A Saturn entry probe mission: what can be learnt from the measurements of heavy noble gas abundances and isotopic ratios?

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Science goals and measurement requirements

Science goals	Science objectives/questions	Measurement objectives
I. Determine the formation conditions of the Saturn system	A. How did form Saturn (what were the thermodynamic conditions of the nebula)? Did Saturn form in situ or migrated inwards the Solar nebula?	1. Noble gas abundances 2. Noble gas isotopes 3. Elemental abundances of H, C, N, O, S 4. D/H in satellite ices
	B. Where did form the building blocks of the Saturn's satellites (source: Saturn's subnebula or Solar nebula)?	
	C. Are noble gases present in the satellites and Saturn's building blocks? How were noble gases incorporated in the Saturn's subnebula?	
	D. What is the C/O ratio in Saturn? Did Saturn form in a carbon-rich environment?	
	E. What are the relative abundances of refractories, ices, and gases? How do these compare with jovian abundances?	1. $^{14}N/^{15}N$ ratio in NH_3 & N_2 2. $^{12}C/^{13}C$ ratio in CH_4 3. D/H ratio in H_2, CH_4, NH_3 4. H_2S, NH_4SH

Science goals and measurement requirements

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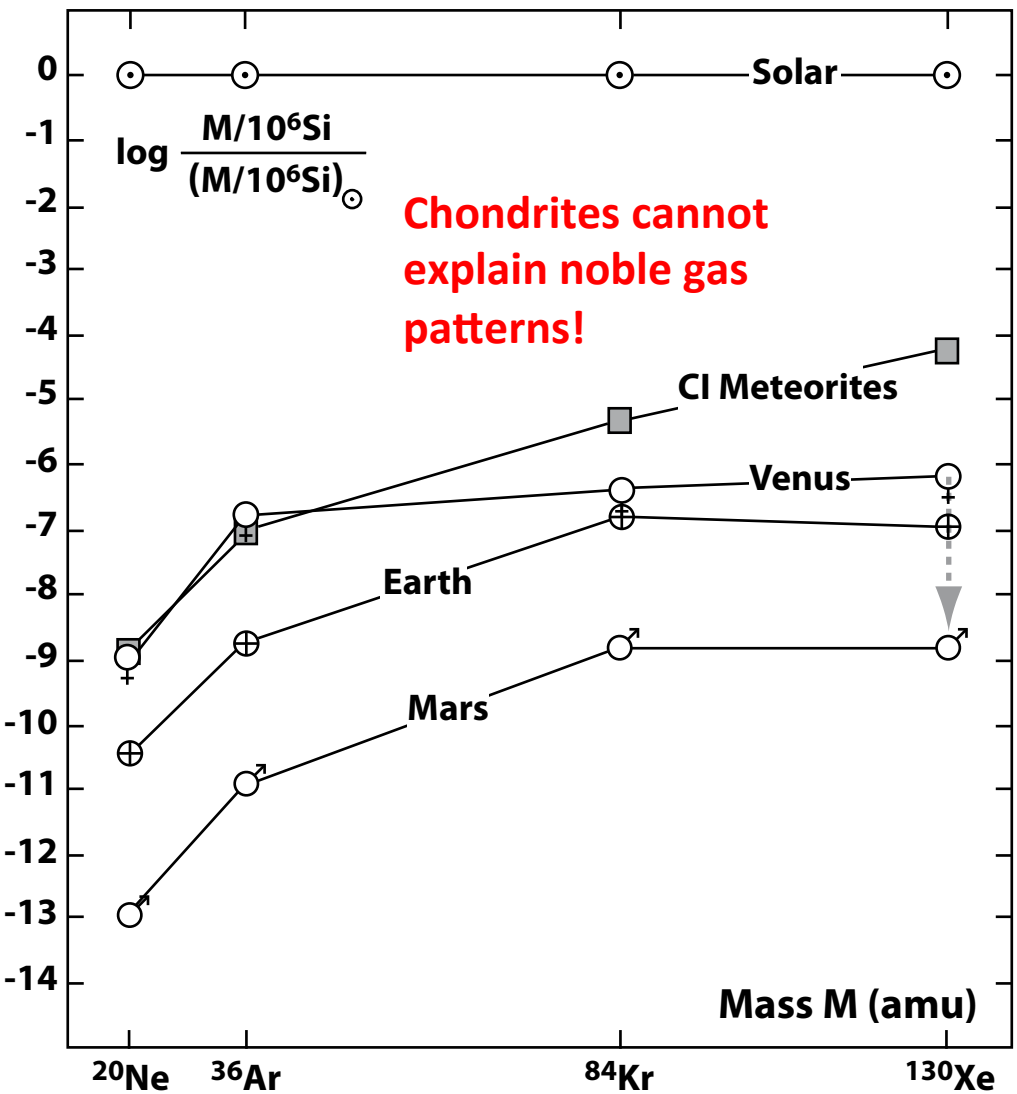
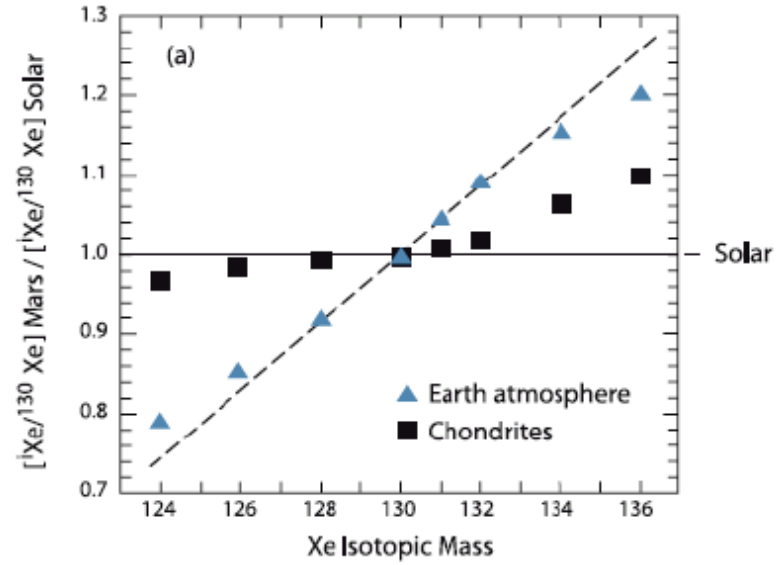
II. Characterize the dynamics and chemistry of Saturn's atmosphere and its interaction with the interior	A. How do transport and chemistry affect the thermal & dynamical structure of the deep interior?	1. He/H_2 ratio 2. Ne/H_2 ratio
	B. What are the relative roles of photochemistry & recycling in the interplay between the upper and lower atmosphere?	1. CH_4, C_2H_2, C_2H_6, C_3H_8 2. N_2, CO, PH_3, P_xH_y
	C. What is the magnitude of the external influx of oxygen into Saturn's atmosphere?	1. CO
	D. How and where are cloud condensates and aerosols formed in Saturn's atmosphere?	1. CH_4, NH_3, H_2S, PH_3

Noble gases in terrestrial planets

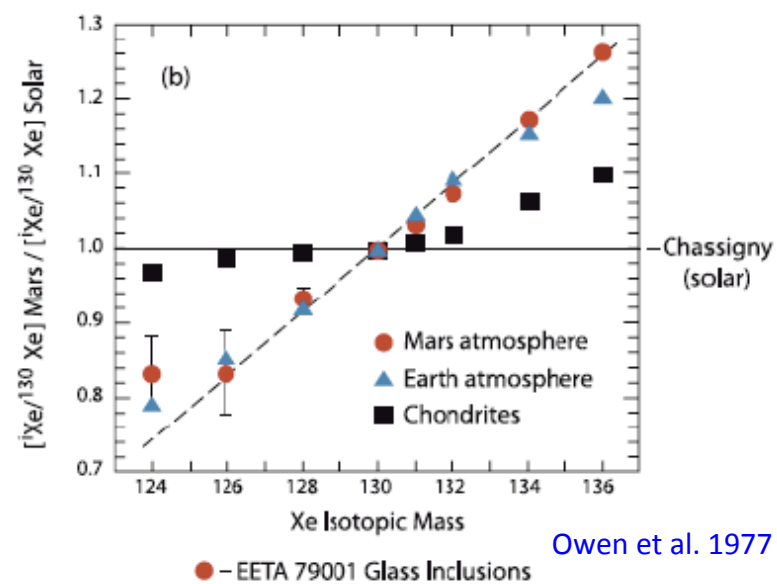


Pepin 1991; Mousis et al. 2010

Xenon Isotopes – I

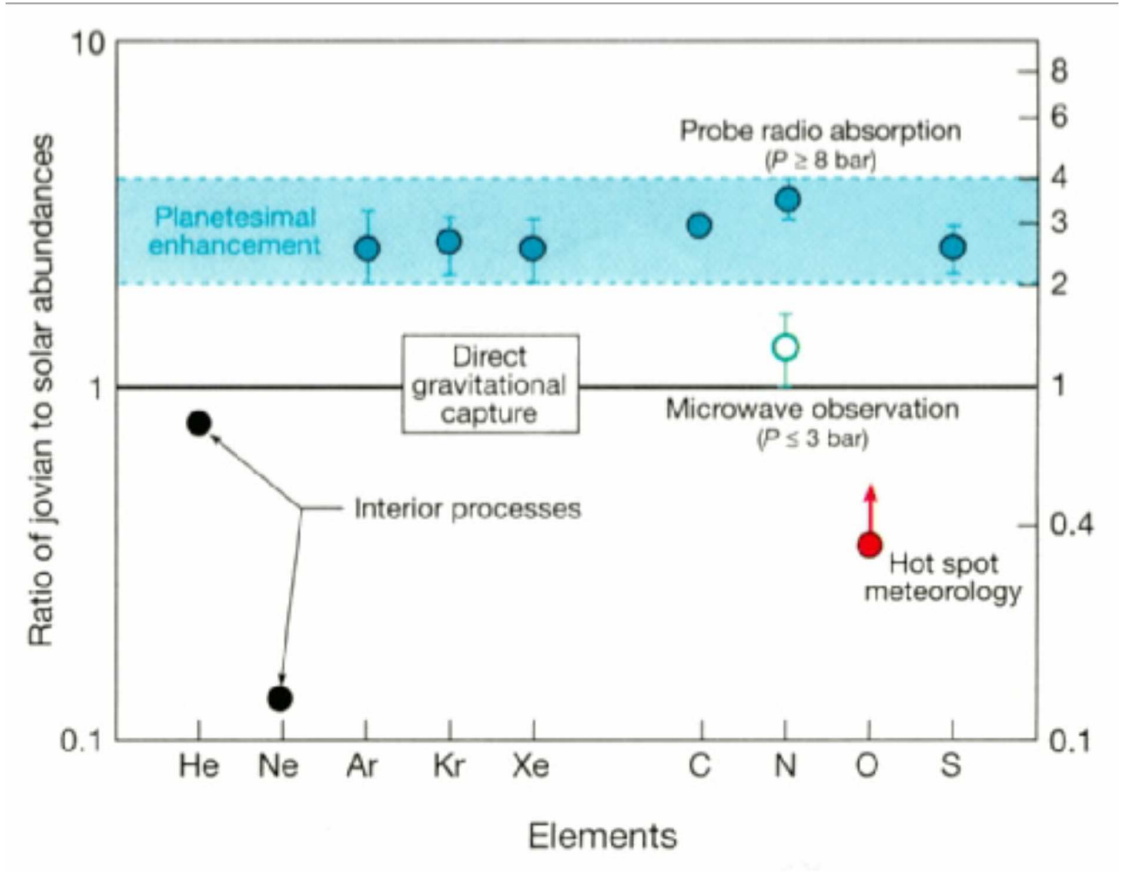


Xenon Isotopes – II
Mars= Earth!



Owen et al. 1977

In situ measurements by the Galileo probe of the volatile enrichments in Jupiter



Owen et al. (1999)

Noble gases in the outer solar system

- **Titan is impoverished in primordial noble gases**. No heavy noble gases other than argon were detected by the GCMS aboard the Huygens probe during its descent to Titan's surface in 2005 January (Niemann et al. 2005 , 2010).

  Detected argon includes primordial ^{36}Ar, present in subsolar abundance in Titan's atmosphere ($^{36}Ar/^{14}N$ is found to be about six orders of magnitude lower than the solar value), and the radiogenic isotope ^{40}Ar, which is a decay product of ^{40}K (Niemann et al. 2005). The other primordial noble gases ^{38}Ar, Kr, and Xe were not detected by the GCMS instrument, yielding upper limits of 10^{-8} for their atmospheric mole fractions (Niemann et al. 2005, 2010).

- ✓ **Despite many attempts, no firm detection of noble gases in comets (Rosetta will make soon in situ measurements)**

- ✓ **The noble gas abundances in Saturn, Uranus and Neptune are unknown (require deep atmospheric probes).**

The heavy element content of gas giants

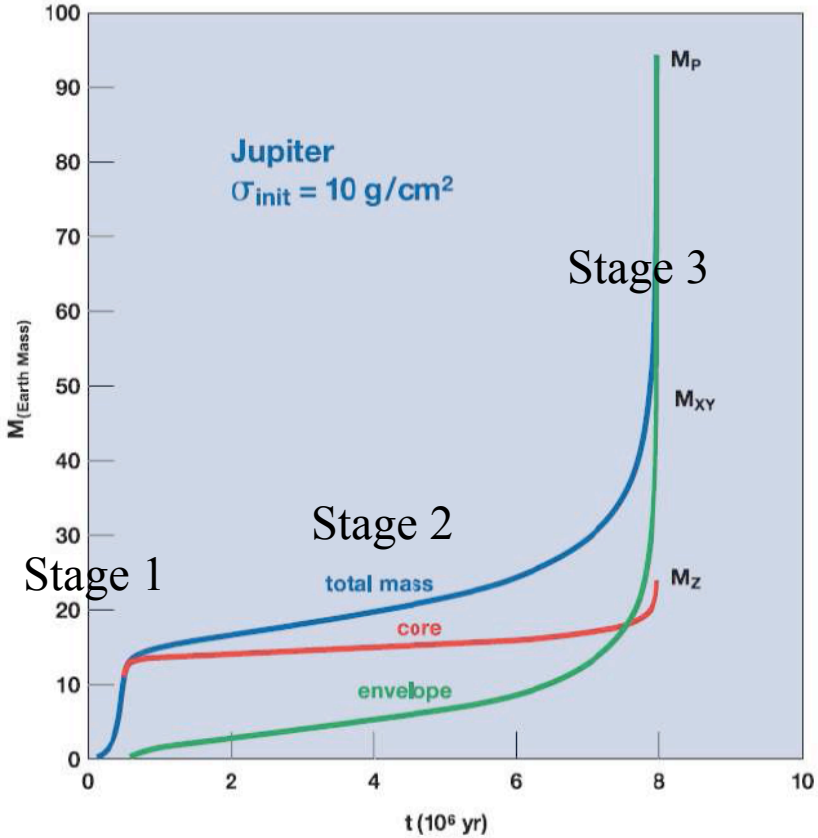
- Three steps in the formation of gas giants:

  1. Core accretion
  2. Gas accretion until $M_{gas} \sim M_{core}$

  3. Runaway accretion of **gas + gas-coupled solids**

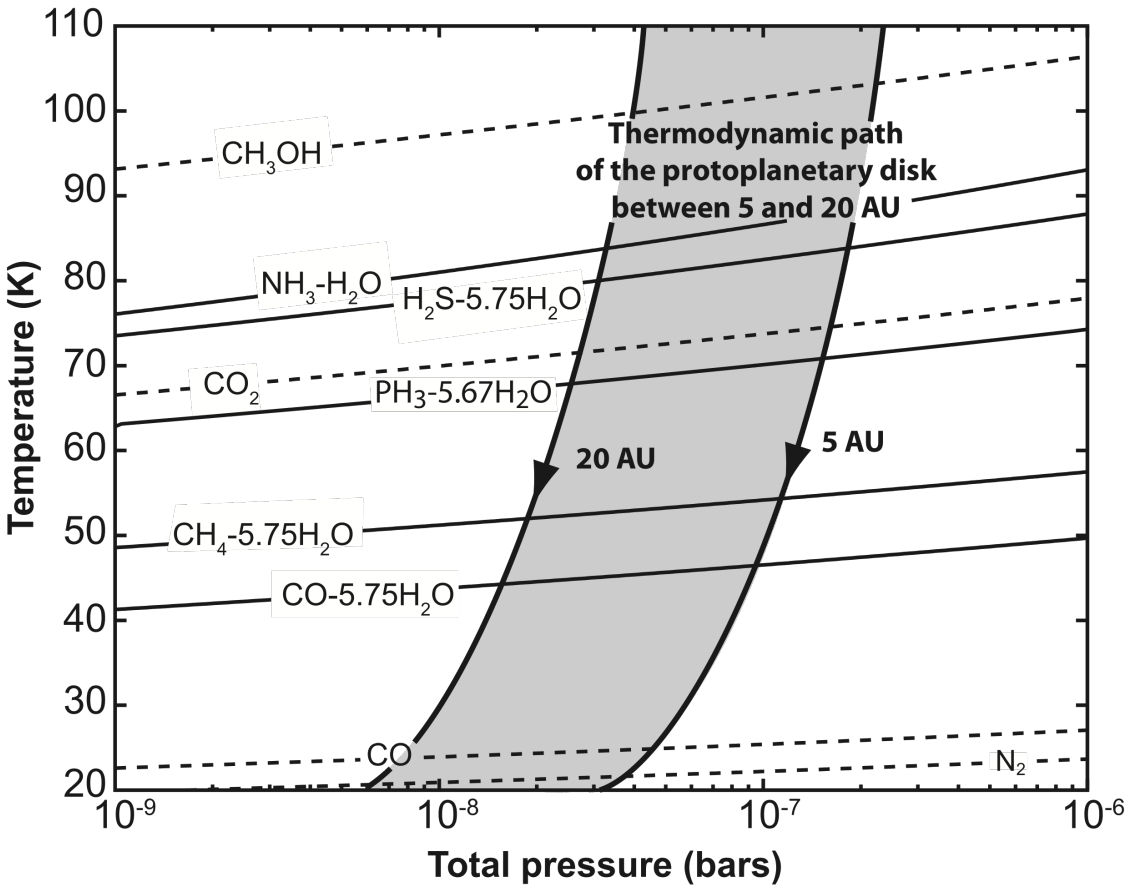
     $\Rightarrow M_{gas} >> M_{core}$

- See Pollack et al. (1996)

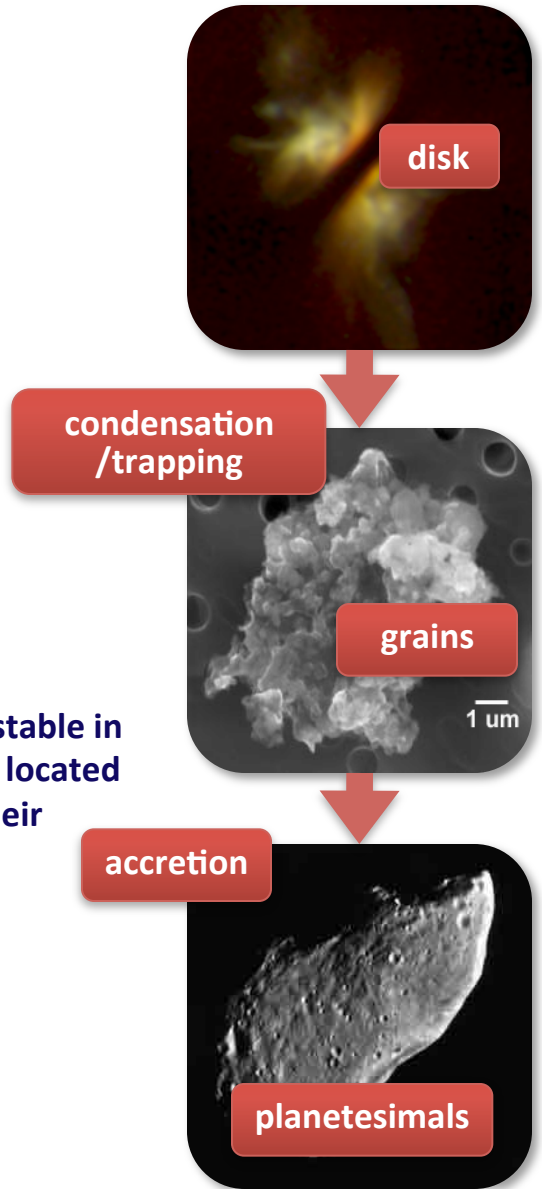


Formation of ices in the solar nebula

CO:CO2:CH3OH:CH4 = 70:10:2:1 and N_2:NH_3 = 1:1 in the gas phase

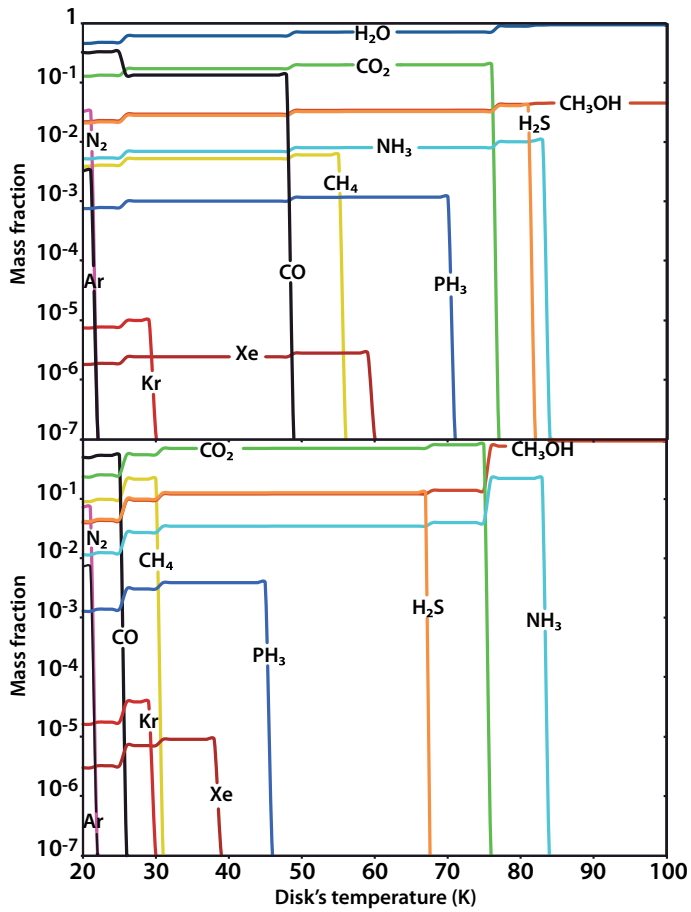


Ices are stable in domains located below their stability curves



Formation of clathrates and pure condensates in the outer solar nebula

Composition of planetesimals in the solar nebula as a function of the oxygen abundance in the disk and their formation temperature



C/O = 0.5 (solar case)

C/O = 1
(carbon-rich case)

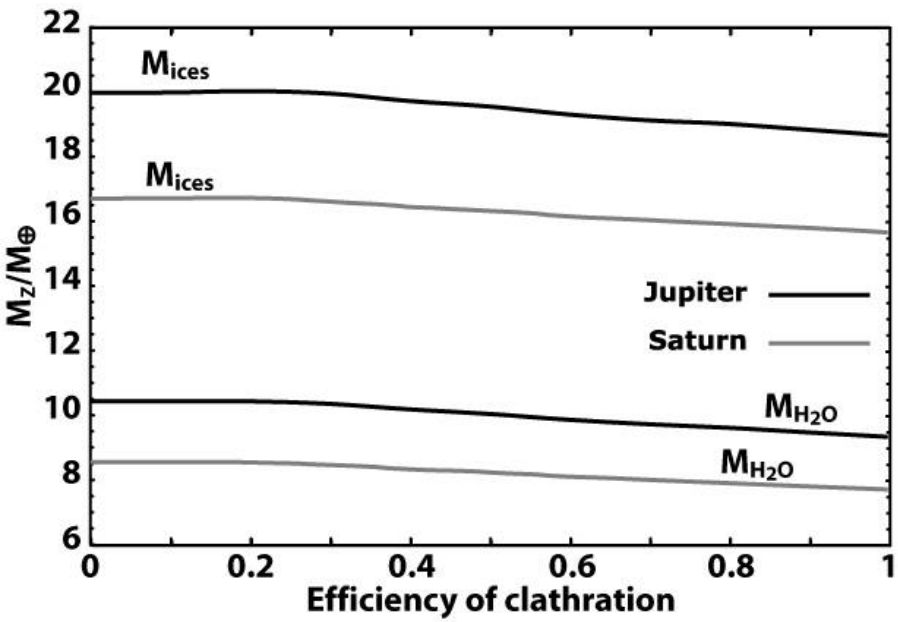
Observed and calculated enrichments in volatiles in Jupiter and Saturn

100% clathration efficiency, CO_2:CO:CH_3OH:CH_4 = 70/10/2/1 and N_2/NH_3 = 1/1 in the nebula gas phase

	Jupiter		Saturn	
Species	**Observed**	**Calculated**	**Observed**	**Calculated**
O		5.1		14.1
C	4.1 ± 1	3.1	8.8 ± 1.7	8.8
N	4.15 ± 1.6	3.1		8.9
S	2.4 ± 0.6	2.6		7.1
P	3.2 ± 0.15	4.8	8.9 – 13.5	13.1
Ar	2.15 ± 0.4	2.0		6.1
Kr				7.7
Xe				12.1

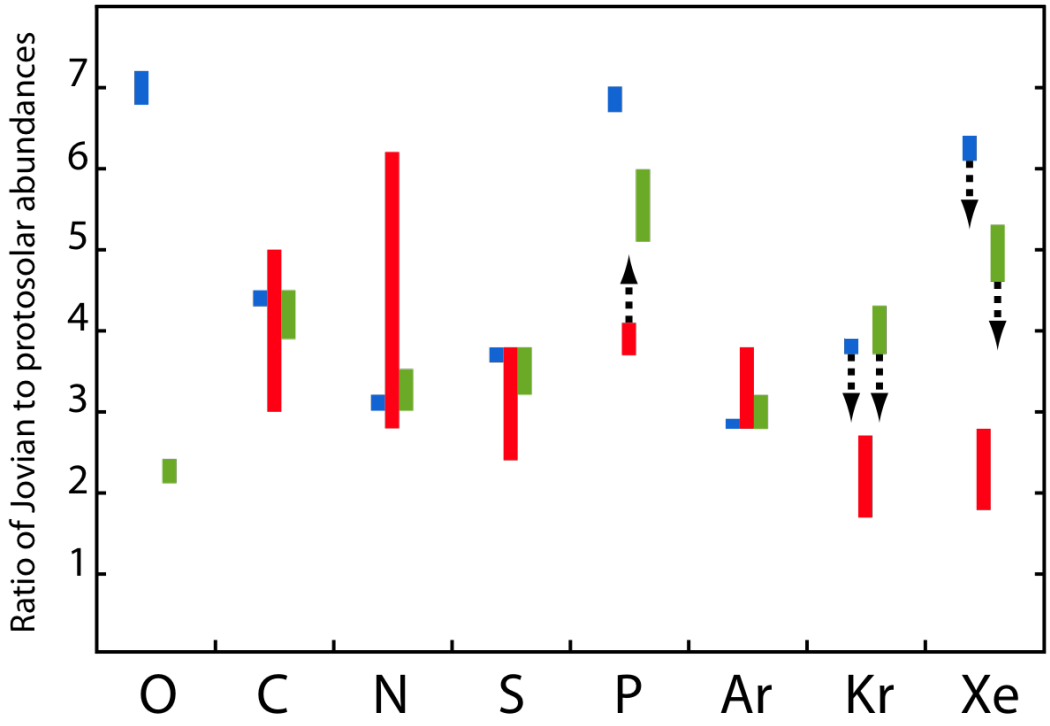
P is out of equilibrium in Jupiter's atmosphere and could be underestimated (Fletcher et al. 2009)

Minimum masses of heavy elements required in the atmospheres of Jupiter and Saturn to match the observed enrichments



Mousis et al. (2009)

Matching the volatile enrichments in Jupiter from different disk's gas phase compositions



Red bars correspond to observations. Green and blue bars correspond to calculations based on the assumption that C/O = 0.5 (solar case) and C/O = 1 (C-rich case) in the disk.

Conclusion: Jupiter could be carbon rich!!!!

Testing this hypothesis requires the measurement of O in Jupiter by Juno

Mousis et al. (2012)

Noble gas abundances in Saturn - what can we infer from the study of Titan's origin?

Conditions required to explain the current composition of Titan's atmosphere:

- **Volatiles were trapped in Saturn's feeding zone in the form of hydrates, clathrates or pure condensates (see condensation sequence in previous slide)**

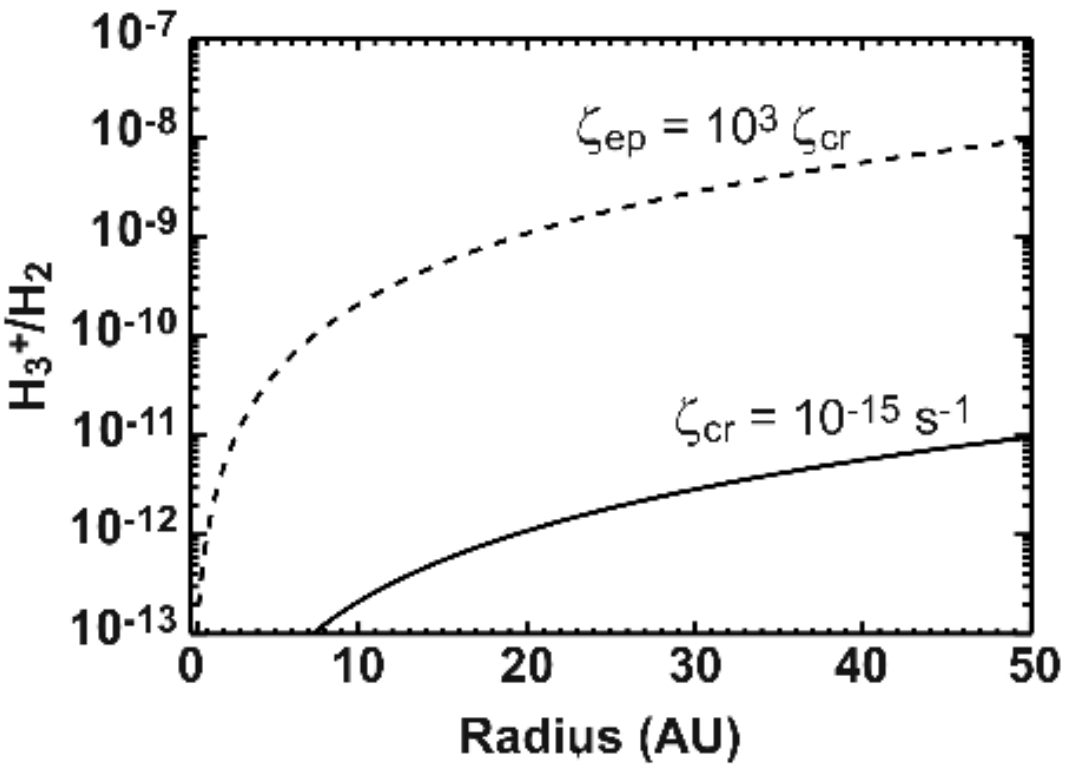
- **The question of noble gas trapping in Titan's building blocks remains open. Two competing theories, depending on the abundance of H_3^+ ion at Saturn's position in the nebula:**

✓ **If H_3^+ was underabundant in the nebula, noble gases were incorporated in planetesimals. They would have been devolatilized or hidden during the formation and subsequent evolution of the body (Mousis et al. 2009, 2012)**

✓ **If the H_3^+ abundance was higher than that of noble gases in the disk: formation of Ar-H_3^+, Xe-H_3^+ and Kr-H_3^+ complexes in the solar nebula would impede the condensation of Xe and Kr or their incorporation in planetesimals (Mousis et al. 2008; Pauzat et al. 2012).**

Formation of noble gas-poor planetesimals in presence of H_3^+ in the gas phase

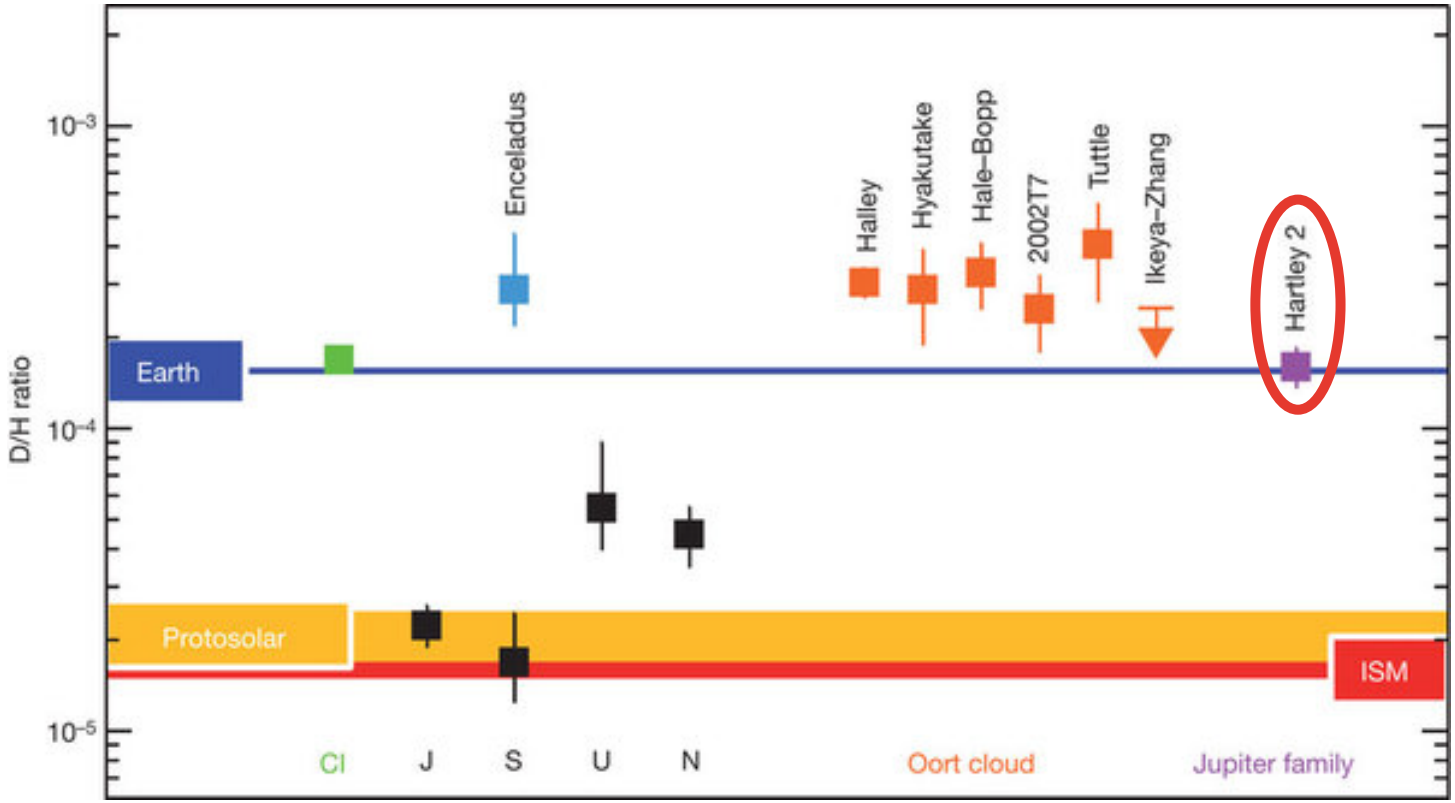
H_3^+ abundance in the disk midplane as a function of the heliocentric distance.



Formation of XH_3^+ complexes in the gas phase of the nebula (with X = Kr and Xe) would impede the formation of X-$6H_2O$ clathrates or pure condensates X

Mousis, Pauzat, Ellinger & Ceccarelli (2008) ApJ 673, 637-646

D/H ratios measured in H_2O in the Solar System



Adapted from Hartogh et al. 2011

Modeling the D/H chemistry in the primitive nebula

- ✓ ISM ices that fell onto the solar nebula are **highly enriched in deuterium**
- ✓ The isotopic exchange between HD and HDO is described by the following reversible equation in the gas phase dominated by H_2:

$$\mathbf{H_2O + HD = HDO + H_2}$$

- ✓ **The efficiency of the isotopic exchange increases at high temperature. The exchange stops once water is condensed.**

Equation of diffusion describing the evolution of D:H in water in the solar nebula

$$\partial_t f = \underbrace{k(T)P(A(T) - f)}_{\text{Isotopic exchange}} + \underbrace{\frac{1}{\Sigma R}\partial_R(\kappa R \Sigma \partial_R f)}_{\text{Turbulent diffusion}}$$

$$f = \frac{1/2}{1/2}\frac{\mathrm{HDO/H_2O}}{\mathrm{HD/H_2}}$$

Modeling the D/H chemistry in the primitive nebula

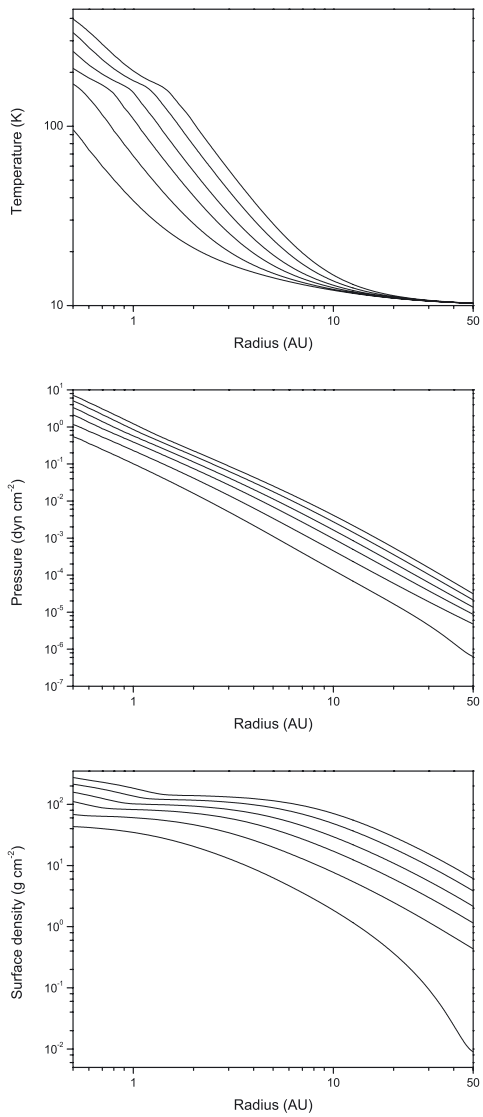
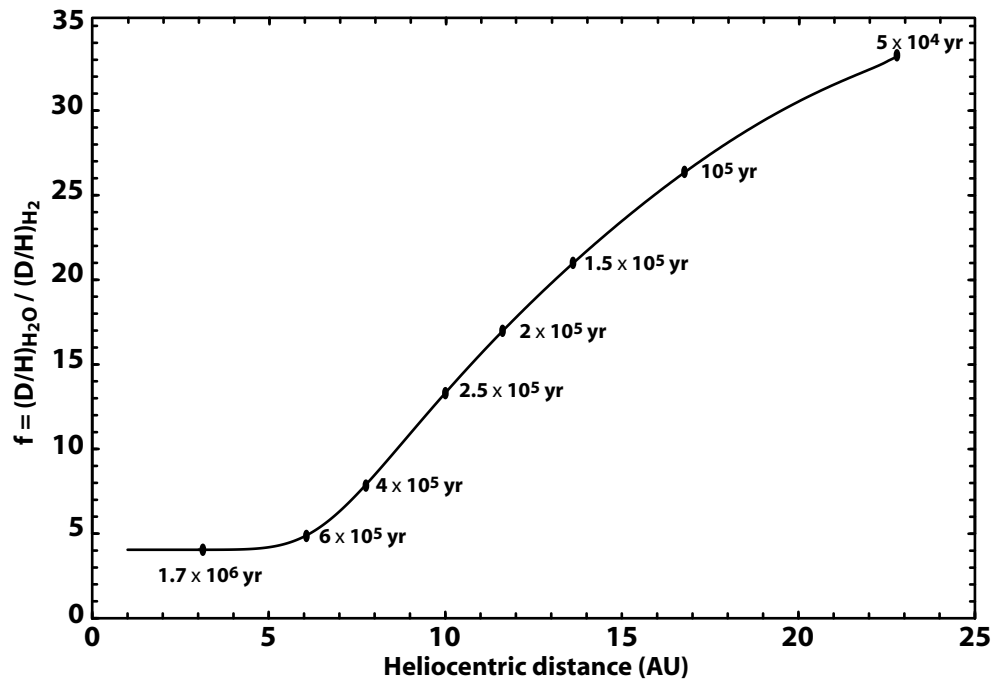
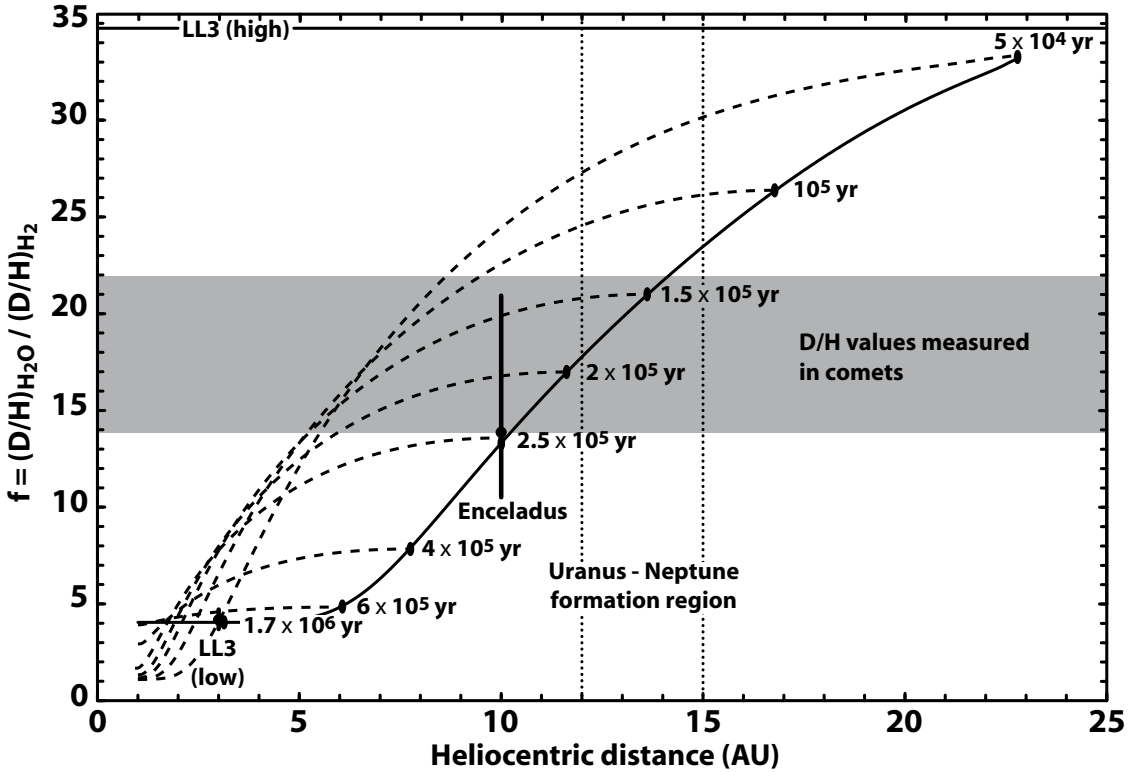


Fig. 1. Temperature, pressure and surface density profiles in the mid-plane of the disk characterized by a mass of 0.03 $M_\odot$ and a lifetime of 6 Myr. *From top to bottom* in each panel, times are 1, 2, 3, 4, 5, and 6 Myr.



Enrichment factor *f* (defined as the ratio of D/H in H_2O to protosolar D/H) as a function of the heliocentric distance in the primordial nebula. The solid curve represents the value of *f* acquired by ice as a function of its formation distance in the nebula. Condensation epochs at various heliocentric distances are also indicated in the plot.

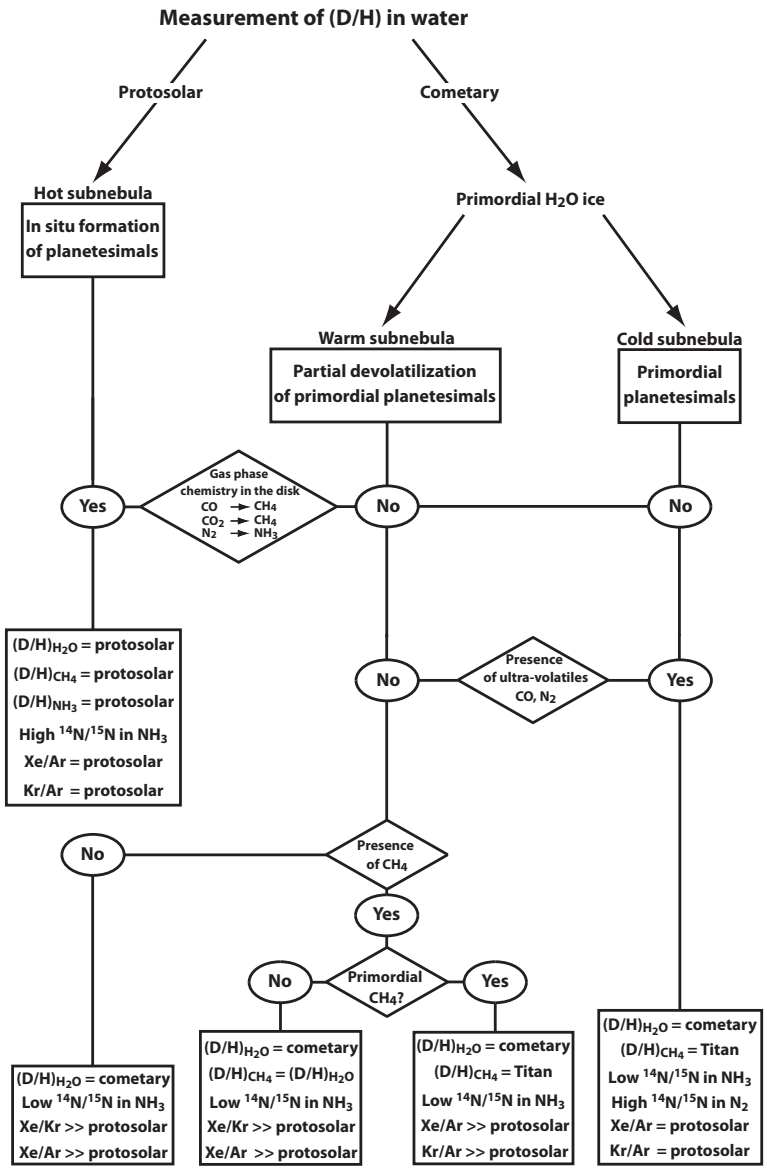
Isotopic composition of ices in the primordial nebula



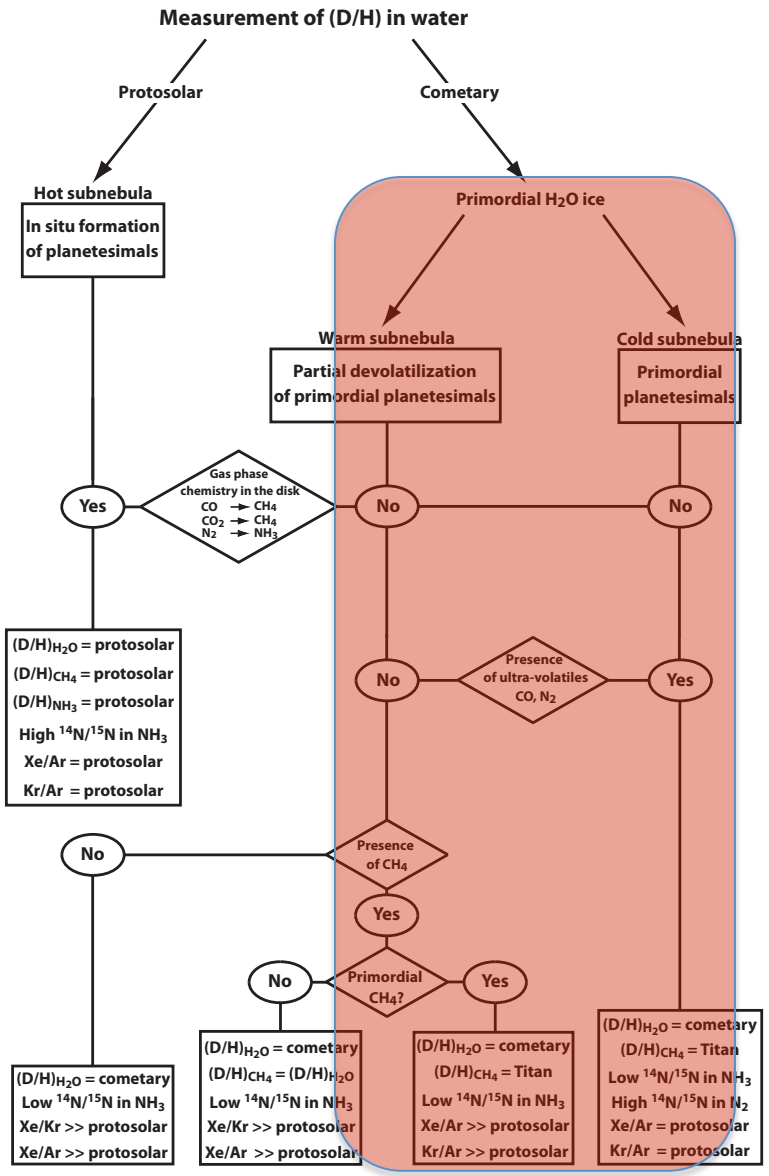
Kavelaars et al. (2011)

The solid curve represents the value of *f* acquired by ice as a function of its formation distance in the nebula. **The vertical dotted lines enclose the source region of Uranus and Neptune in the Nice model. The gray area corresponds to the dispersion of the central values of the *f in* the comets for which measurements are available.**

D/H measurement in satellite ices



D/H measurement in satellite ices



Case of Enceladus (Waite et al. 2009)!!

Conclusions

- In situ measurements of the chemical and isotopic composition of Saturn's atmosphere are mandatory if one wants disentangling the different existing formation scenarios

- Noble gases are particularly relevant because (1) they are chemically inert and (2) their isotopic compositions present large scale inhomogeneities in the solar system that make them isotopic tracers

- In situ measurements of the noble gas abundances and the D/H ratios in satellite ices are also important in order to establish the link between the different physical processes that led to the formation of the giant planet and its surrounding satellite system