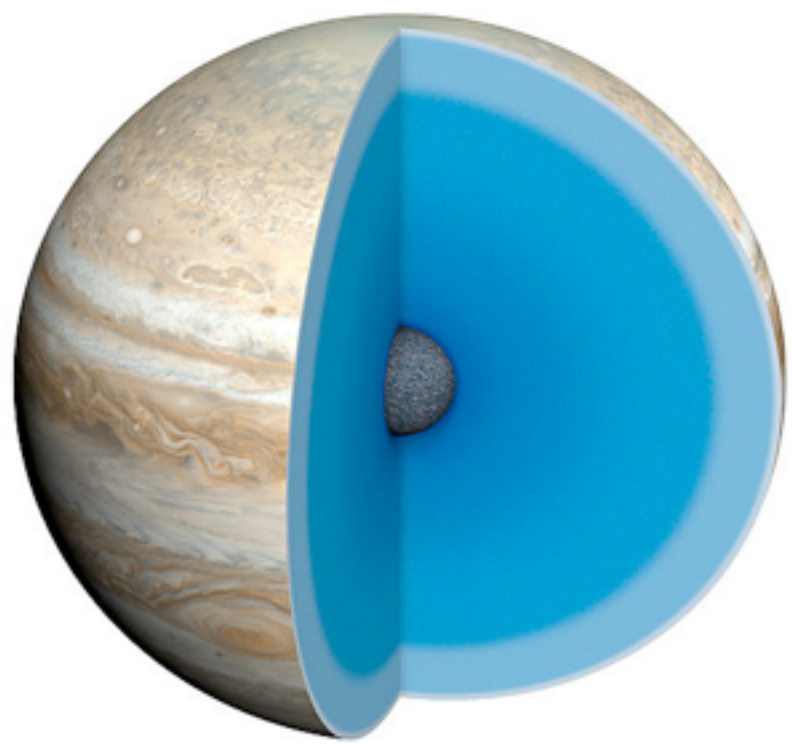
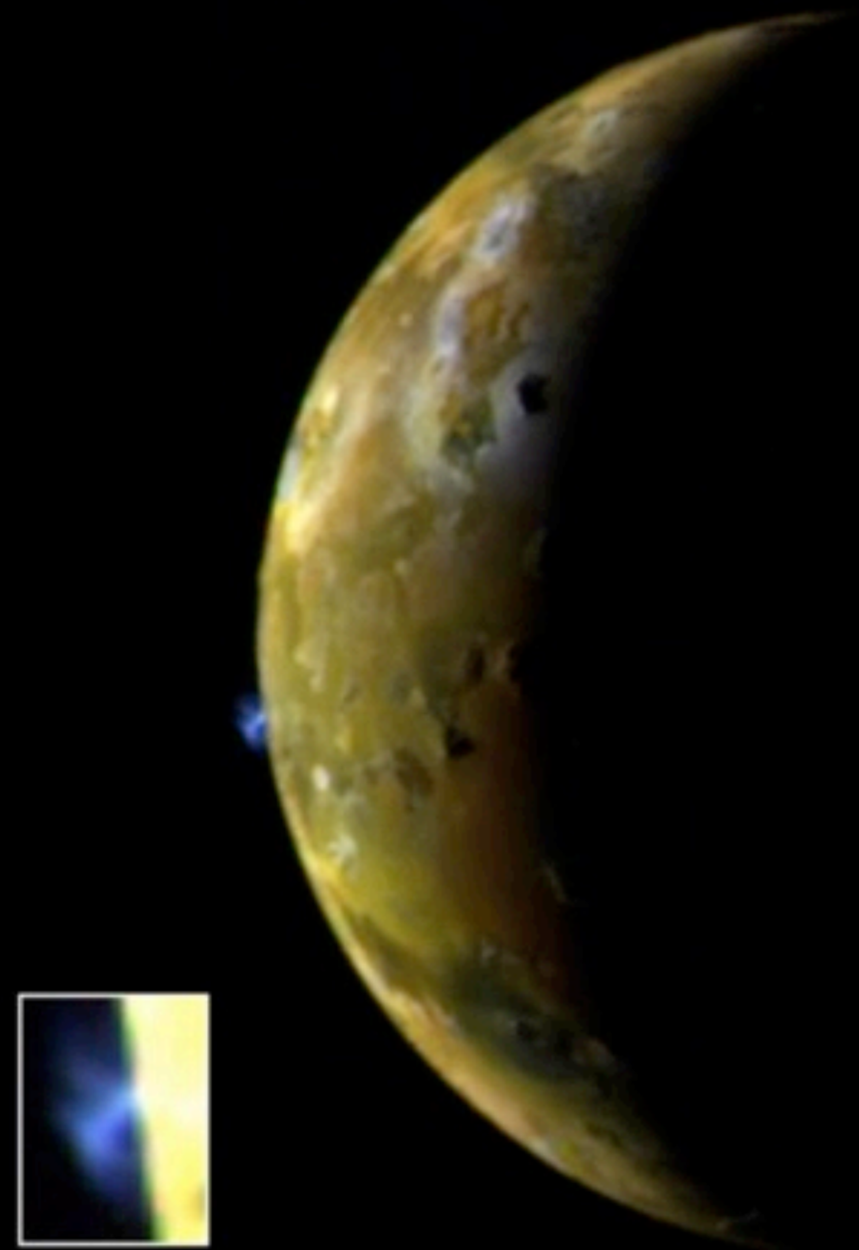
# Waves and Tides in Giant Planets

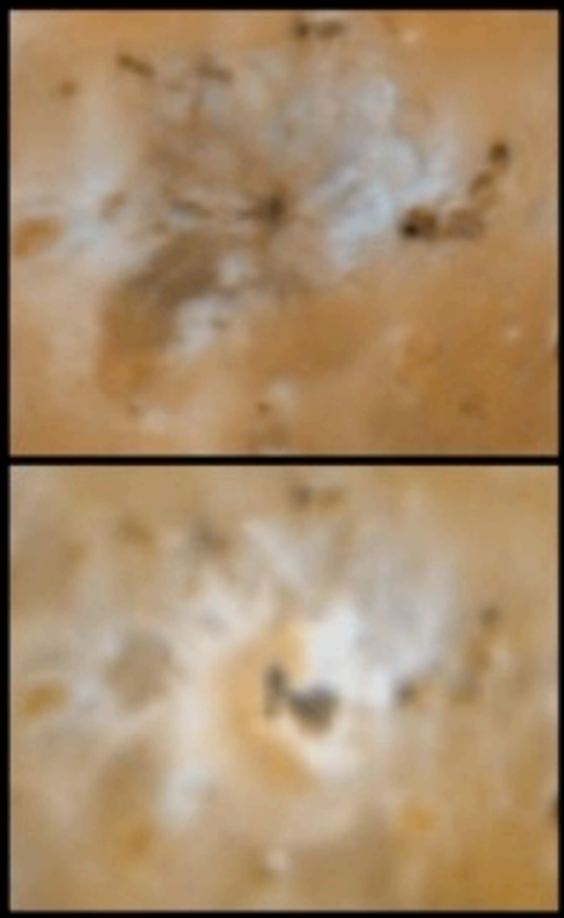
Yanqin Wu (Toronto)



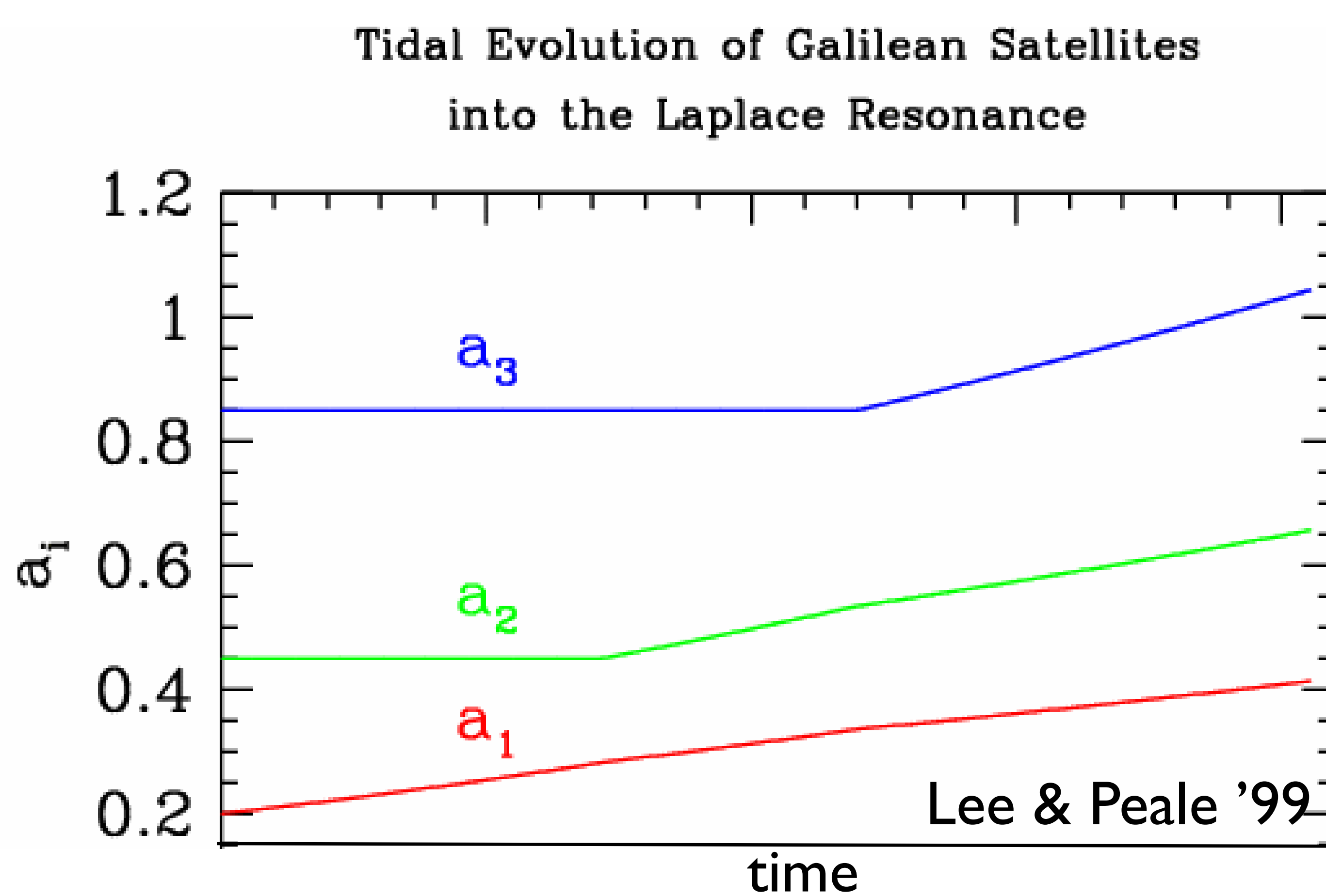
works by Ogilvie, Arras, Goodman, Papaloizou, Ivanov, etc.

# Evidence I.
# Jupiter's fiery/
# orderly satellites





- Tides raised on Jupiter dissipated, spinning it down,
- pushing Io (and others) outward
- occur also for Saturn, Neptune, Uranus...




| | | |
|---|---|---|
| Callisto | 16.689 days | (9.434) |
| Ganymede | 7.154 days | (4.044) |
| Europa | 3.551 days | (2.007) |
| Io | 1.769 days | (1) |

Jupiter’s Q ~ $10^5$ if Io has moved by ~ a over 5 Gyrs

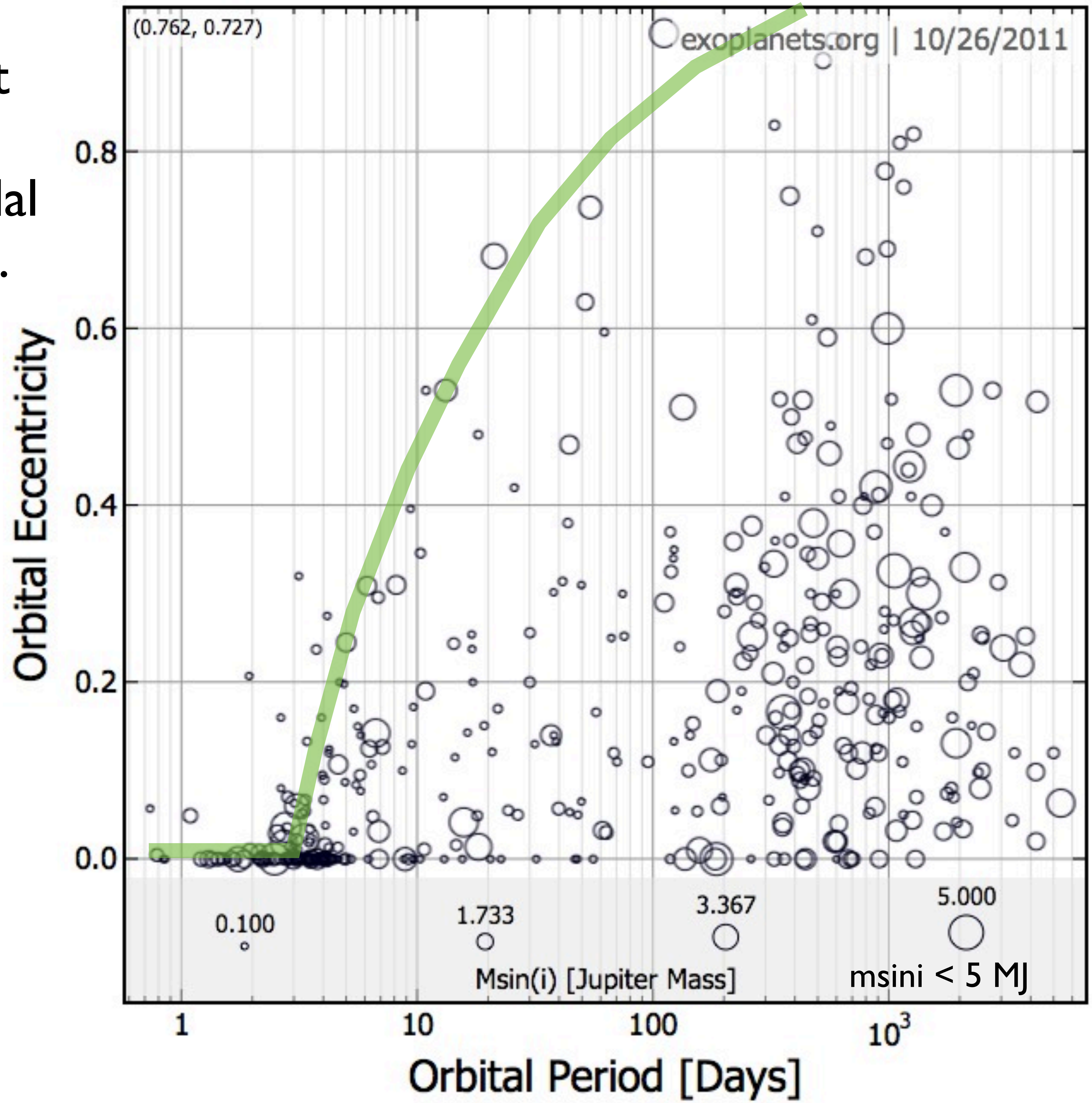
(Goldreich & Soter ’66, Peale & Greenberg ’80)

recent claim of direct measurement Q/k2 ~ 10^5

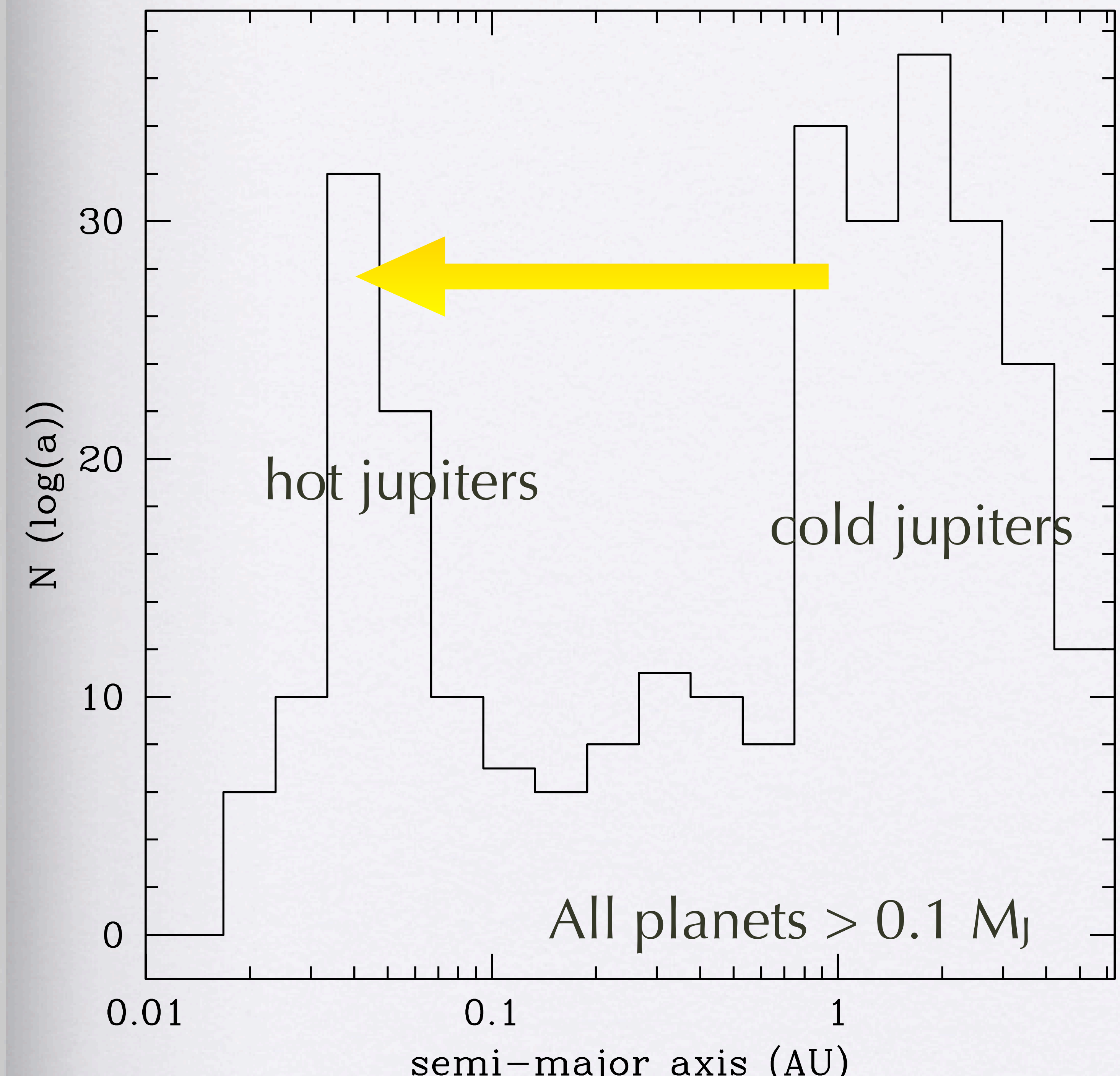
(Lainey et al ’09)

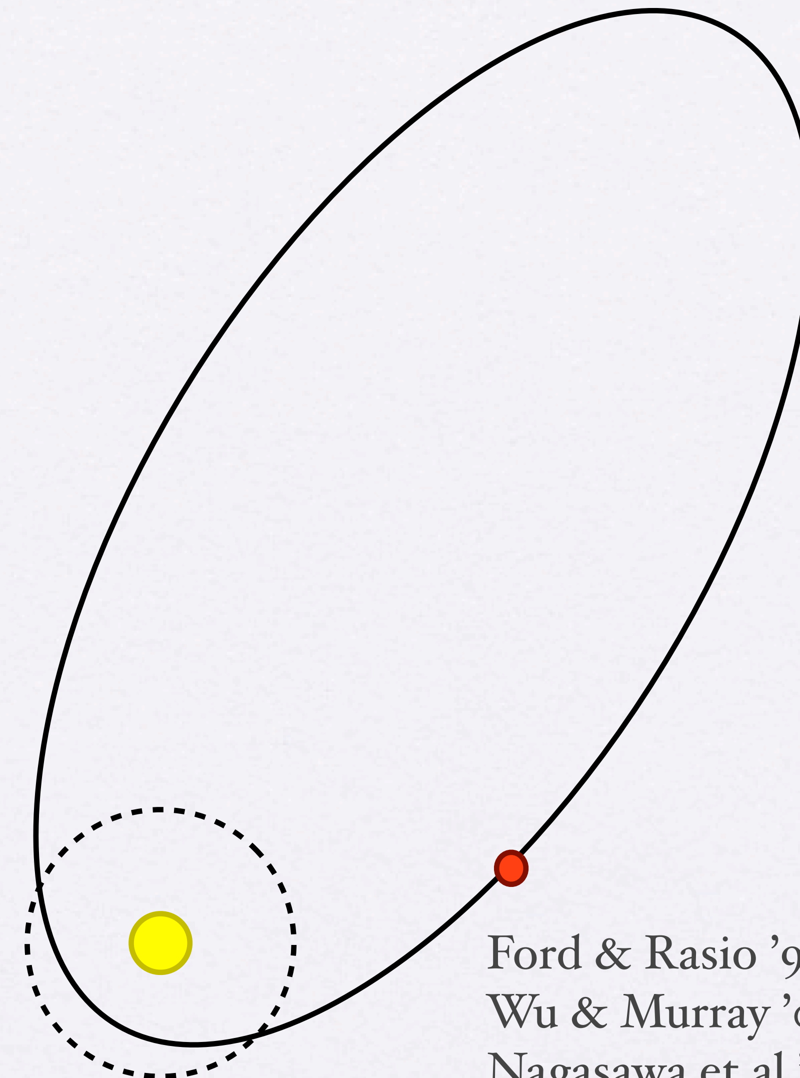
Evidence II. Close-in Giant planets have experienced tidal circularization.

exoplanet $Q \sim 10^5$



# Evidence III. origin of hot jupiters



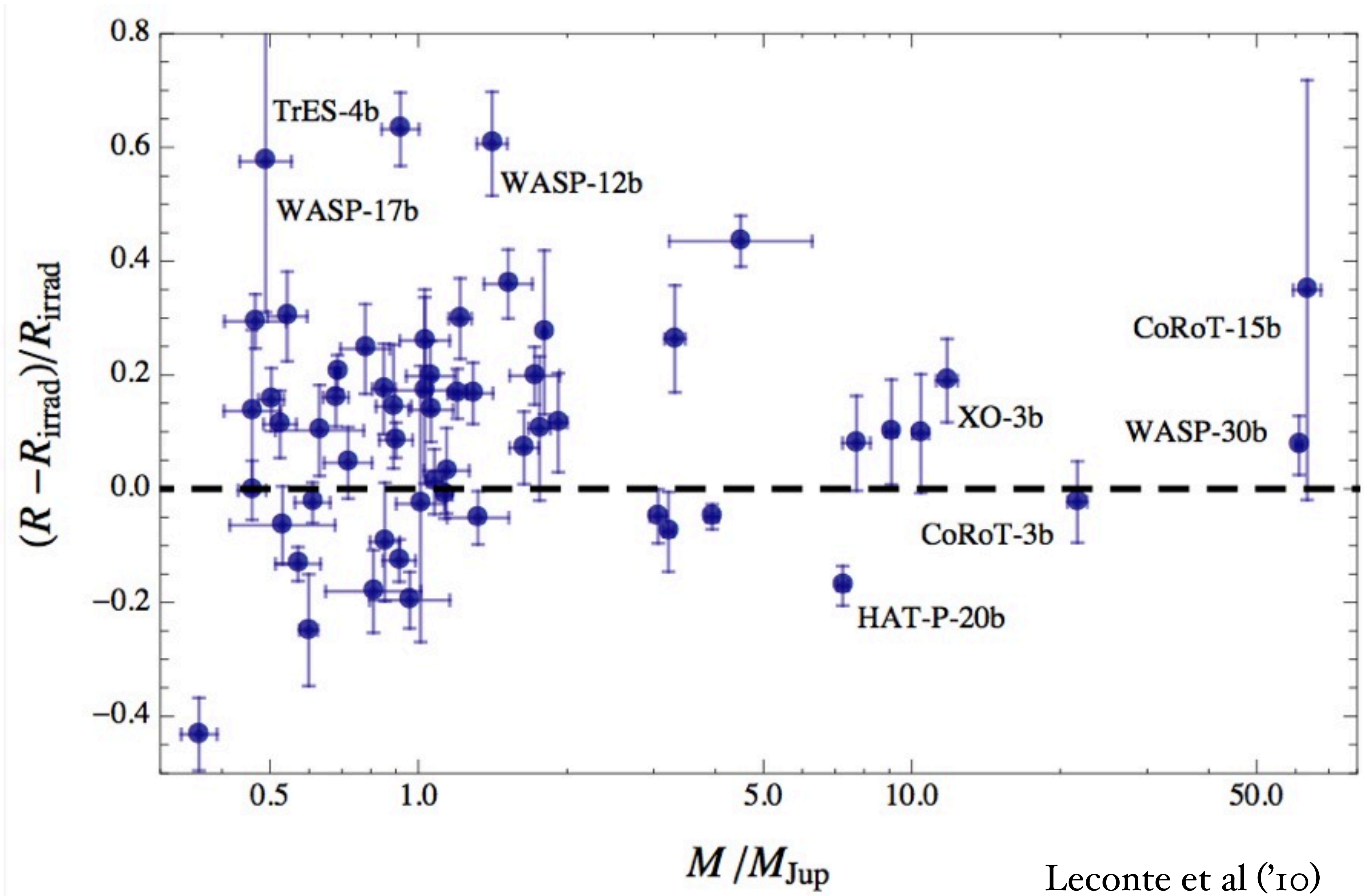



Ford & Rasio '99
Wu & Murray '03,
Nagasawa et al '10
Wu & Lithwick '11

~1% stars have hot jupiters (Marcy et al '06)

# Evidence IV.
# tidal inflation (?)

orbital energy: ~ 400 eV/baryon
binding energy: ~ 30 eV/baryon




Leconte et al ('10)

For these applications, need physics of Tidal dissipation inside giant planets

Tidal dissipation (dynamical tides)

1) Tidal Potential excites internal oscillations

2) internal oscillations damped

and energy/angular momentum transferred

TIDAL DISSIPATION IN ROTATING GIANT PLANETS

G. I. OGILVIE[1,2] AND D. N. C. LIN[1,2]

ORIGIN OF TIDAL DISSIPATION IN JUPITER. I. PROPERTIES OF INERTIAL MODES

YANQIN WU

**Tidal dissipation in rotating fluid bodies: a simplified model**

Gordon I. Ogilvie★

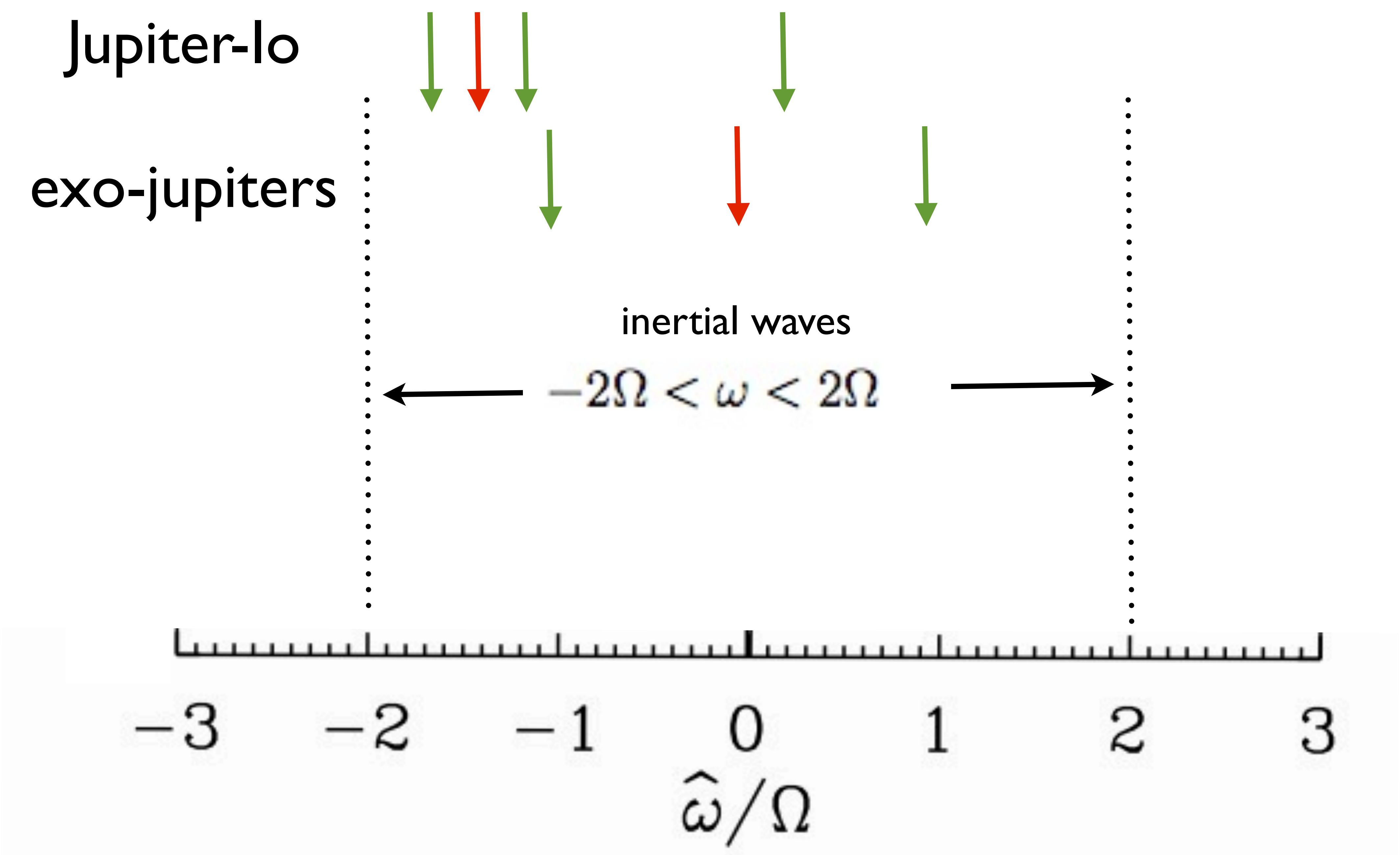
**Dynamic tides in rotating objects: orbital circularization of extrasolar planets for realistic planet models**

P. B. Ivanov[1,2★] and J. C. B. Papaloizou[1]

DYNAMICAL TIDES IN ROTATING PLANETS AND STARS

J. GOODMAN AND C. LACKNER

# Tidal forcing frequency (in the rotating frame)

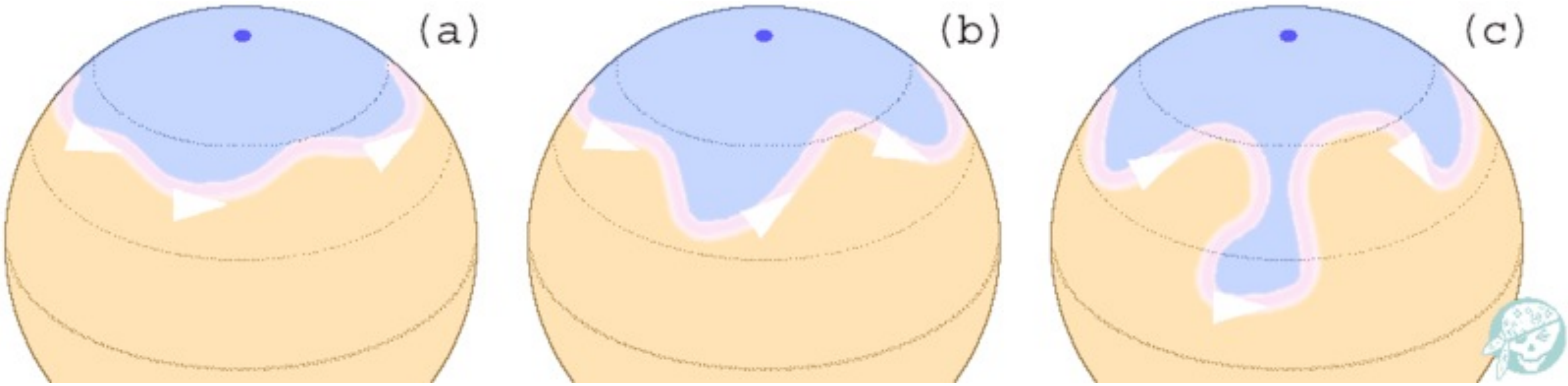



synchronization, circularization

$$\hat{\omega}_2 = 2(n - \Omega), \quad \hat{\omega}_3 = n, \quad \hat{\omega}_4 = n - 2\Omega, \quad \hat{\omega}_5 = 3n - 2\Omega.$$

# Inertial waves in Earth atmosphere (Rossby waves, vortex)

## jet stream



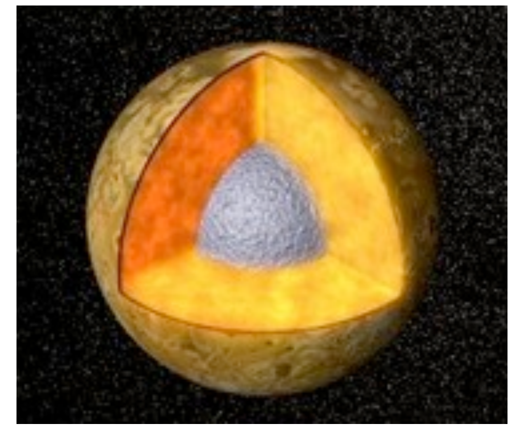

## Inertial waves in experiments

(Courtesy of A. J. Faller)

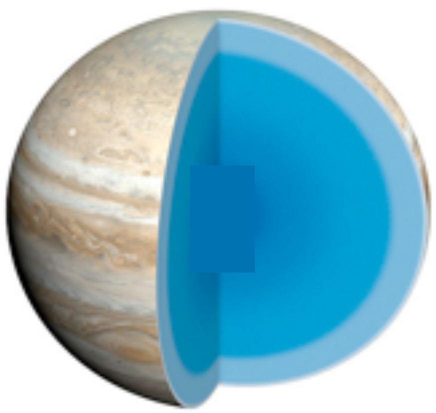
Figure 14. Stationary Rossby waves generated by an obstacle in a rotating annulus of liquid with a free surface.

# inertial waves in a convective sphere

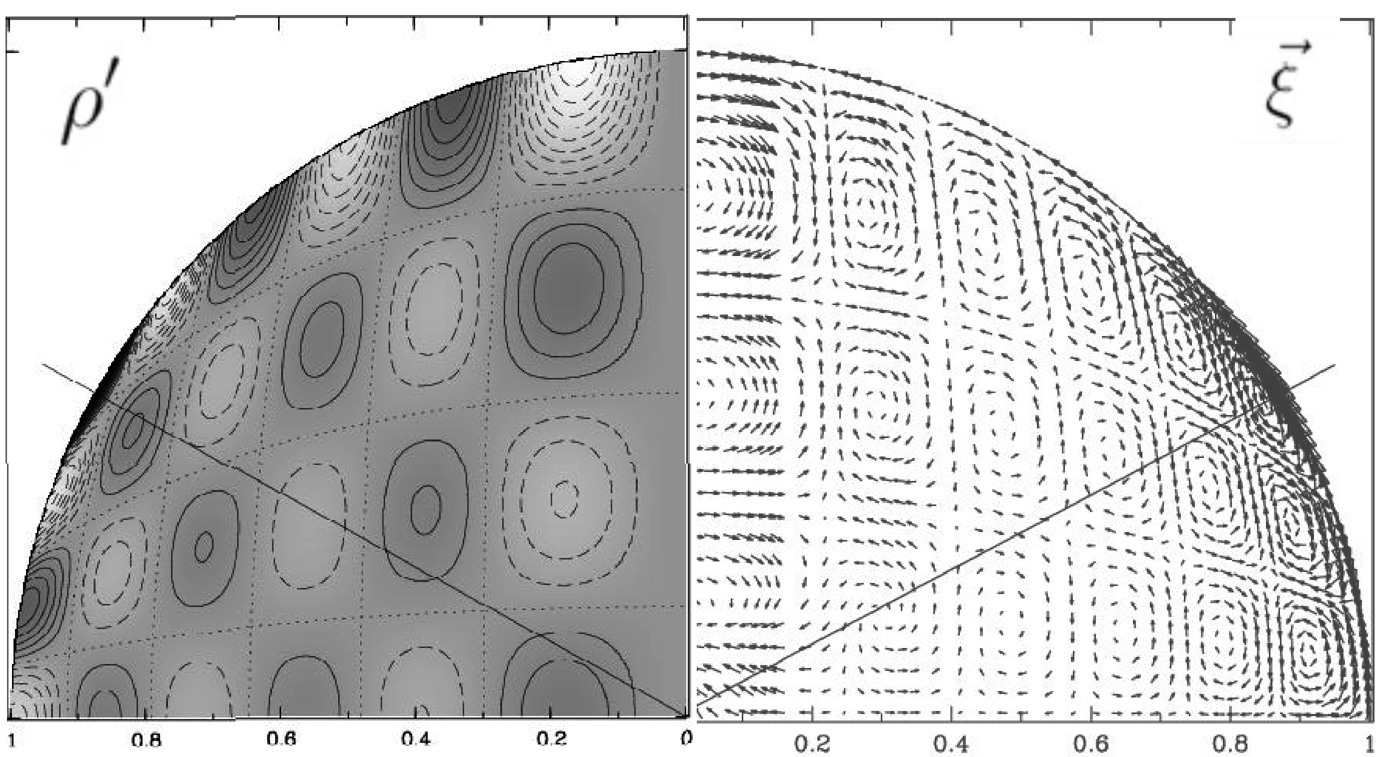
$$\rho\ddot{\boldsymbol{\xi}} + 2\rho\boldsymbol{\Omega}\times\dot{\boldsymbol{\xi}} = -\nabla p' + \frac{\nabla p}{\rho}\rho' - \rho\nabla\Phi',$$
$$\rho' + \nabla\cdot(\rho\boldsymbol{\xi}) = 0,$$



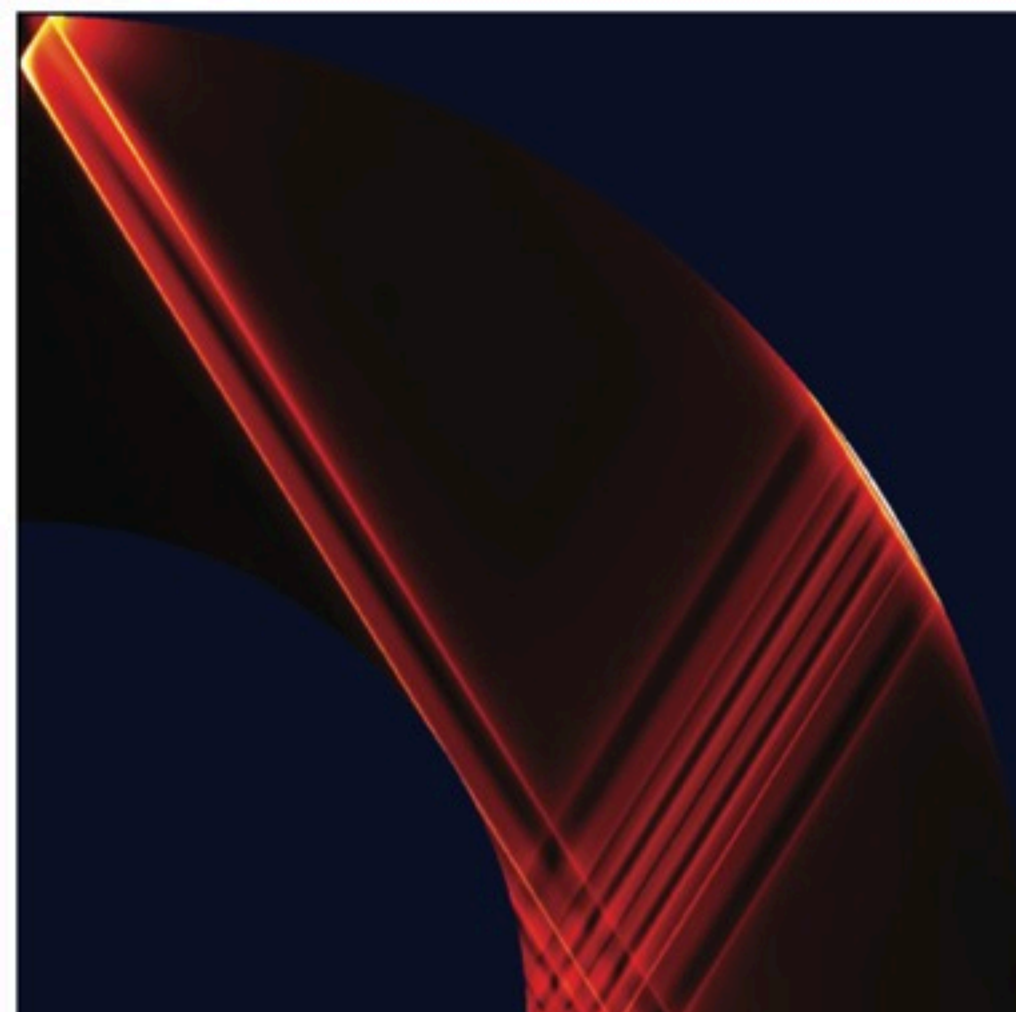
cored



core-less

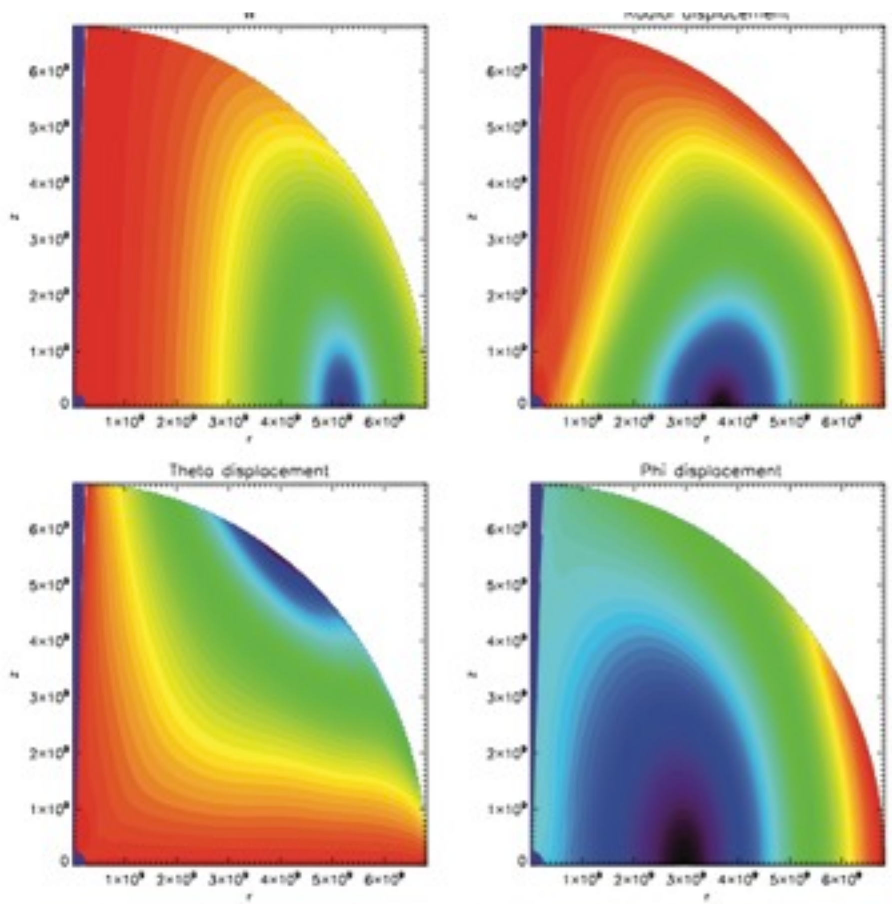



Wu '05a



Ogilvie & Lin '04

# Papaloizou & Ivanov '10




3. Contour plots for the real parts of the $m = 2$ Fourier components of $W$ (upper left panel), $\xi_r$ (upper right panel), $\xi_\phi$ (lower right panel) and $\xi_\theta$
nel) after $t = 2.523$ d for the model with $\eta = 4$ and $\Omega/\Omega_* = 0.36$. In this and other similar figures, lengths are expressed in cgs units. For n
$\times 10^9$.

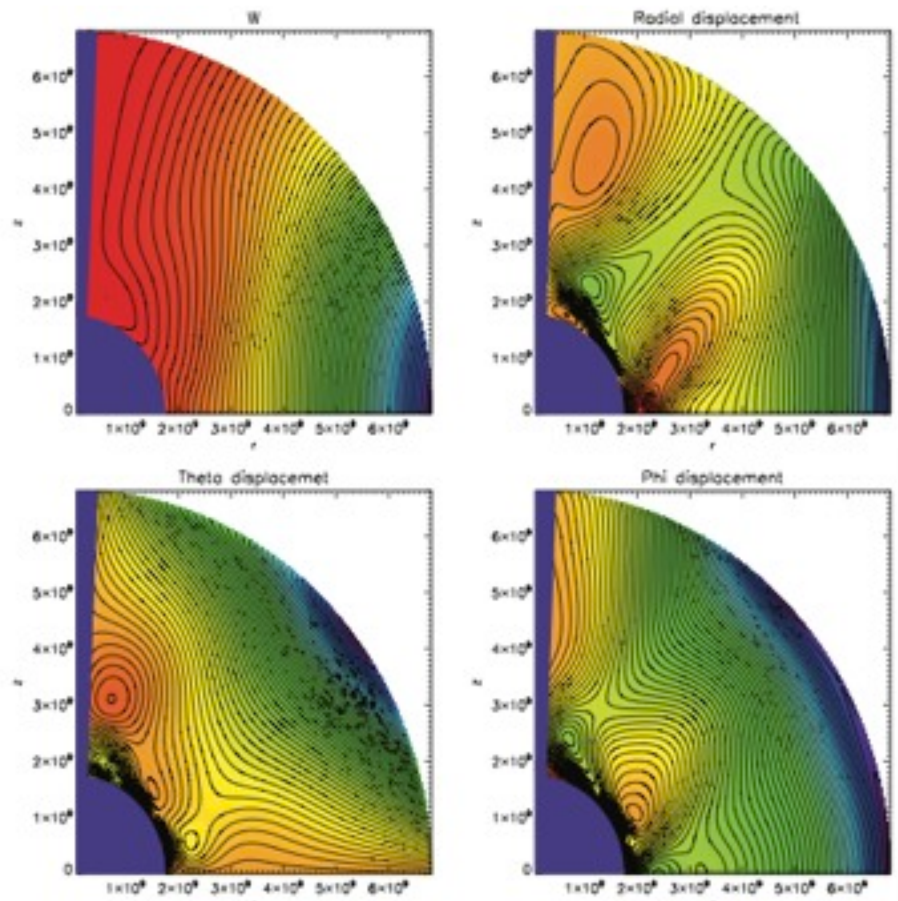



**Figure 9.** As in Fig. 3 but for a model with core radius of $0.25R_*$ and $\Omega/\Omega_* = 0.8$ after $t = 0.408$ d.

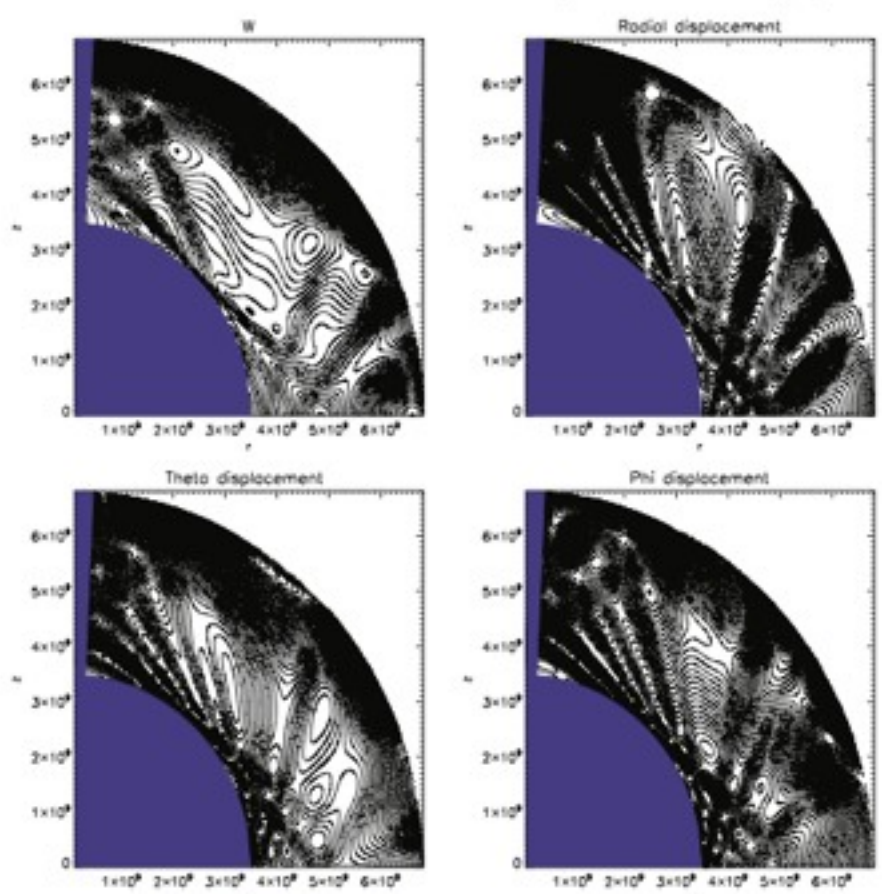
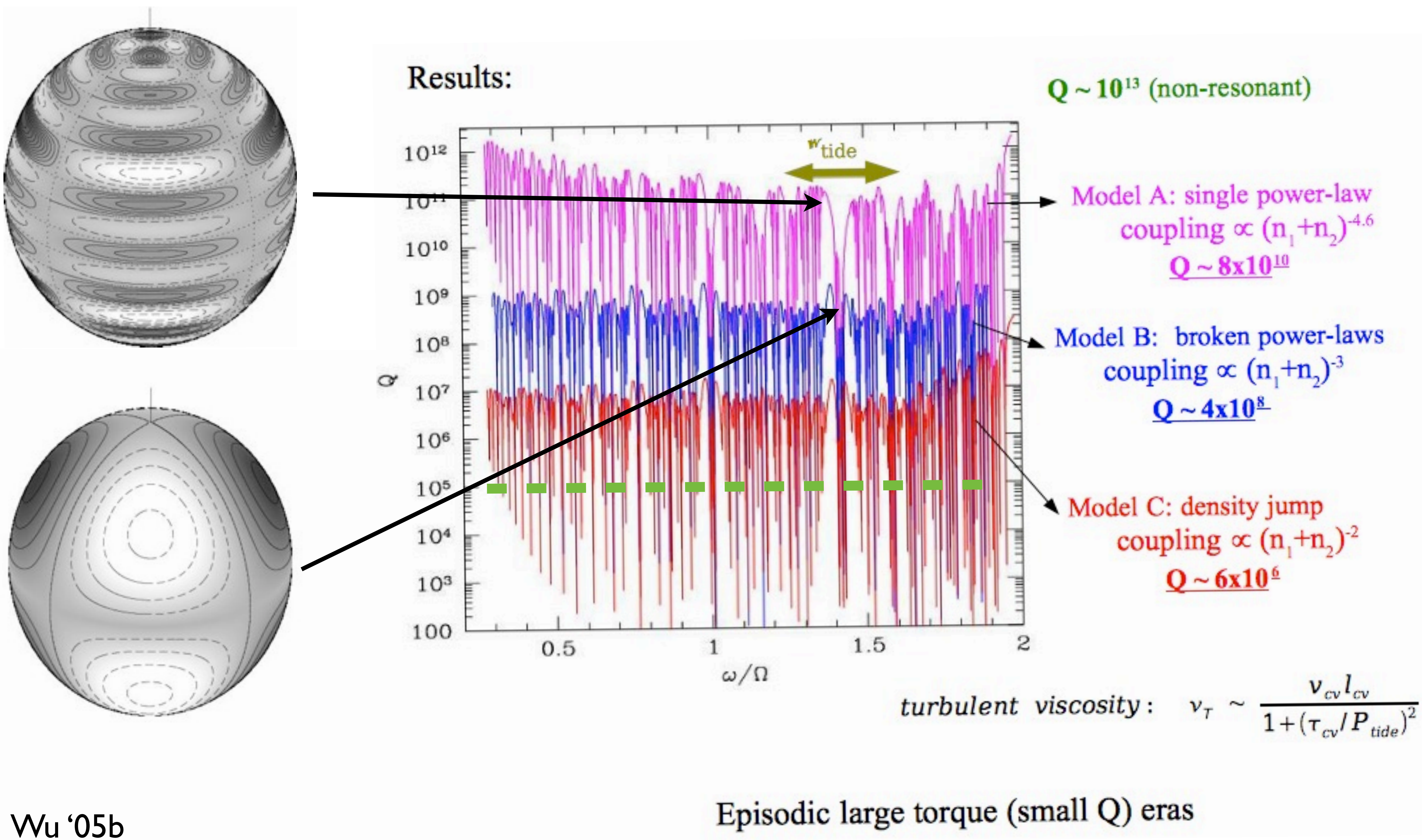
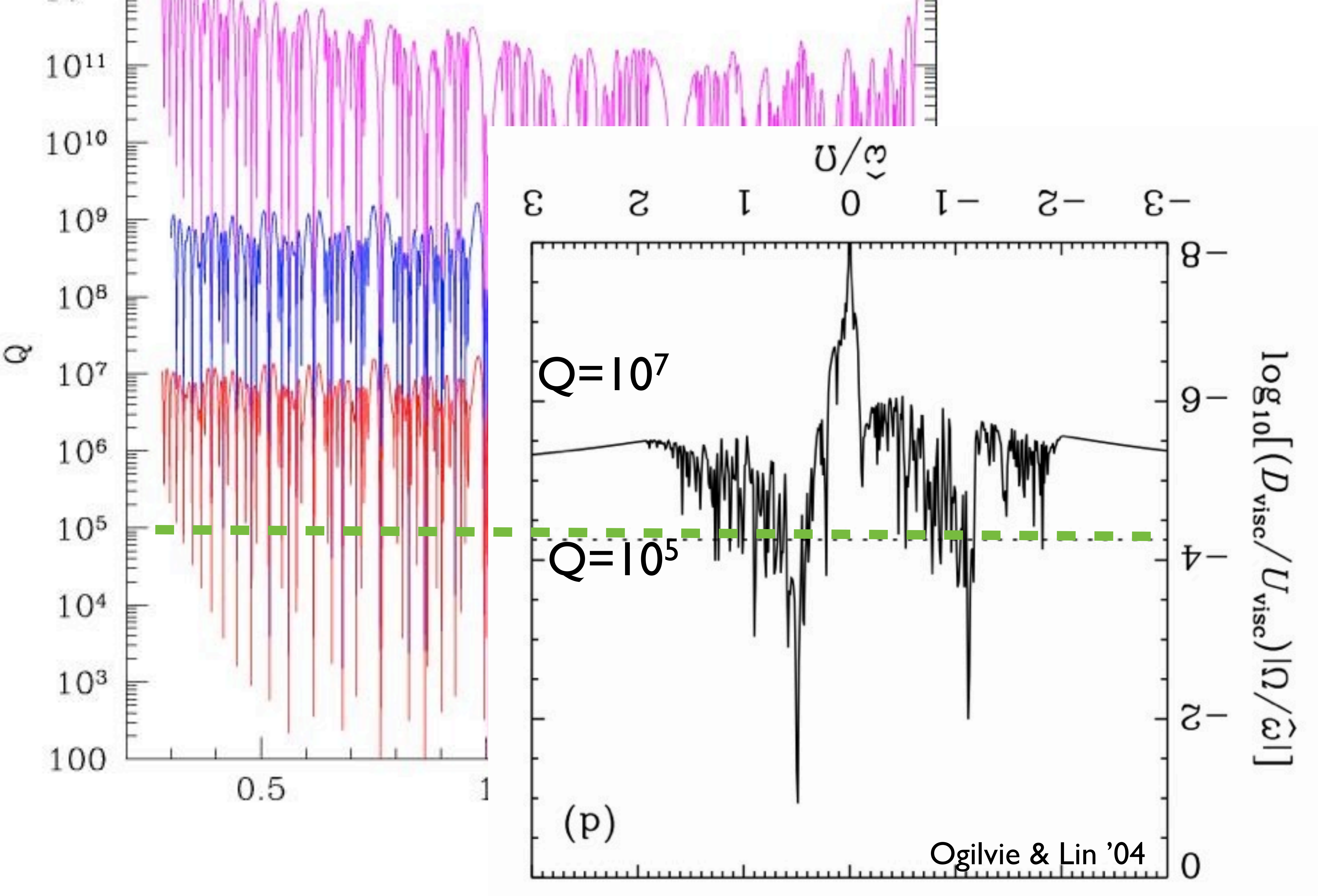



**Figure 13.** As in Fig. 10 but for the model with a core radius of $0.5R_*$ at $t = 0.589$ d.

# Coreless model:




Wu '05b



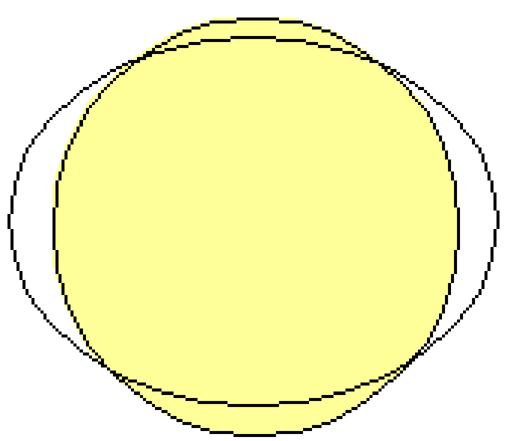

cored model: bigger dissipation? or numerics?

# Why do inertial waves fail?
## 1) spatial mismatch

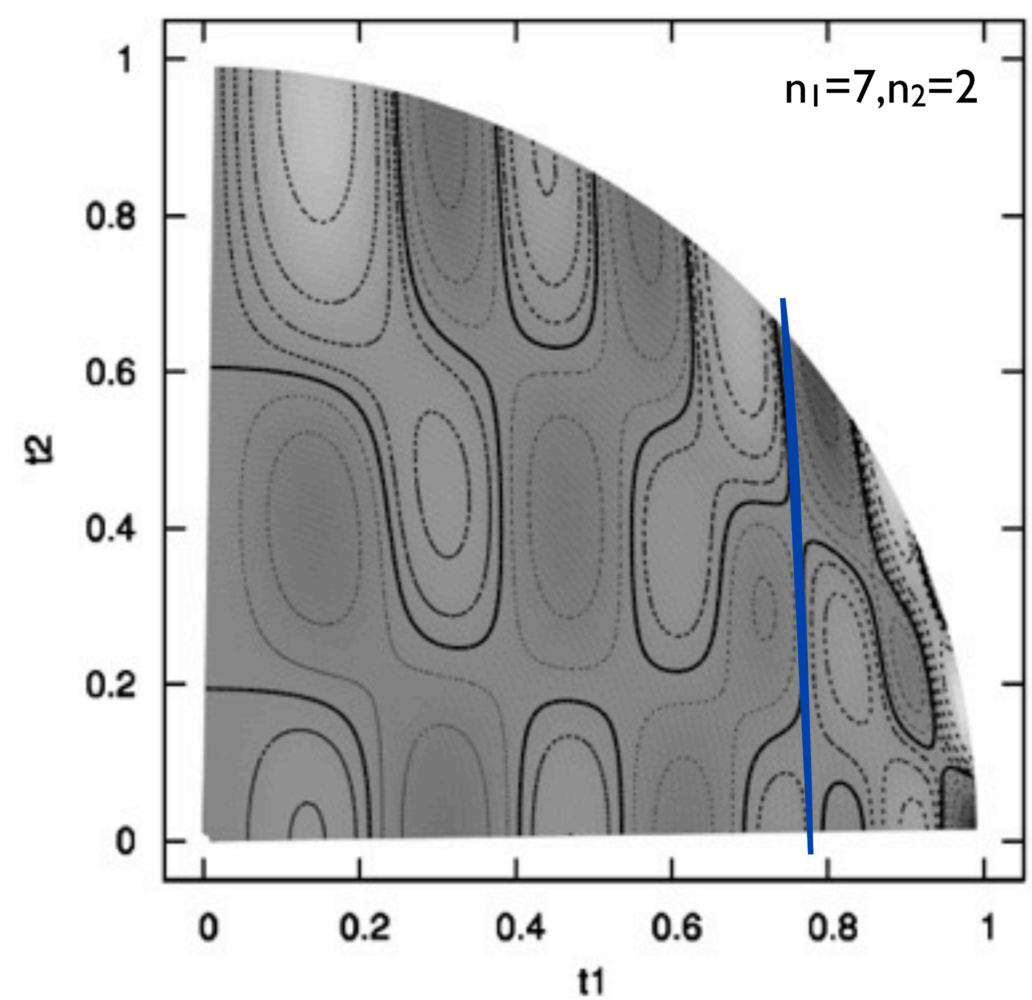
Tidal Overlap $E = -\int d^3r\, \delta\Phi_{\rm tide}\, \rho'$

tidal potential: long wavelength

$$\delta\Phi_{\rm tide} = -\frac{3GM}{a^3} r^2 \sin^2\theta \cos(2\phi + \omega_{\rm tide} t)$$



inertial waves: short wavelengths

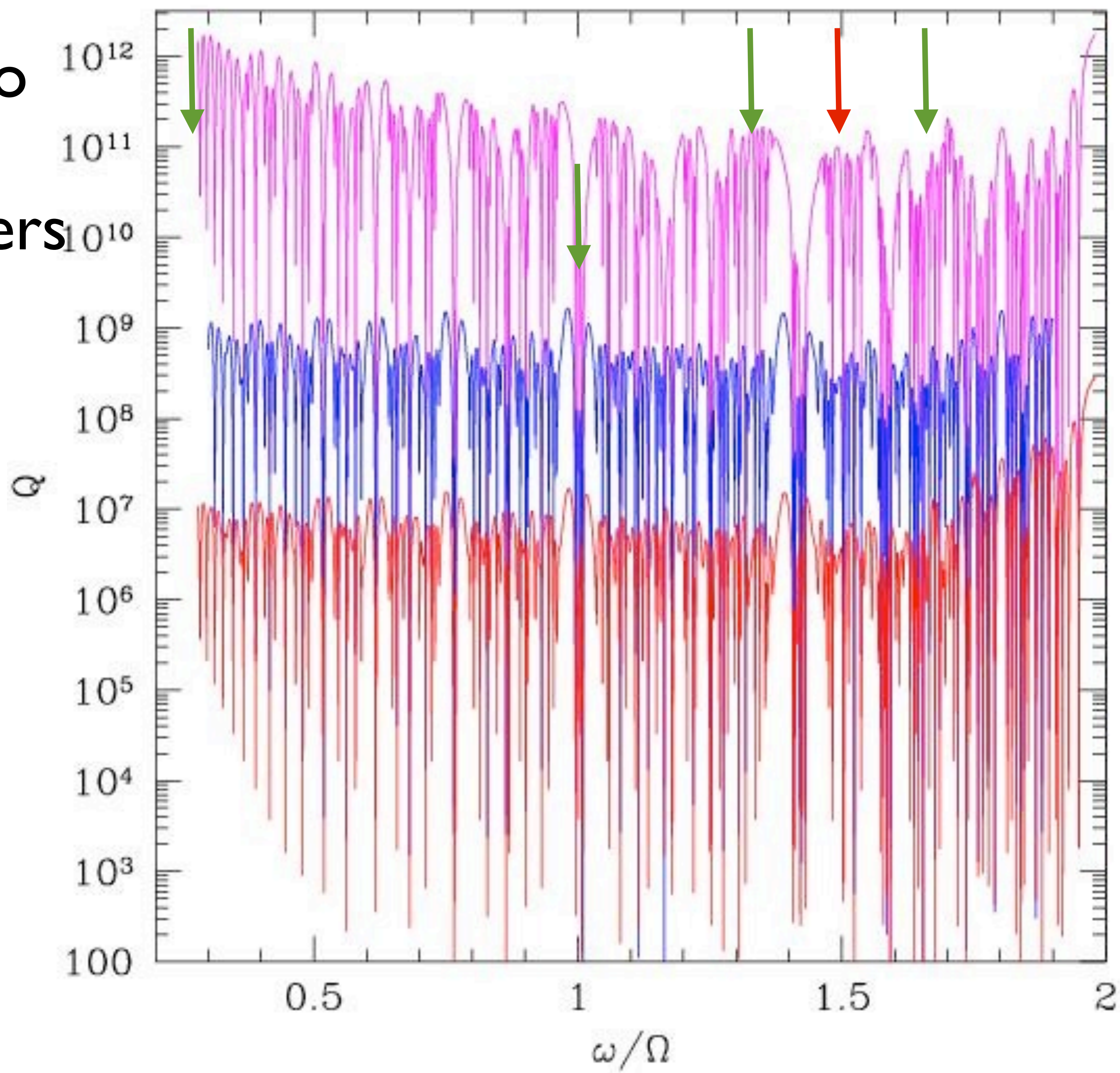



Pena & Wu 'in prep

# Why do inertial waves fail?
# 2) sweep through strong resonances too fast

Jupiter-Io

exo-jupiters



# Same failure for stellar tides

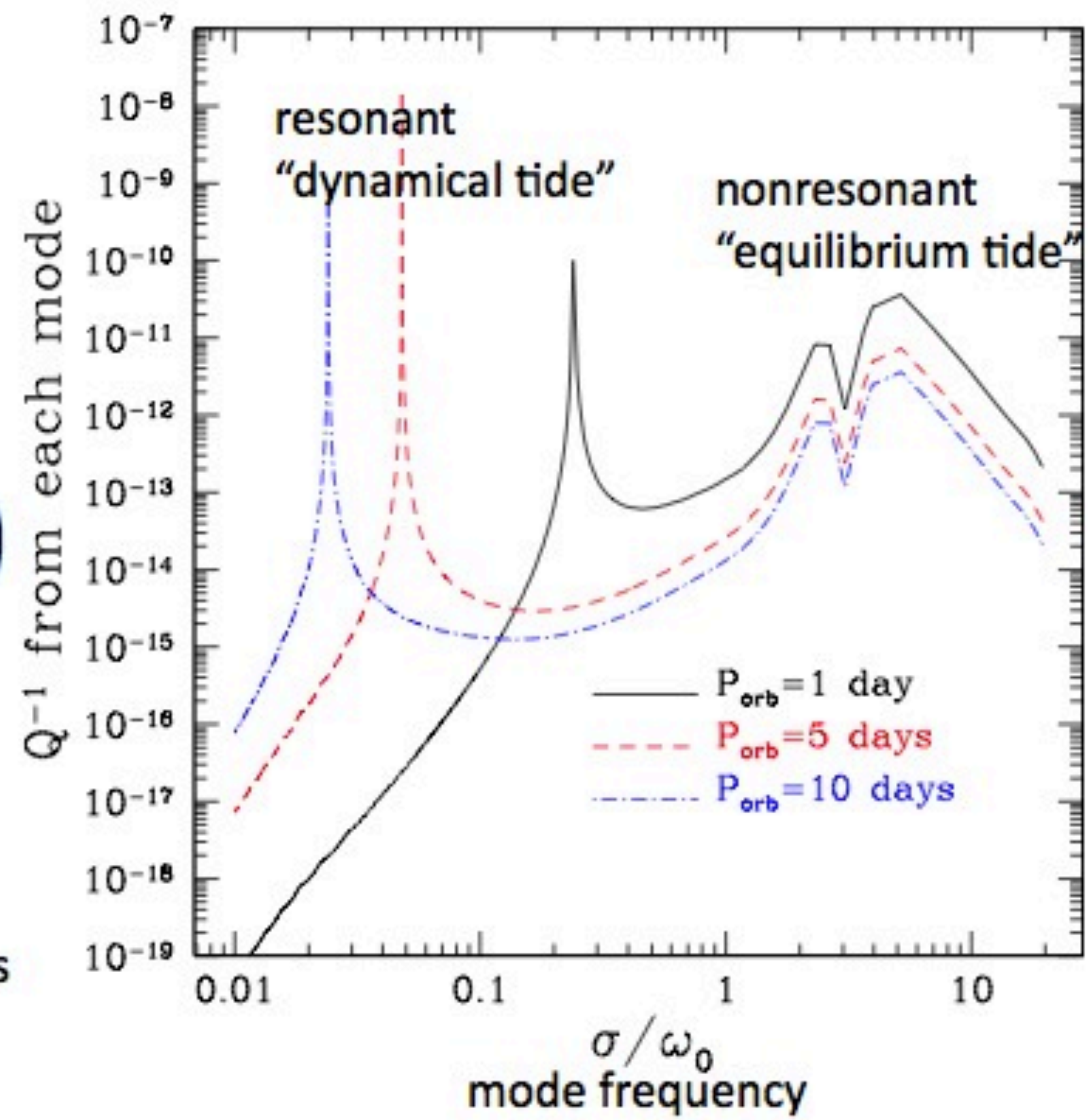
## Linear theory for tidal Q

Solar model.
Radiative diffusion + turbulent viscosity.

$$Q_{\mathrm{eq\ tide}} \sim 10^{10} \left( \frac{P_{\mathrm{orb}}}{1\ \mathrm{day}} \right)$$

$$Q_{\mathrm{dyn\ tide}} \sim 5 \times 10^{10} \left( \frac{1\ \mathrm{day}}{P_{\mathrm{orb}}} \right)^{4/3}$$

$$t_{\mathrm{decay,dyn}} > 100\ \mathrm{Gyr} \left( \frac{\mathrm{M_J}}{\mathrm{M_p}} \right)$$




Decay time very long, but....

beware! This same theory under-predicts rate for solar-type binaries.

(talk by Arras)

# Summary:

- strong evidences for tidal dissipation in giant planets
- inertial waves fail to explain $Q \sim 10^5$
- failure understood:
  weak coupling between tide and waves
  quick sweeping through resonances
- but future path not
  locking, B, $A^2$, $\nabla\Omega$, $\nabla S$

# KOI 54 (Welsh et al '11, Fuller & Lai '11, Buckart et al '11)

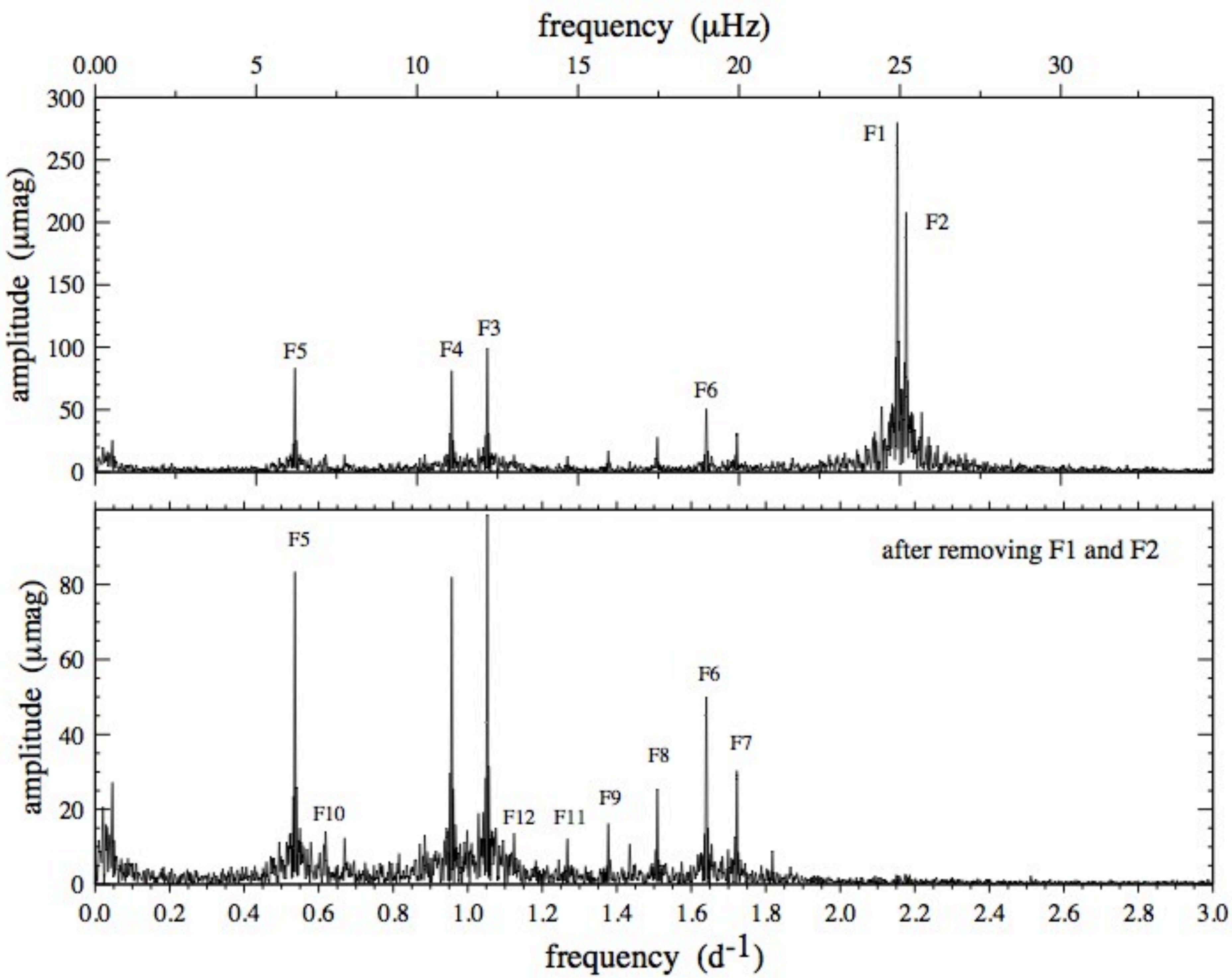
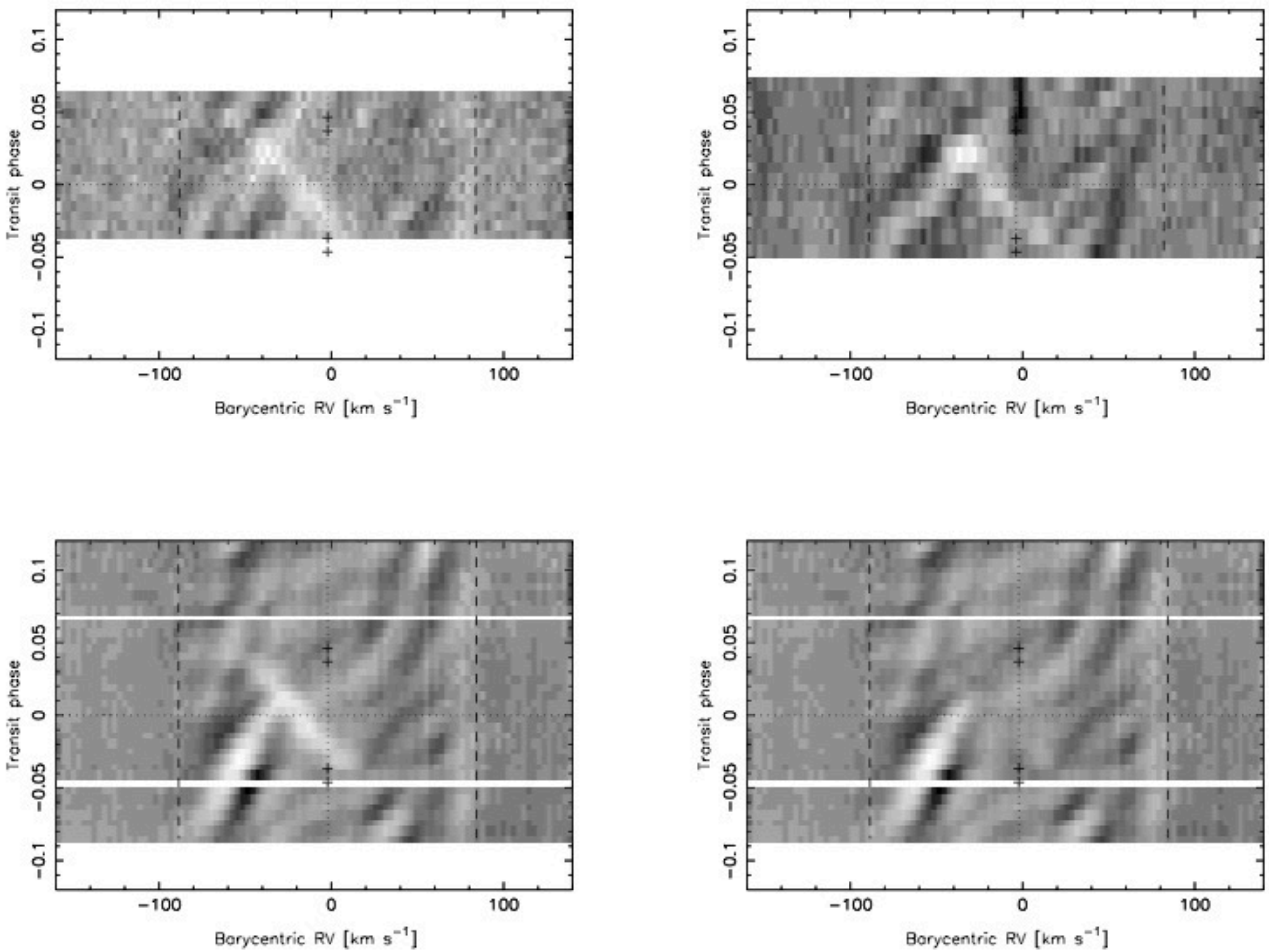



Fig. 5.— Power (amplitude) spectrum of the pulsation-only light curve, with the largest pulsations labeled. The bottom panel shows the power spectrum after prewhitening by removing the two dominant pulsation F1 and F2.

# WASP-33 (Cameron et al '11)

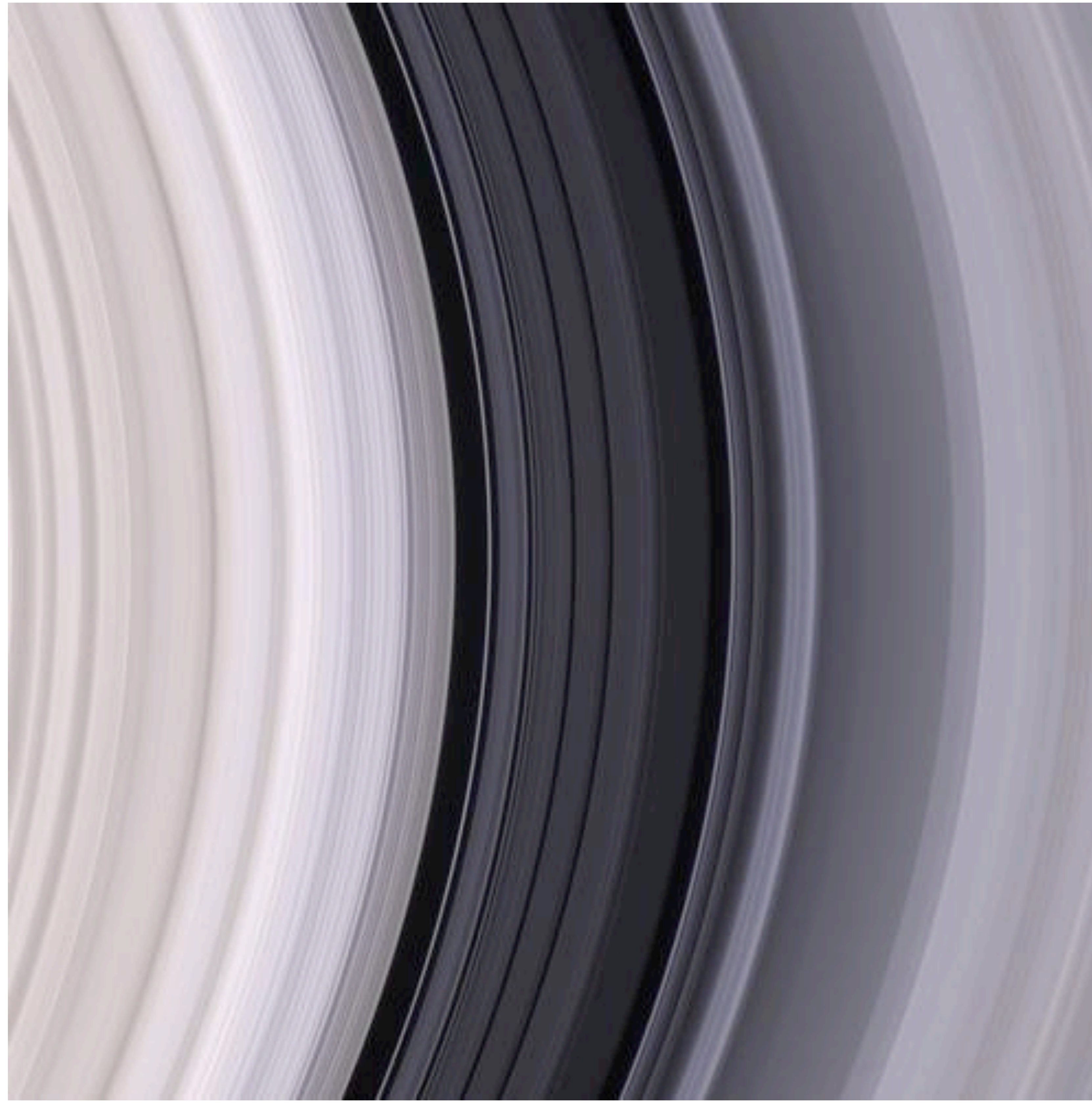



igure 4. Time series of the residual average spectral line profile of HD 15082 during the transits of 2008 October 18 at Tautenburg pper left); 2008 November 11/12 at McDonald (upper right); and 2009 December 8 at the NOT (lower left). Wavelength or radial

# More data!

## Hope for detecting internal waves in giant planets

mass resolution $1/10^{17}$
freq. resolution $1/10^{6}$

a natural seismometer