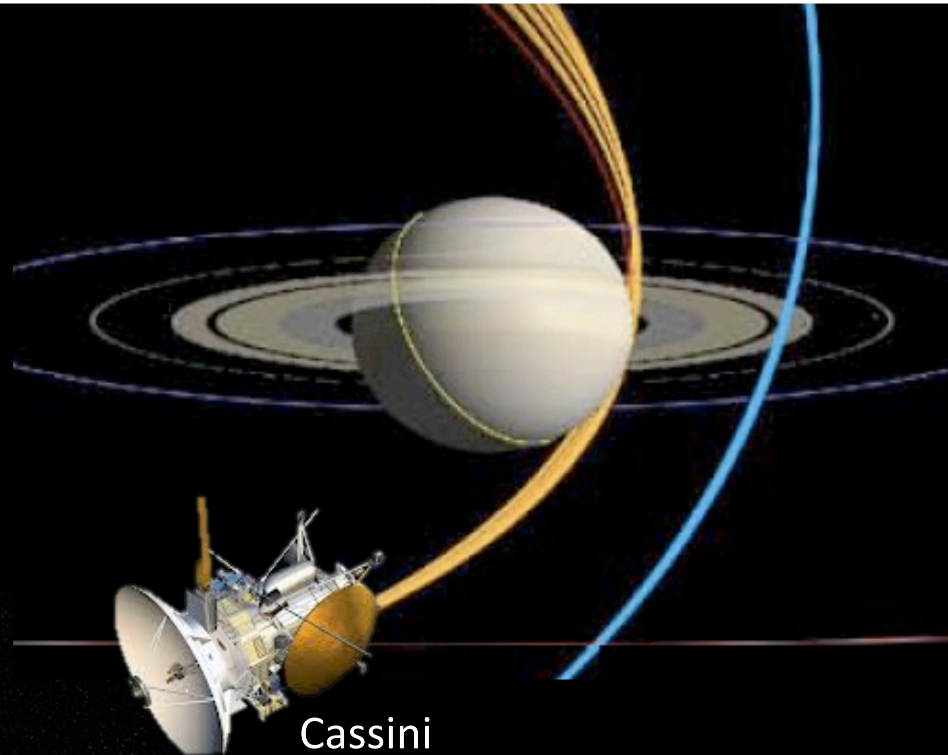
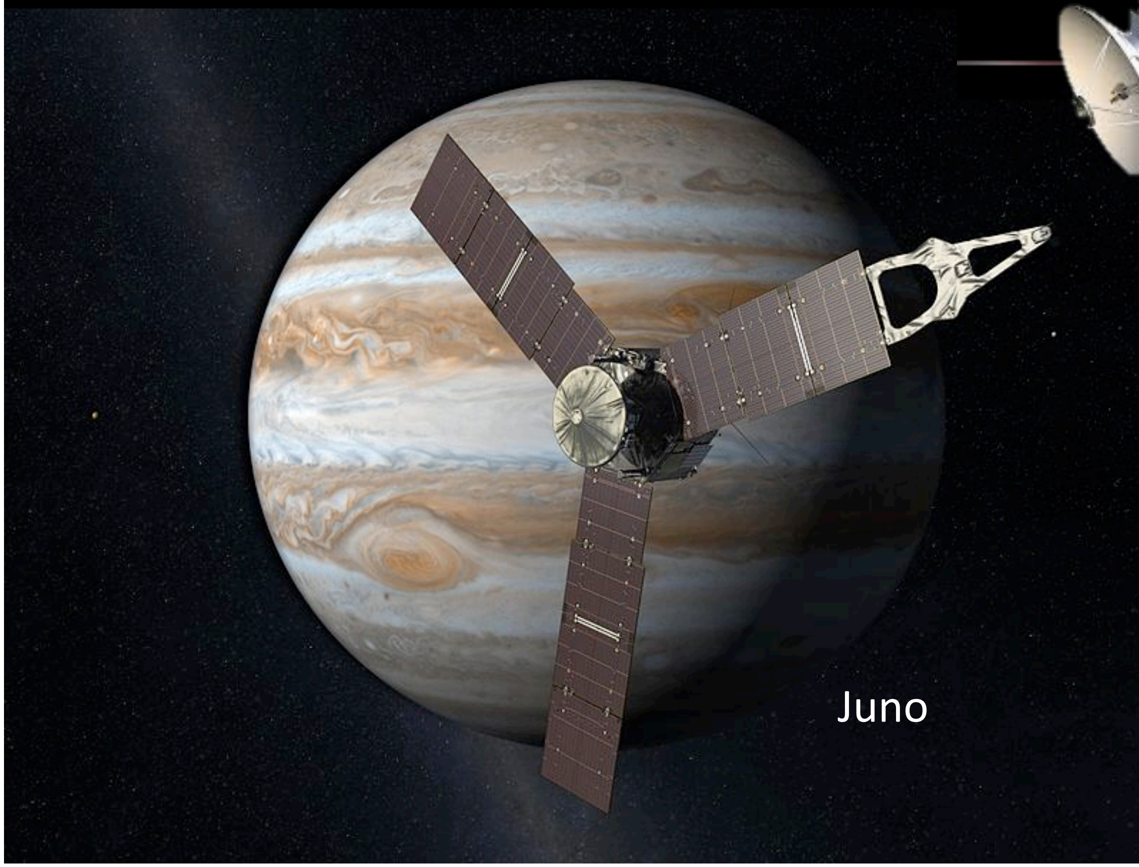
Kronoseismology:

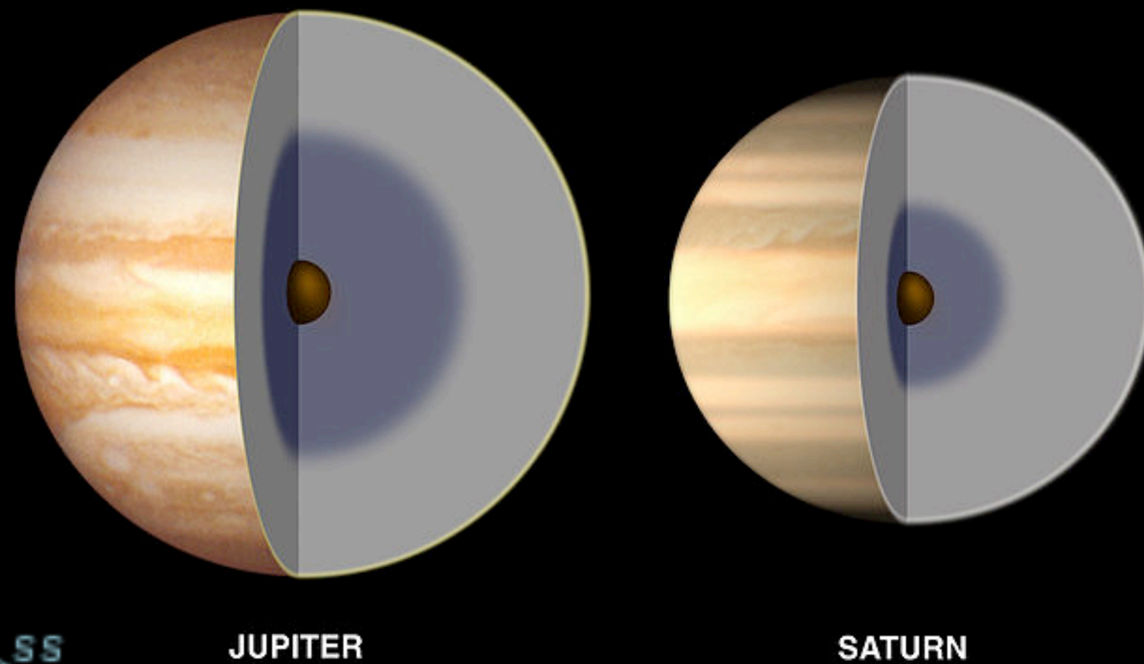
Using Saturn’s rings to study the planet’s internal structure

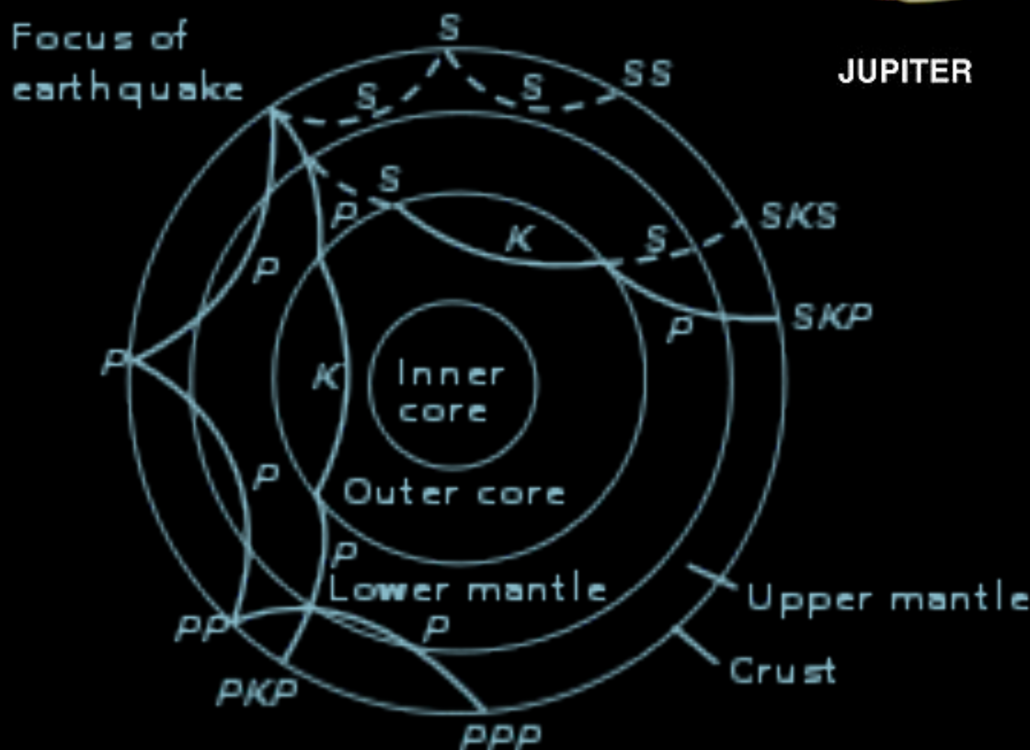
Information from the rings could complement other attempts to understand the internal structures of Jupiter and Saturn

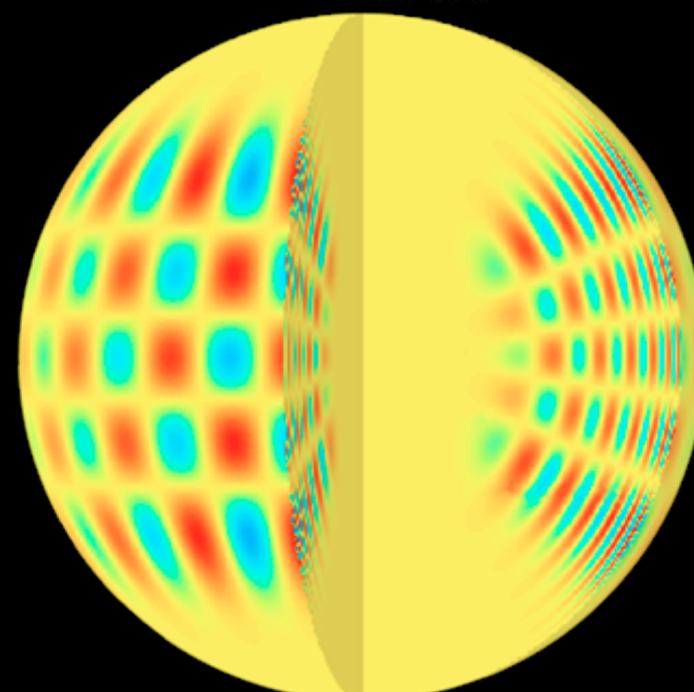




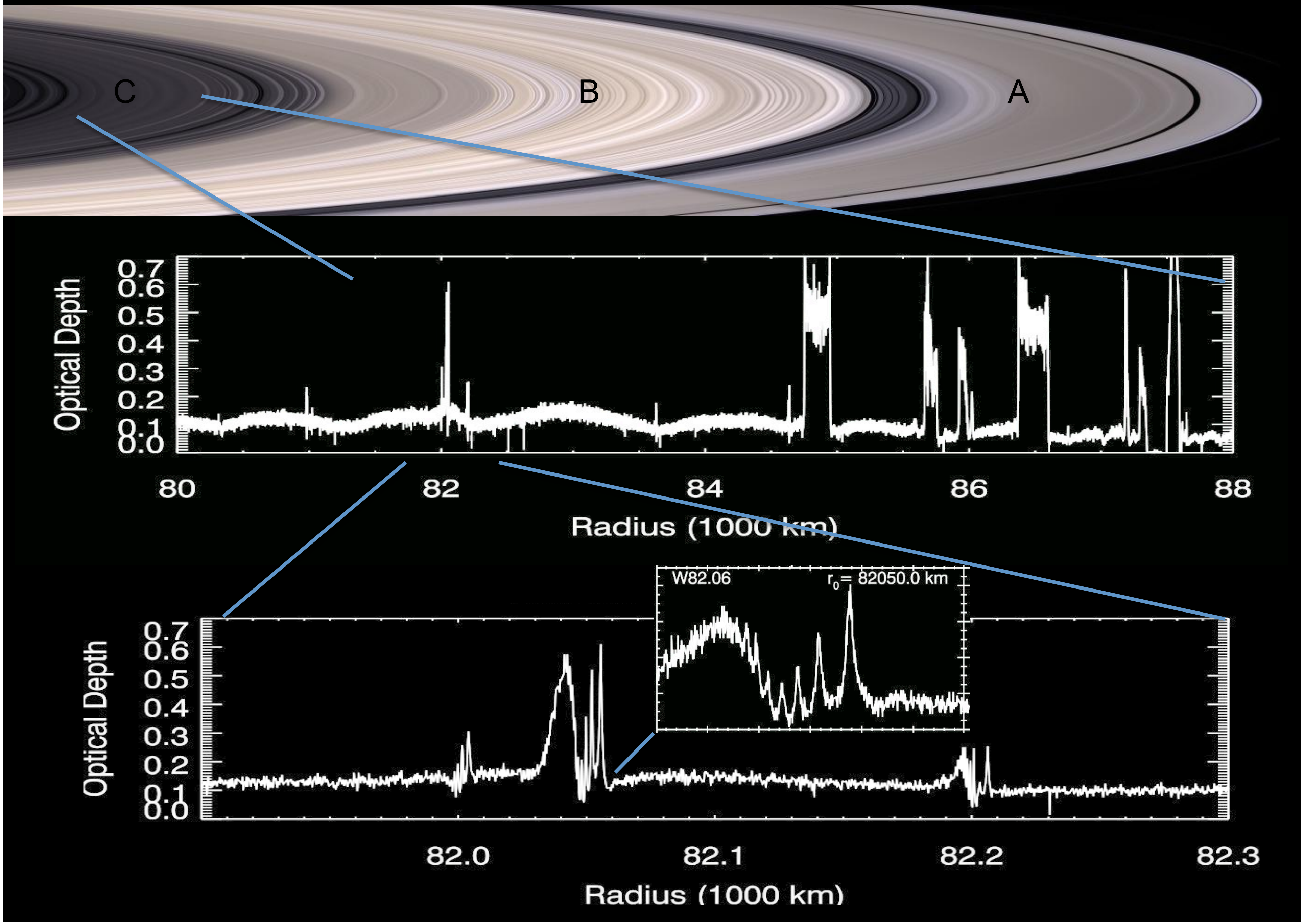
Seismology is a powerful tool for studying interior structures



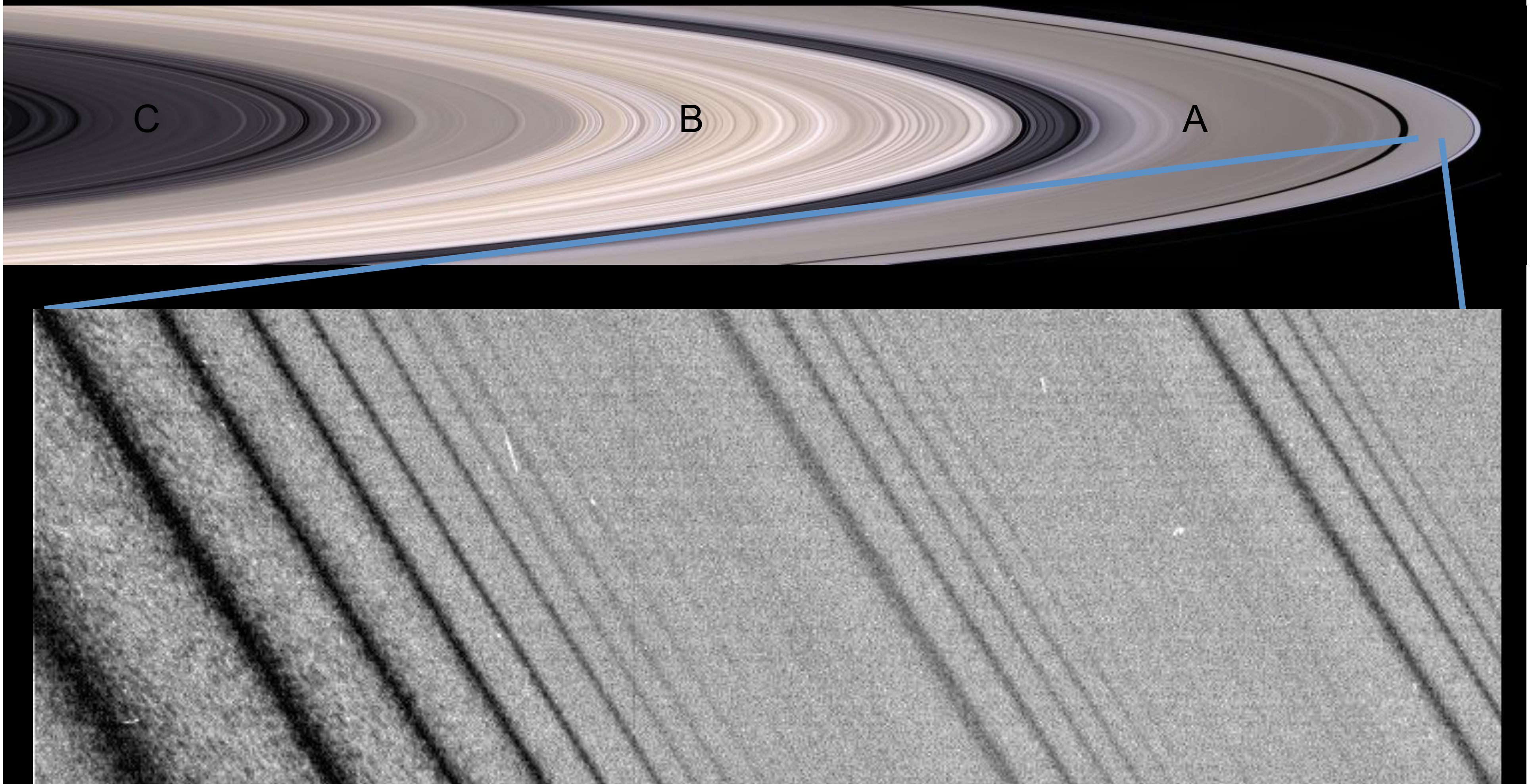




Voyager uncovered spiral patterns in Saturn's C ring



Similar patterns are found in the A ring, near mean-motion resonances with Saturn's moons

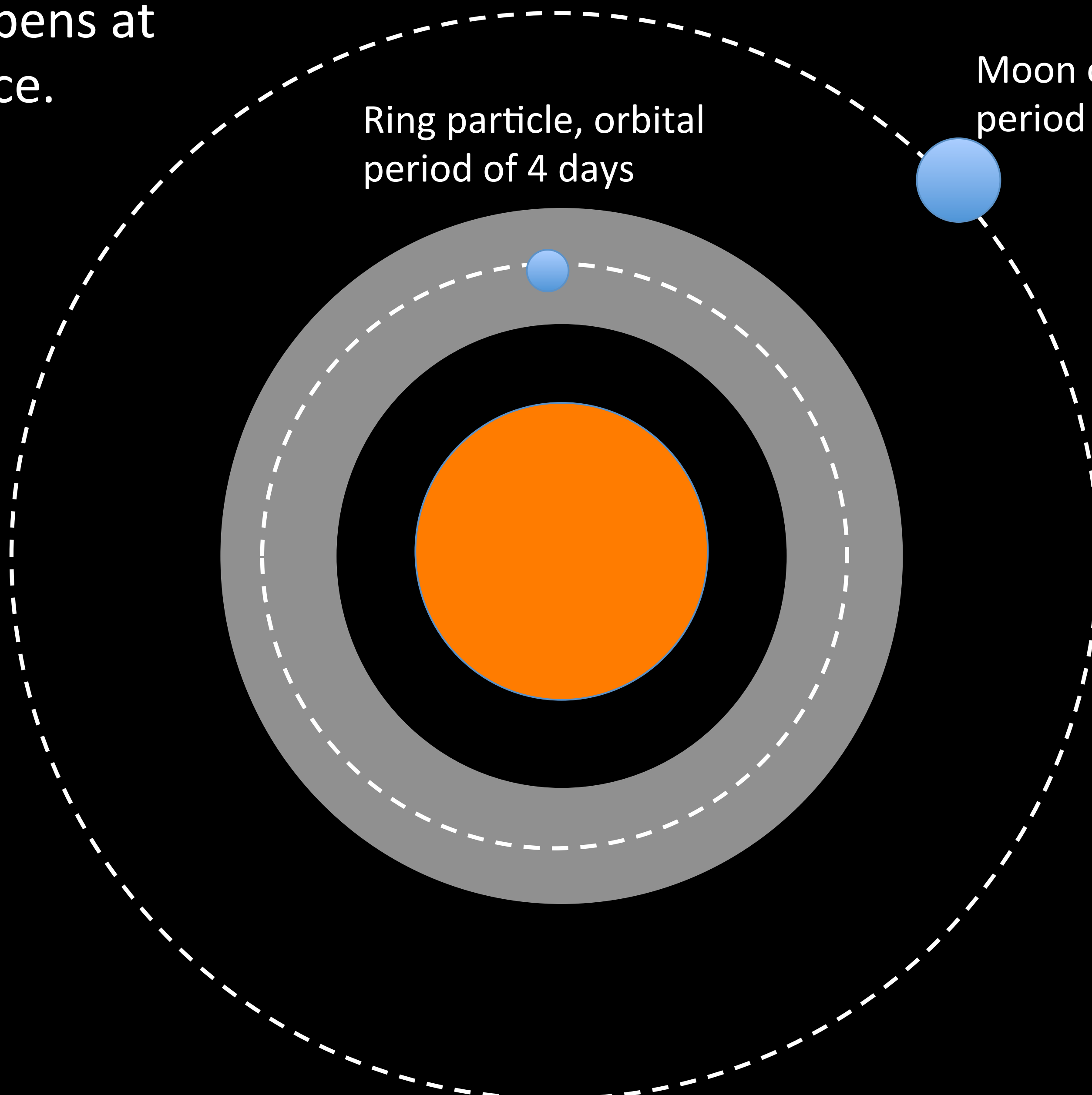


Ring Particle Orbital Period= 5/6 Janus' Orbital Period

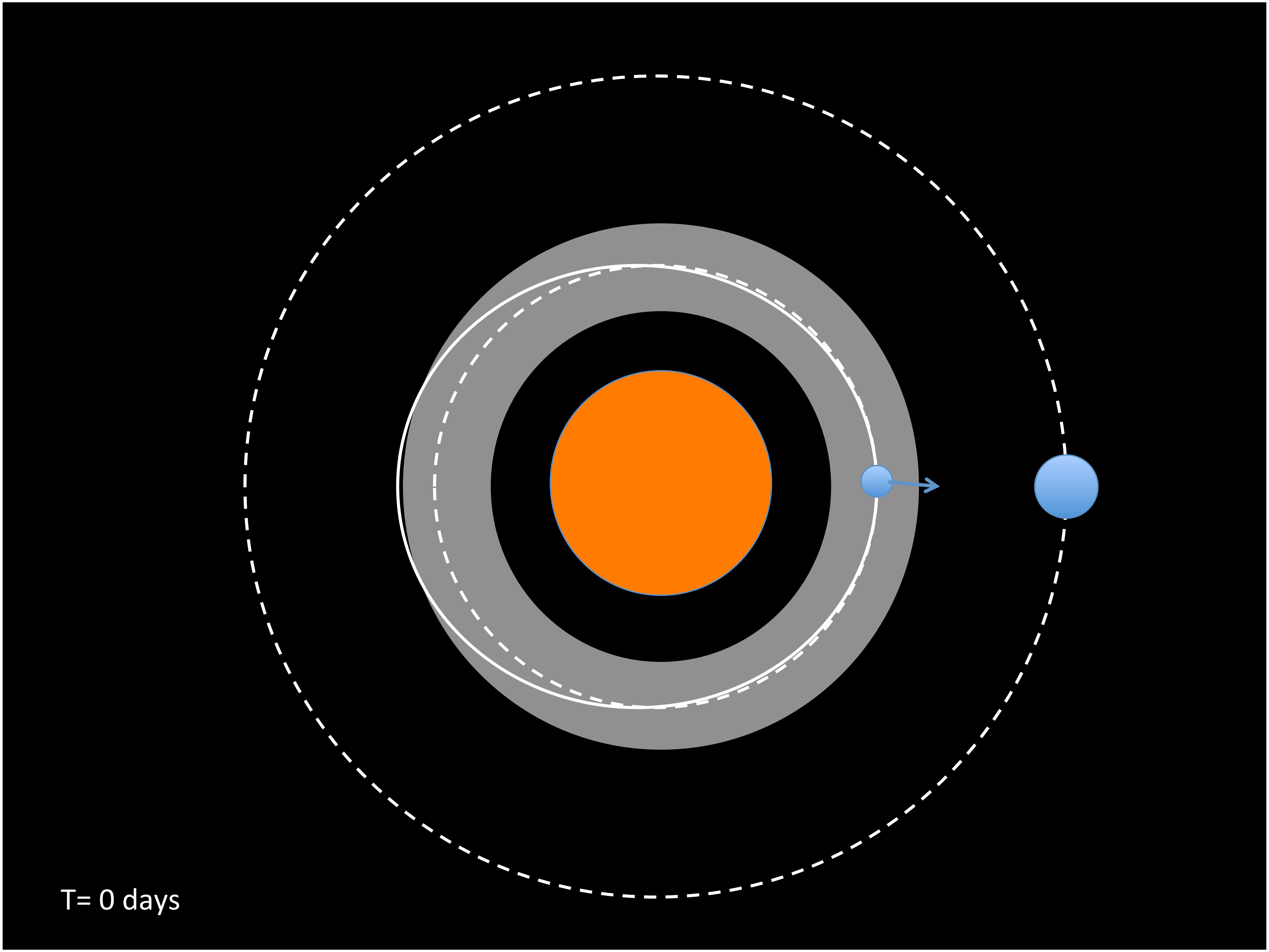
Ring Particle Orbital Period= 12/13 Pandora's Orbital Period

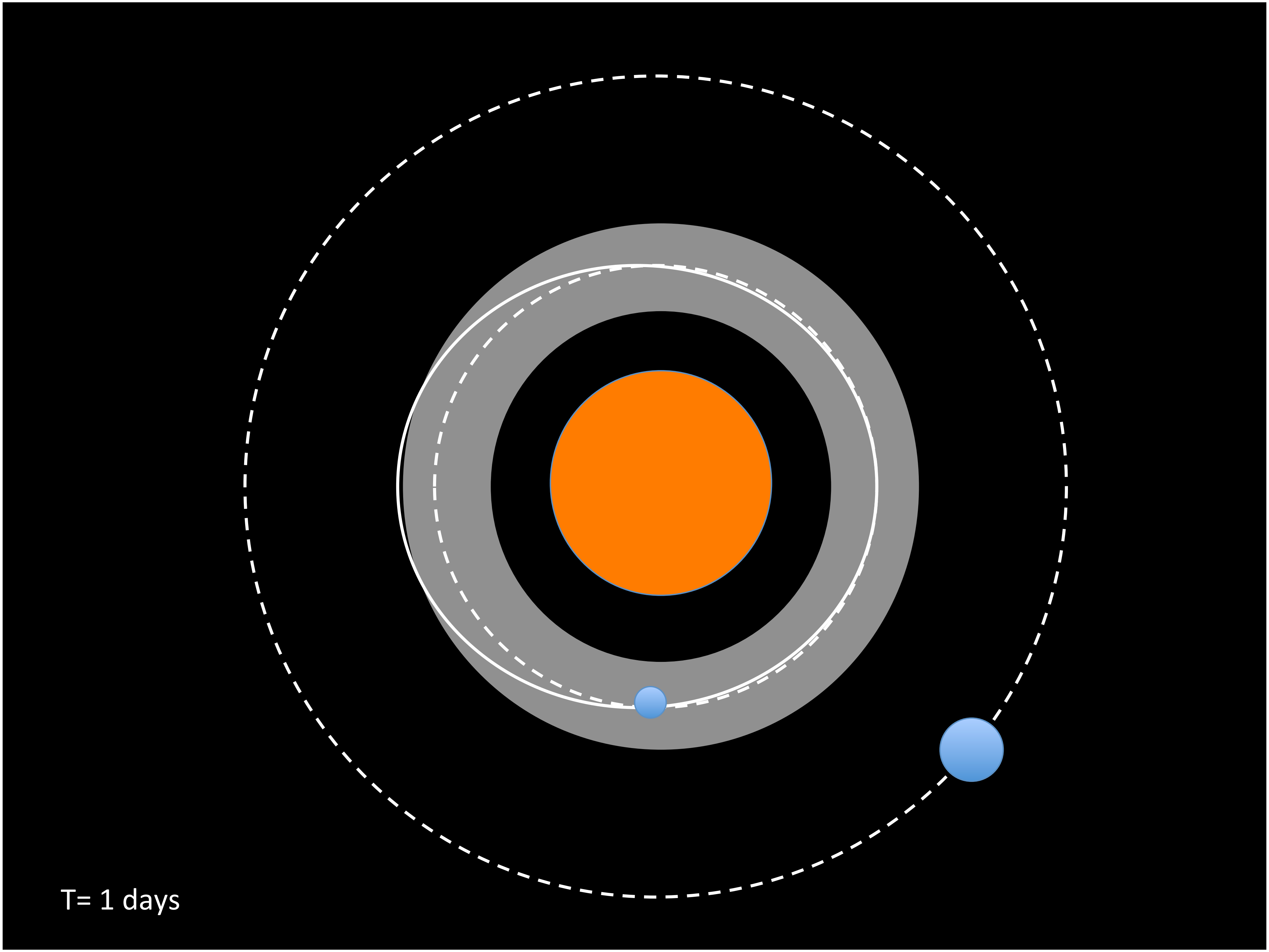
Ring Particle Orbital Period= 18/19 Prometheus' Orbital Period

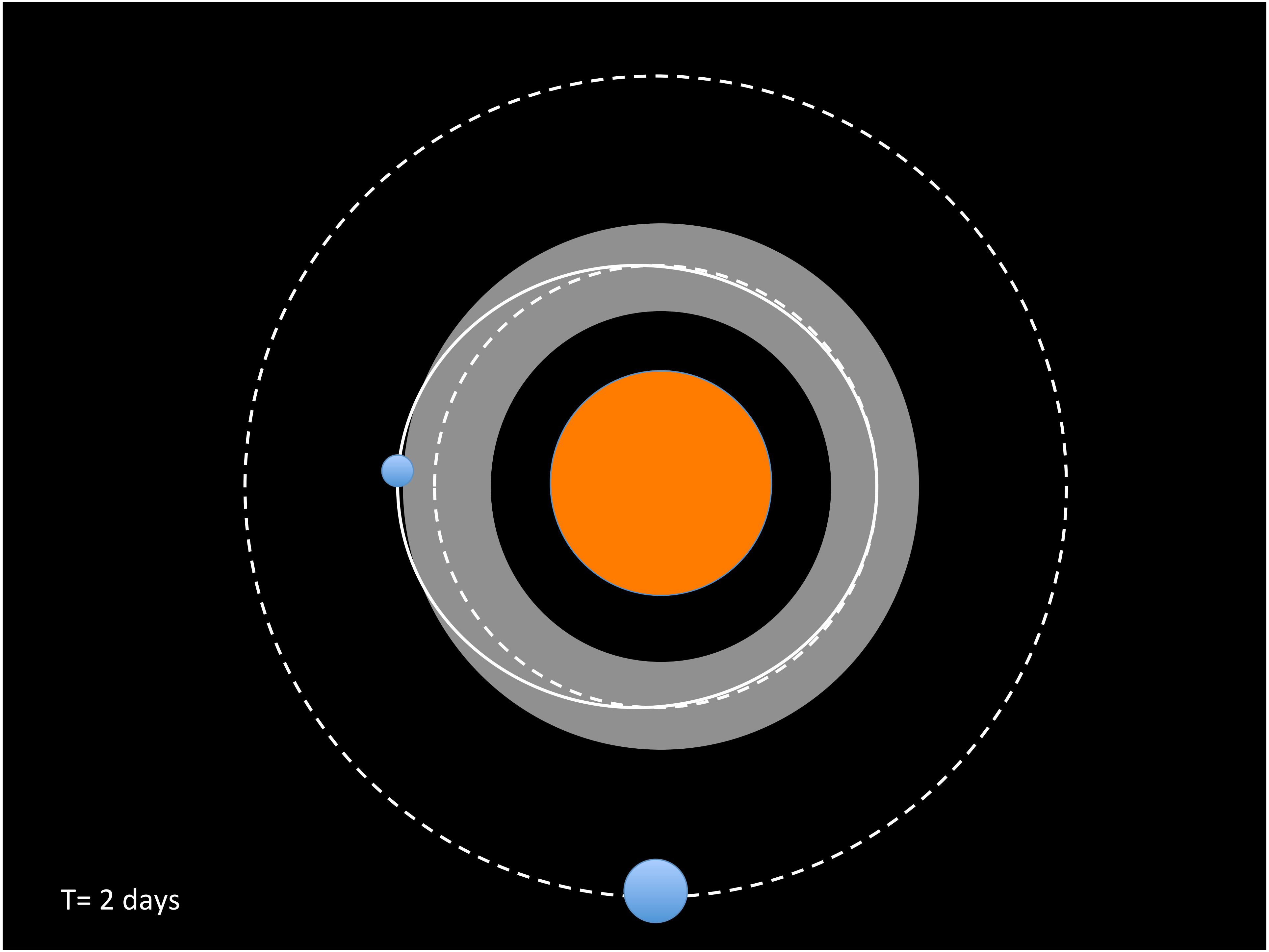
What happens at a resonance.

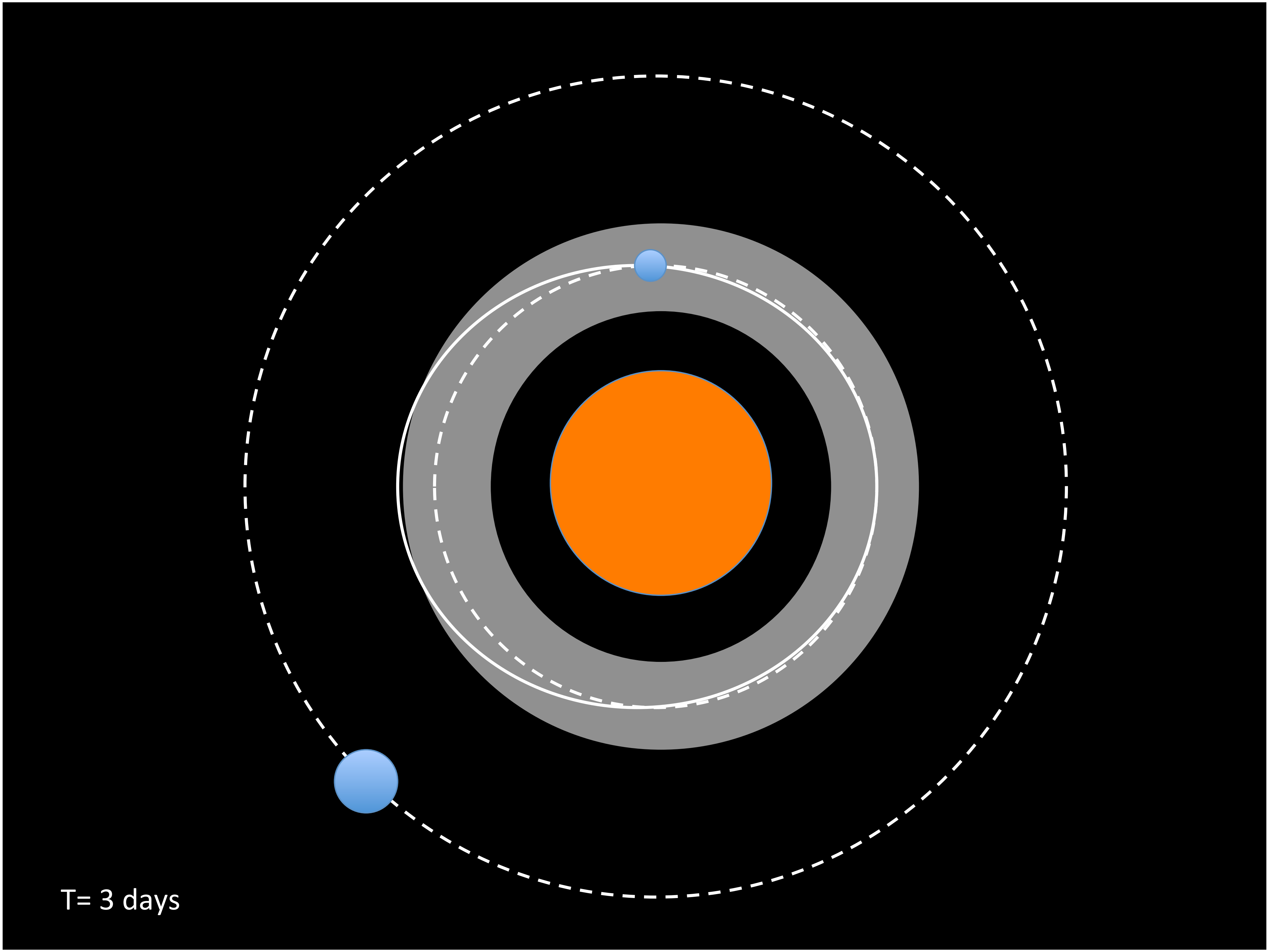


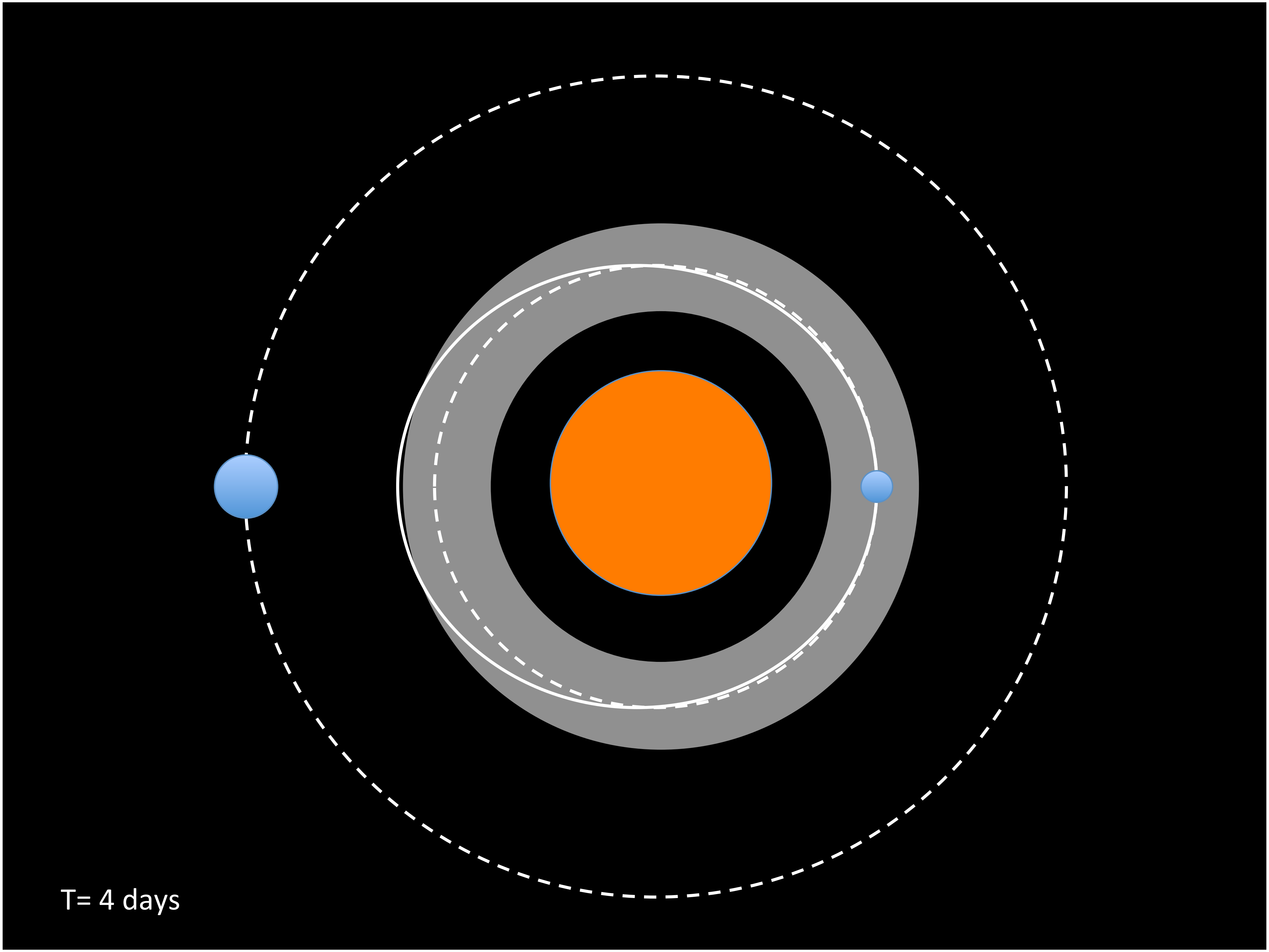
T= -1 days

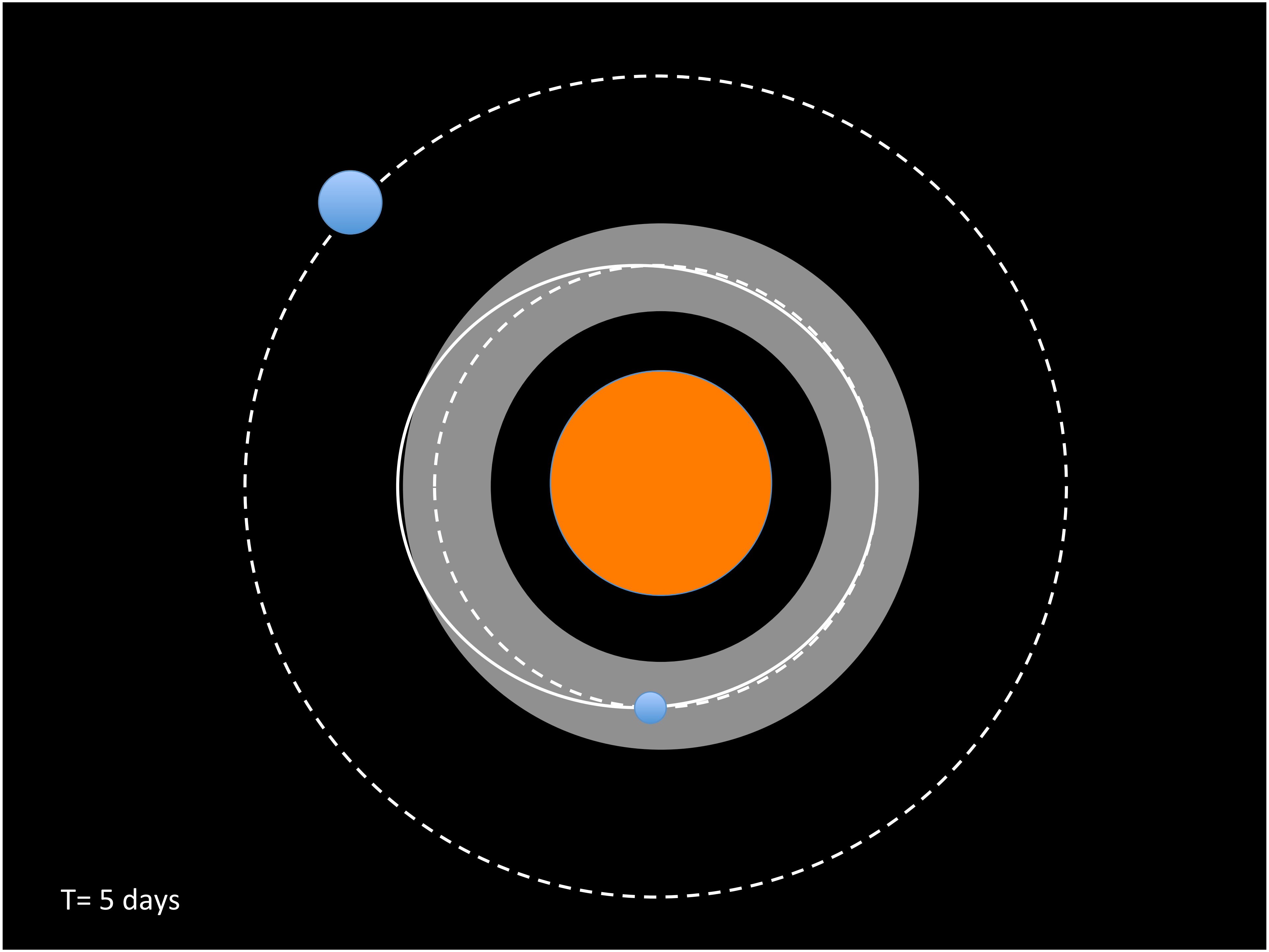

T= 0 days

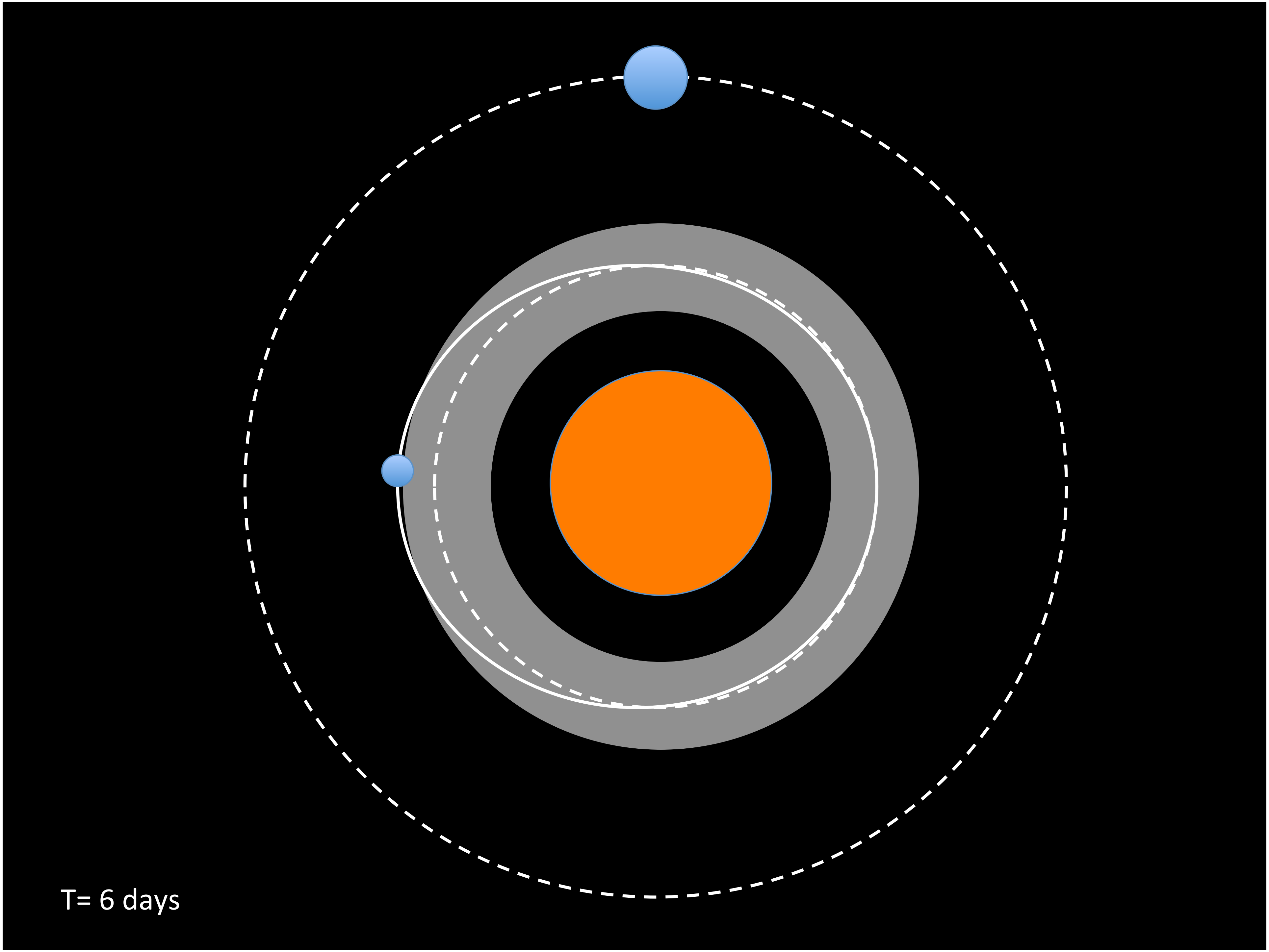

T= 1 days

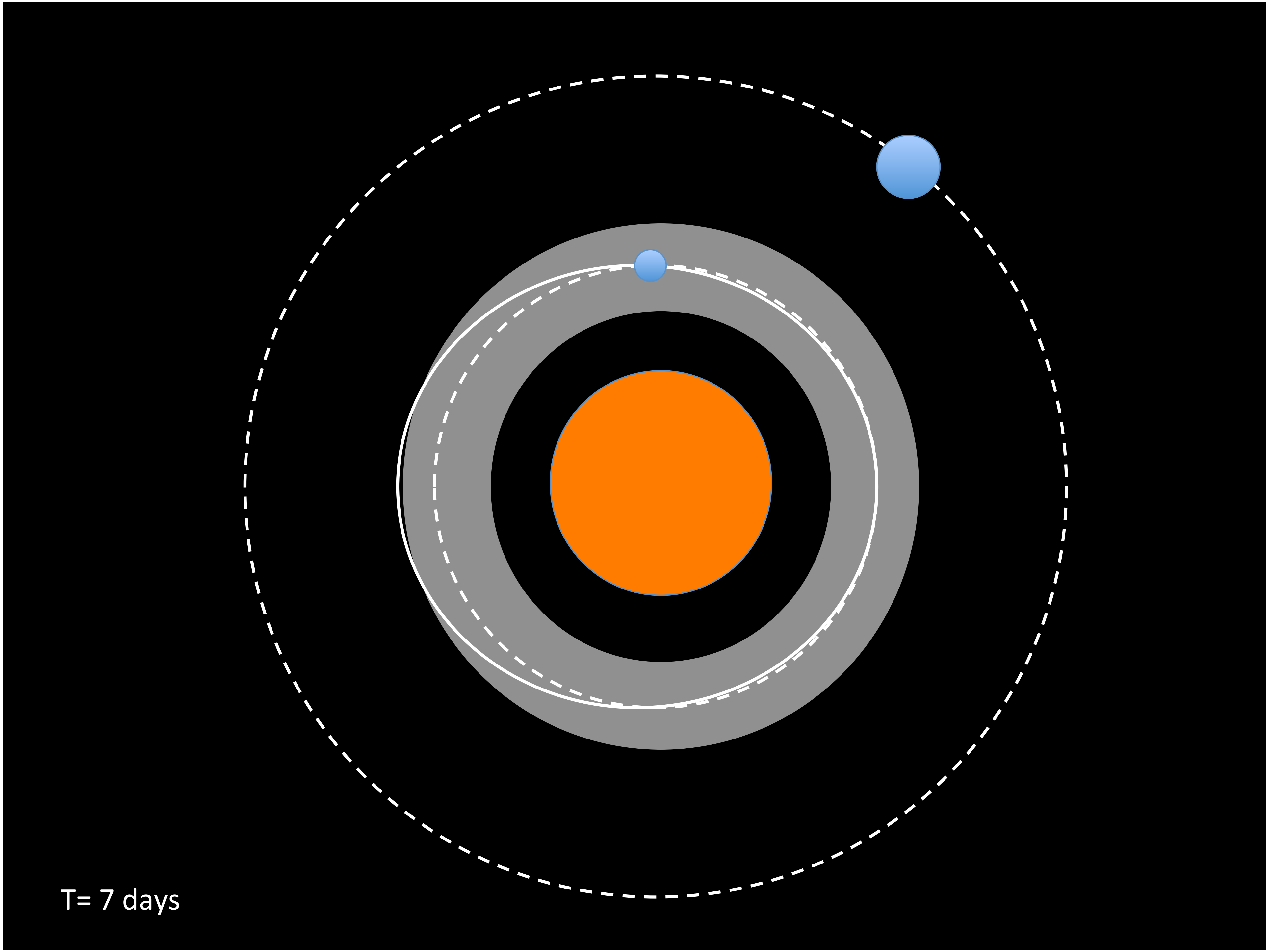

T= 2 days

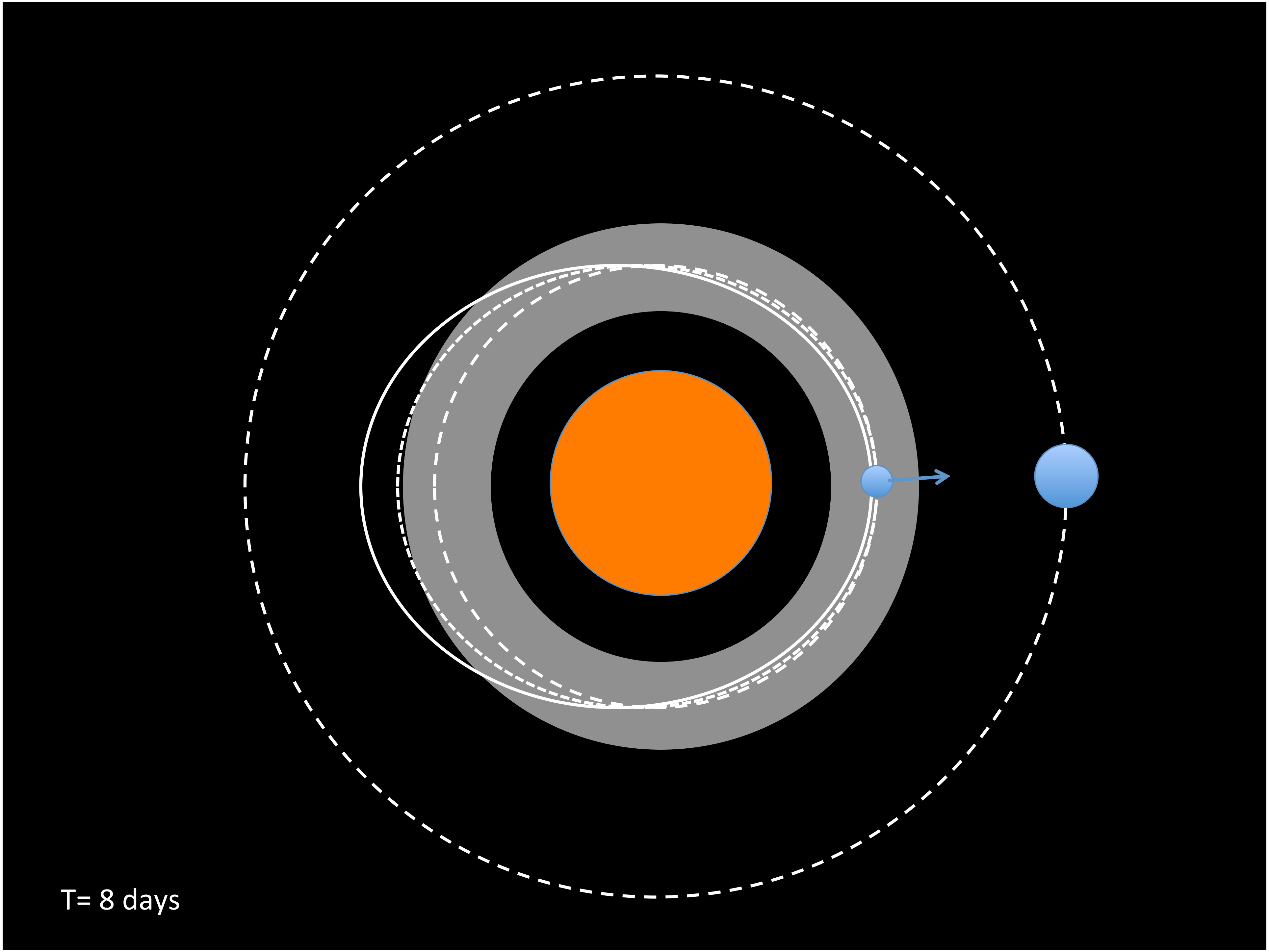

T= 3 days


T= 4 days

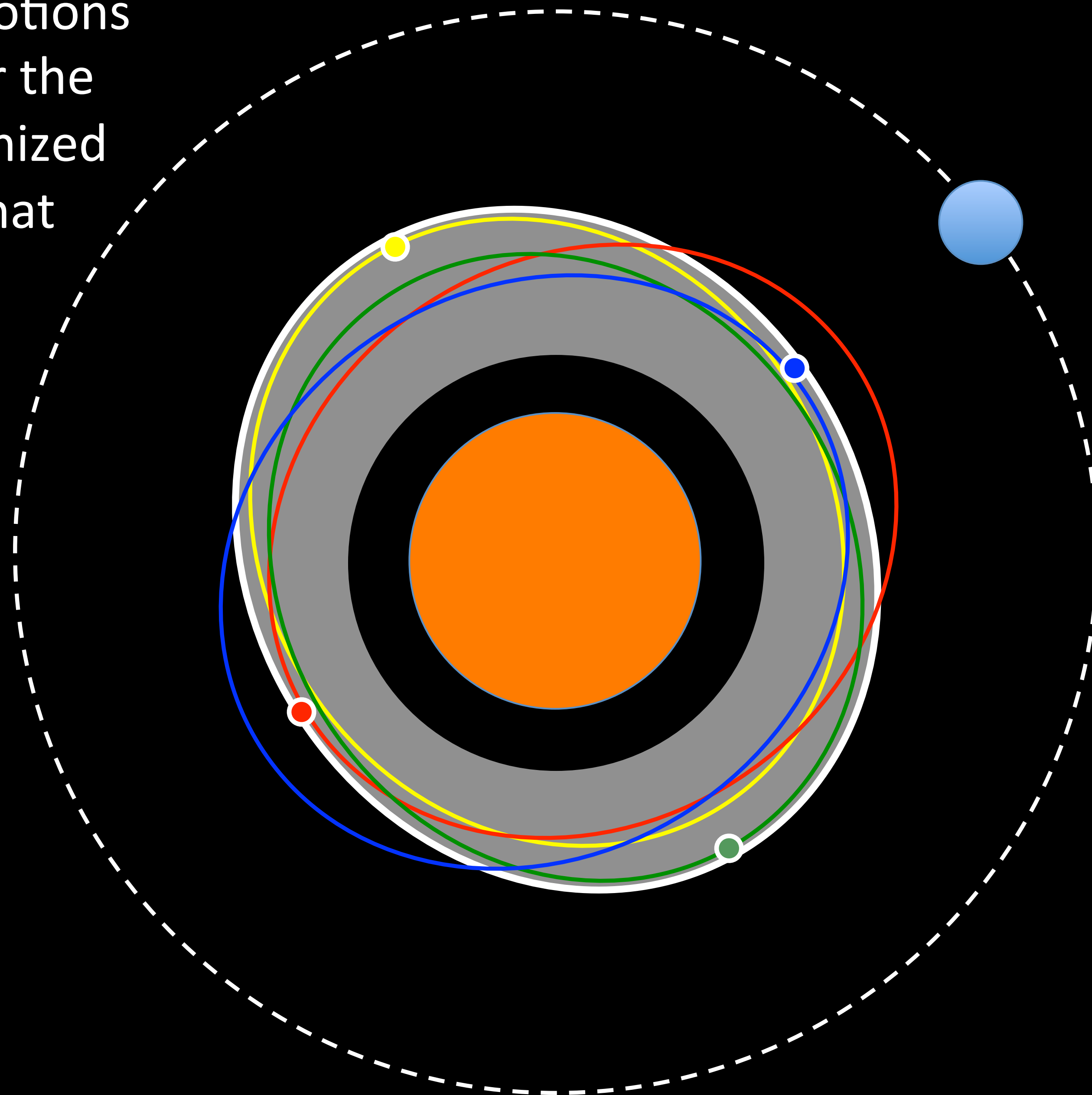

T= 5 days


T= 6 days

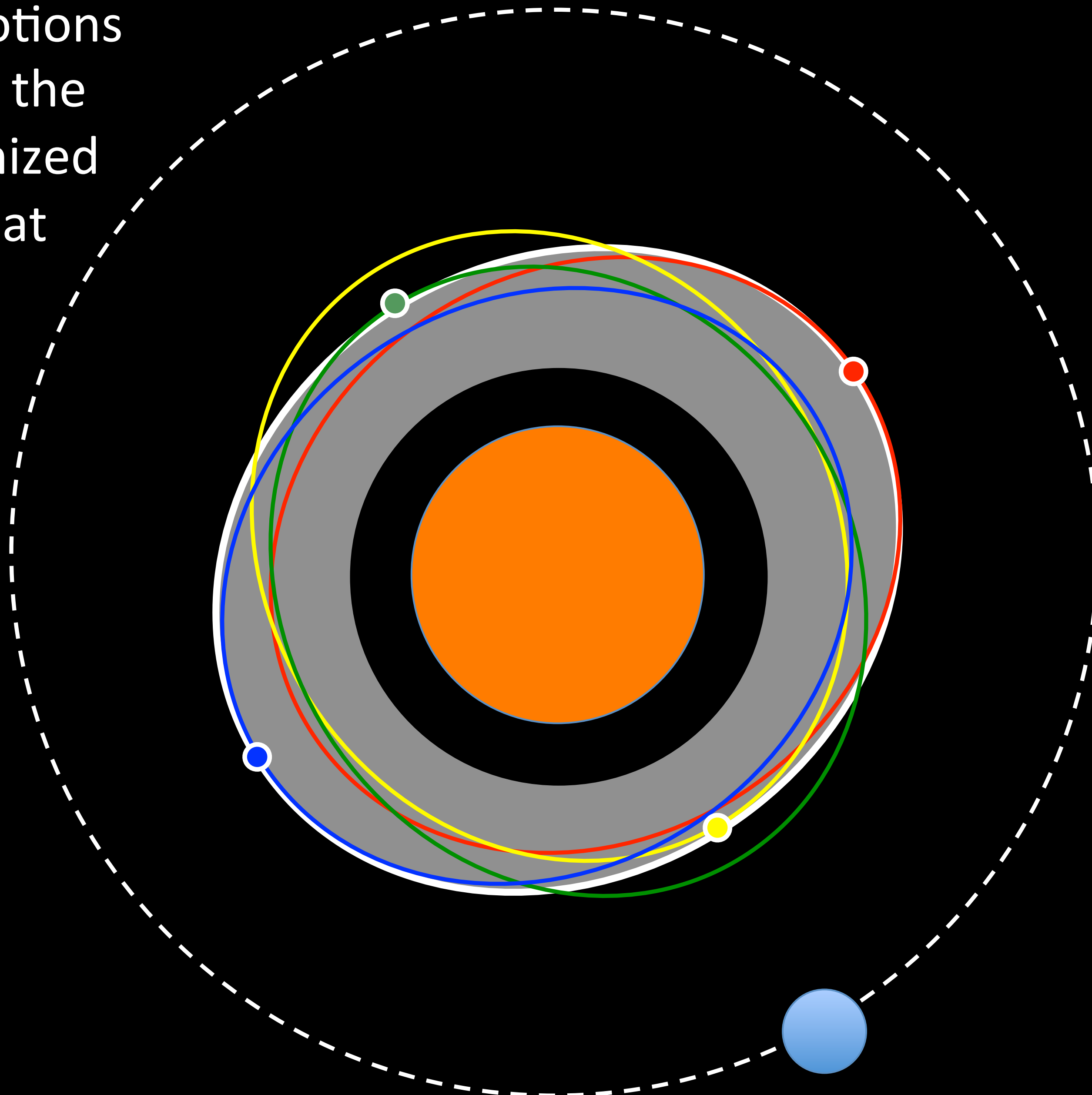

T= 7 days


T= 8 days

The non-circular motions of the particles near the resonance are organized forming a pattern that tracks the moon.



The non-circular motions of the particles near the resonance are organized forming a pattern that tracks the moon.



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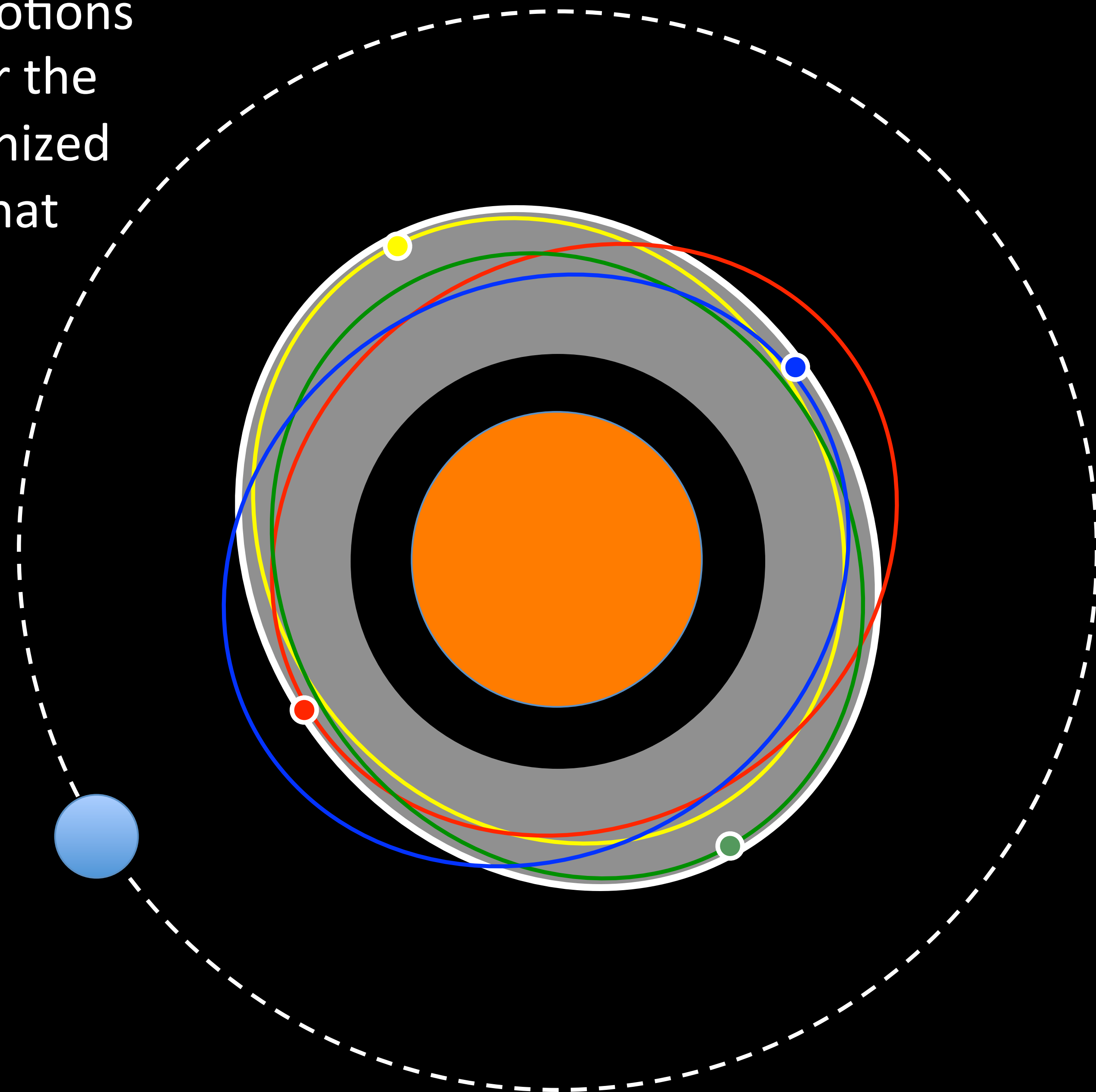
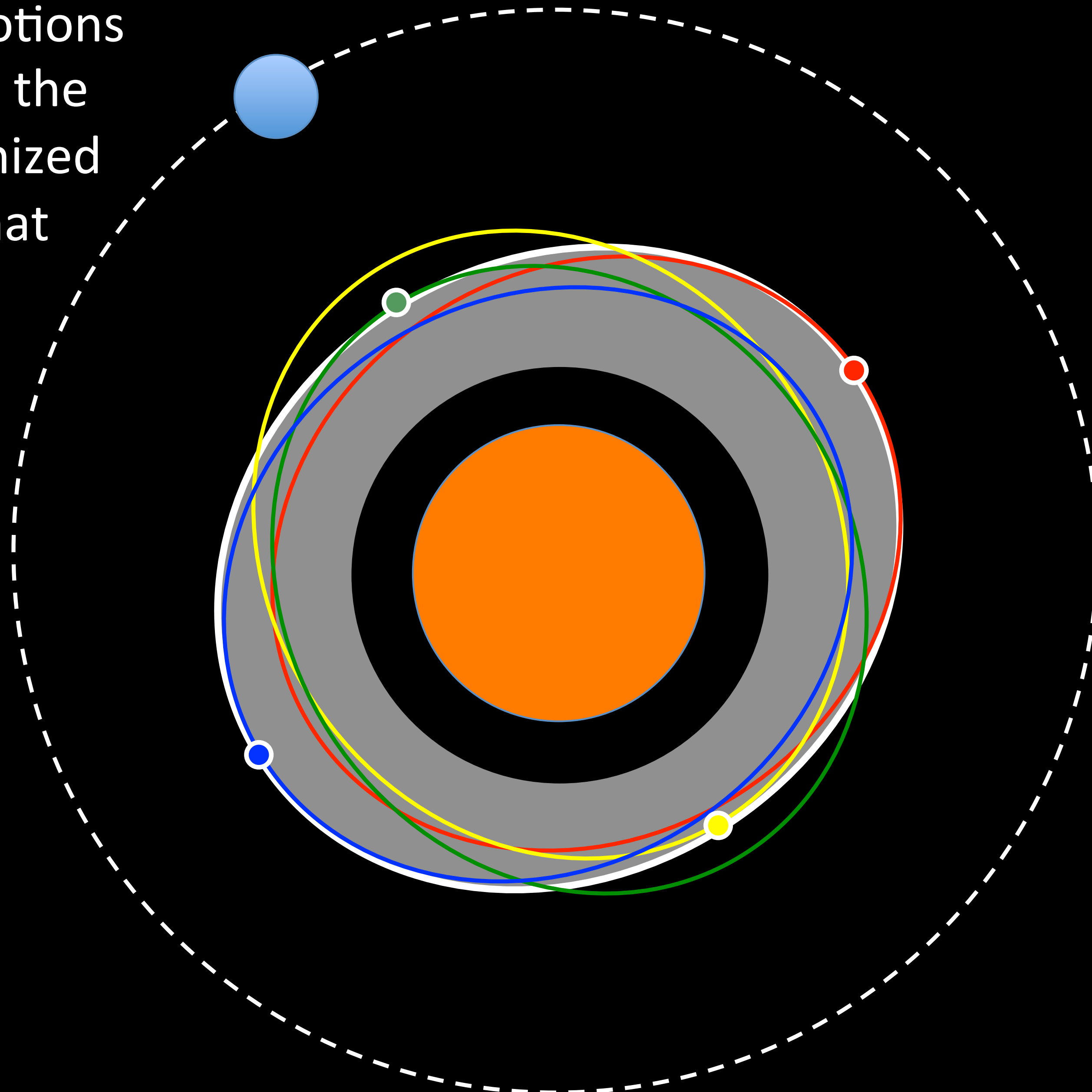
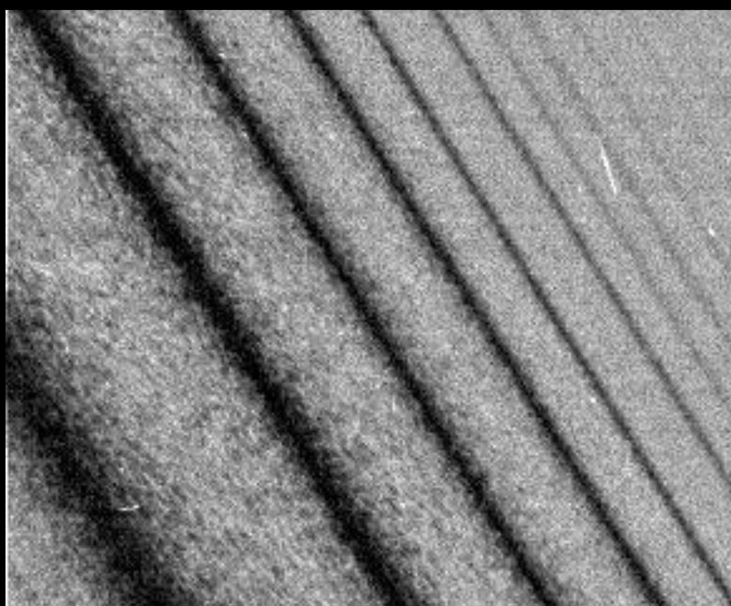


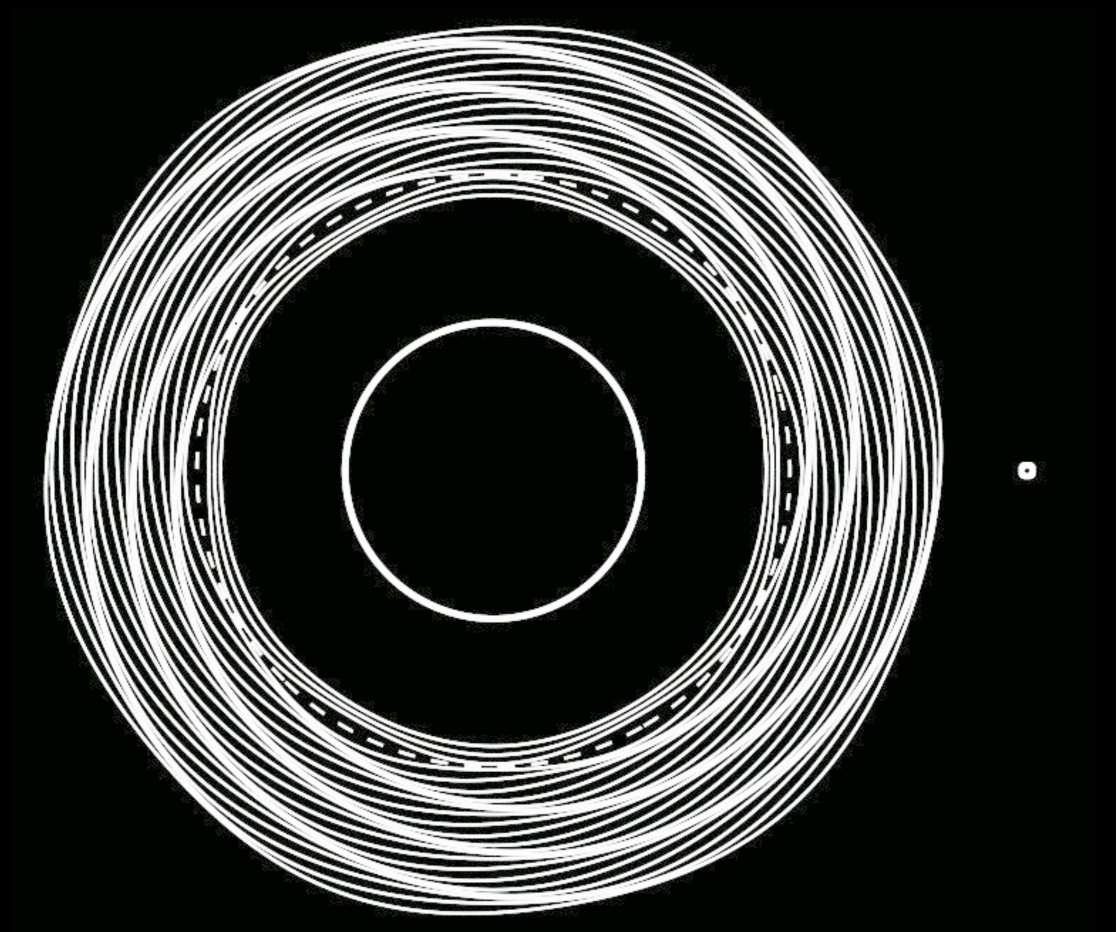
The non-circular motions of the particles near the resonance are organized forming a pattern that tracks the moon.



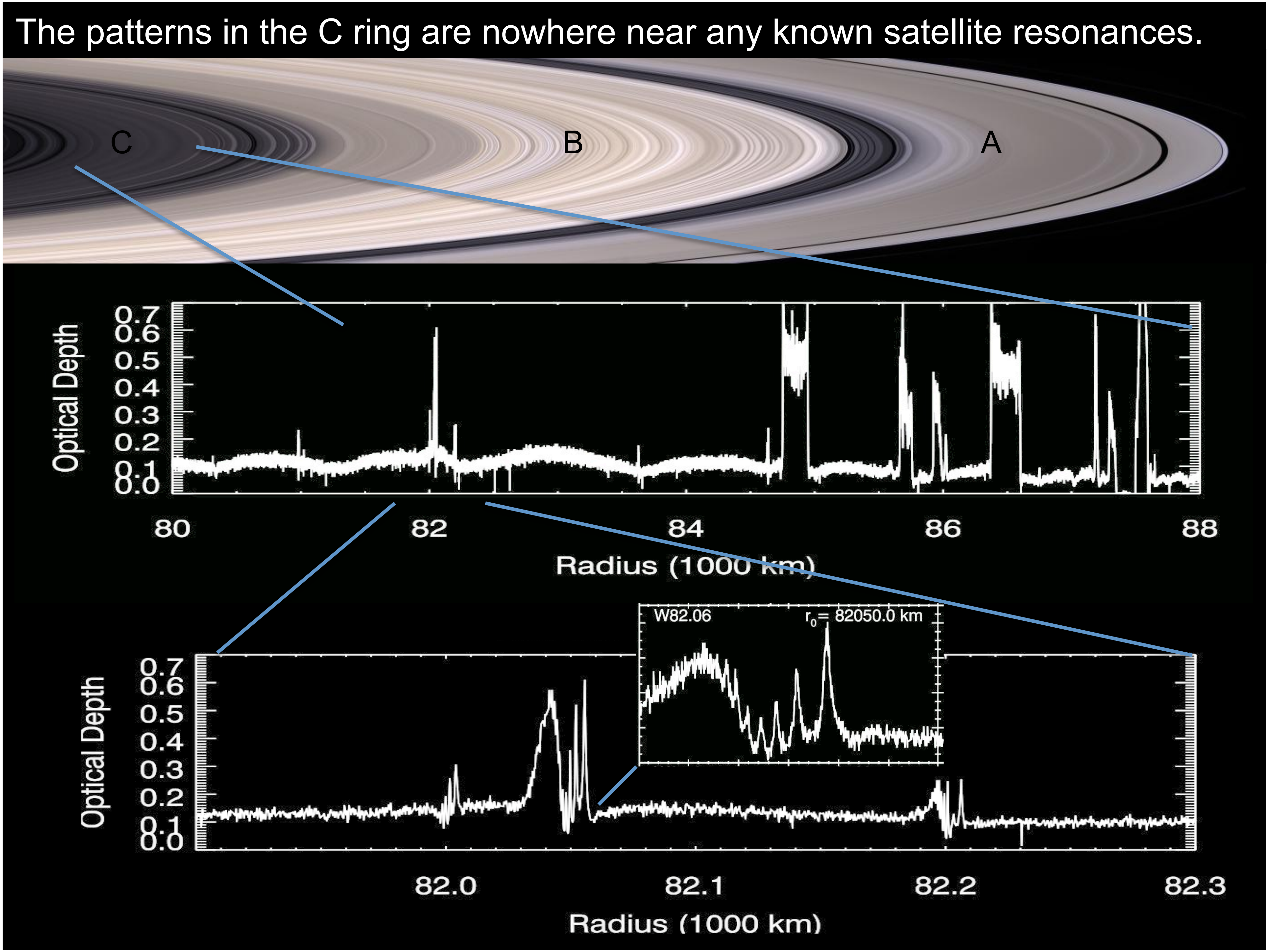
In dense rings, these organized motions drive a propagating spiral wave through the ring



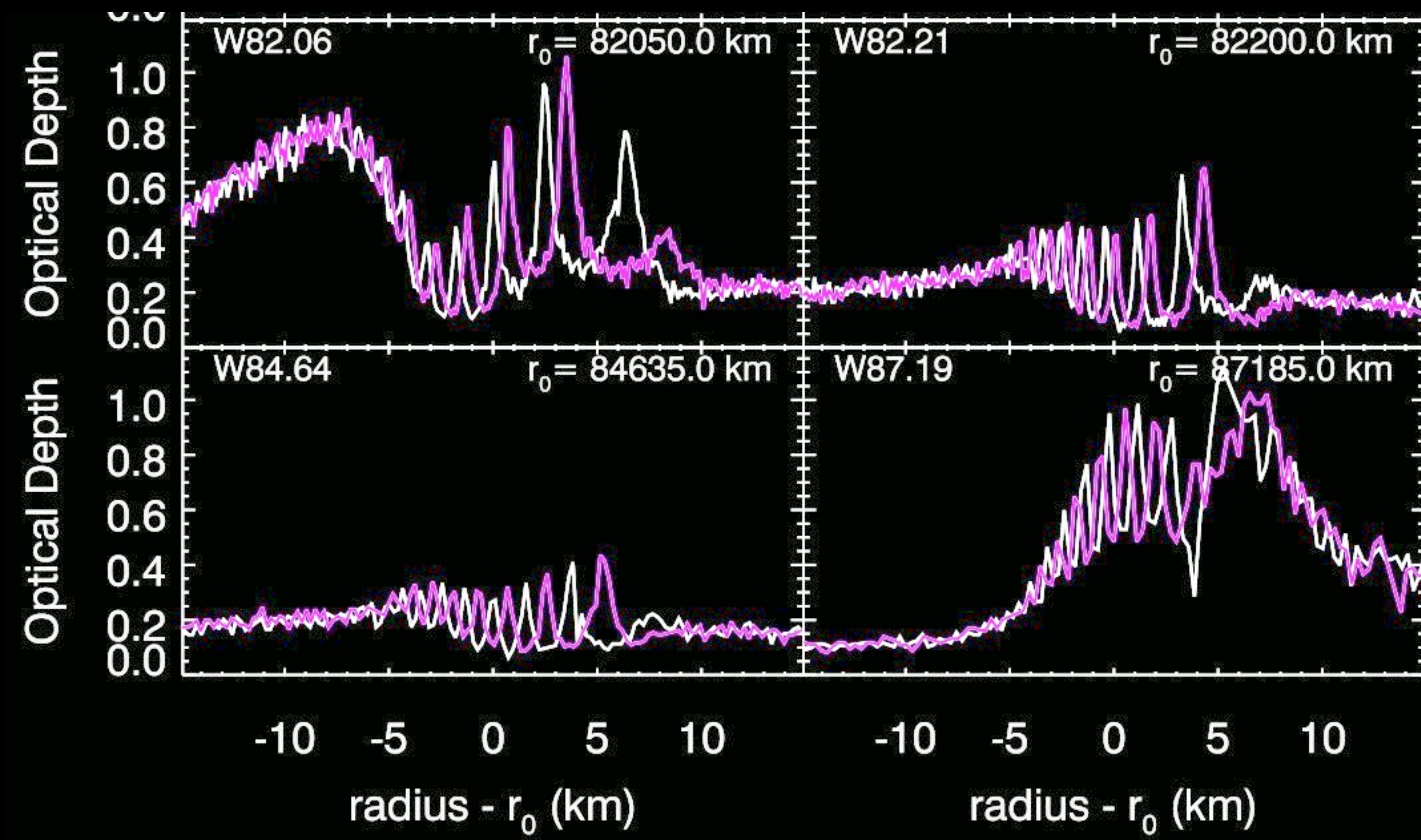
Ring Particle
Orbital Period=
5/6 Janus'
Orbital Period



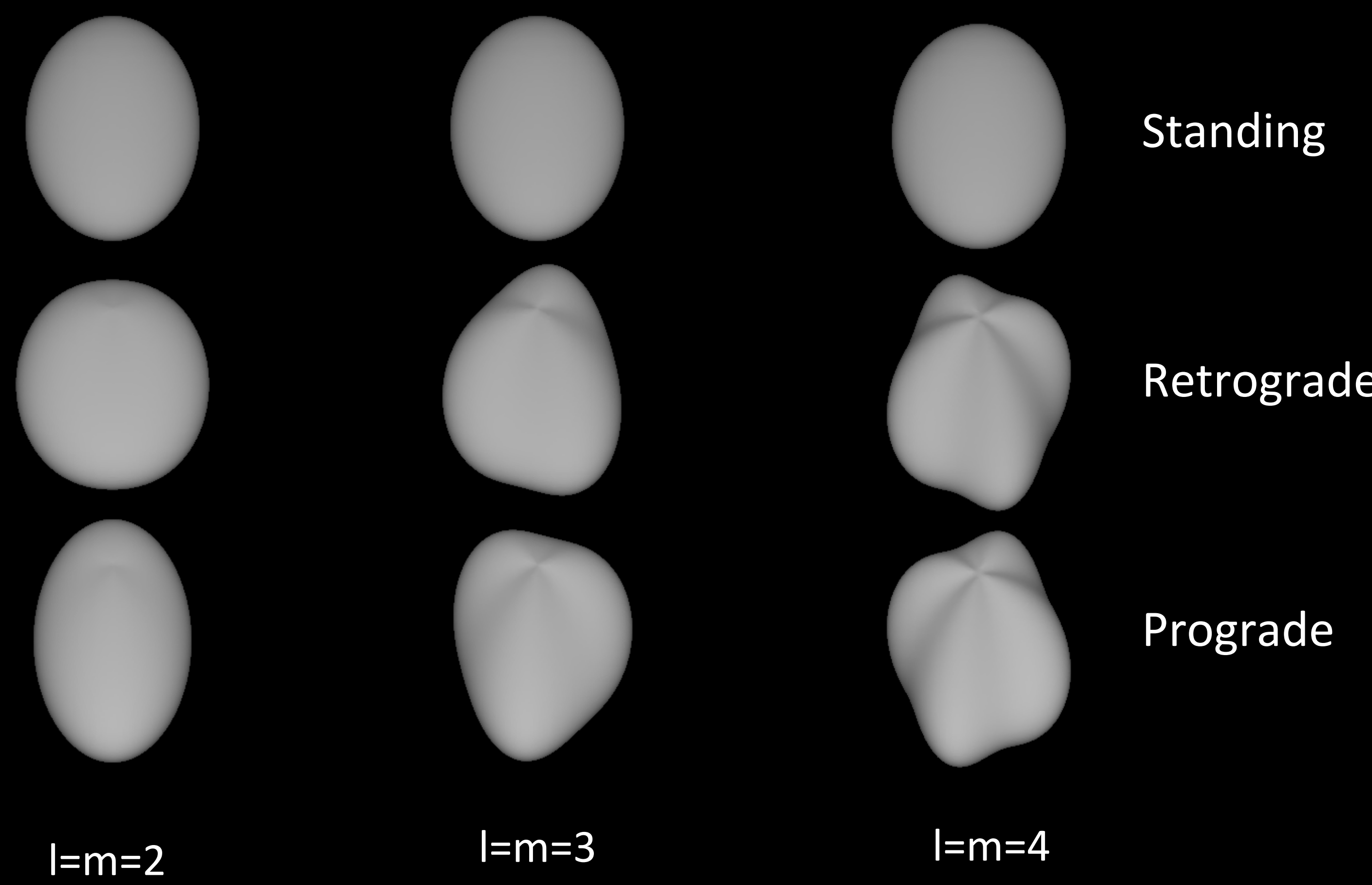
The wave pattern maintains a fixed orientation relative to the moon.


The patterns in the C ring are nowhere near any known satellite resonances.
C
B
A
Optical Depth
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
80
82
84
86
88
Radius (1000 km)
W82.06
r_0 = 82050.0 km
Optical Depth
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
82.0
82.1
82.2
82.3
Radius (1000 km)

Shifts in the peak locations between observations made at different times and longitudes confirm that these are spiral patterns.



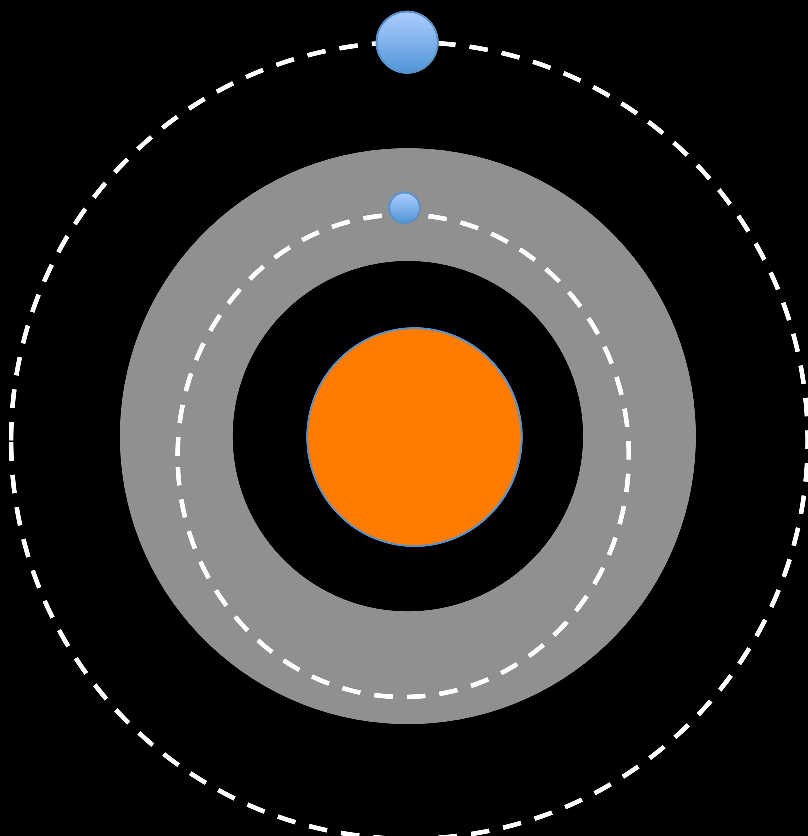
At least some of these waves may be due to sectoral normal mode oscillations within the planet.



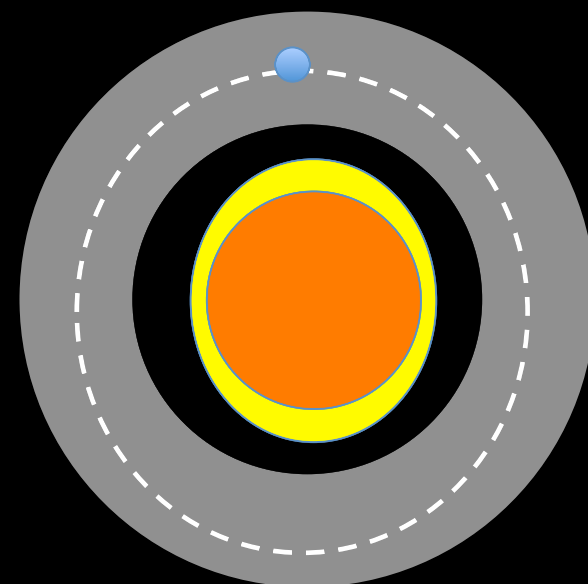
Marley 1991, Marley and Porco 1993

The prograde-propagating oscillations can organize particle motions near resonances much like a moon can

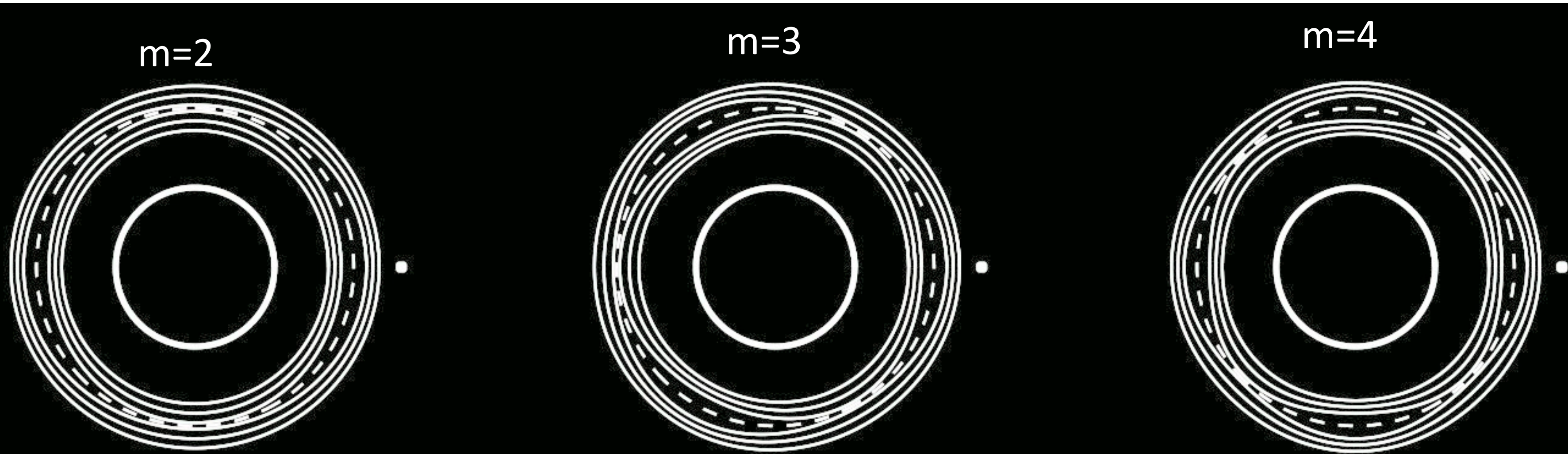
The strongest patterns are found at first-order resonances:
Mode rotation period ≈ *m/(m-1)* x Ring-particle's orbit period



Moon orbit period=
1/2 Ring particle orbit period



Mode rotation period=
3/2 Ring particle orbit period

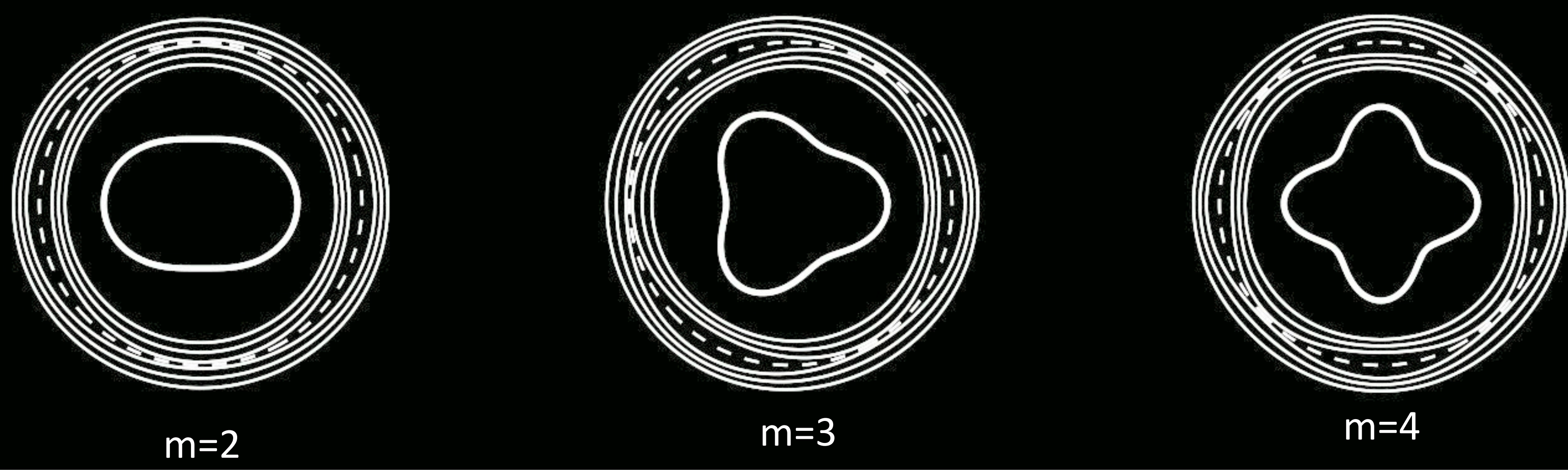


A single moon can generate multiple resonant structures

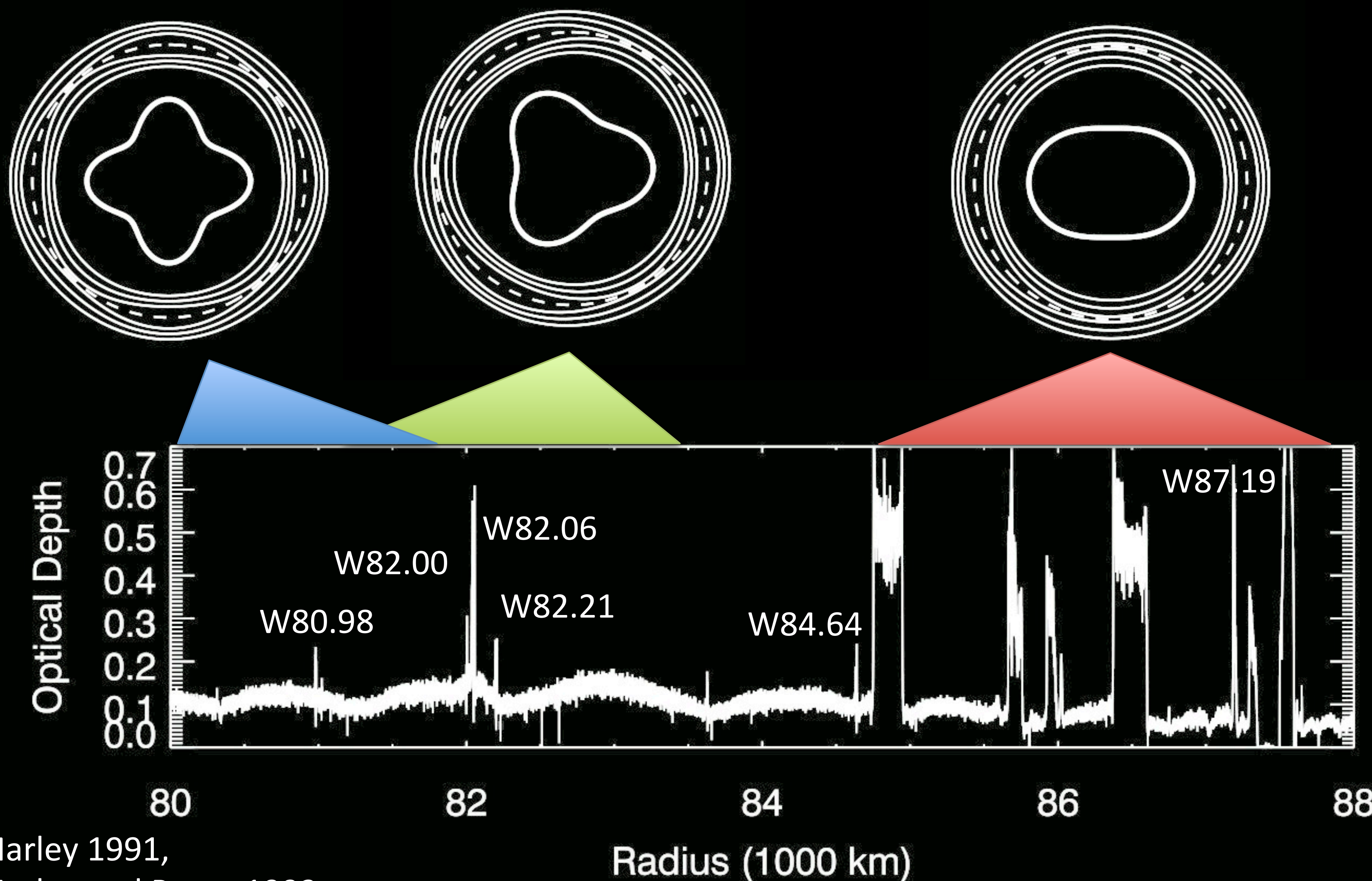
All the patterns rotate around the planet at the same speed

A planetary oscillation mode generates a single resonant structure

Each pattern rotates around the planet at a different speed.

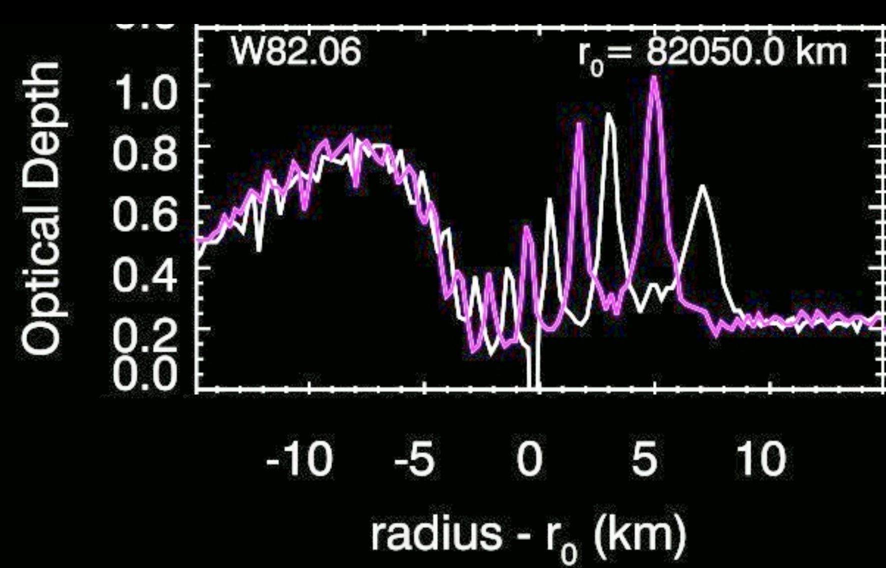


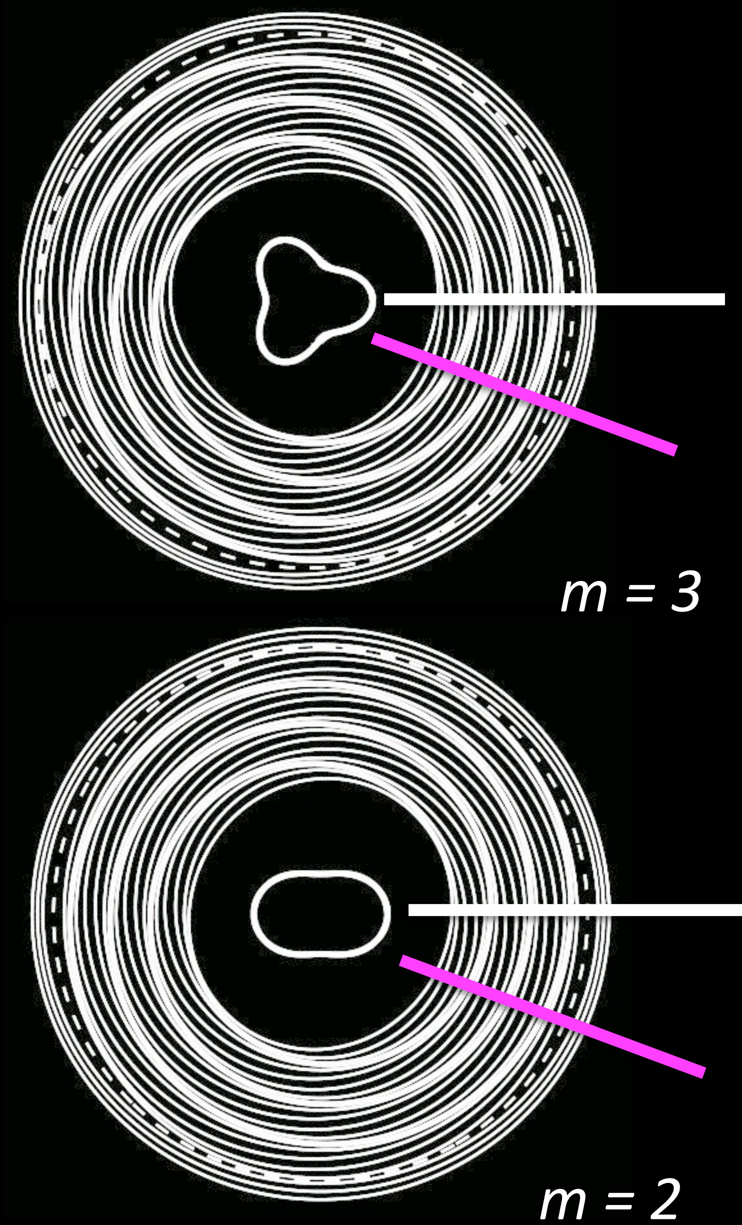
Previous theoretical calculations had shown that some of the unidentified waves could be close to resonance with these modes

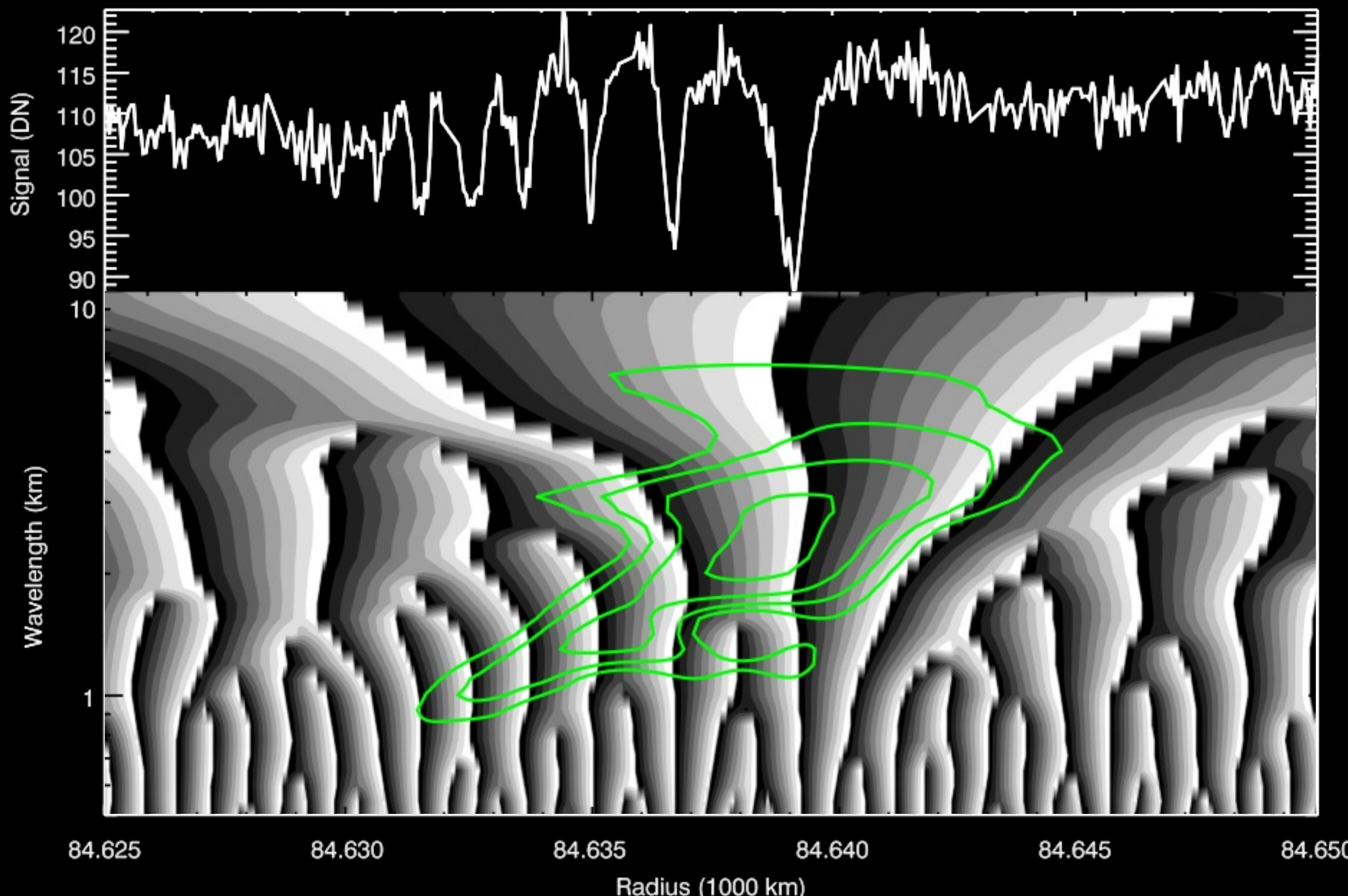


Marley 1991,
Marley and Porco 1993

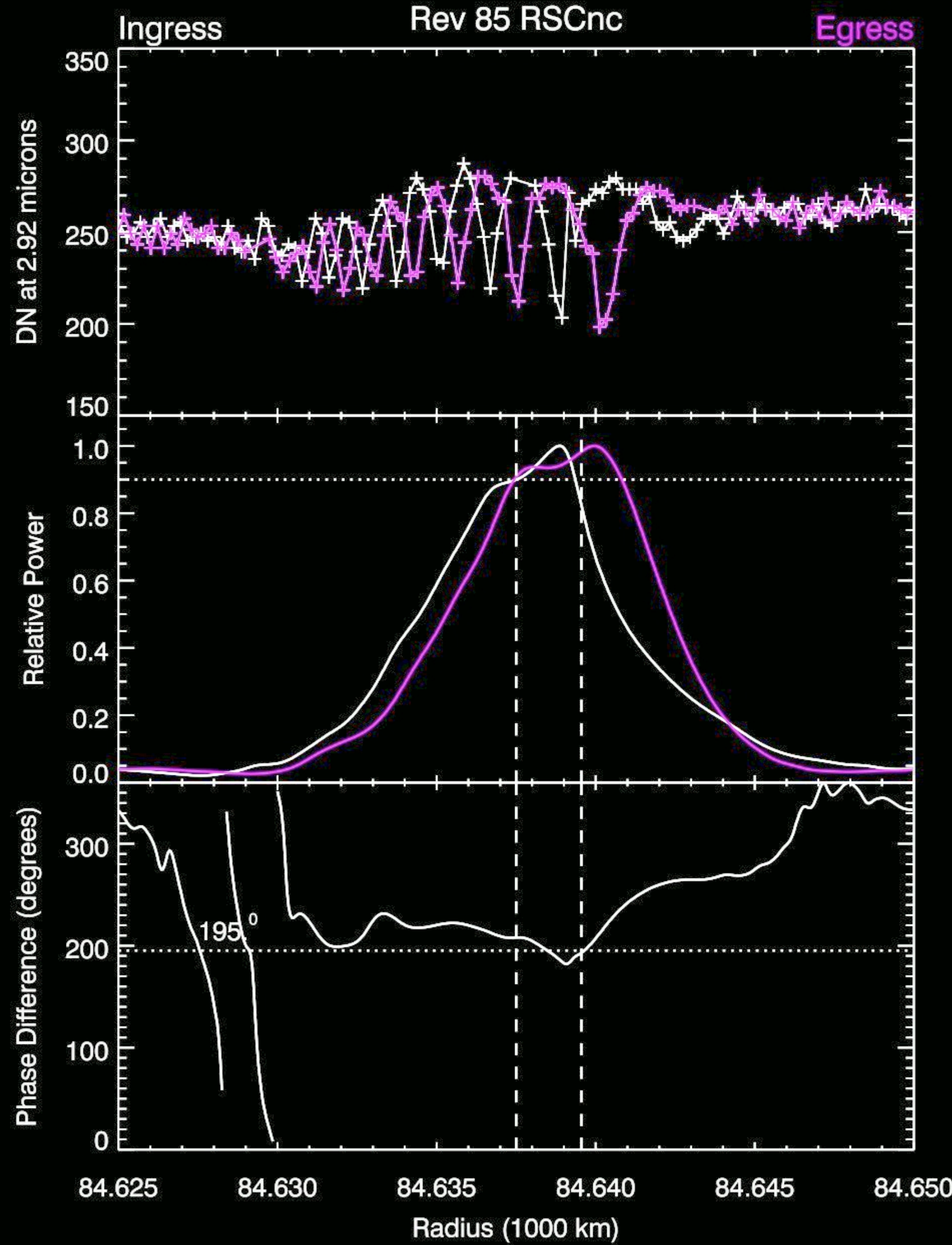
We can determine the m-numbers and pattern speeds of these waves by comparing observations taken at different times and longitudes.



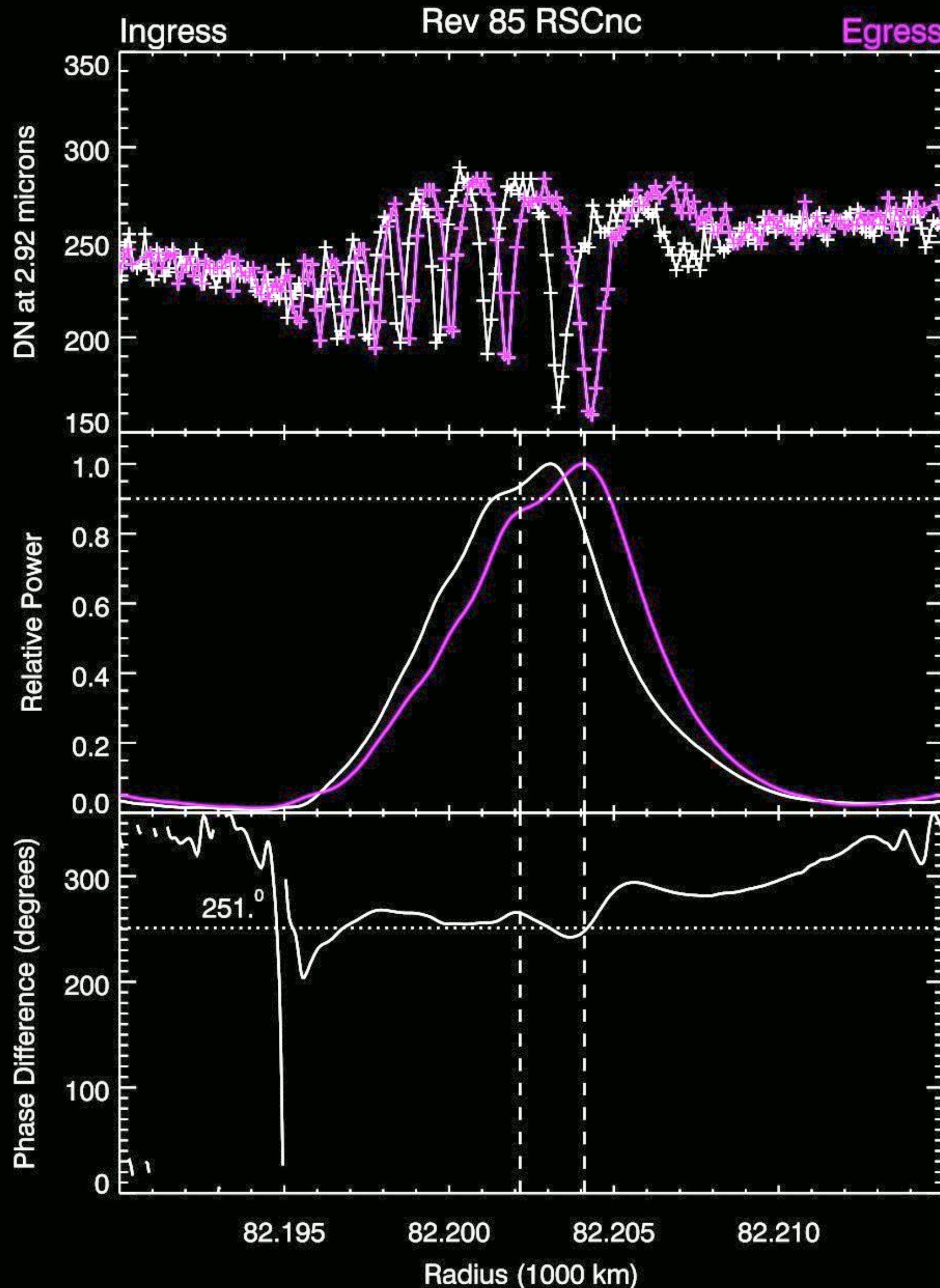



Signal (DN)
120
115
110
105
100
95
90
Wavelength (km)
10
1
84.625
84.630
84.635
84.640
84.645
84.650
Radius (1000 km)

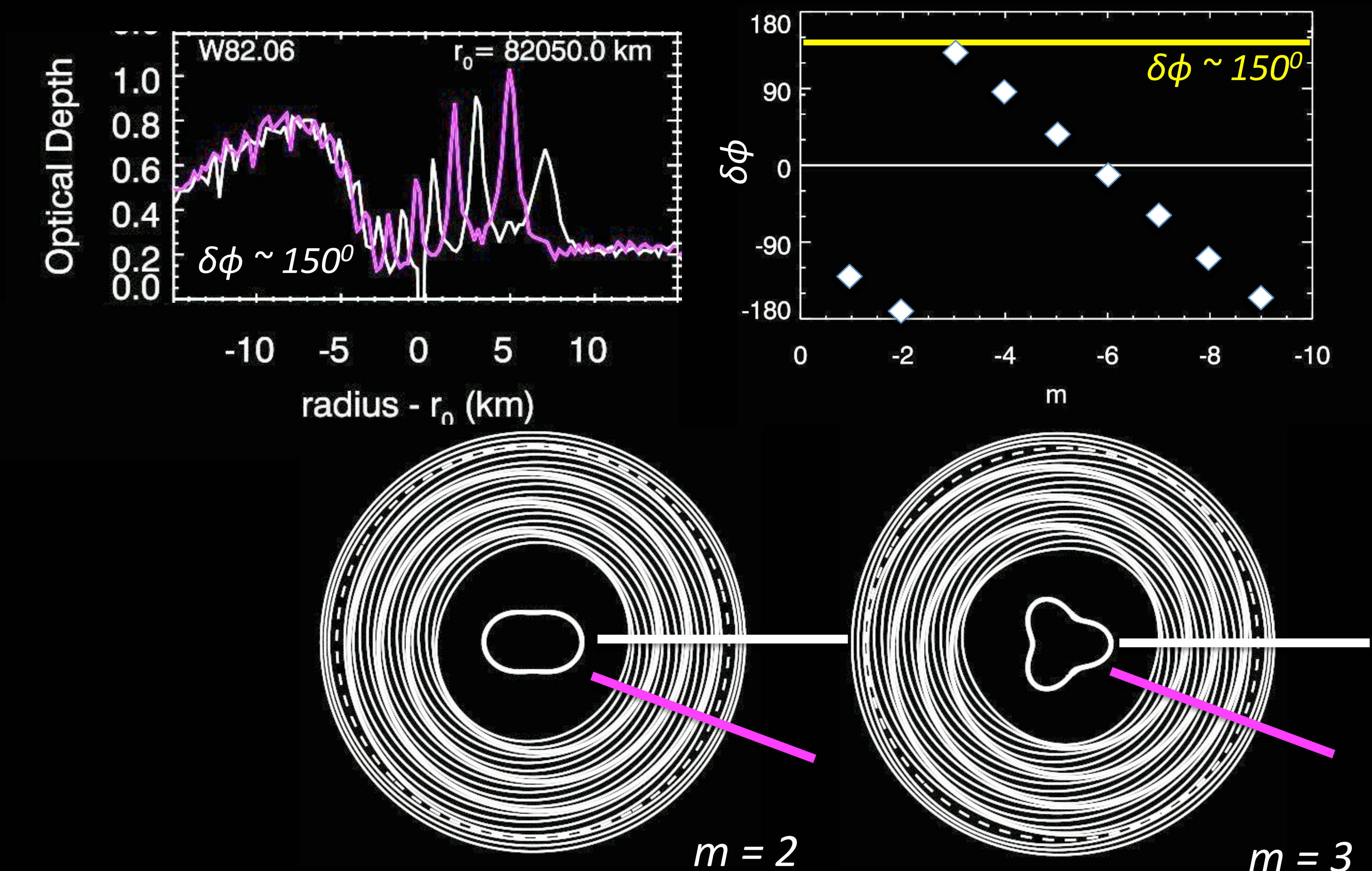
For any pair of occultations, we can compute a *phase difference δφ* that quantifies how much the peaks and troughs are out of line.



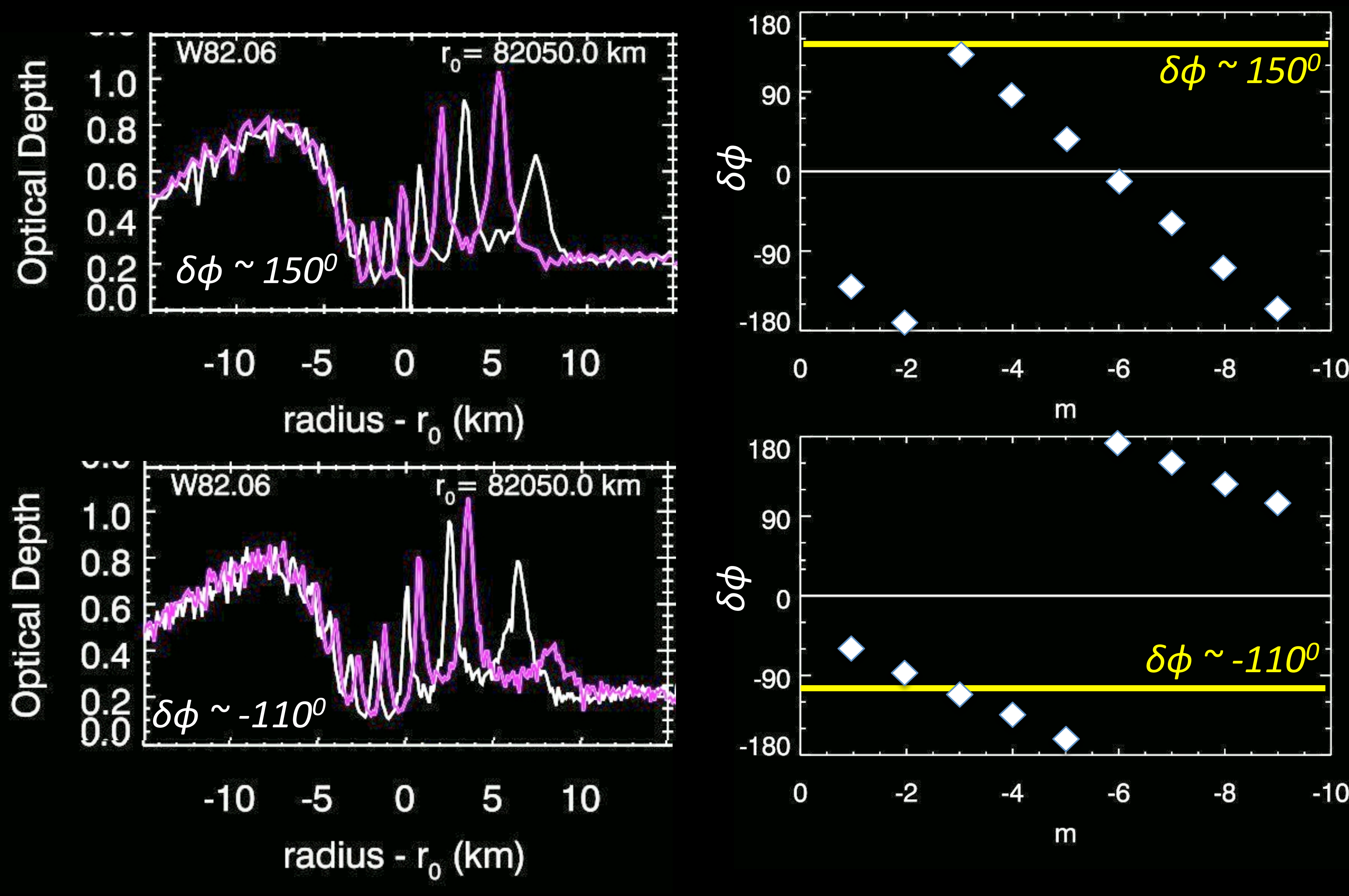
For any pair of occultations, we can compute a *phase difference* $\delta\phi$ that quantifies how much the peaks and troughs are out of line.



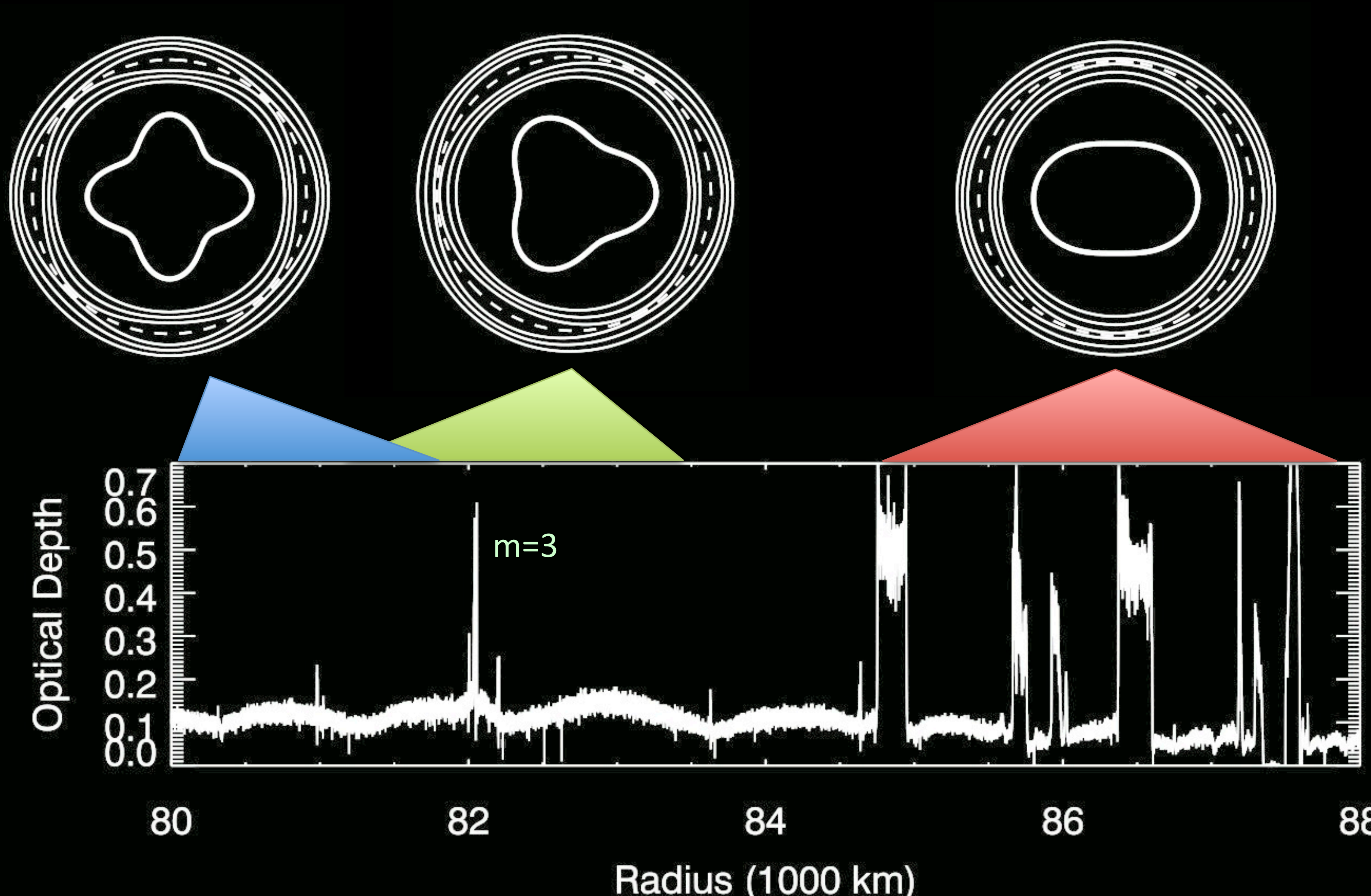
The expected $\delta\phi$ matches the observed $\delta\phi$ for the m=3 mode

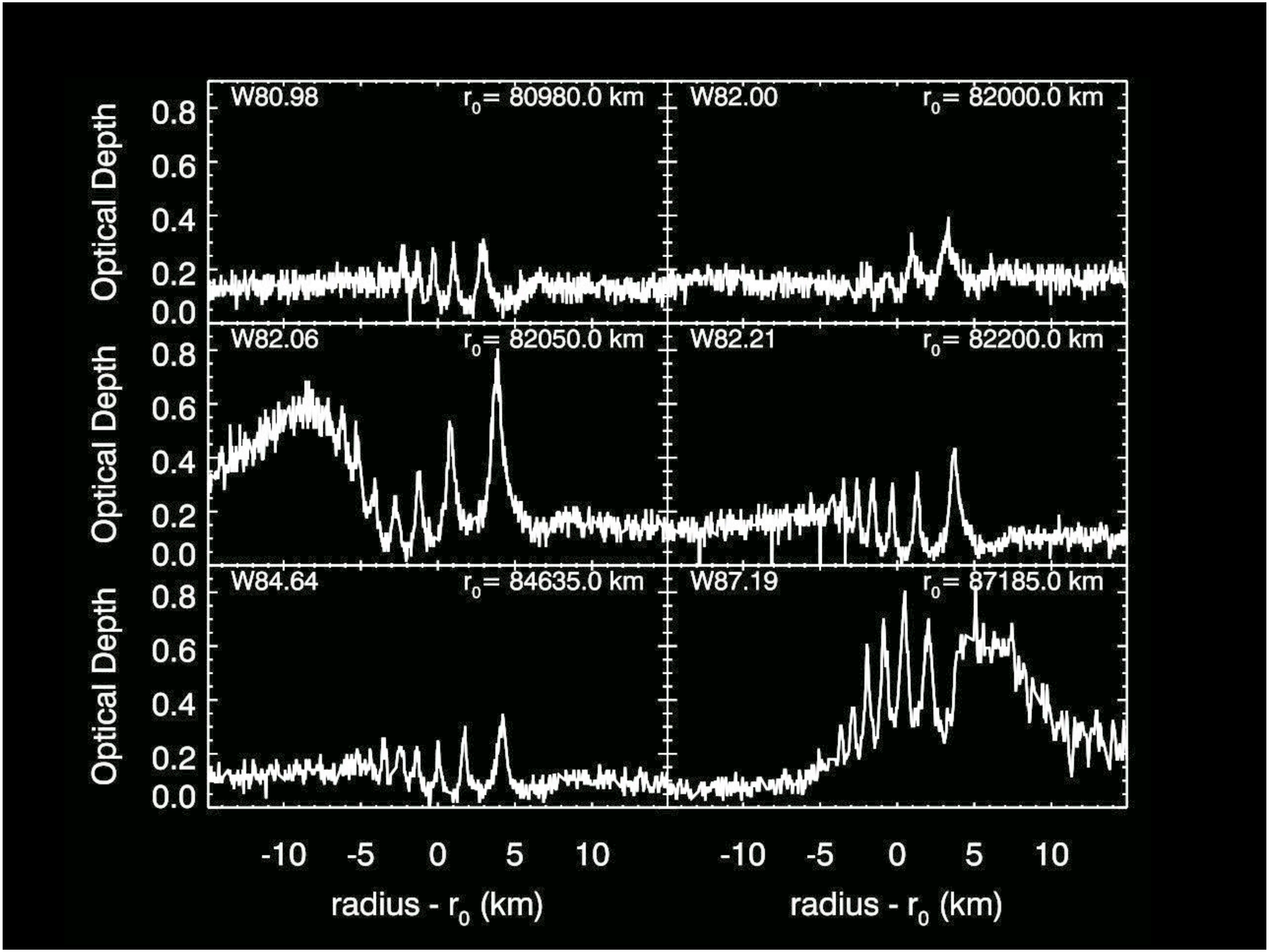


The expected $\delta\phi$ matches the observed $\delta\phi$ for the m=3 mode

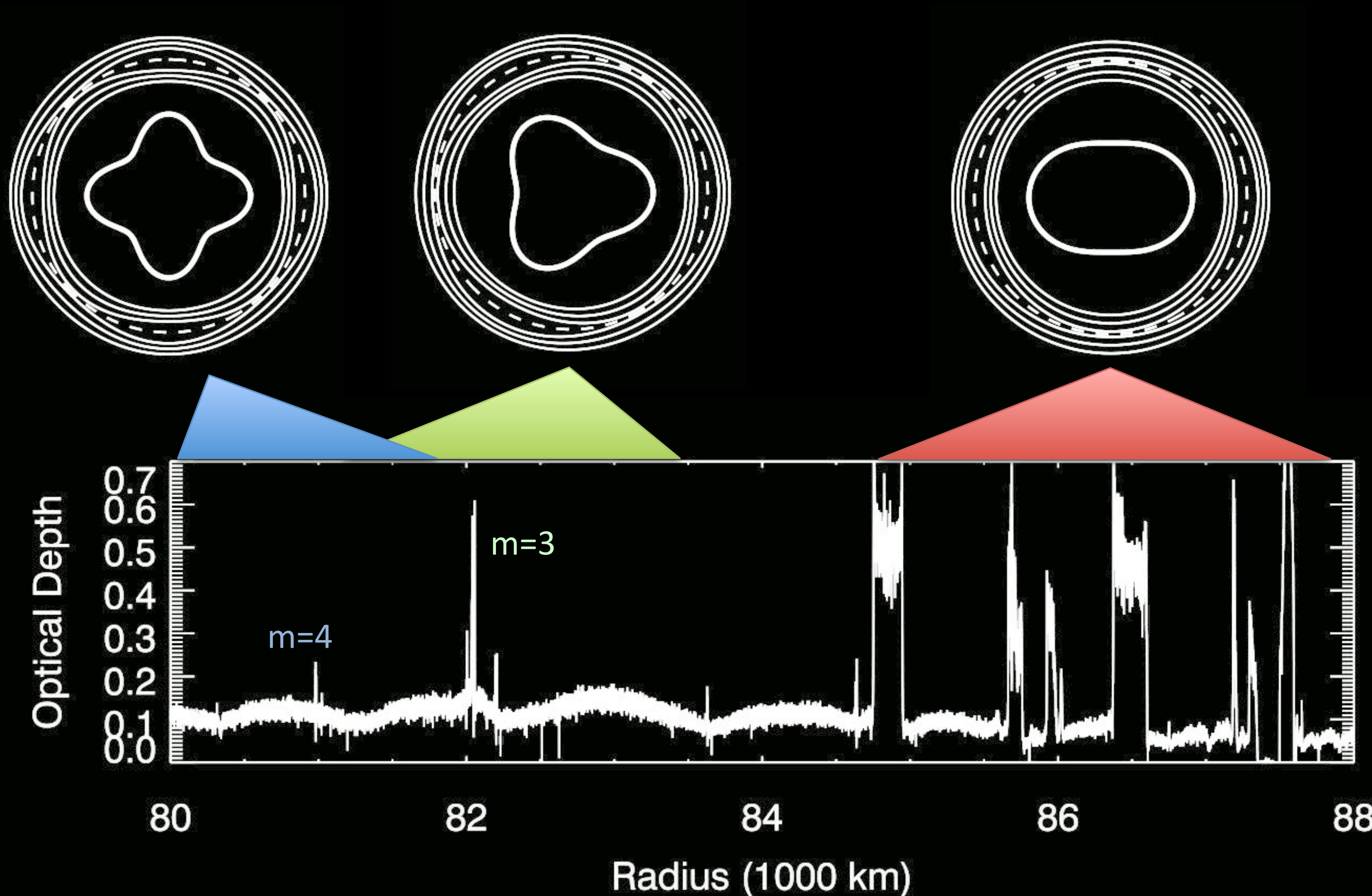


For several waves, the derived mode-number is close to the predicted value,

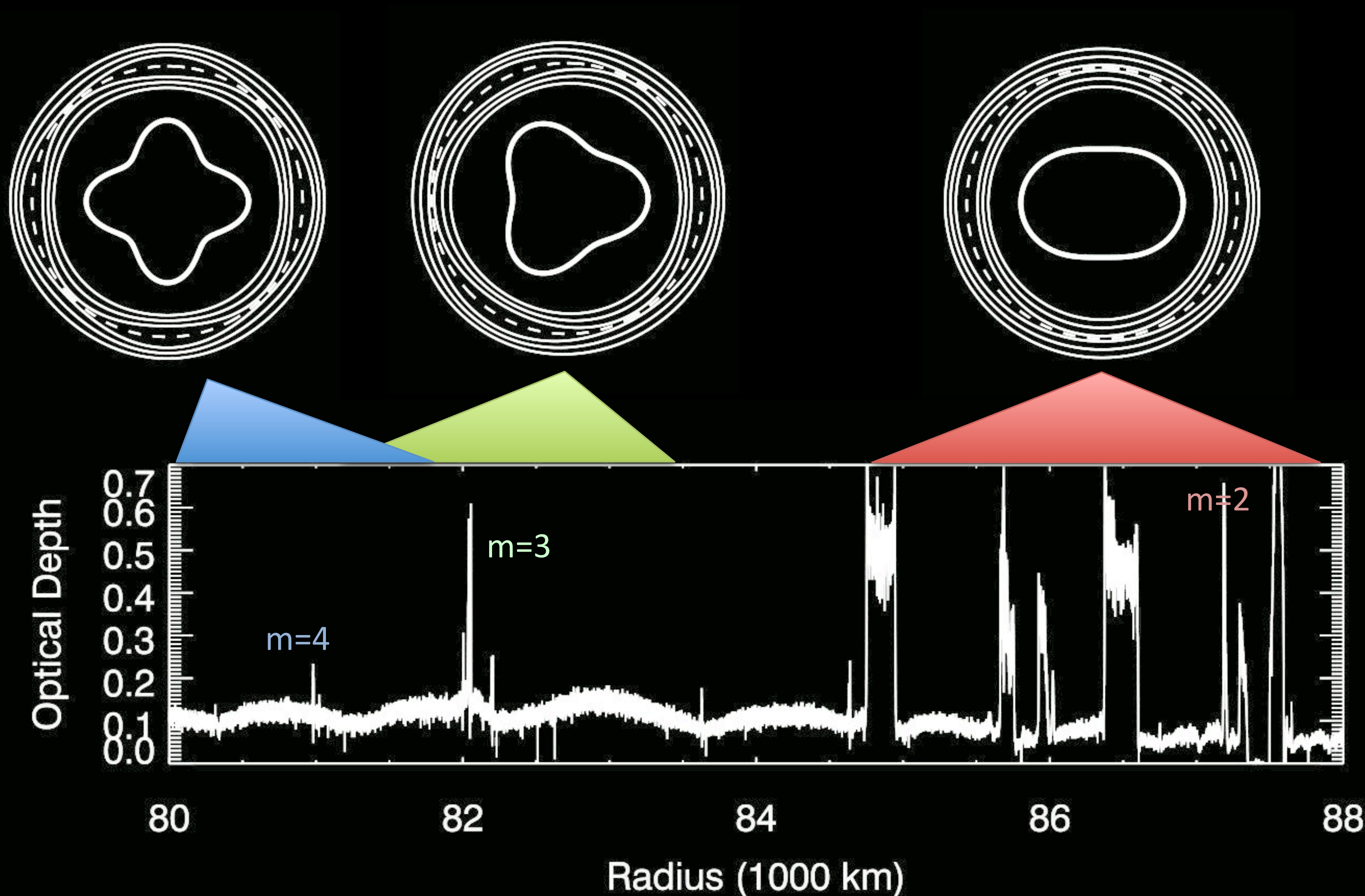


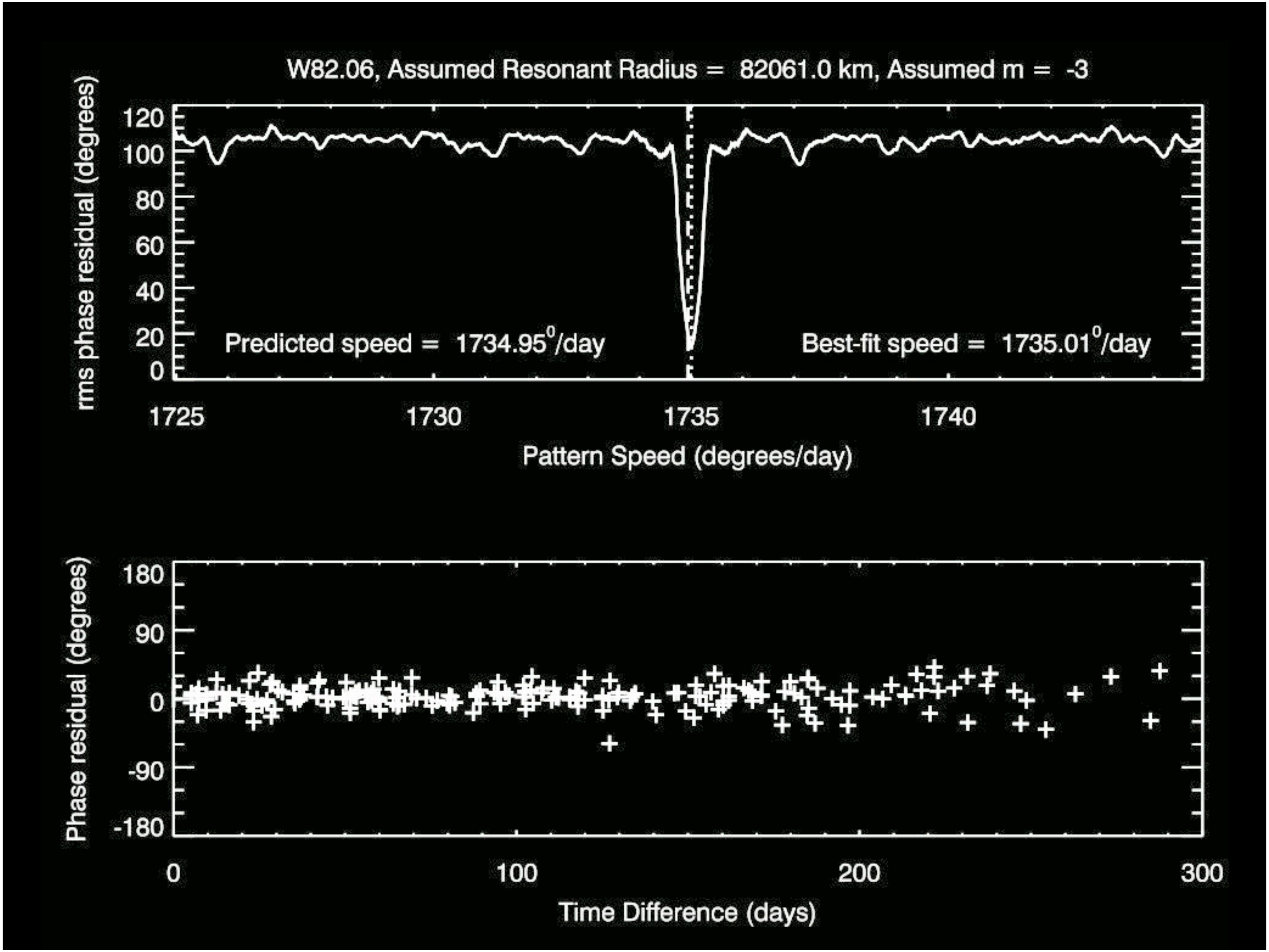

W80.98
r_0= 80980.0 km
W82.00
r_0= 82000.0 km
W82.06
r_0= 82050.0 km
W82.21
r_0= 82200.0 km
W84.64
r_0= 84635.0 km
W87.19
r_0= 87185.0 km
Optical Depth
0.0
0.2
0.4
0.6
0.8
-10
-5
0
5
10
radius - r_0 (km)

For several waves, the derived mode-number is close to the predicted value,



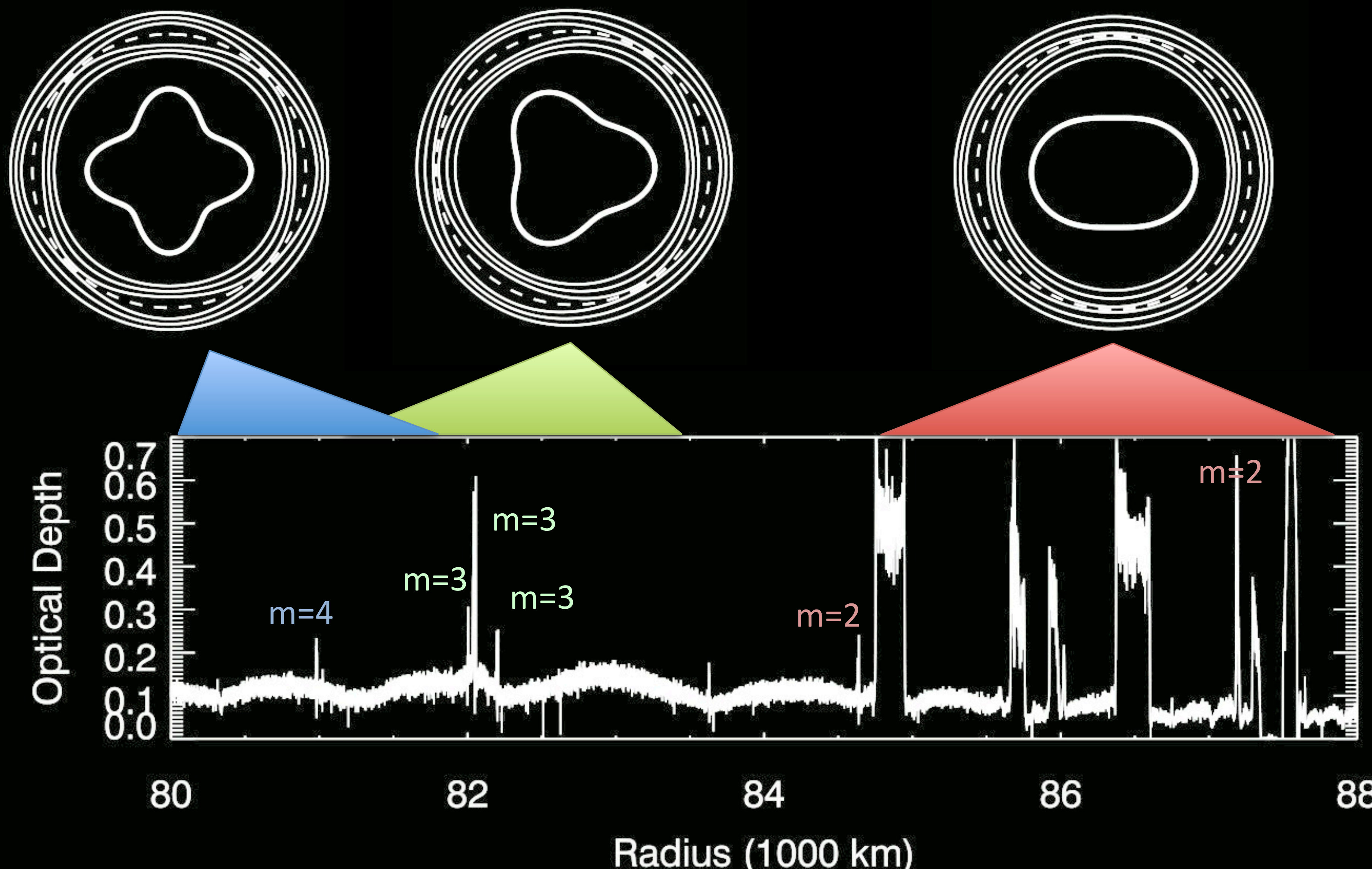
For several waves, the derived mode-number is close to the predicted value,





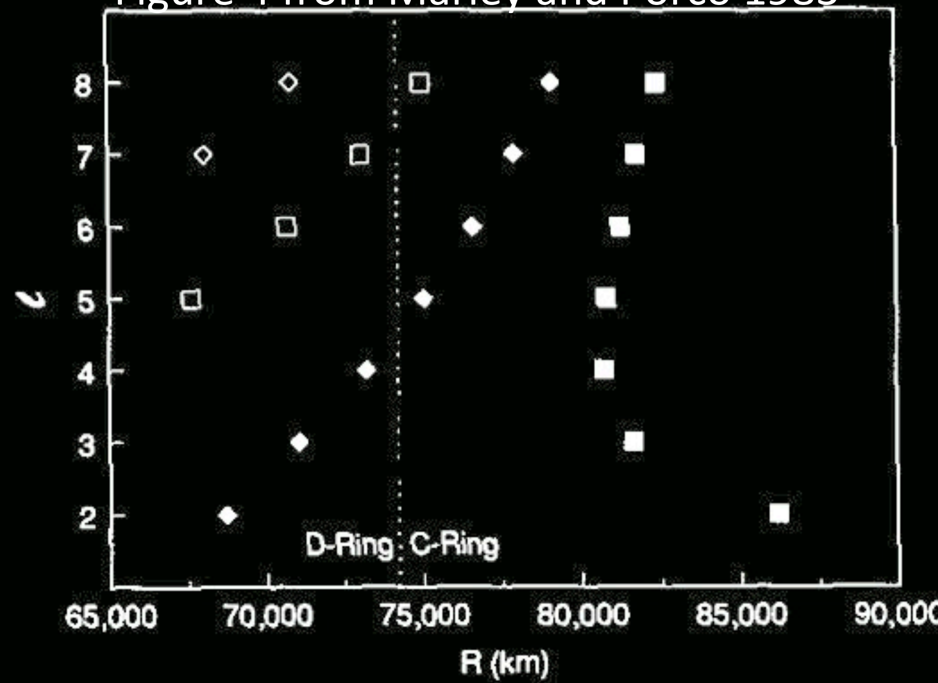
W82.06, Assumed Resonant Radius = 82061.0 km, Assumed m = -3
rms phase residual (degrees)
120
100
80
60
40
20
0
Predicted speed = 1734.95°/day
Best-fit speed = 1735.01°/day
1725
1730
1735
1740
Pattern Speed (degrees/day)
Phase residual (degrees)
180
90
0
-90
-180
0
100
200
300
Time Difference (days)

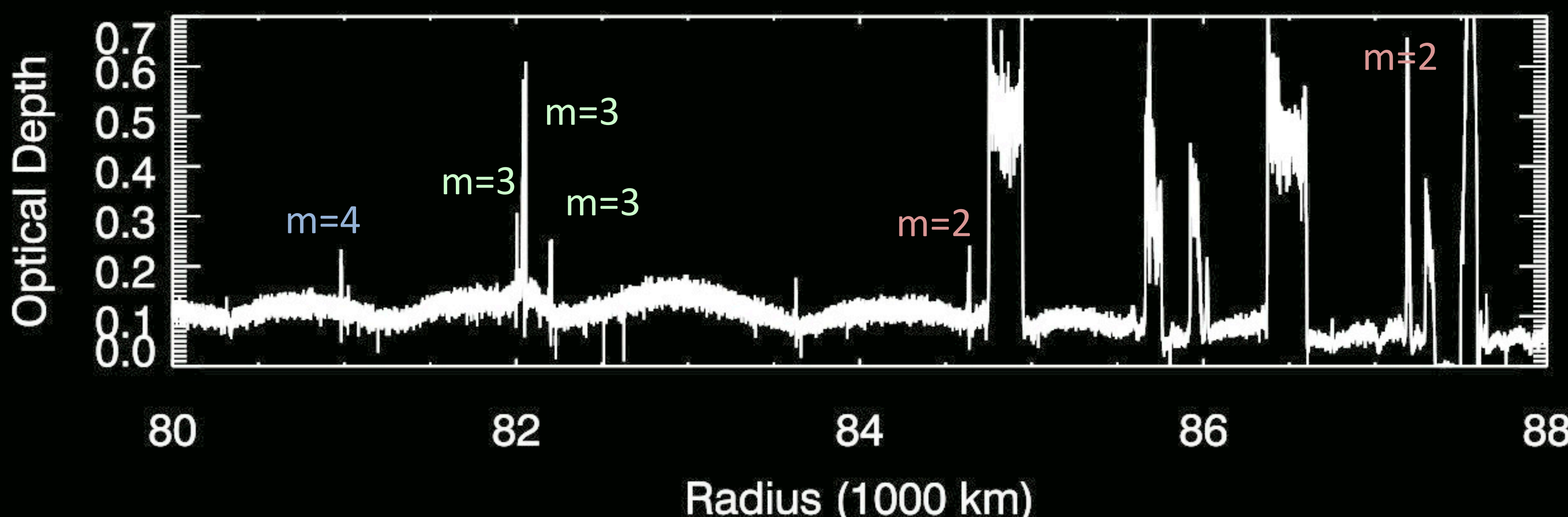
For several waves, the derived mode-number is close to the predicted value, but there appear to be multiple waves generated by resonances with the m = 2 and m = 3 modes!



Marley and Porco also predicted additional resonances with m=5,6,7,8 and 9 in this region.

Figure 4 from Marley and Porco 1983

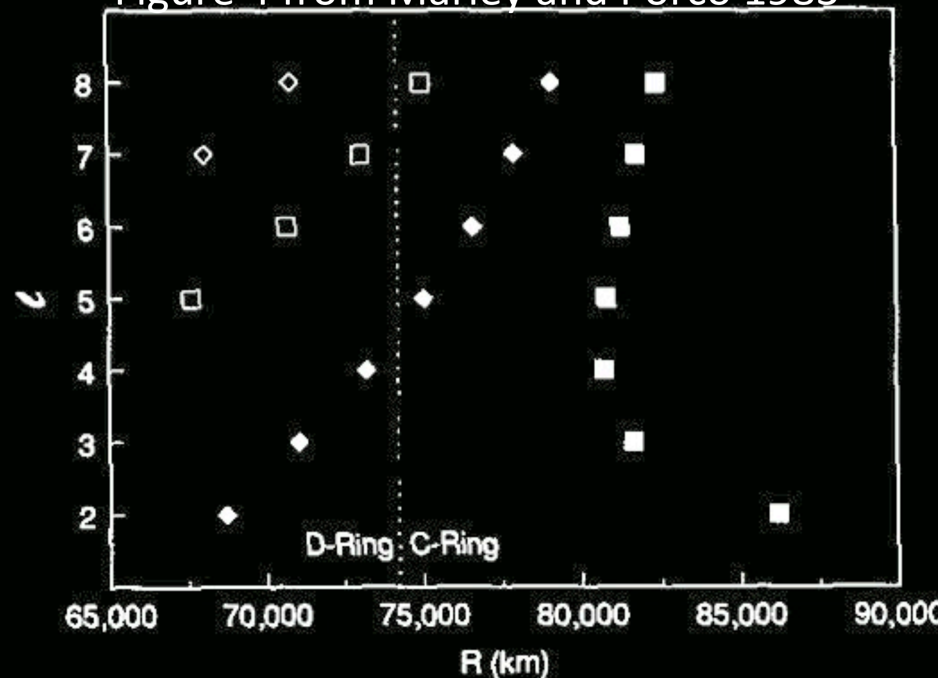


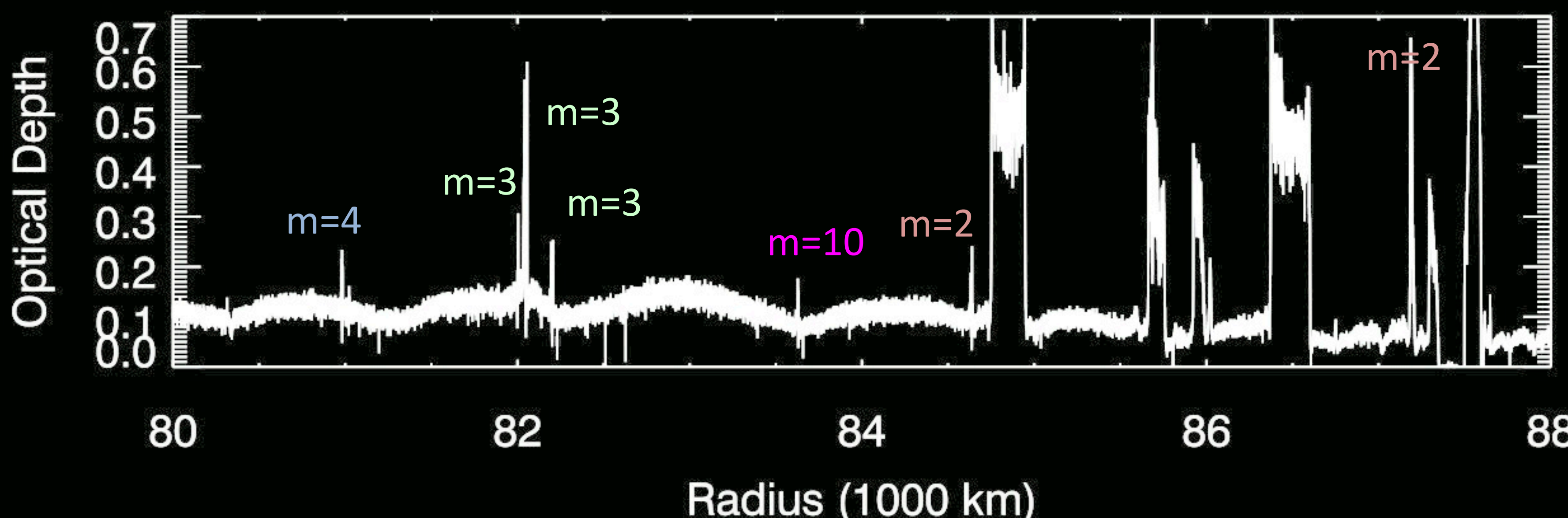


Marley and Porco also predicted additional resonances with m=5,6,7,8 and 9 in this region, but a comprehensive search has only uncovered m=10 thus far

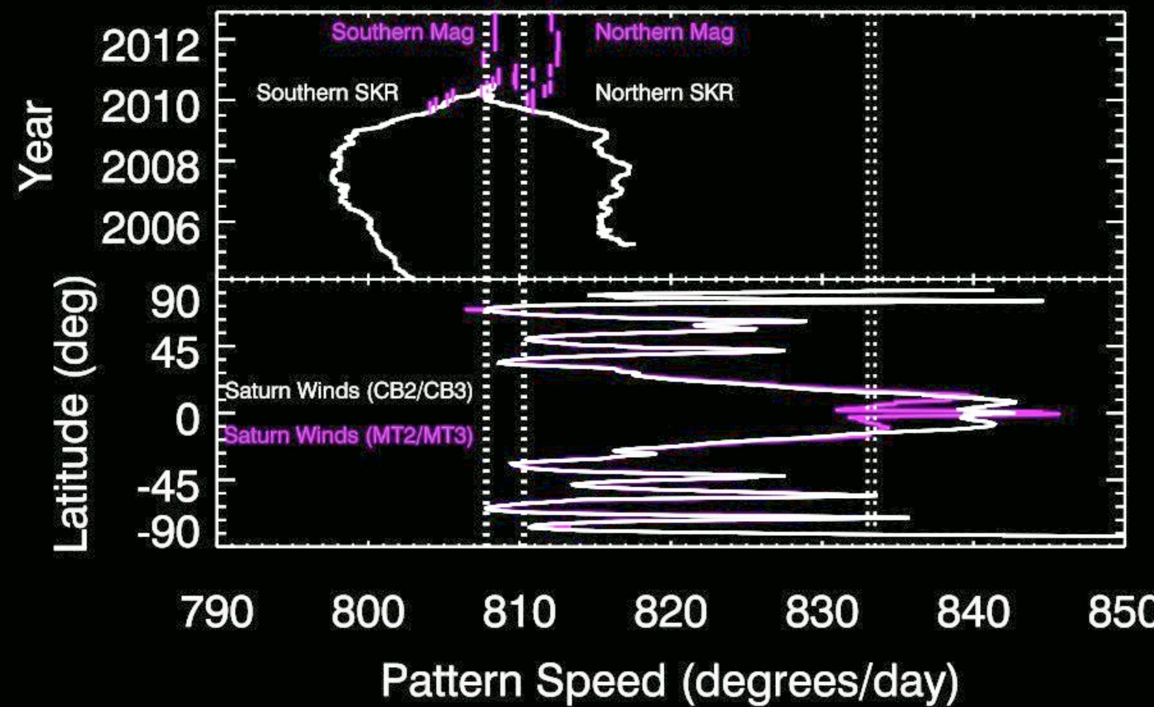
Something is odd about the excitation spectrum of Saturn's normal modes

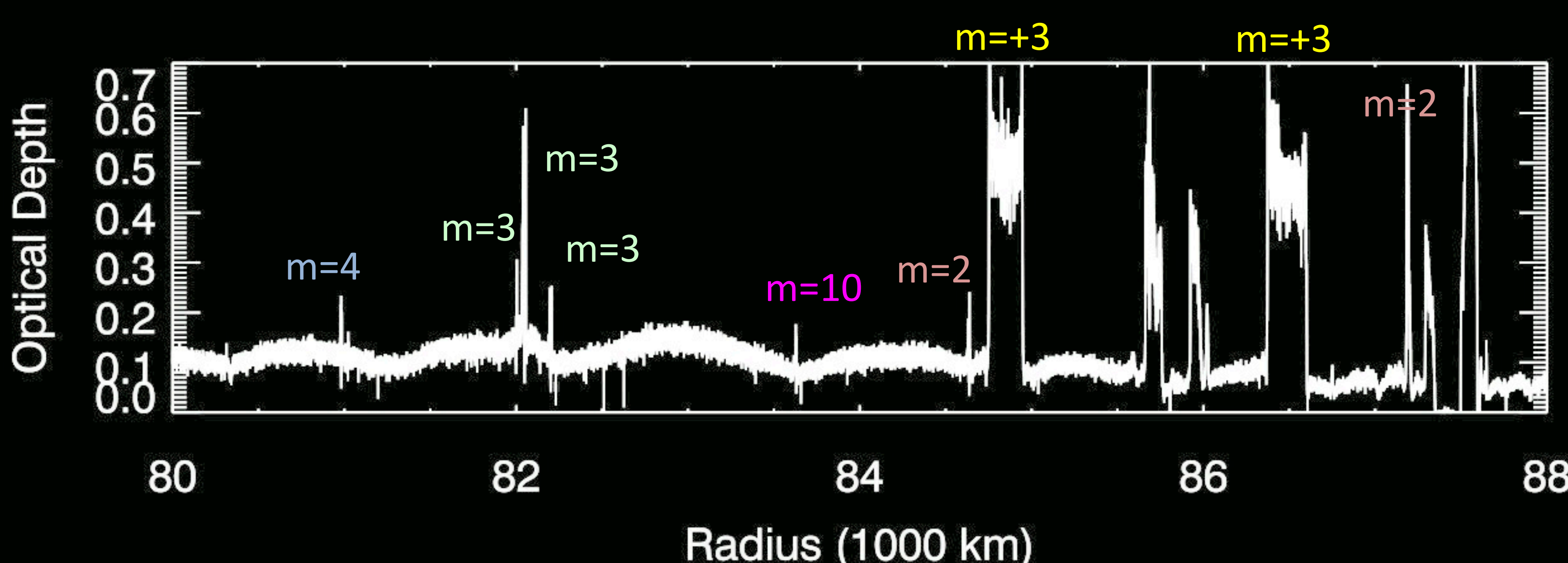
Figure 4 from Marley and Porco 1983



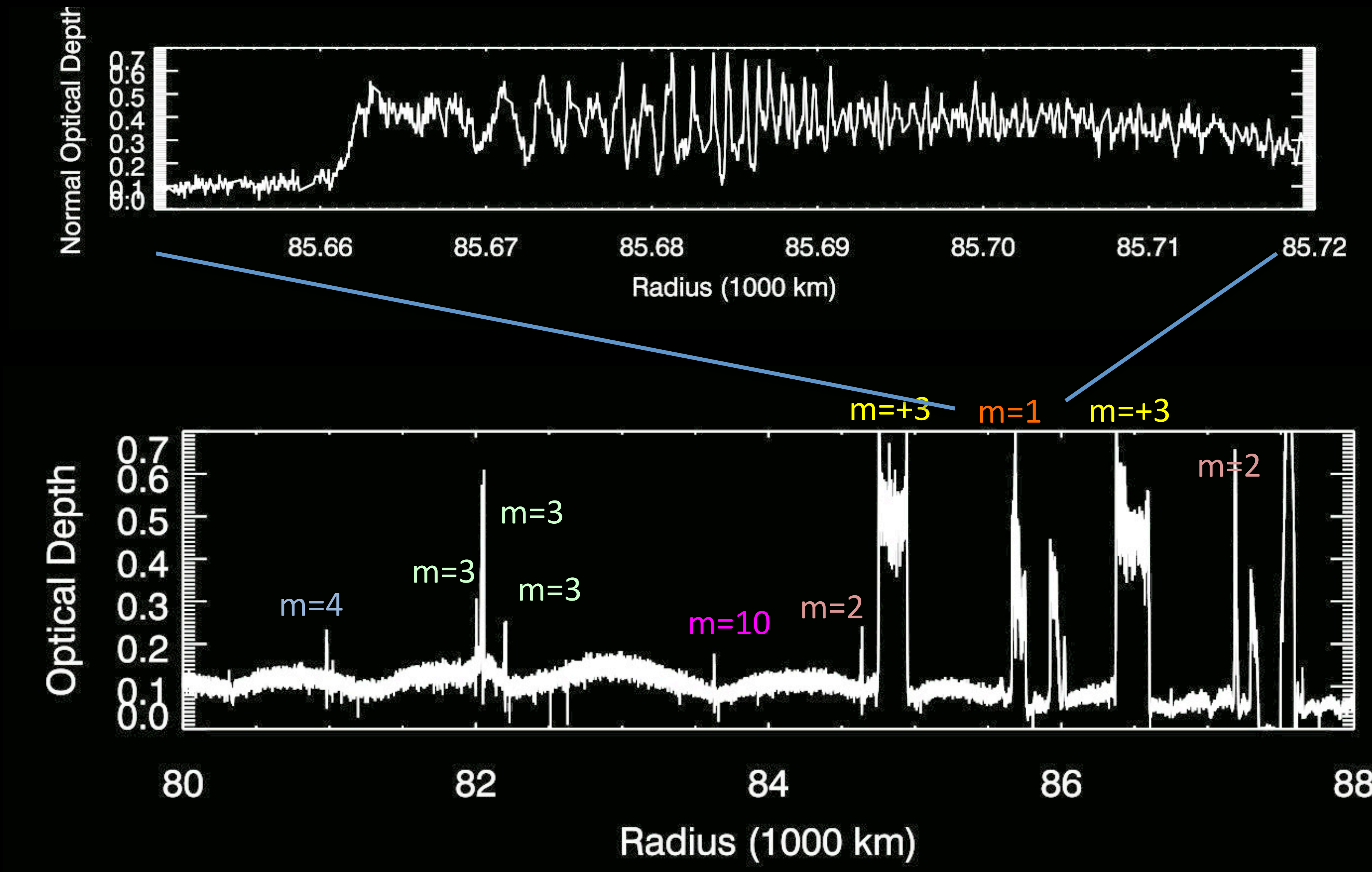


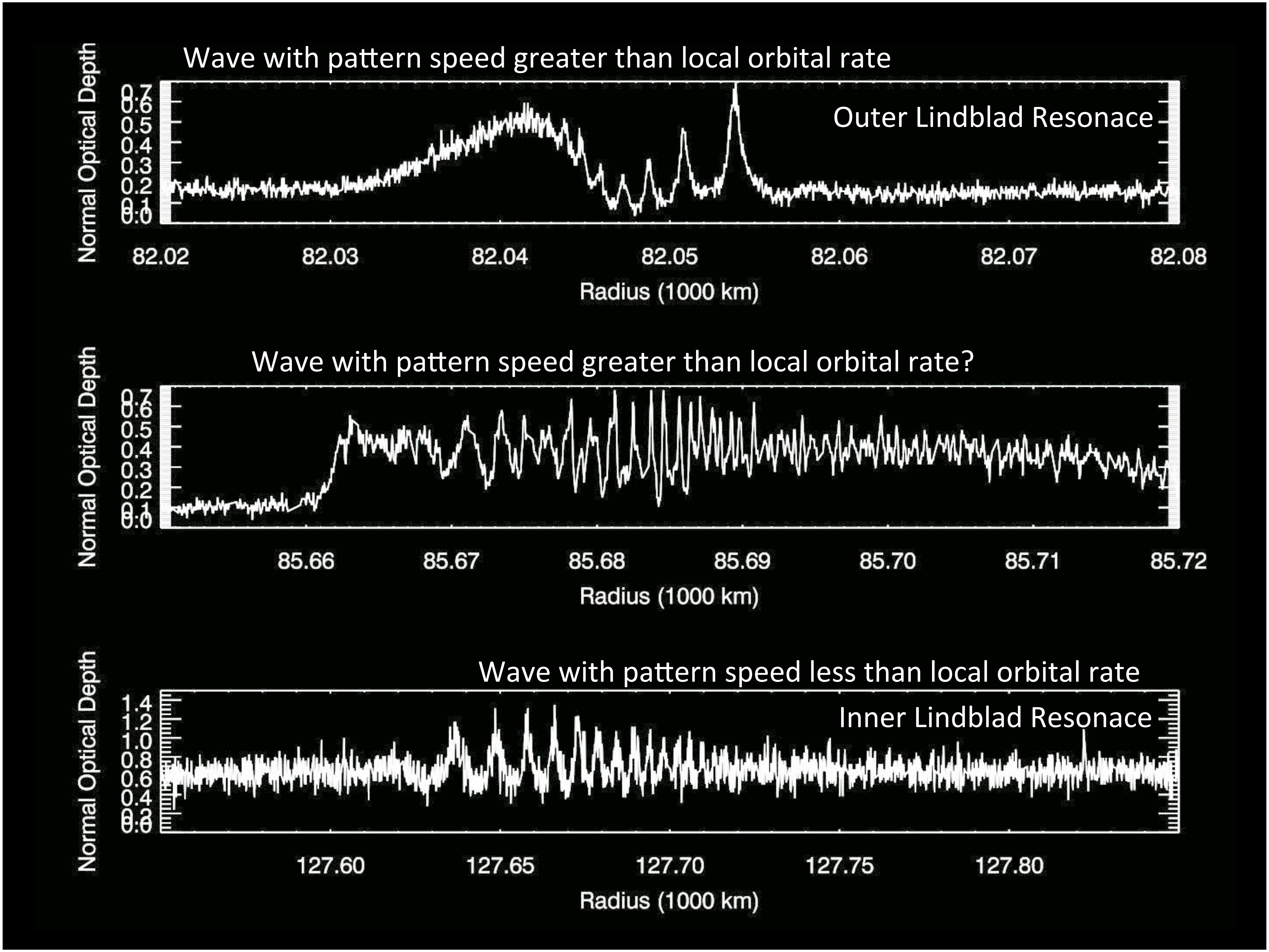
We have also found five waves with pattern speeds between 805^0/day and 835^0/day , which are close to Saturn's rotation rate



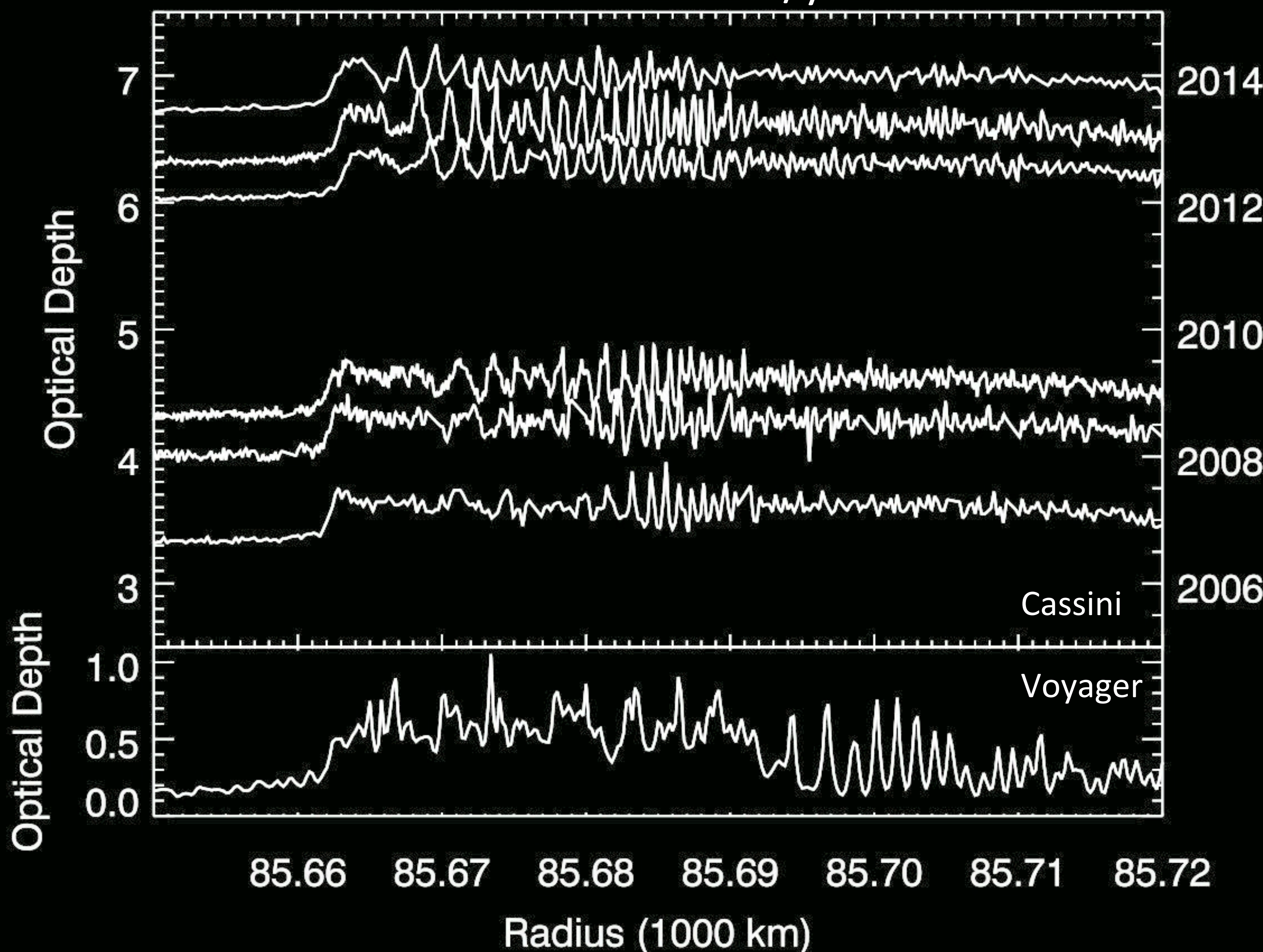


Finally, we found a very strange, “backwards” wave that appears to be an m=1 wave with a pattern speed equal to twice the local orbital speed




Wave with pattern speed greater than local orbital rate
Outer Lindblad Resonace
Normal Optical Depth
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
82.02
82.03
82.04
82.05
82.06
82.07
82.08
Radius (1000 km)
Wave with pattern speed greater than local orbital rate?
Normal Optical Depth
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
85.66
85.67
85.68
85.69
85.70
85.71
85.72
Radius (1000 km)
Wave with pattern speed less than local orbital rate
Inner Lindblad Resonace
Normal Optical Depth
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
127.60
127.65
127.70
127.75
127.80
Radius (1000 km)

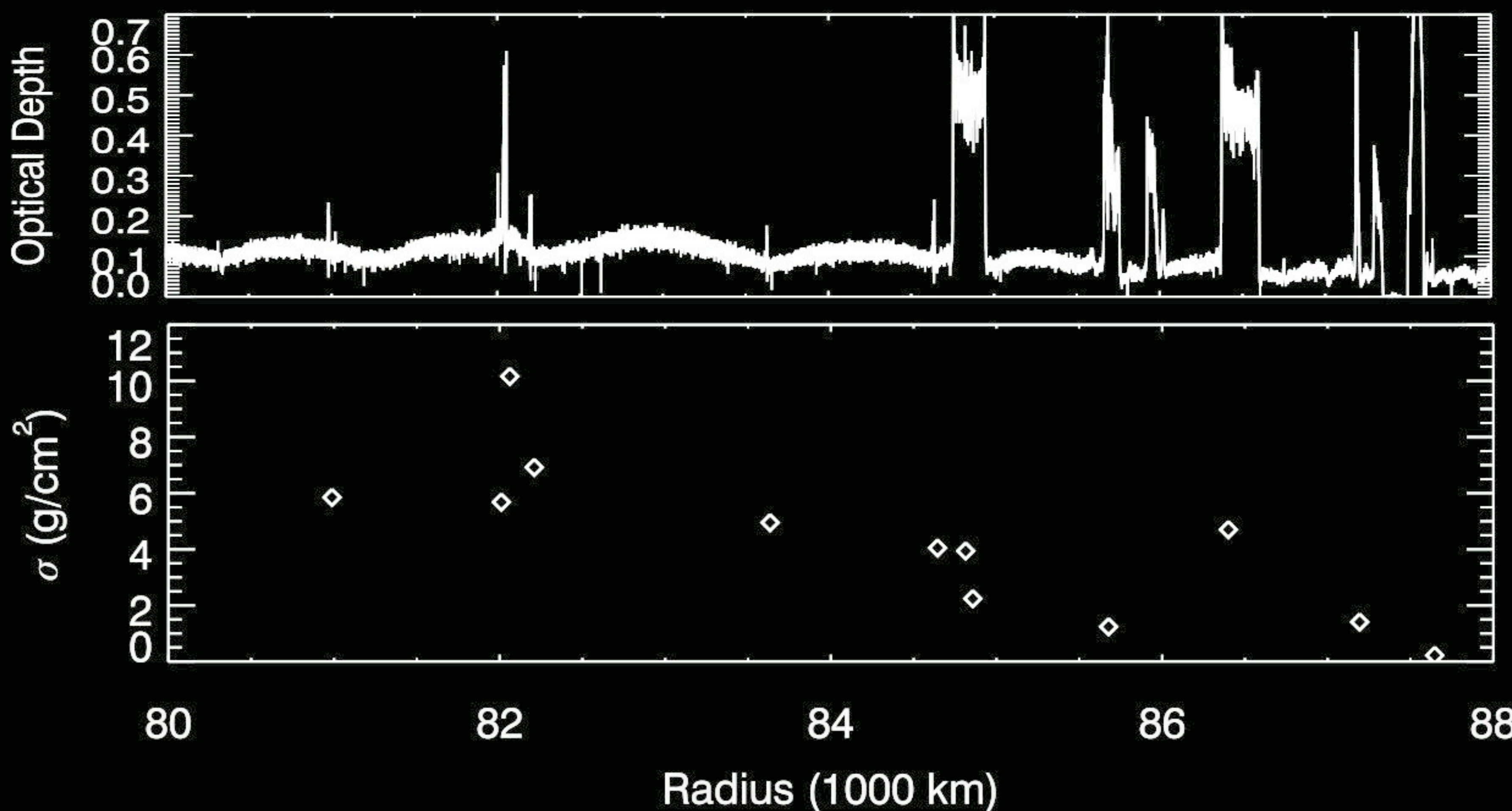
This wave appears to be drifting steadily inwards at a rate of 0.8 km/year



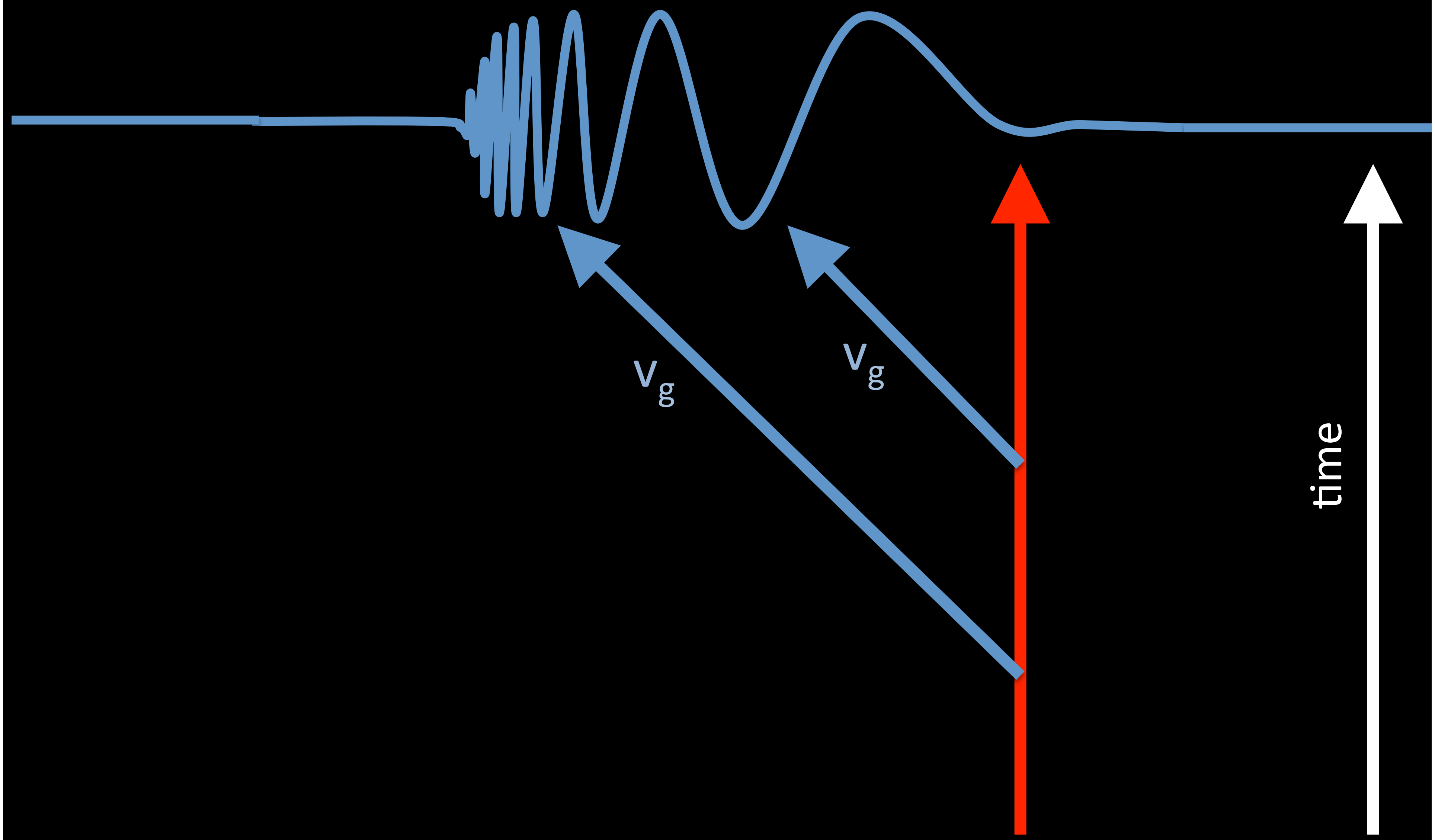
The group velocity of density waves is

$v_g = \pi G\sigma/\kappa$ = 0.26 km/year(σ/1g/cm^2)

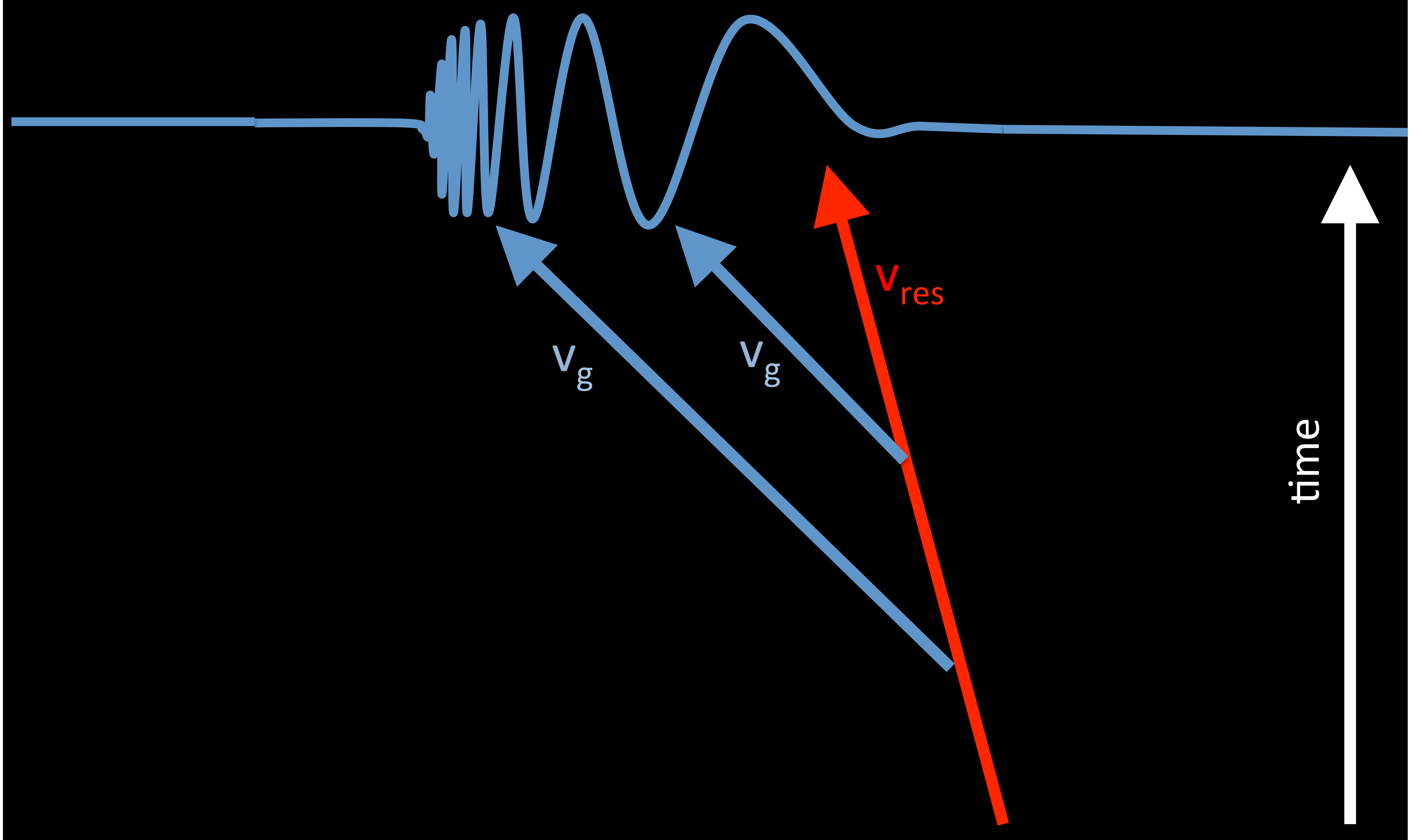
So the resonance is moving faster than the wave!



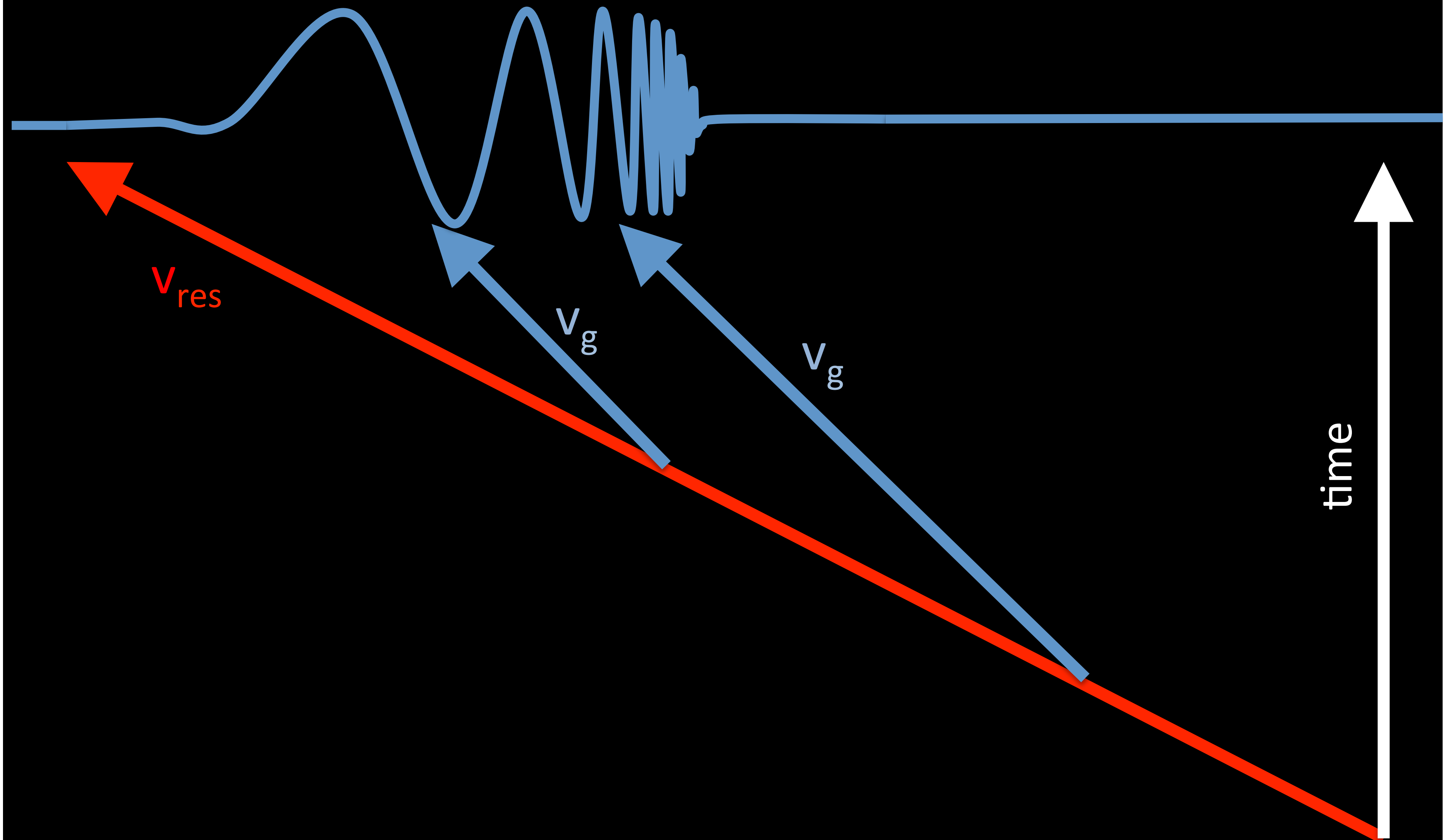
Normally, the wavelength of the density wave declines as it propagates away from the resonance



If the resonance location moves, the wave becomes distorted



If the resonance location moves faster than the wave can propagate, the wave can be turned inside out.



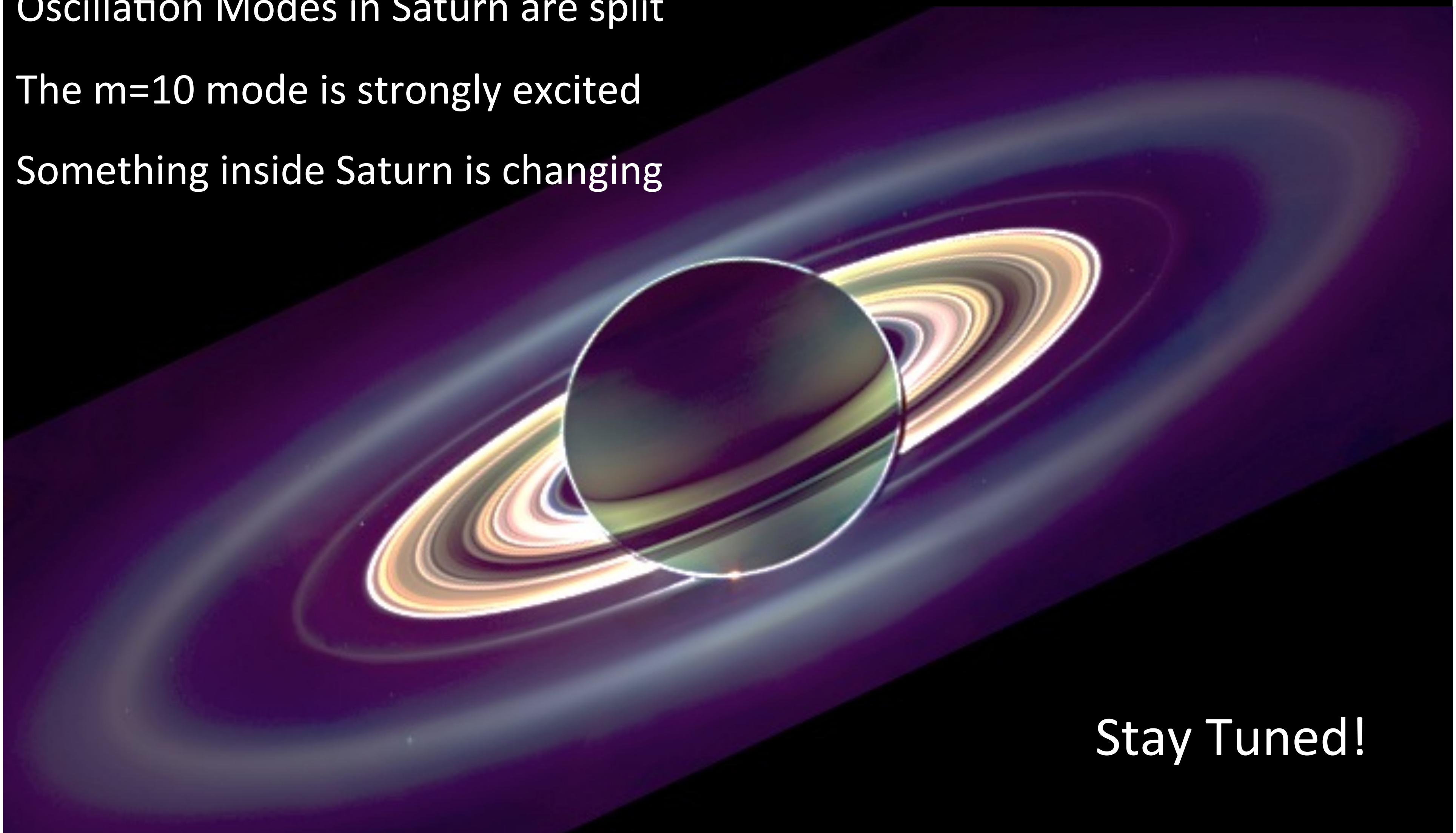
Summary:

The C ring data suggests Saturn’s oscillations behave in unexpected ways

Oscillation Modes in Saturn are split

The m=10 mode is strongly excited

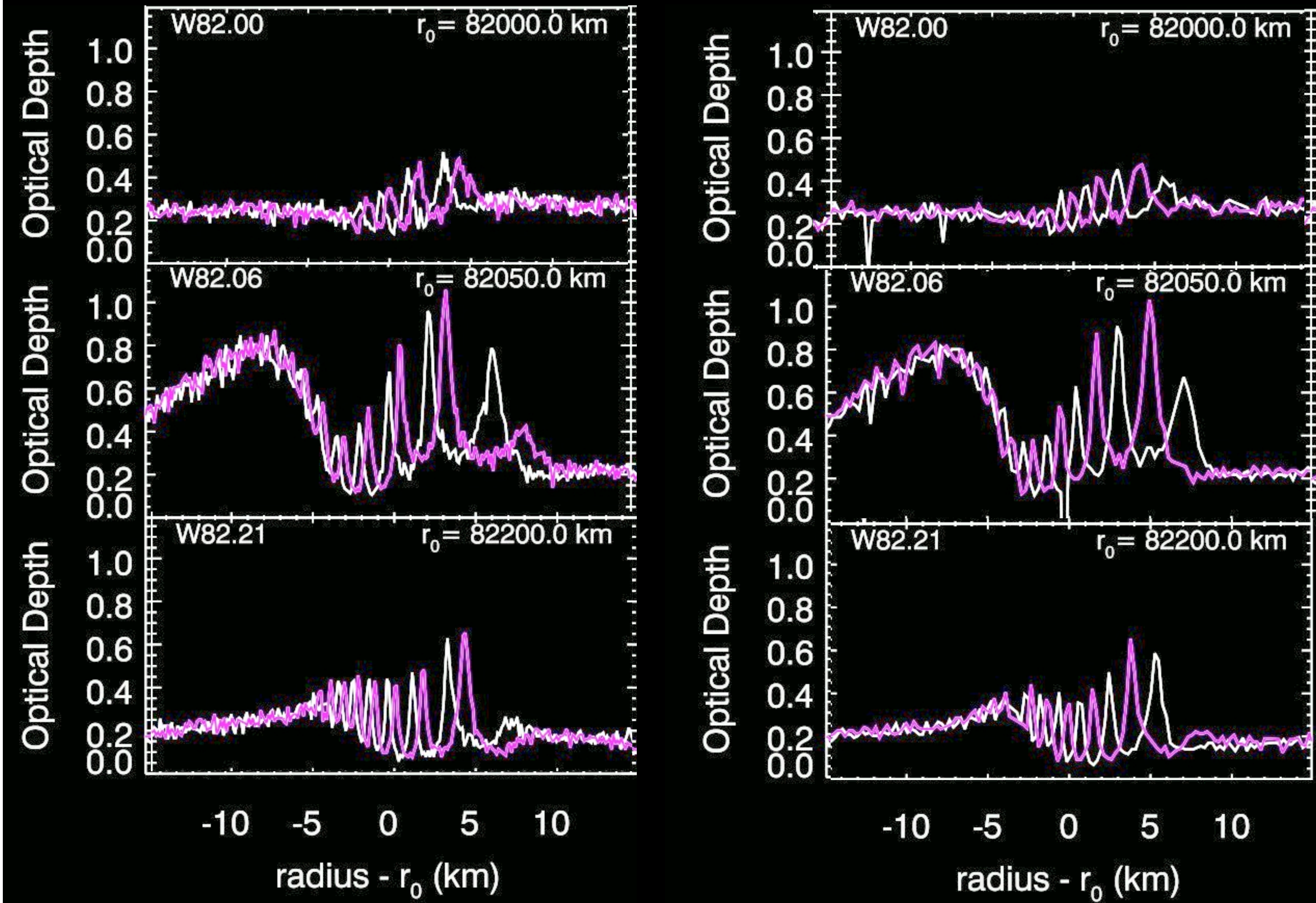
Something inside Saturn is changing

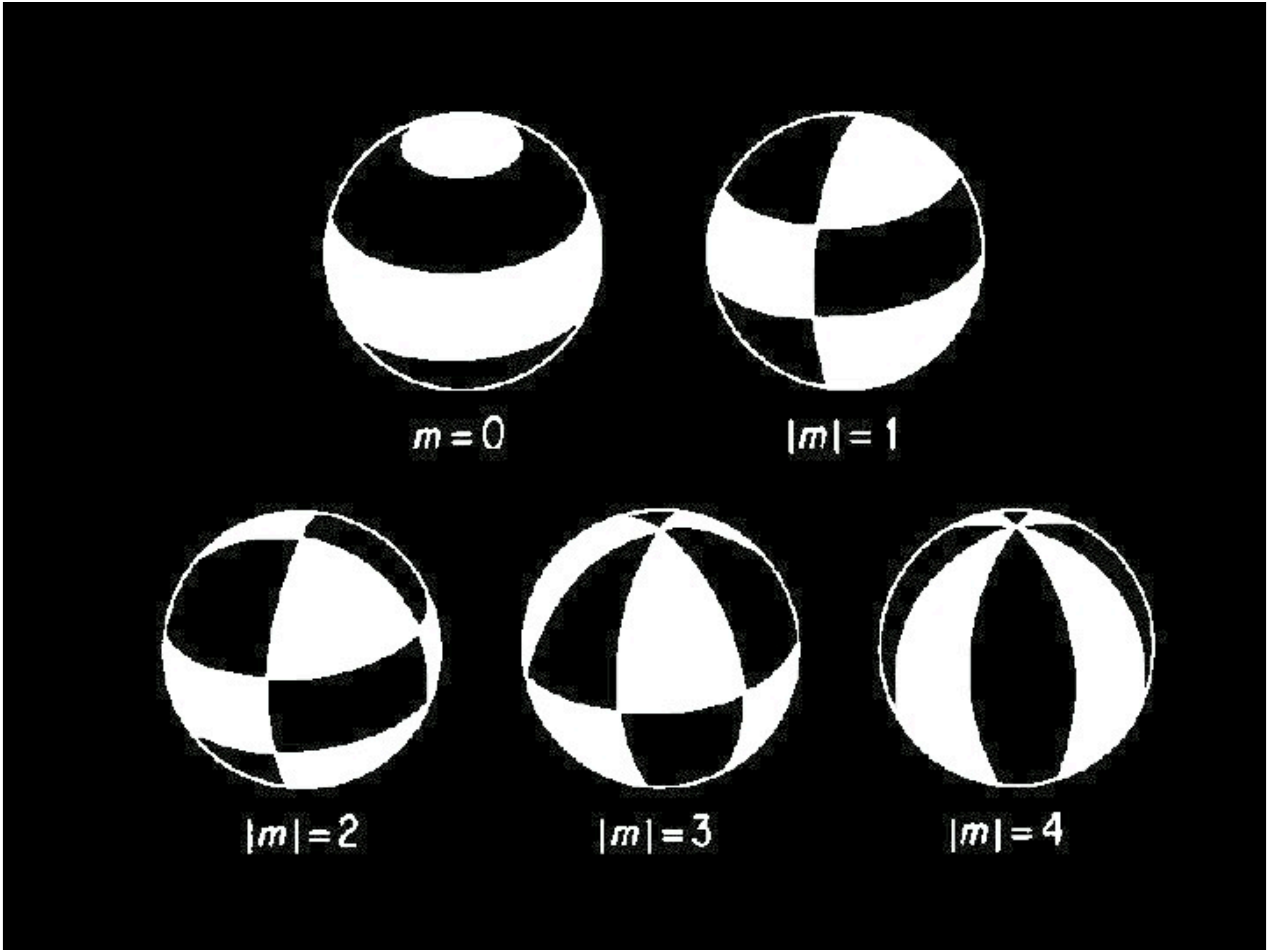


Stay Tuned!

Supplemental Material

Spot checks of particular pairs of occultation cuts confirm this result.




$m = 0$
$|m| = 1$
$|m| = 2$
$|m| = 3$
$|m| = 4$

Previous calculations had shown that some of these resonances should lie in the C ring.

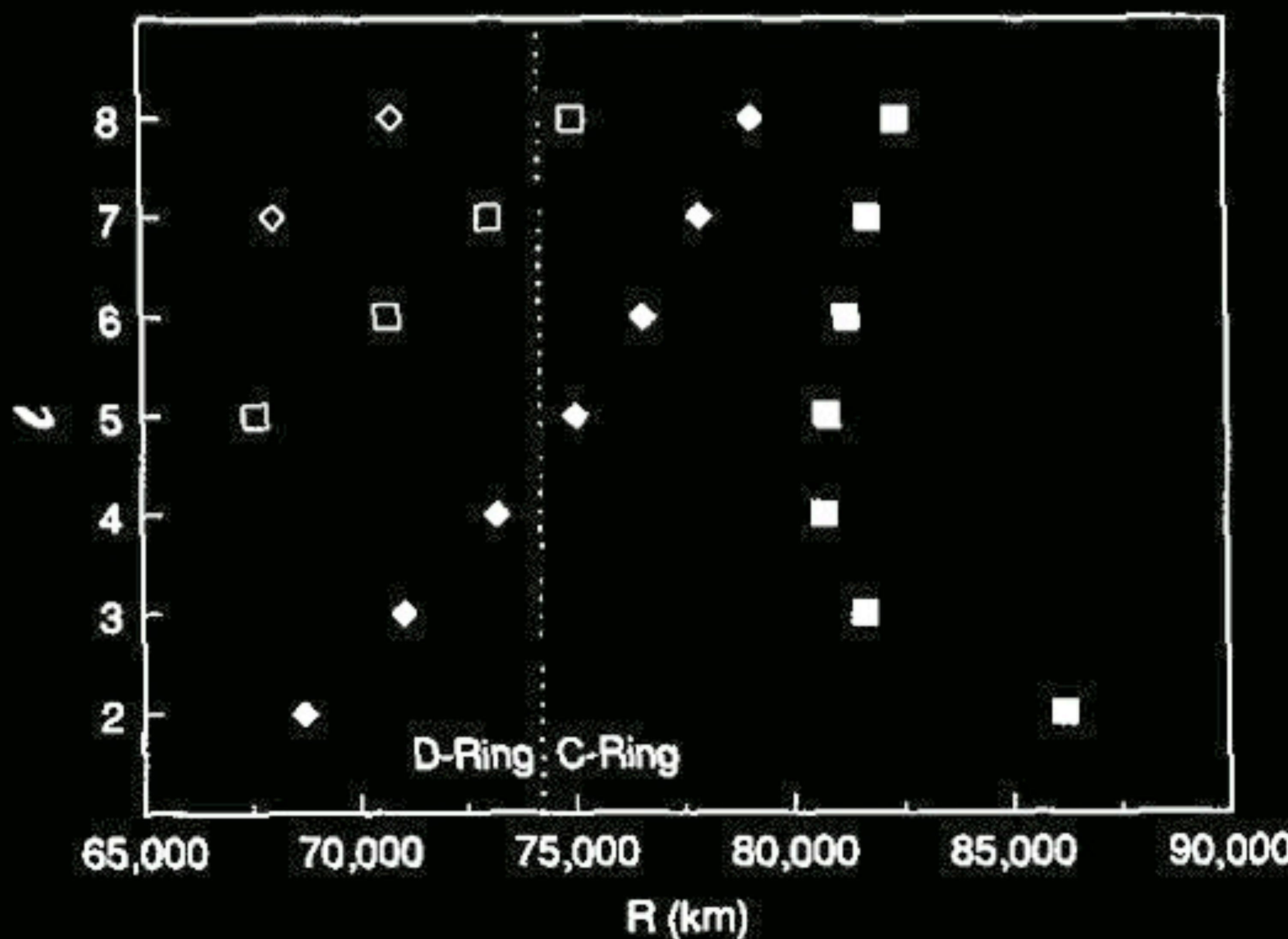
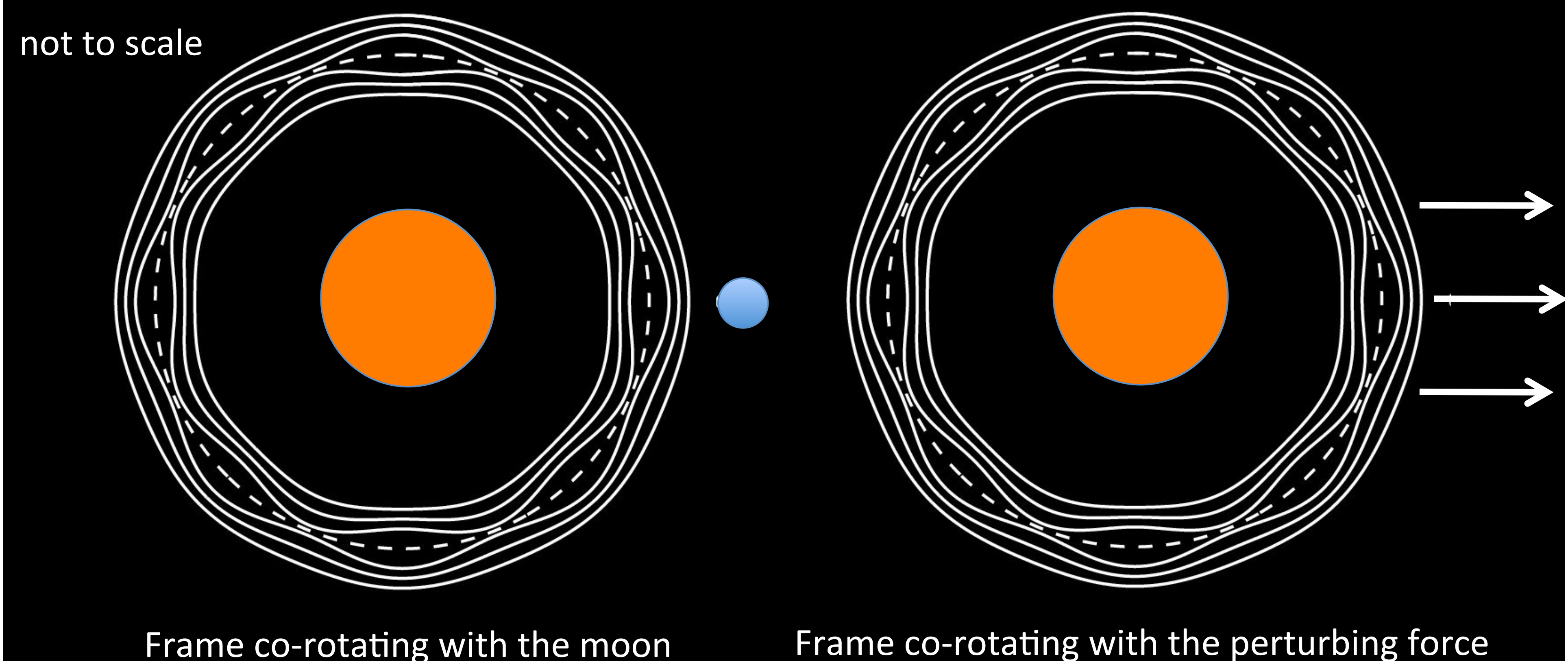


Figure 4 from Marley and Porco 1983

Organized motions can be produced by any periodic perturbing force

Orbit period of ring particle $\approx \frac{m-1}{m}$ x Rotation period of perturbing force

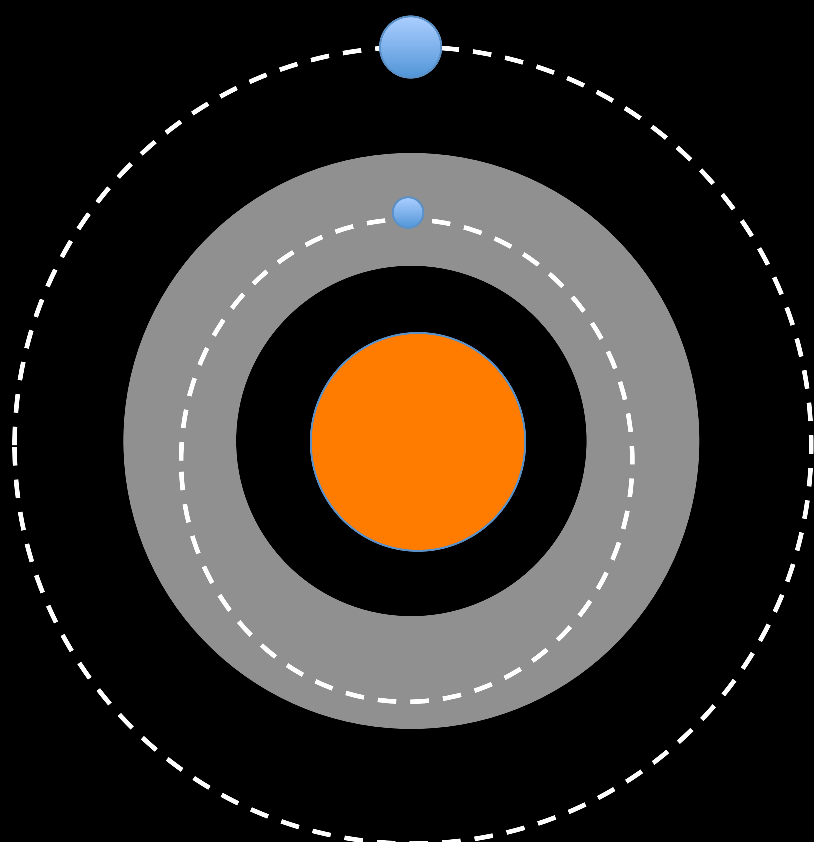
Synodic period of the periodic force ≈ m x Epicyclic period of ring particle



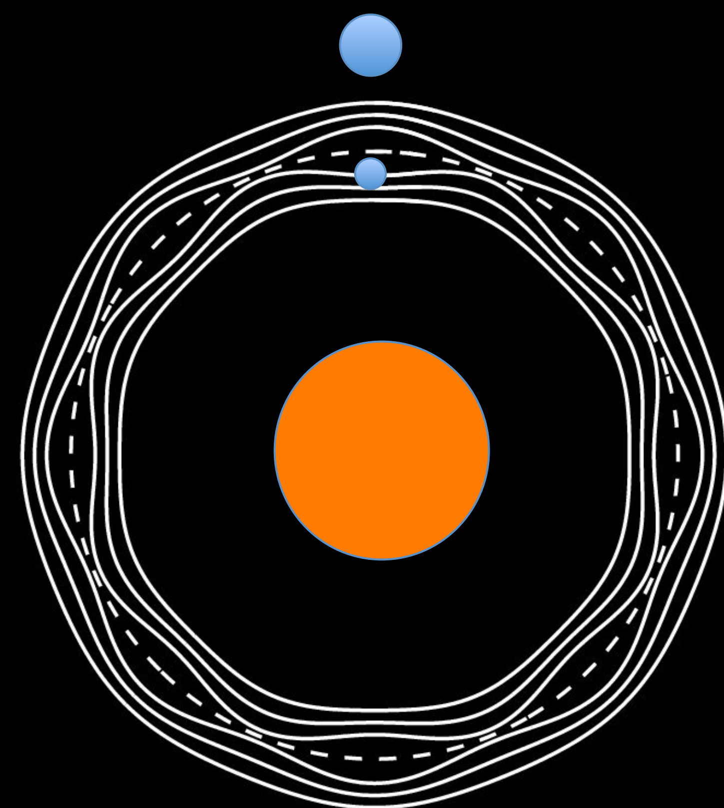
At this resonance, Mimas' periodic perturbations produce patterns by organizing the radial motions of the ring particles

Orbit period of ring particle $\approx \frac{7}{8} \times$ Orbital period of moon

Time between ring-moon conjunctions ≈ 8 x Epicyclic period of ring particle



Inertial frame

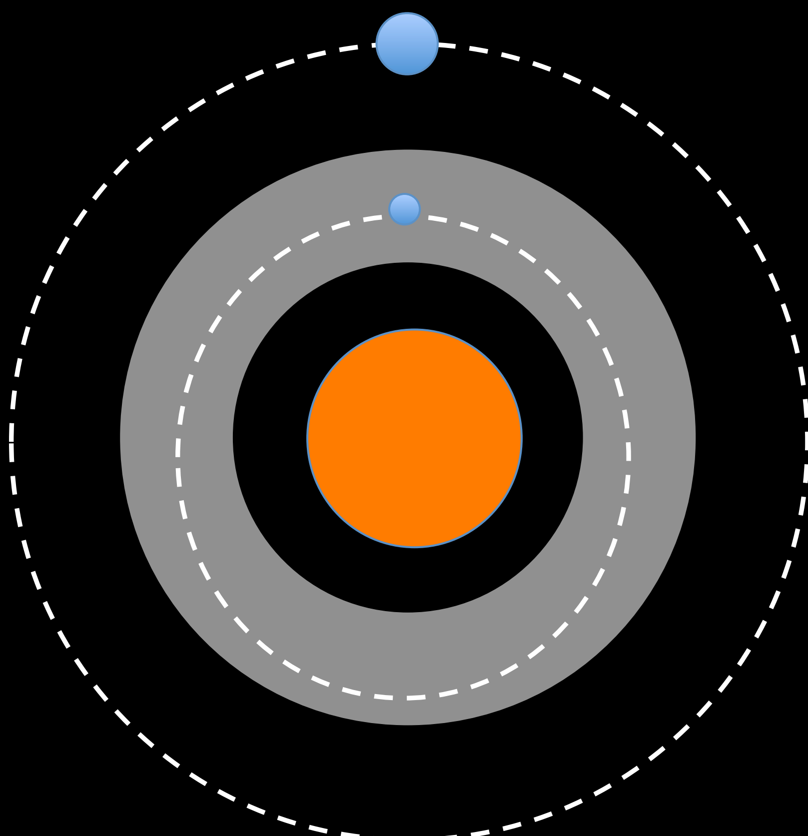


Frame co-rotating with the moon

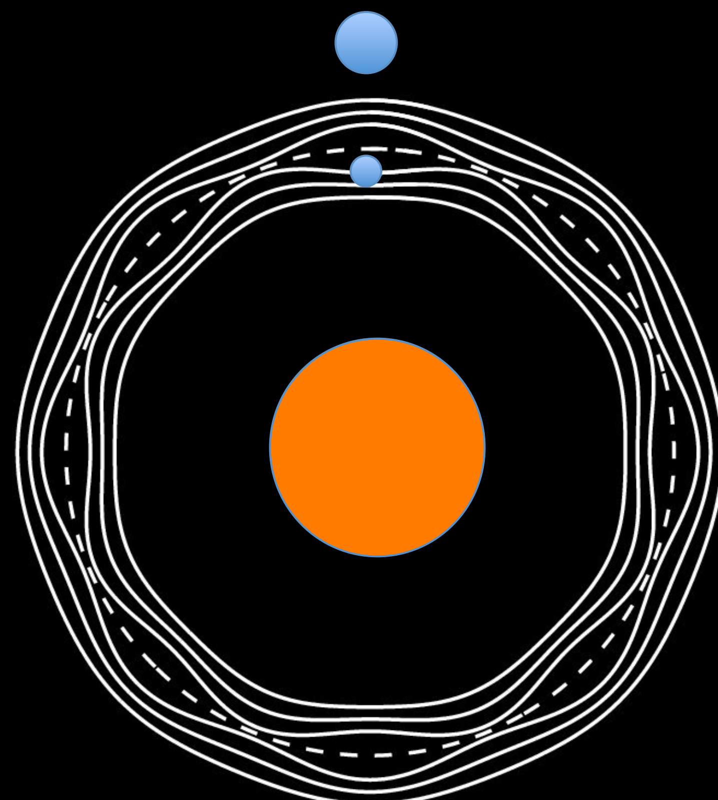
What happens at a (first order) Lindblad resonance?

Orbit period of ring particle $\approx \frac{m-1}{m}$ x Orbital period of moon

m x Epicyclic period of ring particle $\approx$ Period between ring-moon conjunctions

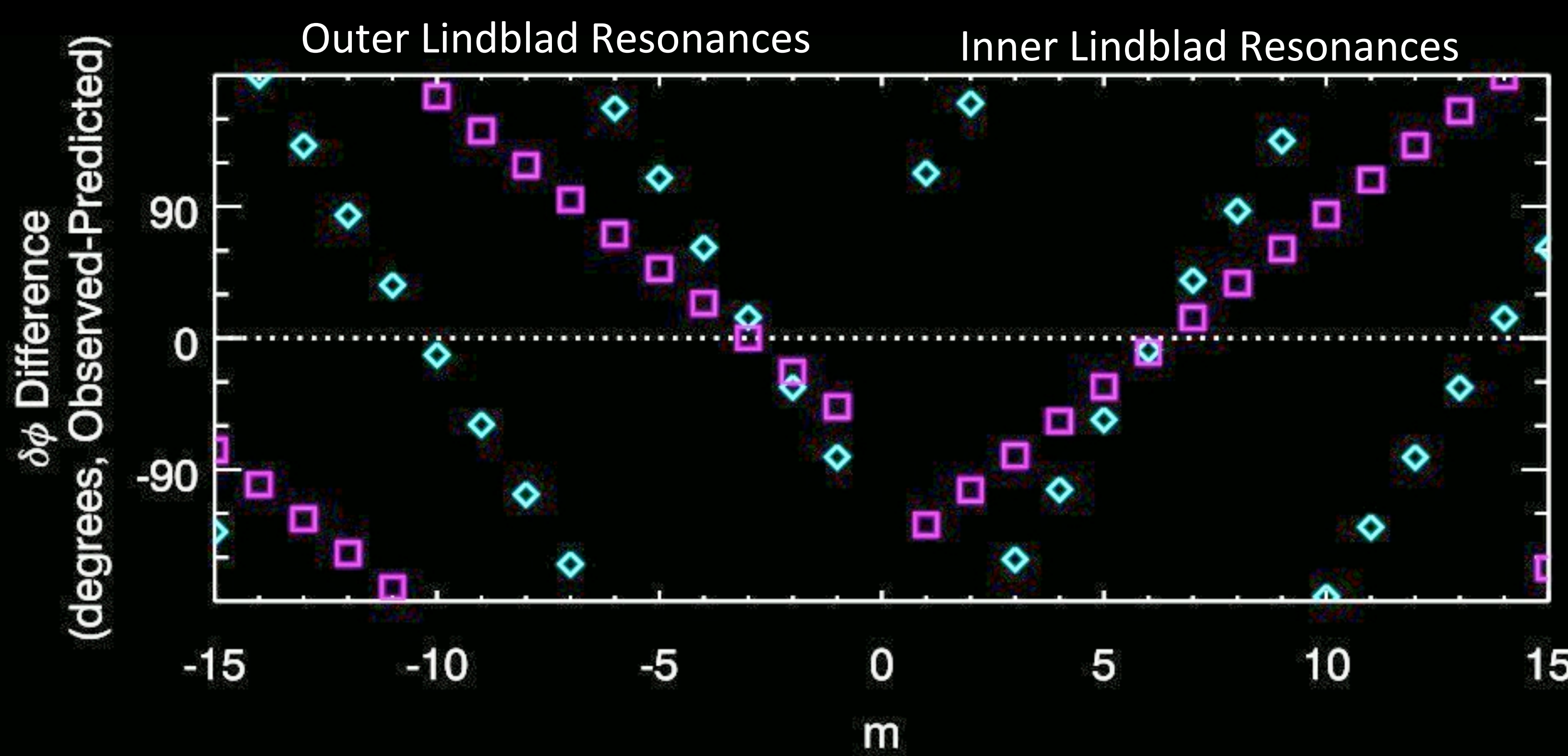


Inertial frame

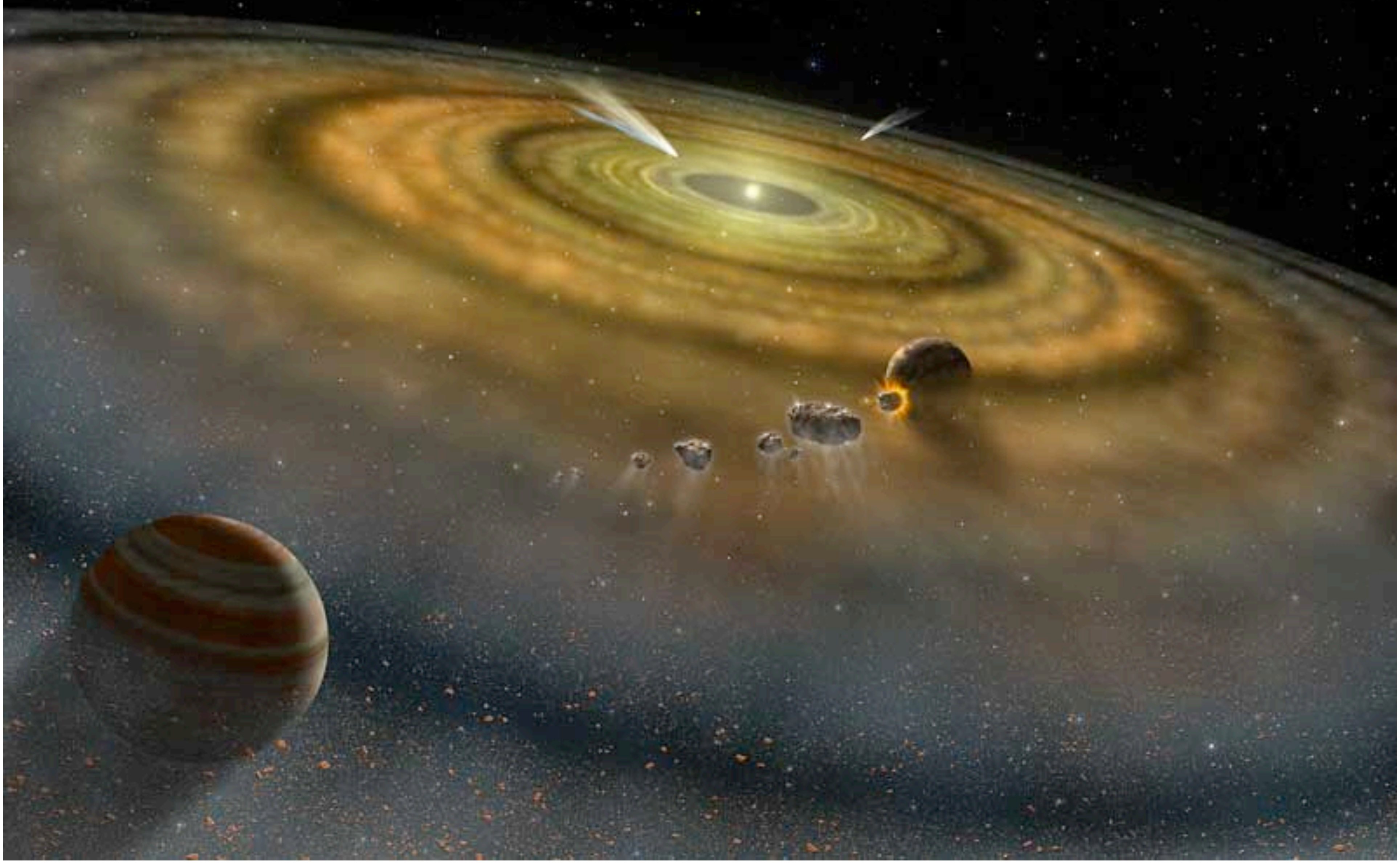


Frame co-rotating with the moon
(assuming m=8)

Given the occultation times and longitudes, we can predict what $\delta\phi$ we should observe if the pattern has a given number of arms, and compare that to the observed value of $\delta\phi$



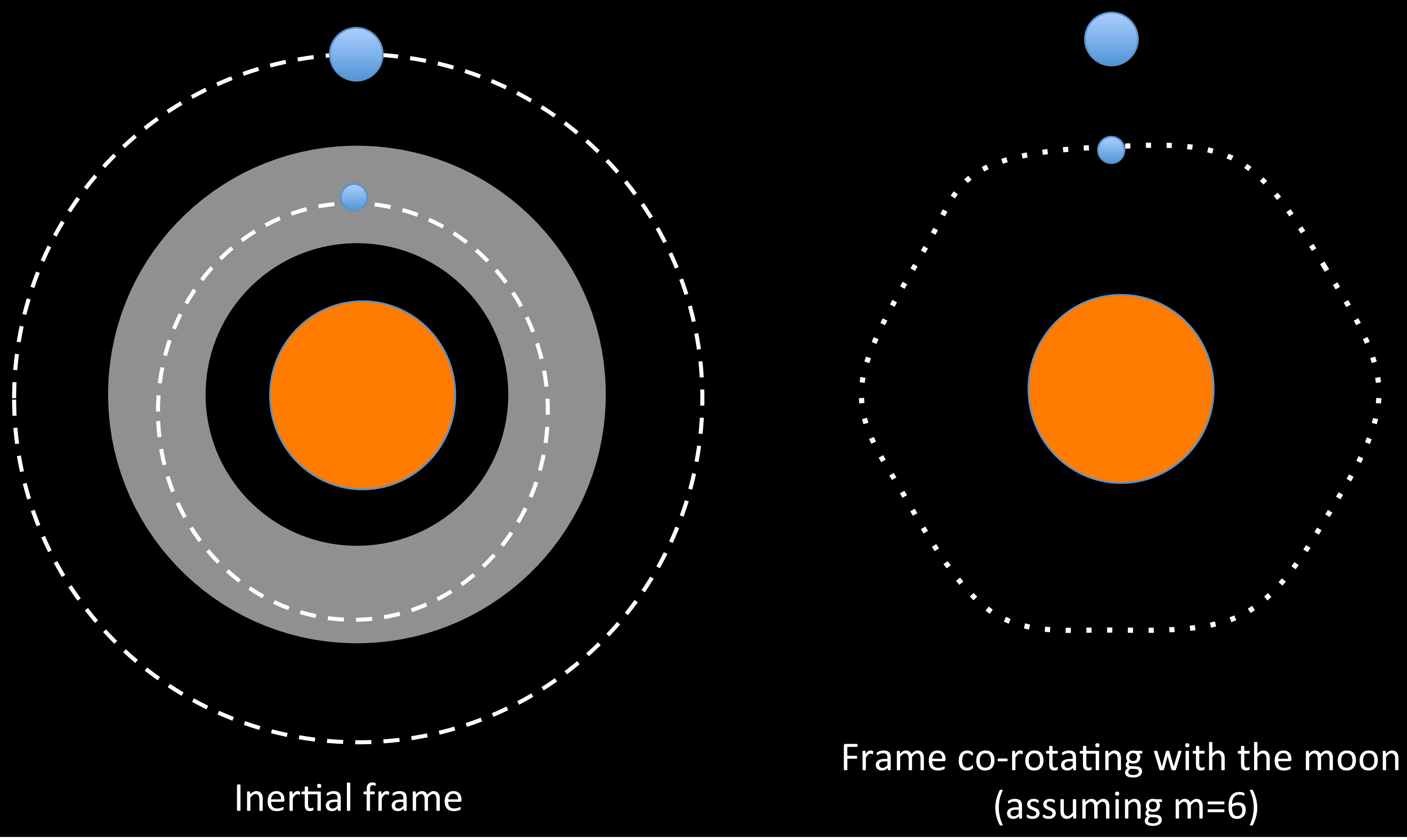
The internal structure of the giant planets can hold clues to how the solar system formed.



What happens at a (first order) Lindblad resonance?

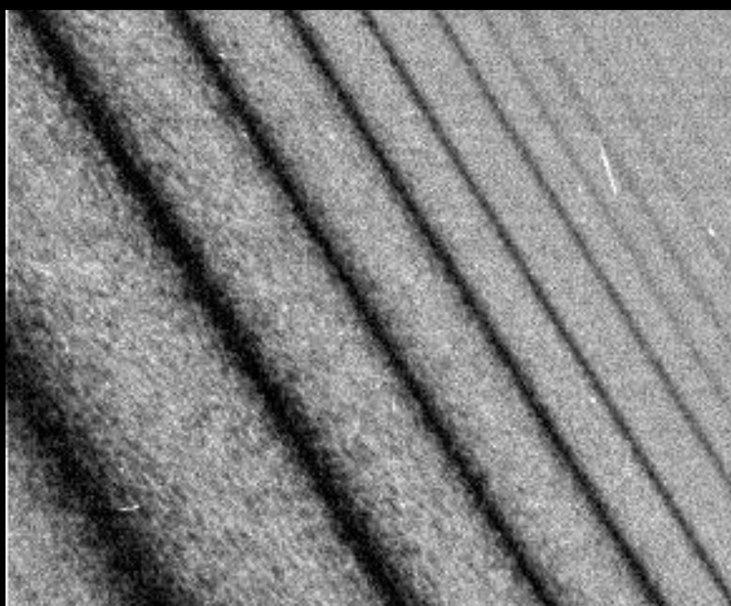
Orbit period of ring particle $\approx \frac{m-1}{m}$ x Orbital period of moon

m x Epicyclic period of ring particle ≈ Period between ring-moon conjunctions

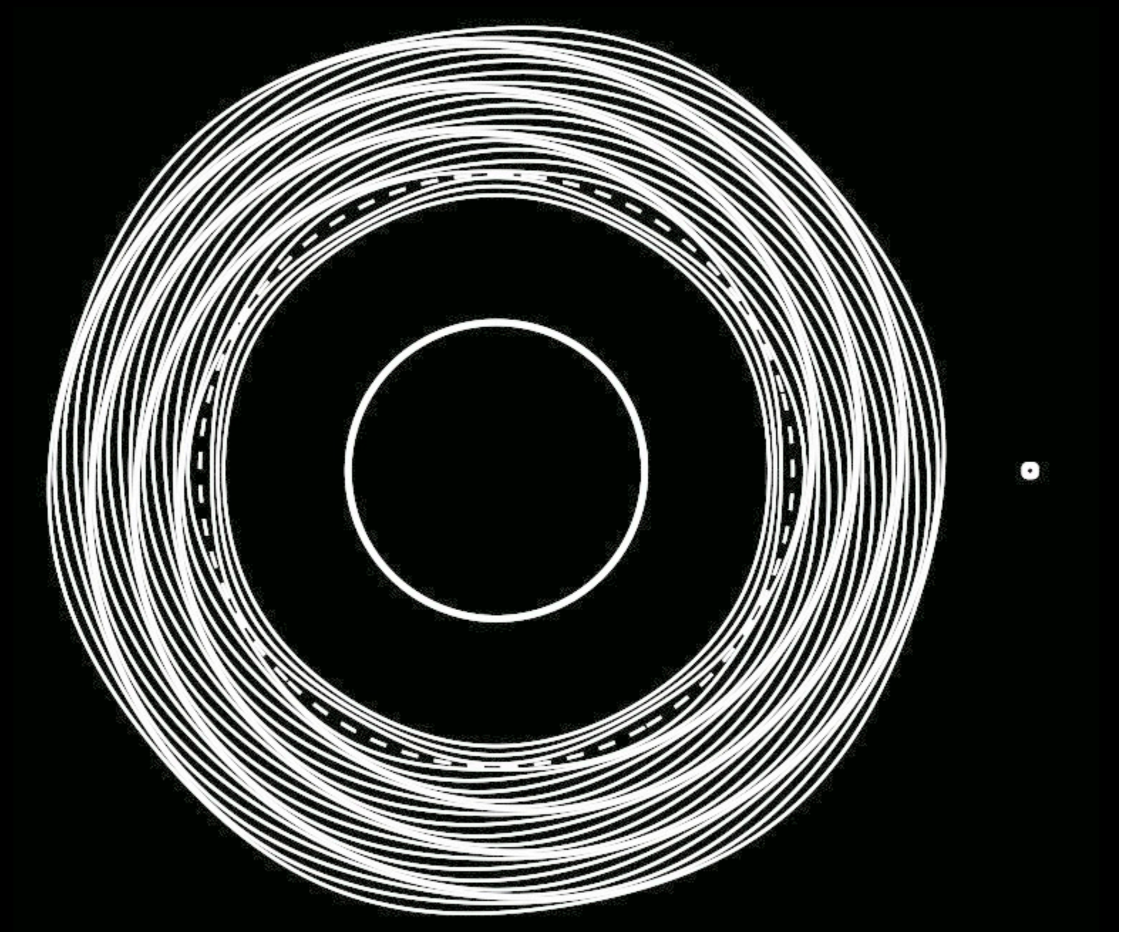


The A-ring spiral wave patterns are generated by Lindblad resonances

The strongest patterns are found at first-order resonances:
Moon's orbit period ≈ *m/(m-1)* x Ring-particle's orbit period



Ring Particle
Orbital Period=
5/6 Janus'
Orbital Period



In dense rings, the resonant perturbations drive spiral waves through the ring