2015 IEEE International Symposium on
Antennas and Propagation and
North American Radio Science Meeting
19–24 July 2015 • Vancouver, BC, Canada

# *Planetary Discoveries with Radio Science from Mariner to New Horizons*

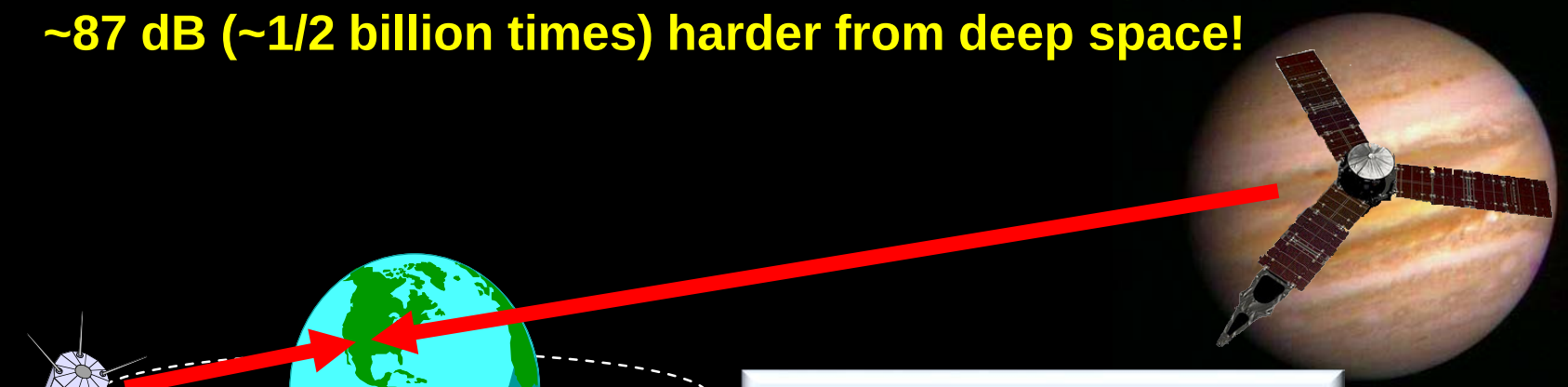
**Sami Asmar**
**NASA's Jet Propulsion Laboratory**
**California Institute of Technology**

**Jet Propulsion Laboratory**
California Institute of Technology

© 2015 California Institute of Technology.
Government sponsorship acknowledged.

# Challenge of Deep Space Communications with Radio Signals

- Communications performance decreases as the square of the distance
- Jupiter is nearly 1 billion  km away, while a GEO Earth satellite is about 40 thousand km away
  - ~87 dB (~1/2 billion times) harder from deep space!



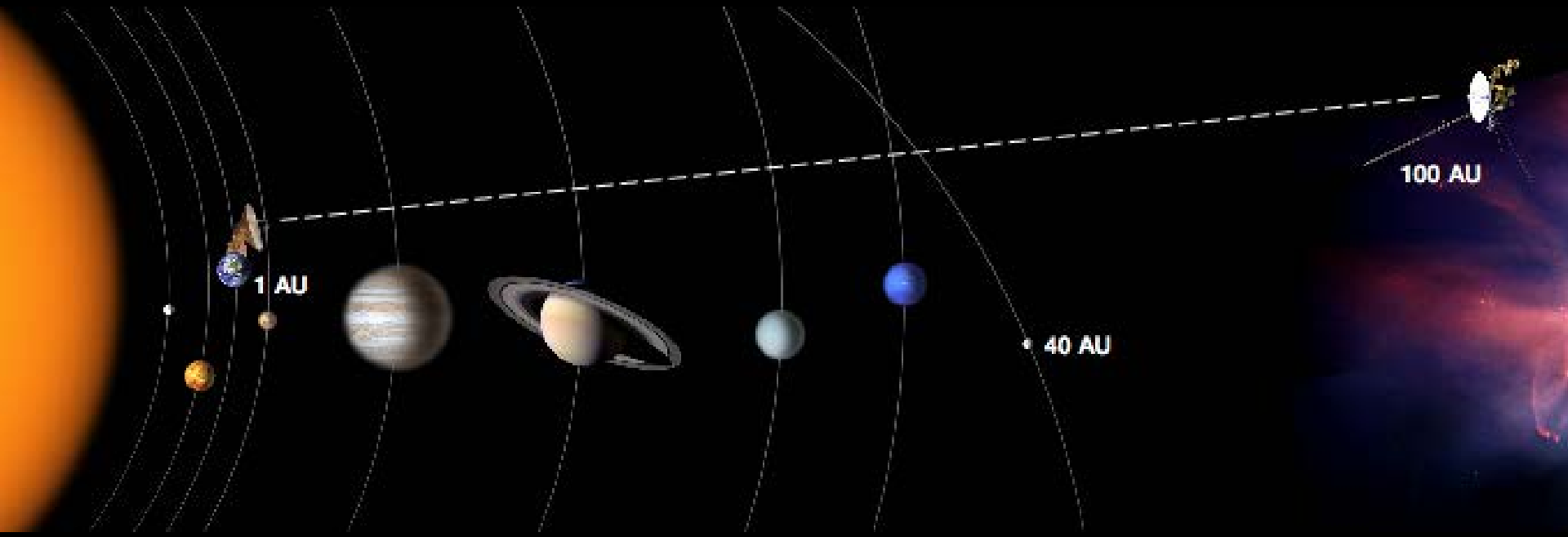
Relative Difficulty

| Place | Distance | Difficulty |
|---|---|---|
| Geo | $4 \times 10^4$ km | Baseline |
| Moon | $4 \times 10^5$ km | 100 |
| Mars | $3 \times 10^8$ km | $5.6 \times 10^7$ |
| Jupiter | $8 \times 10^8$ km | $4.0 \times 10^8$ |
| Pluto | $5 \times 10^9$ km | $1.6 \times 10^{10}$ |

# Challenge of Deep Space Communications

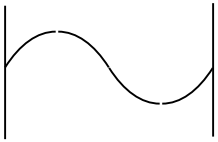
**Power received by the 70m DSN antenna from Voyager is so small that if it were to be accumulated for 10 trillion years it can power a refrigerator light bulb for**

***ONE SECOND***

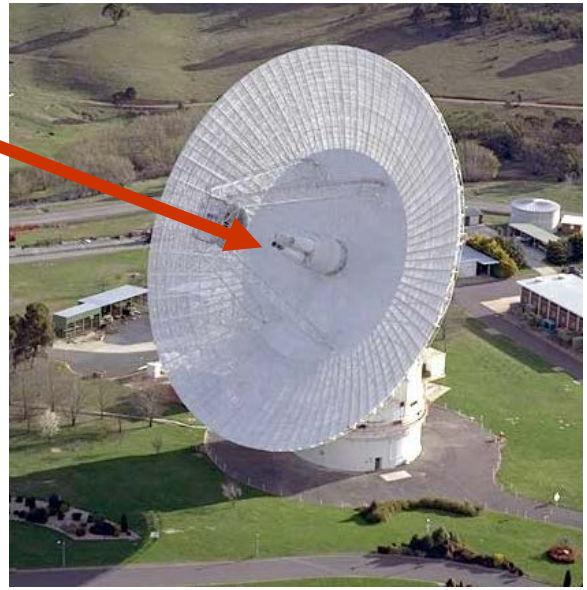


# EM Wave Communication

**Spacecraft communications are carried on electromagnetic waves that travel between ground stations and spacecraft at the speed of light**



**Electromagnetic waves are generally cm in length. The wave shown here is 3.6 cm in length – the wavelength of a 8.4 GHz signal**



# The Start of *Radio Science*

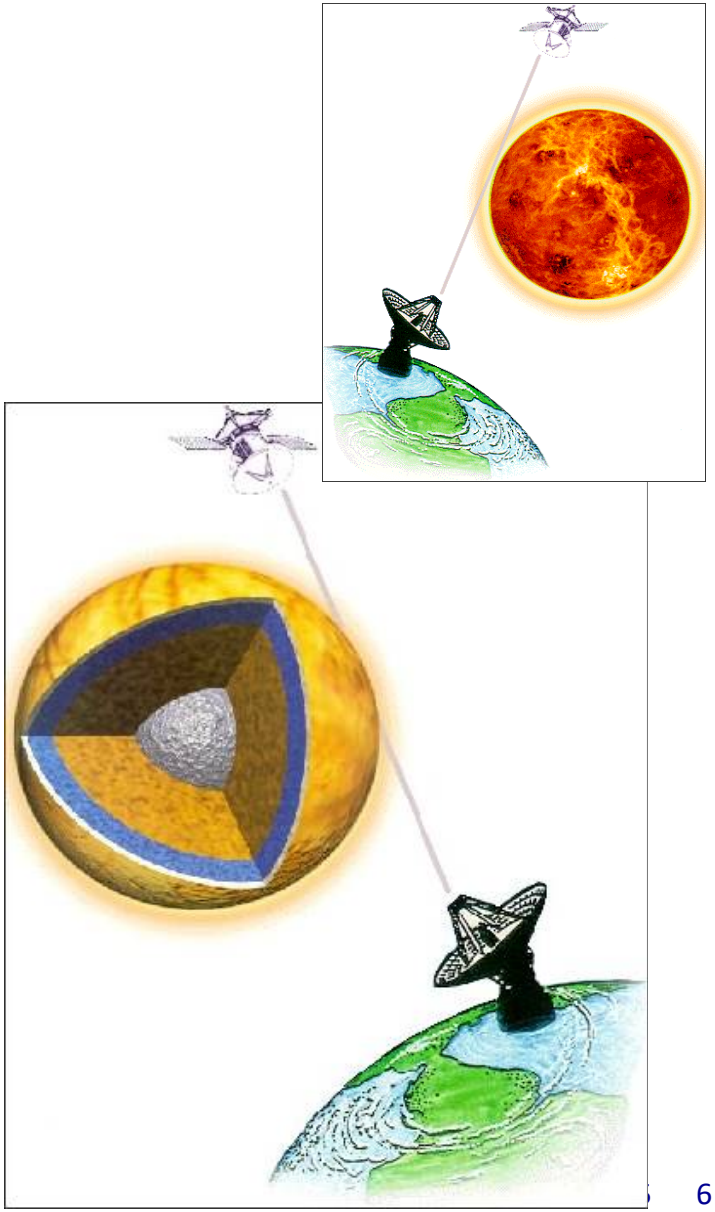
**Interaction between gas constituents of planetary atmosphere and electromagnetic signals!**

**Perturbations in phase and amplitude due to "optical" properties of gas.**

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}_0 \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \phi_0)$$
$$\mathbf{B}(\mathbf{r},t) = \mathbf{B}_0 \cos(\omega t - \mathbf{k}\cdot\mathbf{r} + \phi_0)$$

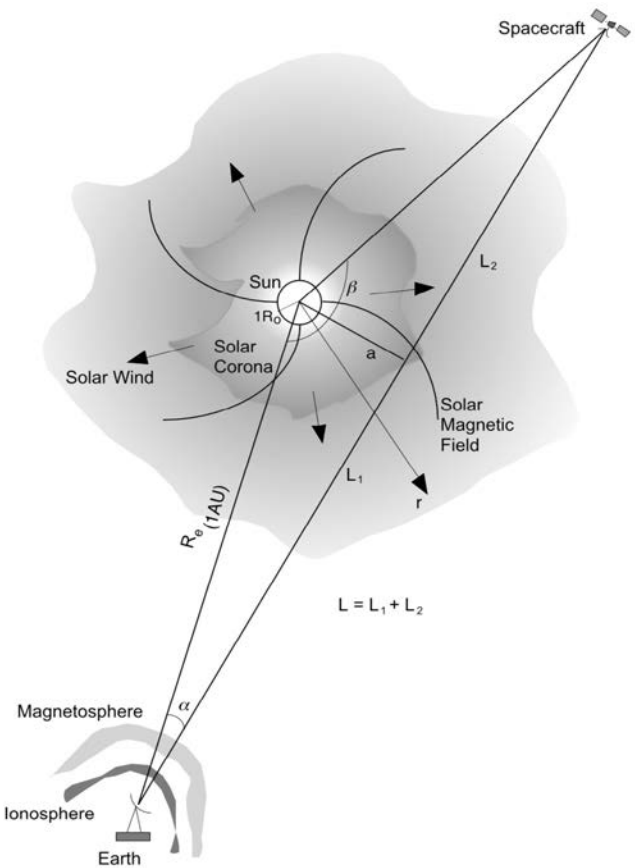
# The Field of *Spacecraft* Radio Science

- **It became apparent with early missions that occultations by planetary atmospheres would affect the quality of radio communications**
- ***One person's noise is another's data***
- **Study the atmospheric properties**
  - **And other aspects of planetary science, solar science, and fundamental physics**
- **A recognized field of solar system exploration with instrument distributed between spacecraft & ground stations**

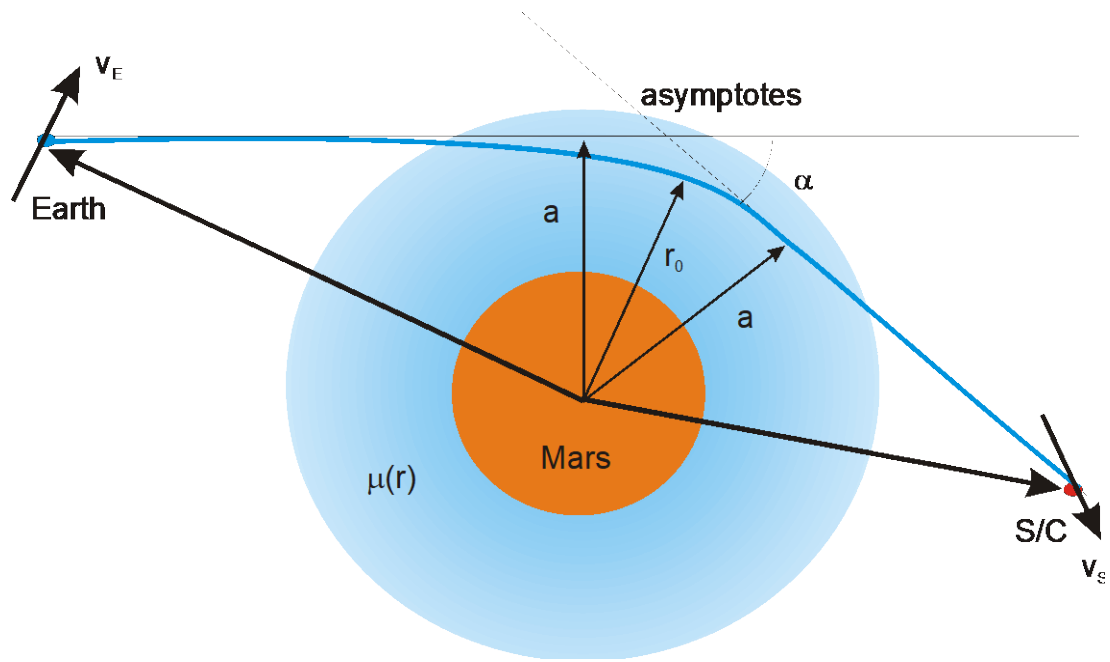


# Radio Occultation

## Powerful Tool to Investigate Structure of Planetary Atmosphere



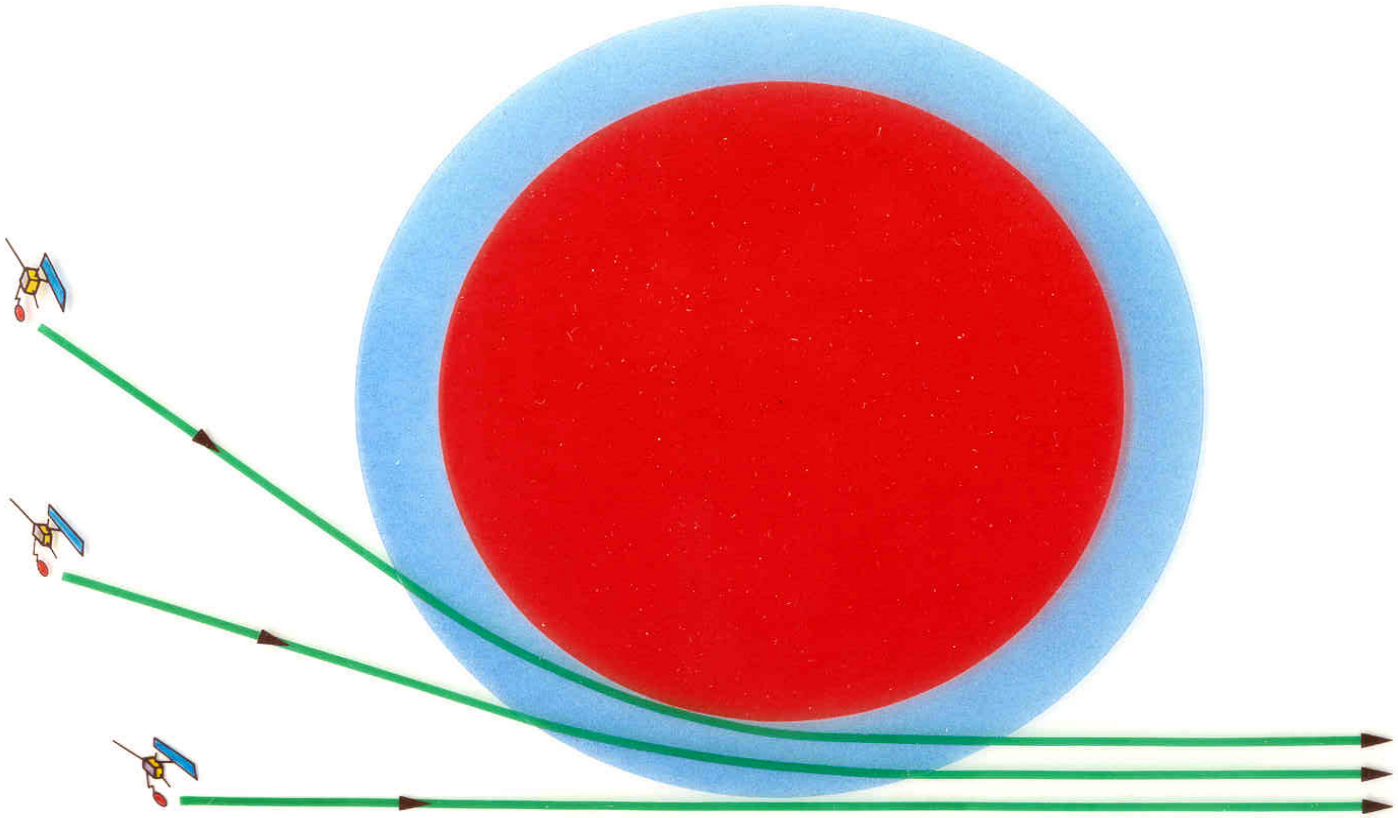

**Occultation by the atmosphere of Mars**



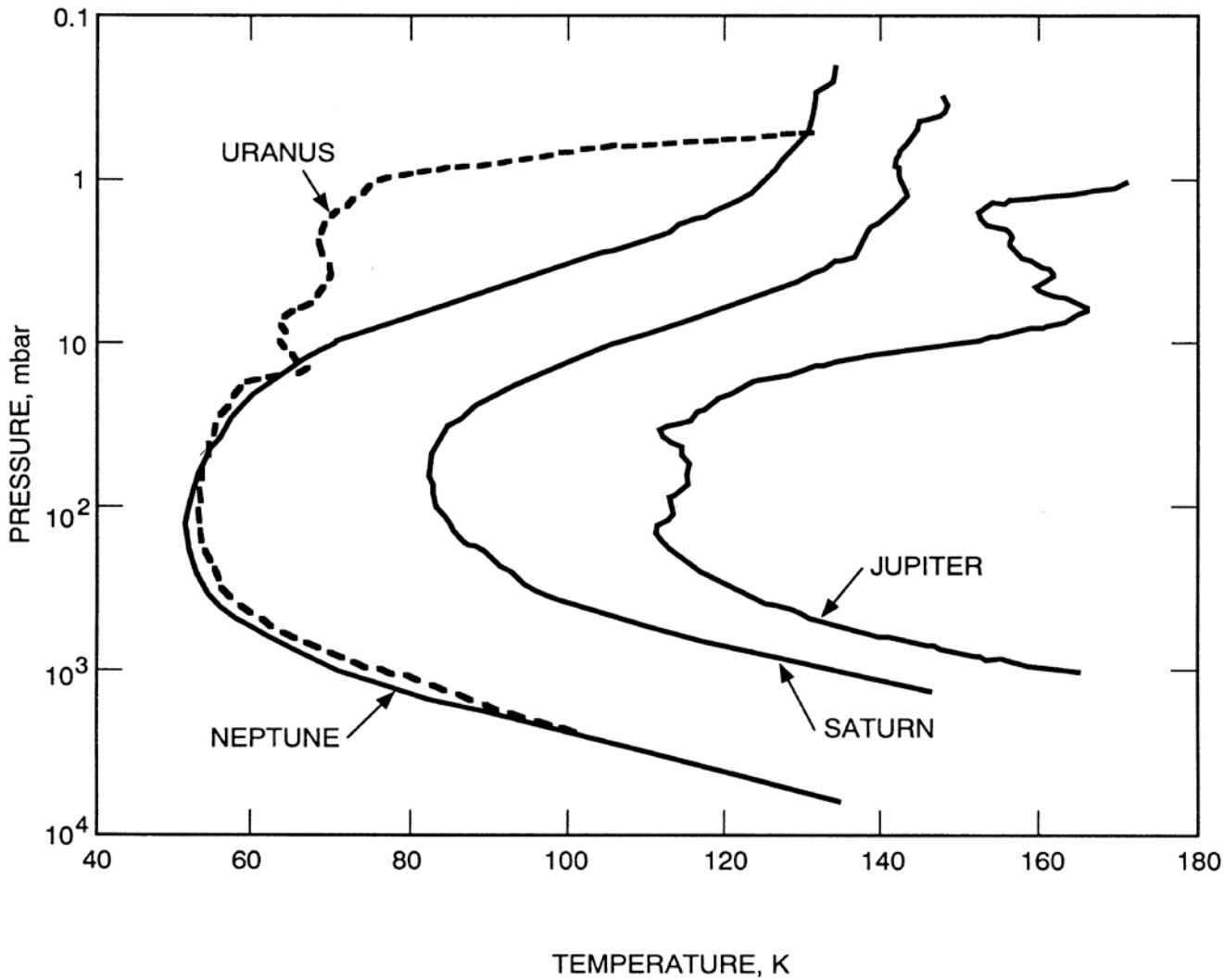

**Occultation by the atmosphere of the Sun**

# Radio Atmospheric Occultation Methodology

**Phase ==> length ==> refractive angle ==> refractivity ==> number density ==>column pressure ==> temperature**



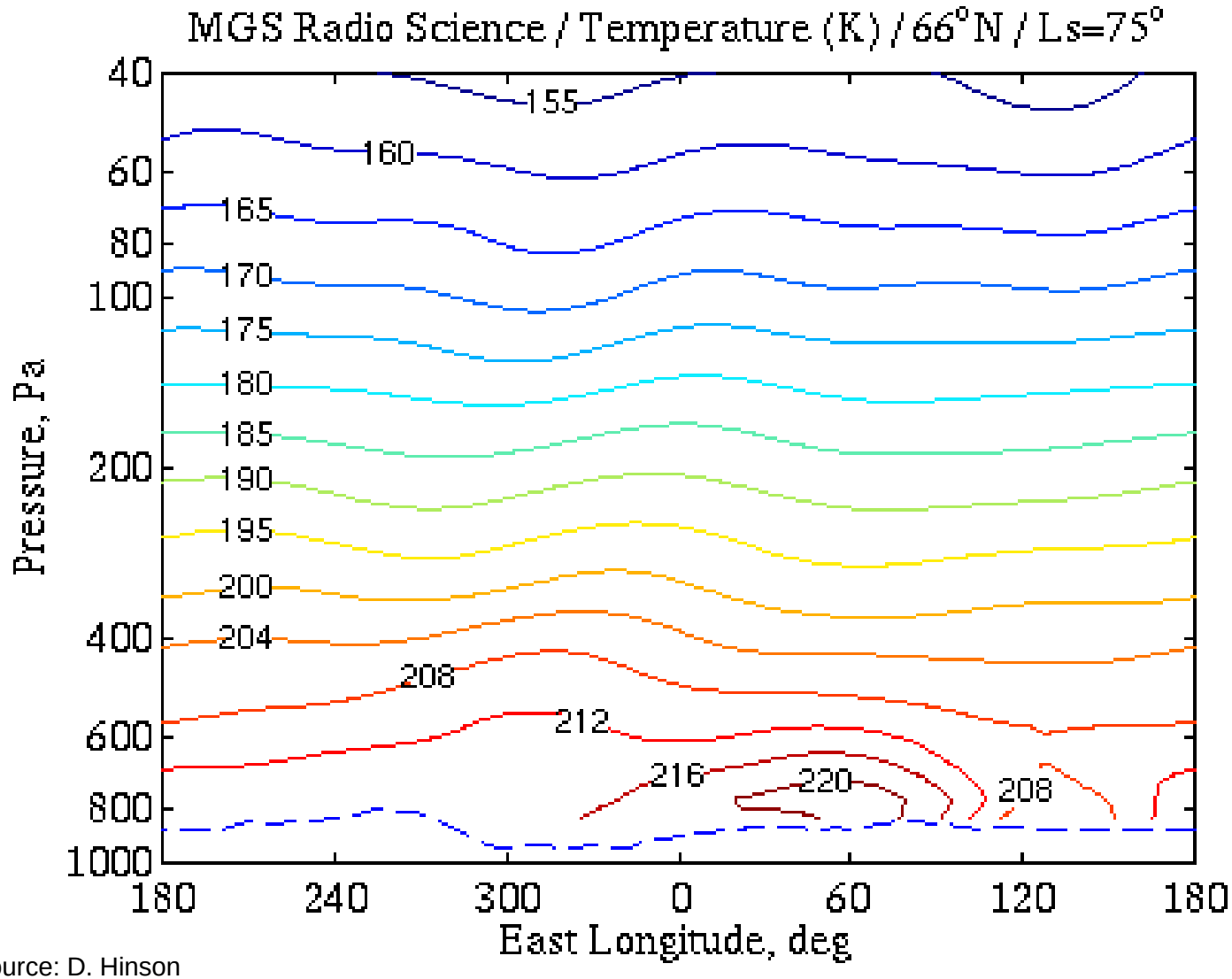
# Atmospheres of Giant Planets




**Occultations of Voyager 2 by 4 outer planets**

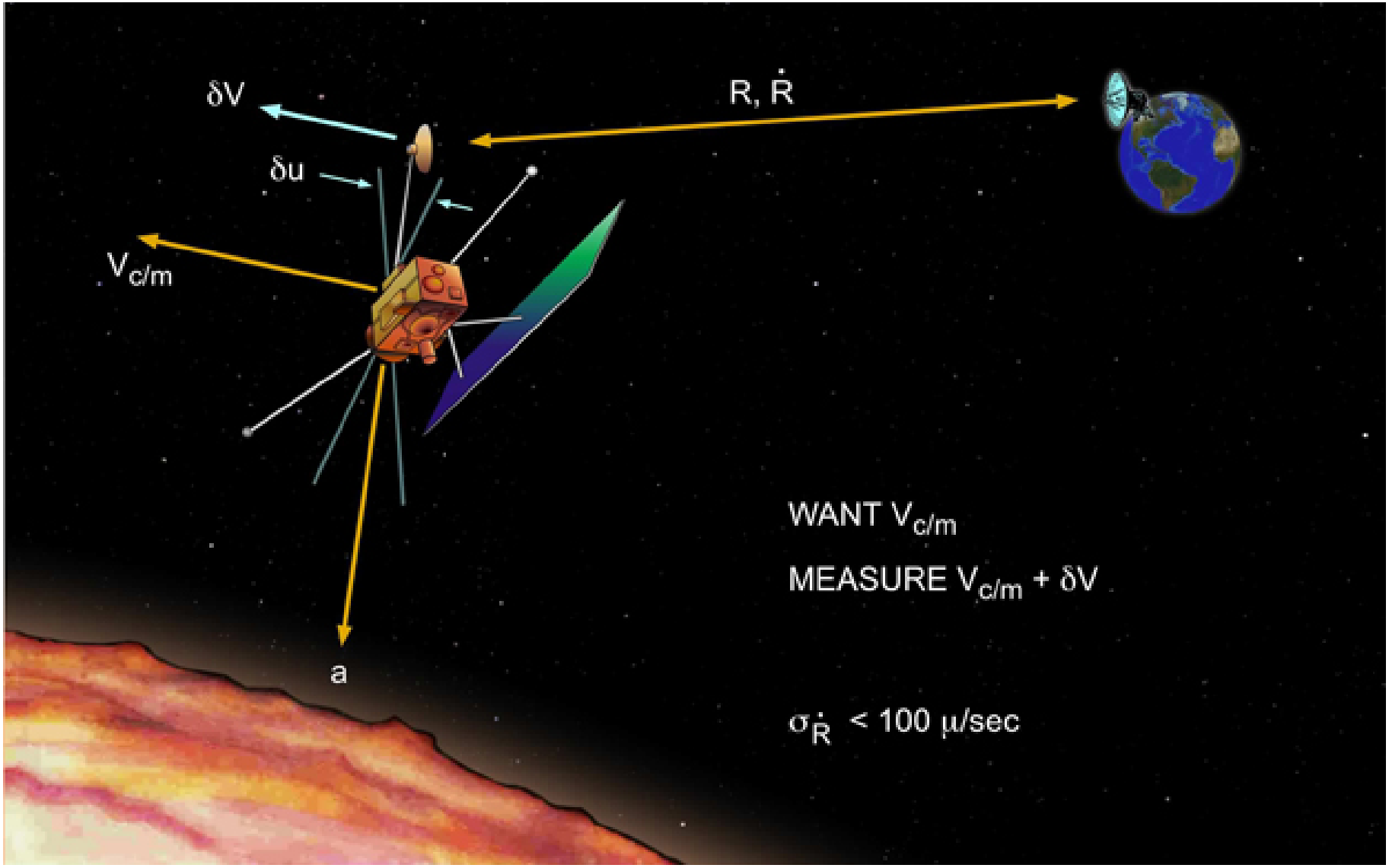
**Temperature profiles for the giant planets derived from radio occultation data acquired with the Voyager spacecraft (from Lindal, 1992)**

# Atmosphere of Mars from MGS Occultations



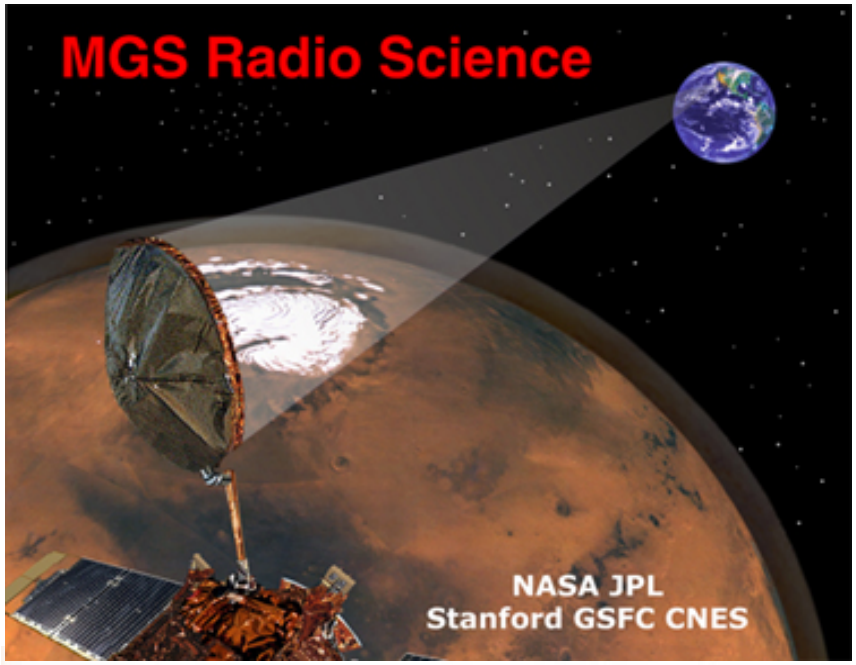

Source: D. Hinson

# Doppler Observable



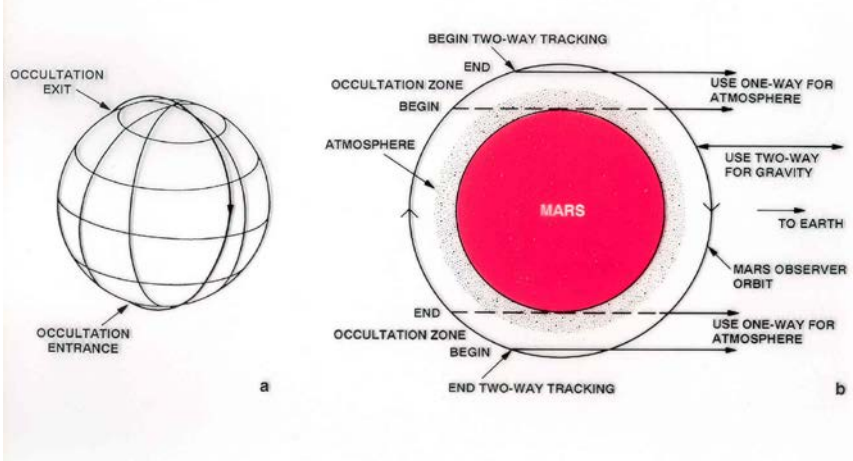
# Radio Science Experiment Types

- **Propagation**
  - **Study media**
  - **Remove effects of forces**
- **Gravitation**
  - **Study forces**
  - **Remove effects of media**




**Time Share Example**

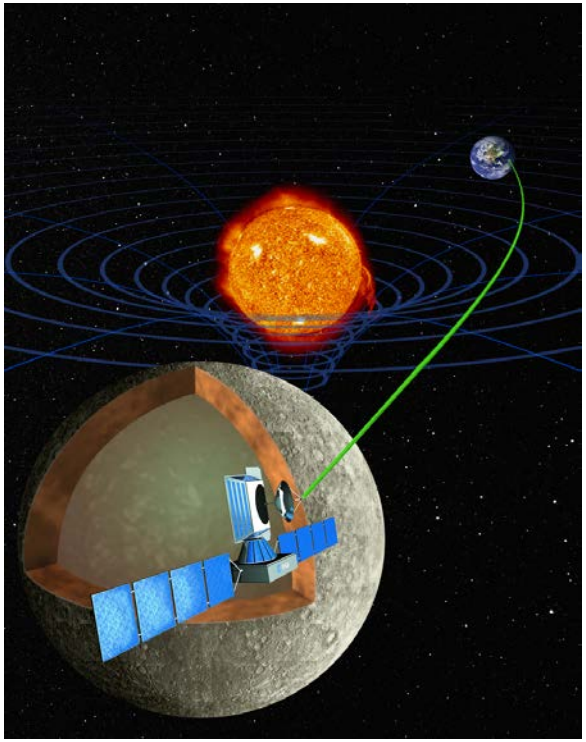
**Mars Global Surveyor Radio Science Team conducted both types of experiments back-to-back every orbit for thousands of orbits: *Propagation* to study the atmosphere and *Gravitation* to study the interior**



# Radio Science Investigations

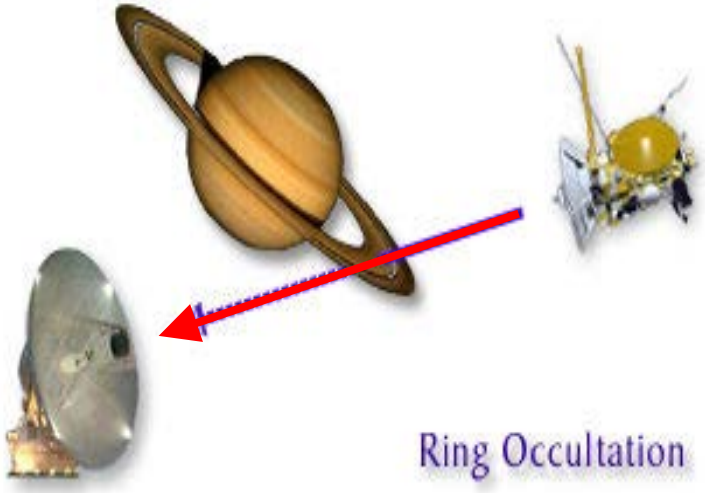
**Utilize the telecommunication links between spacecraft and Earth to examine changes in the phase/frequency, amplitude, and polarization of radio signals to investigate:**

- **Planetary atmospheres**
- **Planetary rings**
- **Planetary surfaces**
- **Planetary interiors**
- **Solar corona and wind**
- **Comet mass flux**
- **Fundamental Physics**

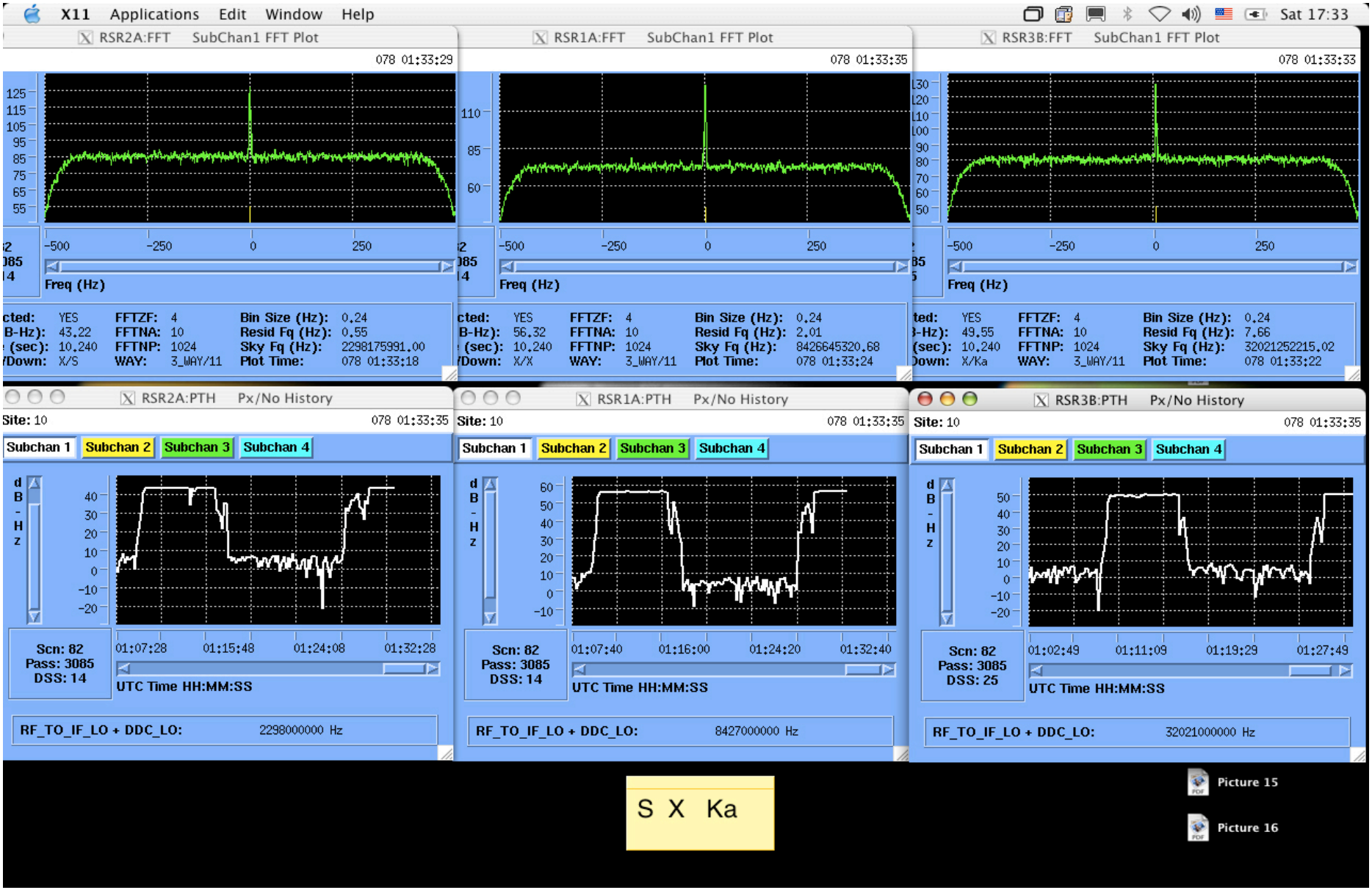


# Radio Occultations

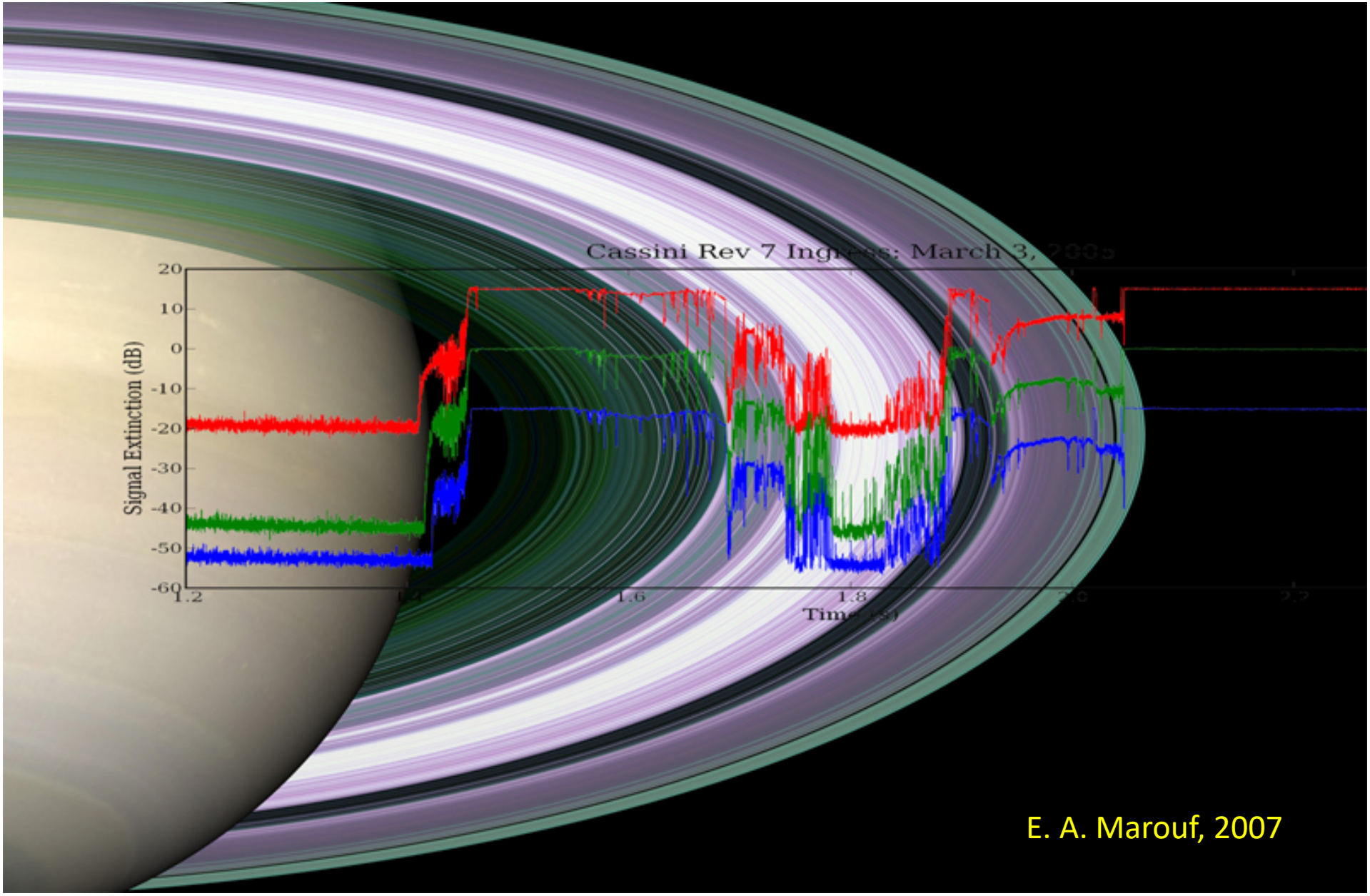
- Study properties of planetary media along propagation path
  - Atmosphere: temperature-pressure profile
  - Ionosphere: electron density
  - Rings: particle structure and size distribution
  - Byproducts: planetary shapes
- Observables:
  - Amplitude and phase
    - Refraction
    - Scattering
    - Edge diffraction
    - Multi-path



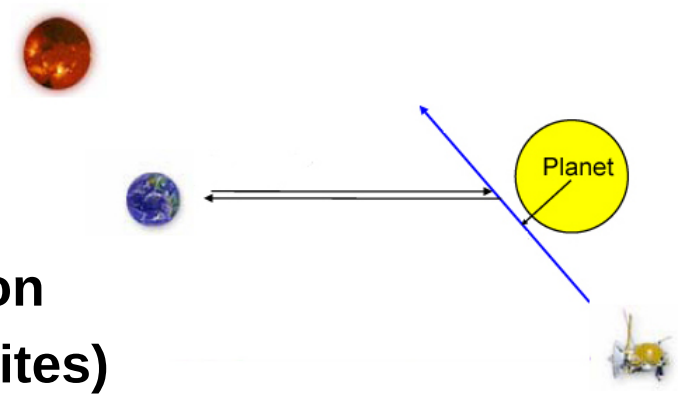
# Three Cassini Signals Occulted by Titan



# Saturn's Rings In the Cassini Era

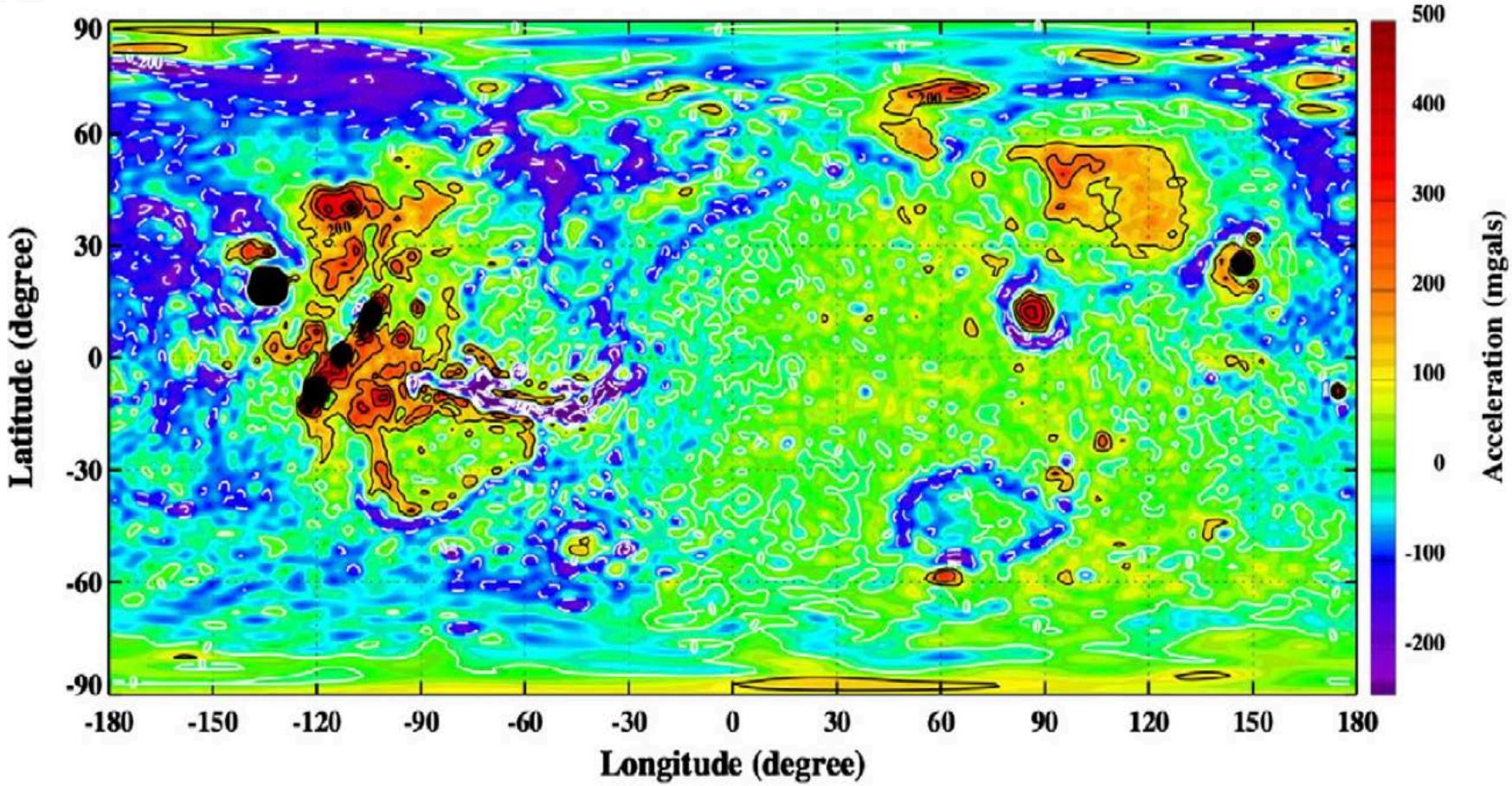


# Gravity and Planetary Interiors




- Determine the mass and mass distribution
  - GM of body or system (planet + satellites)
  - Gravity field: higher order expansion of mass distribution
- Constrain models of internal structure
  - Examples: ocean on Europa
- Improve orbits and ephemerides
- Observables:
  - Doppler and range: precise measurement of relative motion
    - Doppler accuracy ~ 0.03 mm/s at X, few microns/s at Ka-band
    - Ranging accuracy to ~ 1 meter

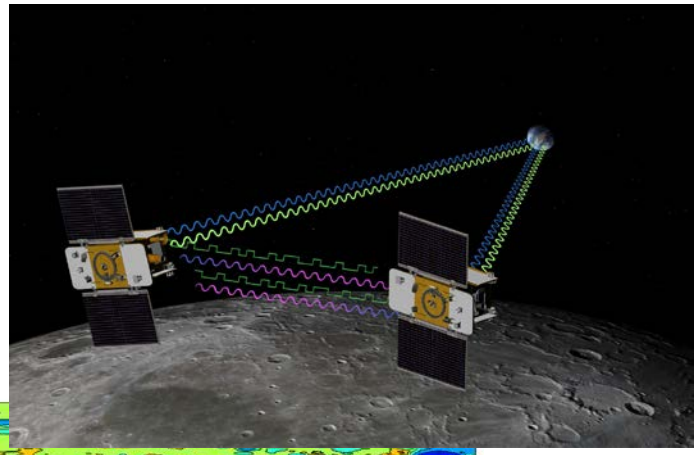
# The Gravity Field of Mars

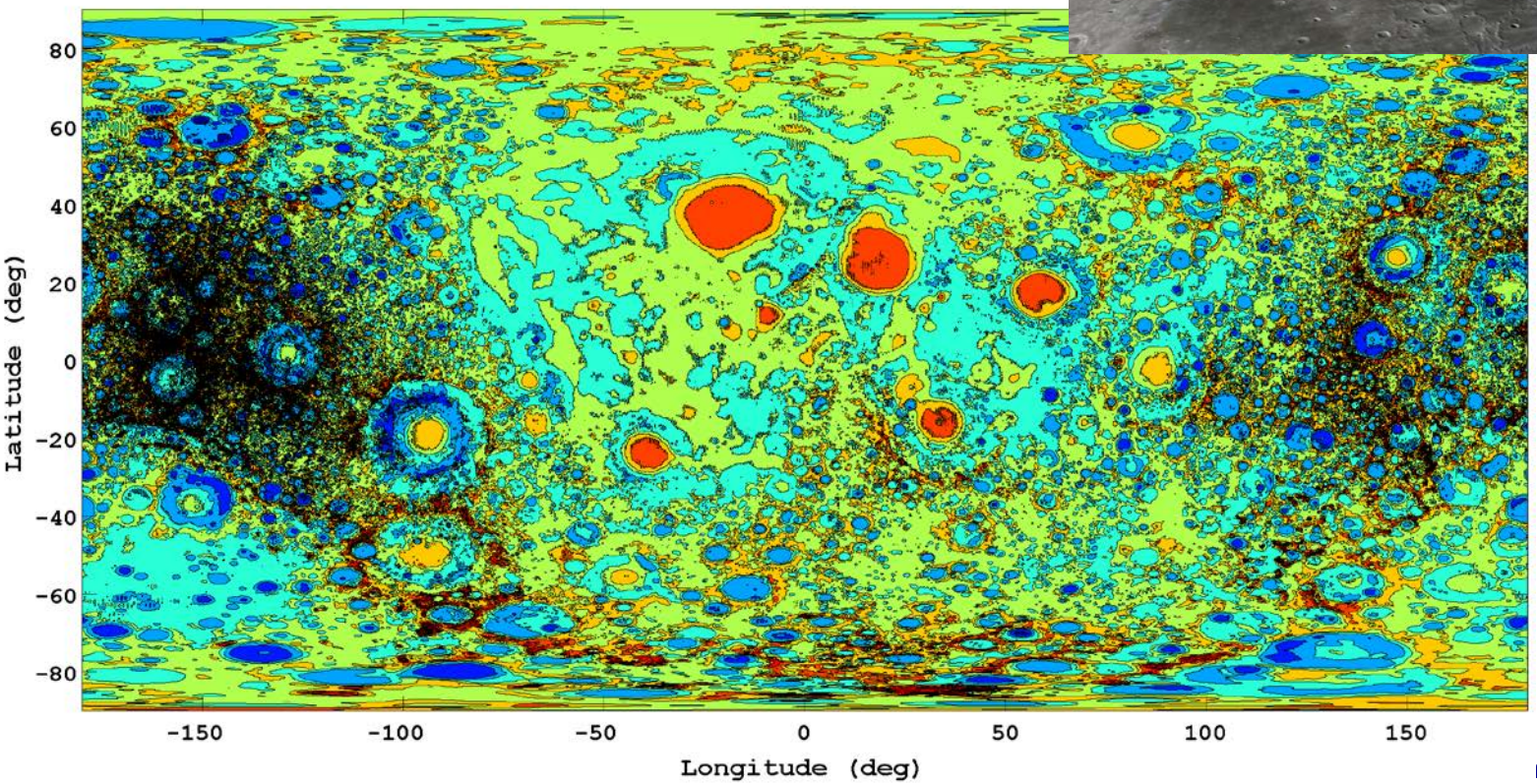


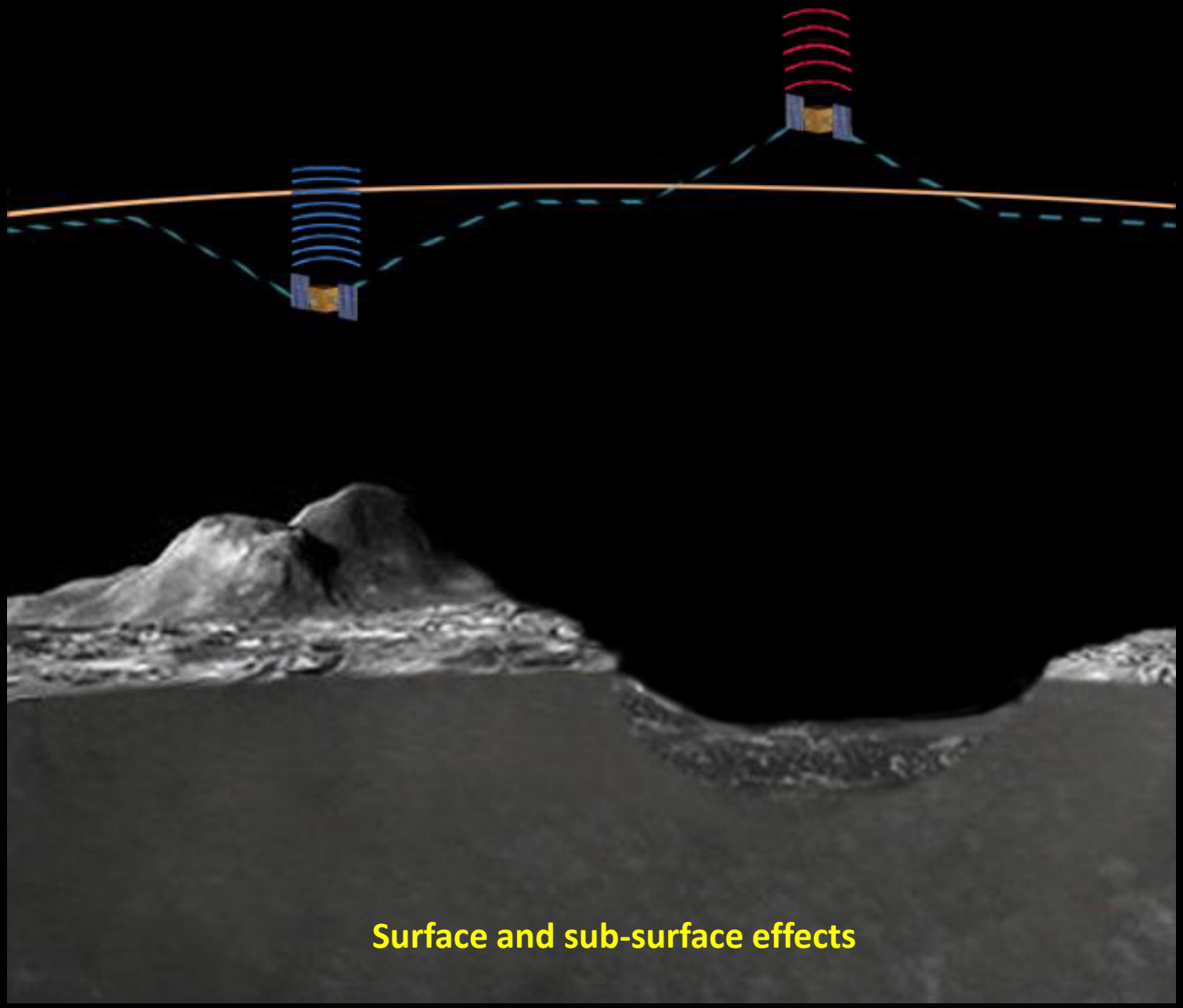

**Surface gravity anomalies complete to degree and order 90 with respect to a reference ellipsoid (model MRO110B)**

**Konopliv et al., 2011**

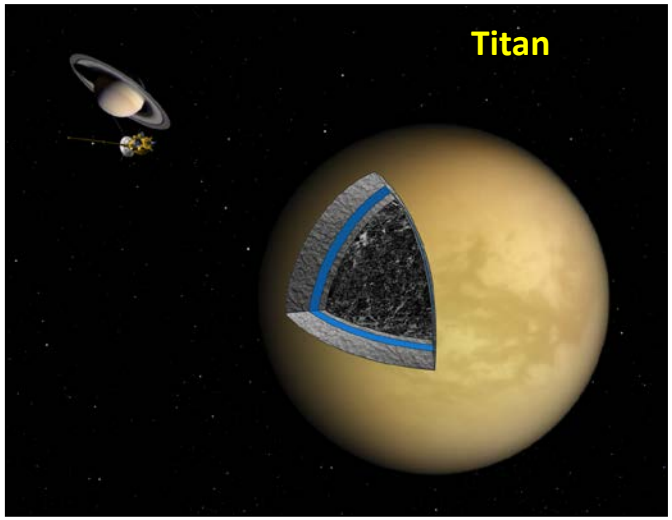
# GRAIL Reveals Lunar Interior Structure

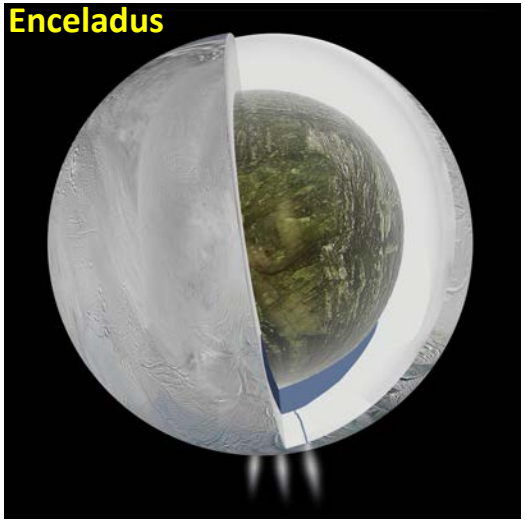




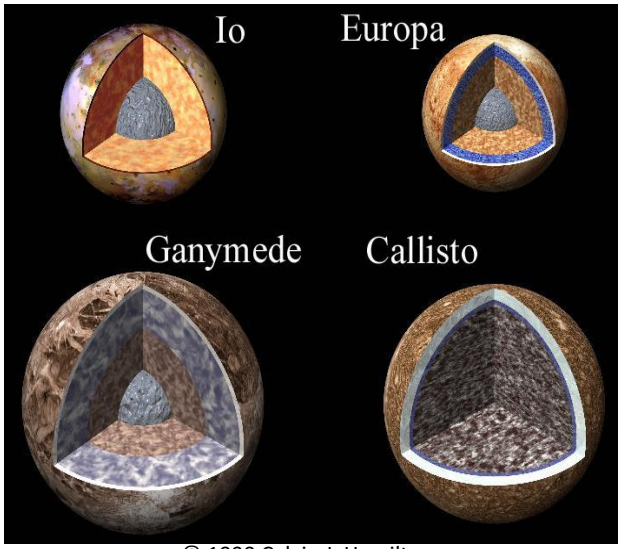

Surface and sub-surface effects

# Moons of Large Planets




**Models of the interiors of the Galilean satellites based on magnetic and gravity measurements**



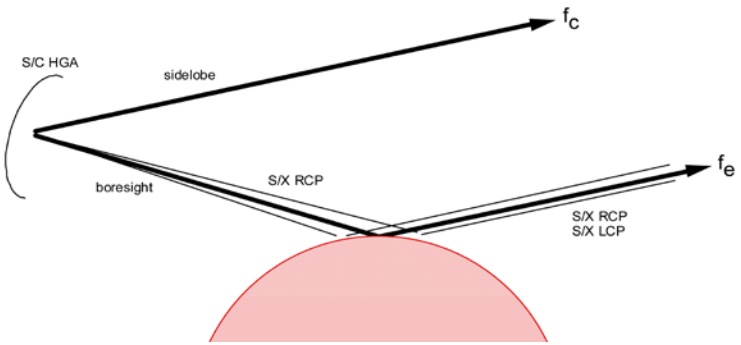

© 1999 Calvin J. Hamilton

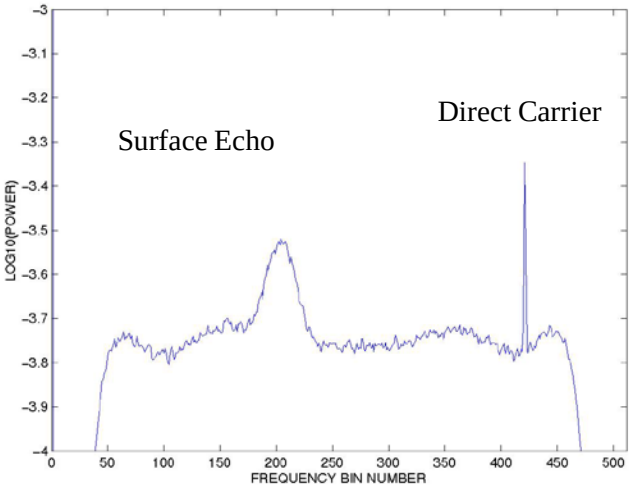
**Tidal observations by Cassini gravity team**

***Titan: Iess et al., 2011 & 2012***
***Enceladus: Iess et al., 2014***

# Surface Characteristics

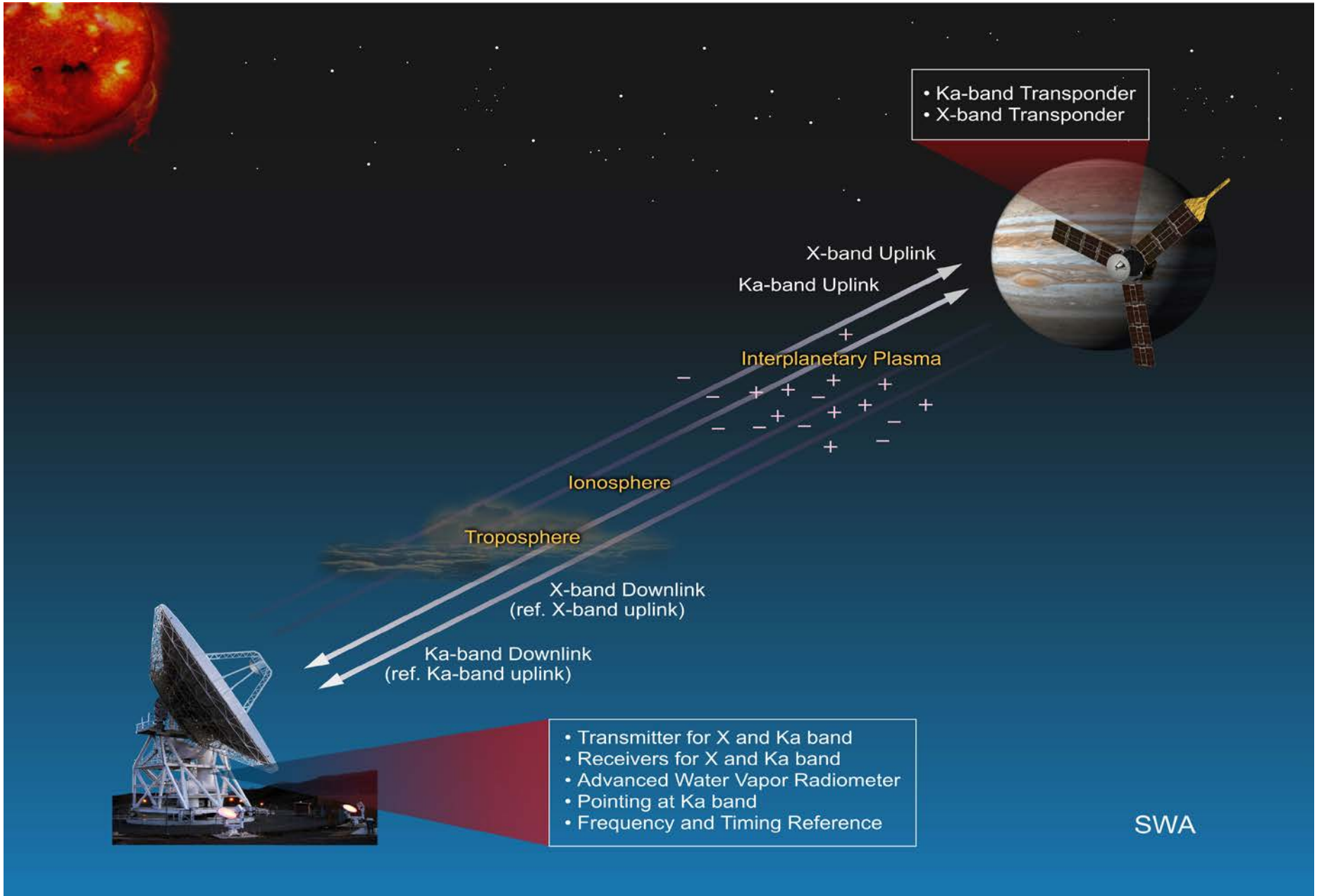
- **Study properties of planetary surfaces**
  - **Roughness & dielectric constant**
- **Observables:**
  - **Ratio of received energy in same and opposite polarizations**
- **Configuration:**
  - **Point to planet's surface and receive echo on Earth**
  - **Record both polarizations**
  - **Special noise calibration procedures**
  - **Open-loop receivers**
  - **One-way downlink**



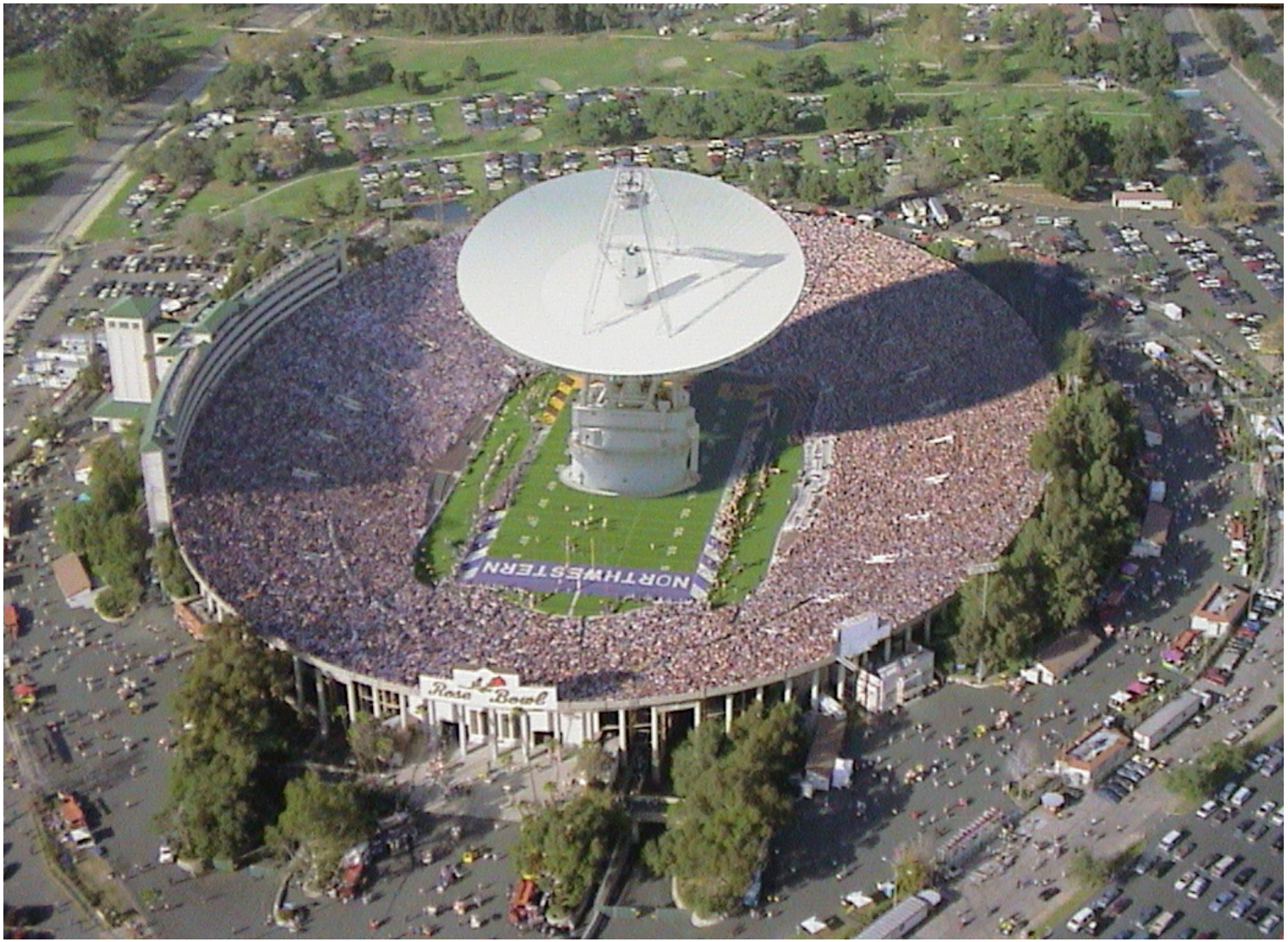




Source: R.A. Simpson & M. Patzold

# Largest Instrument in Solar System



# Not possible without Deep Space Network




**Composite image to show relative size of 70-meter diameter station**

# Cassini Meets Marconi

**Uplink Possibilities**

X-band ~ 7.9 GHz

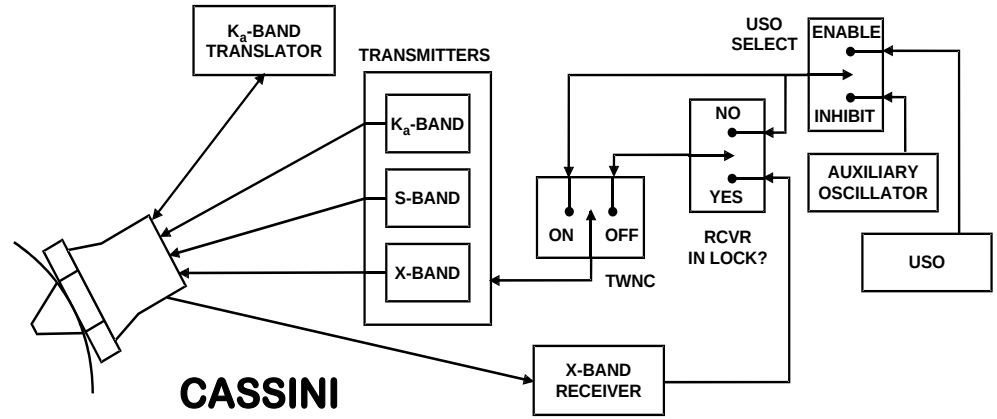
$K_a$-band ~ 34 GHz

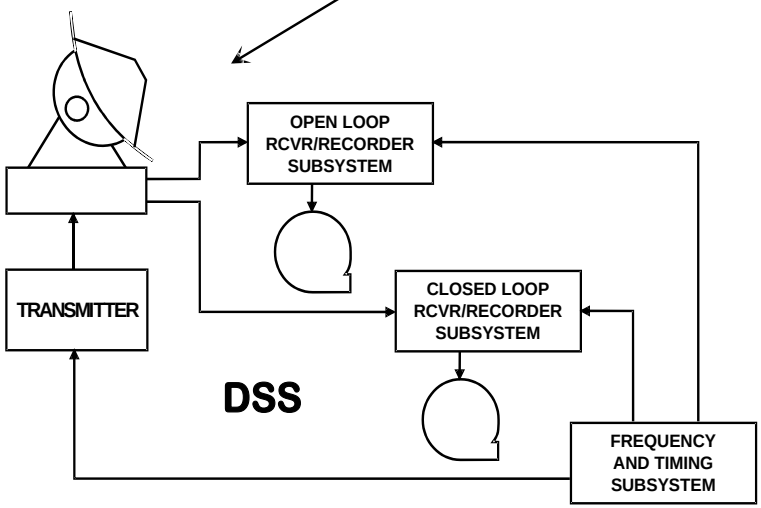
**Downlink Possibilities**

S-band ~ 2.3 GHz

X-band ~ 8.4 GHz

$K_a$-band ~ 32 GHz




**HGA Gain ~ 47 dBi**

**Power ~ 20 W**

**EIRP ~ 88.6 dBm**

**Digital communication: BPSK**

**Bit rates: 5 bps to 248 kbps**

**Phase modulated onto carrier**
**or subcarriers of 360 or 22.5 kHz**

**Reed-Solomon outer code**
**Convolutional inner code**

# Can You Hear Me Now?

$P_R$= Received power

$$P_R = P_T L_T G_T L_{TP} L_S L_A L_P L_{RP} G_R L_R$$

$P_T$=Total transmitted power

$L_T$= Transmission Circuit loss

$G_T$=Transmitting antenna gain

$L_{TP}$= Pointing loss of transmitting antenna

**$L_S$=space loss (distance squared)**

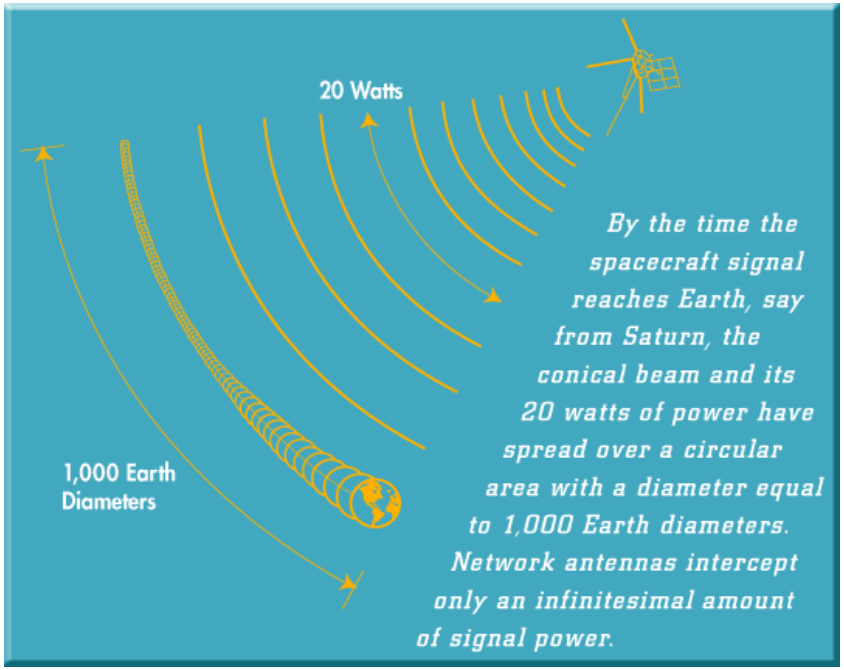
$L_A$= Atmospheric attenuation

$L_P$=Polarization loss

$L_{RP}$=Pointing loss of receiving antenna

$G_R$=Receiving antenna gain

$L_R$= Receiving circuit loss



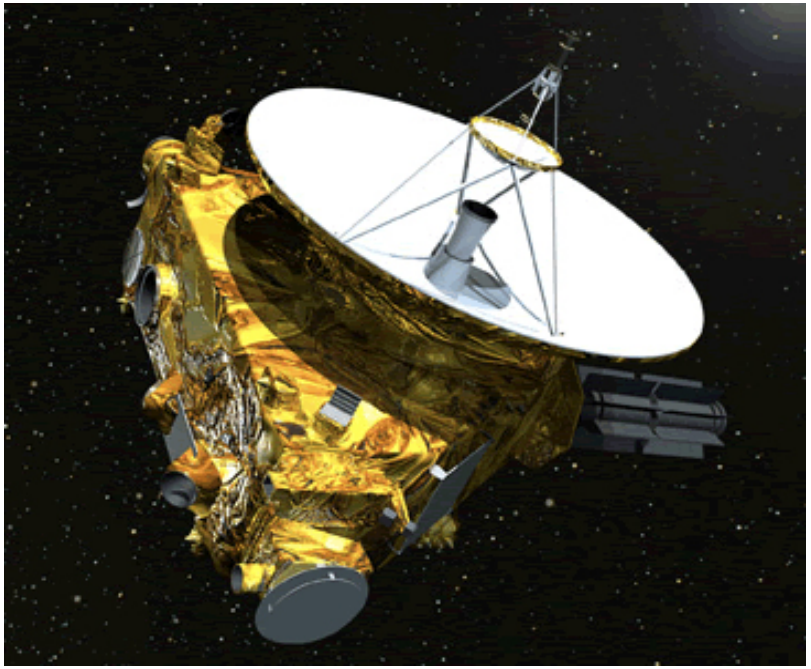
# Future Directions

**Fundamental limits on Radio Science experiments, especially radio occultation is received signal-to-noise ratio. This can be improved by:**

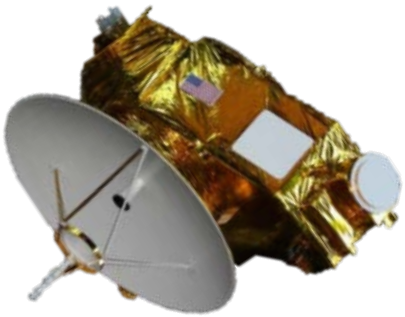
- **Arraying of Stations**
- **Uplink Radio Science**
- **Optical Science**
- **Spacecraft-to-spacecraft link science**

# The Future Is Now

- New Horizons pioneered a new mode of Radio Science
- Occultation in uplink mode
  - Transmit from Deep Space Network and receive onboard the spacecraft
  - Special processor onboard
  - Signal-to-Noise advantage of ~1000 times!
- Key to REX success at vast distance across the solar system



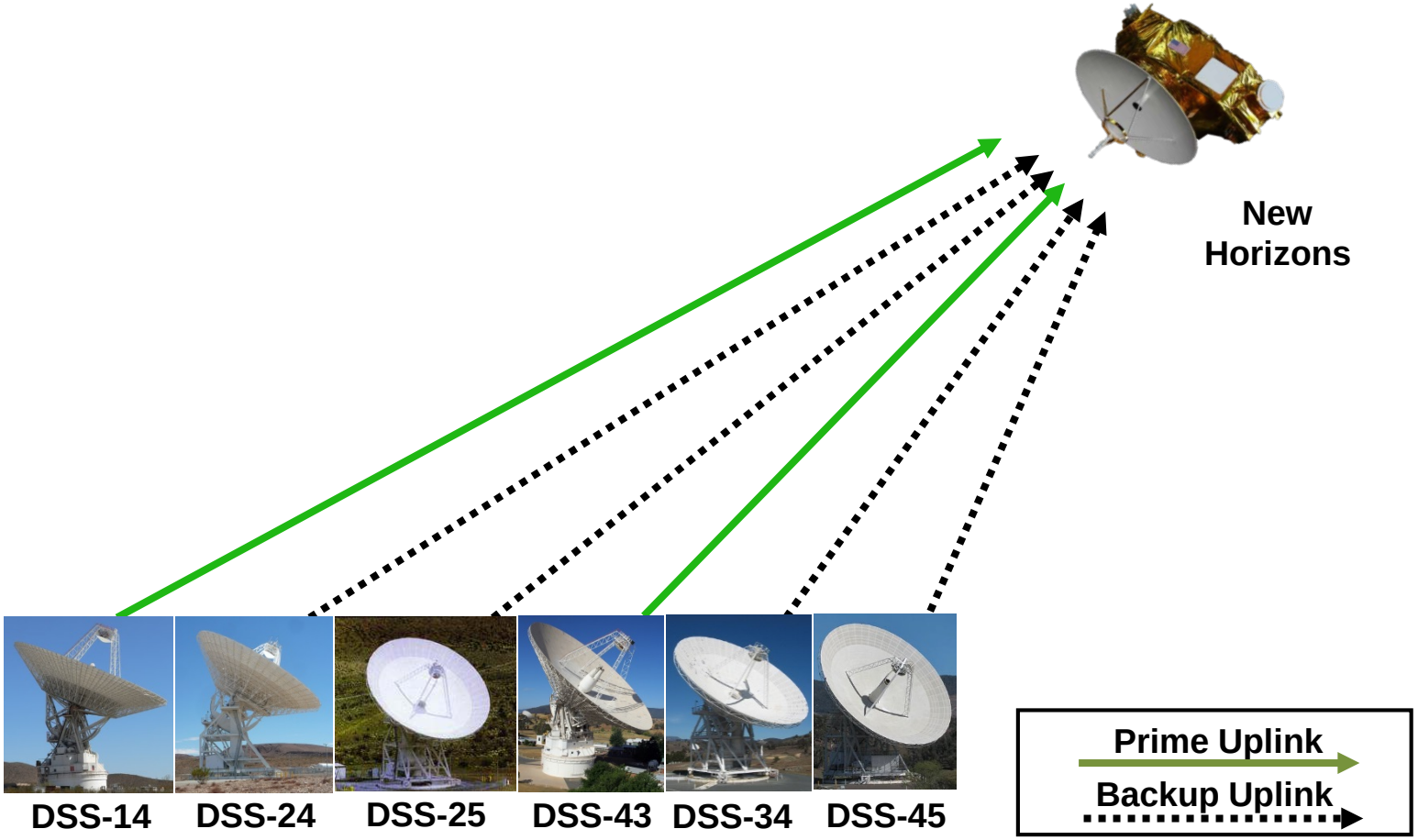
# New Horizons REX Uplink Radio Occultation



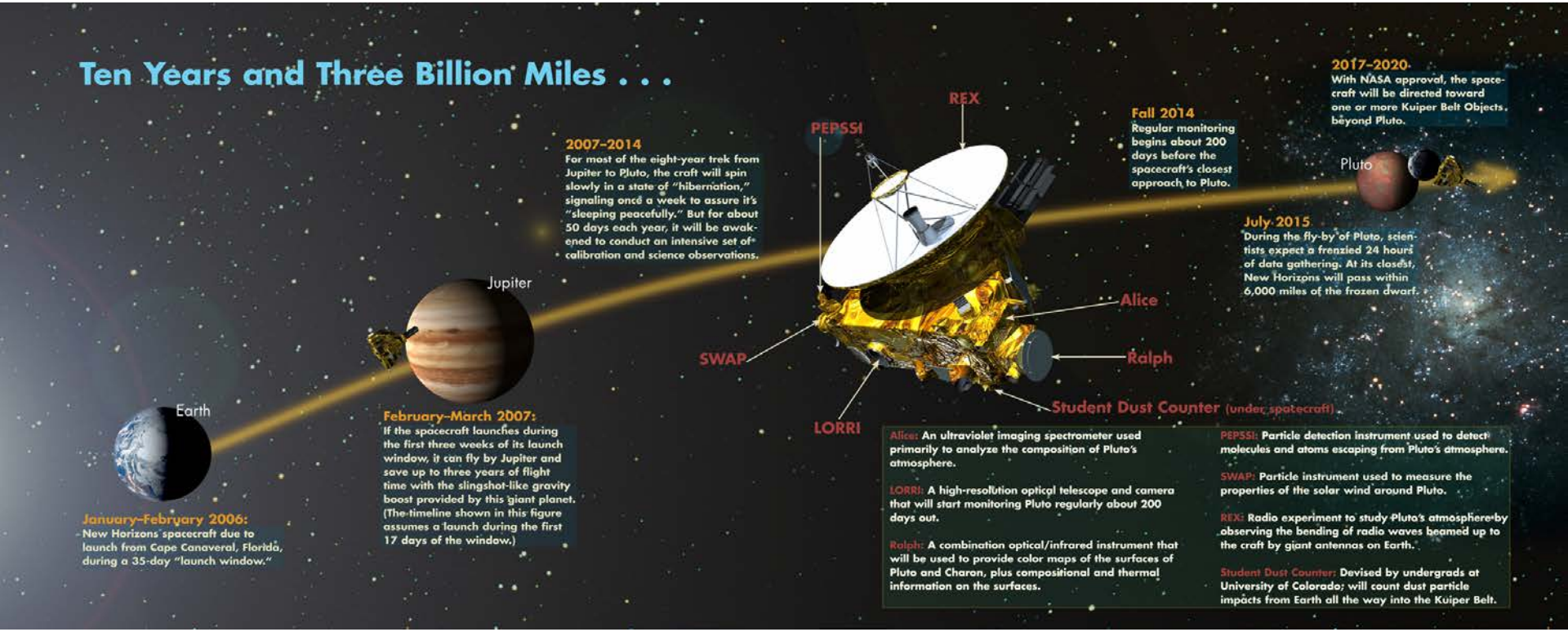
**New Horizons**

Through Pluto's Atmosphere

# New Horizons REX Configuration



MADRID
ROSE
63
65
THB
54
M01O MVN
55
GOLDSTONE
NHPC
14
MMS4
15
NHPC
24
NHPC
25
NHPC
26
CANBERRA
NHPC
43
NHPC
45
NHPC
34
35
ANTENNAS
WORLD MAP
UTC 195/07:48:36
View 1
2
3
4
5


Ten Years and Three Billion Miles . . .
Earth
January–February 2006:
New Horizons spacecraft due to launch from Cape Canaveral, Florida, during a 35-day "launch window."
Jupiter
February–March 2007:
If the spacecraft launches during the first three weeks of its launch window, it can fly by Jupiter and save up to three years of flight time with the slingshot-like gravity boost provided by this giant planet. (The timeline shown in this figure assumes a launch during the first 17 days of the window.)
2007–2014
For most of the eight-year trek from Jupiter to Pluto, the craft will spin slowly in a state of "hibernation," signaling once a week to assure it's "sleeping peacefully." But for about 50 days each year, it will be awakened to conduct an intensive set of calibration and science observations.
PEPSSI
REX
SWAP
LORRI
Alice
Ralph
Student Dust Counter (under spatecraft)
Fall 2014
Regular monitoring begins about 200 days before the spacecraft's closest approach to Pluto.
July 2015
During the fly-by of Pluto, scientists expect a frenzied 24 hours of data gathering. At its closest, New Horizons will pass within 6,000 miles of the frozen dwarf.
Pluto
2017–2020
With NASA approval, the spacecraft will be directed toward one or more Kuiper Belt Objects beyond Pluto.
Alice: An ultraviolet imaging spectrometer used primarily to analyze the composition of Pluto's atmosphere.
LORRI: A high-resolution optical telescope and camera that will start monitoring Pluto regularly about 200 days out.
Ralph: A combination optical/infrared instrument that will be used to provide color maps of the surfaces of Pluto and Charon, plus compositional and thermal information on the surfaces.
PEPSSI: Particle detection instrument used to detect molecules and atoms escaping from Pluto's atmosphere.
SWAP: Particle instrument used to measure the properties of the solar wind around Pluto.
REX: Radio experiment to study Pluto's atmosphere by observing the bending of radio waves beamed up to the craft by giant antennas on Earth.
Student Dust Counter: Devised by undergrads at University of Colorado; will count dust particle impacts from Earth all the way into the Kuiper Belt.

# New Horizons Radioscience EXperiment (REX)

- New Horizons Radio Science Experiments (REX) is a custom-made instrument from Stanford University
  - Card installed in spacecraft radio
  - Ultra-Stable Oscillator (JHU-APL) for reference

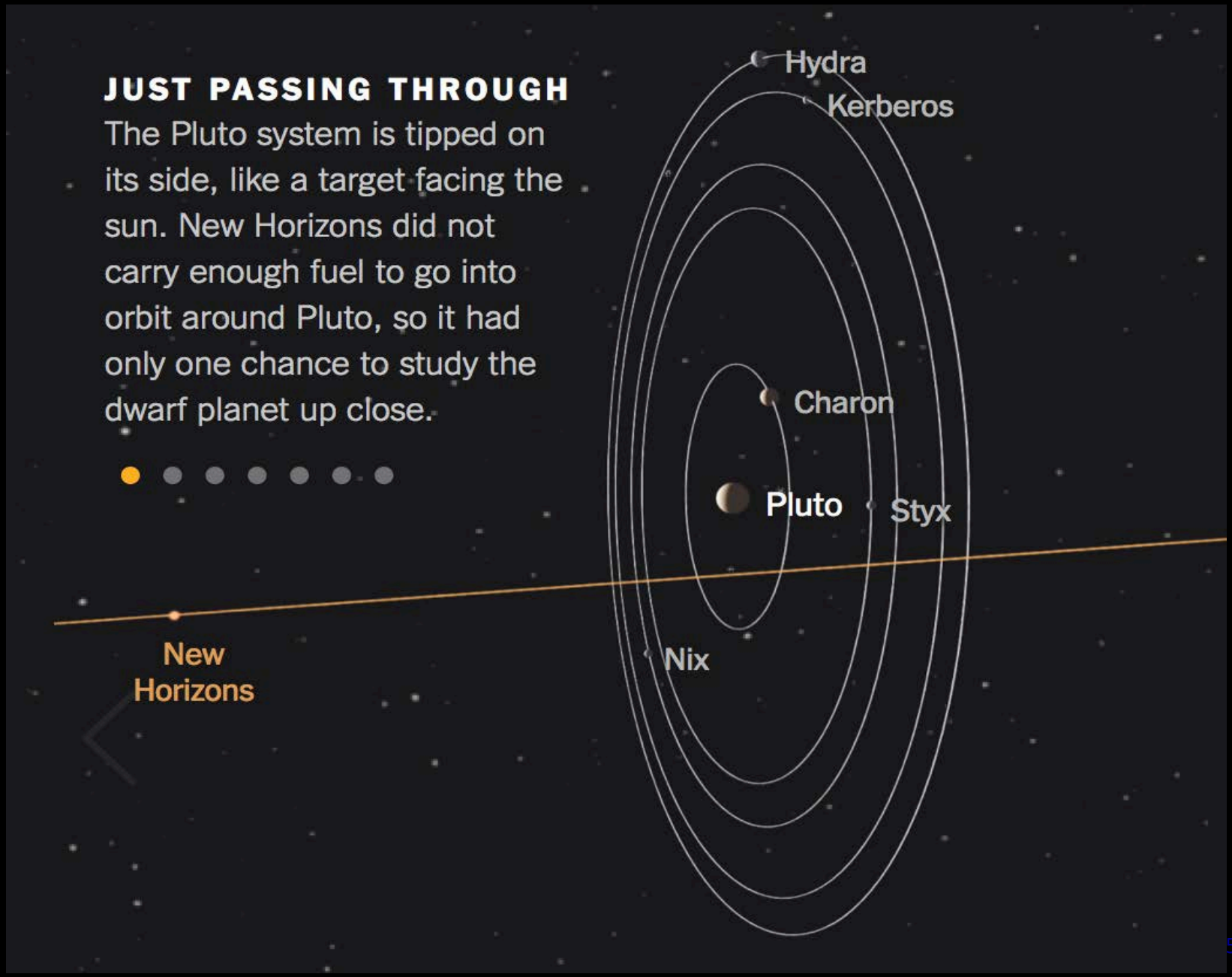
## Science Objectives:

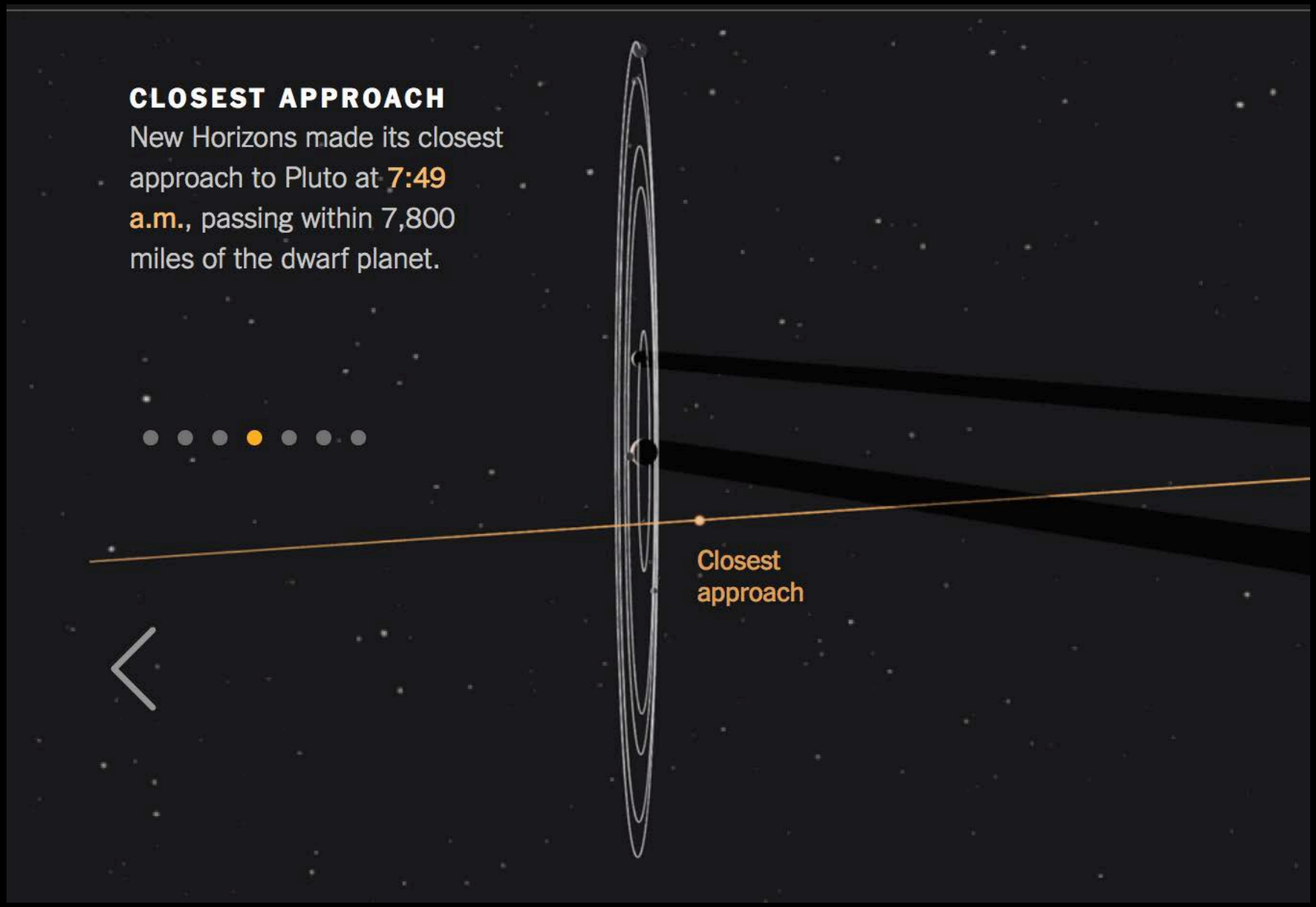
- Investigate the atmospheric structure of Pluto
- Measure the gravity field of the Pluto system
- Explore the surface characteristics of Pluto

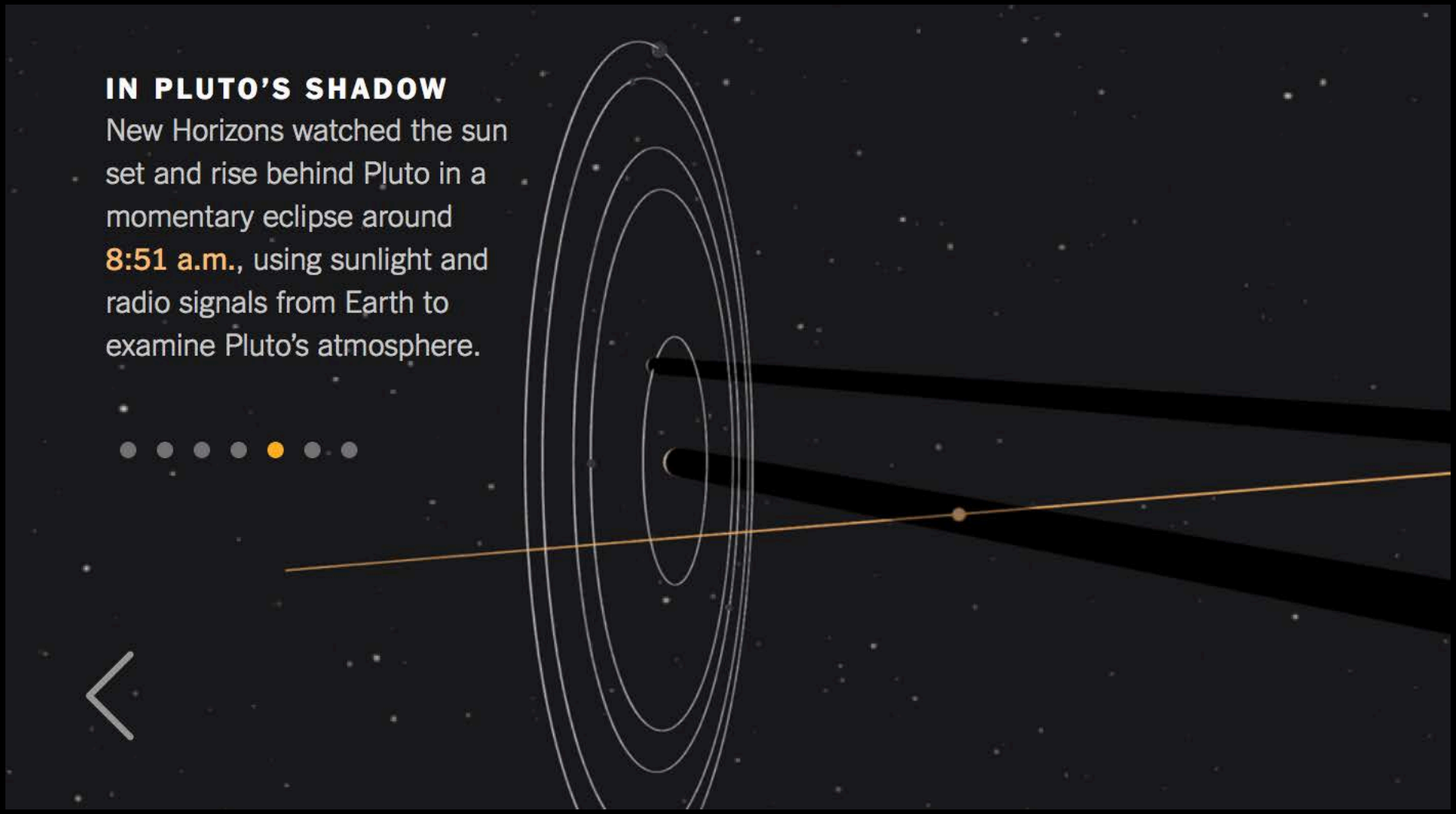
Space Sci Rev (2008) 140: 217–259
DOI 10.1007/s11214-007-9302-3

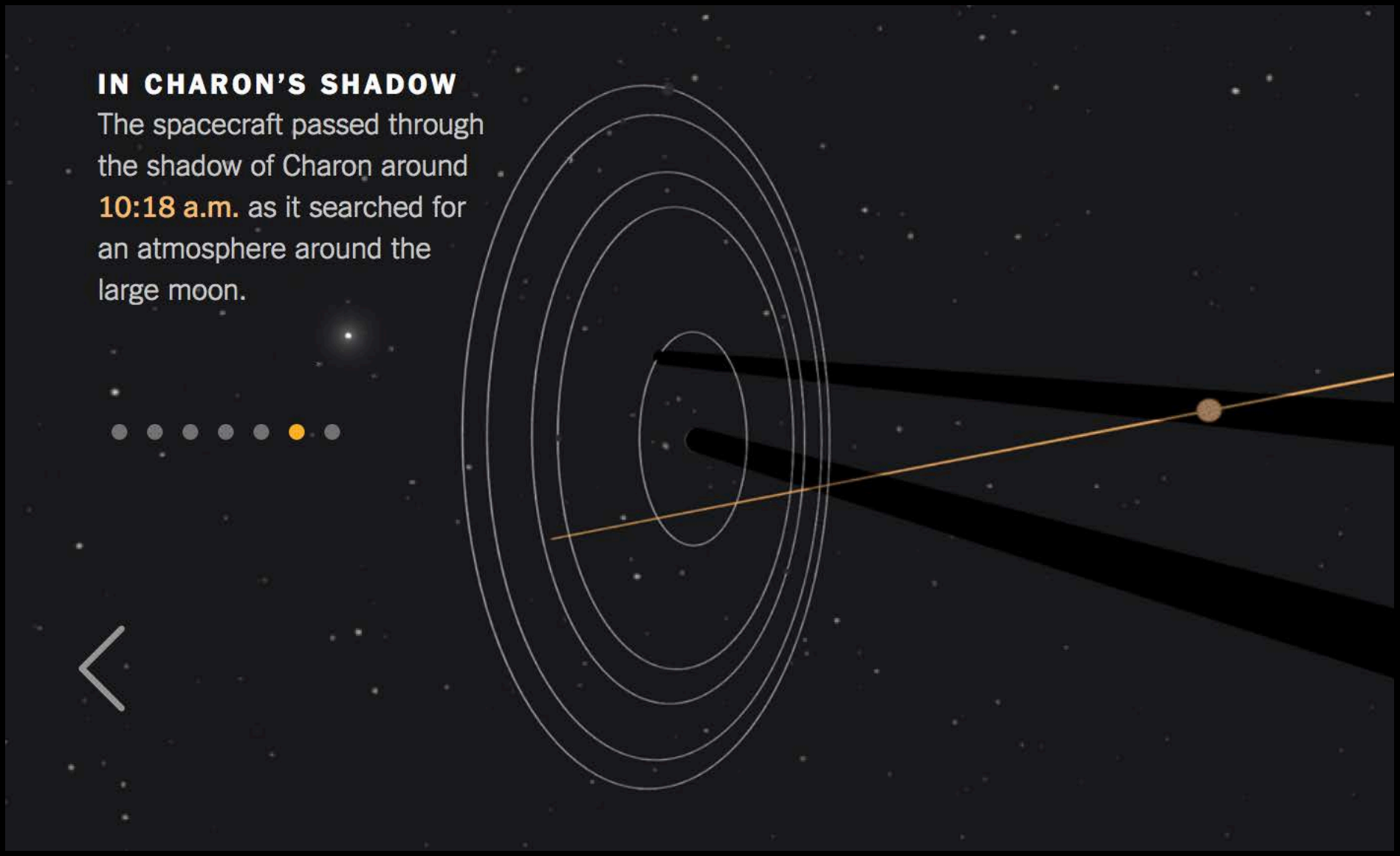
**The New Horizons Radio Science Experiment (REX)**

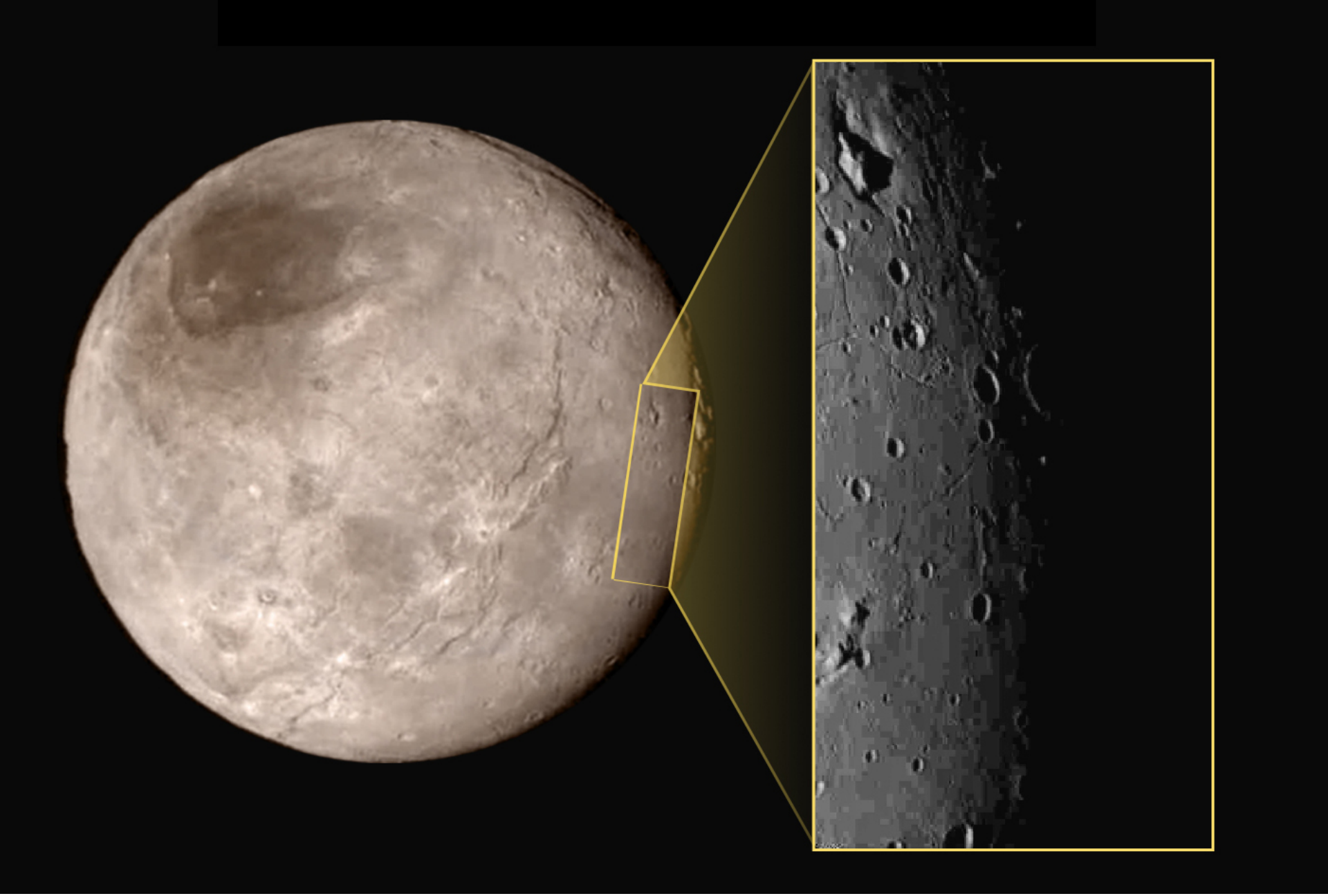
G.L. Tyler · I.R. Linscott · M.K. Bird · D.P. Hinson ·
D.F. Strobel · M. Pätzold · M.E. Summers ·
K. Sivaramakrishnan


JUST PASSING THROUGH
The Pluto system is tipped on its side, like a target facing the sun. New Horizons did not carry enough fuel to go into orbit around Pluto, so it had only one chance to study the dwarf planet up close.
Hydra
Kerberos
Charon
Pluto
Styx
Nix
New Horizons


CLOSEST APPROACH
New Horizons made its closest approach to Pluto at 7:49 a.m., passing within 7,800 miles of the dwarf planet.
Closest approach

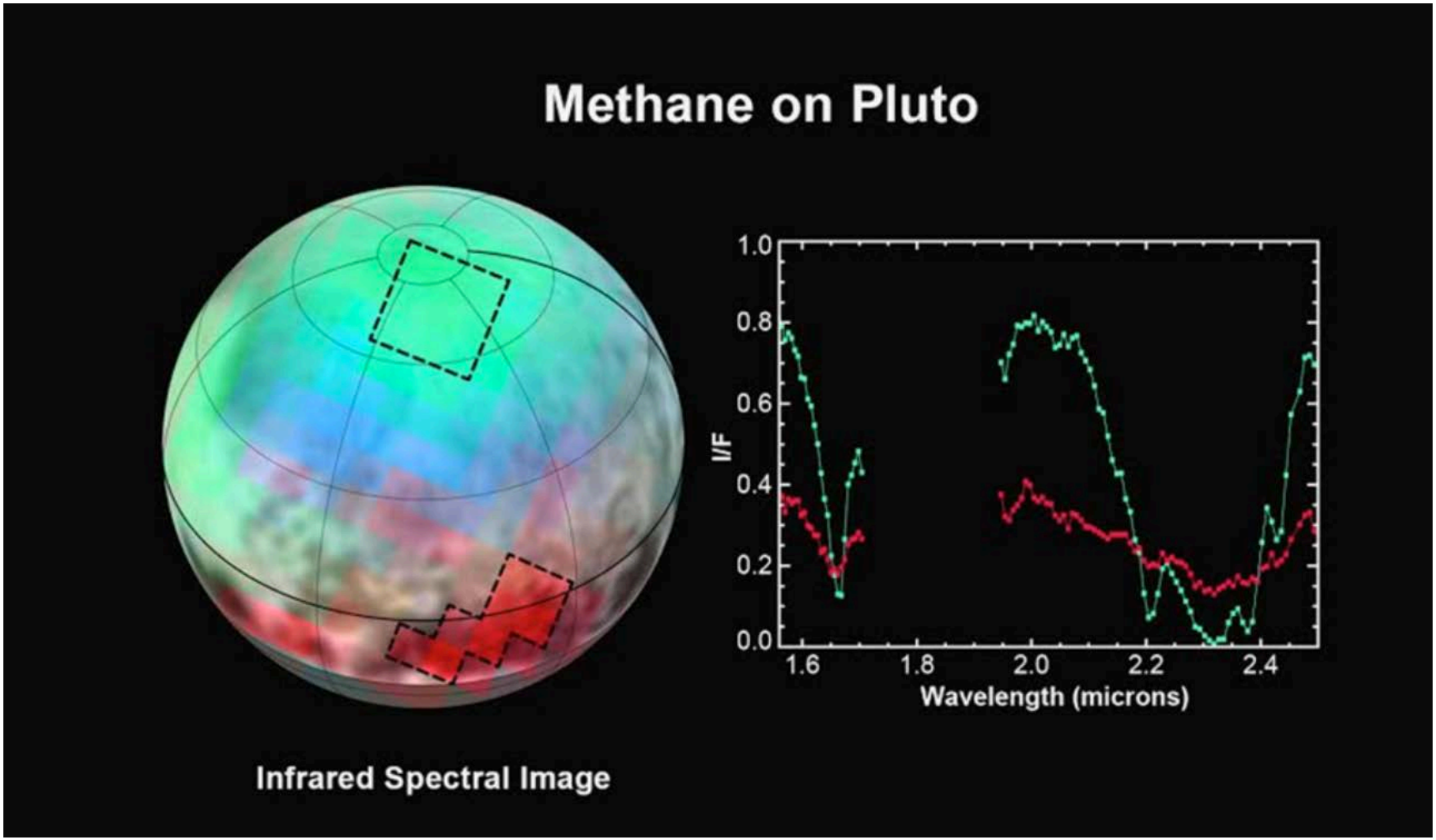

IN PLUTO'S SHADOW
New Horizons watched the sun set and rise behind Pluto in a momentary eclipse around 8:51 a.m., using sunlight and radio signals from Earth to examine Pluto's atmosphere.


IN CHARON'S SHADOW
The spacecraft passed through the shadow of Charon around 10:18 a.m. as it searched for an atmosphere around the large moon.



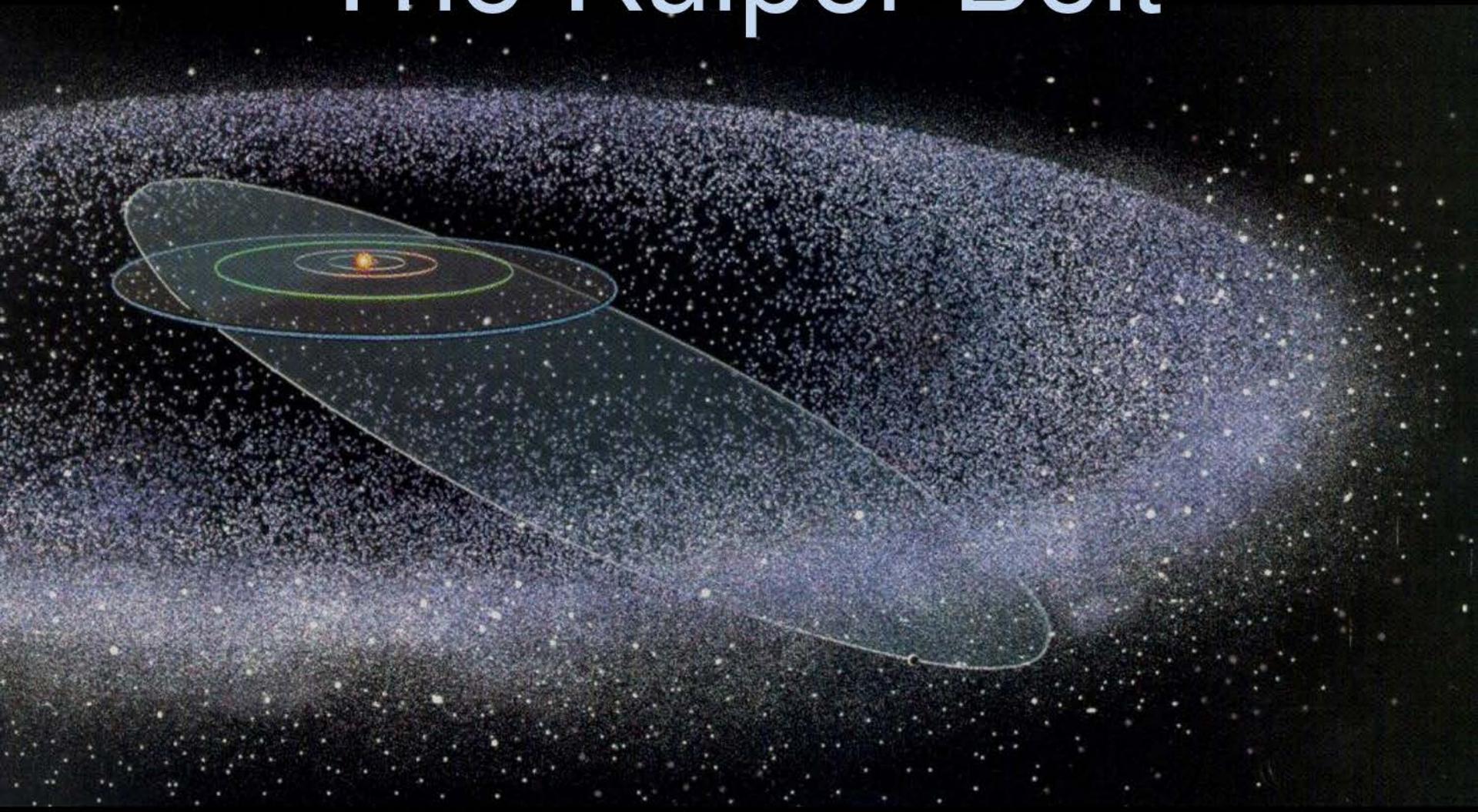
This new image of an area on Pluto's largest moon Charon has a captivating feature, a depression with a peak in the middle, shown here in the upper left corner of the inset.

NASA/JHU-APL/SWRI – DAMIAN PEACH

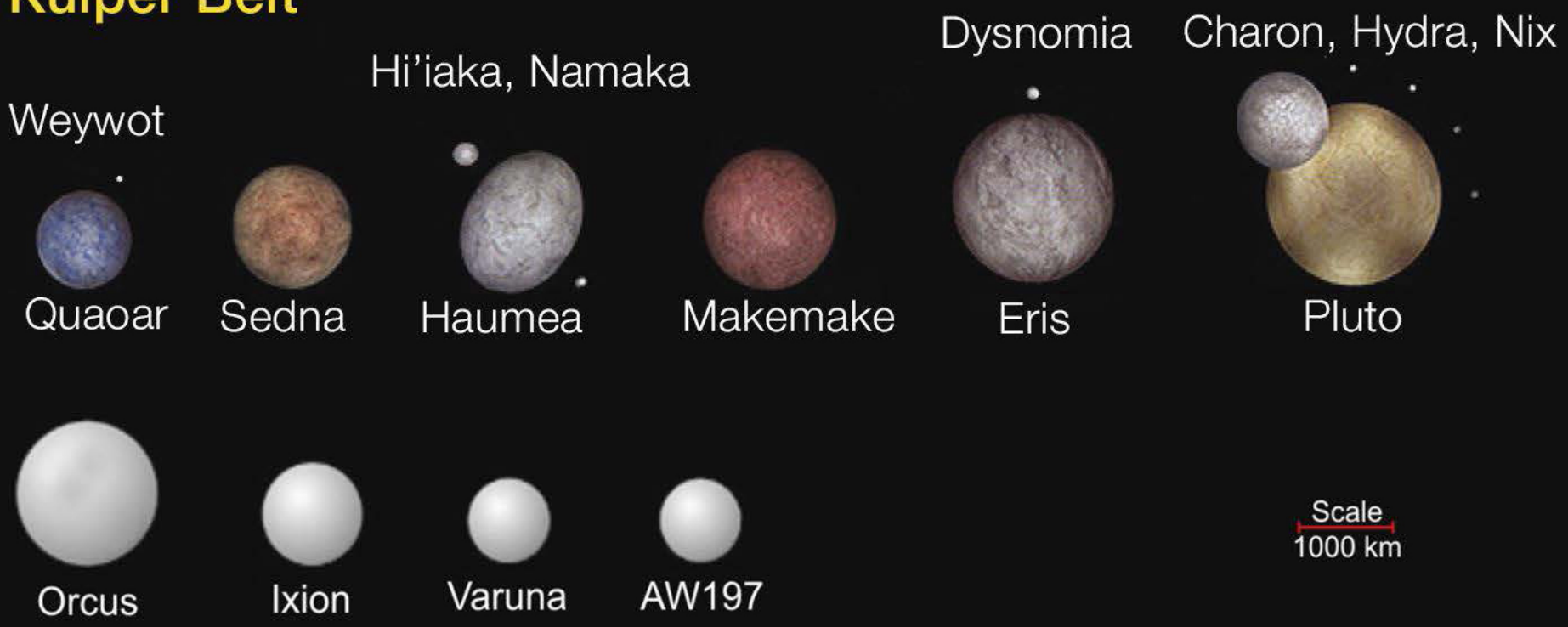



**The latest spectra from New Horizons Ralph instrument reveal an abundance of methane ice, but with striking differences from place to place across the frozen surface of Pluto.**

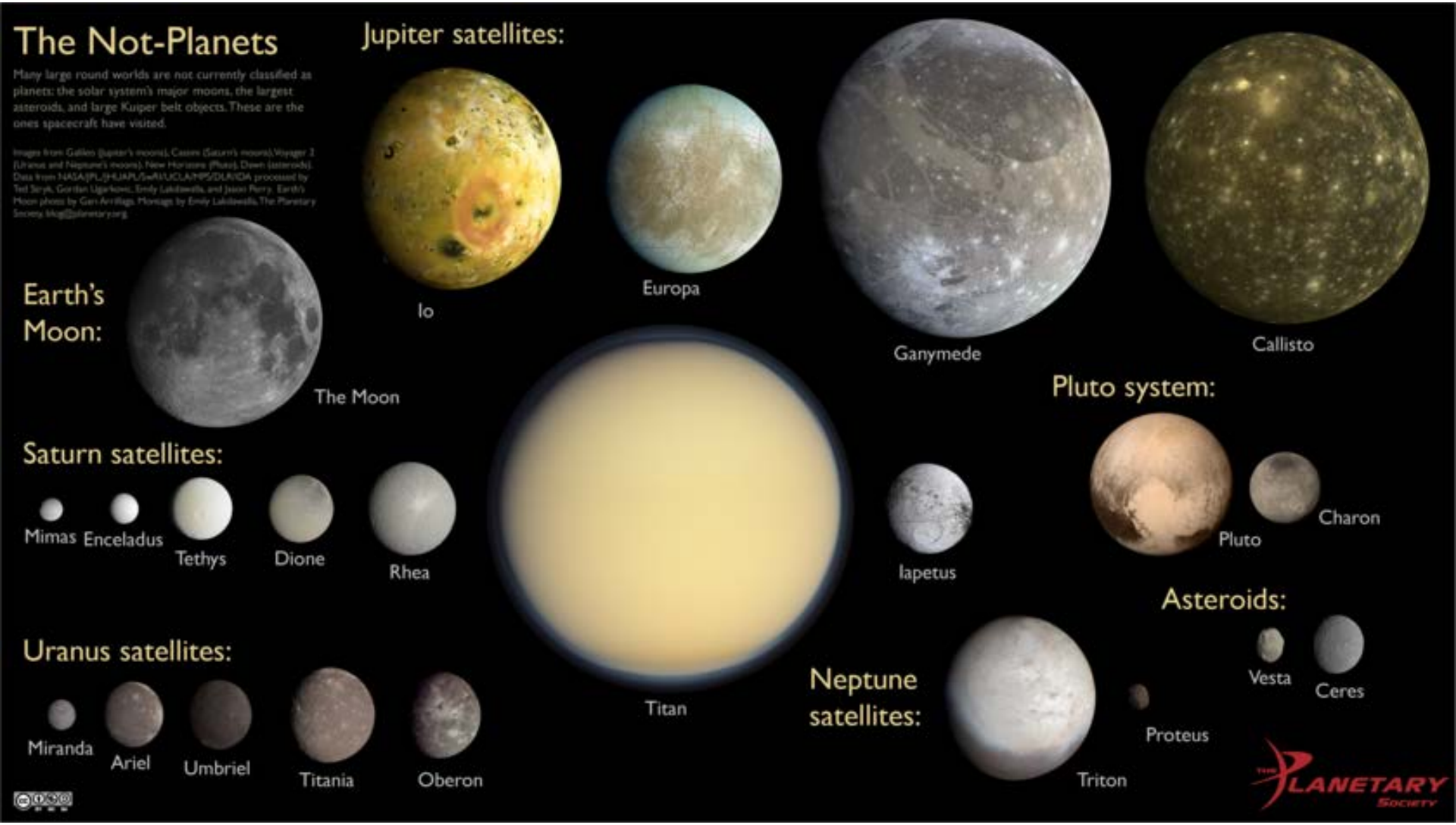
# The Kuiper Belt



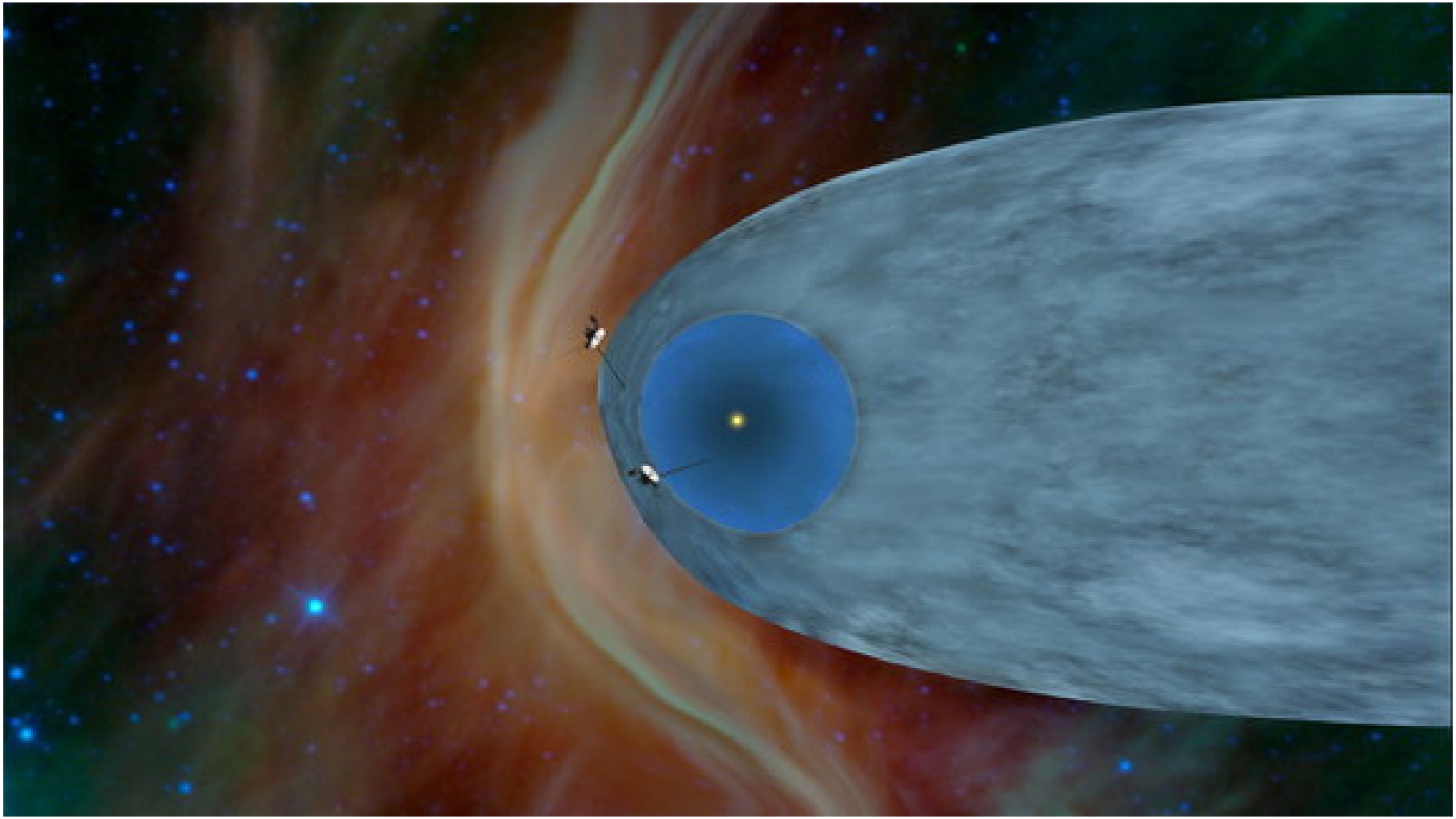
# Kuiper Belt


Weywot
Hi'iaka, Namaka
Dysnomia
Charon, Hydra, Nix
Quaoar
Sedna
Haumea
Makemake
Eris
Pluto
Orcus
Ixion
Varuna
AW197
Scale
1000 km

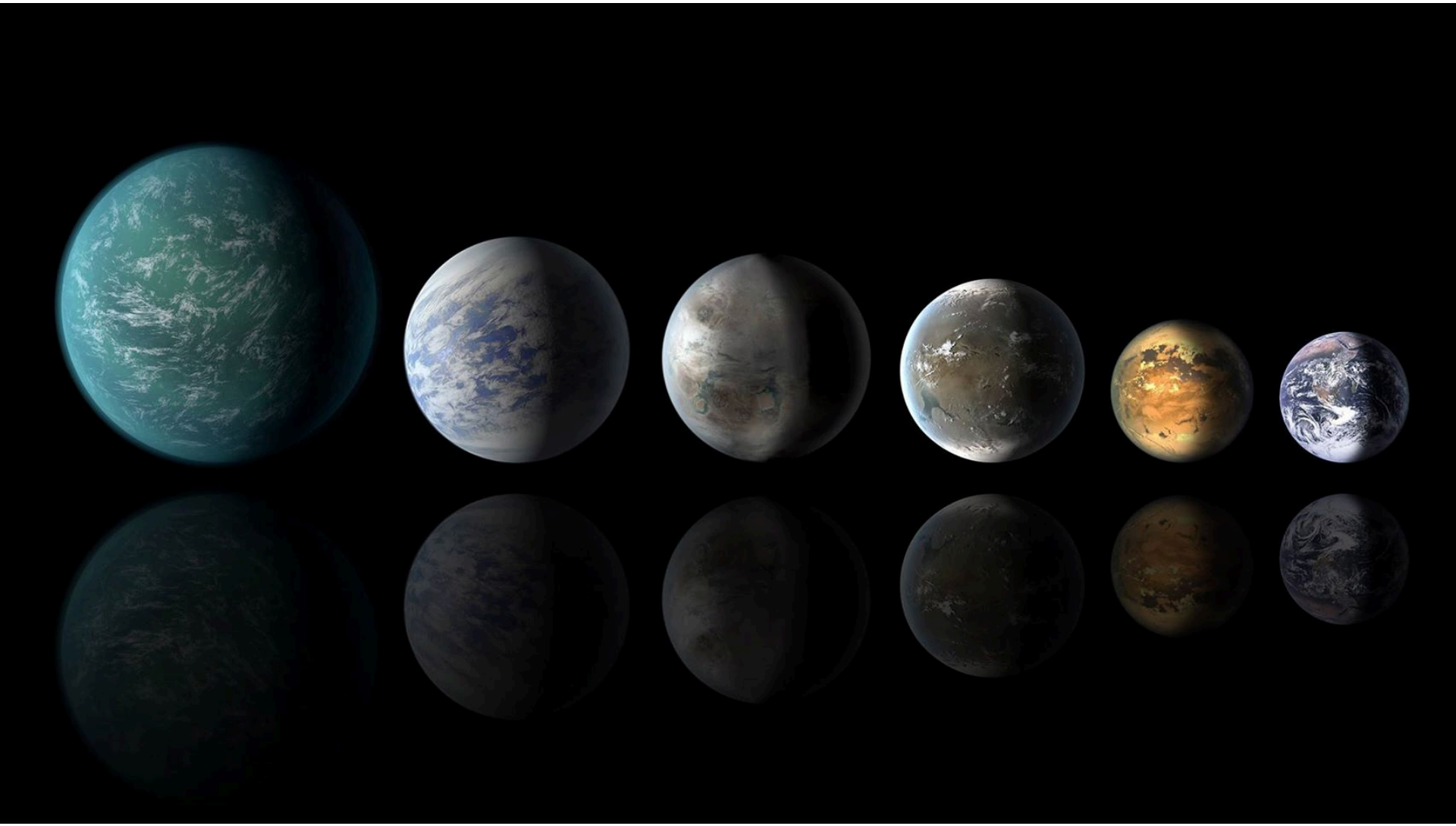
# Largest known Kuiper Belt objects


The Not-Planets
Many large round worlds are not currently classified as planets: the solar system's major moons, the largest asteroids, and large Kuiper belt objects. These are the ones spacecraft have visited.
Jupiter satellites:
Io
Europa
Ganymede
Callisto
Earth's Moon:
The Moon
Titan
Saturn satellites:
Mimas
Enceladus
Tethys
Dione
Rhea
Iapetus
Pluto system:
Pluto
Charon
Asteroids:
Vesta
Ceres
Uranus satellites:
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune satellites:
Triton
Proteus
THE PLANETARY SOCIETY

# What Defines the Solar System



# Earth-Like Exo-Planets



Dear Earth, Thanks for visiting!
Love, Pluto