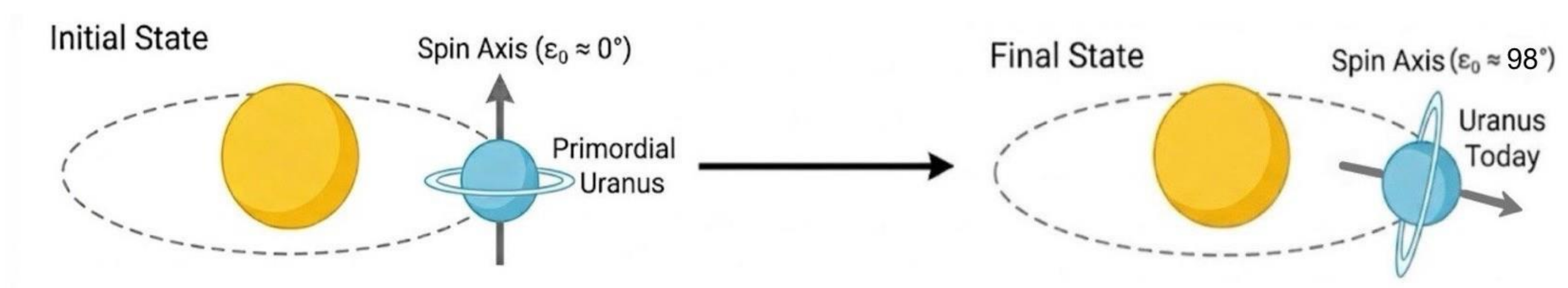
The Weird Case of Uranus' Rotation Axis Tilt

Leonor Bernardo[1], Pedro Machado[2,1], Alexandre C. M. Correia[3], and Sérgio Gomes[4]

[1]Faculdade de Ciências da Universidade de Lisboa (FCUL), Portugal
[2]Instituto de Astrofísica e Ciências do Espaço (IA), Portugal
[3]CFisUC, Department of Physics, University of Coimbra, Portugal
[4]Anton Pannekoek Institute for Astronomy (API), Univ. of Amsterdam, Netherlands

Abstract:

Motivation



Uranus is currently tilted 98°. How could that have happened?

- **Giant Impact Hypothesis (Common Justification)**

A **grazing collision** with a 1 – 3 $M_{\oplus}$ body can explain the tilt but **lacks self-consistency** due to highly constrained impact parameters.

- **Dynamical Alternative (This Work)**

Outward tidal migration of a massive ancient satellite drives the planet into secular **spin-orbit resonances.** [1, 2]

***Saillenfest et al. (2022)* [2]** show that an ancient satellite with $M_{sat} \geq 4{\times}10^{-4}\, M_U$ **could successfully tilt Uranus**.

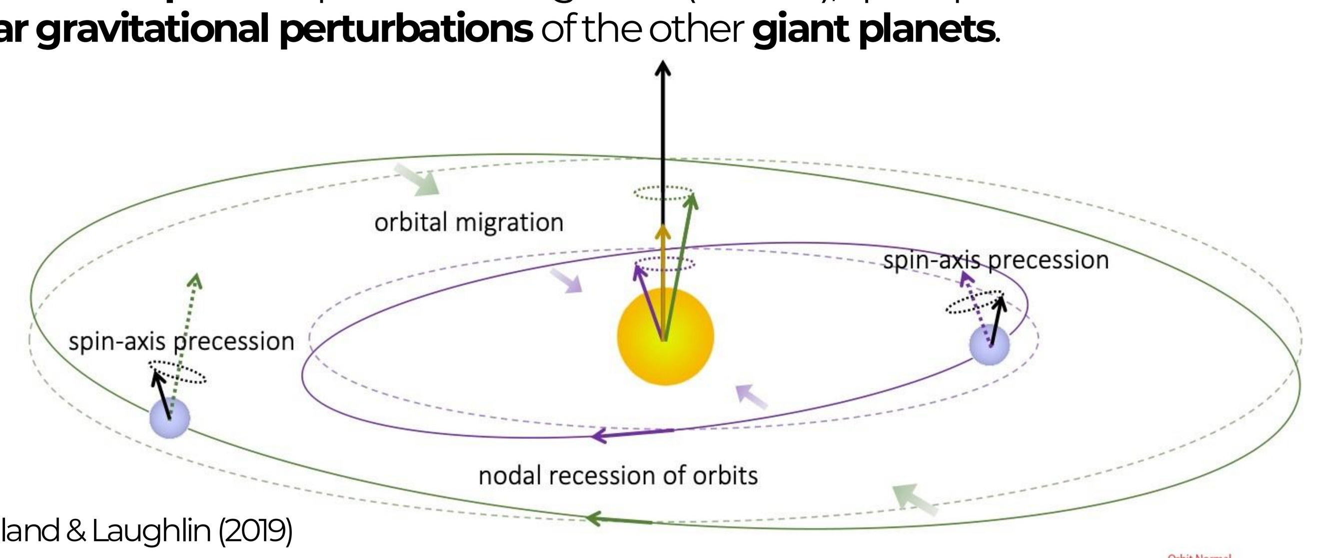
- **Project Goal**

Numerically revisit and extend these findings using the **self-consistent** open-source *N*-body code **TIDYMESS** [3].

Spin-Axis Dynamics – How Uranus Tilts

- **Secular Perturbations**

Uranus' **orbital plane** experiences long-term (secular), quasi-periodic variations due to the **secular gravitational perturbations** of the other **giant planets**.



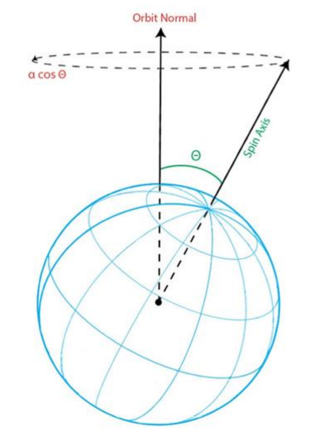
Millholland & Laughlin (2019)

These perturbations continuously shift ν_k, which is the **orbital plane precession frequency**.

- **Resonance Trigger**

When the planet's spin precession frequency matches a ν_k a **spin-orbit resonance** is triggered:

$$\alpha \cos(\varepsilon) \approx \nu_k$$



Lu & Laughlin (2022)

- **The Resonant Hamiltonian**

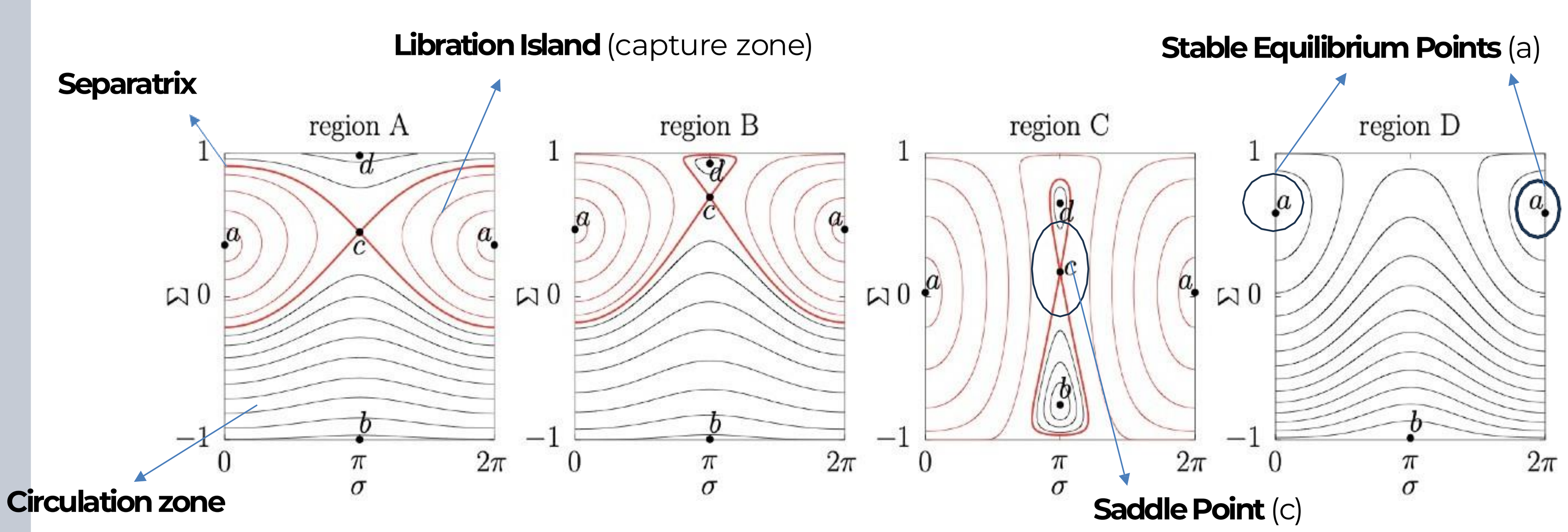
Analytical **mapping** of the **capture (resonance) zones is described by** the reduced Hamiltonian

$$\mathcal{H} = -\frac{1}{2}X^2 + \gamma X + \beta\sqrt{1 - X^2}\cos\sigma\,,$$

Where X = cos(obliquity), σ is the **resonant angle**, γ, β control the **location** and **width** of the **resonance**.

- **The Driving Mechanism**

As the satellite migrates, it **modifies** α, **changing** γ **and** β. This causes the **capture zones** to **shift**, and if caught inside it **tilts** the planet.



Phase portraits [1] illustrating the Hamiltonian level curves.
Parameters from A to D: (γ, β)= (0.4,0.1); (0.55,0.15); (0.05,0.7); (0.8,0.3). $\Sigma = -X$

Methodology

Building on the scenarios proposed by [2] using **TIDYMESS** , we **investigate and broaden the parameter space** of a migrating satellite (especially M_{sat} and migration rate τ) to **determine the conditions** that drive Uranus **to its current state**.

Steps implemented to expedite the simulations:

- **Setup Simplification**

All bodies (Sun, Giants, and the Satellite) are treated as **point masses** (R_{sat} = 0) except for Uranus.

- **The Multiplier Factor**

A linear tidal model **numerical multiplier** $\tau' = \tau \times mult$ **accelerates** the **migration rate** by that factor.

Results

Parameter Space Exploration

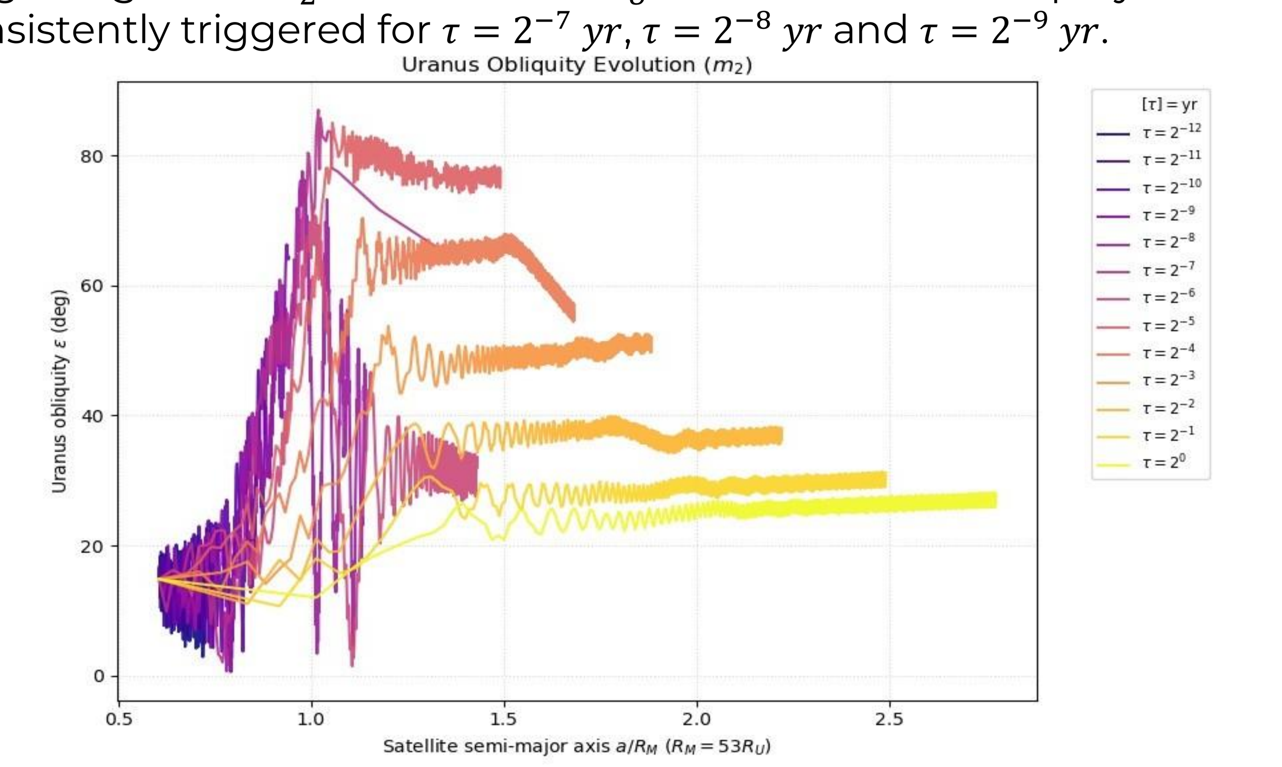
The results of our simulations are summarized in the following table:

Scenario	Mass (M_U)	Initial ε_0	Obliquity Increase ($\Delta\varepsilon$)	Regime
m_2	233×10^{-5}	$\leq 15°$	$> 70°$	Resonant Capture
m_8	244×10^{-5}	$< 30°$	$> 70°$	Resonant Capture†
m_6	368×10^{-5}	$\geq 10°$	$> 60°$	Resonant Capture†
m_3, m_5, m_7	Lower-mass	Any	$\Delta\varepsilon_{max} \sim 15°$	Insufficient Tilting

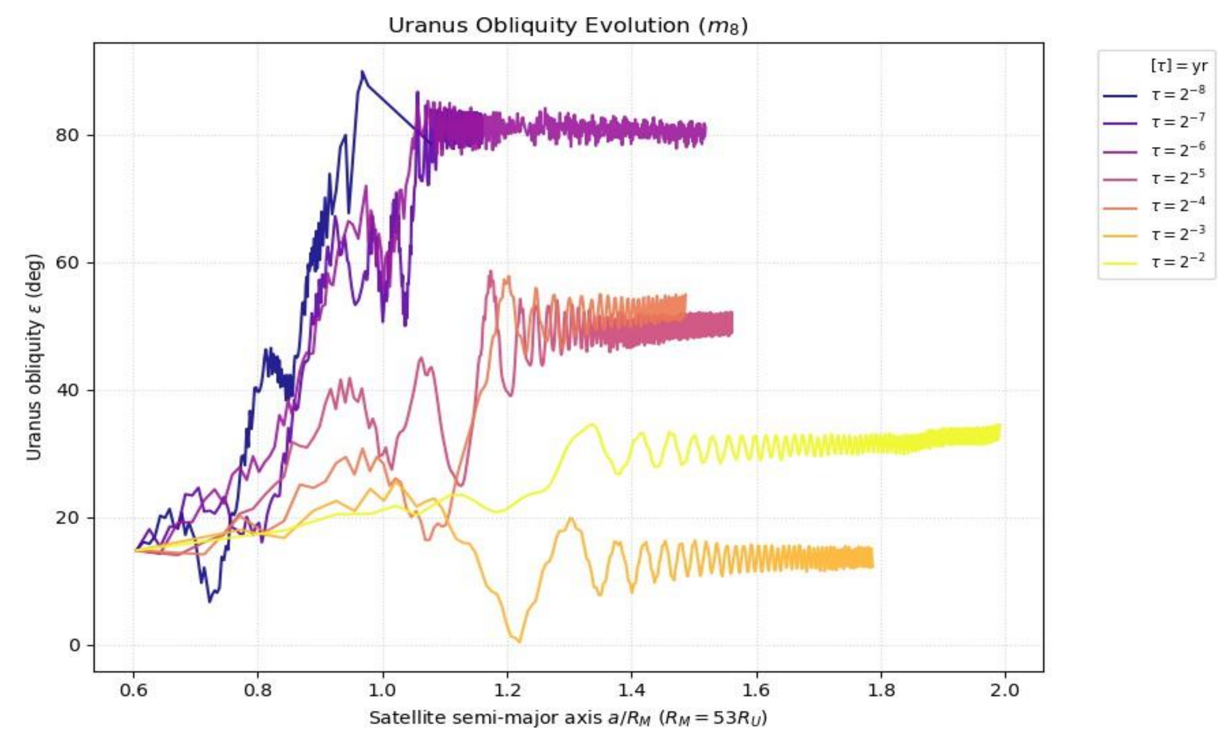
†Novel parameter runs not reported in previous literature.

Examples of successful configurations:

- Migrating mass m_2= $233 \times 10^{-5}\, M_U$. Most relevant obliquity increases were consistently triggered for $\tau = 2^{-7}\, yr$, $\tau = 2^{-8}\, yr$ and $\tau = 2^{-9}\, yr$.



Another successful configuration is for the migrating mass $m_8 = 244 \times 10^{-5}\, M_U$:



Multiplier & Scaling Validation

- Optimal Simulated Lag of $\boldsymbol{\tau = 2^{-9}\, yr}$ → numerical acceleration factor of 10^3

$\tau_{\text{eff}} = \frac{2^{-9}}{10^3} \approx 1.95 \times 10^{-6}$ yr → $\boldsymbol{Q \approx 80}$, value for rocky planets and moons.

- Within 8 × of Uranus' current τ_U ($\tau_U \approx 2.31 \times 10^{-7}\, yr$, $Q_U = 678$).

Post-Capture Instabilities

- $a \approx r_M = 53\, R_U$ and $\varepsilon \approx 90°$ → Instability Region.
- Triggers three distinct pathways: **satellite ejection**, **unpredictable satellite behaviour** and **orbit stabilizing near** resonance **peak**.

Precession Angle (ψ_0) Sensitivity Test

- m_8 modeled ($\varepsilon_0 = 15°, \tau = 2^{-9}\, yr$) and random sampling of ψ_0 from 0 to 2π.
- Indication that capture might be sensitive to ψ_0 (contrary to assumptions by [2]): **70% Capture Success** rate via σ_2 resonant angle to drive $\varepsilon > 83°$.

Conclusions & Future Work

- **Tidal migration** of an ancient satellite **drives high tilting for Uranus** without giant impact under some circumstances.
- **Extended parameter space** to higher masses (m_6, m_8).
- Indication that **final obliquity might depend** on Uranus' primordial precession angle.

Next Steps

- Adding **presente-day satellites**.
- Simulating **hybrid impact + tidal migration scenarios**.
- **Continuing to vary the parameter space** (*eg.* satellite densities (ρ_{sat}) and exploring non-synchronicity).

References

[1] Saillenfest, M., etal. (2021). Astronomy& Astrophysics, 647:A92.
[2] Saillenfest, M., etal. (2022). Astronomy& Astrophysics, 668:A108
[3] Boekholt, T. C. N. & Correia, A. C. M. (2023). Monthly Notices of the Royal Astronomical Society, 522(2):2885-2900.
[4] Morbidelli, A., etal. (2012).Icarus219(2):737-740.

Acknowledgements

I would like to express my gratitude towards my supervisors and Dr. Tjarda Boekholt for their crucial help and guidance.

PORTUGUESE SPACE AGENCY
ANTON PANNEKOEK INSTITUTE
Ciências ULisboa