Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Dynamic reorientation of tidally locked bodies: Application to Pluto

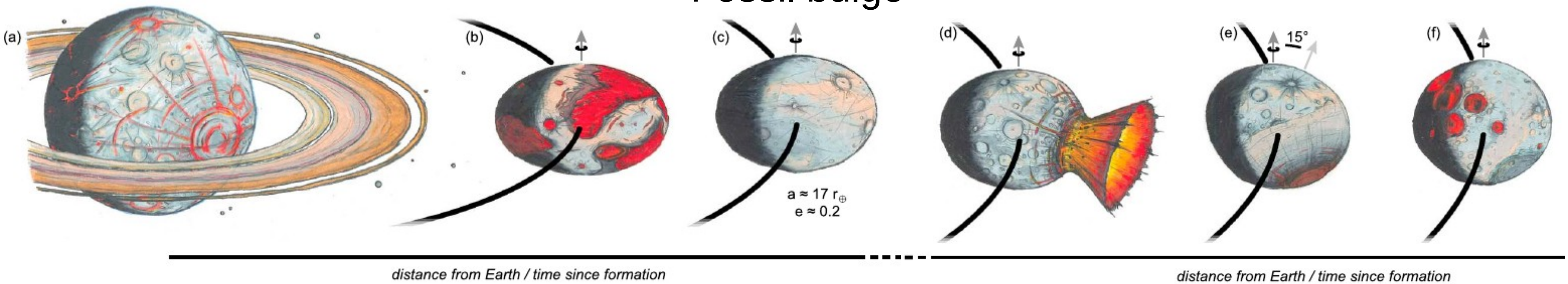
Vojtěch Patočka [a,*], Martin Kihoulou [a,b]

[a] Charles University, Faculty of Mathematics and Physics, Department of Geophysics, V Holešovičkách 2, 180 00 Prague, Czech Republic
[b] Laboratoire de Planétologie et Géosciences, Université de Nantes, 2 rue de la Houssinière, 44322 Nantes, France

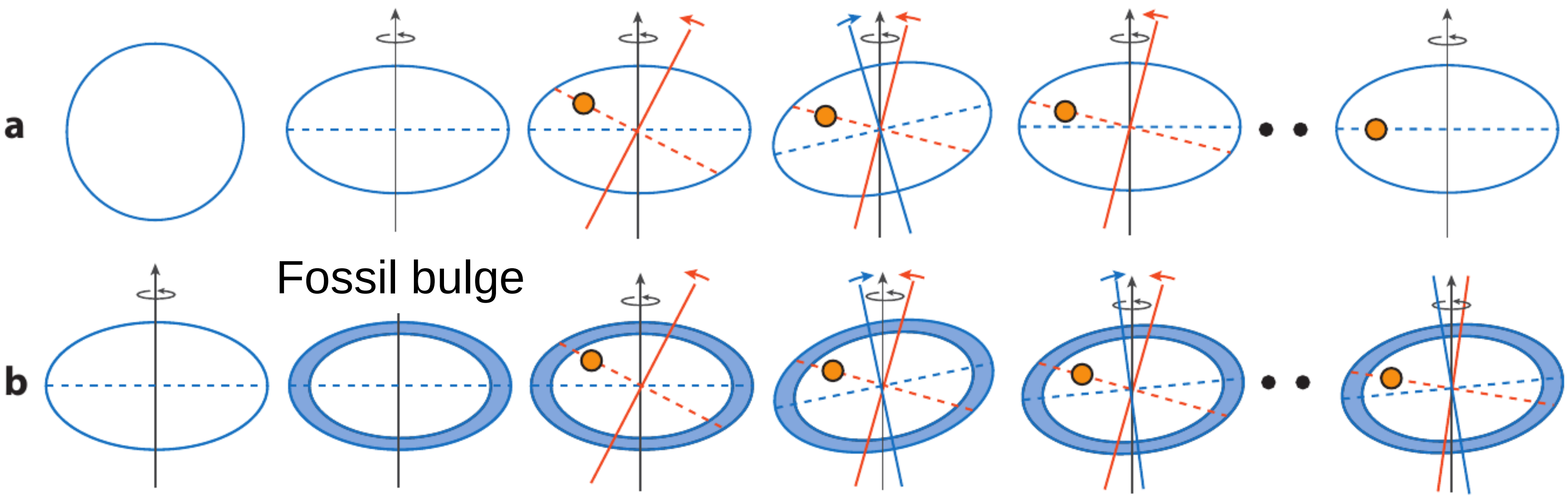
- Method: new? old new...
- Longitudinal vs. Latitudinal Reorientation
- Pluto – position of Sputnik Planitia

Well understood: equilibrium orientation

Fossil bulge

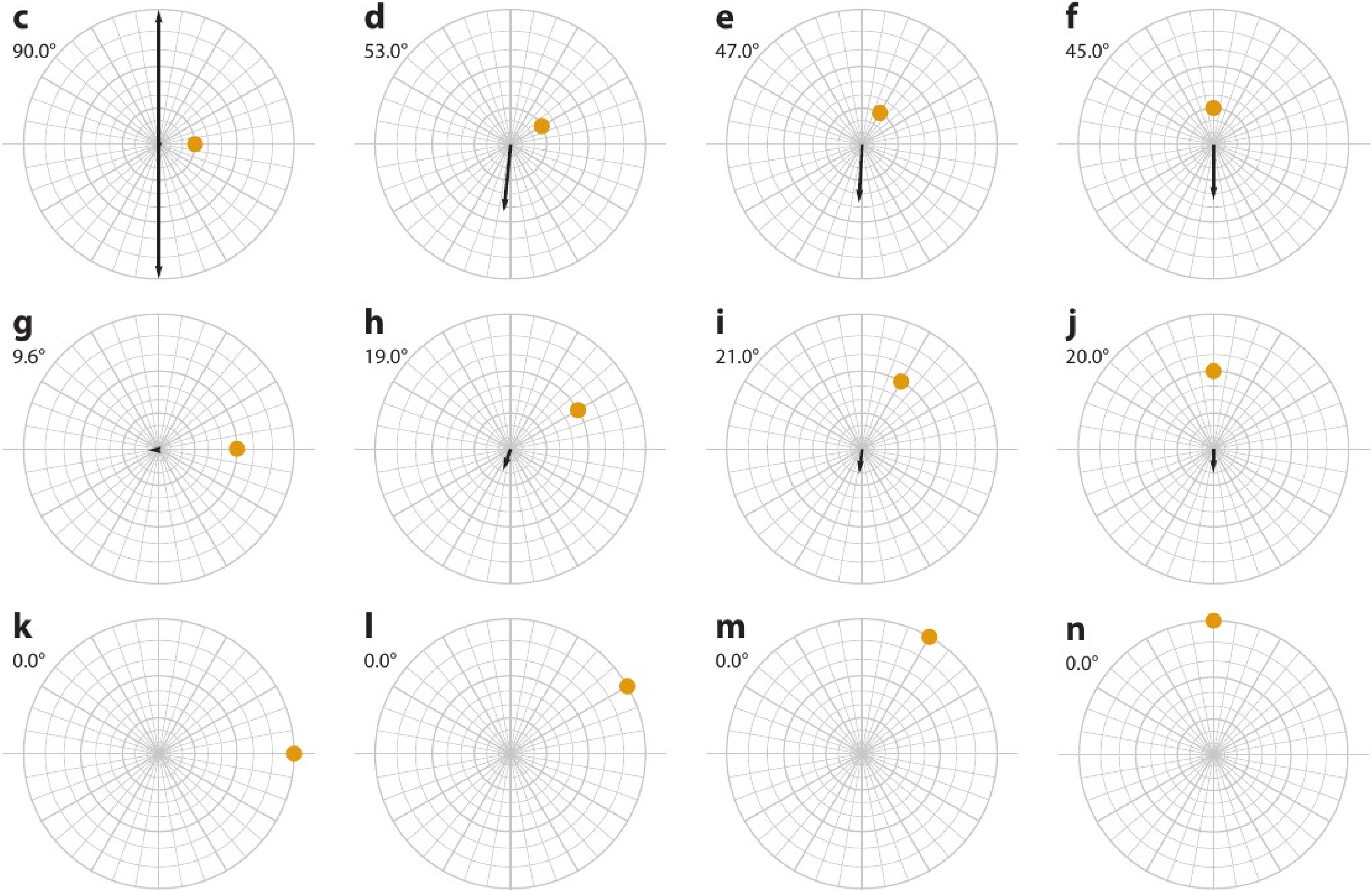


Keane and Matsuyama (2014): Evidence for lunar true polar wander and past low-eccentricity,...



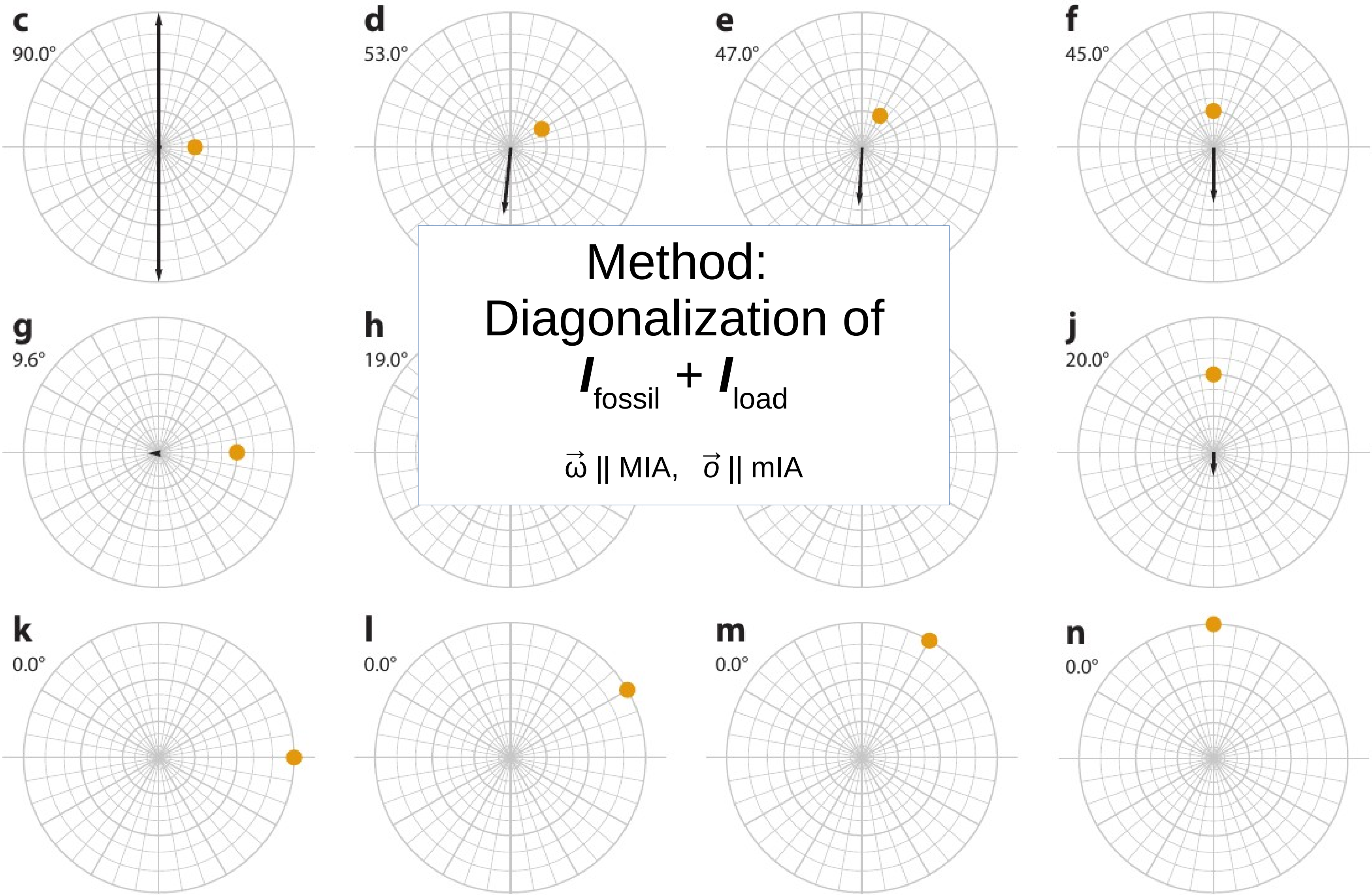
Matsuyama I., Nimmo F., and Mitrovica J.X. (2014): Planetary reorientation. *Ann. Rev. Earth Planet. Sci.*

Well understood: equilibrium orientation



Matsuyama I., Nimmo F., and Mitrovica J.X. (2014): Planetary reorientation. *Ann. Rev. Earth Planet. Sci.*

Well understood: equilibrium orientation

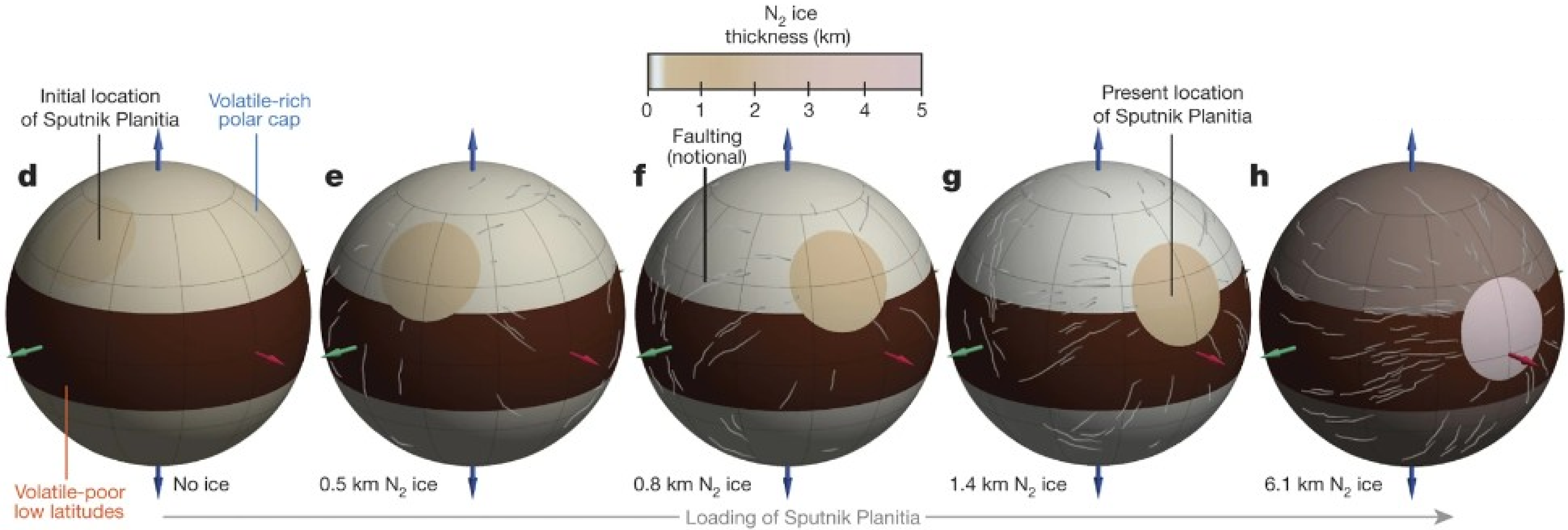


Method:
Diagonalization of
$\boldsymbol{I}_{\text{fossil}} + \boldsymbol{I}_{\text{load}}$

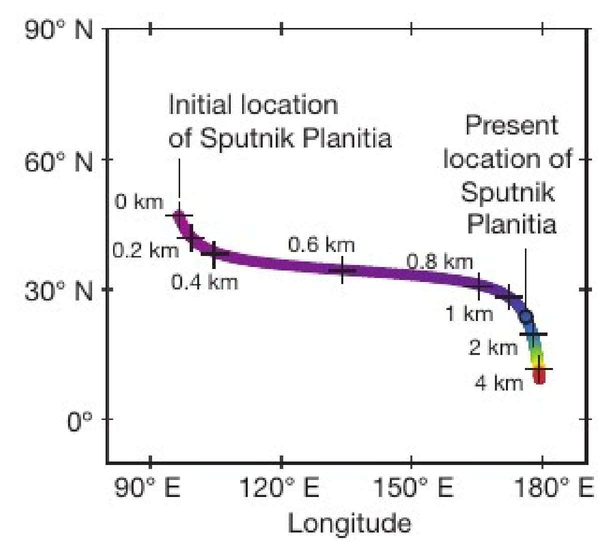
$\vec{\omega}$ || MIA, $\vec{o}$ || mIA

Matsuyama I., Nimmo F., and Mitrovica J.X. (2014): Planetary reorientation. *Ann. Rev. Earth Planet. Sci.*

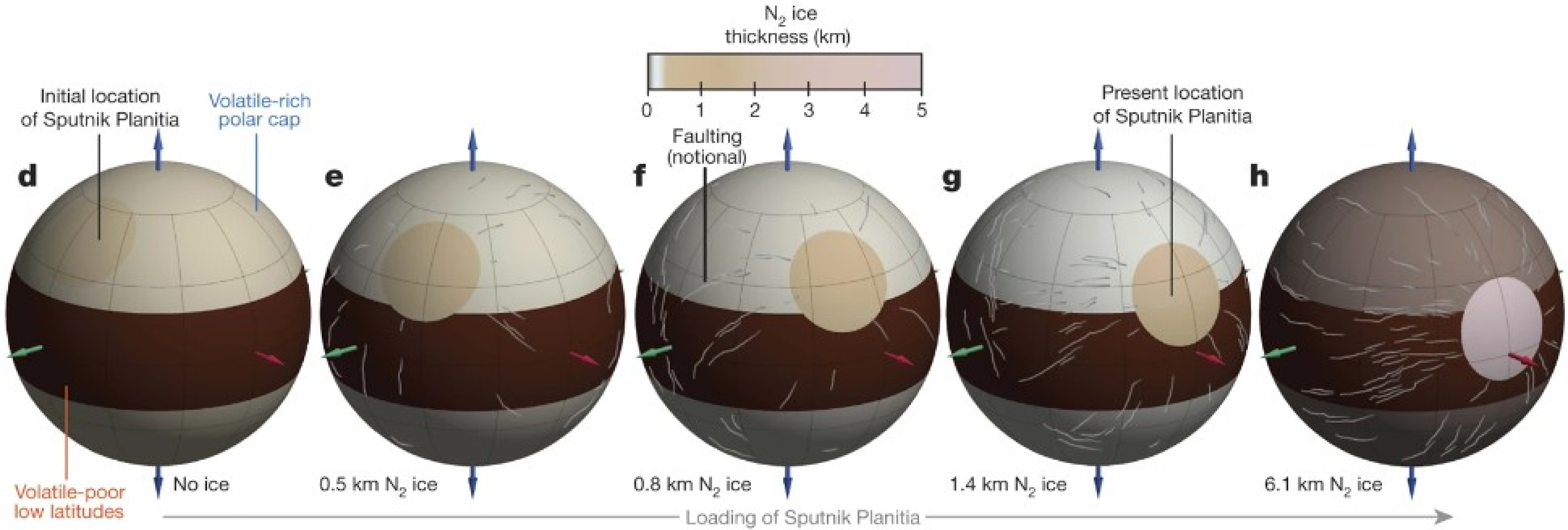
Visualizing reorientation: bulge-fixed frame



Keane et al., 2016



Dynamics: fluid-limit method?

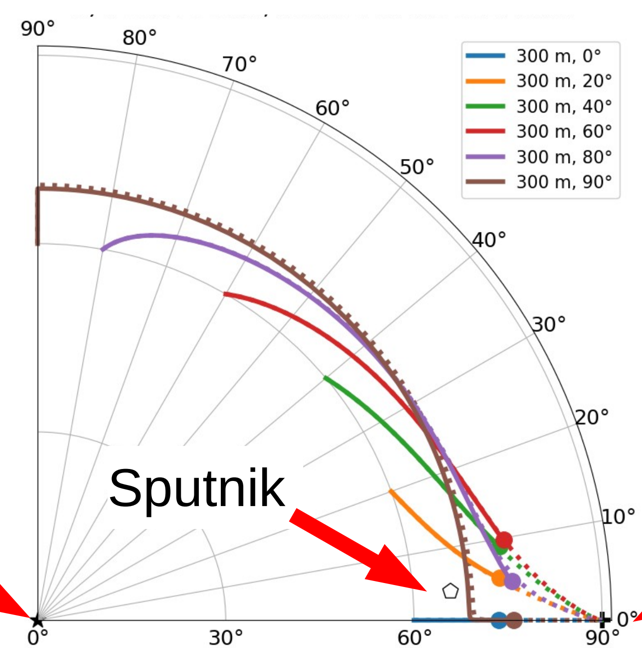


polar coordinates

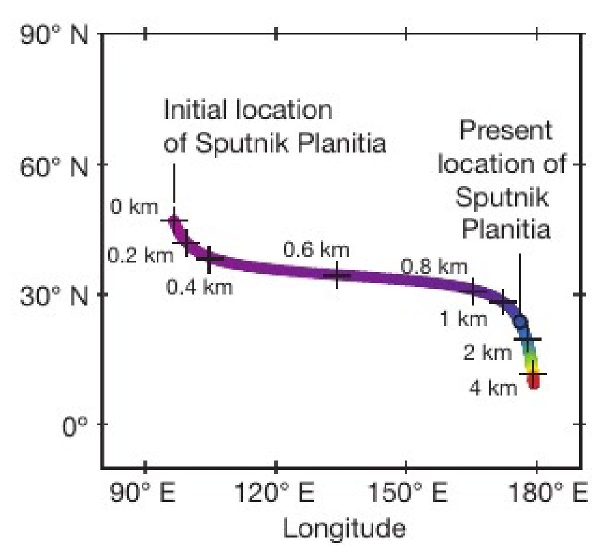
north pole

Sputnik

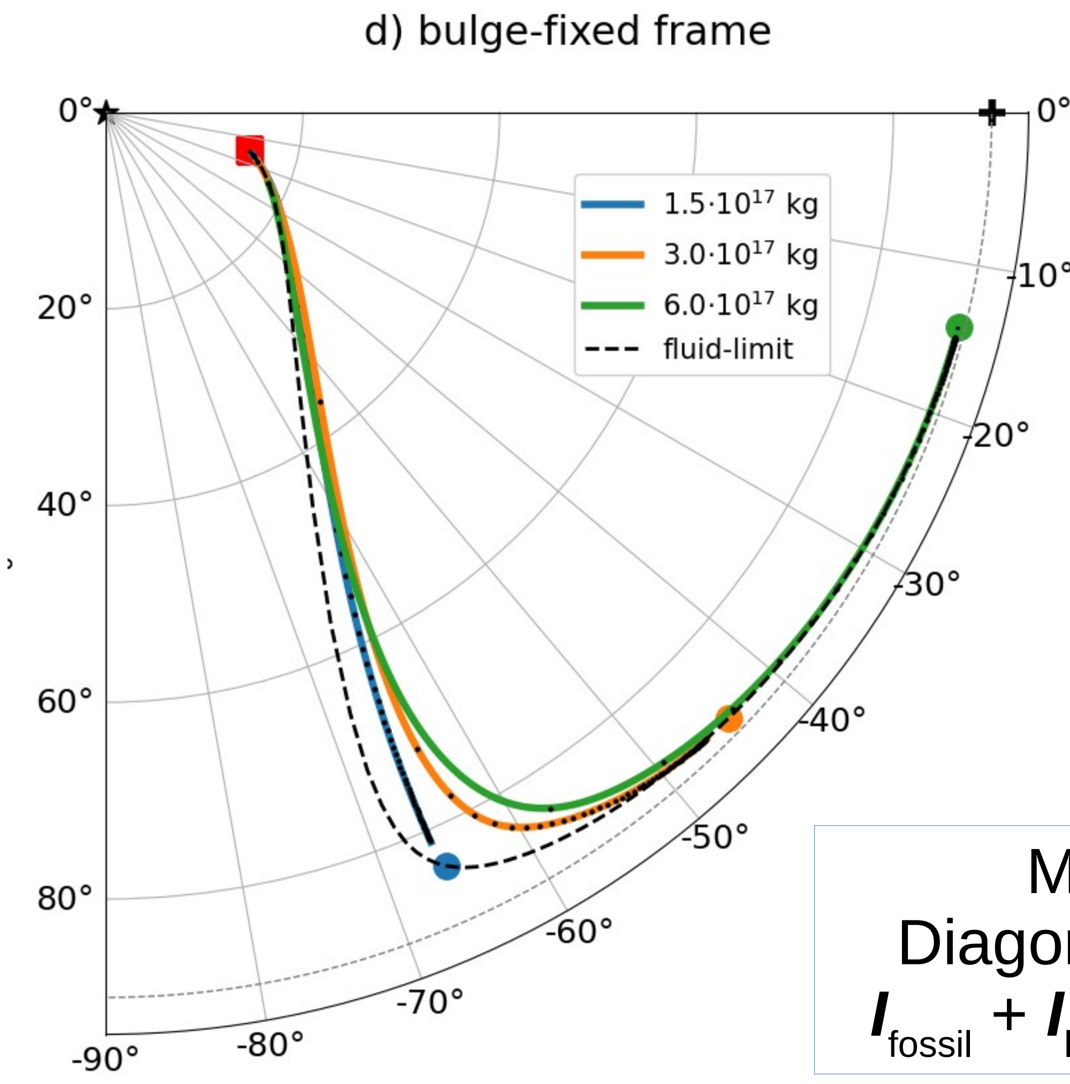
sub-host p.



Keane et al., 2016

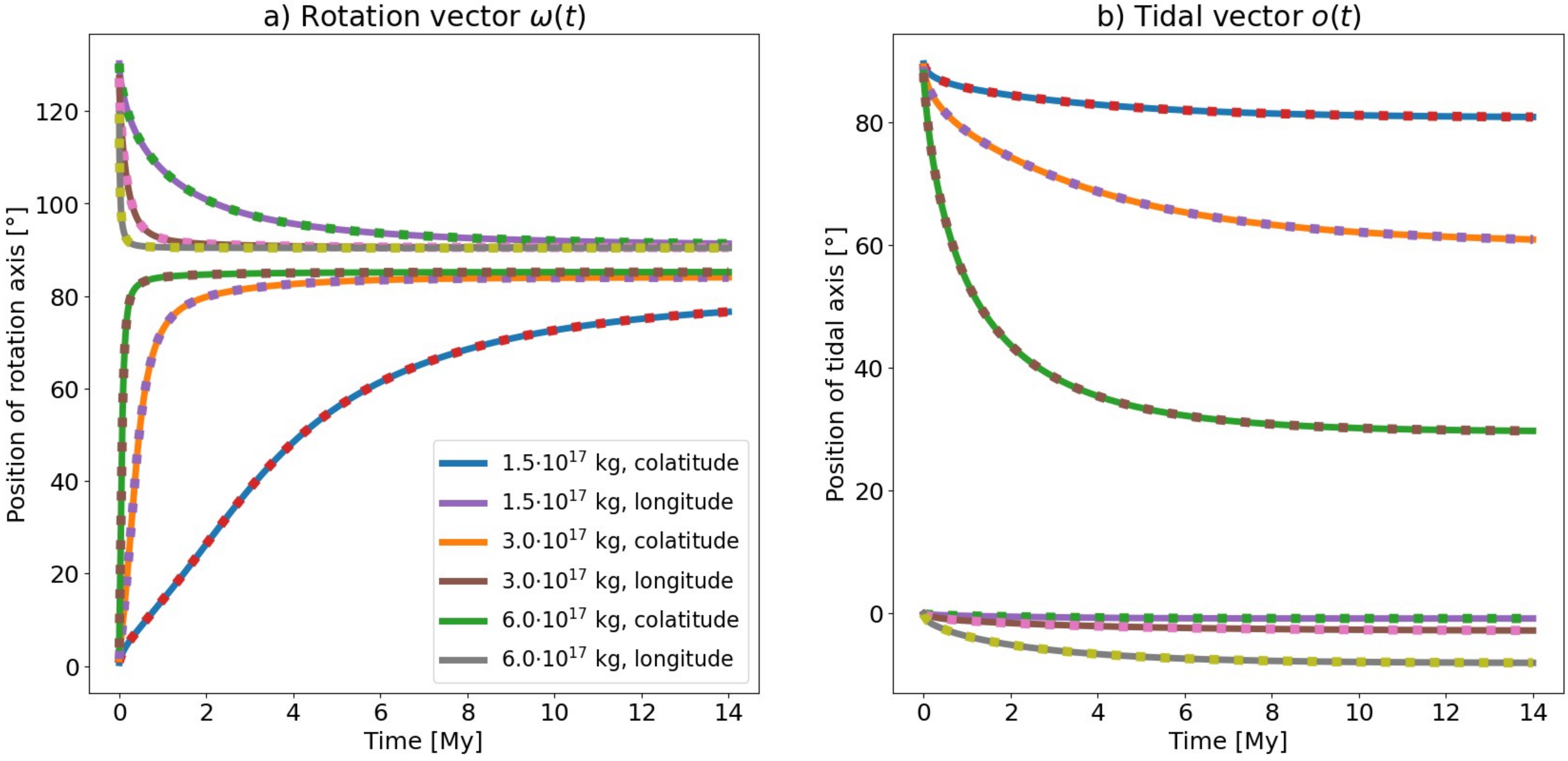


ow||mMIA approach: “old new” method



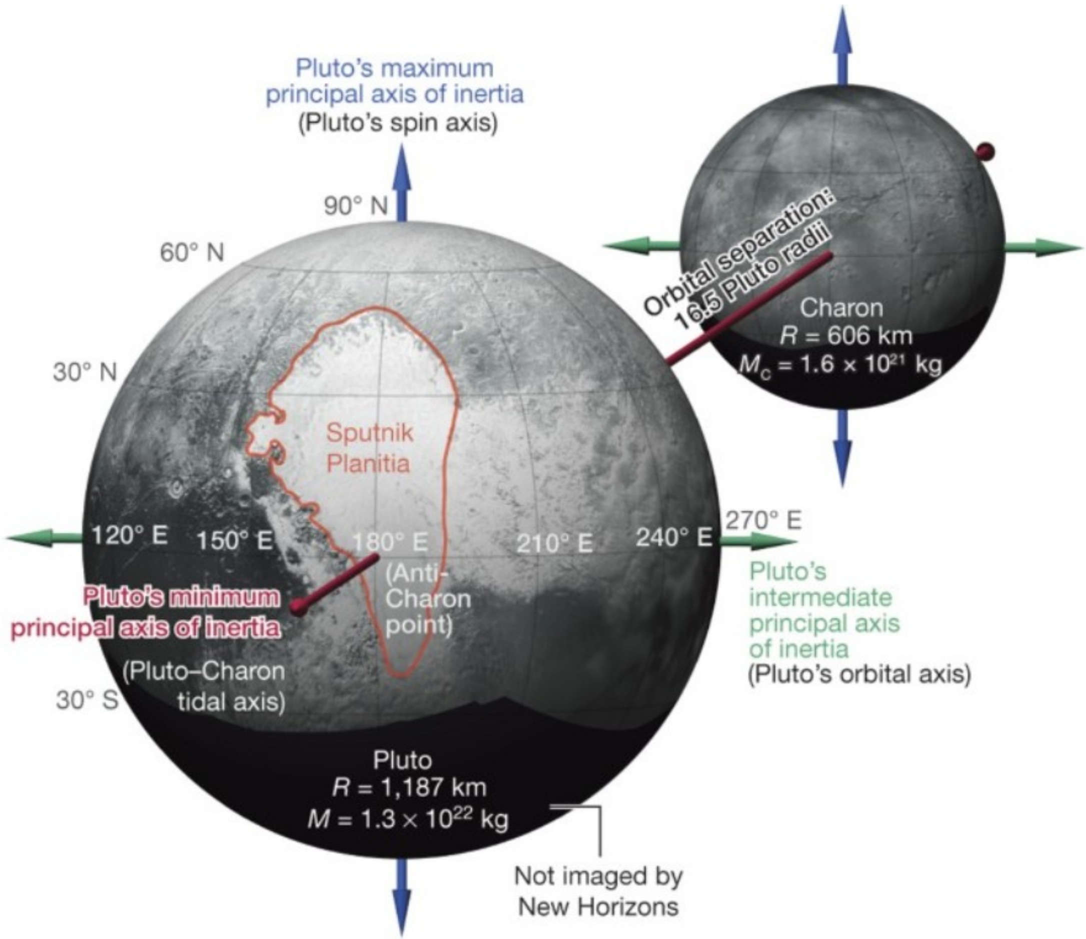
Method:
Diagonalization of
$\boldsymbol{I}_{\text{fossil}} + \boldsymbol{I}_{\text{load}}(t) + \boldsymbol{I}_{\text{bulge}}(t)$

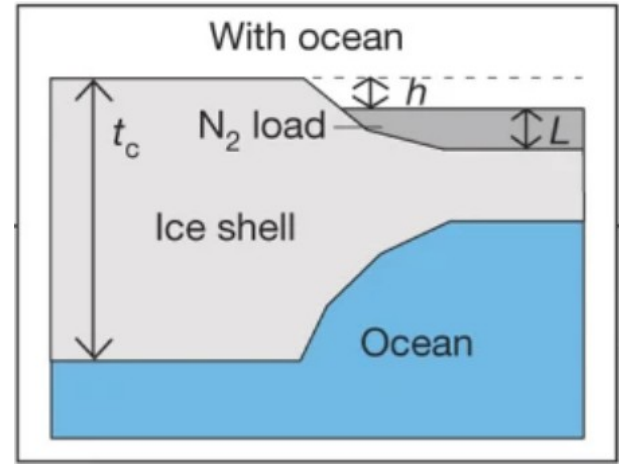
$ow||$mMIA:
Diagonalization of
$\boldsymbol{I}_{\text{fossil}} + \boldsymbol{I}_{\text{load}}(t) + \boldsymbol{I}_{\text{bulge}}(t)$

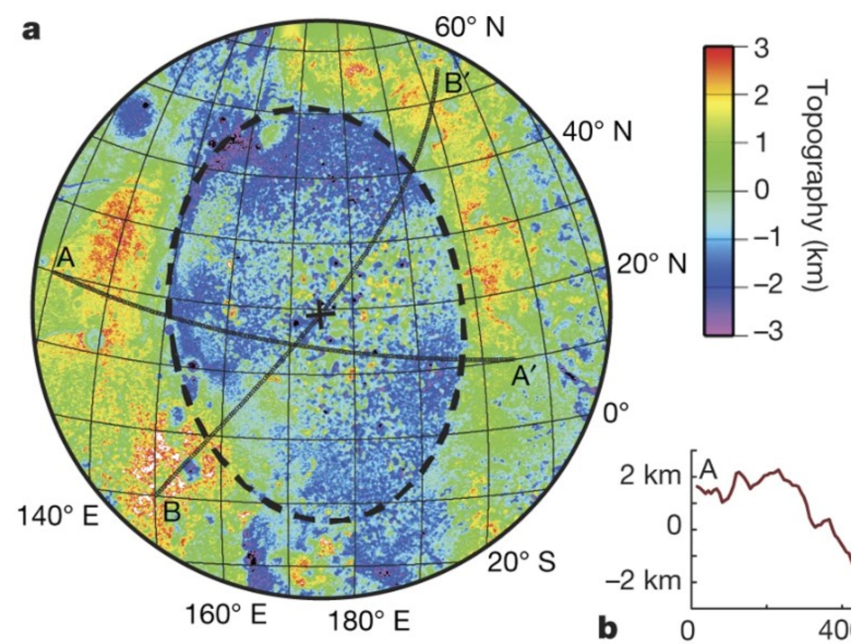


Comparison with the method of Hu et al. (2019) – perfect match

Pluto: Sputnik Planitia basin





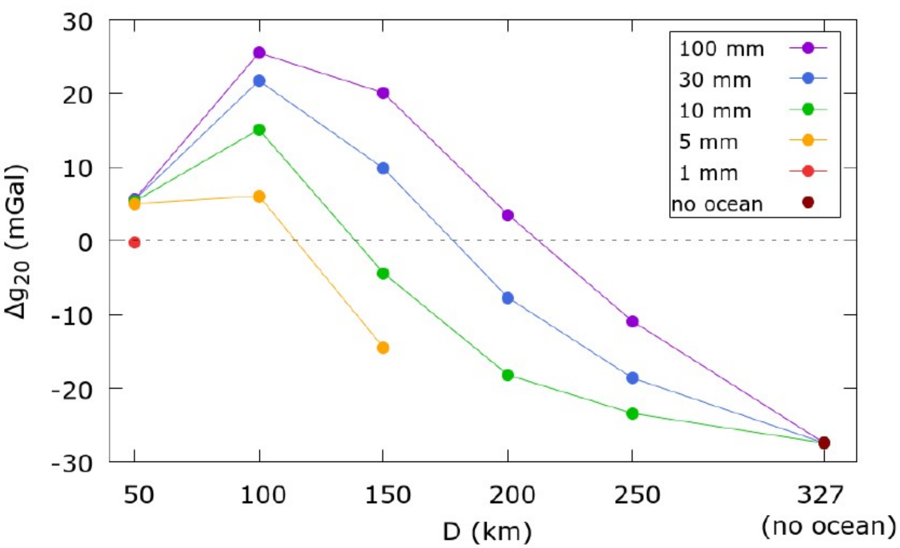


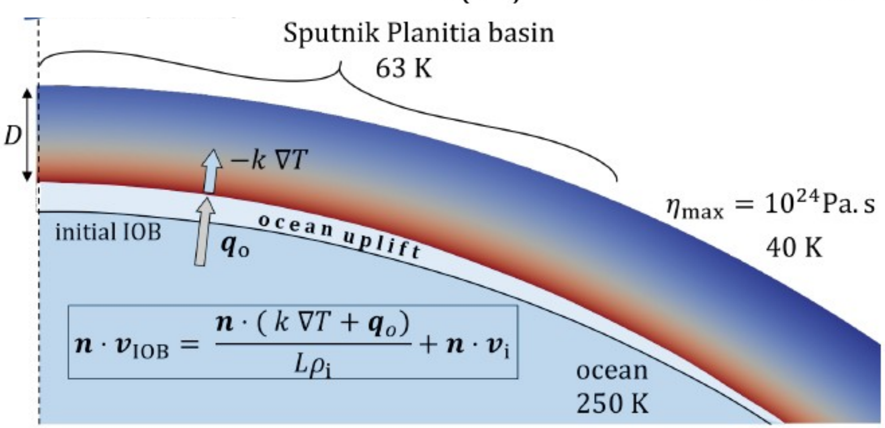
Keane et al., 2016: Reorientation and faulting of Pluto due to volatile loading within Sputnik Planitia (Nature)

Nimmo et al., 2016: Reorientation of Sputnik Planitia implies a subsurface ocean on Pluto (Nature)

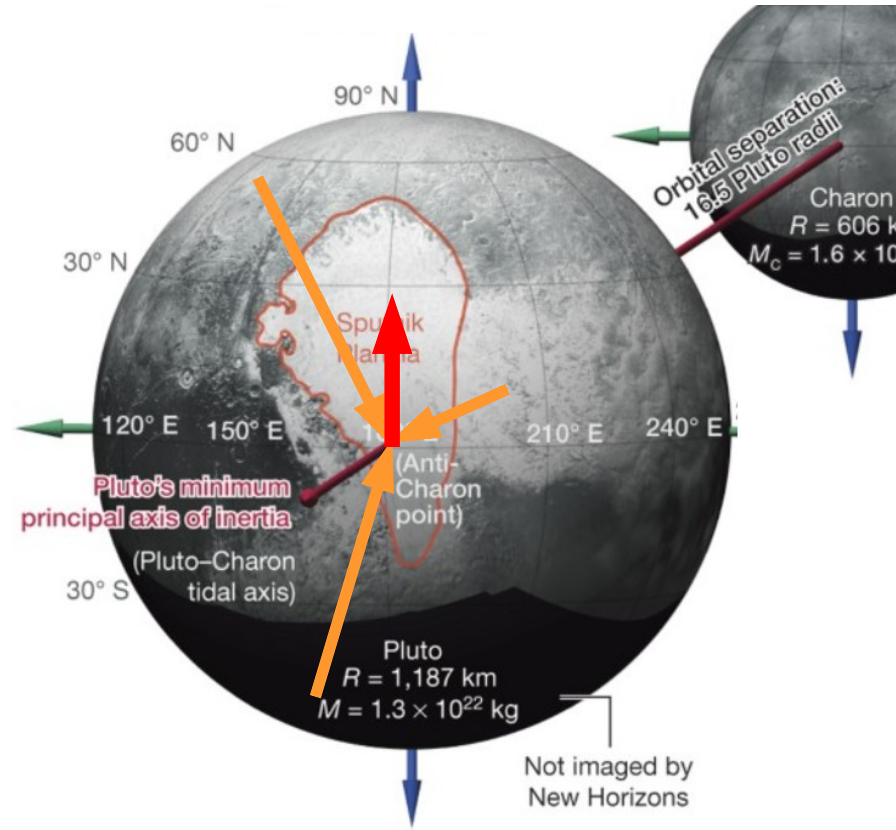
Alternative story: Pluto completely frozen?

SPUTNIK PLANITIA BASIN AS A TRIGGER FOR MELTING AND REORIENTATION OF PLUTO'S ICE SHELL.
M. Kihoulou[1] and V. Patočka[1]. [1] Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 18000 Prague, Czech Republic





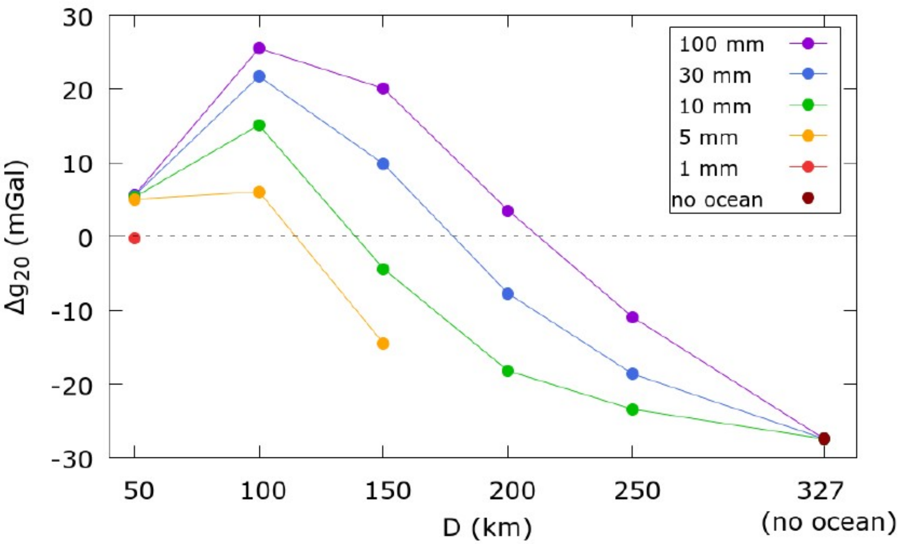
Pluto: An unexpected journey there and back again?

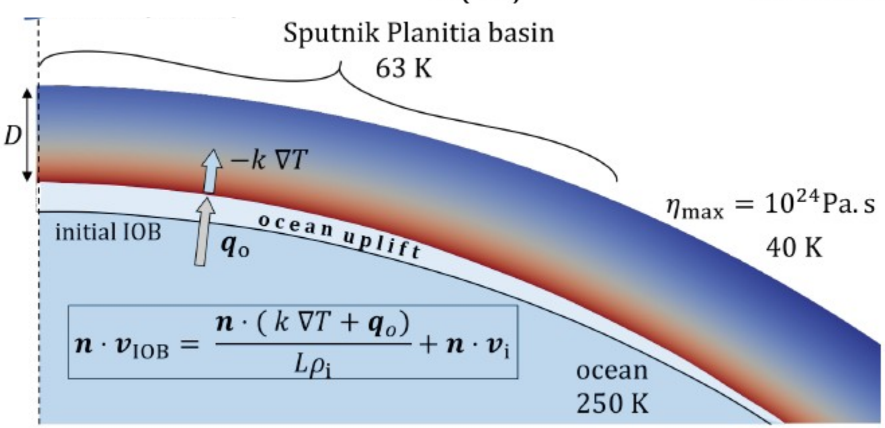


Alternative story: Pluto completely frozen?

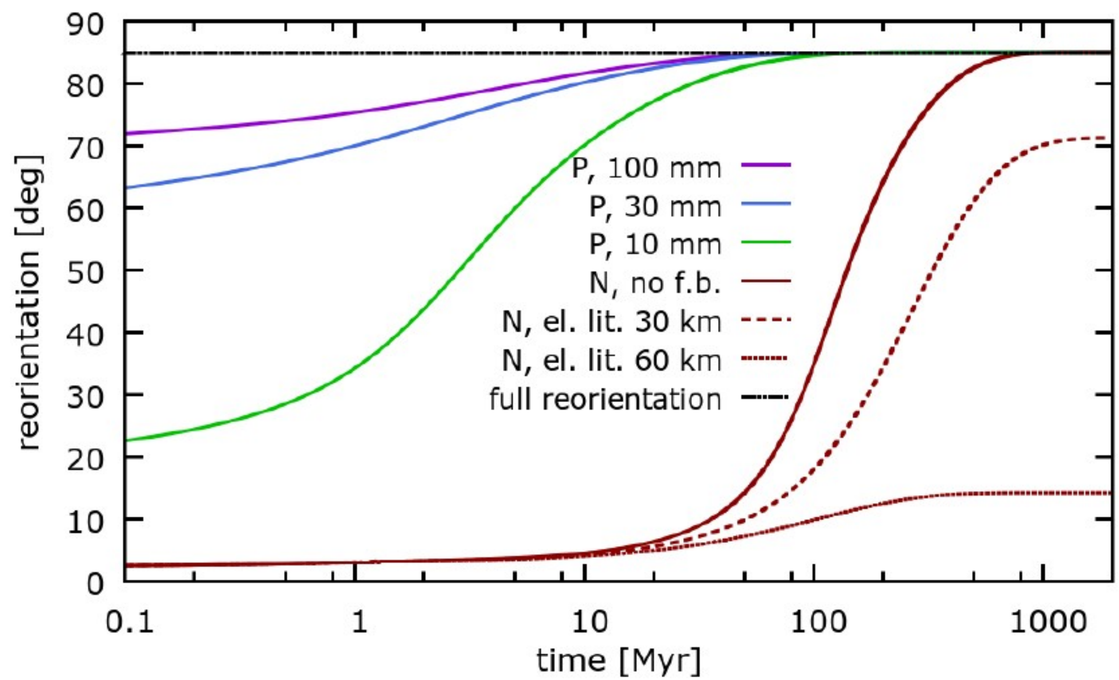
SPUTNIK PLANITIA BASIN AS A TRIGGER FOR MELTING AND REORIENTATION OF PLUTO'S ICE SHELL.

M. Kihoulou[1] and V. Patočka[1]. [1] Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 18000 Prague, Czech Republic





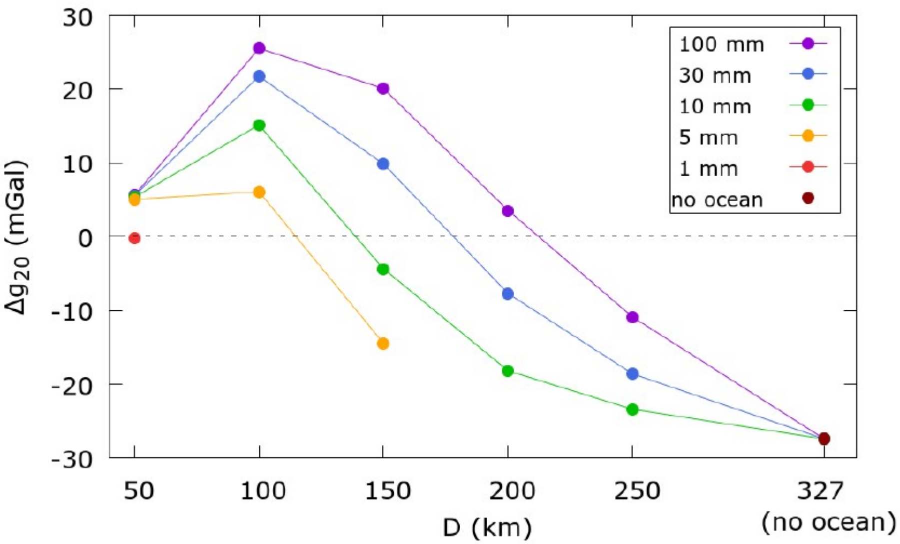
TPW distance along the 180th meridian:

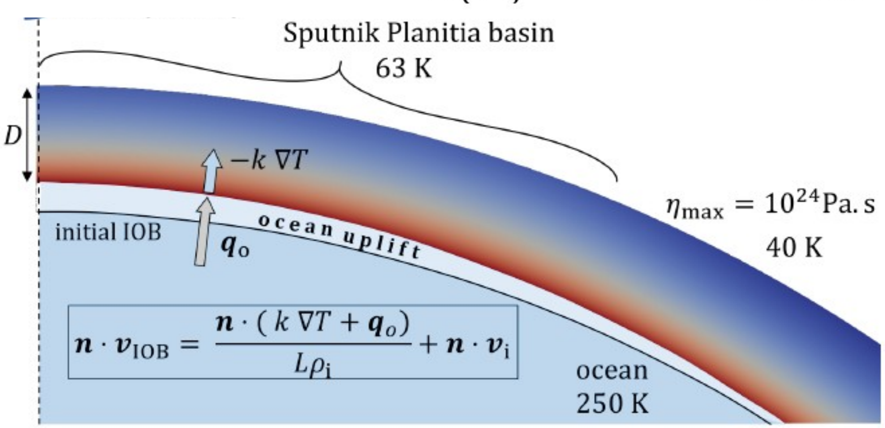


7km Nitrogen, 50 km el. thickness, no uplift

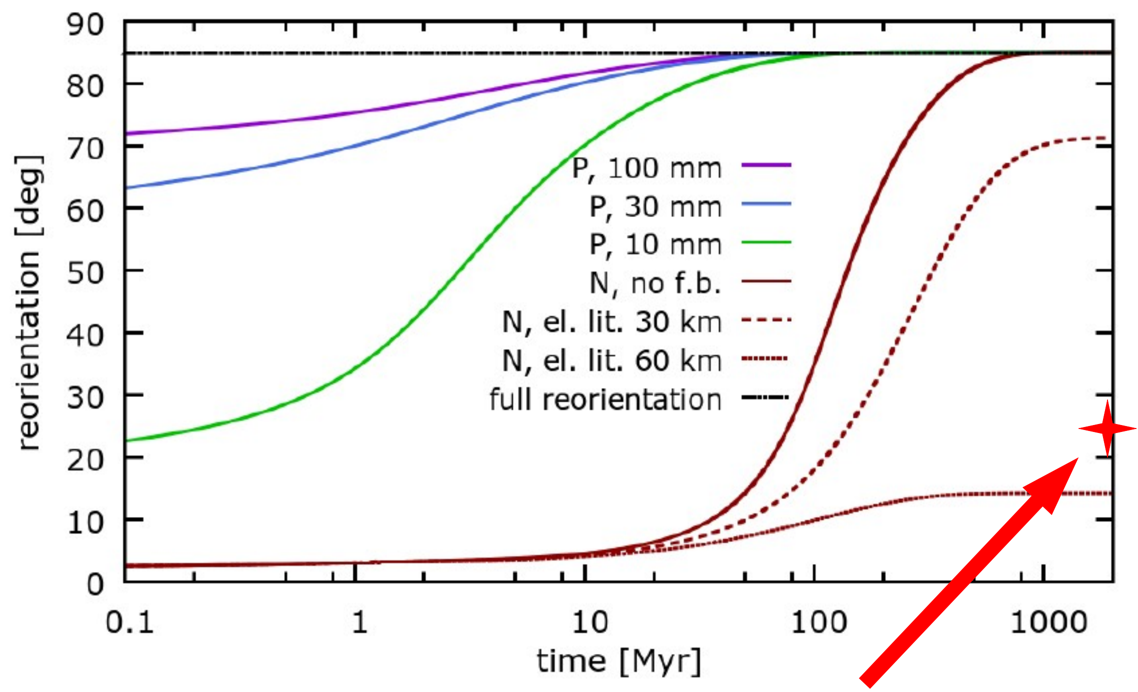
Alternative story: Pluto completely frozen?

SPUTNIK PLANITIA BASIN AS A TRIGGER FOR MELTING AND REORIENTATION OF PLUTO'S ICE SHELL. M. Kihoulou[1] and V. Patočka[1]. [1] Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holesovickach 2, 18000 Prague, Czech Republic



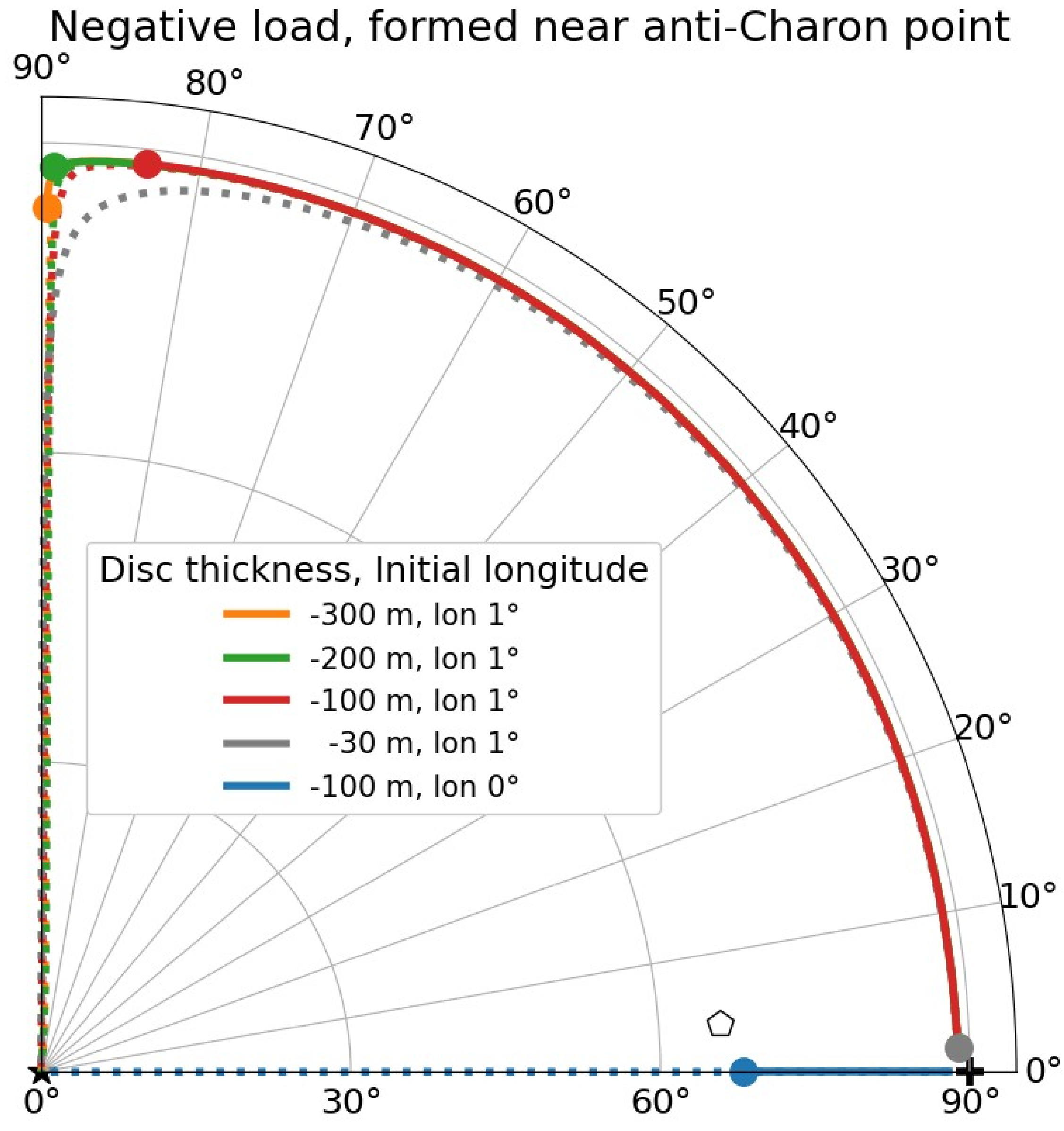


TPW distance along the 180th meridian:

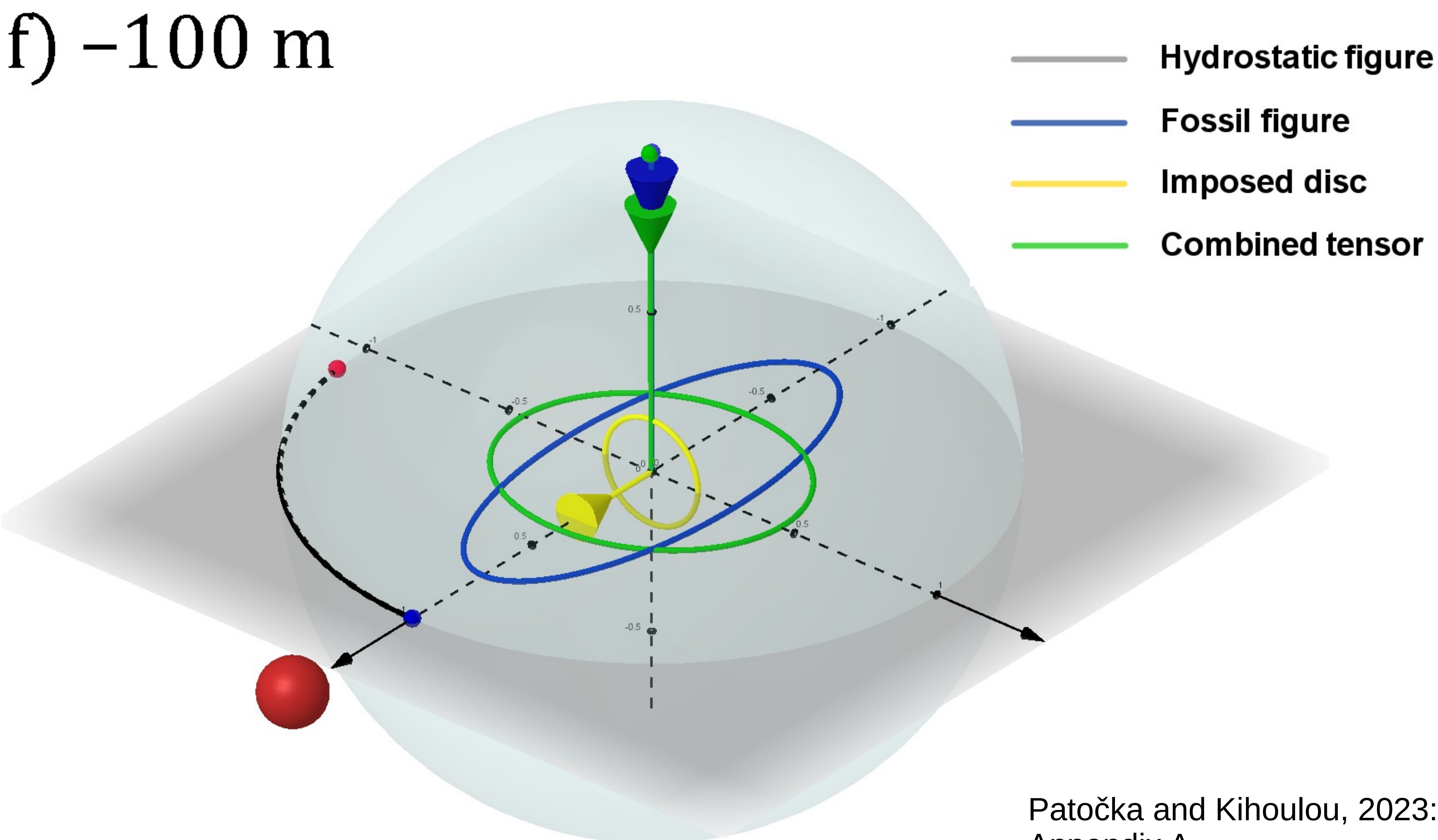


7km Nitrogen, 50 km el. thickness, no uplift

Straight to the north, or not?

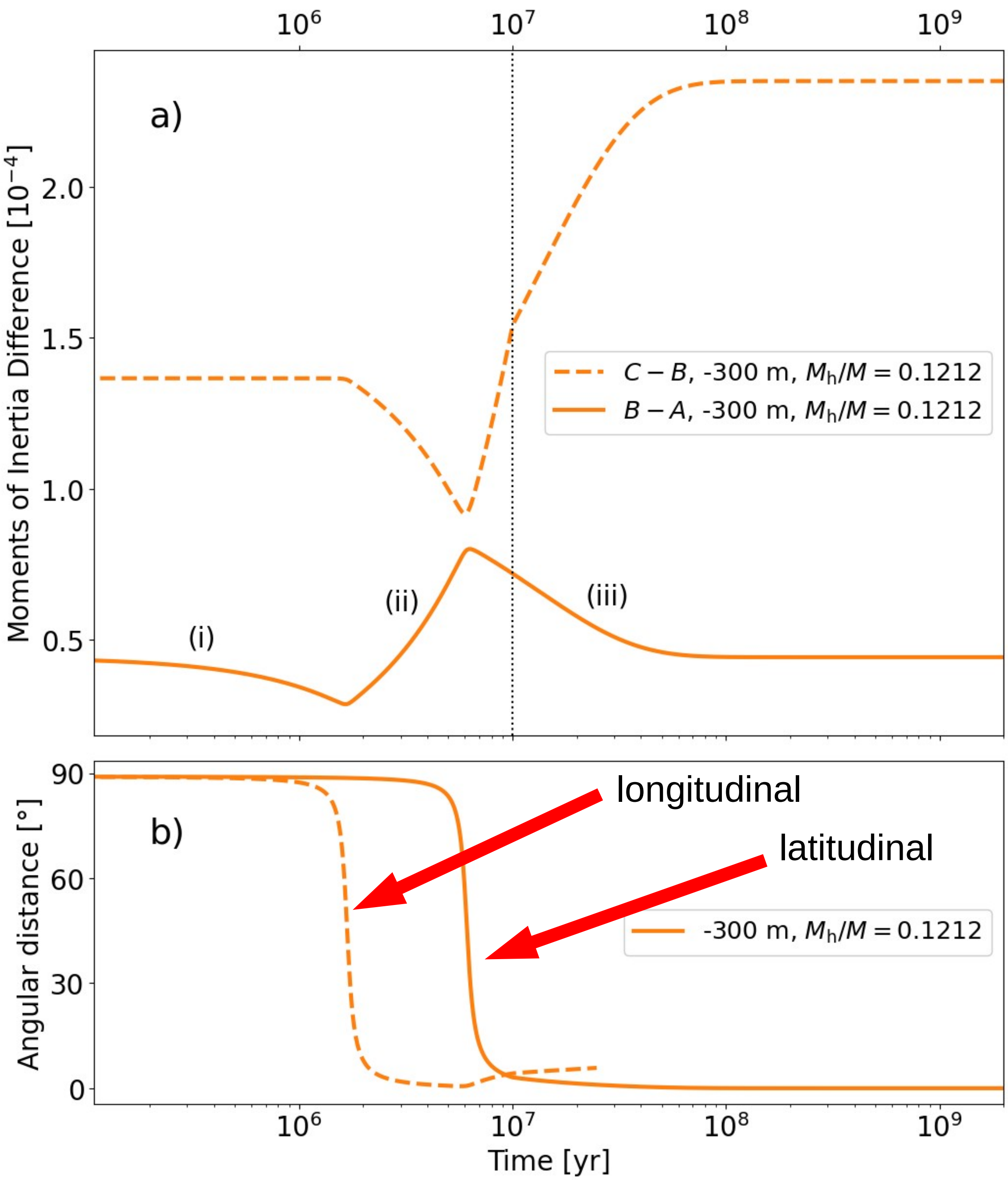


Straight to the north, or not?



Patočka and Kihoulou, 2023:
Appendix A

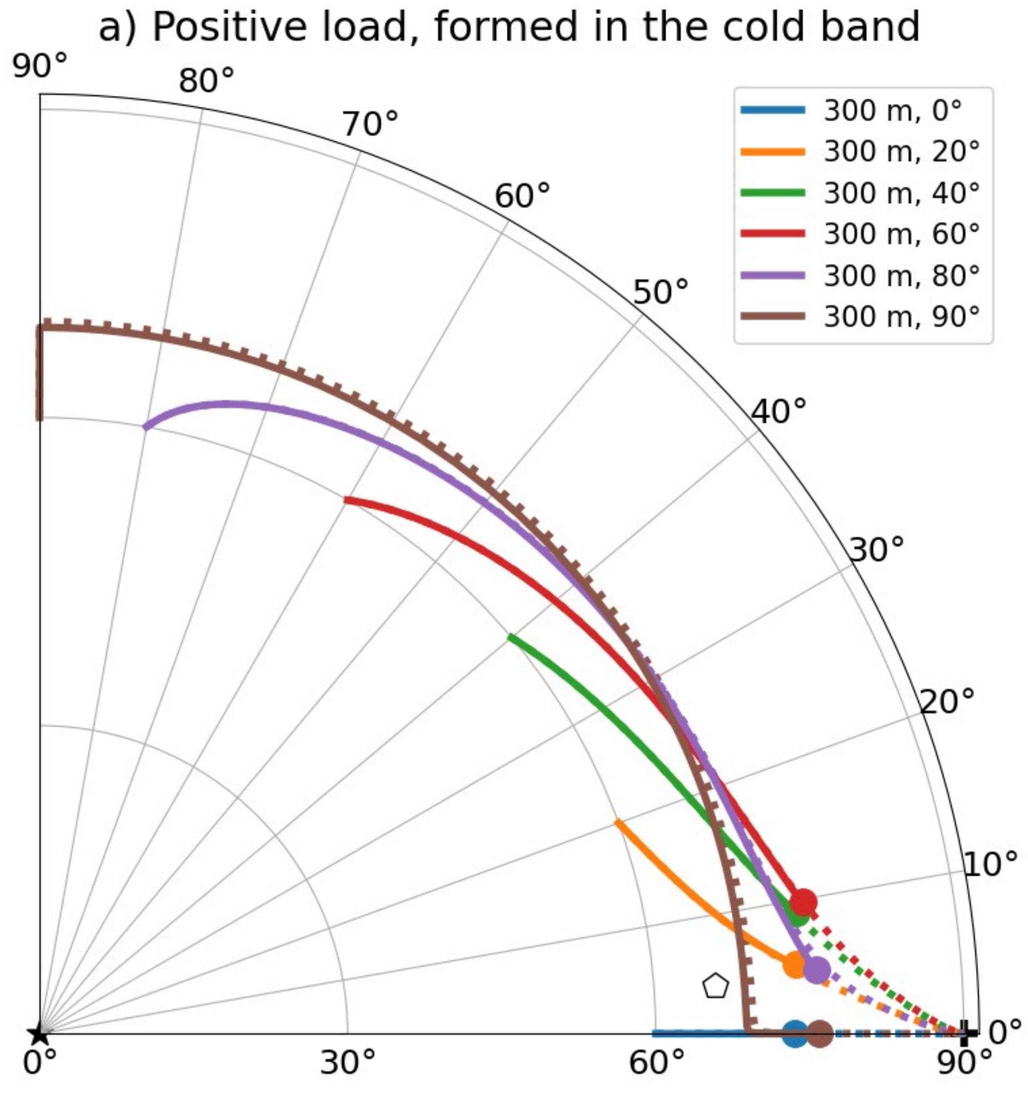
TPW time-scales revisited



a) Time evolution of the principal moments of inertia differences C-B and B-A. The moments are normalized by one third of the trace of **I**. Full onset of the load is marked by the vertical dotted line.

b) The temporal progress of reorientation. Solid lines show the colatitude of the negative load, dashed lines show how far the longitude of the load is from 90°E.

Sputnik Planitia: early formation?



Patočka and Kihoulou, 2023, *EPSL*

Conclusions

- The “ow||mMIA” method – at your command for building coupled interior evolution models

- TPW rates can differ significantly from the bulge relaxation rate

- Sputnik Planitia is most likely not a negative anomaly, but sustaining a subsurface ocean on Pluto is difficult

- David Pastrňák: hard “r”, soft “n”

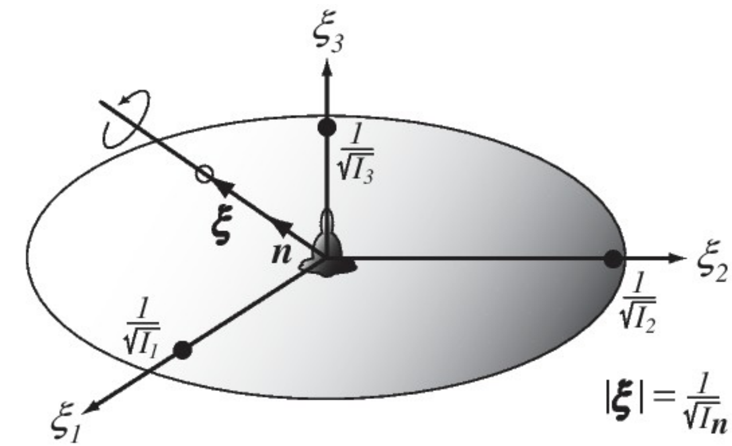
Key terminology: The LE, Inertia, Bulge

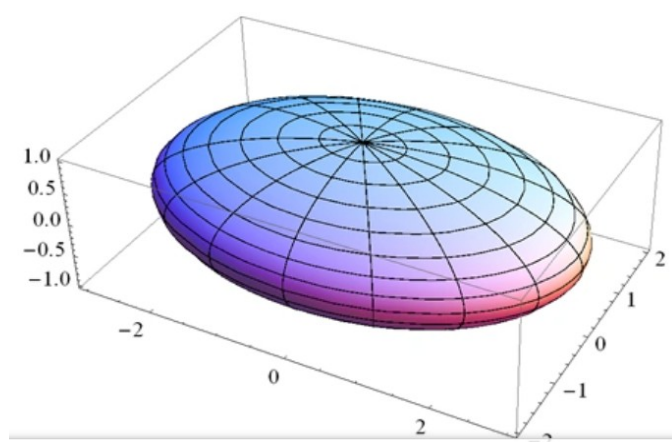
LE: $$\boldsymbol{M} = \frac{\mathrm{d}\boldsymbol{H}}{\mathrm{d}t} + \boldsymbol{\omega} \times \boldsymbol{H} = \frac{\mathrm{d}(\boldsymbol{I}\cdot\boldsymbol{\omega}+\boldsymbol{h})}{\mathrm{d}t} + \boldsymbol{\omega} \times (\boldsymbol{I}\cdot\boldsymbol{\omega}+\boldsymbol{h})$$

Inertia tensor: $$\boldsymbol{I} = \int_{v(t)} ((\boldsymbol{r}\cdot\boldsymbol{r})\,\mathbb{1} - \boldsymbol{r}\otimes\boldsymbol{r})\,\rho\,\mathrm{d}v,$$

Tisserand frame: $$\boldsymbol{h} = \int_{v(t)} \boldsymbol{r} \times (\rho\boldsymbol{v})\,\mathrm{d}v = \boldsymbol{0}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{I}\cdot\boldsymbol{\omega}) + \boldsymbol{\omega} \times (\boldsymbol{I}\cdot\boldsymbol{\omega}) = \boldsymbol{M}$$





Key terminology: Potentials, Torques

centrifugal: $$\Psi = \frac{1}{2}\left((\boldsymbol{\omega}\cdot\boldsymbol{r})^2 - \omega^2 r^2\right)$$

tidal: $$\Theta = \frac{1}{6}o^2 r^2 - \frac{1}{2}(\boldsymbol{o}\cdot\boldsymbol{r})^2 \qquad o = \frac{3\,G M_\mathrm{h}}{a^3}$$

locked body: $$\omega = \sqrt{\frac{G(M_\mathrm{h}+M)}{a^3}} = o\sqrt{\frac{M_\mathrm{h}+M}{3M_\mathrm{h}}}$$

$$\int_{v(t)} \boldsymbol{r}\times(-\nabla\Psi)\,\rho\,\mathrm{d}v = \int_{v(t)} \boldsymbol{r}\times(\boldsymbol{r}\,\omega^2 - \boldsymbol{\omega}\,(\boldsymbol{\omega}\cdot\boldsymbol{r}))\,\rho\,\mathrm{d}v = \boldsymbol{\omega}\times\int_{v(t)} \boldsymbol{r}\,(\boldsymbol{\omega}\cdot\boldsymbol{r})\,\rho\,\mathrm{d}v = -\boldsymbol{\omega}\times(\boldsymbol{I}\cdot\boldsymbol{\omega}).$$

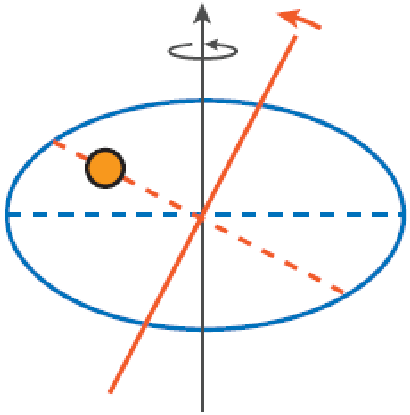
$$\boldsymbol{M} = \int_{v(t)} \boldsymbol{r}\times(-\nabla\Theta)\,\rho\;\mathrm{d}v = \boldsymbol{o}\times(\boldsymbol{I}\cdot\boldsymbol{o})$$

LE: $$\frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{I}\cdot\boldsymbol{\omega}) + \boldsymbol{\omega}\times(\boldsymbol{I}\cdot\boldsymbol{\omega}) = \boldsymbol{o}\times(\boldsymbol{I}\cdot\boldsymbol{o}).$$

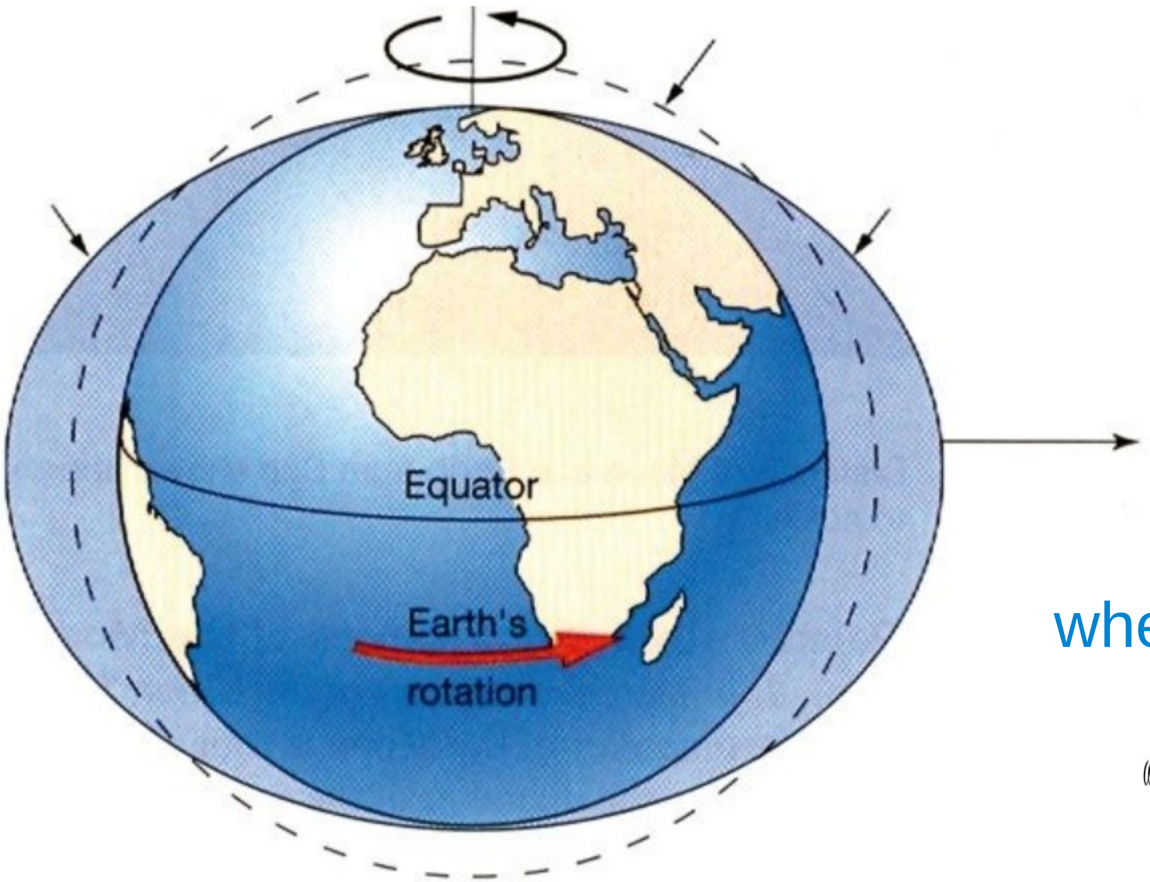
Mechanism: rotation vs. tides

Rotation: bulge perpendicular to ω axis
Tides: bulge along the tidal axis

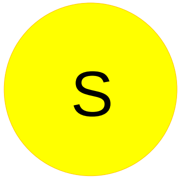
rotational axis



rotational axis



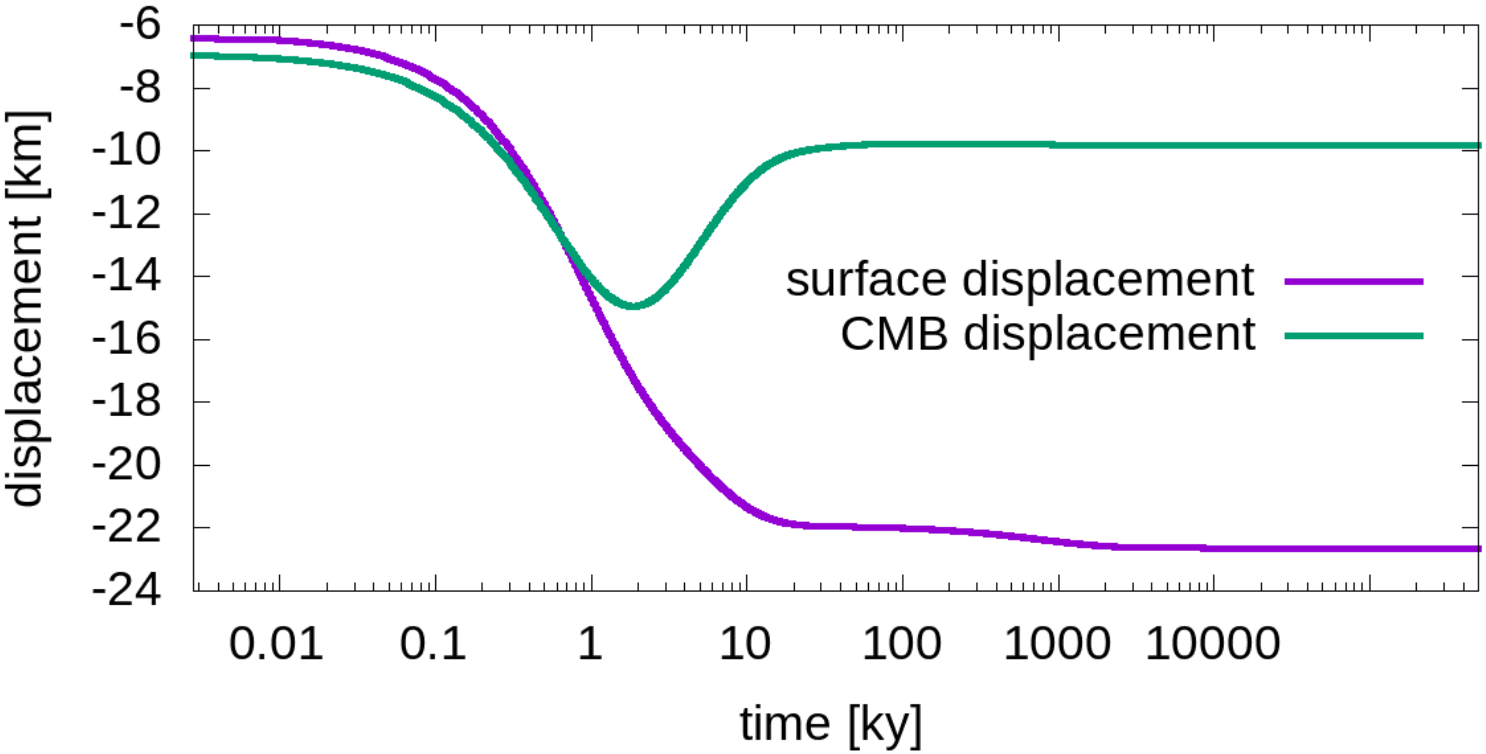
tidal axis



when tidally locked:

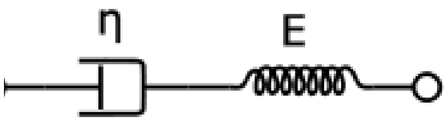
$$\omega = \sqrt{\frac{G(M_h + M)}{a^3}} = o\sqrt{\frac{M_h + M}{3M_h}}$$

Timescale of reorientation



$$\nabla \cdot \boldsymbol{\tau} + \boldsymbol{f} = 0 \,,$$

$$\nabla \cdot \boldsymbol{u} = 0 \,,$$



$$0 = \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{I} \cdot \boldsymbol{\omega}) + \boldsymbol{\omega} \times (\mathbf{I} \cdot \boldsymbol{\omega})$$

- bulge relaxation
- load formation

TPW: methods (Earth)

$$0 = \frac{\mathrm{d}}{\mathrm{d}t}(\mathbf{I} \cdot \boldsymbol{\omega}) + \boldsymbol{\omega} \times (\mathbf{I} \cdot \boldsymbol{\omega})$$

Peltier, W. R. (1974). The impulse response of a Maxwell Earth.

Willemann, R. (1984). Reorientation of Planets with Elastic Lithospheres.

Ricard, Y., Spada, G., & Sabadini, R. (1993, MAY). Polar wandering of a dynamic

Lefftz, M., Legros, H., & Hinderer, J. (1991, MAR). Non-linear equations for the rotation of a viscoelastic planet taking into account the influence of a liquid

Adhikari et al. (2018, EPSL): What drives 20th century polar motion?

TPW: methods (moons)

$$\boldsymbol{I}_{\mathrm{disc}} + \boldsymbol{I}_{\mathrm{foss}}$$

Equilibrium: Matsuyama, I., Nimmo, F., & Mitrovica, J. X. (2014) Planetary Reorientation. *Annual Review of Earth and Planetary Sciences*

Recently: Dynamics

Hu, H., van der Wal, W., & Vermeersen, L. L. A. (2017a, JAN). A numerical method for reorientation of rotating tidally deformed viscoelastic bodies.

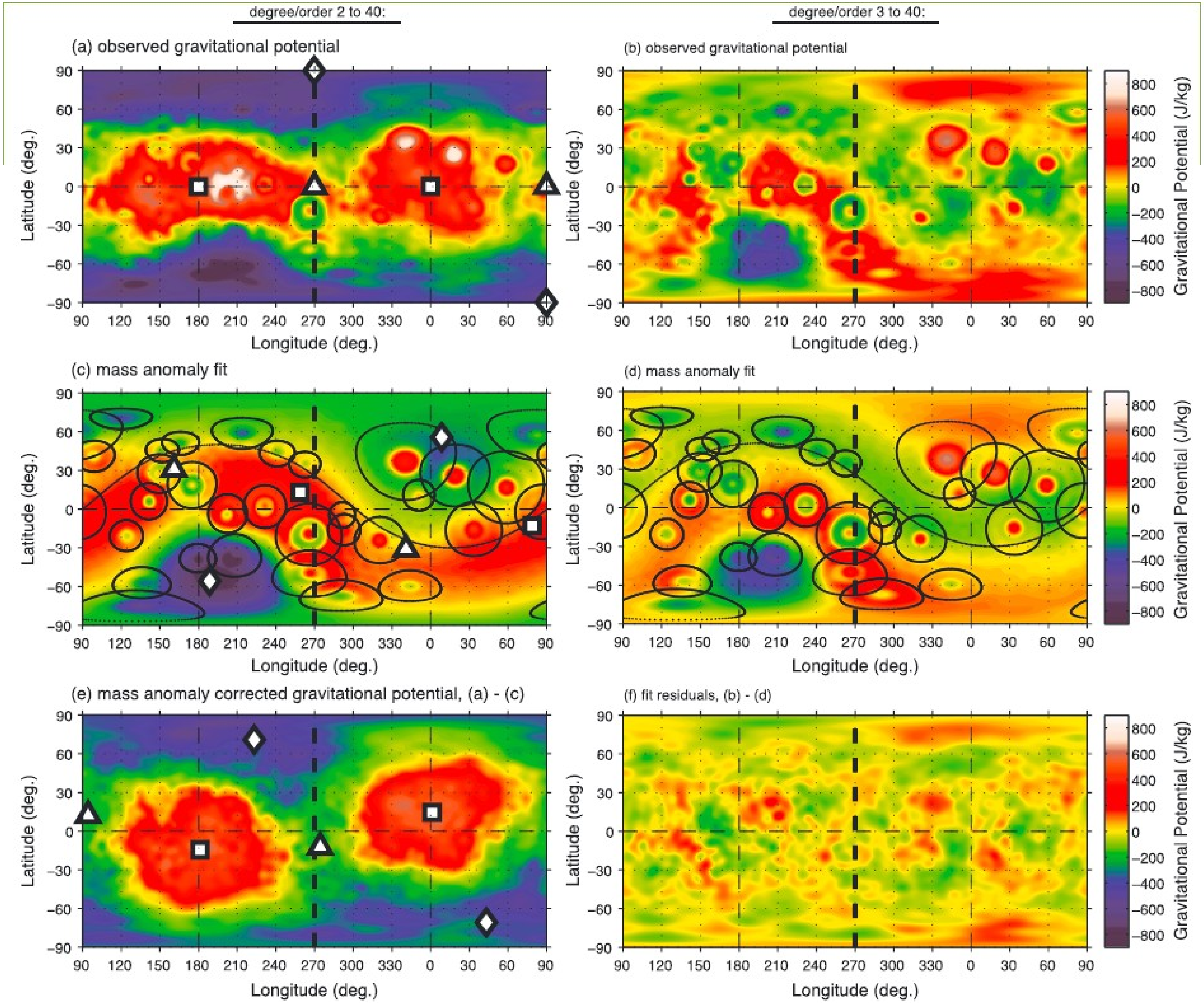
Hu, H., van der Wal, W., & Vermeersen, L. L. A. (2017b, DEC). A Full-Maxwell Approach for Large-Angle Polar Wander of Viscoelastic Bodies.

Hu, H., van der Wal, W., & Vermeersen, L. L. A. (2019, MAR 15). Rotational dynamics of tidally deformed planetary bodies and validity of fluid limit and quasi-fluid approximation.

$$\frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{I} \cdot \boldsymbol{\omega}) + \boldsymbol{\omega} \times (\boldsymbol{I} \cdot \boldsymbol{\omega}) = \boldsymbol{o} \times (\boldsymbol{I} \cdot \boldsymbol{o}).$$

The Moon

Keane and Matsuyama, 2014: Evidence for lunar true polar wander...



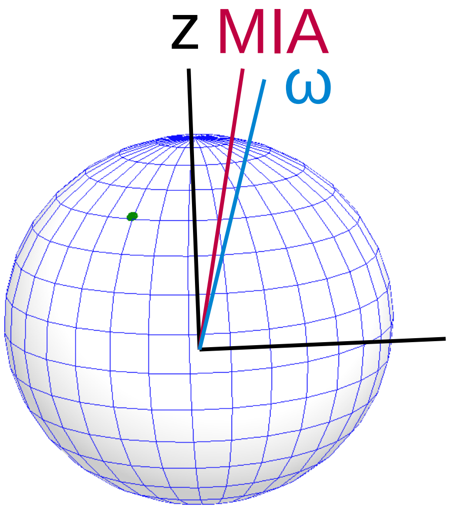
Dynamics: PWL approach of Hu et al.

Linearized Liouville equation:

$$m_1(t) = \frac{\Delta I_{13}(t)}{C-A} + \frac{C\Delta \dot{I}_{23}(t)}{\Omega(C-A)(C-B)}$$

$$m_2(t) = \frac{\Delta I_{23}(t)}{C-B} - \frac{C\Delta \dot{I}_{13}(t)}{\Omega(C-A)(C-B)}$$

$$m_3(t) = -\frac{\Delta I_{33}}{C}$$



$$\nabla \cdot \boldsymbol{\tau} + \boldsymbol{f} = 0\,,$$

$$\nabla \cdot \boldsymbol{u} = 0\,,$$

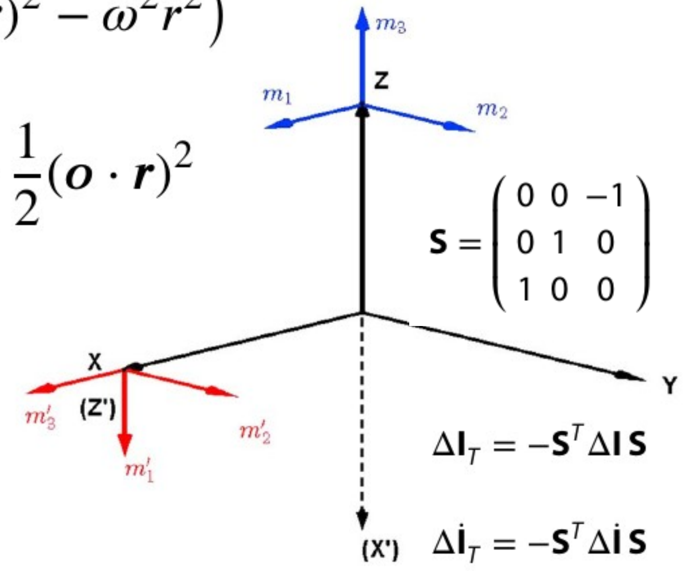
Transformation of coordinates:

$$\mathbf{Q} = \begin{pmatrix} \omega_3 + \frac{\omega_2^2}{1+\omega_3} & -\frac{\omega_1\omega_2}{1+\omega_3} & \omega_1 \\ -\frac{\omega_1\omega_2}{1+\omega_3} & 1 - \frac{\omega_2^2}{1+\omega_3} & \omega_2 \\ -\omega_1 & -\omega_2 & \omega_3 \end{pmatrix}$$

Tidal axis wander:

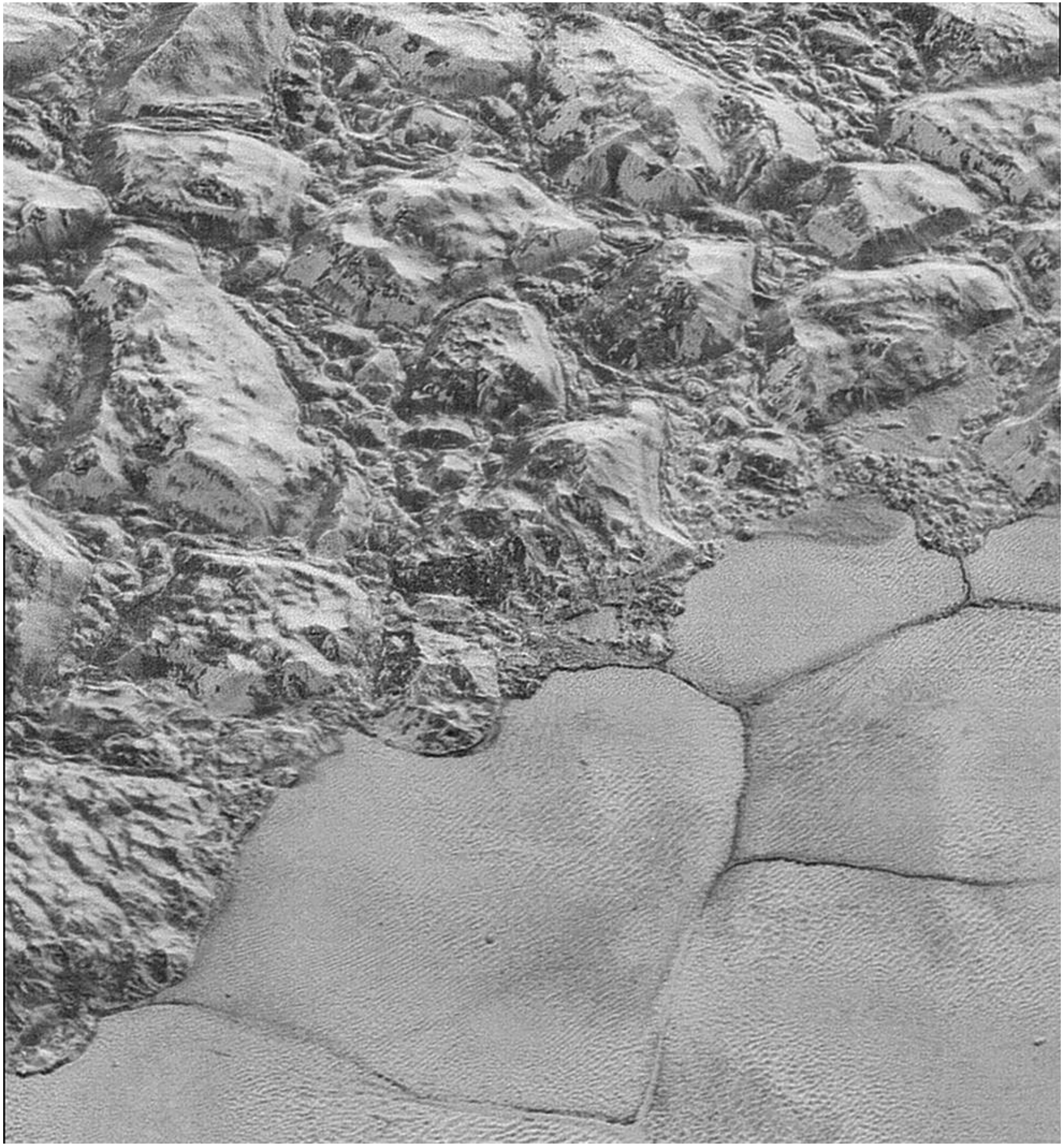
$$\Psi = \frac{1}{2}\left((\boldsymbol{\omega}\cdot\boldsymbol{r})^2 - \omega^2 r^2\right)$$

$$\Theta = \frac{1}{6}o^2 r^2 - \frac{1}{2}(\boldsymbol{o}\cdot\boldsymbol{r})^2$$



$$\frac{\mathrm{d}}{\mathrm{d}t}(\boldsymbol{I}\cdot\boldsymbol{\omega}) + \boldsymbol{\omega}\times(\boldsymbol{I}\cdot\boldsymbol{\omega}) = \boldsymbol{o}\times(\boldsymbol{I}\cdot\boldsymbol{o}).$$

NASA:
New Horizons
Dec 2015



Dynamics of reorientation: is TPW straight?

Equilibrium orientation
- only the final state
- “quasi-steady” dynamics

Small satellites
- M_h / M large

Are load paths in the bulge-fixed frame straight when $M_h/M \ll 1$?

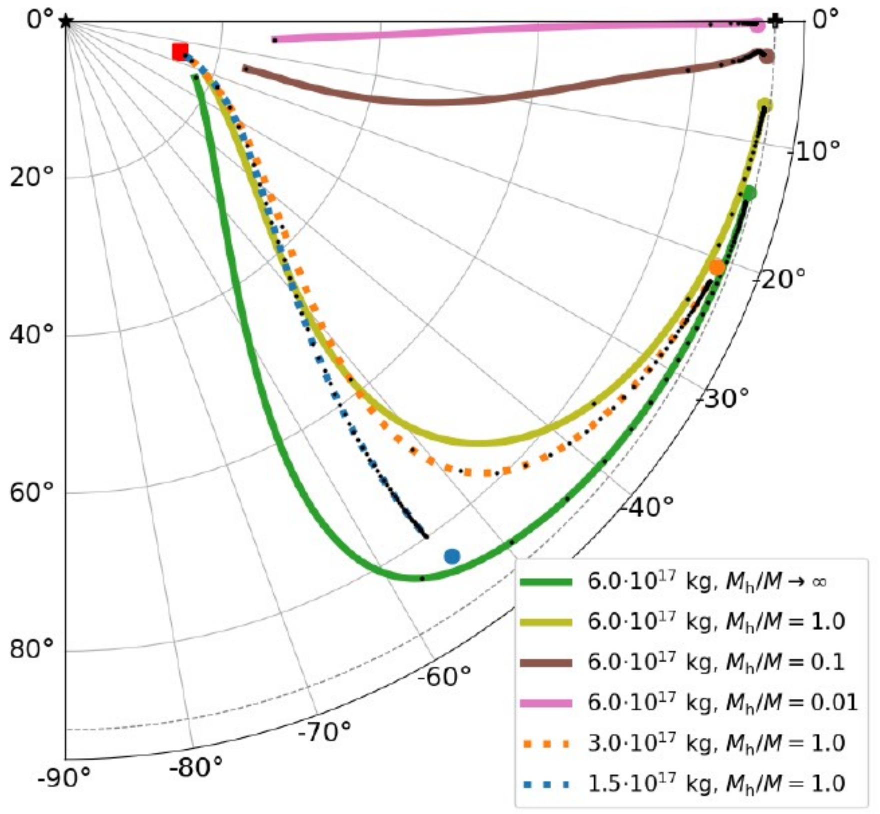
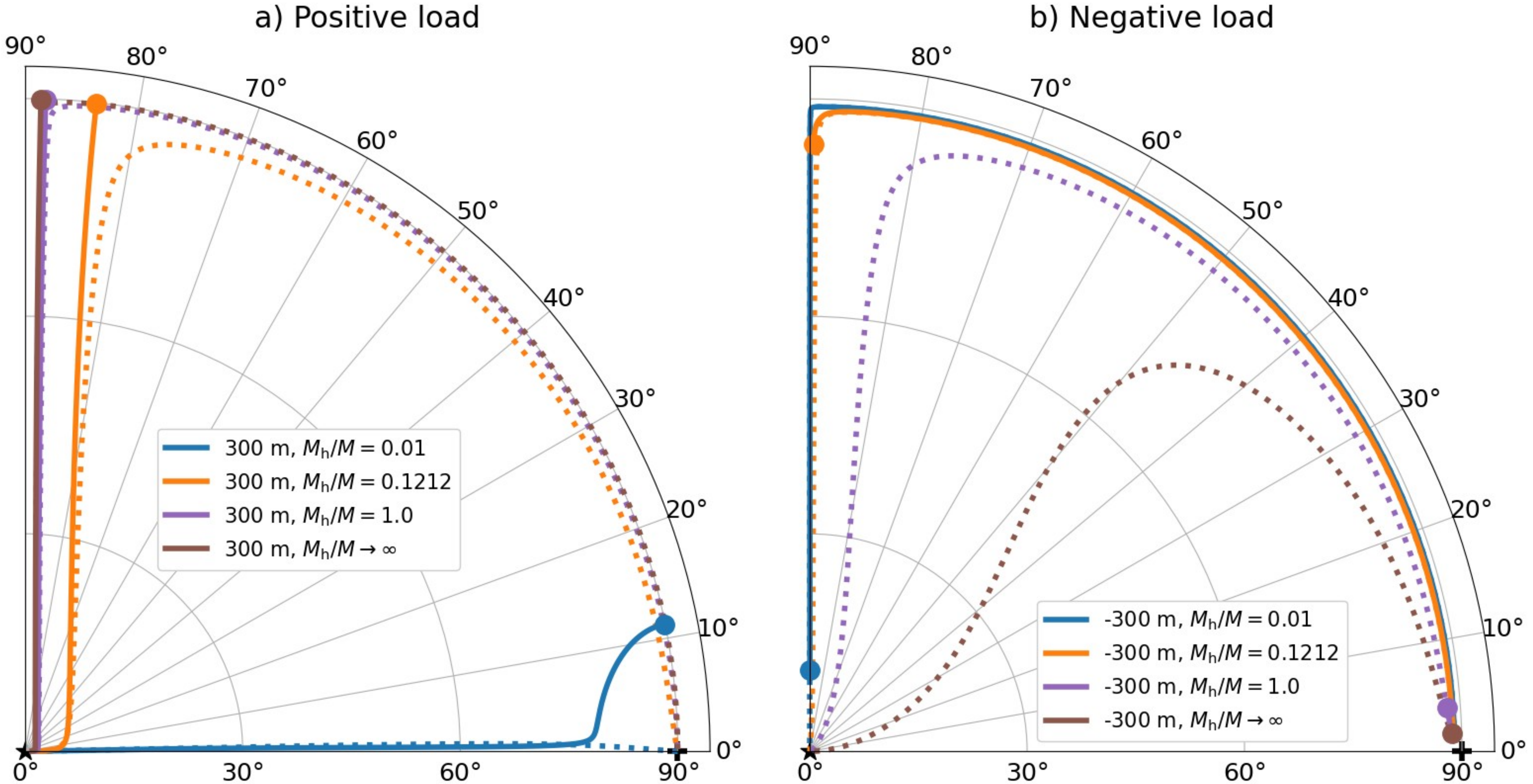


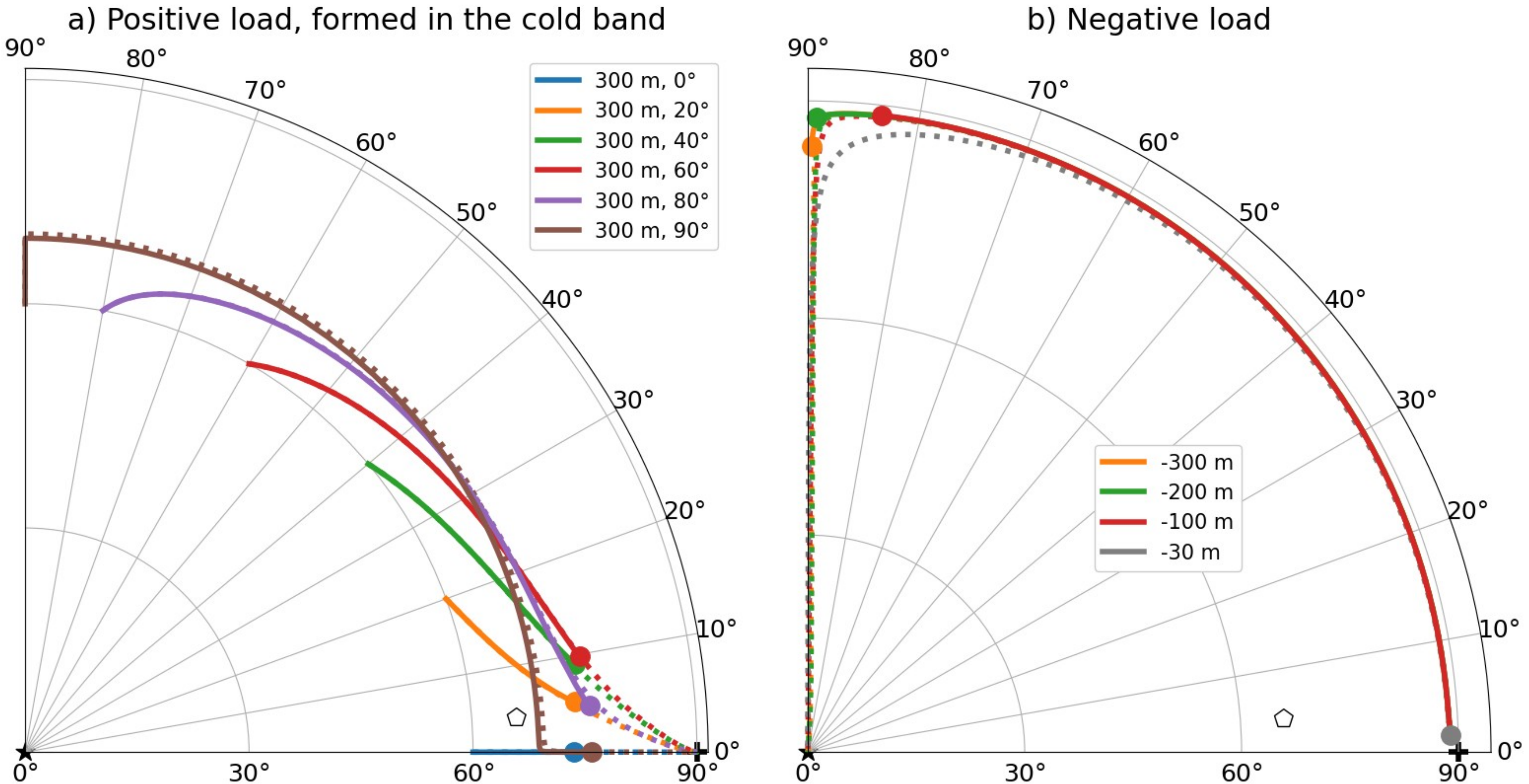
Figure 2: The influence of M_h/M on the path of a positive load, depicted in the bulge-fixed frame (cf. Fig. 1d). Temporal evolution is illustrated by the small black dots that are evenly sampled in time at intervals of 250 ky. The red square marks the initial position of the load.

Dynamics of reorientation: TPW paths



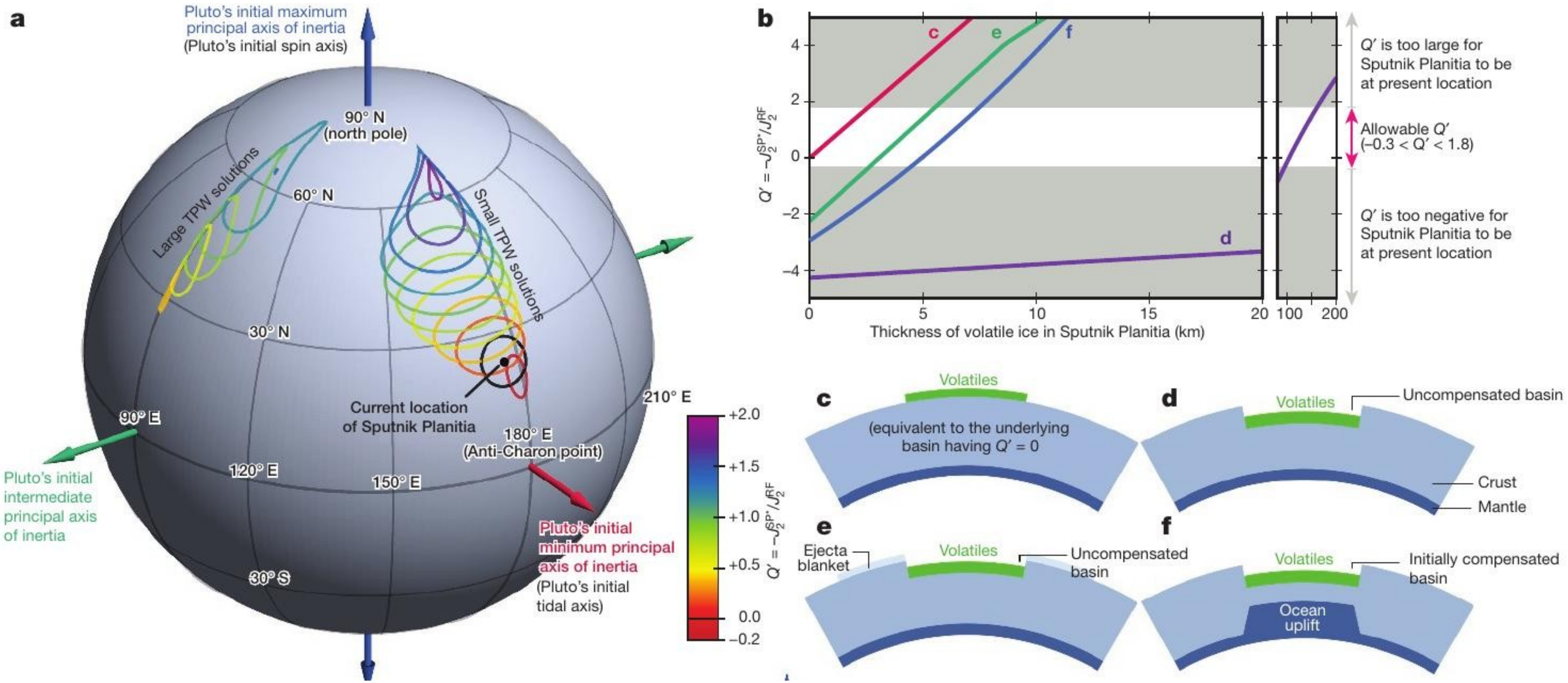
Patočka and Kihoulou: Dynamic reorientation of tidally locked bodies: application to Pluto, *submitted*

Sputnik Planitia: formation scenarios



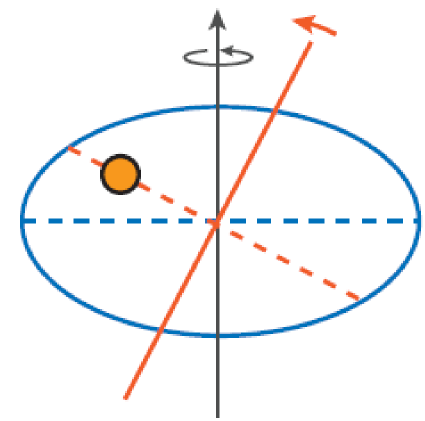
Patočka and Kihoulou: Dynamic reorientation of tidally locked bodies: application to Pluto, *submitted*

Pluto: Sputnik Planitia basin



Keane et al., 2016: Reorientation and faulting of Pluto due to volatile loading within Sputnik Planitia (Nature)

Mechanism: basic concept



$$E_{\text{rot}}^{0} = \frac{1}{2}\boldsymbol{\omega}_0 \cdot \boldsymbol{I}_0 \cdot \boldsymbol{\omega}_0 = \frac{1}{2} C_0\, \omega_0^2$$

$$\boldsymbol{H} = \boldsymbol{I} \cdot \boldsymbol{\omega} = C_0\, \omega_0 = \text{const}$$

$$\omega_{\text{new}} = \omega_0\, \frac{C_0}{C_{\text{new}}}$$

$$E_{\text{rot}}^{\text{new}} = \frac{1}{2} C_{\text{new}}\, \omega_{\text{new}}^2 = E_{\text{rot}}^{0}\, \frac{C_0}{C_{\text{new}}} < E_{\text{rot}}^{0}$$