Solar System science with AtLAST

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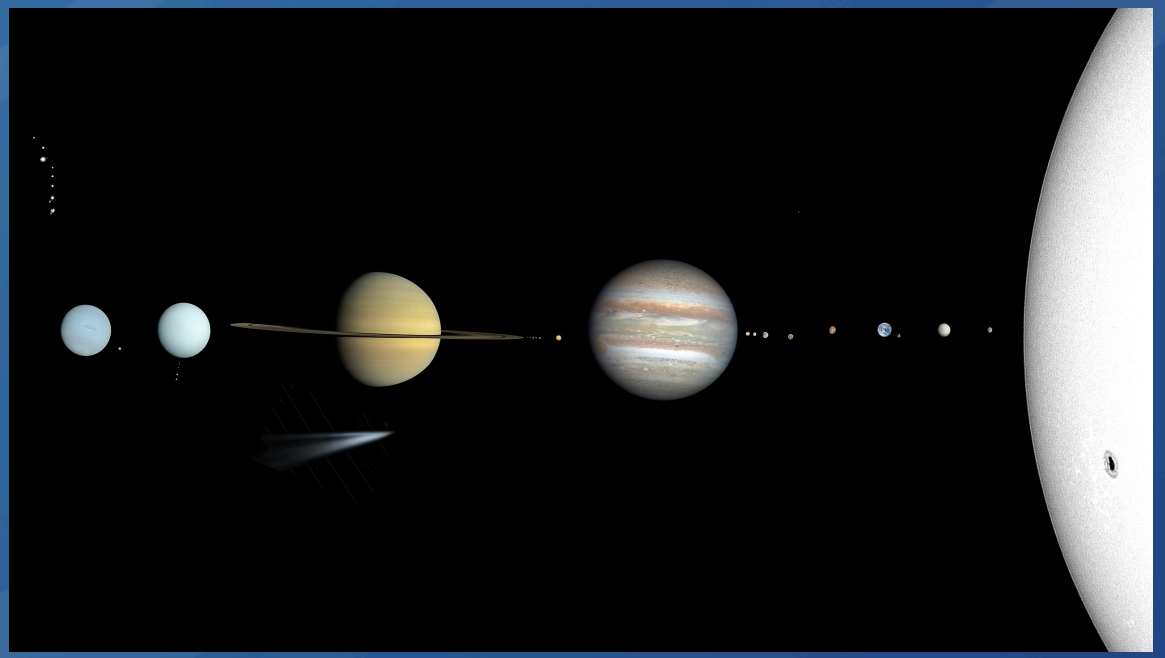

Outline

- **Why studying the Solar System?**
- **Solar system science in the mm**
  - A great variety of sources
  - Observing Solar System objects in the mm
  - Science questions
- **Why AtLAST for Solar System?**
- **Conclusion**

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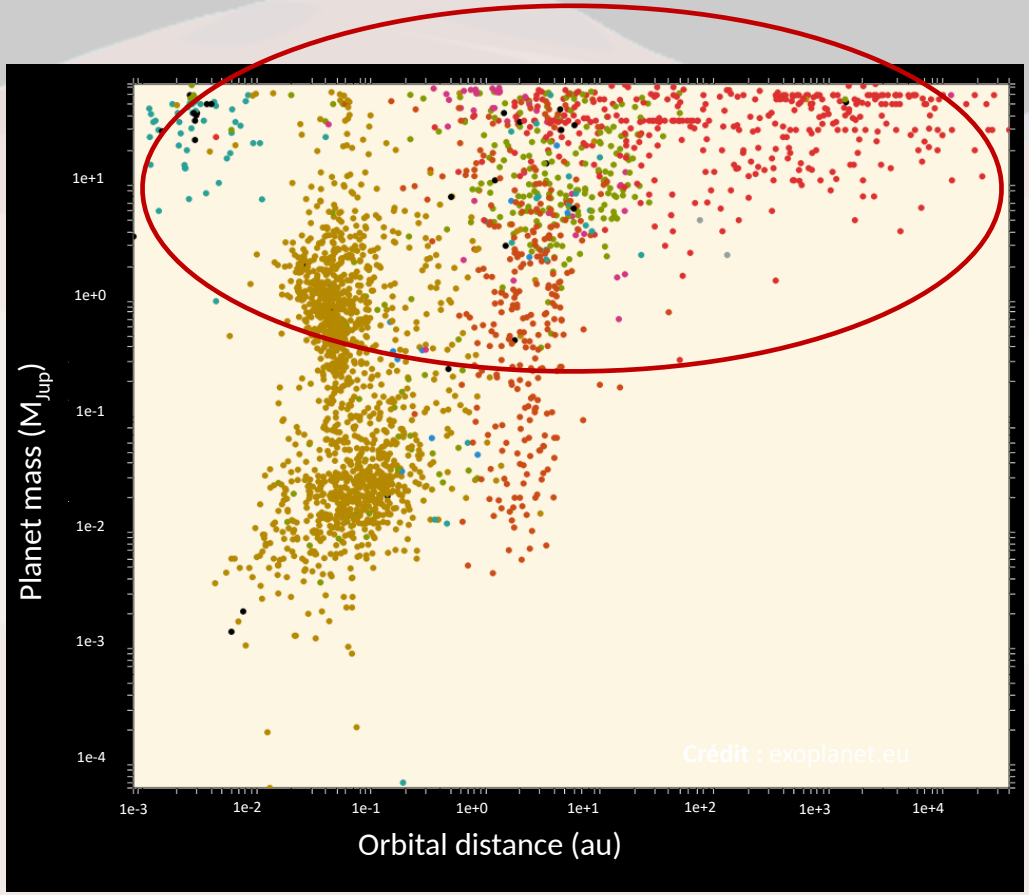
Why studying the Solar System?

Overarching theme: Formation and evolution of the Earth and other planets

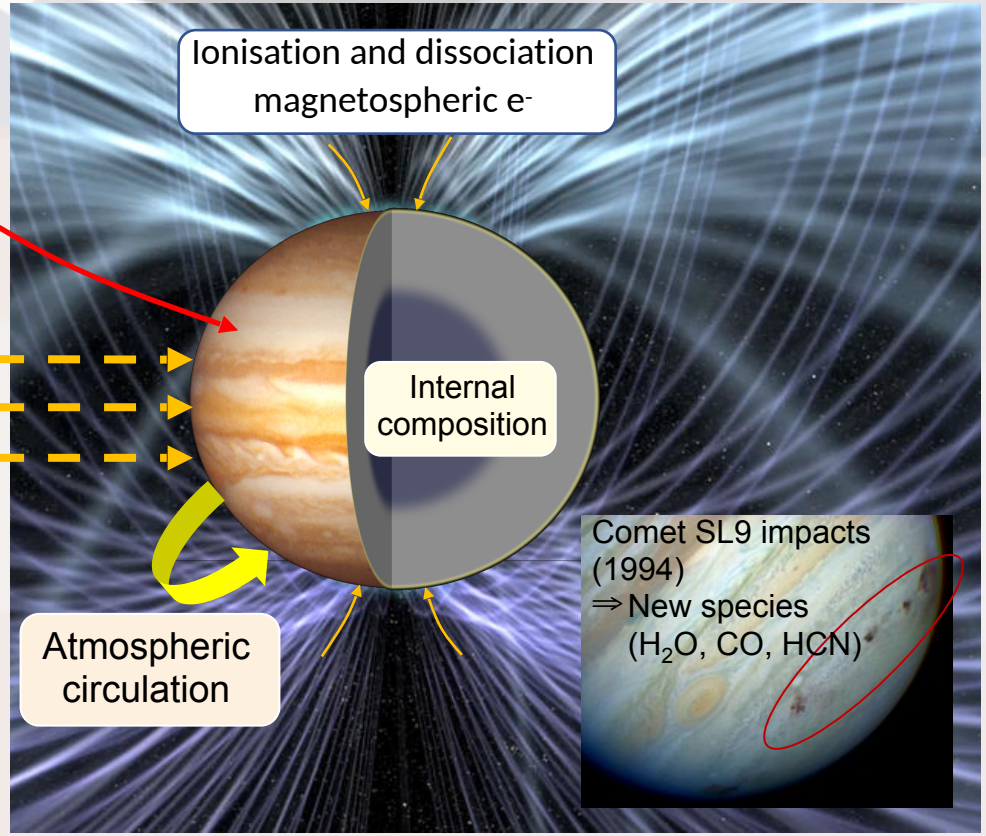
Giant planets are the most commonly found planets in our Galaxy

Natural laboratories to study chemistry and dynamics



External sources

Solar UV photochemistry

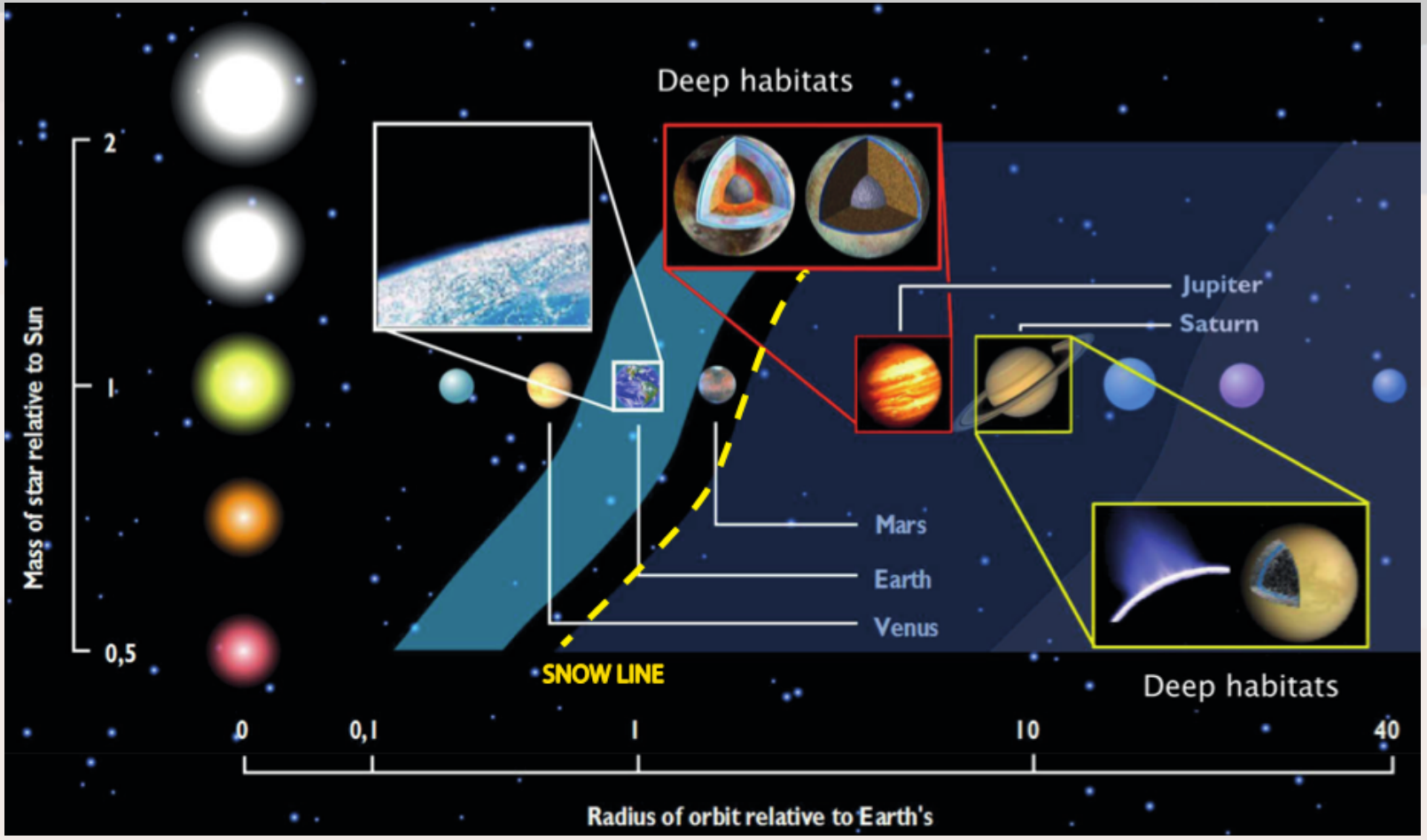


Why studying the Solar System?

Overarching theme: Formation and evolution of the Earth and other planets

Terrestrial planets, moons, and comets

Insights on habitability, its evolution and emergence of life



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Solar System science in the mm

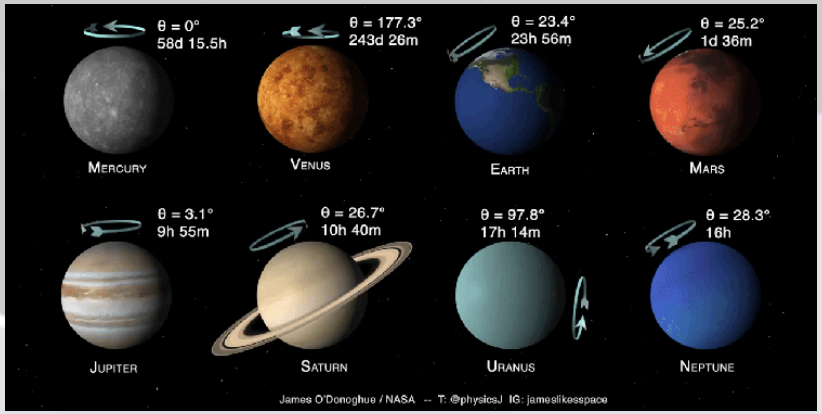
- **A great variety of sources**
  - Planets
    - Telluric
    - Gas/Ice giants

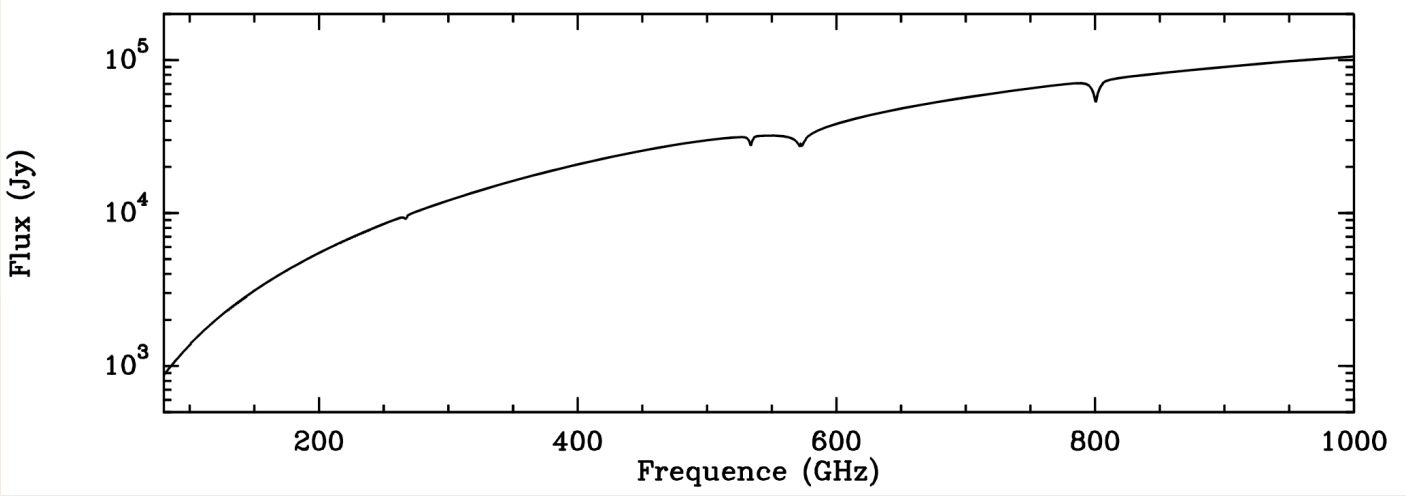
    and their satellites
  - Comets
  - Asteroids
  - Trans-Neptunian Objects
  - And others

Solar System science in the mm

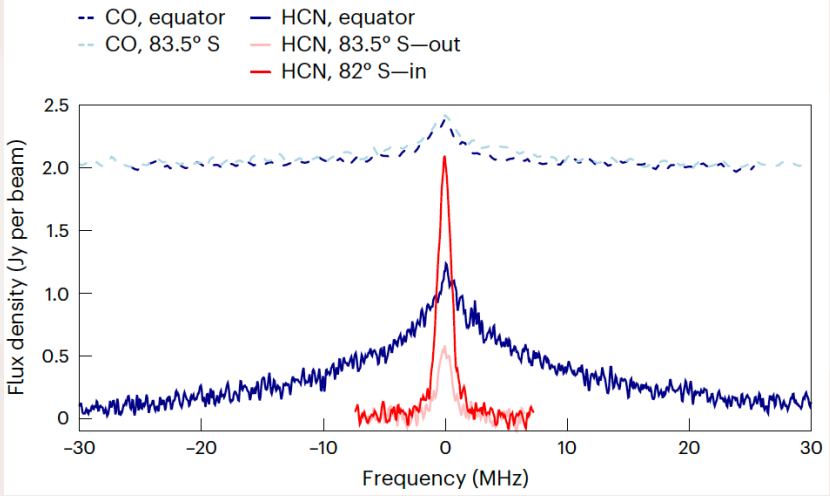
Observing Solar System objects in the mm

- A variety of observation conditions
  - Moving targets
  - From fast to slow rotators
  - From extended towards point-like
  - From faint to strong continuum
  - With/without atmospheres
    - From 10s of K to 100s of K temperatures => From faint to strong line intensities
    - From nbar to bar pressures => From narrow to broad lines





Jupiter mm spectrum (Moreno 1998)

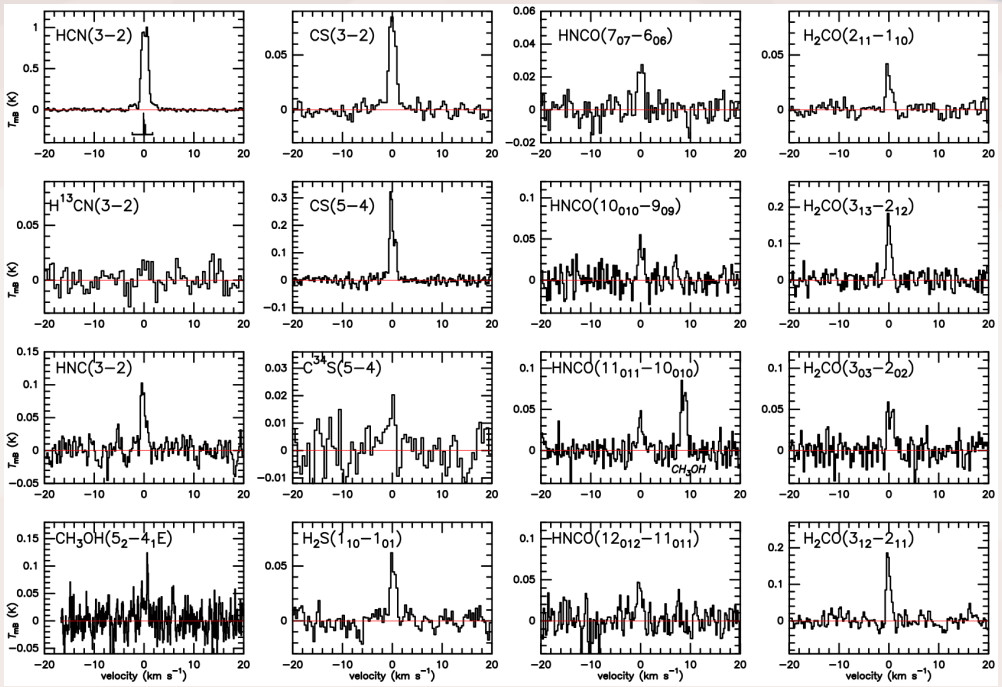


ALMA band 7 – HCN and CO in Jupiter (Cavalié et al. 2021)

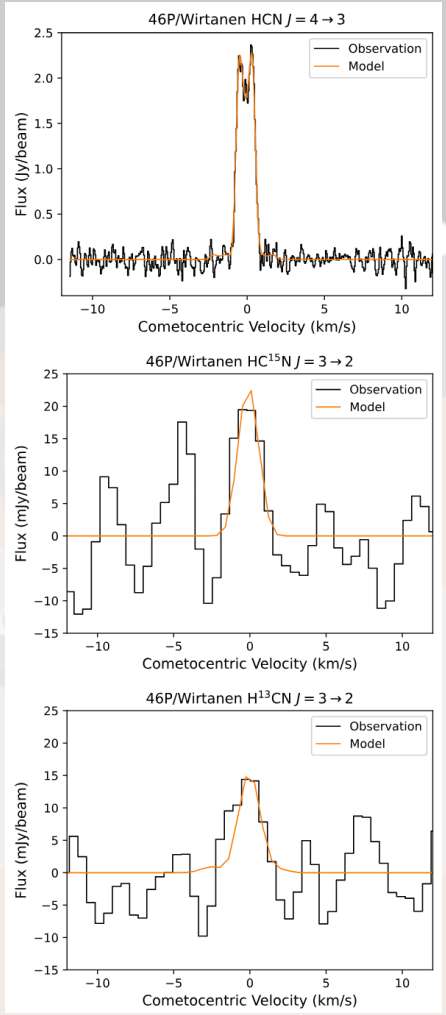
Solar System science in the mm

Observing Solar System objects in the mm

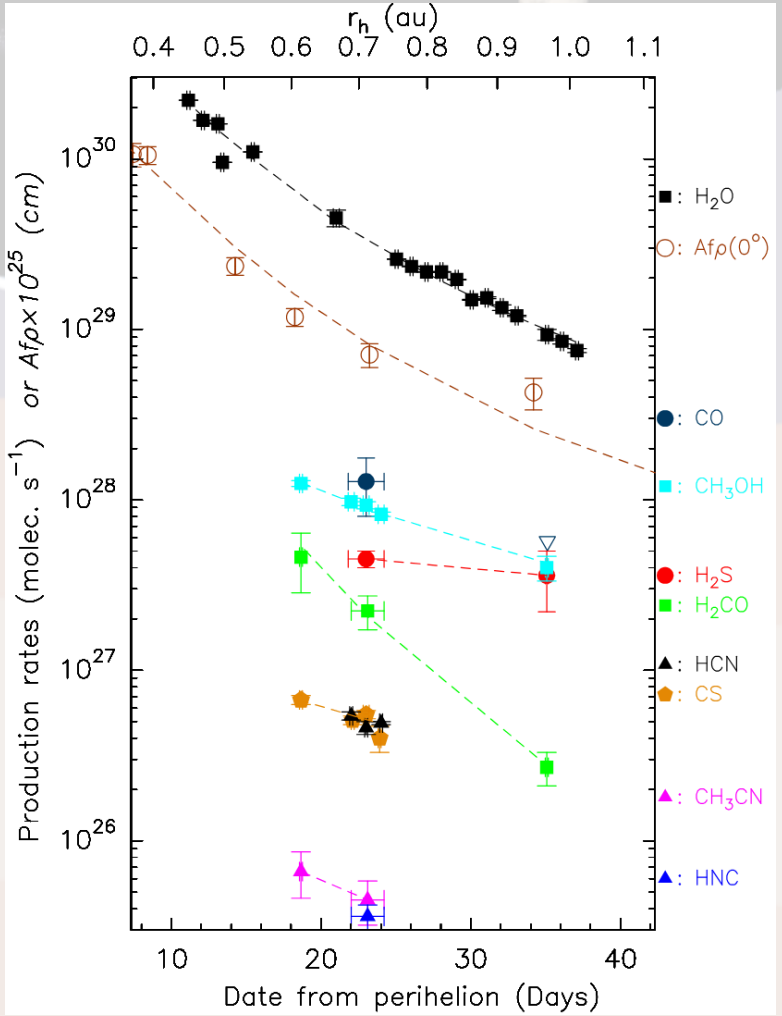
- Line spectroscopy
  - Composition (+isotopic ratios)
  - Dynamics (temperature and winds)
  - Temporal evolution



IRAM-30m – comet C/2021 A1 (Leonard)
(Biver et al. 2024)



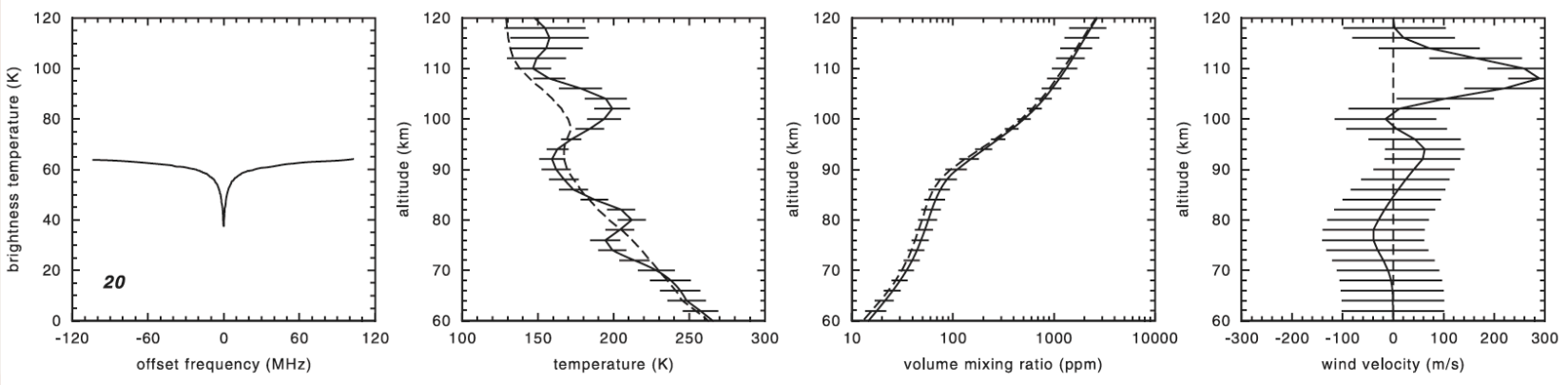
ALMA – isotopic ratios in comet
46P Wirtanen (Cordiner et al. 2024)



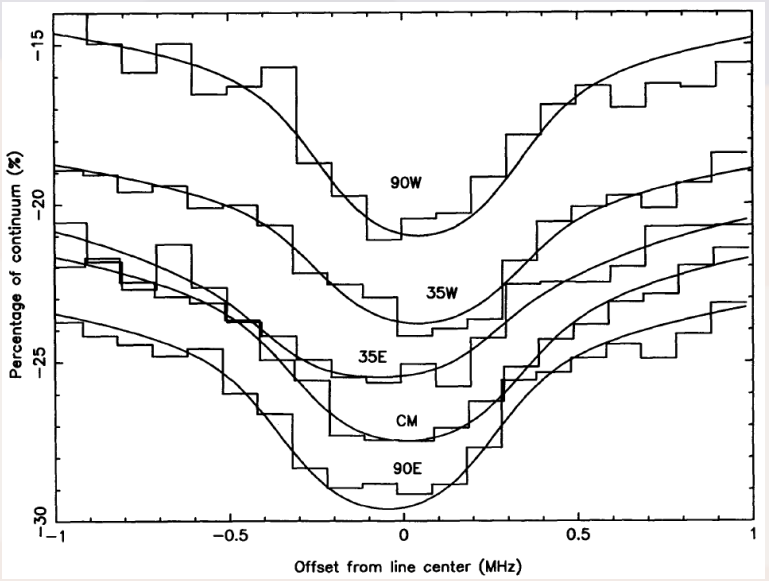
IRAM-30m & NOEMA – comet C/2020 F3 (Neowise)
production rate evolution (Biver et al. 2022)

Solar System science in the mm

- **Observing Solar System objects in the mm**
  - Line spectroscopy
    - Composition (+isotopic ratios)
    - Dynamics (temperature and winds)
    - Temporal evolution



HHSMT – CO lines in Venus, temperature, abundance and wind retrievals (Rengel et al. 2008)

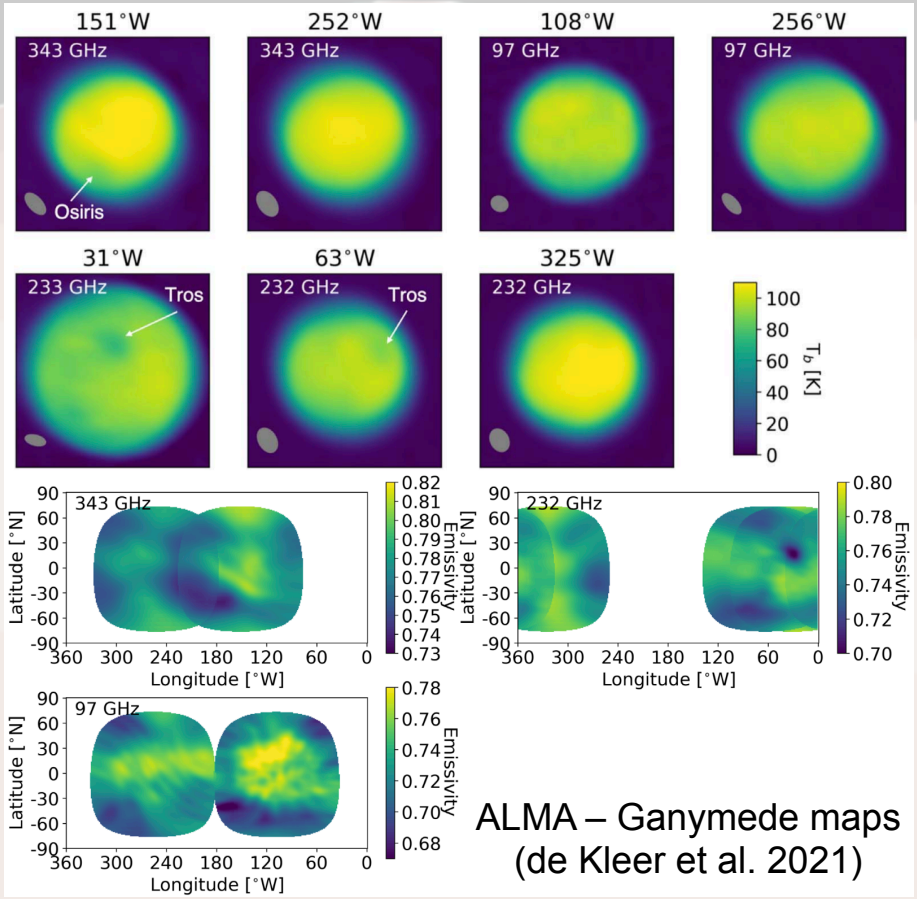


IRAM-30m – CO lines in Mars (Lellouch et al. 1991)

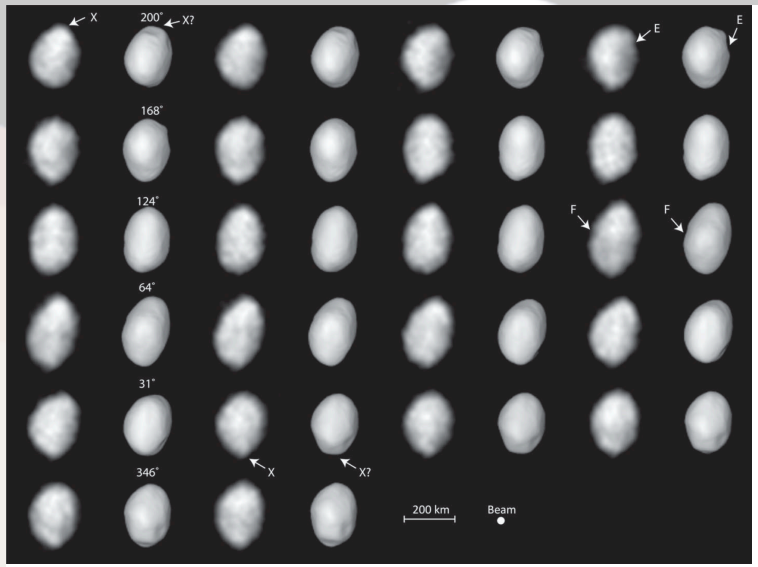
Solar System science in the mm

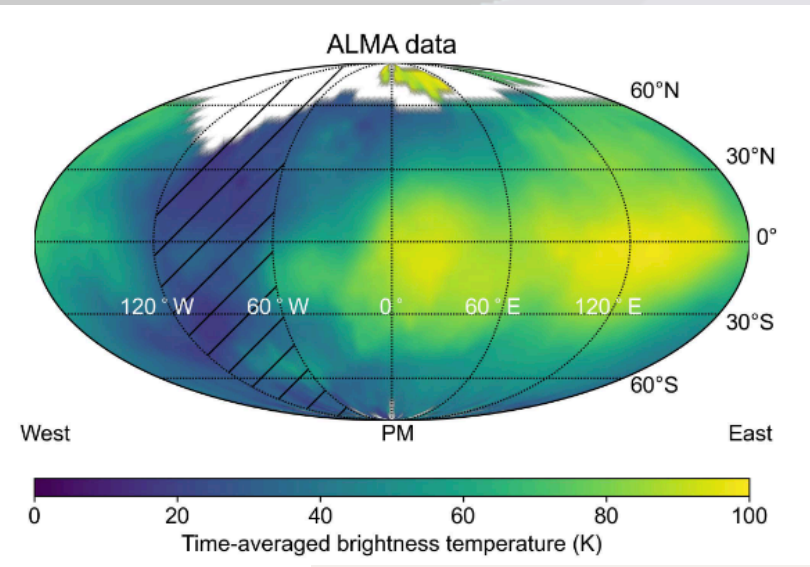
Observing Solar System objects in the mm

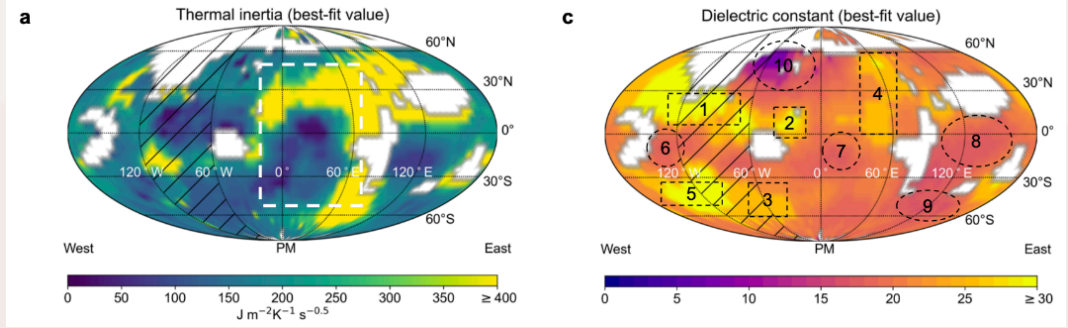
- Continuum spectroscopy
  - Surface shape & features
  - (near-surface) Temperature and electrical properties (tied to composition, porosity, etc.)



ALMA – Ganymede maps (de Kleer et al. 2021)





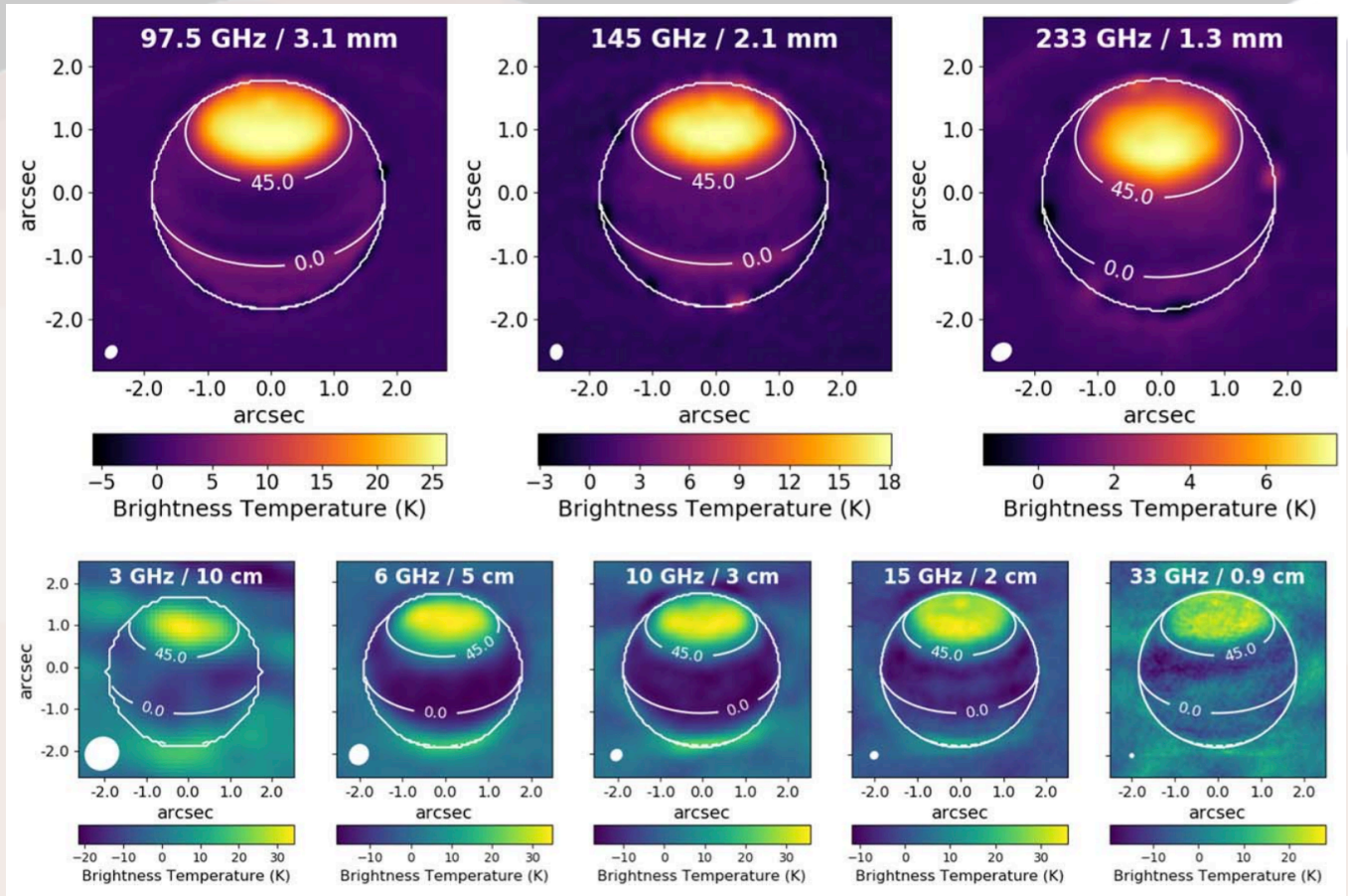


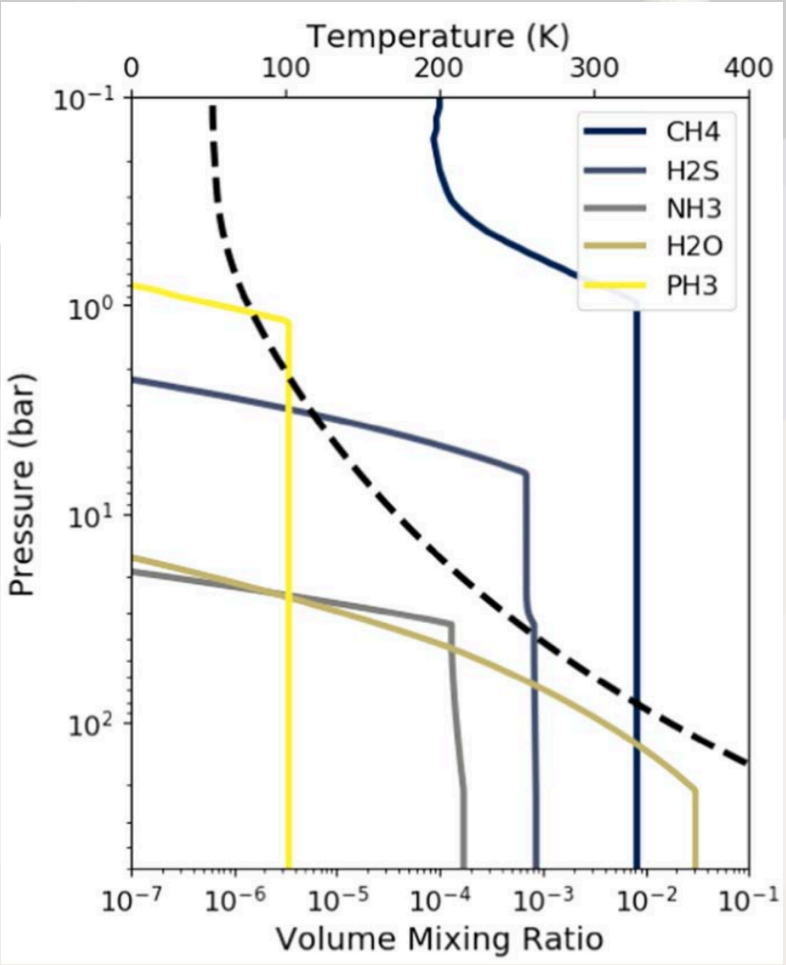
ALMA – Psyche asteroid (Shepard et al. 2021, Saverio et al. 2022)

Solar System science in the mm

Observing Solar System objects in the mm

- Continuum spectroscopy
  - (deep) Temperature
  - (deep) Composition



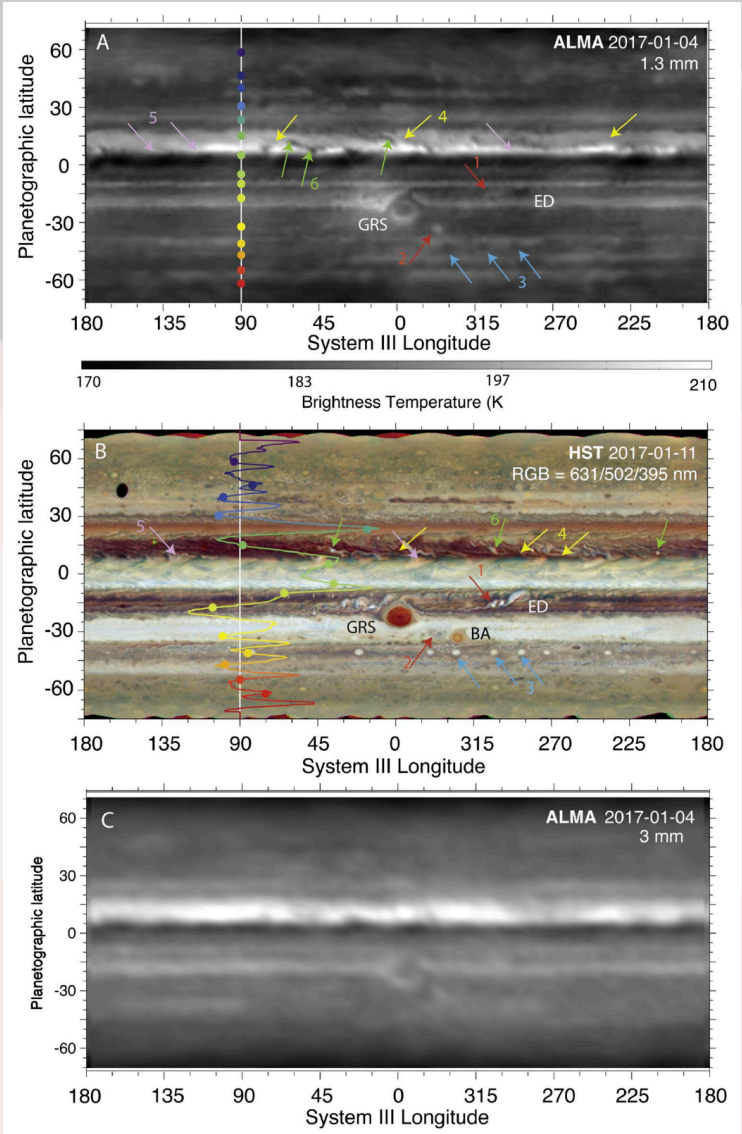


ALMA & VLA – Uranus brightness temperature and retrieved deep composition (Molter et al. 2021)

Solar System science in the mm

Observing Solar System objects in the mm

- Continuum spectroscopy
  - (deep) Temperature
  - (deep) Composition
  - Tropospheric meteorology

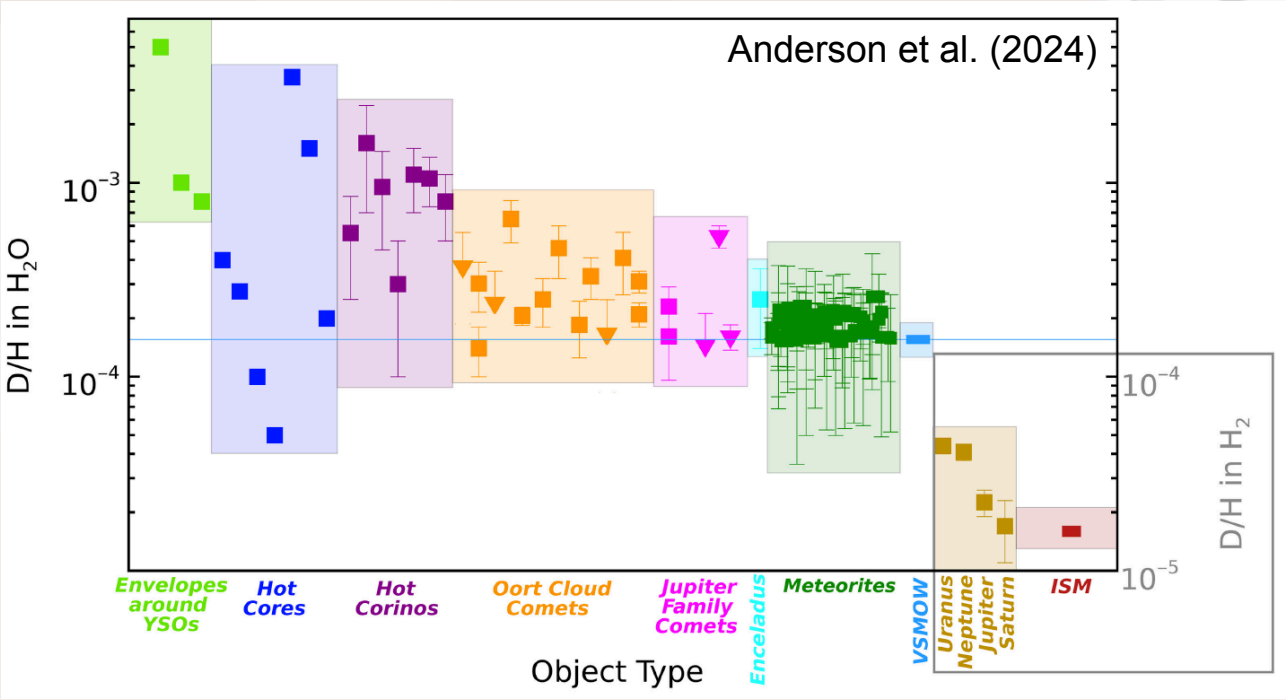


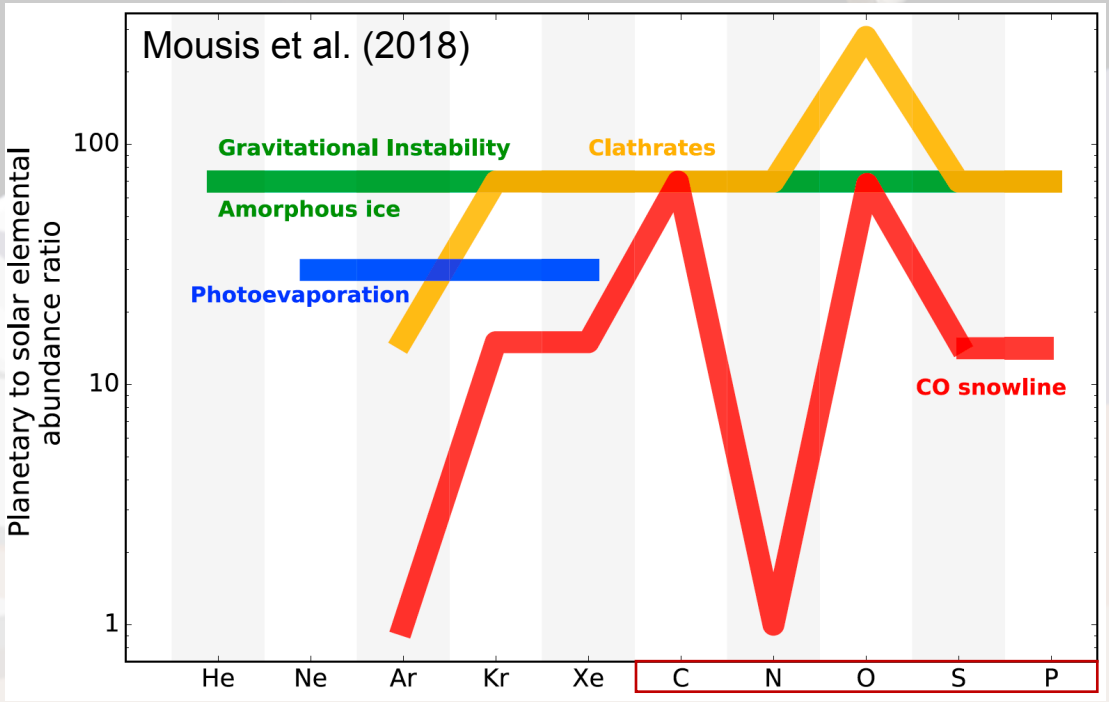
ALMA – Jupiter continuum maps
(de Pater et al. 2019)

Solar System science in the mm

Science questions

- How did the Solar System form?
  - Composition of the comets
  - Deep composition of the Giant Planets
  - Isotopic ratios (e.g., D/H)



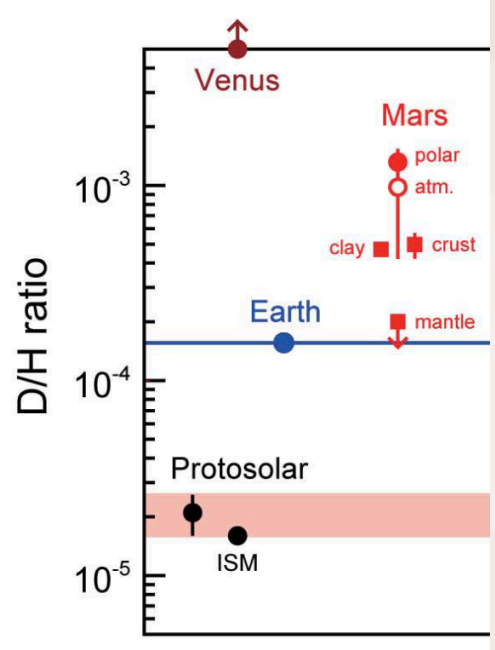


Constraints on temperature and compositon of the protoplanetary disk

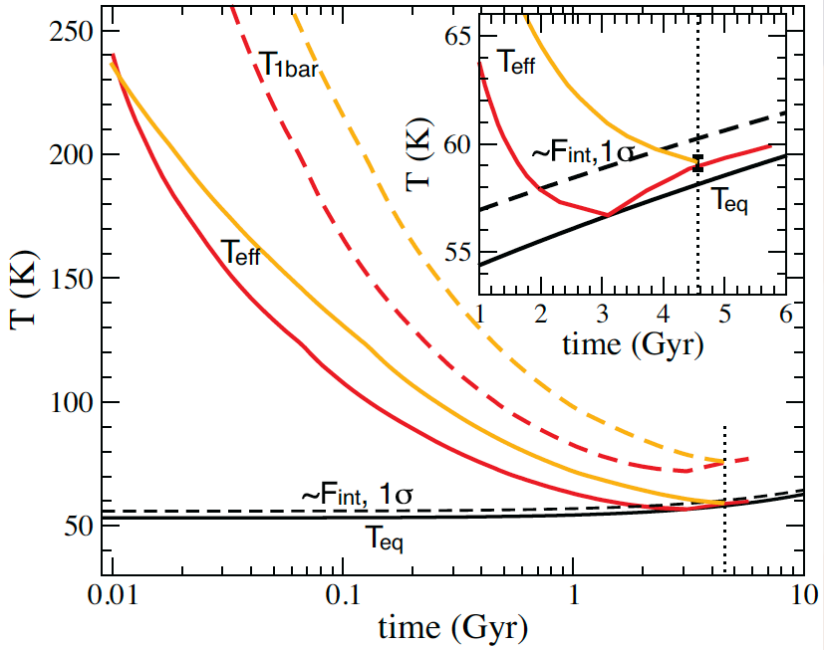
Solar System science in the mm

Science questions

- How did the Solar System evolve since its formation?
  - D/H in terrestrial planets – evolution of water reservoirs
  - Tropospheric temperature of giant planets – planet cooling history
  - Composition of different families of asteroids and comets



Hidenori et al. (2016)



Nettelmann et al. (2016)

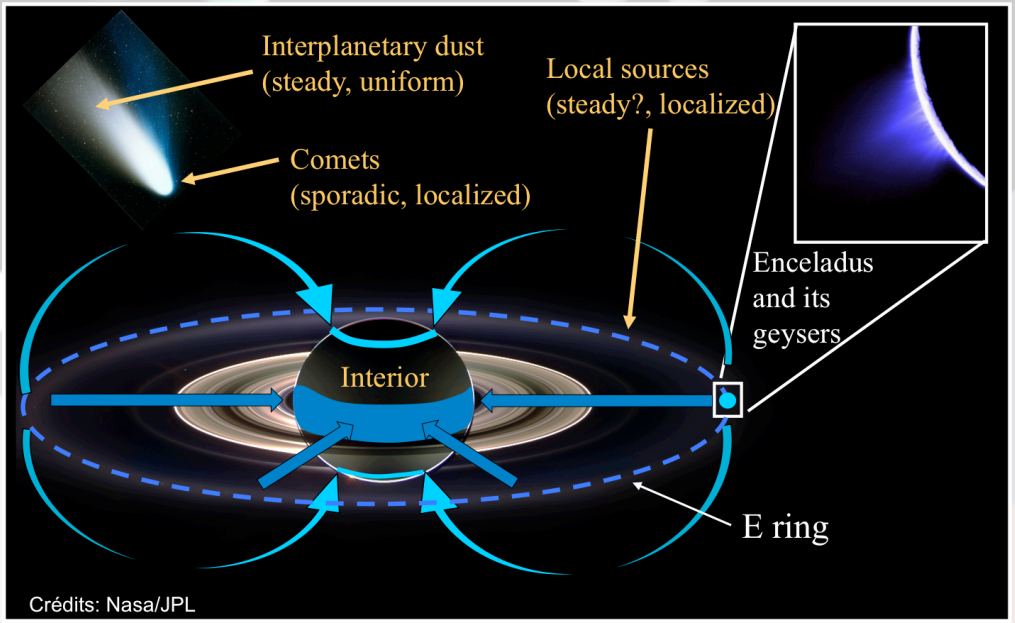
Solar System science in the mm

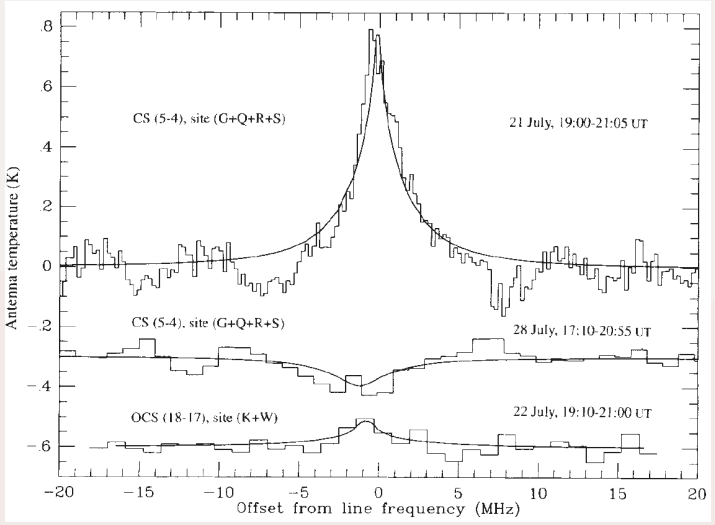
Science questions

How does the Solar System work?

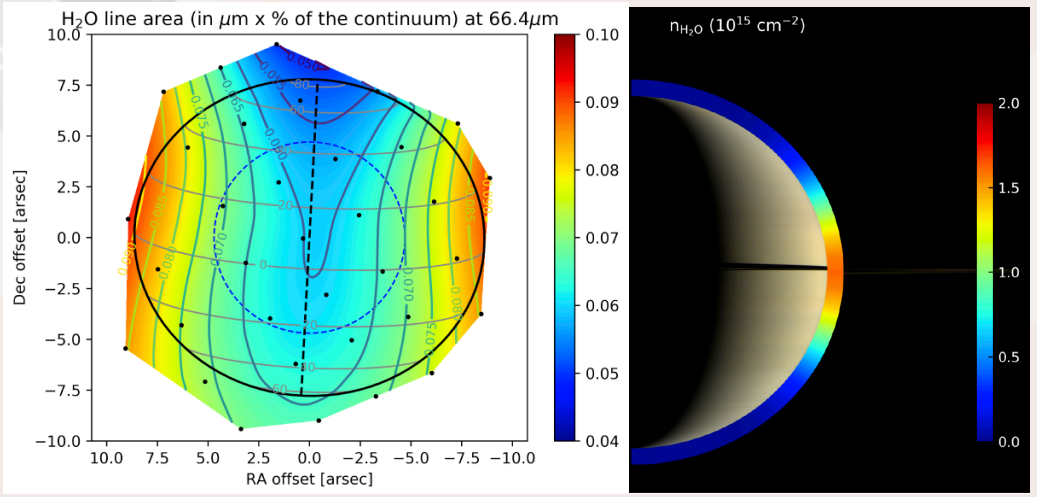
Interactions with close and farther environment

Jupiter-SL9 impacts





IRAM-30m - Lellouch et al. (1995)

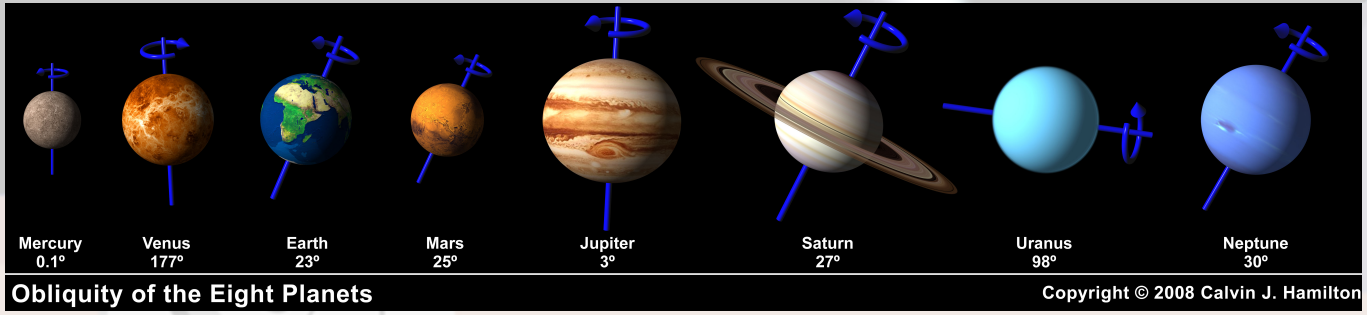


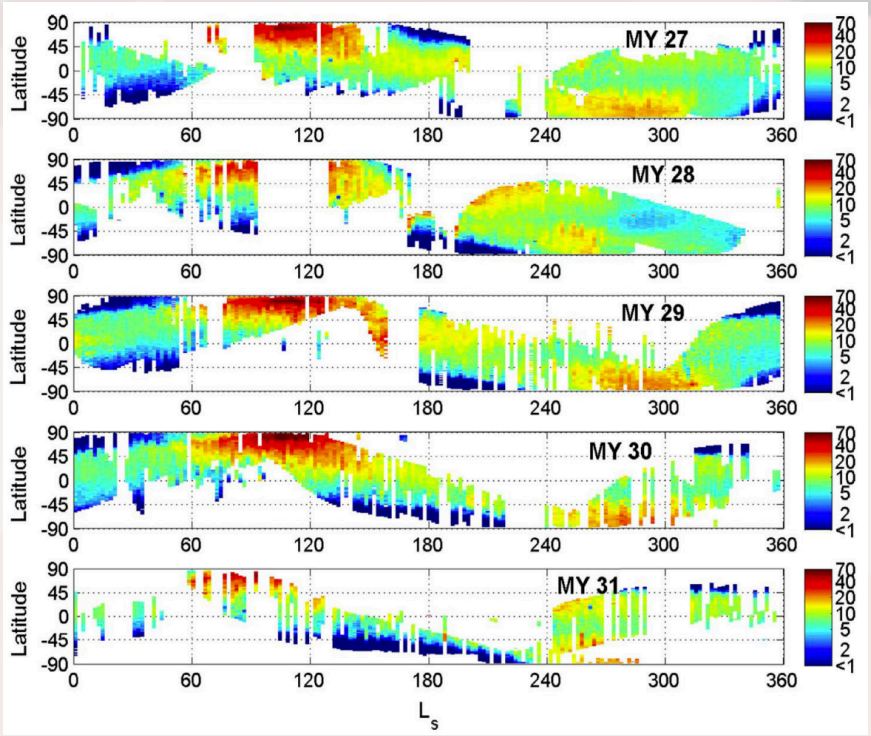
Herschel - Cavalié et al. (2019)

Solar System science in the mm

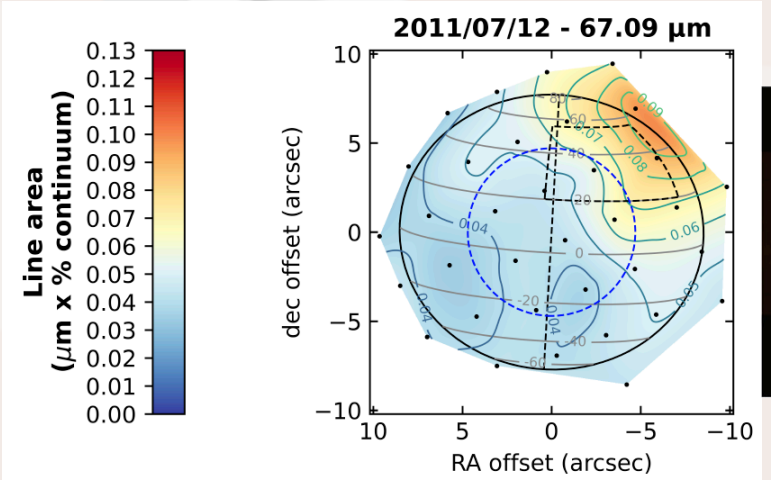
Science questions

- How does the Solar System work?
  - Interactions with close and farther environment
  - Seasonal evolution

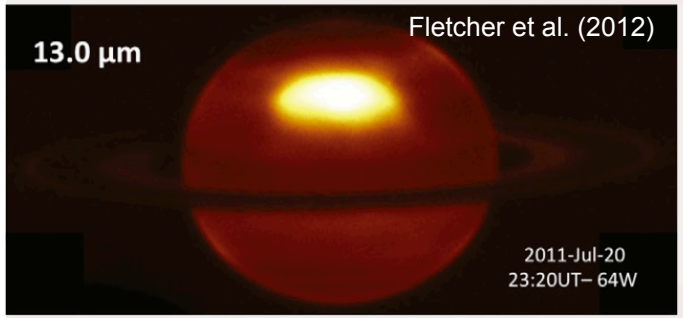




H_2O cycle in Mars (Trokhimovskiy et al. 2015)



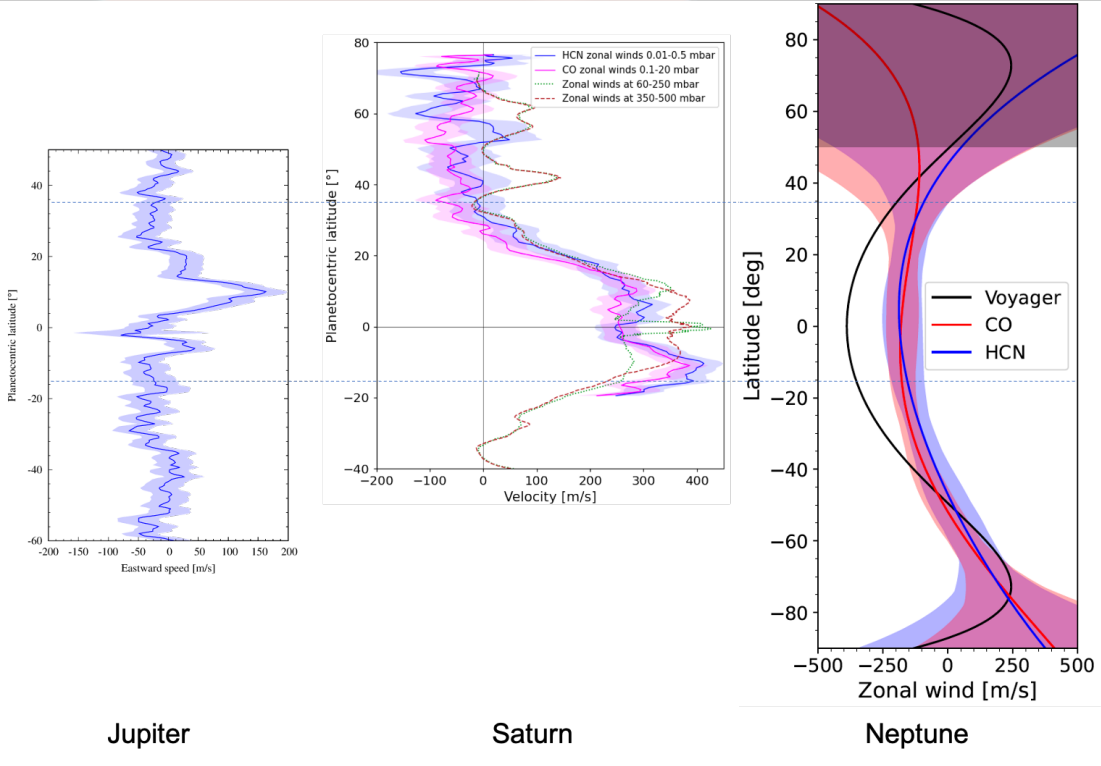
Herschel – H_2O variability during Saturn's 2010-2013 storm (Lefour et al. 2025)



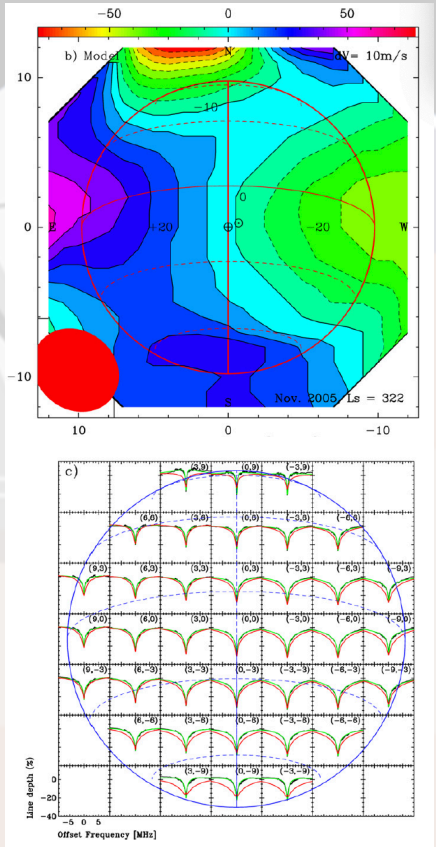
Solar System science in the mm

Science questions

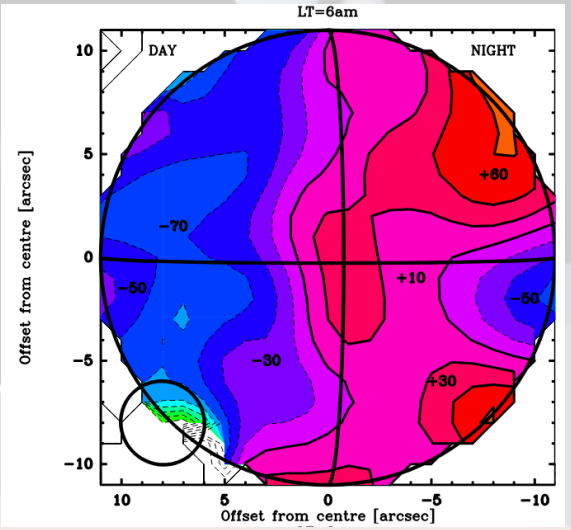
- How does the Solar System work?
  - Interactions with close and farther environment
  - Seasonal evolution
  - General circulation



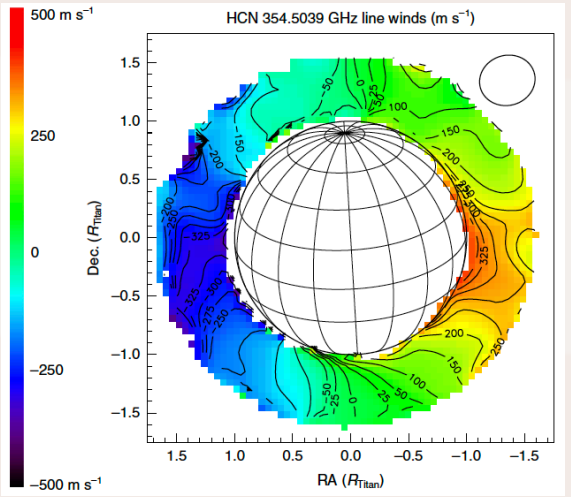
ALMA - Winds in the stratopsheres of giant planets
(Cavalié et al. 2021, Benmahi et al. 2022, Carrion-Gonzalez et al. 2023)



IRAM-30m & PdB – Winds in the martian mesosphere
(Moreno et al. 2009)



IRAM PdB – Winds in the venusian mesosphere (Moullet et al. 2012)



ALMA – Winds in the thermosphere of Titan (Lellouch et al. 2019)

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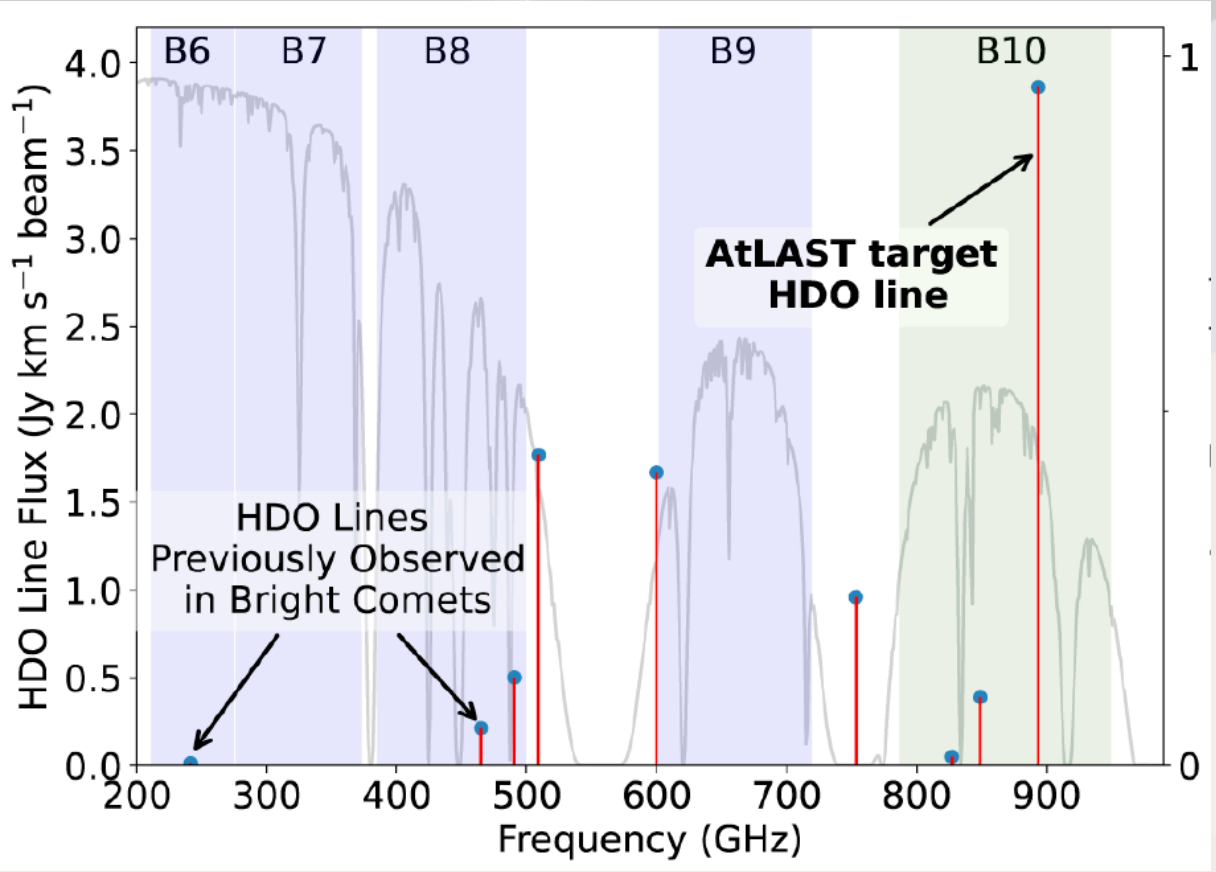
Why AtLAST for Solar System?

Inspired from Cordiner et al. (2024. Open Research Europe 4, 78)

- Advantages of AtLAST
  - Improved sensitivity
  - Smaller beam
  - High frequencies
  - Multi-beam (large scale structures)

- Comets
  - Detect smaller (and more numerous) comets
  - Focus on the denser inner coma and get better line detection capability
  - Conduct HDO surveys
  - Map cometary comae and constrain thermal and photochemical processes

→ **Keys to understand the formation of the Solar System**



HDO line simulations in a typical comet at 1AU from the Earth and Sun, with average HDO/H_2O ratio, as observed with AtLAST

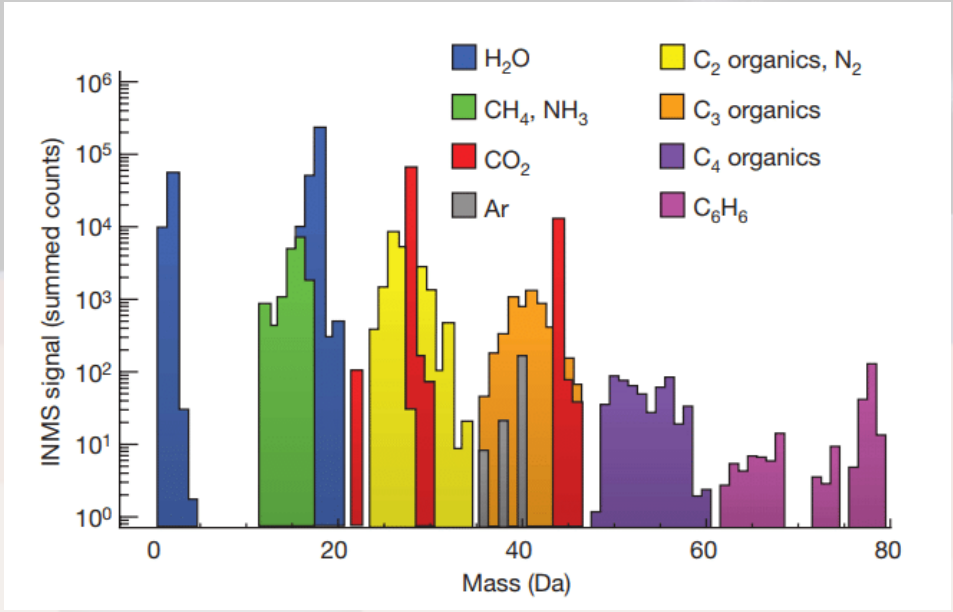
Why AtLAST for Solar System?

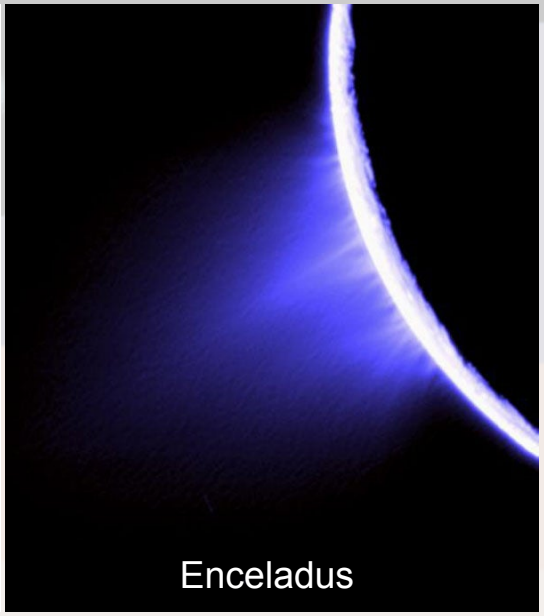
Inspired from Cordiner et al. (2024. Open Research Europe 4, 78)

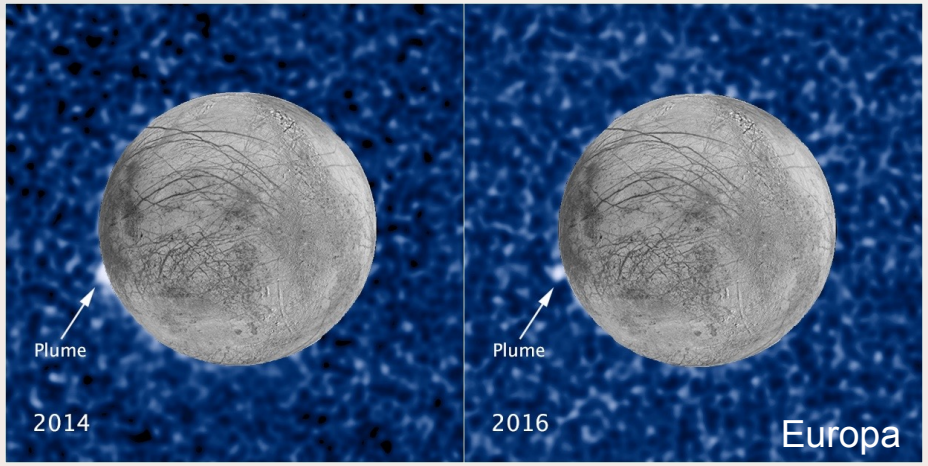
- Advantages of AtLAST
  - Improved sensitivity
  - Smaller beam
  - High frequencies
  - Multi-beam (large scale structures)

- Icy moons:
  - Detect faint lines (incl. isotopic lines) to better constrain composition
  - Map the plumes

→ **Keys to understand the formation of the Solar System and its present-day habitability**







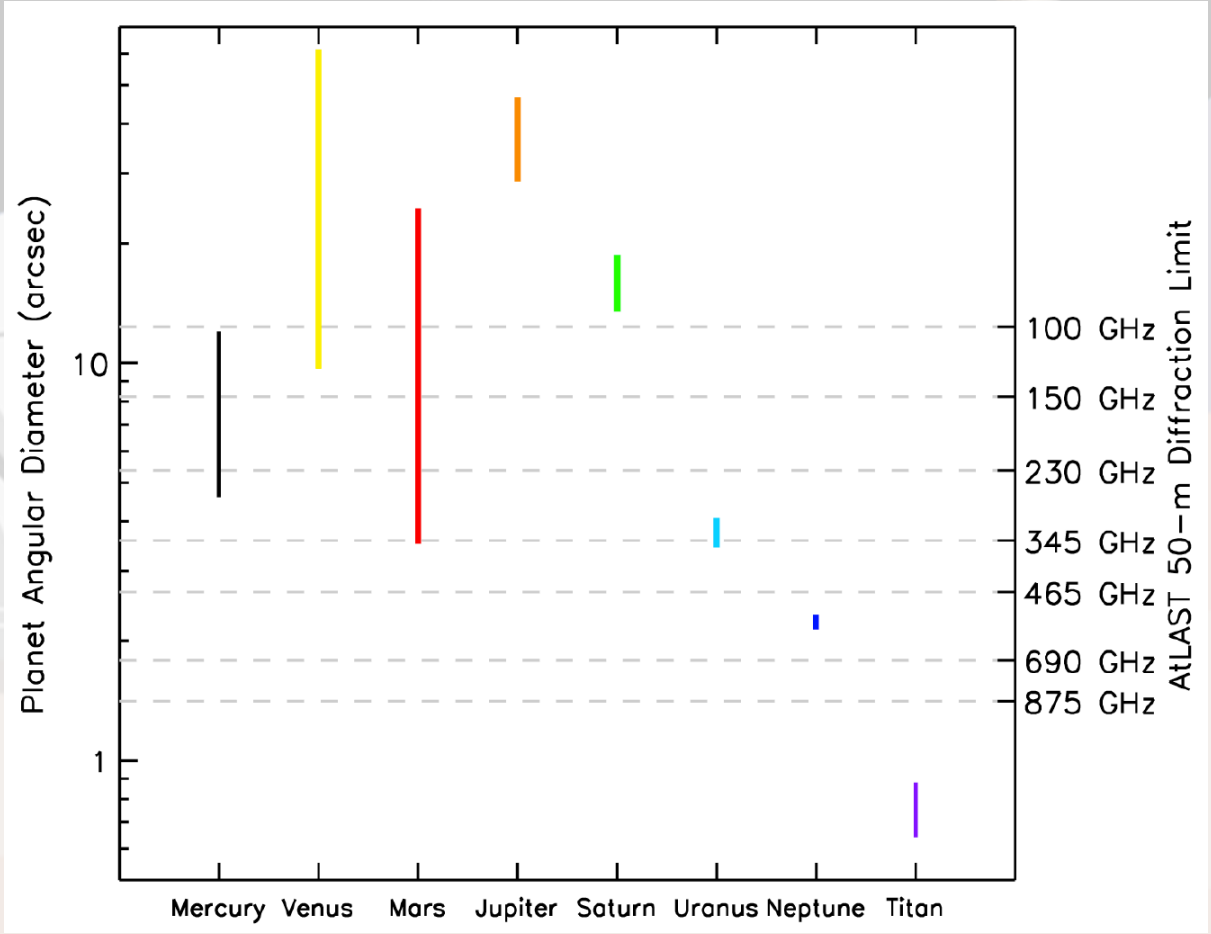
Waite et al. (2006, 2009), Hansen et al. (2006), Roth et al. (2014)

Why AtLAST for Solar System?

Inspired from Cordiner et al. (2024. Open Research Europe 4, 78)

- Advantages of AtLAST
  - Improved sensitivity
  - Smaller beam
  - High frequencies
  - Large bandwidth
  - Multi-beam (large scale structures)

- Terrestrial & giant planets
  - Detection of faint lines (incl. isotopic lines)
  - Constrain deep composition of giant planets (broad lines)
  - Full disk mapping
  - Monitor temporal evolution (seasons, impacts, storms, etc.)



Keys to understand how the Solar System formed and works

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Conclusion

AtLAST will offer:

- Improved sensitivity
- Smaller beam
- Higher frequencies
- Large bandwidth
- Multi-beam

compared to other mm single dish facilities

→ **Keys to understand the formation and evolution of the Solar System**
+ New insights on habitability across the Solar System
+ Improved contextualization for concomitant space missions

Special care should be given to
- Spectral dynamic range
- Standing waves mitigation
- Pointing accuracy

for AtLAST to be competitive for Solar System science

Questions?