# Saturn Ring Seismology

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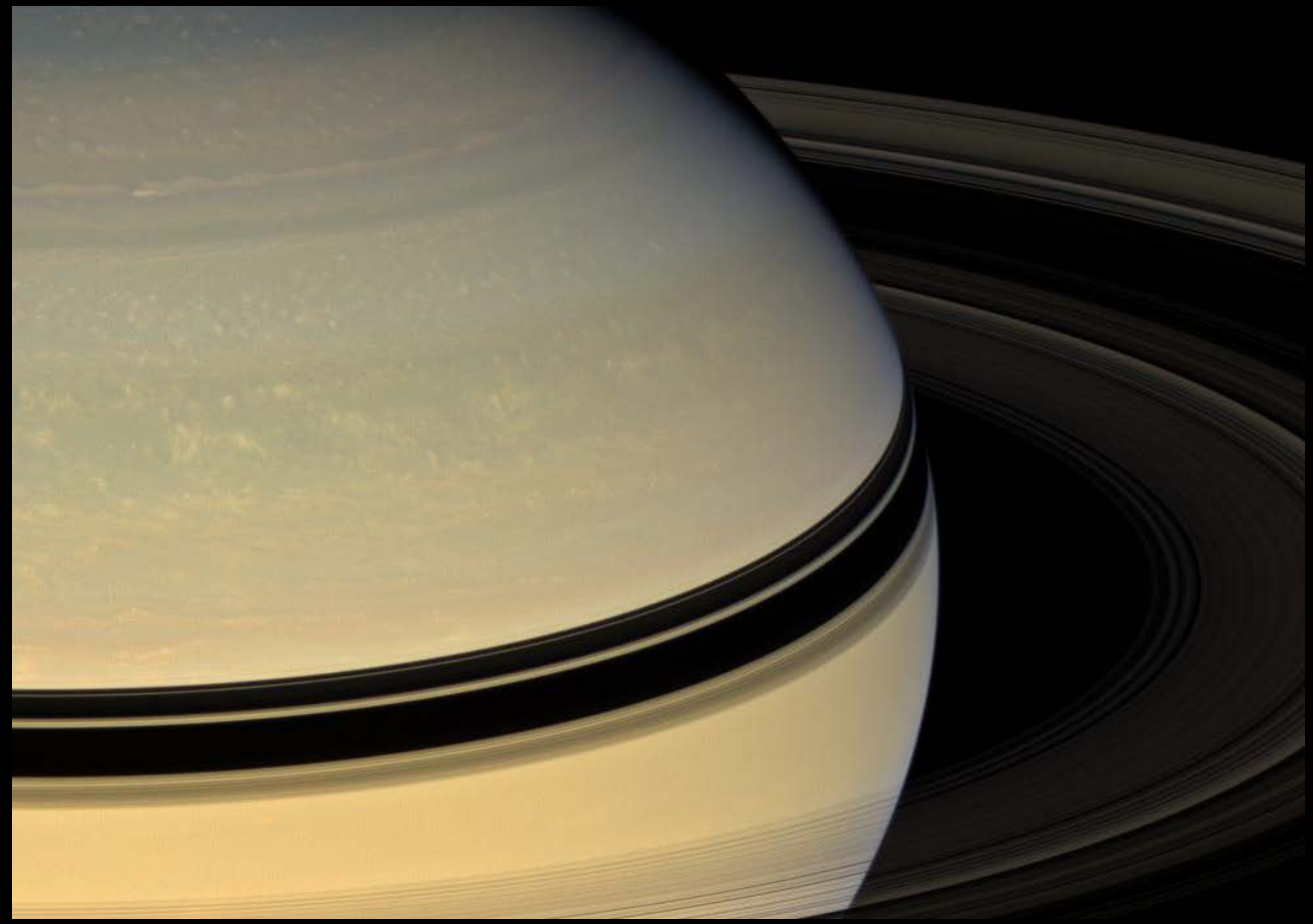
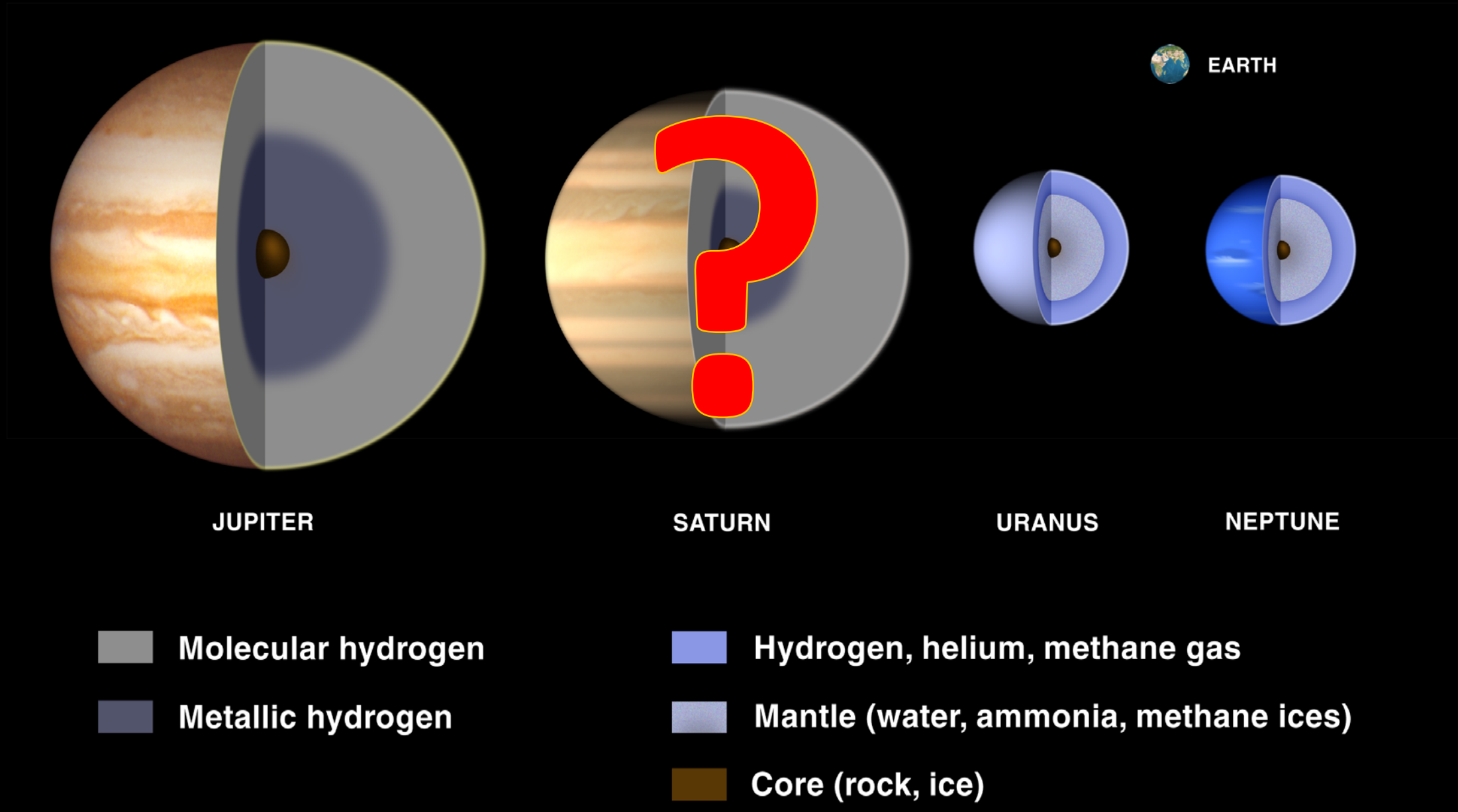
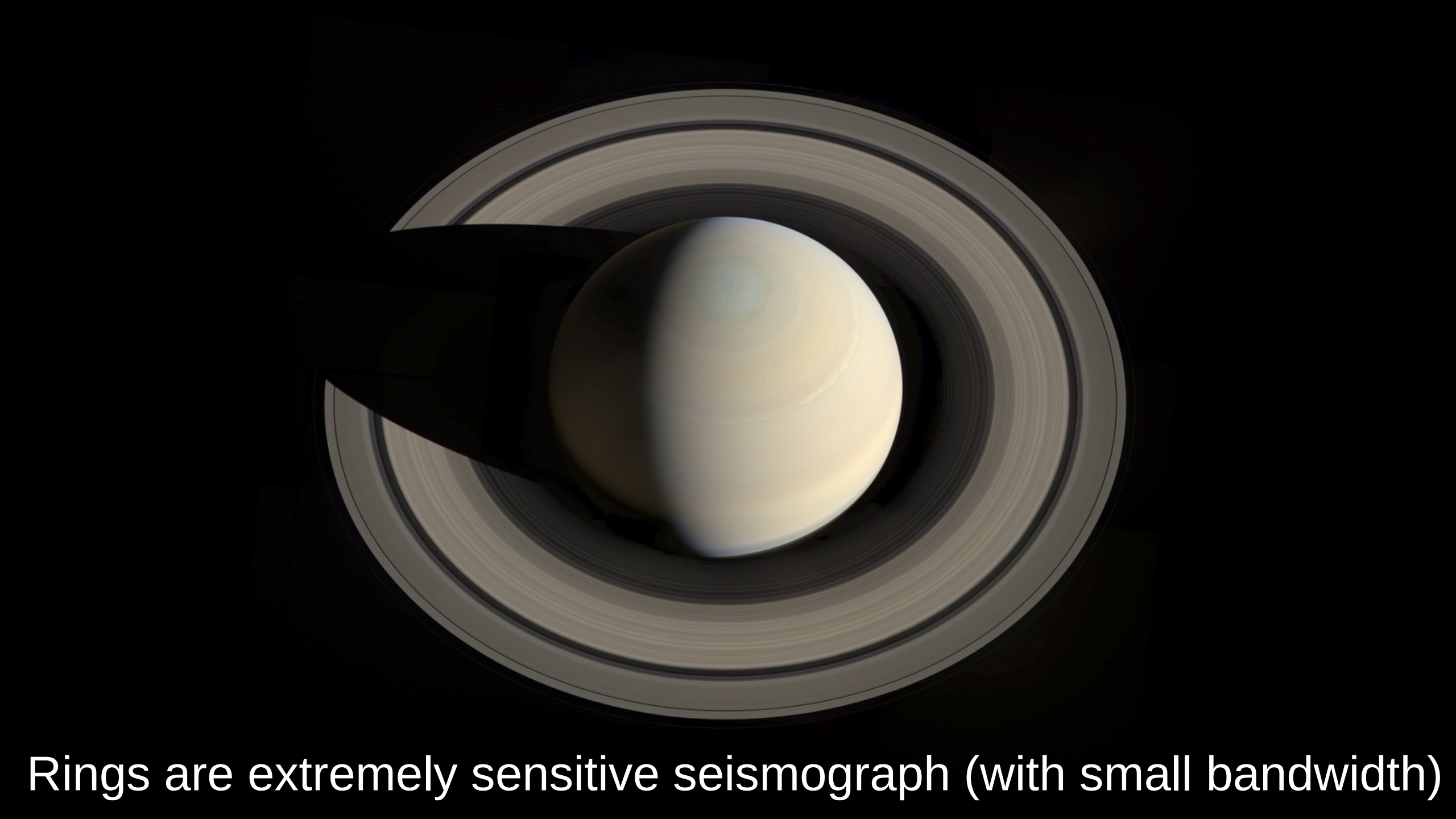


Credits: Matt Hedman, Phil Nicholson, Dave Stevenson, Mark Marley, Carolyn Porco

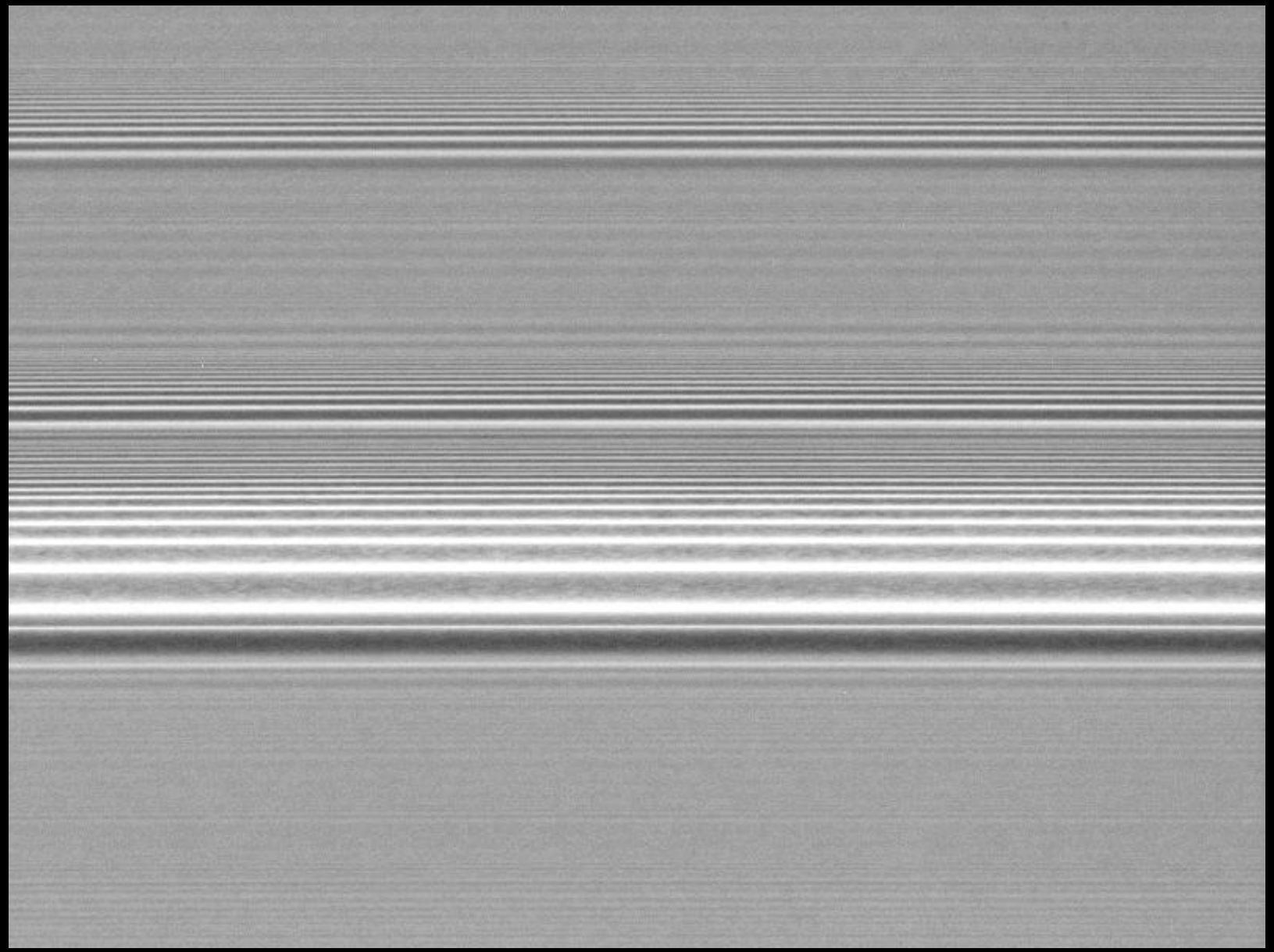


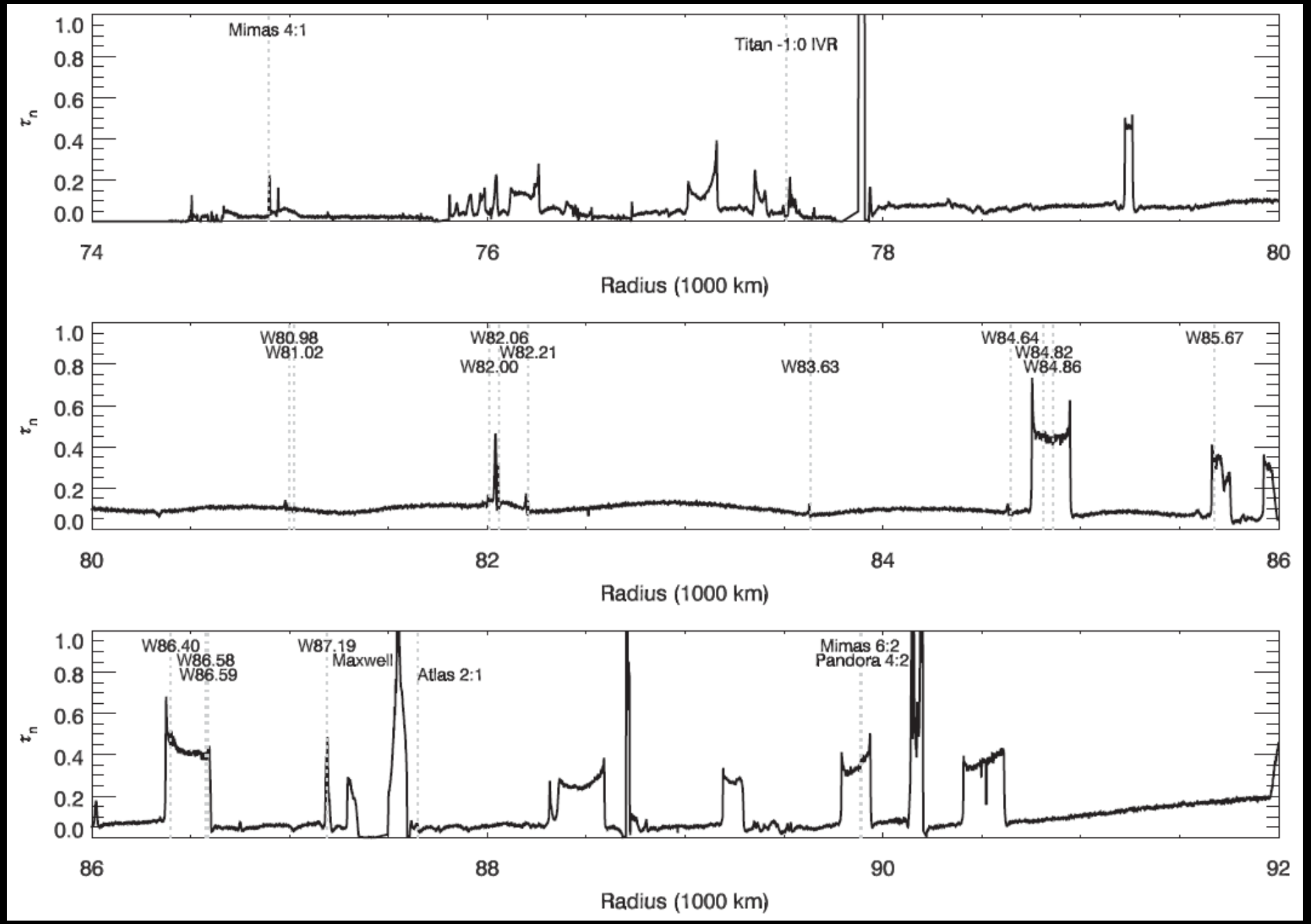

Internal structures poorly constrained



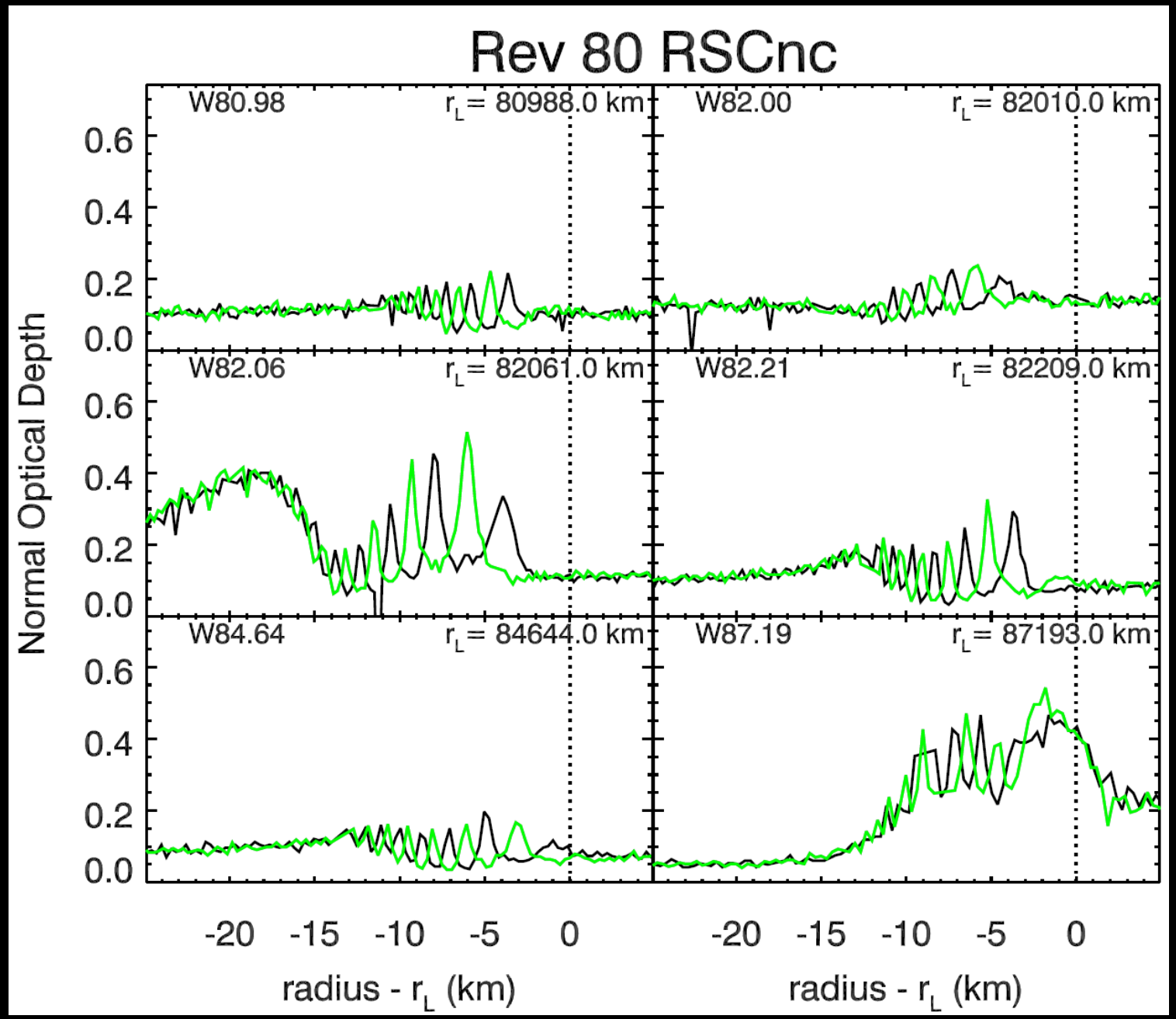
Rings are extremely sensitive seismograph (with small bandwidth)

# Spiral Density Waves






Hedman & Nicholson 2014




Hedman & Nicholson 2013

# Wave Excitation

- Waves excited at outer Lindblad resonances

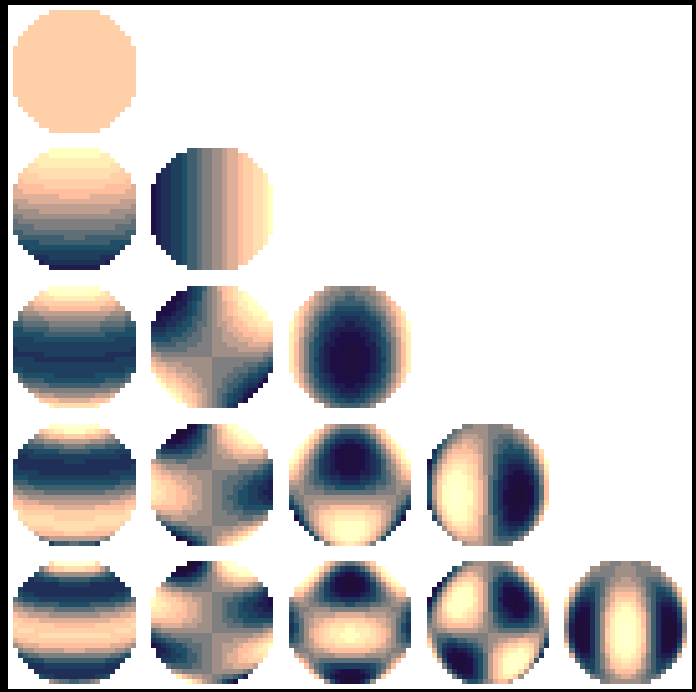
$$m(\Omega - \Omega_p) = \kappa$$

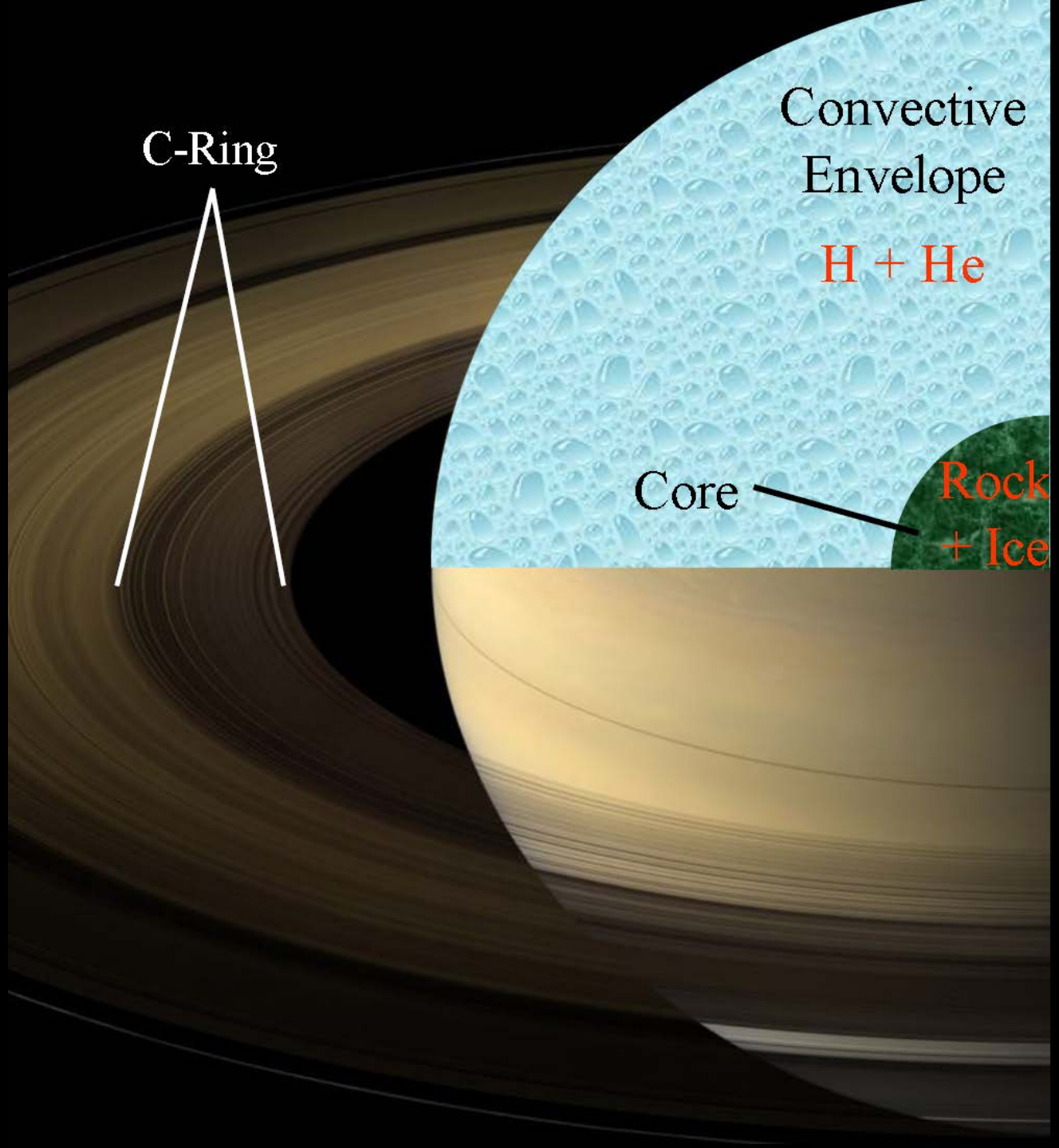
- Wave frequency tells us mode frequency

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

Mode Periods: ~hours

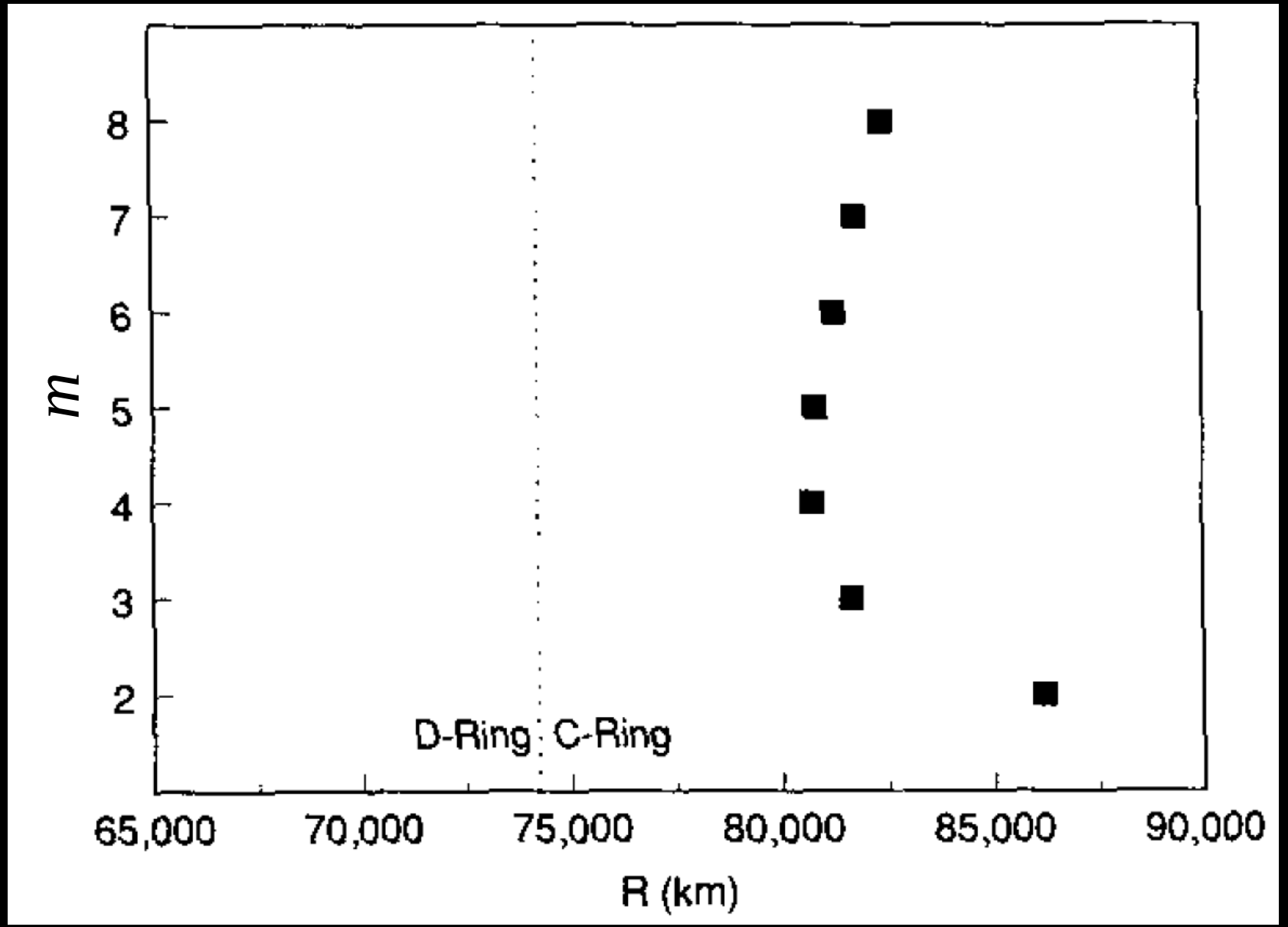
Mode Amplitudes: ~1m






# Simplistic planet model

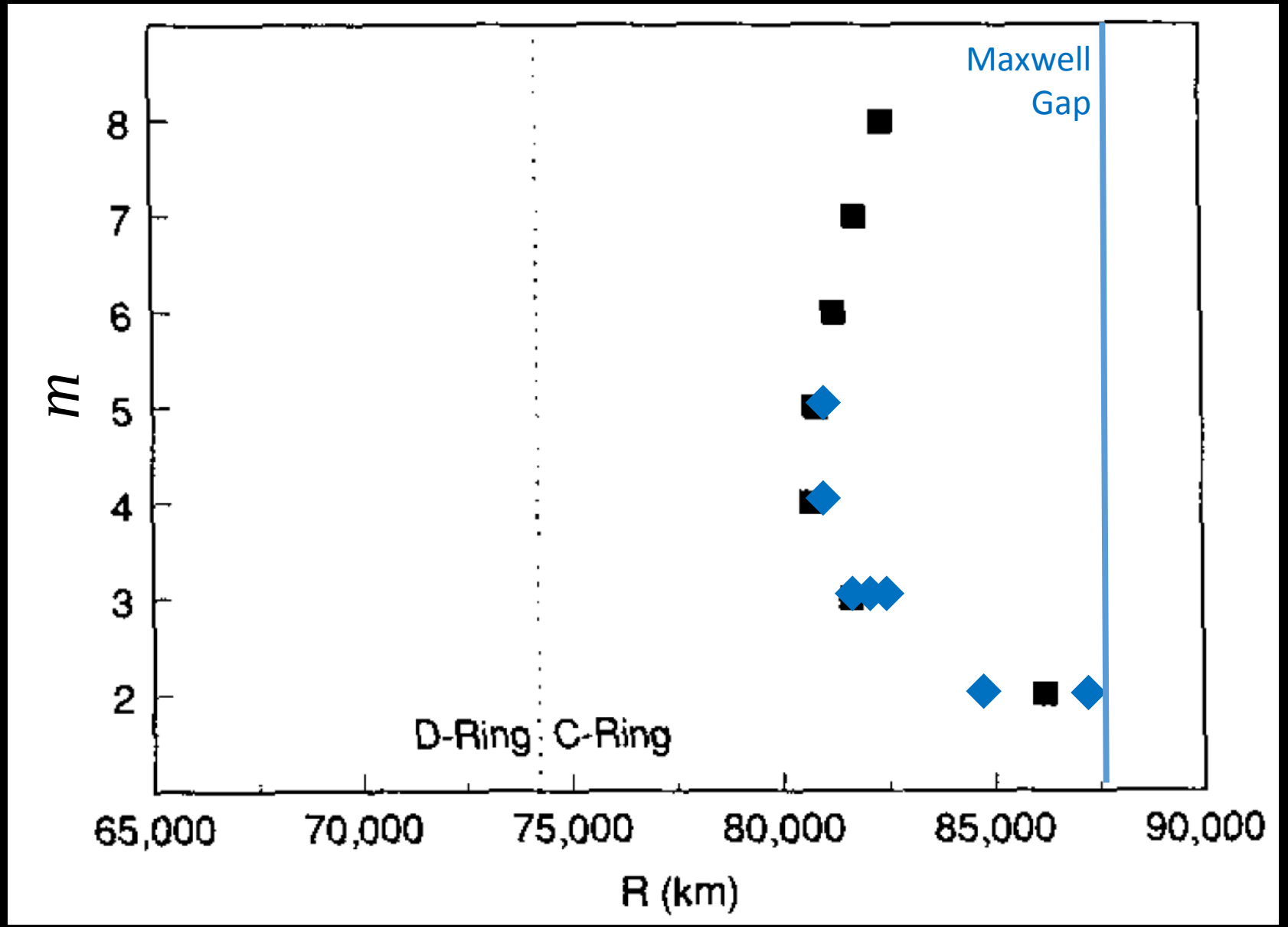
# Predicted:




Resonances with $l=m$ f modes

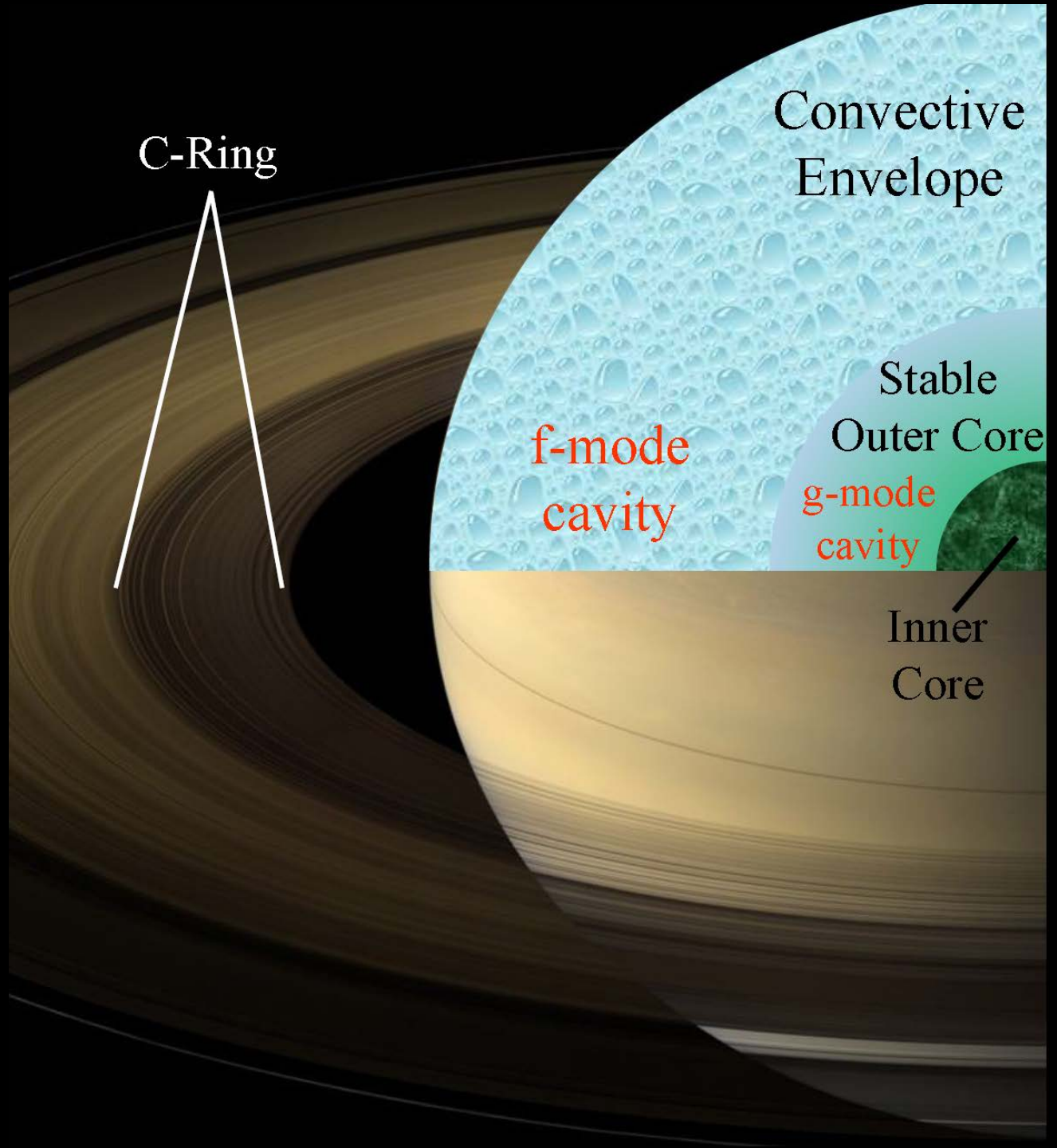
Marley & Porco 1993

# Observed:

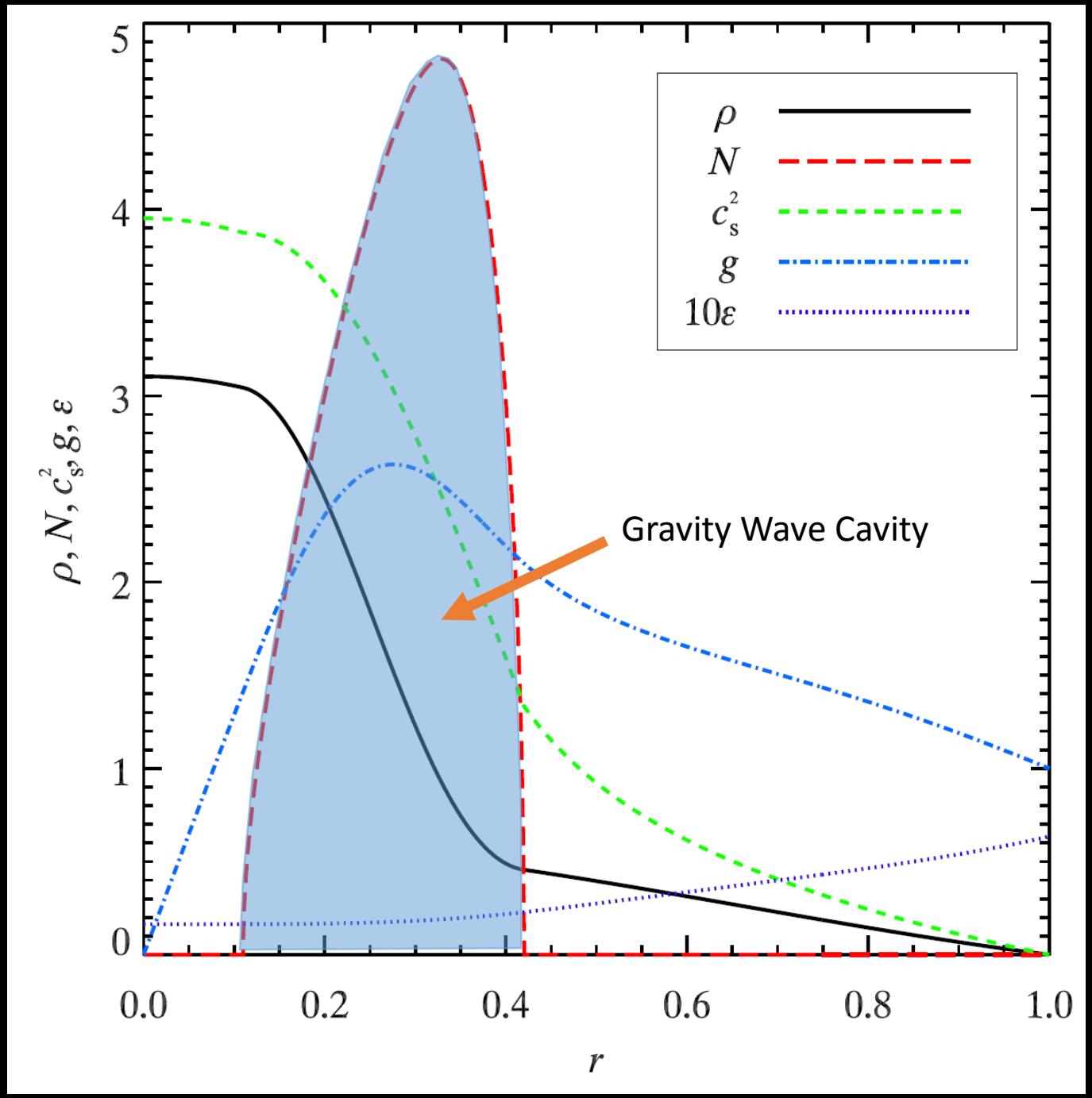


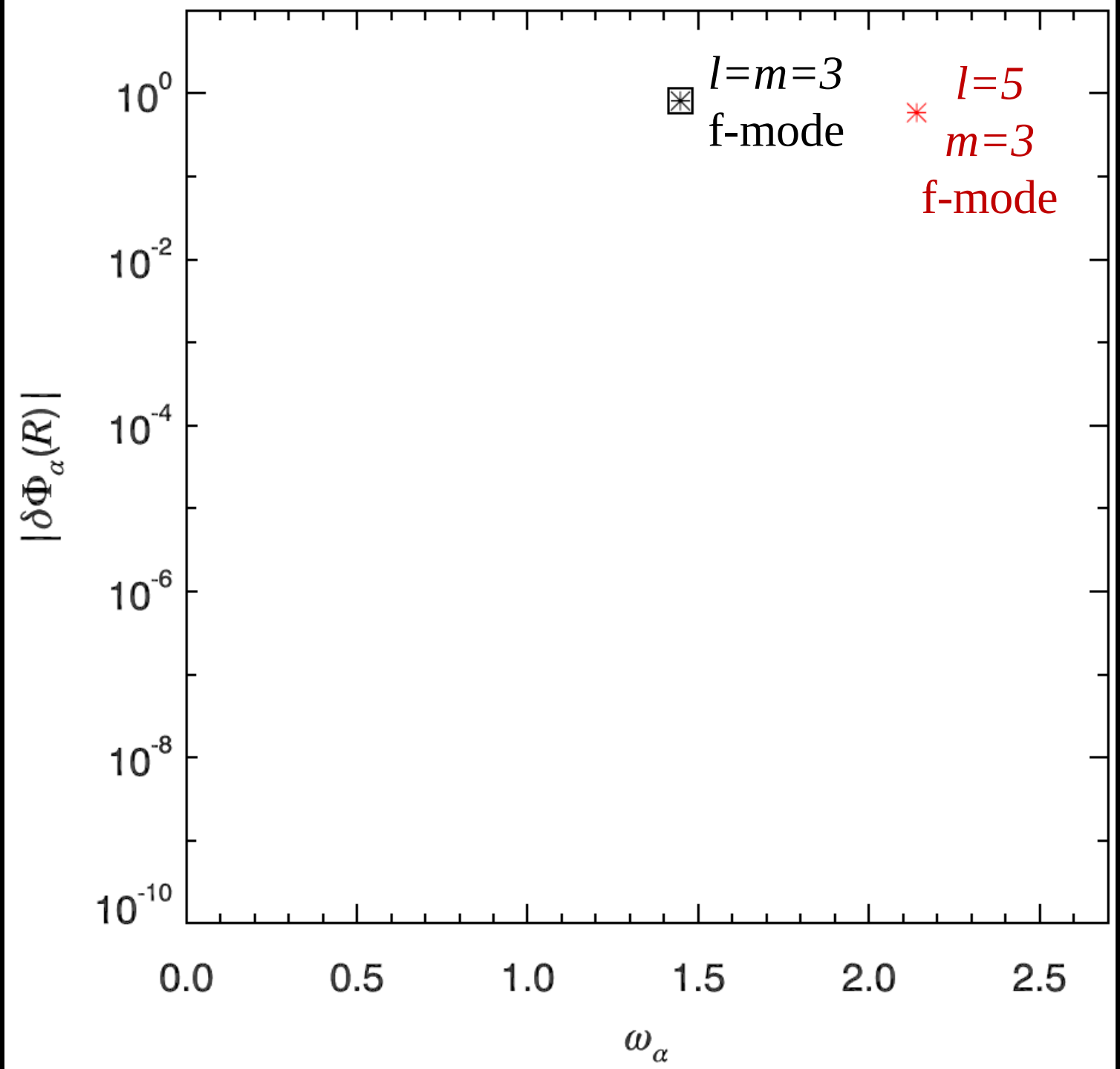

Fine-splitting in frequencies unexpected!

Marley & Porco 1993

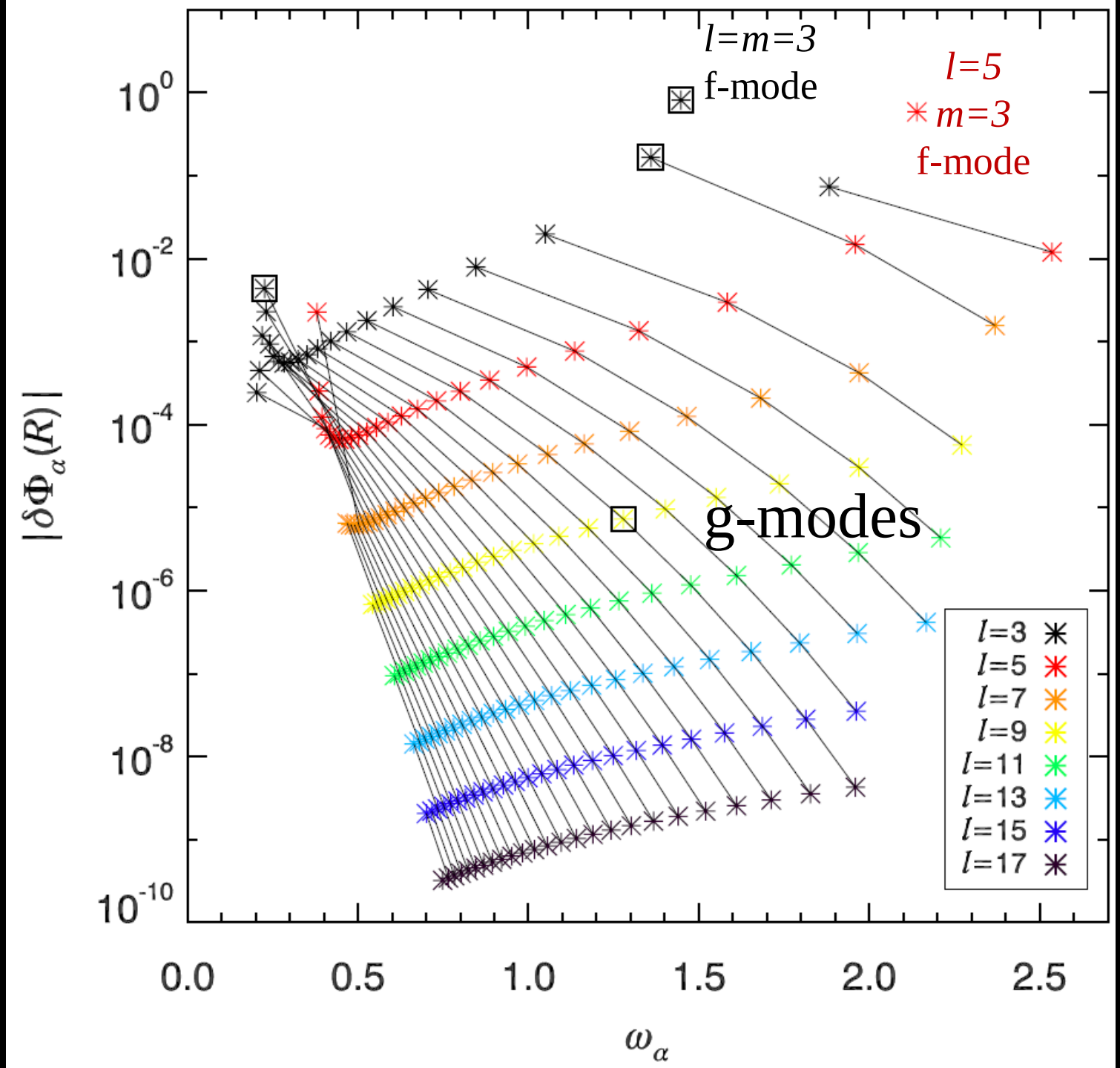



# Better planet model


ρ
N
$c_s^2$
g
10ε
Gravity Wave Cavity
$\rho, N, c_s^2, g, \varepsilon$
r
0
1
2
3
4
5
0.0
0.2
0.4
0.6
0.8
1.0




# Modes of simple planet model




# Modes of better planet model

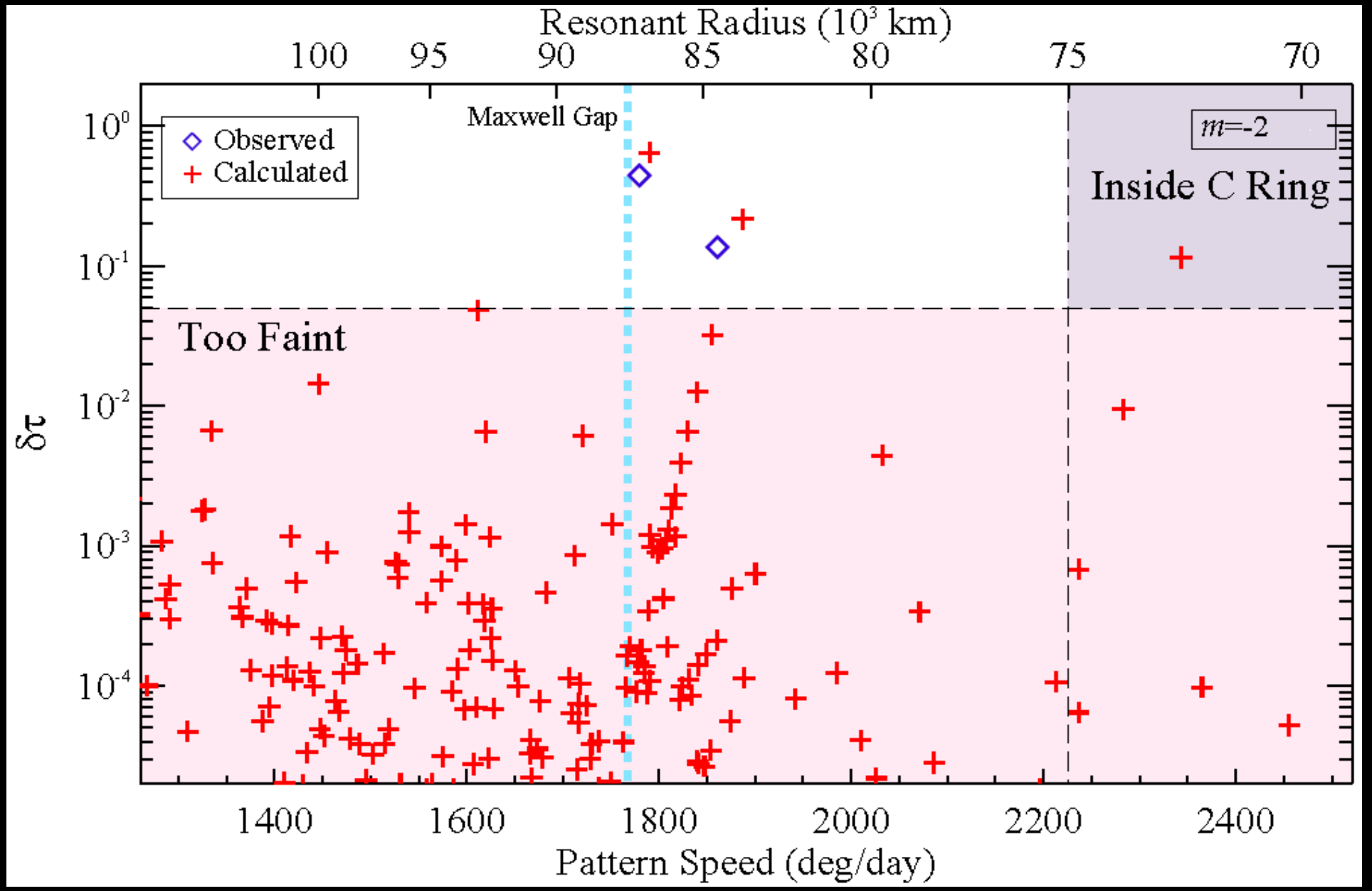
# Rotation makes things ugly…

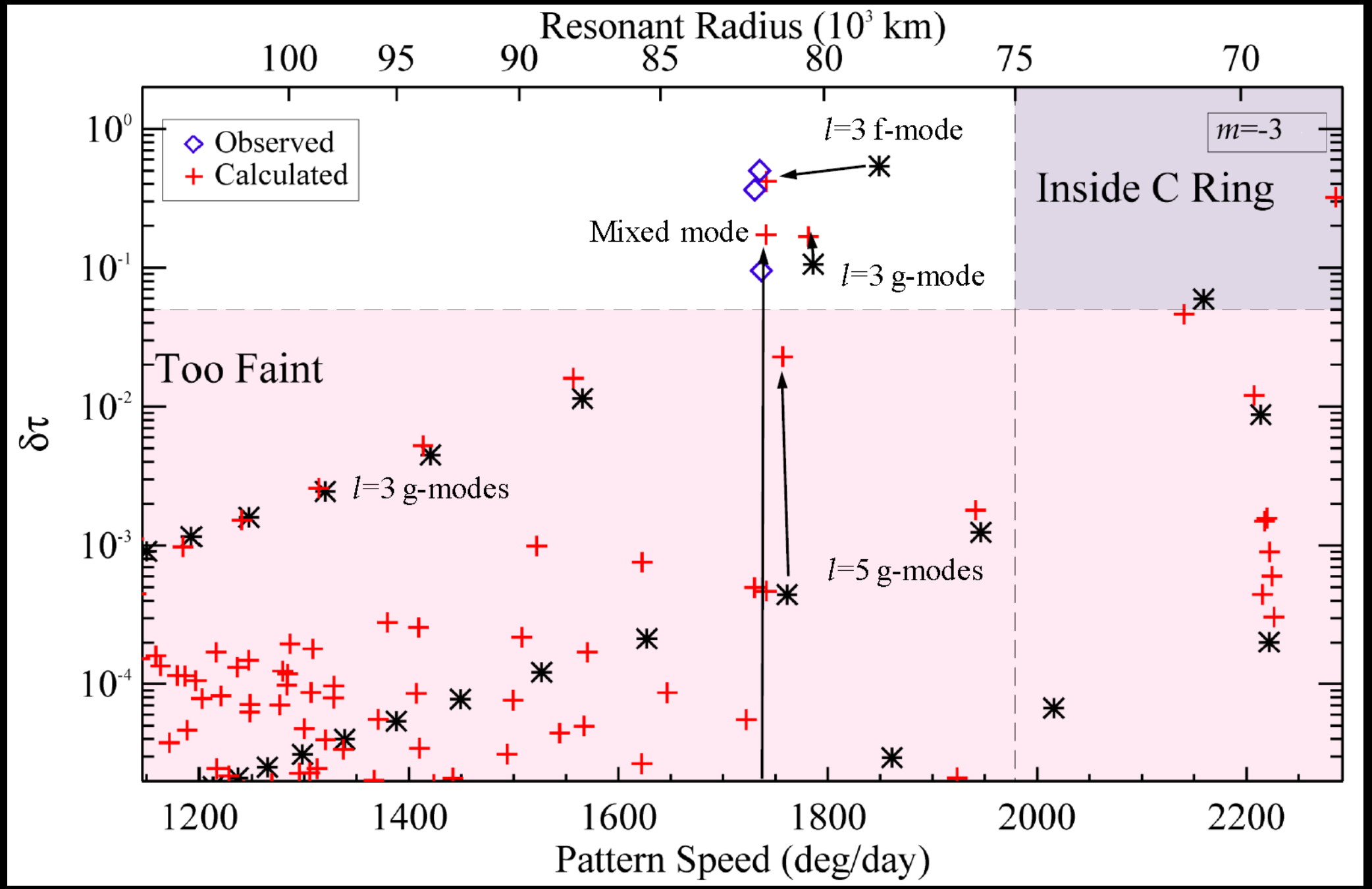
- Saturn rotates rapidly
- Rotation causes modes to “mix”

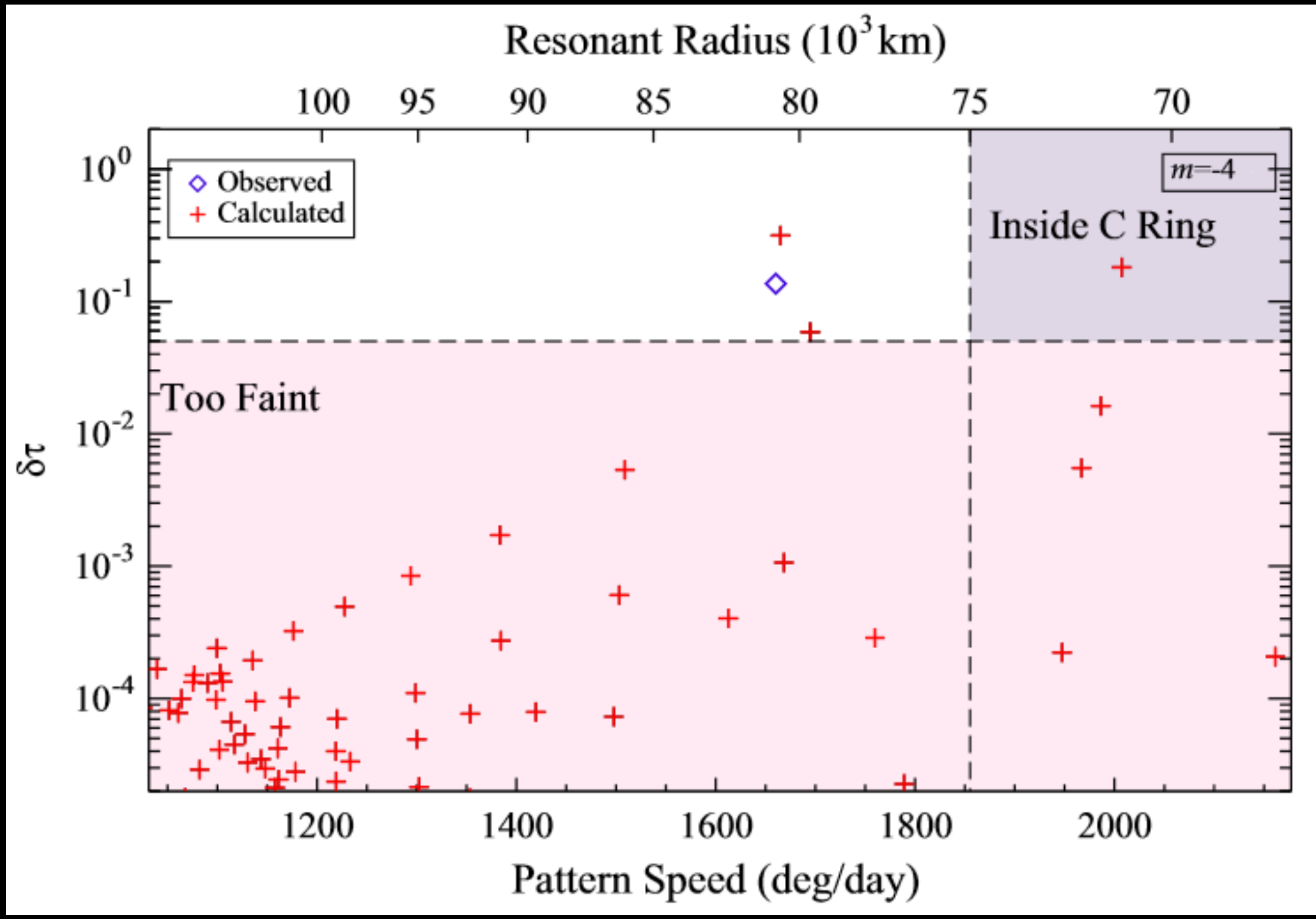
$$\begin{bmatrix} 0 & \nu+\delta\nu \\ \nu+\delta\nu & 2w \end{bmatrix}\mathbf{z} = \omega\begin{bmatrix} \nu+\delta\nu & 0 \\ 0 & \tau+\delta\tau \end{bmatrix}\mathbf{z}$$

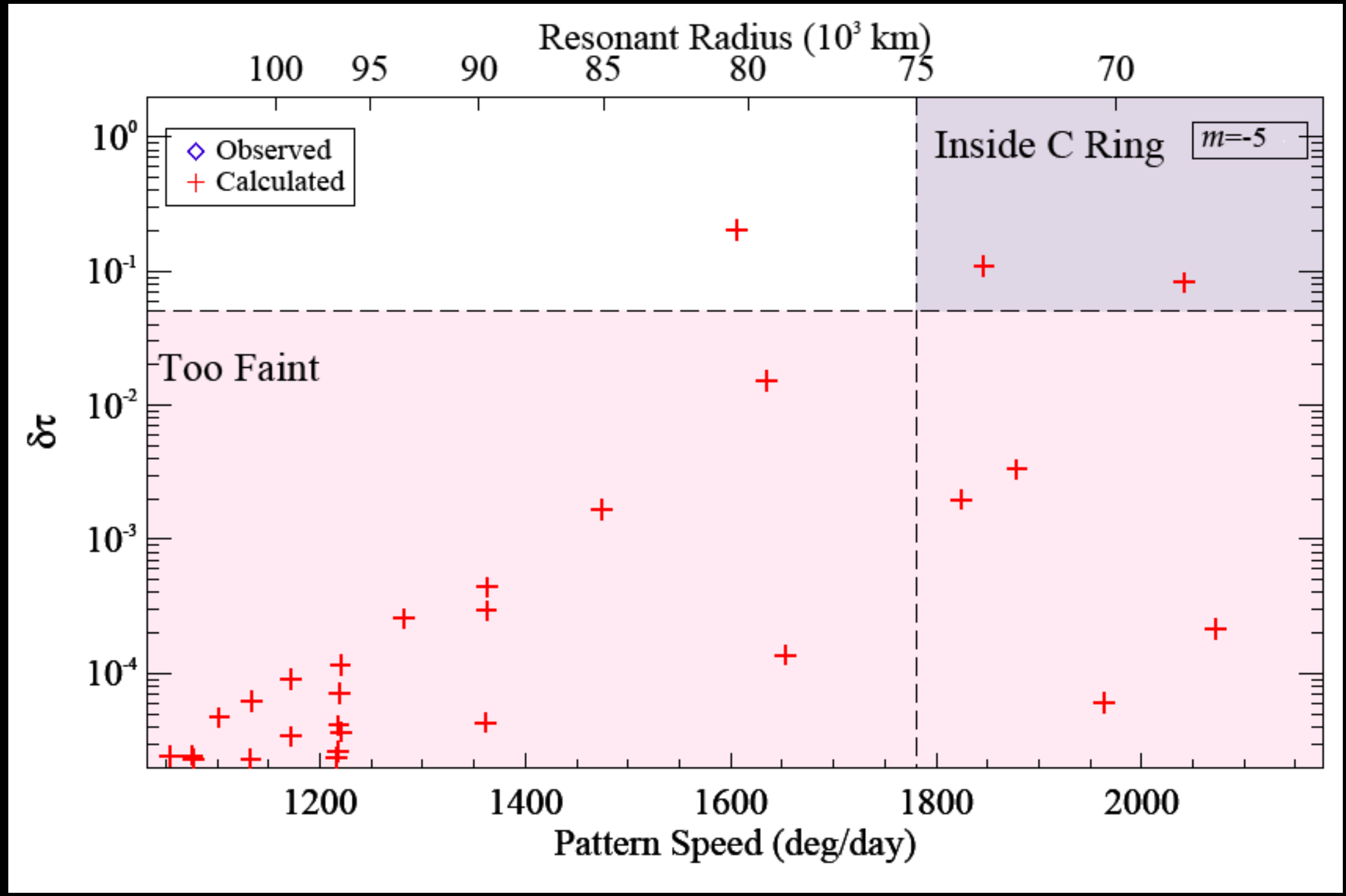
- New modes are superposition of old modes

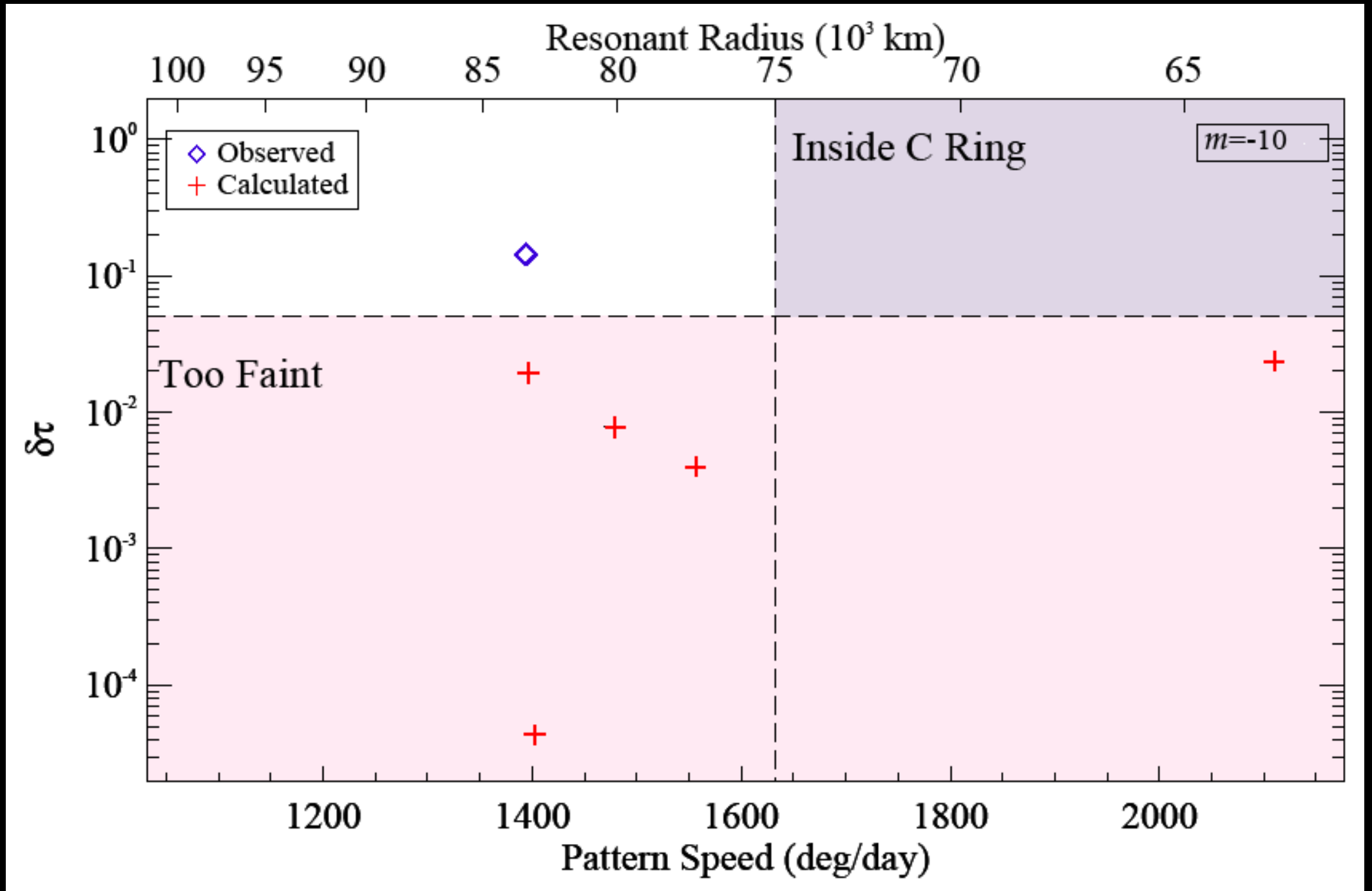
# Effect on Rings




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
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
δτ
Observed
Calculated
m=-4
Inside C Ring
Too Faint
1200
1400
1600
1800
2000
Pattern Speed (deg/day)


Resonant Radius ($10^3$ km)
100
95
90
85
80
75
70
Observed
Calculated
Inside C Ring
m=-5
Too Faint
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
δτ
1200
1400
1600
1800
2000
Pattern Speed (deg/day)


Resonant Radius ($10^3$ km)
100
95
90
85
80
75
70
65
Observed
Calculated
Inside C Ring
m=-10
Too Faint
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
δτ
1200
1400
1600
1800
2000
Pattern Speed (deg/day)

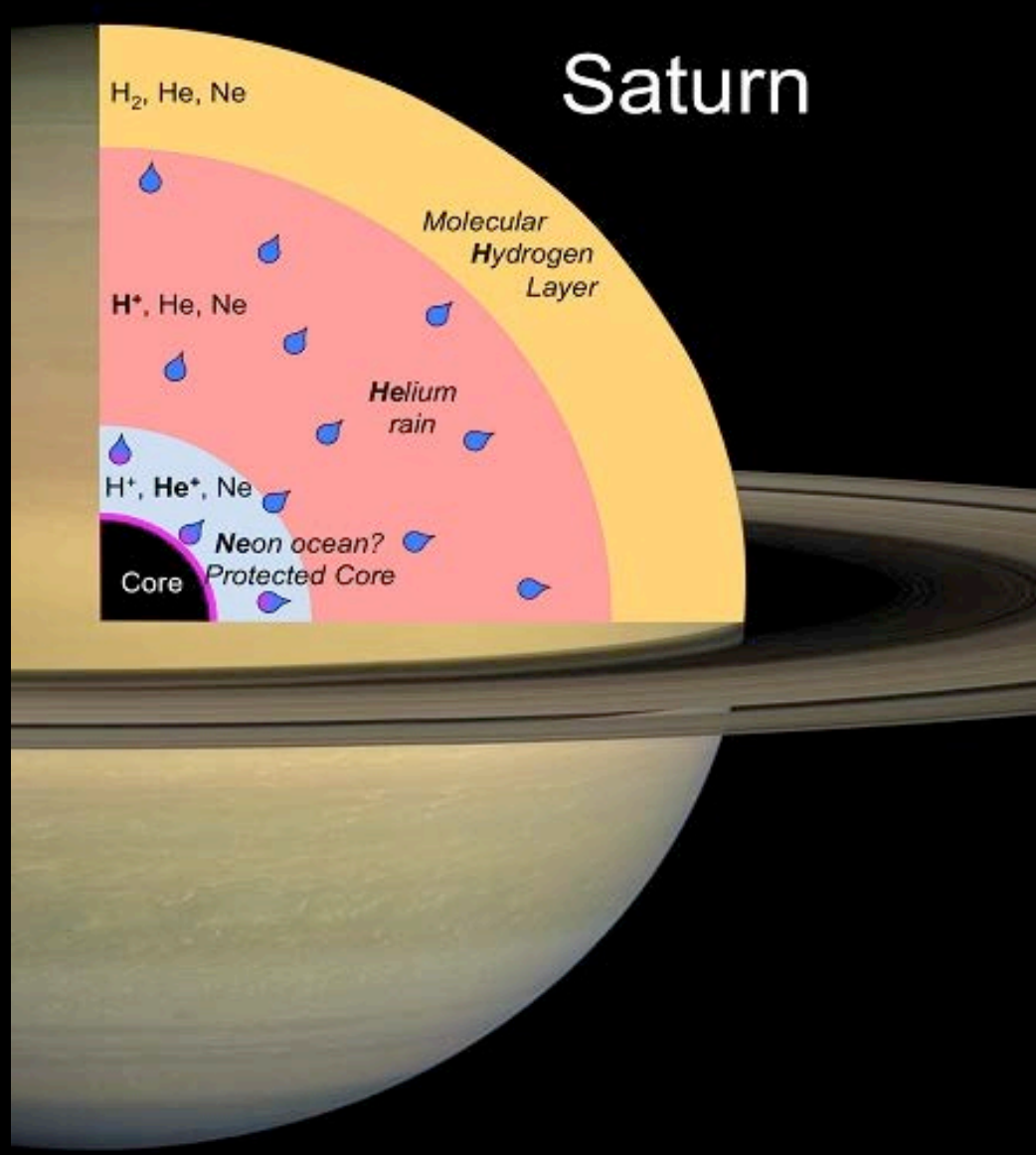
# What creates stable stratification?

- Likely caused by molecular composition gradient

Helium rain

Dissolving core

Relic of formation



# Mode Energetics

| Planet | Saturn | Jupiter | Sun |
|---|---|---|---|
| Modes detected | f modes/g modes | p modes | p modes |
| Frequency | ~100 $\mu$Hz | ~1200 $\mu$Hz | ~3000 $\mu$Hz |
| Surface Displacement | ~100cm | ~4000 cm | ~1000 cm |
| Surface Velocity | ~0.1 cm/s | ~40 cm/s | ~20 cm/s |
| Energy | ~$10^{-17}$ $GM^2/R$, ~$3\times10^{25}$ erg | ~$3\times10^{-15}$ $GM^2/R$, ~$10^{29}$ erg | ~$10^{-21}$ $GM^2/R$, ~$3\times10^{27}$ erg |
| Lifetime | > years | ~days??? | ~days |
| Power source | ~$10^{-10}$ Lsun | ~$10^{-9}$ Lsun | ~Lsun |

# Conclusions

- Evidence for stable stratification (non-adiabatic interior) of Saturn
  - Likely produced by composition gradients
  - Helium sedimentation, core erosion, or formation?

- Differential rotation in Saturn measured in rings
  - How deep does this extend?