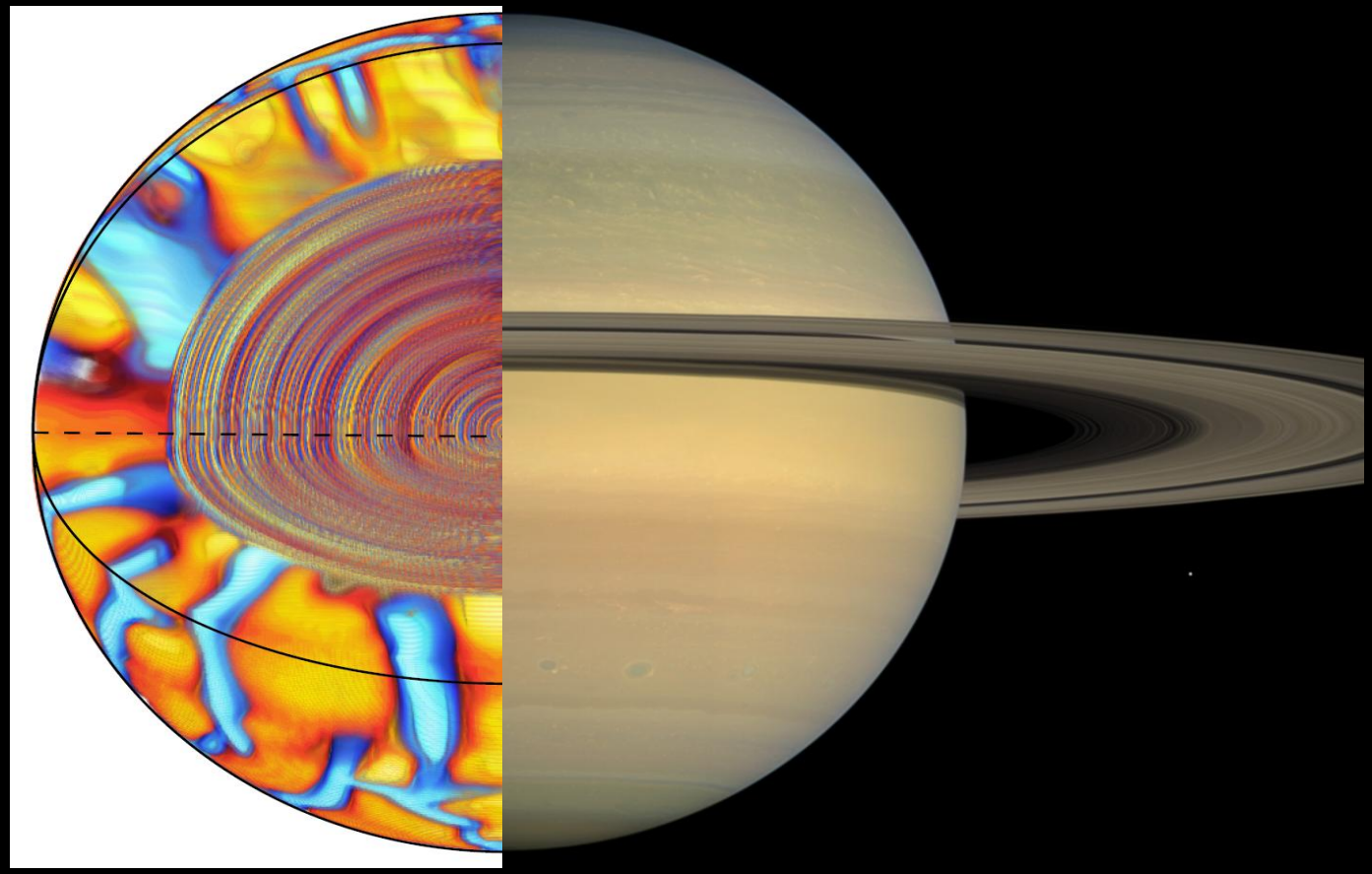
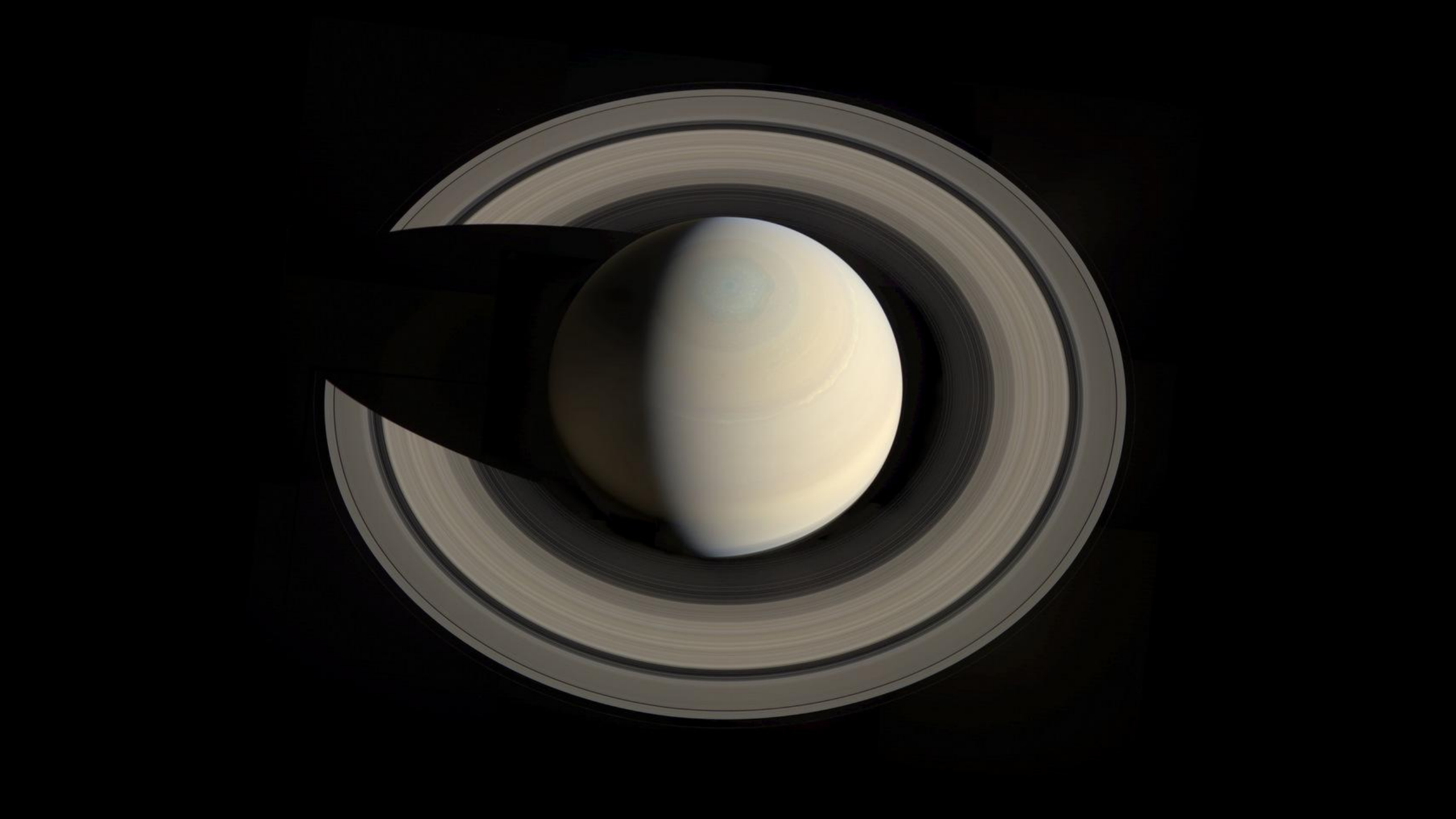
New Frontiers in Seismology

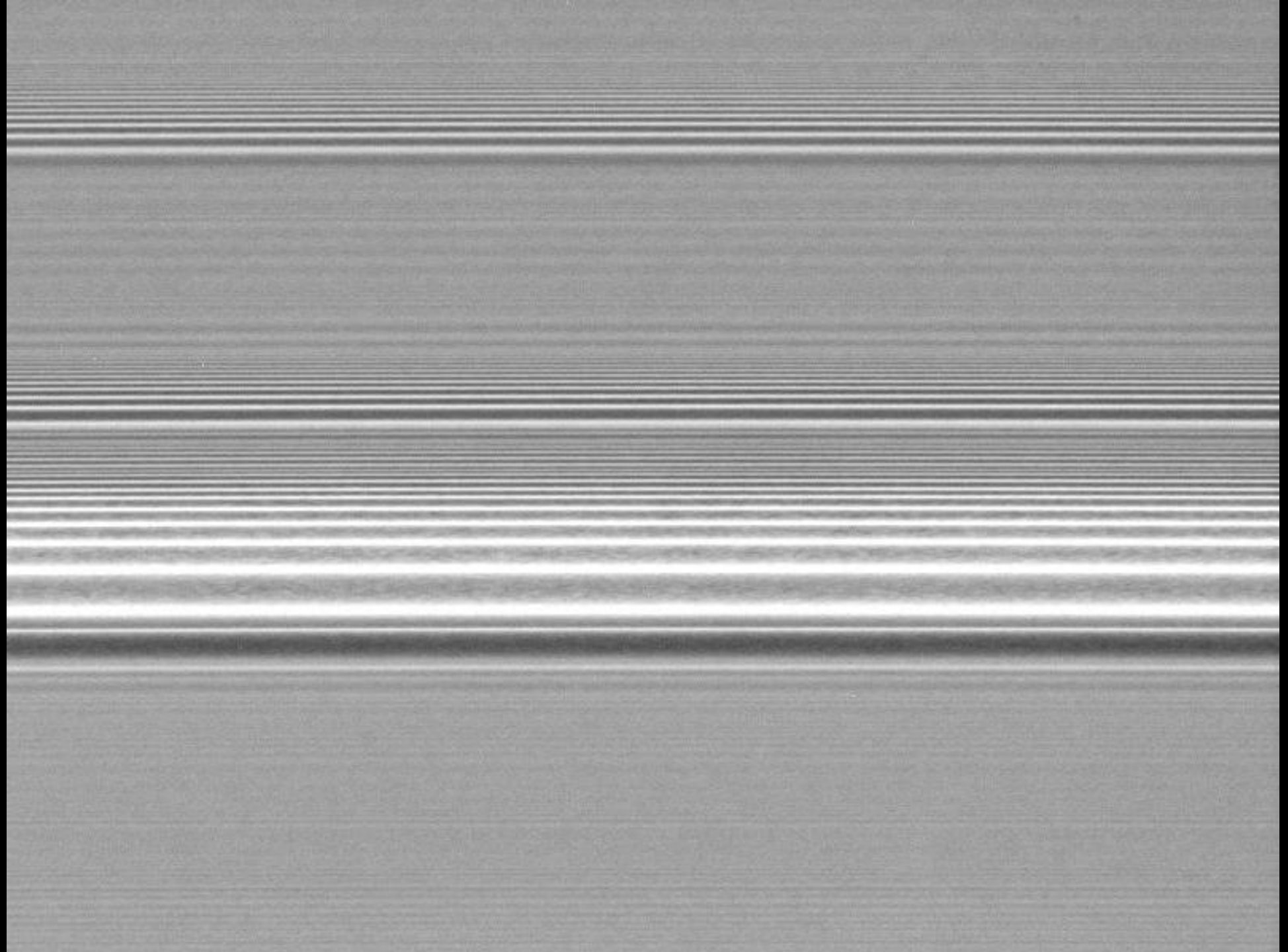
Jim Fuller

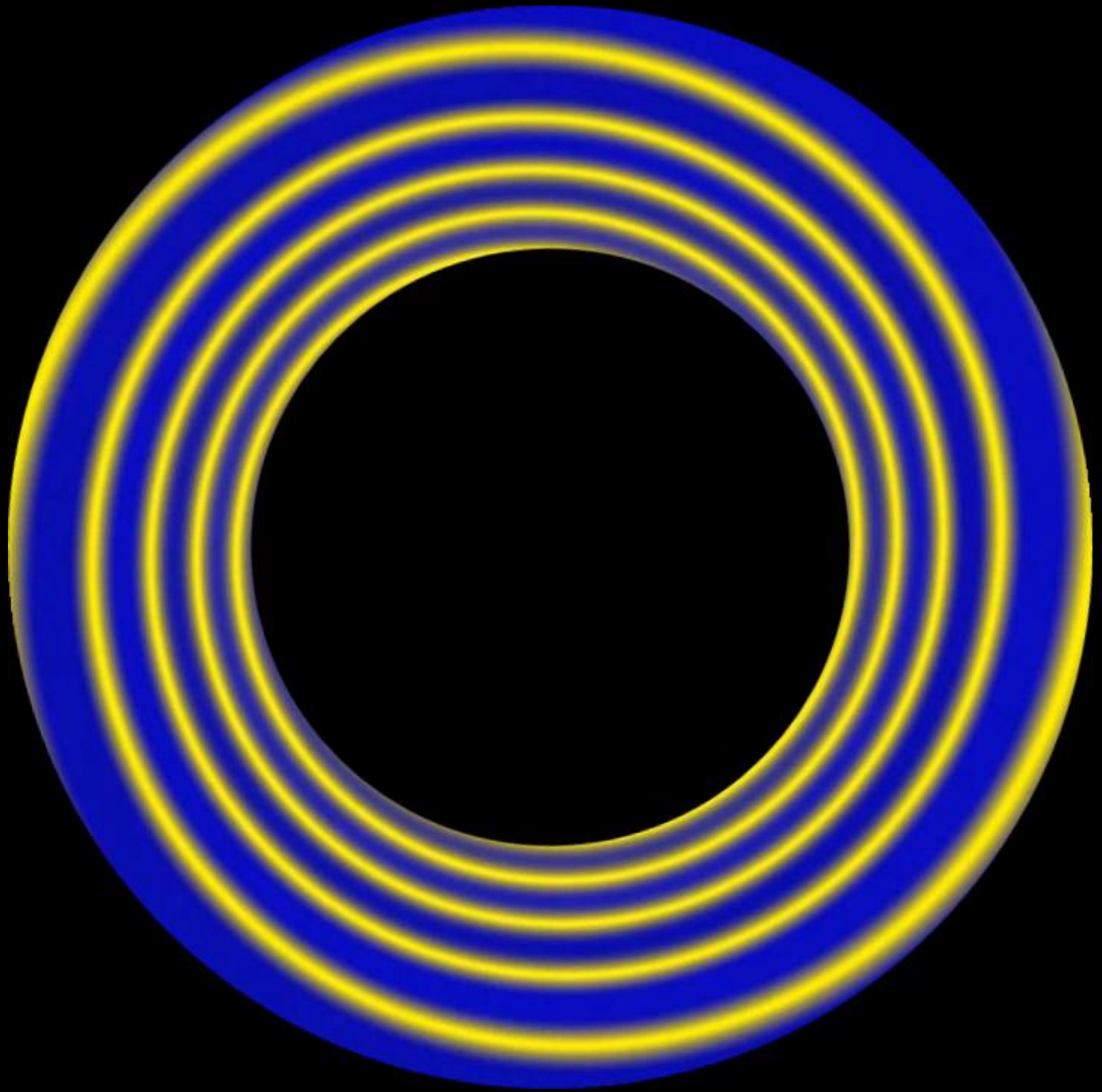
Caltech/KITP



Credits: Matt Hedman, Phil Nicholson, Mark Marley, Carolyn Porco







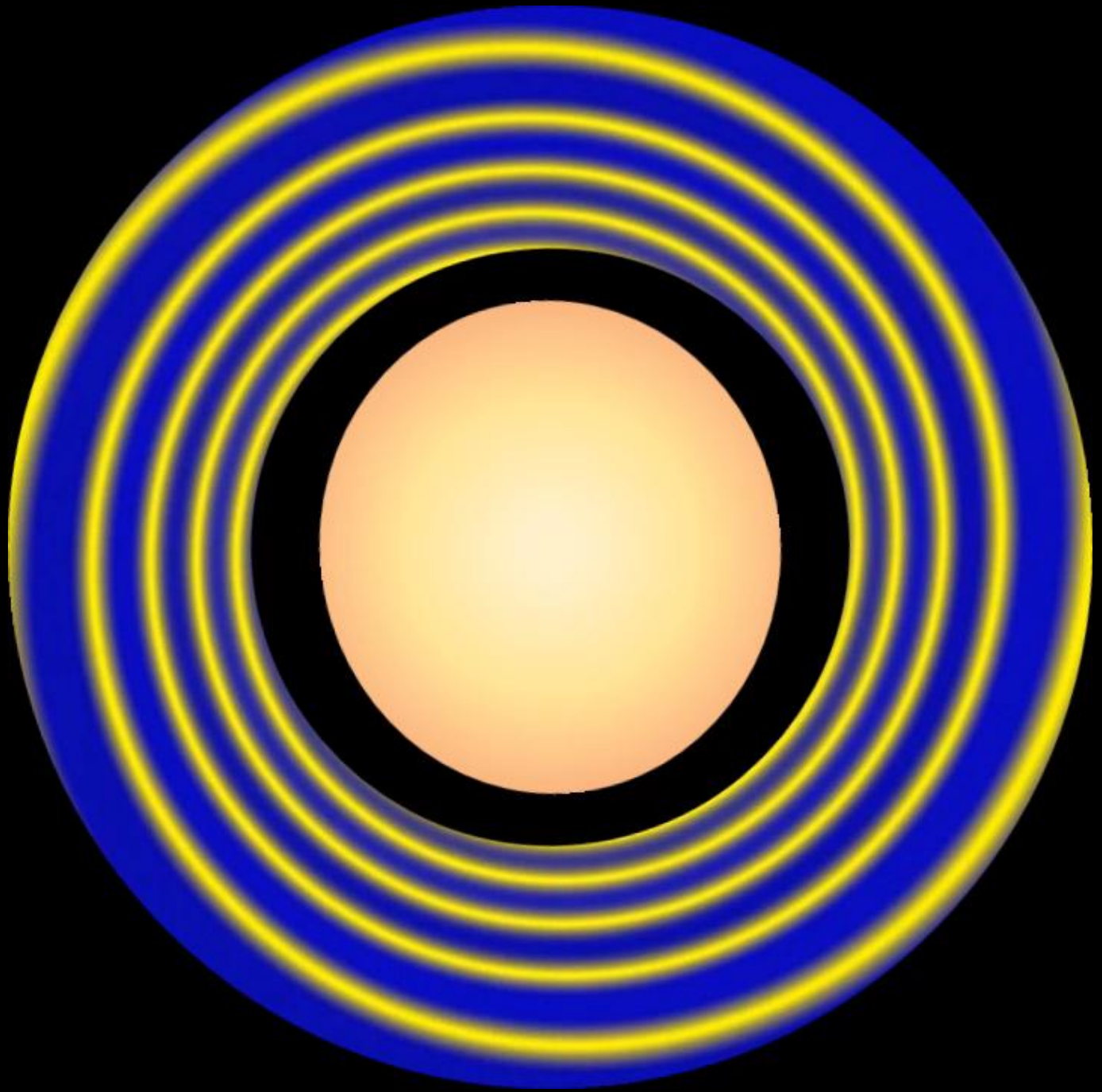
Wave Excitation

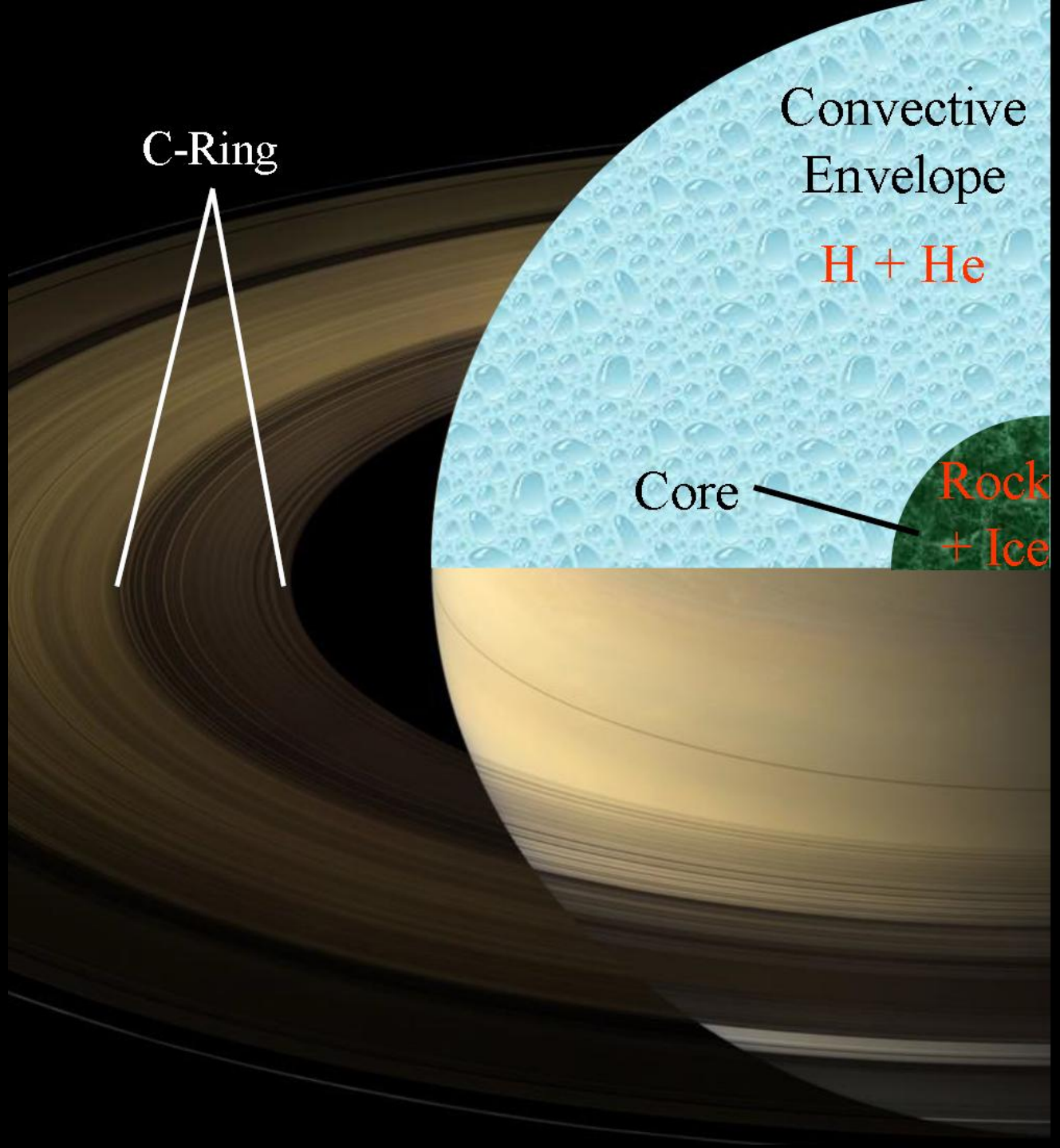
- Waves excited at Lindblad resonances

$$m(\Omega - \Omega_p) = \kappa$$

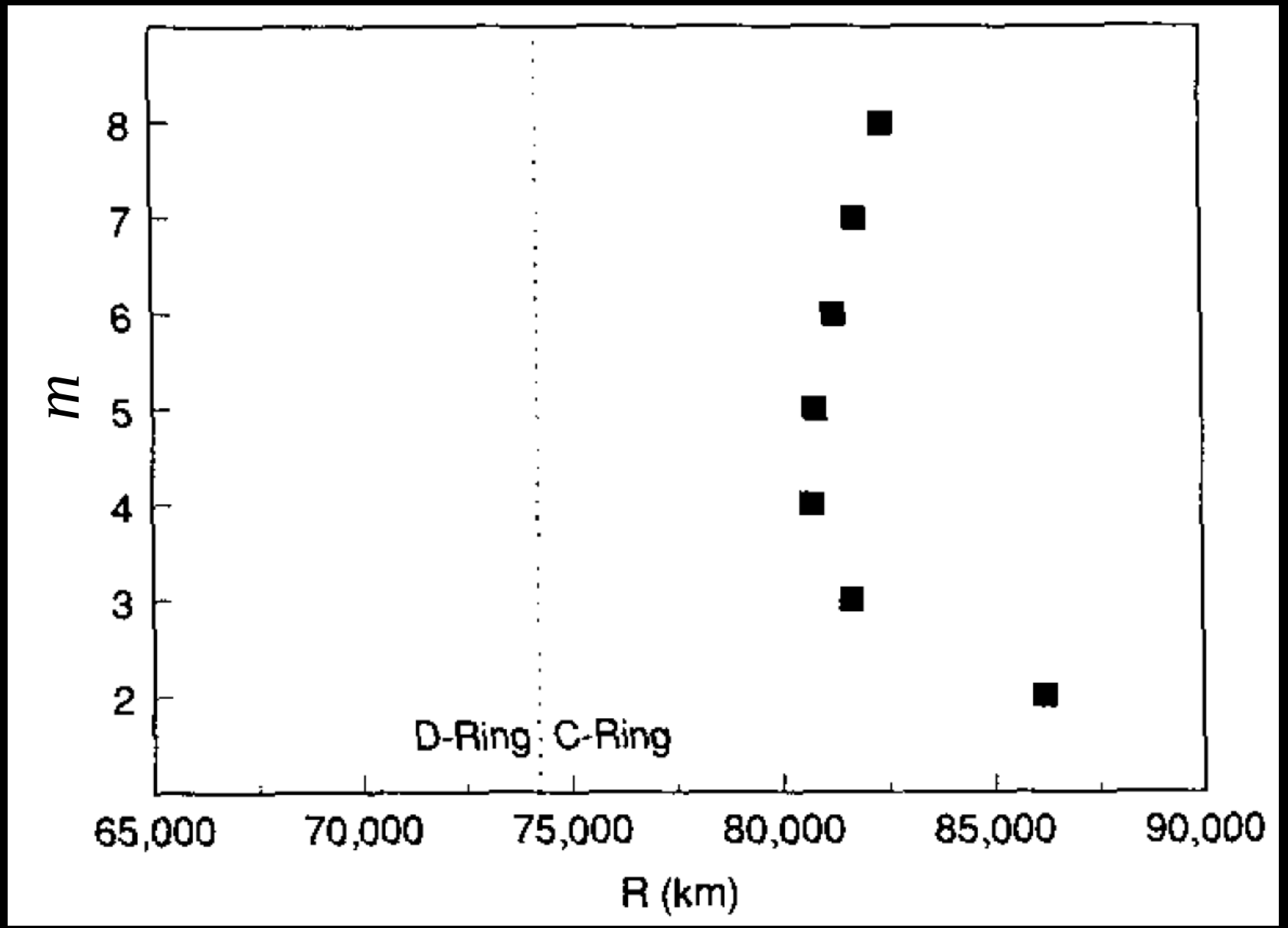
- Wave frequency tells us mode frequency

$$\Omega_p = -\sigma_\alpha / m$$



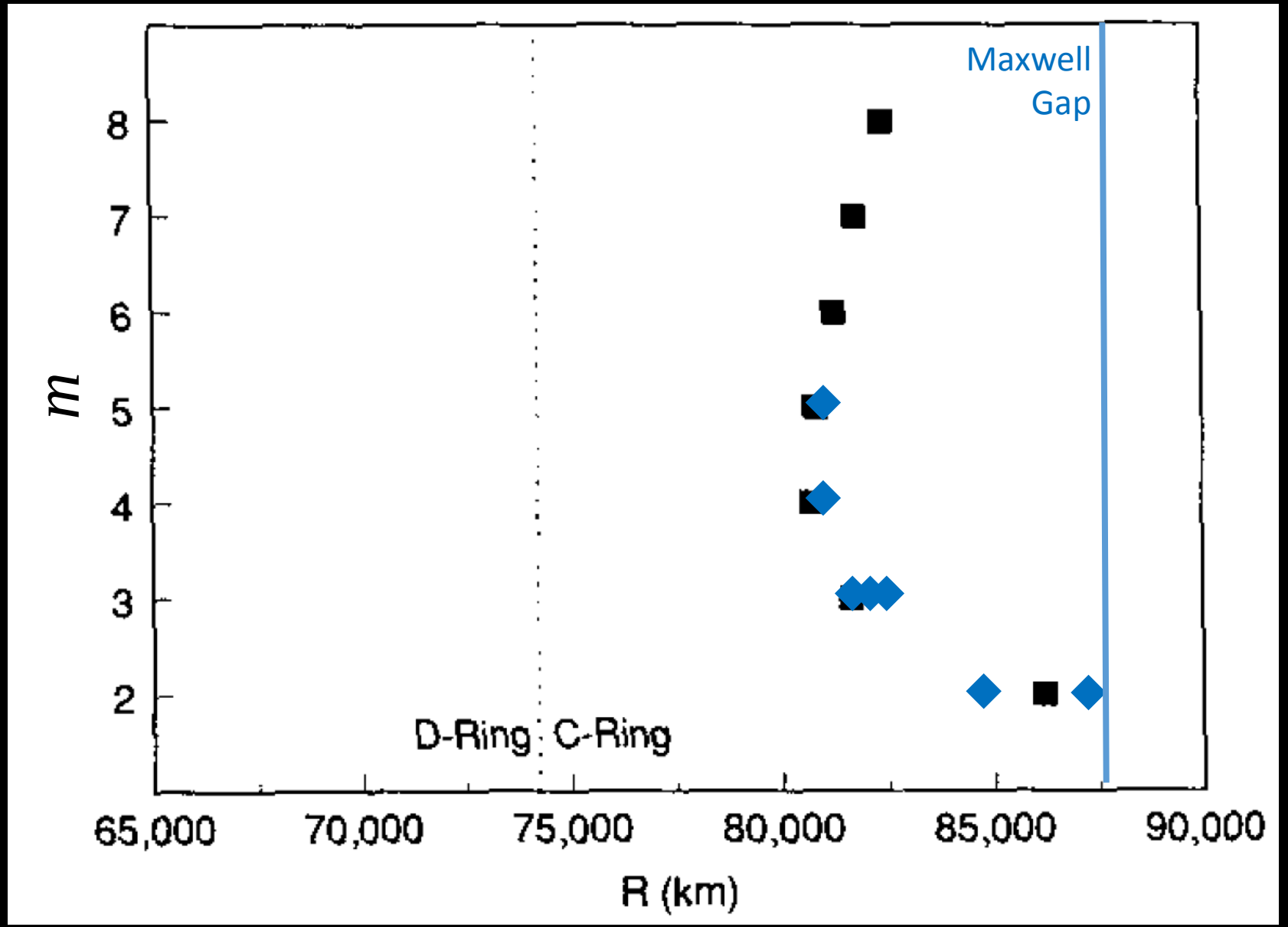

C-Ring
Convective
Envelope
H + He
Core
Rock
+ Ice

Predicted:

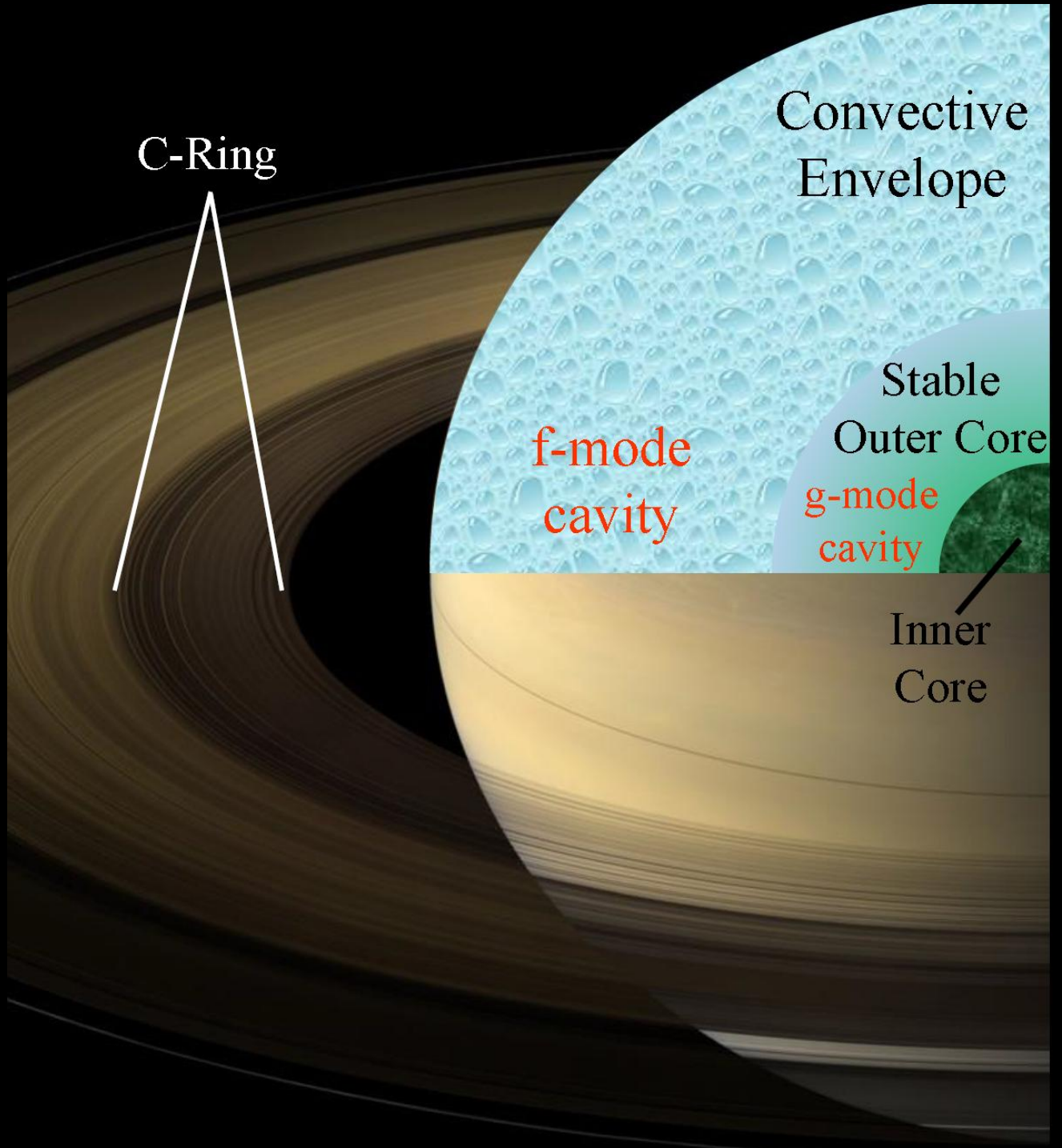


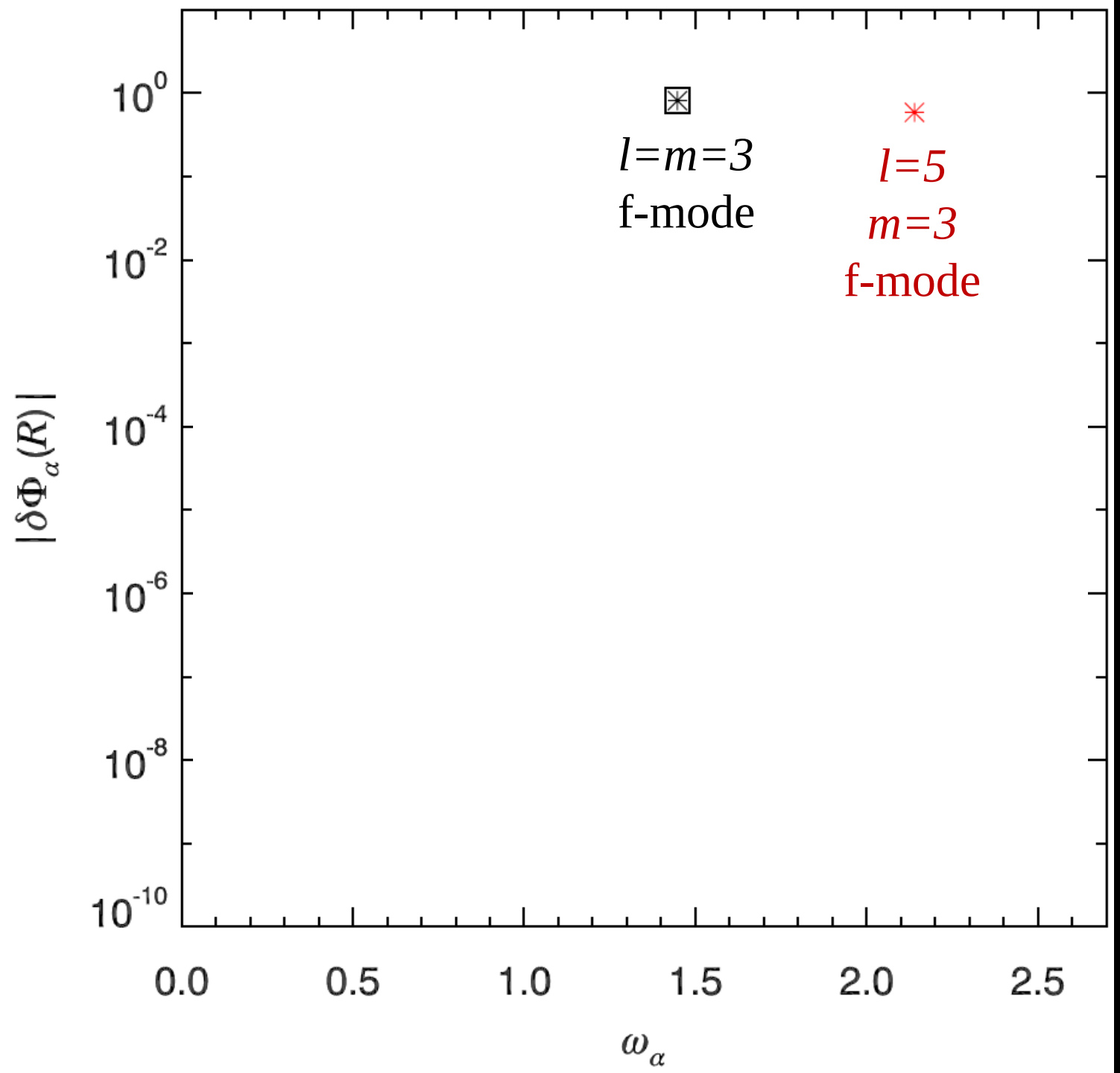
Marley & Porco 1993

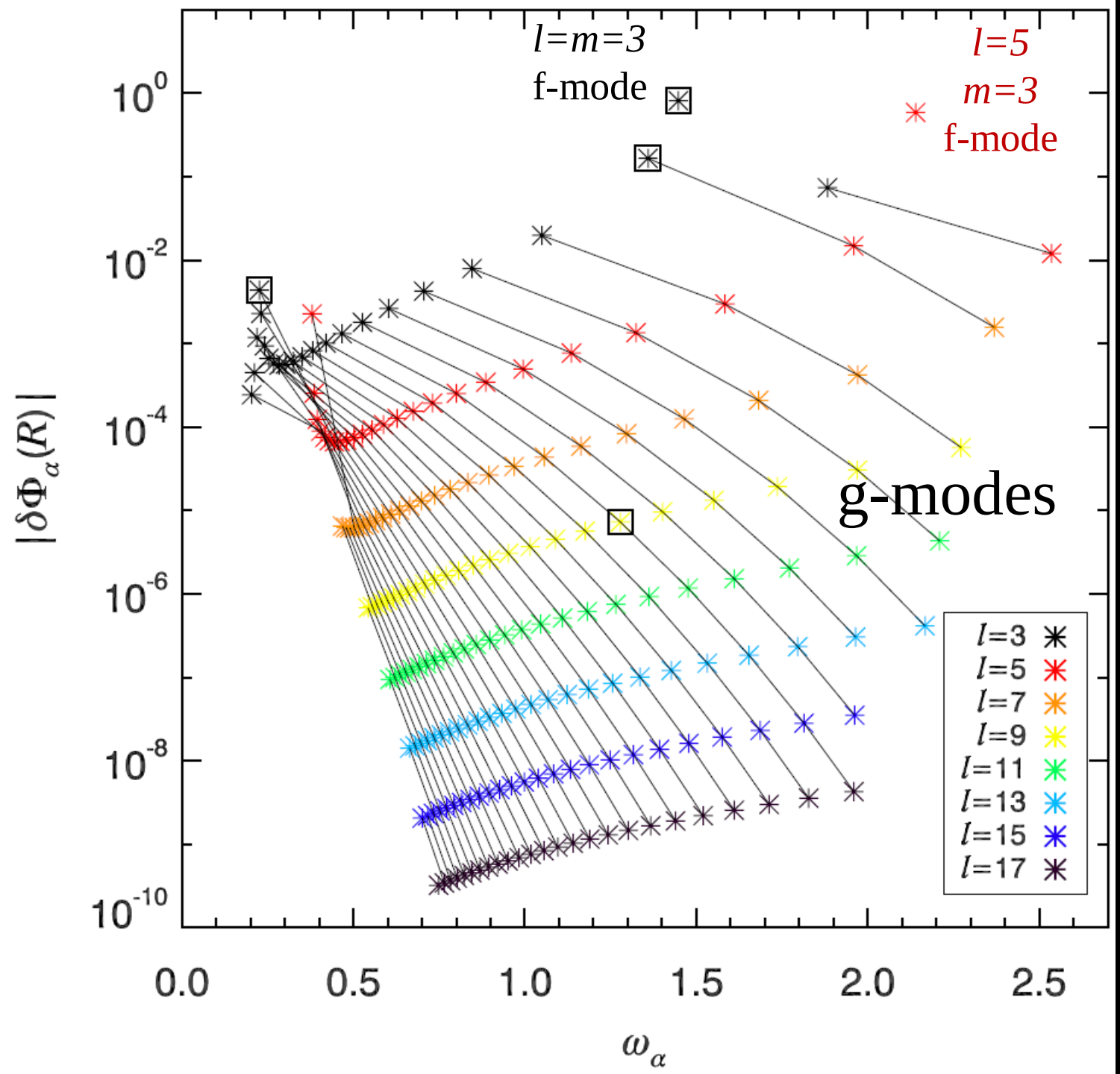
Observed:

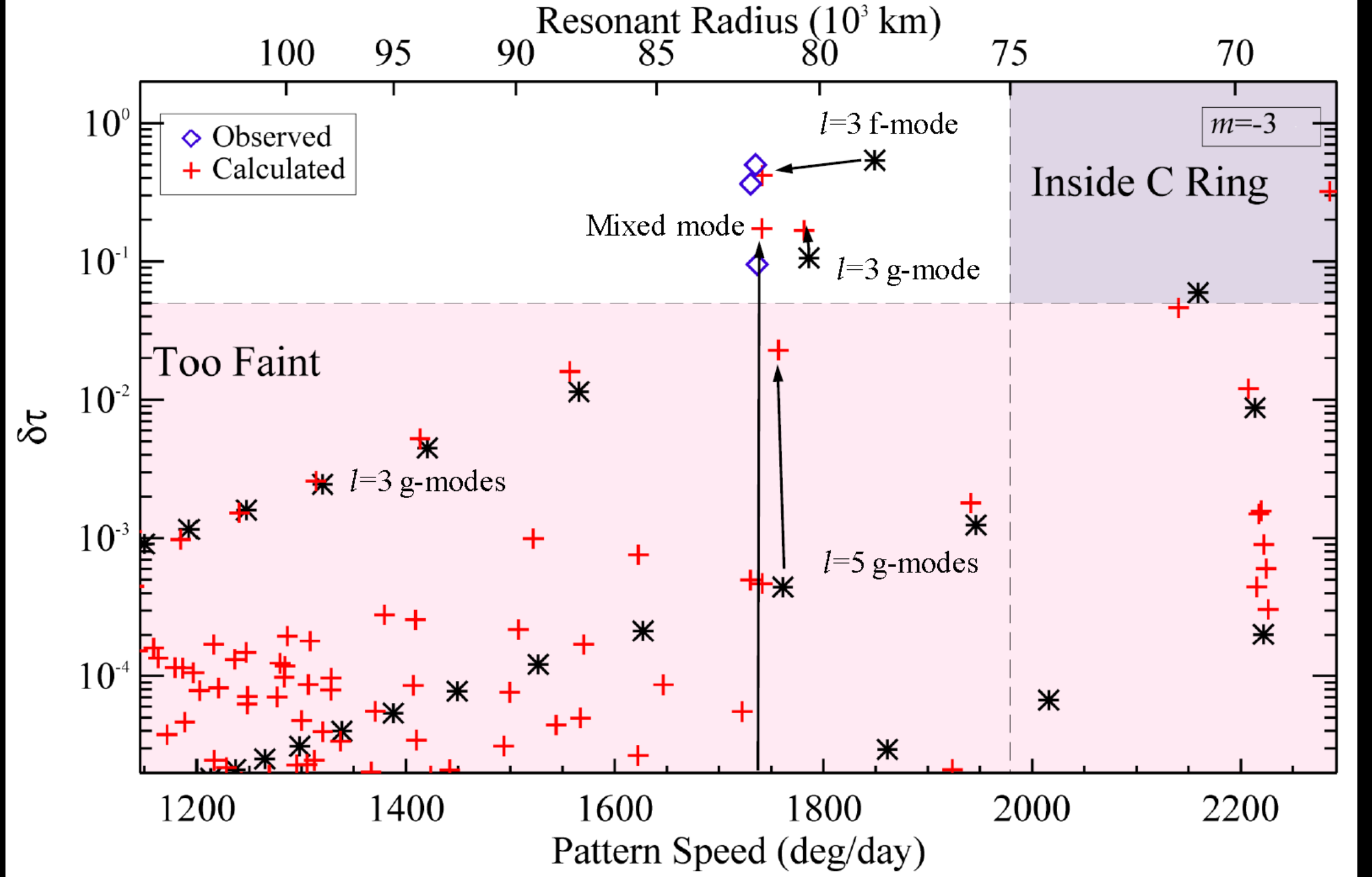


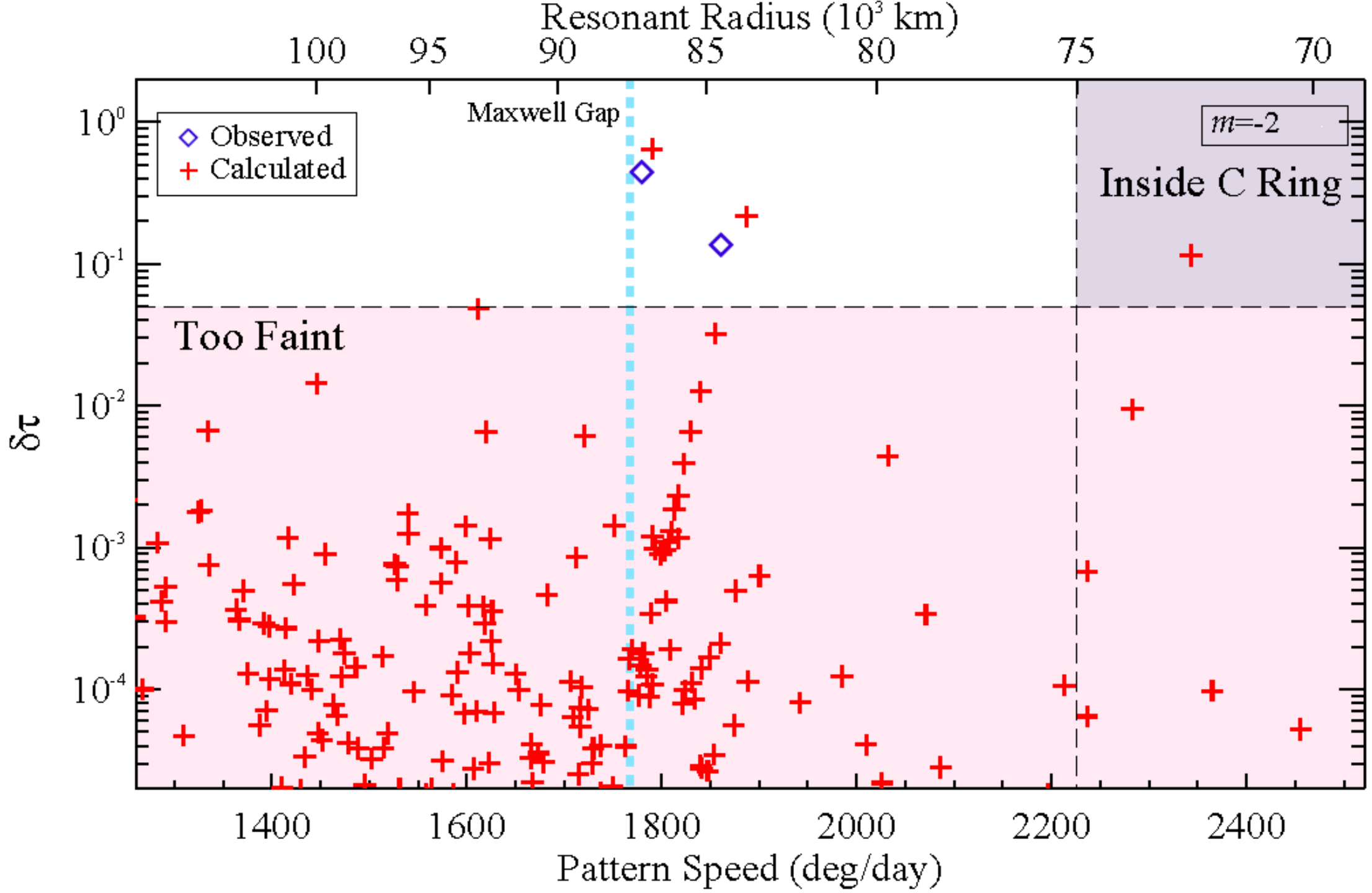
Marley & Porco 1993


C-Ring
Convective
Envelope
Stable
Outer Core
f-mode
cavity
g-mode
cavity
Inner
Core


10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$|\delta\Phi_\alpha(R)|$
0.0
0.5
1.0
1.5
2.0
2.5
ω_α
$l=m=3$
f-mode
$l=5$
$m=3$
f-mode


l=m=3
f-mode
l=5
m=3
f-mode
g-modes
$|\delta\Phi_\alpha(R)|$
ω_α
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0.0
0.5
1.0
1.5
2.0
2.5
l=3
l=5
l=7
l=9
l=11
l=13
l=15
l=17


Resonant Radius (10^3 km)
100
95
90
85
80
75
70
Observed
Calculated
l=3 f-mode
m=-3
Inside C Ring
Mixed mode
l=3 g-mode
Too Faint
l=3 g-modes
l=5 g-modes
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\delta\tau$
1200
1400
1600
1800
2000
2200
Pattern Speed (deg/day)

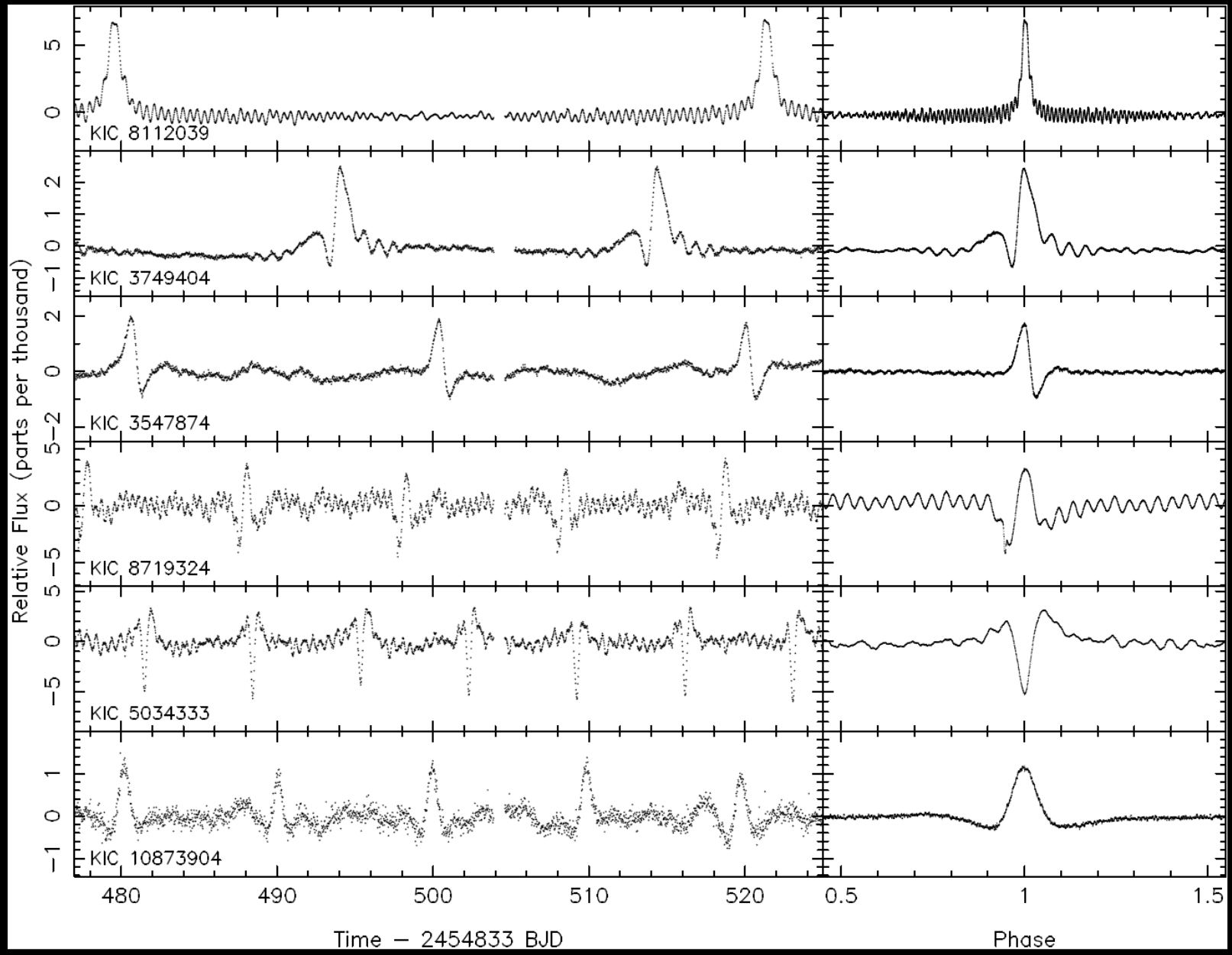

Resonant Radius (10^3 km)
100
95
90
85
80
75
70
Maxwell Gap
Observed
Calculated
m=-2
Inside C Ring
Too Faint
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
δτ
1400
1600
1800
2000
2200
2400
Pattern Speed (deg/day)

Conclusions

- Evidence for stable stratification (non-adiabatic interior) of Saturn

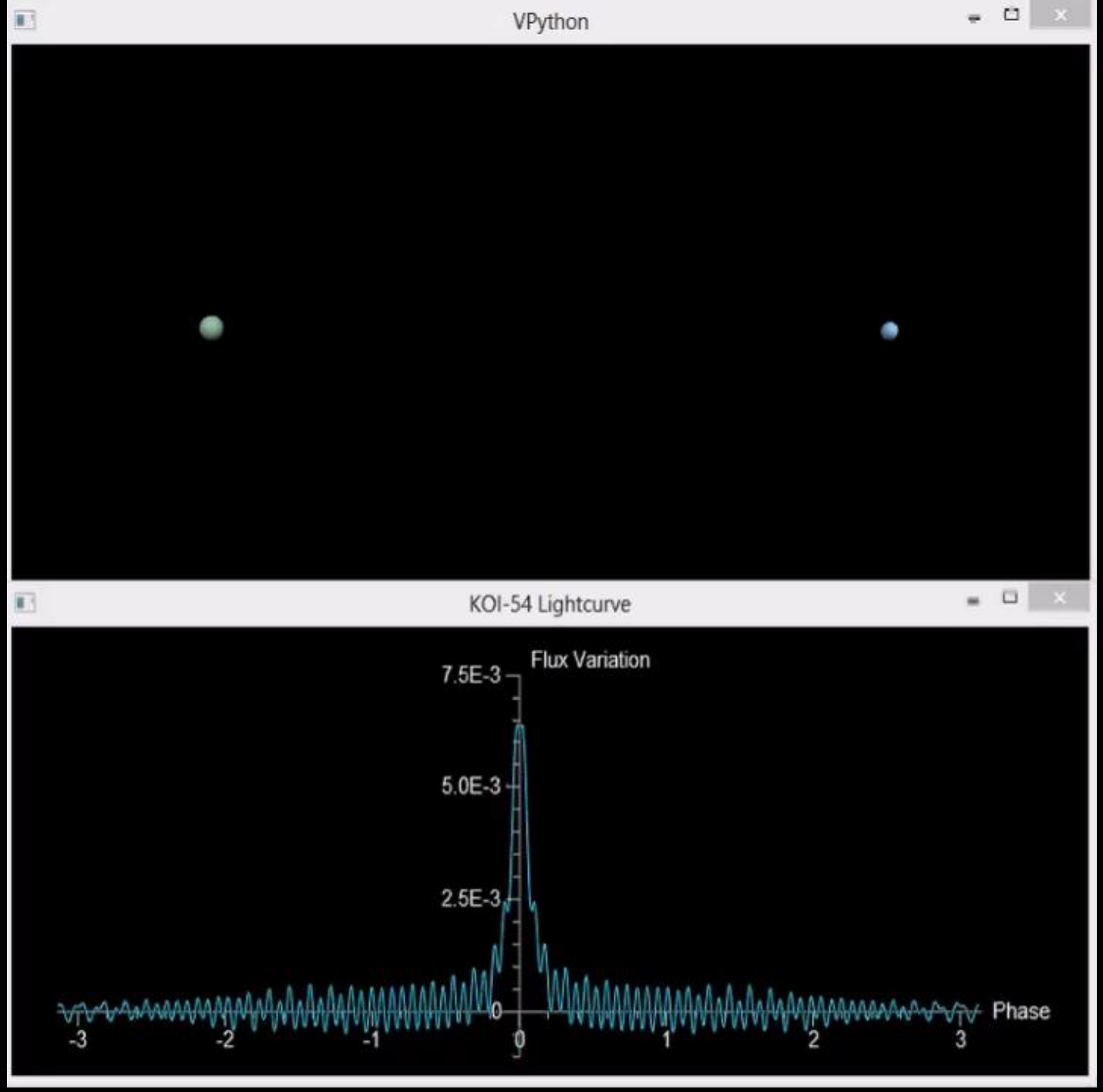
- Missing ingredient: Differential rotation? Layered Convection?

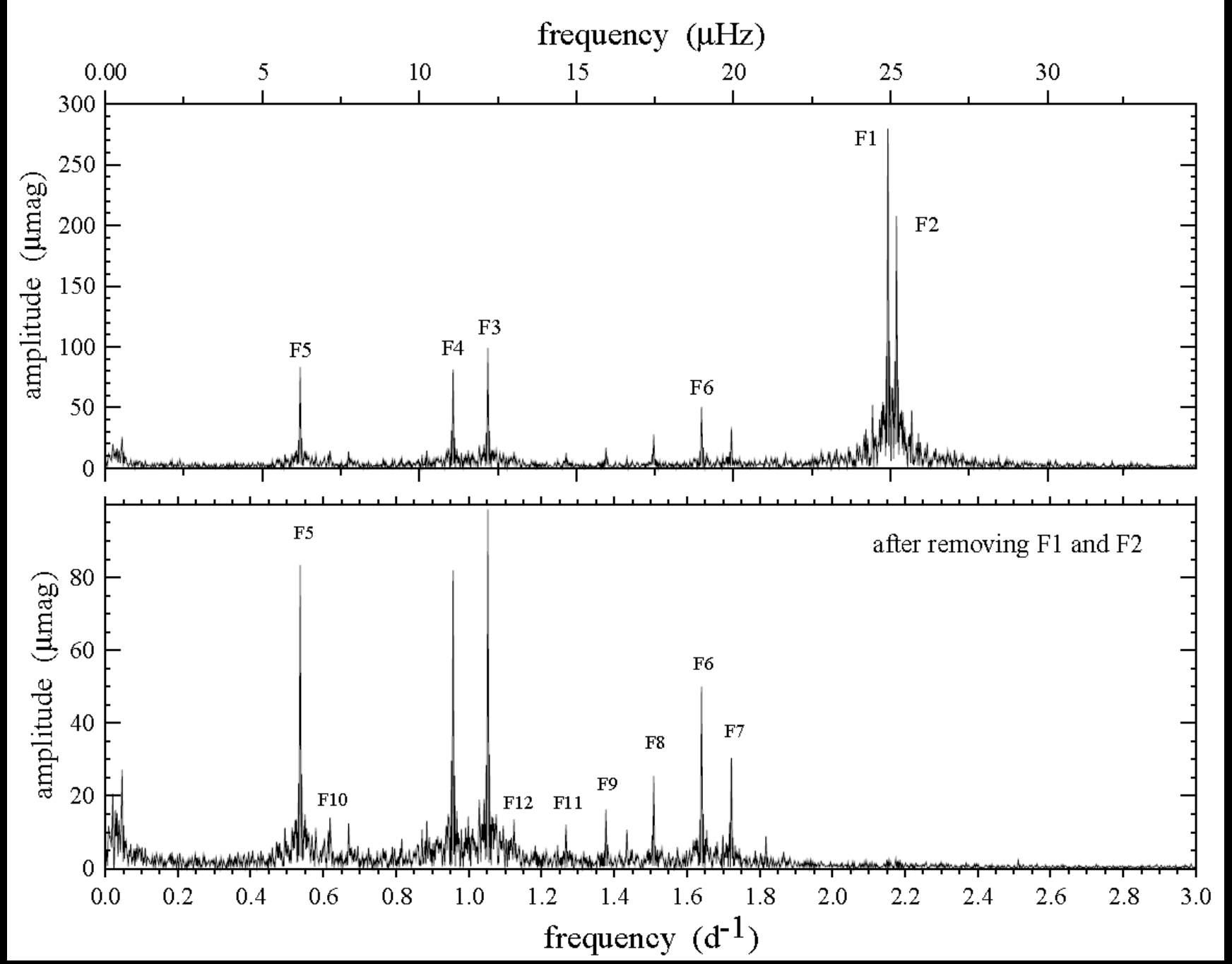
Heartbeat Stars



Collaborators: Kelly Hambleton, Susan Thompson, Don Kurtz, Avi Shporer, Ryan O'Leary

Heartbe


VPython
KOI-54 Lightcurve
Flux Variation
7.5E-3
5.0E-3
2.5E-3
0
-3
-2
-1
0
1
2
3
Phase



Welsh et al. 2011

Exact Integer Harmonics!

Tidally Induced Luminosity Fluctuations

- Tidal forcing can be written as sum over orbital harmonics

$$U_{lm} = -\frac{GM' W_{lm} r^l}{a^{l+1}} Y_{lm}(\theta, \phi_i) \sum_{N=-\infty}^{\infty} F_{Nm}\, \mathrm{e}^{-\mathrm{i}N\Omega t}$$

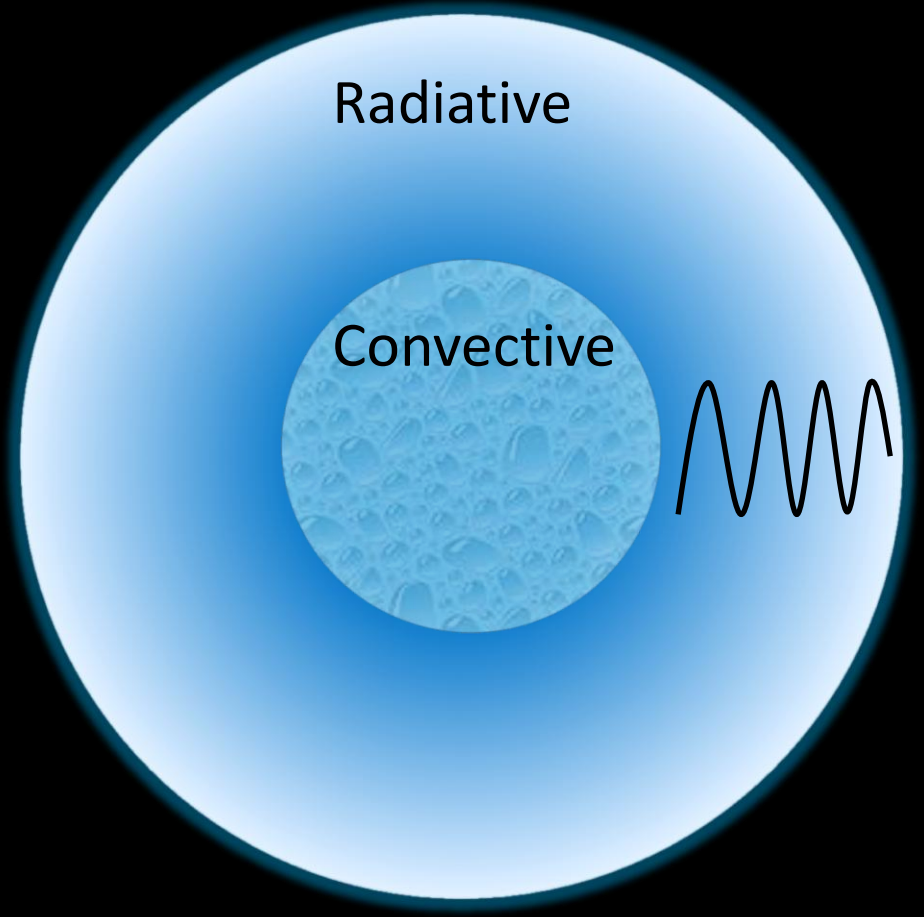
- Luminosity fluctuations occur at integer harmonics

$$\frac{\Delta L_{|N|}}{L} \simeq A_\beta \sin(N\Omega t + \Delta_\beta)$$

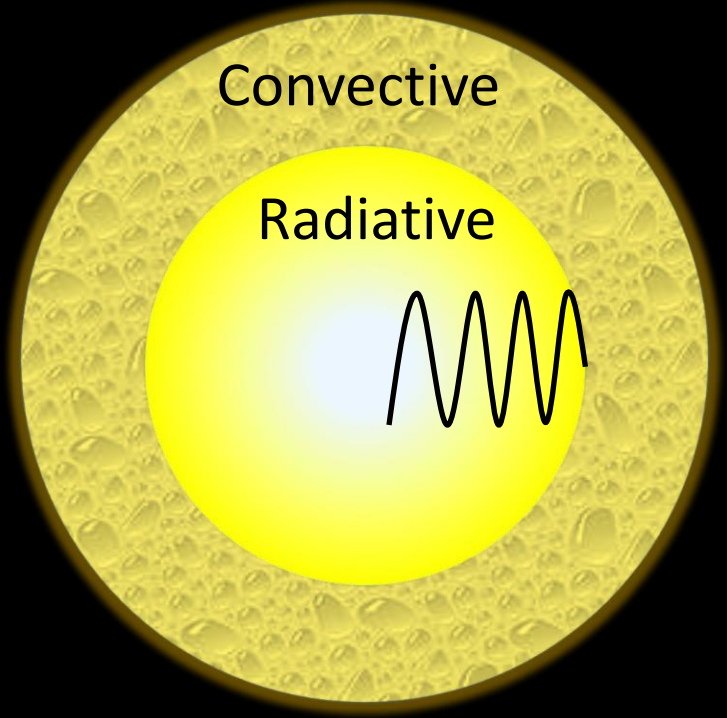
$$A_\beta = \epsilon_{lm} h_{klm} Q_\beta F_{Nm} P_{lm}(\theta_o) \left| L_\beta \right| \frac{\omega_{Nm}}{\sqrt{(\omega_\beta - \omega_{Nm})^2 + \gamma_\beta^2}}$$

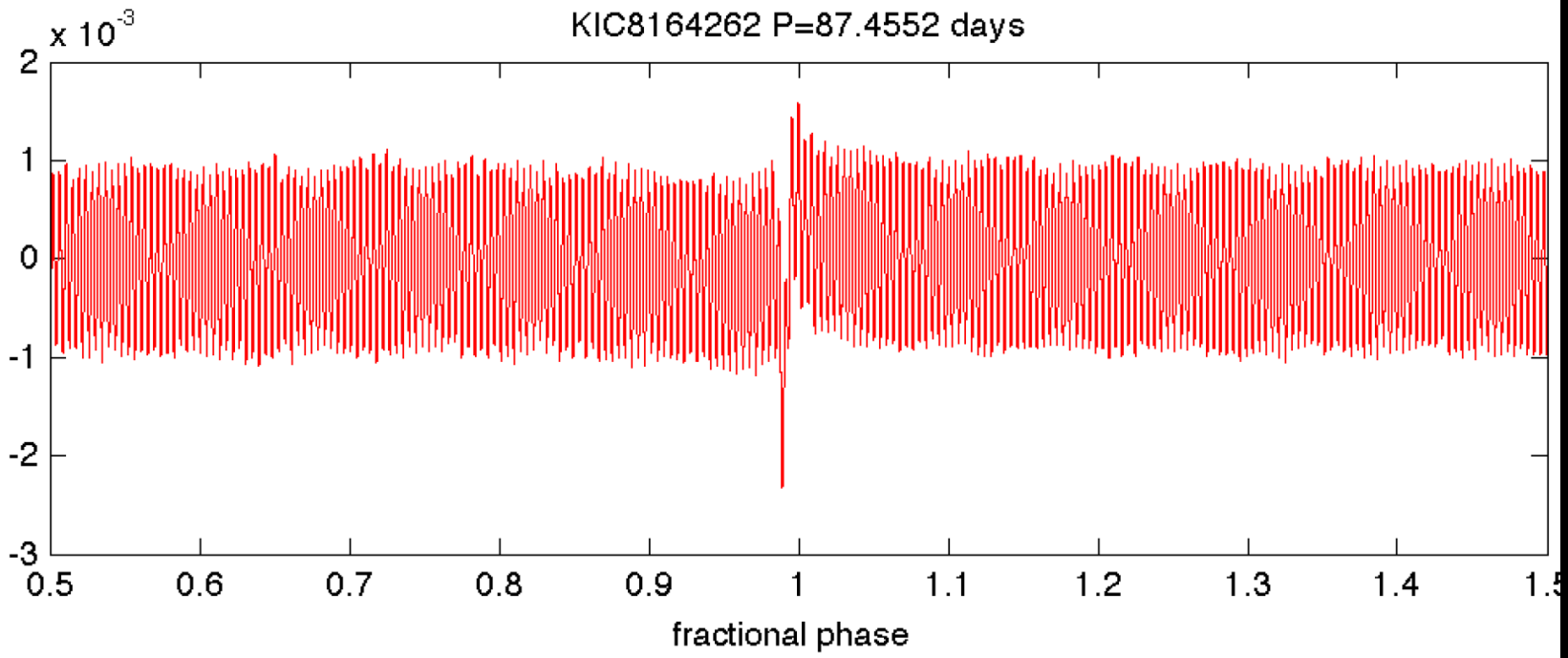
Gravity waves in stars

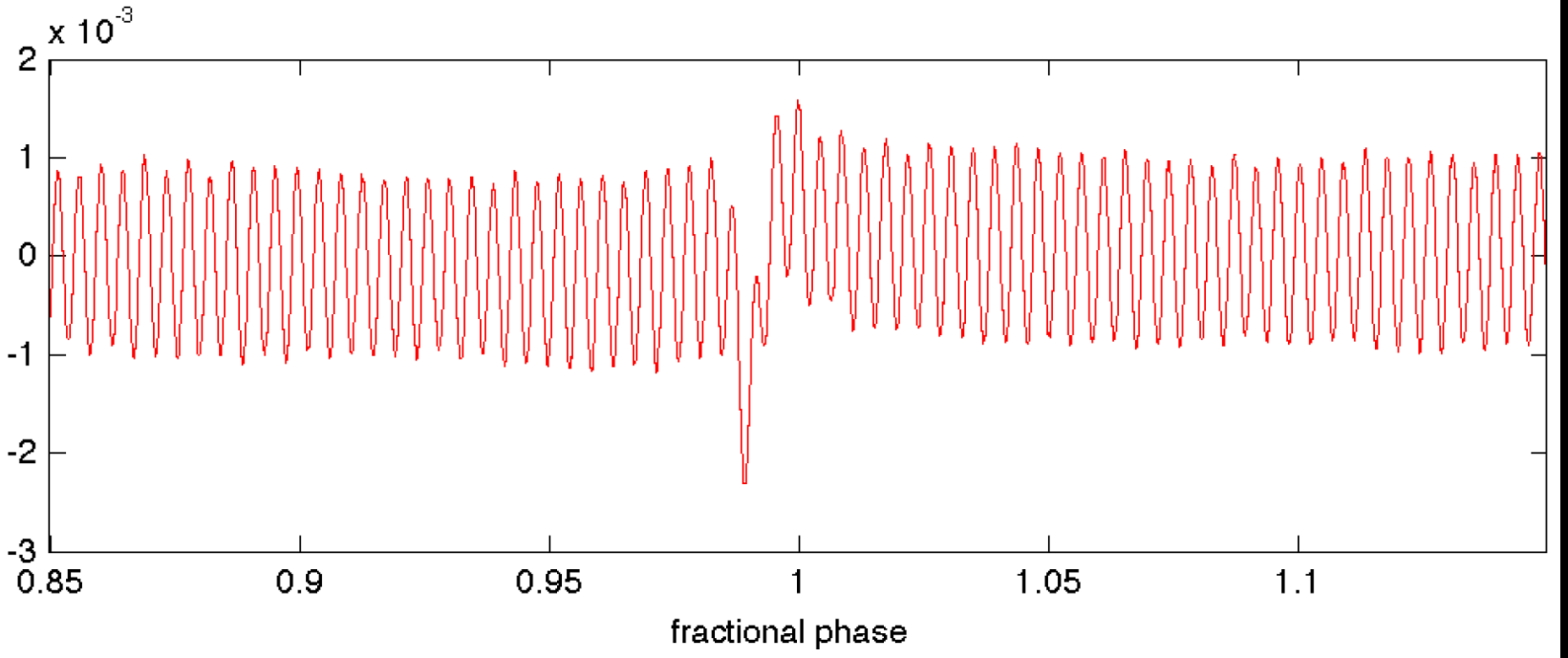
High Mass Star



Low Mass Star







Preliminary:

M=1.7 M_sun

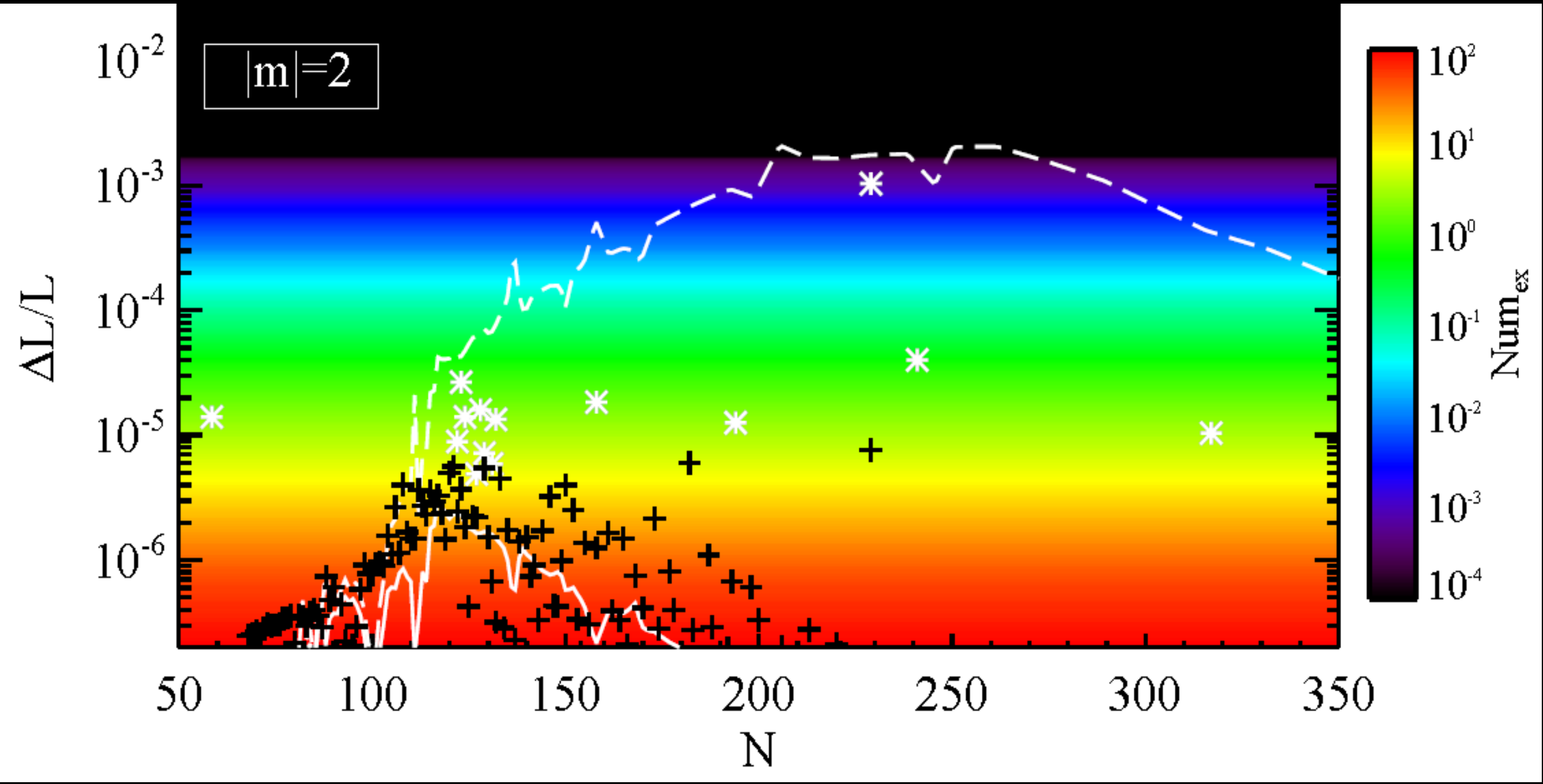
R=2.05 R_sun

T=7000 K

M'=0.3 M_sun

e=0.89

Credits: Kelly Hambleton, Susan Thompson, Don Kurtz


|m|=2
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
ΔL/L
50
100
150
200
250
300
350
N
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Num_{ex}

Resonance Locking

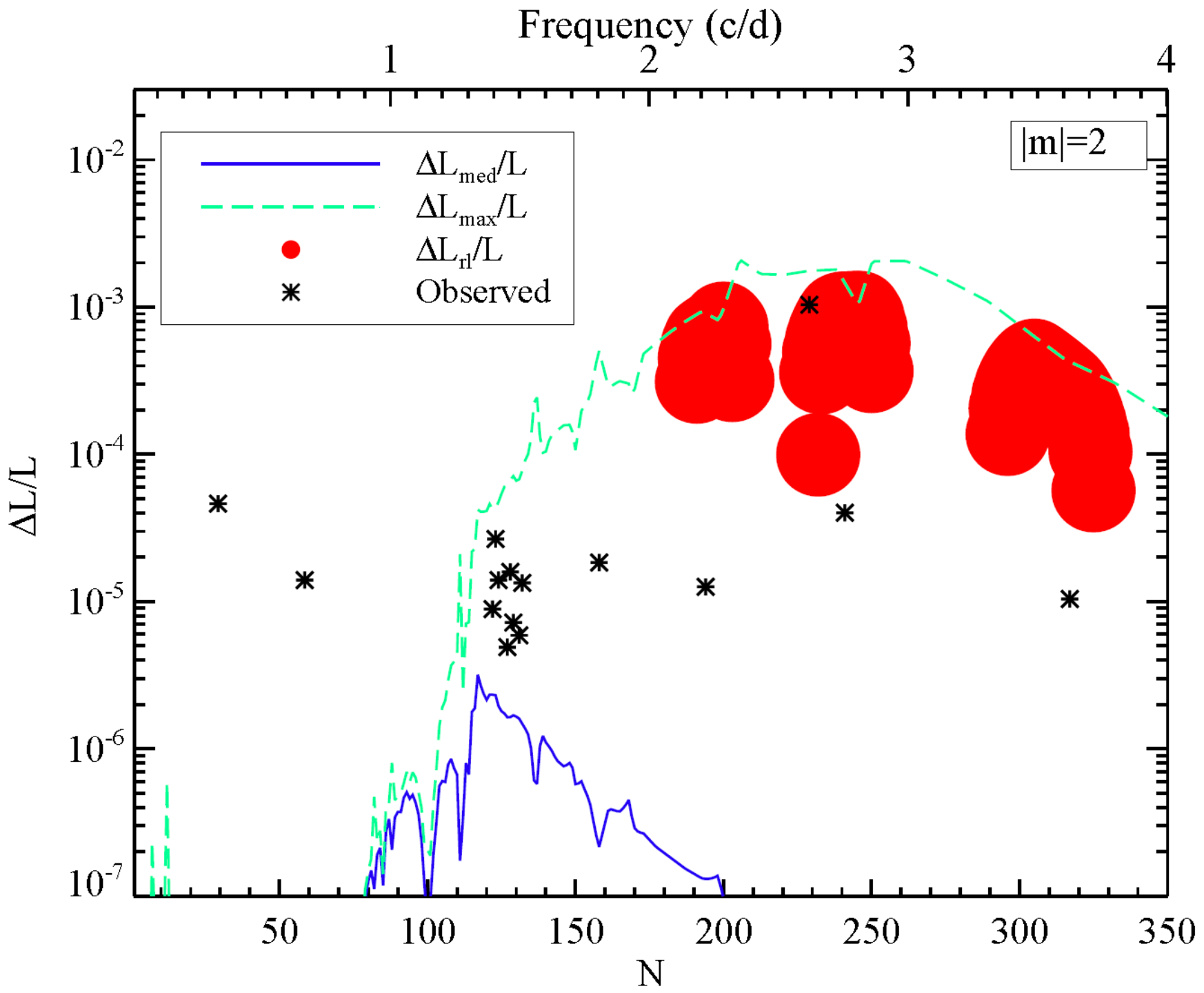
- Stellar mode frequencies evolve with time
- When they cross a resonance with tidal forcing frequency, mode can become locked in resonance such that

$$\dot{\sigma}_\alpha \simeq \dot{\sigma}_N = N\dot{\Omega}$$

- In this case, tidally excited mode amplitude can be calculated:

$$|a_\alpha|_{\rm lock} = \frac{1}{2}\left[\frac{N\Omega}{N\Omega - m\Omega_s}\frac{1}{\chi\gamma_\alpha t_{\alpha,{\rm ev}}}\right]^{1/2}$$

- Resonantly locked amplitudes are large, generate enhanced tidal dissipation



Effective tidal quality factor:

$$Q \sim 2 \times 10^4$$

Conclusions

- Coupled stellar/orbital evolution can lead to resonance locking, enhanced tidal dissipation

- Much more to be done!