Astrometry and tidal migration

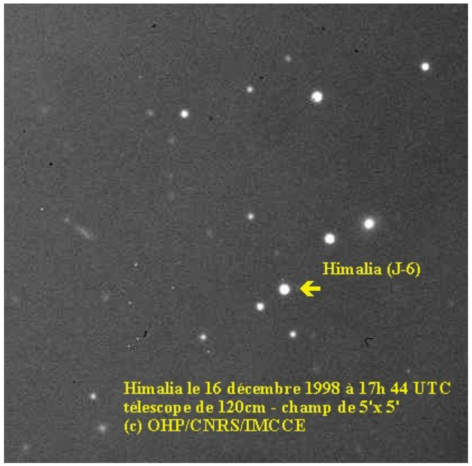
V. Lainey (JPL/IMCCE), J.Fuller (Caltech)

valery.j.lainey@jpl.nasa.gov

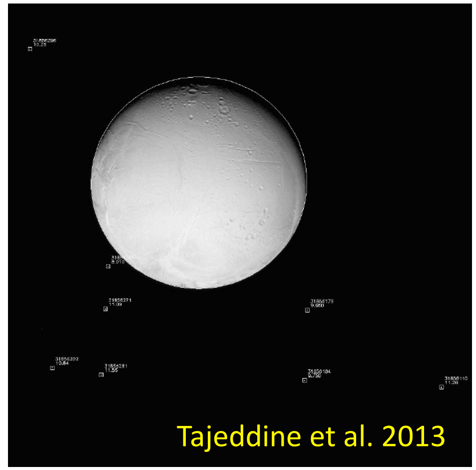
Astrometric measurements

Example 1: classical astrometric observations (the most direct measurement)

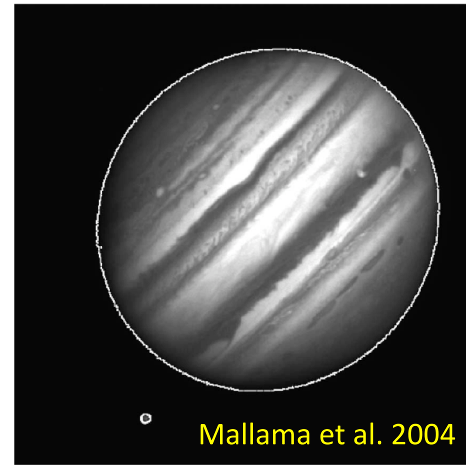
Images suitable for astrometric reduction from ground or space



CCD obs from ground



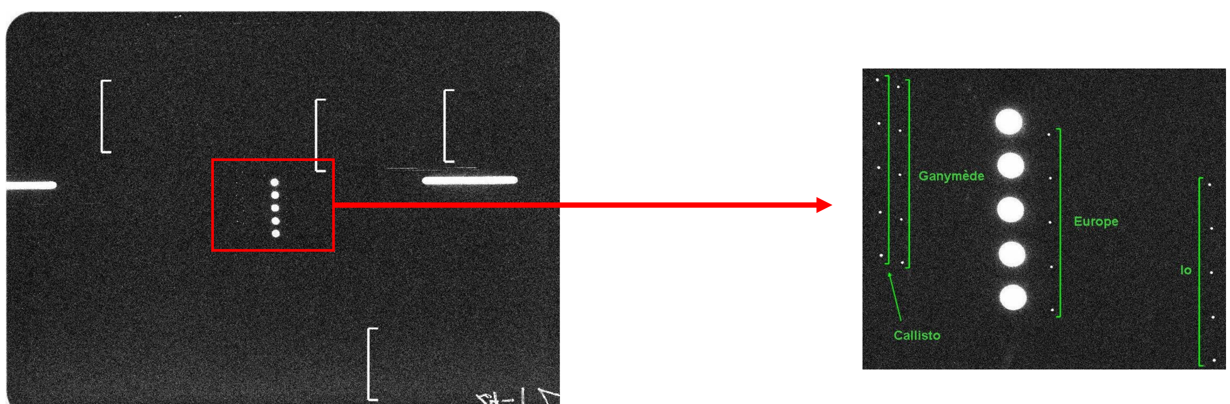
Cassini ISS image



HST image

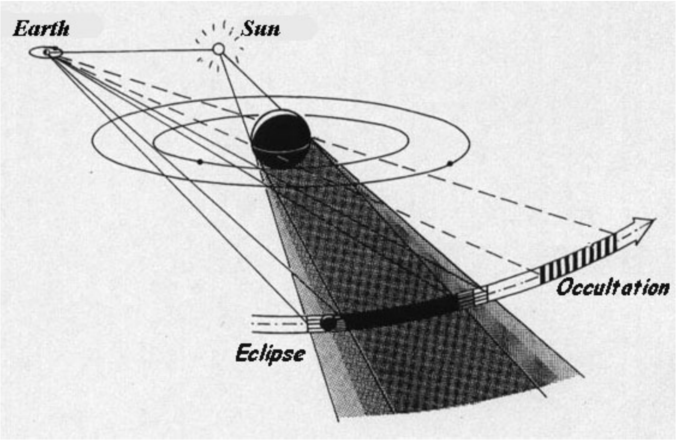
Photographic plates

(not used anymore
BUT re-reduction now benefits from modern scanning machine)

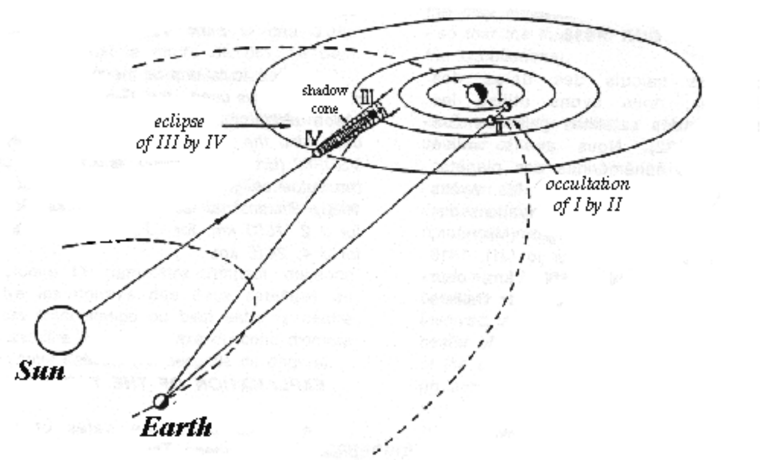


Astrometric measurements

Example 2: photometric measurements (undirect astrometric measurement)



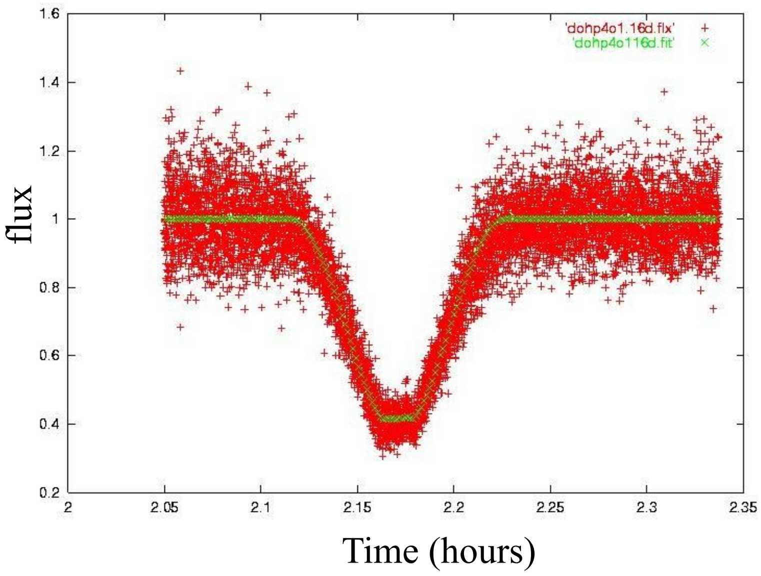
Eclipses by the planet
(barely used those days…)



Mutual phenomenae
(arising every six years)

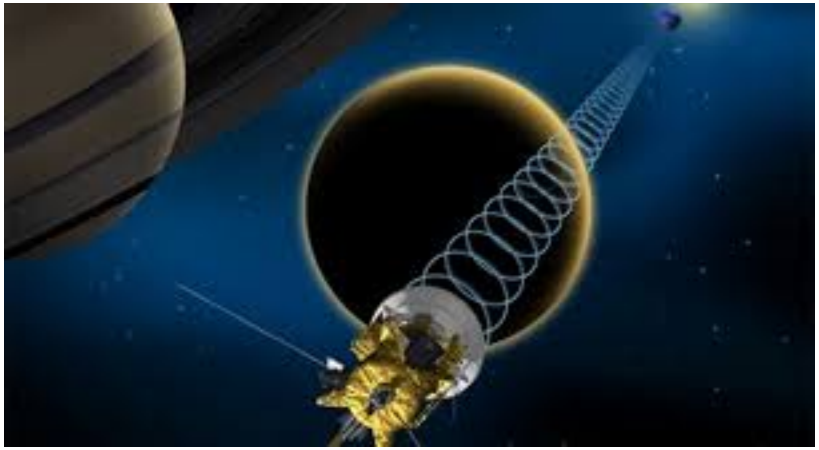
By modeling the event, one can solve for mid-time event and minimum distance between the center of figure of the objects

→ astrometric measure



Astrometric measurements

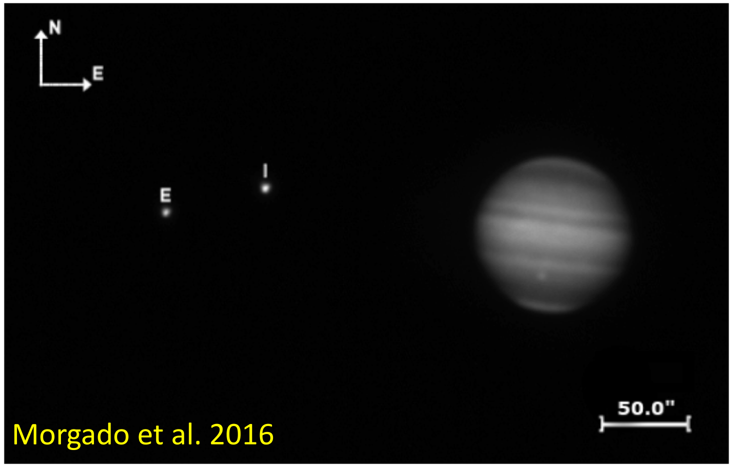
Example 3: other measurements (non exhaustive list)



Radio science measurement (orbital tracking)

During flybys of moons, one can (sometimes!) solved for a correction on the moon ephemeris

Radar measurement (distance measurement between back and forth radio wave travel)



Mutual approximation (measure of moons' distance rate)

Astrometric accuracy

Remark:

1- Accuracy of specific techniques STRONGLY depends on the epoch

2- Total number of observations per observation opportunity can be VERY different

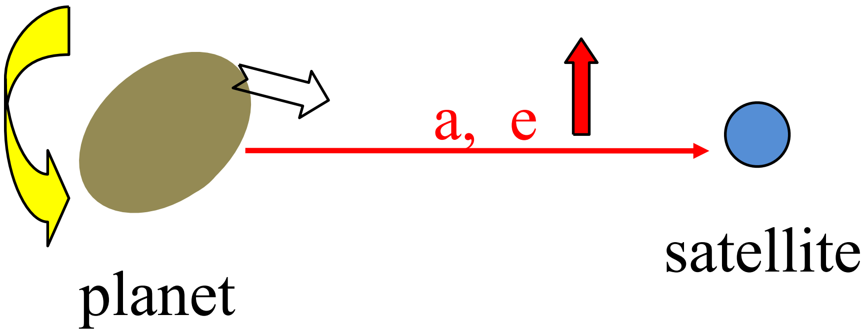
For the Galilean system: (numbers are purely indicative)

From ground
Direct imaging: 100 mas (300 km) to 20 mas (60 km) –stacking techniques-
Mutual events: typically 20-80 mas (60-240 km)
Mutual approximation: 20 mas (60 km)
Stellar occultation (few km) –requires bright stars-
Radio observations: 1 km

From space
HST: 100 mas (300 km) -strong bias-

Spacecraft flybys (Titan's flyby by Cassini): 100 m - few km

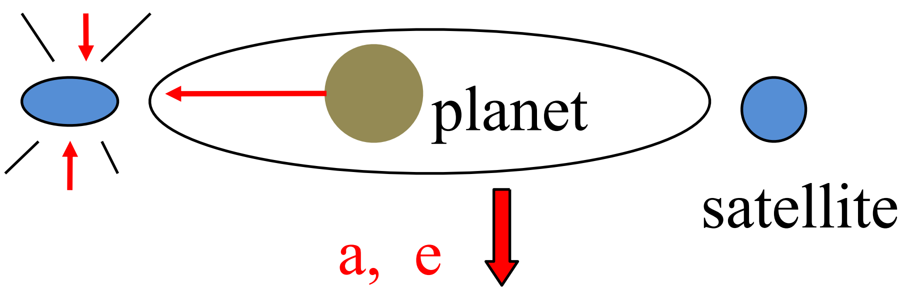
Implication of tidal dissipation on orbital motion



Secular deceleration on the mean motion

Jovian k2/Q

Competition between tidal dissipation effects



Secular acceleration on the mean motion

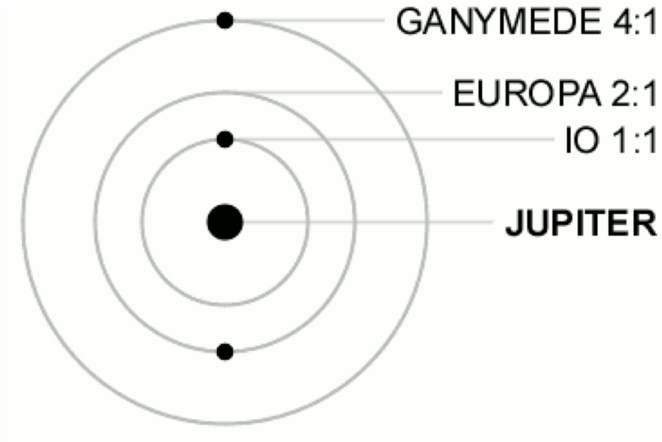
Moon's k2/Q

Implication of tidal dissipation on orbital motion

A matter of dynamics…

n_1-$2n_2$=v
n_2-$2n_3$=v
n_1-$3n_2$+$2n_3$=0

$< L_1 - 3L_2 + 2L_3 > = 180°$



The Laplace resonance is dynamically stable

The three moons *share* their orbital energy and angular momentum

IMPORTANT:
Any perturbation affecting one of the moons will affect immediately the two others!

Estimations of tides in the Galilean system

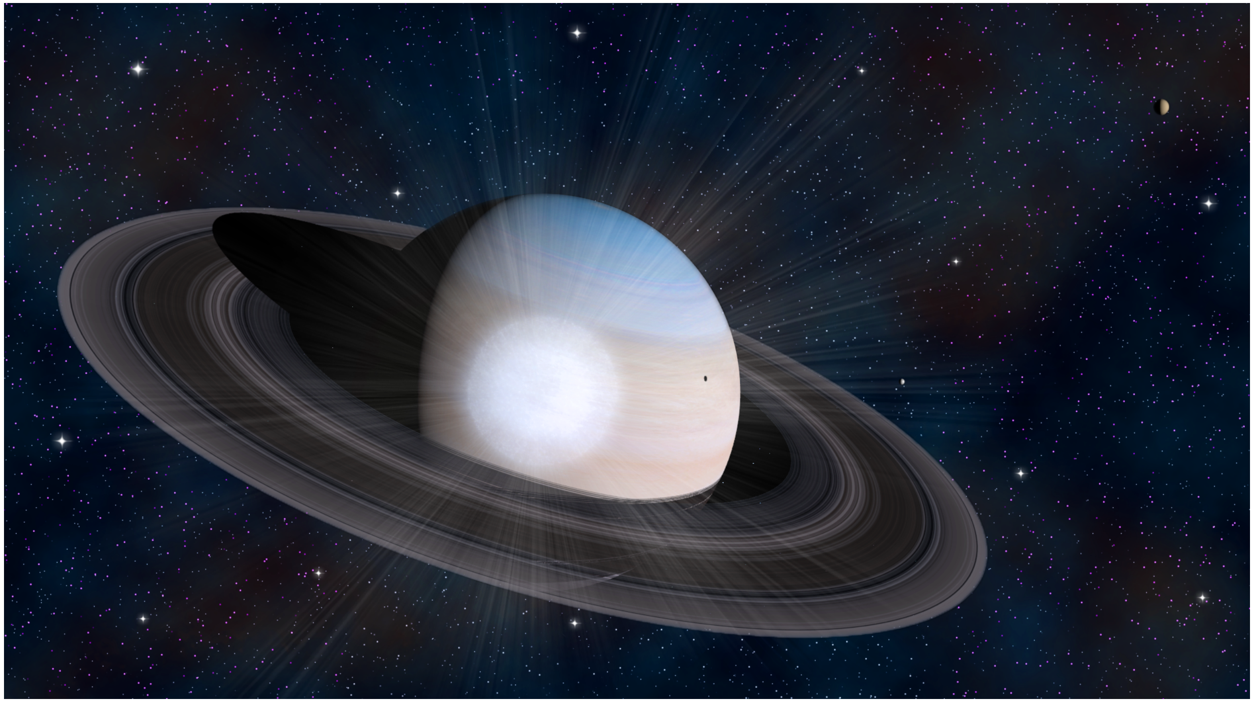
The Galilean satellites: the tidal acceleration in question

Acceleration or deceleration?

References	$\dot{n}_1/n_1$	$\dot{n}_2/n_2$	$\dot{n}_3/n_3$	Units in $10^{-10}yr^{-1}$
de Sitter (1928)	3.3+/-0.5	2.7+/-0.7	1.5+/-0.6	
Lieske (1987)	-0.074+/-0.087	-0.082+/-0.097	-0.098+/-0.153	
Vasundhara et al. (1996)	2.46+/-0.73	-1.27+/-0.84	-0.022+/-1.07	
Aksnes & Franklin (2001)	3.6+/-1.0			
Lainey et al. (2009)	**0.14+/-0.01**	**-0.43+/-0.10**	**-1.57+/-0.27**	

All these accelerations were obtained assuming a constant Jovian k_2/Q…

But wait, lessons learned from the Saturn system…

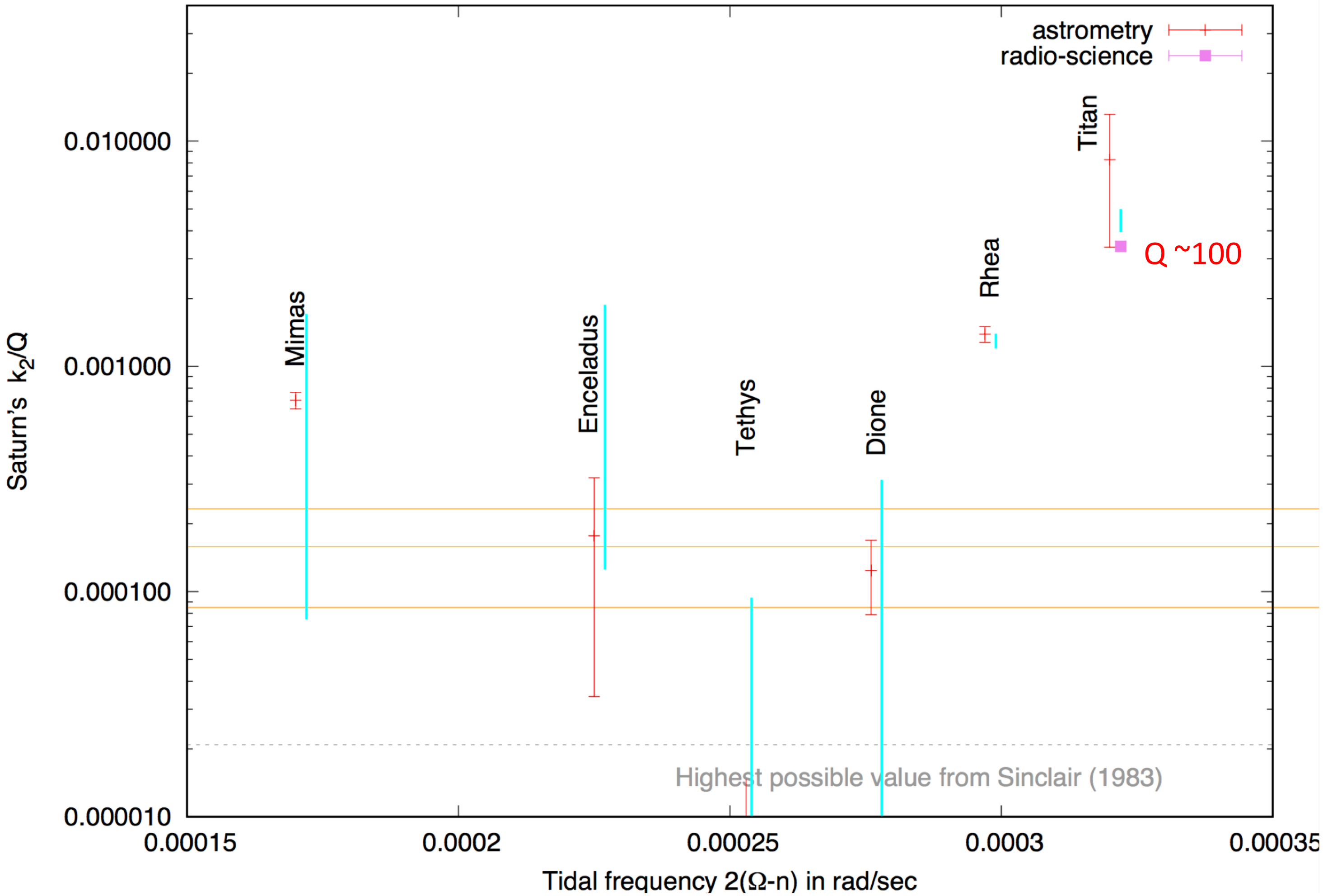


Last results about Saturn's tidal dissipation

Keywords: astrometry, celestial mechanics, ephemerides, planetology

Keywords: radio-science, celestial mechanics, planetology

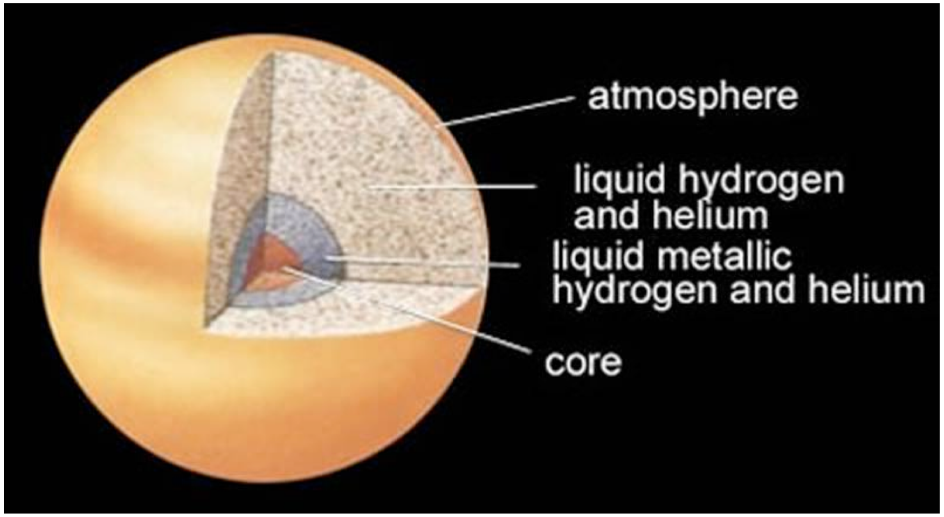
Quality factor and migration timescale



Titan's migration timescale of ~10Gyr , implying that has migrated by a substantial amount over the lifetime of the solar system.

$$t_{\rm tide} = \frac{a}{\dot{a}} \approx 10\,{\rm Gyr}\,\frac{{\rm Im}(k_{22})}{3.8\times 10^{-3}}$$

What causes tidal dissipation in giant planets?



Equilibrium Tides:

Viscoelastic deformation of core
(Dermott 1979, Remus et al. 2015)

Convective viscosity in envelope

Problem: predicts (nearly) constant Q

Dynamical Tides:

G-modes in stably stratified layers
(Morales et al. 2009, Fuller et al. 2016)

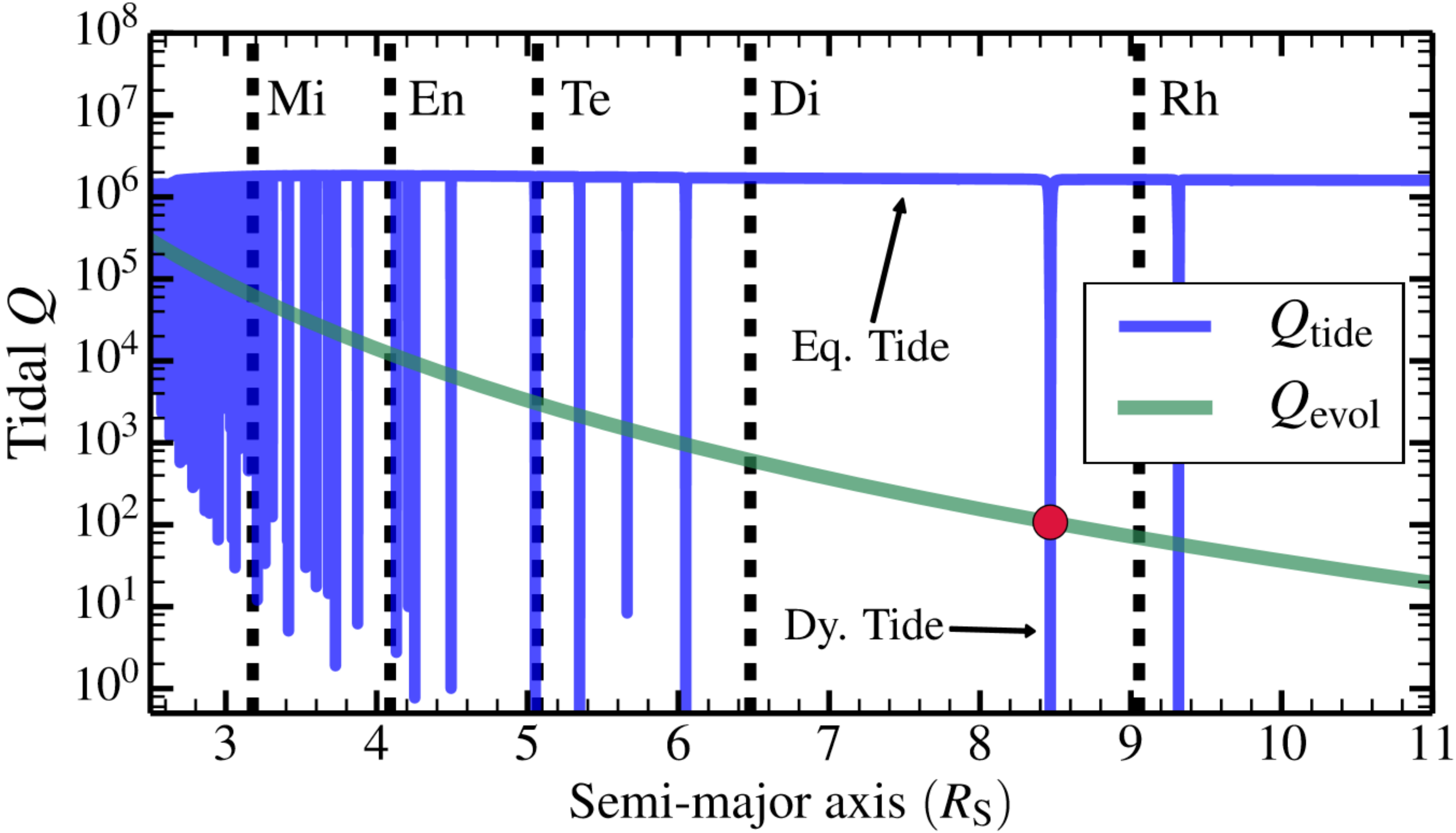
Inertial waves in convective envelope
(Ogilvie & Lin 2007, Guenel et al. 2014)

Sensitivity to tidal frequency

$Q(X)$?

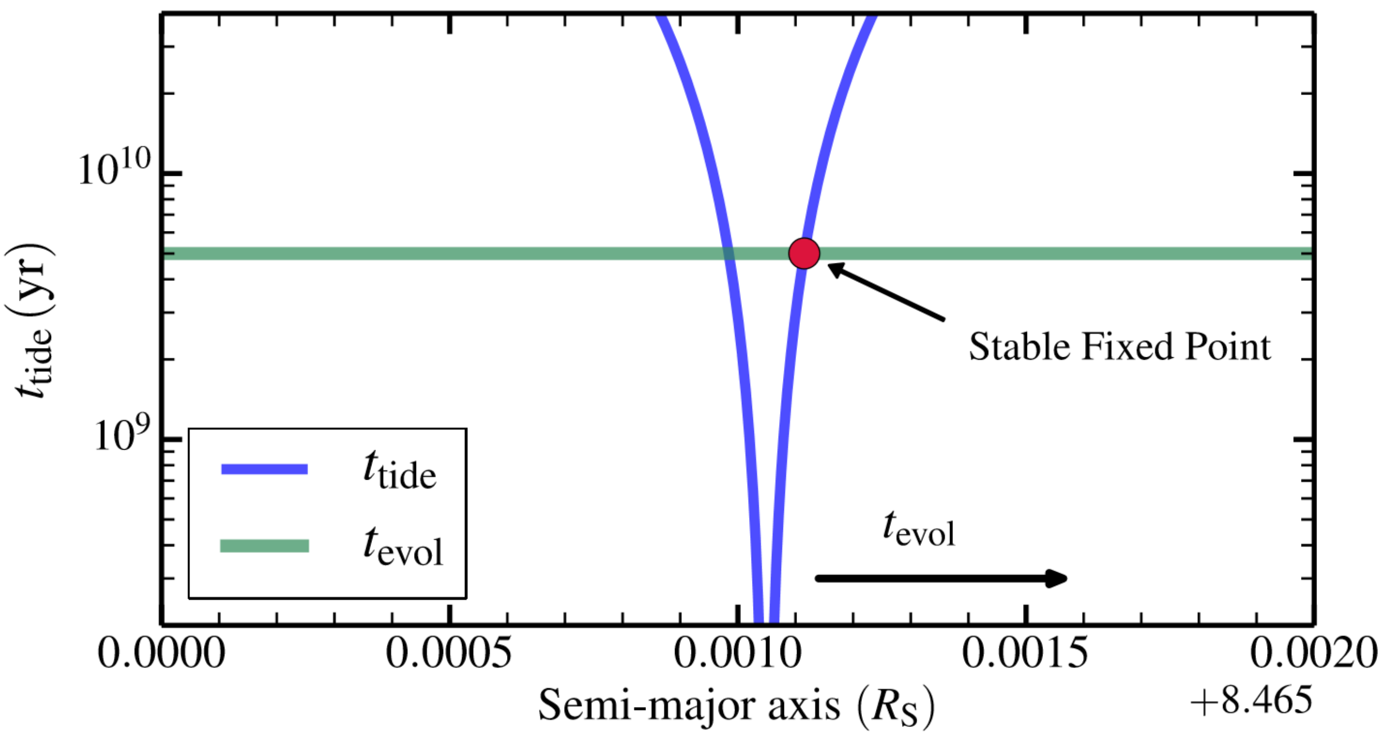
IMPORTANT: Most (all?) dynamical studies of the Galilean system, including short-term, long-term dynamics and ephemerides modeling assume a constant Jovian k_2/Q

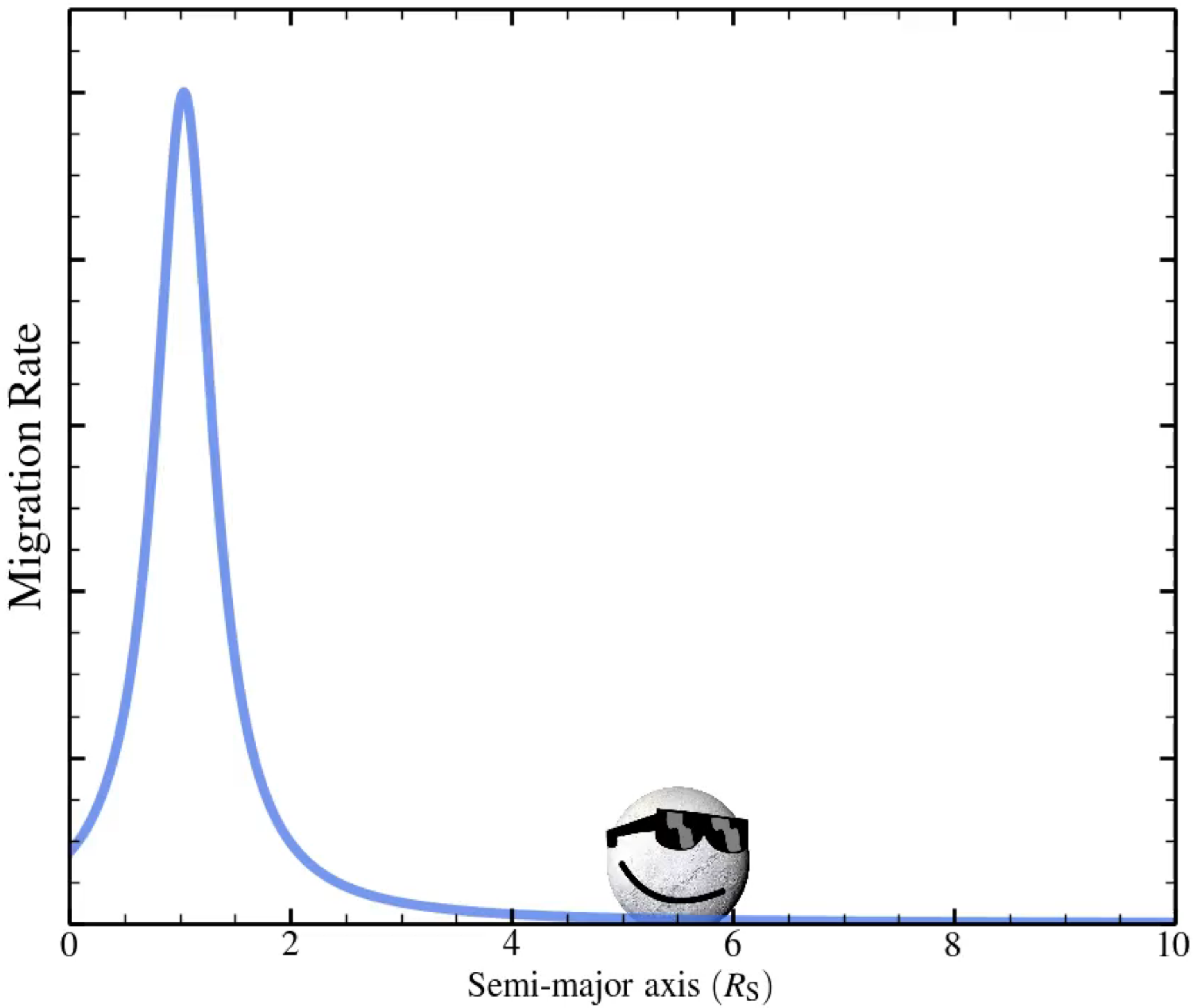
Dynamical Tides in Saturn



Resonance Locking

- Frequencies of resonant peaks are dependent on planet's internal structure
- Planet's internal structures gradually evolve
  - Cooling
  - Compositional settling, e.g., Helium rain
- Frequencies of resonant peaks evolve on planetary evolution timescale
- Moon can get trapped at stable fixed point when resonance sweeps past





Migration Rate
0
2
4
6
8
10
Semi-major axis (R_S)

Tidal Dynamics in Resonance Lock

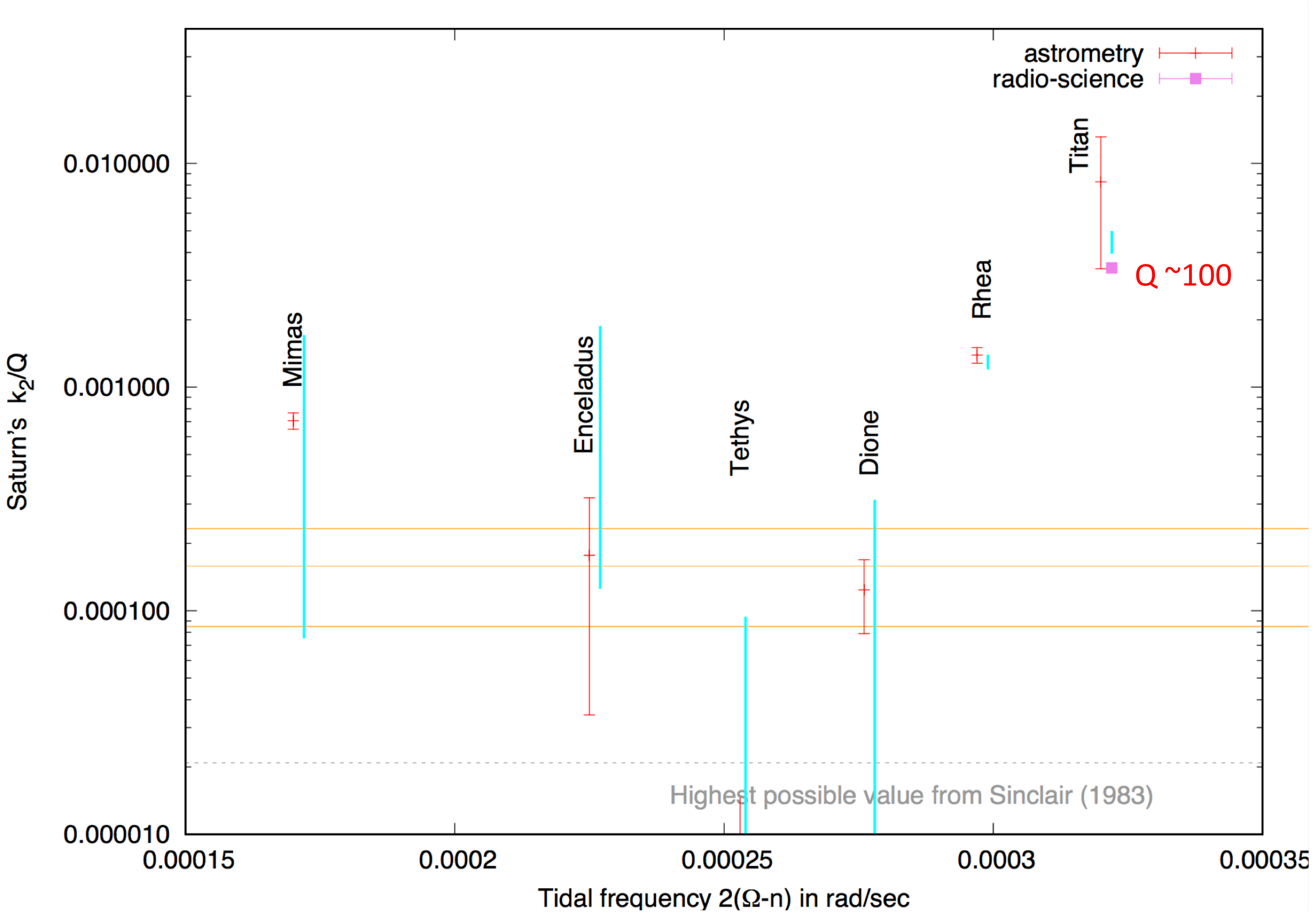
- Tidal timescale is closely related to planetary evolution timescale

$$t_{\rm tide} \approx \frac{3}{2} \frac{\Omega_{\rm m}}{\Omega_{\rm p} - \Omega_{\rm m}} t_\alpha$$

- Effective tidal *Q* is usually much smaller than frequency-averaged *Q*

$$Q_{\rm ResLock} = \frac{9k_2}{2} \frac{M_{\rm m}}{M_{\rm p}} \left(\frac{R}{a}\right)^5 \left[\frac{\omega_\alpha}{m\Omega_{\rm m}^2 t_\alpha} - \frac{\Omega_{\rm p}}{\Omega_{\rm m}^2 t_{\rm p}}\right]^{-1}$$

Quality factor and migration timescale



Titan's migration timescale of ~10Gyr , implying that has migrated by a substantial amount over the lifetime of the solar system.

$$t_{\rm tide} = \frac{a}{\dot{a}} \approx 10\,{\rm Gyr}\,\frac{{\rm Im}(k_{22})}{3.8 \times 10^{-3}}$$

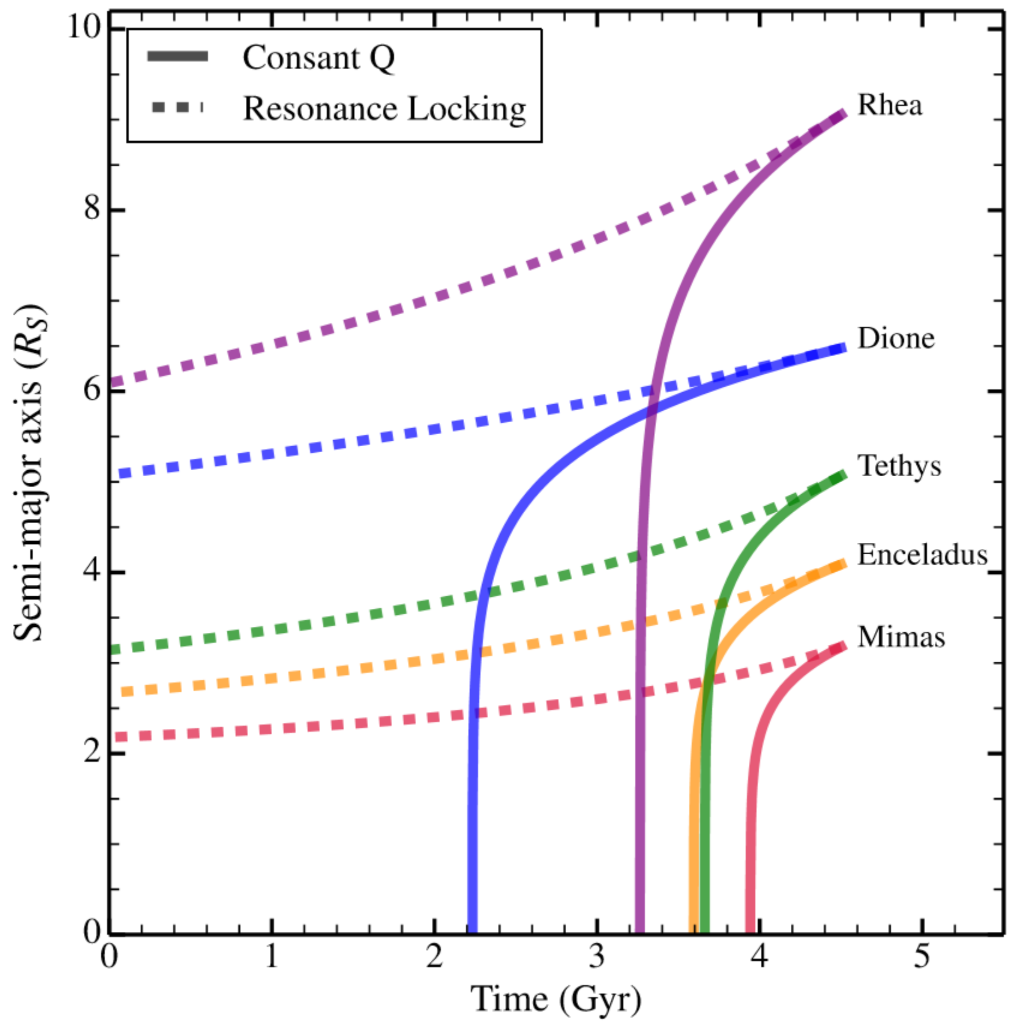
Evolutionary History

- In equilibrium tidal theory, migration rate strongly dependent on semi-major axis

$$Q \equiv 3k_2 \frac{M_{\rm m}}{M_{\rm p}} \left(\frac{R_{\rm p}}{a_{\rm m}} \right)^5 \Omega_{\rm m} t_{\rm tide}$$

- According to resonance locking, tidal migration rate is only weakly dependent on semi-major axis

$$t_{\rm tide} \approx \frac{3}{2} \frac{\Omega_{\rm m}}{\Omega_{\rm p} - \Omega_{\rm m}} t_\alpha$$



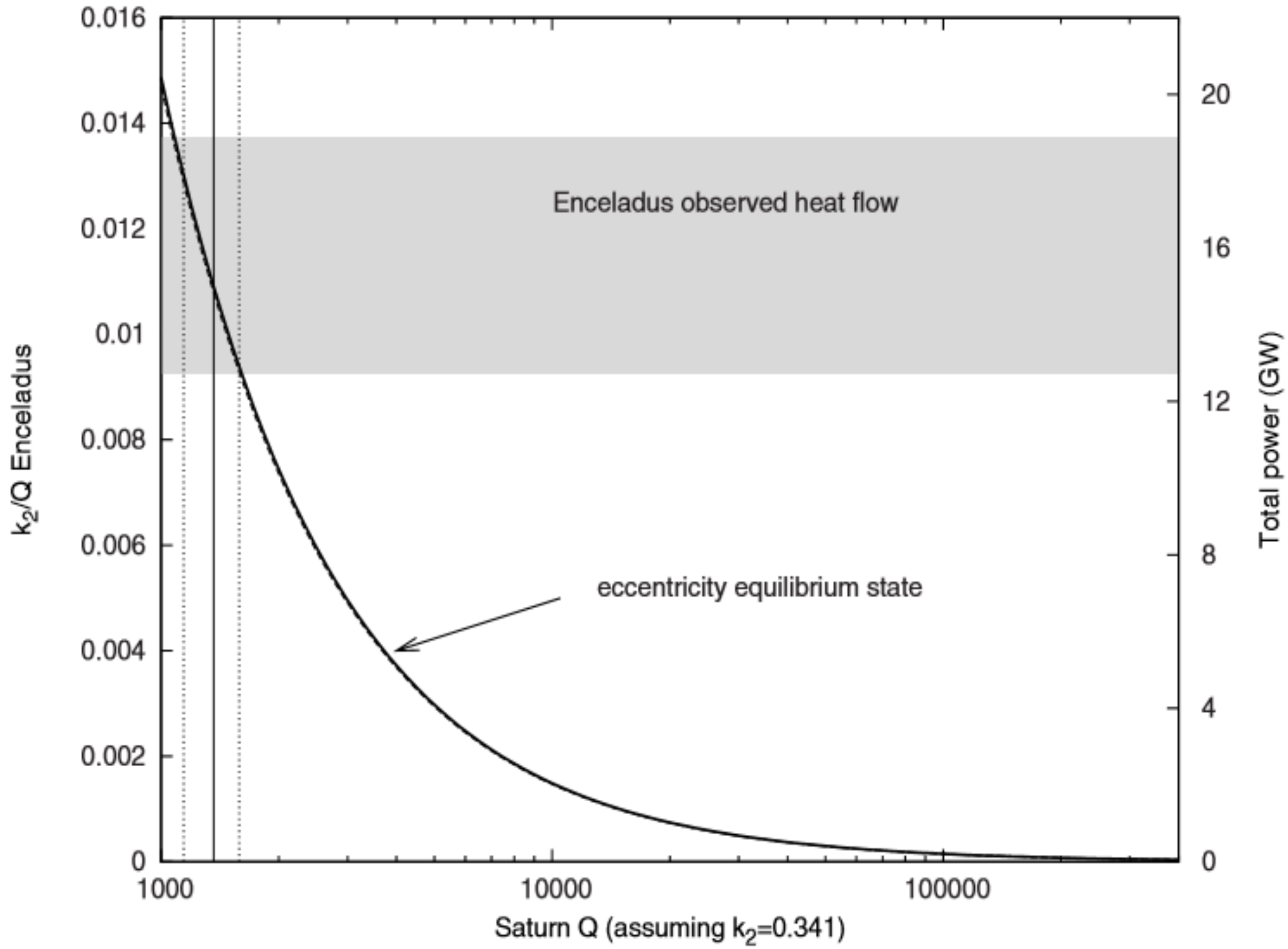
Tidal Heating

- If inner moon pushes outer moon outward via mean motion resonance, at equilibrium eccentricity, tidal heating rate of inner moon is

$$\dot{E}_{\mathrm{heat},1} \simeq \frac{1}{j-1}\frac{|E_{2,\mathrm{orb}}|}{t_{\mathrm{tide}}}$$

- For Enceladus:

$$\dot{E}_{\mathrm{heat}} \approx 50\,\mathrm{GW}$$



Lainey et al. 2012

Conclusions

- Resonance locking mechanism (Fuller et al. 2016) may be operating within Saturn…
- Such mecanism could occur within Jupiter too!
- It is of extreme importance to rely on a proper frequency dependence model of Jovian k2/Q before making any inference on orbital history and tidal dissipation of the moons