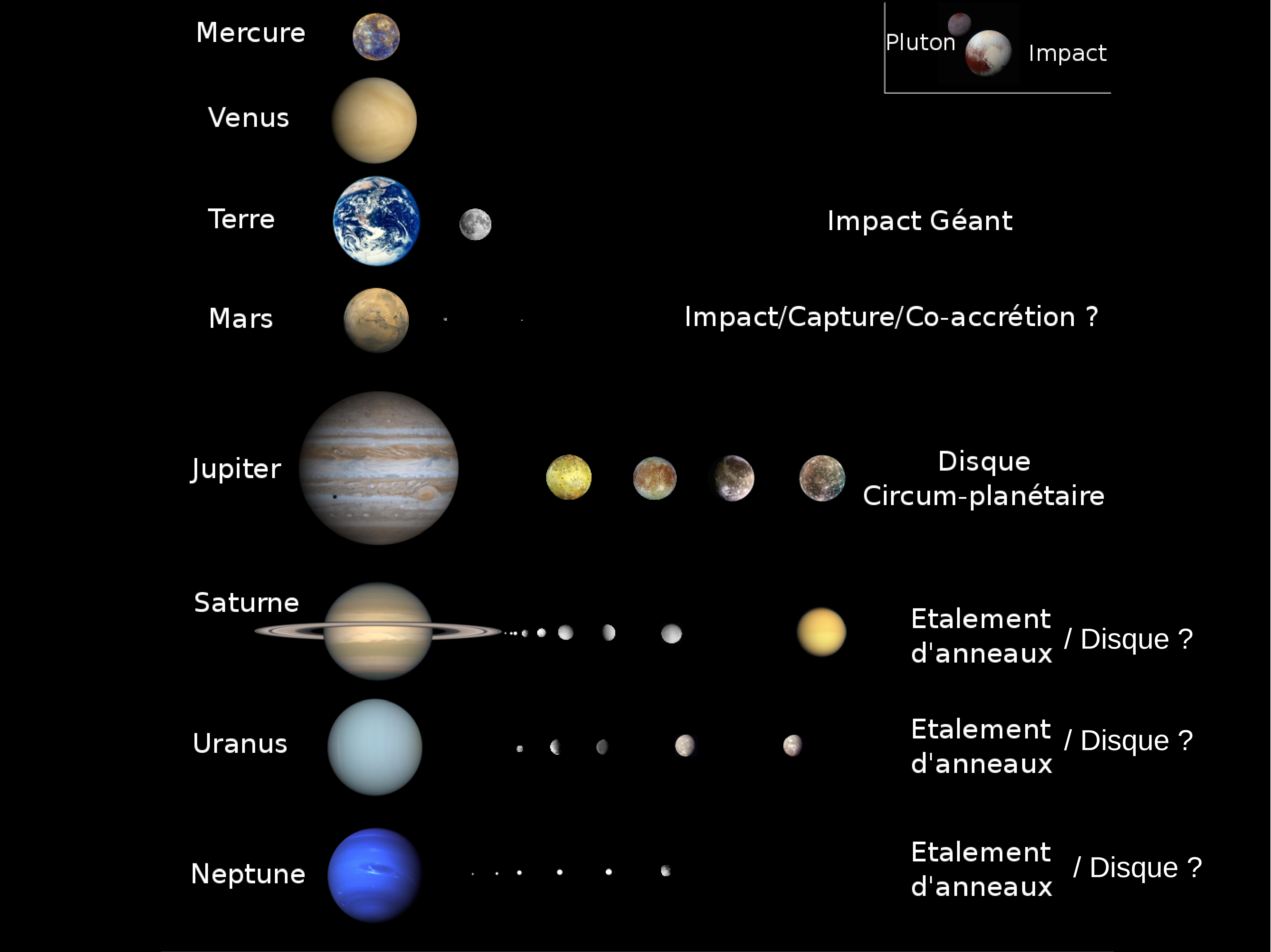
Formation of satellites around planets : the case of Jupiter’s icy moons in the context of the esa JUICE mission

Thomas Ronnet
3rd year

Supervisors : Olivier Mousis (Prof.) and Pierre Vernazza (HDR)


Mercure
Pluton
Impact
Venus
Terre
Impact Géant
Mars
Impact/Capture/Co-accrétion ?
Jupiter
Disque
Circum-planétaire
Saturne
Etalement
d'anneaux
/ Disque ?
Uranus
Etalement
d'anneaux
/ Disque ?
Neptune
Etalement
d'anneaux
/ Disque ?

Why study satellites and their formation ?

- The satellites exhibit a wide **diversity** in terms of mass, **composition** and **activity** :

  - Io is the most volcanically active body of the entire Solar System

  - Europa and Enceladus exhibit plume activities, giving the chance to probe their interior composition
  - Europa, Ganymede and Enceladus have confirmed icy ocean underneath their crust, making them bodies of great biological interest
  - Ganymede possesses its own, internally generated magnetic field

Why study satellites and their formation ?

- The satellites of the giant planets are therefore the **best target** to find extra-terrestrial **life**.
- Hence, both **Nasa** and **Esa** planned **missions** to study Jupiter's **icy satellites**.
- Understanding the **formation** of such objects is of great interest to find potentially **habitable wolrds** around giant **extrasolar planets** (i.e. where to search these objects, how massive would they be etc...)

Why study satellites and their formation ?

- The **satellites** also tell us a lot about the **conditions** that reigned in the **early Solar System**.
- **Understanding** the important **steps** of their **formation** gives **hints** on the **distribution of objects** during the formation of the planets and also helps **constraining** the **migration** of the planets (i.e. the variation of their radial distance to the Sun)

How do satellites form ?

- There are **two** main **accretion mechanisms** that are thought to have led to satellites formation :

  - Accretion within a **circum-planetary disk**, much **alike** the **formation of terrestrial planets** around stars, scenario favored for the jovian satellites

  - Accretion from the **spreading** of a **disk of debris**, scenario favored for the formation of the Moon and some of Saturn's satellites

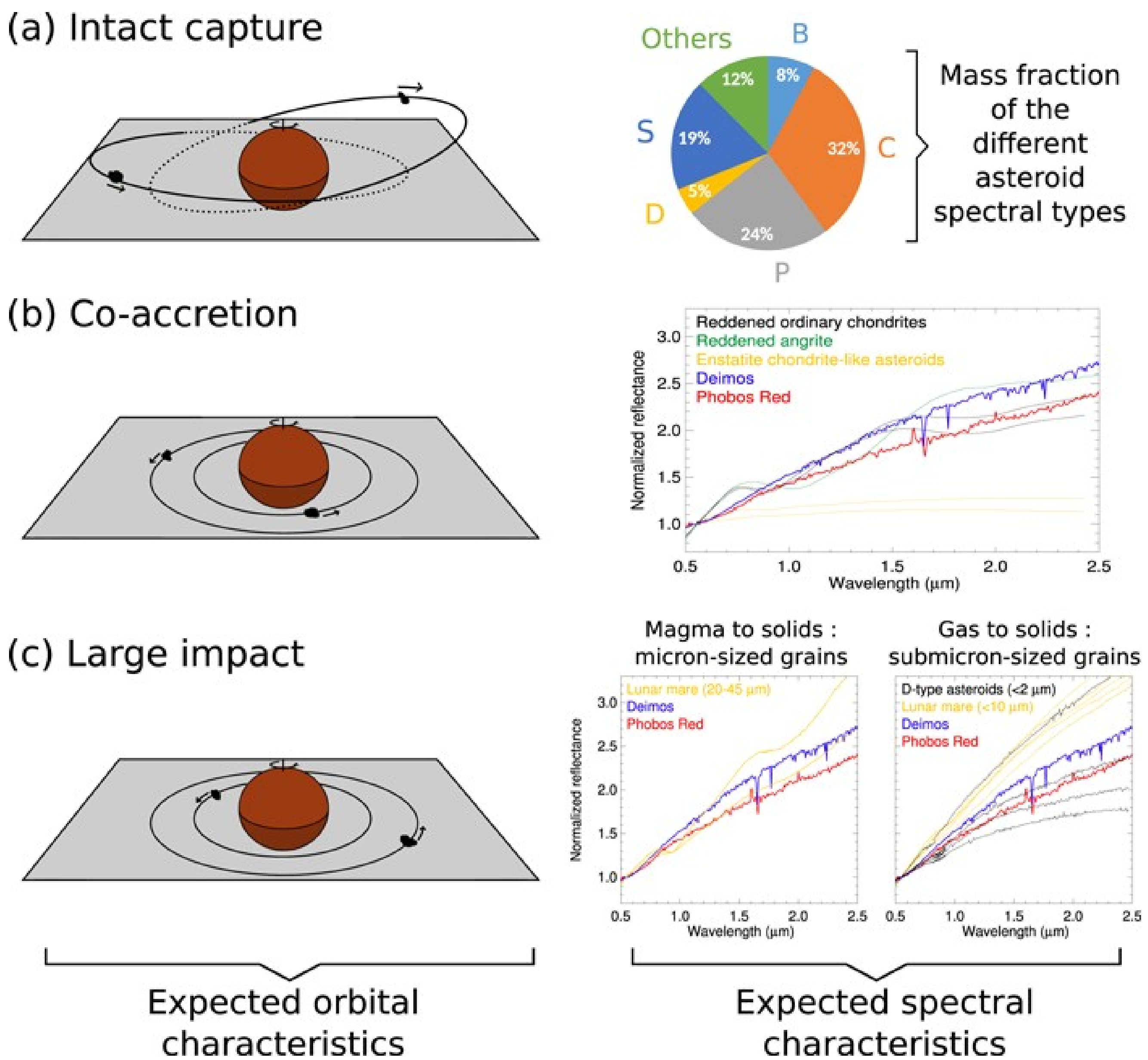
The Martian moons Phobos and Deimos

- The **origin** of the martian moons Phobos and Deimos has been a **longstanding puzzle** :
  - Their size, shape and spectra make them resemble two small and **primitive asteroids**. This would make them gravitationaly **captured objects**
  - Their nearly **circular** and **coplanar** orbits are very hardly reconcilable with those of captured objects, pointing towards an **in-situ formation** of the satellites

The Martian moons Phobos and Deimos

- We showed that the **physical properties** of the martian moons can be **explained** if they **formed** out of a **disk of debris** following a **giant impact**
- In this context the **accretion history** of **Mars** would be very much **alike** that of the **Earth** in the sense that both planets experienced a late and violent impact that lead to the formation of satellite(s)
- The **differences** in the **architecture** of the Earth-Moon and Mars-Phobos/Deimos systems would be due to the **different tidal evolution** experienced by their satellites

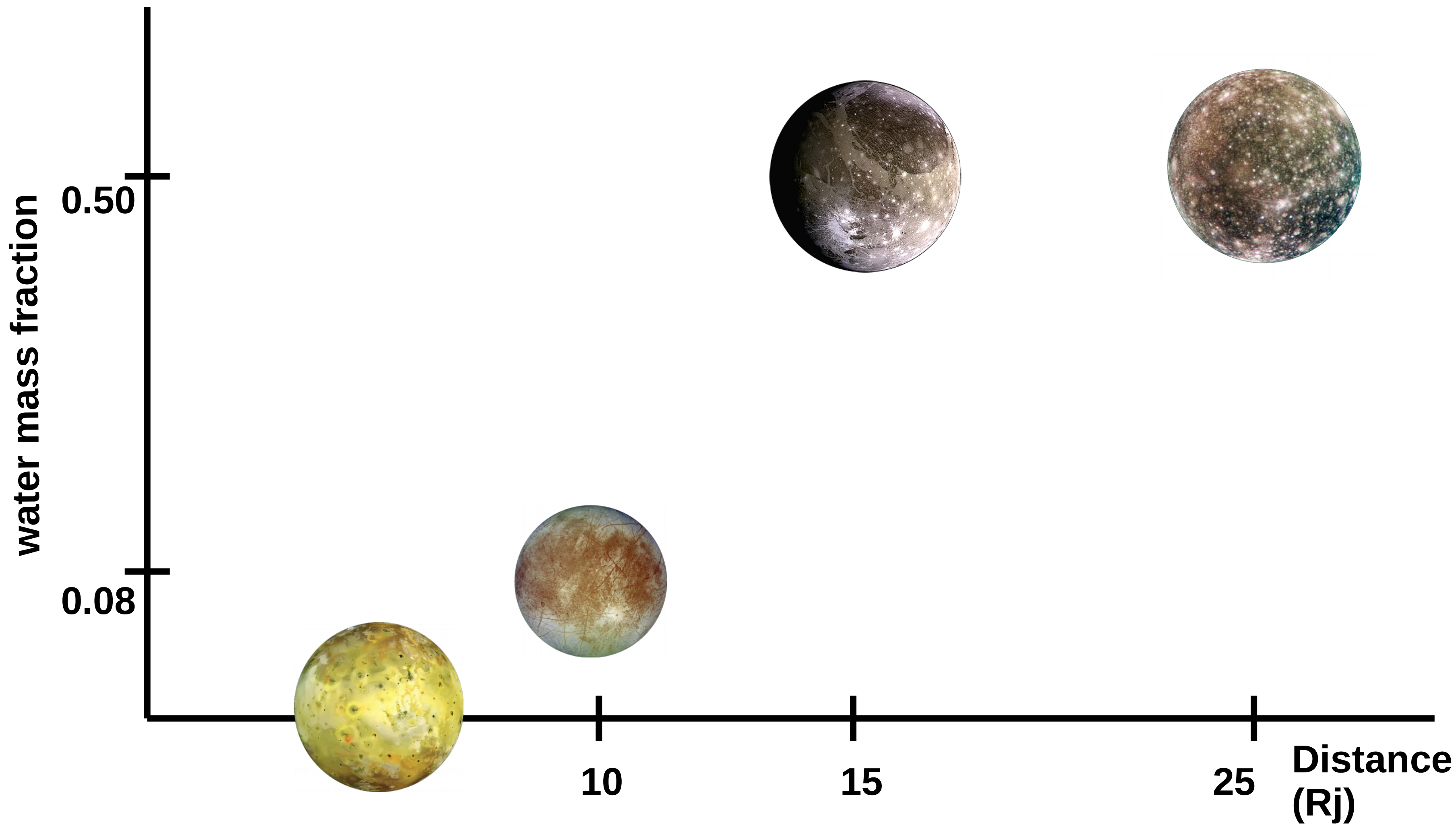
The Martian moons Phobos and Deimos



The massive Galilean satellites

- Jupiter possesses a cortege of satellites including **four massive moons** known as the **Galilean satellites** (from their discovery by Galileo)
- They are thought to have formed within a **circum-jovian disk** at the **end** of **Jupiter's accretion**, like planets around stars
- One of the most **peculiar feature** of the system is the **gradient** in the **water ice fraction** of the satellites as a function of the **distance** from Jupiter

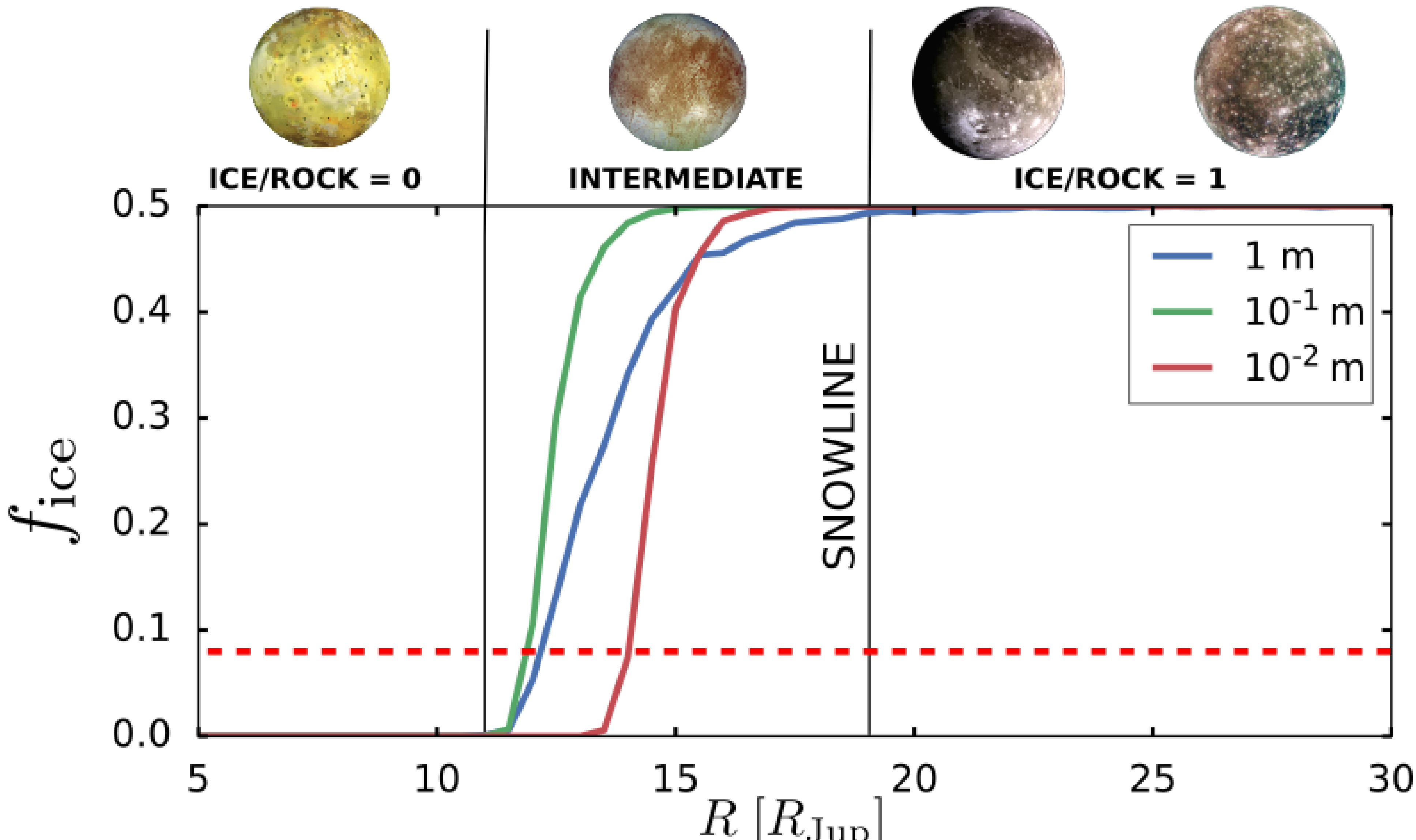
Compositional gradient among the Galilean satellites



Revisiting the formation of the Galilean satellites

- While the **composition** of Io and Ganymede/Callisto are easily **accounted for** by a formation in **warm** (water in the form of **vapor**) and **cold** (water in the form of **ice**) environments, respectively, the **composition** of **Europa** requires more **subtle processes**
- We showed that the **composition** of the **whole system** could be **accounted for** if the satellites **accreted** from solids in the **centimeter** to **meter** size range in a process called **pebble accretion**

Revisiting the formation of the Galilean satellites

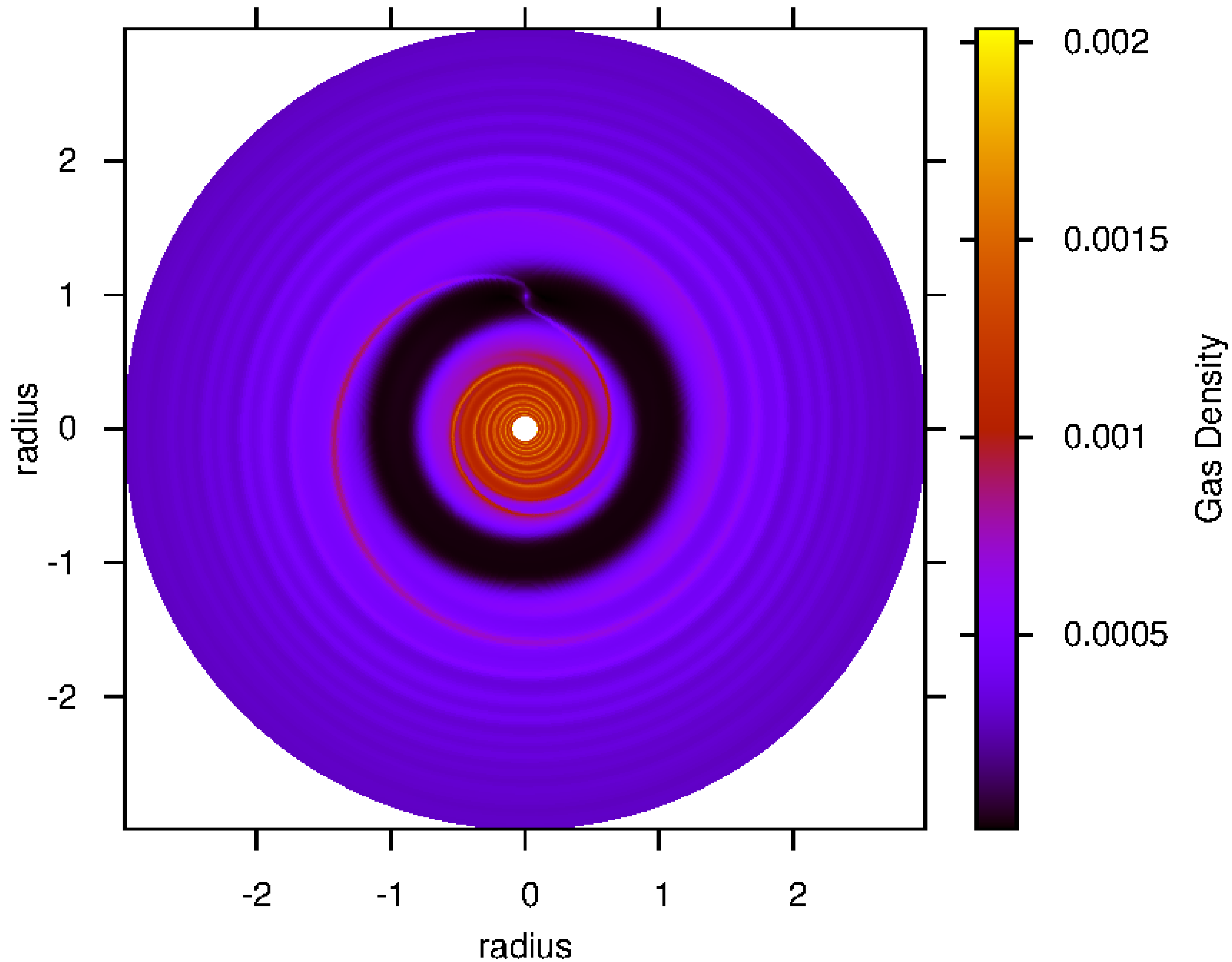


Revisiting the formation of the Galilean satellites

- One of the **major issues** remaining in the **formation** scenario of the Galilean satellites is the **mechanism** of **delivery of solids**
- **Jupiter** should have **opened a gap** in the protosolar nebula at the time its satellites formed
- This gap **isolated** the planet from the main **sources** of **solid material** needed to **form** the **satellites**

Revisiting the formation of the Galilean satellites

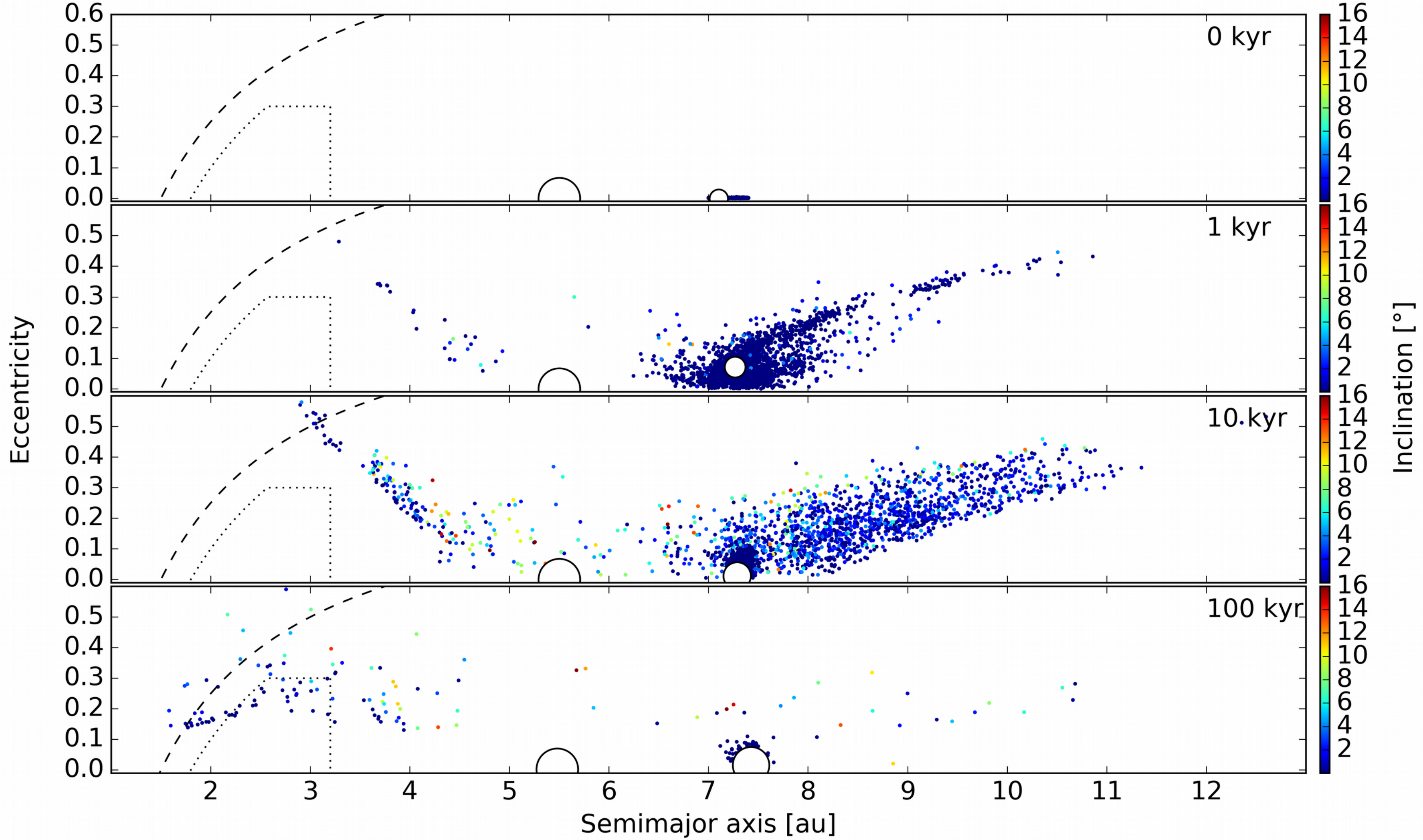
- Simulation of a Jupiter mass planet in a gaseous disk :



- Any **grains** larger than ~10 microns are **trapped** by the **pressure perturbation** created by Jupiter
- **Larger objects** (e.g. asteroids) could **easily form** at the **gap** edge but would remain **out of Jupiter's** gravitational **reach**

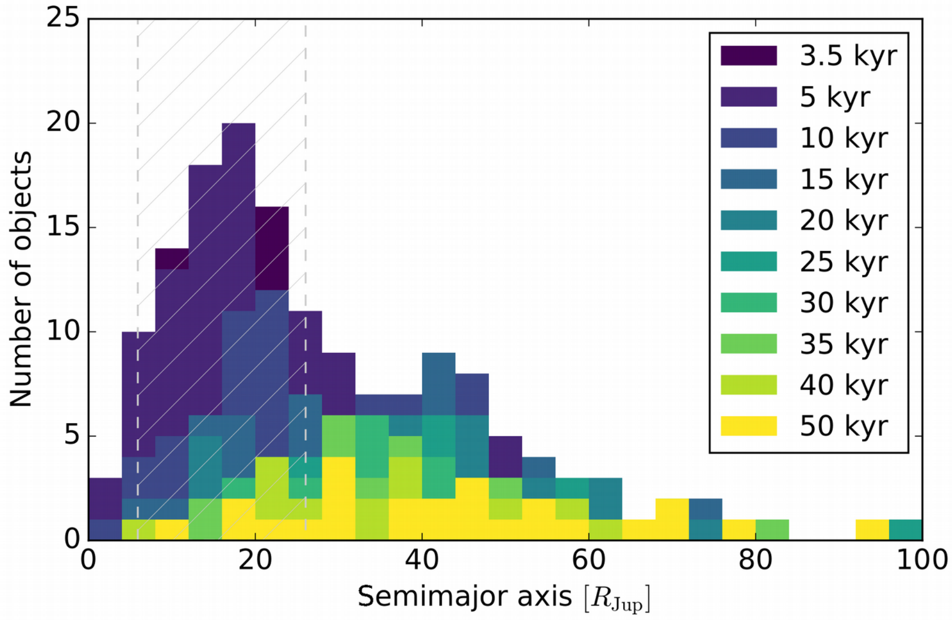
Revisiting the formation of the Galilean satellites

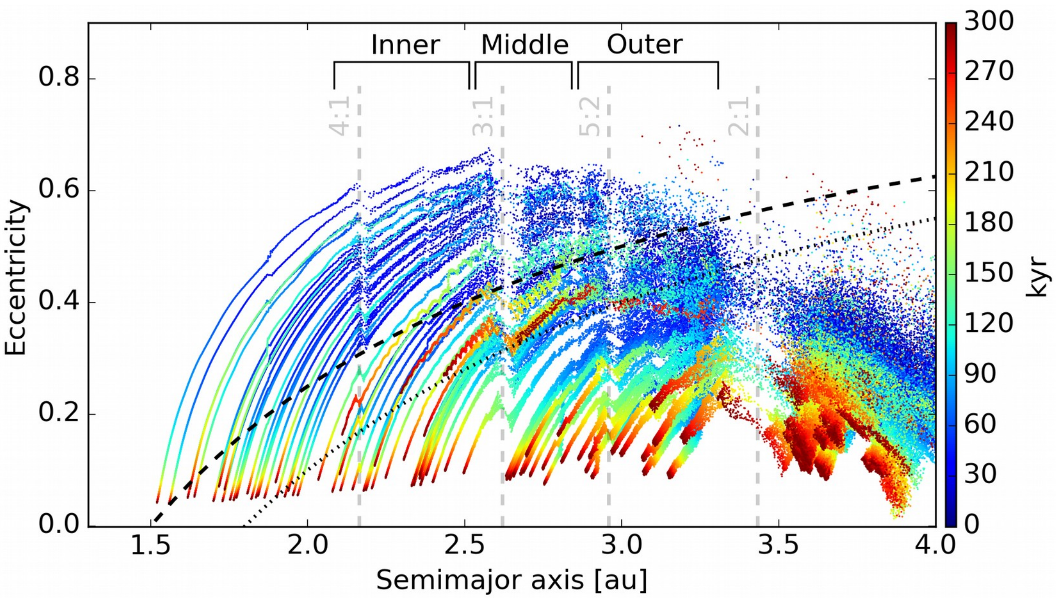
- Using **Saturn** to **push** the objects **towards Jupiter** and **provide** the **material needed** to form its satellites :



Revisiting the formation of the Galilean satellites

- Distribution of the objects in the circum-jovian disk and the asteroid belt :





Conclusion

- During the course of my PhD I studied the **formation** of the **satellites** around planets with an emphasis on the massive **Galilean satellites** orbiting around Jupiter
- I try to **revisit** the **scenarios of formation** considering the **recent strides** made in the theories of planetesimal formation and giant planet accretion
- I am also interested in the **transport** of **dust grains** and **chemical species** in protoplanetary **disks** which I study using **numerical tools** I developped

Prospects

- My work provides **constraints** on the formation scenarios of the planet's satellites with **testable implications** by future in situ spatial mission and observations :

    - Link between Galilean satellites and primitive asteroids / Origin of the satellite's water (ESA JUICE mission and NASA Mission to Europa)

    - Impact origin of Phobos and Deimos (JAXA Martian Moons eXploration mission)

    - No massive moons expected around isolated extrasolar giant planets (PLATO, CHEOPS, JWST,...)

- I have now the **different numerical tools** allowing to study the **transport** of material through **gravitational interactions** (N-body code) and **disk processes** (code developped during my PhD). This is important to **understand** the **composition** and **origin** of the **Solar System bodies** combining **numerical simulations** and **data** collected by missions and observation programs (cometary composition [Rosetta,...], Giant planets atmospheres composition [Juno, Cassini, Hera,..], asteroids composition [Dawn, Lucy, ...])

Publications

- *Pebble accretion at the origin of water in Europa.* **T. Ronnet**, O. Mousis & P. Vernazza 2017, ApJ, 845, 92
- *Stability of sulphur dimers in cometary ices.* O. Mousis *et al.* 2017, ApJ, 835,134.
- *Reconciling the orbital and physical properties of the martian moons.* **T. Ronnet** *et al.* 2016, ApJ, 828, 109.
- *Origin of molecular oxygen in comet 67P/Churyumov-Gerasimenko.* O. Mousis, **T. Ronnet** *et al.* 2016, ApJL, 823, L41.