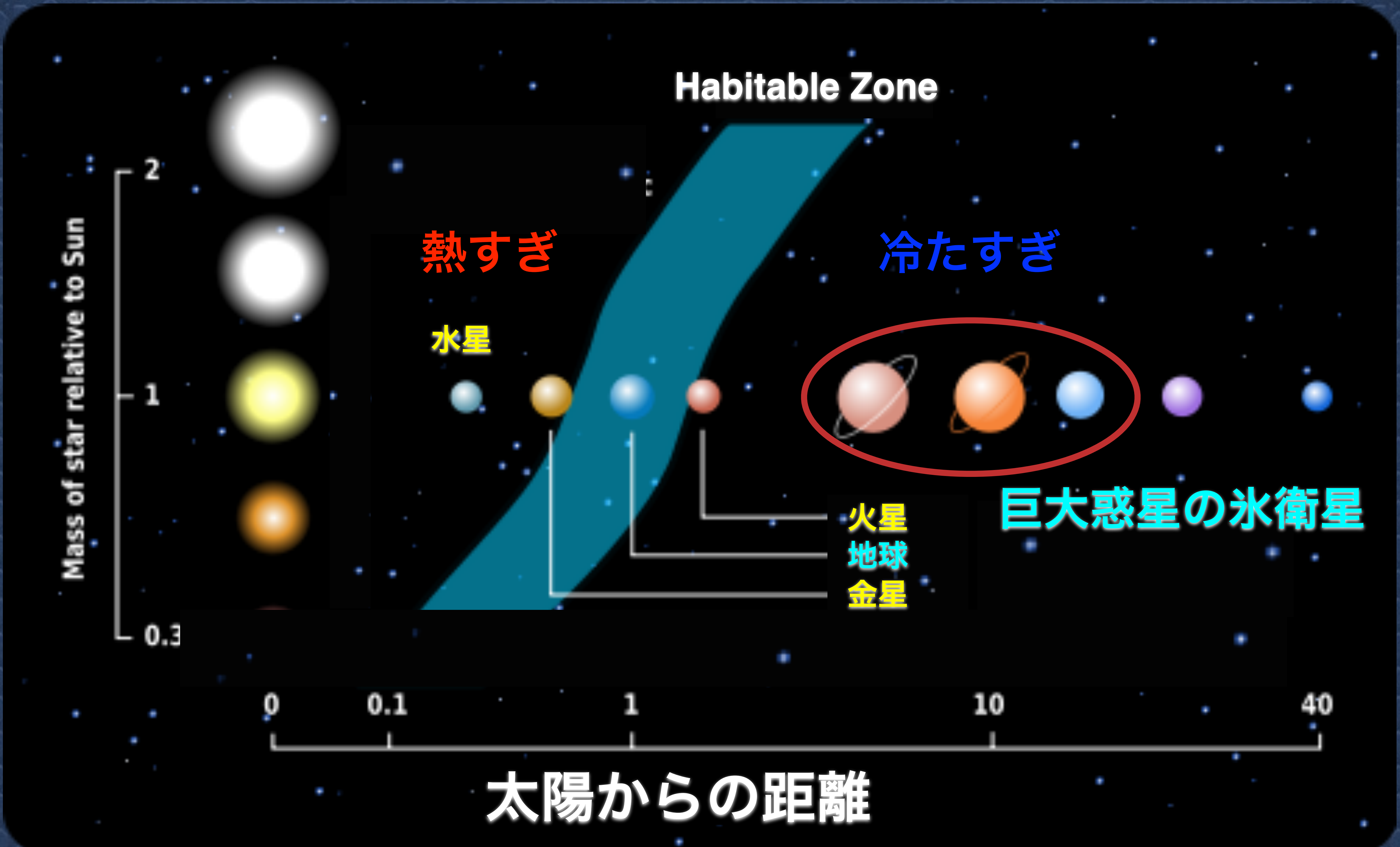
Role of Tidal Dissipation in Thermal Evolution of Satellites

K.Kurita
ERI, Univ. of Tokyo

contents;

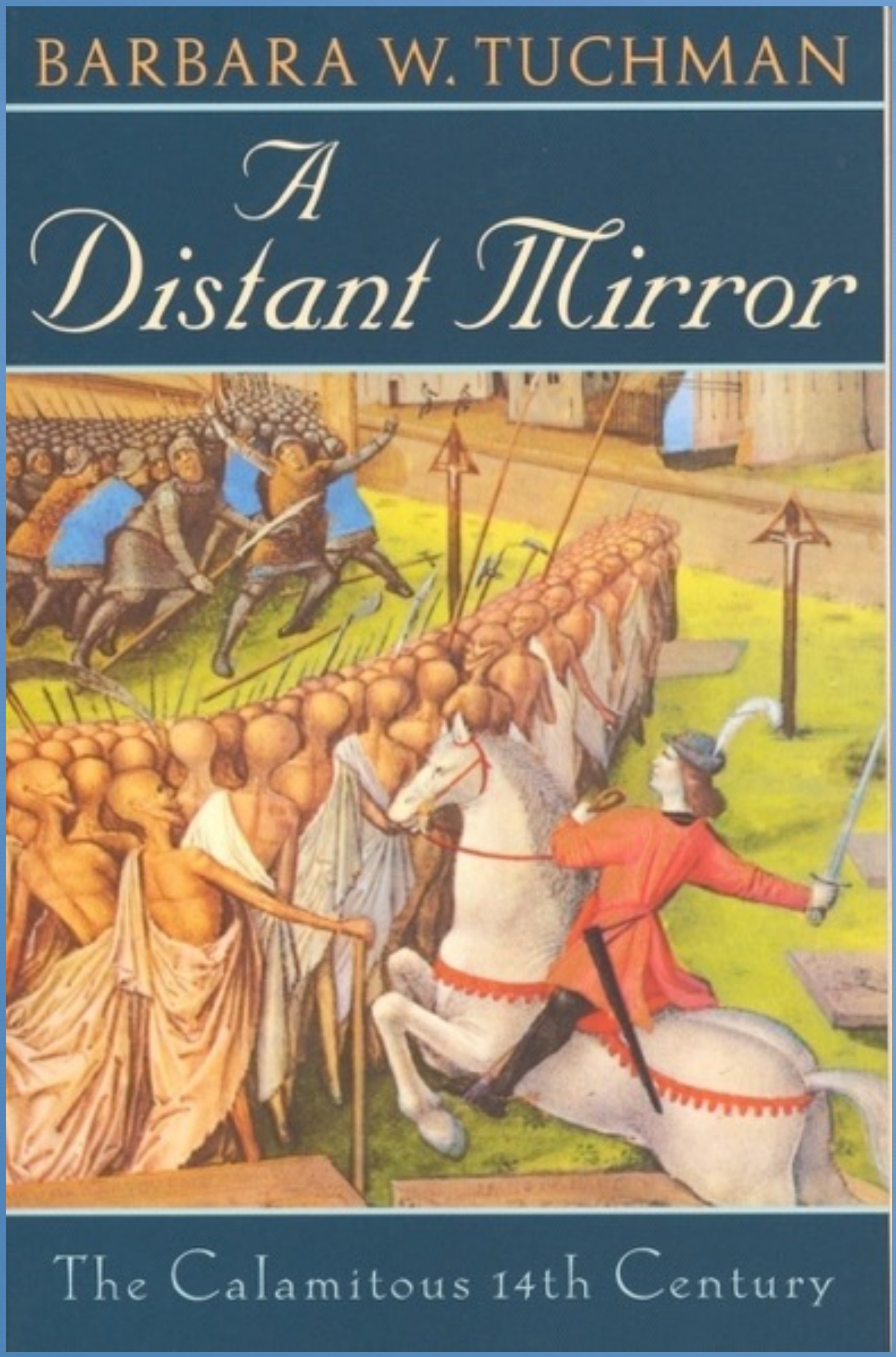
- *tidal dissipation*
- *unsolved problems*

20150721 北大低温研・衛星の噴火現象



氷衛星＋潮汐発熱＝内部海 → 生命体の誕生・生育

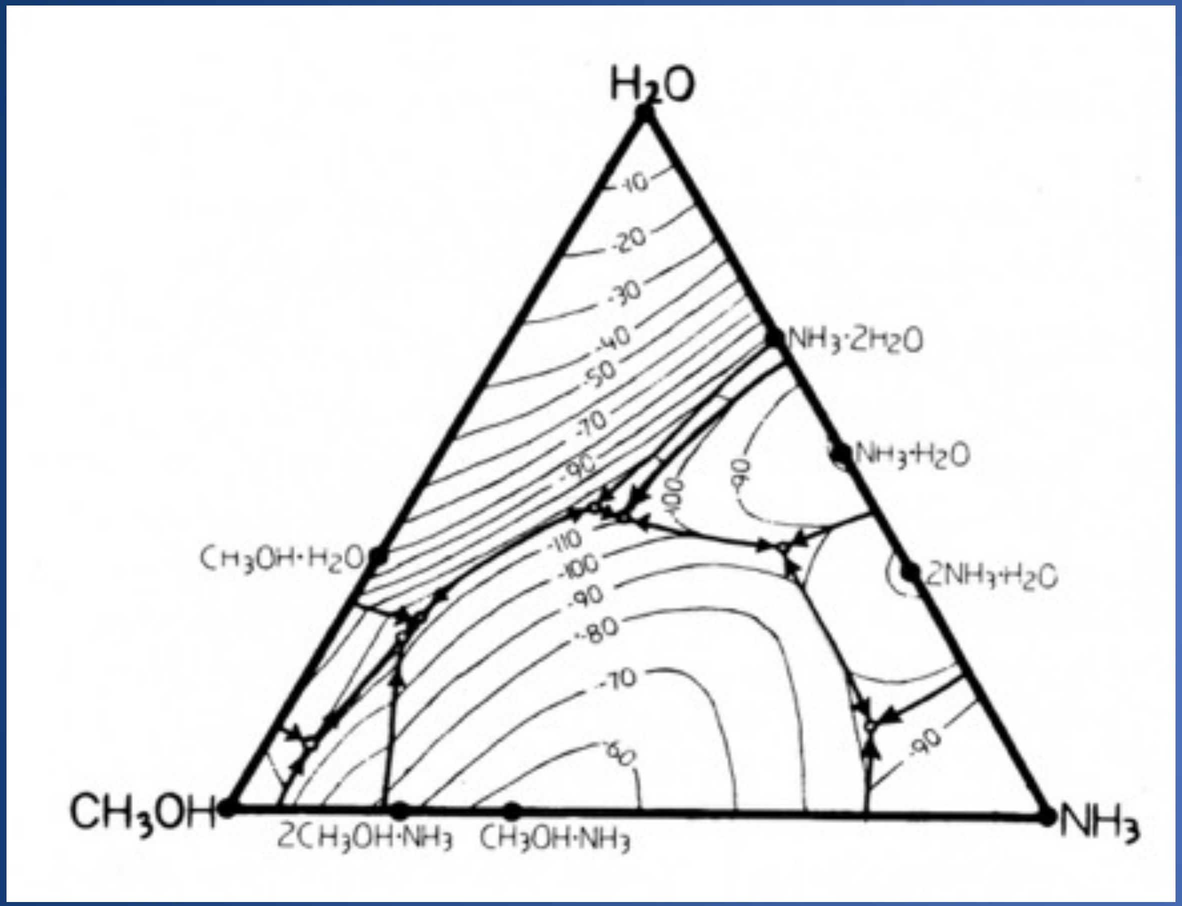
Distant Mirrors

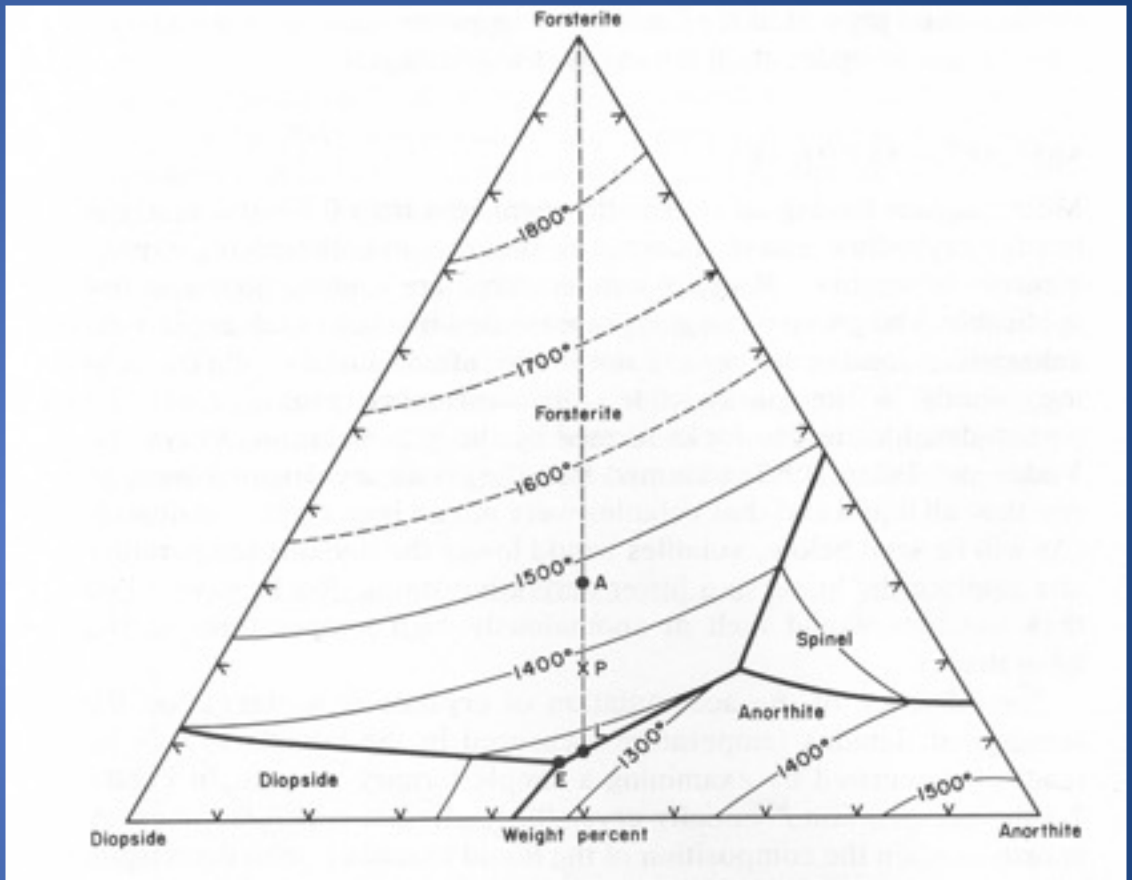


氷衛星の科学は地球の理解に貢献するのか？

遠くにいると見えること

Similarity 1:Melting Relationship



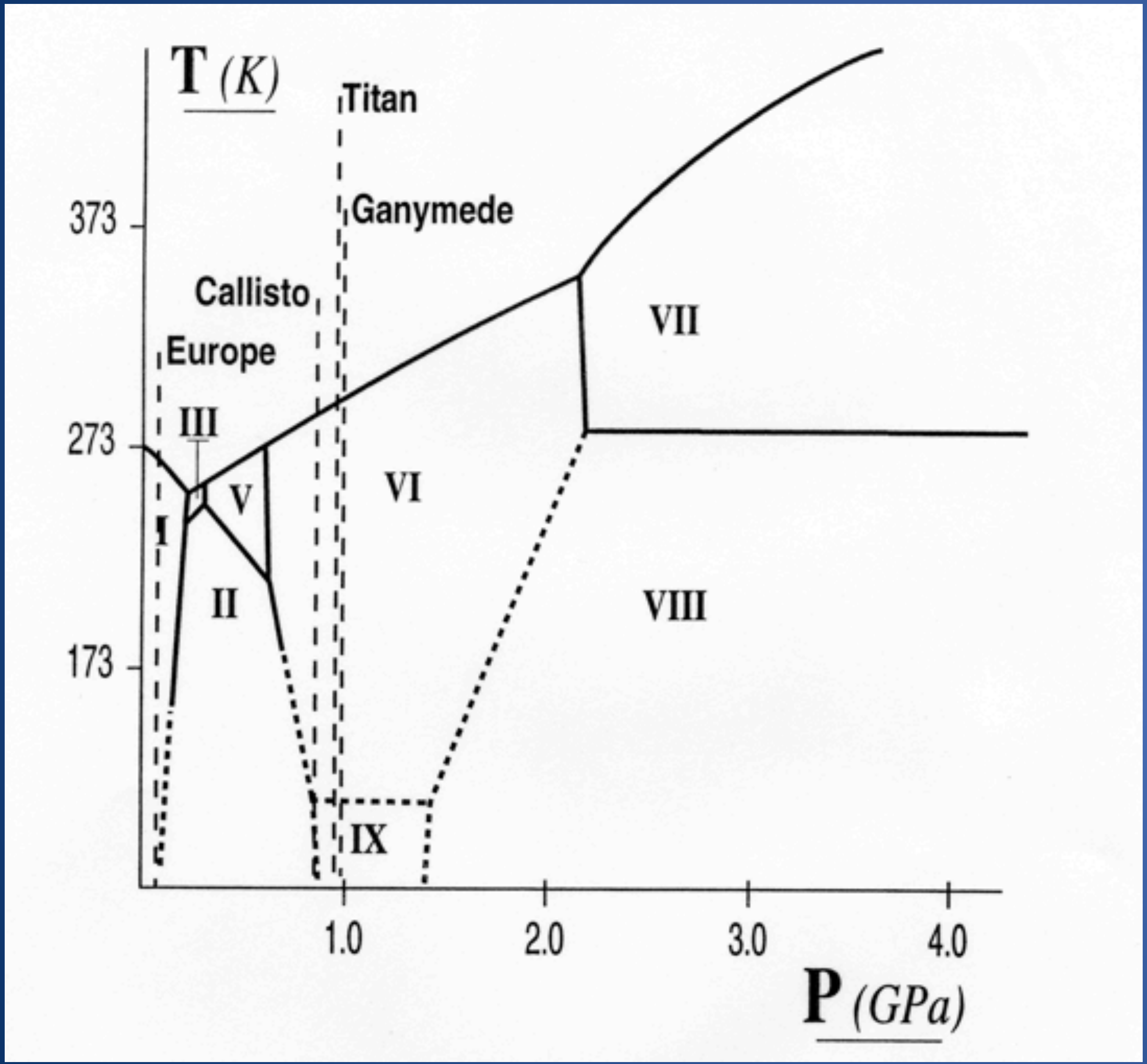


H2O-Methanol-Ammonia System

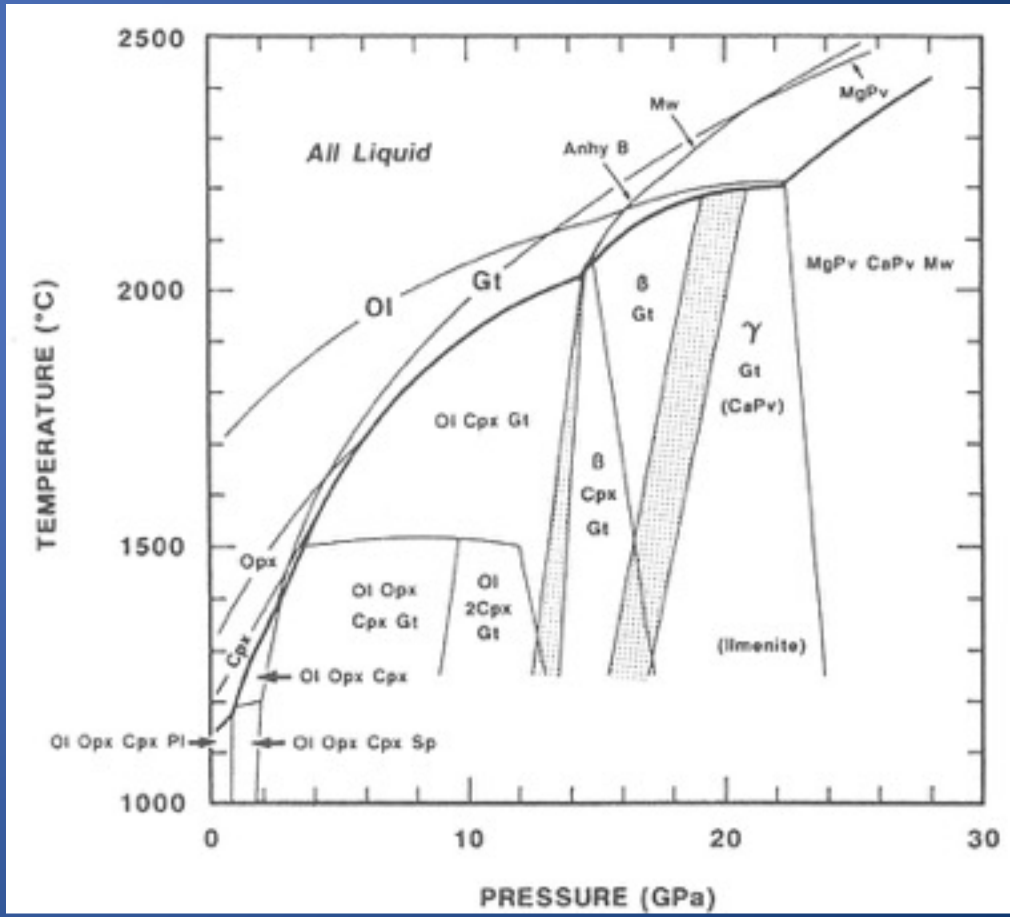
Fo-Di-An System

Cryovolcanism

Similarity 2:Phase Change

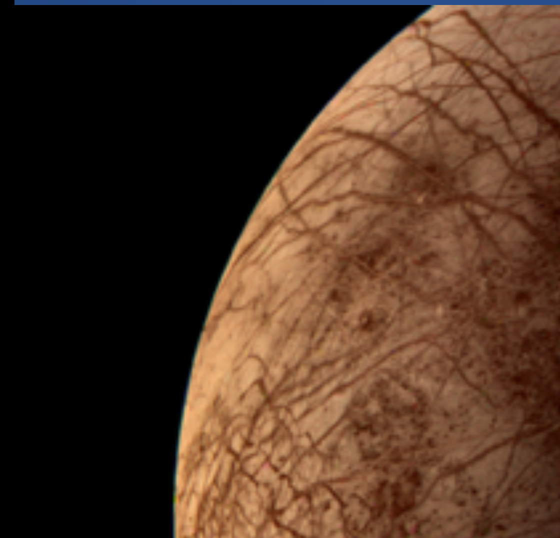


- Small : Ice Ih
- Large : Ice Ih + HighP Ices



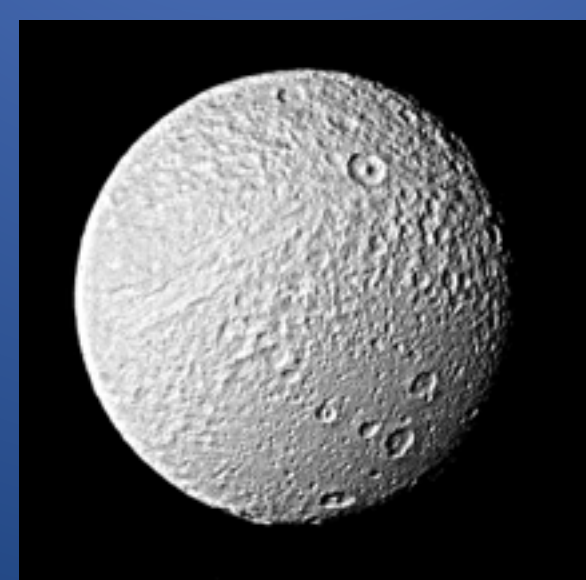
Negative & Positive Clapeyron Curves

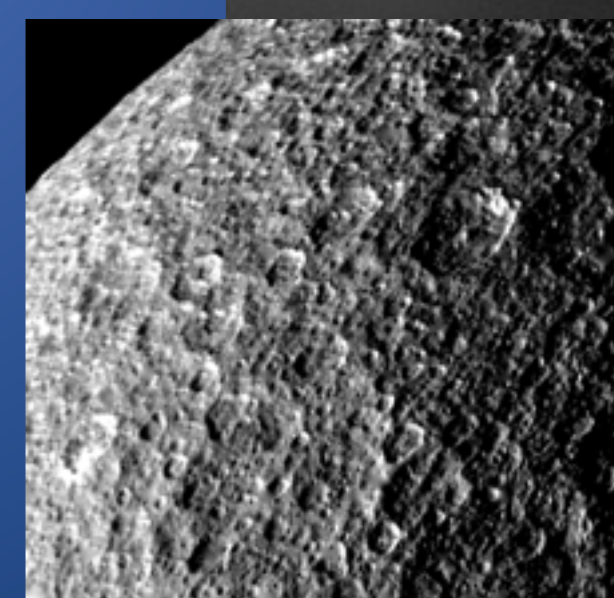
Wide Variation



客観的視座
相対的視座

Where is my position?



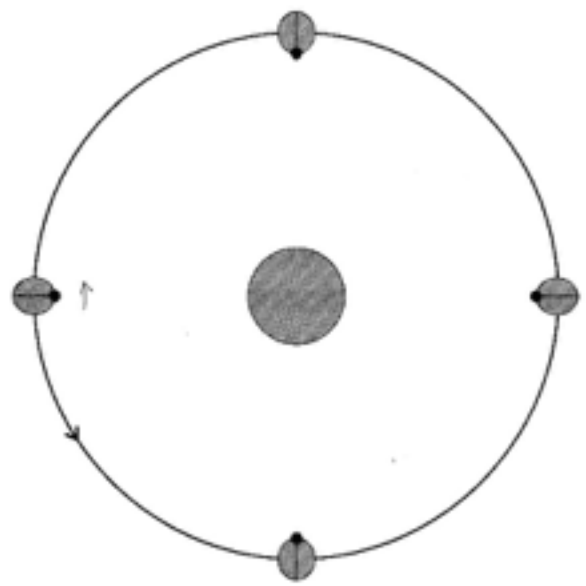


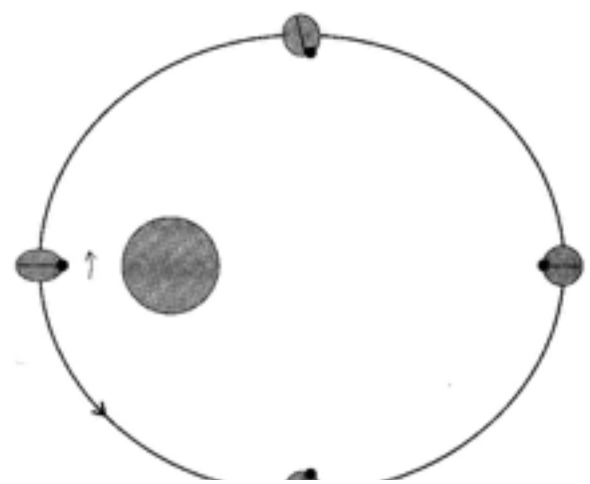
潮汐散逸の問題

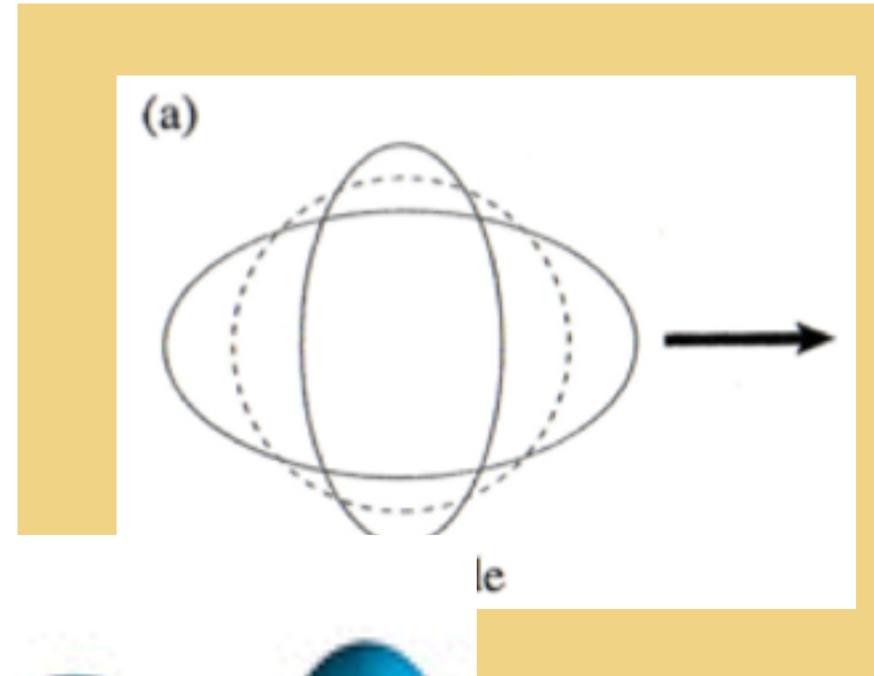
- 大きな天体
- 近くの軌道
- 散逸を生みやすい状況

Elliptical Orbit

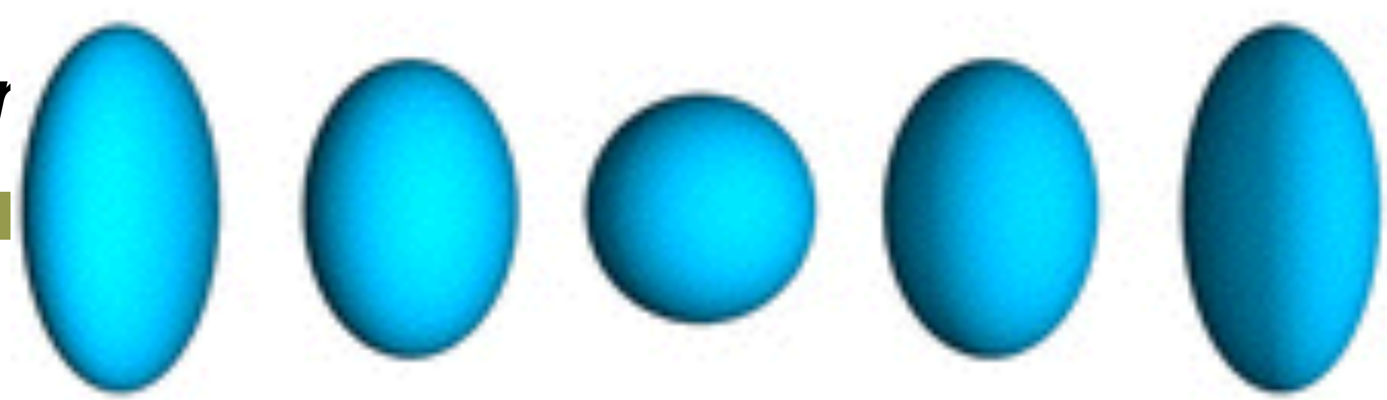
two deformation modes

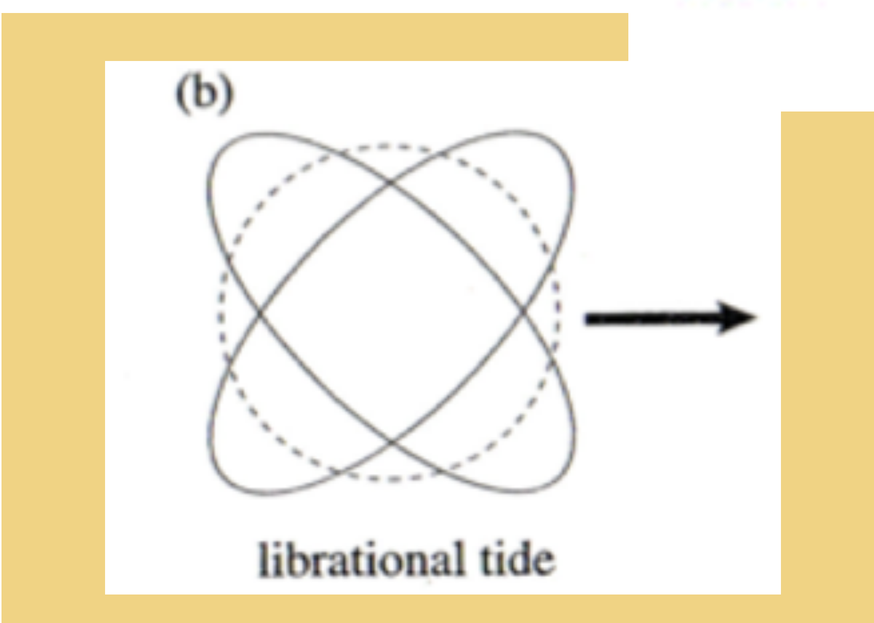




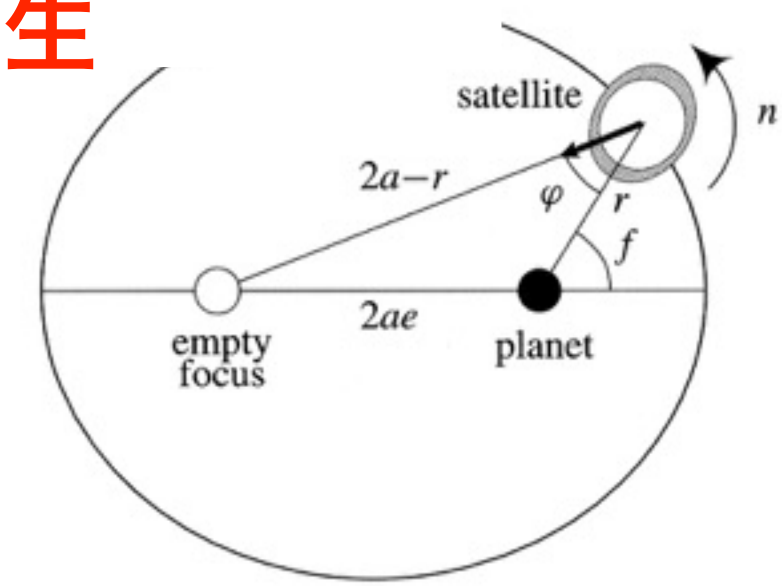


variation ir

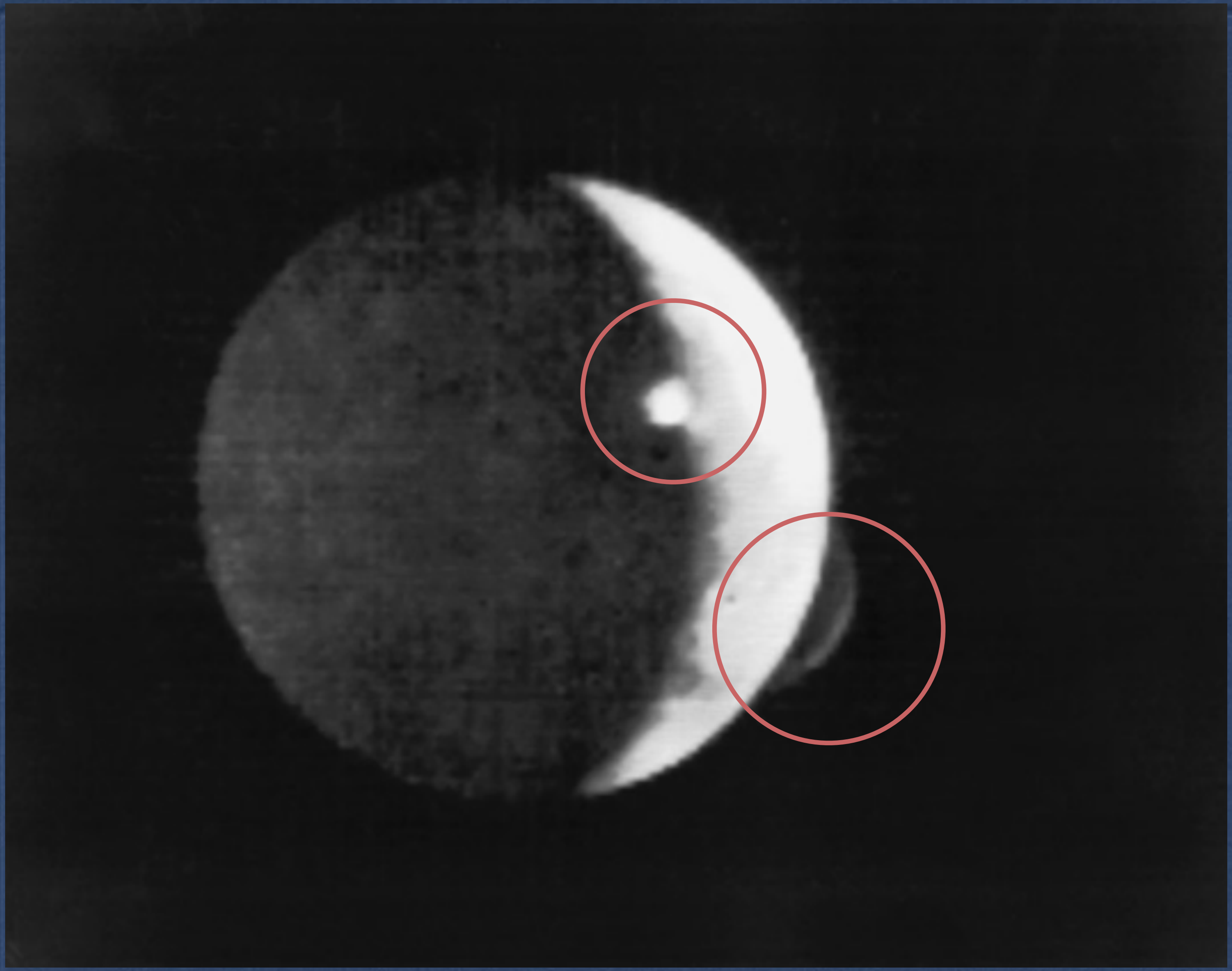




摩擦熱の発生



Tidal dissipation in Io



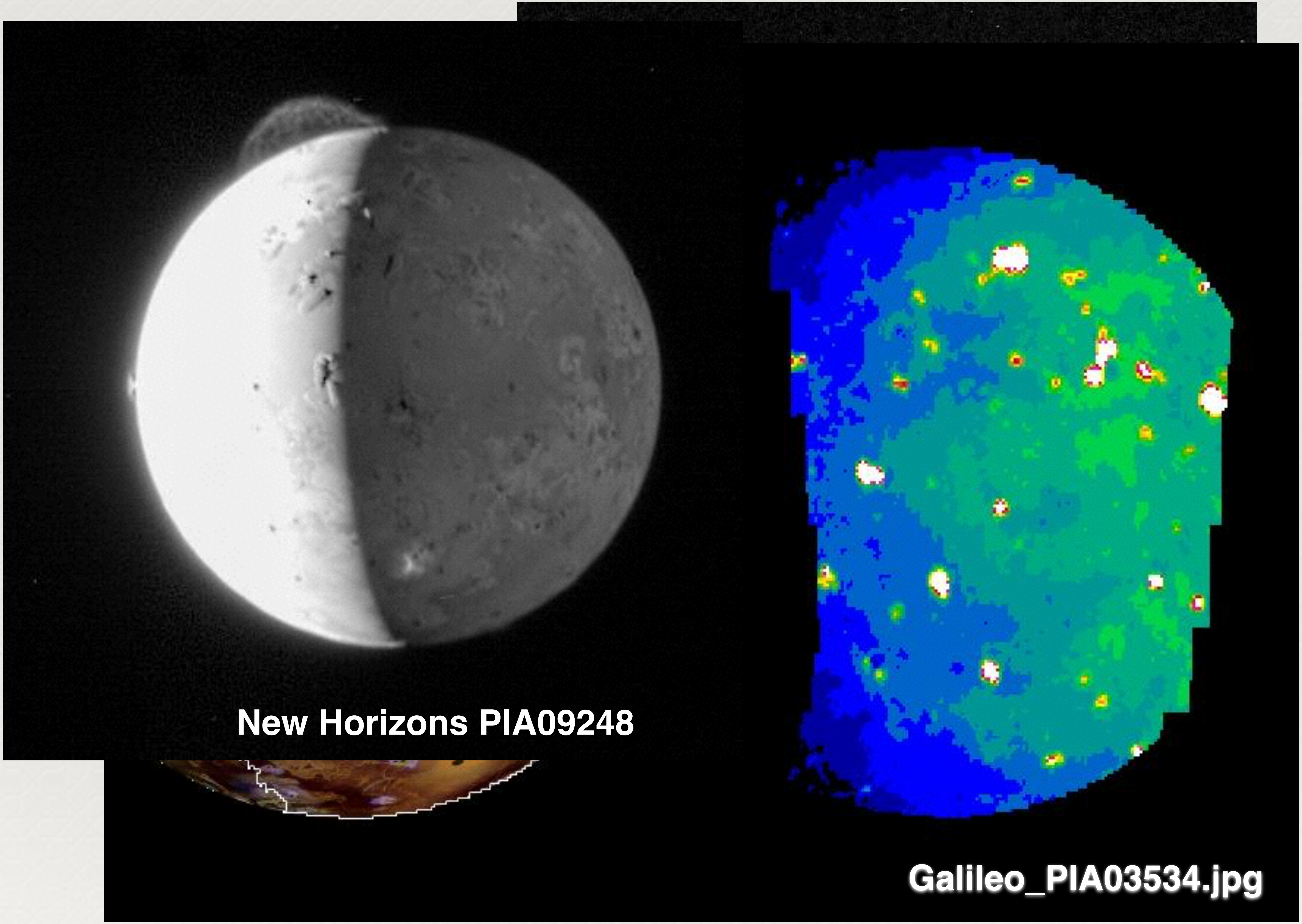
1979年3月5日

ボイジャー1号最接近

NASA JPL で *Mission Engineer*として働く。
当時*25*歳、その後天文学者となる.

1979年3月7日

モラビト　軌道解析用の画像にノイズ発見



New Horizons PIA09248

Galileo_PIA03534.jpg

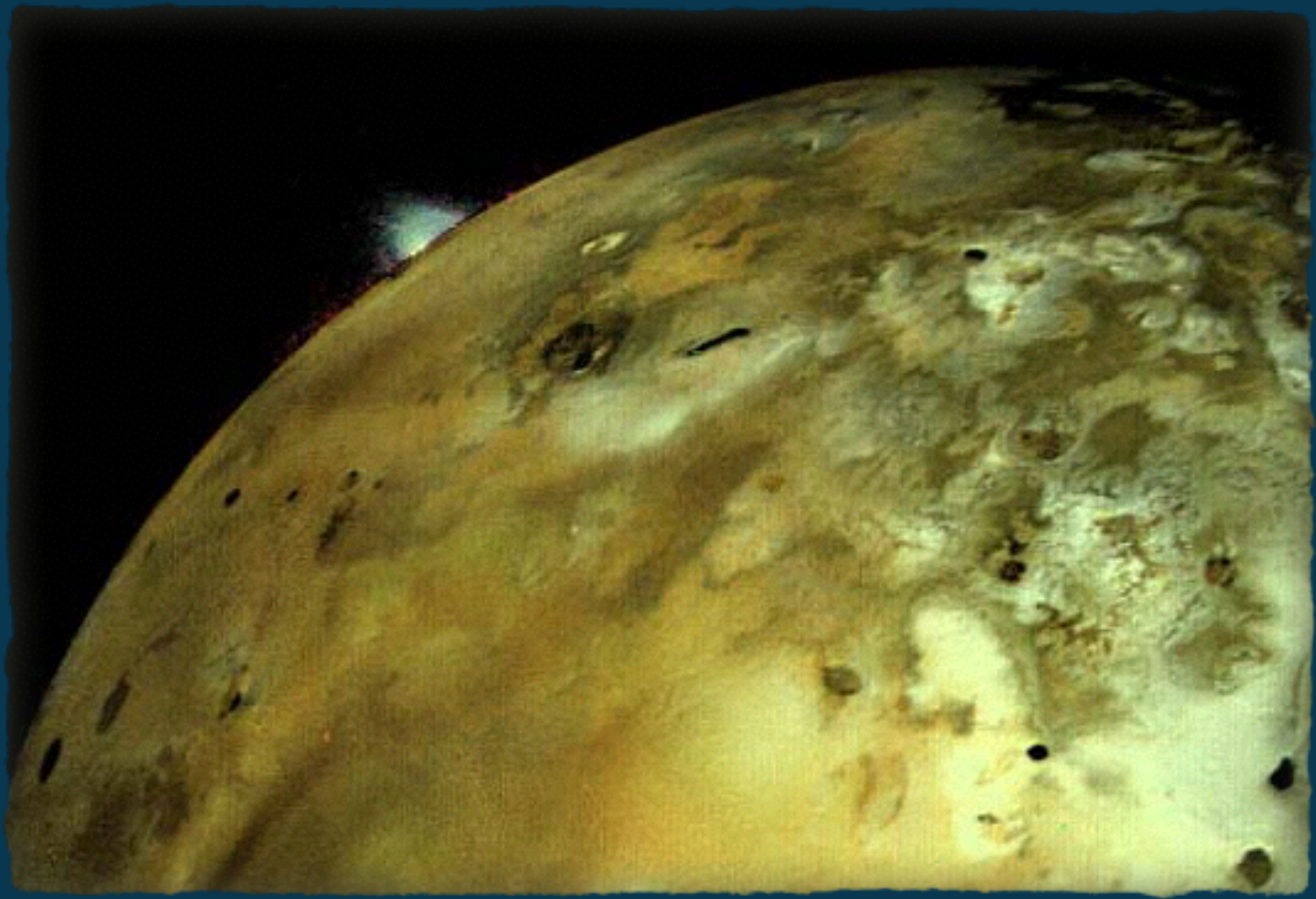
Melting of Io by Tidal Dissipation

Abstract. The dissipation of tidal energy in Jupiter's satellite Io is likely to have melted a major fraction of the mass. Consequences of a largely molten interior **may be evident in pictures of Io's surface returned by Voyager I.**

by S.Peale, P.Cassen and R.Reynolds

Science 203,892,1979

Jan. 1979/pub. March 2



Average heat flux:2.5 W/m²
Veeder et al, 1994

Terrestrial heat flux:
Continental regions: 65 mW/m²
Oceanic regions: 94 mW/m²

Jaupart et al, 2004

イオの活発な火山活動
エネルギー源

潮汐散逸

$$\frac{dE}{dt} = \frac{36}{19}\,\frac{\pi\rho^2 n^5 R_s^7 \boxed{e^2}}{\mu \boxed{Q}}$$

- *internal structure*
- *rheology*

- *decreasing with dissipation*
- *increasing with resonance*

Kawakami, S., & Mizutani, H. (1987). Thermal History of the Jovian Satellite Io. Icarus, 70, 78–98.

Ojakangas, G., & Stevenson, D. (1986). Episodic Volcanism of Tidally Heated Satellites, Icarus, 66, 341–358.

Laplace Resonance

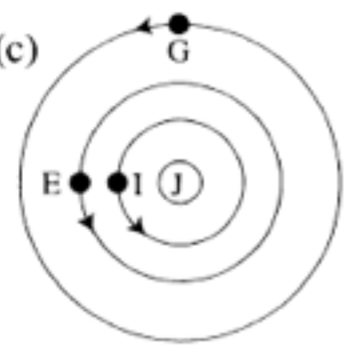
	Io	Europa	Ganymed	Callisto
R,10^3 km	422	671	1071	1884
Revolution,d	1.769	3.551	7.155	16.689
Spin,d	1.769	3.551	7.155	16.689
eccentricity	0.0041	0.0101	0.0015	0.0073
inclination	0.03	0.46	0.18	0.25

$$\frac{P(Europa)}{P(Io)} = \frac{3.551}{1.769} = 2.007$$

$$\frac{P(Ganymede)}{P(Europa)} = \frac{7.155}{3.441} = 2.014$$

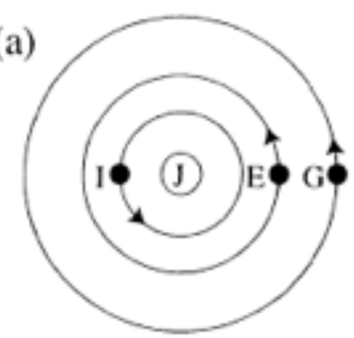
$$\frac{P(Callisto)}{P(Ganymede)} = \frac{16.689}{7.155} = 2.332$$

(c)



Conjuction Io-Europa
At
Apojove(aphelion) of Europa

(a)



Conjuction Europa-Ganyme
At
Perijove(periphelion) of Europa

Eccentricity is variable!

$$\dot{e_I} = \frac{0.32 M_J c_1}{M_E \alpha C_1} e_I^2 (\underbrace{1}_{\text{resonance pumping}} - \underbrace{13 D_I e_I^2}_{\text{dissipation dumping}})$$

resonance pumping

dissipation dumping

平衡状態の離心率

$$\boxed{e_{Ieq} = \frac{1}{\sqrt{13 D_I}}}$$

$$c_I = \frac{9}{2}\left(\frac{R_J}{a_I}\right)^5 \left(\frac{M_I}{M_J}\right) n_I \left(\frac{\kappa_J}{Q_J}\right)$$

$$D_I = \left(\frac{R_I}{R_J}\right)^5 \left(\frac{M_J}{M_I}\right)^2 \left(\frac{Q_J}{\kappa_J}\right) \boxed{\left(\frac{\kappa_I}{Q_I}\right)}$$

J:Jupiter, I:Io and E:Europa

Eccentricity couples with dissipation!

Ojakangas & Stevenson (1986)

Tidal dissipation

$$\frac{dE}{dt} = (1/P) \oint \langle \sigma e^* \rangle dt$$

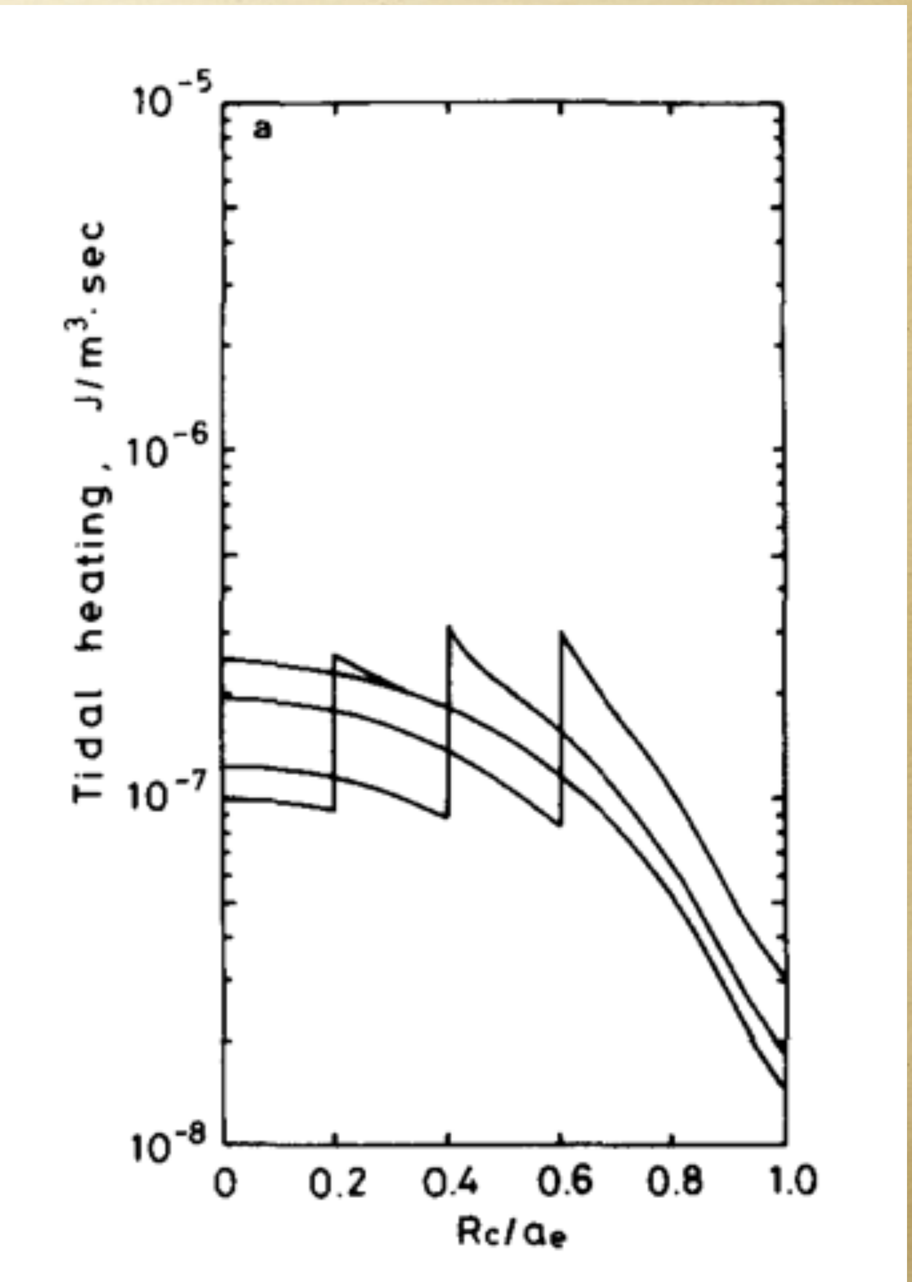
$$\sigma = f(r, \theta, \phi, t) = F(\kappa, V(t))$$

κ : **Love number**

V(t): **tidal potential**

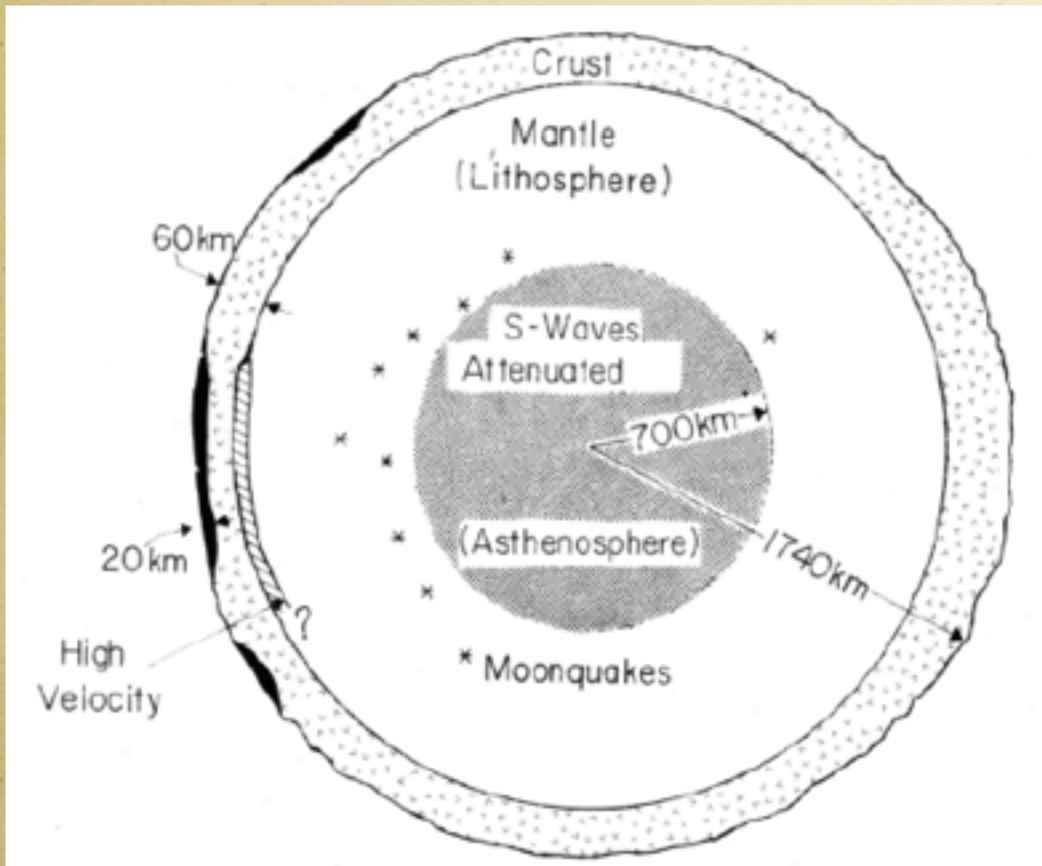
$$\Delta\phi_2 = k(\frac{R_e}{r})^3 \phi_2^J$$

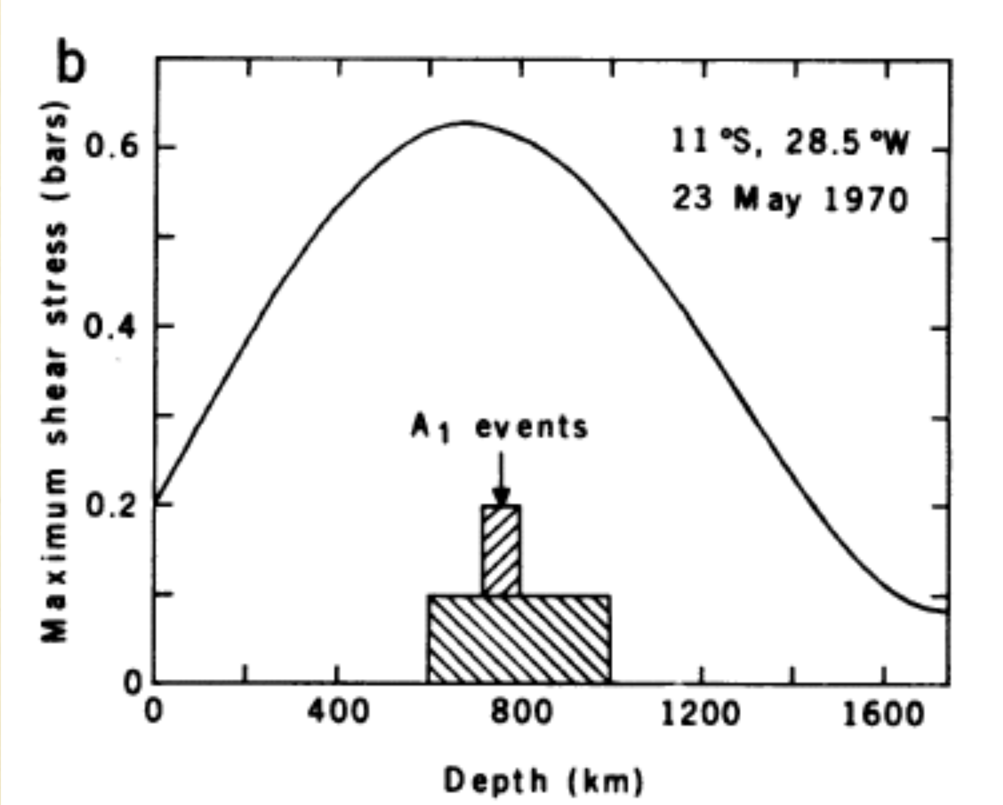
non-homogeneous dissipation

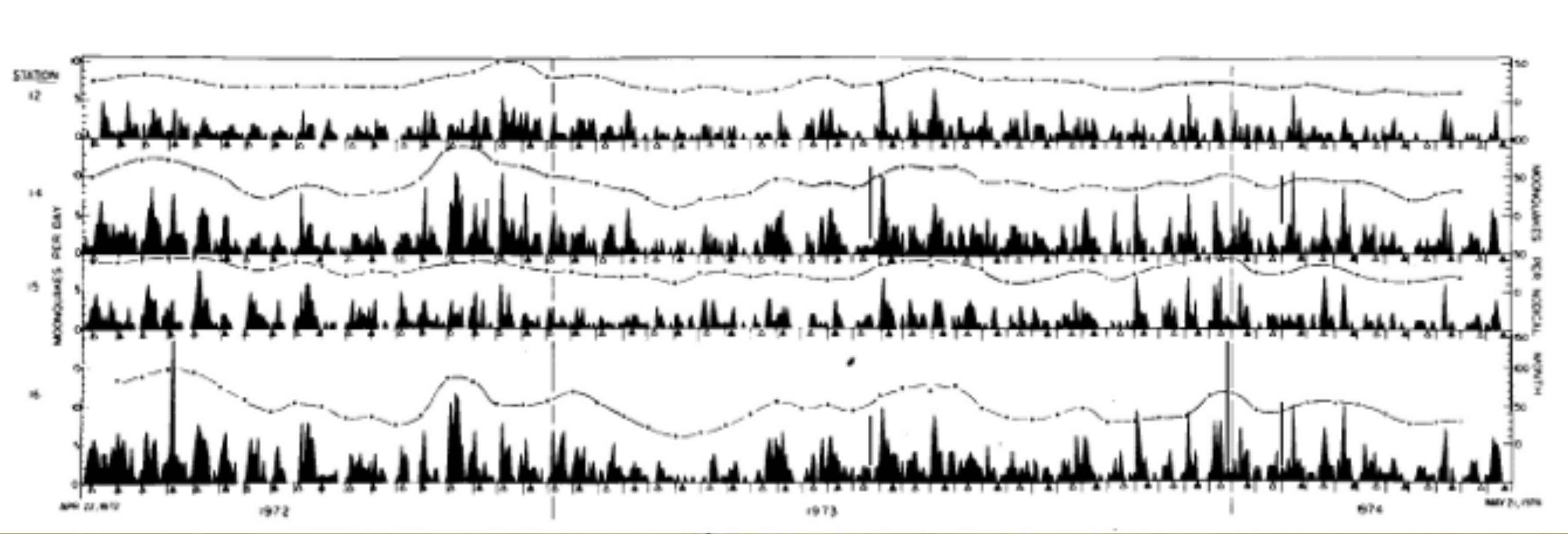


Kawakami & Mizutani (1987)

Place where tidal dissipation is significant example of Deep Focus Moonquakes







Example: internal structure controls tidal deformation

tidal stress in Europa shell as a function of the thickness

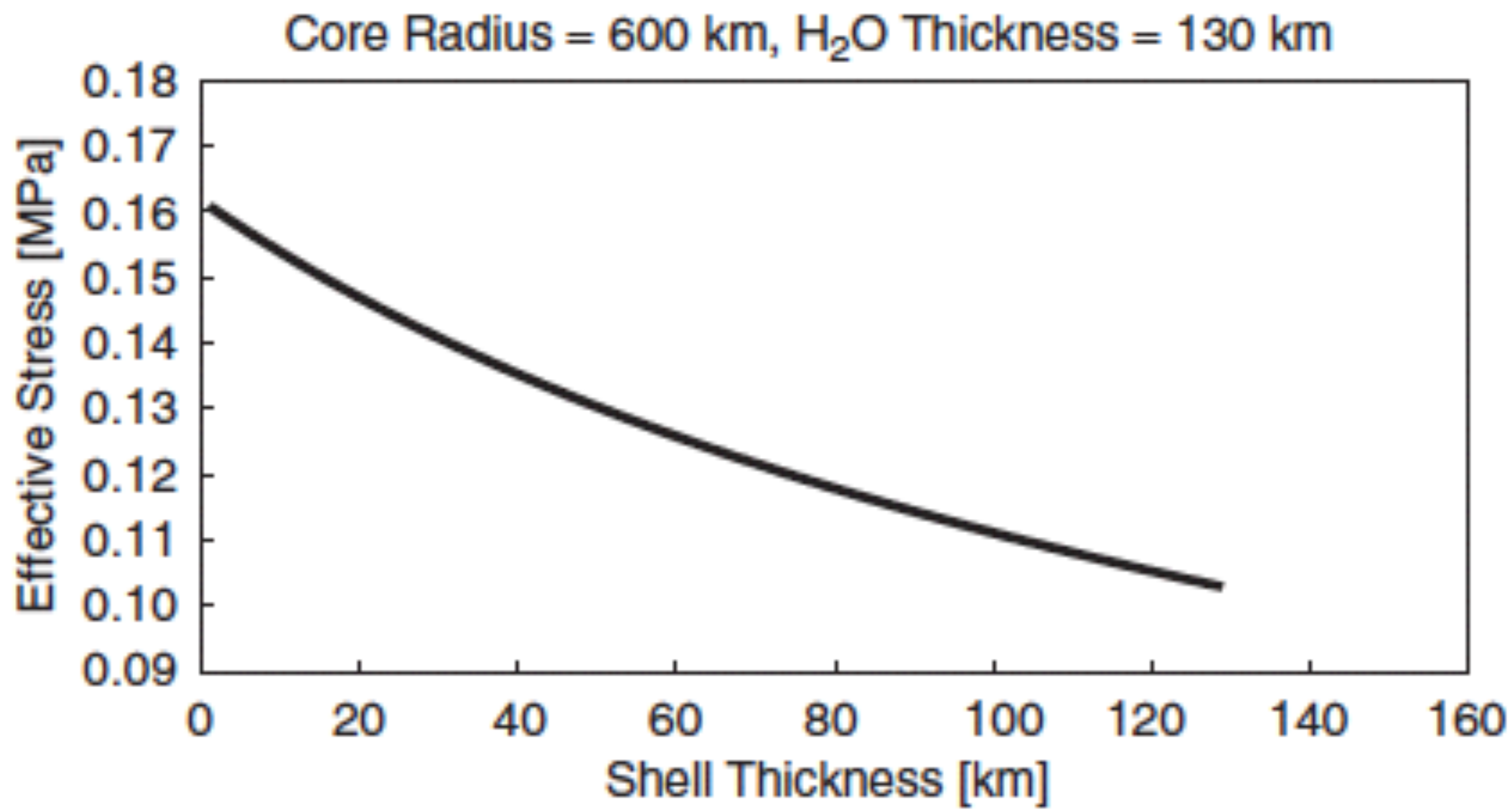
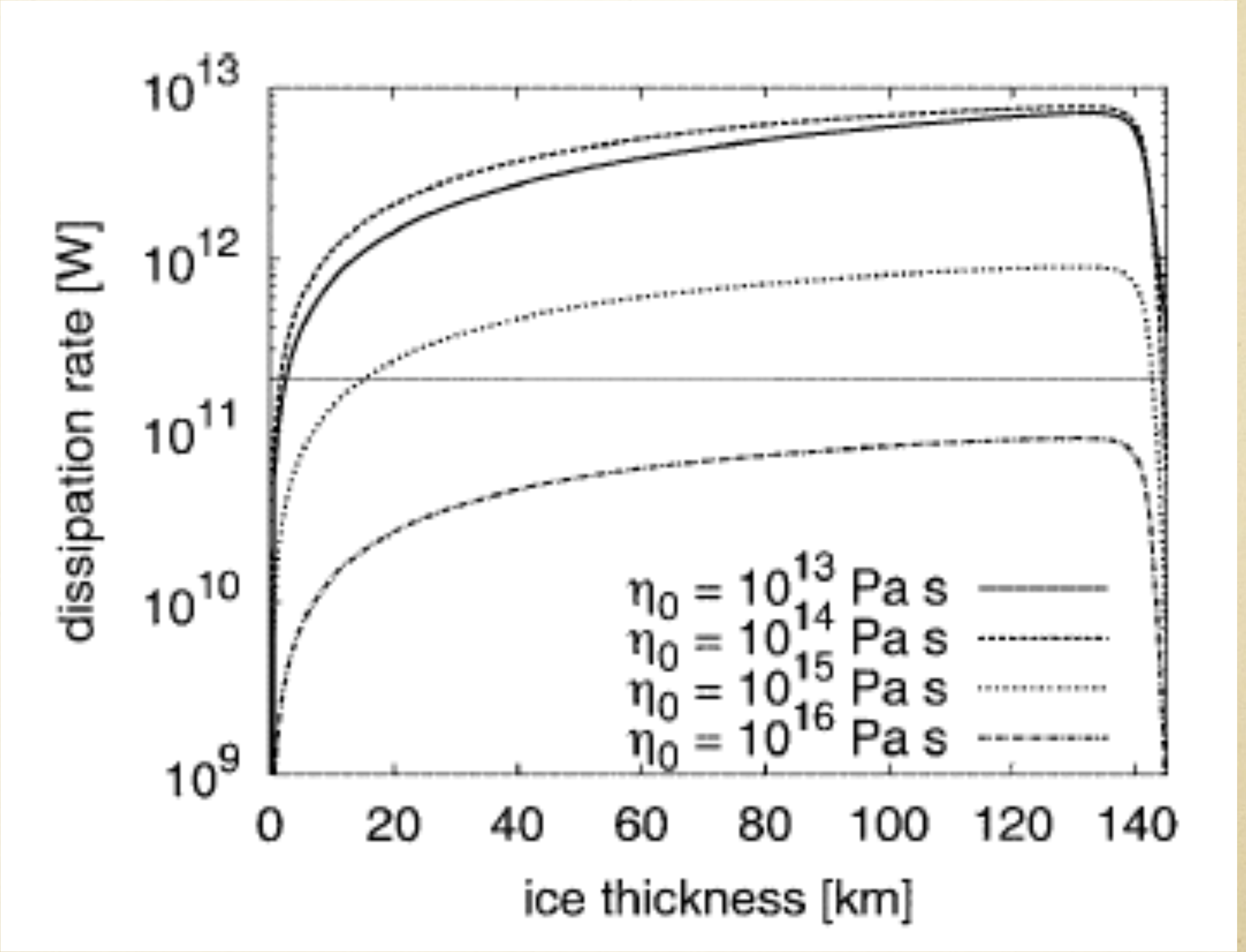


Fig. 3. The variation of the effective stress with respect to the shell thickness at the sub-Jovian point under the peri-Jove.

Harada & Kurita,PSS 54,2006

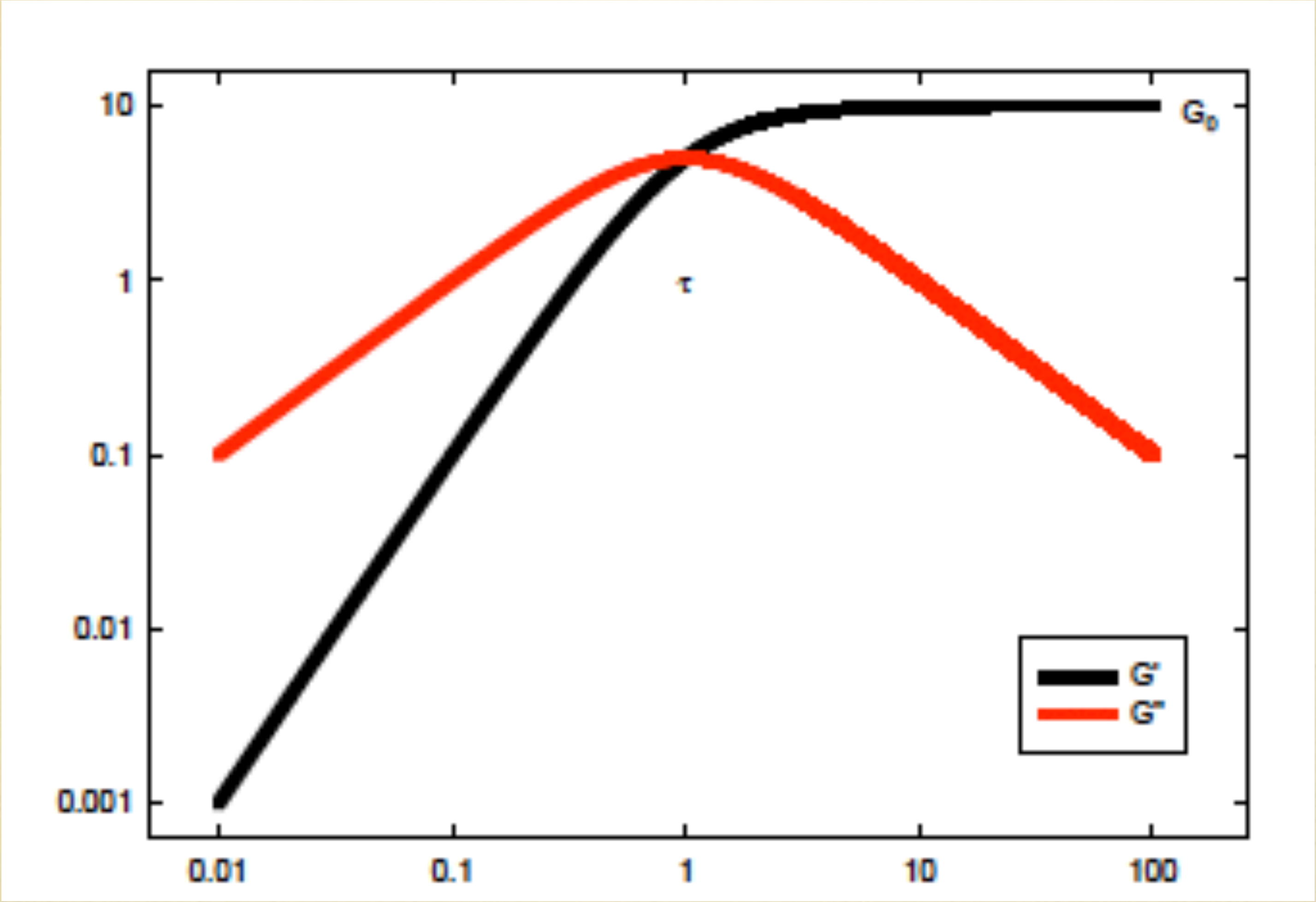
Tidal dissipation is controlled by internal structure



case for Europa

Hussmann et al ,Icarus 156,(2002)

Why rheology is important?



$$\omega\tau_M$$

$$\tau_M = \frac{\eta}{\mu}$$

Maxwell model

$$\mu = 4 \times 10^9 \ Pa$$

$$\eta = 10^{14} \ PaS$$

$$\tau_M \sim 10 \ hours$$

Summary:Tidal Dissipation

$$\dot{E} = -\frac{21}{2}\frac{R^5 n^5 e^2}{G} Im(\kappa_2)$$

Segatz et al 1988

orbit

dissipation, internal structure

Orbit

$\downarrow\uparrow$

Dissipation

$\downarrow\uparrow$

Internal Structure

Enigma(Paradox) for Tidal Dissipation

1. Io
    1. Heat budget?
    2. Episodicity/Oscillation
    3. Hard lithosphere?
2. Enceladus
    1. why Enceladus?
    2. Heat budget?
    3. Resonance
3. Phobos
    1. Martian interior
4. Ganymede

1.1 Io Paradox-1:heat generation

Upper limit of heat dissipation in Io

3.3×10^{13} W ($0.8\,Wm^{-2}$)

Peale 1986

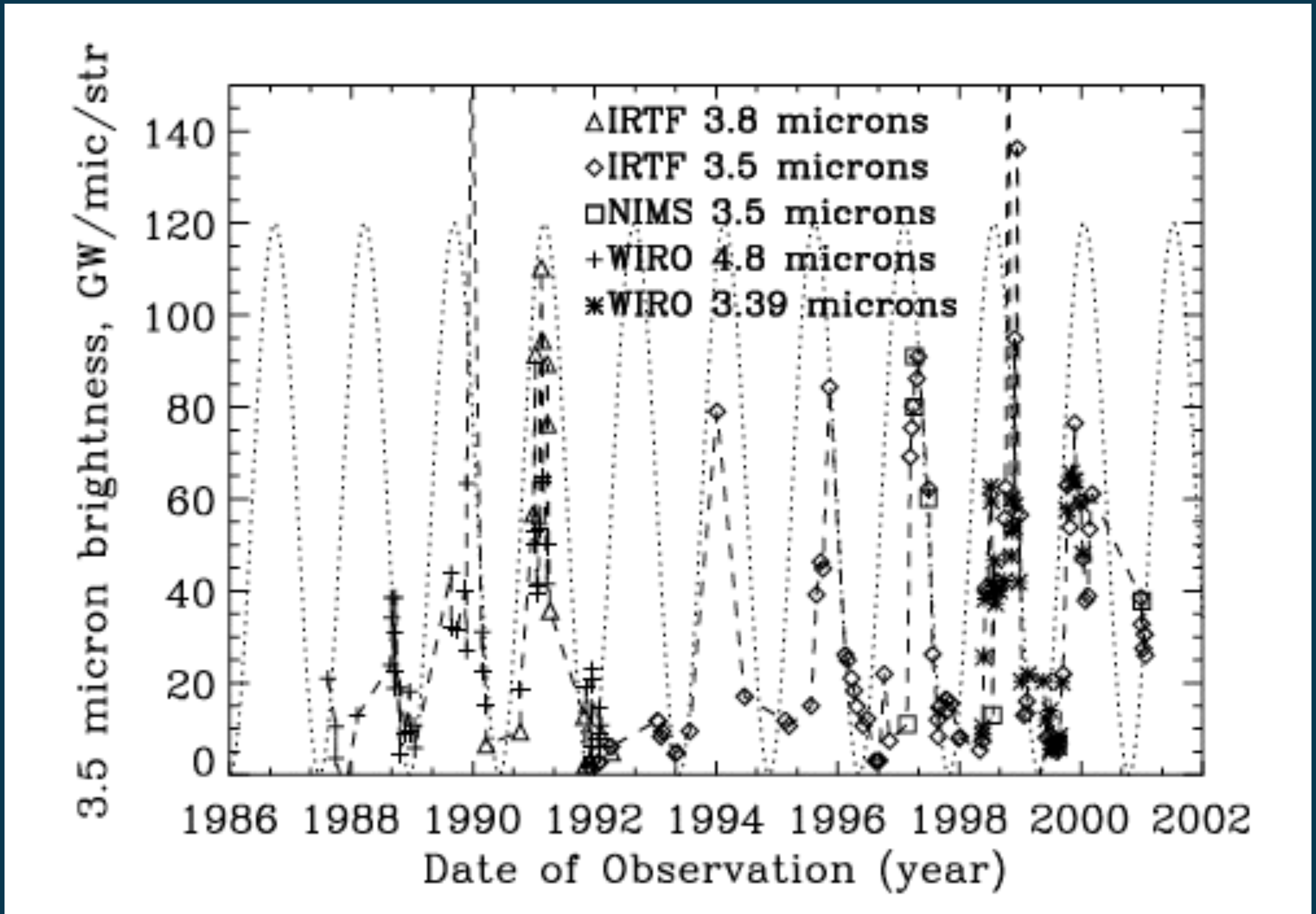
uncertainty of Q_j

Observed heat flow

1-2 $\times10^{14}$ W (2.5-5.0 Wm^{-2})

Veeder et al, 1994

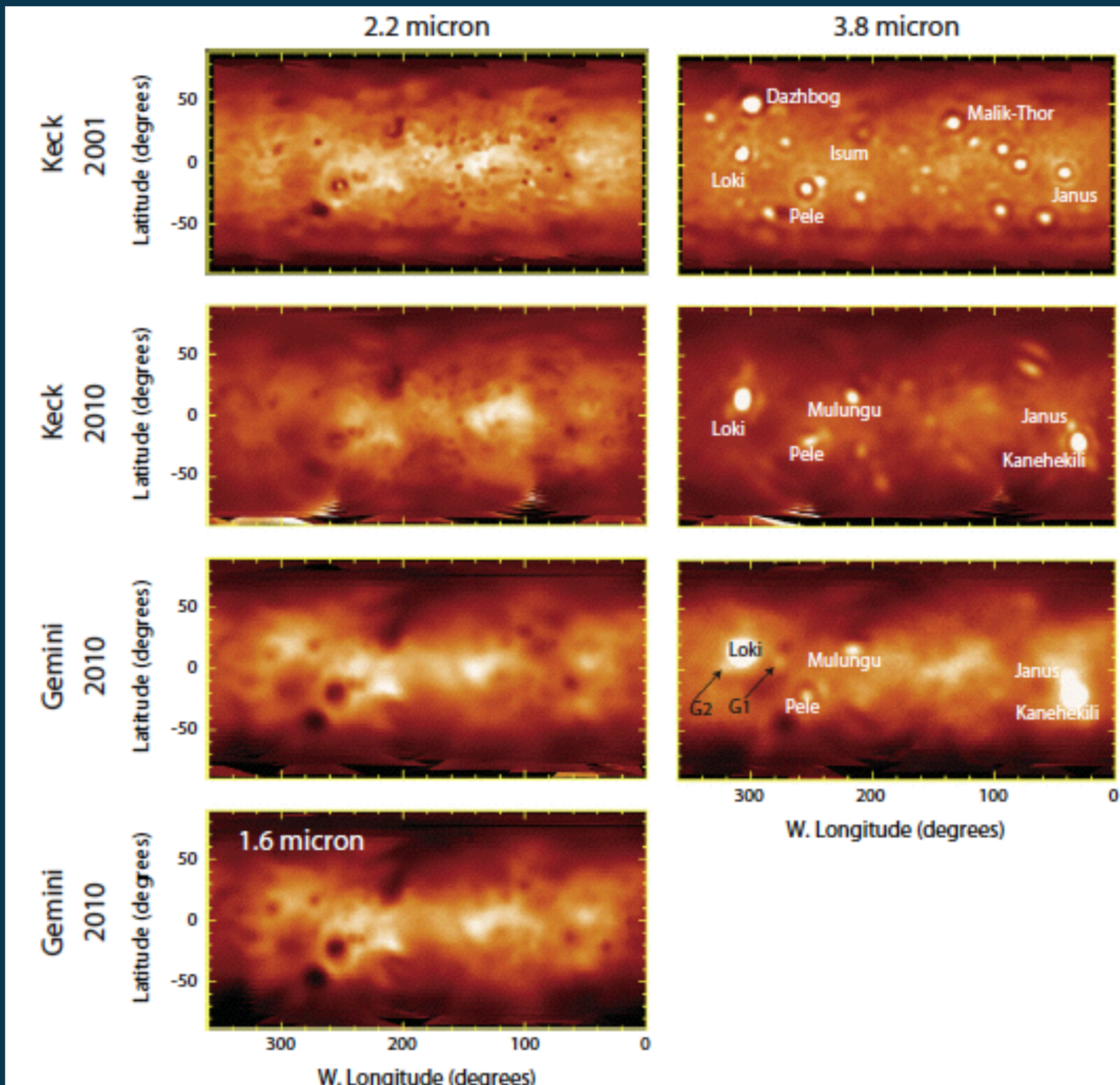
1.2 Io Paradox-2: Periodicity in flux from Loki

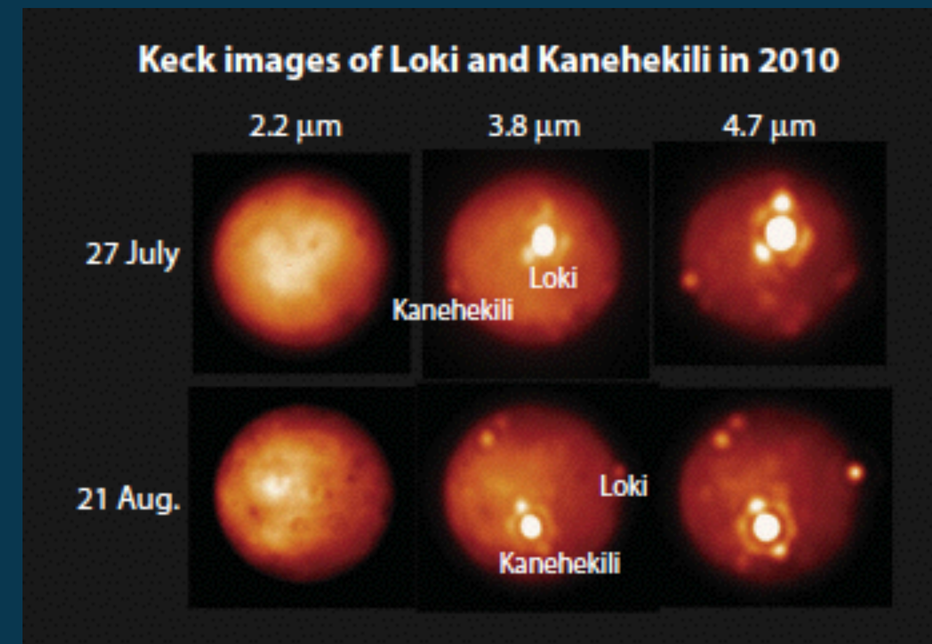


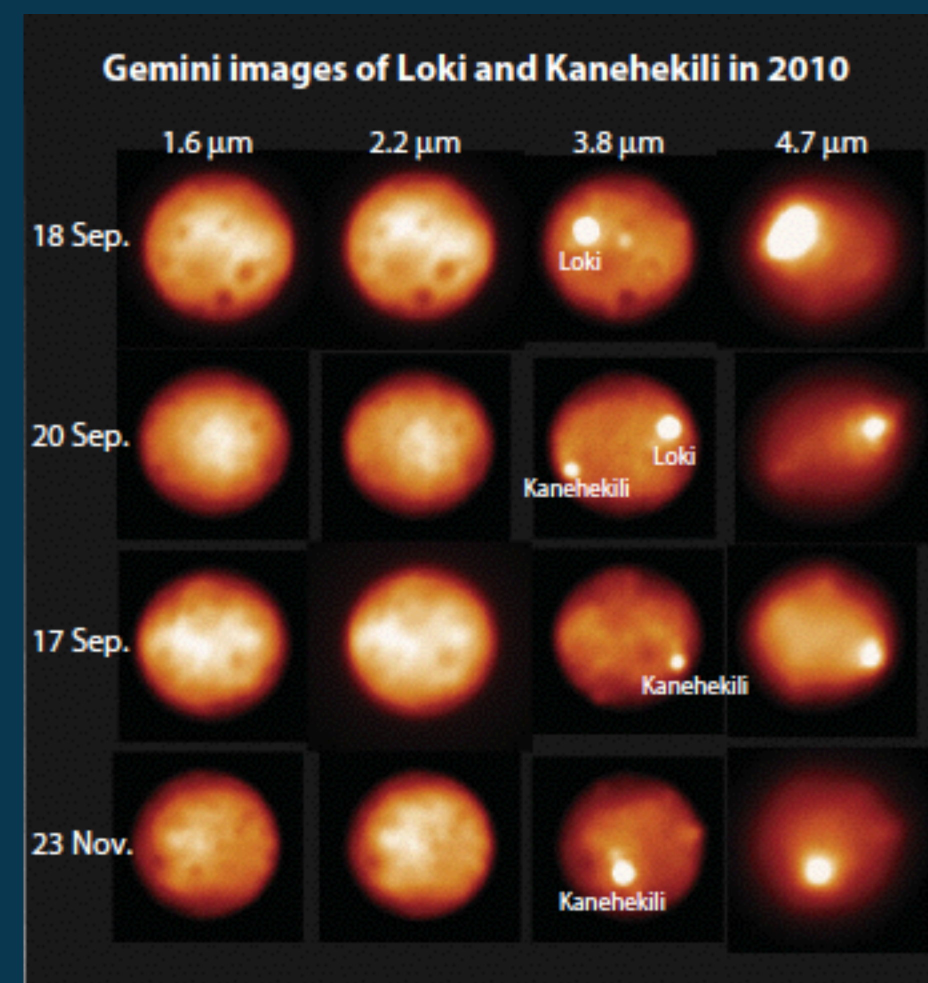
Periodicity in flux from Loki 540 days

Rathbun, J. A., Spencer, J. R., Davies, A. G., Howell, R. R., & Wilson, L. (2002). Loki, Io: A periodic volcano. *Geophysical Research Letters*, *29*(10), 84–1–84–4.

Ground-based observations

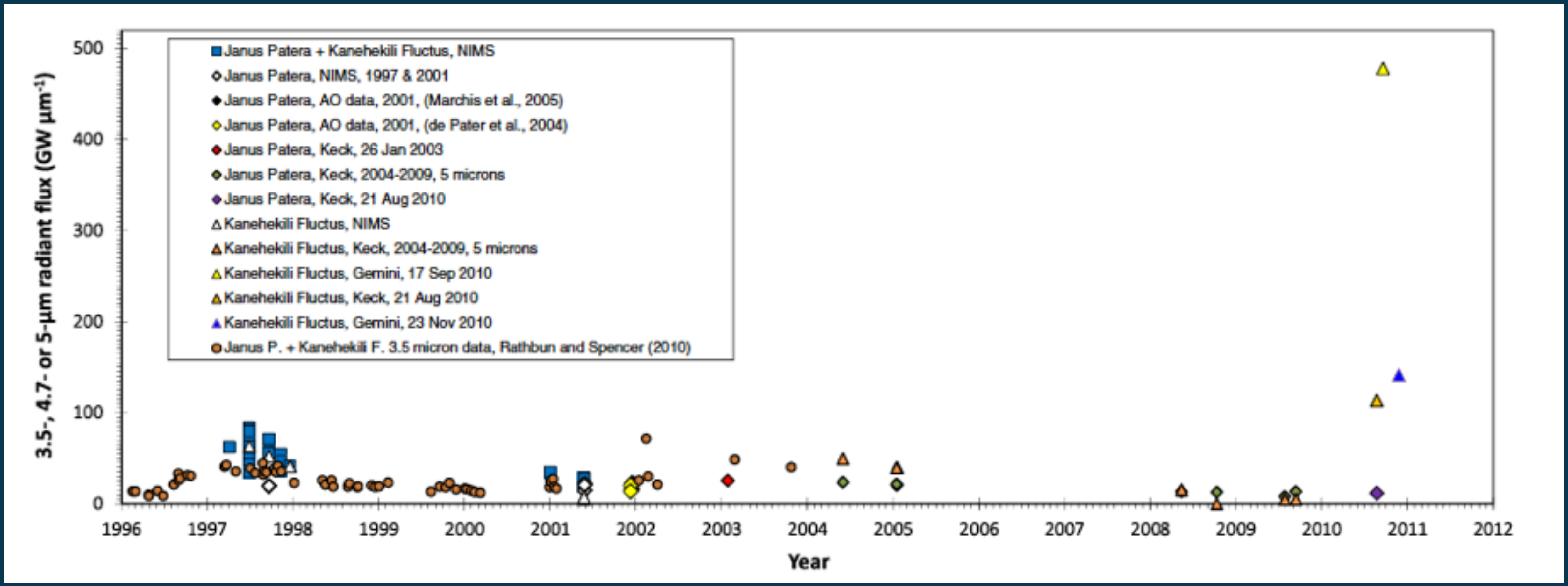






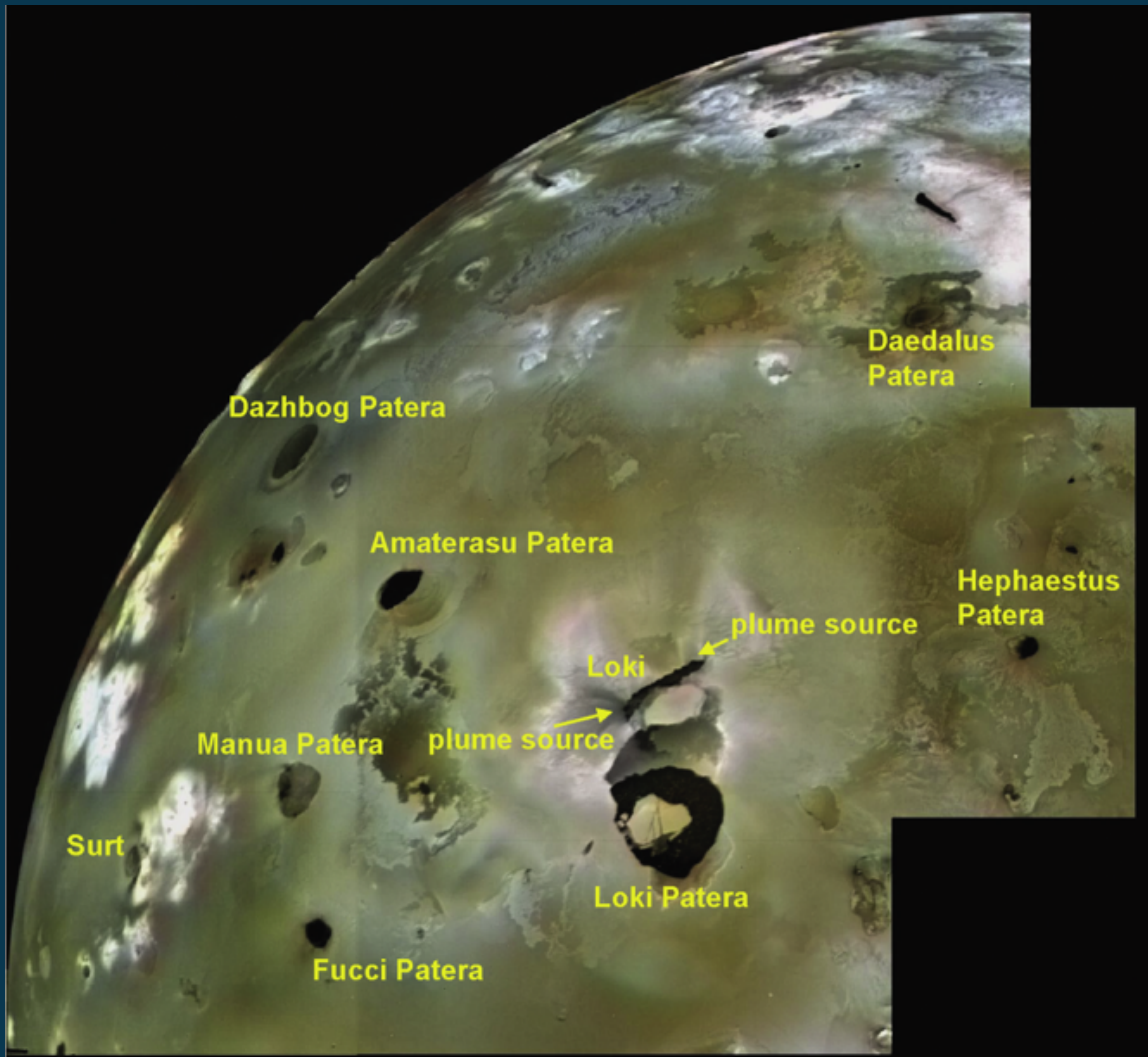
de Pater et al, Icarus 242,(2014)

Radiant flux fromJanus Patera & Kanehekili Fluctus



de Pater, I., Davies, A. G., McGregor, A., Trujillo, C., Ádámkovics, M., Veeder, G. J., et al. (2014). Global near-IR maps from Gemini-N and Keck in 2010, with a special focus on Janus Patera and Kanehekili Fluctus. *Icarus*, *242*, 379–395. http://doi.org/10.1016/j.icarus.2014.06.019

Loki Patera



JGR 111,2006 Matson et al

1.3 Io Paradox-3: Hard lithosphere

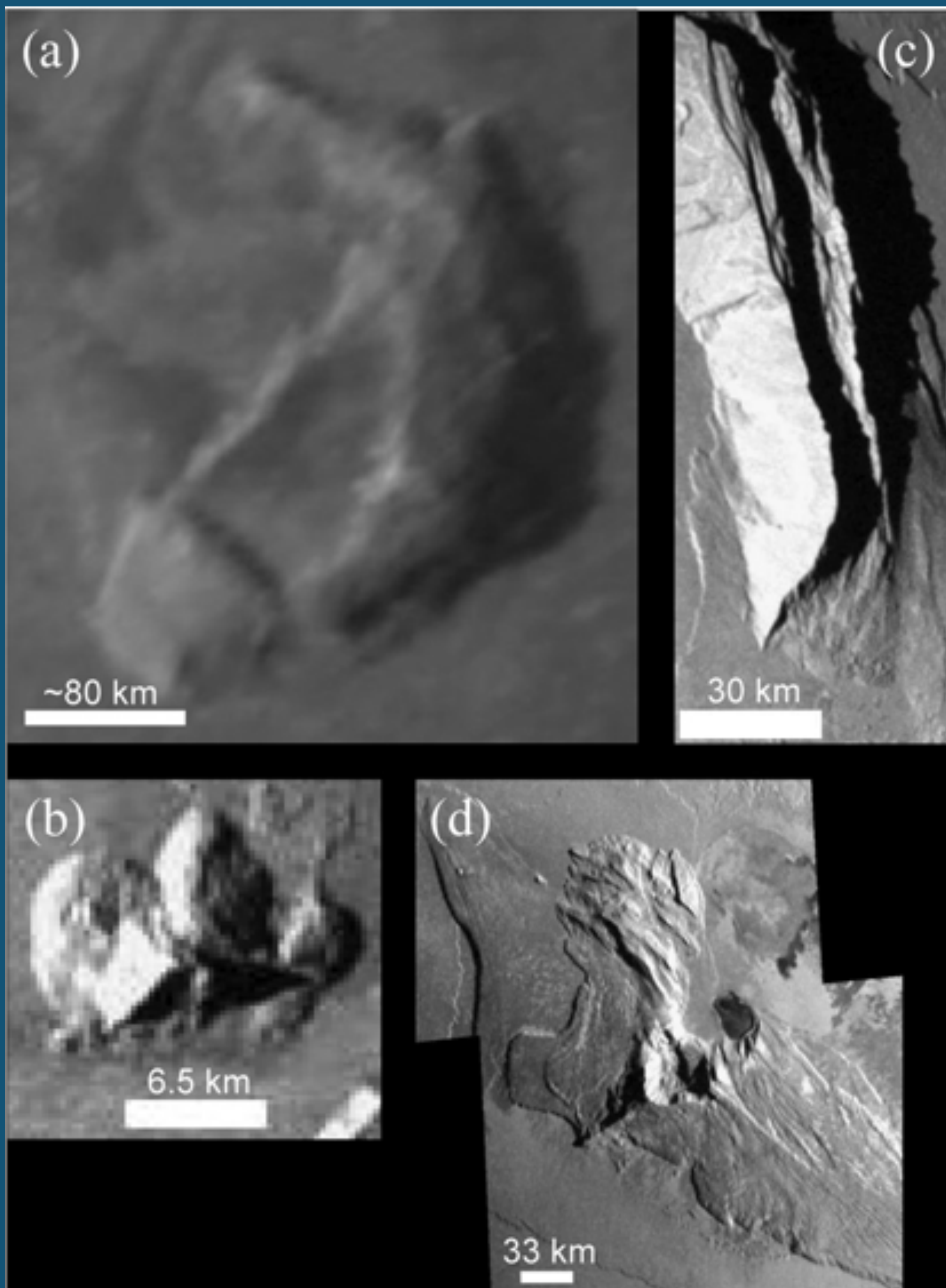
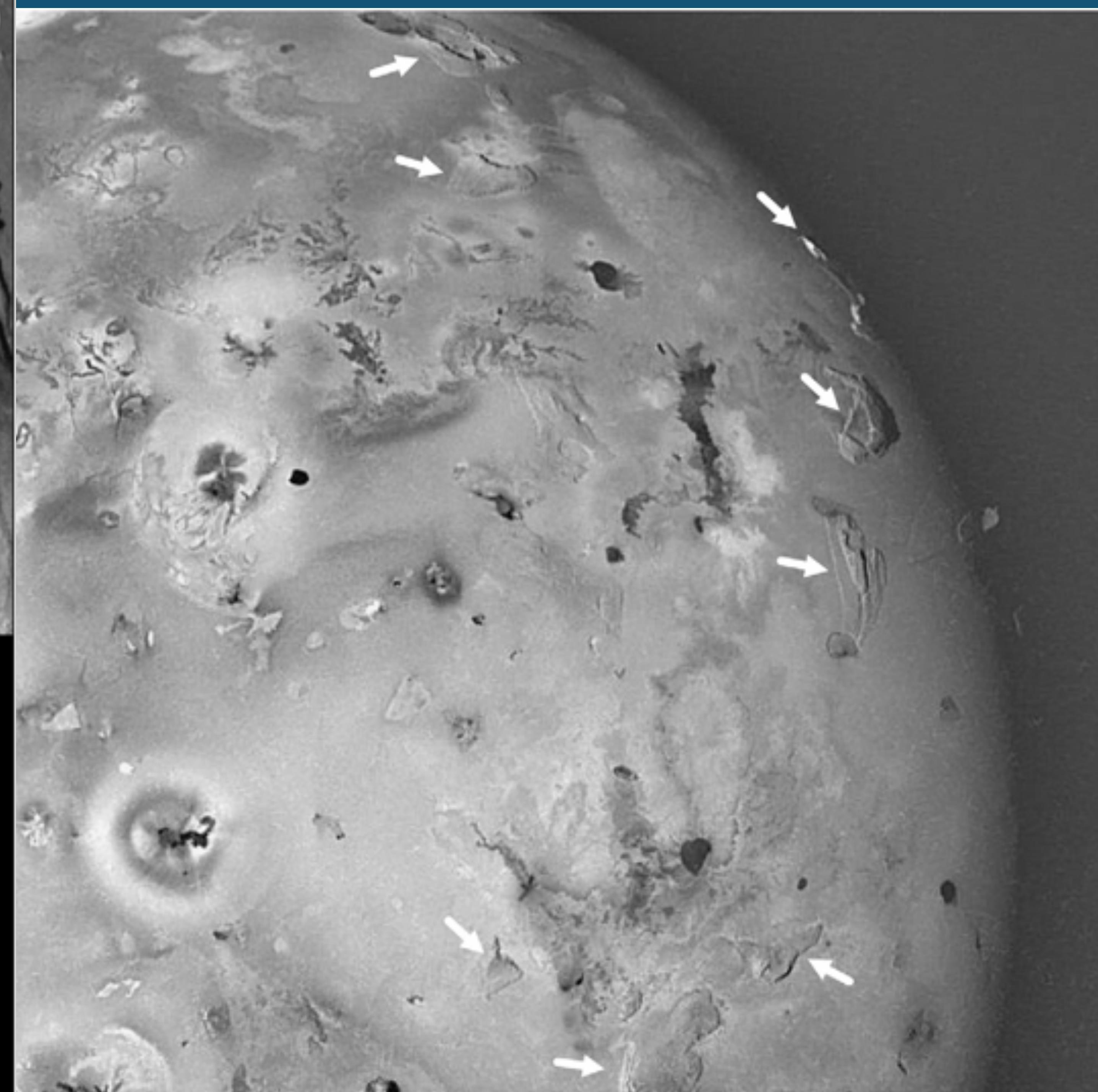
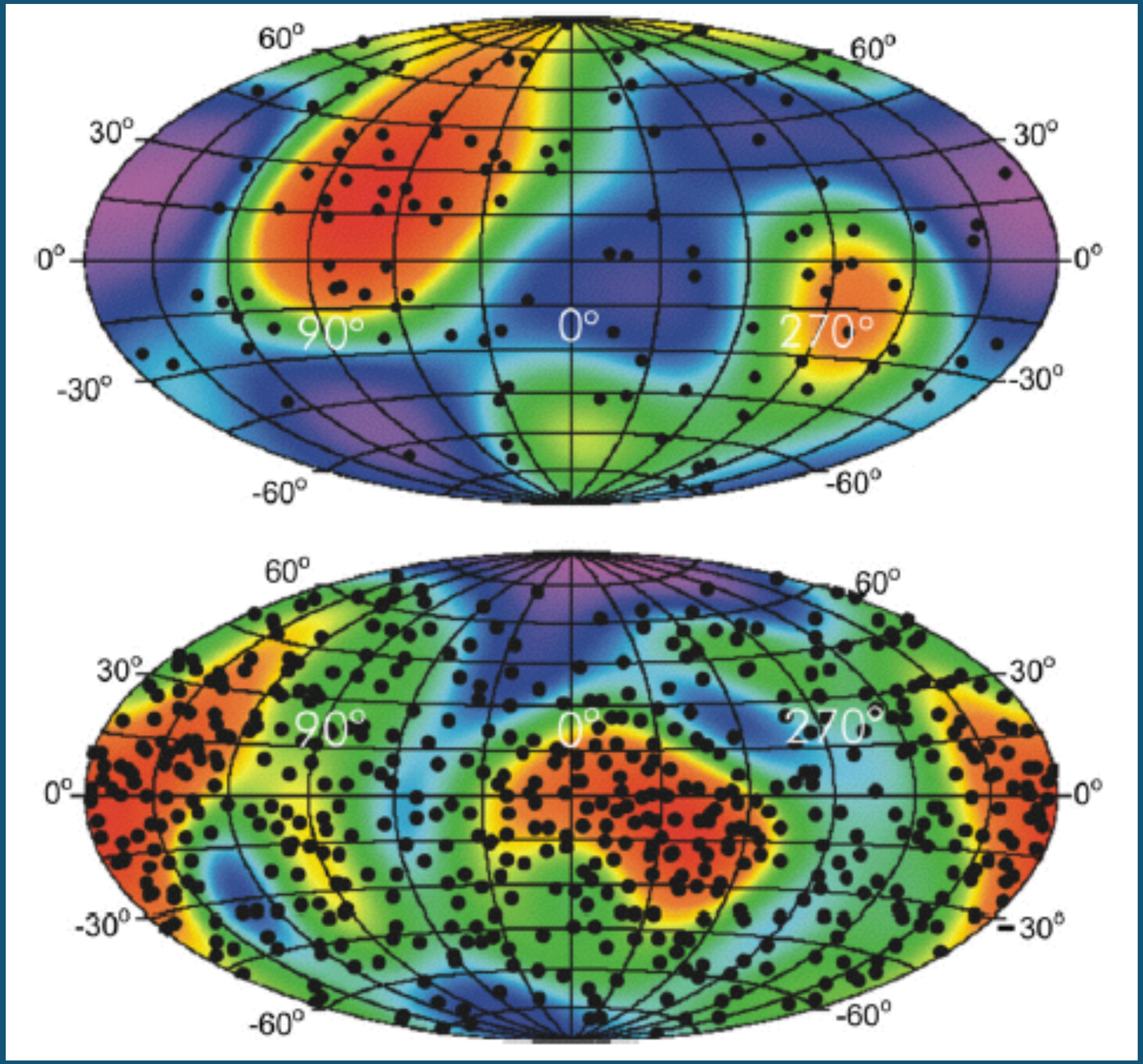


Fig. 1. Examples of mountains on Io. (a) Skythia Mons with plateau morphology located at 16.0○ N and 104.3○ W; (b) Isolated peak in the Hi'iaka Montes is a good example of the peak morphology and has a height of ~4 km; (c) Mongibello Mons is an example of a ridge on Io and has a double rise that reaches 8.6 km; and (d) Tohil Mons is a massif complex rising to a maximum height of ~9 km. Data and nomenclature from Schenk et al. (2001). Modified from NASA Planetary Photojournal images PIA03600, PIA02540, PIA01103, and PIA03886.



High mountains on Io

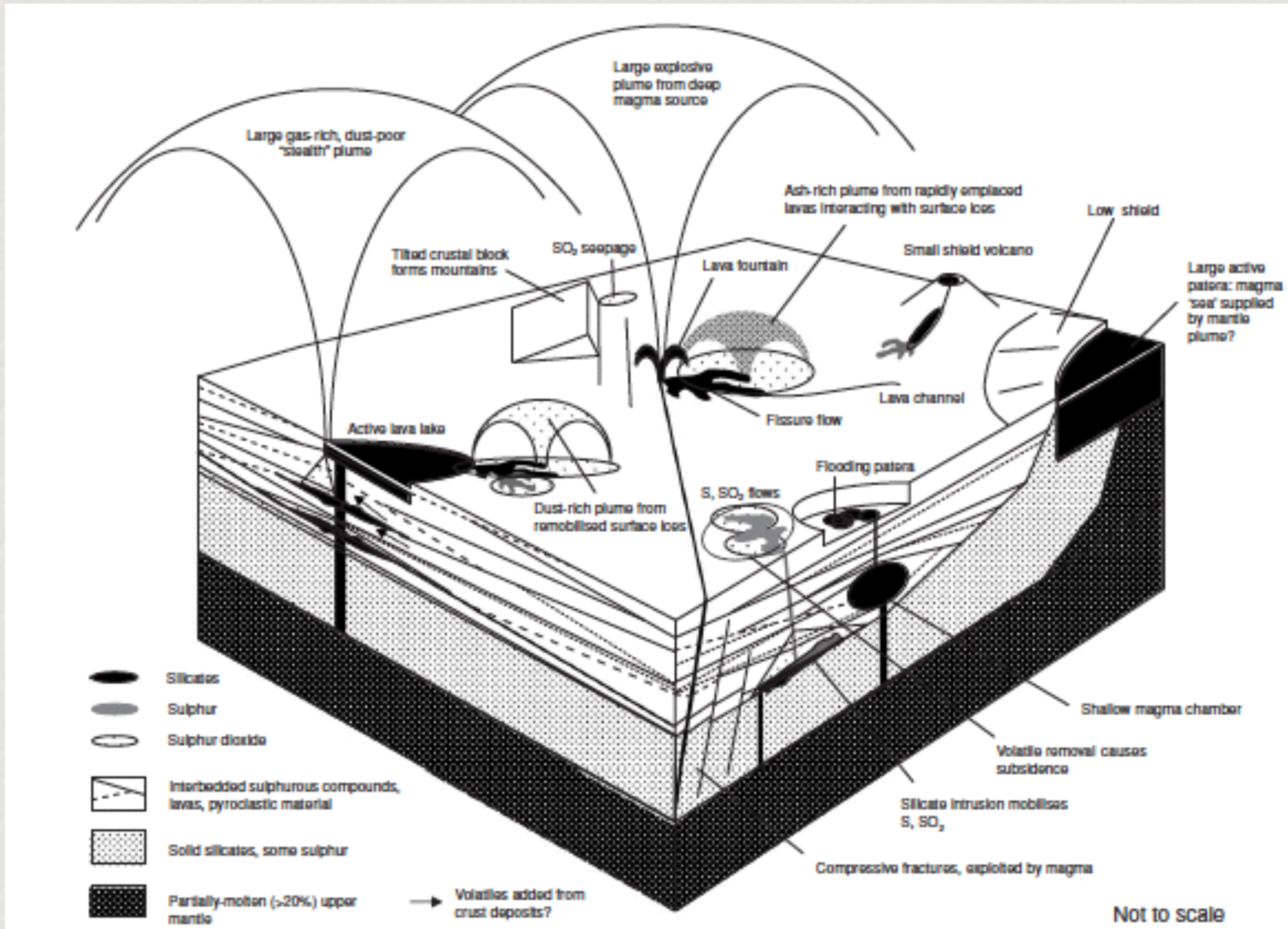


mountain

volcano

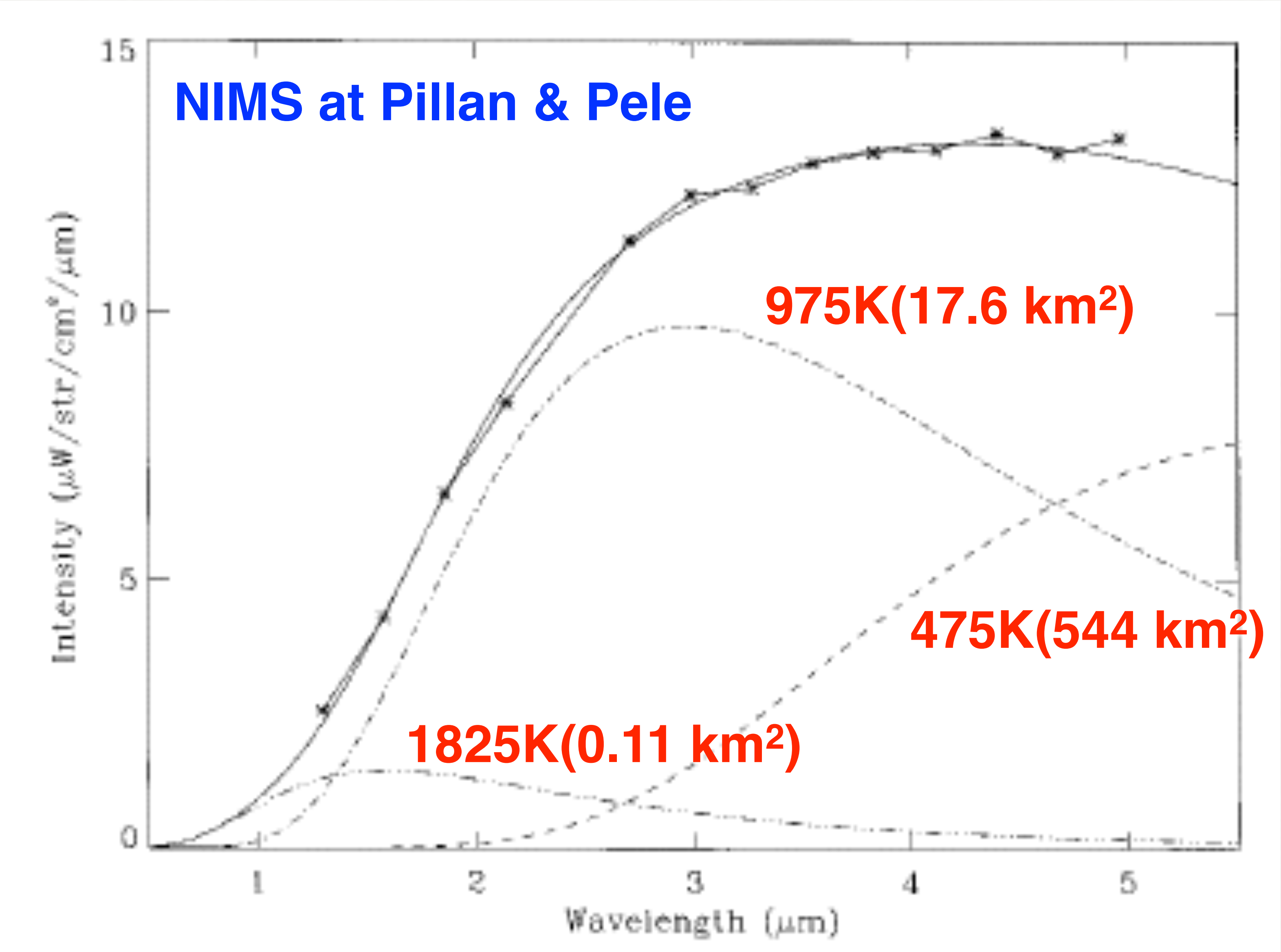
Kirchoff, M. R., & Mckinnon, W. B. (2009). Formation of mountains on Io: Variable volcanism and thermal stresses. Icarus, 201(2), 598–614.

Styles of volcanic activities on Io



Davies Volcanism on Io, Ch18,

Heat Flow of Io



McEwen, A., LKeszthelyi, JRSpencer, & GSchubert. (1998). High-temperature silicates volcanism on Jupiter's moon Io. Science, 281, 87–90.

2.1 Enceladus Paradox-1:why Enceladus?

Satellite Orbital Position

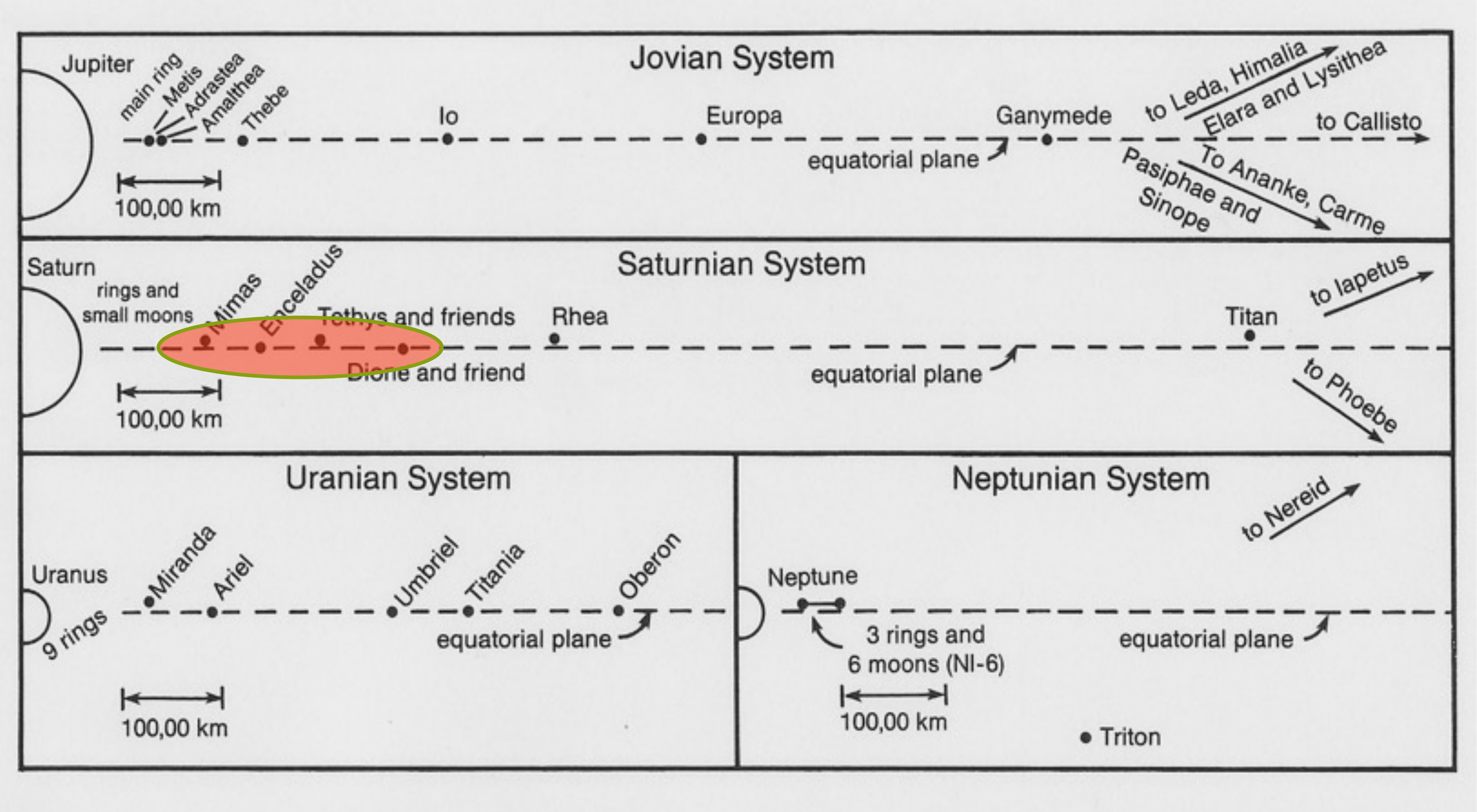
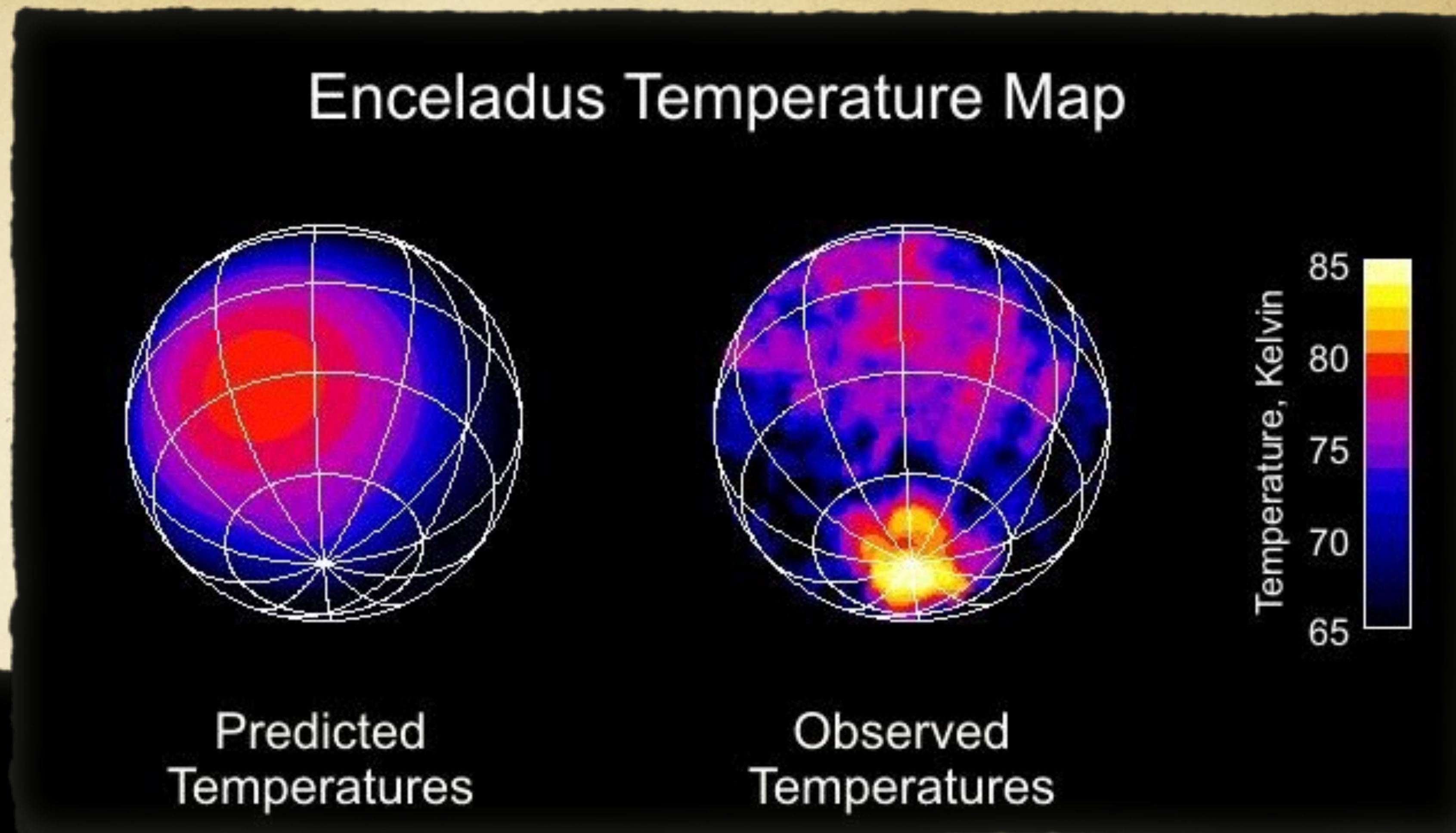


Fig. 6.1.1. *An overall view of the satellite and ring systems of the giant planets. After Elliot J. and Kerr R. (1984) Rings, p. 181, Fig. 10.1, MIT, Cambridge.*



Plume activity at Enceladus

2.2 Enceladus Paradox-2

Heat budget & enigma

- present total heat flux: 4.7-15.8 GW
- present radiogenic heat generation:0.3 GW
- tidal dissipation at equilibrium resonance:
  1.1 GW   Meyer and Wisdom 2007

$$Q = k\frac{T_b - T_s}{D} \times 4\pi R^2$$

with existence of ocean
D~100km,DT~100-200K

3-6 GW

エンケラドスの問題

	軌道半径 km	公転周期 d	離心率	半径 km
Io	4.2×10^5	1.77	0.0041	1822
Enceladus	2.4×10^5	1.37	0.0047	252
Europa	6.7×10^5	3.55	0.0101	1561
Moon	3.8×10^6	27.3	0.055	1738
Charon	2.0×10^4	6.4	0	600
Phobos	9378	0.32	0.0151	11

$$
\begin{aligned}
F_t &= \frac{GMm}{(R-r)^2} - \frac{GMm}{(R+r)^2} \\
&= GMm\left[\frac{(R+r)^2-(R-r)^2}{(R-r)^2(R+r)^2}\right] \\
&\approx GMm\frac{4Rr}{R^4} = GMm\frac{4r}{R^3}.
\end{aligned}
$$

$$\frac{de}{dt} = \left[\frac{0.49 M_s c_e}{M_d \alpha C_a}\right] e^2 (1 - 30.69 D_e e^2),$$

$$D_e = \left(\frac{R_e}{R_s}\right)^5 \left(\frac{M_s}{M_e}\right)^2 \left(\frac{Q_s}{k_{2s}}\right) \left(\frac{k_{2e}}{Q_e}\right).$$

s: Saturn, ***e***: Enceladus, ***d***:Dione

In case for viscoelastic body

$$Q_e = \frac{Re(\tilde{k}_{2e})}{\mathrm{Im}(\tilde{k}_{2e})} \approx \frac{|\tilde{k}_{2e}|}{\mathrm{Im}(\tilde{k}_{2e})}$$

$$D_e = \left(\frac{R_e}{R_s}\right)^5 \left(\frac{M_s}{M_e}\right)^2 \left(\frac{Q_s}{k_{2s}}\right) |\mathrm{Im}(\tilde{k}_{2e})|$$

散逸量

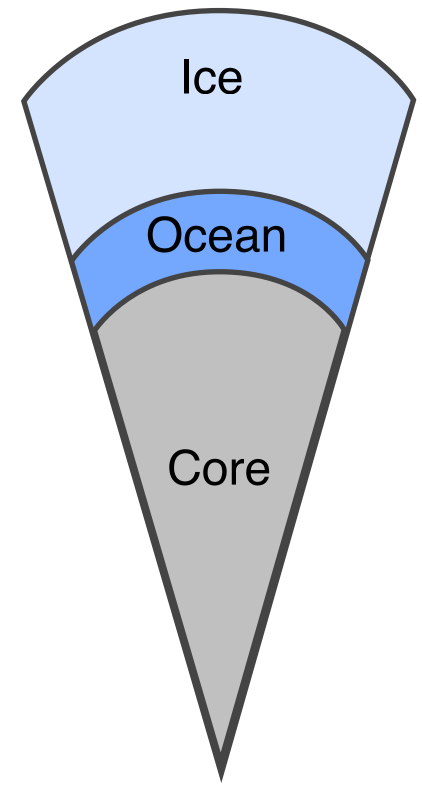
（内部構造の変化）

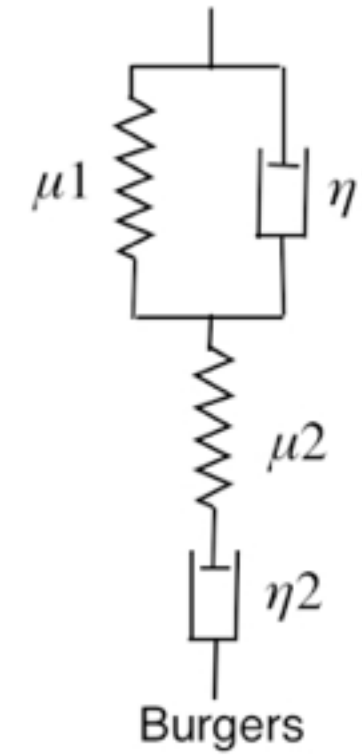
離心率の変化

Results by Shoji, Hussmann, Sohl & Kurita (2014) Icarus, 235 75-85, 2014

Model

- parameters:core radius,Tb,$\mu 2/\mu 1$, $\eta 2/\eta 1$,Qs.
  - Core radius:155km-165km
    - Schubert et al., 2007
  - Tb>175K
  - $\eta 2/\eta 1>50$ (Robuchon et al., 2012), $\mu 2/\mu 1>1$
  - Qs>18,000(Meyer and Wisdom, 2007)





$$\eta_2 = \eta_0 \exp\left(\frac{E_a}{RT_m}\left(\frac{T_m}{T} - 1\right)\right),$$

Ea=35 kJ/mol (Kargel et al., 1991)

T_m =176 K (Durhan et al., 1993)

$\eta_0=10^{17}$ Pa s (Arakawa and Maeno, 1994)

$\mu 2$=3.3 GPa

Initial condition

- Initial T linearly changes with r
- initial eccentricity:0.0047

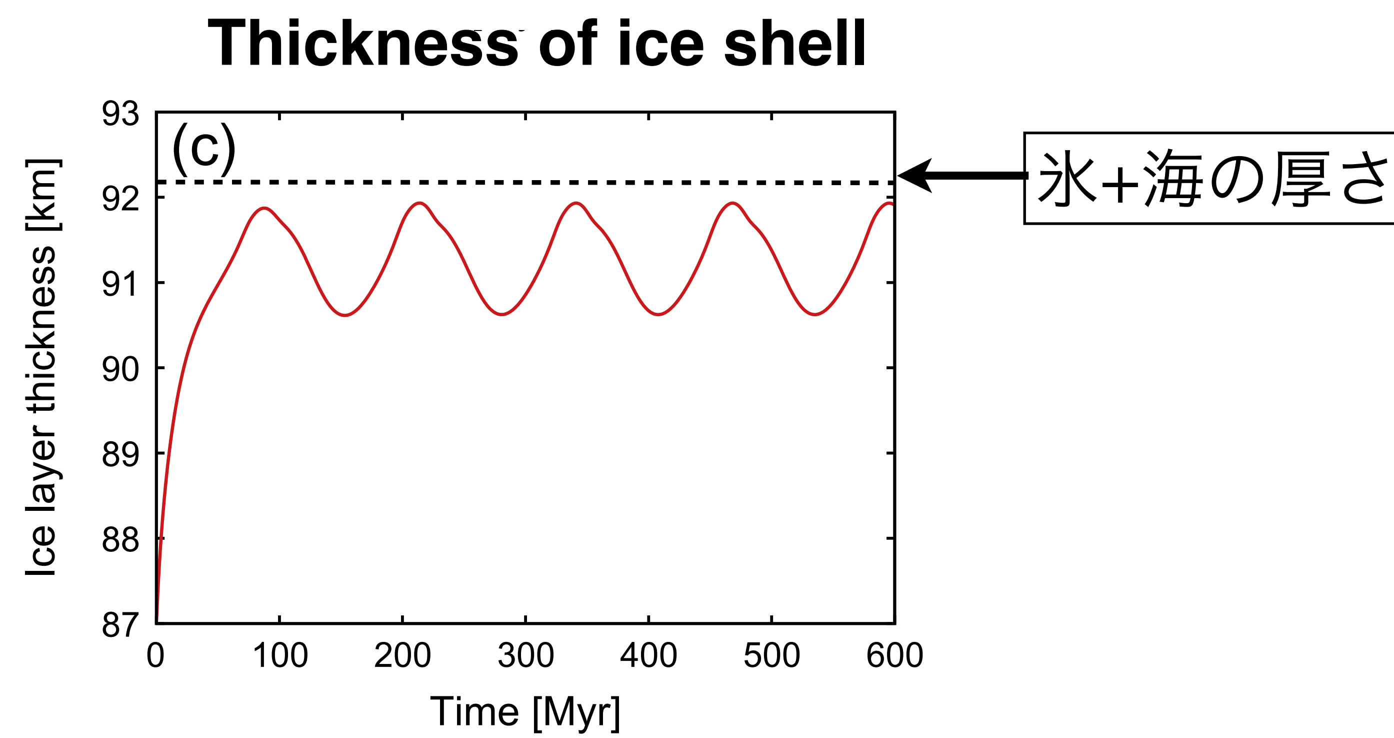
Results

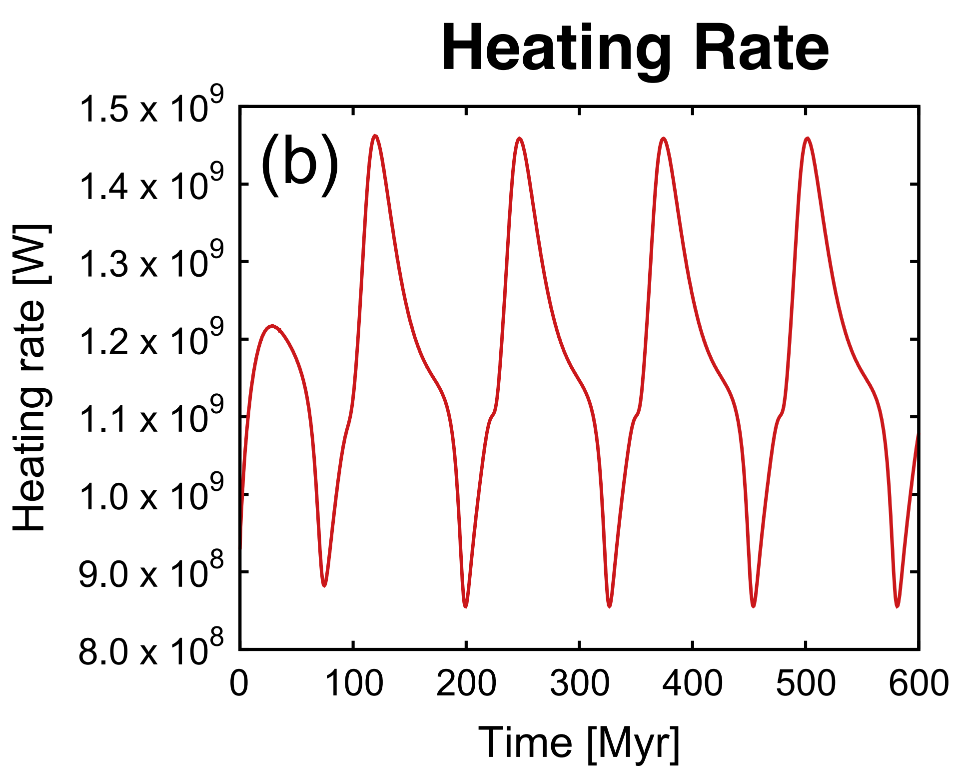
$\mu 2/\mu 1=30$, $\eta 2/\eta 1=6\times10^4$

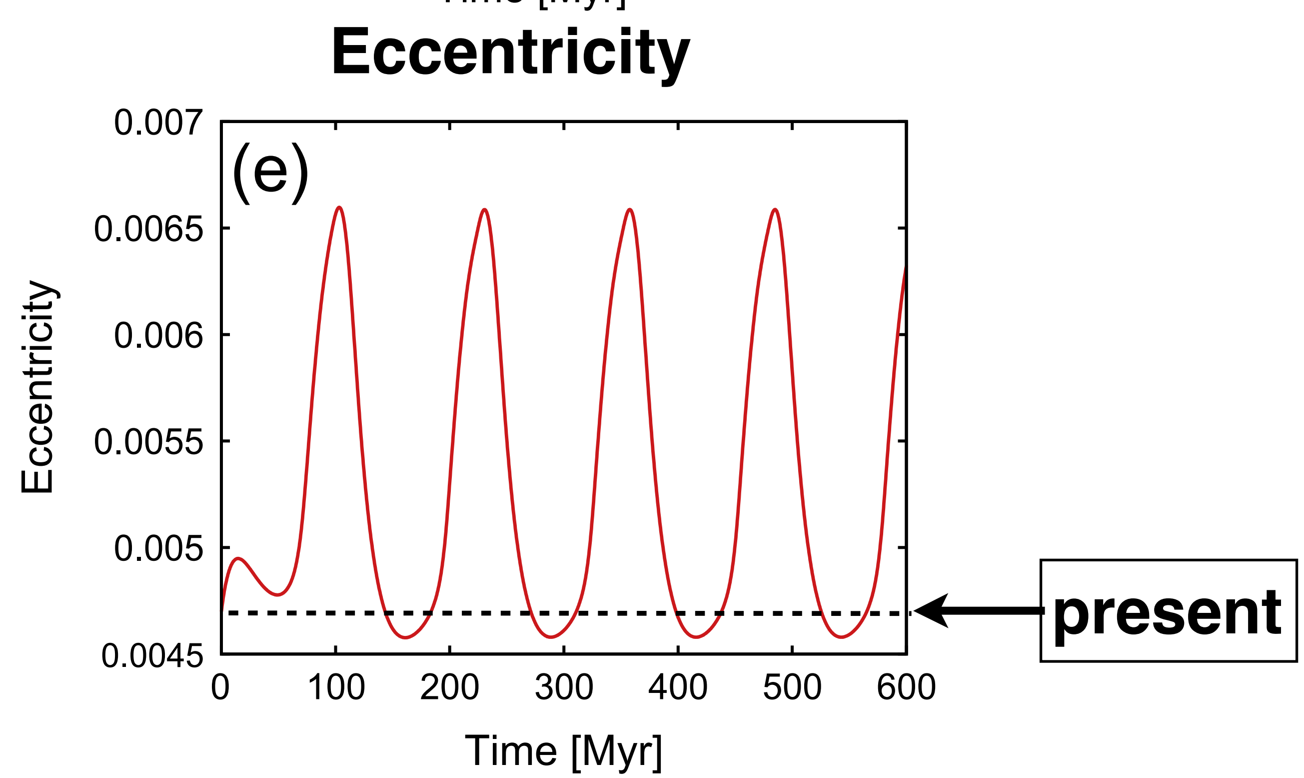
silicate core:160km

Tb: 175 K

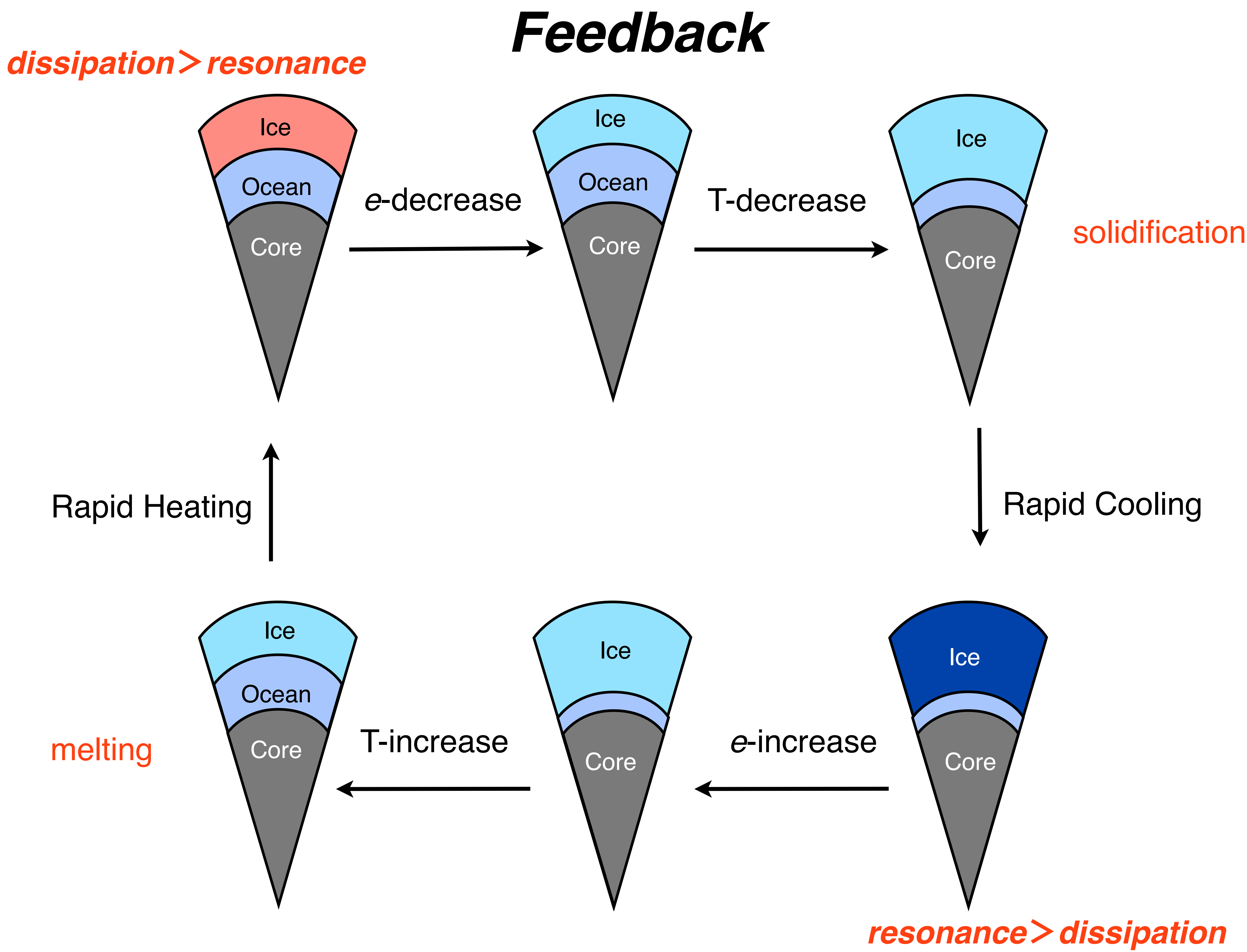
Qs=18,000





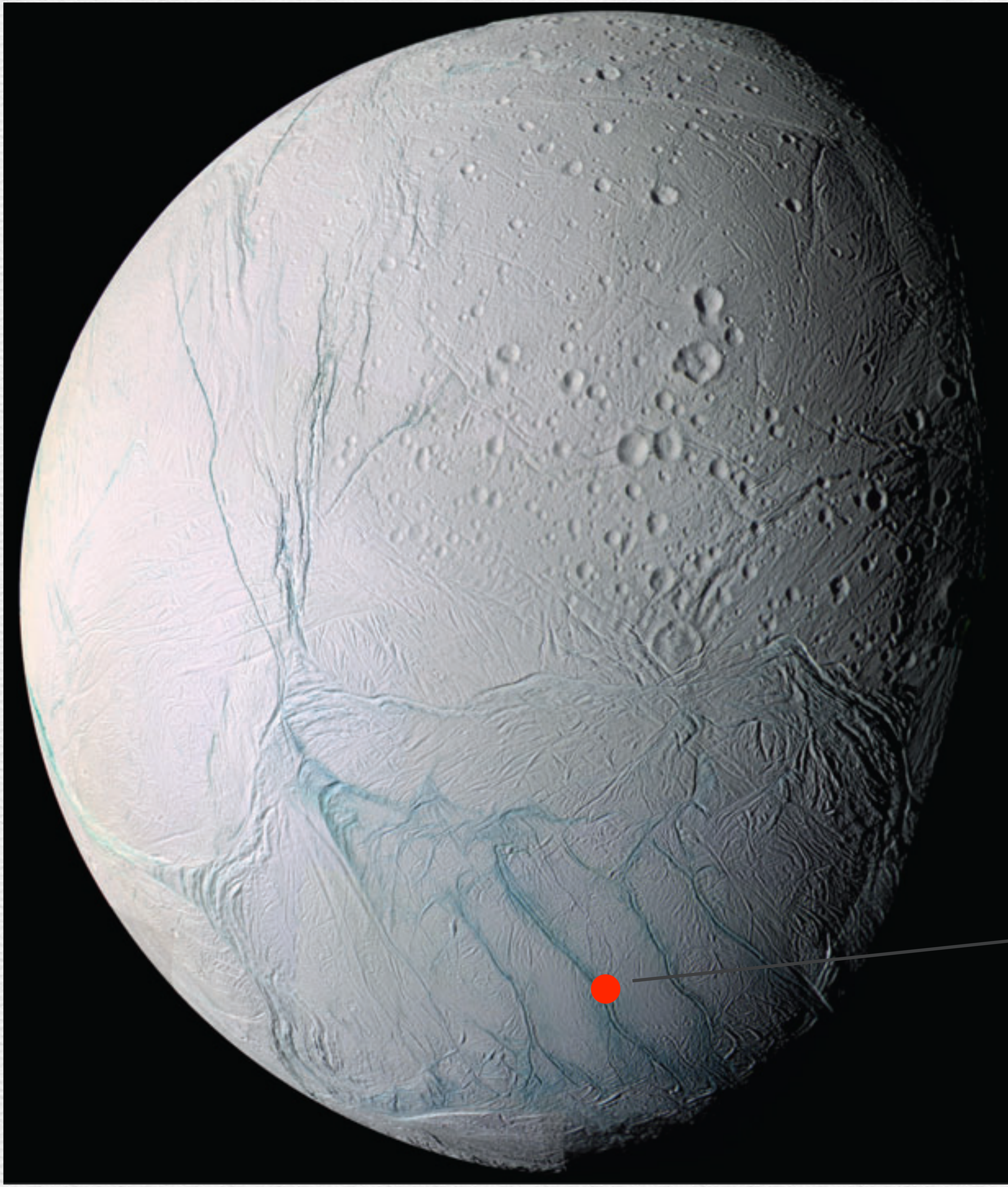


氷の厚さと離心率は振動する．海は凍らず、離心率は観測値を満たす.


Feedback
dissipation > resonance
Ice
Ocean
Core
e-decrease
Ice
Ocean
Core
T-decrease
Ice
Core
solidification
Rapid Heating
Rapid Cooling
Ice
Ocean
Core
melting
T-increase
Ice
Core
e-increase
Ice
Core
resonance > dissipation

Still problems have been remained

1. Heterogeneoud dissipation pattern
   - *why south pole?*
2. Strange resonant pair
   - *why with Dione?*
3. Origin of high density
   - *why 1608,highest?*
4. Young origin
   - *why recent activation?*



Mean density

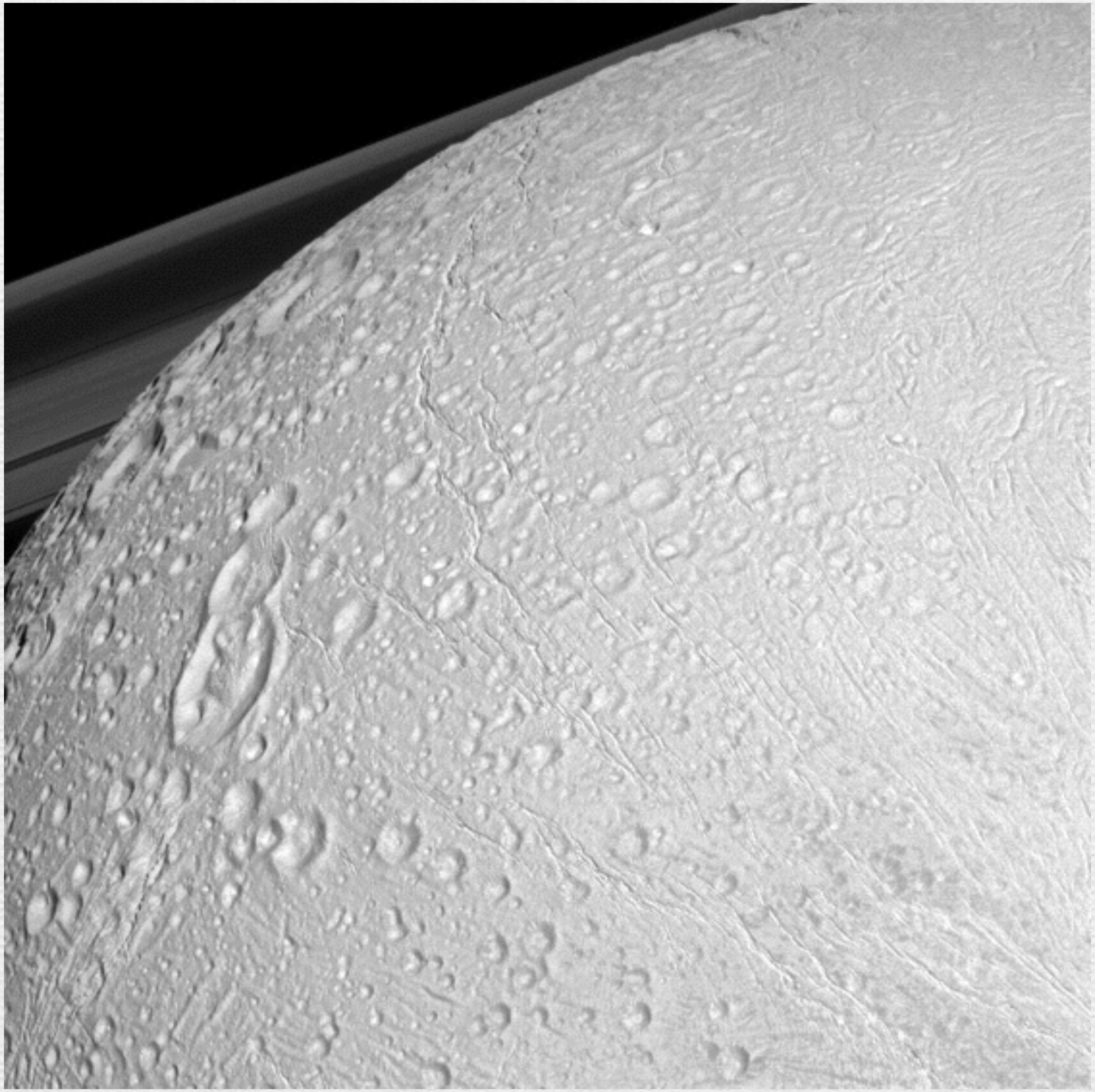
$$1.609 \pm 5 \ kgm^{-3}$$

Thomas 2010

density	
1.15	Mimas
1.608	Enceladus
0.973	Tethys
1.476	Dione
1.233	Rhea

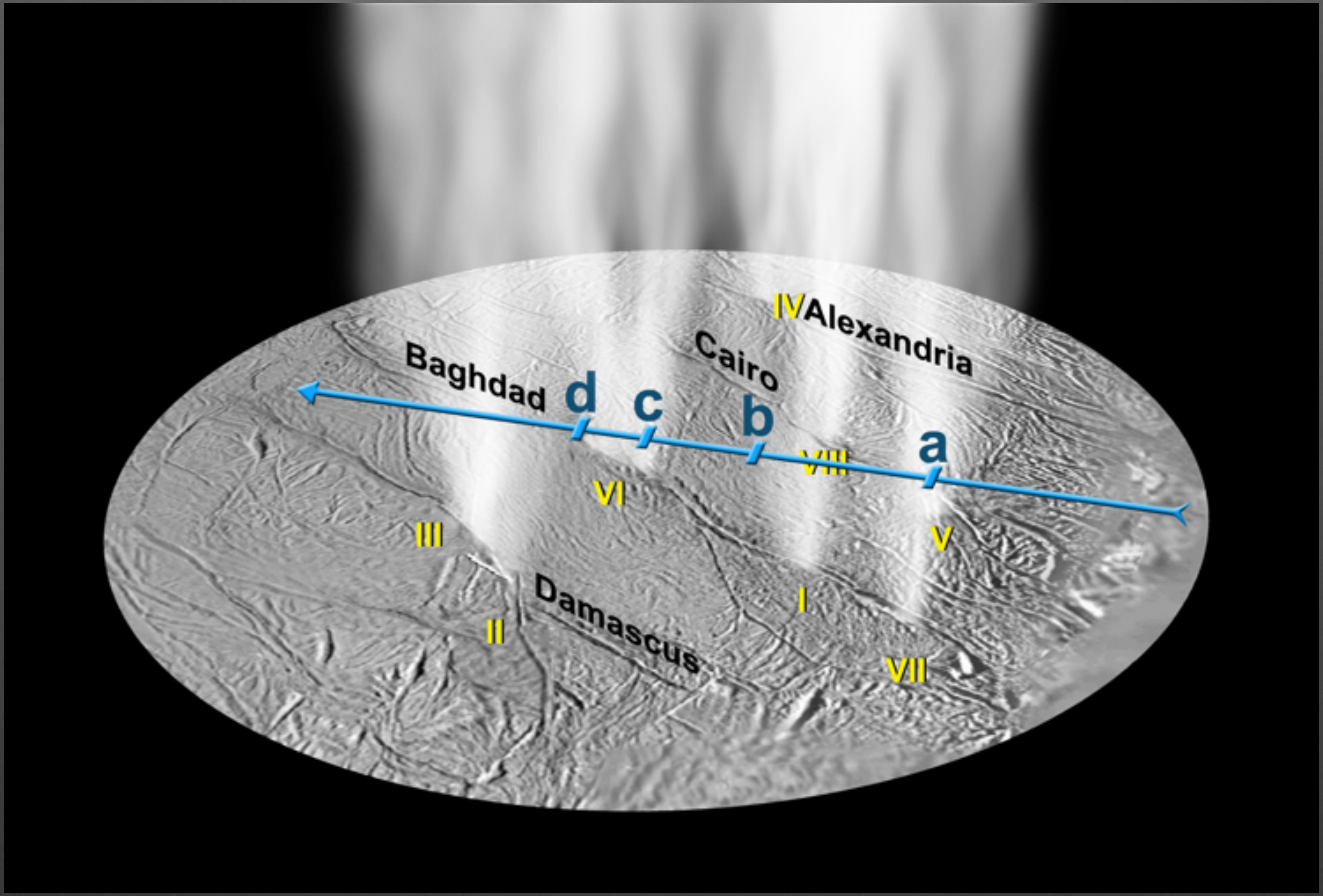
Cassini camera

PIA12757 Northern Hemisphere



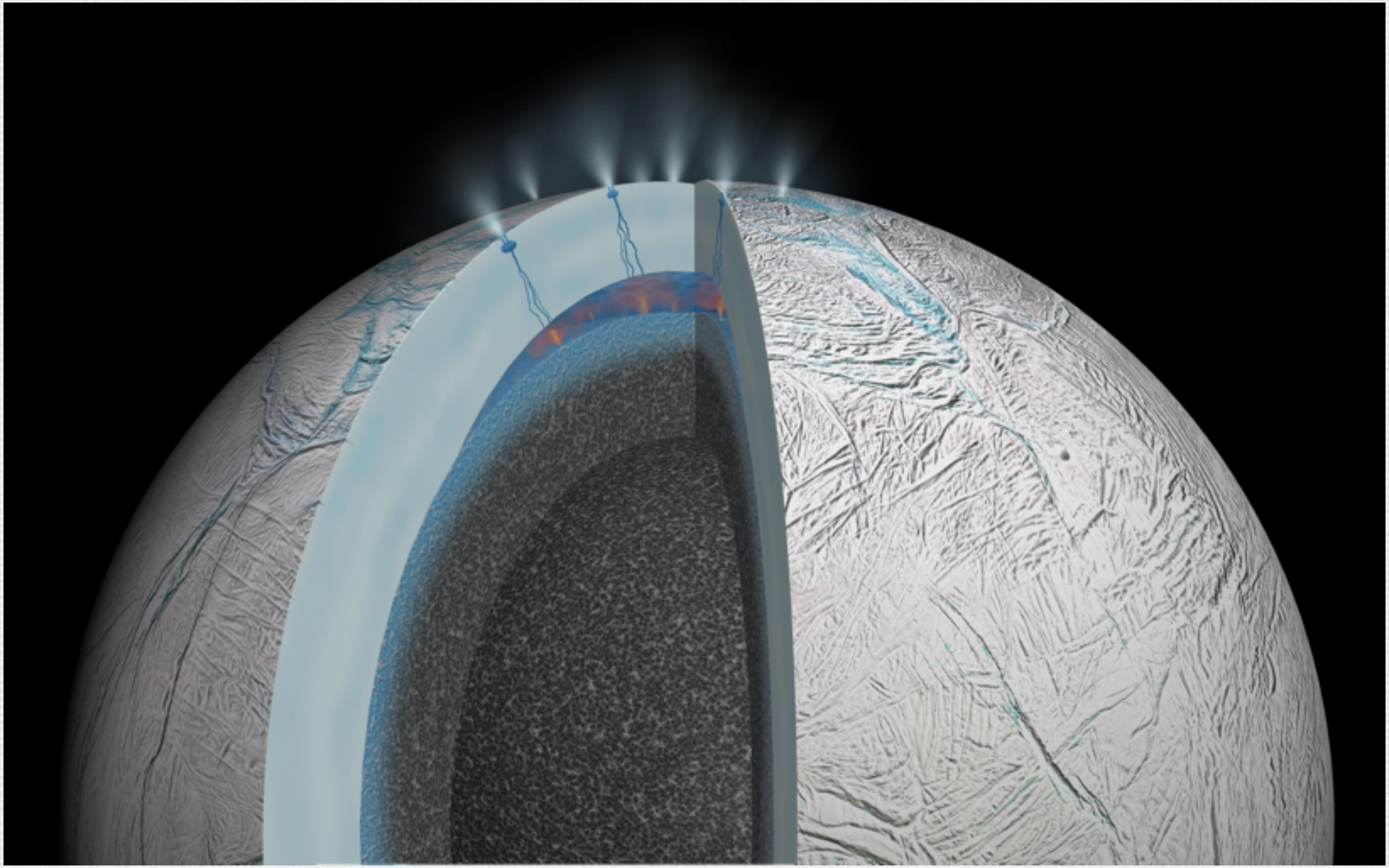
Why old terrains have been preserved?

→ ***recent activation?***



http://www.astronomy.ohio-state.edu/~pogge/TeachRes/Ast161/Enceladus/Enceladus_plumes_PIA10355.jpg

Plume activities around south pole



Why heterogeneous activation?

http://photojournal.jpl.nasa.gov/jpeg/PIA19058.jpg

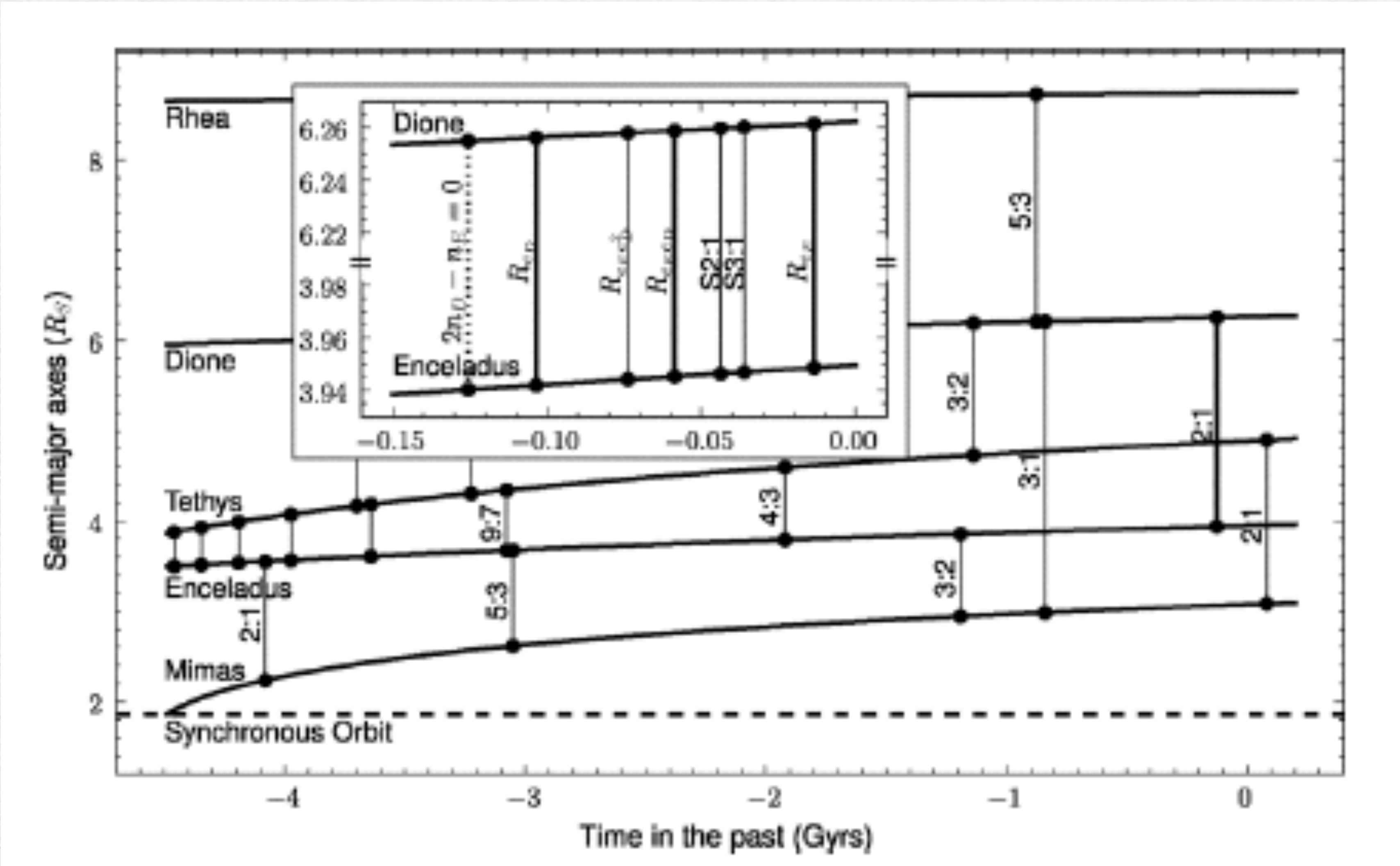
Orbital Information

	orbit size,km	mean radius	density	eccentricity	rotation,days
Mimas	185539	198.2	1.15	0.0196	0.942
Enceladus	238037	252.1	1.608	0.0047	1.37
Tethys	294672	533	0.973	0.0001	1.888
Dione	377415	561.7	1.476	0.0022	2.737
Rhea	527068	764.3	1.233	0.001	4.518

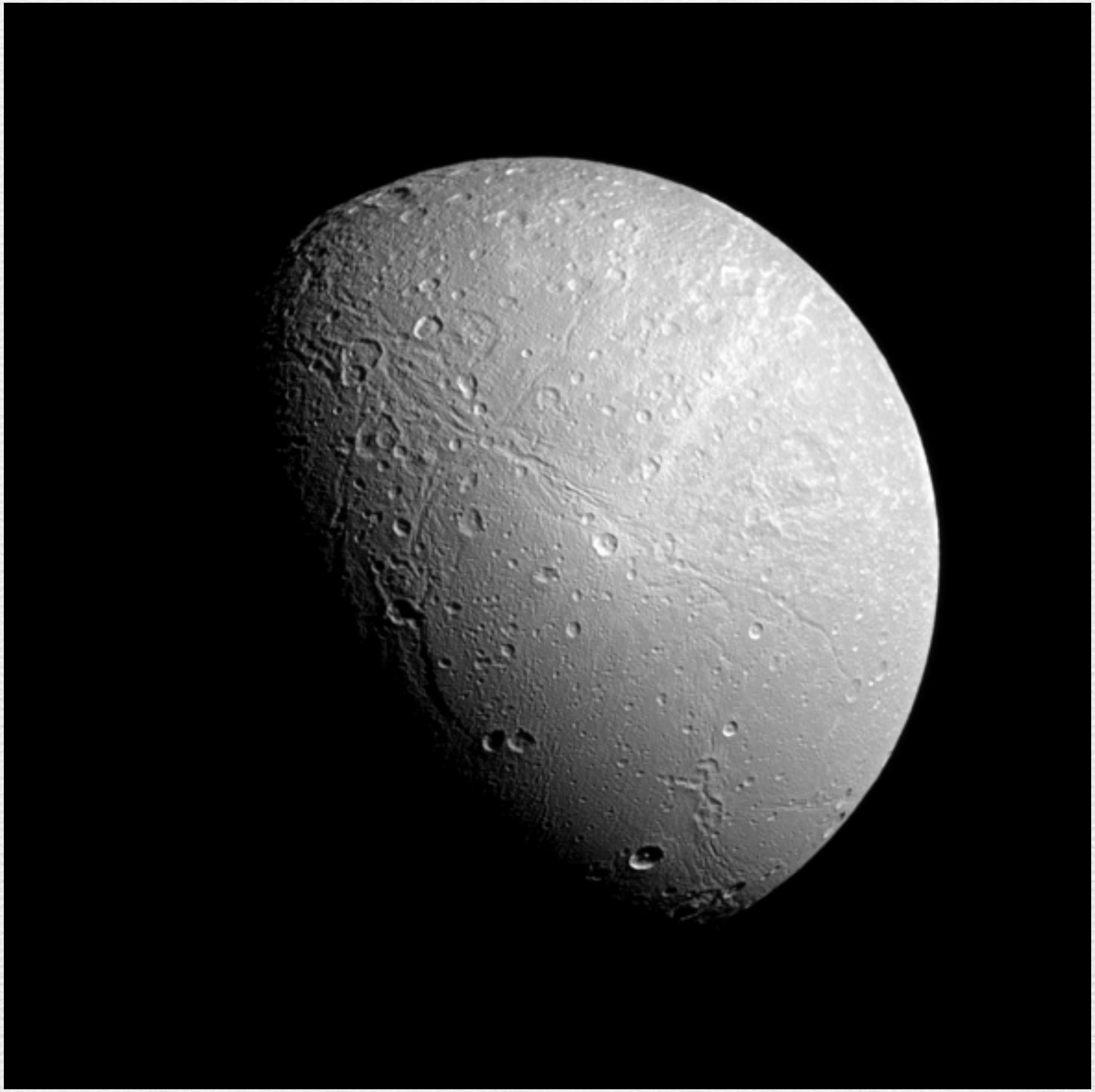
Saturn spin
0.44 d

- ***Why with Dione?***
- ***Why not Mimas?***

Orbital Evolution?

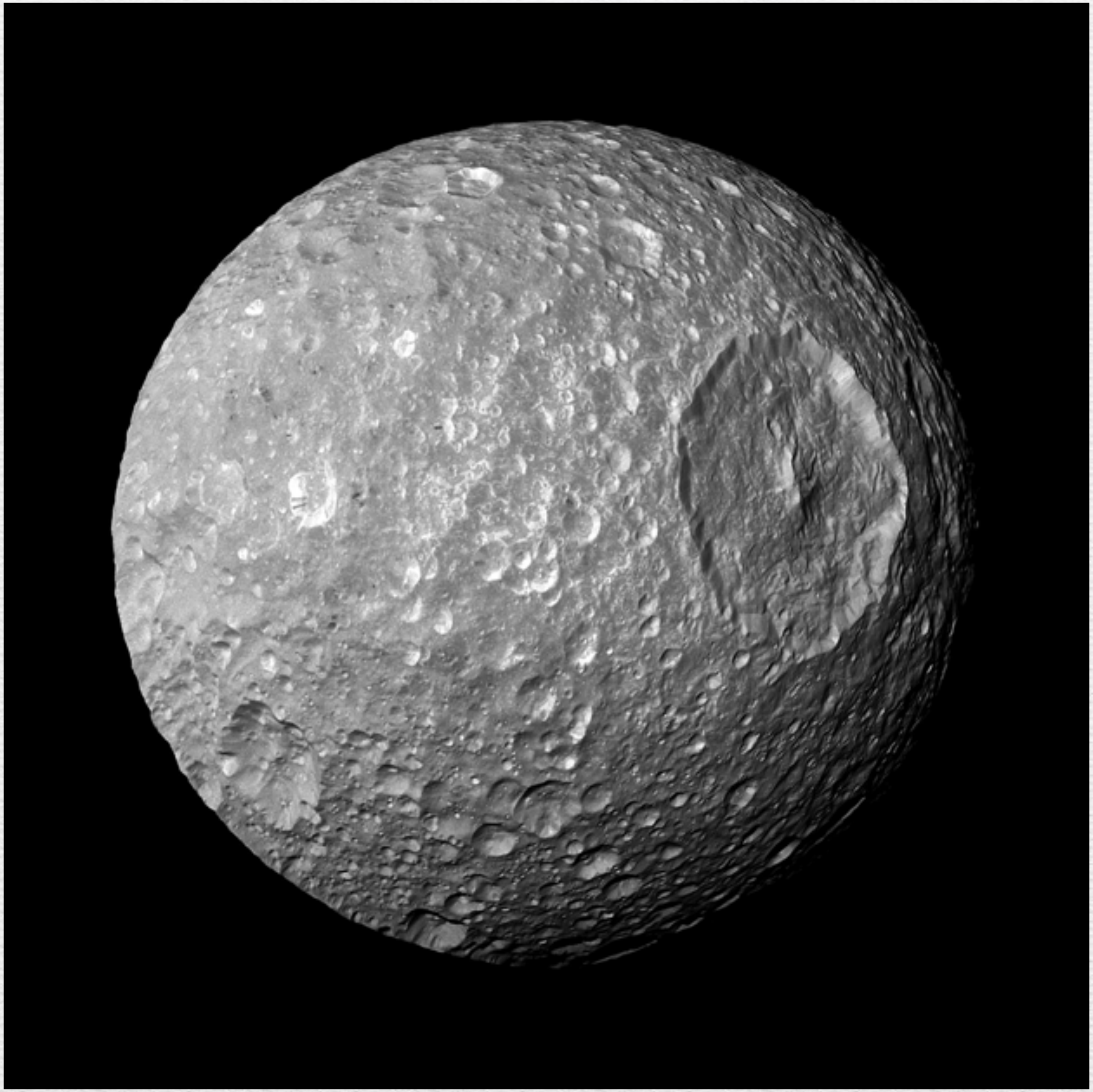


Dione

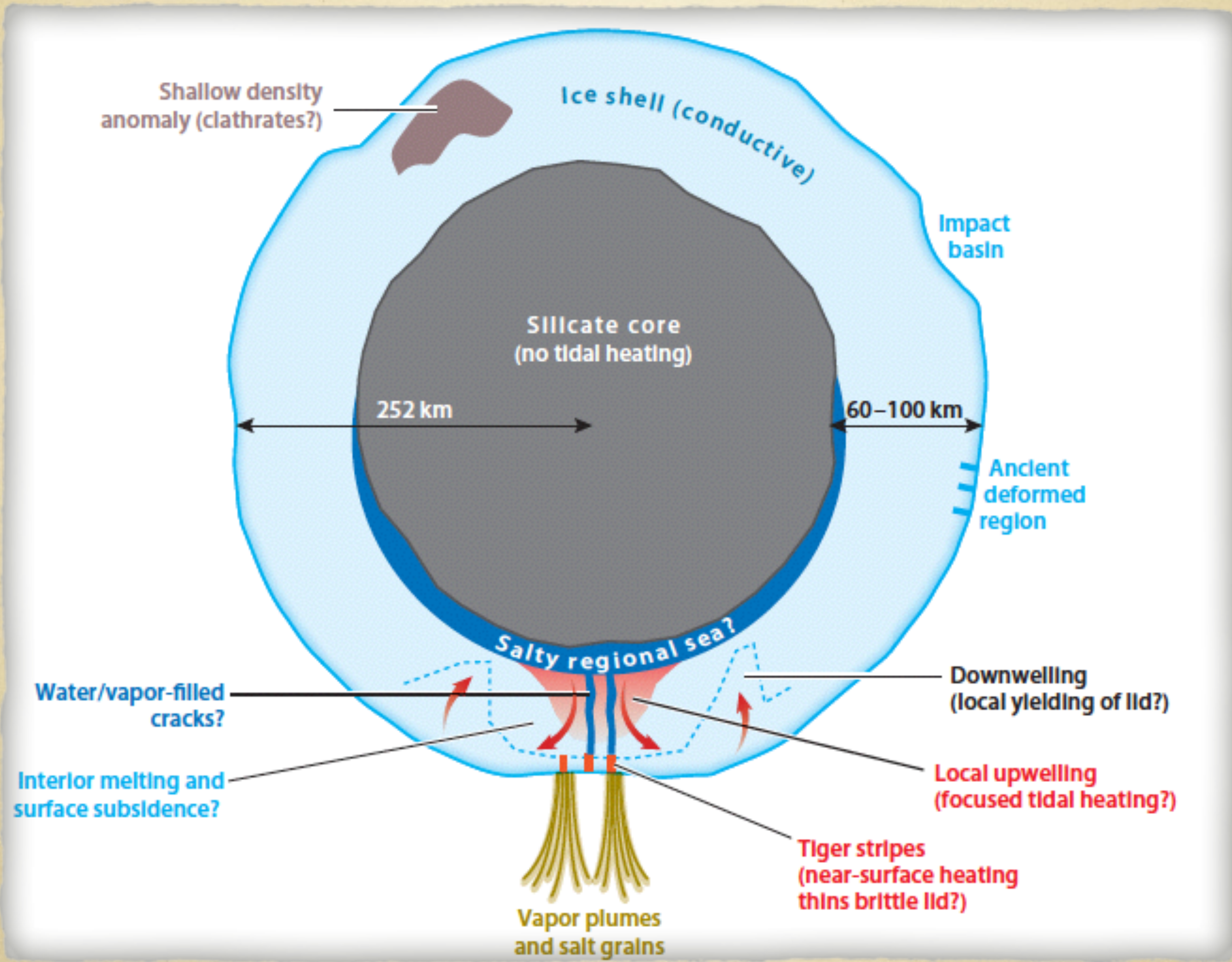


PIA14650

Mimas:PIA12570



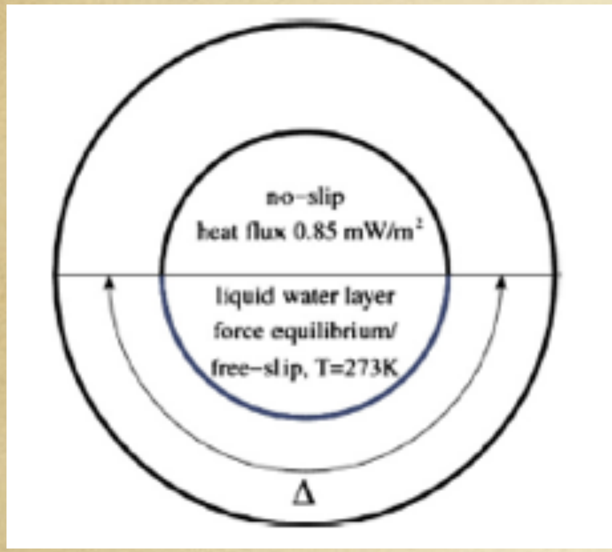
Global Ocean vs Localized Ocean ?

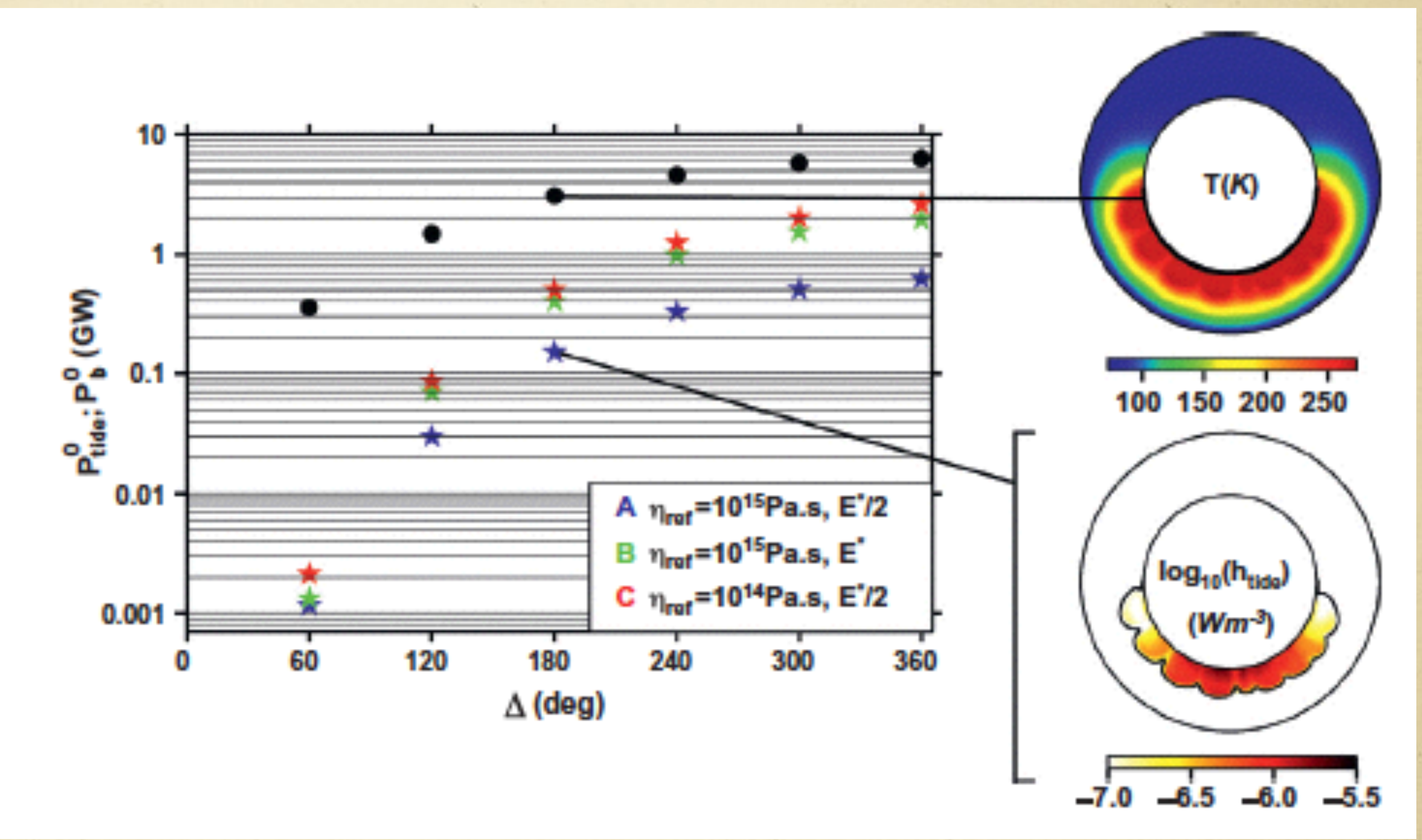


Spencer & Nimmo, AREPS 41,693,2013

Behounkova et al 2012

Heterogeneous Structure:localized ocean





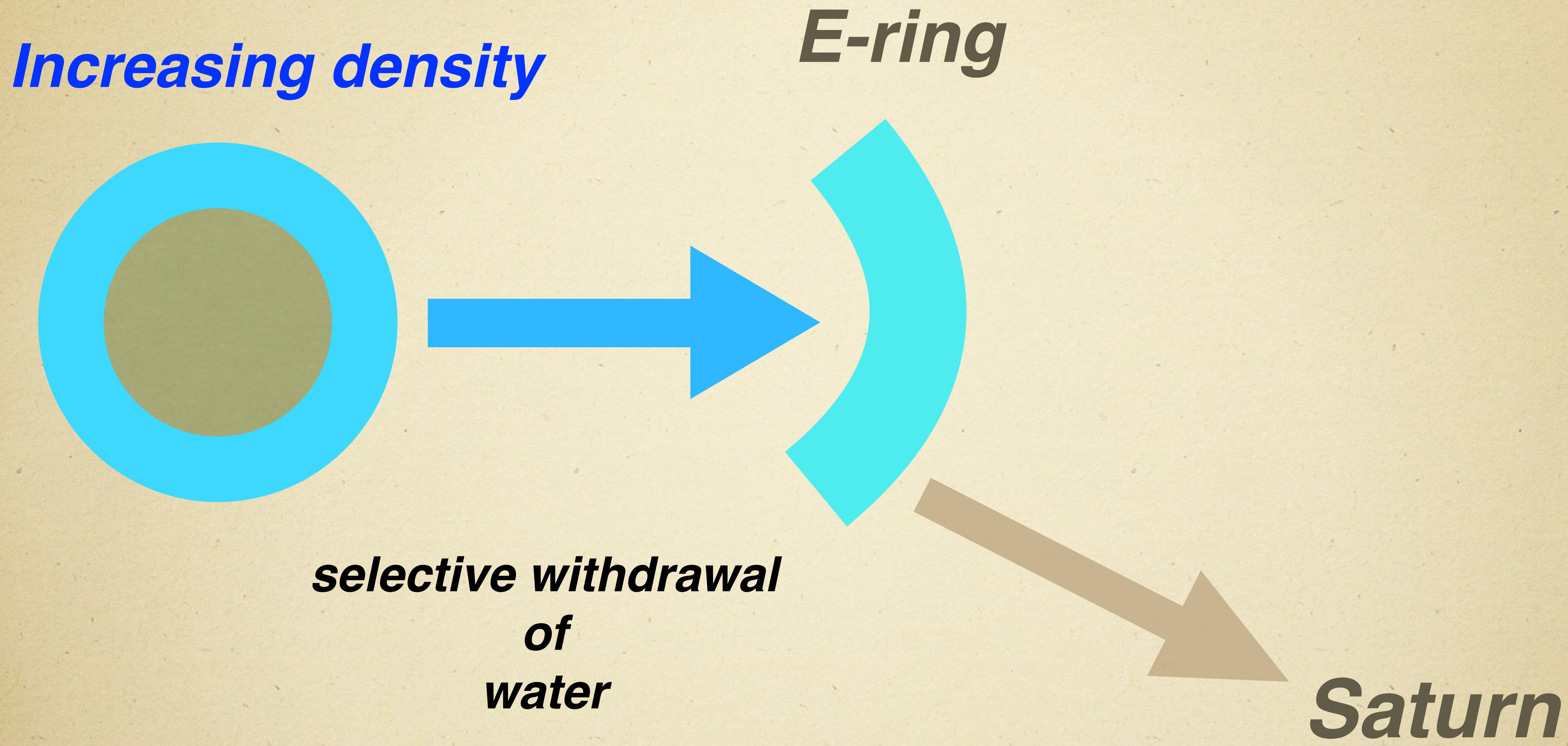
Behounkova, M., Tobie, G., Choblet, G., & Cadek, O. (2012). Tidally-induced melting events as the origin of south-pole activity on Enceladus. *Icarus*, *219*(2), 655–664.

Love numbers

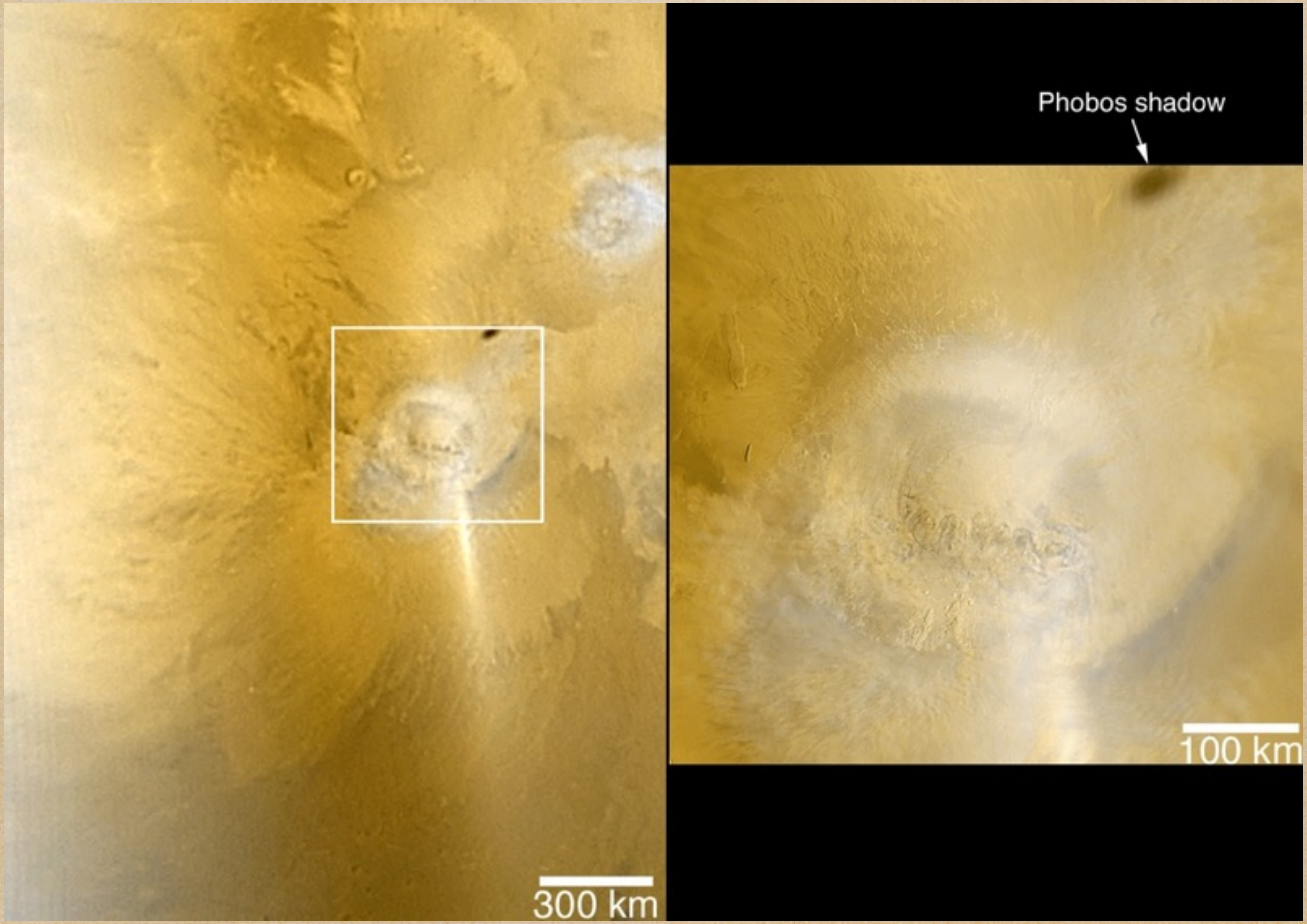
不均質構造での潮汐散逸の計算

非球対称不均質構造でのLove 数の計算

妄想？

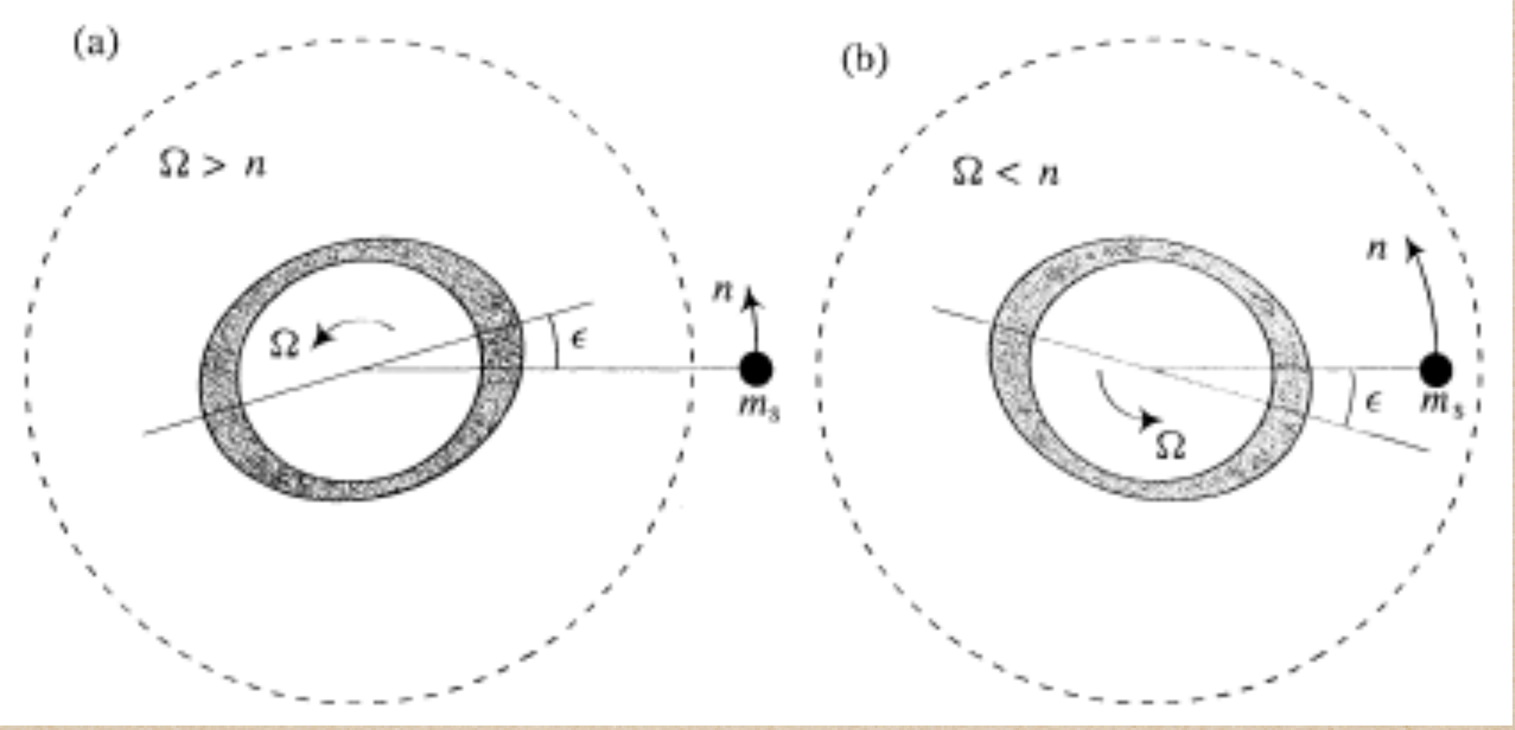

Increasing density
E-ring
selective withdrawal of water
Saturn

Phobosの潮汐摩擦（Billsの主張）



Phobos on Arsia

潮汐摩擦



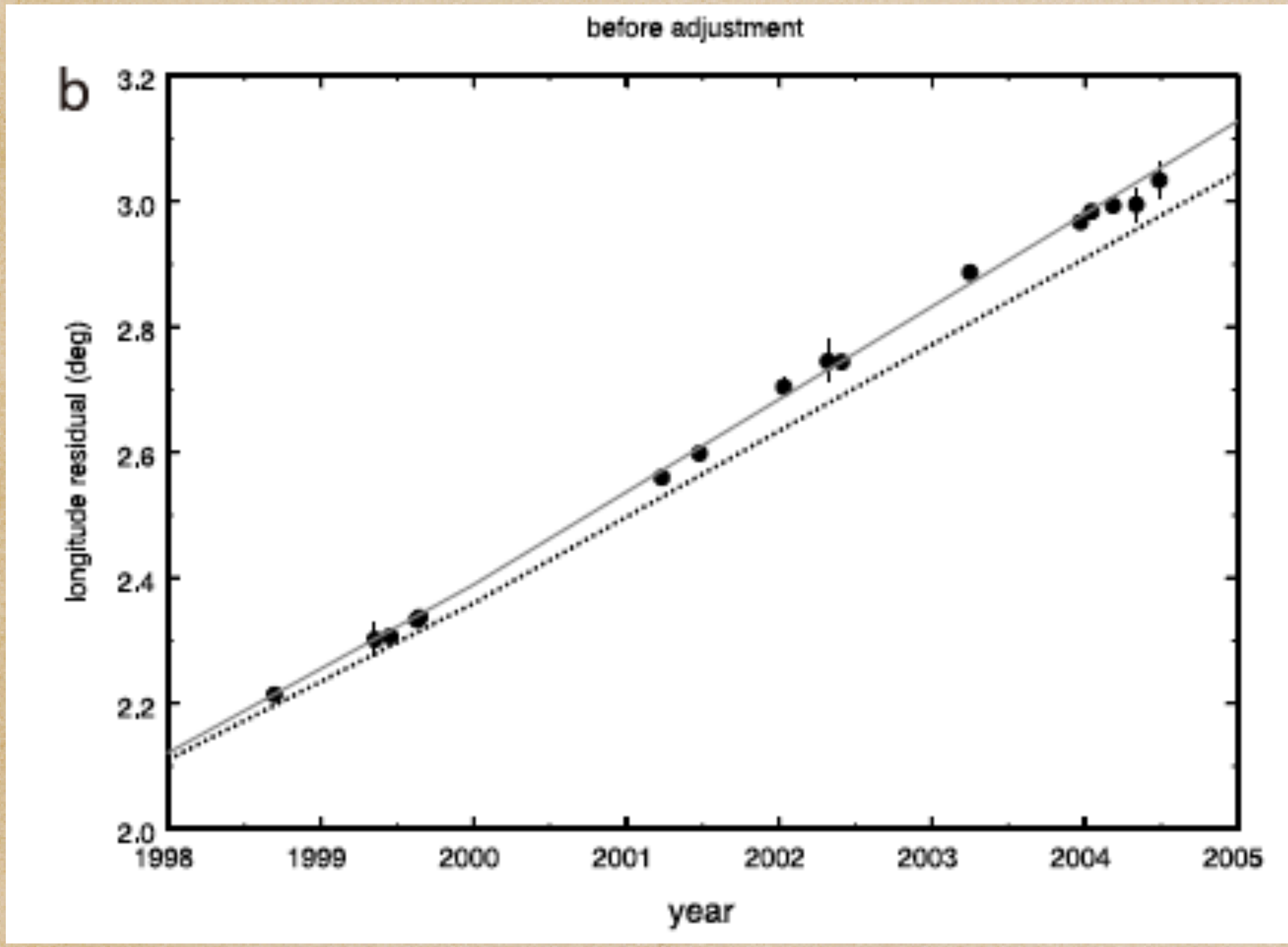
Moon:27.3d
Earth:24.h

Phobos:7h39m
Mars:24.6h

$$\frac{da}{dt} = 3.7\ cm/yr$$

$$\frac{da}{dt} = -4.03\ cm/yr$$

潮汐摩擦



$$\gamma = (0.6694 \pm 0.0029)^\circ$$

$$Q = 85\ for\ Mars$$

きわめて大きな散逸

Bills et al (2006)

Q=85 in Mantle？

グローバルな部分溶融層？

融点に近い温度

$$\mathbf{Q_{tidal} = 80}$$

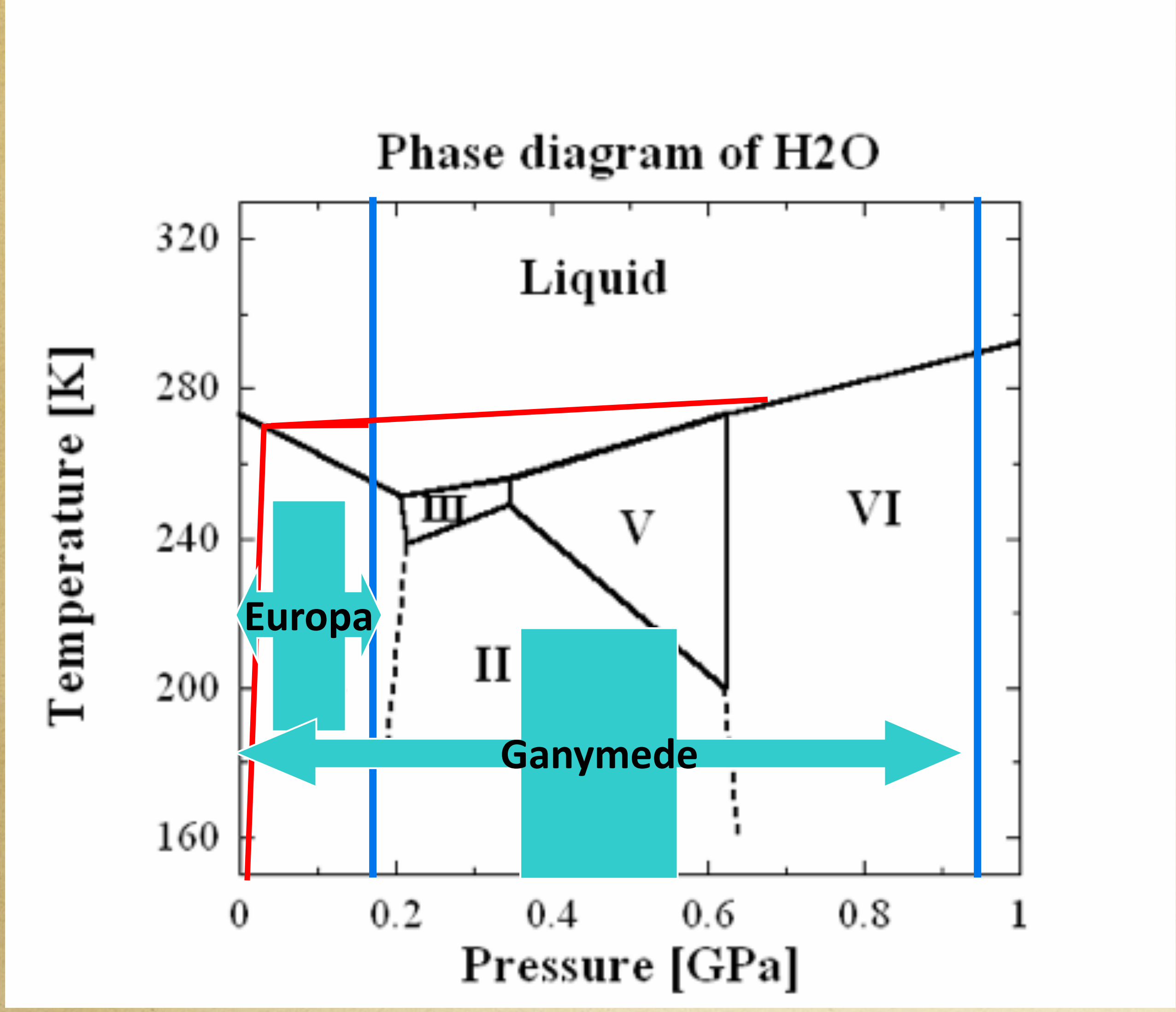
Mars

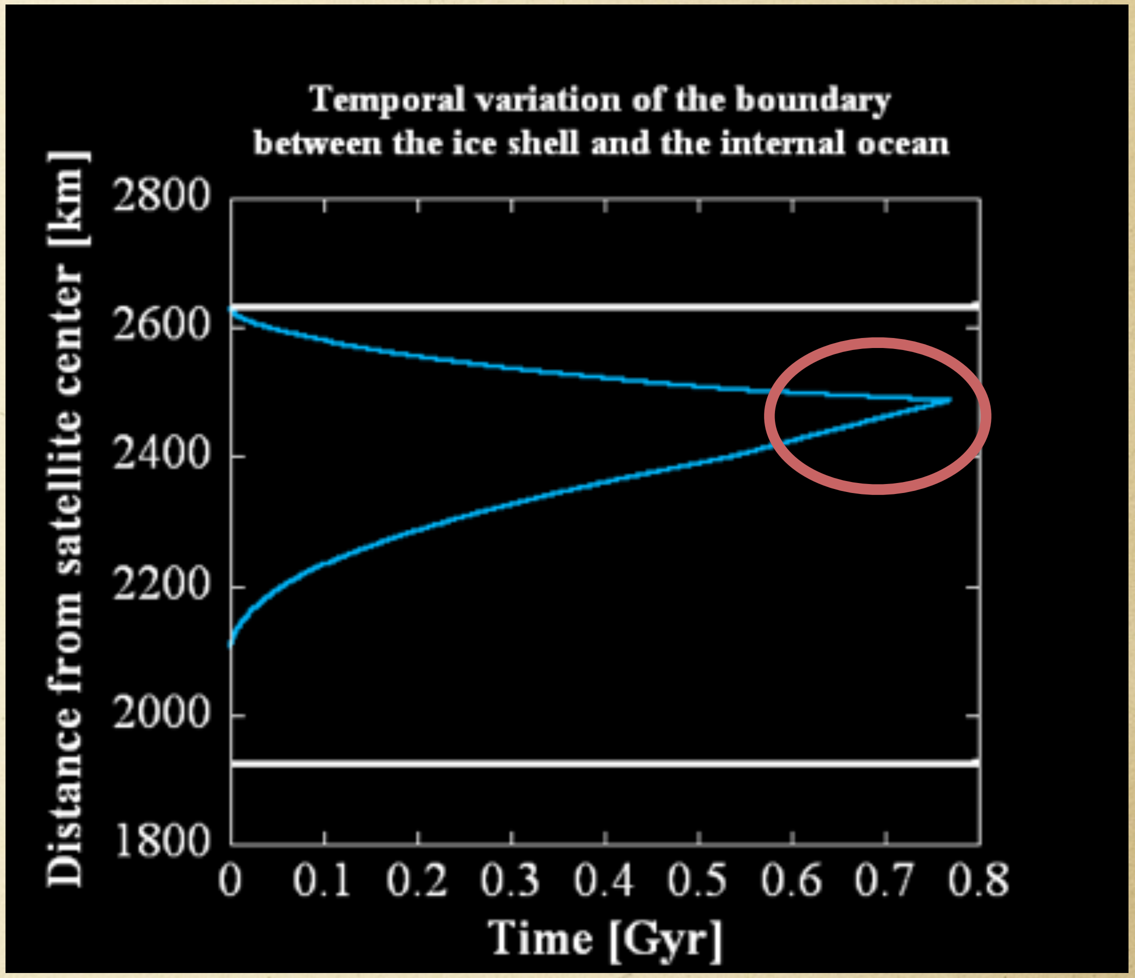
$$\mathbf{Q_{tidal} = 10}$$

$$\mathbf{Q_{tidal}(mantle) = 280}$$

Earth

Ganymede

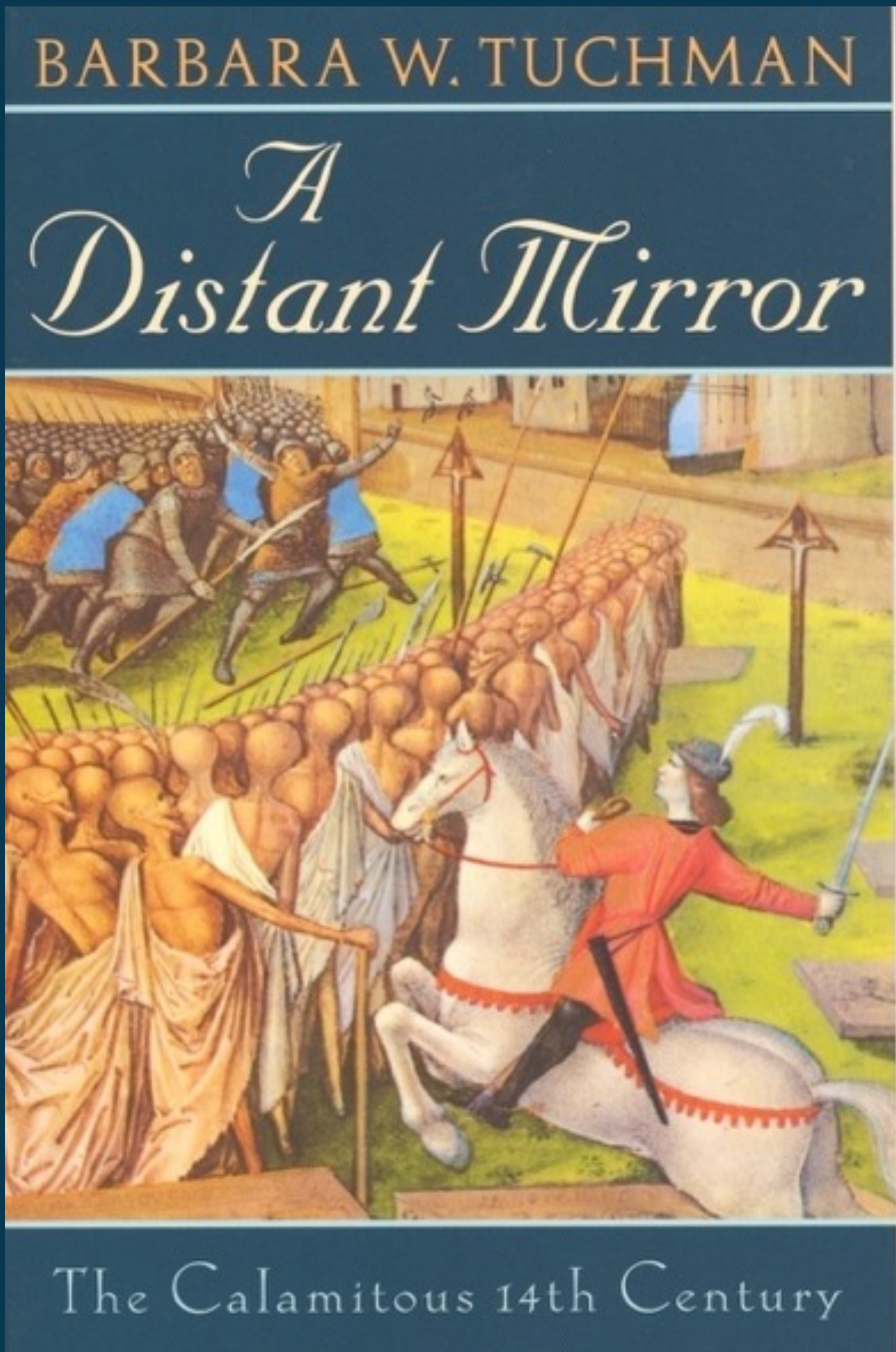




after Kimura 2008

内部海が閉じるとき

氷衛星の科学は地球の理解に貢献するのか？



遠くにいると見えること

多様性の森