Conditions for the long term stability of Pluto's azimuthal and latitudinal perihelion librations

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Abstract

Many of the unusual properties of the dwarf planet Pluto's orbit are widely accepted as evidence for the orbital migration of the giant planets in early solar system history. However, some properties remain an enigma. Pluto's long term orbital stability is supported by two special properties of its orbit that limit the location of its perihelion in azimuth and in latitude. We revisit Pluto's orbital dynamics with a view to elucidating the individual and collective gravitational effects of the giant planets on its perihelion location. In this presentation we demonstrate with numerical experiments that, while the resonant perturbations from Neptune account for the azimuthal constraint on Pluto's perihelion location, the long term and steady persistence of the latitudinal constraint is possible only in a narrow range of additional secular forcing which arises fortuitously from the particular orbital architecture of the other giant planets. Our numerical investigations also find that Jupiter has a largely stabilizing influence whereas Uranus has a largely destabilizing influence on Pluto's orbit.

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Ref. Malhotra and Ito, "Pluto near the edge of chaos", PNAS, **119**, issue 15, e2118692119, 2022.

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Summary (takeaway)

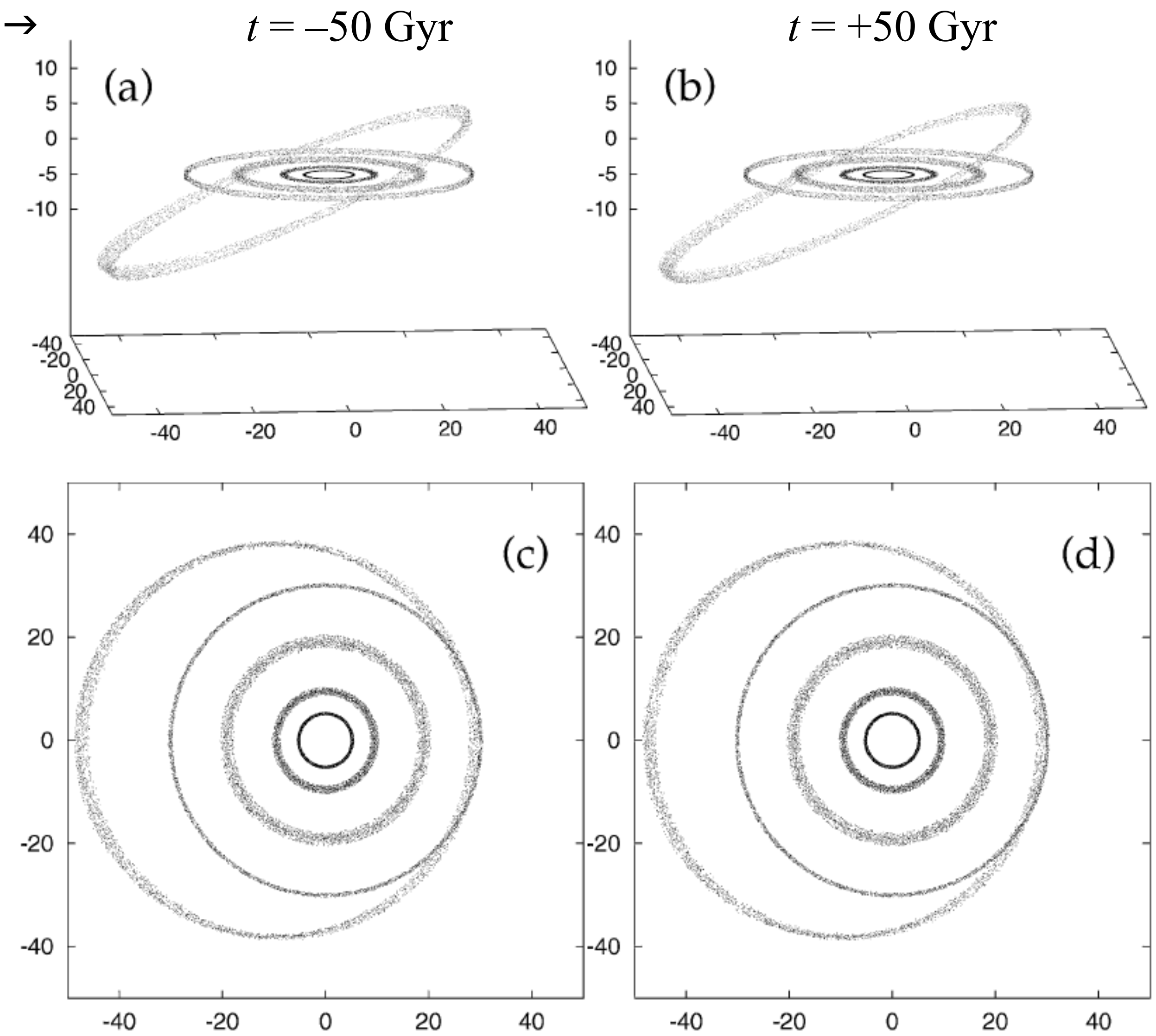
- Pluto’s orbit is peculiar. In particular, the motion of its perihelion has two characteristics
  - (a) Pluto always encounters Neptune near Pluto's aphelion, not perihelion
    - A consequence of the 3:2 mean motion resonance between Pluto and Neptune
  - (b) Pluto’s argument of perihelion always stays around 90 deg

- Question: What would happen if the orbital architecture of the three major planets is different from the current state?
- Answer from our numerical experiments
  - (a) remains in many cases even with different planetary configuration
  - (b) disappears if we remove or significantly change any of the three giant planets (Jupiter, Saturn or Uranus) from the system

- These facts may serve as evidence of the origin and evolution of Pluto’s (and Plutino’s) peculiar orbit

Pluto's orbit – peculiar and stable

1.814 x 10^9 years around →



Note: Pluto's perihelion is fixed along the x-direction

[Ito & Tanikawa (2002)](https://example.com)

Characteristics of Pluto's perihelion motion

- Pluto always encounters Neptune near Pluto's aphelion
  - Pluto's perihelion stays ~90 deg away from Neptune's longitude
    - Consequence of the 3:2 mean motion resonance (mmr)
      - $\phi = 3\,\lambda_{\mathrm{Pluto}} - 2\,\lambda_{\mathrm{Neptune}} - \varpi_{\mathrm{Pluto}} \sim 180$ deg
  - "azimuthal libration"

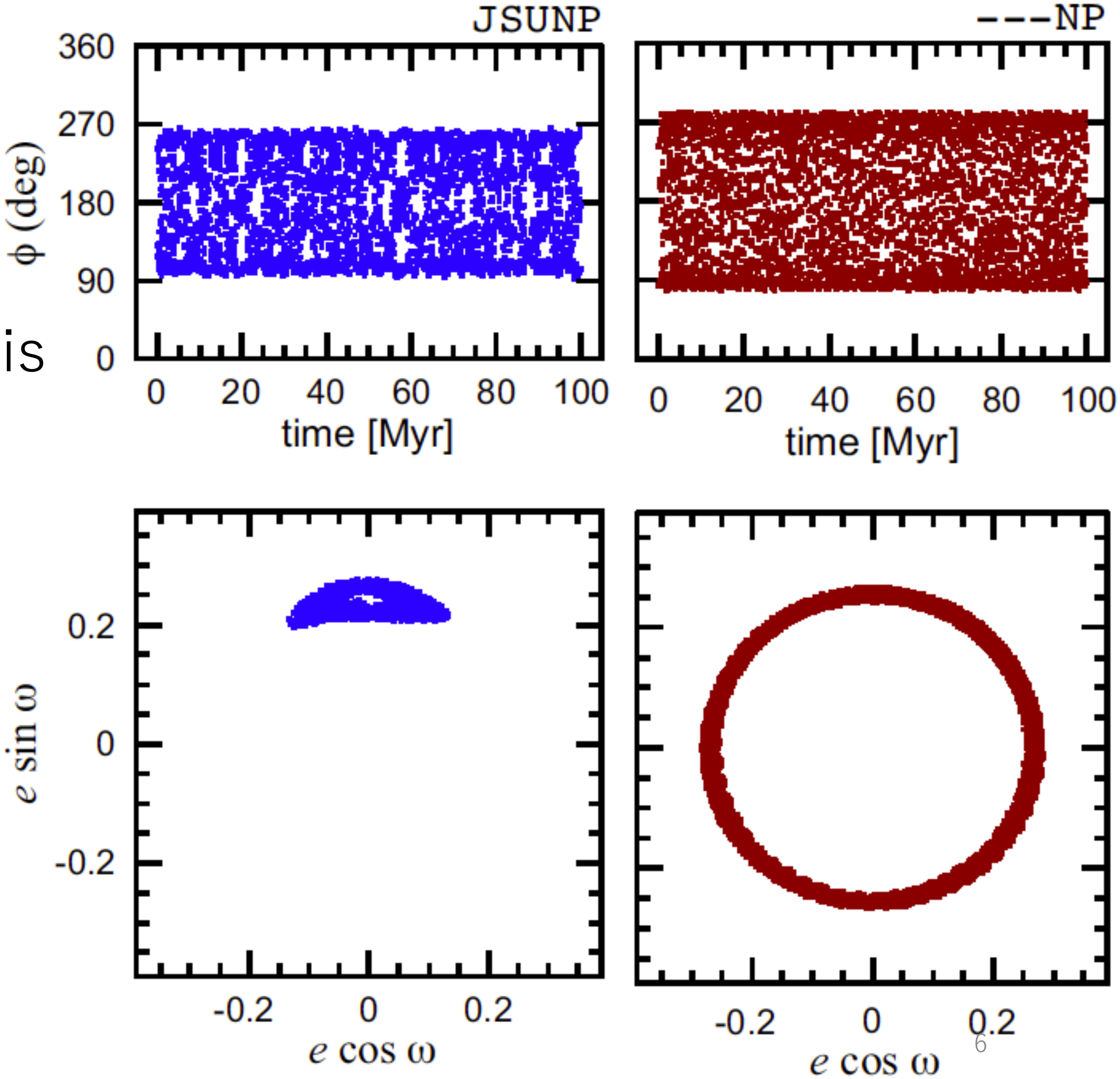
- Pluto's argument of perihelion always stays around 90 deg
  - $\omega \sim 90$ deg
  - "latitudinal libration"

  ➢ Both characteristics contribute to Pluto's orbital stability

- Question:
  - How robust are these two librations?
  - What about the role of other giant planets? (Jupiter, Saturn, Uranus)

Experiment 1

- The azimuthal libration remains even when there is no other giant planet
  - (the "---NP" system)
- The latitudinal libration over long term requires all of Jupiter, Saturn, and Uranus
  - (the "JSUNP" system)



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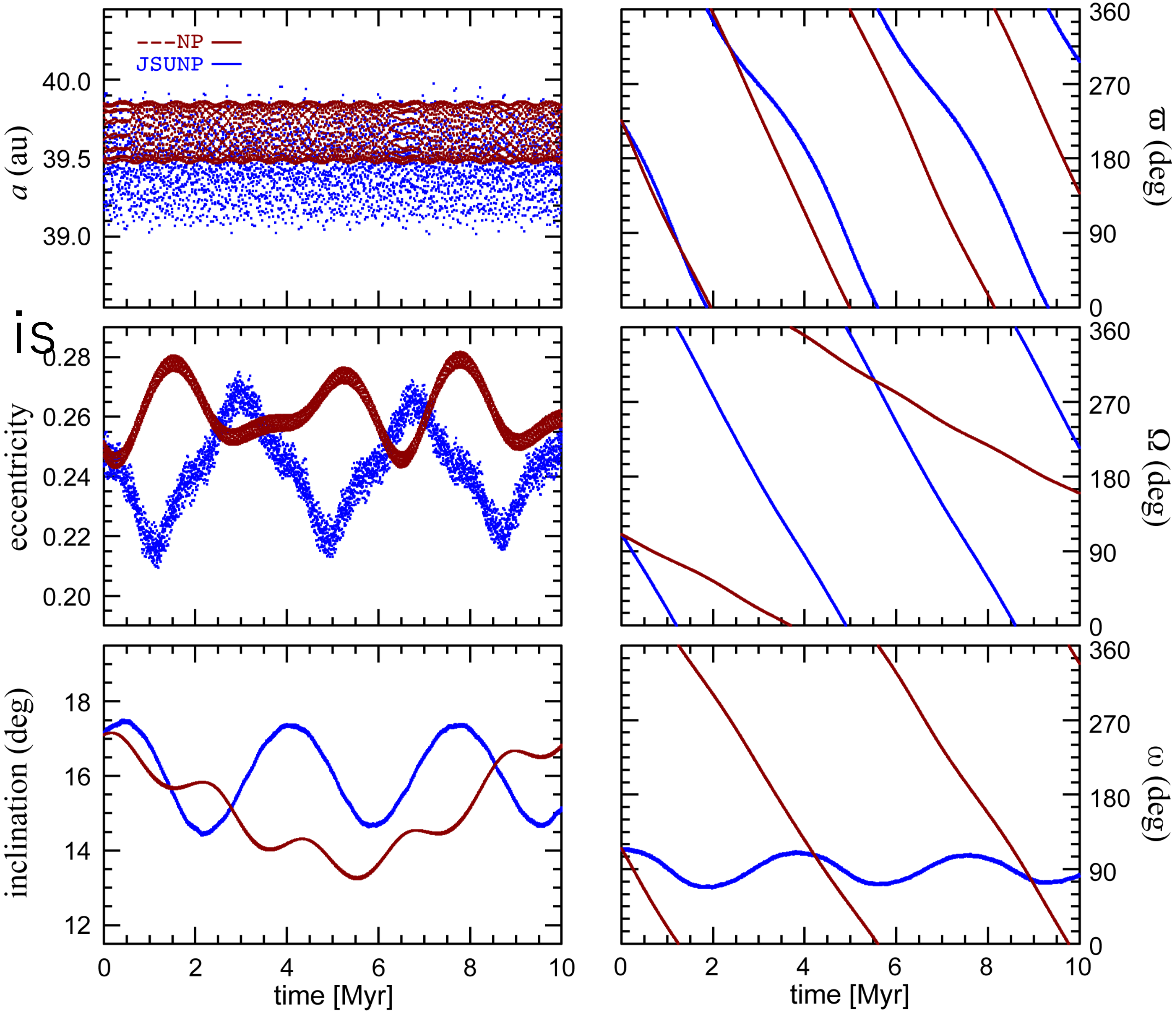
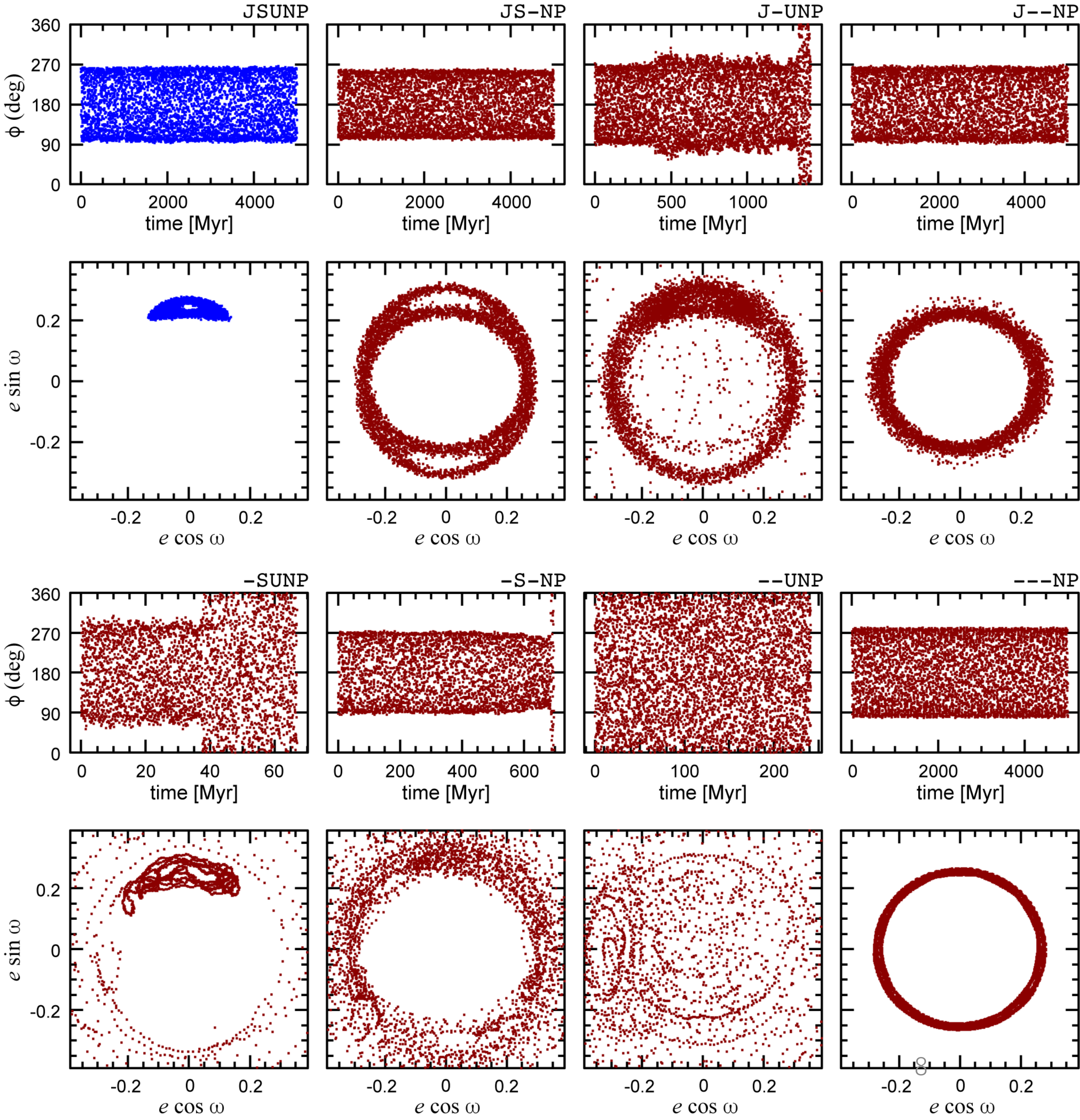


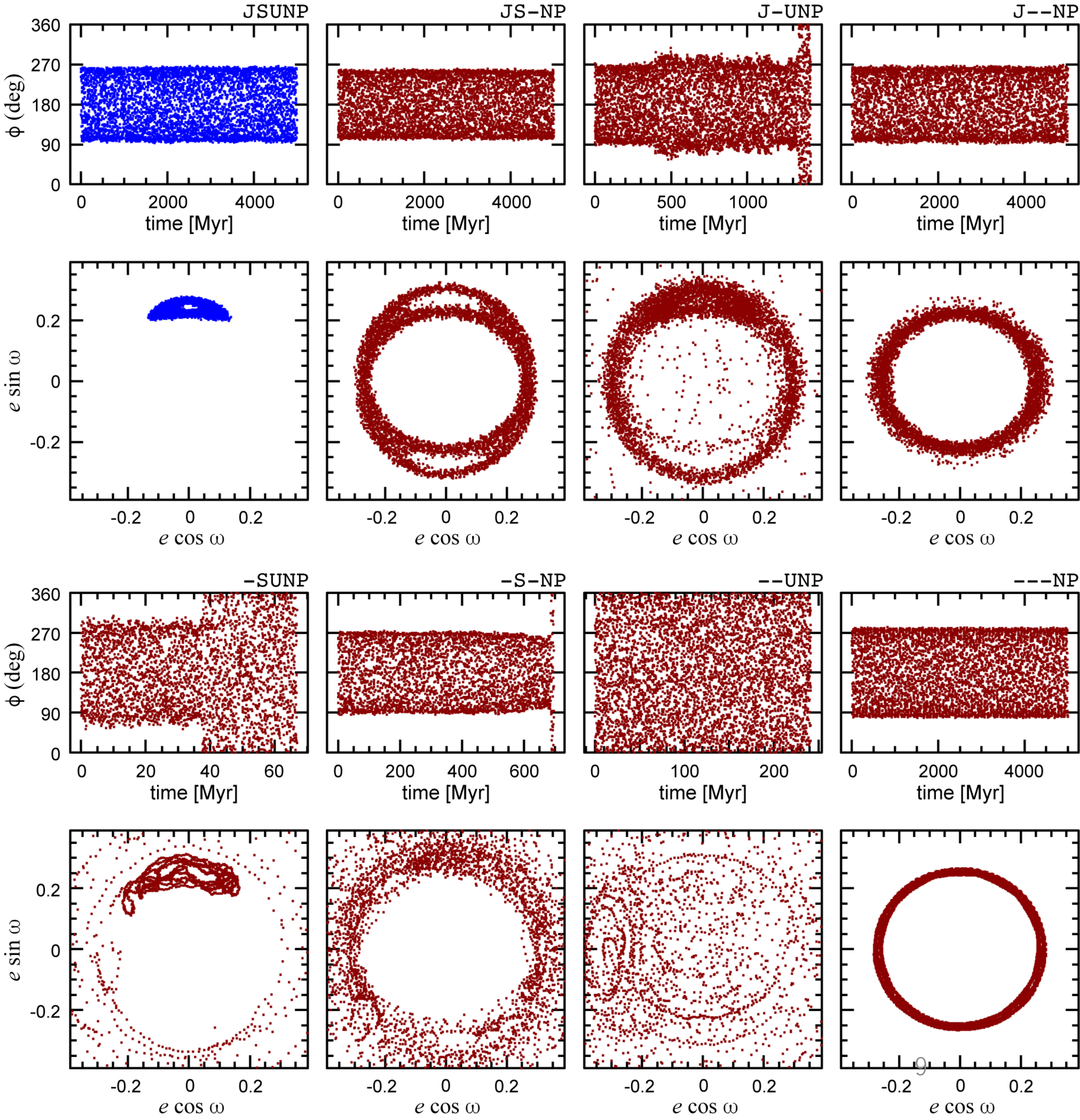
Experiment 2

- The azimuthal libration (the 3:2 mmr) remains in some cases, and it breaks in some other cases:
  - J-UNP, -SUNP, -S-NP, --UNP
  - Pluto's orbit gets unstable

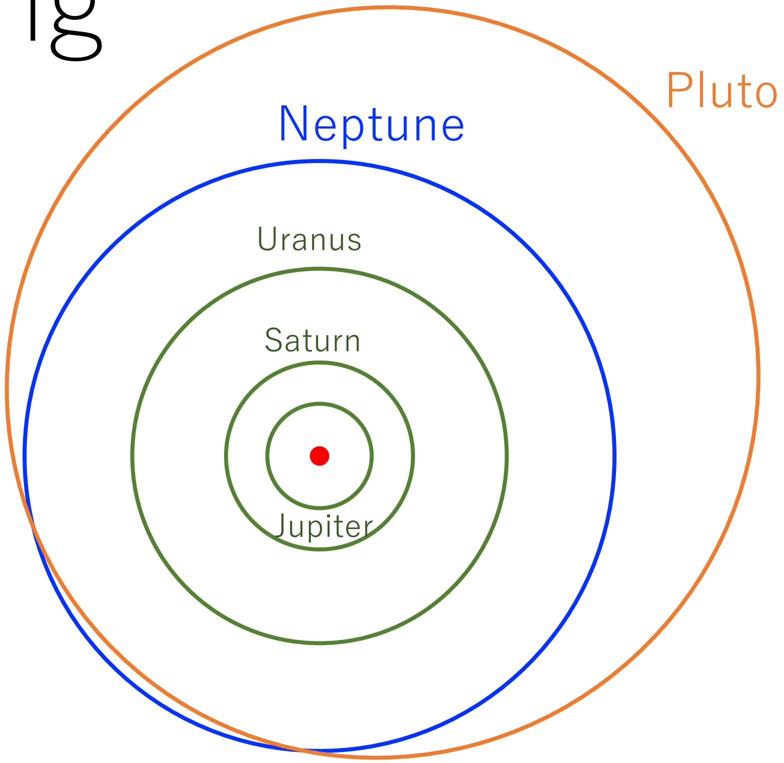


Experiment 2

- The latitudinal libration ($\omega \sim 90$ deg) remains only in the JSUNP system



Quantification of planet's forcing



- Averaged (secular) perturbation from the inner three giant planets can be modeled as the effective oblateness of the Sun
  - The potential caused by an averaged ring

$$V_{\rm ring} = -\frac{Gm_{\rm p}}{r}\left[1 + \sum_{k=1}^{\infty}\left(\frac{a_{\rm p}}{r}\right)^{2k} P_{2k}(0)P_{2k}\left(\frac{z}{r}\right)\right]$$

  - The Sun's non-sphericity causes the potential

$$V_{\odot} = -\frac{Gm_{\odot}}{r}\left[1 - \sum_{k=1}^{\infty} J_{2k}\left(\frac{R_{\odot}}{r}\right)^{2k} P_{2k}\left(\frac{z}{r}\right)\right]$$

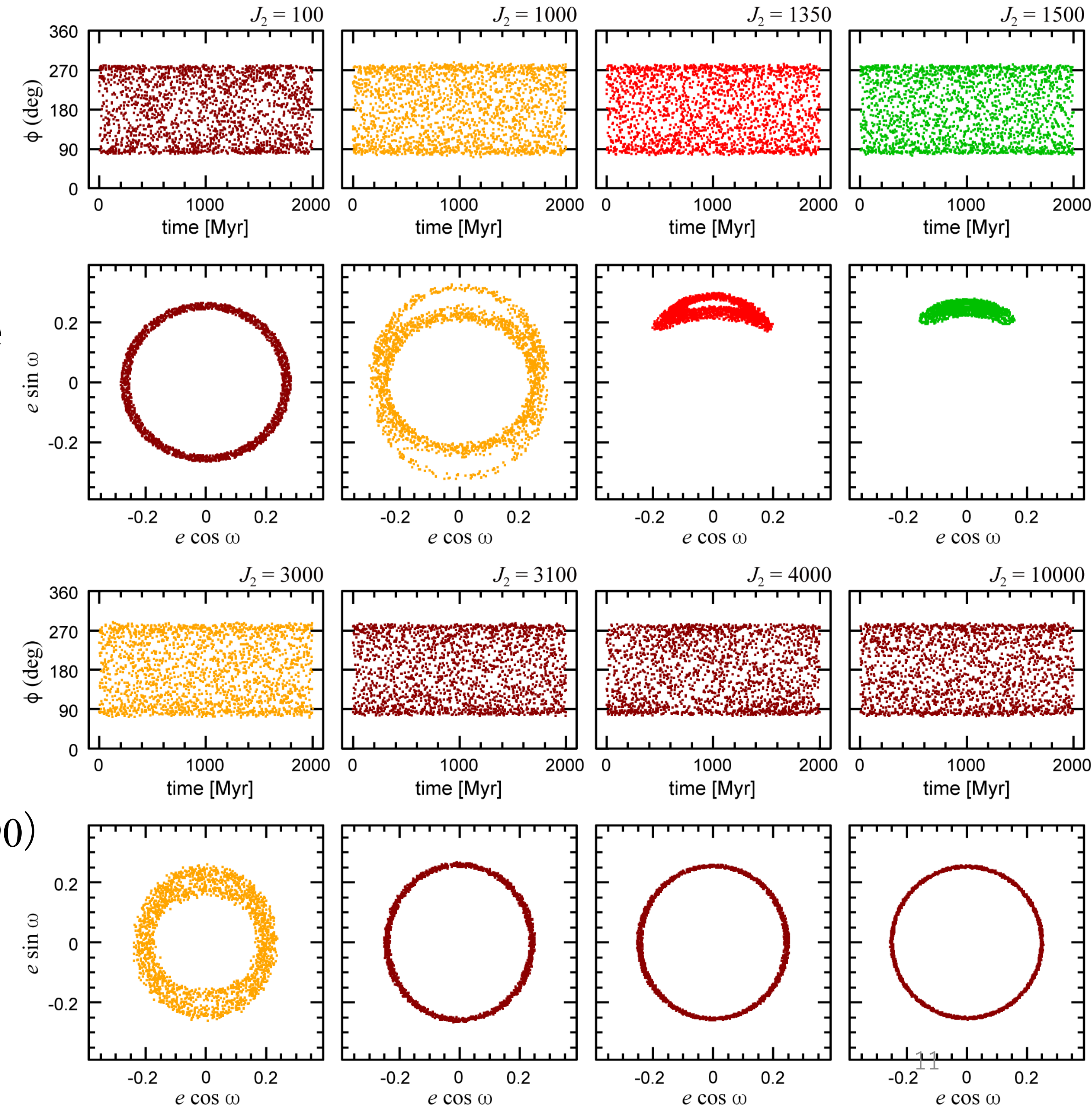
  - The "effective" J_2

$$J_{2,\rm eff} = \frac{1}{2}\frac{m_{\rm p}a_{\rm p}^2}{m_{\odot}R_{\odot}^2}$$

planet	$m_{\odot}/m_{\rm p}$	$a_{\rm p}$ (au)	$J_{2,\rm eff}$
Jupiter	1047.3486	5.2076	592.5
Saturn	3497.898	9.5725	605.5
Uranus	22902.98	19.3038	376.1
Total			1574.1

Experiment 3

- Investigating the influence of other planets on the ---NP 3-body system by varying the effective J_2 of the Sun
  - The azimuthal libration (the 3:2 mmr) remains
  - The latitudinal libration ($\omega \sim 90$) happens only in the narrow rang$1350 \lesssim J_2 \lesssim 1650$: J_2
    -



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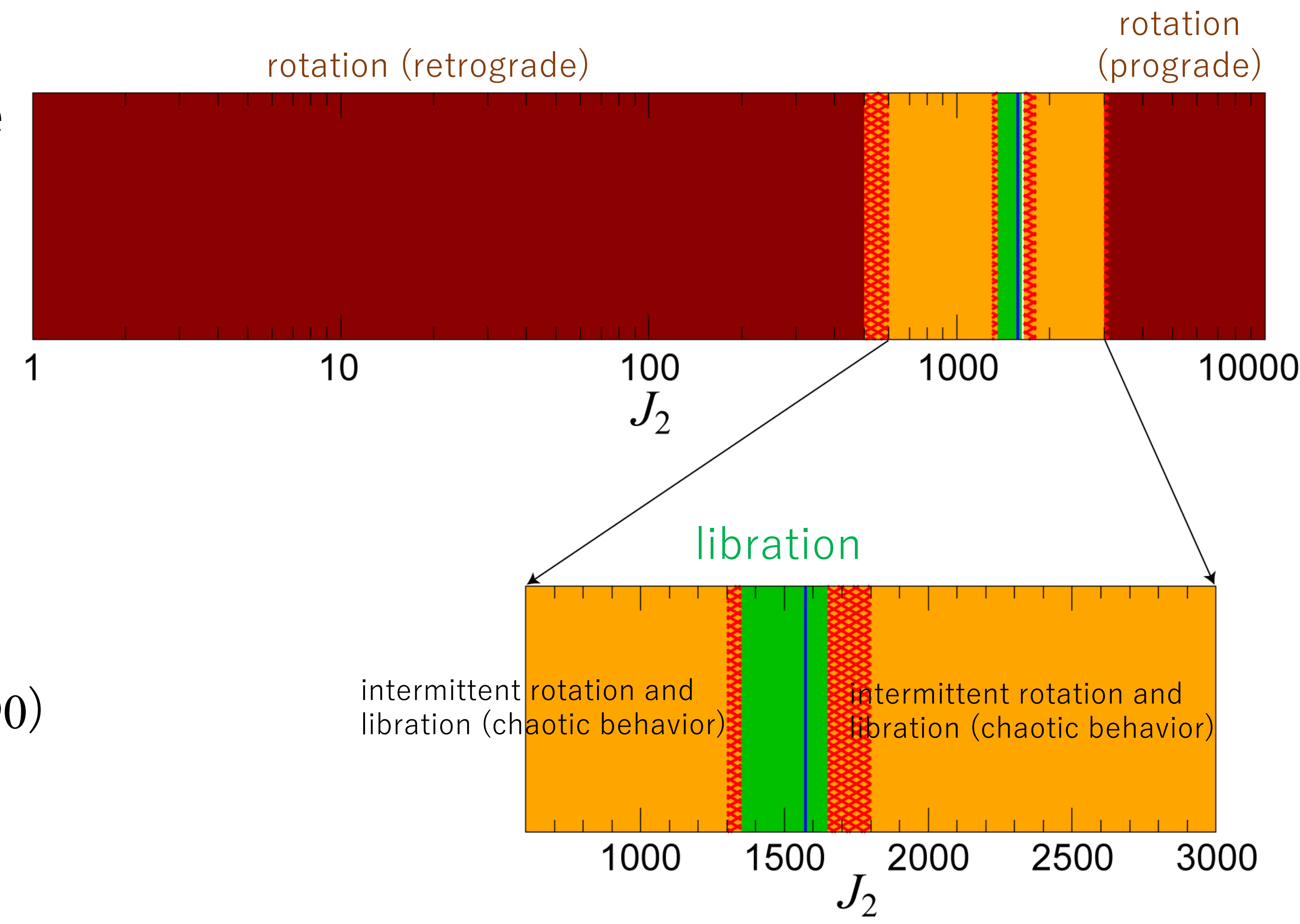
Behavior of Pluto’s argument of perihelion over 2 Gyr



Summary

- The azimuthal libration of Pluto’s can be destroyed if the planetary architecture is different from the present one
- The latitudinal libration can be is sustained only in a very narrow range of giant planet’s secular forcing
- Jupiter has a largely stabilizing influence, while Uranus has a largely destabilizing influence on Pluto's orbit
  - More complicated dynamics must be at work in the actual solar system, such as the near 2:1 mean motion resonance between Neptune and Uranus

Future work

- (semi-)Analytically figure out the dependence of the latitudinal libration on Pluto's inclination – Finding "critical inclination"
  - The classical von Zeipel-Lidov-Kozai (vZLK) three-body framework gives $I_{\mathrm{critical}} > 56$ deg ($\gg$ Pluto's current $I \sim 17$ deg) von Zeipel (1910), Ito & Ohtsuka (2019)
  - So, the current latitudinal libration of ω is far from being obvious

- Quantitatively examine how the radial migration of major planets has affected the latitudinal libration of Pluto's ω
  - This may give constraint on how the Plutinos formed

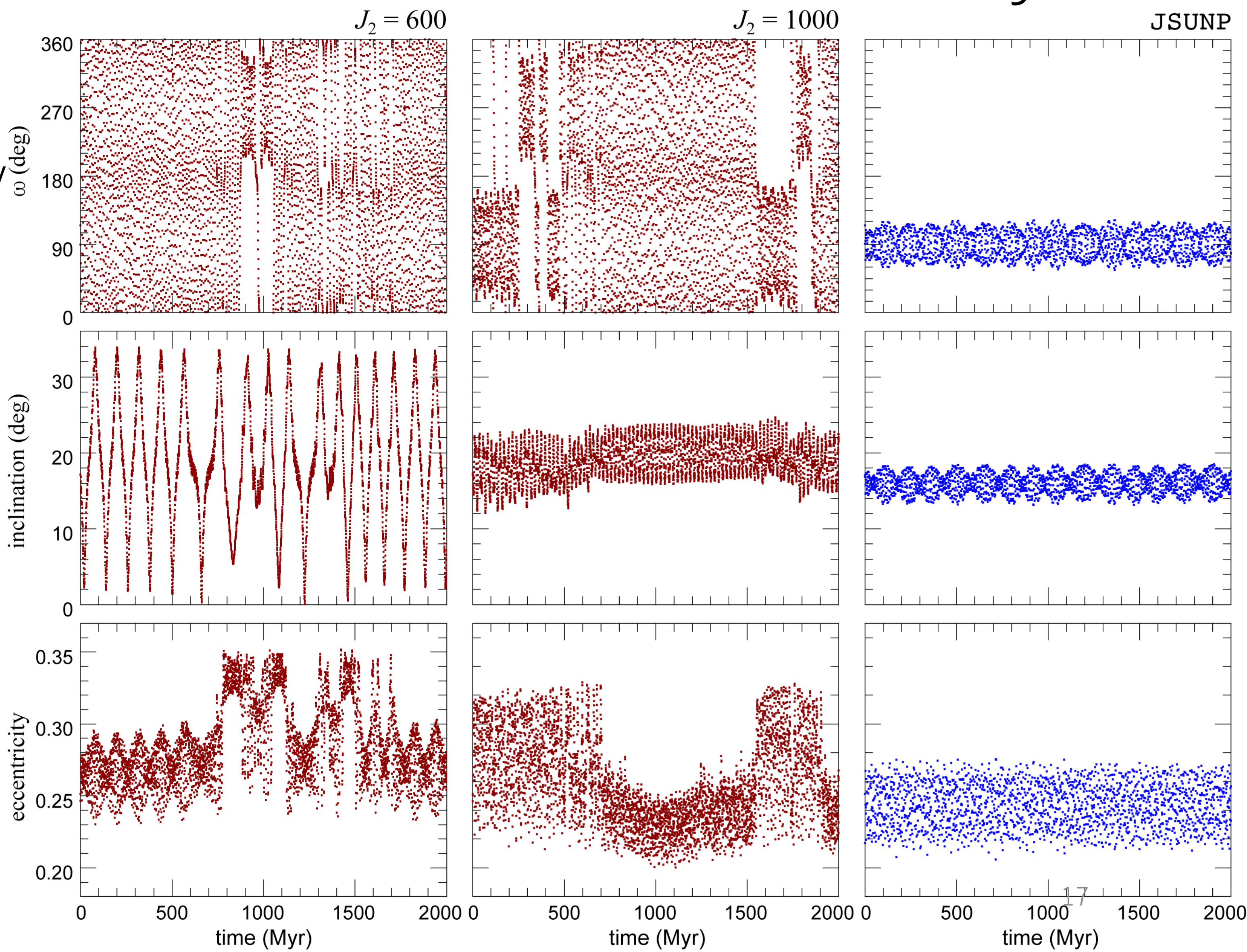
Thank you very much

See for more detail: https://arxiv.org/abs/2204.04121

Appendix

The azimuthal libration and orbital stability

- When Pluto's argument of perihelion ω is not in the steady libration, its eccentricity e gets pumped up to a greater extent
- The smaller perihelion distance $q = a(1\text{-}e)$ that is achieved with larger eccentricity e leads to a larger destabilizing influence
  - Frequency of closer approaches with Uranus increases
- Actual TNOs in the 3:2 mean motion resonance ("Plutinos") are limited to $e < \sim 0.3$
  - e.g. Gladman & Volk (2021)



An estimate about the influence of giant planet's migration

- Time evolution of the total effective J_2 for a simple migration model in which the planets' orbits migrate with an e-folding timescale τ. The magnitude of each planet's migration is indicated in the figure legend.
- The total effective J_2 would have remained within the range 1350–1650, provided that the magnitude of Uranus' outward migration was $< \sim 5$ au. This is what we found for Pluto's long-term stability in its current orbit.
- An outward migration of Uranus by more than 5 au would potentially change the total effective J_2 enough to transition from the latitudinal libration of Pluto's ω being unstable to stable.