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Overview of Galilean moons origins

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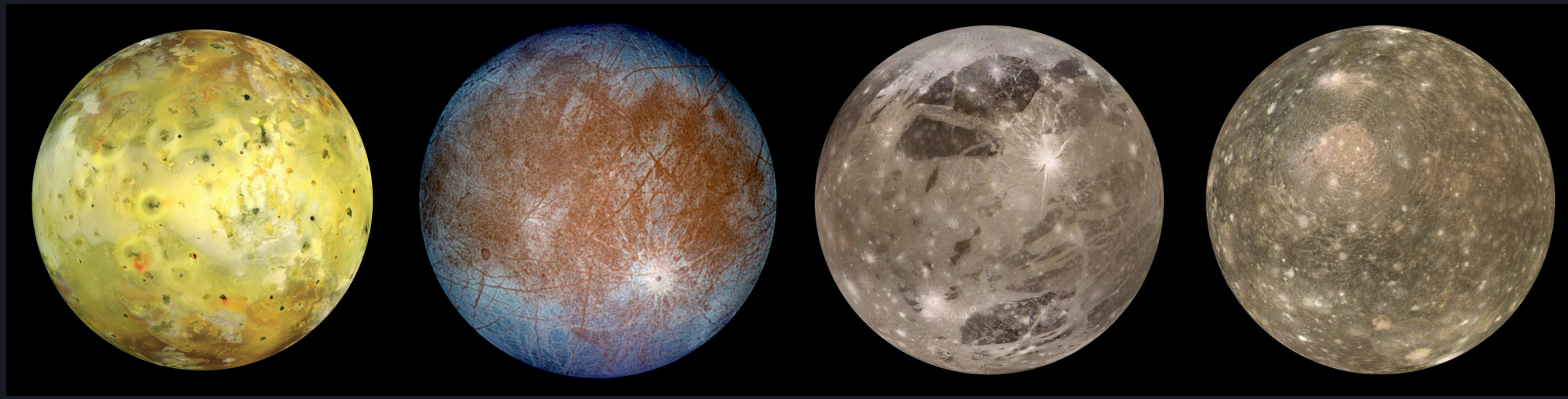
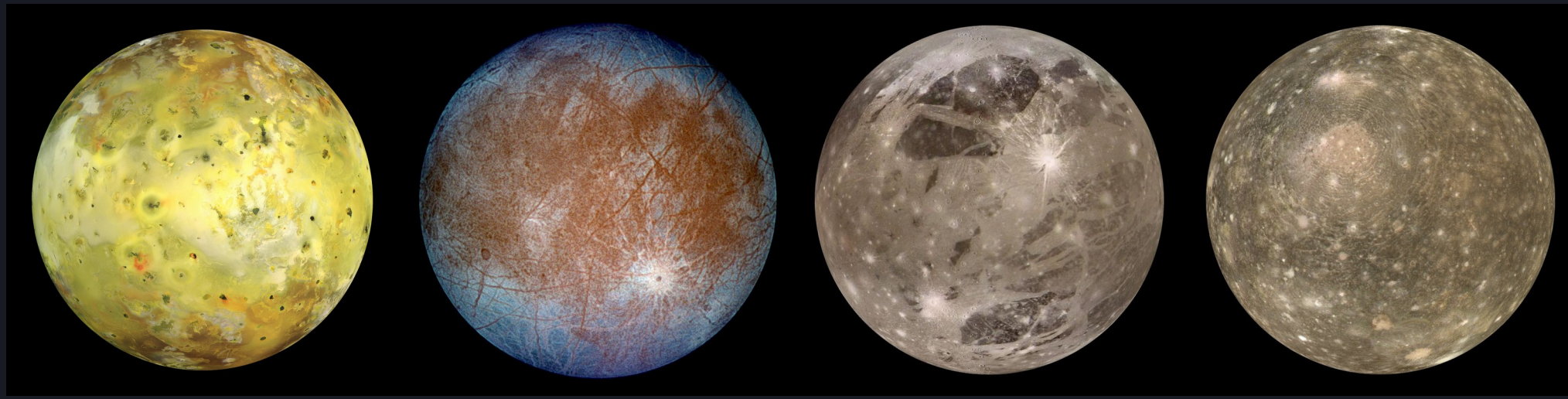
Active
Young



Inactive
Old

Active
Young

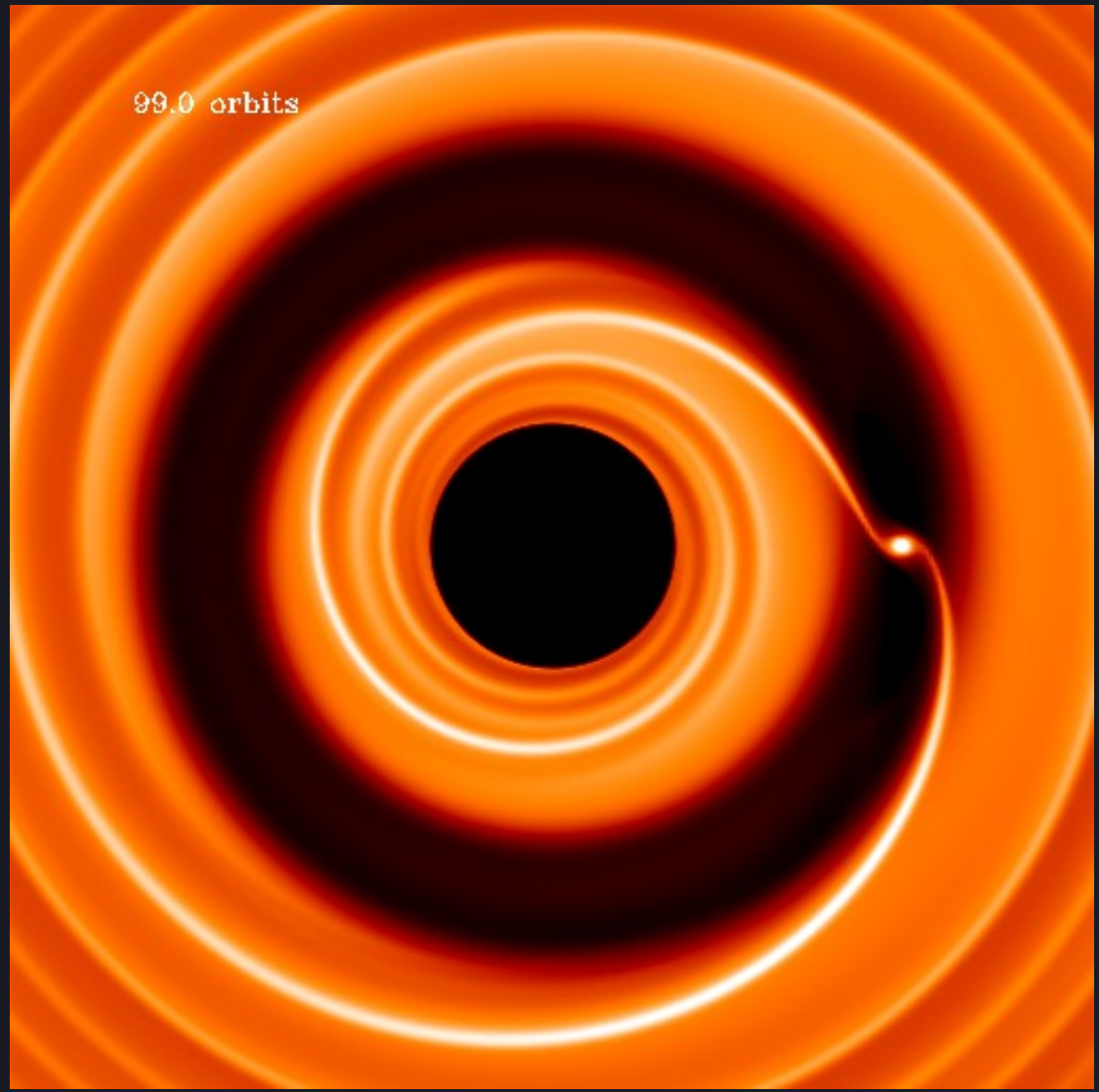
Inactive
Old

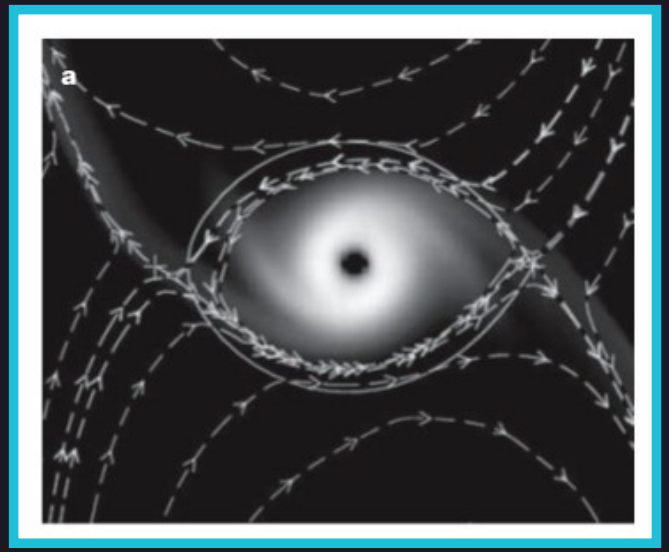


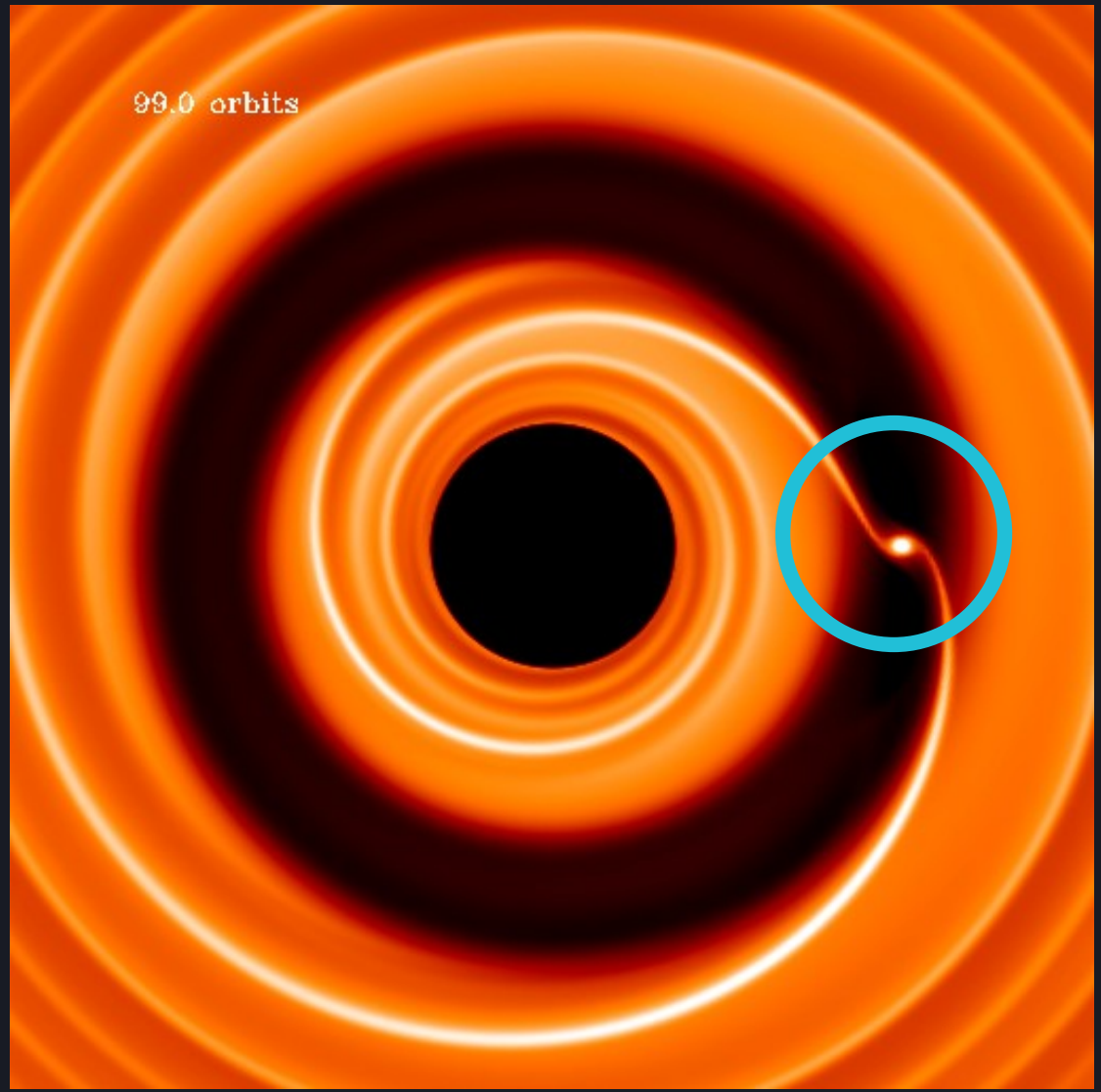
Dry

Water
rich

The moon formed in a circumplanetary disk (CPD)


99.0 orbits

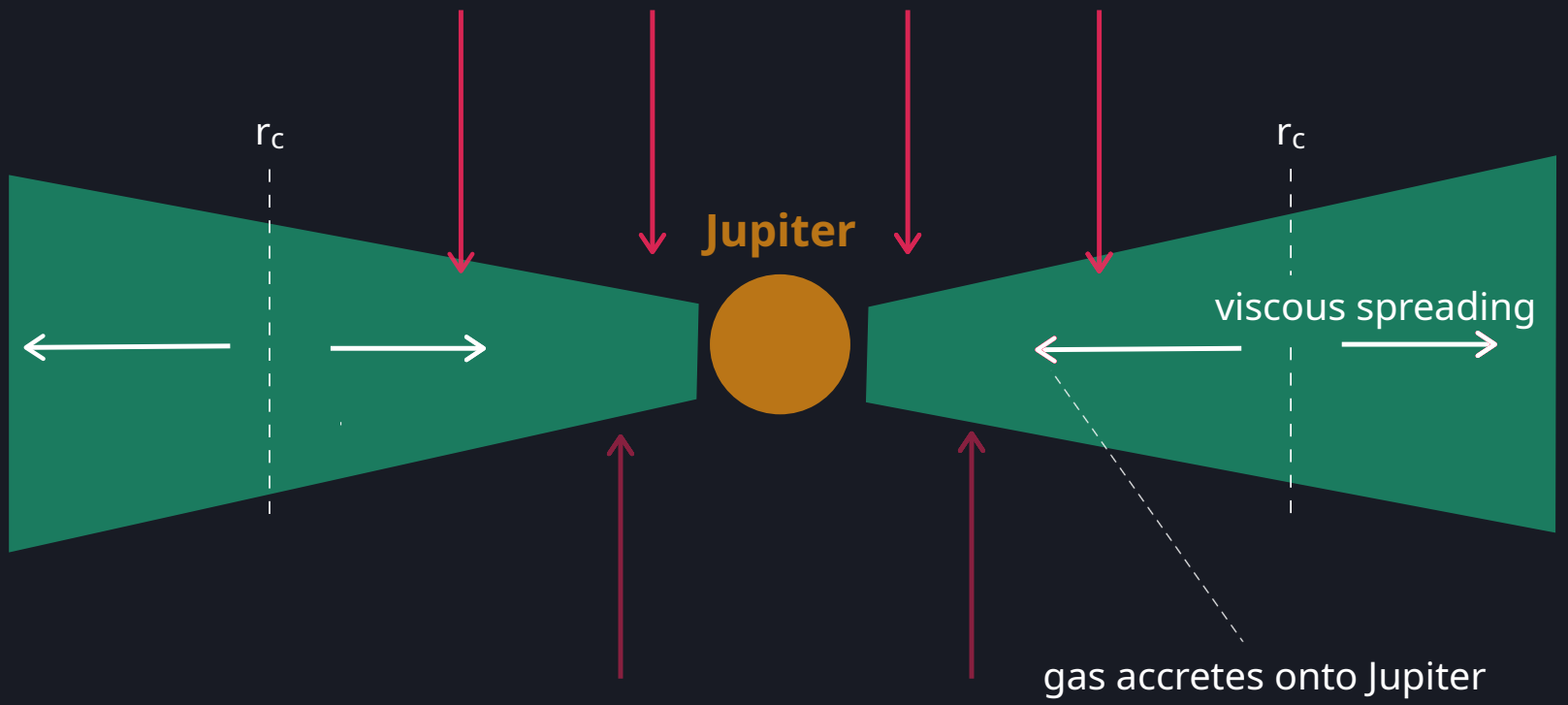

a


99.0 orbits

Analytic models

Minimum Mass Sub-Nebula

Gas Starved Disk



Gas Staved Disk

Canup & Ward 2002

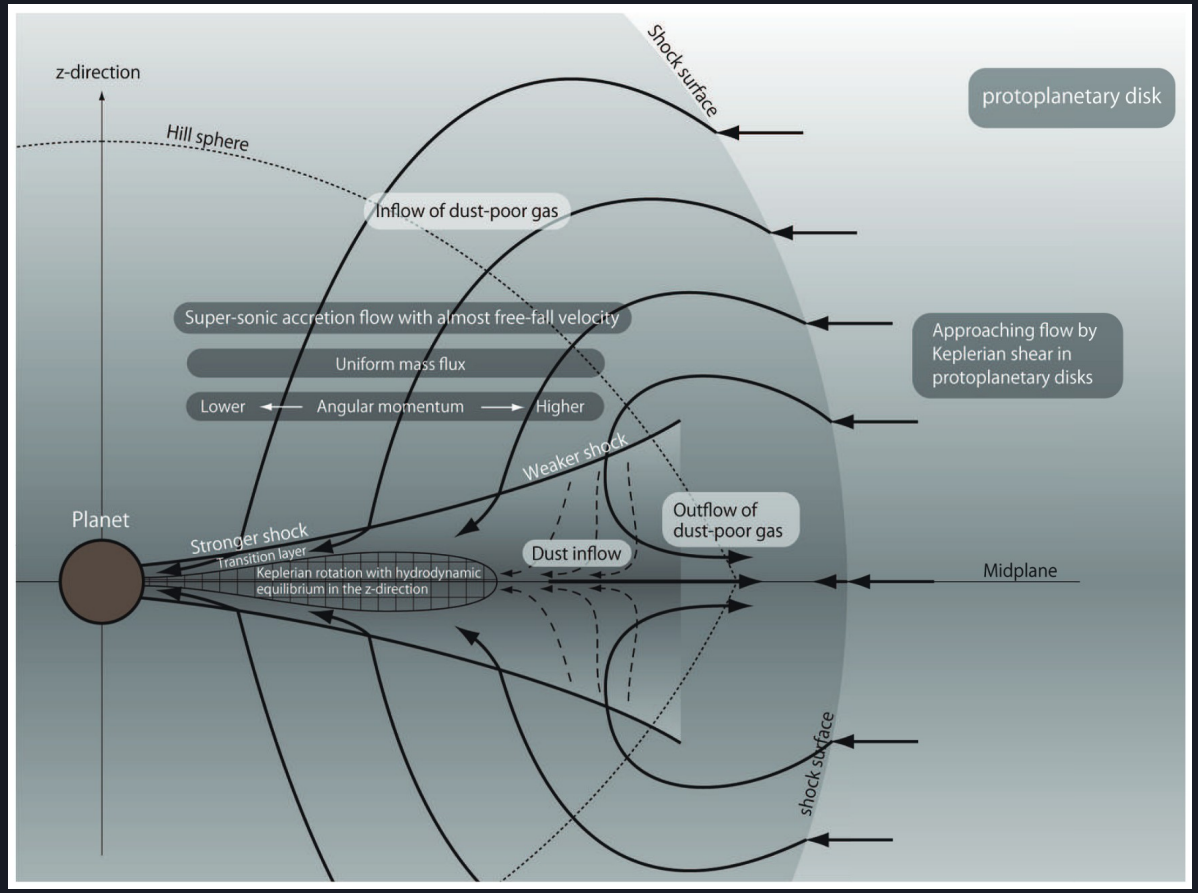
Minimum Mass Sub-Nebula

No Source from the protosolar nebula

Massive enough to form the moons

Very massive and hot

Lunine & Stevenson 1982



Tanigawa et al 2012

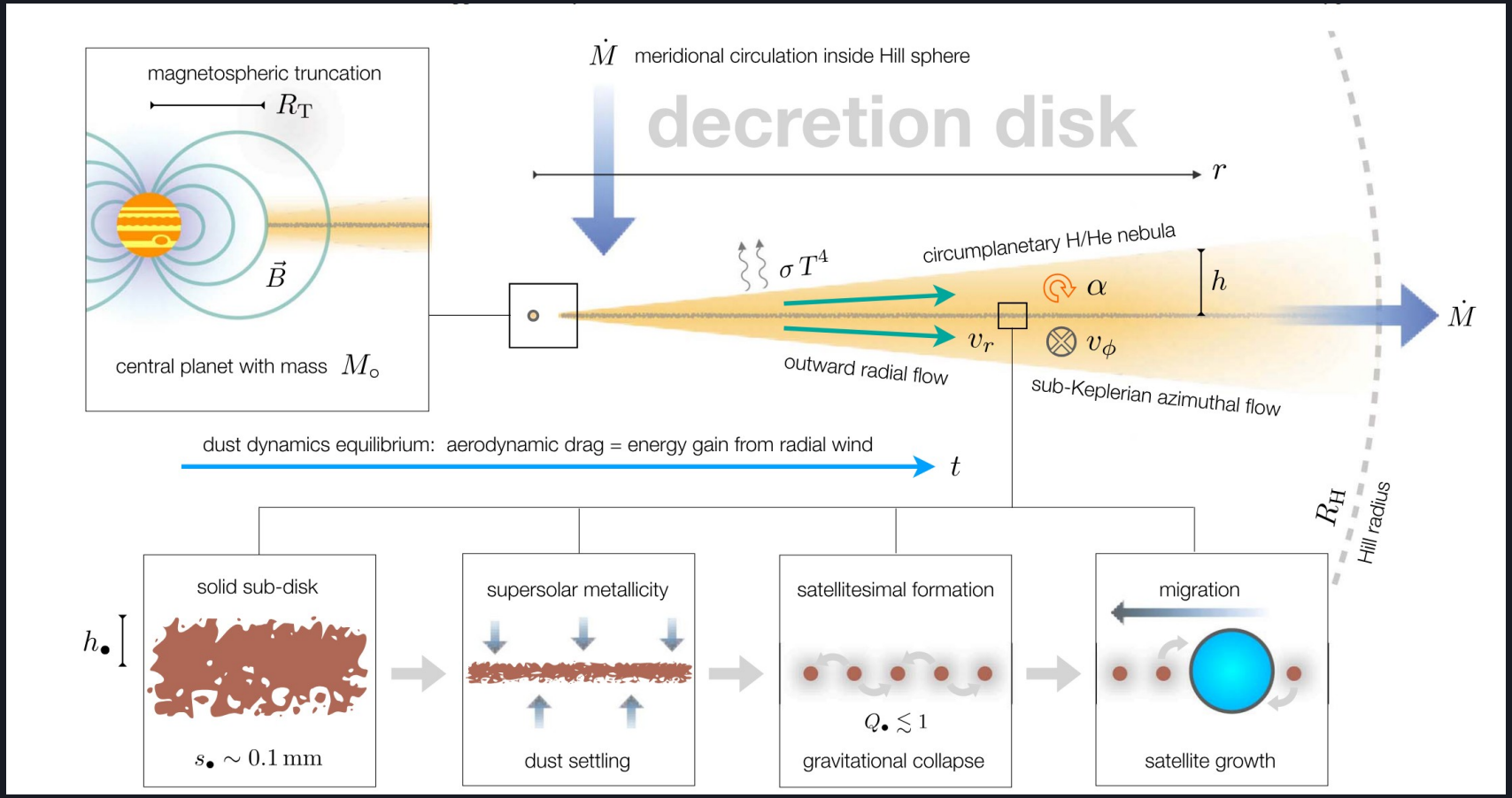
Hydrodynamic models : **meridional circulation**

Hydrodynamic models : large variety

Dependence on :

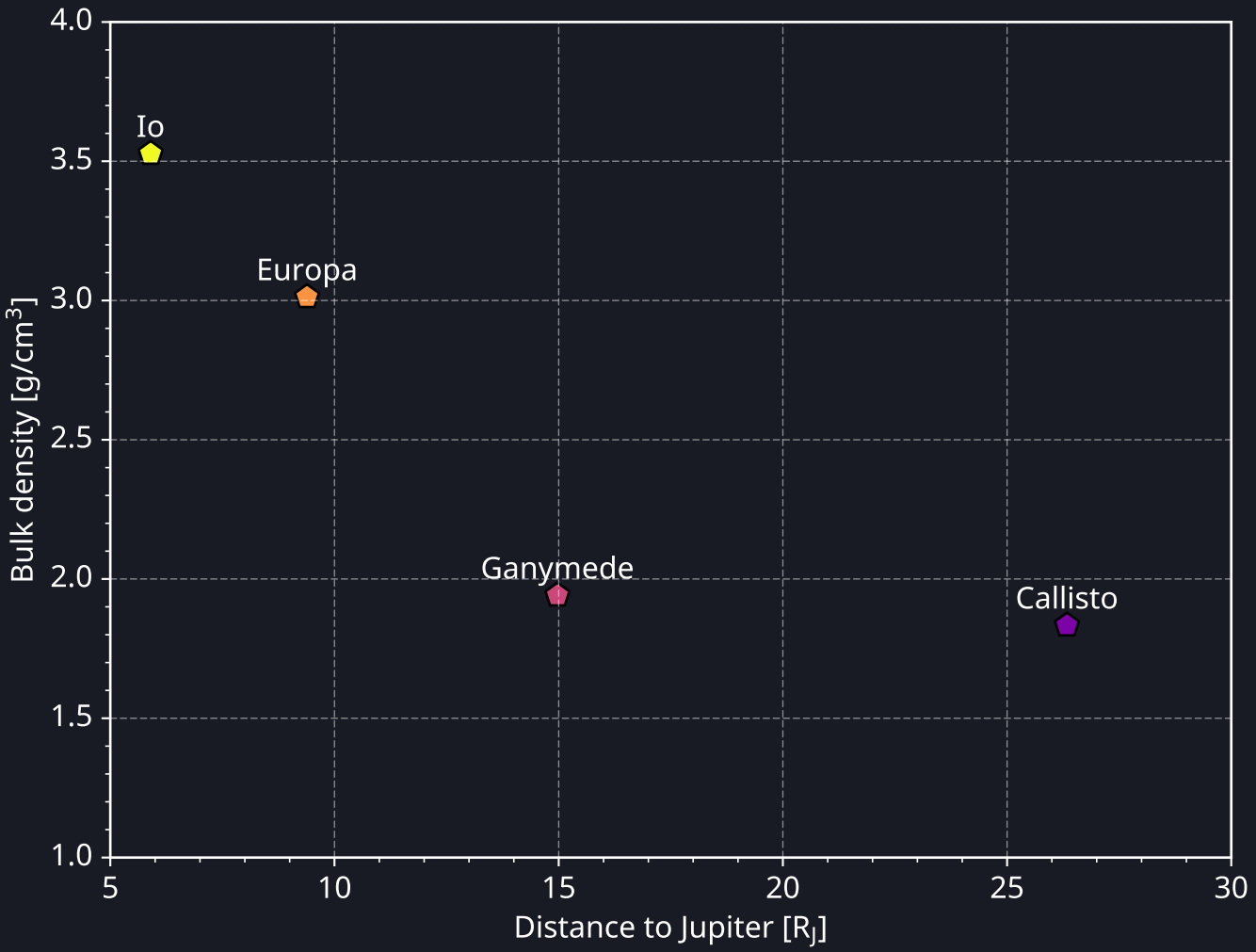
- Gas opacity
- Jupiter timescale of formation
- Jupiter temperature
- Jupiter magnetic field

Decretion disk



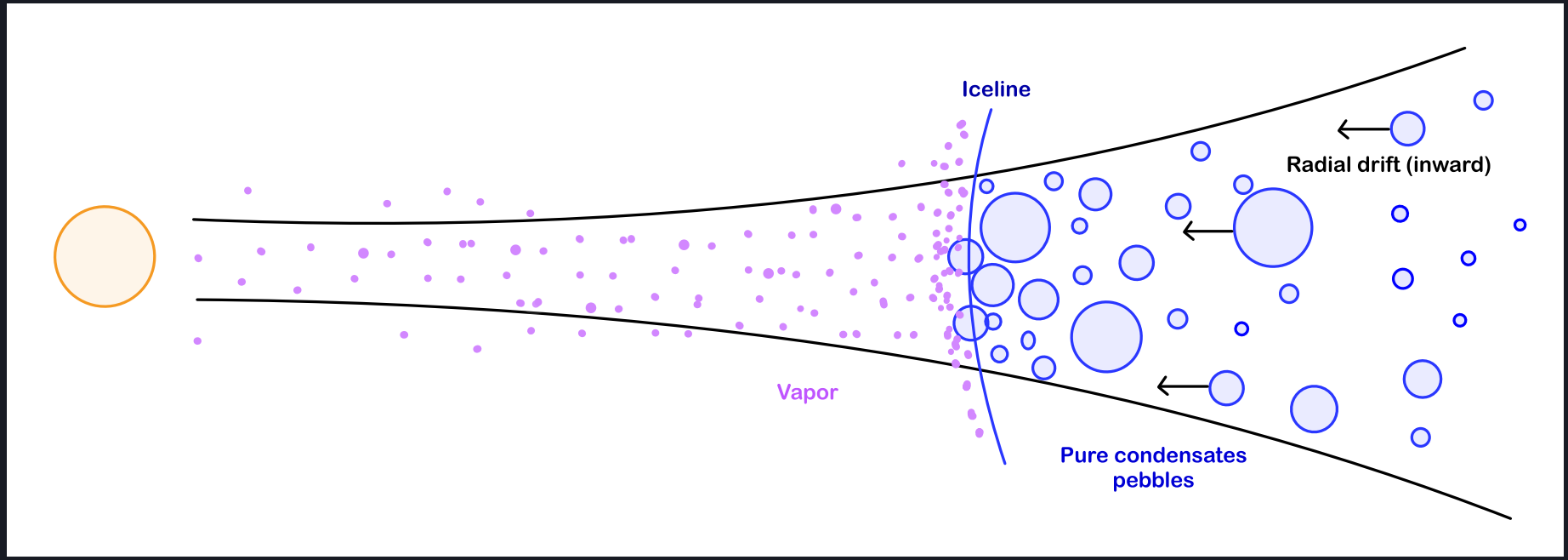
Batygin et al 2020

How to discriminate the models ?

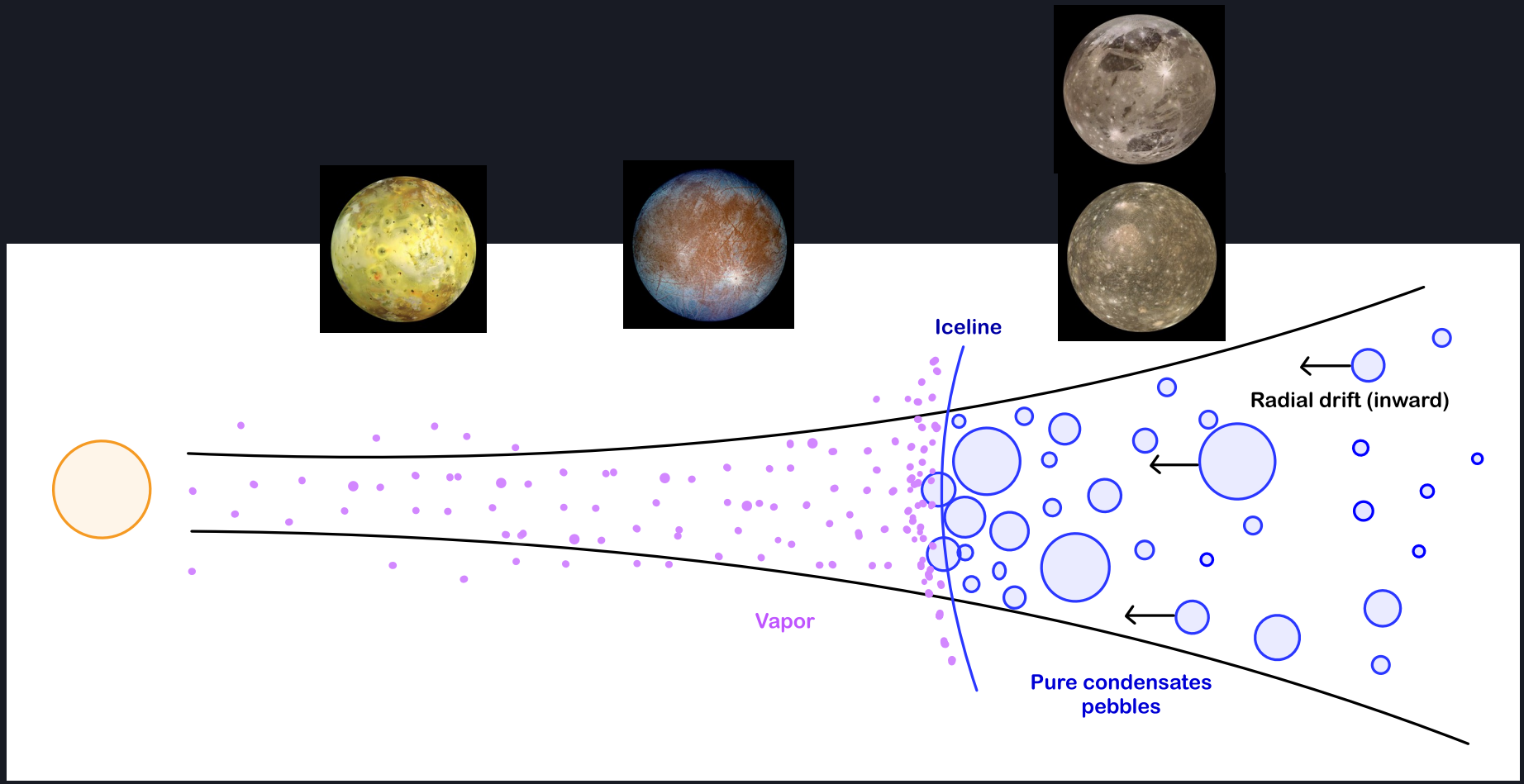


Water mass fraction gradient :

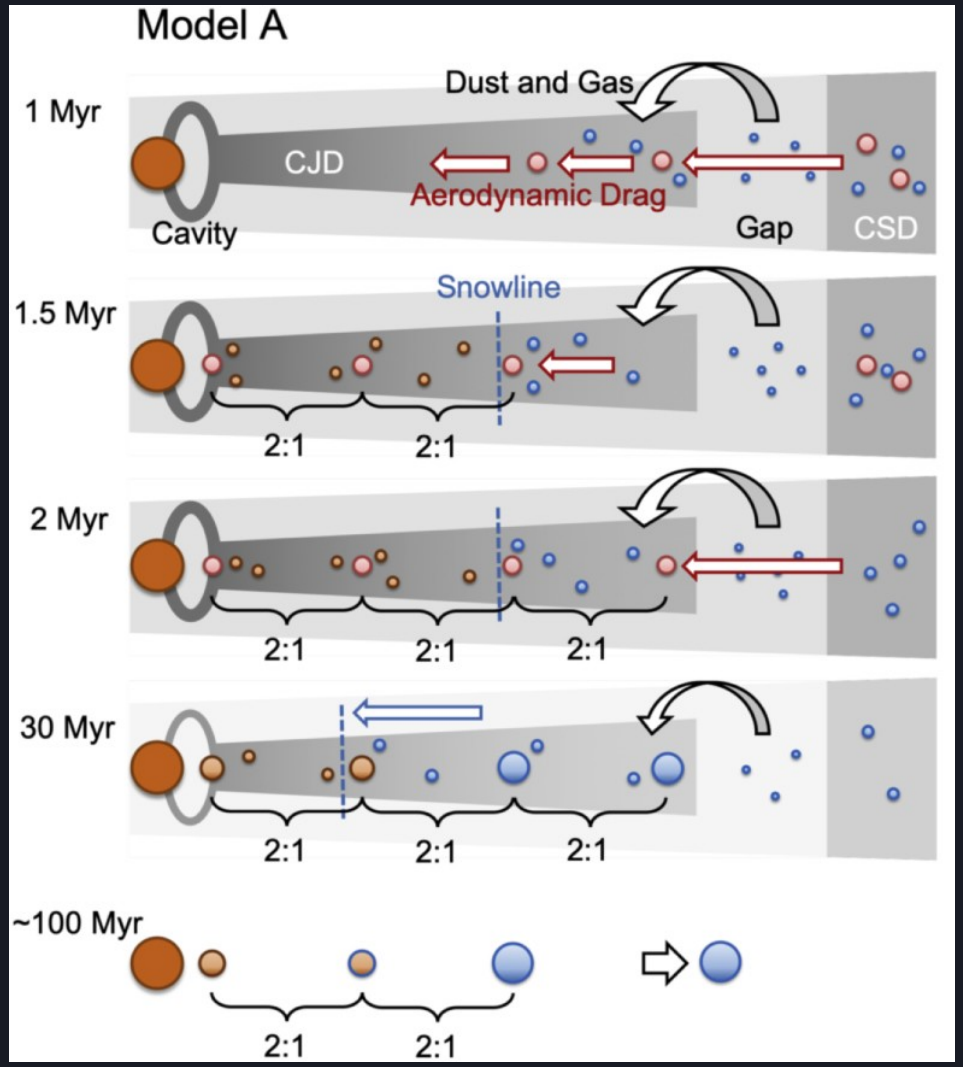
Iceline models



Schneerberger et al 2023

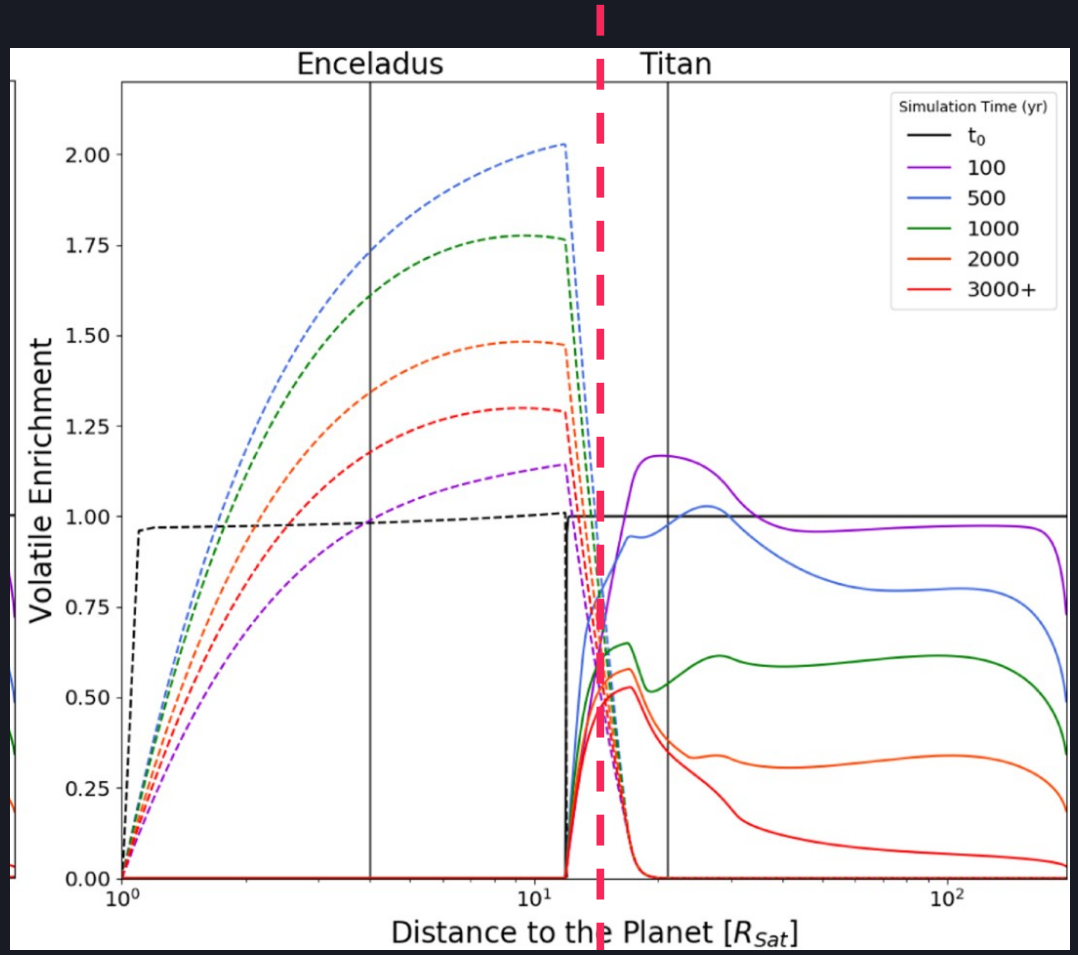


Schneerberger et al 2023



Icelines condition models

Shibaike et al 2019

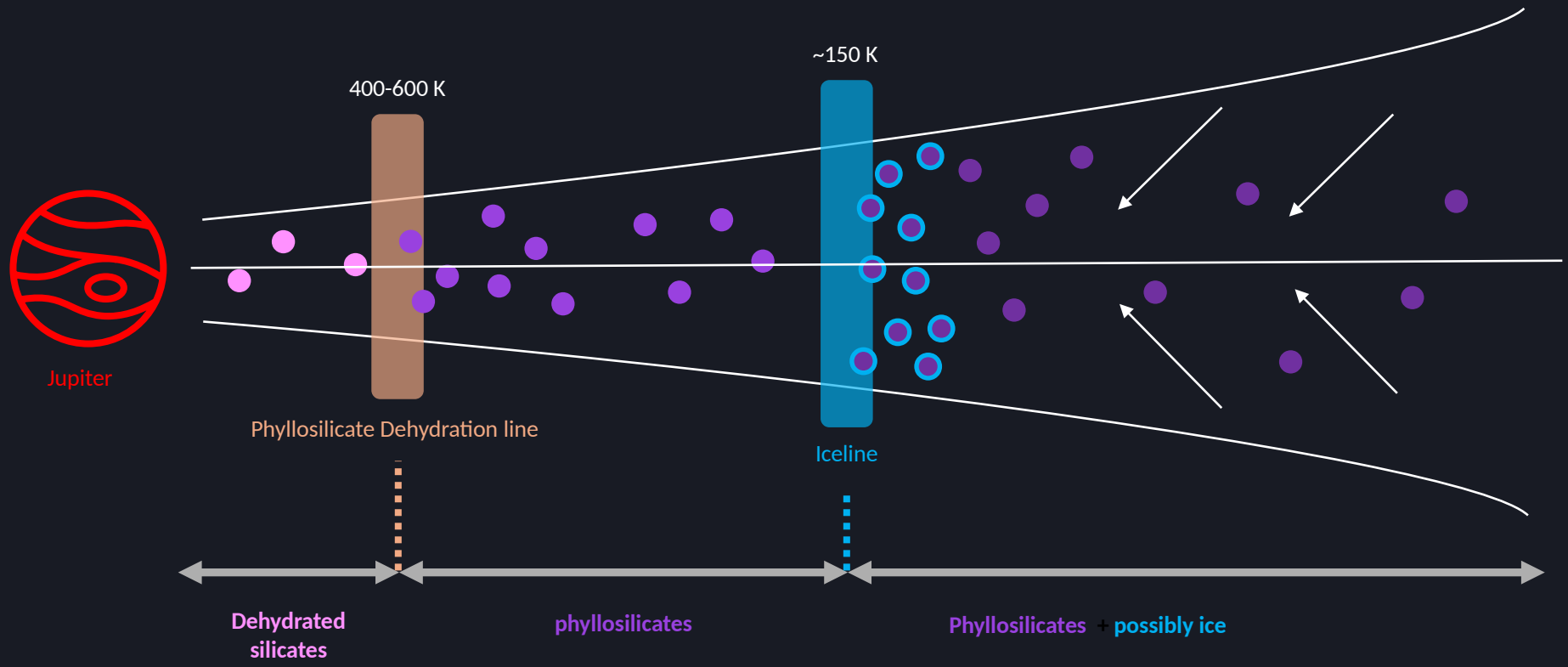


Water iceline in Saturn's CPD

Rapid evolution of icelines

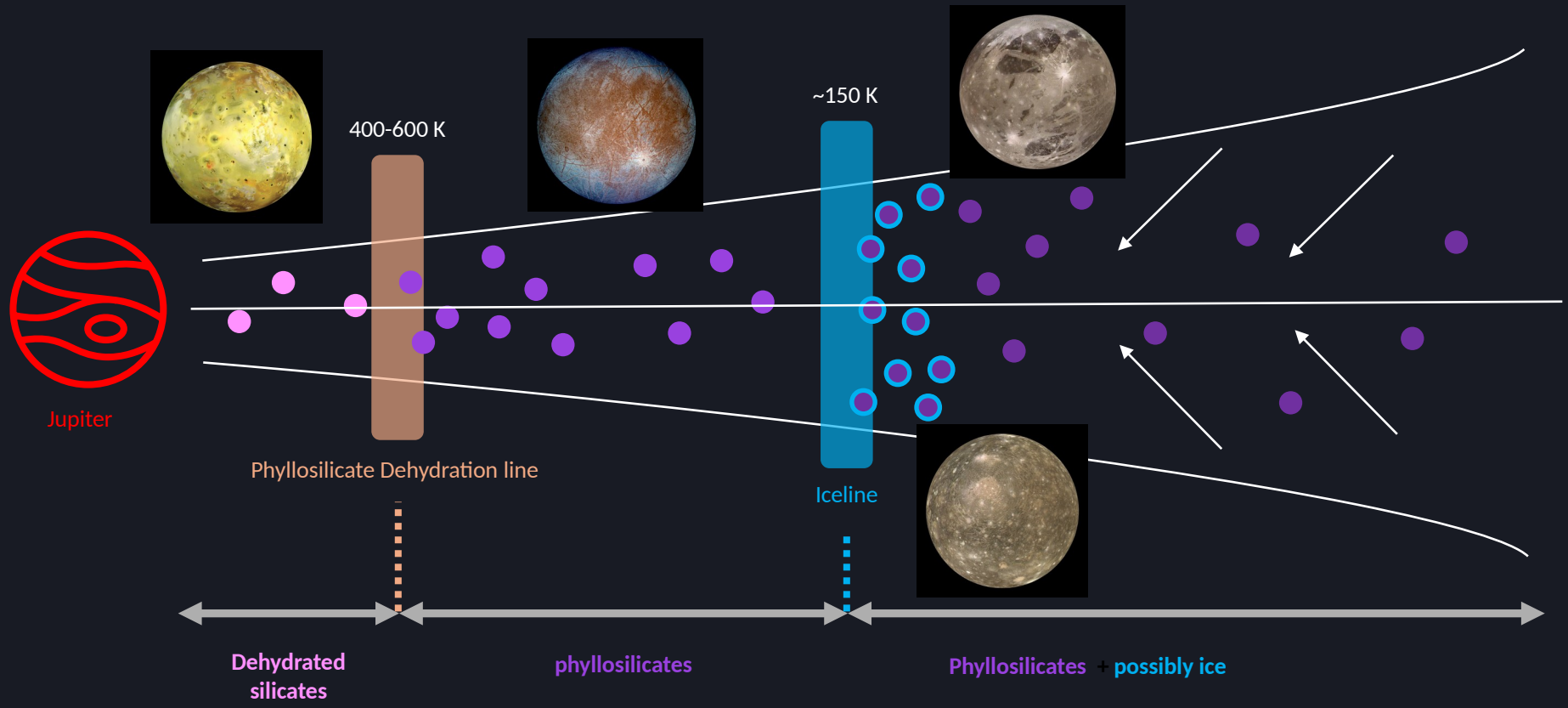
Anderson et al 2021

Hydrated minerals : source of water

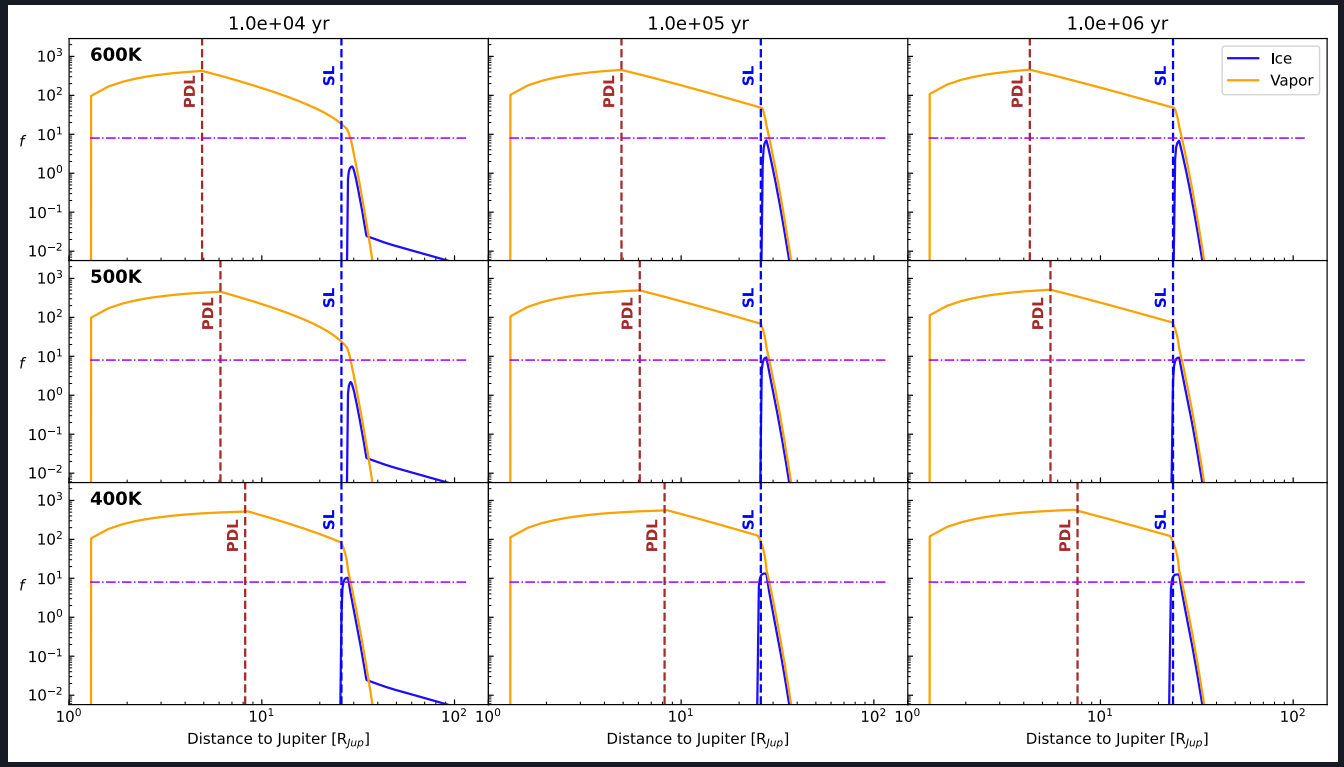


Mousis et al 2023

Hydrated minerals : source of water



Mousis et al 2023

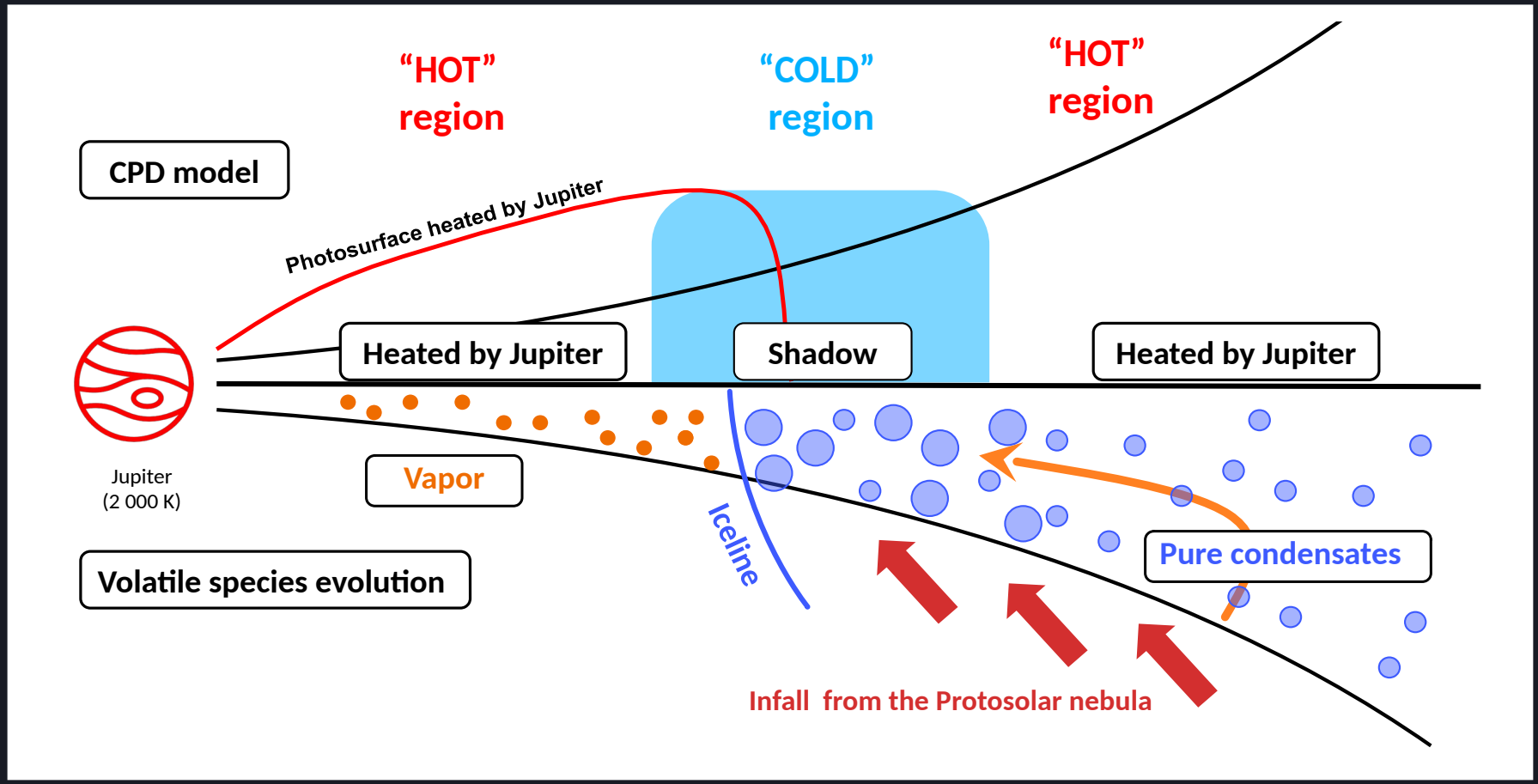


Only injection of hydrated minerals

Water:Rock of 1:1 at snowline

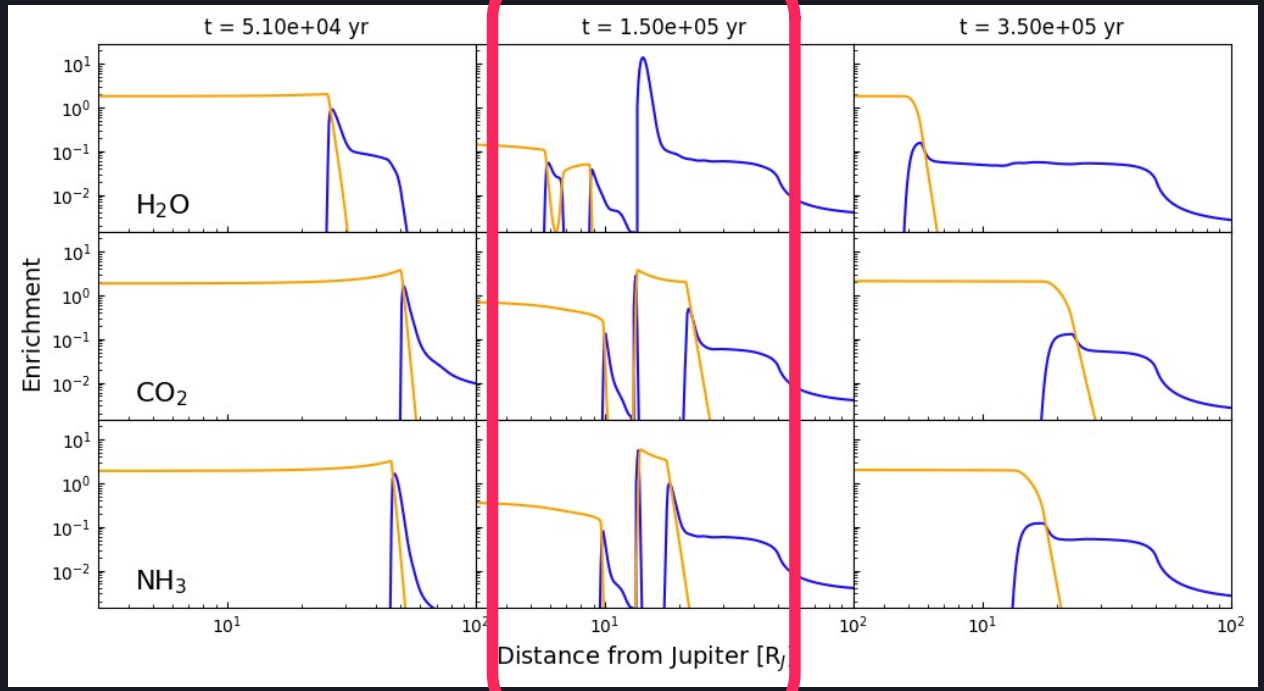
Mousis et al 2023

CPD substructures



Schneeberger et al in prep

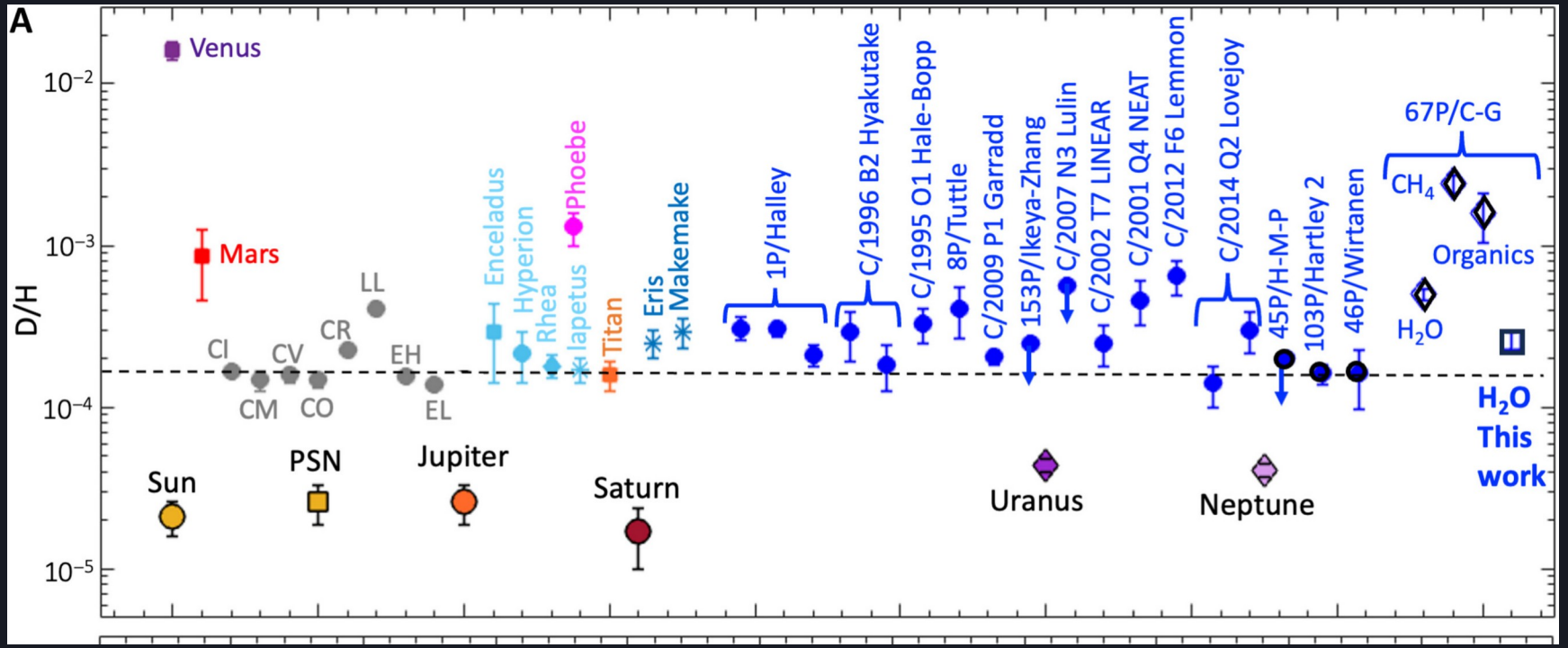
CPD substructures



Formation of a dust trap

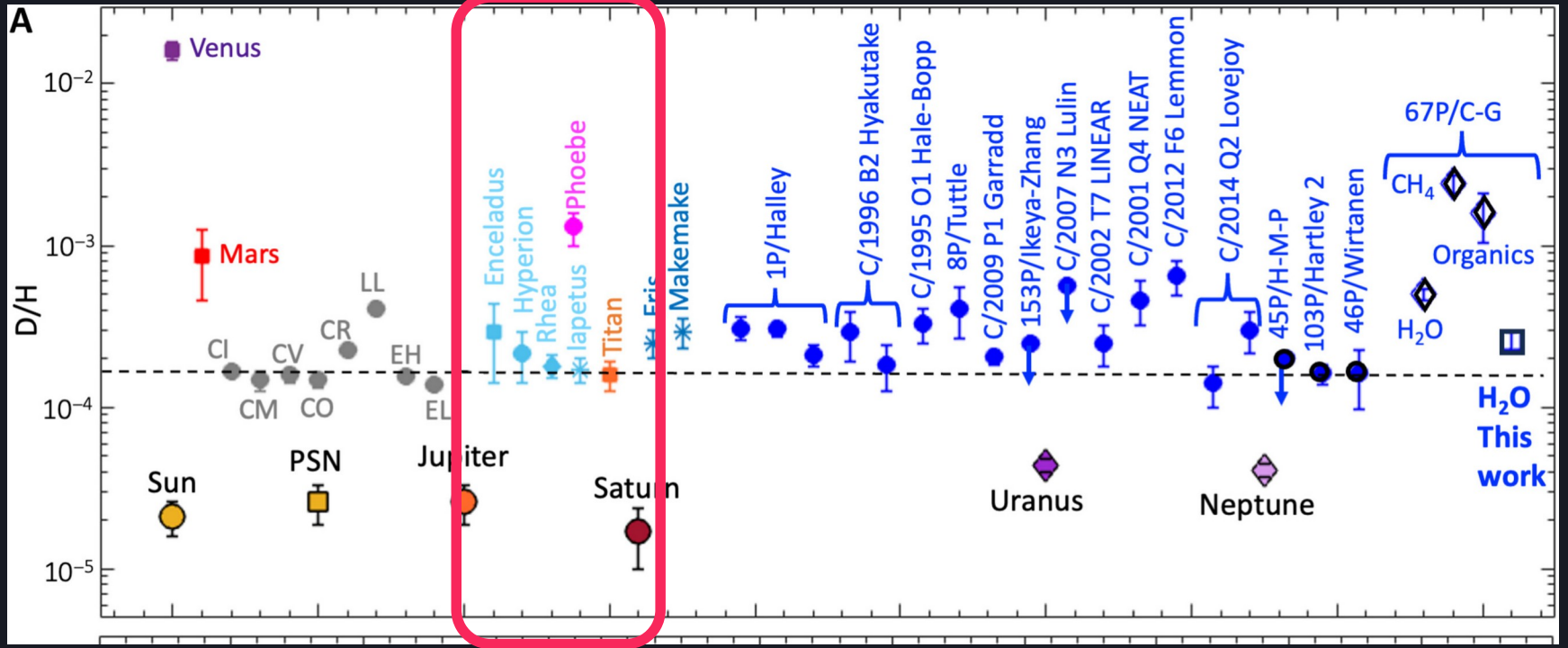
Schneeberger et al in prep

D/H to trace formation conditions and processes



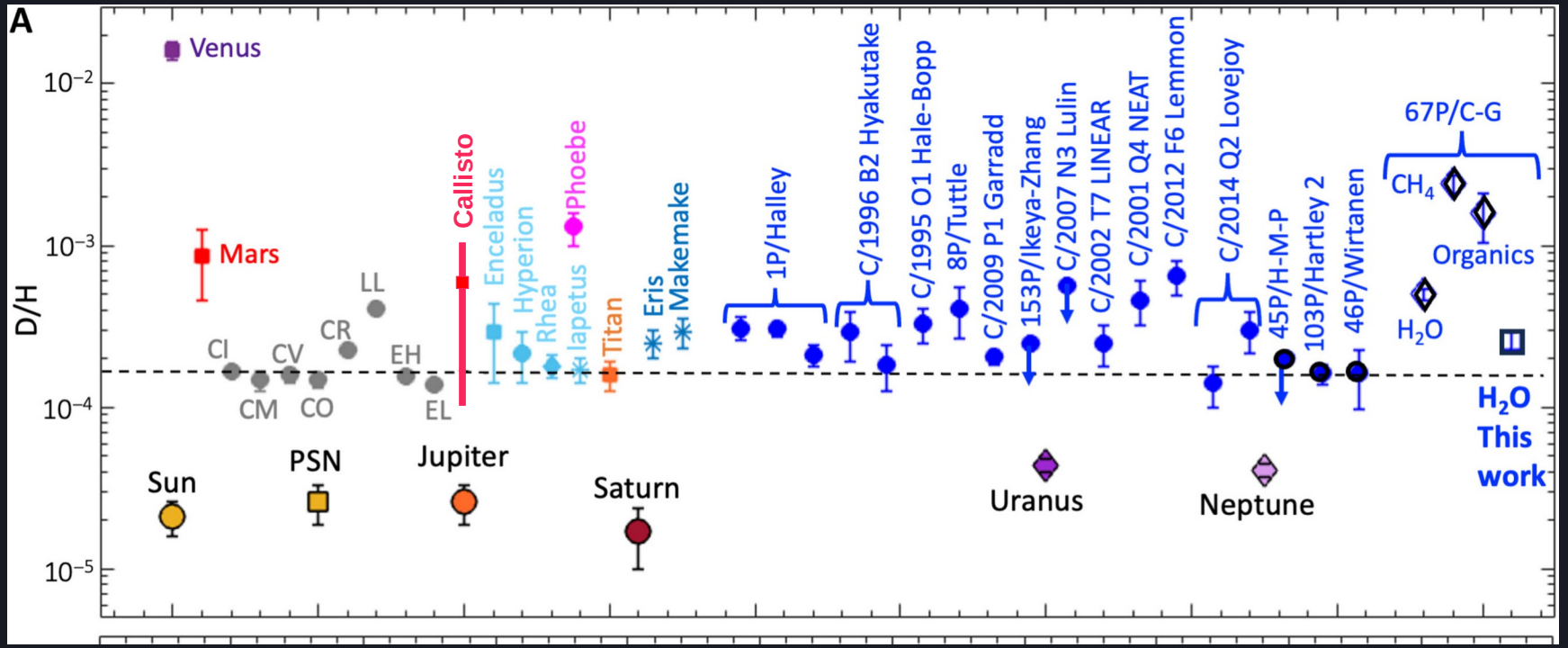
Mandt et al 2024

Saturn moons : supersolar D/H



Mandt et al 2024

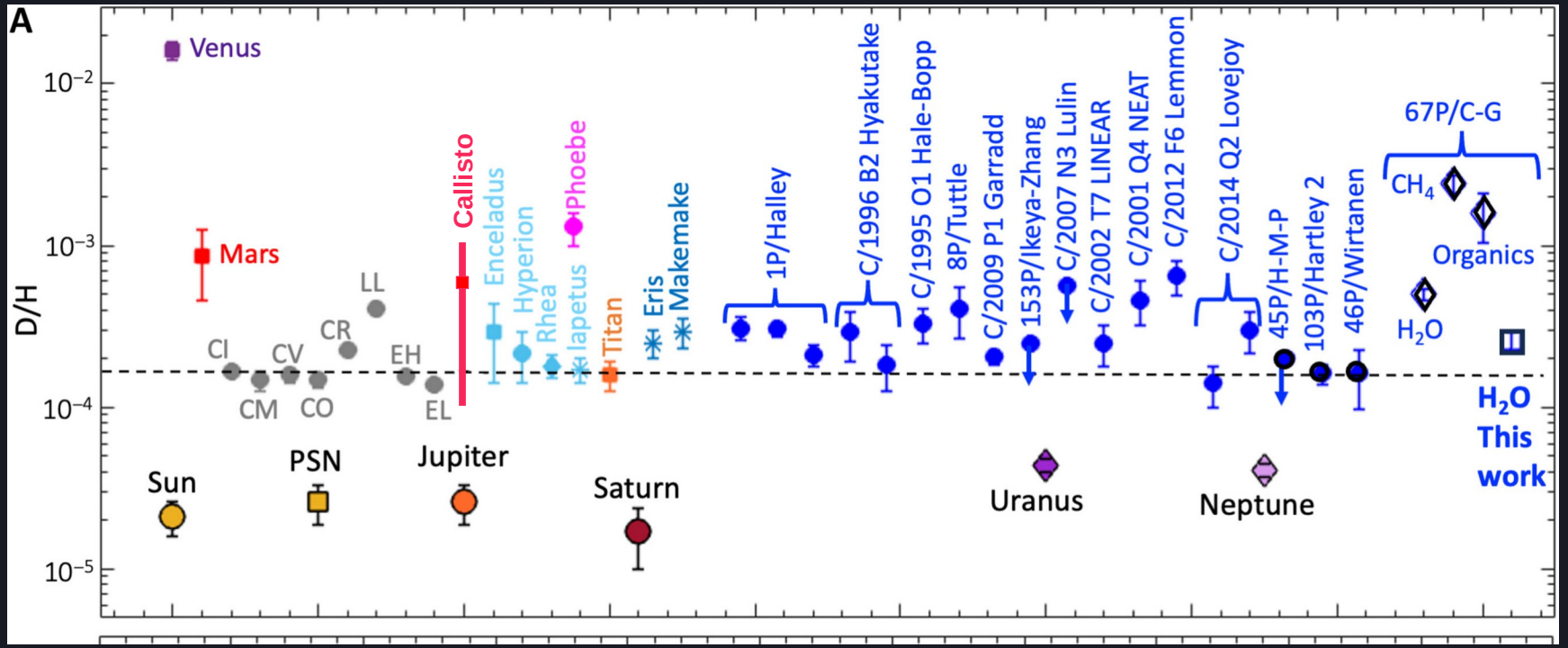
Jupiter moons : Callisto has a supersolar D/H



Waite et al 2009

Mandt et al 2024

Further D/H ratio measurements to come with JUICE and Europa-Clipper



Waite et al 2009

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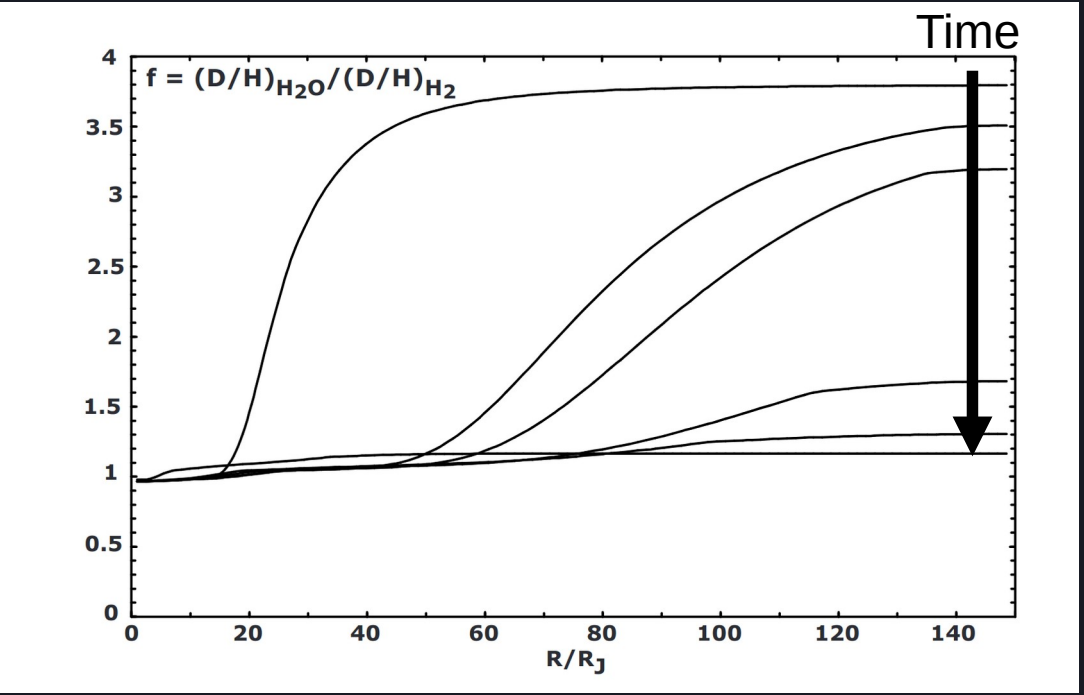
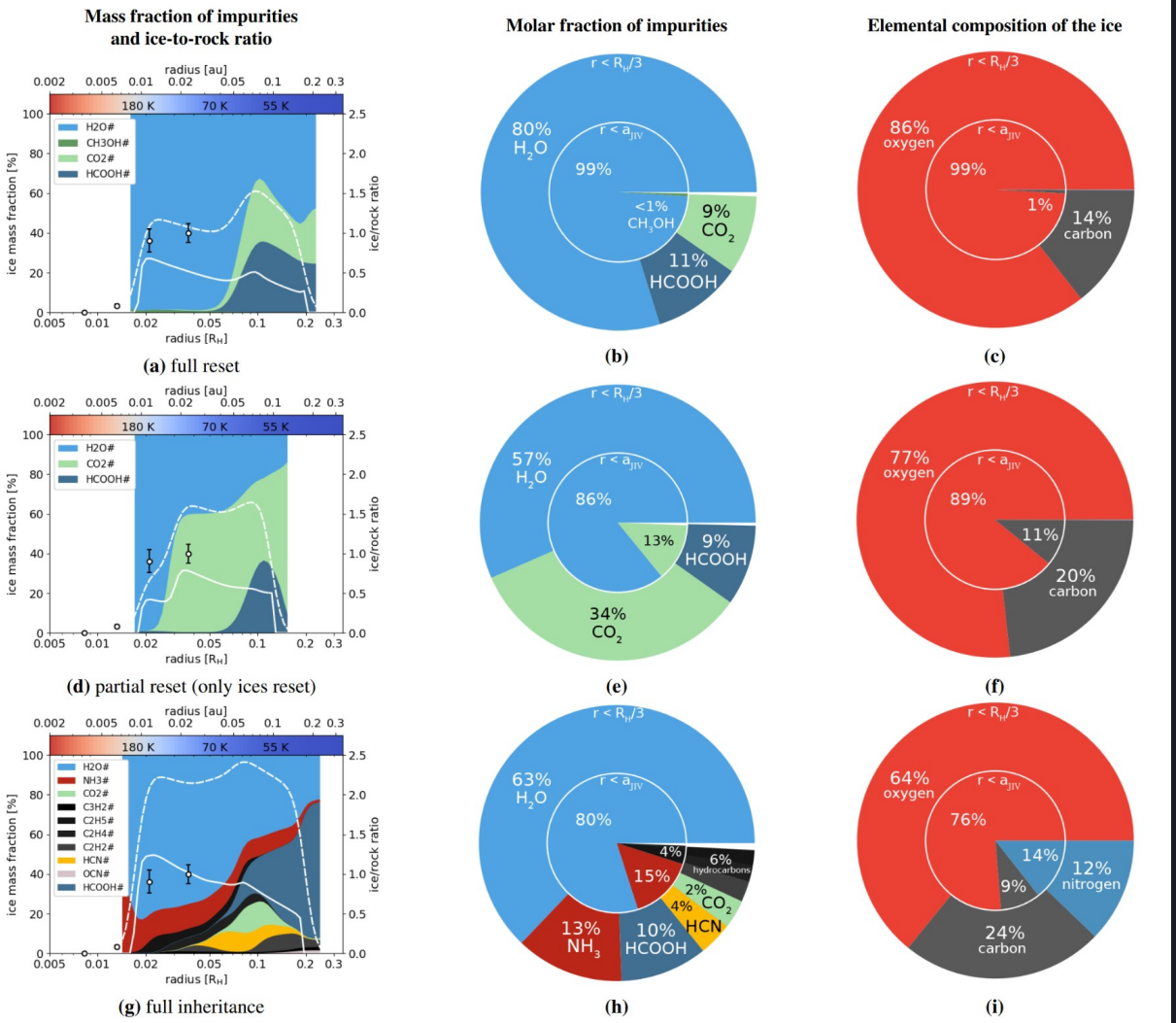


Warm region evolve toward protosolar D/H

Horner et al 2008

Toward thermochemical modelling

Adaptation of protoplanetary disk thermochemical models to CPDs such as *ProDiMo*



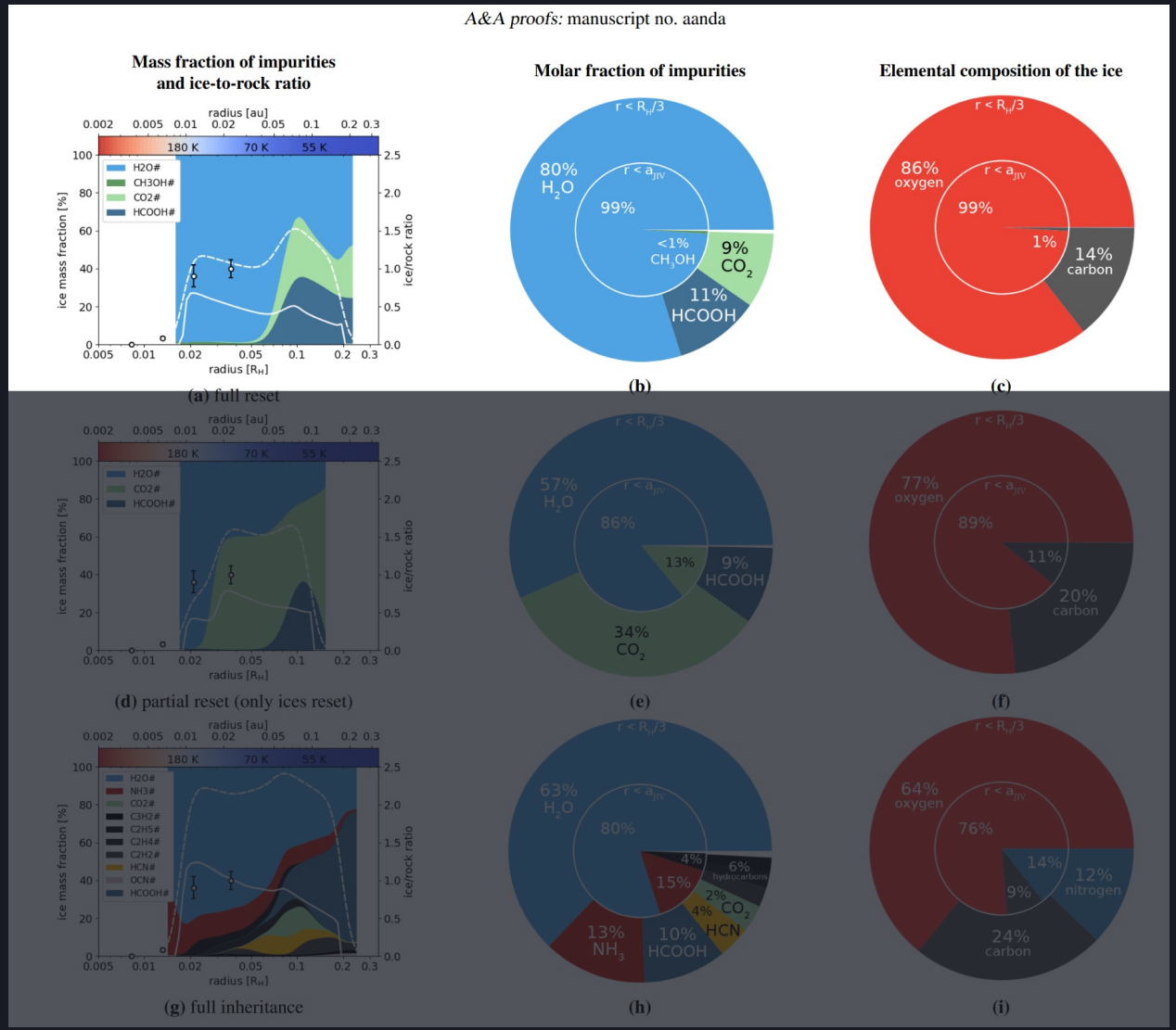
(a) full reset (b) (c)

(d) partial reset (only ices reset) (e) (f)

(g) full inheritance (h) (i)

Large dependence on accretion physics

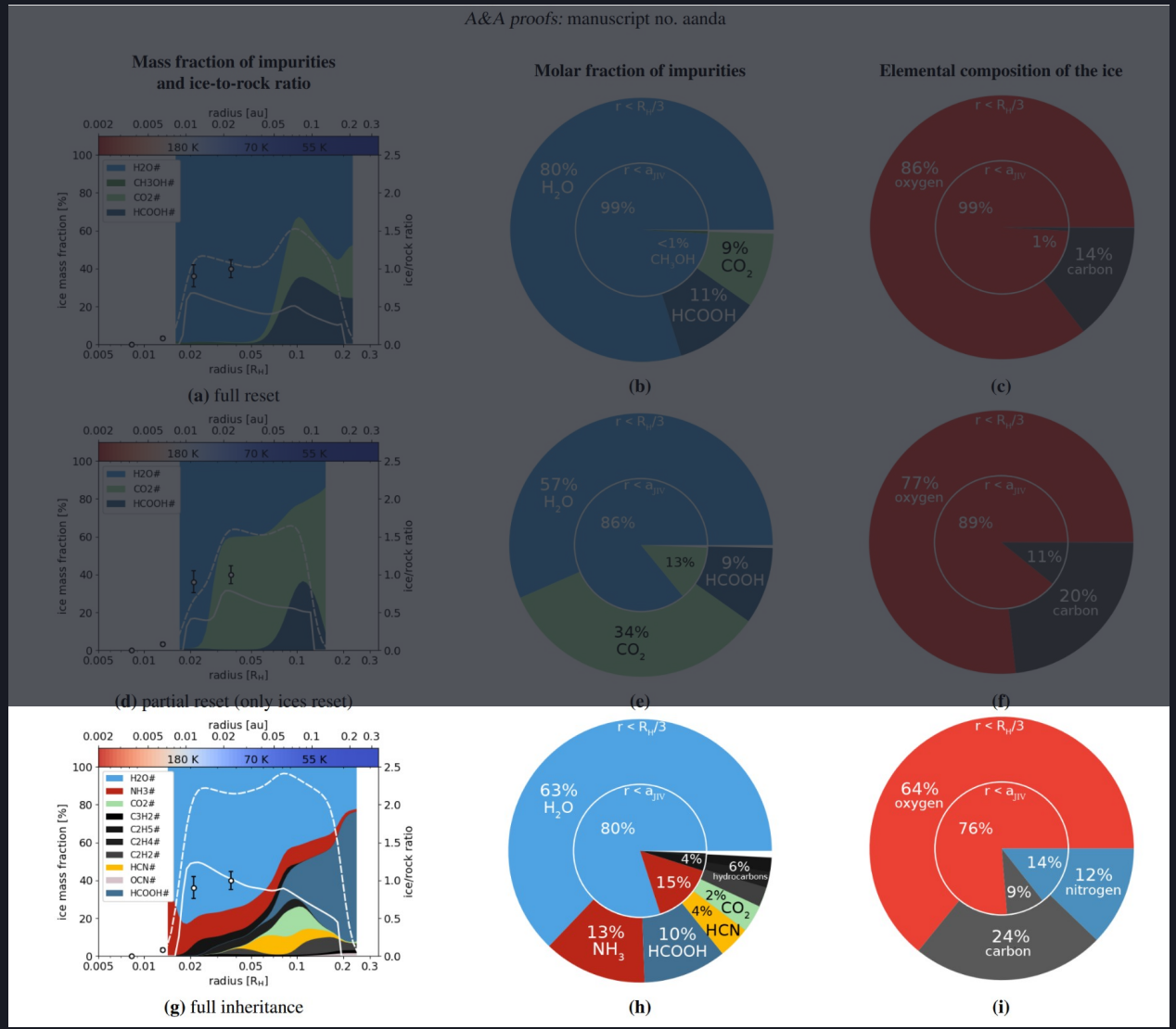
Oberg et al 2023



Atomic gas

Only Water, CO_2 and HCOOH available

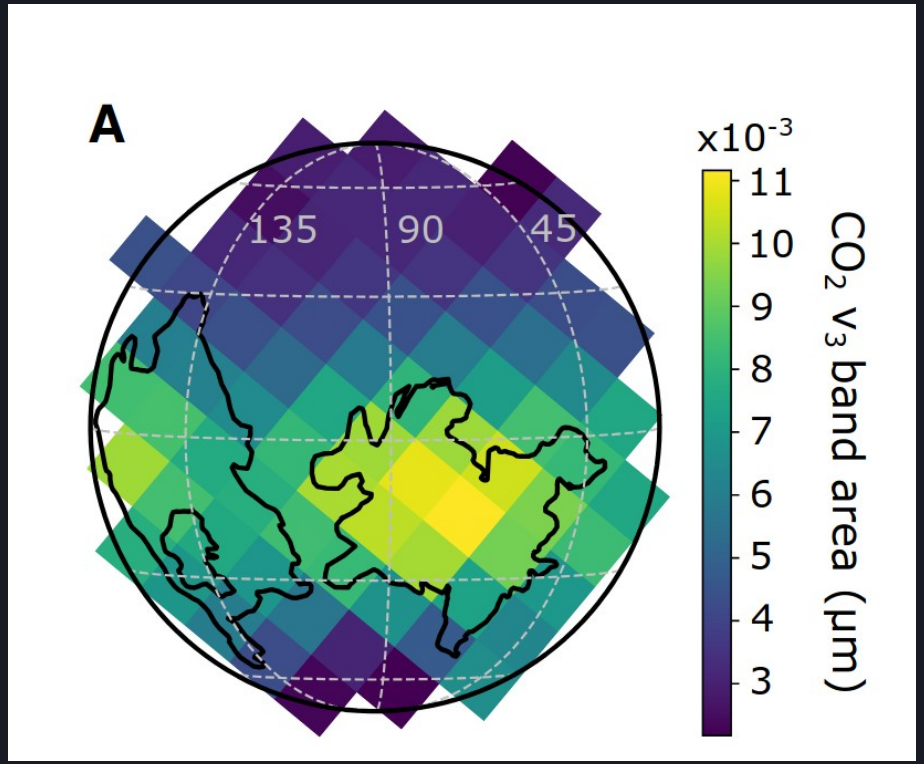
Oberg et al 2023



Inheritance from the protoplanetary disk

Conserve the molecular diversity

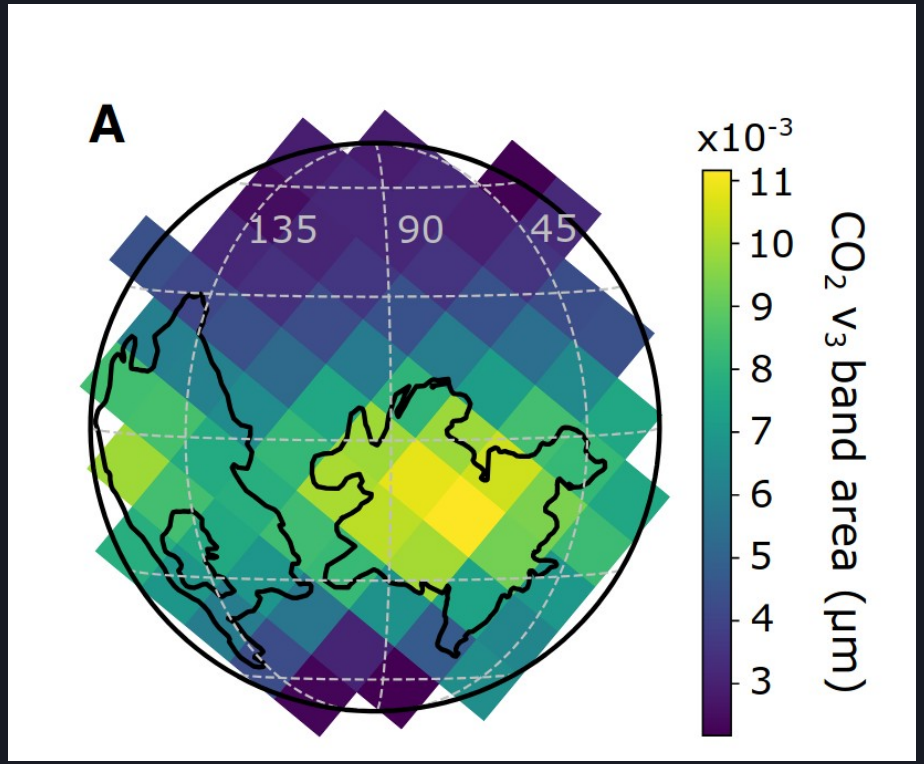
Oberg et al 2023



CO_2 ice in chaos terrains regions

Probably endogenous CO_2

Trumbo et al 2023



Originate from accreted

1. CO_2 ice
2. Complex Organic Matter

Villanueva et al 2023

We need to couple these analysis with

Orbital Evolution

Interior Structure Evolution

Not enough solids to form the moons

Accreted material from the protoplanetary disk is dust depleted by a factor 10–100

Not enough to form the moons

Tanigawa et al 2012

Solutions

Dust is lifted from the midplane (szulagyi et al 2022)

or

We have to find other sources of solids :

- Captured planetesimals (Ronnet et al 2017)
- Captured collision debris

Looking elsewhere

8 systems with tentative detection of CPD

Around very massive planets (>5 M_J)

Looking elsewhere

CPD C/O larger than the disk

Delorme 1 AB, CT Cha b

Mâlin et al 2025

Looking elsewhere

Very hot silicate dust emission (>1000 K)

PDS 70 b-c, YSES b-c, TWA 27 b

Mâlin et al 2025

Takeaways

1. Most of primordial constrains no longer exists.
   - Isotopic ratios
   - Interior structure
2. Combination of CPD structure and composition modelling can produce these observables
3. Study of forming exoplanets will help constrain models in coming years