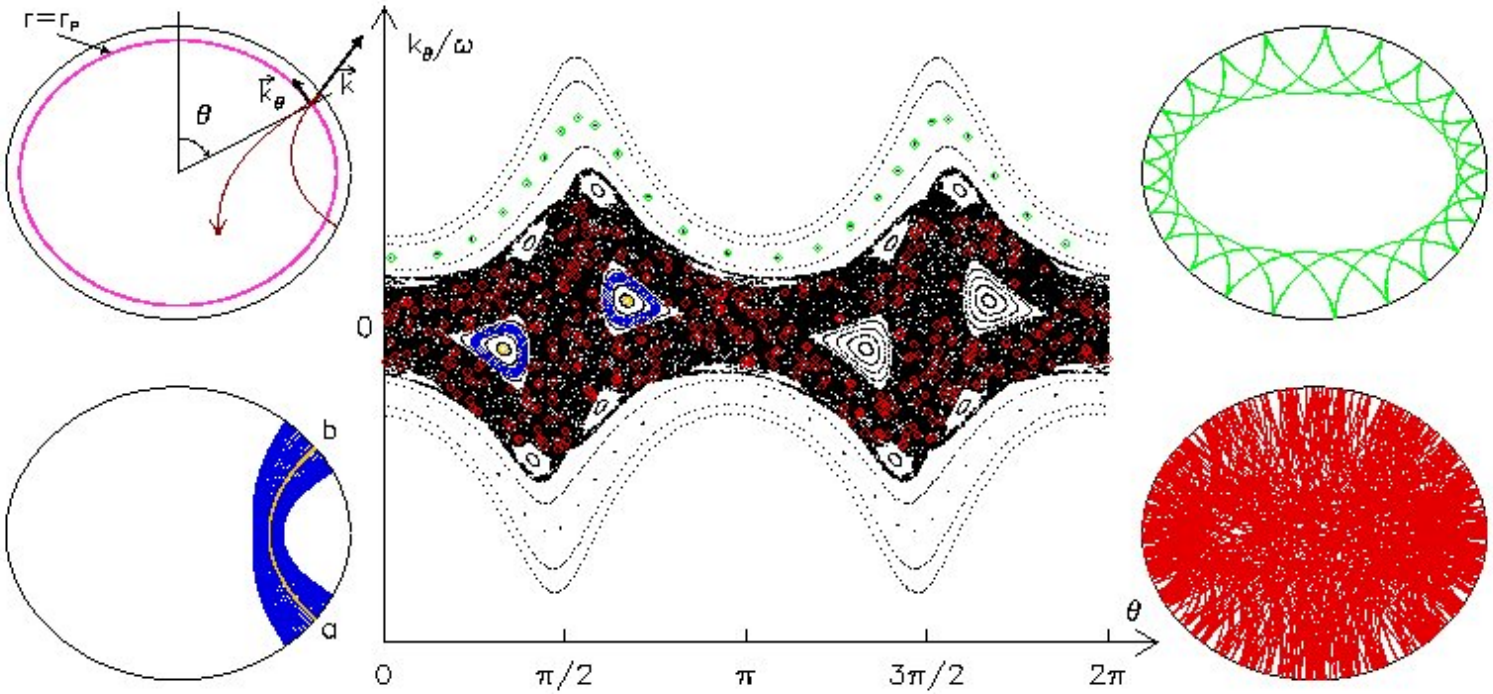
$$\omega_{n,\ell,m} = \tilde{n}\tilde{\Delta}_n + \tilde{\ell}\tilde{\Delta}_\ell + |m|\tilde{\Delta}_m + \tilde{\alpha}$$

Ray dynamics

Question: what is the link with ray dynamics?



(Vidal, 2006)

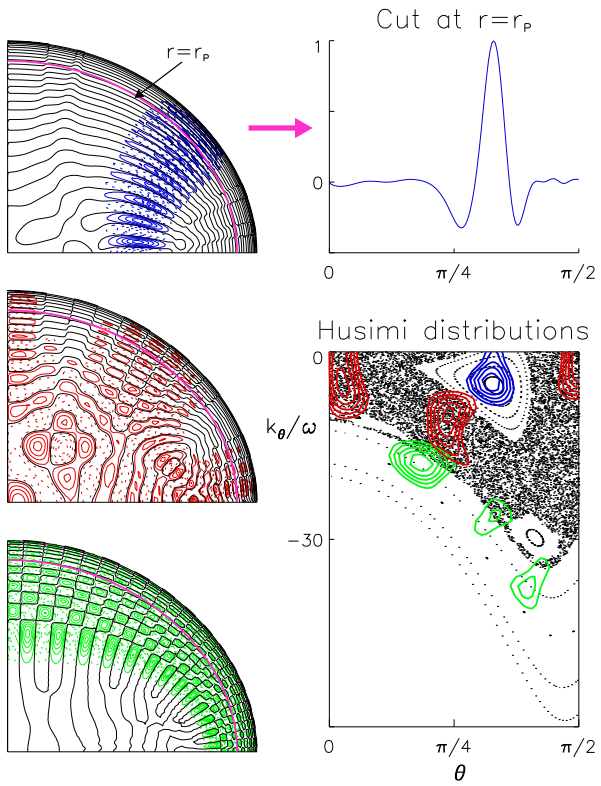


(Lignières & Georgeot, submitted)

A Poincaré section reveals:

- different regions with different behaviours
- the presence of wave chaos

- Husimi functions can be used to "project" eigenmodes onto Poincaré section
- this confirms correspondance between ray dynamics and eigenmode calculations
- likely link between wave travel times and parameters $\tilde{\Delta}_n$, $\tilde{\Delta}_\ell$, and $\tilde{\Delta}_m$



(Lignières & Georgeot, submitted)

Outlook

- few attempts to interpret pulsation modes in rapidly rotating stars

Authors	Star	$v \cdot \sin i$
Aerts et al., 2006	HD 2036645	180
Dziembowski et al., 2007, Savonije, 2007	HD 163868	250
Suárez et al., 2005	Altaïr	230
Saio et al., 2007	ζ Oph	380

- difficulty with obtaining a reliable mode identification
- forthcoming data on other rapid rotators (HD 181555, observed by CoRoT)

What needs to be done:

- search for asymptotic patterns using realistic stellar models
- search for equidistant patterns in observed pulsation spectra
- improve stellar models
- do detailled asteroseismic comparisons