Analysing Possible Scenarios for the Formation of Neptune Arcs

S.M. Giuliatti Winter & G. Madeira
GDOP, UNESP, Brazil
Institut de Physique du Globe de Paris, France

CONTACT: giuliatti.winter@unesp.br

ACKNOWLEDGEMENTS: We thank FAPESP (2016/24561-0, 2018/23568-6), CNPq (312043/2020-5), and CAPES for the financial support.

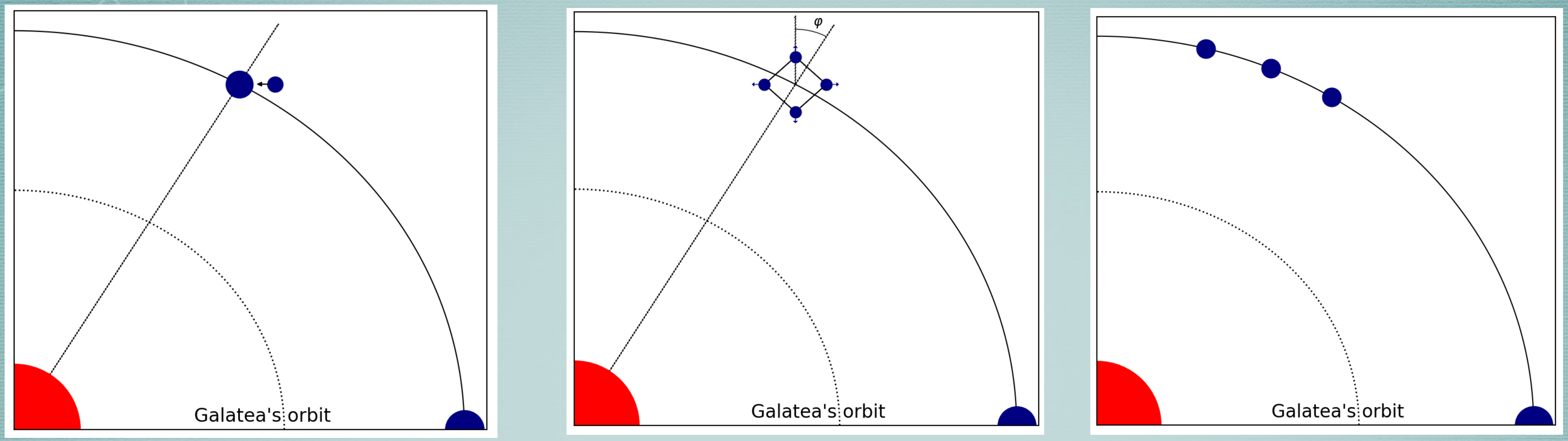
INTRODUCTION

- Confirmed by ground-based observations (Sicardy et al., 1991) and Voyager II images (Smith et al, 1989), the 4 arcs of Neptune, known as Fraternité, Egalité, Liberté and Courage, are the densest parts of the Adams ring;
- Angular widths from 2deg to 9deg and radial width of 15km (Porco et al, 1995);
- Keplerian motion can spread the arcs in about 3yrs, confinement mechanism is necessary to constrain the arcs;
- Renner et al (2014) proposed that the arcs are radially confined by Galatea and azimuthally by 4 small co-orbital satellites;
- Observations showed that the arcs have changed location and intensity (Pater et al, 2005, Showalter et al., 2013, Renner et al, 2014).

- **GOAL**: (i) verify the final location of a sample of fragments, formed near the lagrangian point of a initial satellite S_1 and (ii) analyse three mechanisms of dust production capable of generating the arcs of Neptune.

Formation of the fragments

(a) (b) (c)



In light of the Janus/Epimetheus formation model proposed in Treffenstädt et al. (2015), we envision the following scenario for the formation of a $1+N$ co-orbital satellite system: Initially, we assume an ancient system composed of the moon $S1$ ($R_{S1} = 5.2$ km) and an object located at one of its triangular points (trojan). After an impact with an ongoing object (Figure a), the trojan disrupts forming a set of fragments (Figure b). The fragments perform horseshoe orbits with $S1$ and collide with each other, giving rise to moonlets. Finally, the moonlets settle into equilibrium positions of the system (Figure c).

TEMPORAL EVOLUTION OF FRAGMENTS FROM A SATELLITE DISRUPTION

The minimum trojan mass is $m_{tro} = 4 \times 10^{-2} m_{S1}$, corresponding to an object made of ice with physical radius of $R_{tro} = 1.8$ km. m_{tro} is approximately the sum of the masses of the moonlets S_2, S_3 and S_4 proposed by Renner et al. (2014).

For an impact of 3000 m/s, the minimum incident kinetic energy per mass Q_* required to disrupt the trojan is (Benz & Asphaug 1999)

$$Q_* = 2.7 \times 10^{-12} \left(\frac{R_{\rm tro}}{1\ \rm m}\right)^{-0.39} + 4 \times 10^{-2} \left(\frac{R_{\rm tro}}{1\ \rm m}\right)^{1.26} \ \rm J/kg.$$

The radius R_{imp} required for an ice impactor to disrupt the trojan can be estimated as (Stewart & Leinhardt 2012; Melita et al. 2017)

$$R_{\rm imp} = \left(\frac{3}{2\pi(10^3\ \rm kg/m^3)} \frac{Q m_{\rm tro}}{(3000\ \rm m/s + v_{\rm esc})^2}\right)^{1/3}$$

where v_{esc} is the escape velocity of the trojan and Q is the reduced kinetic energy of the system. For a disruption, $Q \geq Q_*$.

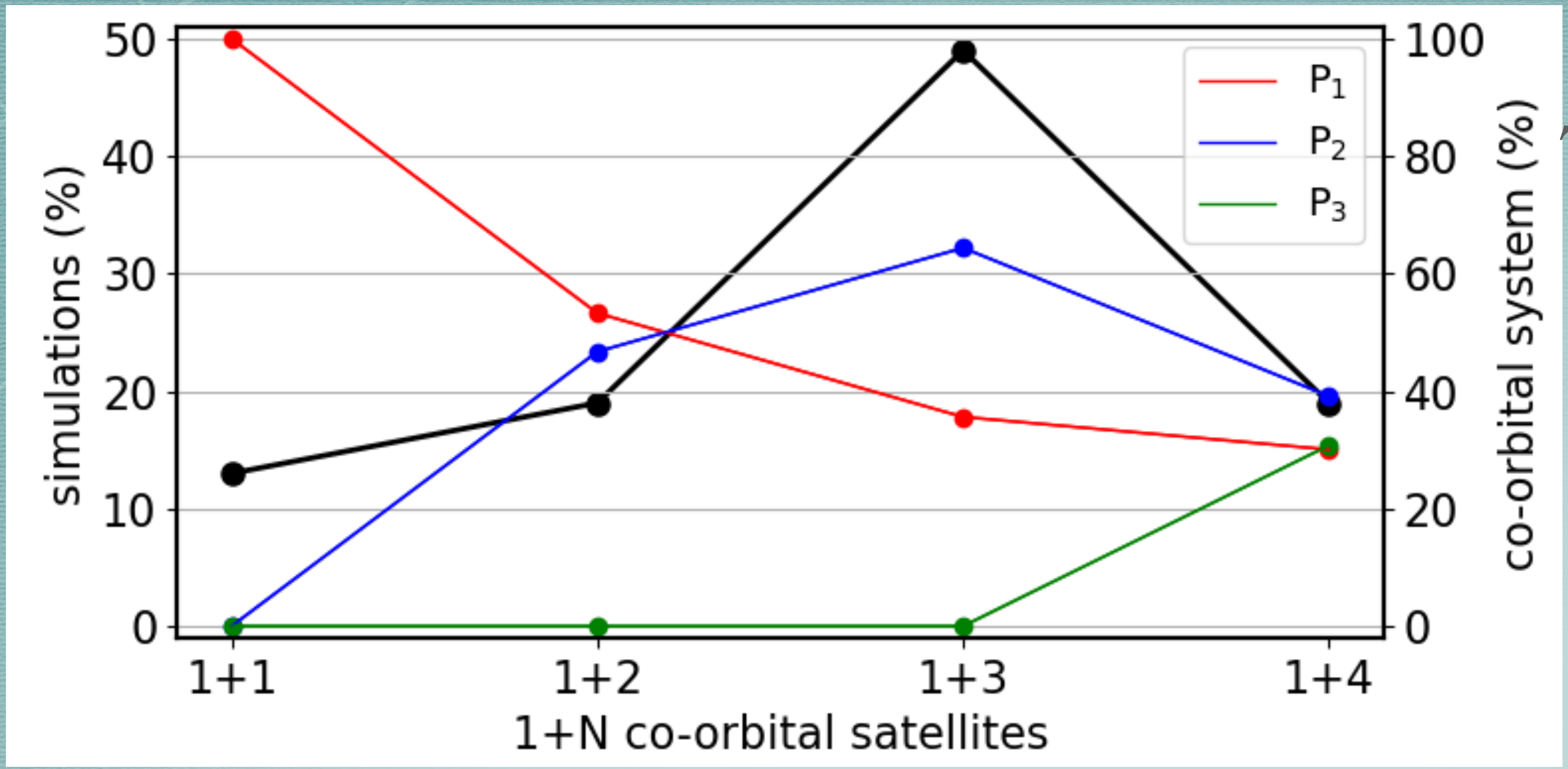
Benz & Asphaug (1999) shows that the mass of the largest remnant m_{lr} produced by the disruption of the trojan can be estimated as

$$m_{lr} = 0.5 - 0.6\left(\frac{Q}{Q_*} - 1\right) m_{tro}.$$

From these relations we find, for example, that a kinetic energy $Q/Q* = 1.4$ and an impactor of $R_{imp} \approx 100$ m are needed for the trojan to be destroyed and its largest remnant has the mass $m_{lr} = m_{tro}/4$.

If we assume that the arcs are composed of particles with physical radius s ranging from 1 μm to 1 m, following a numerical distribution given by $dN \propto s^{-3.5}ds$ (Colwell & Esposito 1992), we obtain that the complete destruction of the ongoing object and the confinement of its material would produce arcs with optical depth $\tau \sim 0.01$. Therefore, an 100 m-sized impactor does not hold the material needed to fill the observed arcs and additional mechanisms of production of material are required.

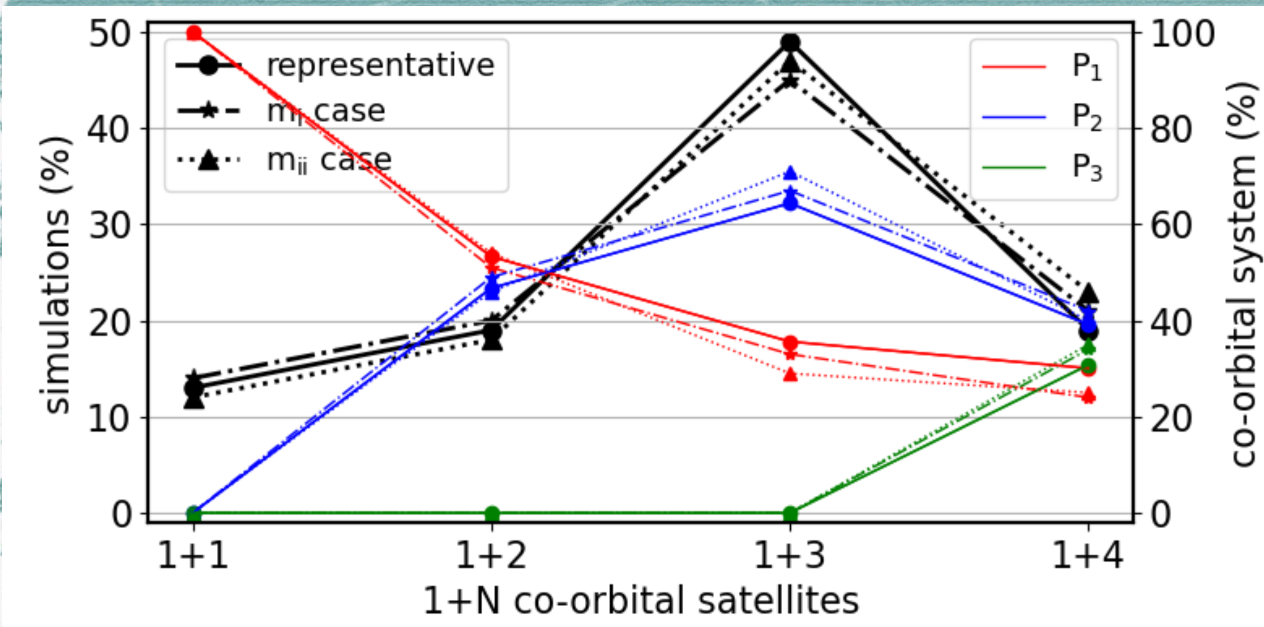
To assess whether the trojan disruption generates a family of co-orbital satellites, we performed a set of simplistic numerical simulations starting right after the trojan disruption. We used the *Mercury* package, with the Bulirsch–Stoer algorithm. The dynamical system is composed by included Neptune and its gravitational coefficients (J_2 and J_4), Galatea, the moon S_1, and the major fragments of the disruption. We also include the non-conservative term for carrying the fragments to the equilibrium positions.



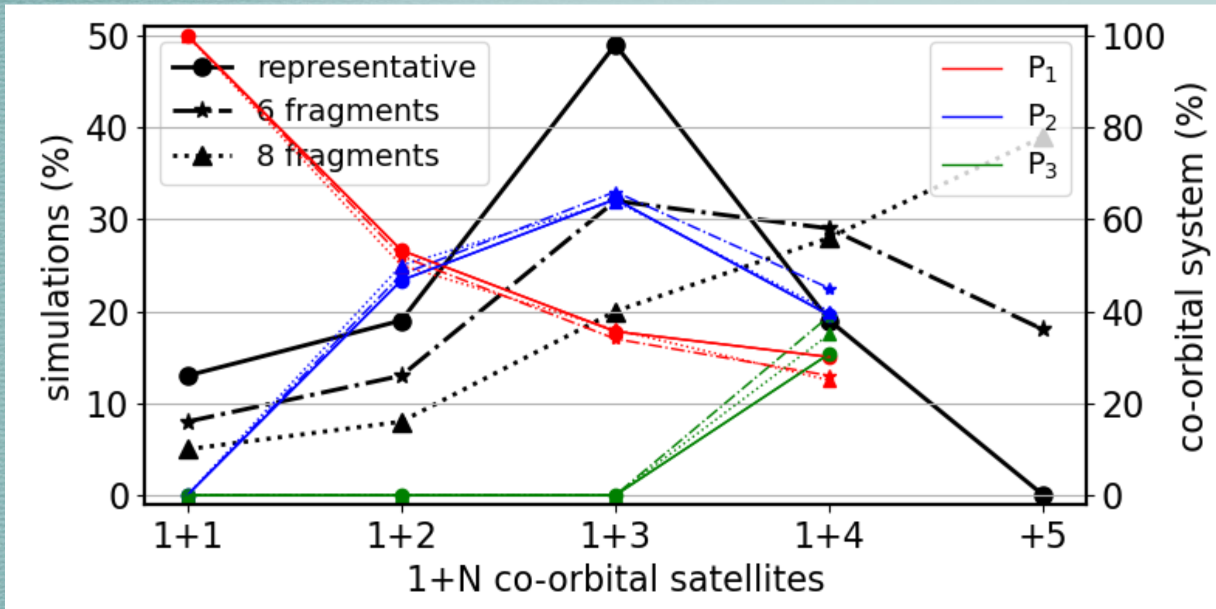
The representative case

Left y-axis give the fraction of 1+N co-orbital satellites obtained in the 3,000 numerical simulations (black line) while the fractions of systems in Pi configuration relative to each set of 1+N co-orbital satellite system (N =1, 2, 3, and 4) are given in the right y-axis (coloured lines). The dynamical system includes four fragments of same mass ($m_{fra} = 10^{-2} m_{S1}$), Neptune and its gravitational coefficients, Galatea, $S1$, and a non-conservative term $\nu = 10^{-4}$ yr^{-1}.

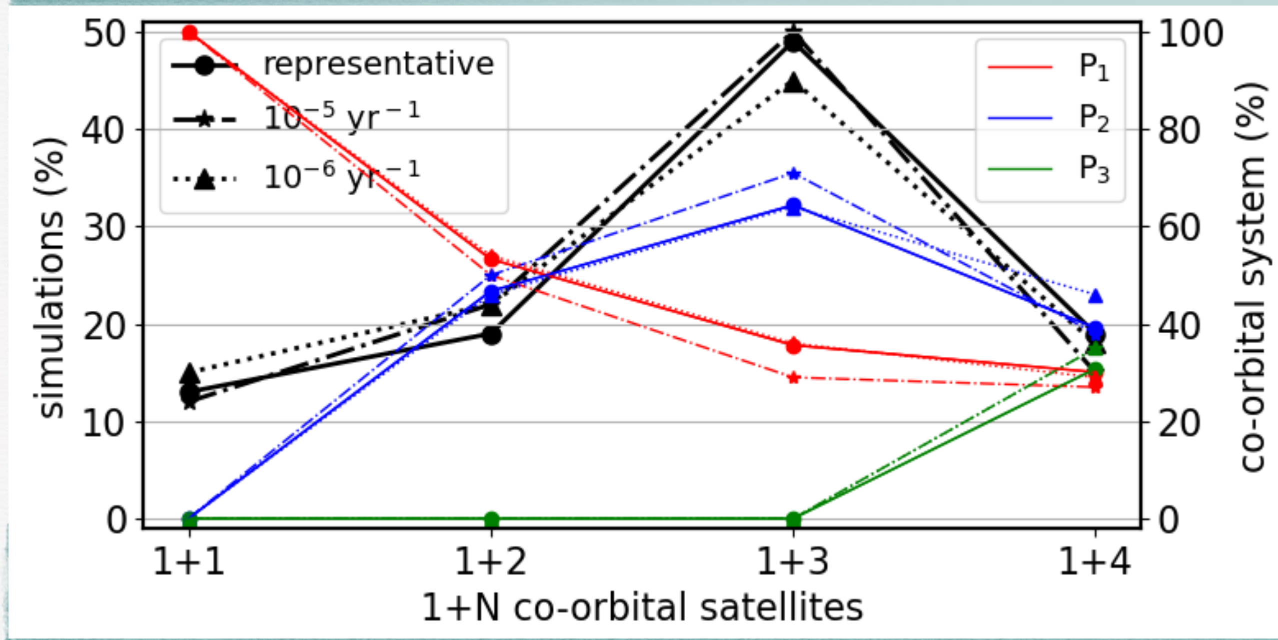
The nomenclatures "P$_i$" correspond to the label we'll use to refer to each equilibrium configuration: (1) all co-orbital are located near the triangular point, (2) the co-orbital are located in both lagrangian points and (3) symmetric configuration.



varying the size of
the fragments
50% and 25% smaller than the
representative case



varying the number of
the fragments



Varying ν

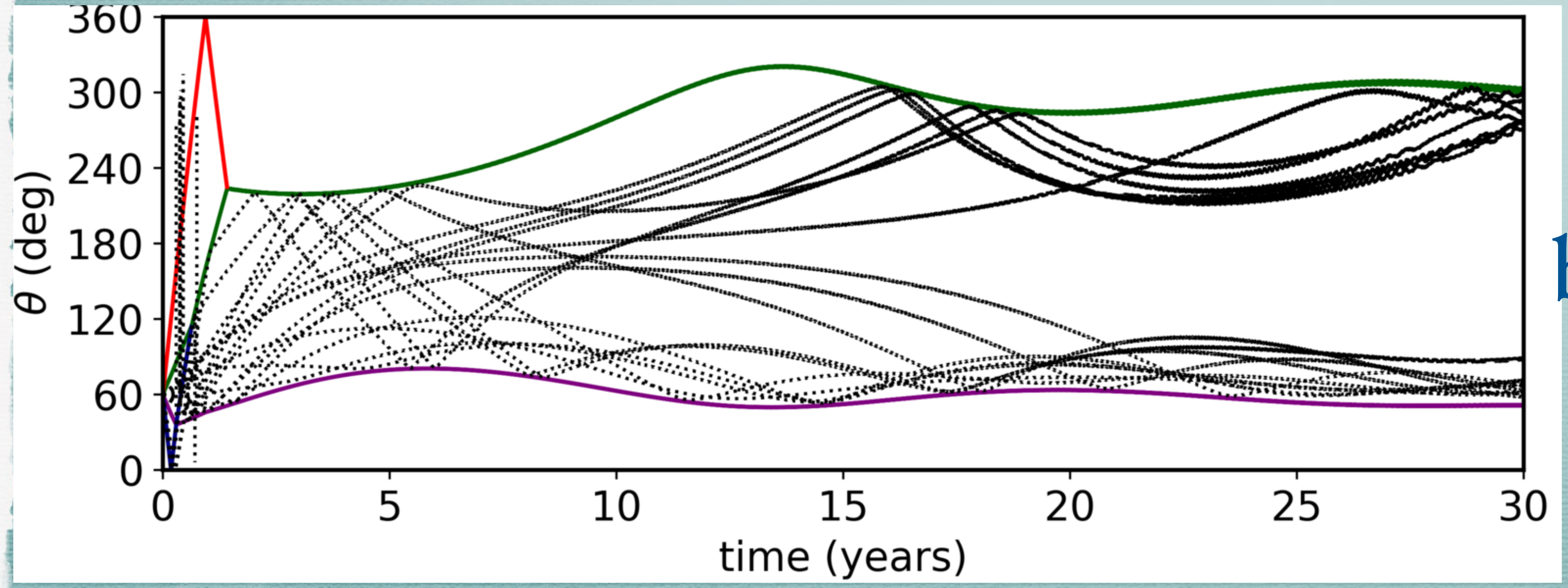
COMMENTS ON THE ARC FORMATION

Somehow, the Neptune arcs are probably composed by material produced by different processes. In the context of the scenario proposed, these material can be thought as produced in three different stages of the system:

I. Moon disruption stage:

To analyse the evolution of a fraction of debris (the collisions can form fragments and a fraction of debris) we did some numerical simulations of the representative case, distributing 500 massless particles randomly in the circle that circumscribes the fragments' polygon, with randomly chosen radial ejection velocities of 0.36 – 0.73 m/s. The non-conservative term was also applied to the particles.

Longitudinal evolution of four fragments (coloured lines) and a set of particles (black lines) initially distributed in the circle circumscribing the polygon of the fragments.



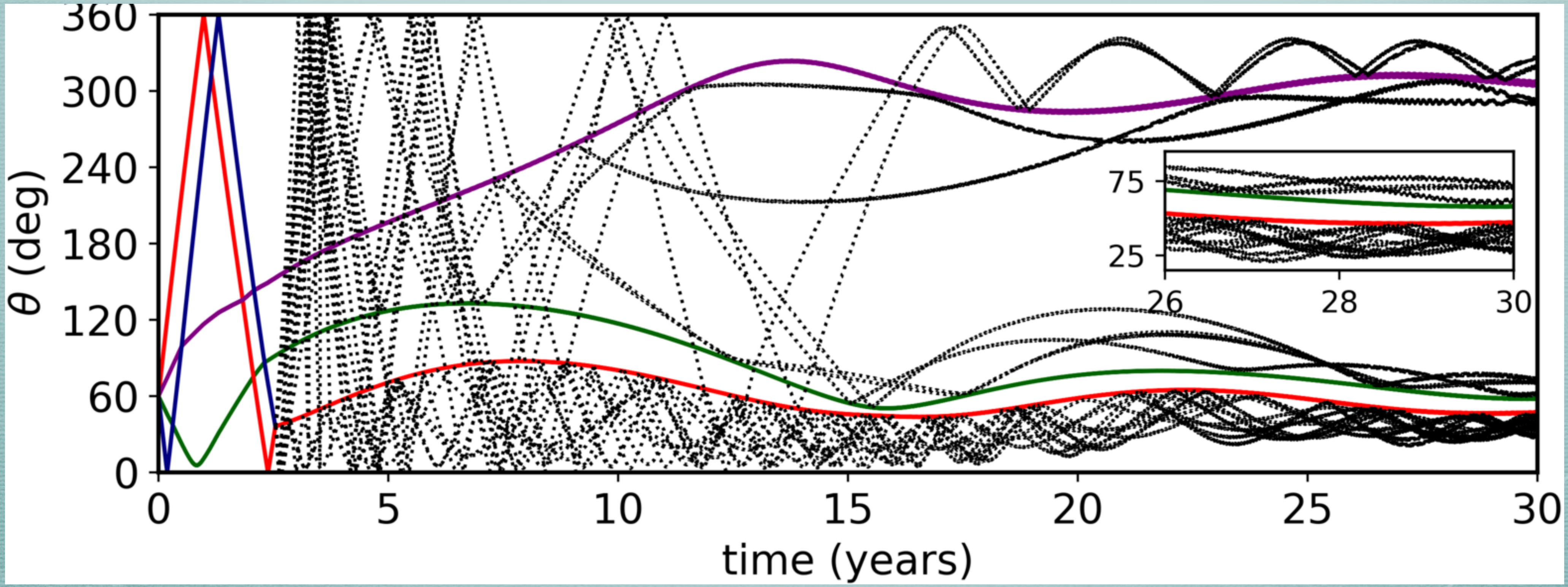
Two arcs are formed near both equilateral lagrangian points

II. During the moonlets formation stage:

Azimuthal confinement due to $S1$ and Galatea's gravitational effect increase collisions between debris, which can be a significant source of material to the arcs.

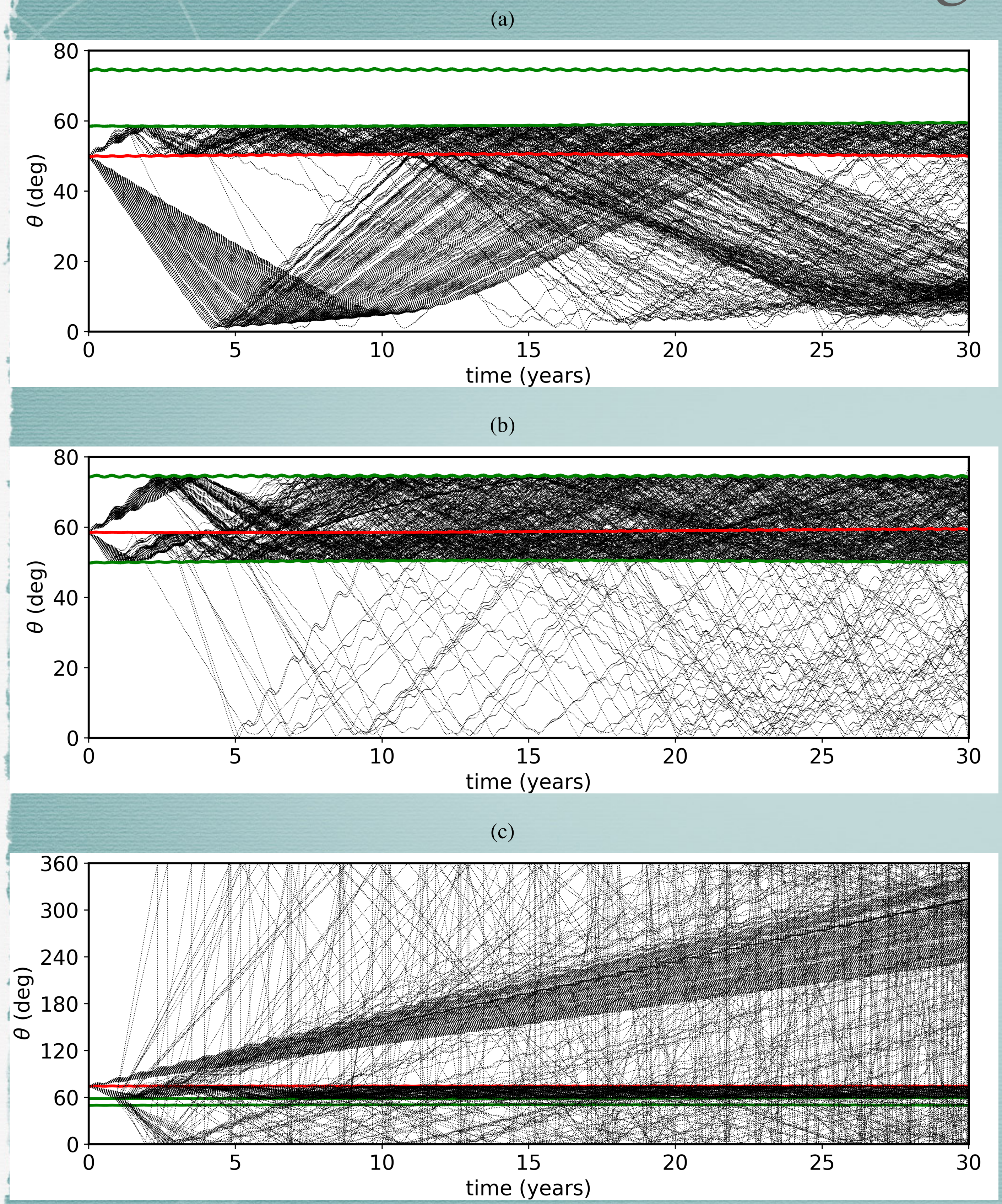
We obtain that impacts can populate the four arcs in $T \sim 10^4$ years (optical depth of $\tau = 0.1$), showing that such events can also be the source of the arcs.

In order to analyse the evolution of the material produced in the impact between fragments, we redid some numerical simulations, distributing 500 massless particles in a disk around the moonlet formed right after a collision.



Evolution of a set of particles produced due to collision of two fragments in $P1$ configuration with 1+3 co-orbital satellites. The particles are initially in a disk around the moonlet formed after the collision. We only show the survived particles (black dotted lines), which is about 8% of the initial set. Fragments that give rise to the satellites are the coloured solid lines.

III. Post formation stage:



After the moonlets are formed, they can suffer impacts of interplanetary dust particles (IDPs) or meteoroids originating mainly from the Kuiper Belt (Poppe 2016; Poppe et al. 2019).

This plots shows the evolution of particles originated in each moonlet (shown in coloured lines). P_1 configuration with 1+3 co-orbital.

*

DISCUSSION

* Revisiting the work of Renner & Sicardy (2004), we obtain that the equilibrium configurations obtained by them are not altered when we consider the moonlets in an orbit with estimated eccentricity located at the Adams ring;

* We obtained a total of three distinct equilibrium configurations that can reproduce the angular width of the arcs – P_1 configuration with 1+3 co-orbital satellites and the P_1 and P_2 configurations with 1+4 co-orbital satellites;

* We propose the formation of moonlets by the disruption of an ancient body due to an impact with a meteoroid. This is a possible scenario since many objects originating in the Kuiper belt crosses the Neptune region (Colwell & Esposito 1992; Levison et al. 2000);

* Our simulations varying the mass of fragments and the intensity of the non-conservative force results in fractions differing less than 10%, showing a self-consistency. In these simulations, we obtain a probability of ~ 30% to a disruption produces a system capable to confine the four arcs;

* In our scenario, these differences on the typical sizes between the arcs can be obtained if the material of the arcs were originated at different stages of the formation of the moonlets. In special, our crude analysis shows that micrometre-sized material are possibly originated from impacts between the disruption outcomes (fragments and debris), being impacts of meteoroids with the already formed moonlets another possible source. However, a number of processes are likely to act to produce the arcs such as impacts, fragmentation, and erosion.

* * **The arcs may have been formed in different stages, with the arcs composed only of dust particles being the final stage of the arc lifetime.**