Non-synchronous rotation of exoplanets in the potentially habitable zone of solar-type stars

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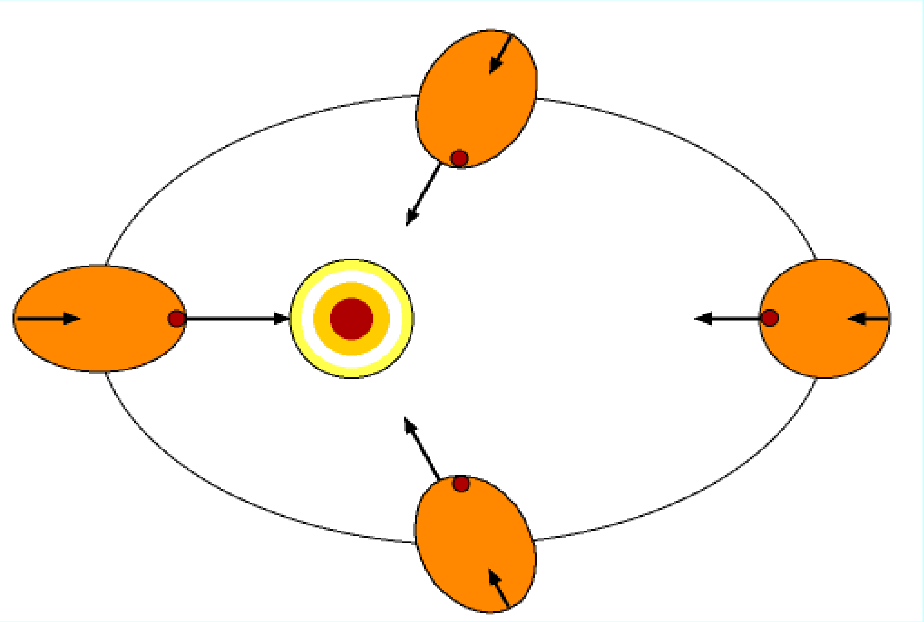
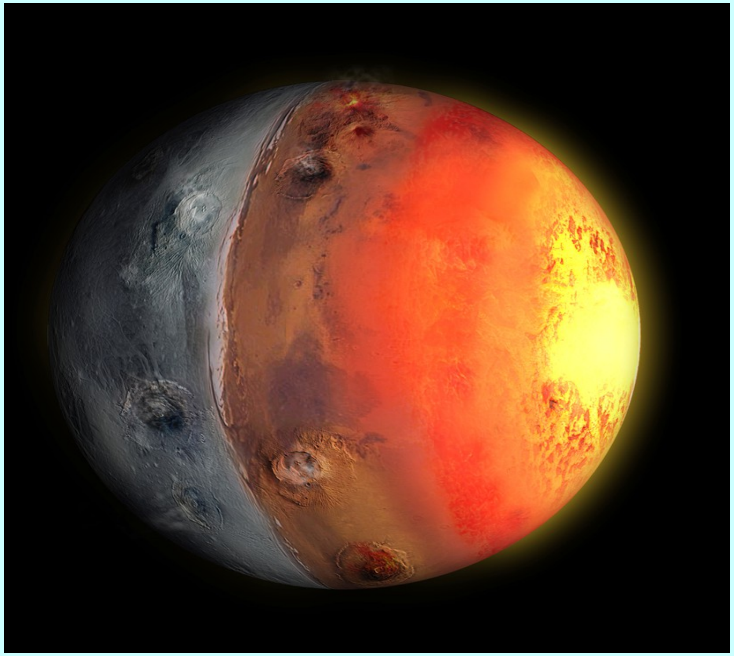
Main Reference:
Astronomical Journal (2026)
(astro-ph 2512.06526)

More important tidal effects on close-in planets:

Synchronization
Dissipation
Circularization

which strongly affect the habitability of the planets





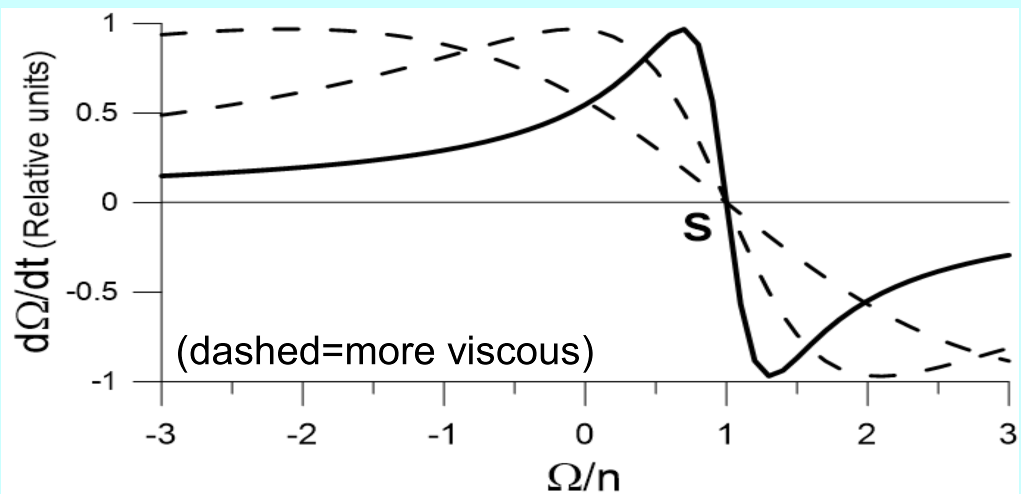
SYNCHRONIZATION of close-in planets

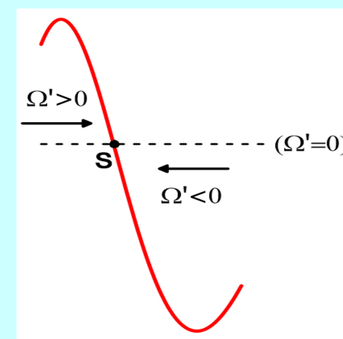
Main equation cf creep (hydrodynamical) theory

$$\langle\dot{\Omega}\rangle = -\frac{GMmR_N^2 k_f \bar{\epsilon}_\rho}{5Ca^3}\sum_{k\in\mathbb{Z}} E_{2,k}^2 \sin 2\sigma_k .$$

$$\sin 2\sigma_k = \frac{2\gamma(\nu + kn)}{\gamma^2 + (\nu + kn)^2} .$$

If e~0, the term k=0 (semi-diurnal tide) is strongly dominant and the rotation of a close-in planet evolves to a **stable synchronous solution** in relatively short times.





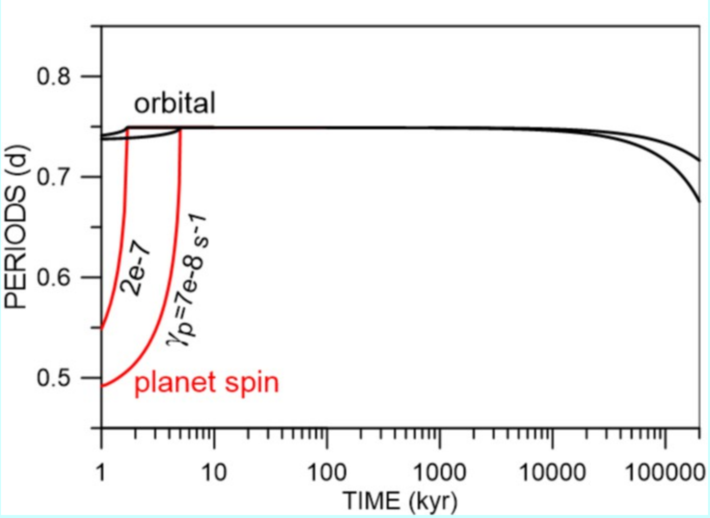
N.B. In the creep theory the ruling o.d.e. Is first-order
(not second-order as in the case of asymmetric rigid bodies)

Example:
55 Cancri Ae

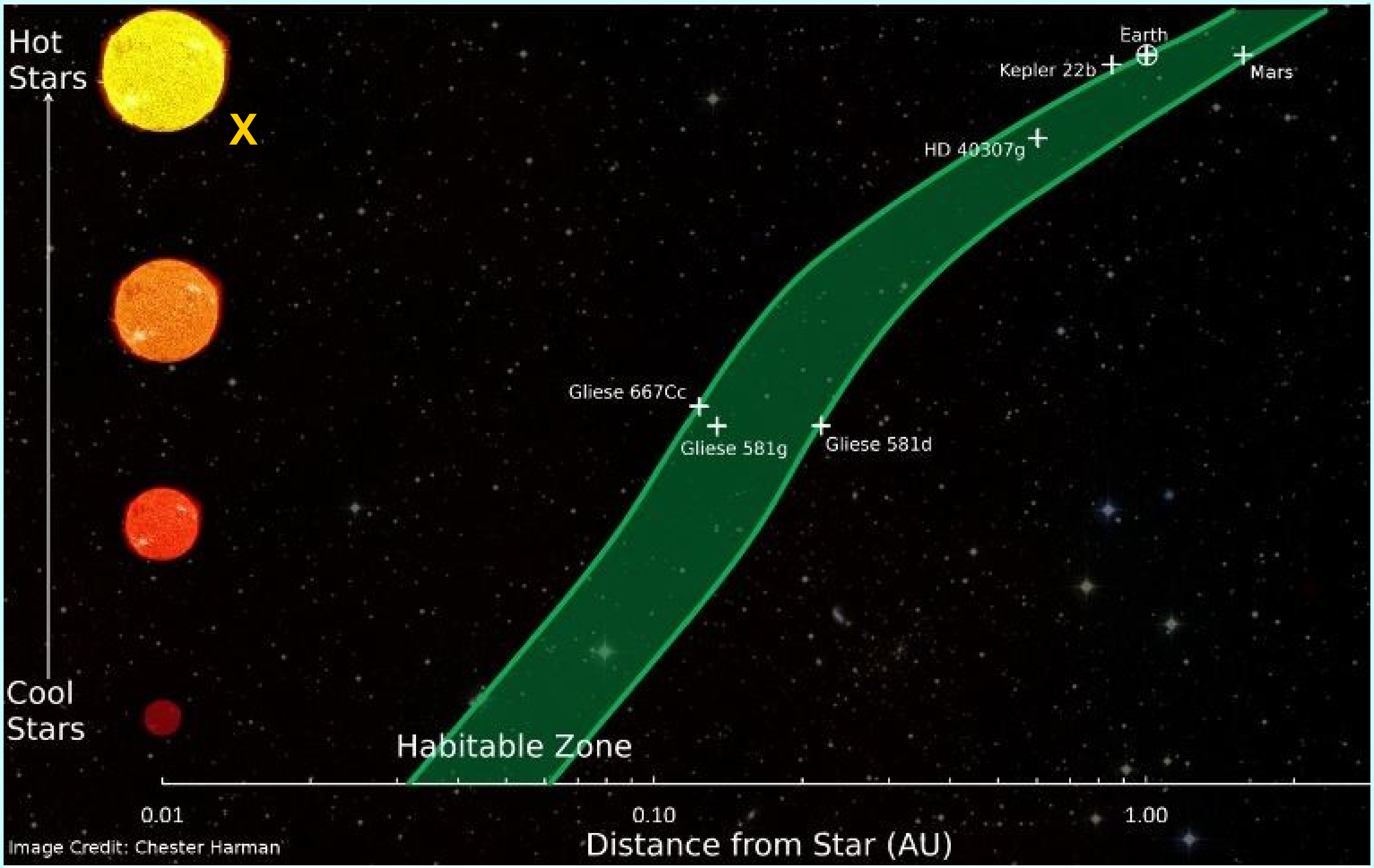
Orbital period: 18h

Synchronization time: O(kyr)

Consequences:
Brightness variations observed
with warm Spitzer and JWST.



N.B. close-in planet. Far from habitabe zone.

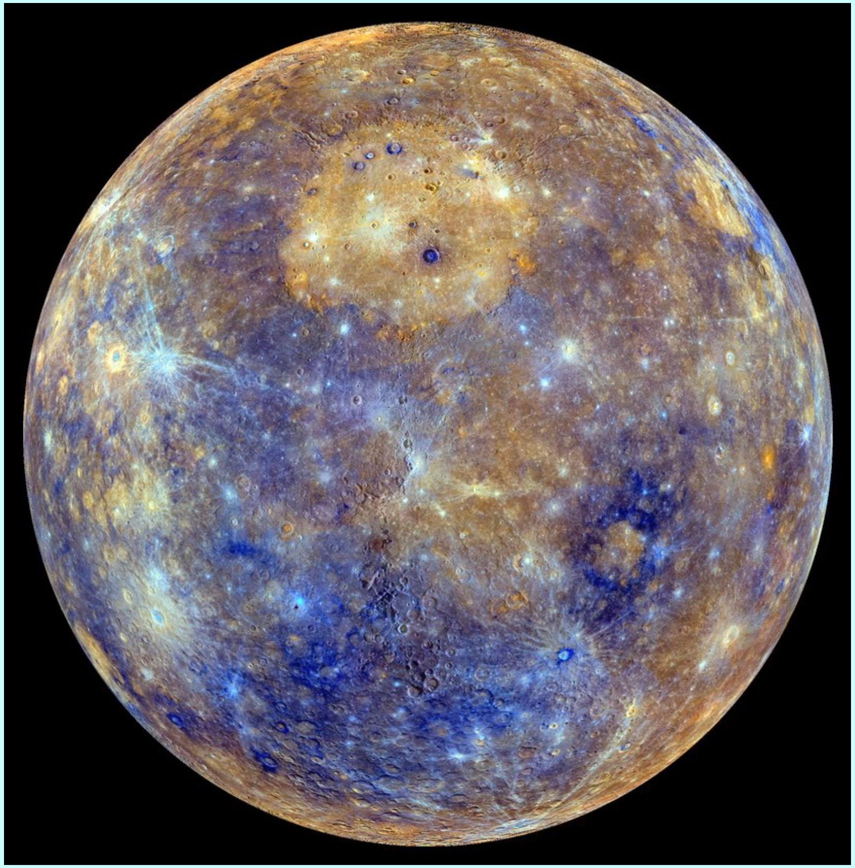


X~55 Cnc Ae

For Sun-like stars, the habitable zone is farther away.
Weaker tidal effects may lead to stable non-synchronous rotations.
Examples are Mercury and Venus.

MERCURY

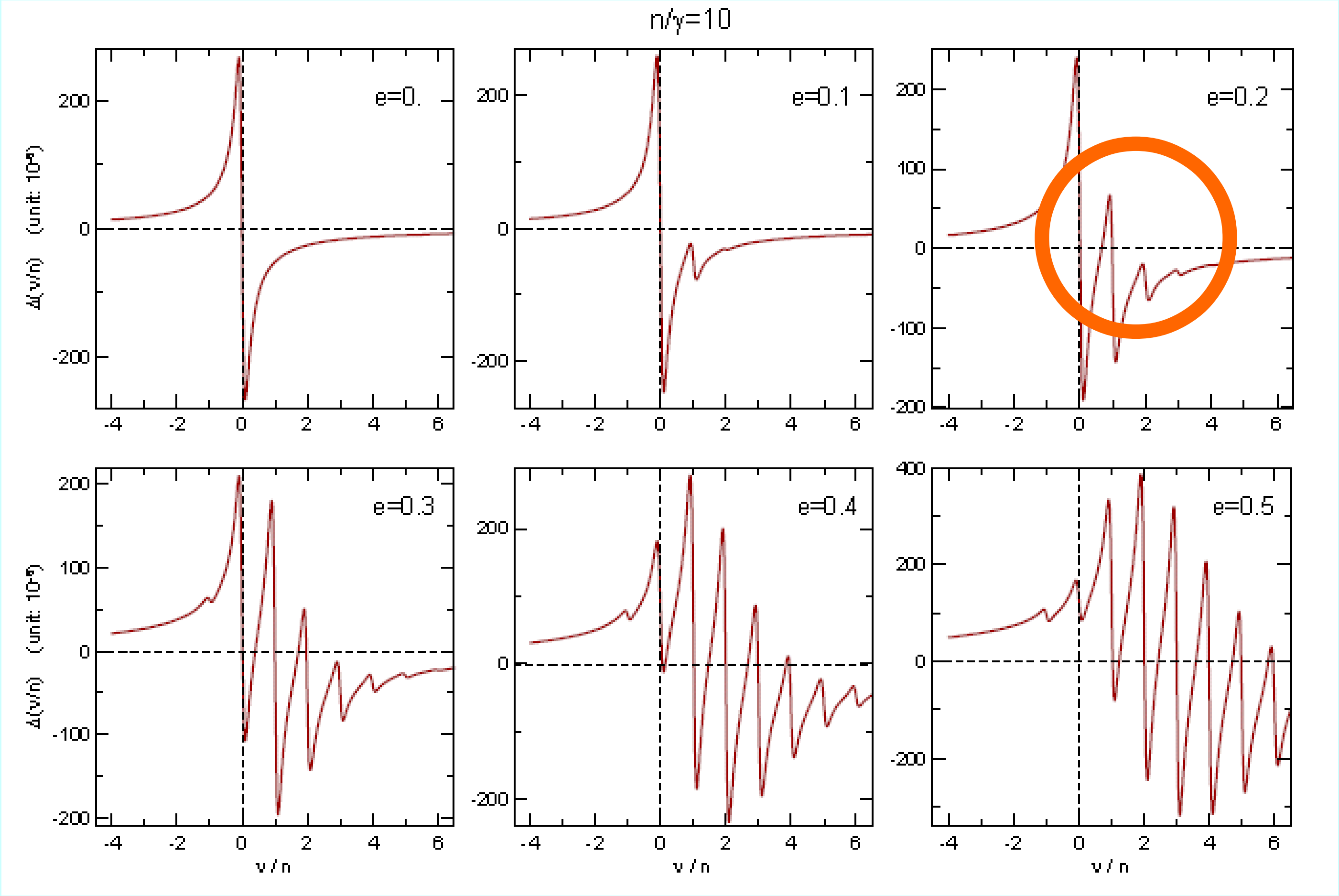
Rotation Period
58.65 days
3:2 resonance with
the orbital motion



Orbital eccentricity ~0.21

$$\langle\dot{\Omega}\rangle = -\frac{GMmR_N^2 k_f \bar{\epsilon}_\rho}{5Ca^3} \sum_{k\in\mathbb{Z}} E_{2,k}^2 \sin 2\sigma_k .$$

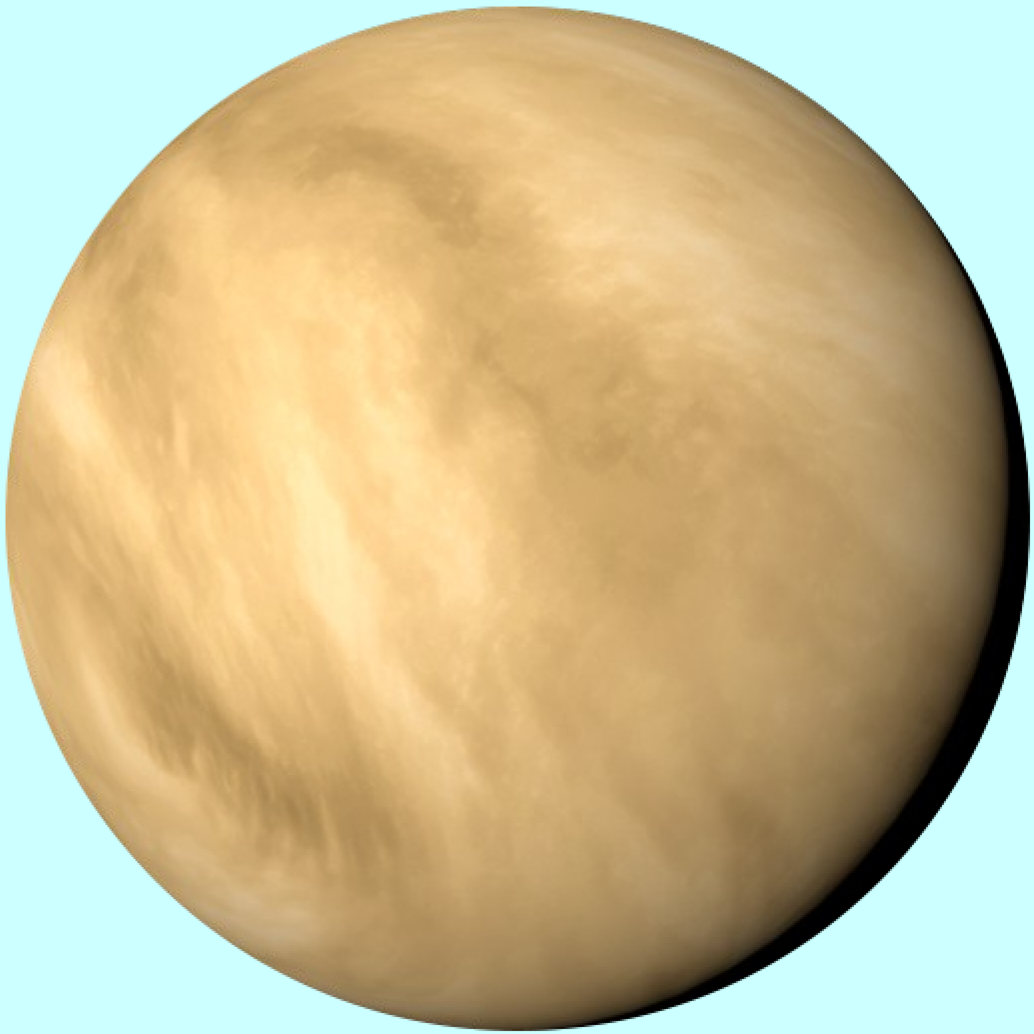
Terms with k=1,2,.. create new stable solutions at frequencies that are semi-integer multiples of the mean motion



Refs: Correia et al. 2014; SFM 2015.

VENUS

Rotation Period
243.0226 d
(Retrograde)

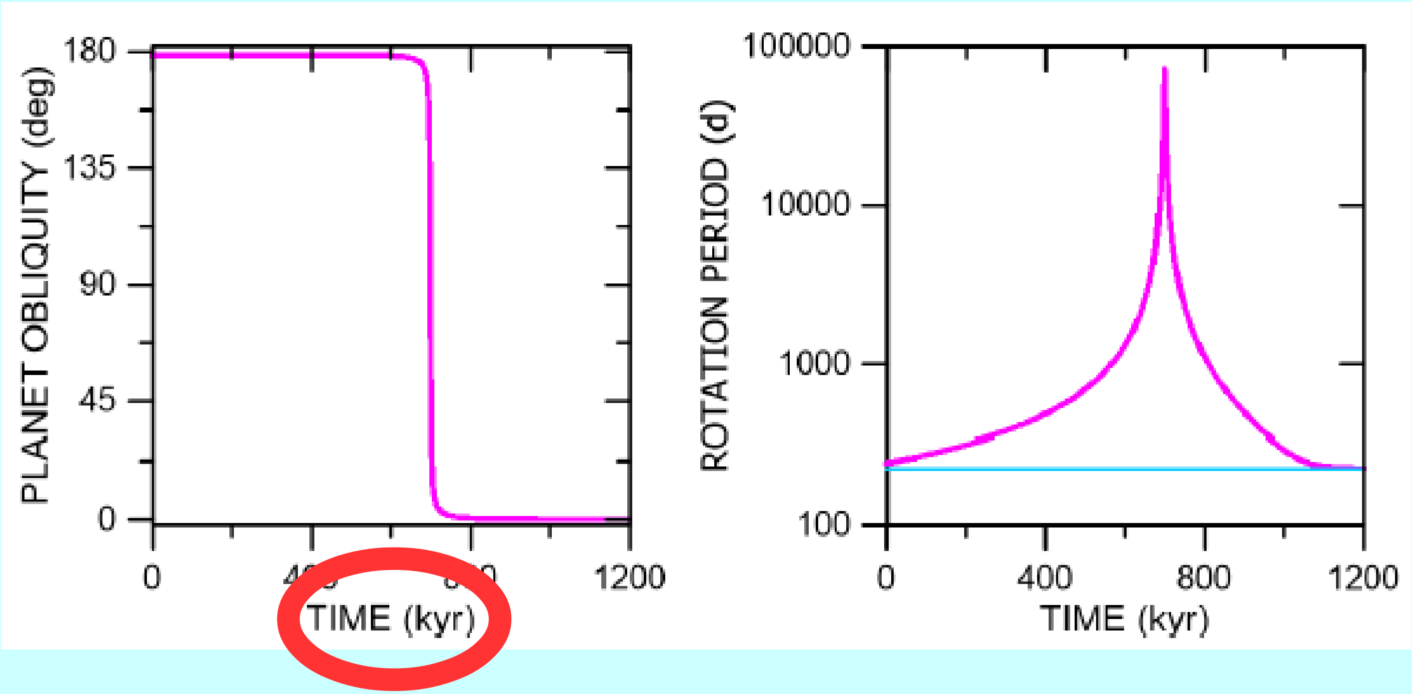


FACT #1

THERE EXISTS A FORCED TORQUE ACTING IN THE DIRECTION OF THE ROTATION

OTHERWISE

- THE TIDAL TORQUES ACTING ON THE PLANET BODY BRAKE THE ROTATION AND INVERT ITS DIRECTION.
- THE ROTATION BECOMES SYNCHRONOUS ....



IN A SHORT TIME
~Myr

FACT #2
THE FORCED TORQUE IS NOT "DARK"

- IT WAS IDENTIFIED 50 yrs AGO AS **MAINLY** DUE TO THERMAL ATMOSPHERIC TIDES.

Gold, T., & Soter, S. 1971, Icarus,

Ingersoll, A. P., & Dobrovolskis, A. R. 1978, Nature,

Correia, A. C. M., & Laskar, J. 2001, Nature

Correia, A. C. M., & Laskar, J. 2003a, Journal of Geophysical Research

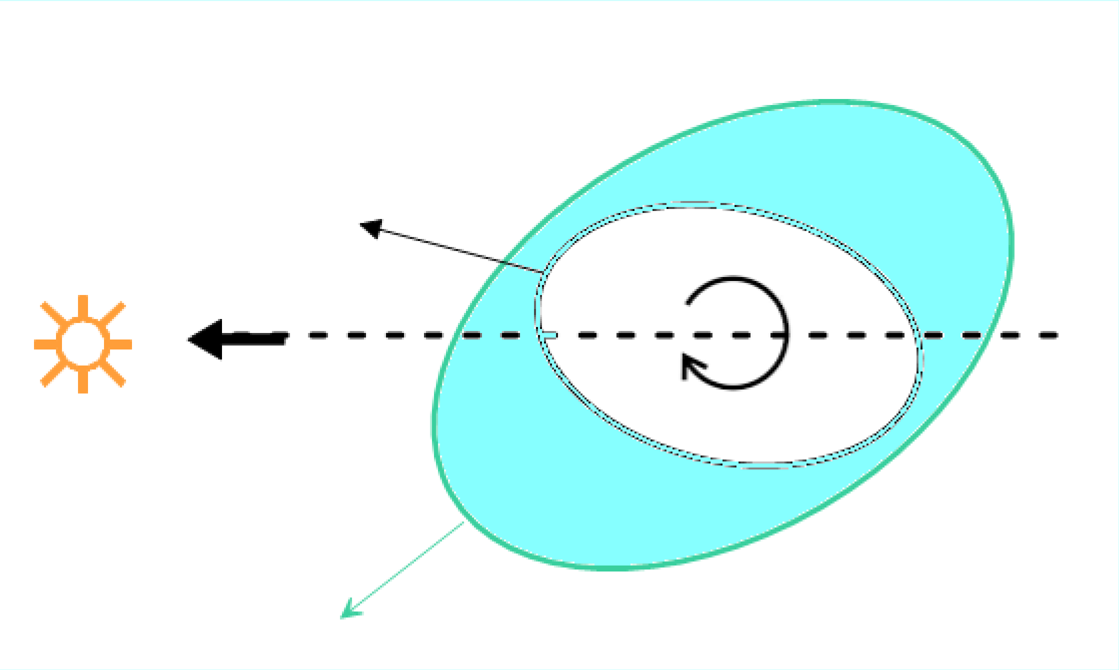
Leconte, J., Wu, H., Menou, K., & Murray, N. 2015, Science,

Auclair-Desrotour, P., Farhat, M., Bou´e, G., Deitrick, R., & Laskar, J. 2024, arXiv e-prints,

ETC.

- THE HEATING OF THE ATMOSPHERE GENERATES A HUGE ASYMMETRY

- THE GRAVITATIONAL ATTRACTION OF THE SUN ON THIS ASYMMETRY GENERATES A TORQUE IN THE DIRECTION OF THE MOTION



BASIC EQUATION:

$$\dot{\Omega} = -A \sin 2\sigma_0 + A' \sin 2\sigma'$$

$$\dot{\Omega} = A \sin 2\sigma_0 \left(b \, \frac{\nu^2 + \gamma^2}{\nu^2 + \gamma'^2} - 1 \right)$$

$$b = \frac{A'\gamma'}{A\gamma}.$$

Ω... ROTATIONAL VELOCITY

A, A' …. COEFFICIENTS

σ_0, σ' …. BULGE LAGS

γ, γ' …. RELAXATION FACTORS OR EQUIVALENT

$\nu=2\Omega-2n$ TIDAL SEMI-DIURNAL FREQUENCY

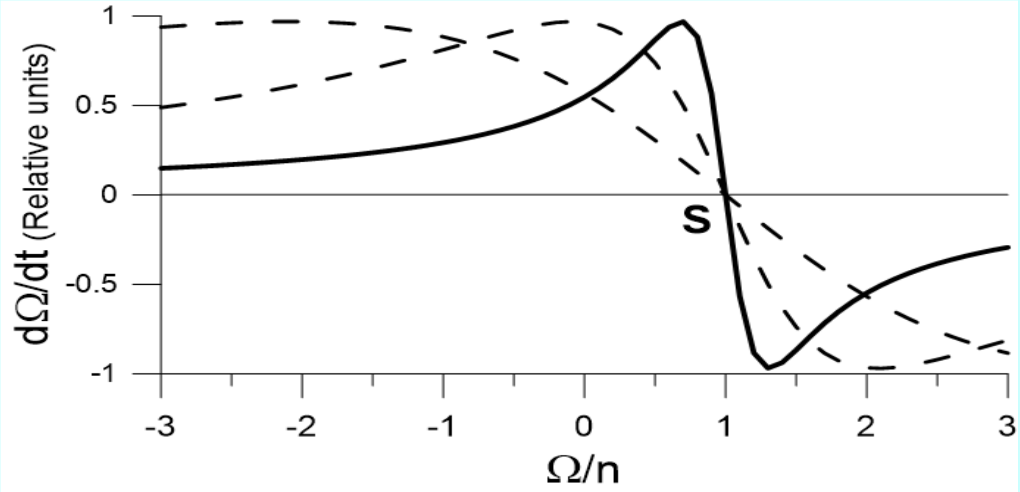
n..... MEAN MOTION (orbital)

N.B.

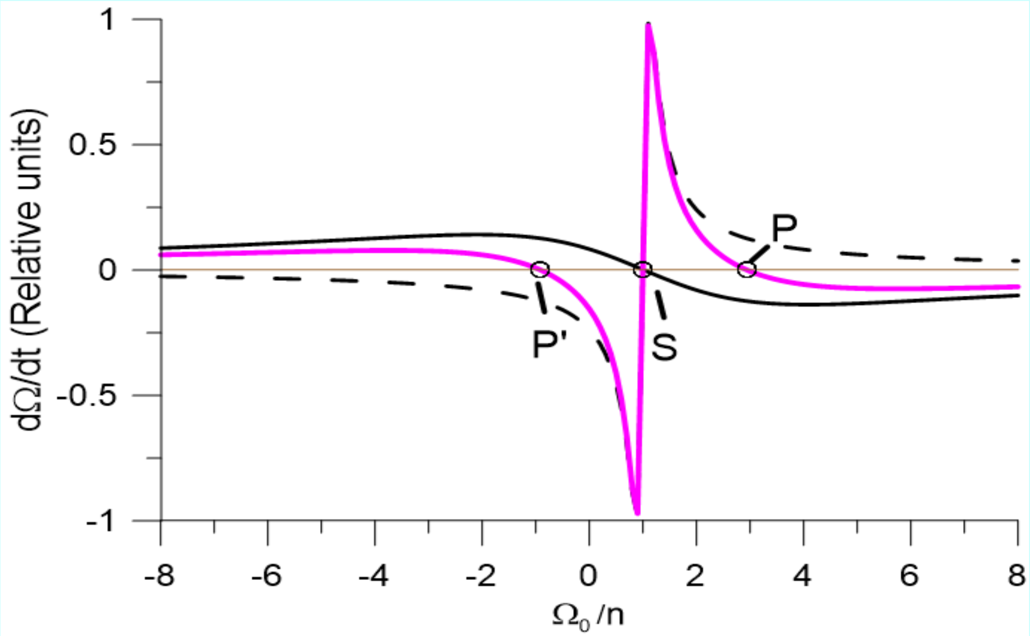
σ_0 = atan (ν/γ) … not arbitrary.

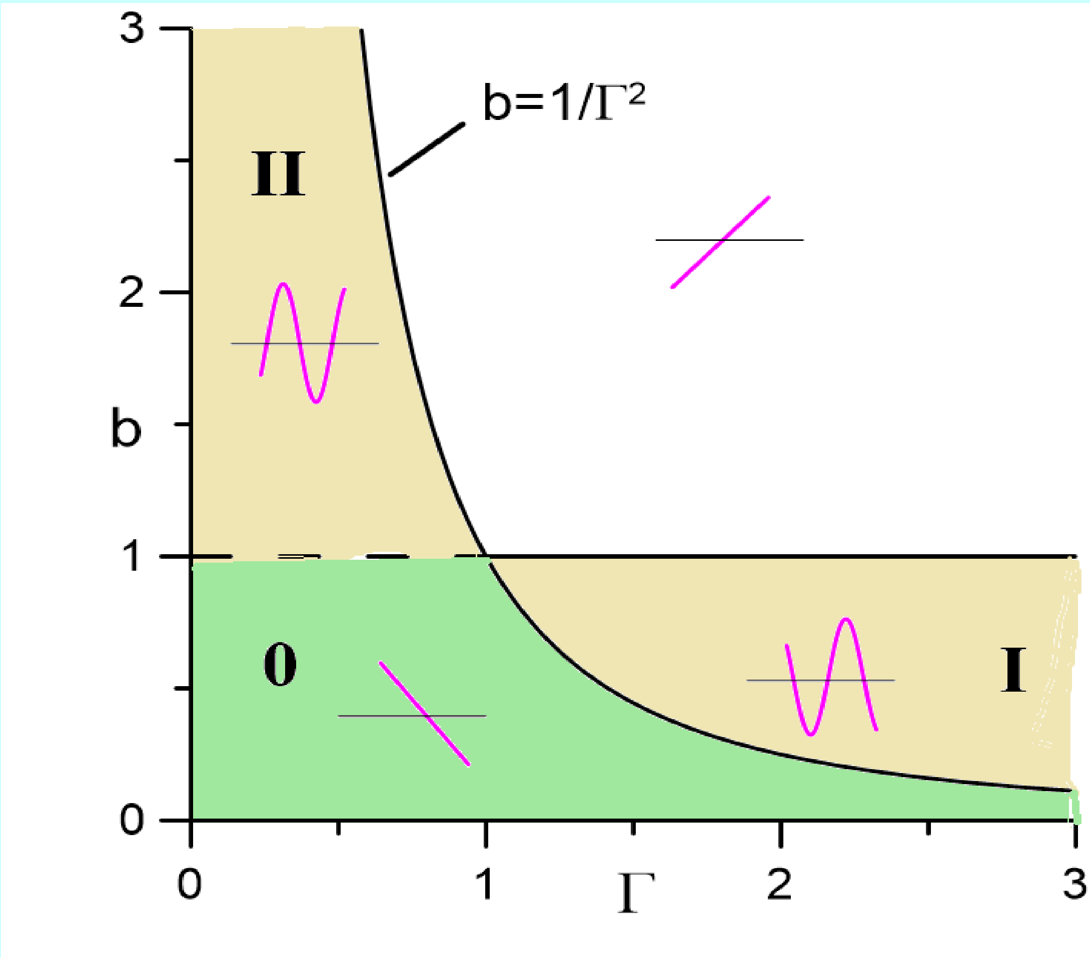
PHASE SPACE $\langle \dot{\Omega} \rangle = f(\Omega)$

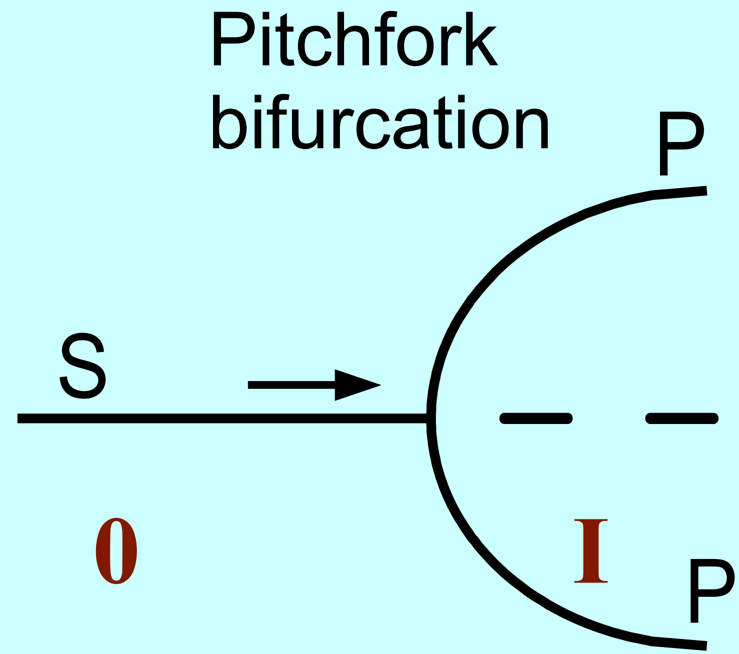
- ONLY THE SOLID BODY TIDE
- ONE **STABLE** SYNCHRONOUS SOLUTION at **S** (Ω=n)



- JOINT SOLID BODY AND THERMAL TIDES
- ONE **UNSTABLE** SYNCHRONOUS SOLUTION at **S** (Ω=n)
- TWO **STABLE** ASYNCHRONOUS SOLUTIONS at **P, P'**







AXES: $b = A'\gamma'/A\gamma$

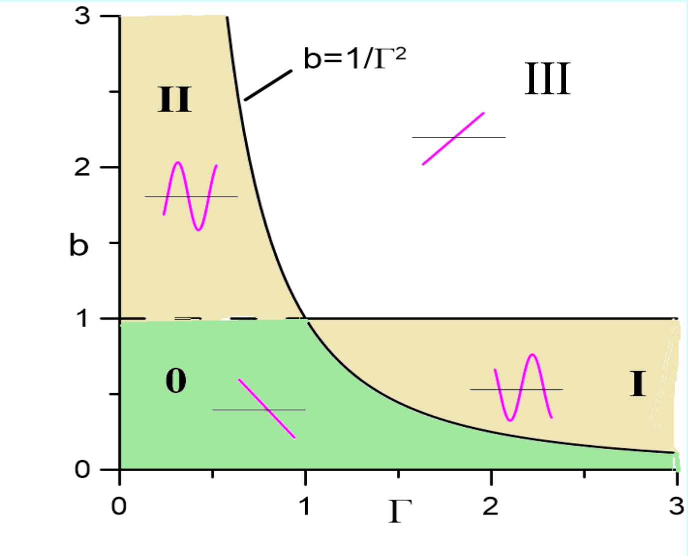
$\Gamma = \gamma/\gamma'$

TOY MODEL - I

$$\dot{y} = D\,\frac{(b-1)y^3 + (b\Gamma^2 - 1)y}{(y^2+1)(y^2+\Gamma^2)}$$

$$y = \frac{\nu}{\gamma'}$$

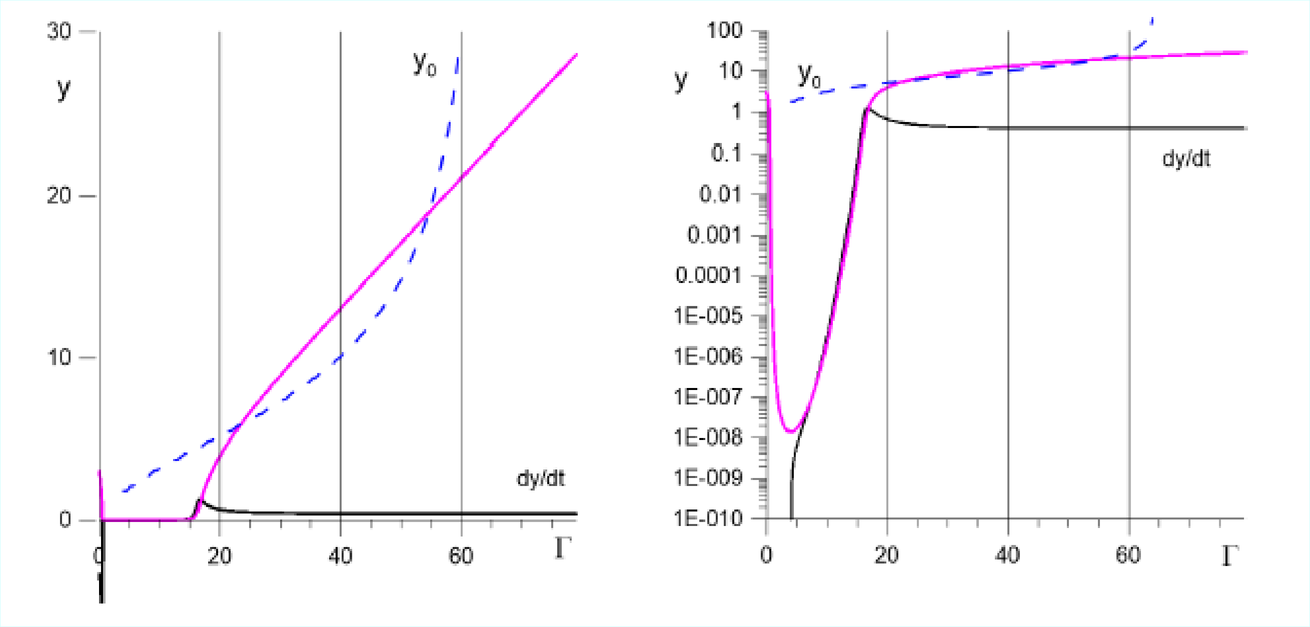
$$D = \frac{4A\Gamma}{\gamma'}.$$



N.B. Cannot cross y=0

Example Path

$0 \rightarrow \mathrm{I} \rightarrow \mathrm{III}$



y_0 = stationary solution

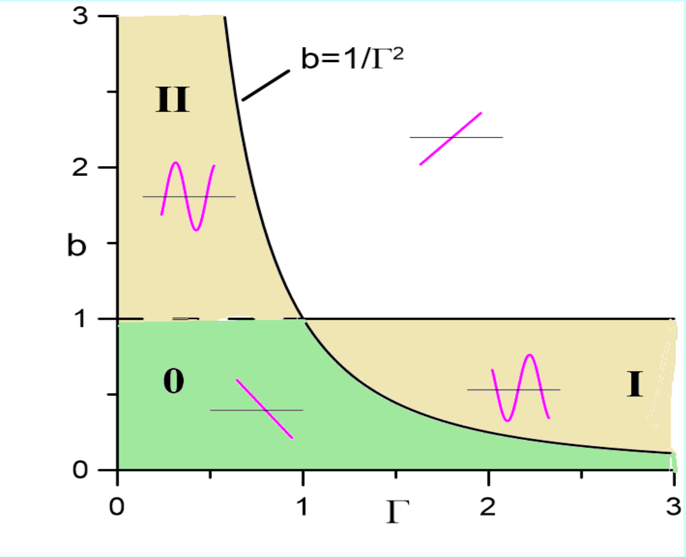
In this example, the planet initially has no atmosphere. It is then created and becomes increasingly denser reaching the region III.

TOY MODEL - II

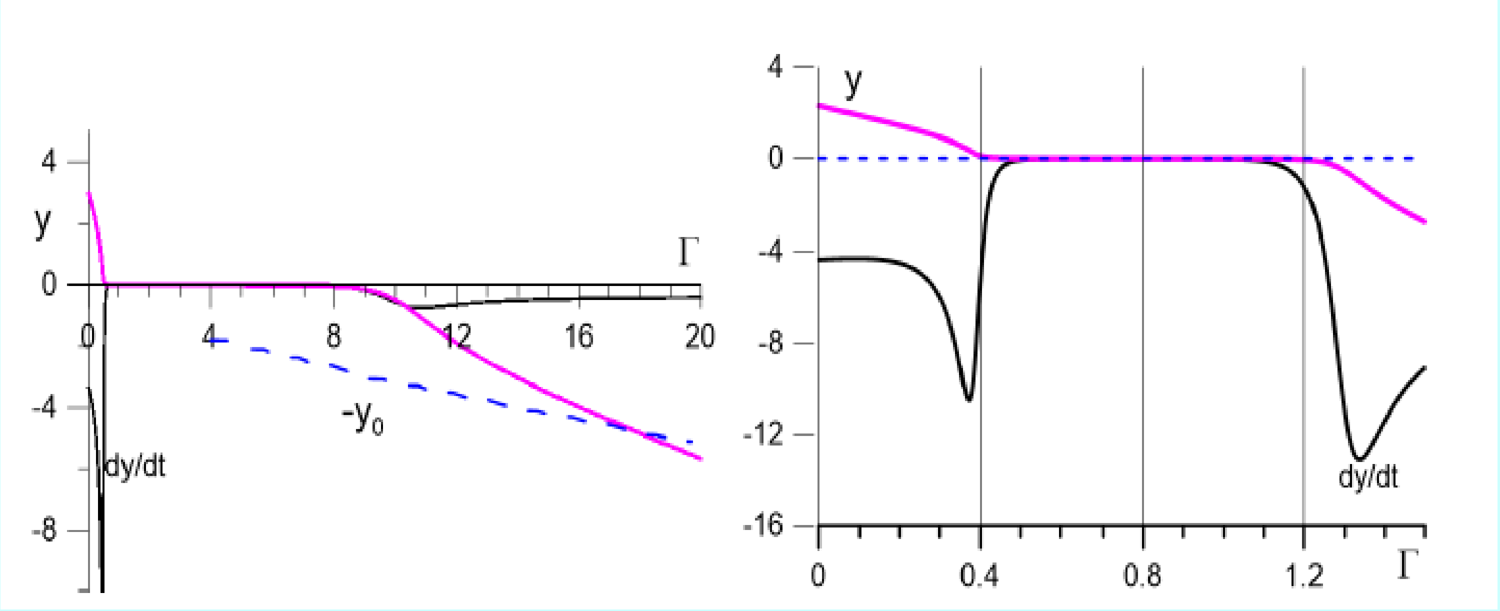
$$\dot{y} = D\,\frac{(b-1)y^3 + (b\Gamma^2 - 1)y}{(y^2+1)(y^2+\Gamma^2)} + \varepsilon$$

$$y = \frac{\nu}{\gamma'}$$

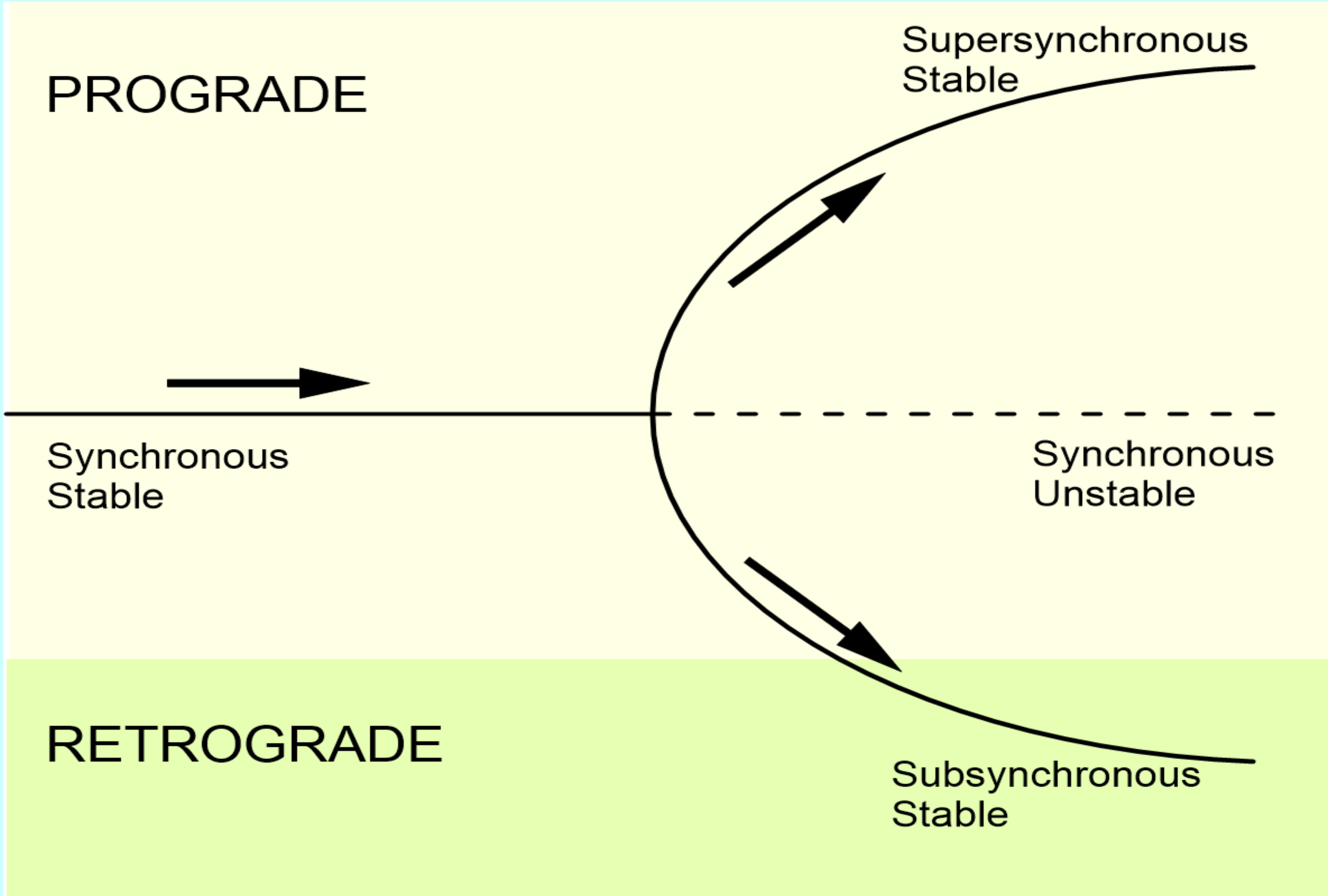
$$D = \frac{4A\Gamma}{\gamma'}.$$



ε … slightly negative noise



In the first example, the atmosphere evolution is the same as in previous slide, but the rotation becomes retrograde. In the second example, the evolution follows the path **0** → **II** → **III**


PROGRADE
Supersynchronous
Stable
Synchronous
Stable
Synchronous
Unstable
RETROGRADE
Subsynchronous
Stable

- No collision with other bodies is necessary to convert the rotation of an Earth or super-Earth with an important atmosphere formed in the course of its evolution into a retrograde rotation.

- It is enough for the planet to be at a distance from the host star short enough to allow the tidal torques to almost synchronize the rotation of the planet before the formation of the bulk of its atmosphere.

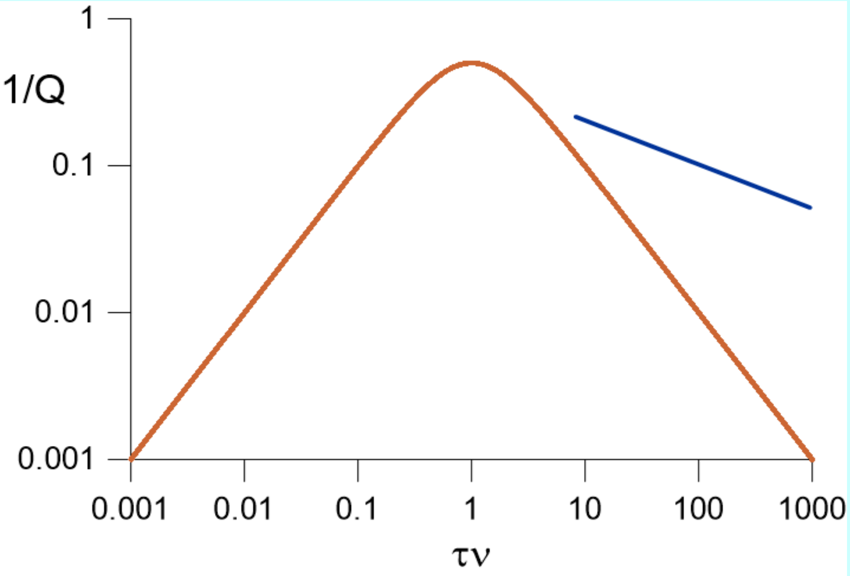
- The conclusions come from simplified models, but they are very robust and they exist even when more realistic models are used.
  (see A. C. M. Correia & J. Laskar, 2003).

- The dense atmosphere of the planet plays a role not only in the inversion of the planet's rotation but also in keeping it retrograde. In the absence of the atmospheric torque, the current retrograde rotation of Venus would become prograde in less than one million years.

- The result does not depend on the tidal theory used to calculate the tidal variation of the rotation speed. Darwin theory for viscous bodies leads to the same results as those found using the creep tide theory.

THE END

THANKS



1
1/Q
0.1
0.01
0.001
0.001
0.01
0.1
1
10
100
1000
τν

TOY MODEL

$$\dot{y} = D\,\frac{(b-1)y^3 + (b\Gamma^2 - 1)y}{(y^2+1)(y^2+\Gamma^2)}$$

$$y = \frac{\nu}{\gamma'}$$

$$D = \frac{4A\Gamma}{\gamma'}.$$