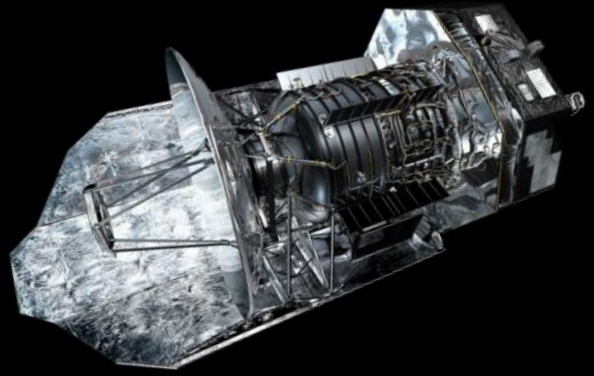


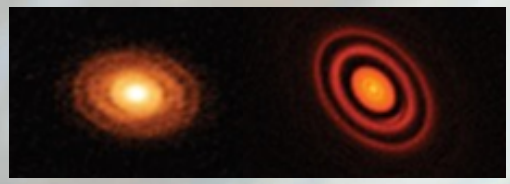
Millimeter observations of atmospheric chemistry and dynamics in the Solar System

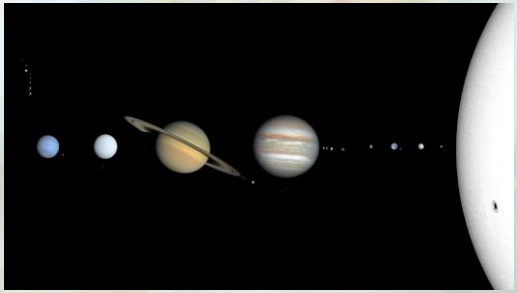
Thibault Cavalié
Laboratoire d'Astrophysique de Bordeaux, CNRS
LESIA, Obs. Paris

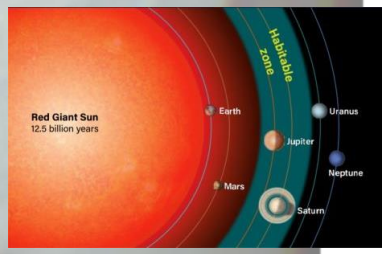
Outline

- Introduction
- Supply of exogenic material
- Atmospheric dynamics
- Formation of the giant planets
- Possible atmospheric science with LLAMA

Introduction







How did the Solar System and the planets form?

How do the planets work?

How will the Solar System evolve?

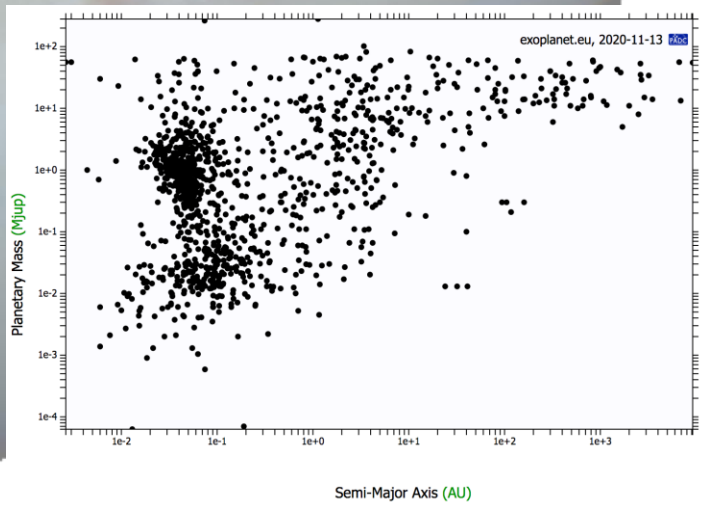
-4.5 Gy

today

(Photo-)Chemistry
Dynamics
Seasonal evolution

Obvious links with:

- protoplanetary disk science
- exoplanet science



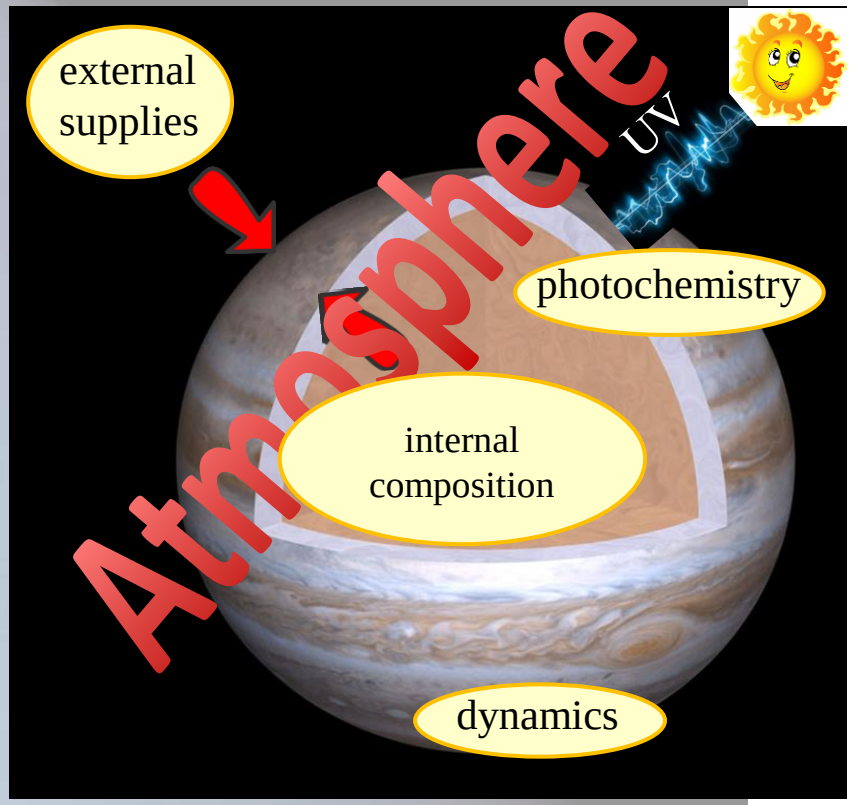
Introduction

- GP are the architects of planetary systems
- Crucial to understand their formation

➡ internal composition

- Our instruments only allow us to characterize the outermost layers of these planets, i.e. their atmospheres

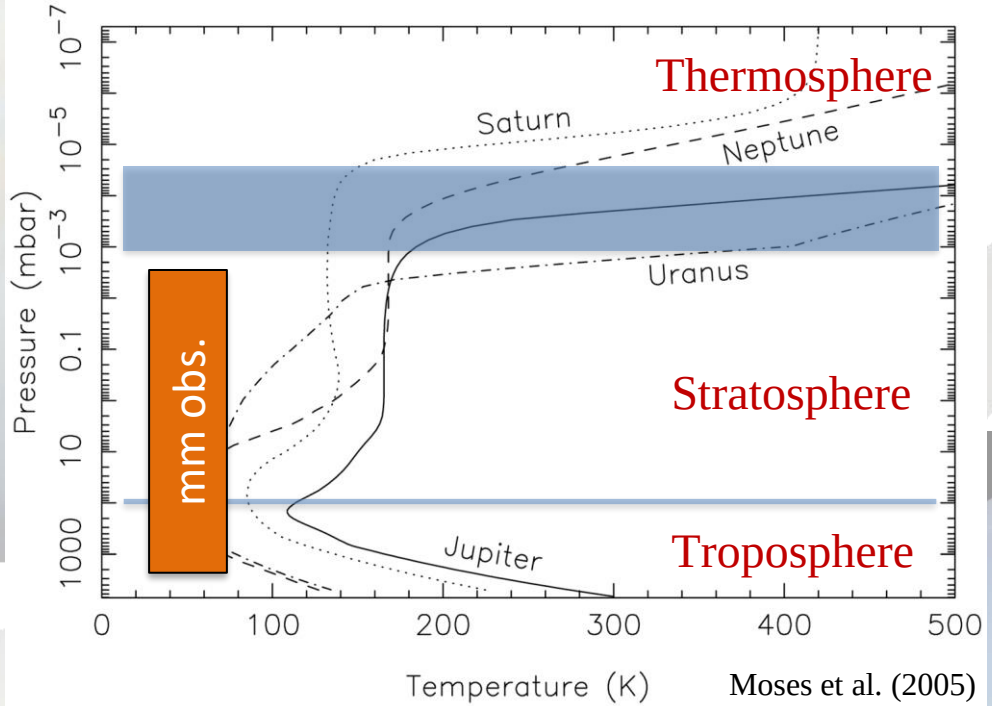
➡ GP atmospheric composition is not only primordial



Determining and modeling their composition in 3D and as a function of time is essential to constrain the formation and evolution of GP

Introduction

- Structure of giant planet atmospheres



Moses et al. (2005)

emission lines

absorption lines

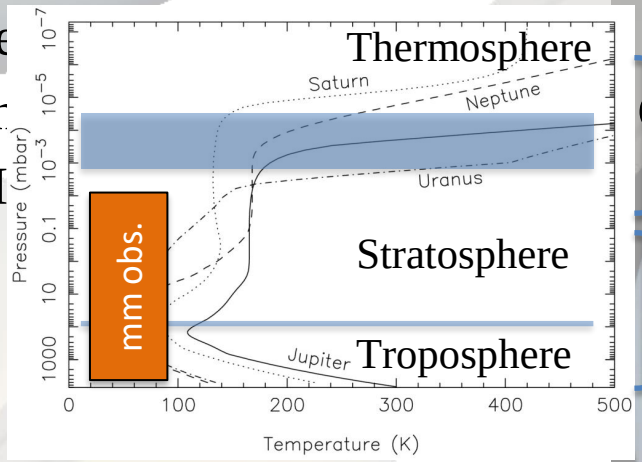
- Composition: H_2, He, CH_4, hydrocarbons, NH_3, PH_3, H_2O, …

>99.9%

Controls the thermal structure

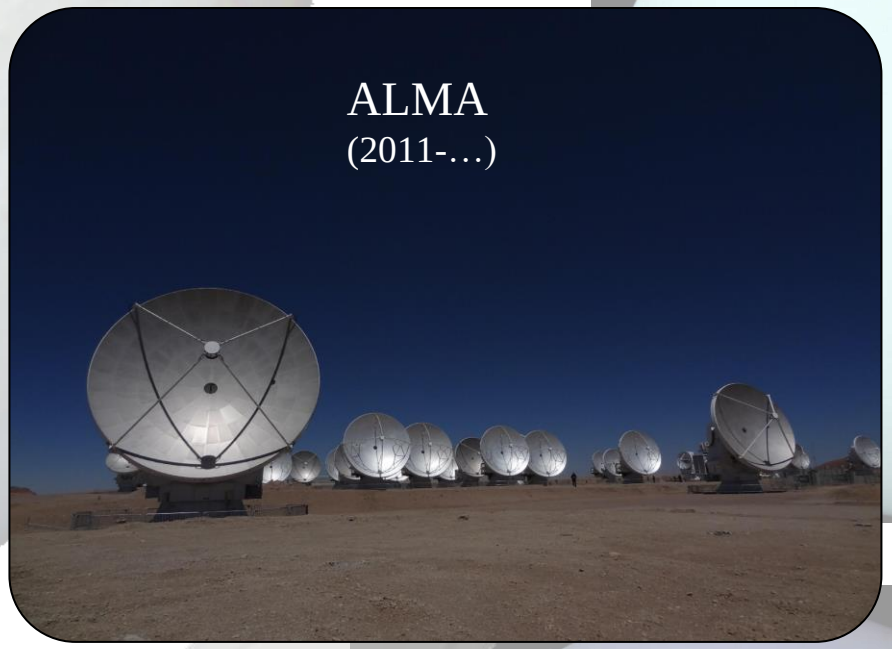
Introduction

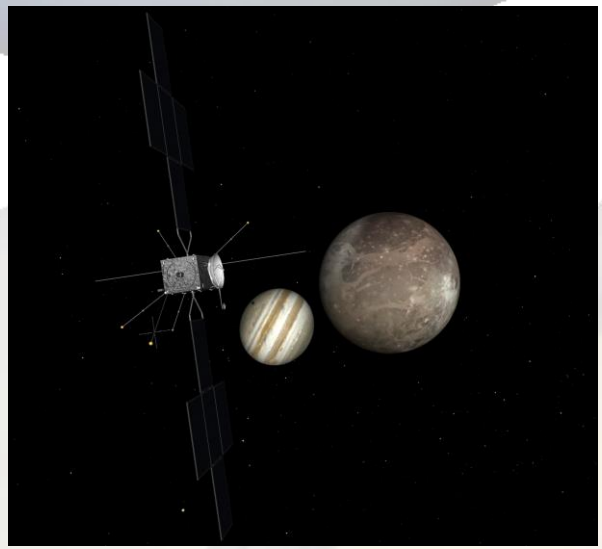
- Why observing GP atmospheres in the (sub)mm range?
  - Less spatial resolution than in the IR and almost no hydrocarbon observable
  - Several species relevant for formation and evolution studies available
  - Heterodyne spectroscopy (spectral resolution)
    - Hydrocarbons: CH_4, C_2H_6, C_3H_8, C_2H_2
    - Oxygen spe
    - Nitrogen ar CS
    - Isotopes: H

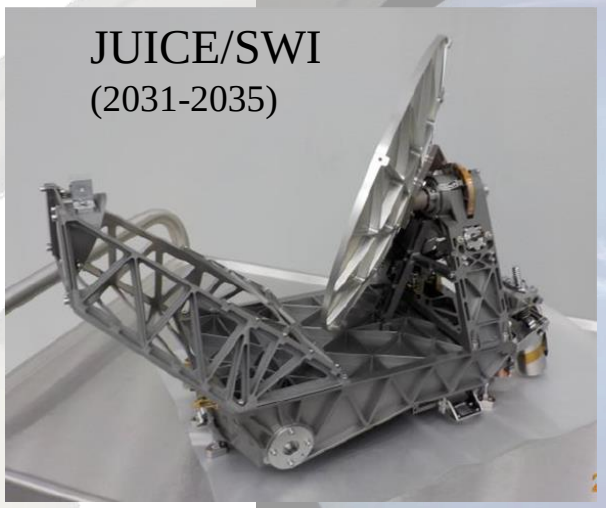


  - Recent instruments/projects (spatial resolution)

Introduction







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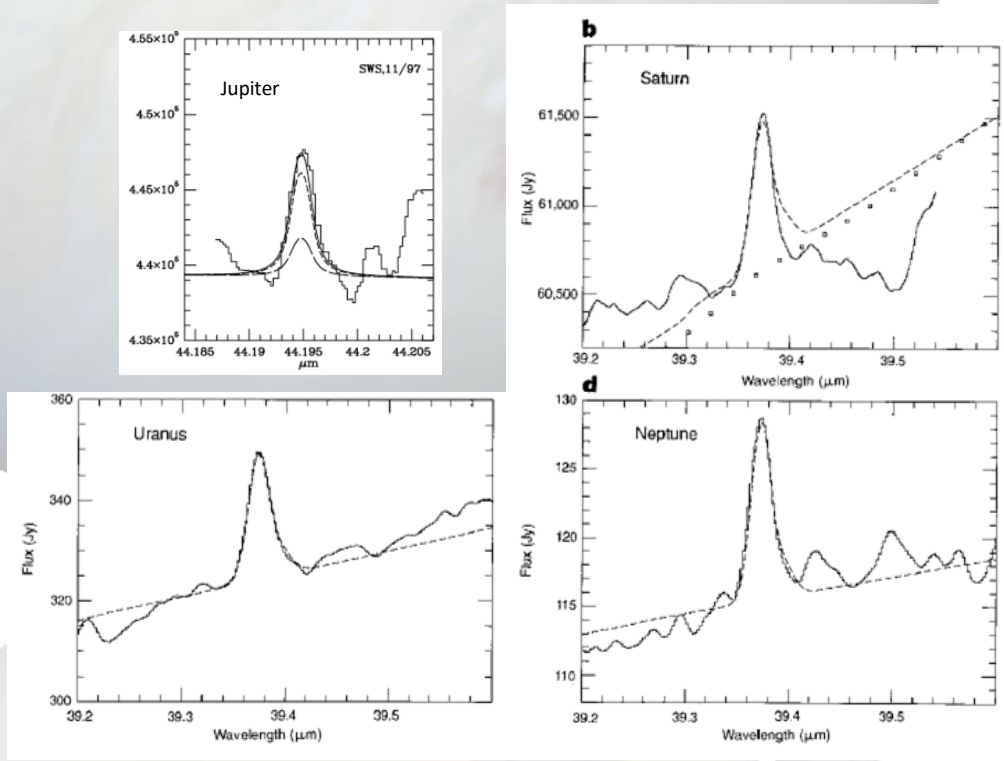
What is the origin of oxygen species in GP?

- Detection of H_2O and CO_2 with ISO in the stratospheres of the giant planets (Feuchtgruber et al, 1997)

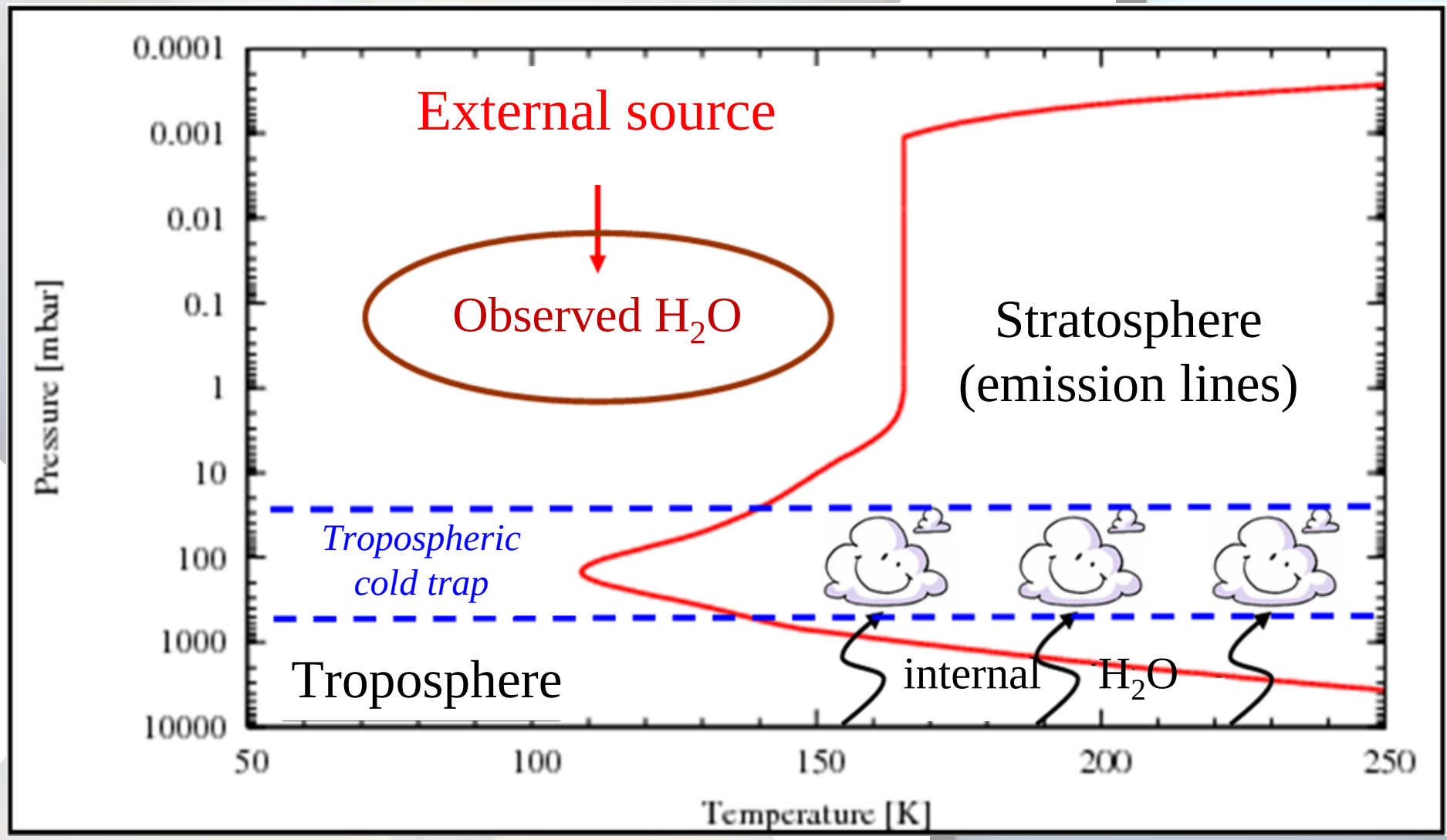


Giant planets
H_2O emission with ISO

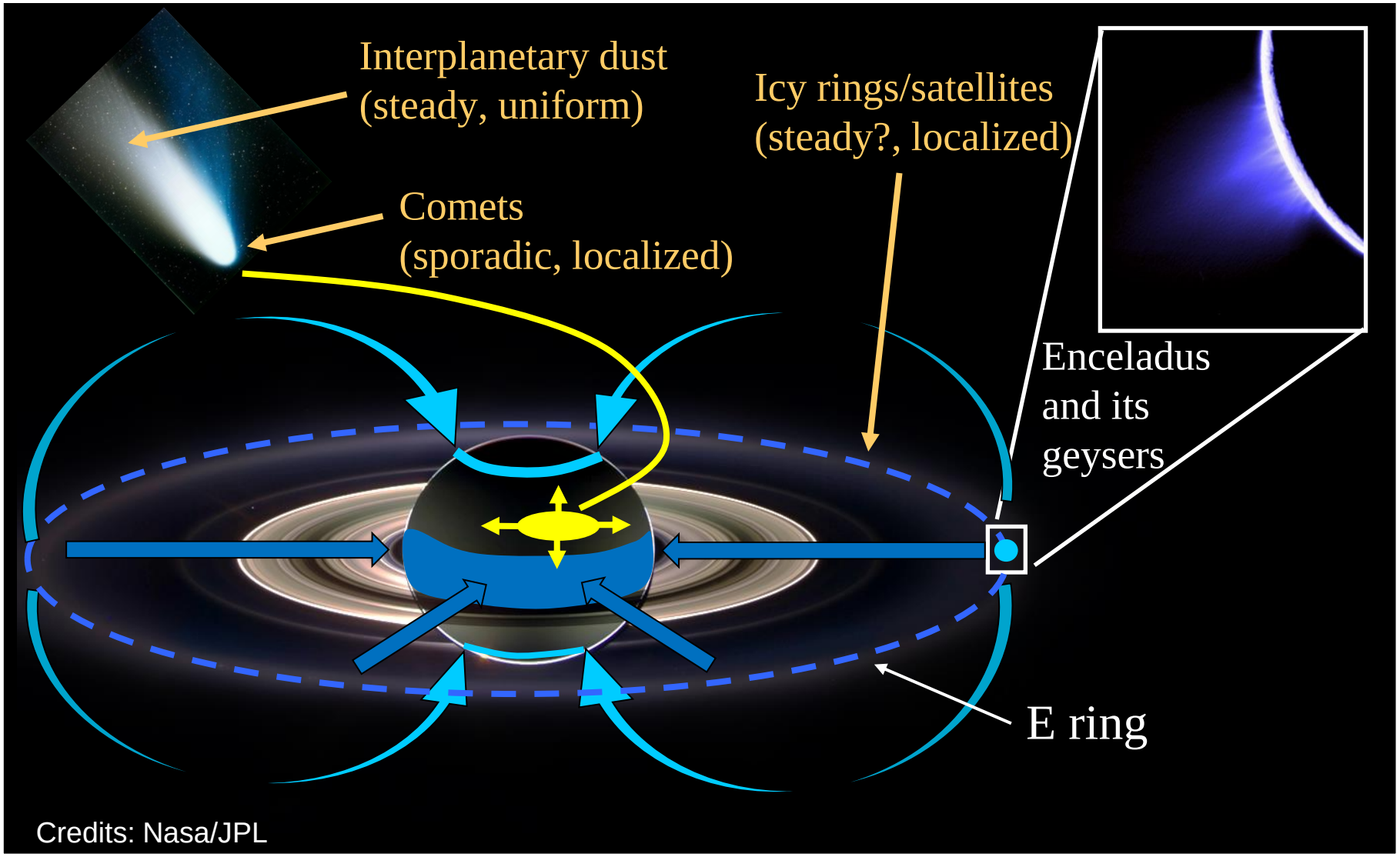
Feuchtgruber et al. (1997)
Lellouch et al (2002)

➡ External origin

What is the origin of oxygen species in GP?



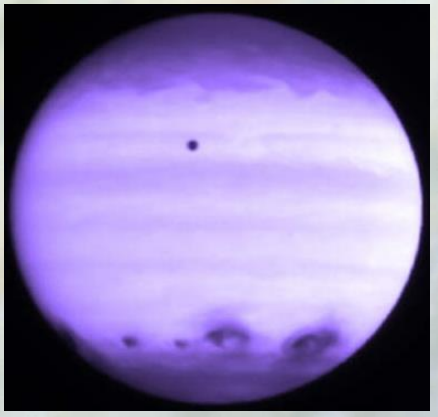
What is the origin of oxygen species in GP?

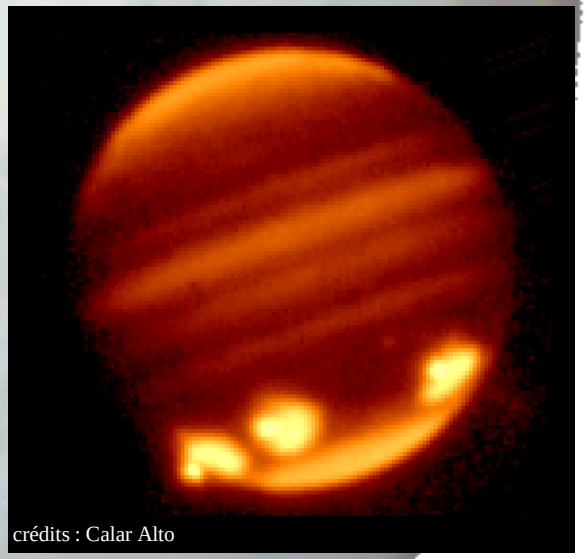


➡ Properties to take advantage of !

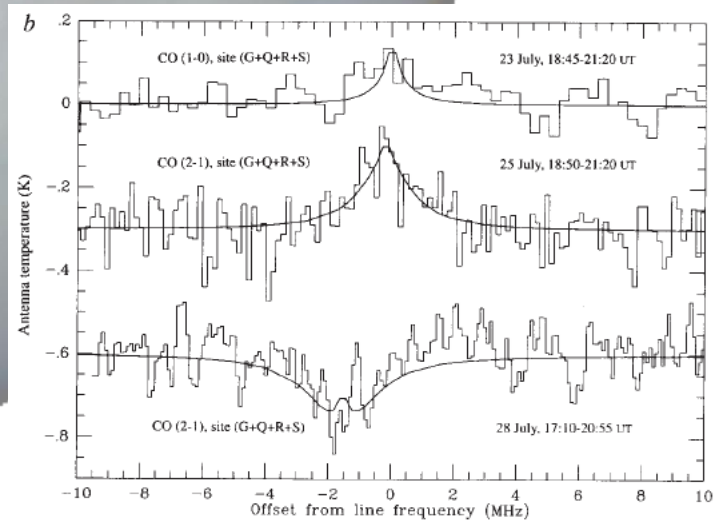
The Shoemaker-Levy 9 comet impacts

- 1st observations of extraterrestrial comet impacts



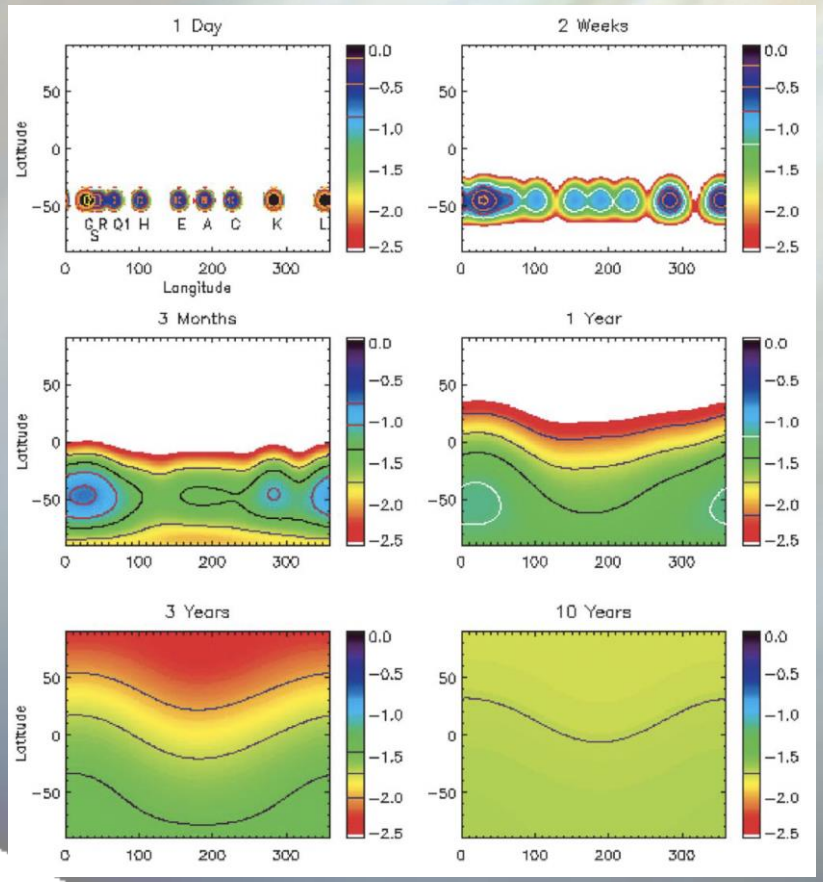


- New molecules formed in the stratosphere: CO, HCN, CS, H_2O in the impact sites
  (Lellouch et al. 1995, Bjoraker et al. 1996)

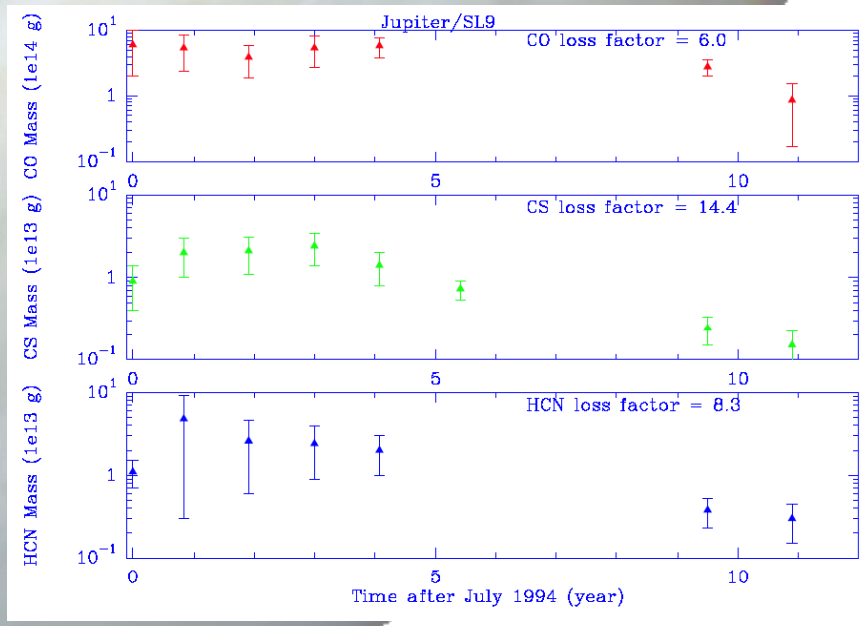


The Shoemaker-Levy 9 impacts

- Long-term monitoring of the abundances and distributions of CO, HCN and CS with IRAM-30m and JCMT



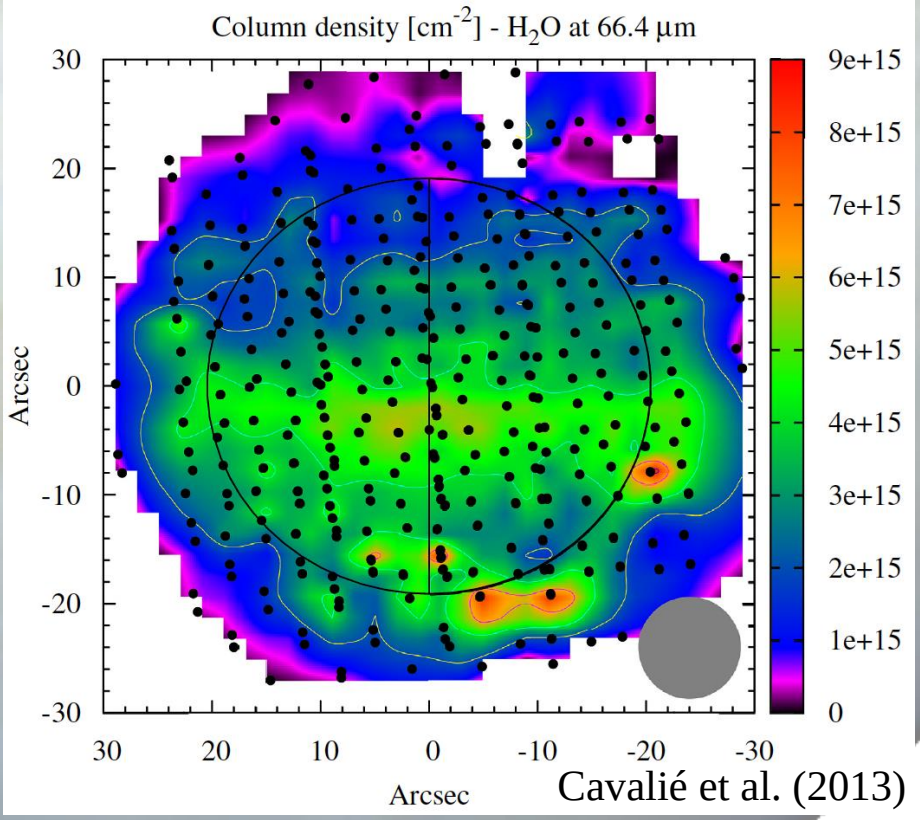
Moreno et al. (2003)



Moreno et al. (2006)

The origin of H_2O in Jupiter's stratosphere

- The origin of H_2O remained controversial until Herschel

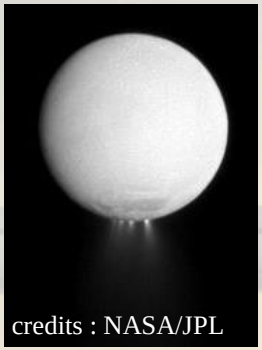


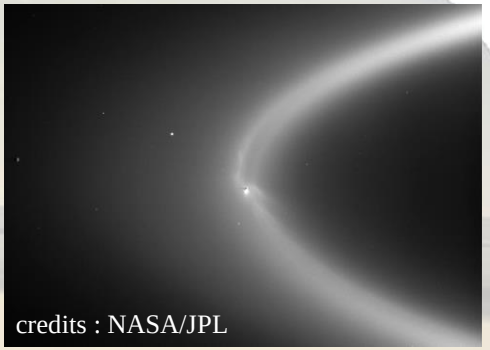
Cavalié et al. (2013)

SL9 is the source of Jupiter's stratospheric H_2O

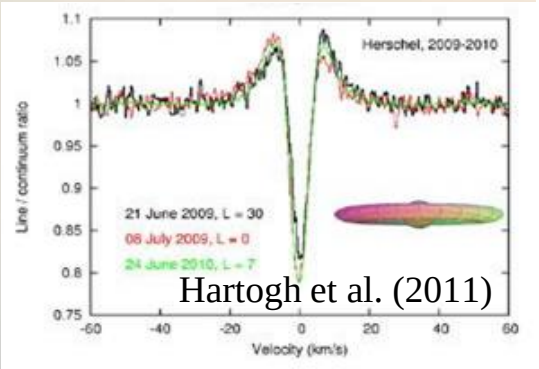
The origin of H_2O in Saturn

- Cassini in 2006 : H_2O ejected from Enceladus in the E-ring

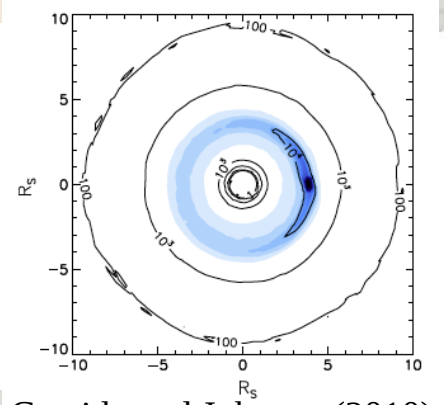

credits : NASA/JPL


credits : NASA/JPL

- Herschel H_2O observations

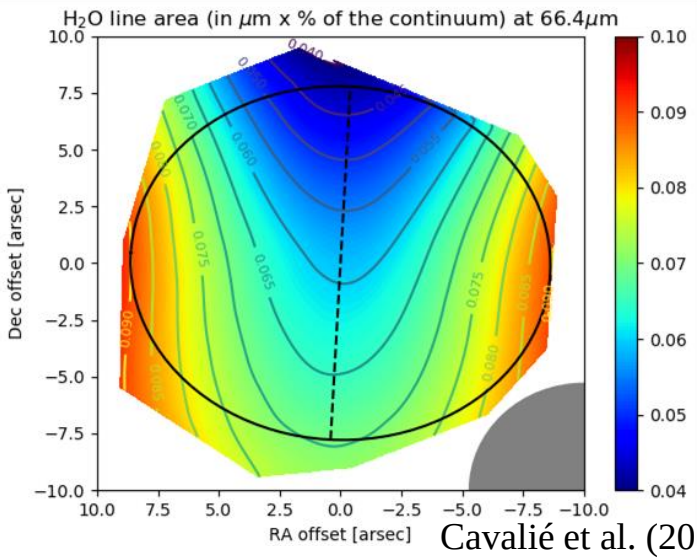


Hartogh et al. (2011)

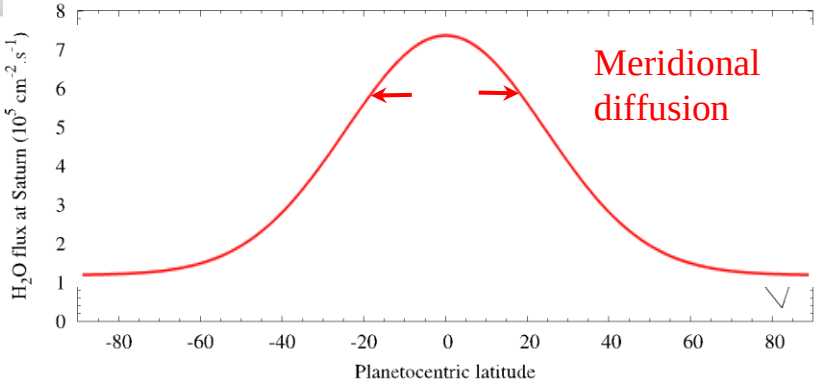


Cassidy and Johnson (2010)

- Herschel 2D mapping



Cavalié et al. (2019)



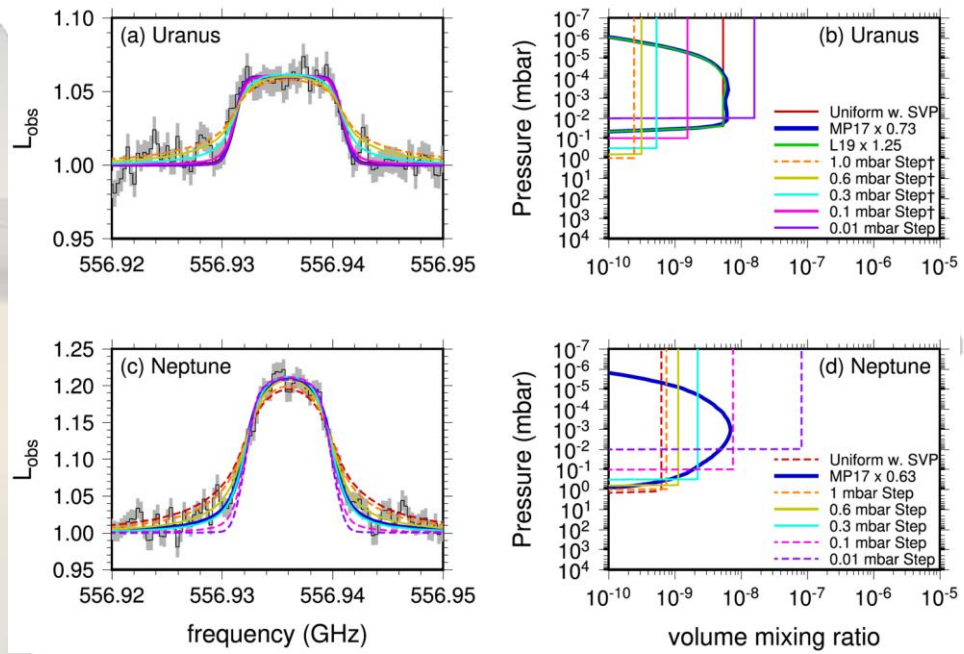
Predicted H_2O flux at Saturn using Cassidy & Johnson (2010)

The origin of H_2O in Uranus and Neptune

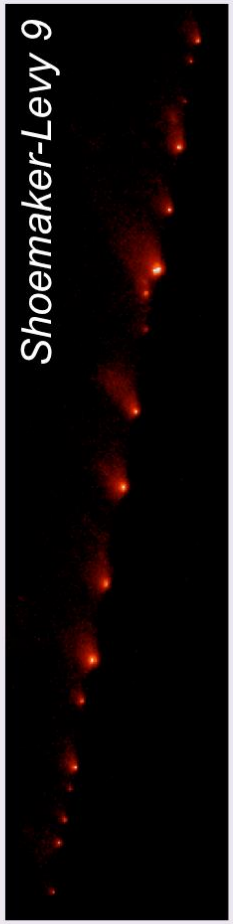
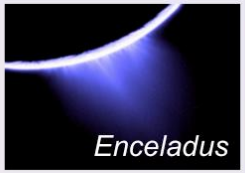
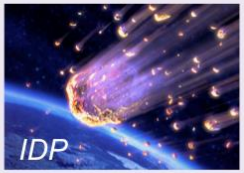
- Model predictions of Moses and Poppe (2017)

  IDP flux significant enough at Uranus and Neptune

- Confirmation from Herschel observations (Teanby et al. 2022)



The current picture

	Jupiter	Saturn	Uranus	Neptune
H_2O				
CO_2		*H_2O/CO photochemistry*		
CO			 or 	
HCN		*not detected*	*not detected*	
CS		*not detected*	*not detected*	

Outline

- Introduction
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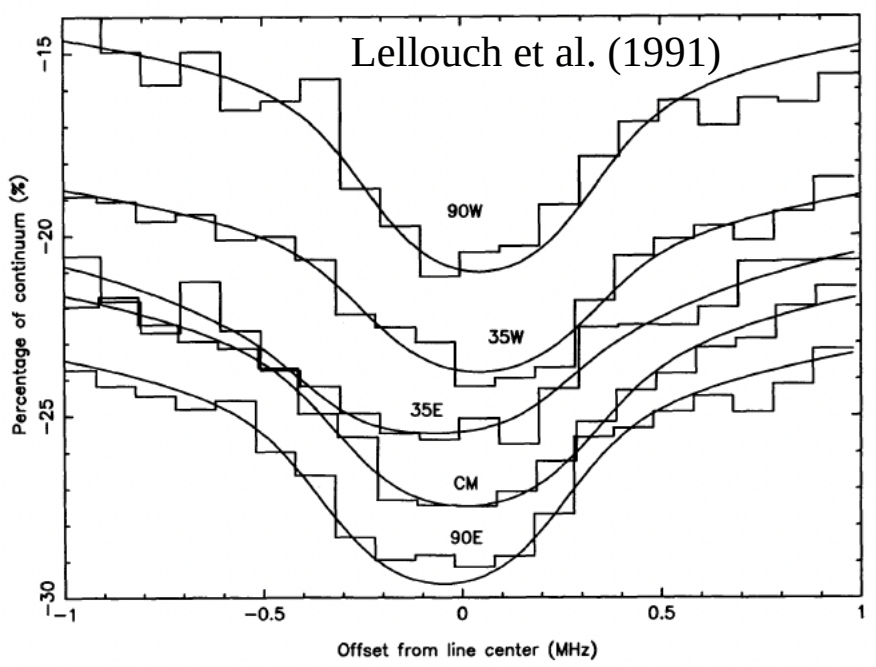
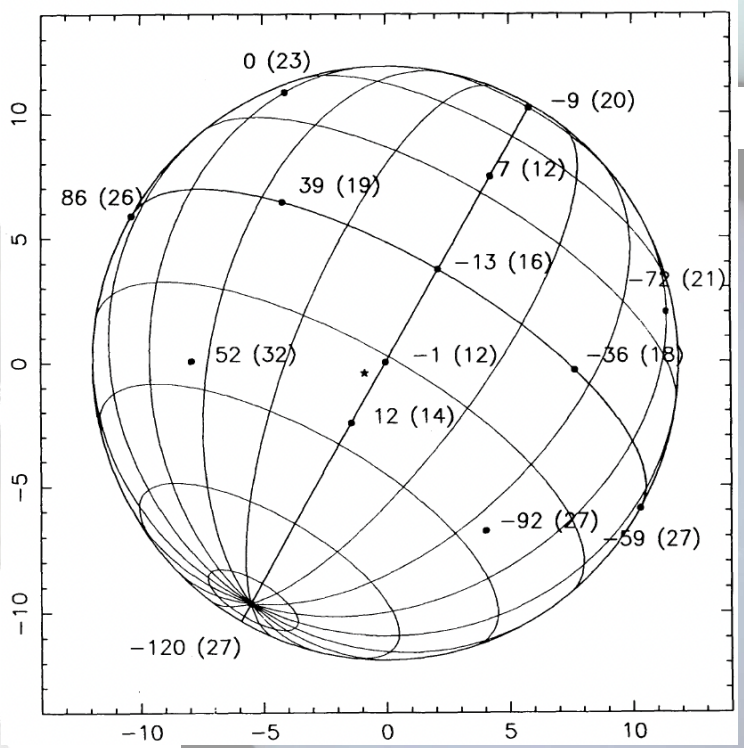
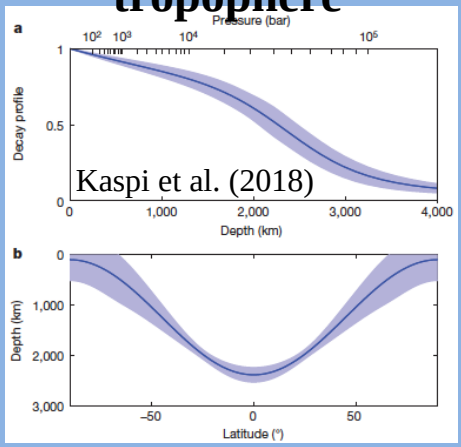
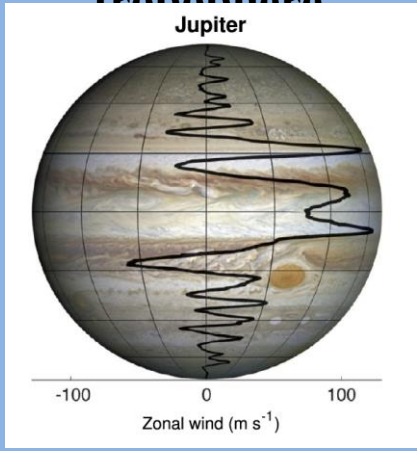
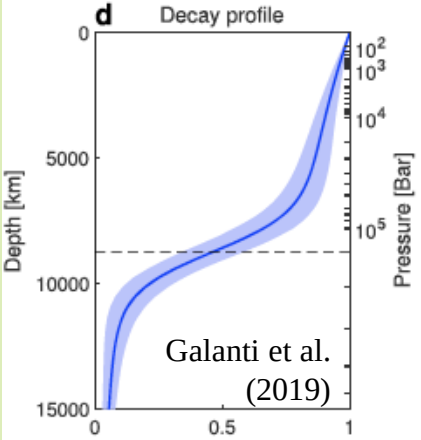
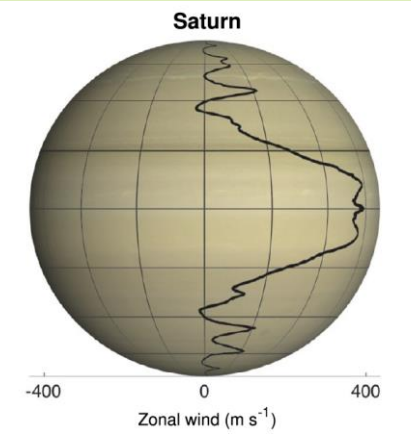
Introduction

- First direct measurements of winds in telluric planets in the millimeter
  - Principle: use very high spectral resolution in the mm to meaure Doppler shifts of lines caused by winds
  - Venus (Shah et al. 1991) and Mars (Lellouch et al. 1991)





Introduction

	Deep tropophere	Upper tropophere	Stratosphere ?
Jupiter	 Kaspi et al. (2018)		
Saturn	 Galanti et al. (2019)	 Kaspi et al. (2020)	

Main challenges

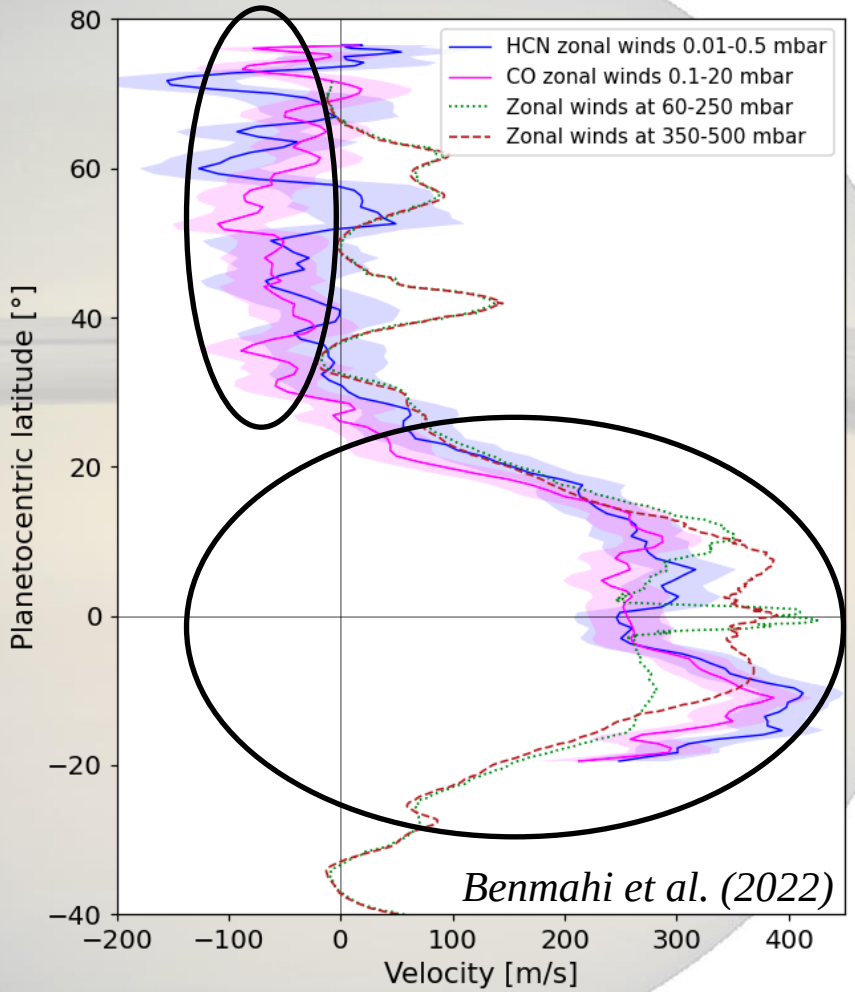
- No tracers like clouds
- Fast rotators
- High spatial resolution required

Observing Jupiter and Saturn with ALMA

	Jupiter	Saturn
Date	22 March 2017	25 May 2018
Target	HCN (4-3) @ 354 GHz	CO (3-2) @ 345 GHz
Spectral resolving power ($\nu/\Delta\nu$)	3×10^6	6×10^6
Spatial resolving power ($\theta_{planet}/\theta_{beam}$)	46	36
Latitudinal resolution @ equator	3°	5°

Saturn

- **ALMA Doppler wind measurements in the stratosphere of Saturn**

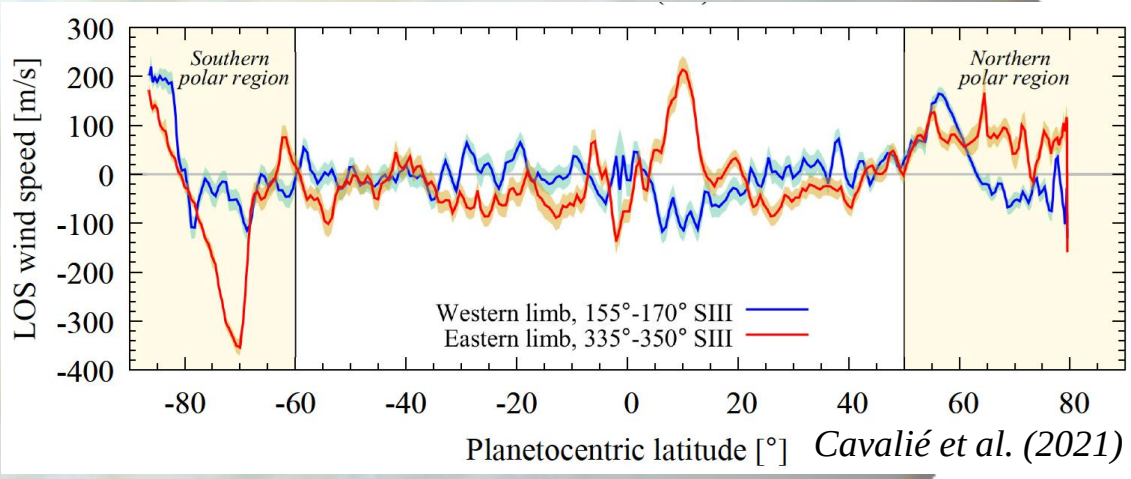


Possible westward circulation in the northern hemisphere

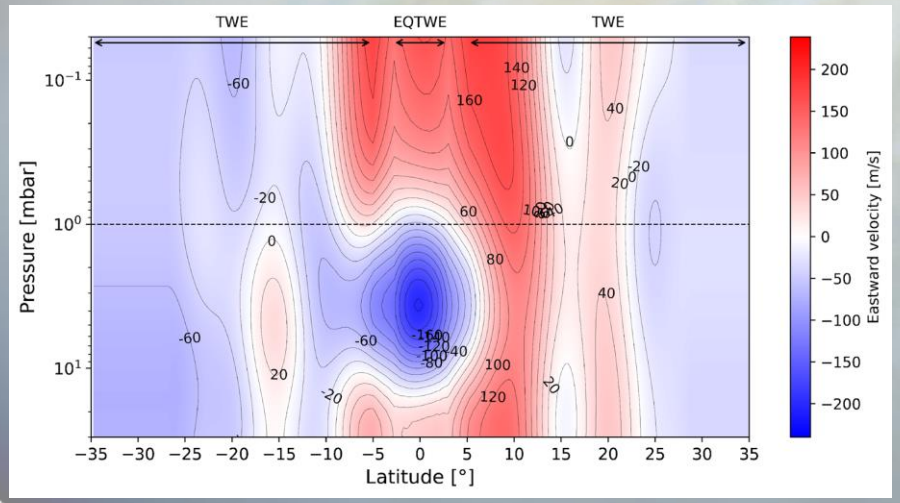
The large equatorial jet extends from the troposphere to the stratosphere

Jupiter

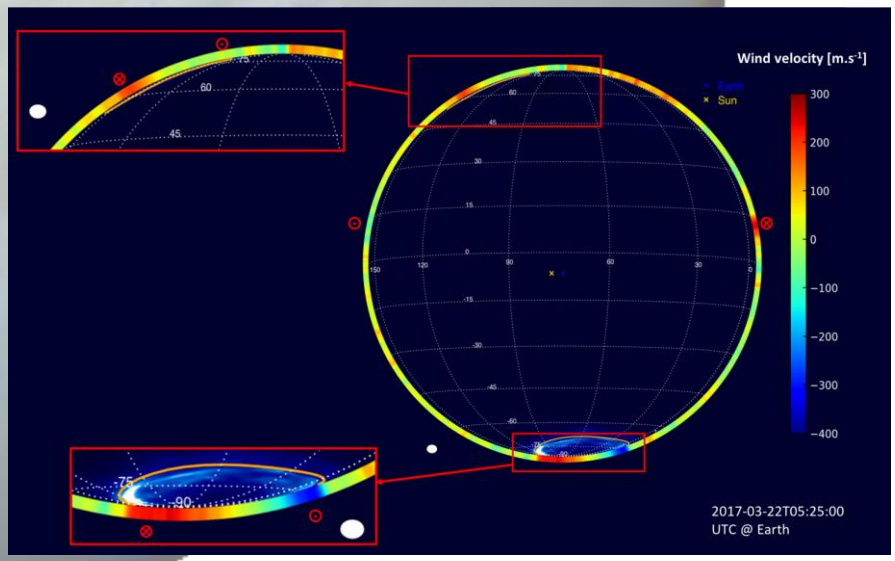
- **ALMA Doppler winds from HCN in the stratosphere of Jupiter**



Cavalié et al. (2021)



Quasi-Quadrennial Oscillation winds
by *Benmahi et al. (2021)*
-200 m/s peak at 4 mbar

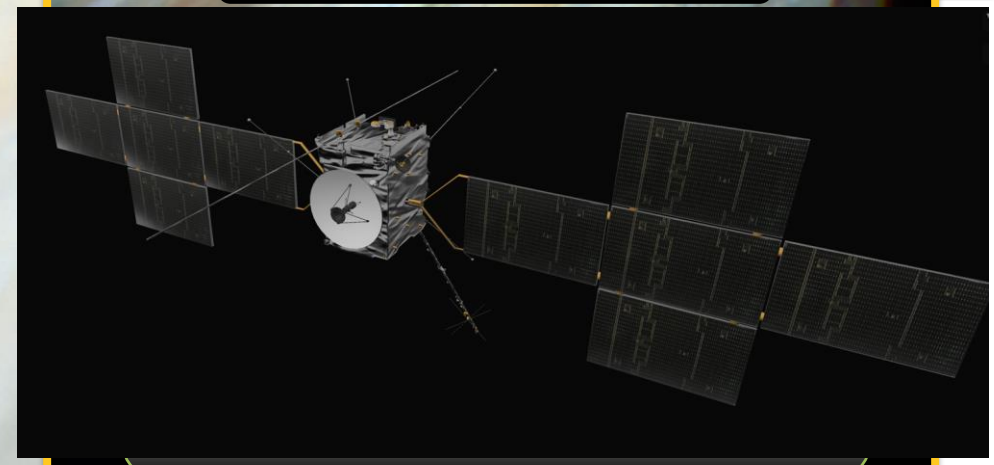


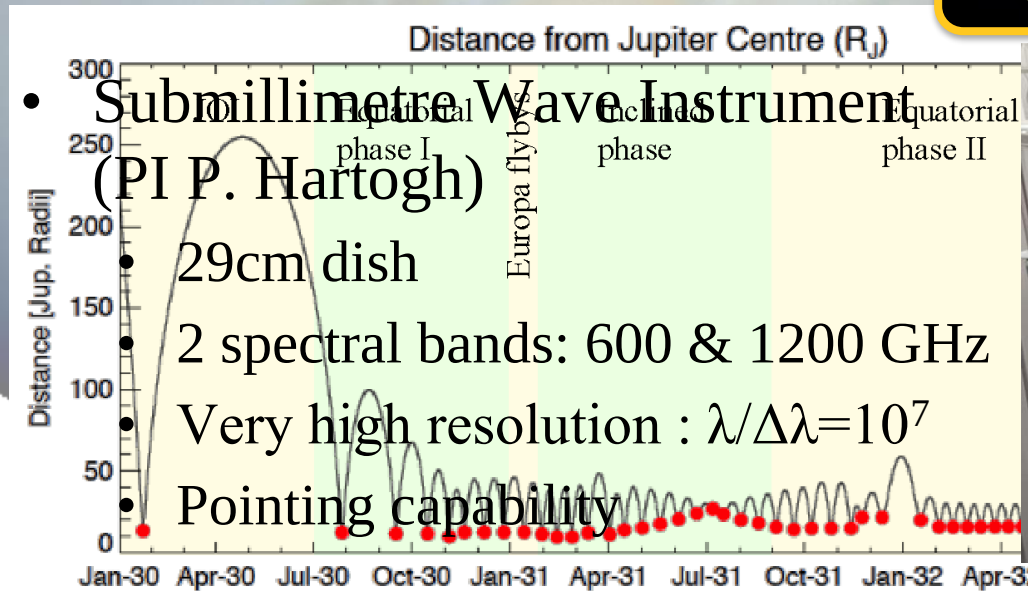
Auroral jets (350-400 m/s) at 0.1 mbar

Perspective for Jupiter: JUICE and SWI

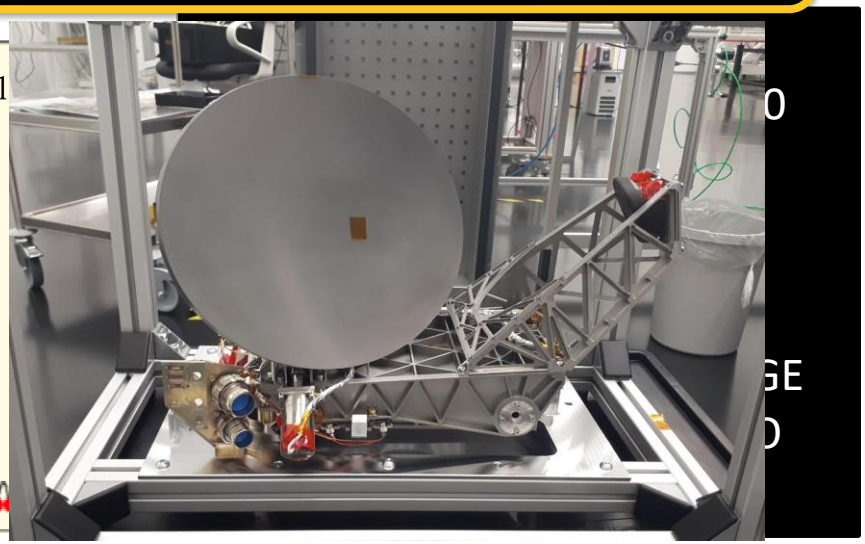
- Jupiter Icy Moons Explorer (ESA flagship)
  - 10 instruments
  - Launch in 2023
  - Jupiter Orbit Insertion in 2031
  - Nominal mission :
    - Jupiter tour : 3.5 years
    - Ganymede tour : 9 months

Jupiter's atmosphere



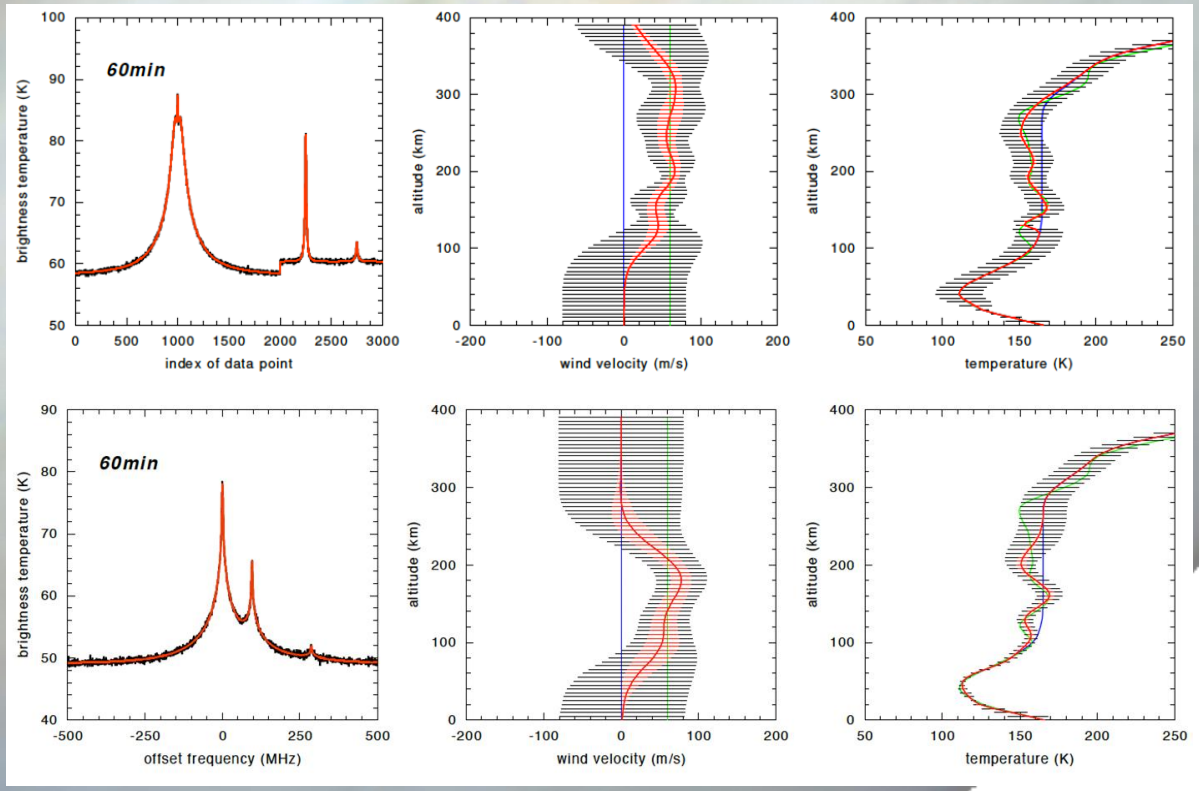


- Submillimetre Wave Instrument (PI P. Hartogh)
  - 29cm dish
  - 2 spectral bands: 600 & 1200 GHz
  - Very high resolution : $\lambda/\Delta\lambda=10^7$
  - Pointing capability



Observing atmospheric dynamics with SWI

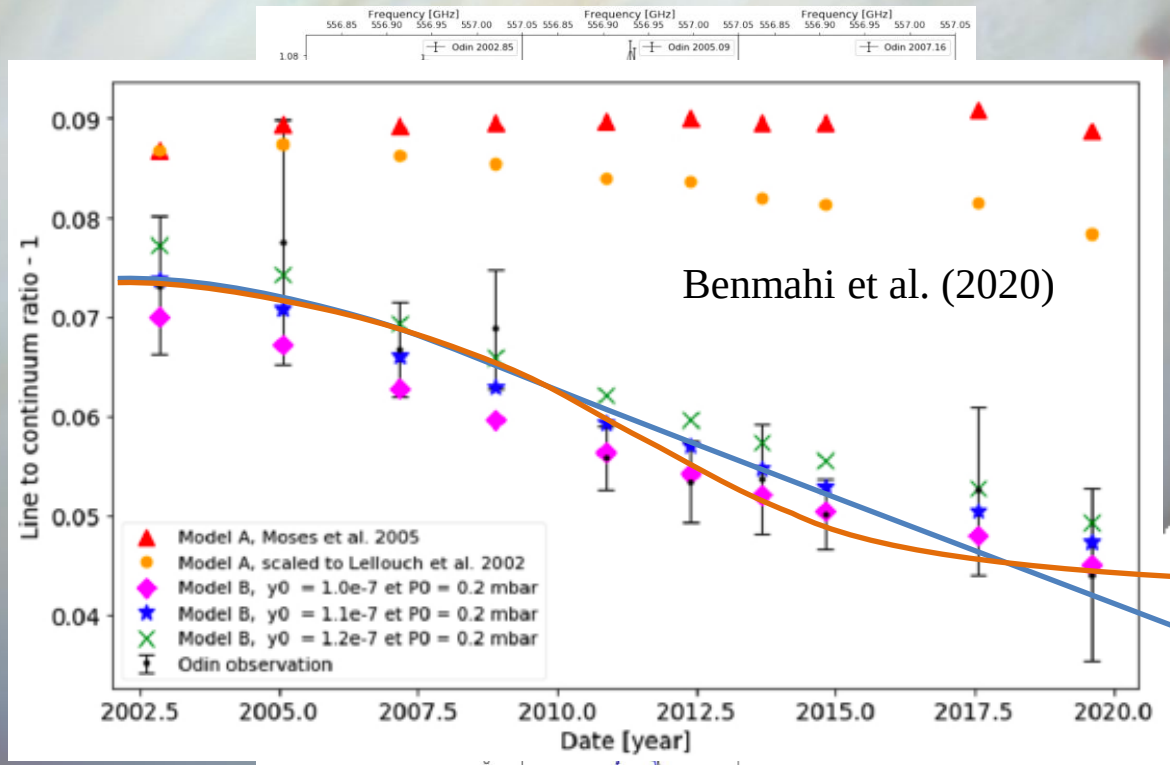
- Temperature and wind retrieval simulation with the 2 bands

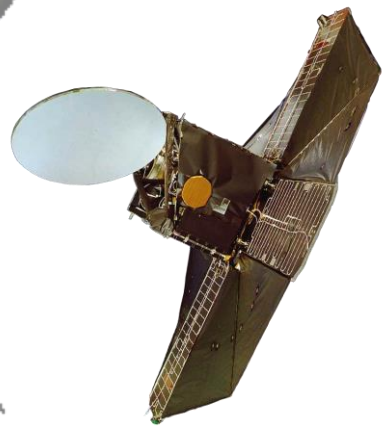


- SWI operation preparation requires a better knowledge of the H_2O distribution to make accurate predictions for the 2030s

Preparing SWI operations at Jupiter

- What will the H_2O abundance be in 2030 ?
- Odin observations (2002-2020)
  + 1D time-dependent photochemical modeling

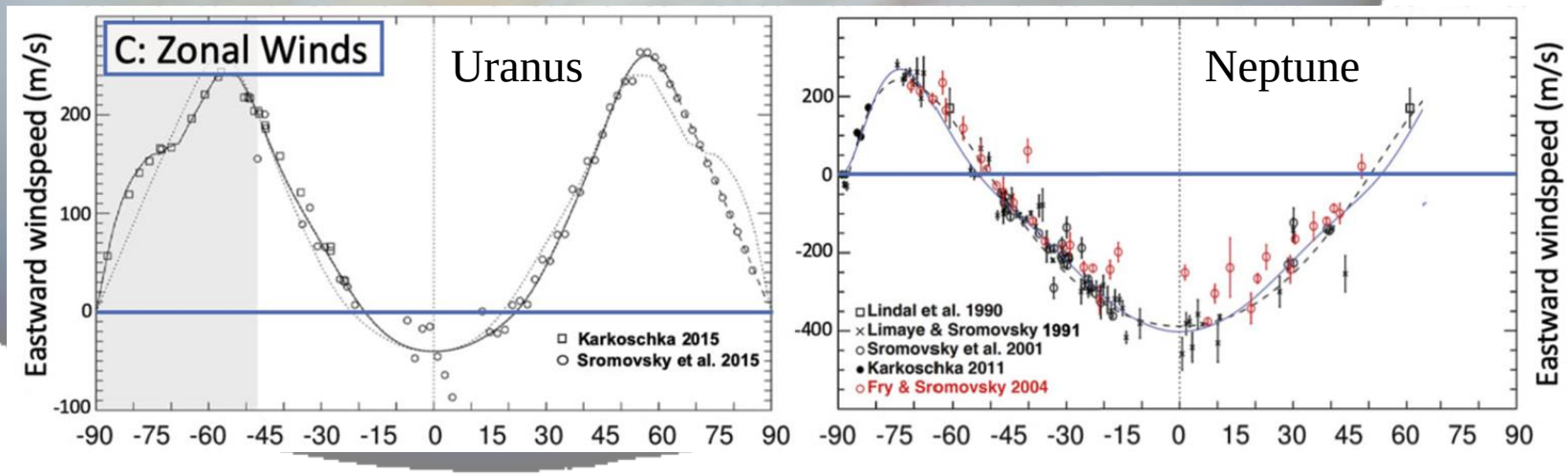




Perspectives

- Continued monitoring of jovian H_2O with Odin
- Continued observations with ALMA and JUICE/SWI
  - Monitor the equatorial oscillations of Jupiter and Saturn
  - Constrain the source and evolution of auroral winds

- Observations of Uranus and Neptune
  - Stratospheric vs. tropospheric circulation
  - Equatorial oscillations?



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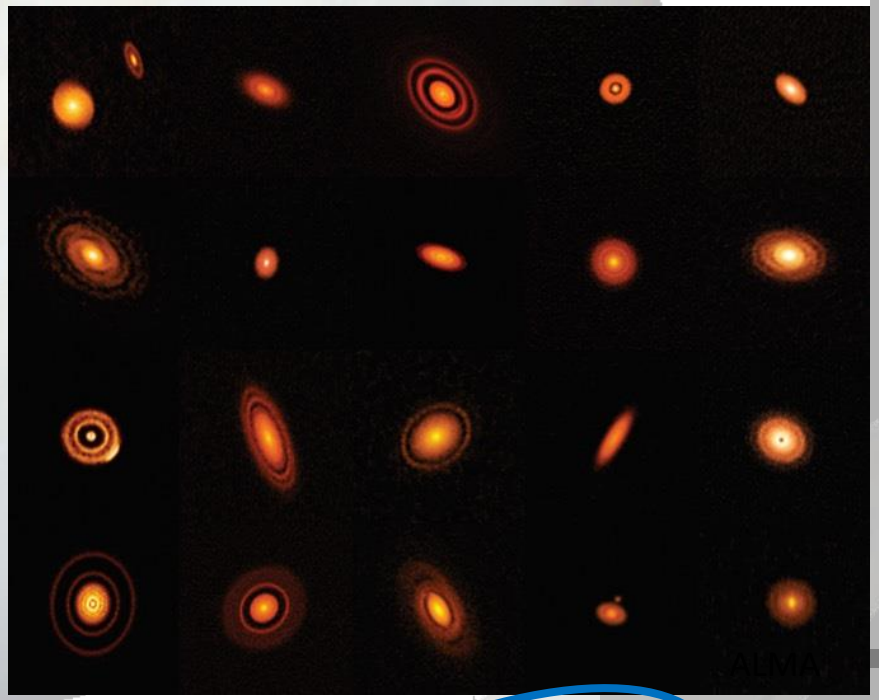
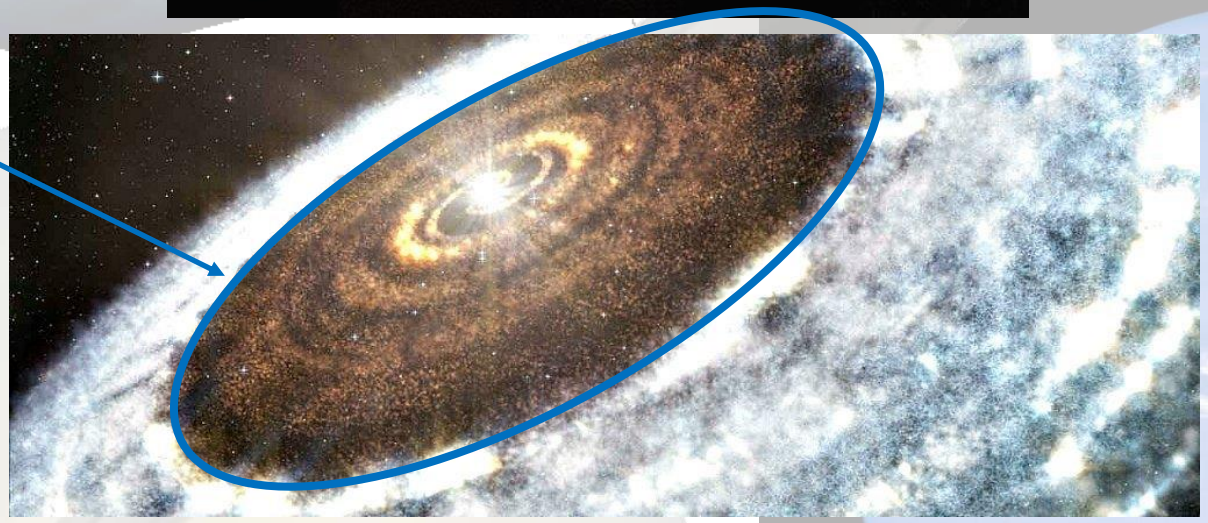
Giant planet formation models



Water snowline



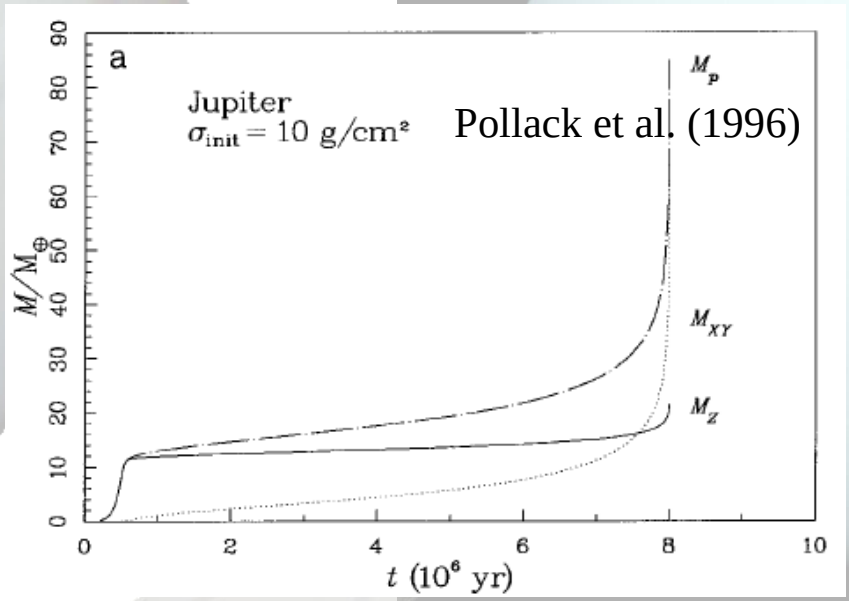
Giant planet formation models

- Core accretion model (Pollack et al. 1996)

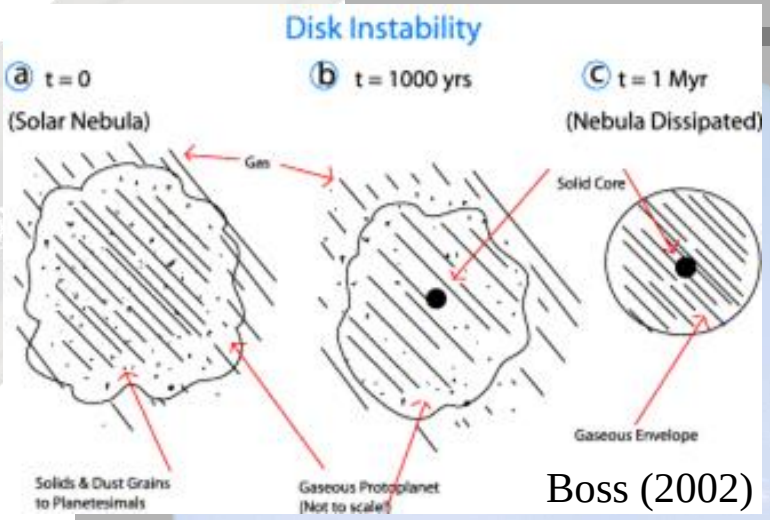
  ~ few Myr

- Gravitational instability model (Boss 1997, 2002)

  ~ 1 Myr



Pollack et al. (1996)



Boss (2002)

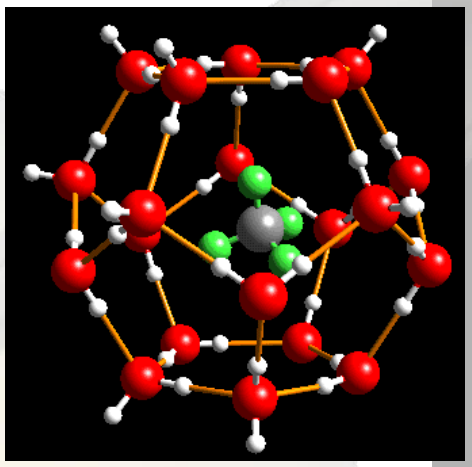
Composition provides constraints on the conditions in the solar nebula, the planetary formation location and formation timescale

How were the heavy elements trapped?

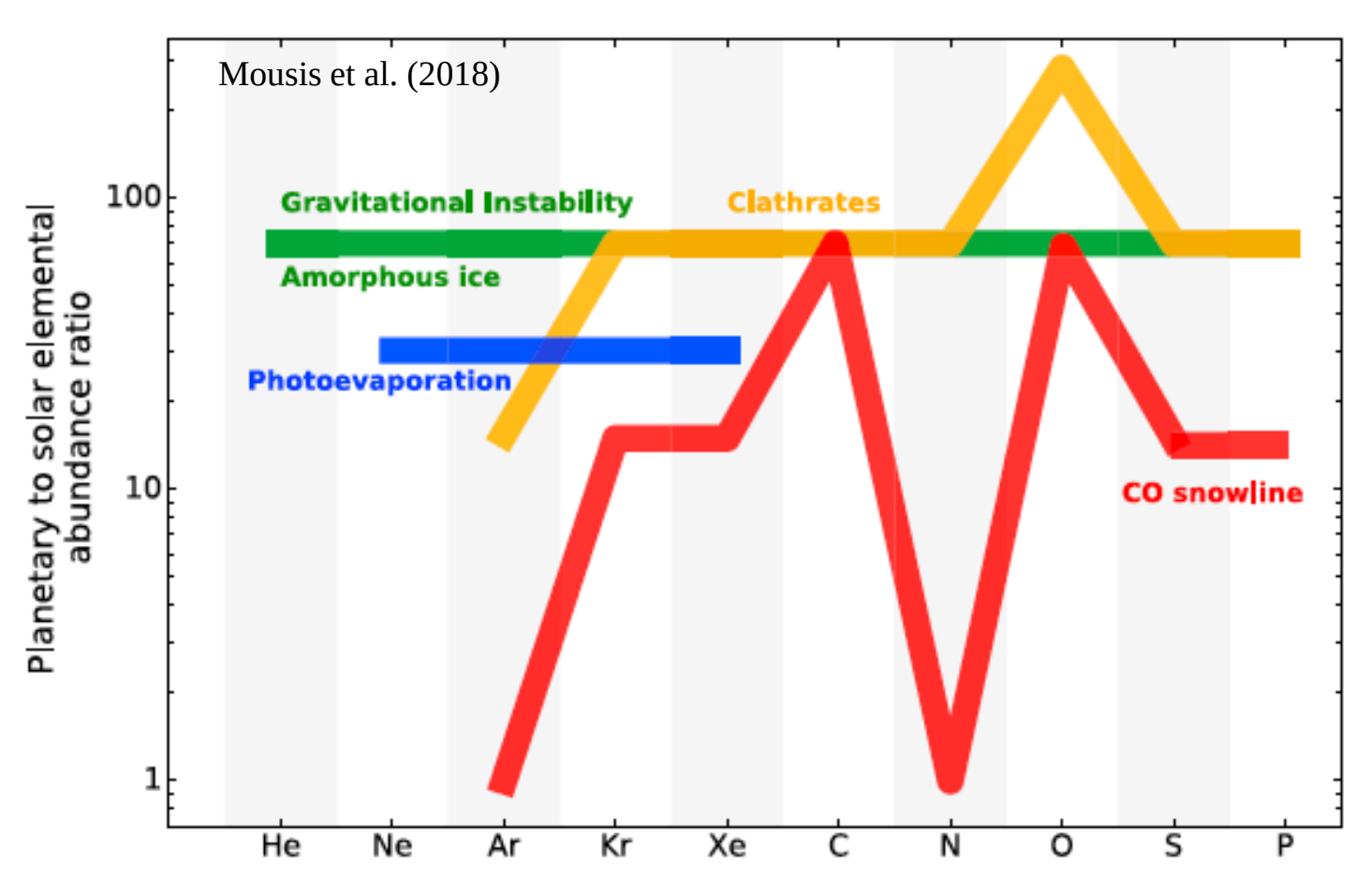
- The O abundance constrains the condensation processes of planetesimal ices and how other heavy elements were trapped

- Amorphous ices (Owen et al. 1999)
  - Heavy elements, including O, should be uniformly enriched

- Cristalline ices (clathrate) (Gautier et al. 2000, 2005)
  - Heavy elements trapped as a function of clathration temperatures
  - High O abundance required



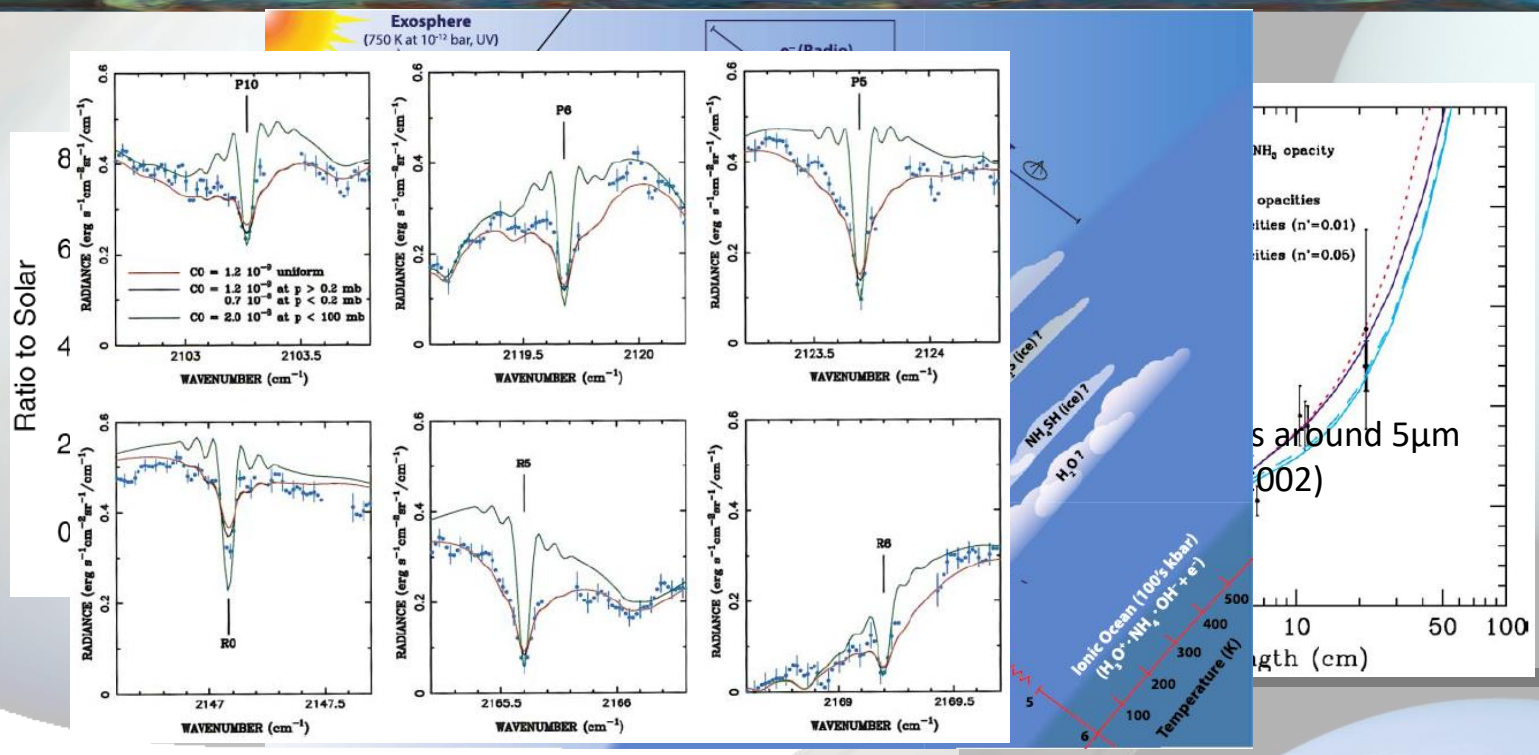
Deep composition as a constraint for formation



Noble gases require an in situ probe

O is a probe to ice condensation and trapping of heavy elements

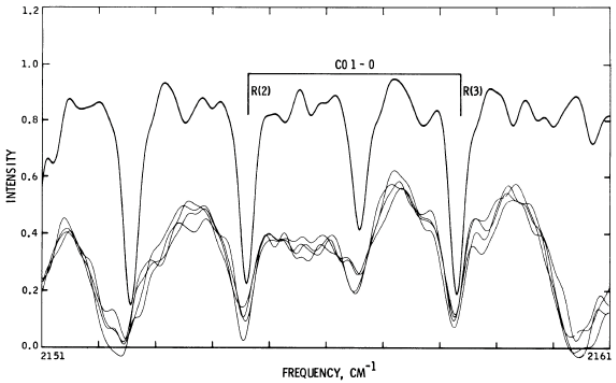
How can we measure deep composition?



- *In situ* with a mass spectrometer (ex: Galileo)
- From photometric and spectroscopic observations (but limitations due to spectral resolution, condensation, etc.)
- From thermochemically coupled species not subject to condensation

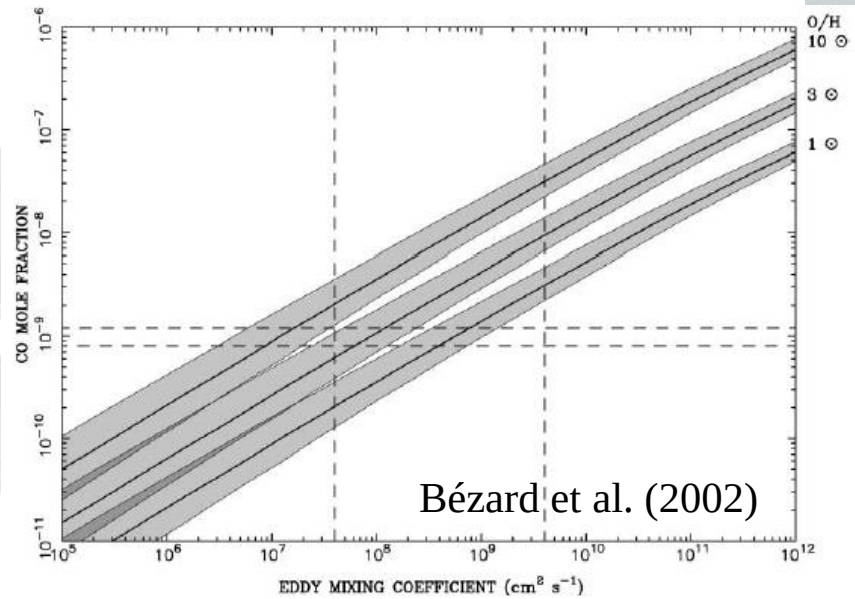
CO in Jupiter and quench level models

- Detection of CO in Jupiter by Beer (1975)



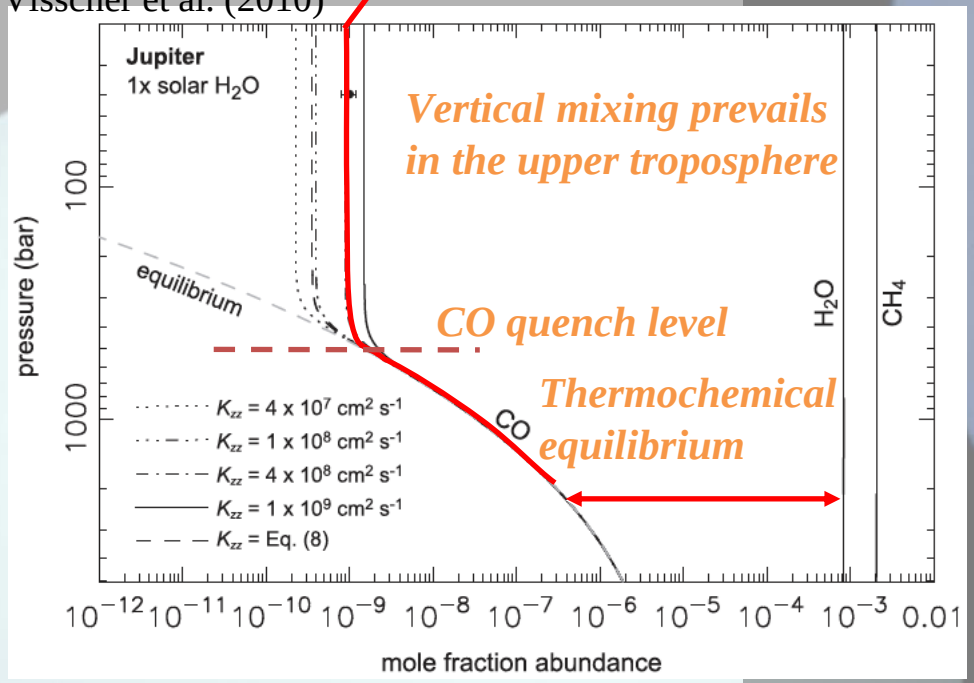
- Quench level models
  - Principle: solve equilibrium reaction $CO + 3H_2 = CH_4 + H_2O$
  - Goal: find the level where the CO chemistry is quenched by vertical dynamics ($\tau_{chem} = \tau_{dyn}$)
  - Depends on a set of chemical reactions and vertical dynamics
  - One bottleneck (rate-limiting reaction) determines the kinetics

$$\frac{q\mathrm{CO}\, q\mathrm{H}_2^3 p^2}{q\mathrm{CH}_4\, q\mathrm{H}_2\mathrm{O}} = e^{-\frac{\Delta_f G^0(\mathrm{CO}) - \Delta_f G^0(\mathrm{CH}_4) - \Delta_f G^0(\mathrm{H}_2\mathrm{O})}{RT}}$$



Thermochemical modeling in the troposphere

Visscher et al. (2010)



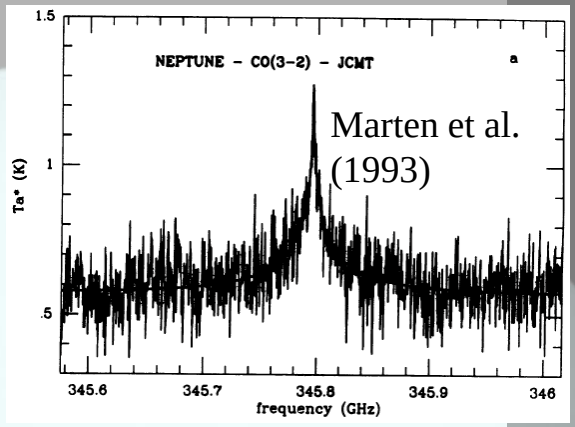
CO as a tracer for deep H_2O

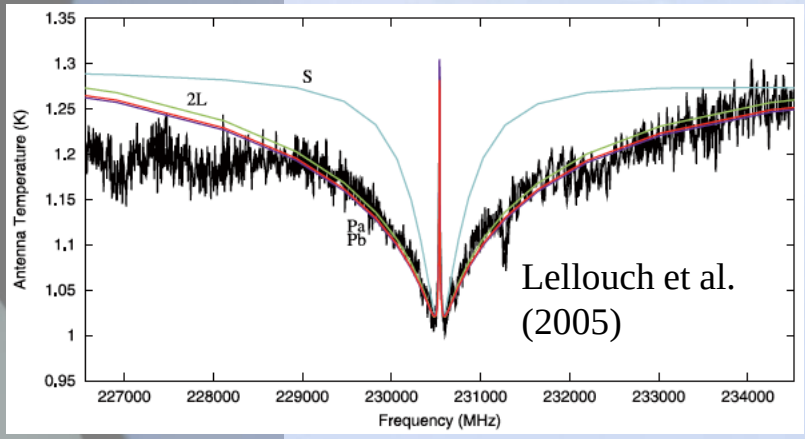
Chemical scheme
Thermal structure
Vertical transport
Abundance measurements

- Initial model for hot Jupiters: Venot et al. (2012)
- Parameter space study for Uranus and Neptune: Cavalié et al. (2017)
- Chemical scheme revision: Venot et al. (2020)

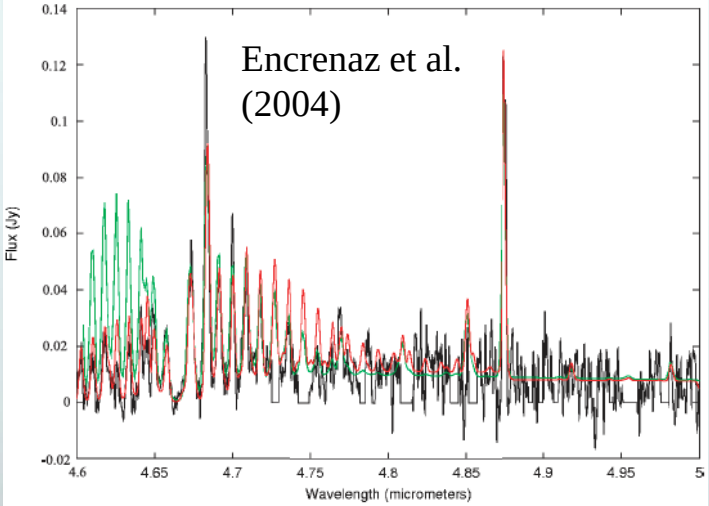
CO in the tropospheres of the other giants

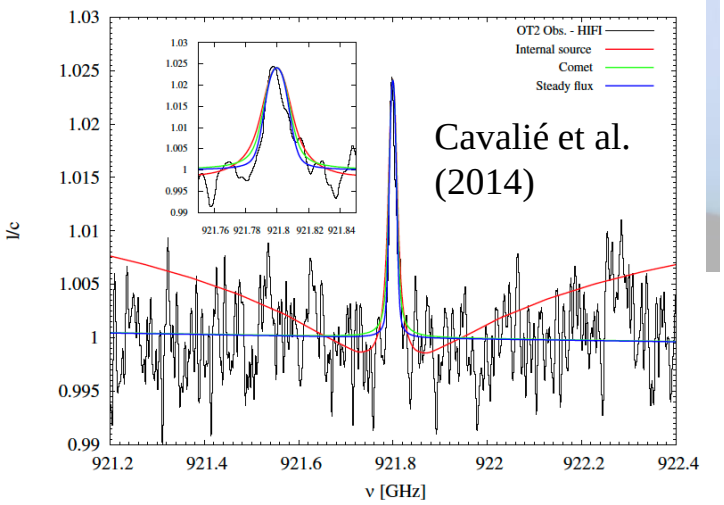
- Neptune: ~ 0.5 ppm of tropospheric CO

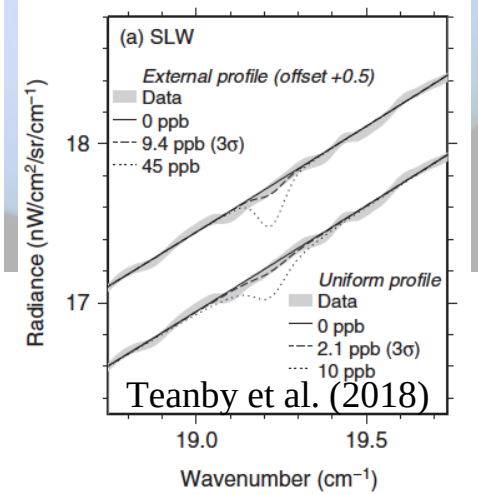




- Uranus: upper limit on internal CO (2.1 ppb)

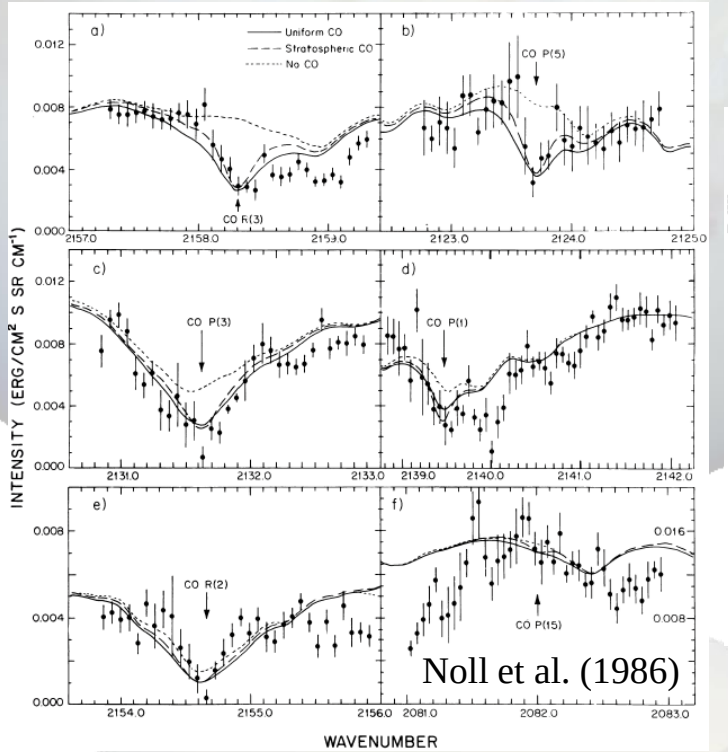




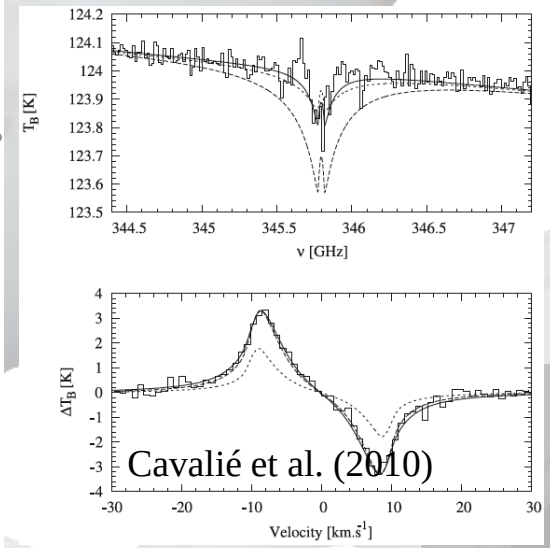


CO in the tropospheres of the other giants

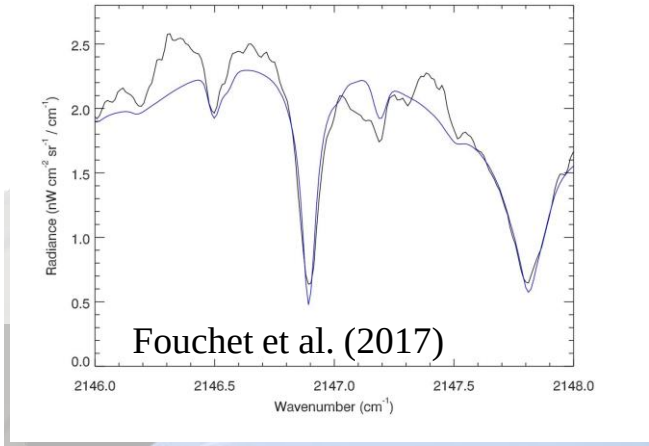
- Saturn: 1.2 ppb of tropospheric CO



Noll et al. (1986)

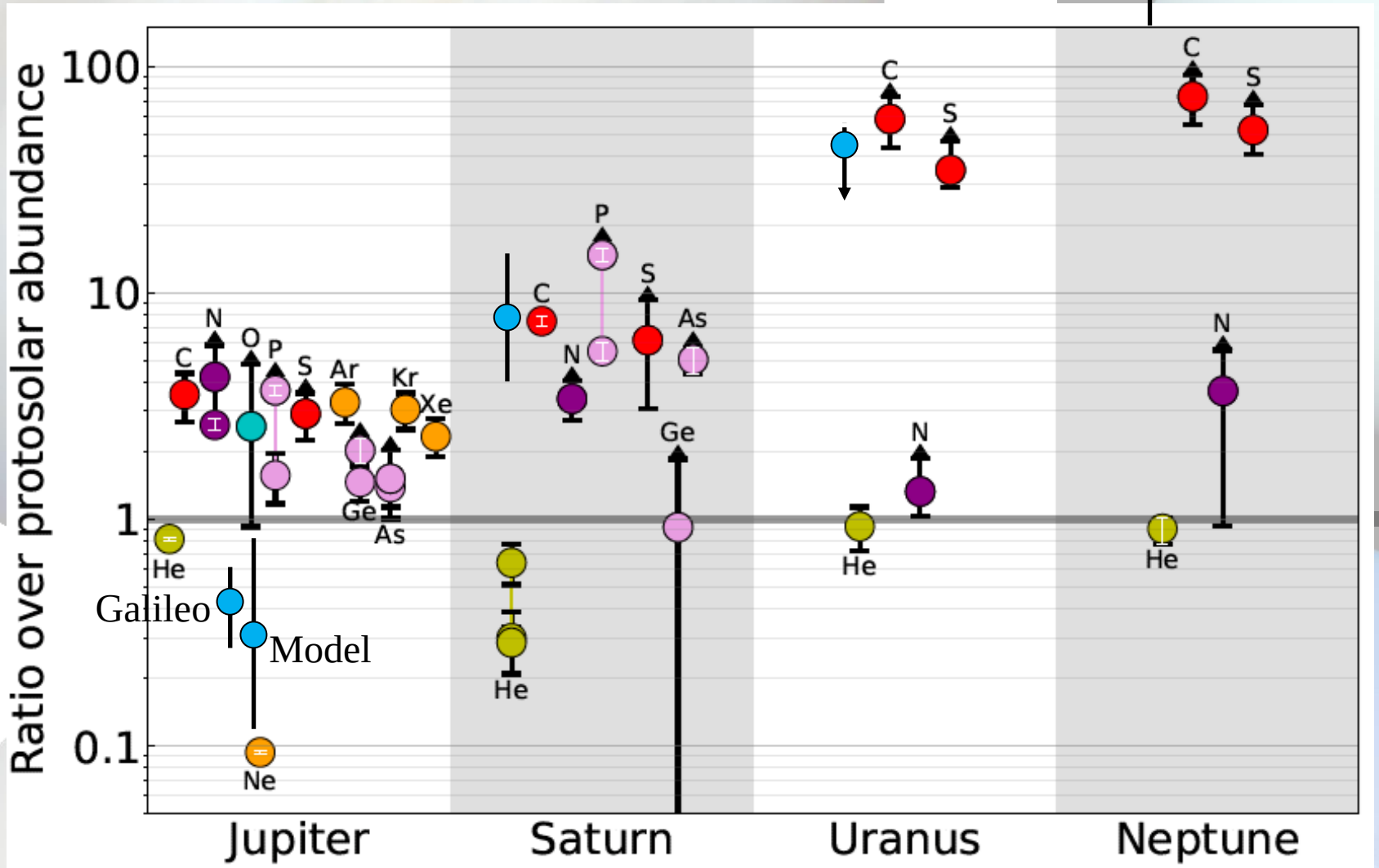


Cavalié et al. (2010)



Fouchet et al. (2017)

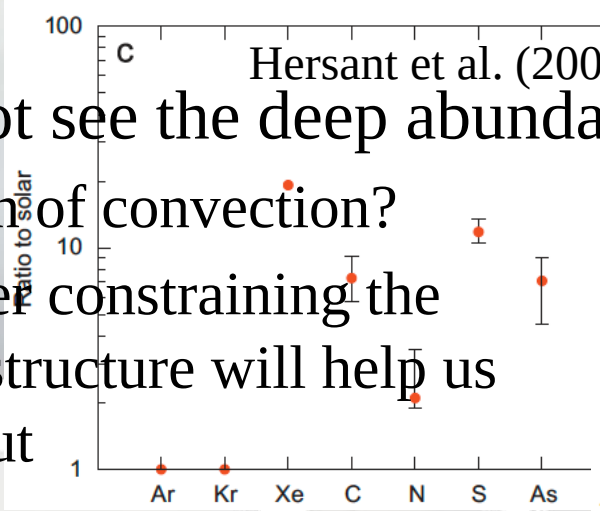
The current picture

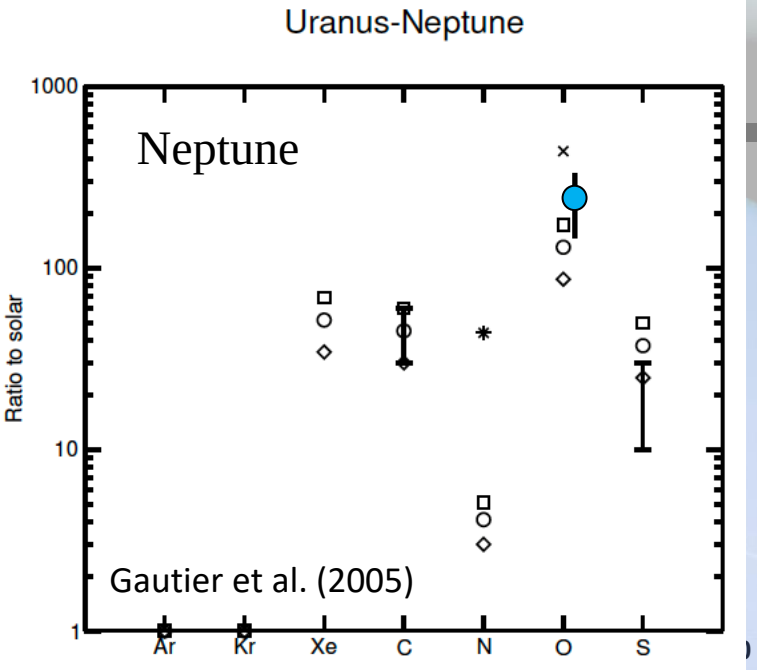


Guillot et al. (2022)

Interpretation

- Jupiter's outer envelope may be carbon-rich
- Saturn may have incorporated clathrates
- We may not see the deep abundance of O in Uranus
  - Inhibition of convection?
  - An orbiter constraining the internal structure will help us to find out
- Neptune probably incorporated clathrates





Next steps

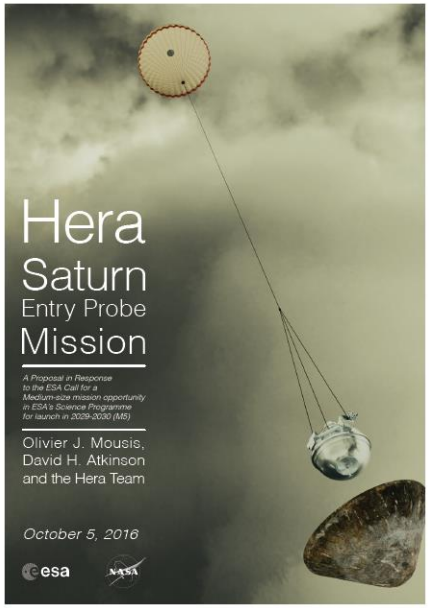
- Saturn probe

NF-6 Mission themes (alphabetical):

- Centaur Orbiter and Lander
- Ceres sample return
- Comet surface sample return
- Enceladus multiple flyby
- Lunar Geophysical Network
- Saturn probe
- Titan orbiter
- Venus In Situ Explorer

NF-7: All non-selected from NF-6 plus

- Triton Ocean World Surveyor



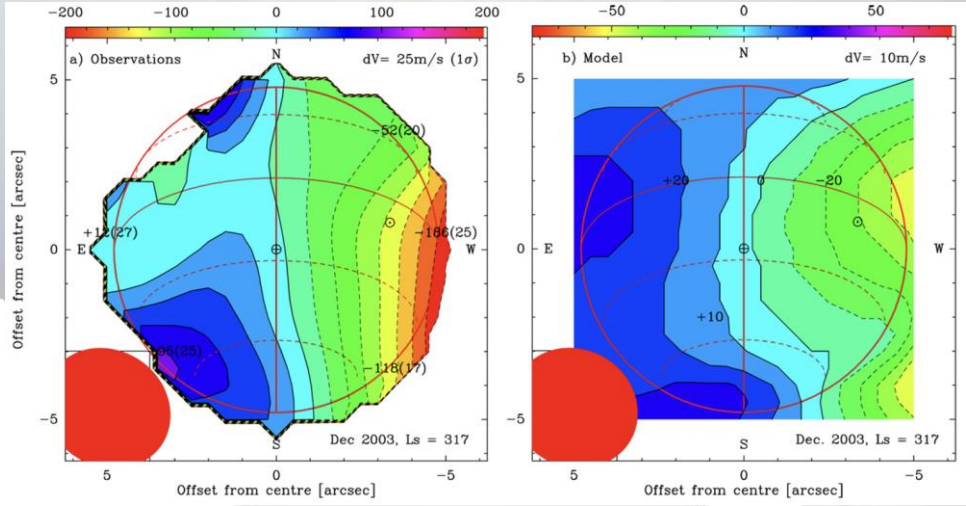
- Uranus Orbiter and Probe

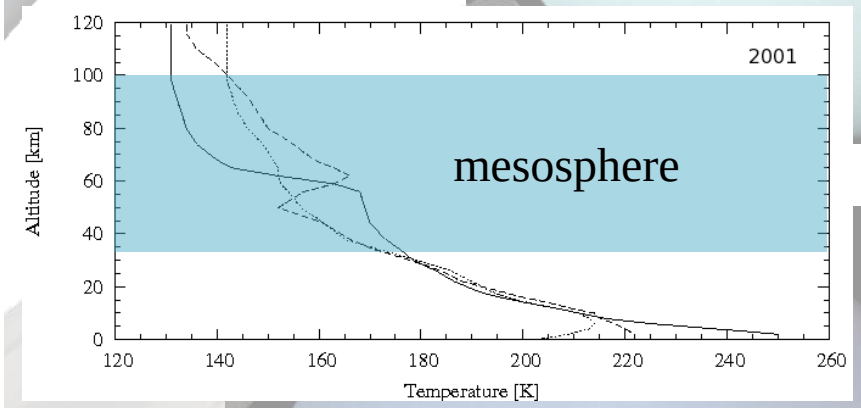
Outline

- Introduction
- Formation of the giant planets
- Supply of exogenic material
- General circulation
- Possible atmospheric science with LLAMA

Terrestrial planets

- Monitoring of Venus and Mars atmospheres (temperature + winds)
  - Last study of Mars mesosphere: Moreno et al. (2009)

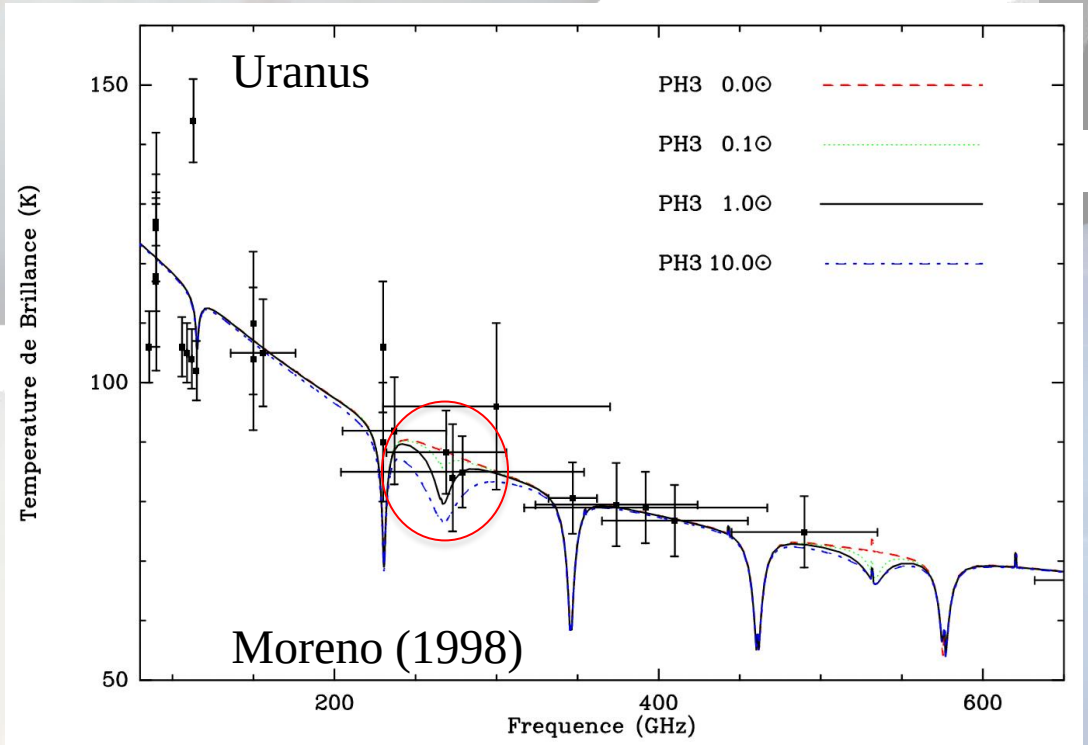




- Support to space missions
  - Mars orbiters and landers are not sensitive to the mesosphere
  - 6 space missions to Venus in the next 10 years

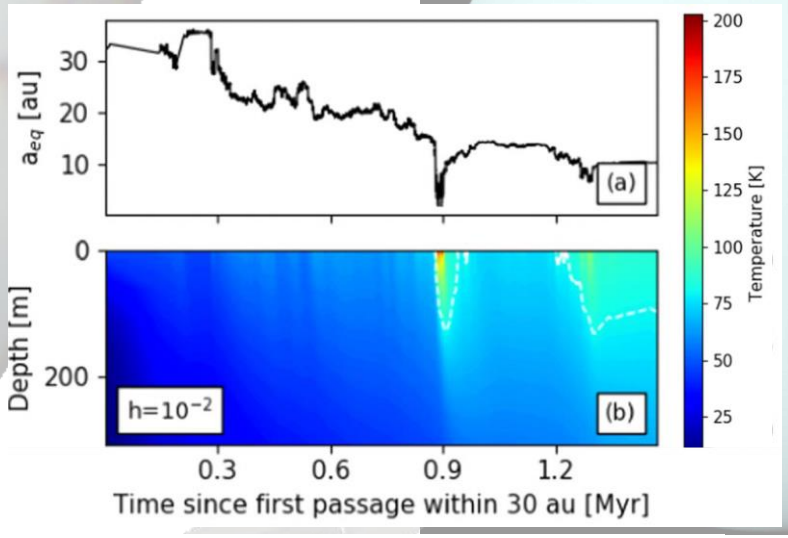
Giant planets

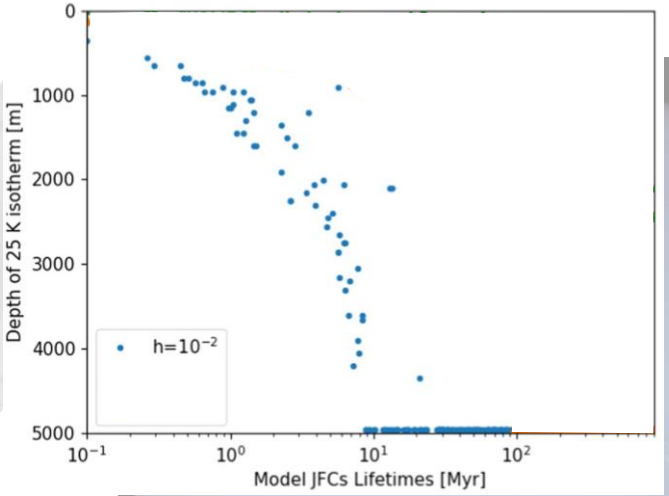
- Deep composition from large band spectroscopy
  - Tropospheric species produce absorption lines over several 10s of GHz
  - Ex: PH_3 still not detected in Uranus and Neptune



Comets

- Comet activity and composition along their orbital paths
  - Comet activity is not necessarily representative of its primordial composition
  - Thermal processing can be significant as for JFCs
  - Long-term observations + models are thus required to constrain the primordial composition of comets



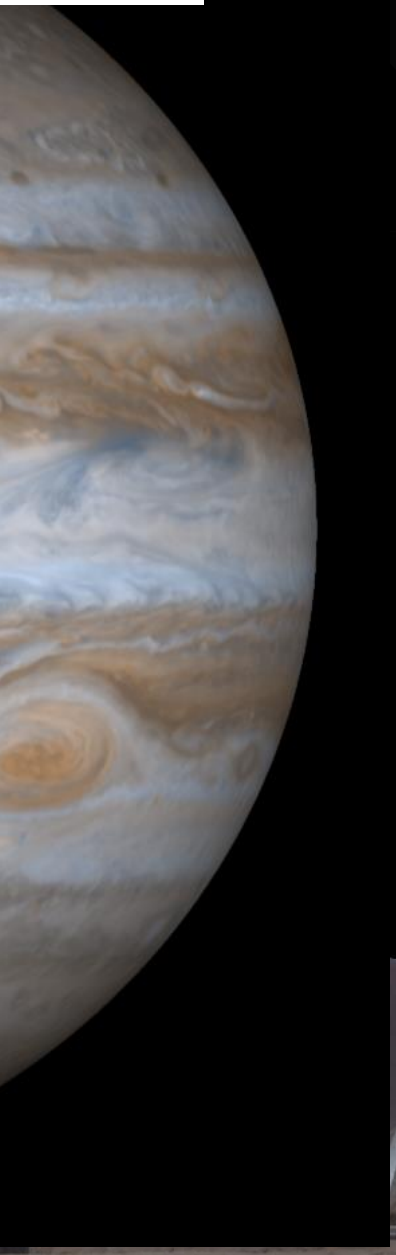


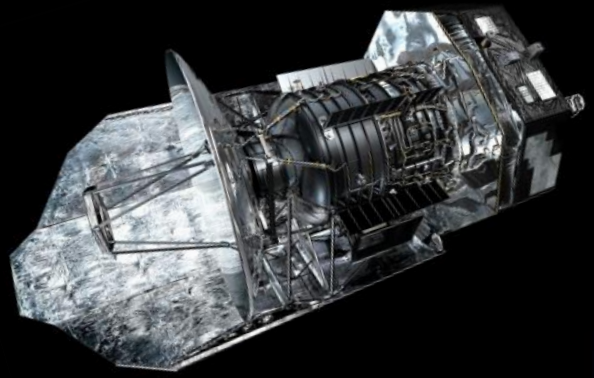
Example of a Jupiter Family Comet
Gkotsinas et al. (2022)

Conclusion

- Millimeter spectroscopy is a fantastic tool to observe composition and dynamics in giant planet atmospheres
  - Deep composition → formation models
  - Stratospheric composition → interactions of planets with their environment
  - Stratospheric dynamics → general circulation

- Wishing the best of luck to project LLAMA to achieve its goals

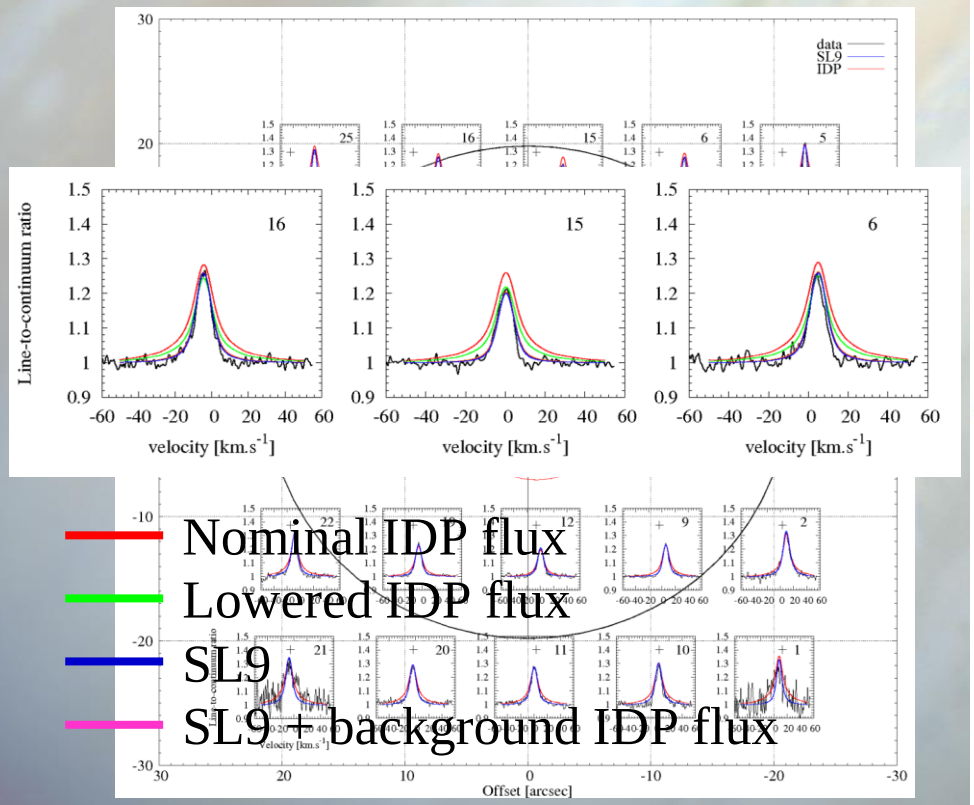


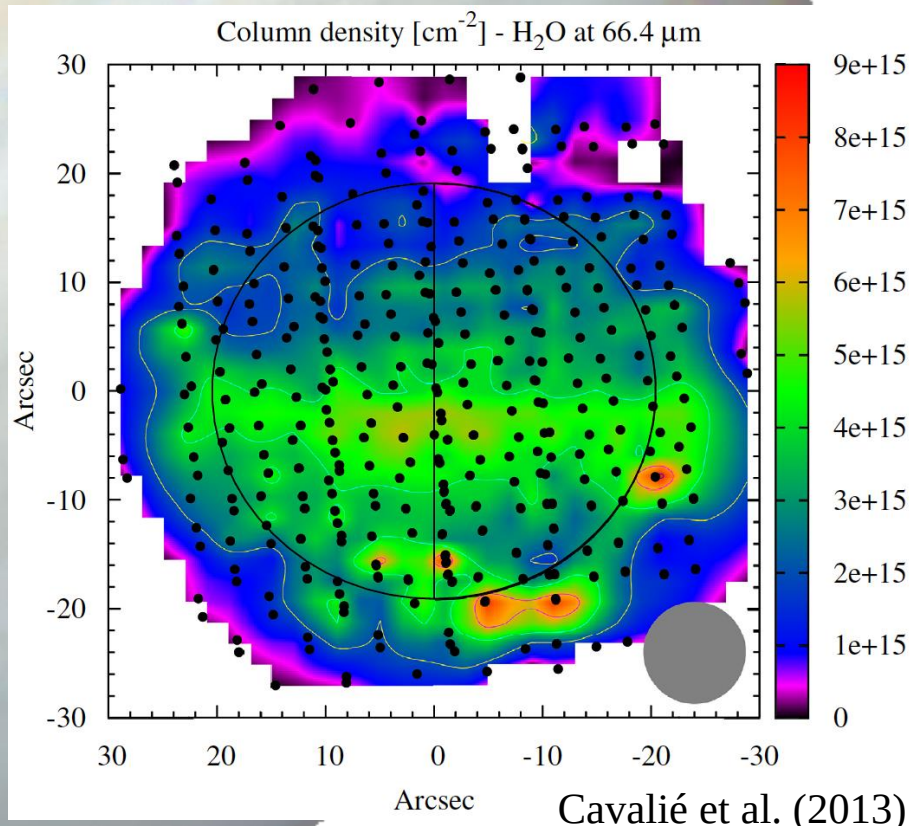


Thank you for your attention !

The origin of H_2O in Jupiter's stratosphere

- Herschel 3D mapping





Cavalié et al. (2013)

SL9 is the source of Jupiter's stratospheric H_2O