# Saturn's exploration beyond Cassini-Huygens

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ORIGINAL ARTICLE

# Kronos: exploring the depths of Saturn with probes and remote sensing through an international mission

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# Outline

- Introduction
- The questions behind Saturn's exploration
  - Saturn's composition
  - Saturn’s evolution & extrasolar giant planets
  - Saturn's atmospheric composition and dynamics
  - Saturn's magnetosphere
  - Saturn's rings
  - Saturn and the formation of the Solar System
- The means
  - Flyby
  - Orbiter
  - Probes
  - Microprobes
  - Ground based observations
- Conclusion

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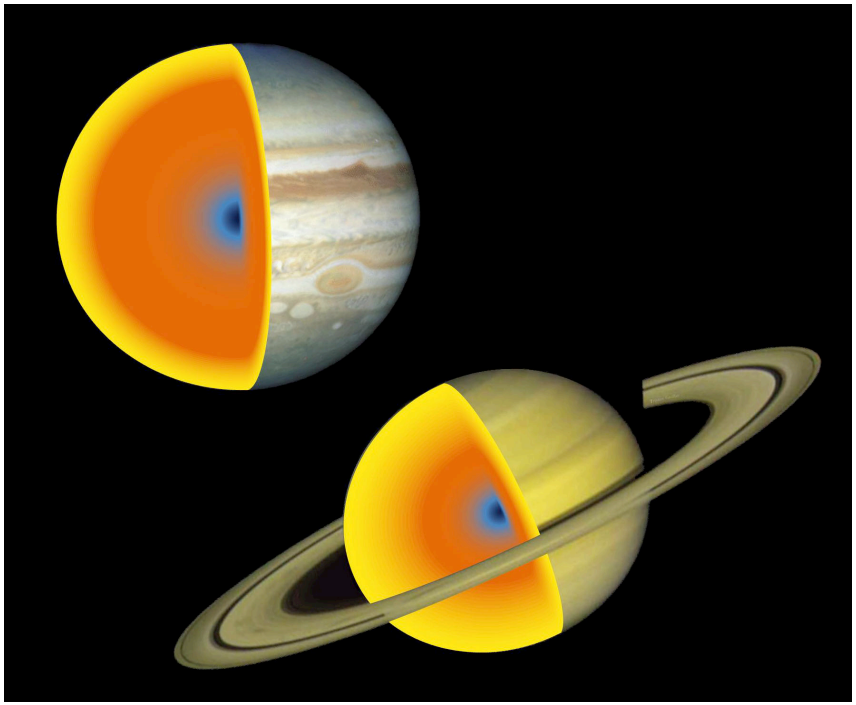
# Saturn's composition

In the atmosphere:

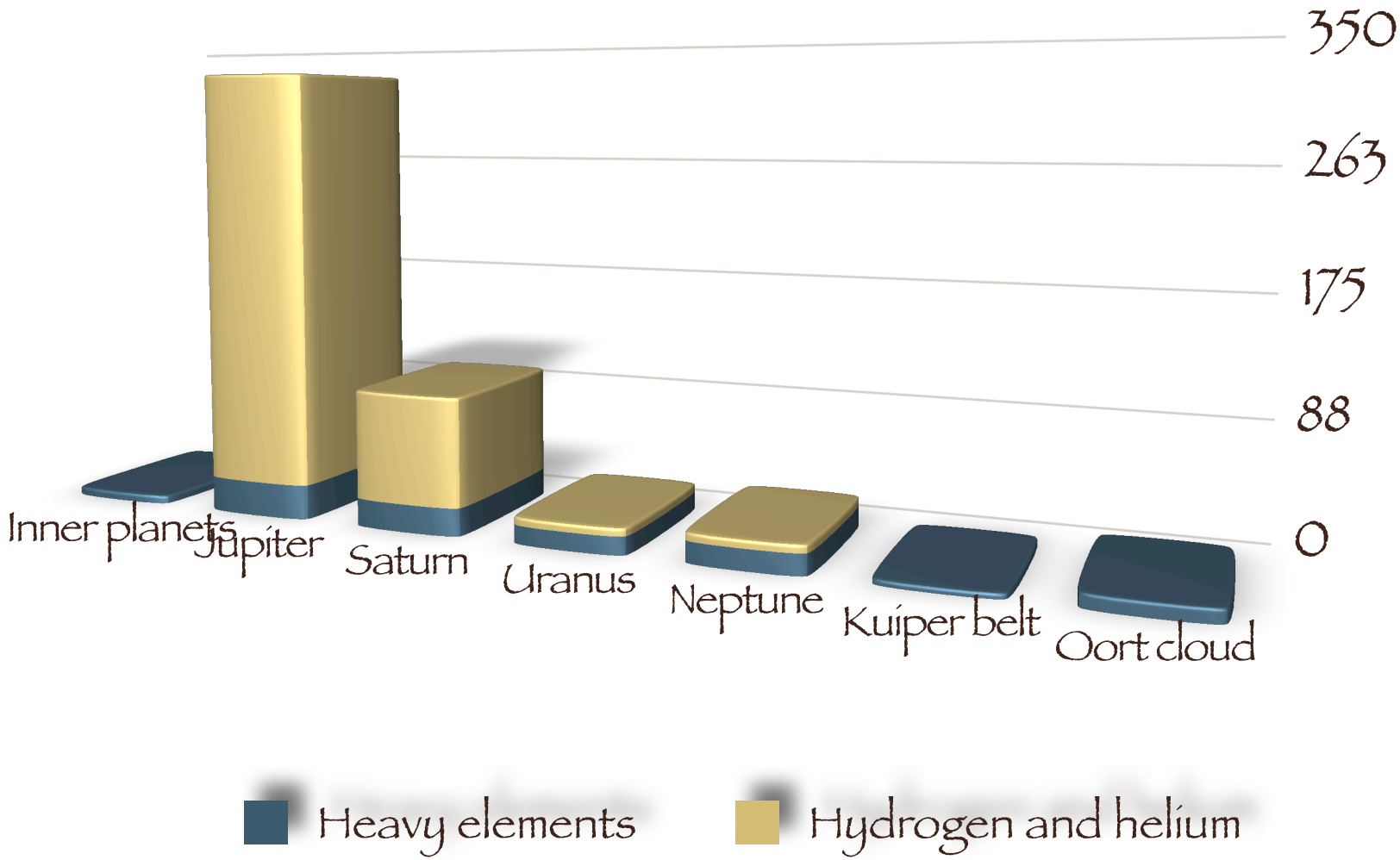
- –CH4 abundance measured by Cassini, NH3 & H2S indirectly (microwave)

Saturn's interior is not well constrained

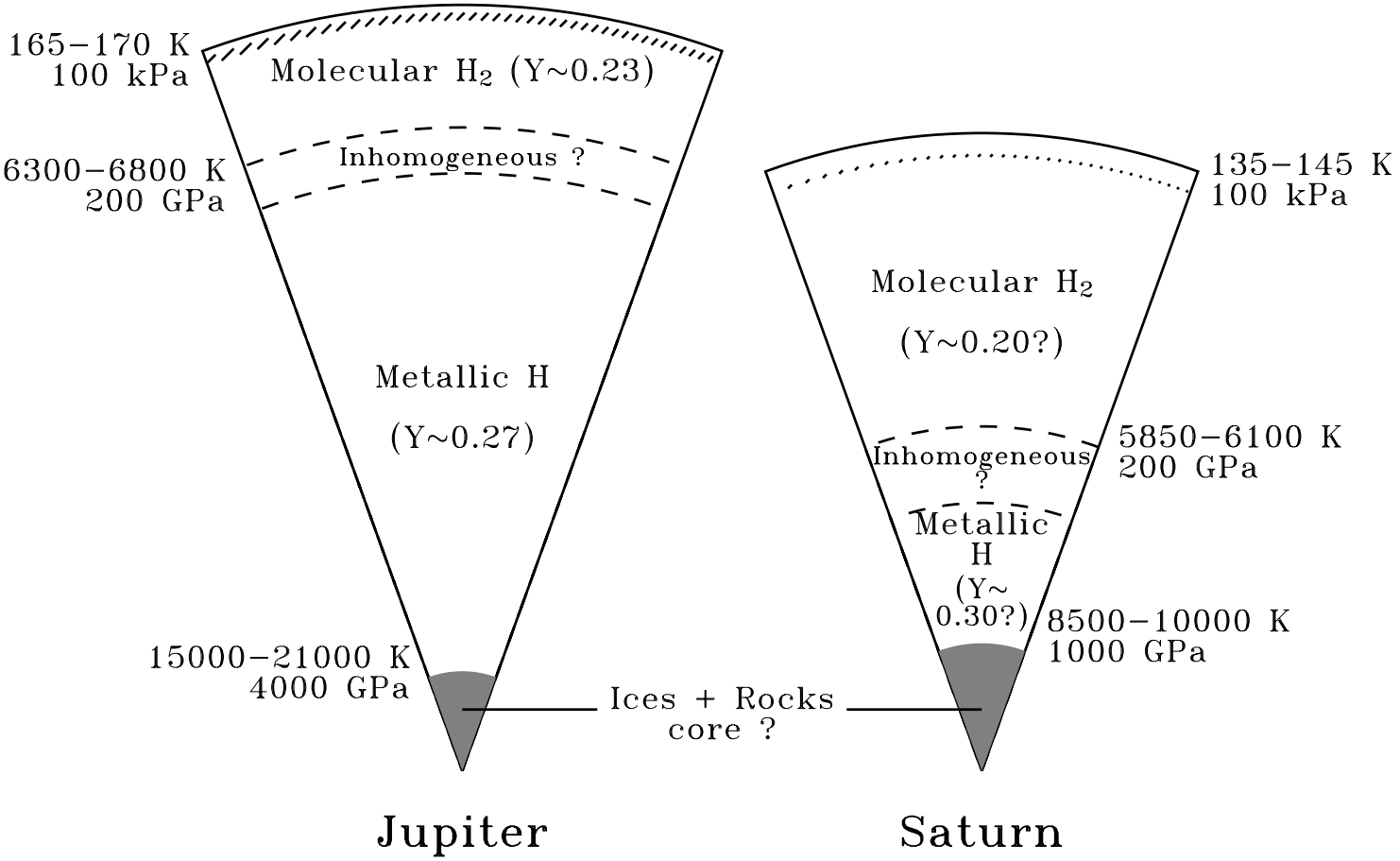
- – Does Saturn have a larger core than Jupiter?
- –What is the amount of heavy elements (especially H2O) in its envelope?
- –We need to complete the inventory of heavy elements in the Solar System



# Saturn's composition vs. the Solar System

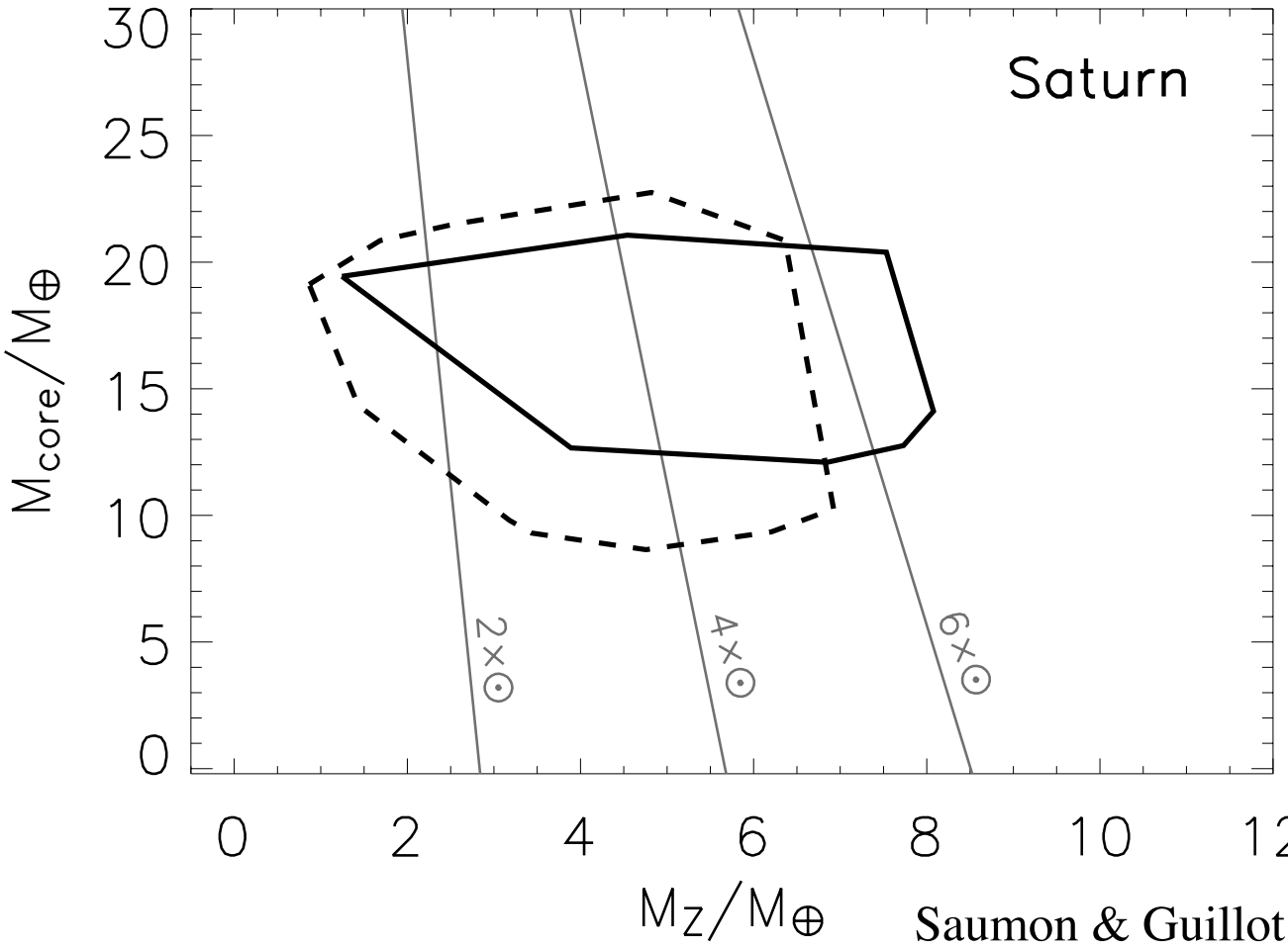


# Saturn's composition: interior models



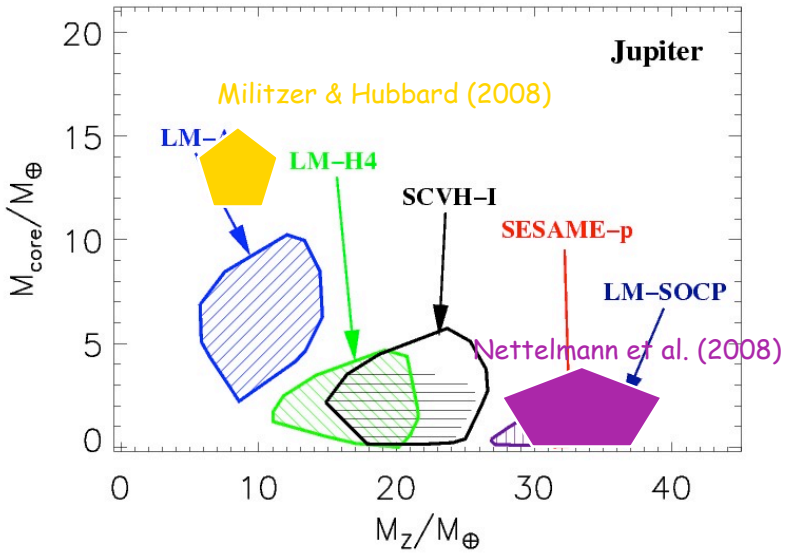

Guillot (2005)

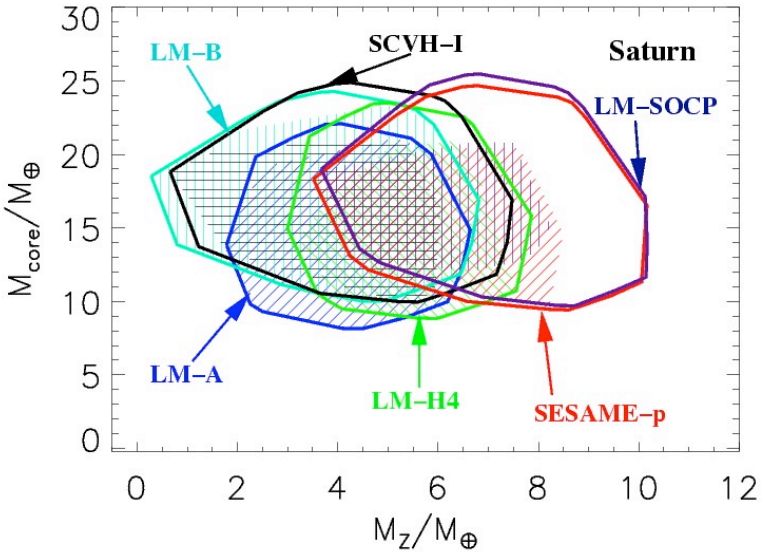
# Saturn's composition: interior models




Saumon & Guillot (2004)
Guillot (2005)

# Saturn's composition: new EOSs



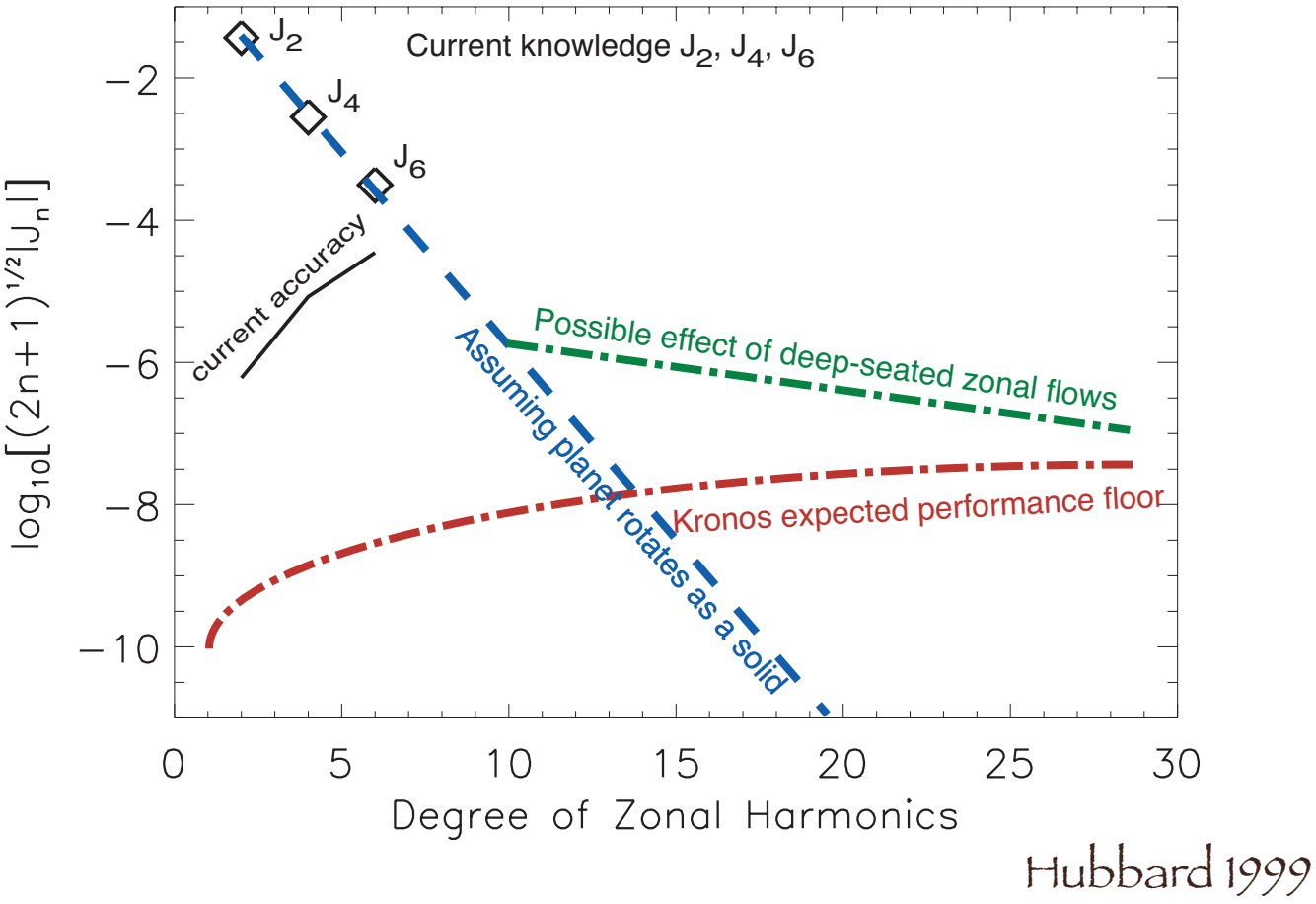




Saumon & Guillot 2004

Large uncertainties on the interior composition

- New EOS work (Militzer et al. 2008, Nettelmann et al. 2008) but do not seem to converge for Jupiter models...
- Saturn's core determination may be altered by a helium layer (Fortney & Hubbard 2004)

# Saturn's composition: importance of interior rotation




Hubbard 1999

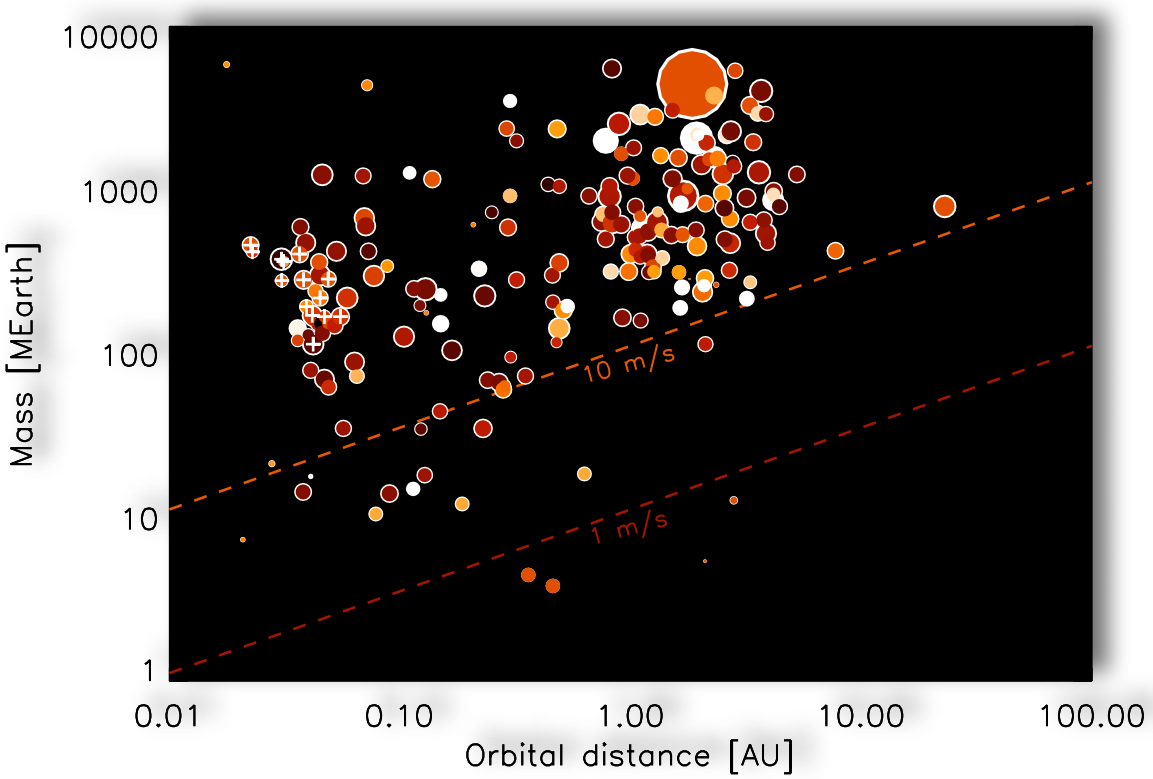
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# Saturn's evolution and extrasolar planets

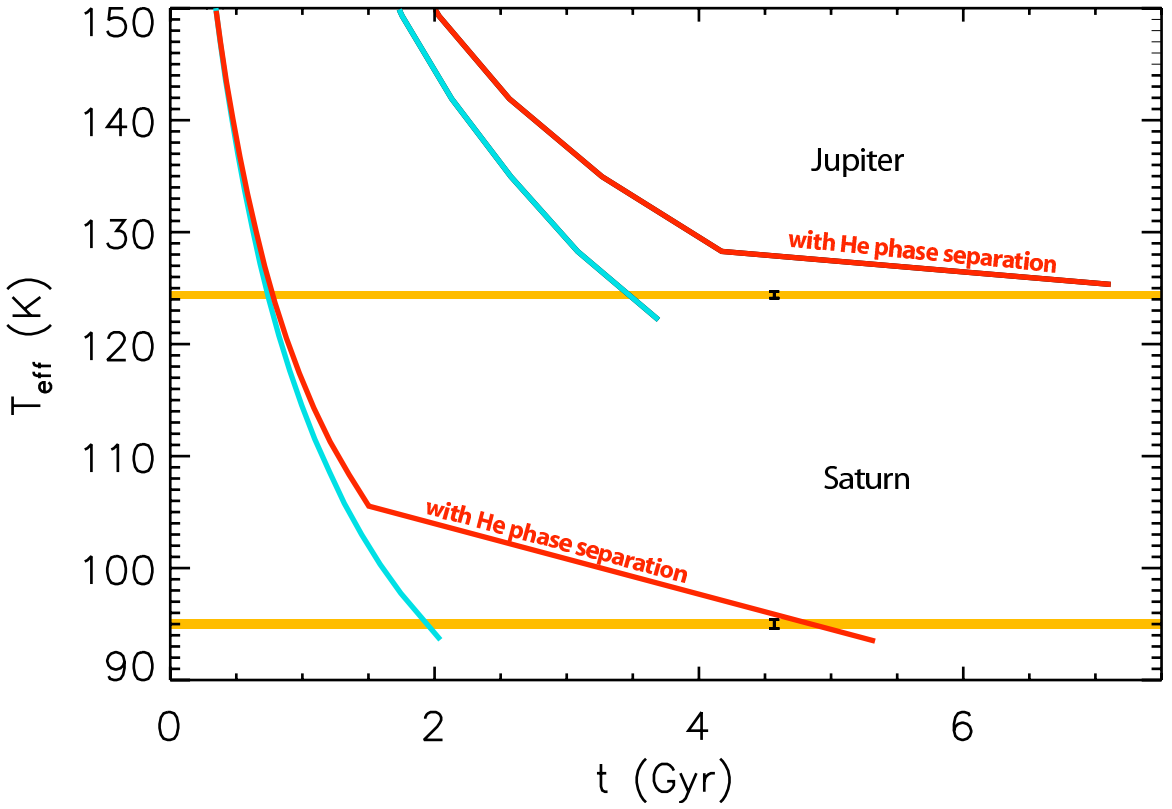
Saturn's evolution is controlled by the H/He phase separation but He atmospheric abundance is unknown

Understanding Saturn's evolution is important to understand the evolution of extrasolar giant planets



# Saturn's evolution and extrasolar planets

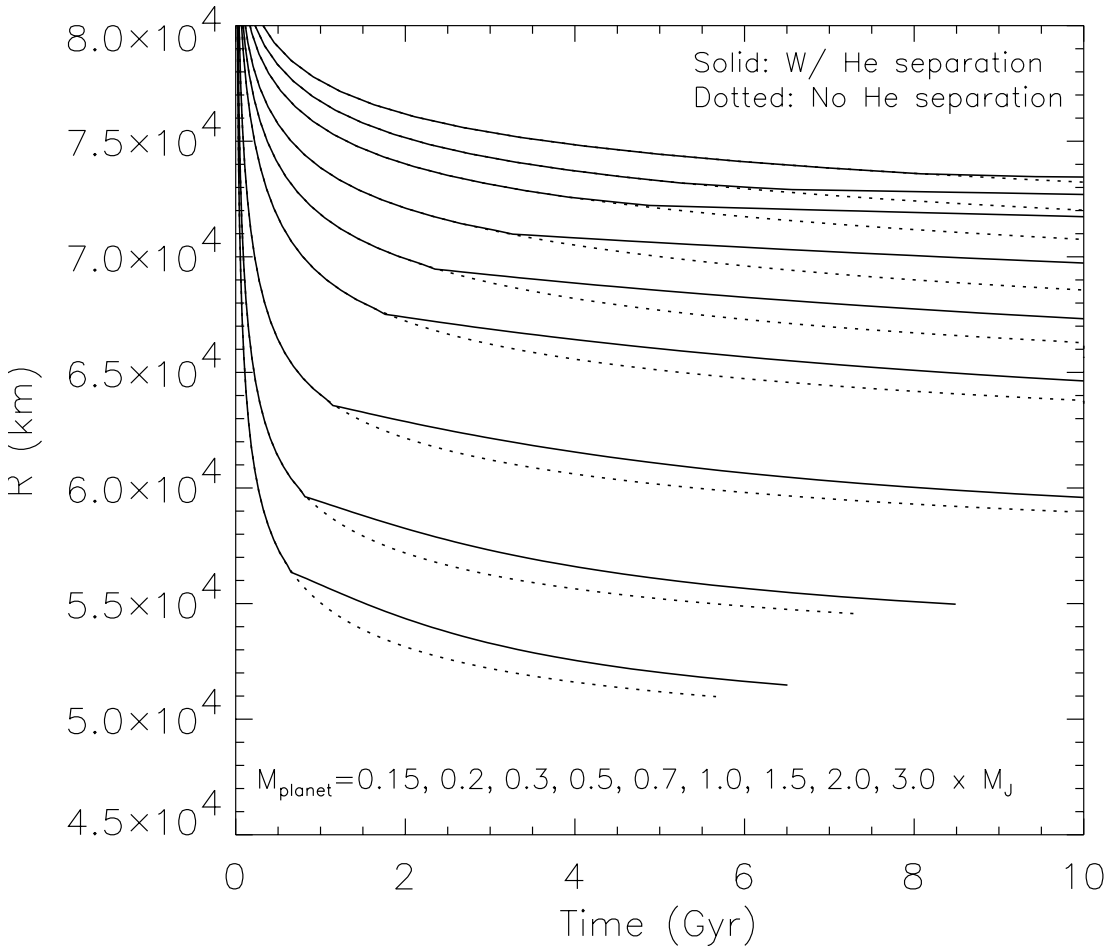
A better knowledge of Saturn's He abundance is primordial to understand its evolution, that of Jupiter and other giant planets




From Fortney & Hubbard 2003
Guillot & Gautier 2007

# Saturn's evolution and extrasolar planets

A better knowledge of Saturn's He abundance is primordial to understand its evolution, that of Jupiter and other giant planets




From Fortney & Hubbard 2003

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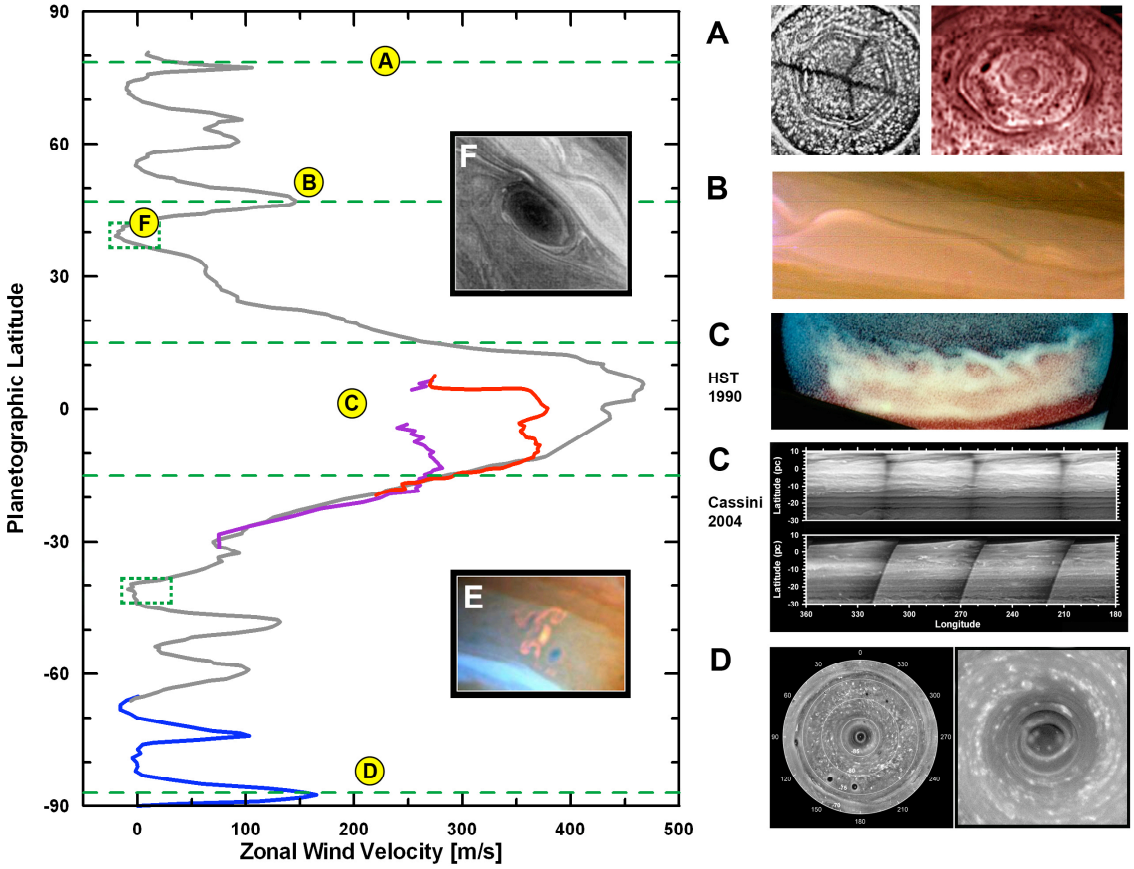
# Saturn's atmosphere

Saturn's atmosphere is characterized by strong seasonal variations

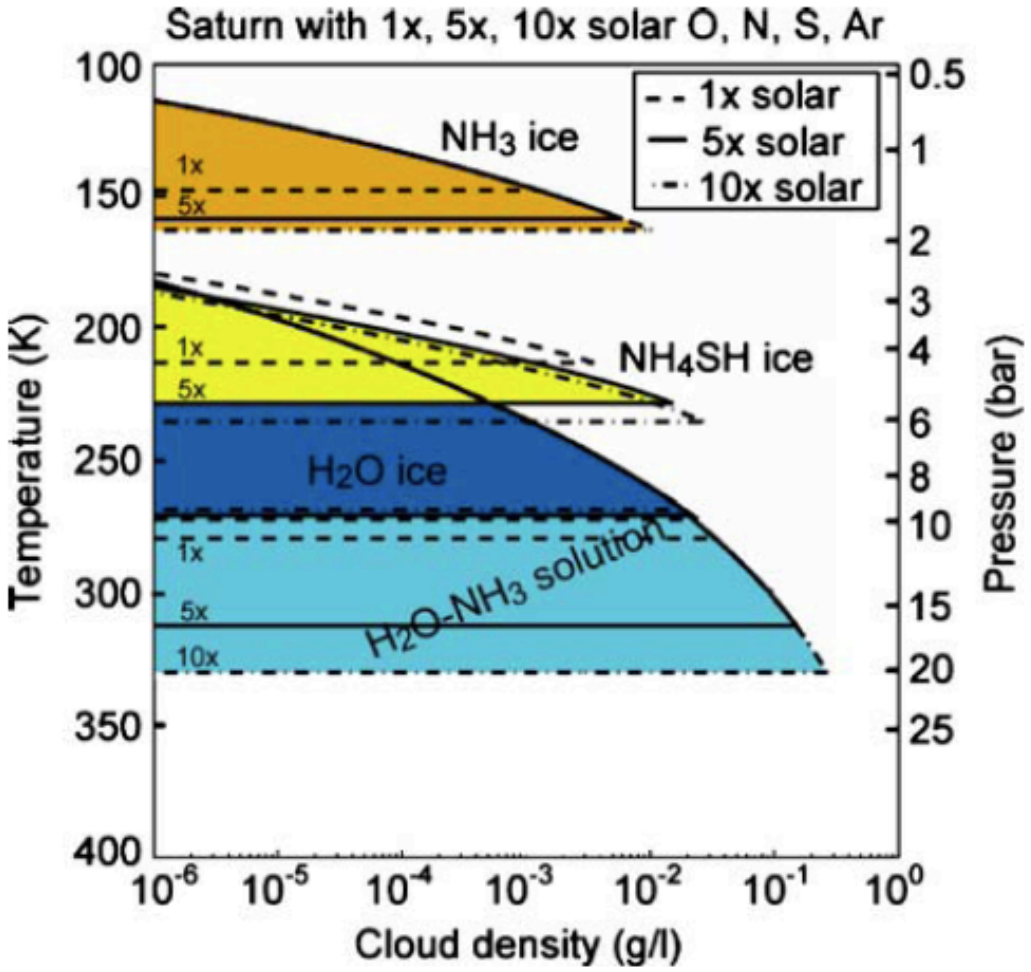
Unexplained variations in wind strength

Stroms are powered by unknown mechanisms

Complex cloud structure

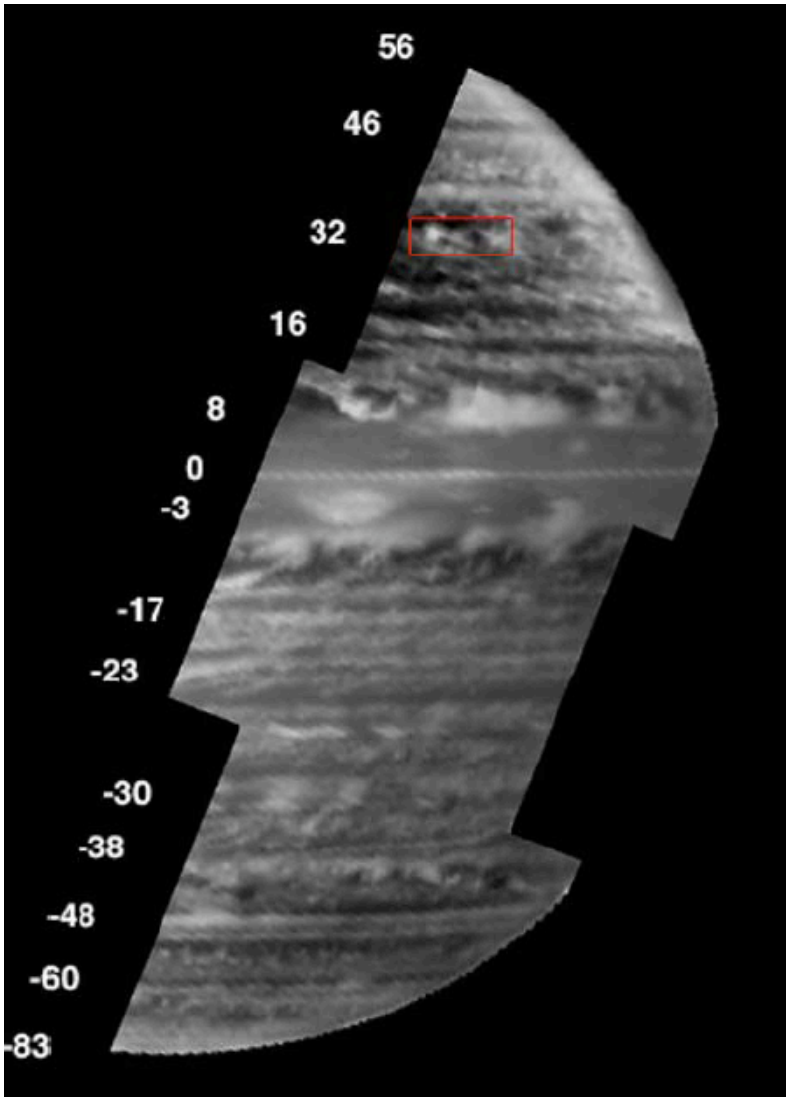


# Saturn's atmosphere: cloudy, hazy, fuzzy

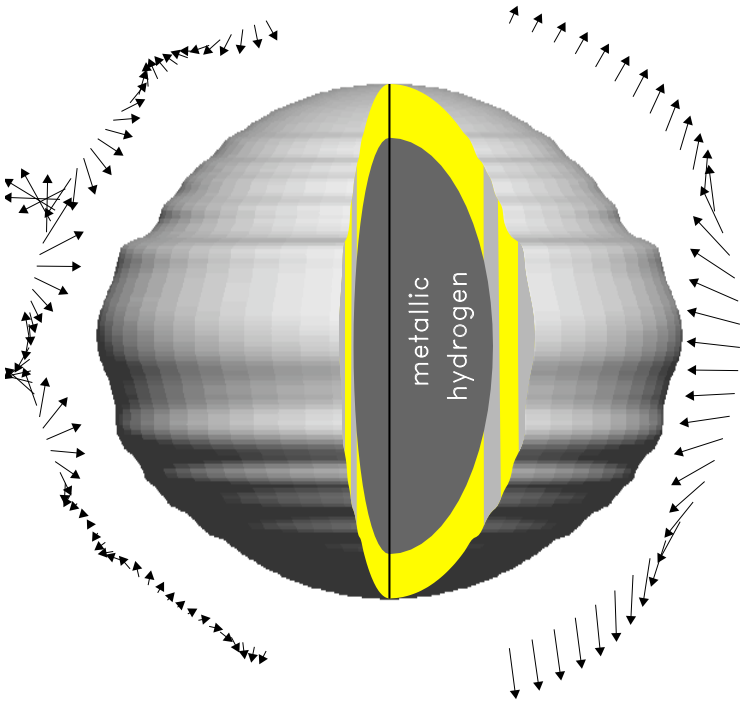


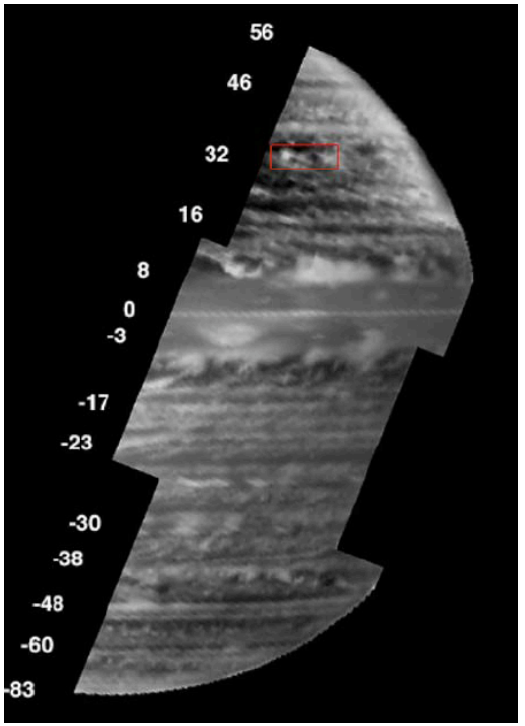
# Saturn's atmosphere: cloudy, hazy, fuzzy

**Fig. 6** Cassini VIMS image of Saturn at a wavelength of 5 μm [40, 41], showing cloud features and zonally banded structures at around 2–4 Bar. Here, the thermal image has been photometrically inverted to show high-opacity clouds as *white* and clearings in the deep cloud structure as *black*. This image mosaic reveals that, at depth, Saturn is an active, dynamic planet. *Bulky clouds near the equator* are likely convective in nature. At depth in mid and high latitudes Saturn exhibits a dense structure of alternating bands of clouds and clearings



# Saturn's atmosphere: jets




How to connect interior rotation to observed jets?

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# Saturn's magnetosphere

The characteristics of Saturn's inner magnetic field are still unknown

Axisymmetric magnetic field?

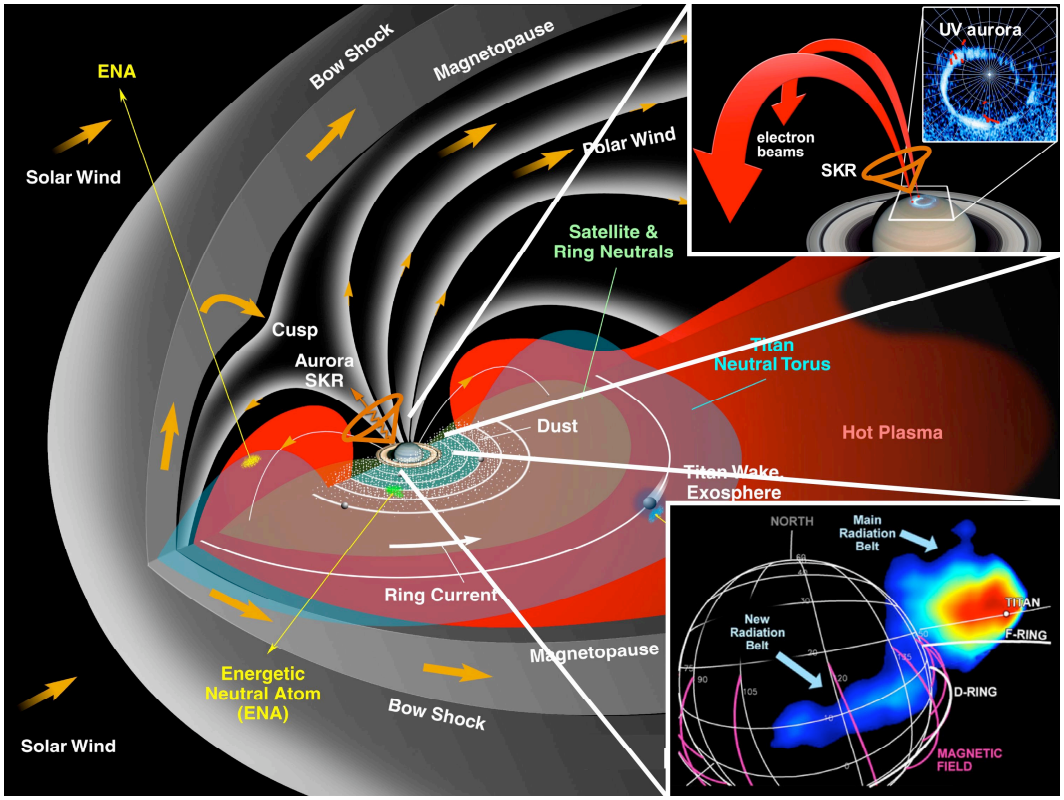
Rotation period?

Drifting signatures of the azimuthal field and kilometric radiation?

Magnetosphere-planet coupling?

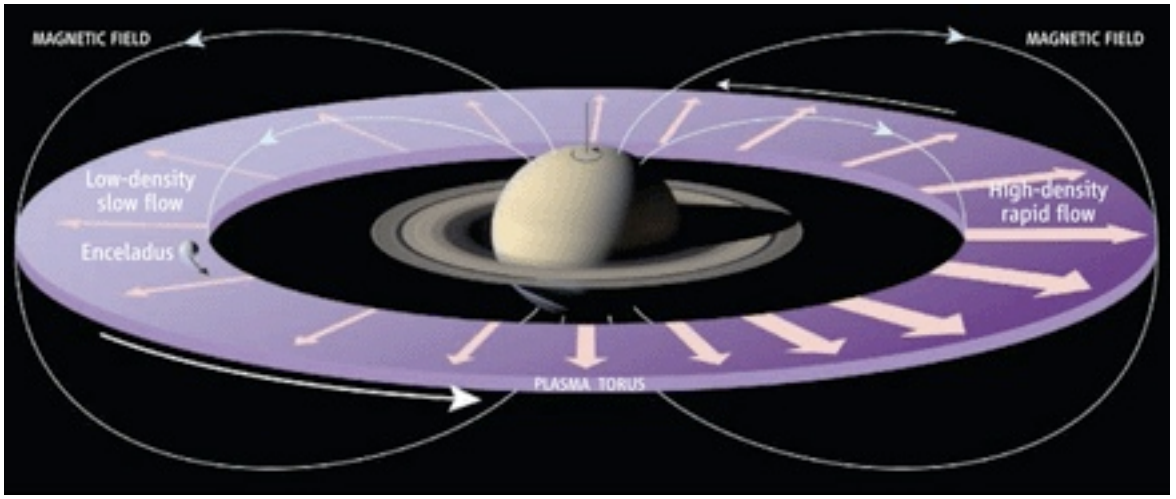
Inner radiation belt inside the D-ring?

-> Requires measurements inside the rings.

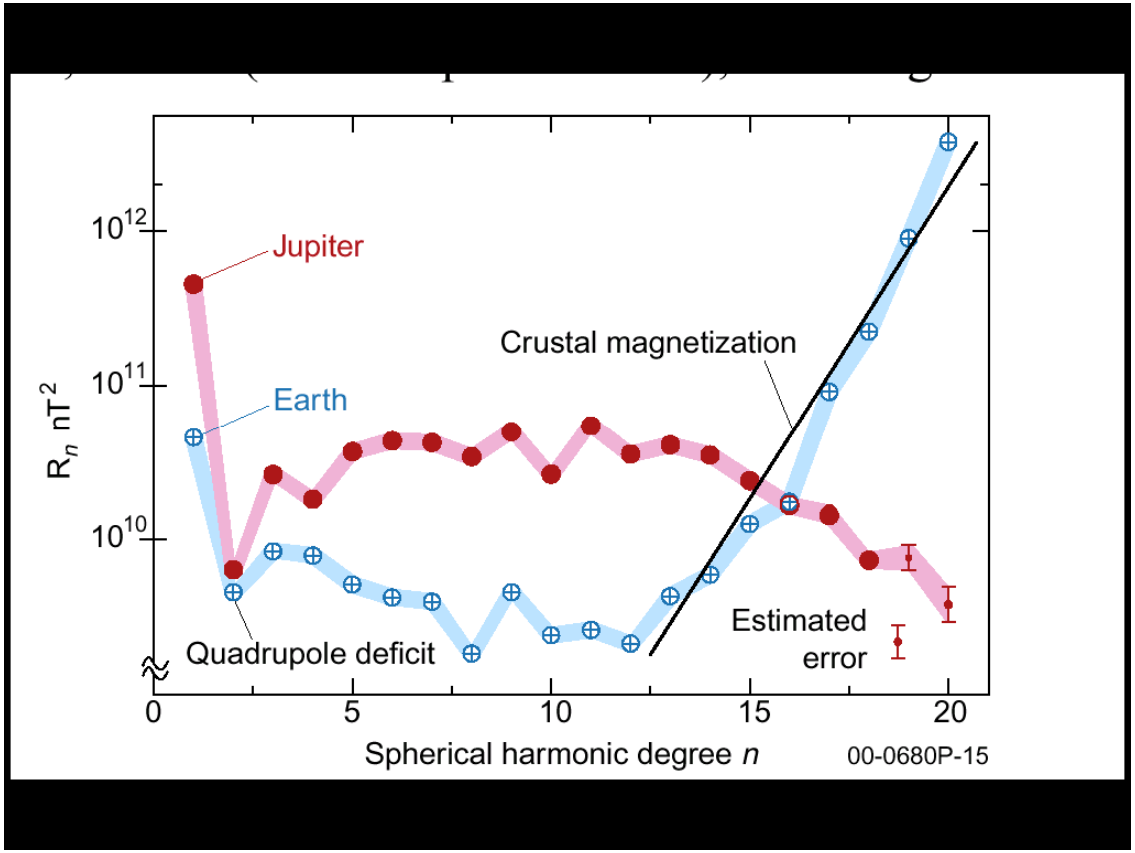


# Saturn's magnetic field and interior rotation rate

- Deep rotation rate determination is crucial for interior, atmospheric and magnetospheric science.



# Saturn's inner magnetic field: similar to Jupiter?



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# Saturn's rings

Origin?

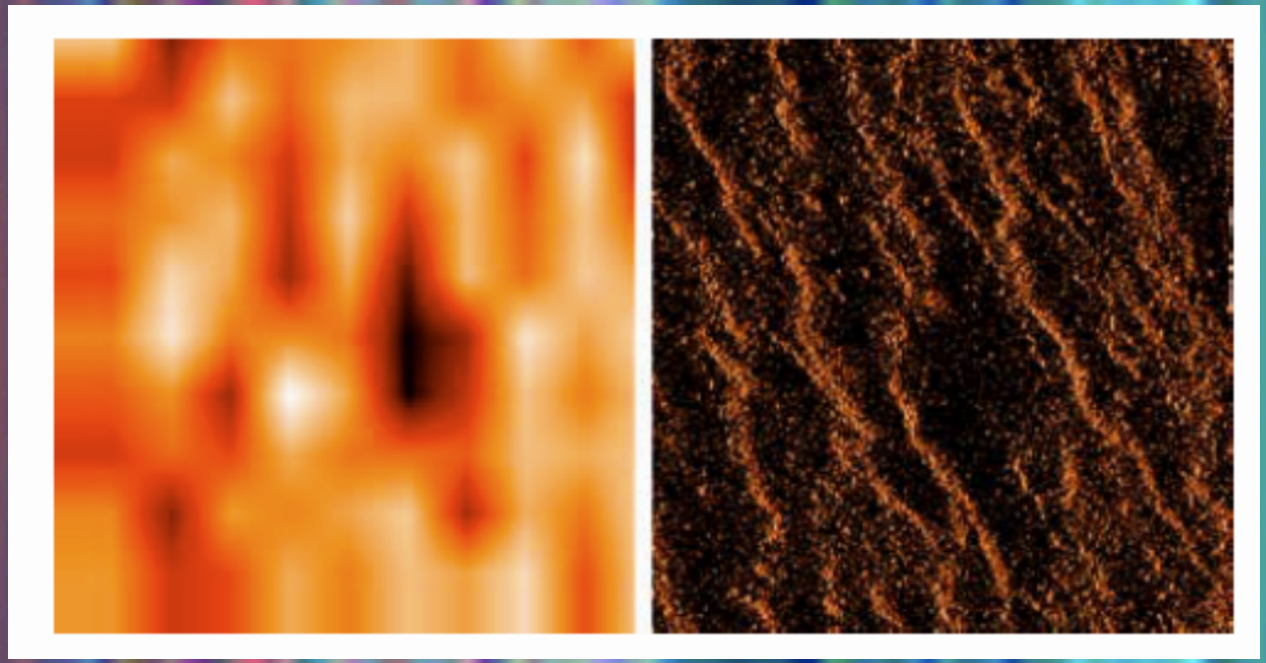
Mass?

Composition?

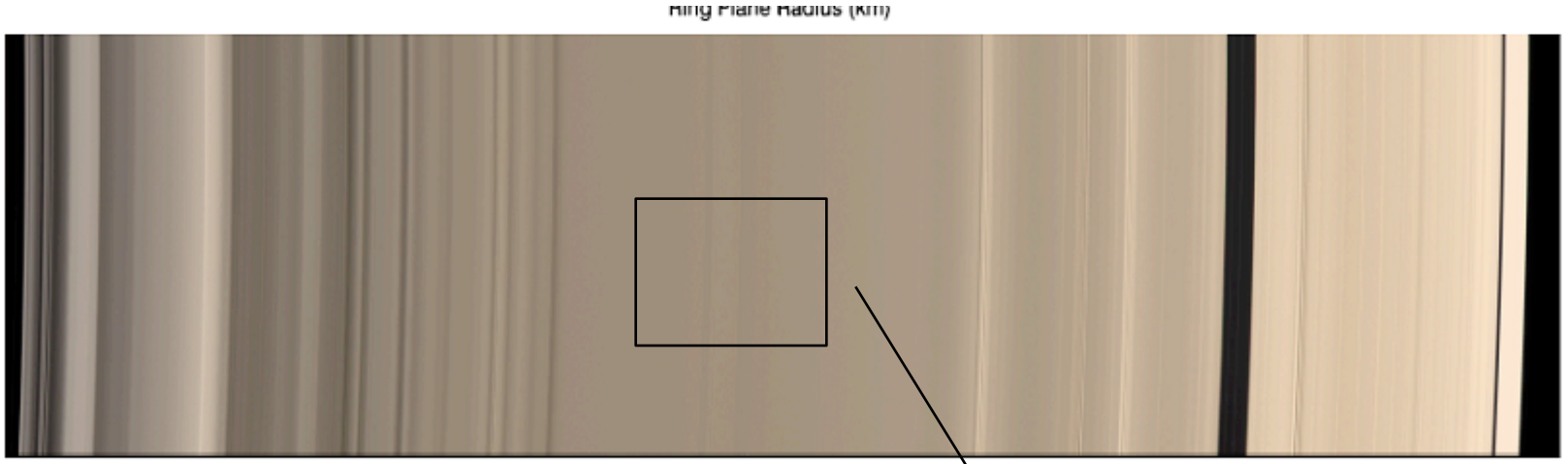
Microstructure?

Fate?

Frequency around other giant planets?



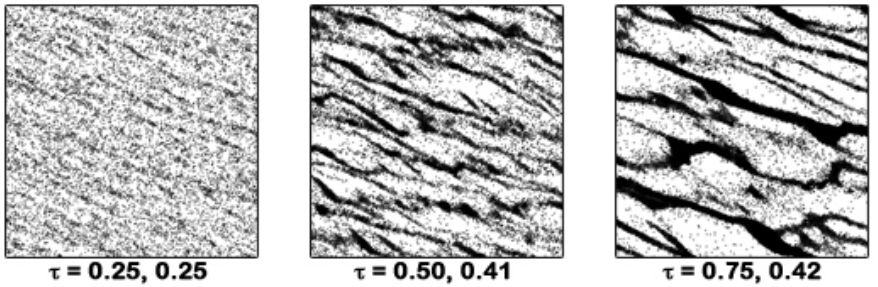
A ring : Gravity Wakes

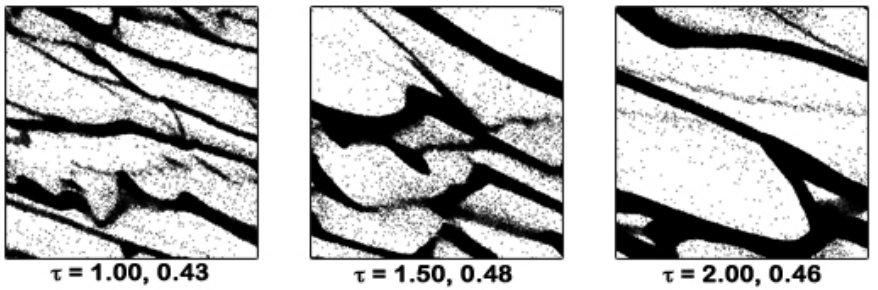


Wakes=Jeans-Toomre waves

Wavelength ~ 50-100 m

Direct imaging => 3D structure
Better constrains on ring surface
Density, mechanical properties
Of particles

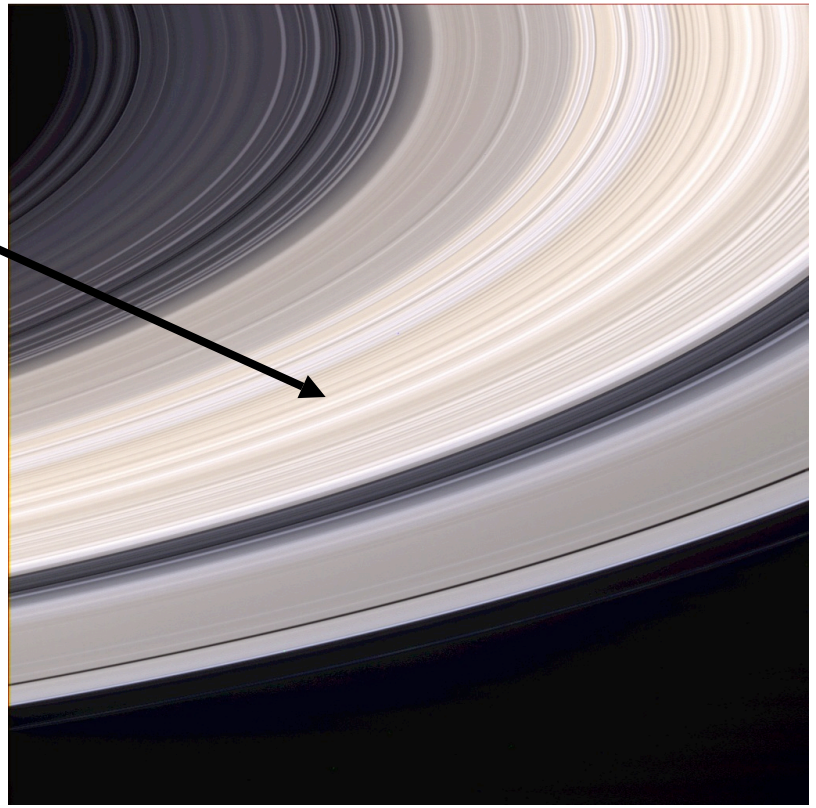


# Rings' Mass

Mass of the rings is poorly constrained , Order of Magnitude : Mimas mass

Most of mass : hidden in the dense B ring



BUT

B ring has too few density waves for measuring its surface density

A Flyby is needed to measure directly The rings' mass

Strong Implications on ring age and long term evolution.
(a high mass could explain why the rings are still bright/still exist)

# Mystery of silicates

Saturn rins seem made of nearly pure ice => very different from the average composition of satellites

INCOMPATIBLE WITH ANY FORMATION MODEL ….
(destruction of a satellite or a comet)

Are the silicates absent ?
Are the silicates hidden ?

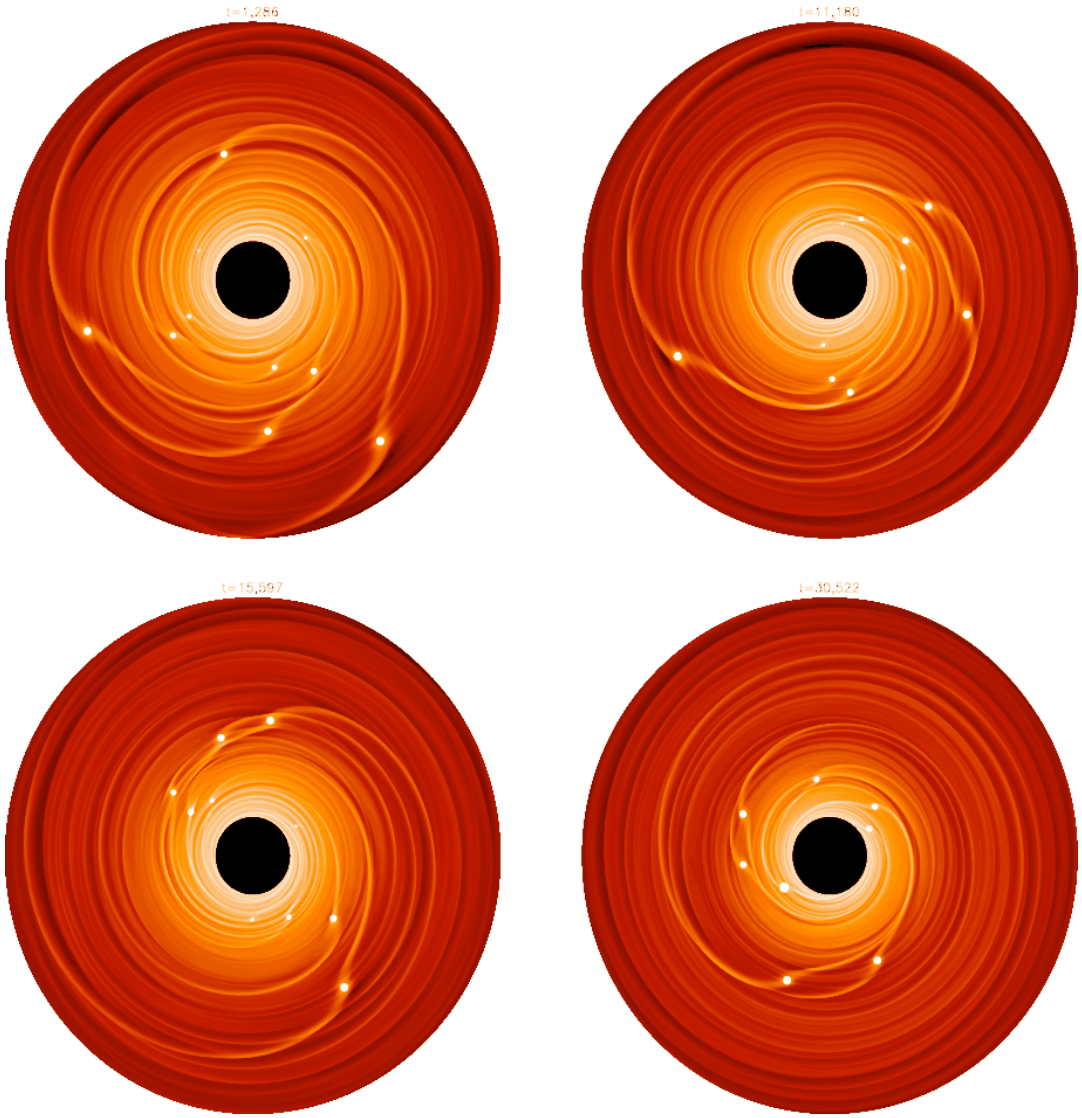
We do not know.

Strong implications on rings origin

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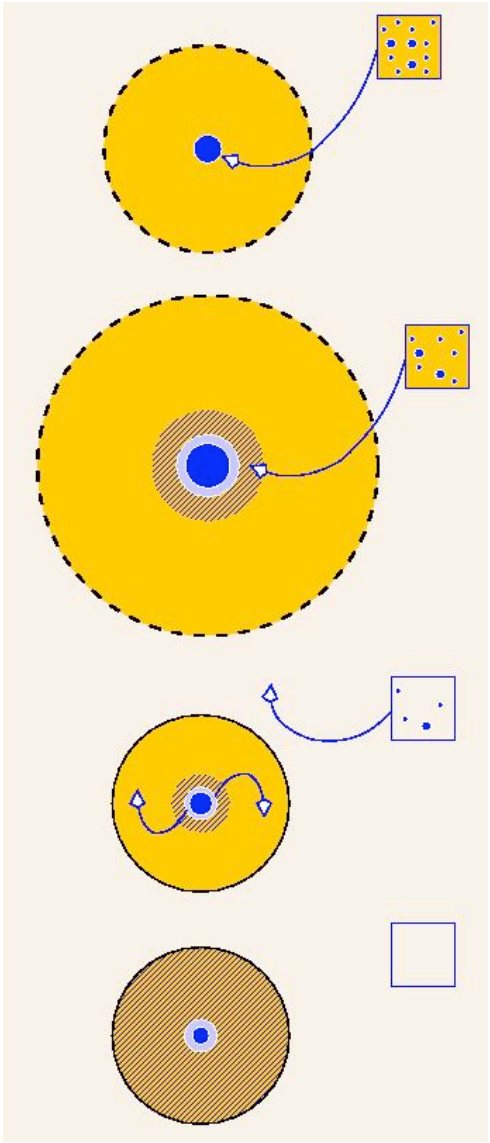
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# Where and when did Saturn form?



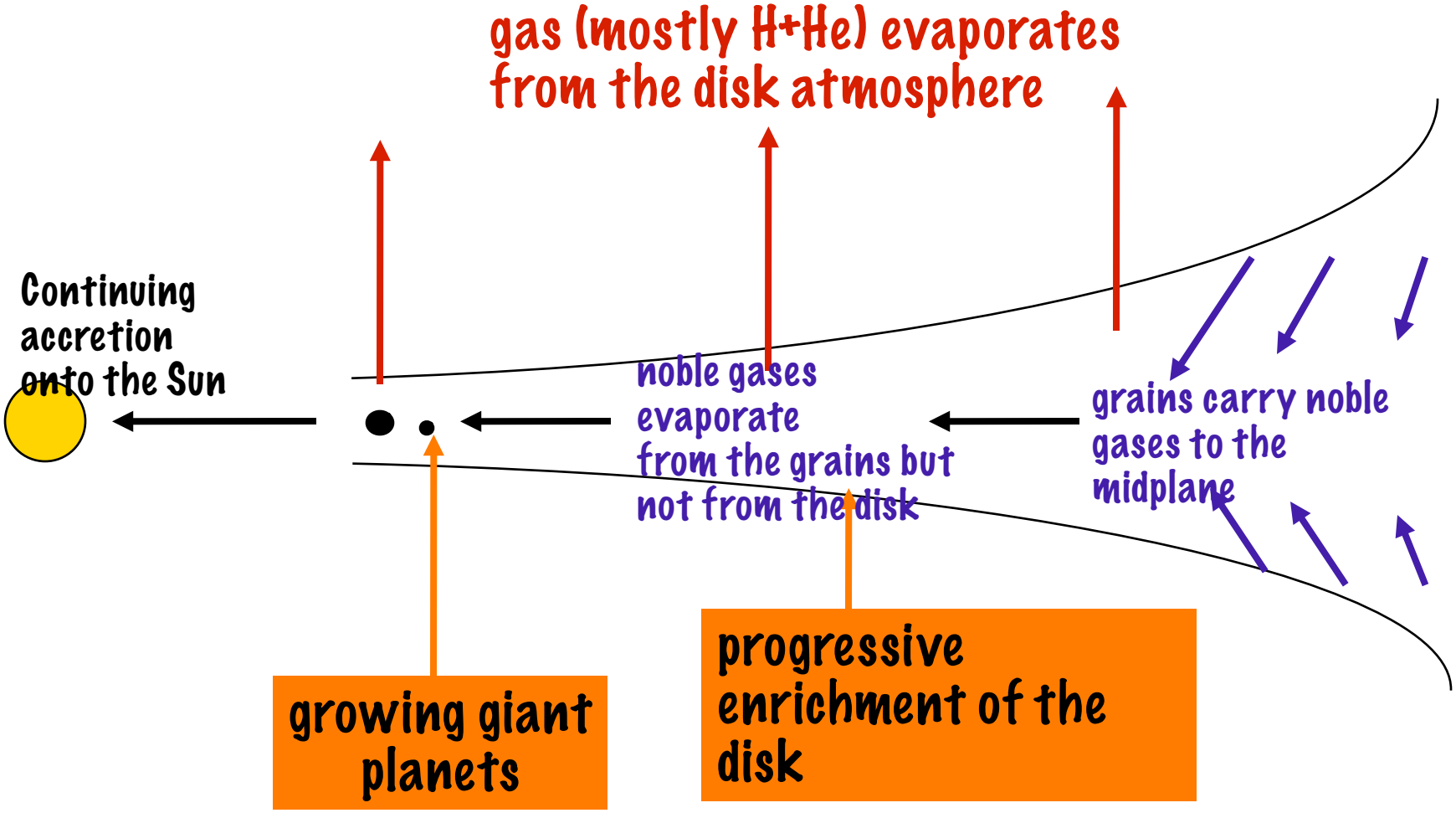

Cresswell & Nelson (2006)

# How are heavy elements delivered?



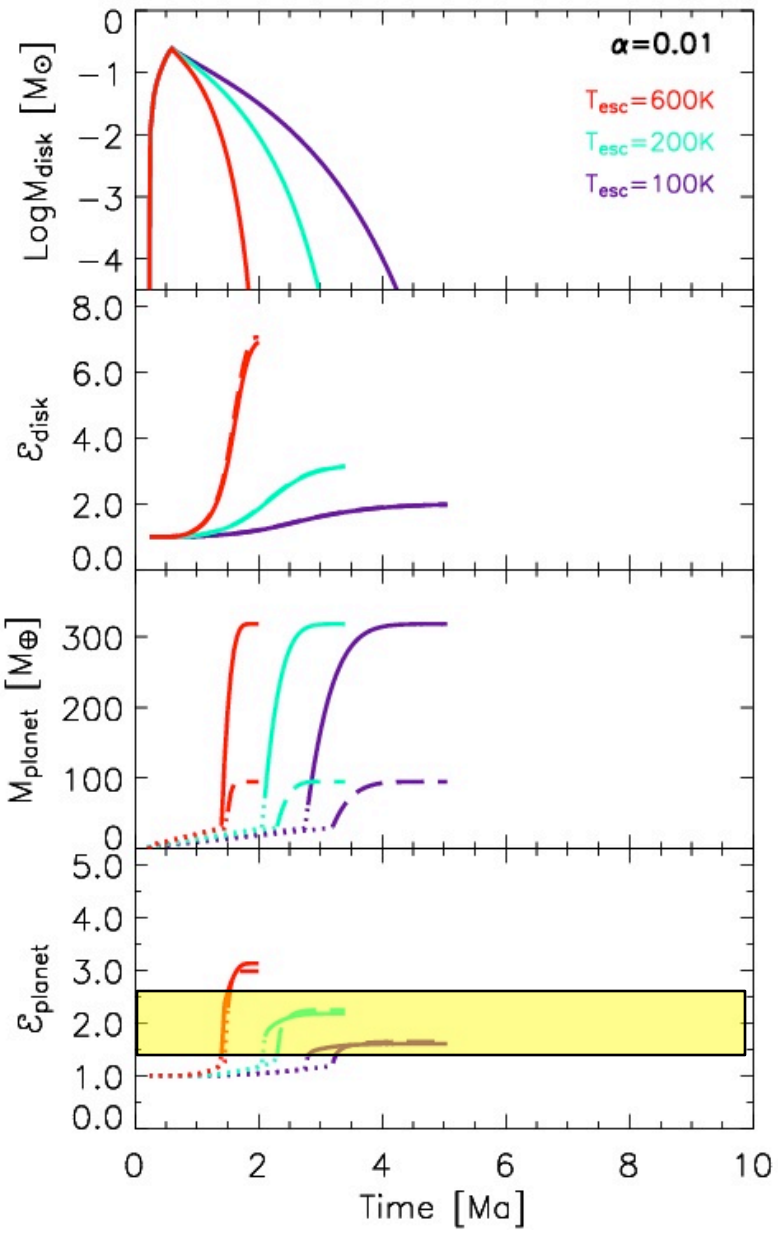
- Core accretion: planetesimals are delivered onto the central core.
- Core accretion: planetesimals cannot reach the core intact.
  - (Podolak et al. 1988; Pollack et al. 1996)
- Envelope capture:
  - accretion efficiency drops (Guillot & Gladman 2000)
  - Gap formation is easier & more pronounced for planetesimals (Tanaka & Ida 1997; Paardekooper 2007; Zhou & Lin)
  - Core may be progressively eroded (Guillot et al. 2004)
- Present: enriched atmospheres.

# Noble gases: A "Nice" model




Guillot & Hueso (2006)

# Noble gases: A "Nice" model




Disk mass

Disk enrichment

Planet mass

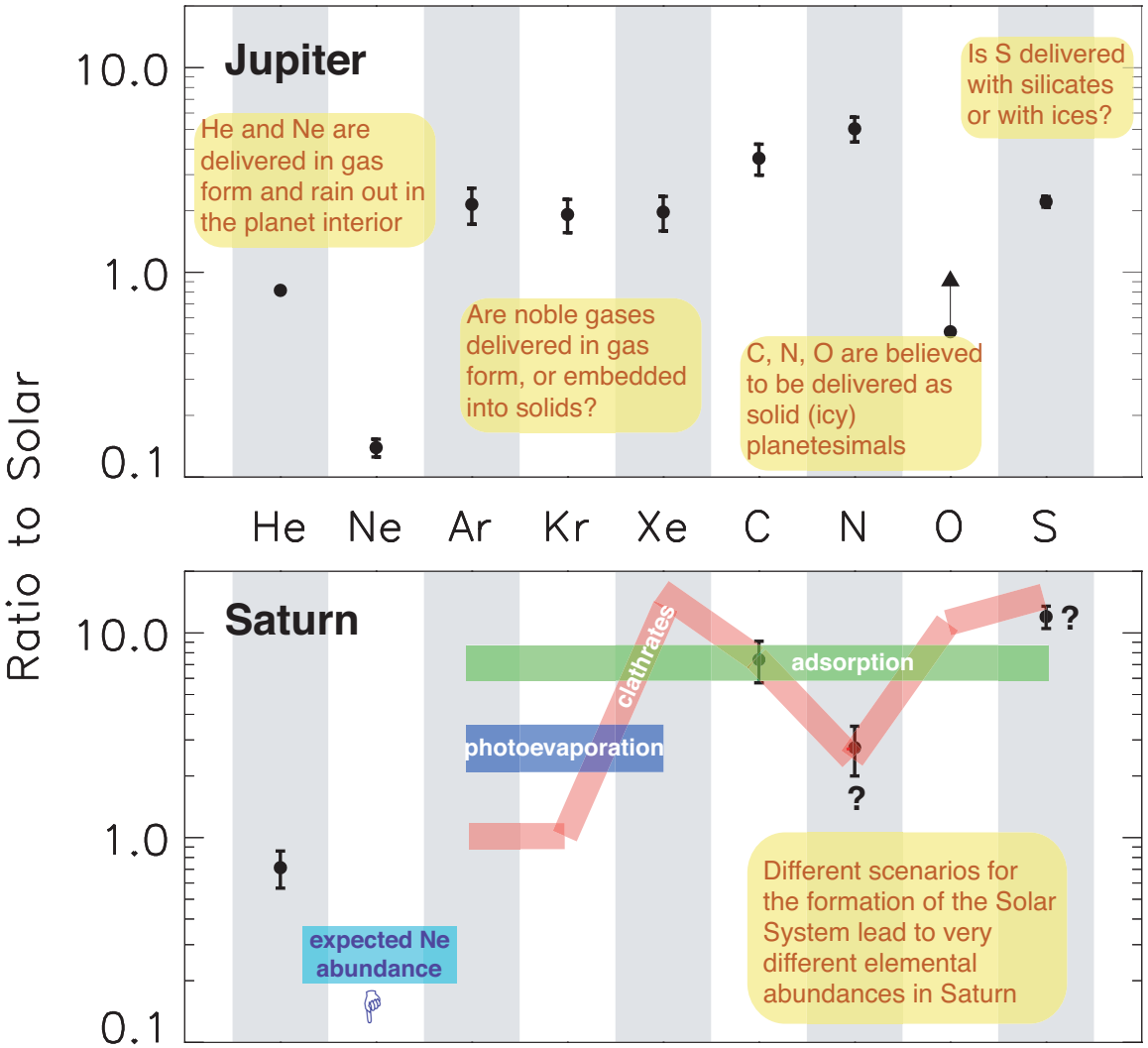
Planet enrichment
Jupiter: plain
Saturn: dashed

Guillot & Hueso (2006)

# Saturn & the formation of the Solar System

Did Saturn form with Jupiter, after?

Saturn's composition and its comparison to Jupiter is key to understand processes that occurred in the early Solar System (clathration, photoevaporation...)

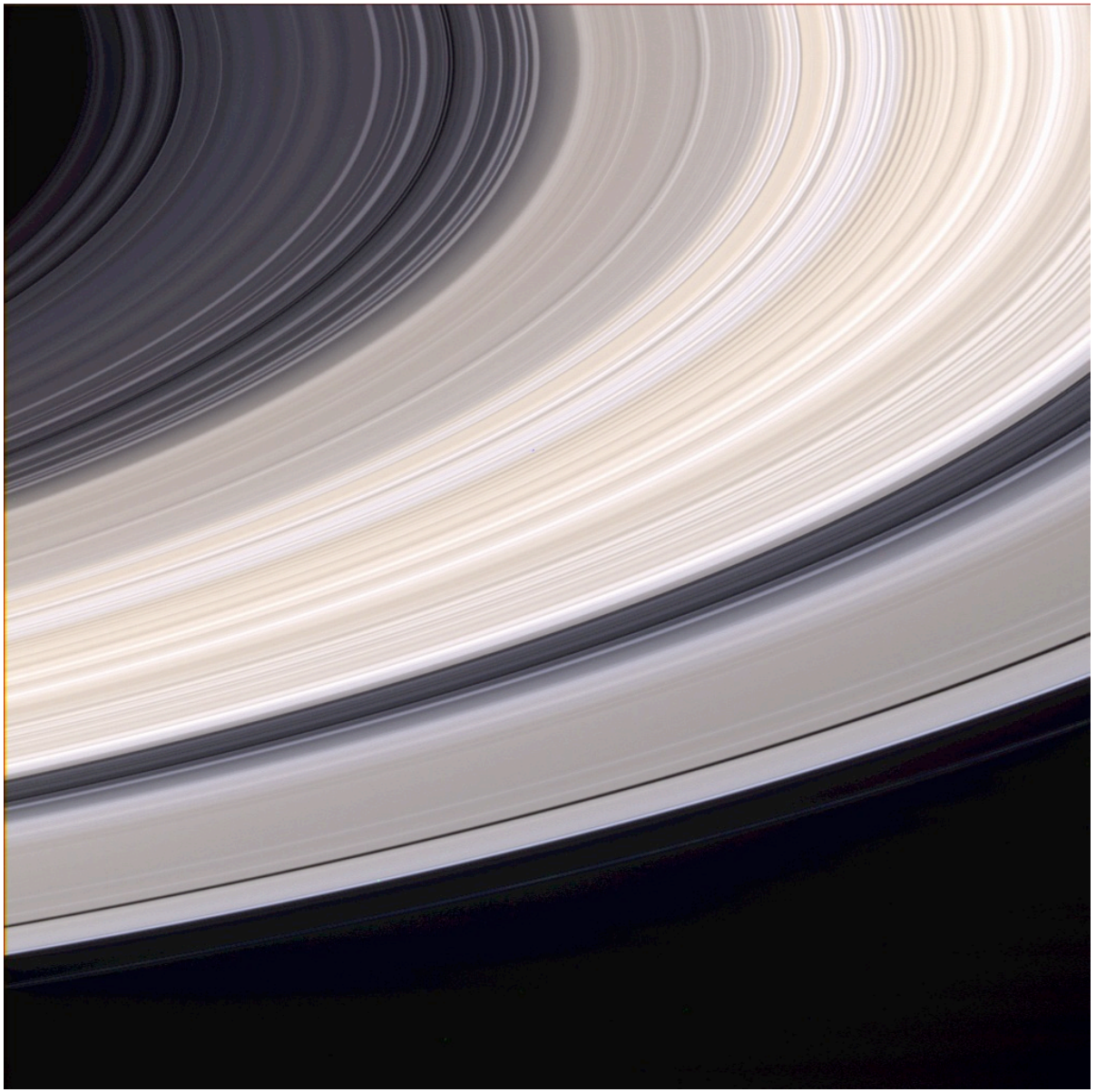



**Models:** Hersant, Gautier et al. (2001, 2007); Encrenaz & Owen (2006); Guillot & Hueso (2006)

# Rings:

When were they formed?

-During the late heavy bombardment (3.7 Gyrs ago)?
    -(work by Charnoz & Morbidelli)



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# The context: Juno

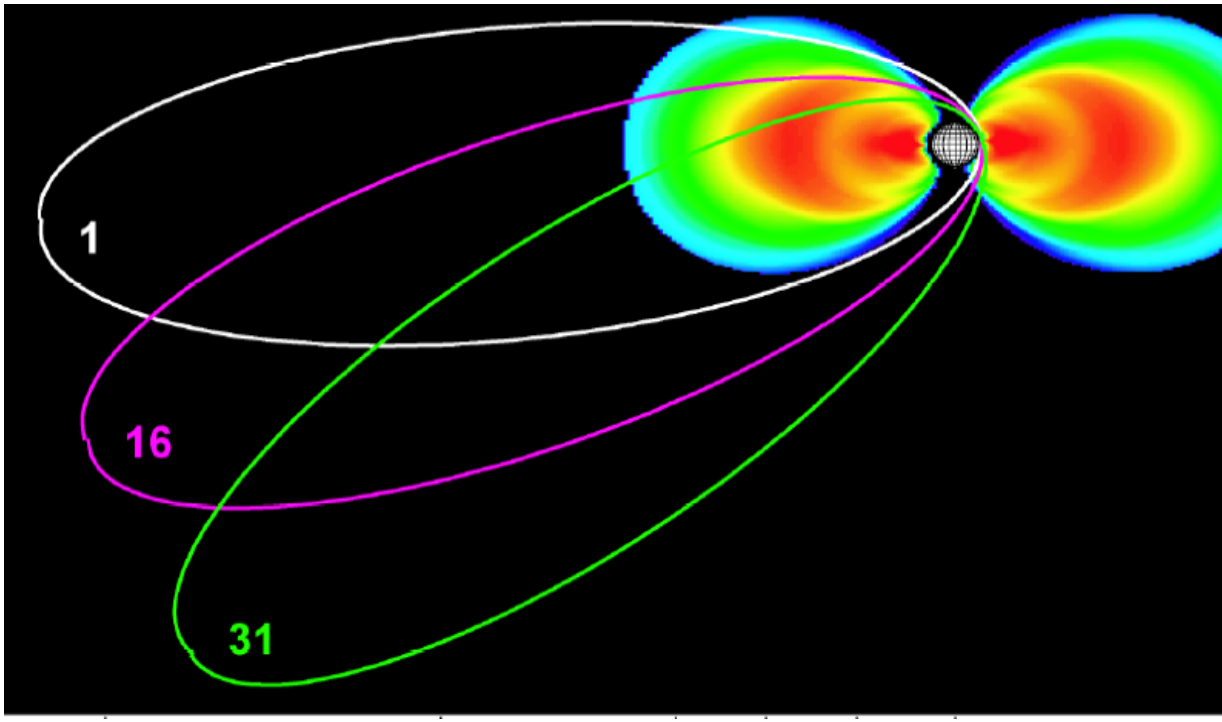
**Passed NASA SMD confirmation**

**Launch: August 2011**

**5 year cruise**

**Baseline mission:**

- 32 polar orbits
- Perijove ~5000 km
- 11 day period
- Spinner
- Solar-powered




**Science Objectives:**

- **Origin of Jupiter**
- **Interior Structure**
- **Atmosphere Composition & Dynamics**
- **Polar Magnetosphere**

# Flyby

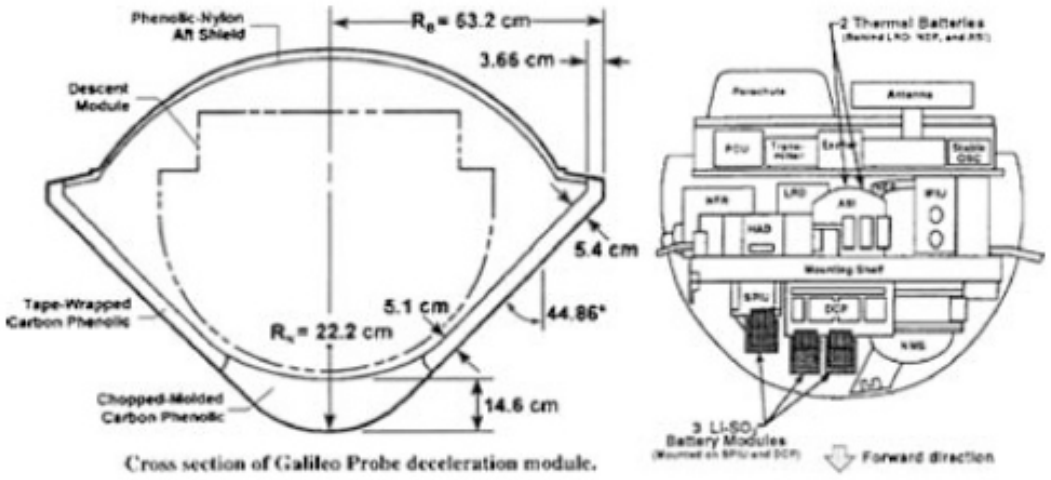
- Ability to measure high order gravitational moments
- Magnetic field measurement
- Global H2O, NH3 composition (microwave)

# Orbiter

- Gravity field measurement. Include time variability
- Magnetic field measurement. Include time variability
- Motinoring of activity
- Global composition (microwave)

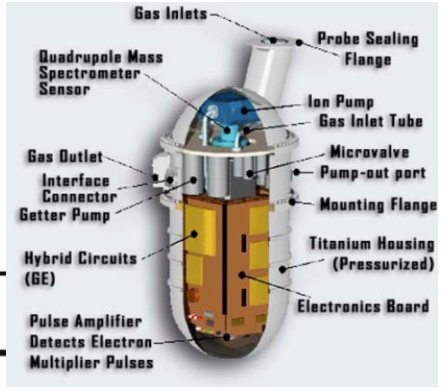
# Probes

- Accurate measurement of atmospheric composition (including minor species)
- Do not need deep probes: ~10 bars is sufficient
- Temperature-pressure profiles
- Several probes (2) are better because of spatial variability



Cross section of Galileo Probe deceleration module.

# Probes: mass spectrometer




| Species | Consequence |
|---|---|
| He | Determine extent of helium sedimentation in Saturn's interior. Crucial for accurate understanding of the thermal evolutions of Saturn and Jupiter |
| Ne | Test prediction of Ne capture in He droplets. Refine H–He phase separation diagram |
| $CH_4$ | Fine determination crucial to understand the formation of the planet |
| $NH_3$ $NH_4SH$ | Key to decide between models of planetesimal delivery and planet formation. Important for Saturn's meteorology |
| $H_2S$ $NH_4SH$ | Key for planetesimal delivery, with possibility that the abundance is linked to that of rocks deep inside. Important for Saturn's meteorology |
| $H_2O$ | (by radiometry); Key to understand the planet's structure, formation, and meteorology |
| Ar, Kr, Xe | Key to decide between models of planetesimal delivery and planet formation. Link with the compositions of the Sun and protosolar disk |
| CO, $PH_3$, $AsH_3$, $GeH_4$ | Disequilibrium species are important to understand convection in Saturn's deep atmosphere. Help to further test planetesimal delivery models |
| D/H | Test models that predict it should be similar to Jupiter and to the protosolar value |
| $^{12}C/^{13}C$ | Test models that predict value similar to Earth |
| $^{14}N/^{15}N$ | Important to understand whether N was delivered as $N_2$ or as $NH_3$. Test models of planetesimals delivery |
| $^{20}Ne/^{22}Ne$ | Origin of gas, Test evaporation processes in the early solar system |
| $^{36}Ar/^{38}Ar$ Kr, Xe isotopes | Origin of gas, Test evaporation processes of these gases in planetesimals |

# Microprobes

- Hi-resolution imaging of the rings
- Altitude need to be <8000km to be better than Cassini
- Maximum scientific return for altitudes <100km

| Time before impact (or ring-plane crossing) | Altitude above rings (km) | Resolution (m/pixel) | Science Objective |
|---|---|---|---|
| −1 h 9 min 21 s | 2,000 | 10 | Microstructure/aggregates |
| −6 min 56 s | 200 | 1 | Ring thickness |
| −41 s | 20 | 0.1 | Particle size distribution |

# Observation from spaced-based & ground based multi-purpose instruments

- Atmospheric composition (major species)
- Monitoring of activity

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# Conclusion:
# critical measurements to be done at Saturn

- Deep water abundance
- Atmospheric composition (noble gases...)
- Saturn's "true" magnetic field
- Saturn's high order gravity field & deep rotation
- Link atmospheric features to compositional variations
- High spatial resolution images of the rings