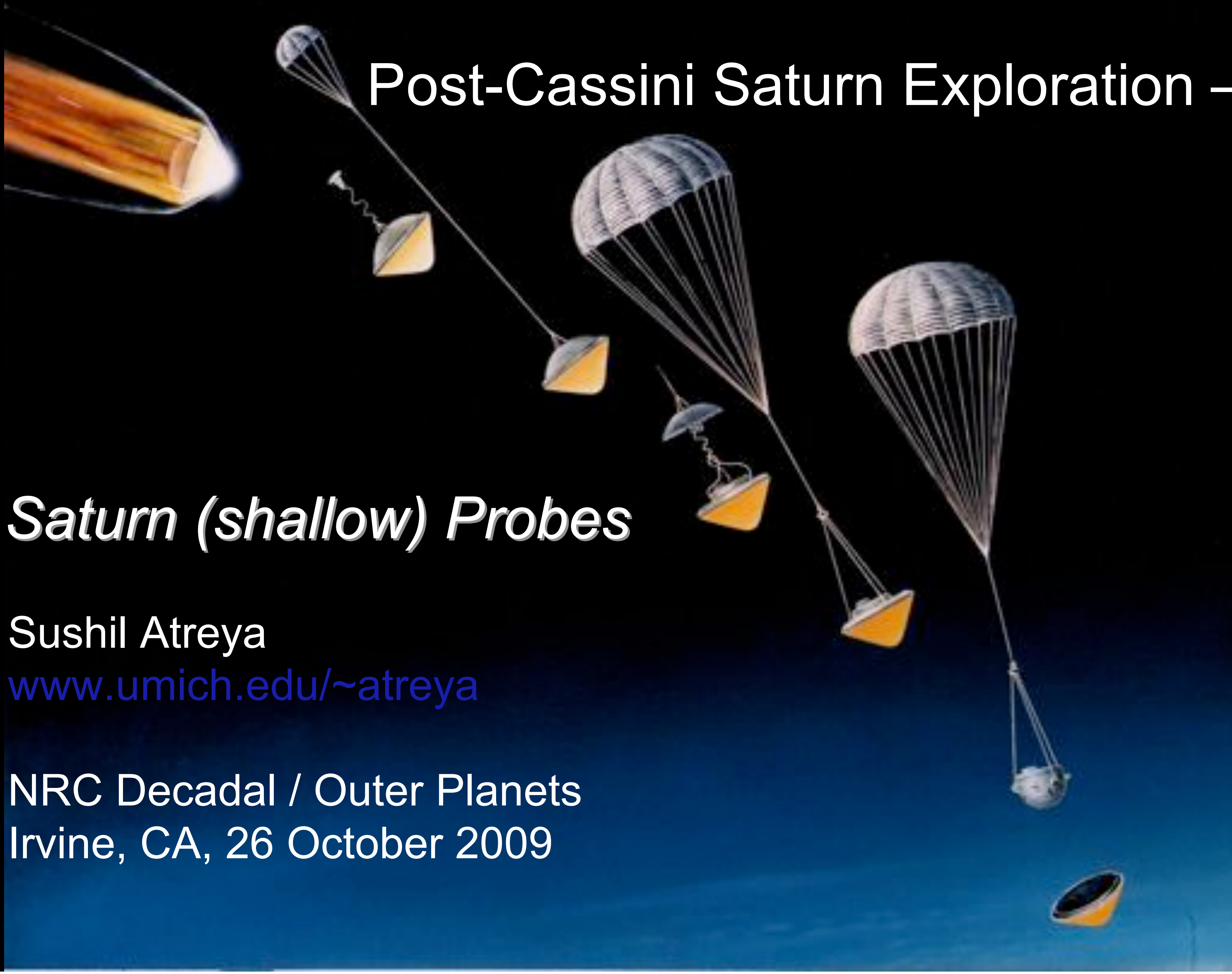
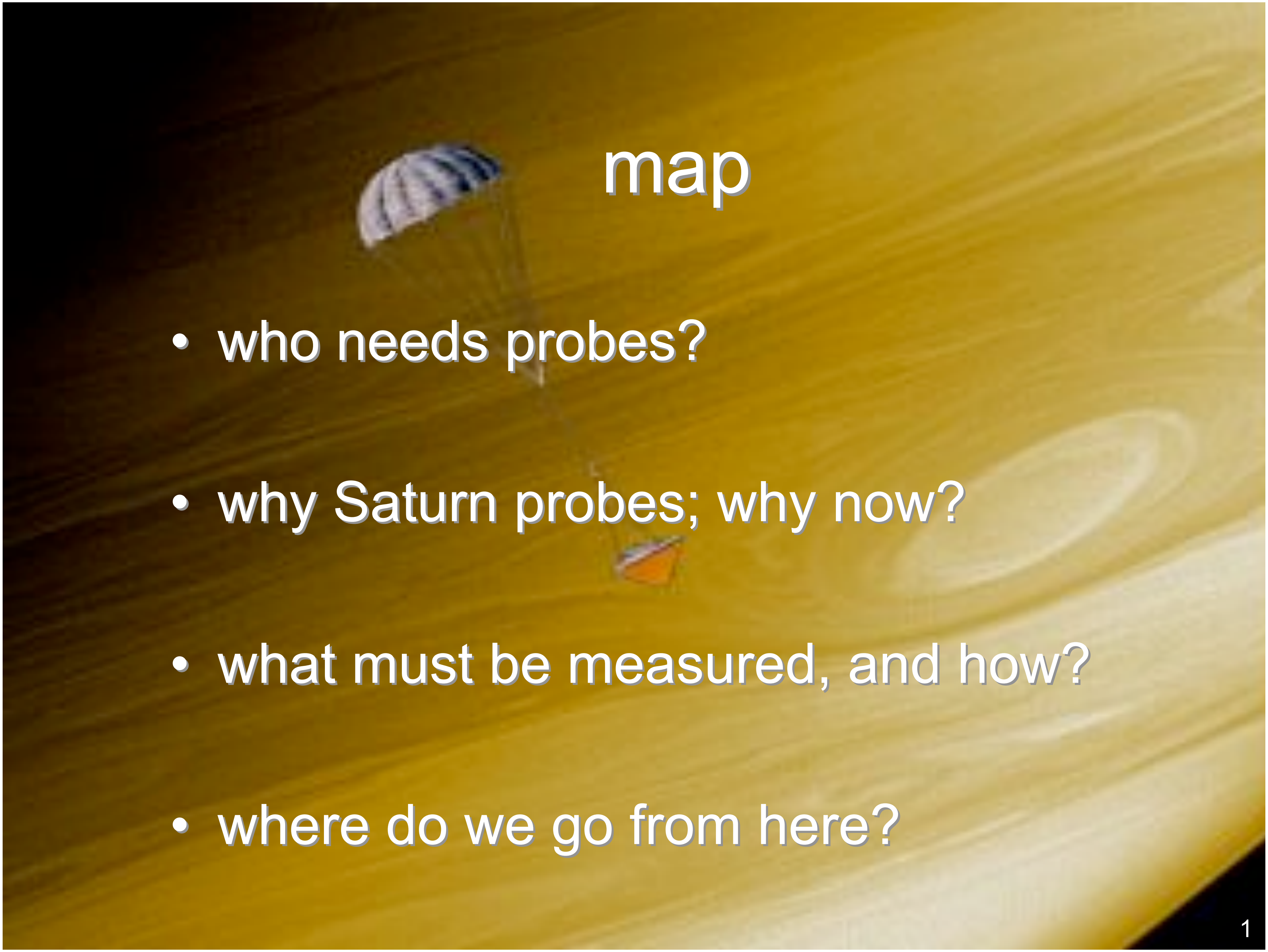


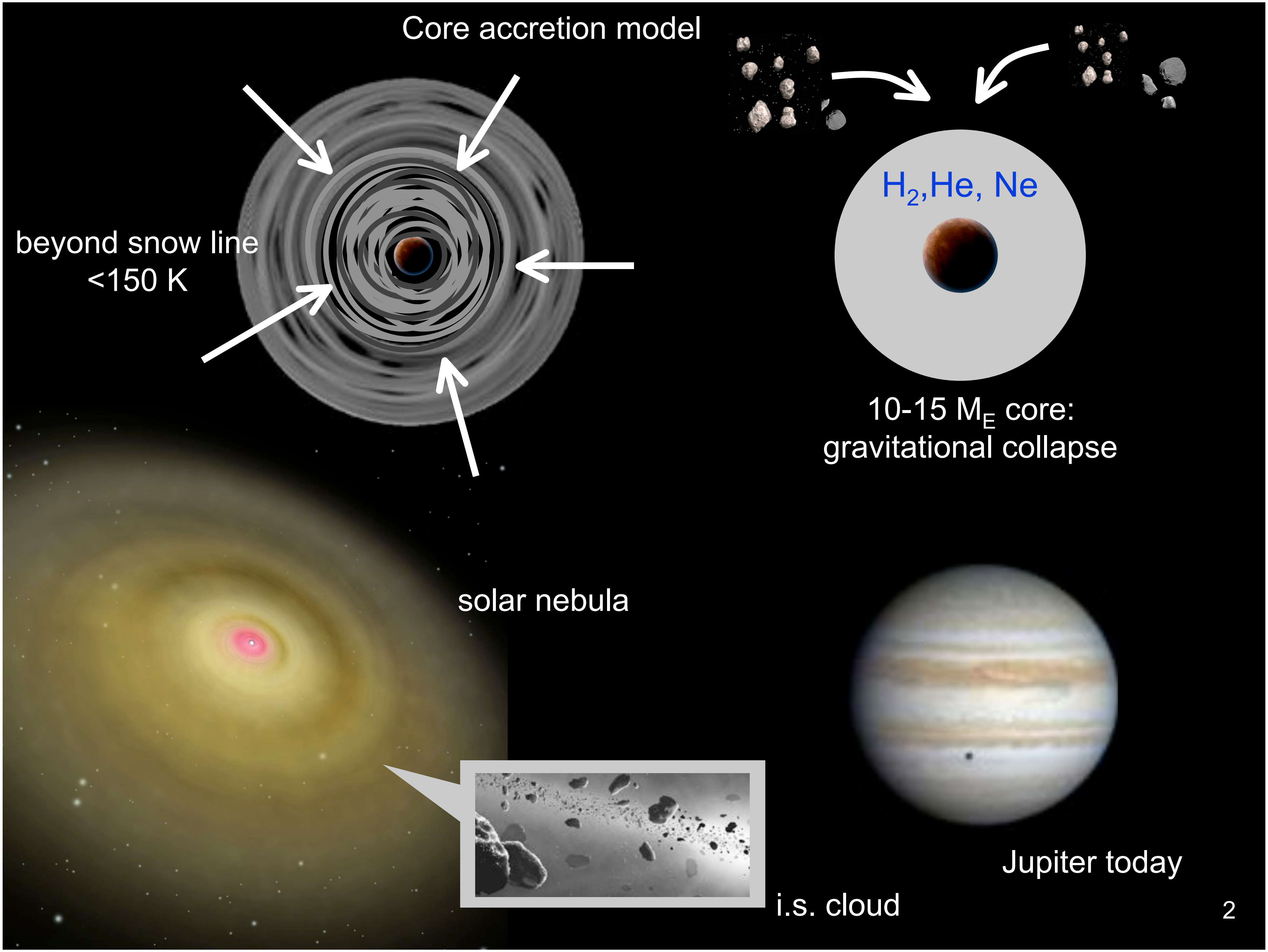
# Post-Cassini Saturn Exploration –

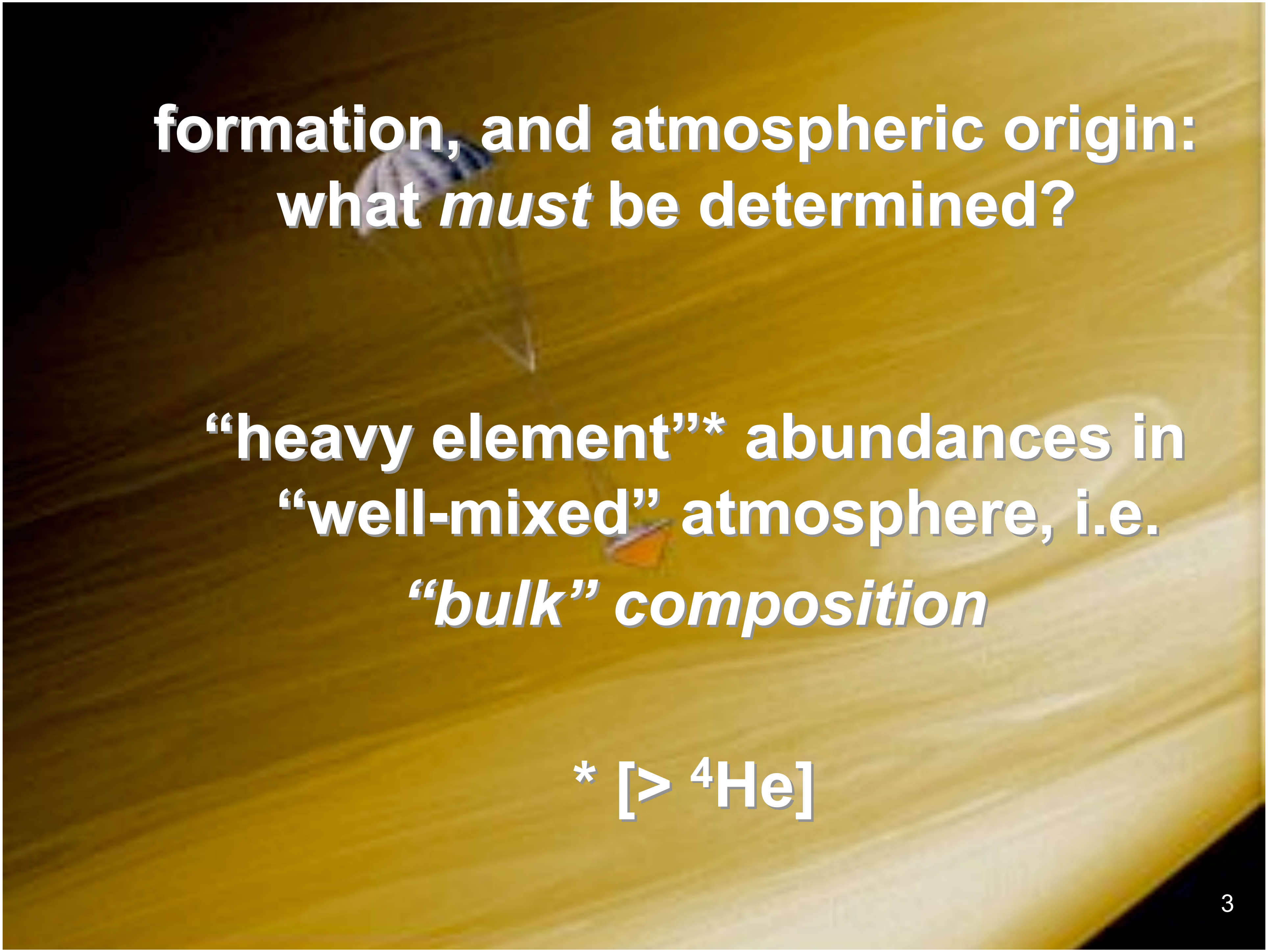
## *Saturn (shallow) Probes*


Sushil Atreya
www.umich.edu/~atreya


NRC Decadal / Outer Planets
Irvine, CA, 26 October 2009

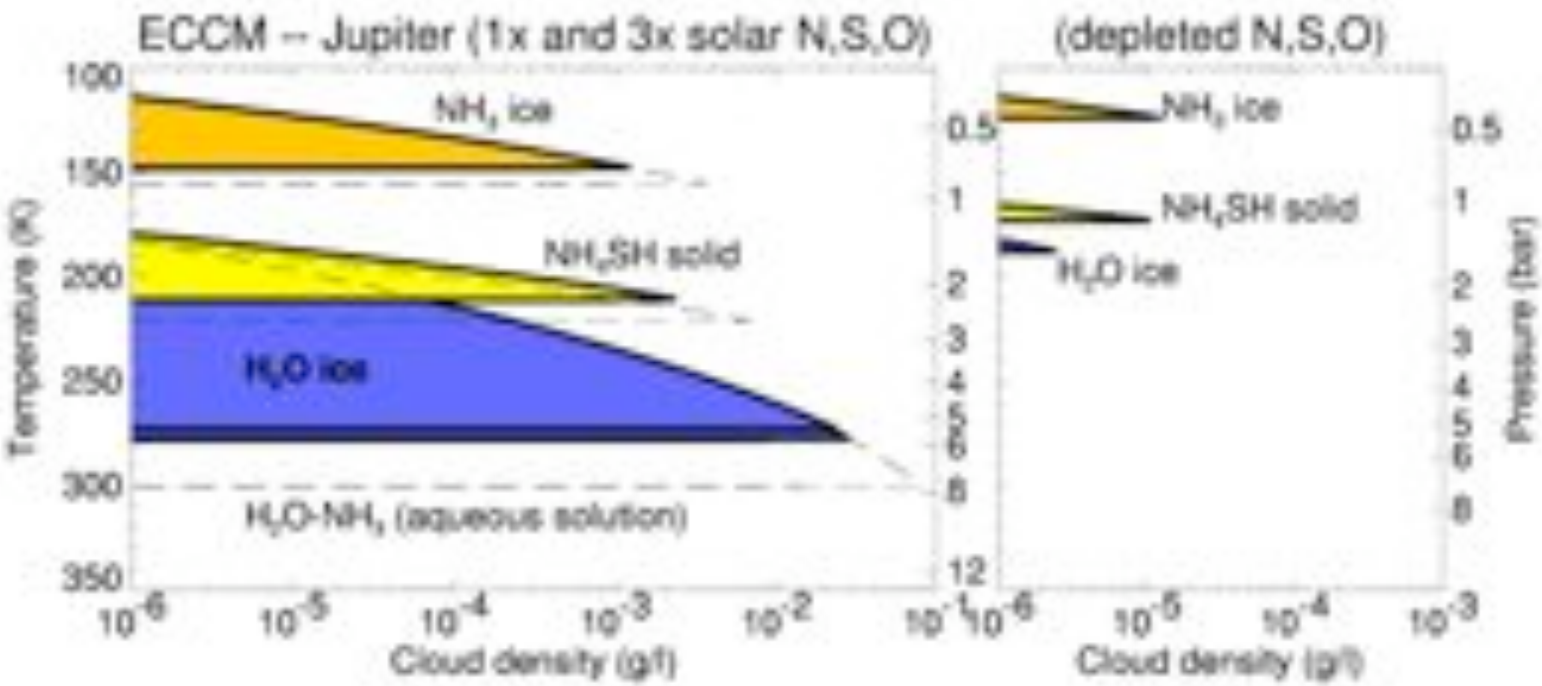

map
who needs probes?
why Saturn probes; why now?
what must be measured, and how?
where do we go from here?
1


Core accretion model
beyond snow line
<150 K
$H_2$,He, Ne
10-15 $M_E$ core:
gravitational collapse
solar nebula
Jupiter today
i.s. cloud
2


formation, and atmospheric origin:
what *must* be determined?
"heavy element"* abundances in "well-mixed" atmosphere, i.e.
*"bulk" composition*
* [> $^{4}$He]


*Jupiter fools Galileo…*

# Jupiter clouds



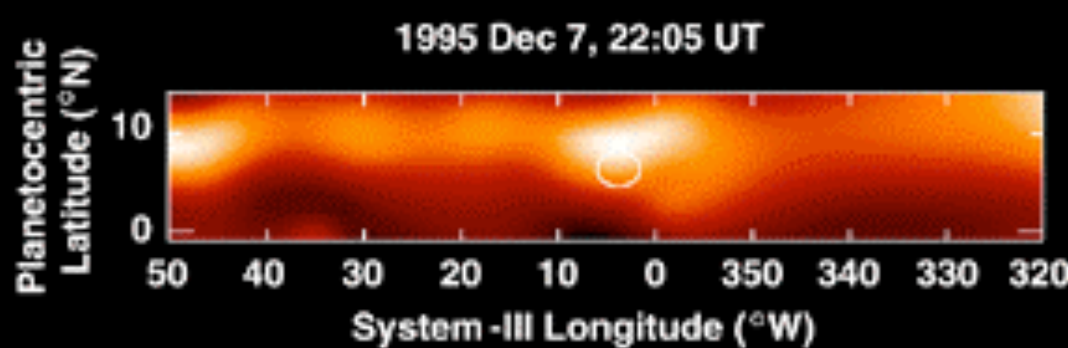

**Equilibrium** **Hot Spot**

(Atreya et al., 1999)

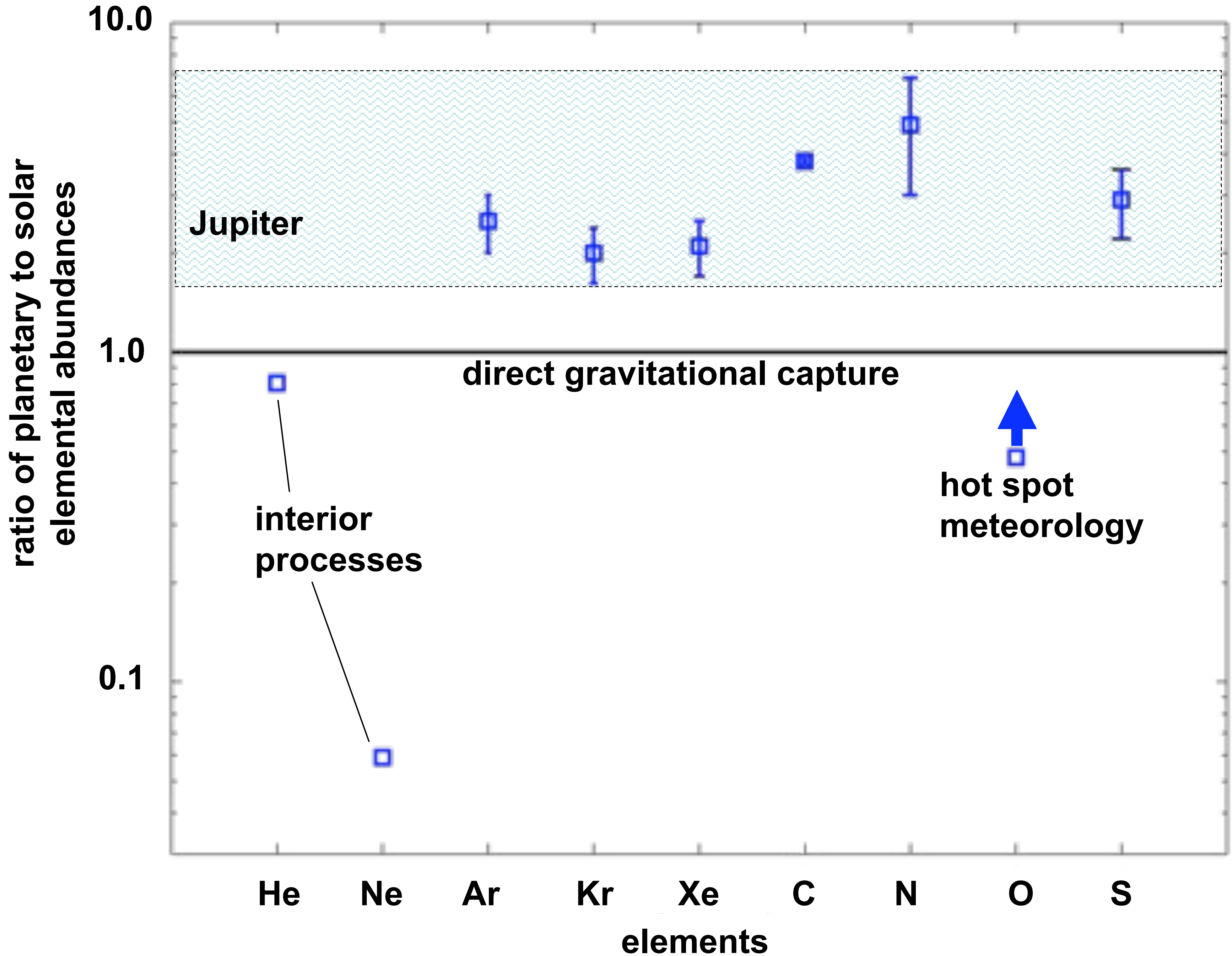
## Cylindrical Maps of Jupiter: 1° S – 14° N

**NASA Infrared Telescope Facility**

**Middle Infrared Array Camera: 4.8μm**



*Galileo probe finds Jupiter's heavy elements are 4±2 times solar!*



# Jupiter: what is missing?

**water**

abundance in “well-mixed” atmosphere

$H_2O$ was presumably the original carrier of heavy elements to Jupiter

Help is on the way!

Juno 2011

# why Saturn probes, why now?

- Comparison between the two gas giant planets required for unassailable models of formation (Saturn probes date back to initial Cassini concepts of dual probes, over 25 years ago!)
- Cassini leaves a hole, despite formidable exploration of atmos/ionos/magnetosph >1 bar
- Unprecedented technical maturity: isotopes of noble gases and other elements to 1% precision
- Outstanding international interest, e.g. KRONOS proposal to ESA's Cosmic Vision call in 2007
- Essential for understanding extrasolar planets

# Cassini at Saturn

*only* heavy element determined is carbon!

C/H = 9 x solar (from $CH_4$)

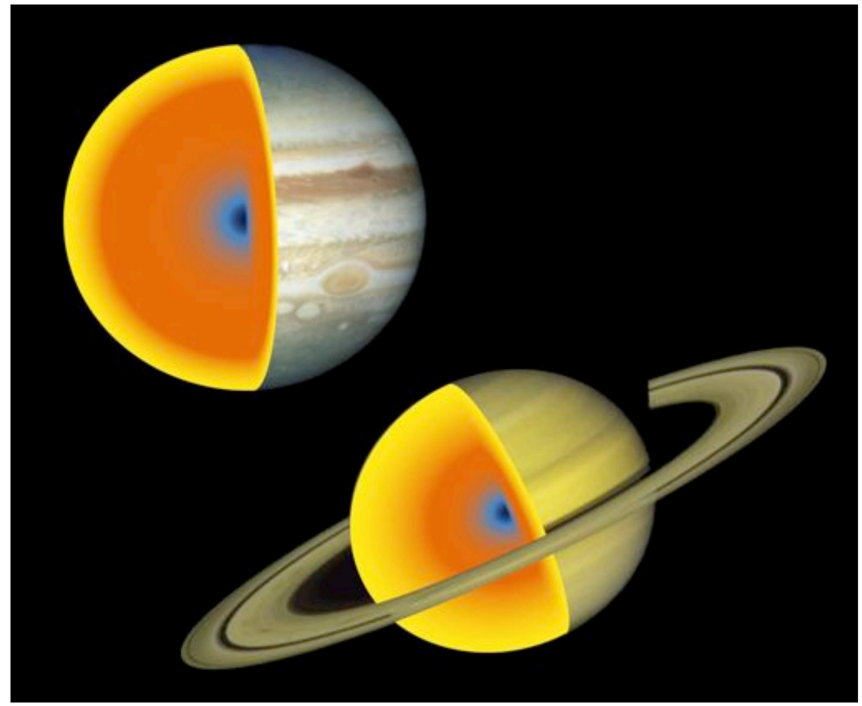
P/H = 5 - 10 x solar (also ISO) → *disequilibrium*

Cassini *cannot* measure the noble gases and other heavy elements, and their isotopes

# Saturn’s composition

Saturn’s interior is not well constrained

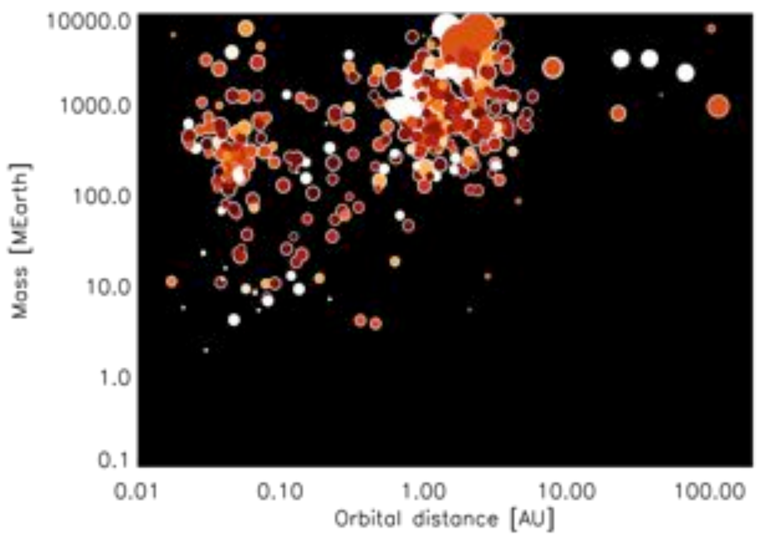
- Does Saturn have a larger core than Jupiter?
- What is the amount of heavy elements in its envelope?
- Heavy element, noble gas, and isotope inventory in the solar system needs to be completed



# Saturn's composition and Interior

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

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

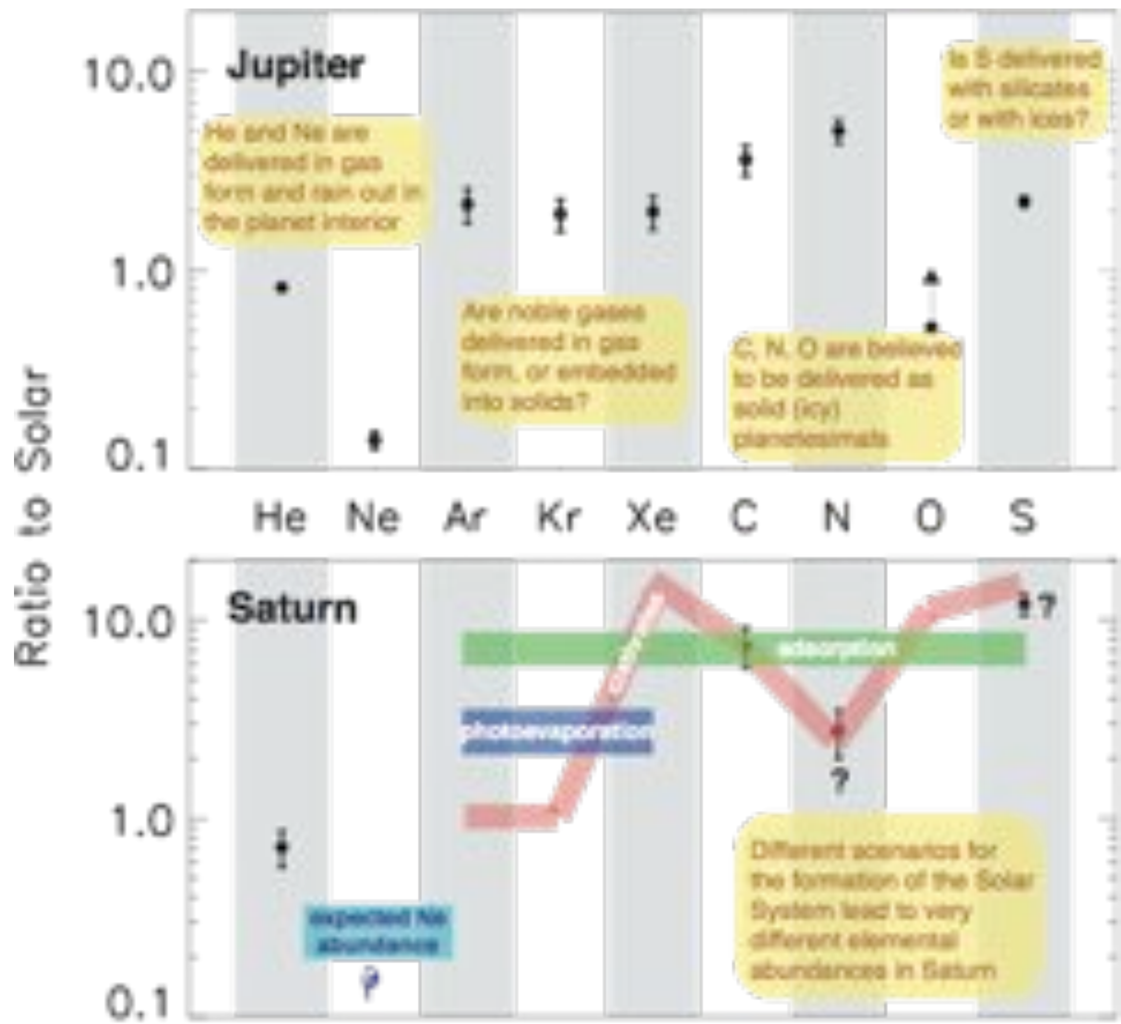



[359 Extrasolar planets as of 9 Sept. 2009.
Size of each planet (circle) is proportional to stellar mass.
Colors: white - low metallicity (Fe/H) to dark red - high metallicity (Fe/H)]
courtesy: T. Guillot

# Saturn and the formation of the solar system

Did Saturn form with Jupiter, or 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)

# Composition: Saturn Probes

Critical measurements

- Composition of *well-mixed* atmosphere

  O, C, N, S (from $H_2O$, $CH_4$, $NH_3$, $H_2S$)

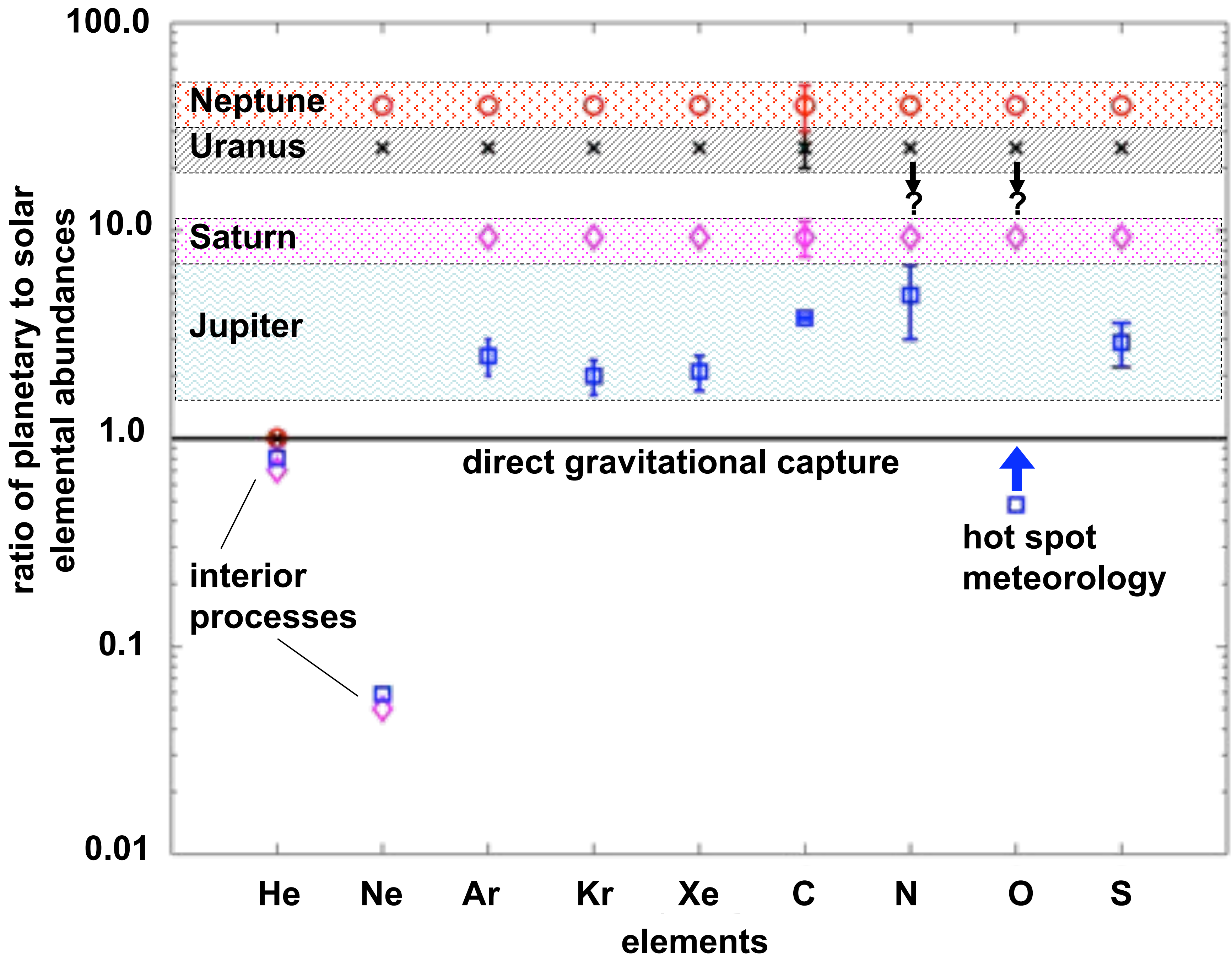
  Ne, Ar, Kr, Xe, and their isotopes

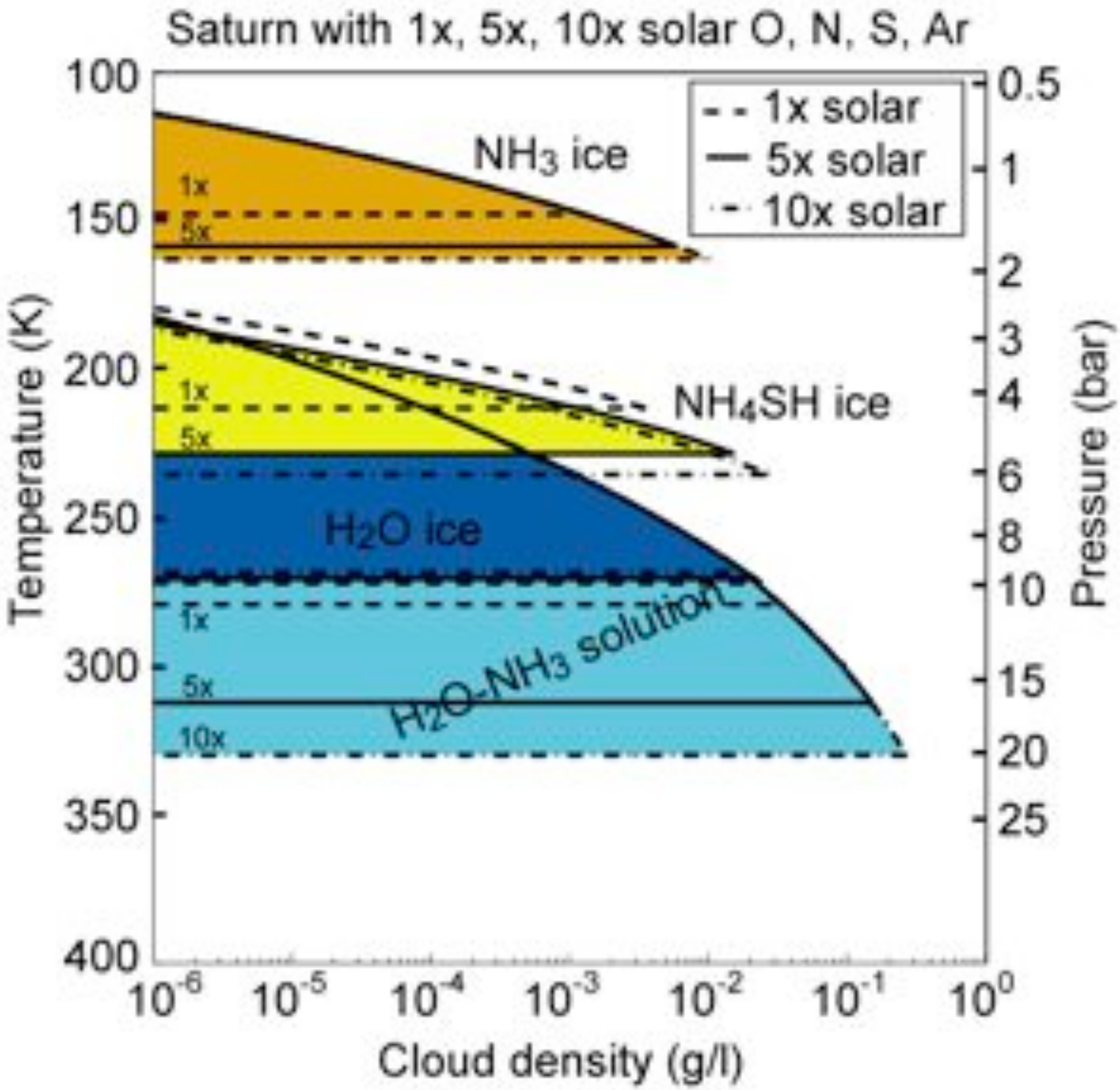
  He, $^3He/^4He$, $^{14}N/^{15}N$, D/H in $H_2$

Complemetary data on

deep winds, dynamics, lapse rate, disequilibrium molecules ($GeH_4$, $SiH_4$, $AsH_3$, $PH_3$, CO)

***Only* Probes can access much of above data**


100.0
10.0
1.0
0.1
0.01
ratio of planetary to solar elemental abundances
Neptune
Uranus
Saturn
Jupiter
?
?
direct gravitational capture
interior processes
hot spot meteorology
He
Ne
Ar
Kr
Xe
C
N
O
S
elements

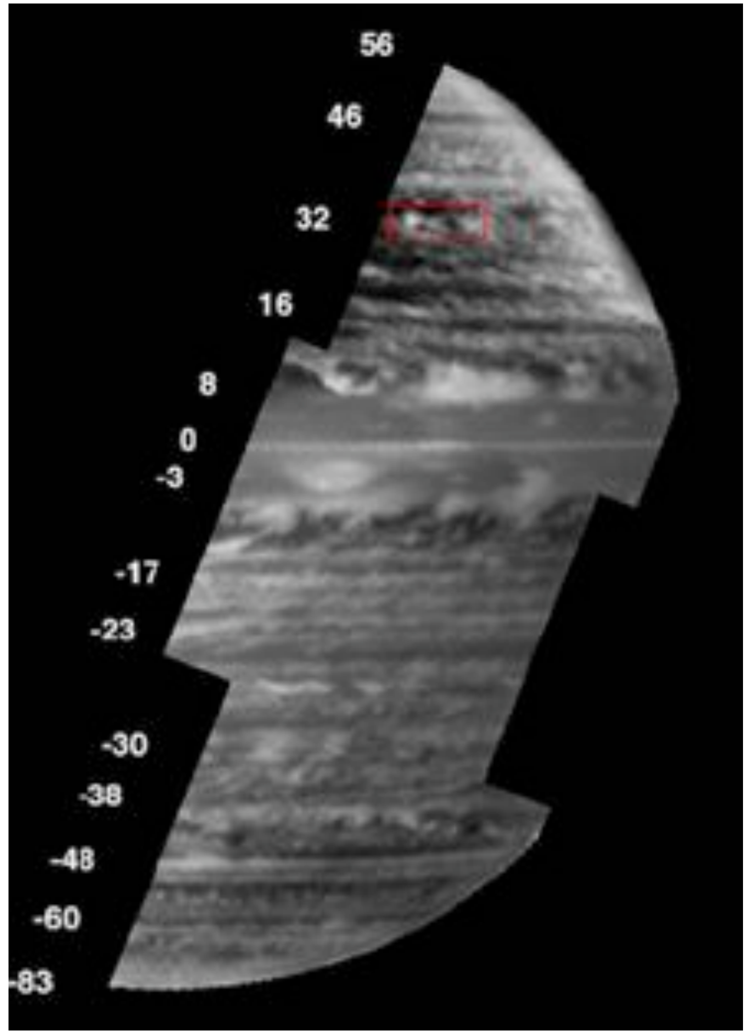



Equilibrium Cloud Condensation Models (Atreya, Wong 2005)

# Saturn's atmosphere: cloudy, hazy, fuzzy: more Jupiter-like than Jupiter…

**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

(courtesy: Baines, VIMS)



# Saturn (*deep*) Probes

*Technological challenges of deep probe (50-100 bar, to reach well-mixed water) are enormous:*

- Communication, i.e. to carrier S/C for relay to earth (or direct-to-earth future technology)
- Survival and operation of payload instruments in extreme p-T (50-100 bar, 400-550 K)
- Power for long duration of operation in high p-T

Consider *shallow* probes, instead!

# Saturn (*shallow*) Probes

- shallow probes to ~10 bar only, adequate for elemental abundance, except for O/H
- O/H (from $H_2O$) with passive microwave radiometry on carrier spacecraft

*how many probes?*

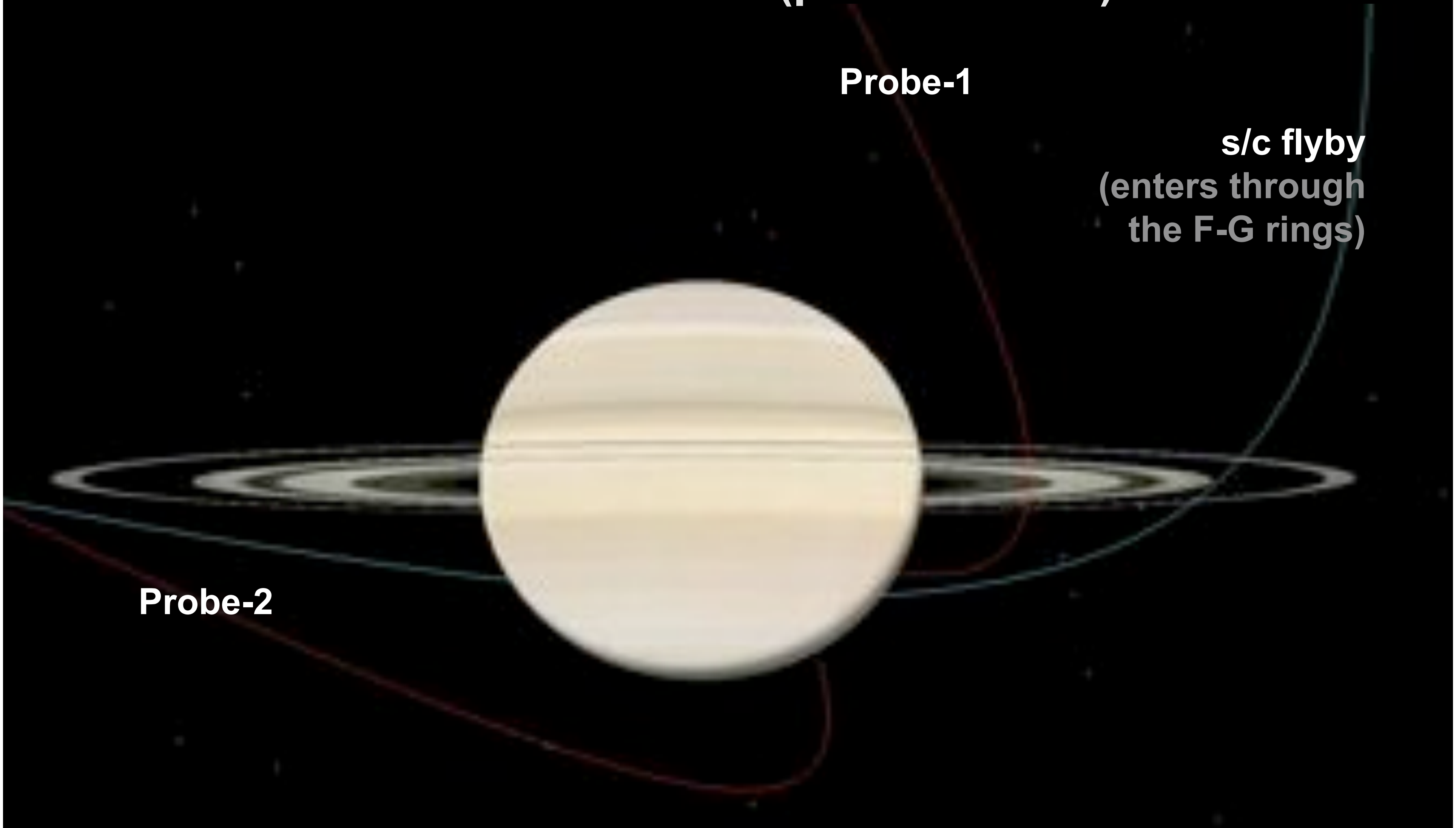
- *>1*;  2 - 3, for diversity and risk mitigation

*where?*

- equatorial, mid- and/or high latitudes

# Mission Design

## Mission Overview (probe entries)




Source: Chuck Baker

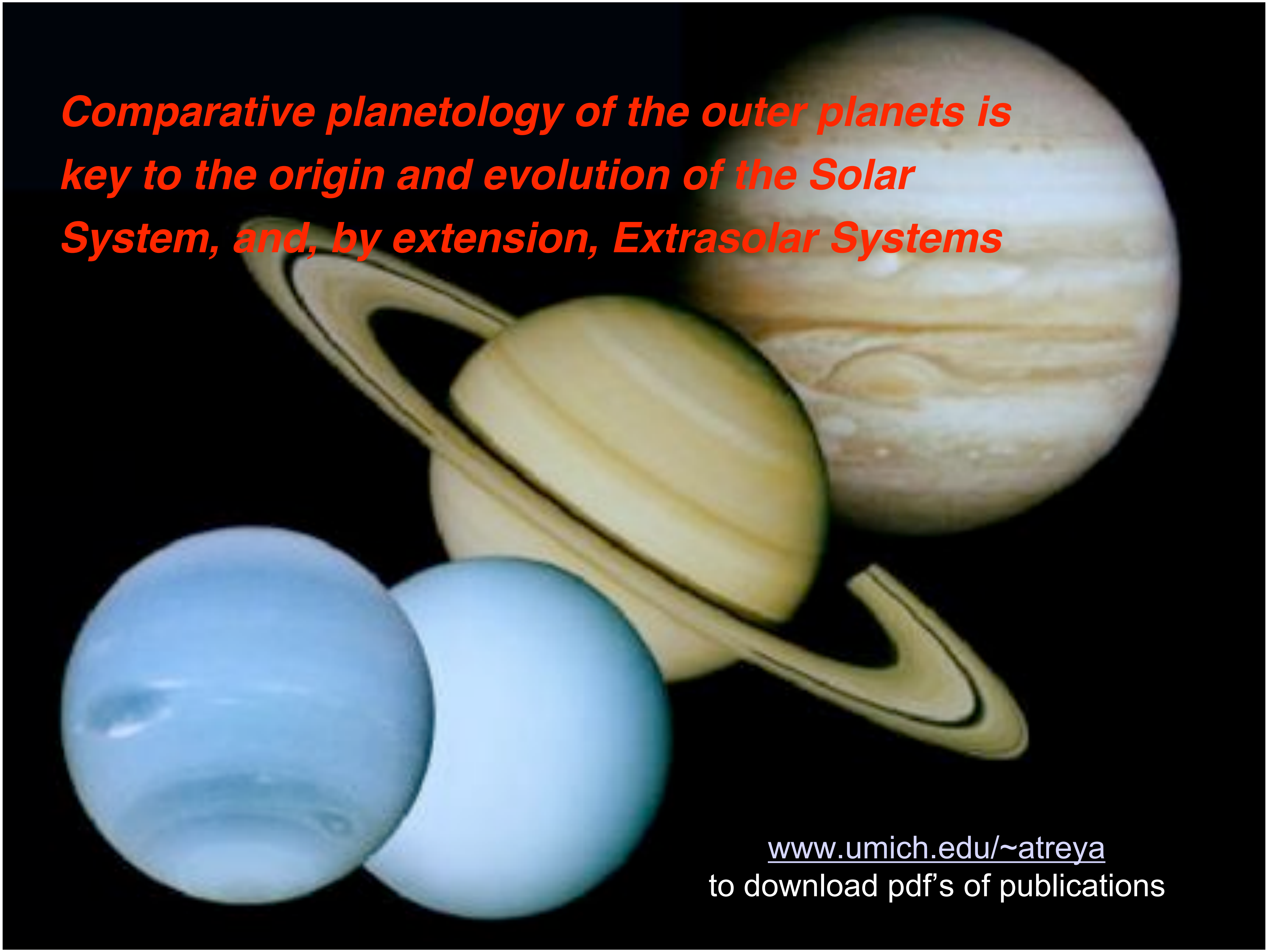
# Recommendations

Consider a *shallow* Saturn dual probe mission with microwave radiometry (MWR) from carrier spacecraft, for a serious in-depth cost analysis study

For carrier, an orbiter is preferred over a flyby, as it alone can *map* the distribution of water (and other volatiles) in Saturn's interior, determine the existence of a core, besides being appealing to a broad community

The cost of a dual probe mission together with MWR on either a flyby or an orbiter may exceed possible New Frontiers (IV) cost cap, which brings me to the final point

Consider a giant planet exploration *program* that includes a new line of *small* Flagship class missions ($1.2-1.5 billion), as a *systematic and sustained* exploration of *all* giant planets is needed to understand the formation and evolution of solar *systems*.


Comparative planetology of the outer planets is key to the origin and evolution of the Solar System, and, by extension, Extrasolar Systems
www.umich.edu/~atreya
to download pdf's of publications

Back-up slides

# Mission Design Report

# Mission Overview

## Interplanetary Trajectory

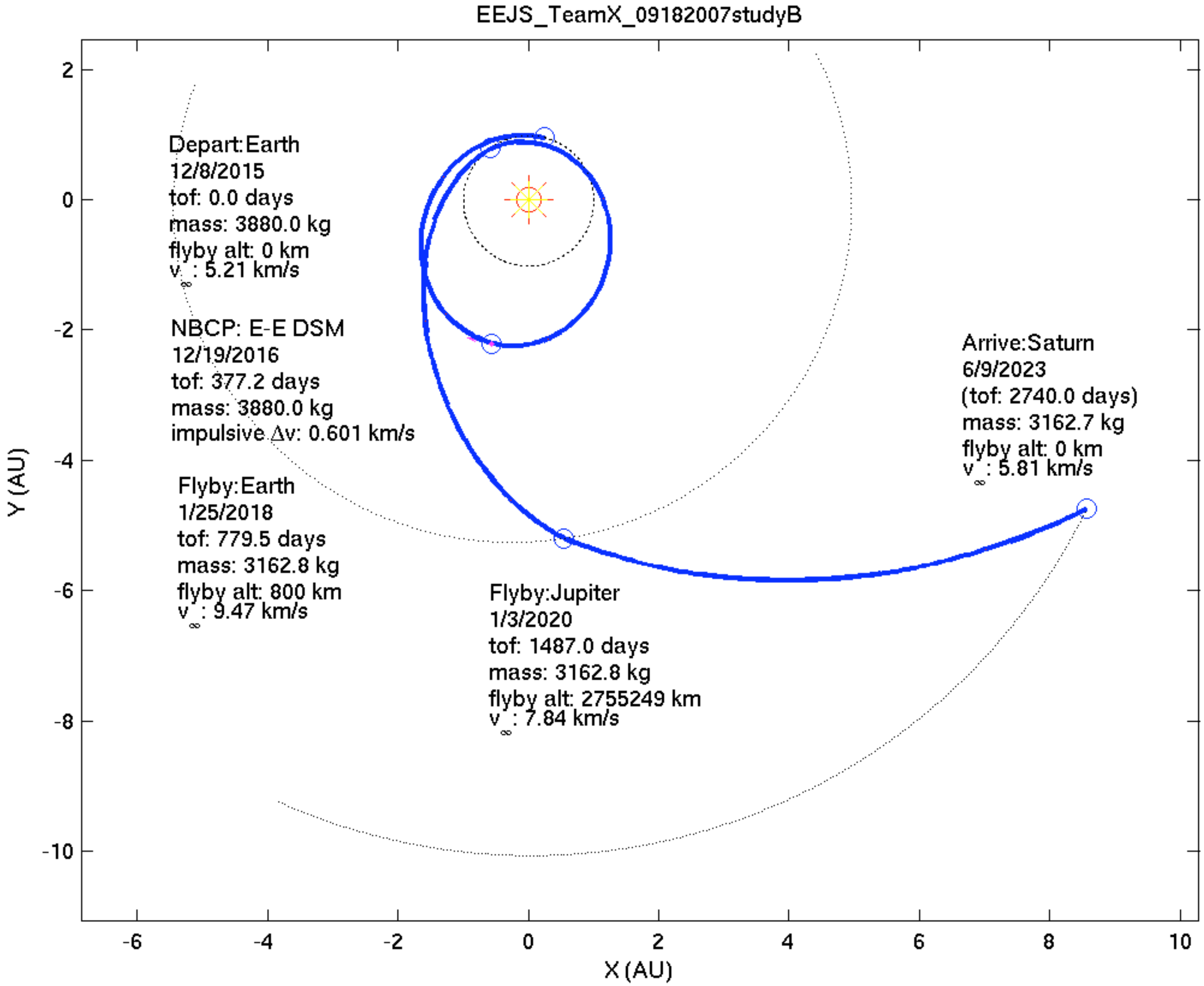
- Trajectory Type: EEJS
- Launch in 12/8/2015
- Atlas V 521 launch vehicle
  - Delivered mass of 2650 kg for C3 = 27.8 (km/s)**2
- 7.5 year flight time
- DSM (615 m/s) on 12/19/2016
- Earth Flyby on 1/25/2018 – 800 km
- Jupiter Flyby on 1/3/2020 – 2.75x10**6 km

## Probe Releases

- Event occurs approximately 6 months before Saturn encounter
- Probe releases are 1 month apart
- Range to Saturn: 9.2x10**7 km for Probe 1 and 7.6x10**7 km for Probe 2

# Mission Design
## Mission Overview (interplanetary plot)

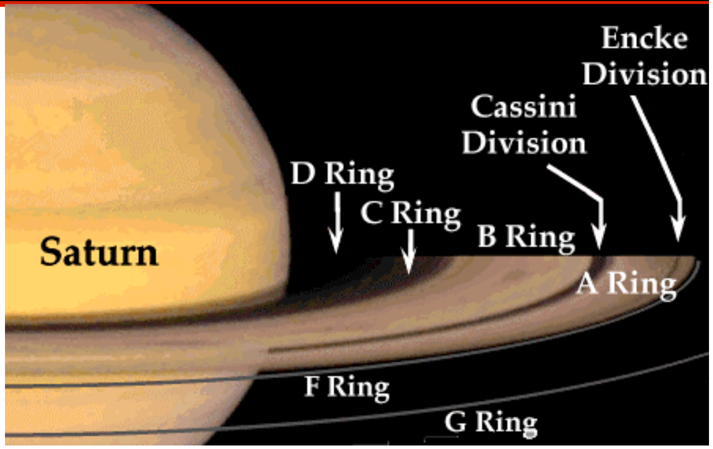


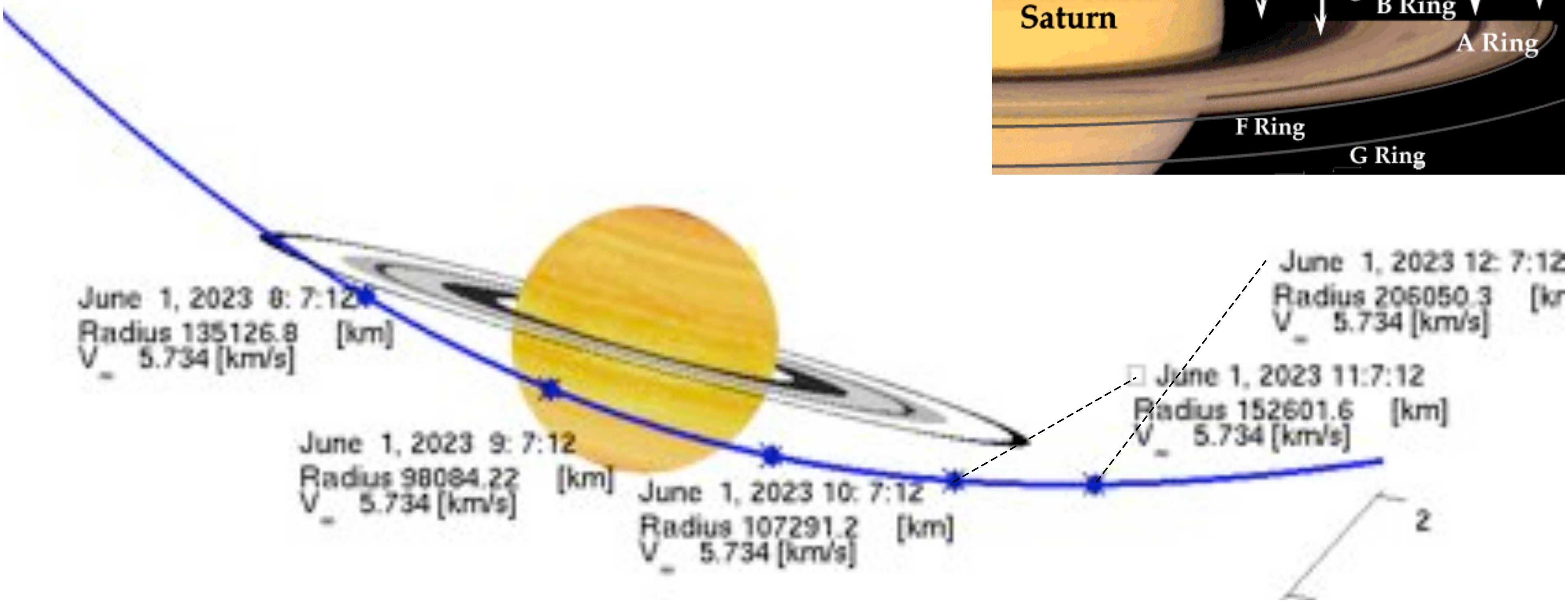


## Saturn Arrival

- Probes enter simultaneously on 6/1/2023 08:07
  - Probe 1 targeted to -25 deg
    - Crosses the ring plane outside the G-ring
    - Arrival V-inf is 5.73 km/s
    - Longitude is 269.6 deg
    - Range to flyby spacecraft at entrance is 1.07x10**5 km
  - Probe 2 targeted to -55 deg
    - Crosses the ring plane outside the G-ring
    - Arrival V-inf is 5.73 km/s
    - Longitude is 277.9 deg
    - Range to flyby spacecraft at entrance is 1.18x10**5 km
- Flyby Spacecraft crosses the ring plane ~ 6/1/2023 07:30
  - Crosses the F-G ring (descending) upon arrival (~140,000 km radius)
  - Crosses outside the G-ring (ascending) when leaving
  - Arrival V-inf is 5.73 km/s

# Mission Design
## Mission Overview (plot at arrival)




**Saturn's Spin Rate:**
~ 10 hrs 14 min @ equator
~ 10 hrs 47 min @ higher latitude

# Mission Design

## Mission Overview (probe entries)


Source: Chuck Baker