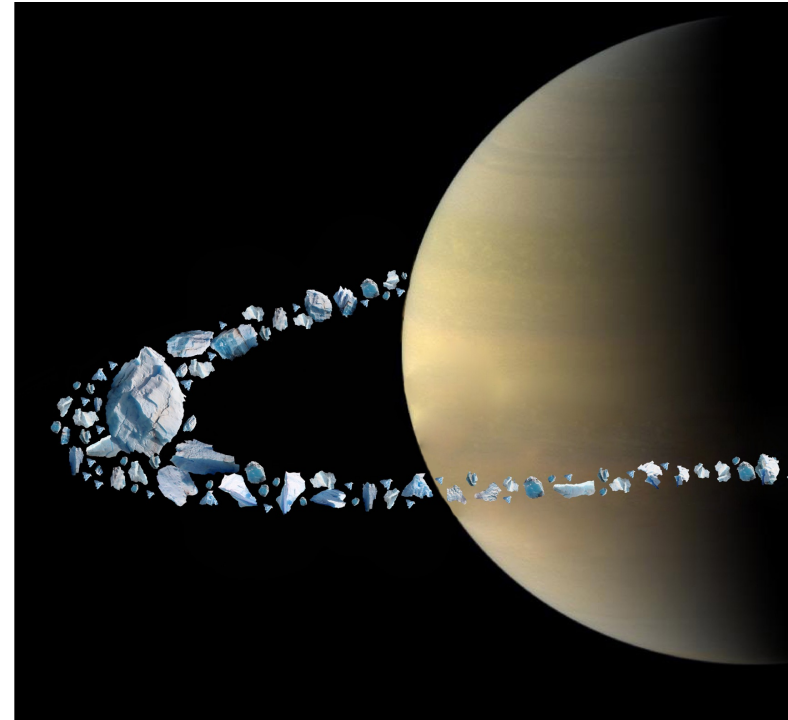
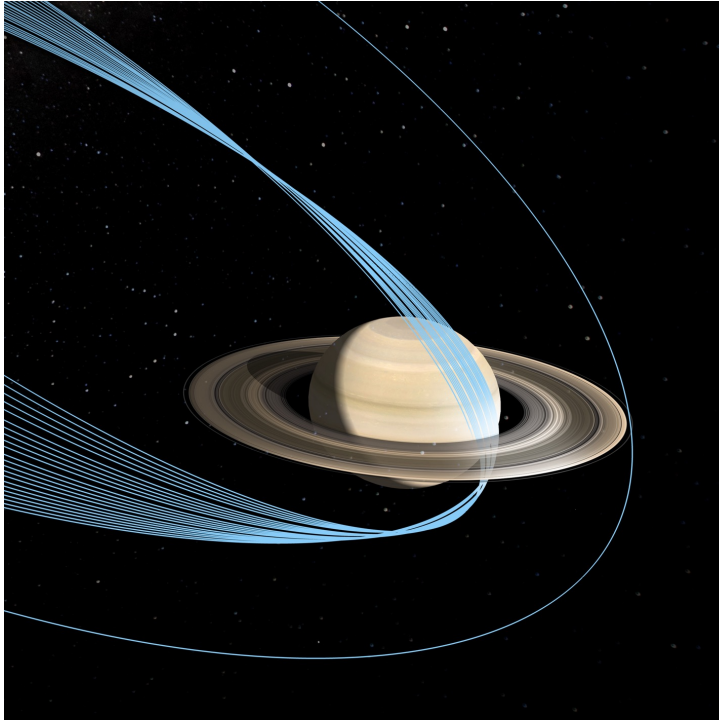


The Origin of Saturn's Obliquity and Young Rings



B. Militzer, W. B. Hubbard, J. Wisdom, R. Dbouk,

UC Berkeley

U Arizona

MIT

MIT

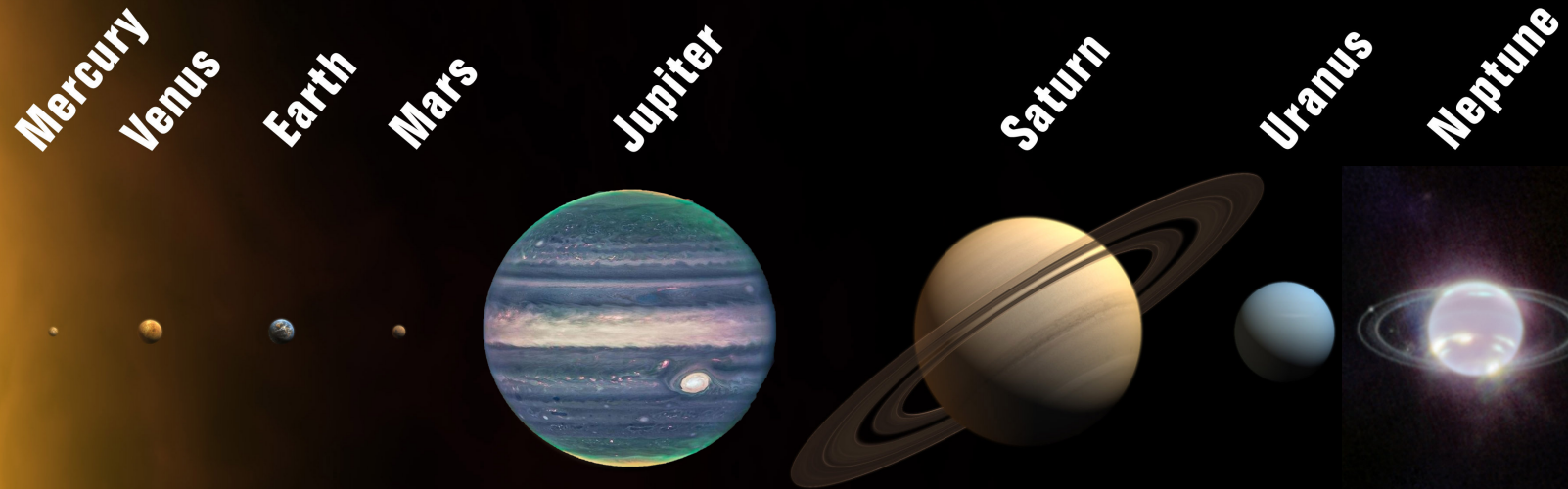
F. Nimmo, B. Downey, R. French

UCSC

UCSC

Wellesley

What is so Unusual About Planet Saturn?



How did Saturn become the Lord of the Rings?

GAS GIANT PLANETS

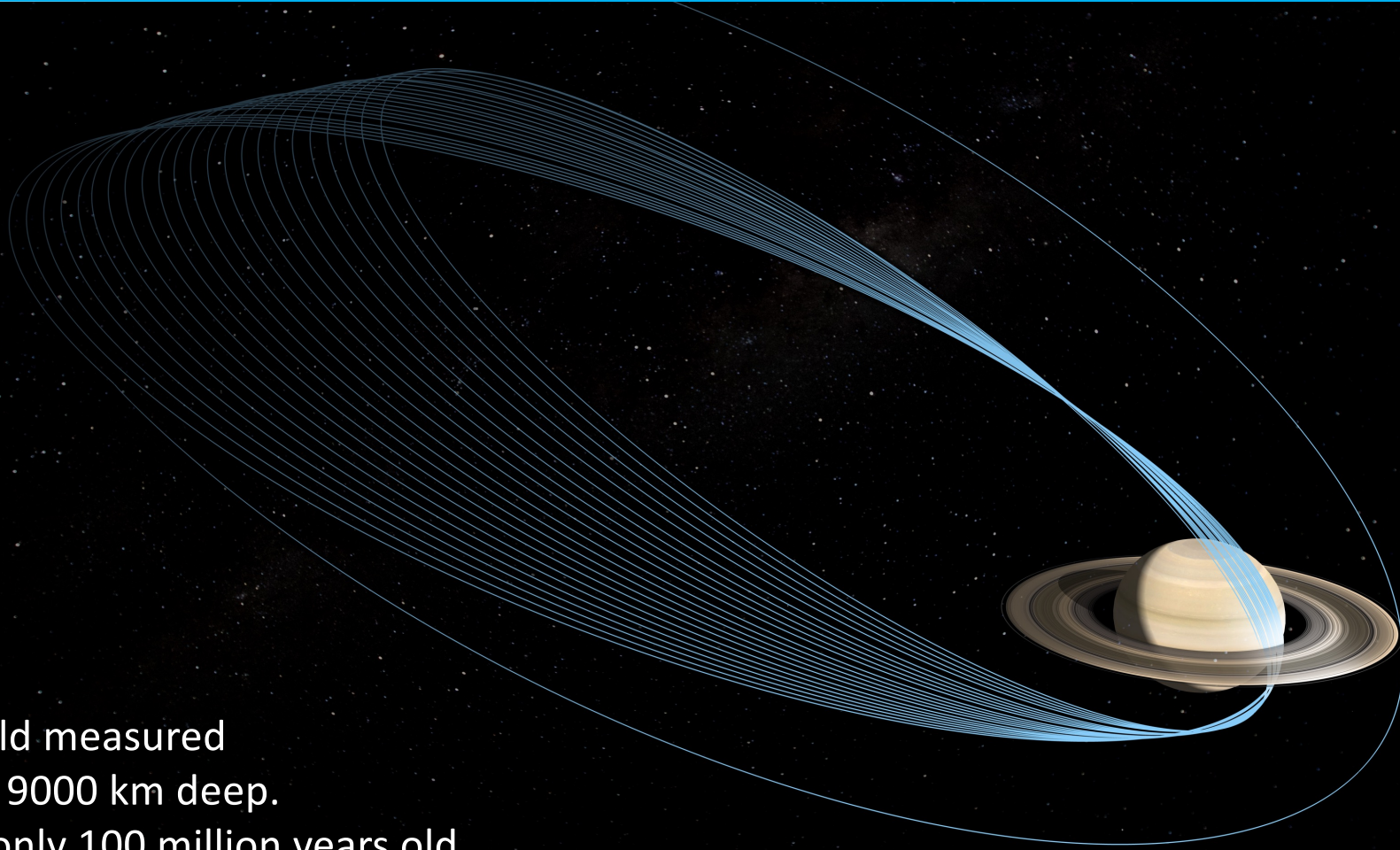
Loss of a satellite could explain Saturn's obliquity and young rings

Jack Wisdom^{1*}, Rola Dbouk¹, Burkhard Militzer^{2,3}, William B. Hubbard⁴, Francis Nimmo⁵, Brynna G. Downey⁵, Richard G. French⁶

Science **377**, 1285–1289 (2022)

16 September 2022

What is so unusual about Planet Saturn?

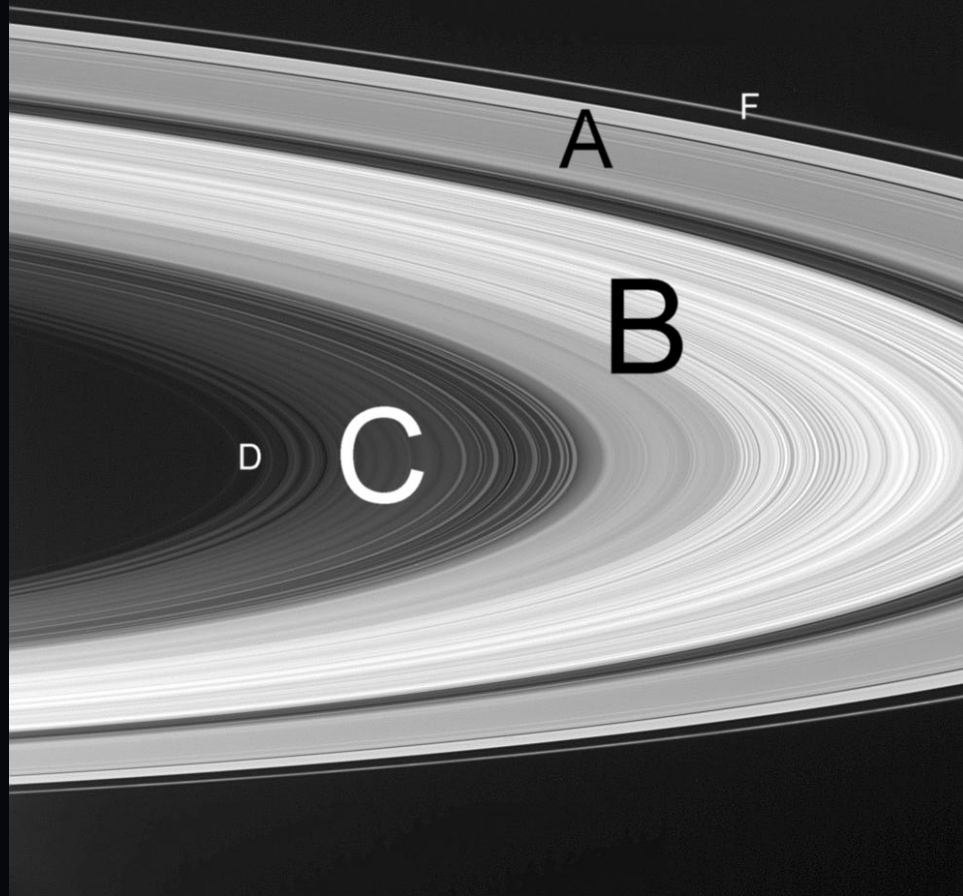


Gravity field measured

Winds are 9000 km deep.

Rings are only 100 million years old.

Mass of Saturn's Rings Measured



Saturn's
rings
labeled
A-F

First Determination of Saturn's Ring Mass from Gravity

Directly from the gravity signal, we determined a total mass of the main rings A, B and C =

0.41 ± 0.13 Mimas masses.

(2000 Mimas masses = 1 lunar mass)
(16000 Mimas masses = 1 Earth mass)

less, BM, et al. Science (2019)

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An indication that the **rings are young,**
were formed only 10-100 million years ago.

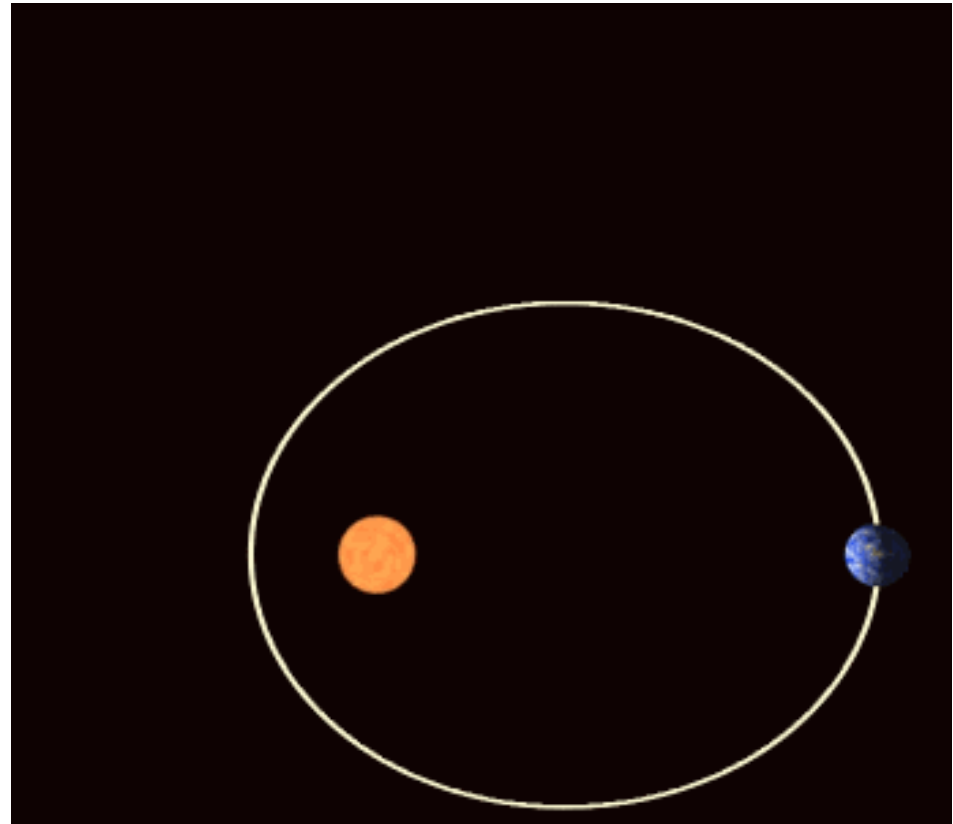
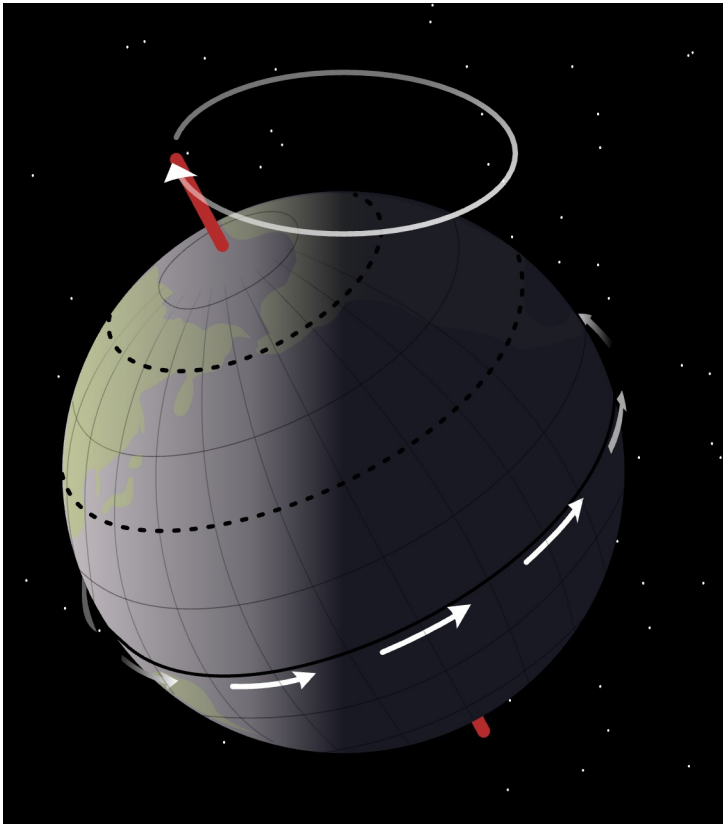
less, BM, et al. Science (2019)

What is a Cassini State?

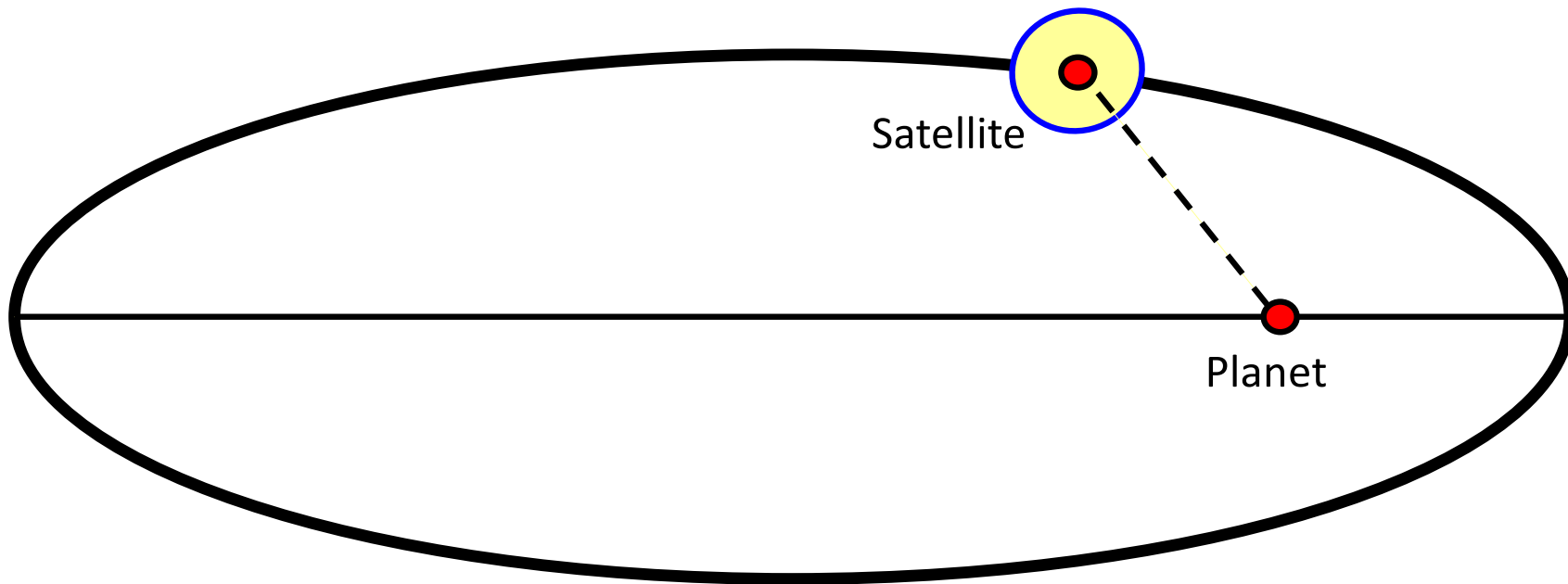
What is a Cassini State?

Answer: Spin-Orbit Coupling
between Planets or Moons

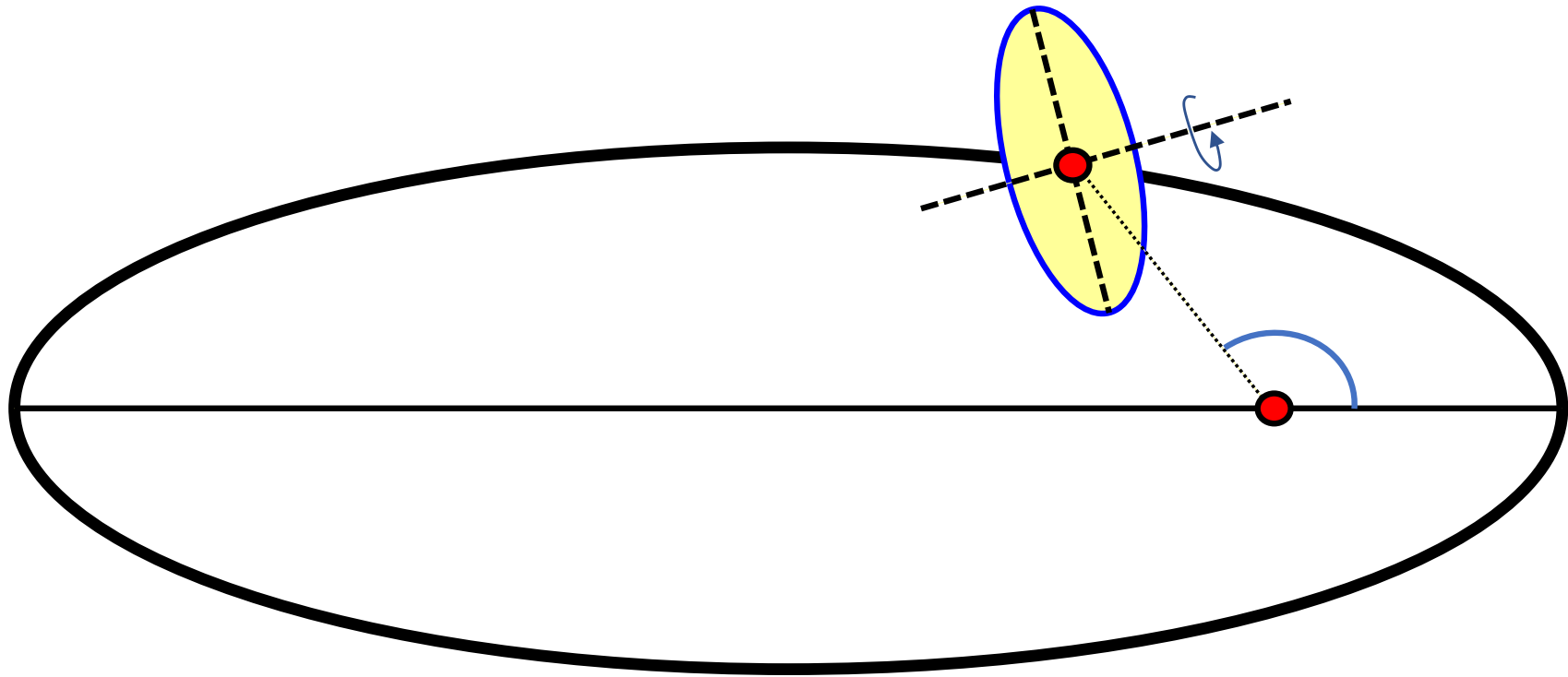
Example for Cassini State: Mercury's Orbit Around the Sun



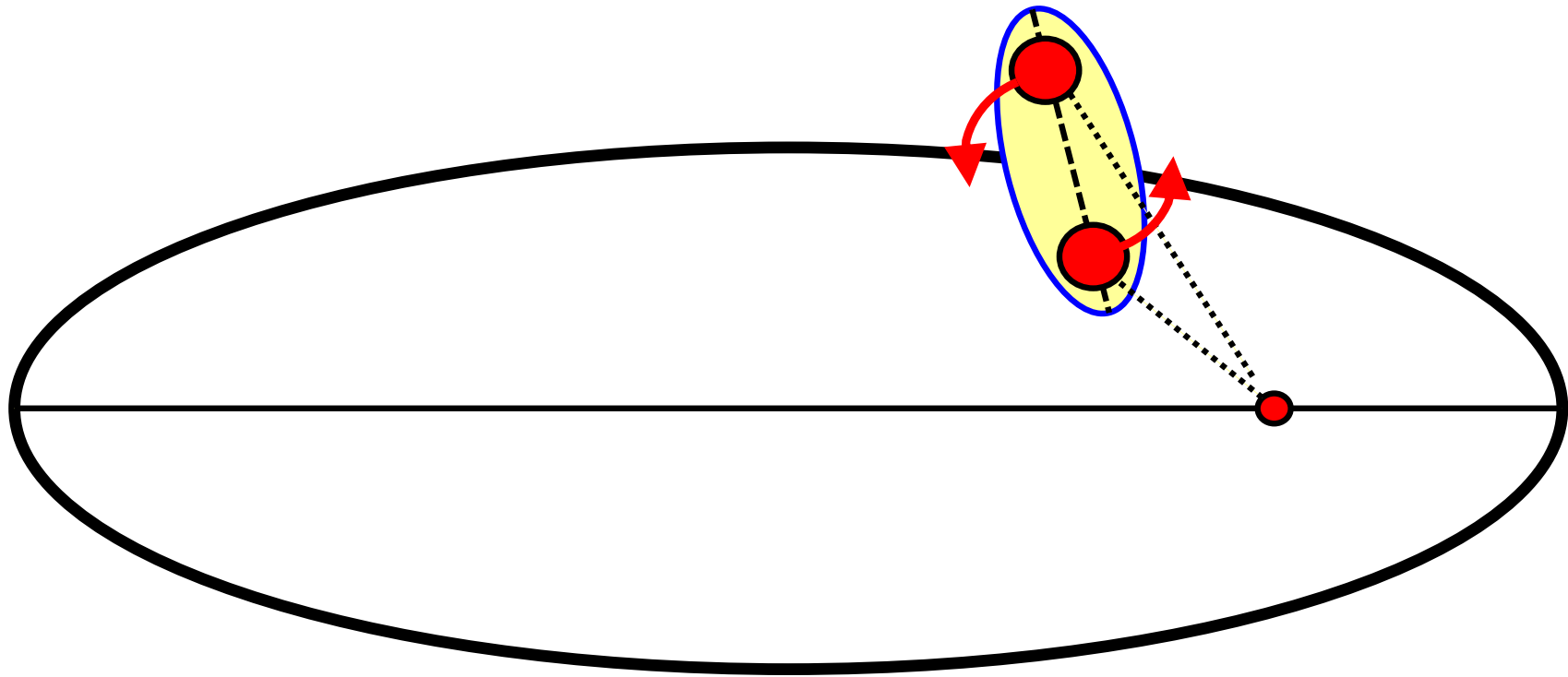
Spin-Orbit Coupling



Spin-Orbit Coupling



Spin-Orbit Coupling



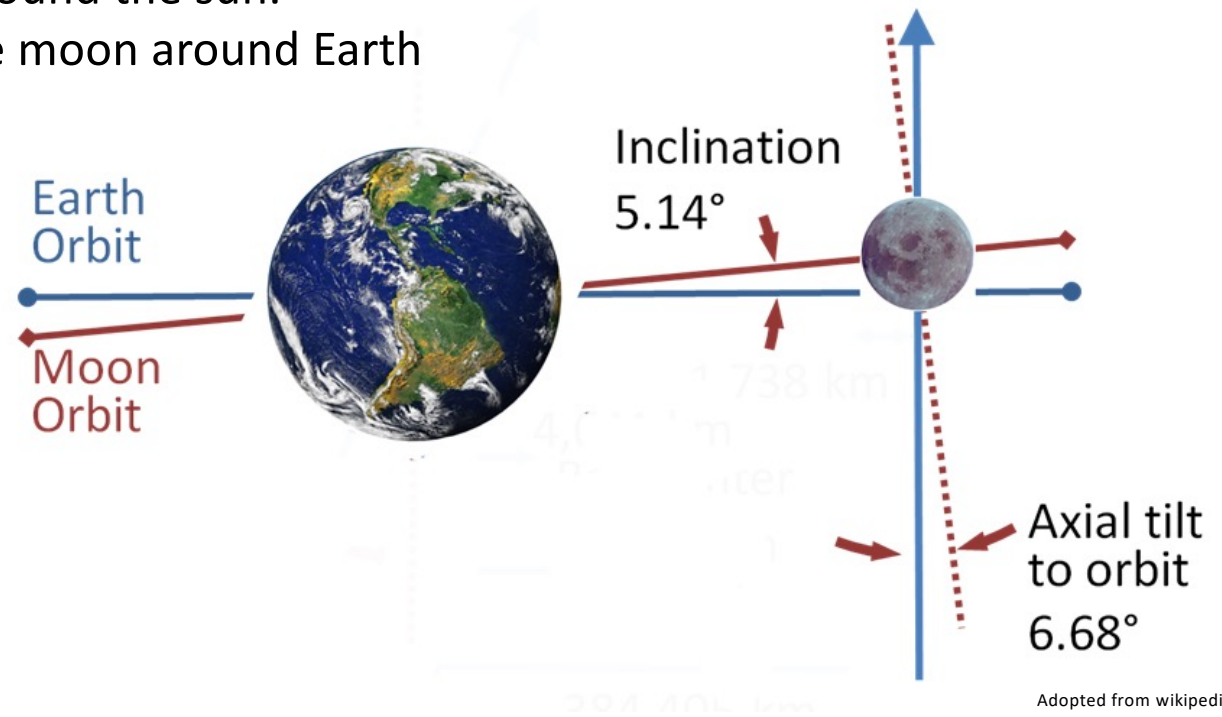
What is a Cassini State?

In 1643 Giovanni Cassini discovered spin-orbital coupling in the moon's motion.

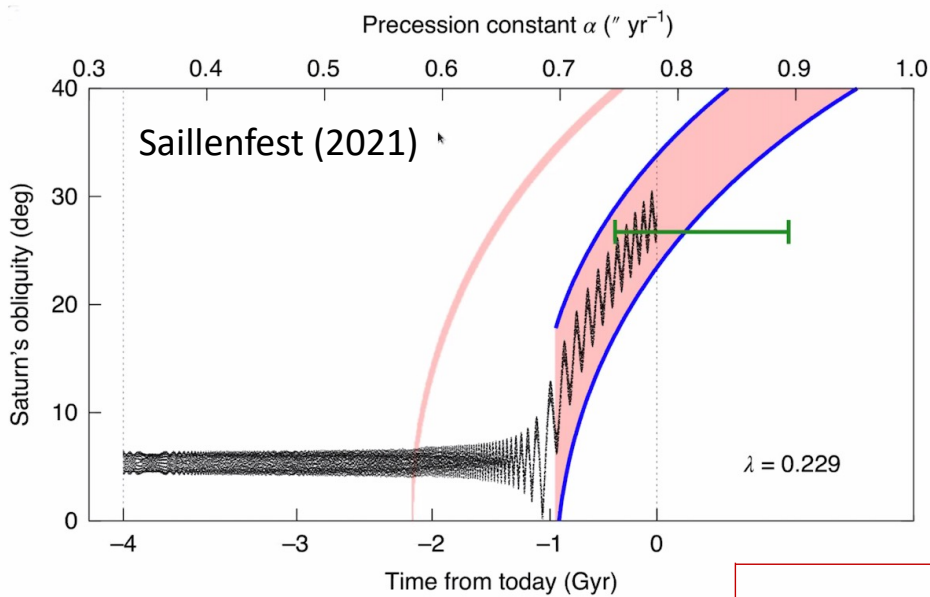
The following three vector always lie in one plane:

- 1) Vector normal to Earth's orbit around the sun.
- 2) Vector normal to the orbit of the moon around Earth
- 3) Spin axis of the moon

The moon regresses with an 18.6 year period. The so-called Cassini state is an example of a secular spin-orbit resonance.



This Saturn in Resonance with Neptune? This depends on Saturn's Angular Momentum



Torques acting on Saturn

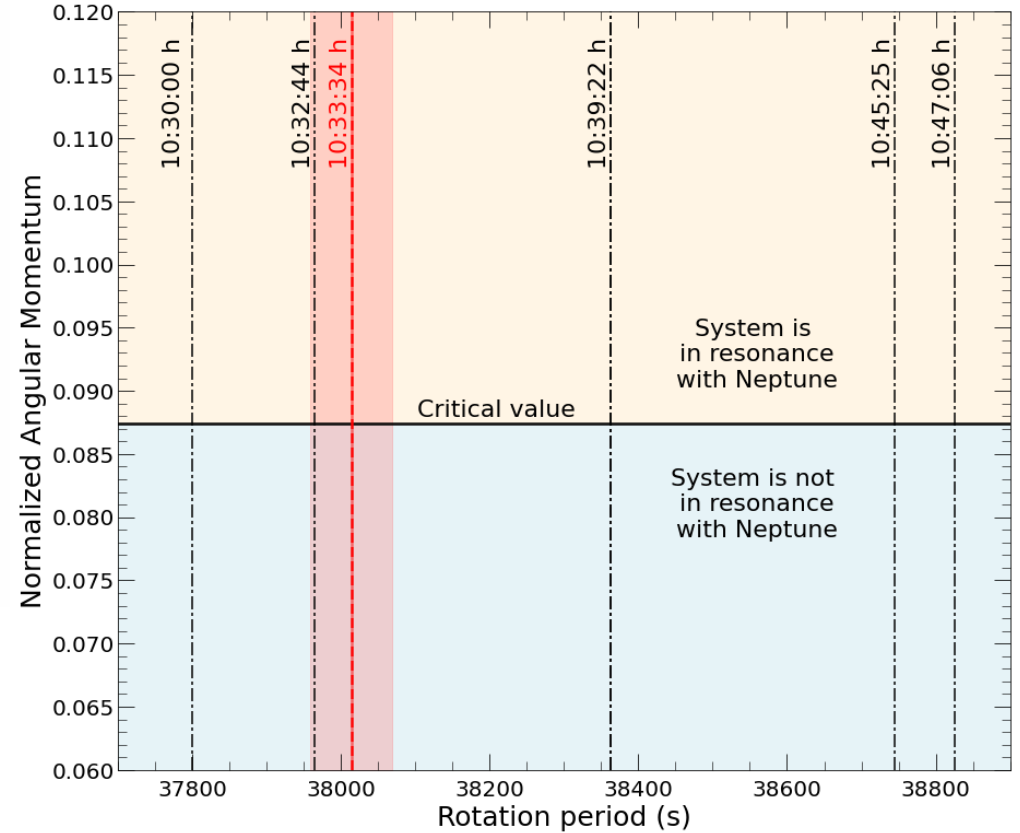
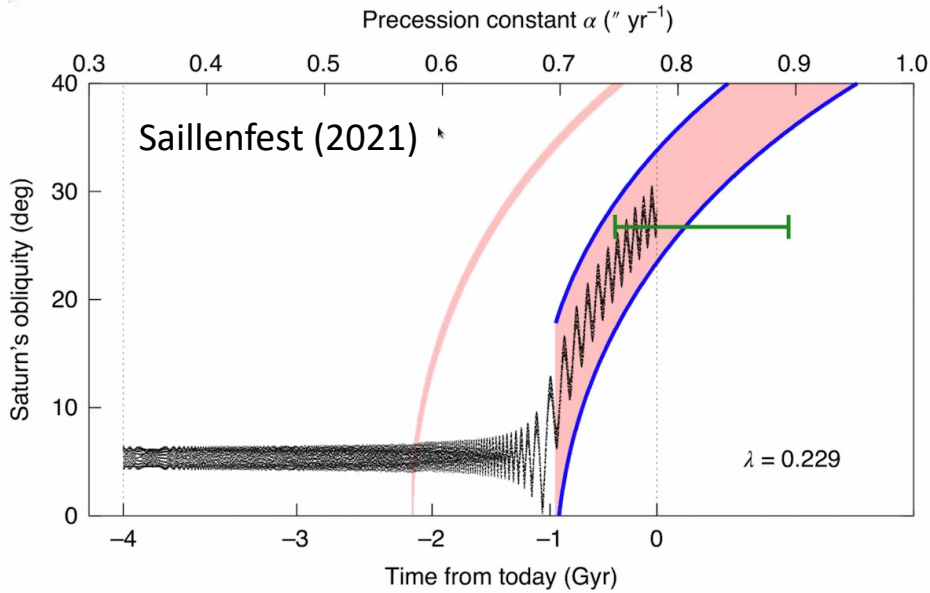
Torques acting on moons' orbits including Titan

Precession constant: $\alpha = \frac{3}{2} n \frac{J_2 + q}{\omega \lambda + l}$

Saturn's moment of inertia: C/MR^2

Moons' contribution to angular momentum

This Saturn in Resonance with Neptune? This depends on Saturn's Angular Momentum

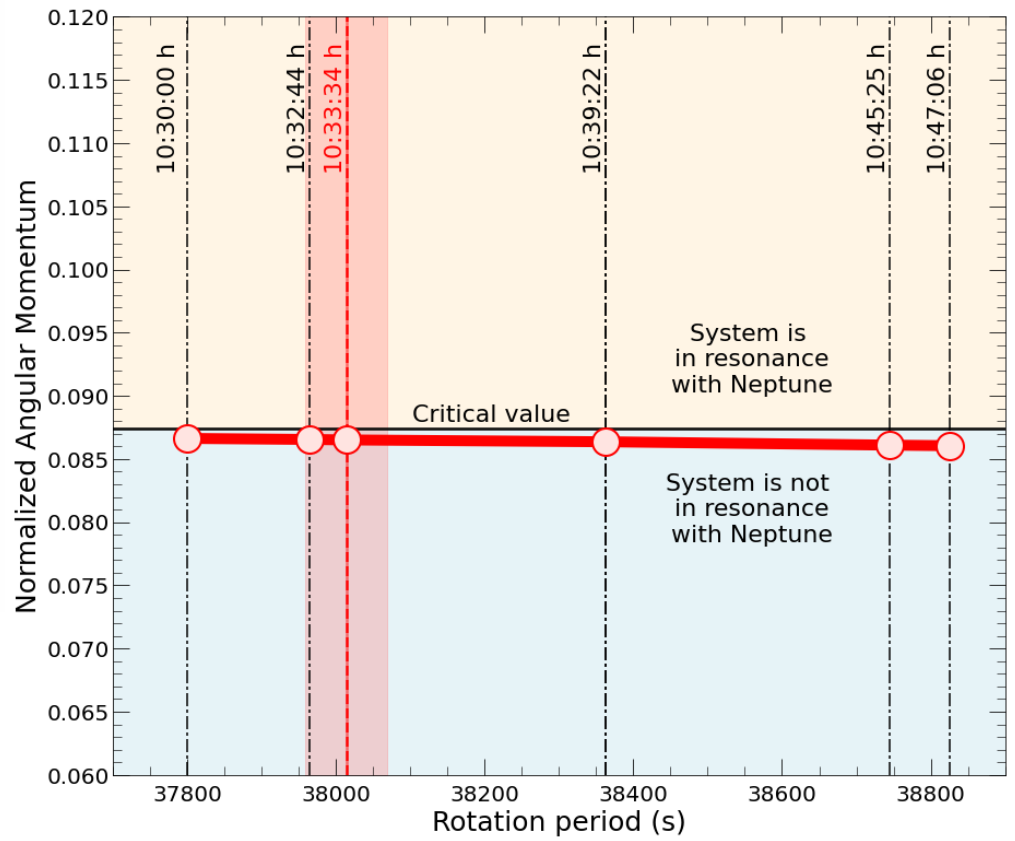
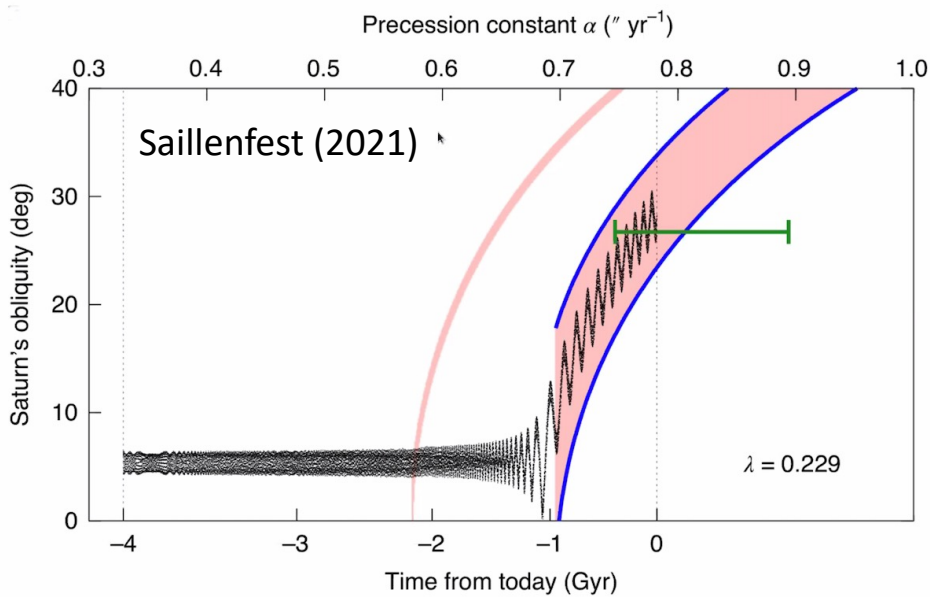


Precession constant:
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This Saturn in Resonance with Neptune? This depends on Saturn's Angular Momentum

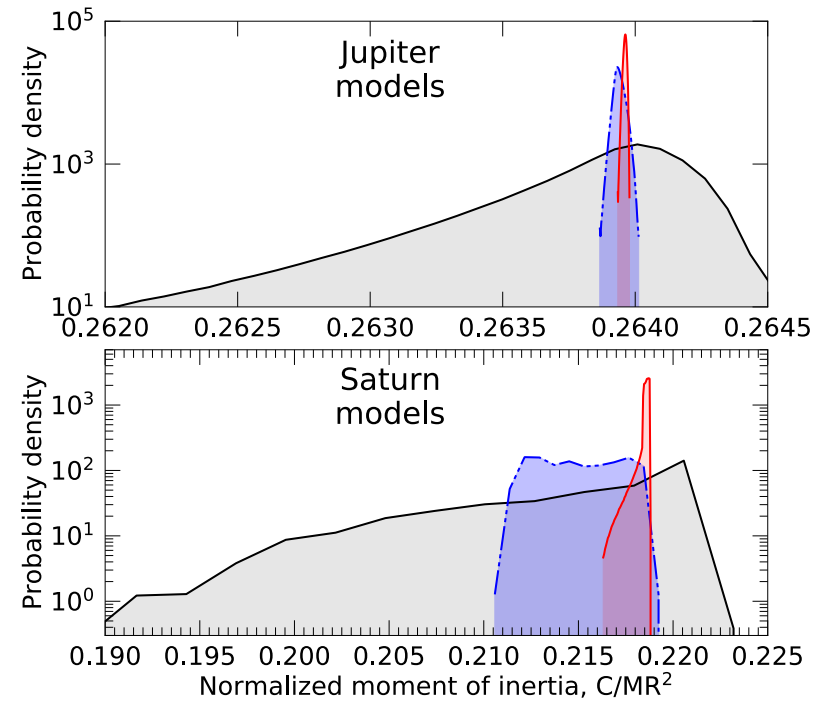
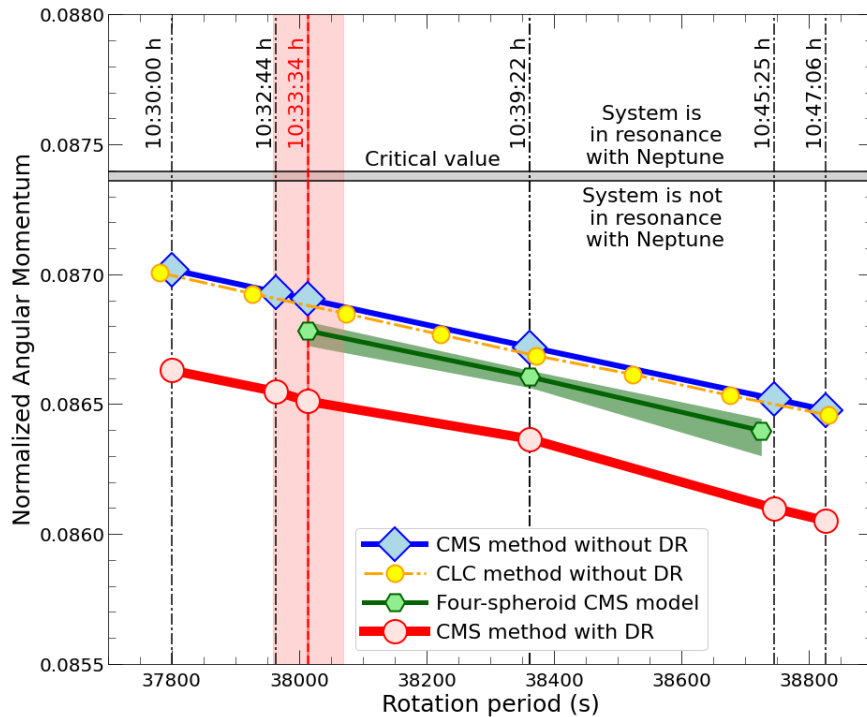


Precession constant:
$$\alpha = \frac{3}{2} n \frac{n J_2 + q}{\omega \lambda + l}$$

Saturn's moment of inertia: C/MR^2

Moons' contribution to angular momentum

Why do J_2 , J_4 , and J_6 constrain the moment of inertia so well?



$$J_n = -\frac{2\pi}{Ma^n} \int_{-1}^1 d\mu \int_0^a r^{n+2} P_n(\mu) \rho(r, \mu) dr$$

$$\text{MoI} \equiv \frac{C}{MR_e^2} = \frac{2\pi}{MR_e^2} \int_{-1}^1 d\mu \int_0^{R(\mu)} dr r^2 l^2 \rho(r, \mu)$$

Our scenario for the formation of Saturn's rings

1. The Saturnian system formed with an **additional moon, Chrysalis**. Saturn's spin axis was perpendicular to its orbital plane.
2. Chrysalis **gave Neptune an extra "handle" to tilt Saturn's spin axis** (via a spin-orbit resonance) to the large value that we see today, 27° .
3. Saturn's moon **Titan started to migrate out**. About 160 million years ago, it entered into a **resonance with the moon Chrysalis** destabilizing its orbit.
4. As a result, Chrysalis came so close to Saturn that it was sheared apart by Saturn's intense gravity (**tidal disruption**). Most of the material fell into Saturn but out of 1%, the rings formed.
5. With Chrysalis gone, Neptune could no longer change Saturn's spin axis. So the planet was left spinning at an angle of 27° .

Our scenario for the formation of Saturn's rings is supported by the following lines of evidence:

1. It predicts a young age for **Saturn's rings of only 100 million years** approximately. This is in agreement with the ring color and Cassini's measurements of the ring mass.
2. It explains **why Saturn's spin axis is tilted** rather than being vertical, which it was when the planet formed.
3. It also explains **why Saturn's moment of inertia is so close to the critical value** to be in a spin-orbit resonance with Neptune but just outside of the critical region.
4. It is consistent with **Titan's observed migration** and offers an explanation why its orbit is slightly elliptical.

The End

Any Questions?