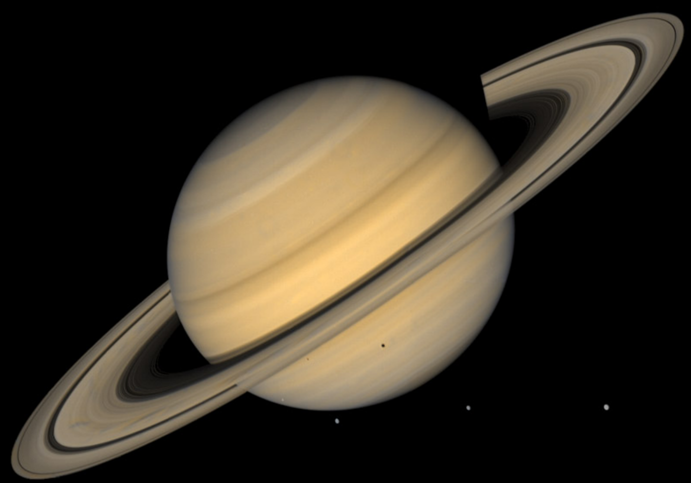
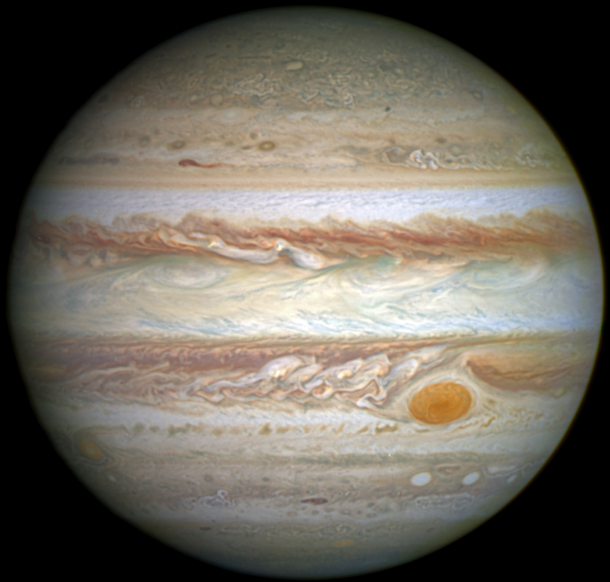
Where is Saturn's Deuterium Hiding?





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B Hesman; R Achterberg; L Fletcher; F M Flasar

Outline

- Introduction to Cassini-Huyguens
  - Specs
  - Instruments
    - The Composite Infrared Spectrometer
- Why do we care?
- Methodology
- Results

Cassini-Huygens Timeline

- October 1997: Cassini-Huygens is launched
- December 2000: Flyby of Jupiter
- July 2004: Arrival at Saturnian System
- January 2005: Huygens probe reaches Titan
- 2004-Present: Orbiting Saturnian system gathering data

CASSINI INTERPLANETARY TRAJECTORY

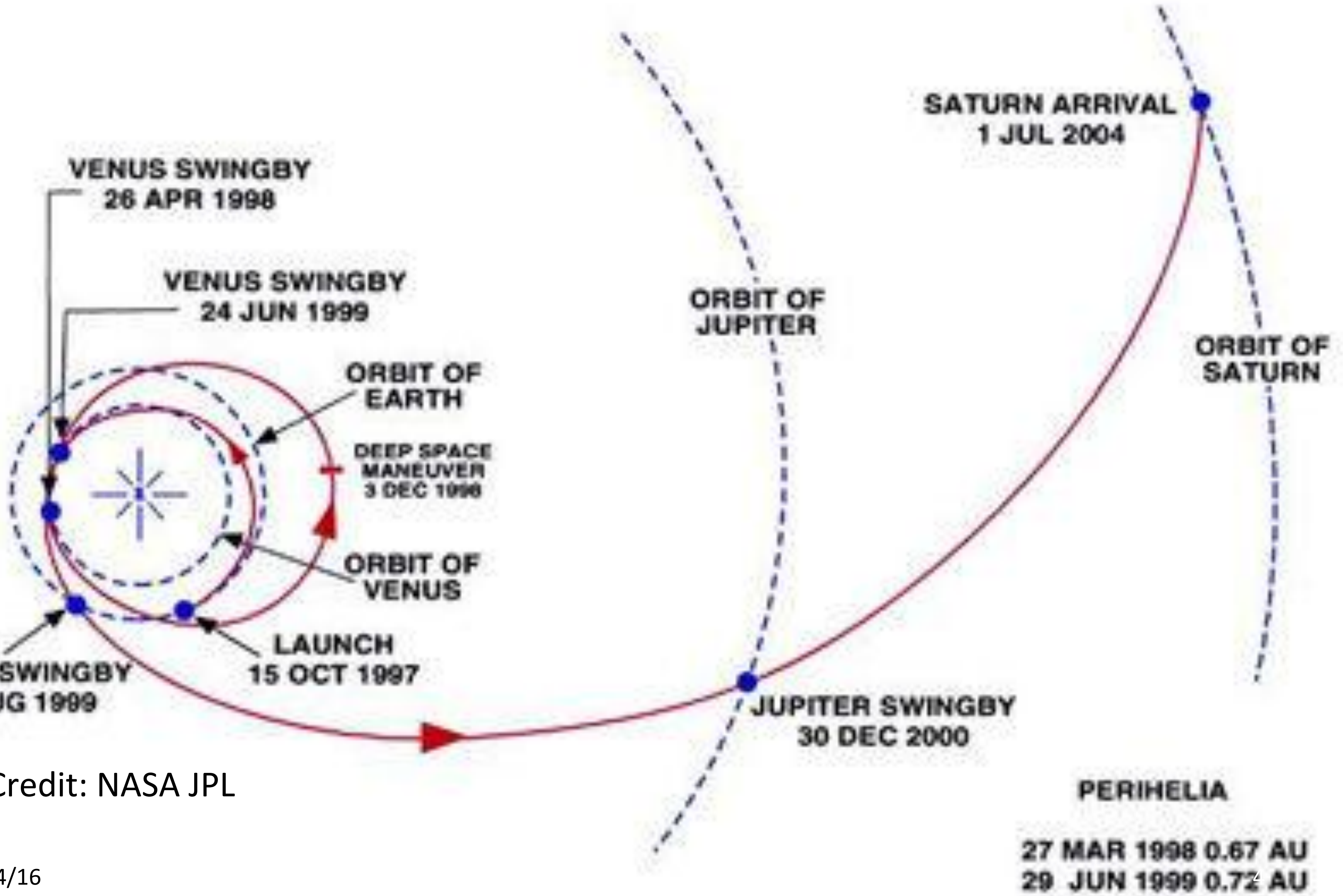
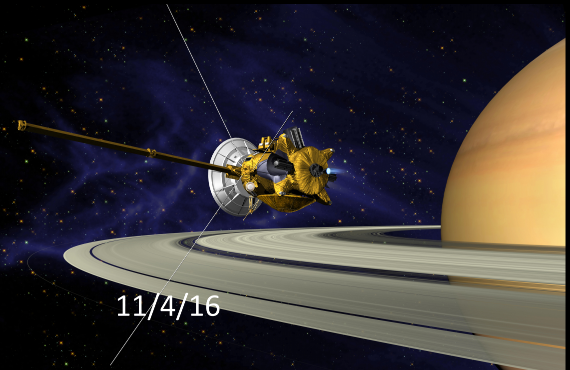
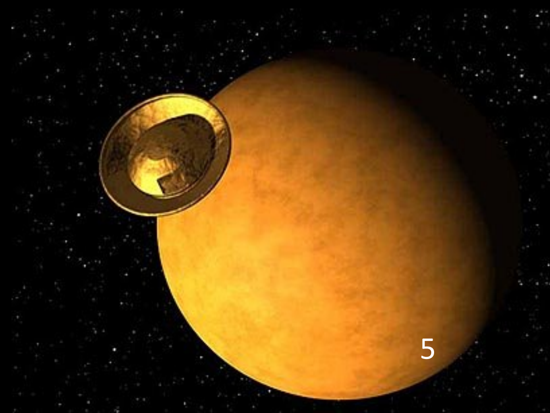


Image Credit: NASA JPL

Specifications

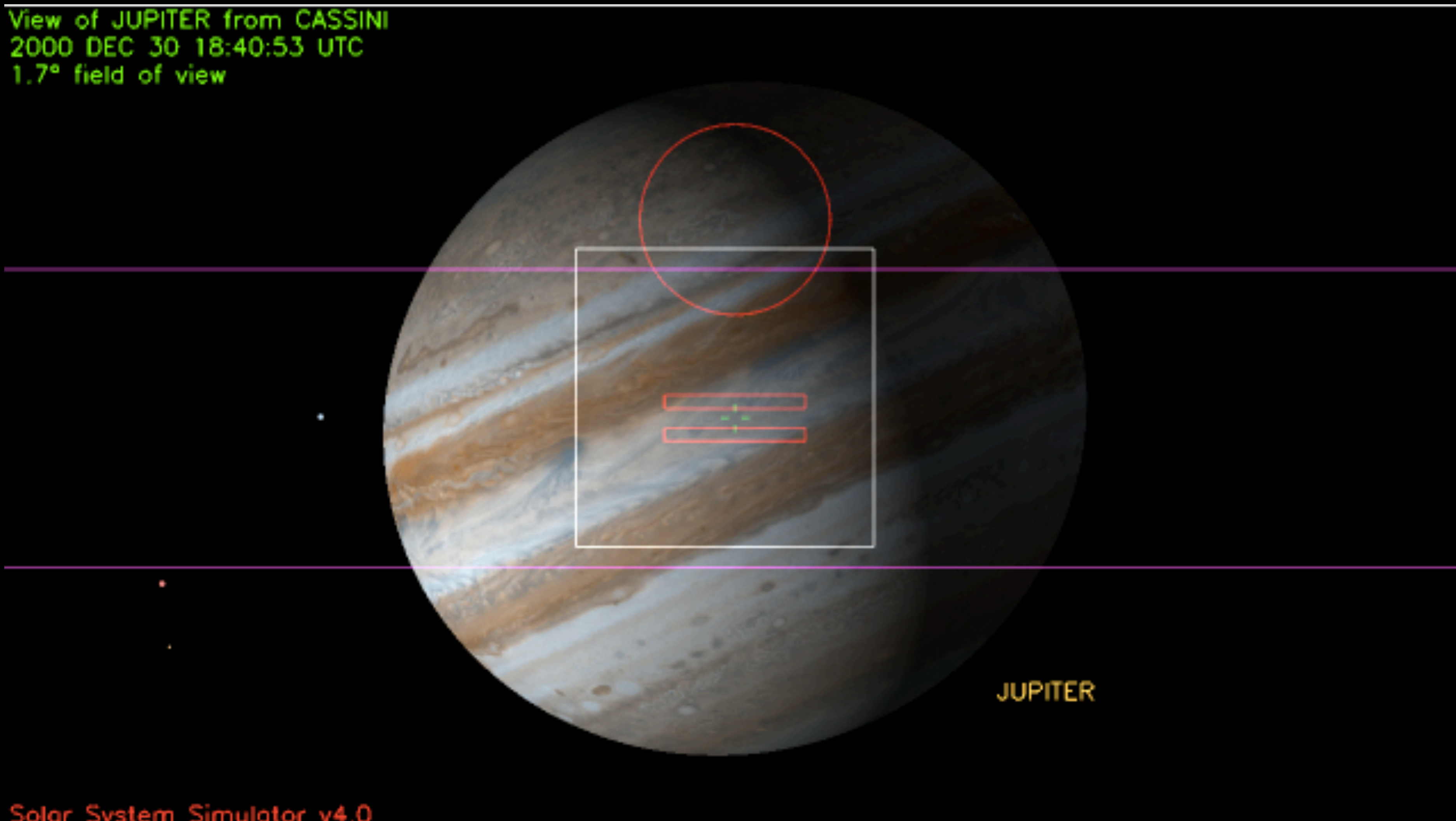
- 700 Watts of power
  - Radioisotope Thermoelectric Generators (RTGs)
- Cassini: 12 science instruments
- Huygens: 6 science instruments
- 27 science investigations

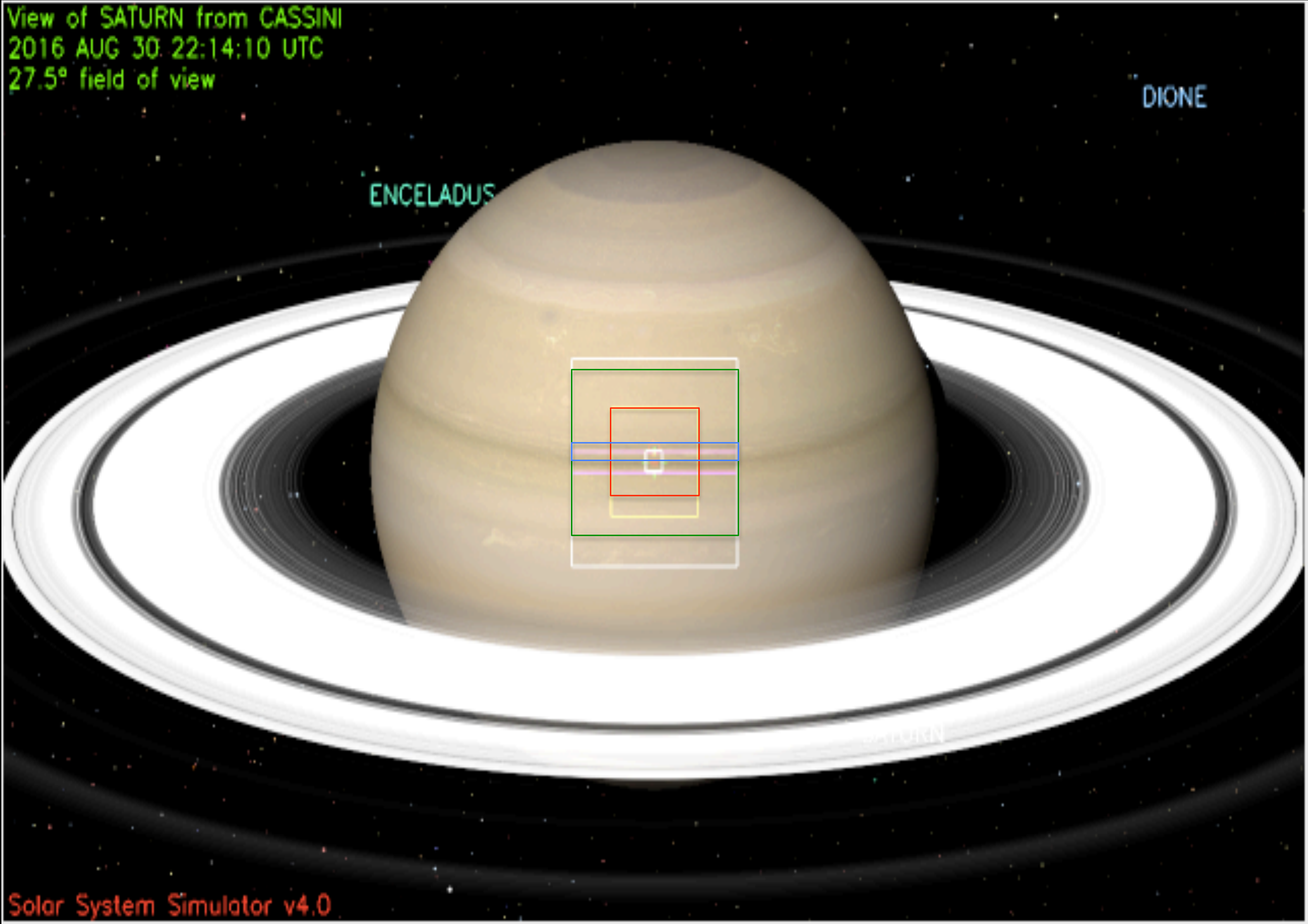


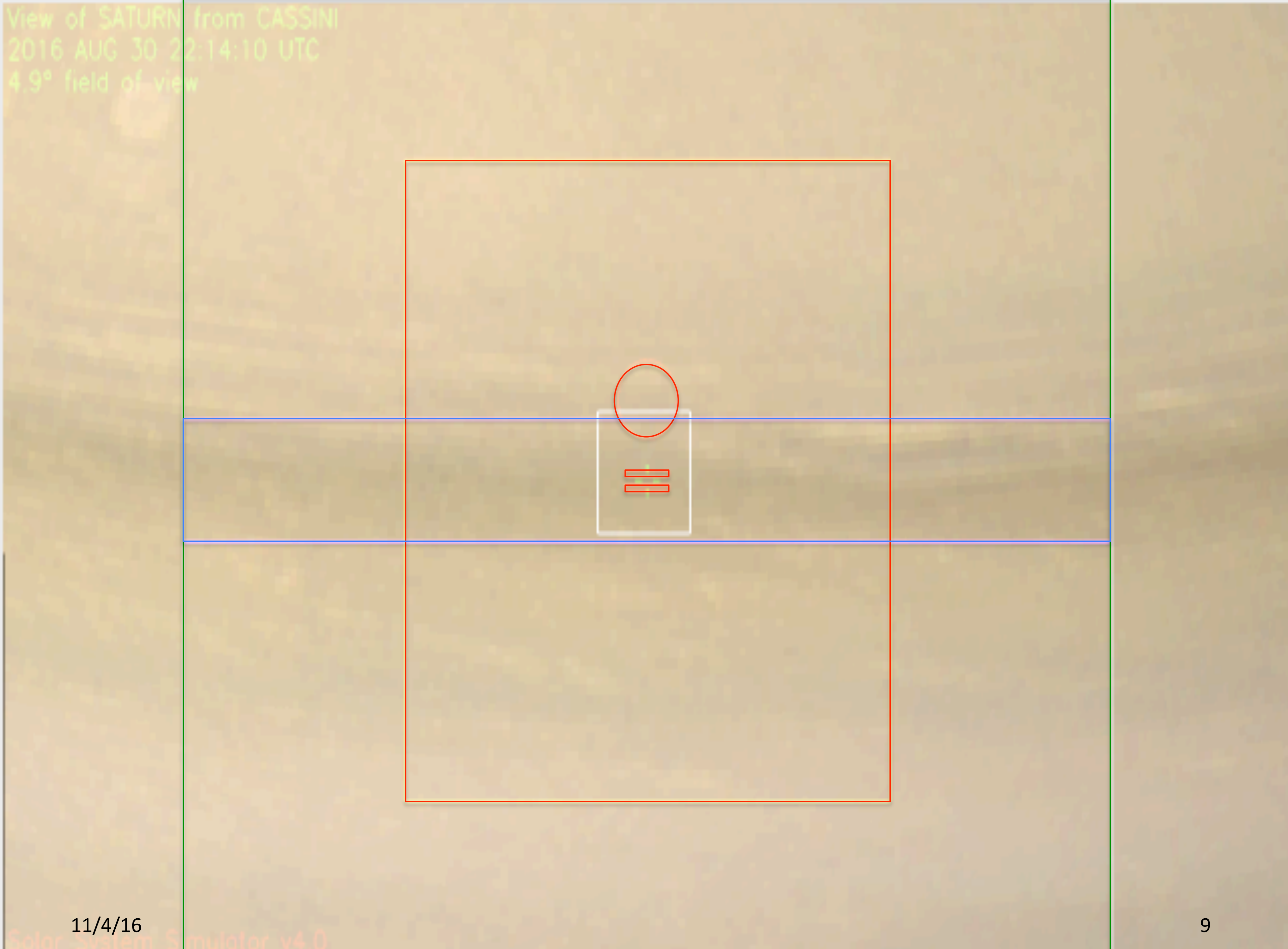


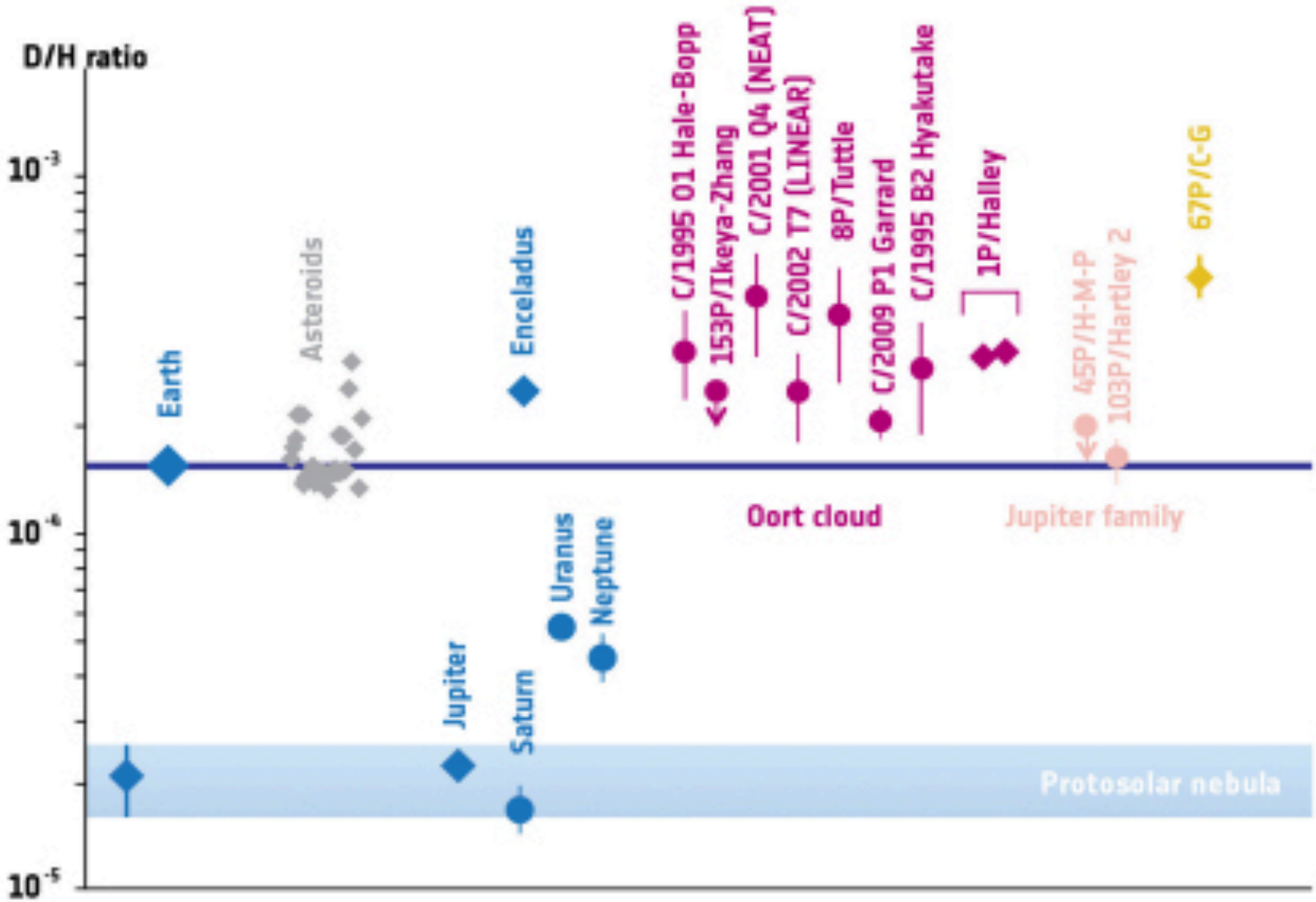
Composite Infrared Spectrometer (CIRS)

- 2 interferometers
  - Mid-Infrared
  - Far-Infrared
- Range of 10-1400 cm^{-1}
- Average operating power: 26.37 W
- Peak Data Rate: 6 KB/sec


View of JUPITER from CASSINI
2000 DEC 30 18:40:53 UTC
1.7° field of view
JUPITER
Solar System Simulator v4.0

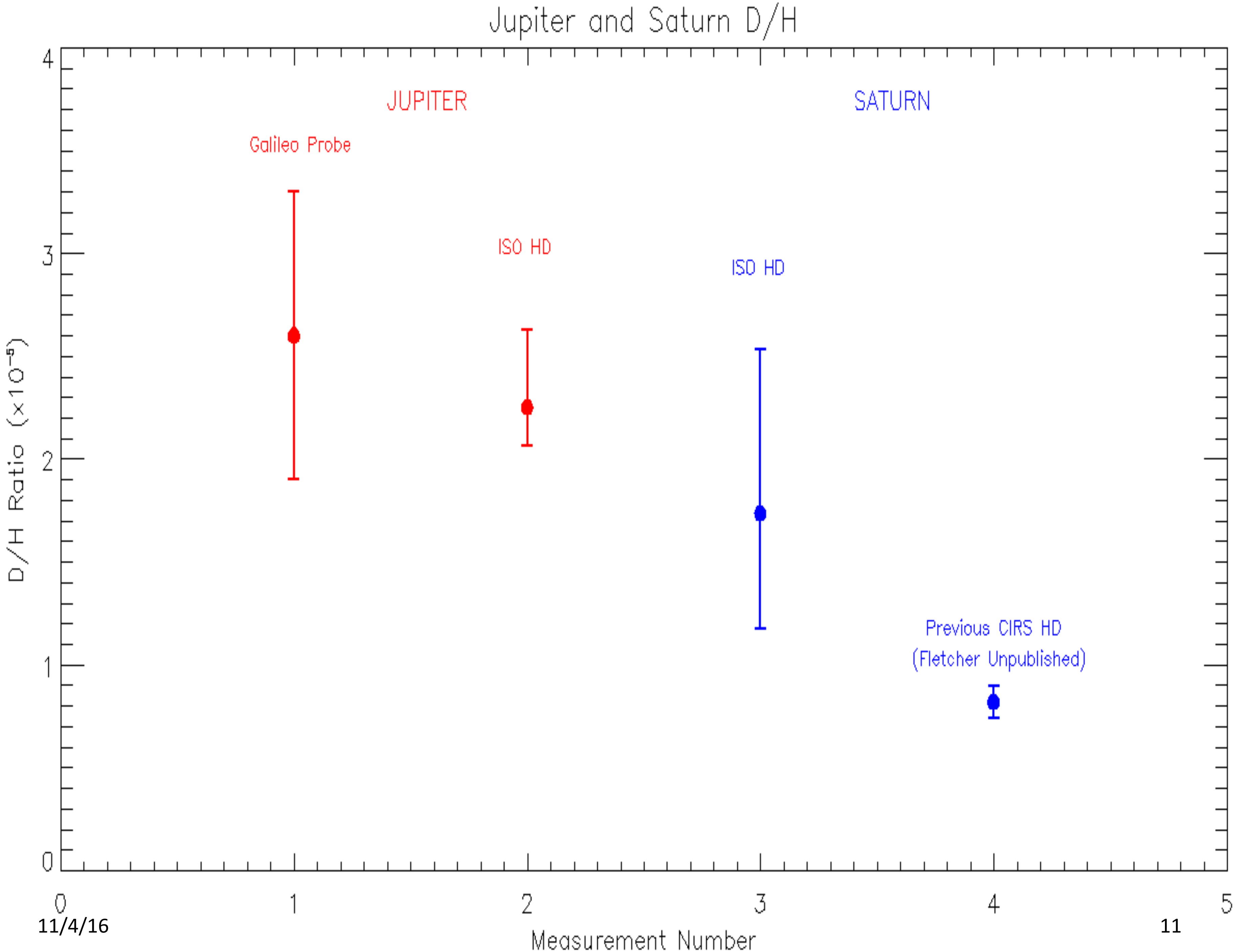

View of SATURN from CASSINI
2016 AUG 30 22:14:10 UTC
27.5° field of view
DIONE
ENCELADUS
Solar System Simulator v4.0


View of SATURN from CASSINI
2016 AUG 30 22:14:10 UTC
4.9° field of view
Solar System Simulator v4.0



D/H ratio
10⁻³
10⁻⁴
10⁻⁵
Earth
Asteroids
Enceladus
Jupiter
Saturn
Uranus
Neptune
C/1995 O1 Hale-Bopp
153P/Ikeya-Zhang
C/2001 Q4 (NEAT)
C/2002 T7 (LINEAR)
8P/Tuttle
C/2009 P1 Garrard
C/1995 B2 Hyakutake
1P/Halley
45P/H-M-P
103P/Hartley 2
67P/C-G
Oort cloud
Jupiter family
Protosolar nebula

Credit: ESA


Jupiter and Saturn D/H
JUPITER
SATURN
Galileo Probe
ISO HD
ISO HD
Previous CIRS HD
(Fletcher Unpublished)
D/H Ratio (×10⁻⁵)
Measurement Number
0
1
2
3
4
5

Methodology: Atmospheric Modeling

- Must model atmospheres when lacking in-situ atmospheric probes
- Observe absorption, reflection and emission spectra remotely
- Two approaches to modeling planetary atmospheres

Method 1

- "Simple" approach
- Compare the observations to a representative range of synthetic spectra
- Best for:
  – Few atmospheric parameters
  – Few spectra

Method 2

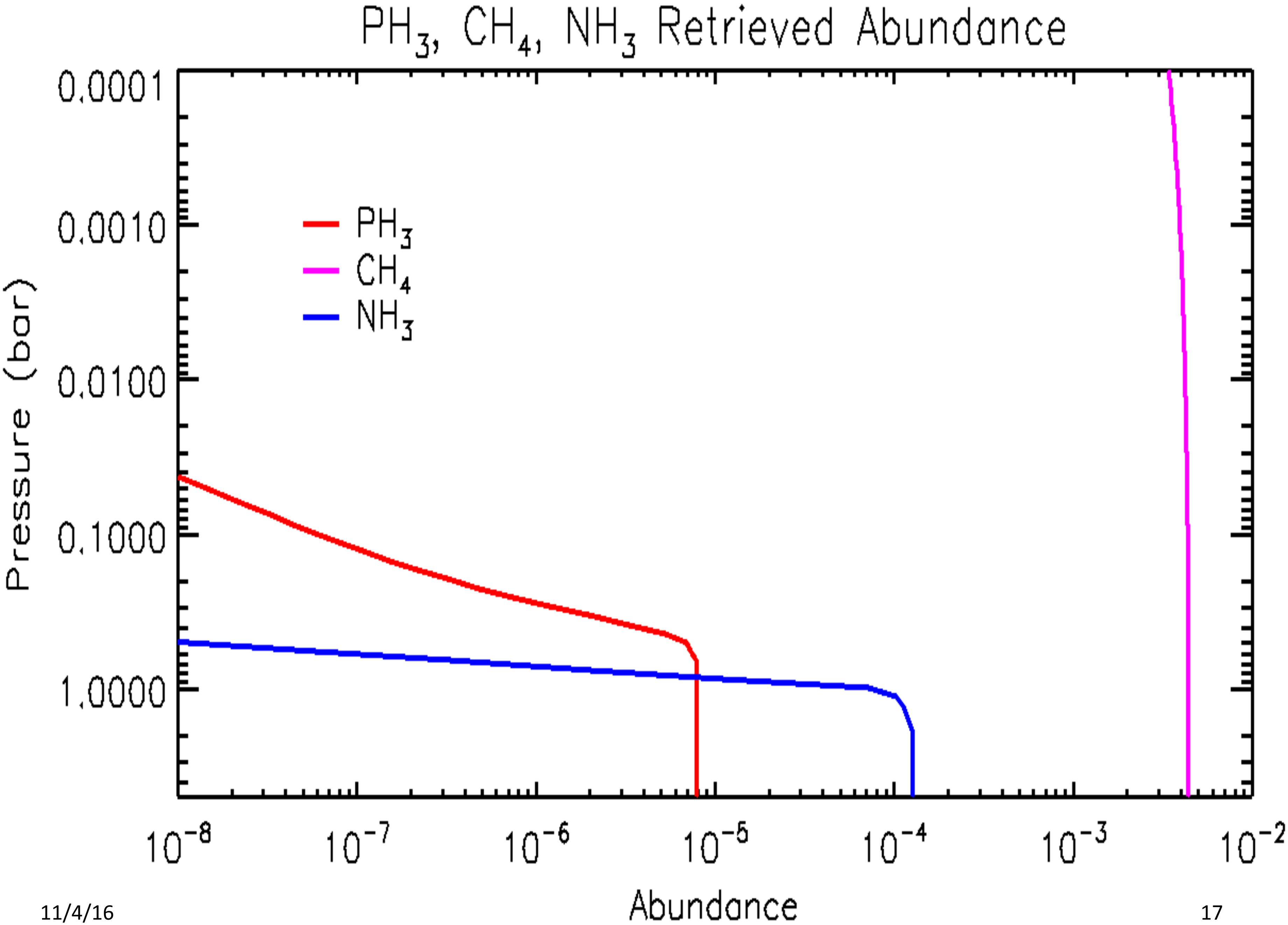
- Retrieval algorithm
  - Processes large quantities of data and returns fitted atmospheric states
  - Extract the maximum amount of atmospheric information from finite sets of data
- Radiative transfer (forward) model
  - Calculates synthetic spectra from assumed parameters
- Inversion (retrieval) model
  - Compares synthetic to measured
  - Varies parameters to minimize discrepancy

NEMESIS (Method 2)

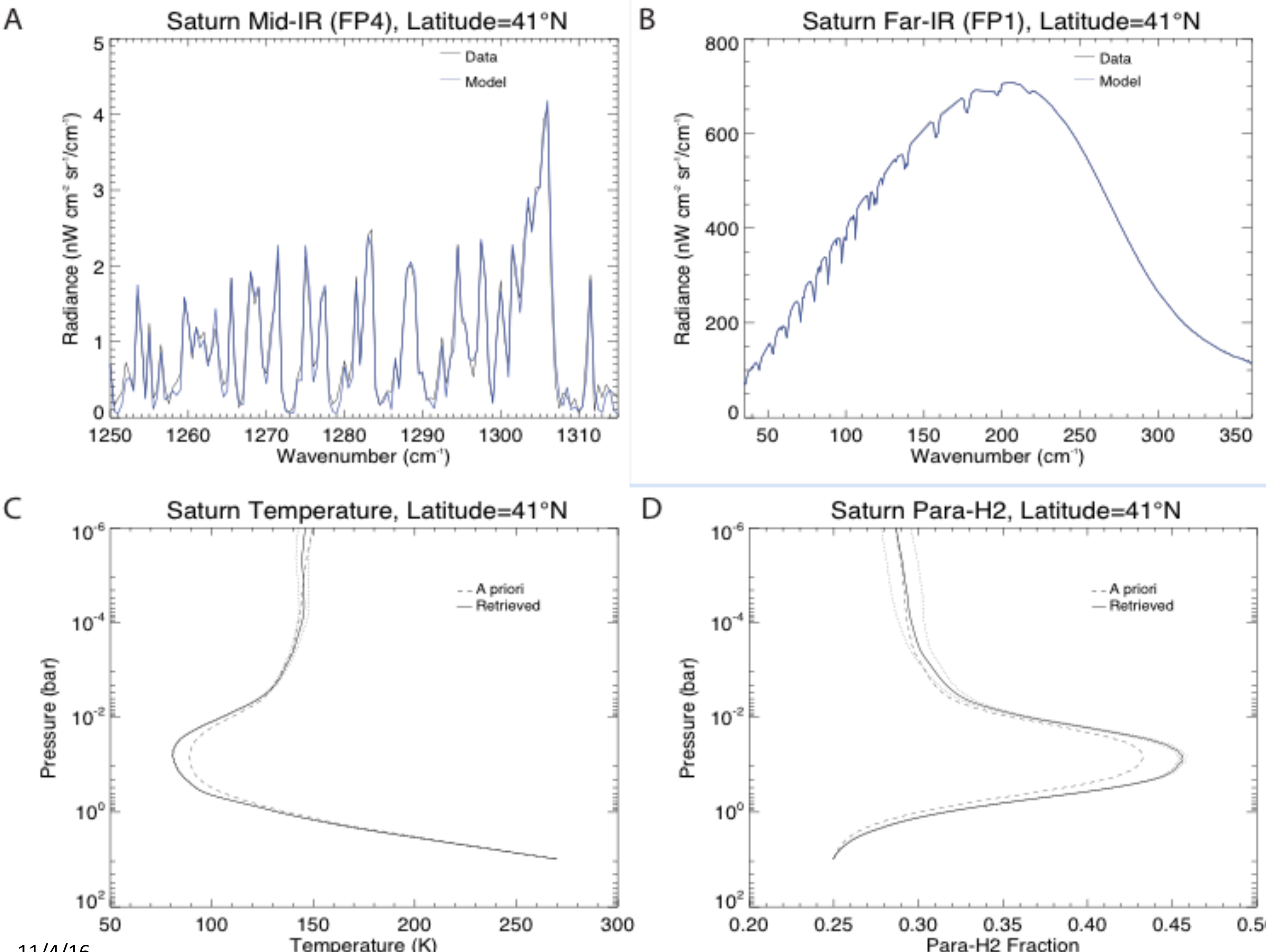
- Originally only observations of Saturn and Titan from CIRS
- Generally applicable to any planetary atmosphere
- Visible/near-infrared to microwave
- Reflected sunlight or thermal emission
  - scattering or non-scattering

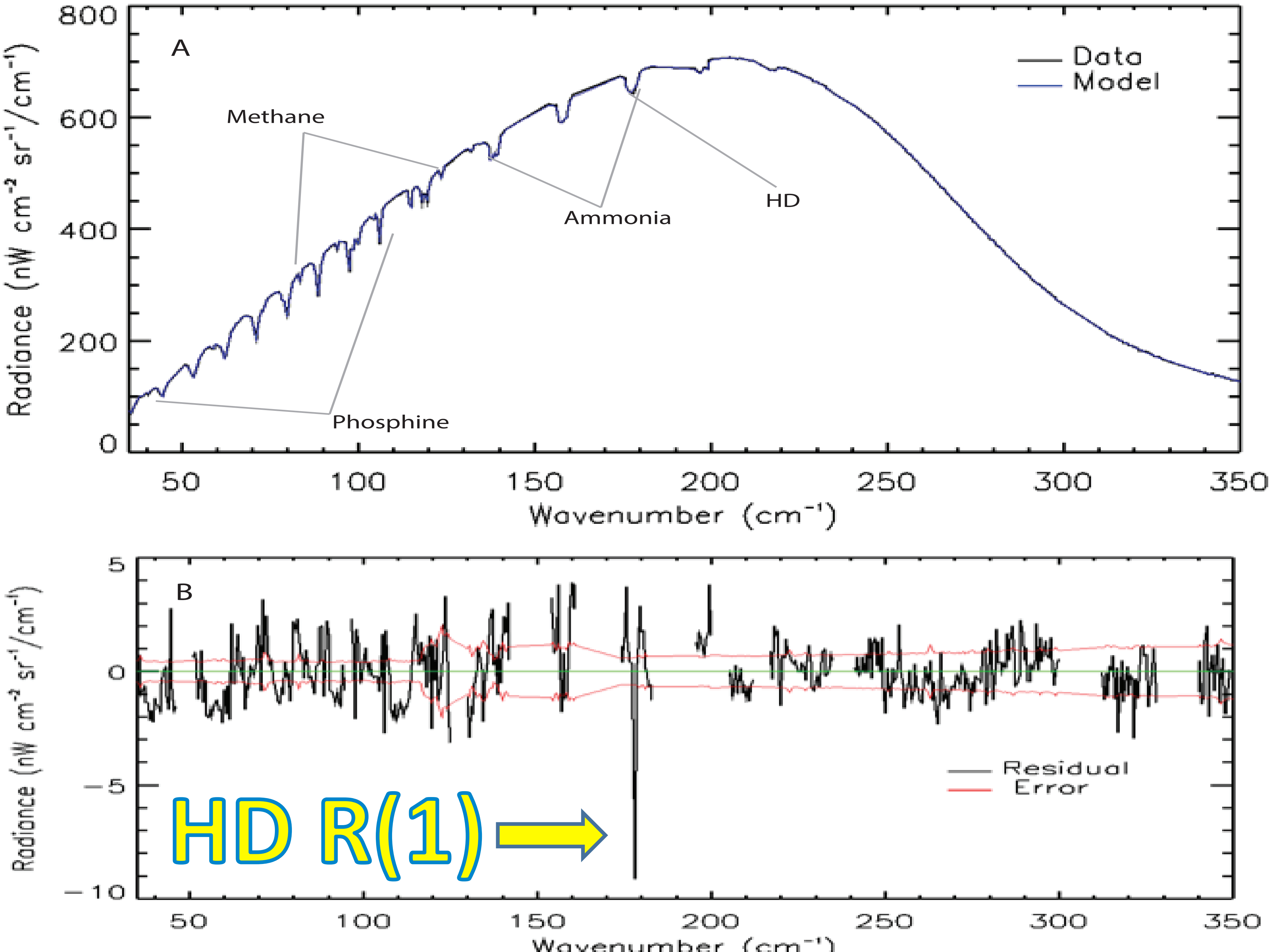
Saturn: NEMESIS Modeling

- Main absorbers
  - NH_3, PH_3, CH_4
- Temperature
- H_2 Ortho-Para Fraction (Nuclear Spin State)
  - Ortho= Two proton spins aligned parallel
  - Para= Two proton spins aligned antiparallel
- HD

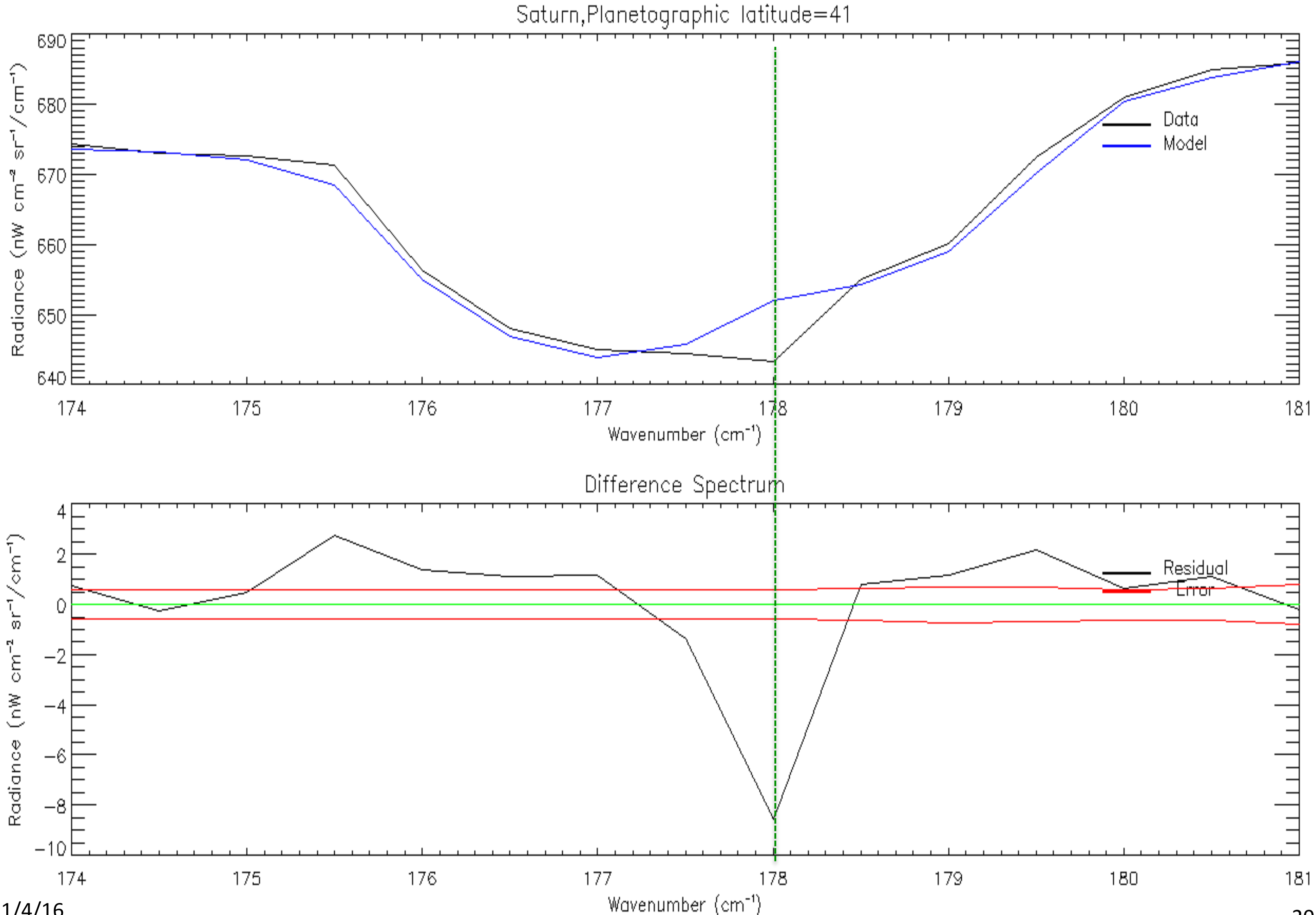


PH3, CH4, NH3 Retrieved Abundance
Pressure (bar)
0.0001
0.0010
0.0100
0.1000
1.0000
PH3
CH4
NH3
10−8
10−7
10−6
10−5
10−4
10−3
10−2
Abundance

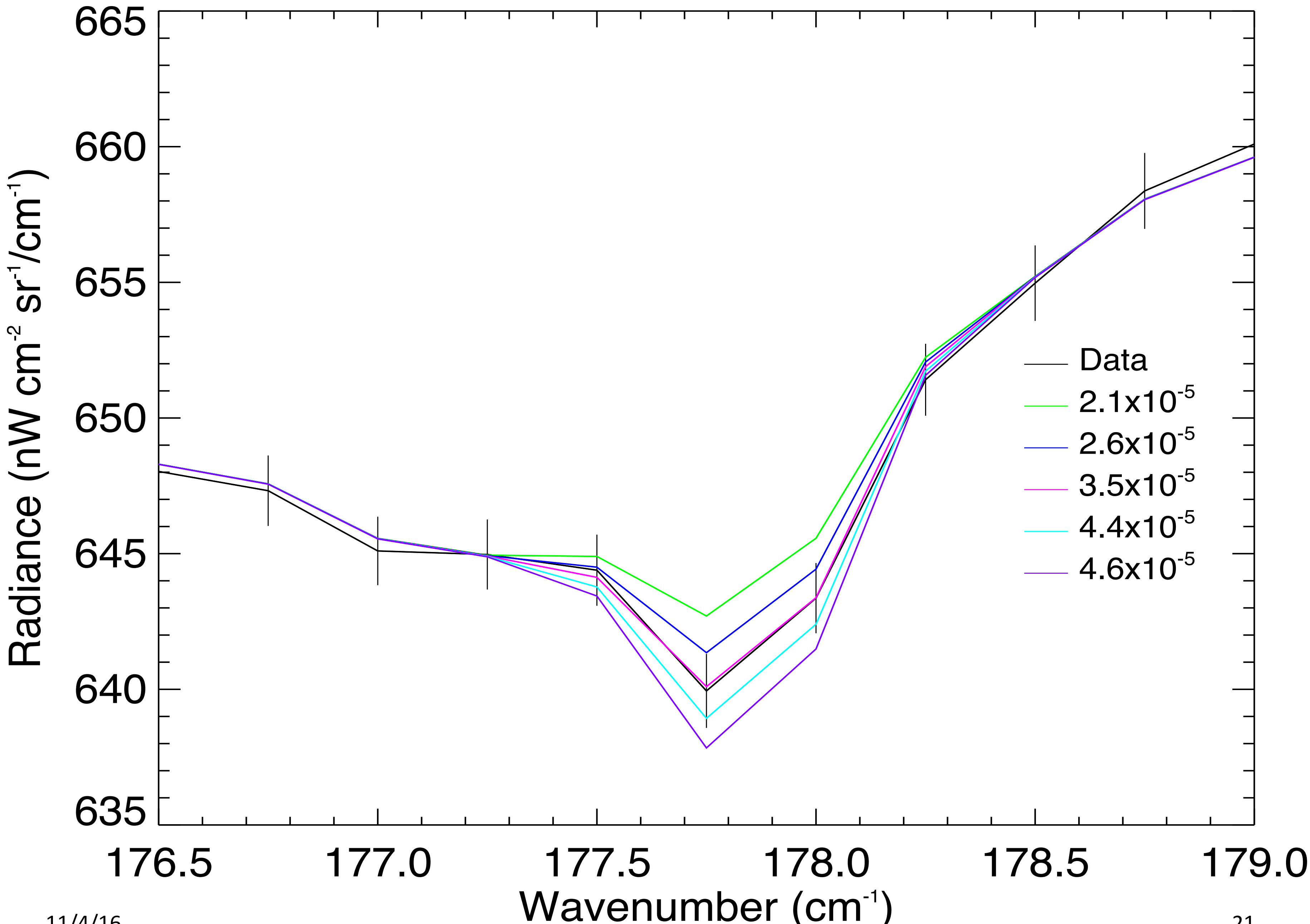

A
Saturn Mid-IR (FP4), Latitude=41°N
Data
Model
Radiance (nW cm⁻² sr⁻¹/cm⁻¹)
Wavenumber (cm⁻¹)
B
Saturn Far-IR (FP1), Latitude=41°N
Data
Model
Radiance (nW cm⁻² sr⁻¹/cm⁻¹)
Wavenumber (cm⁻¹)
C
Saturn Temperature, Latitude=41°N
A priori
Retrieved
Pressure (bar)
Temperature (K)
D
Saturn Para-H2, Latitude=41°N
A priori
Retrieved
Pressure (bar)
Para-H2 Fraction

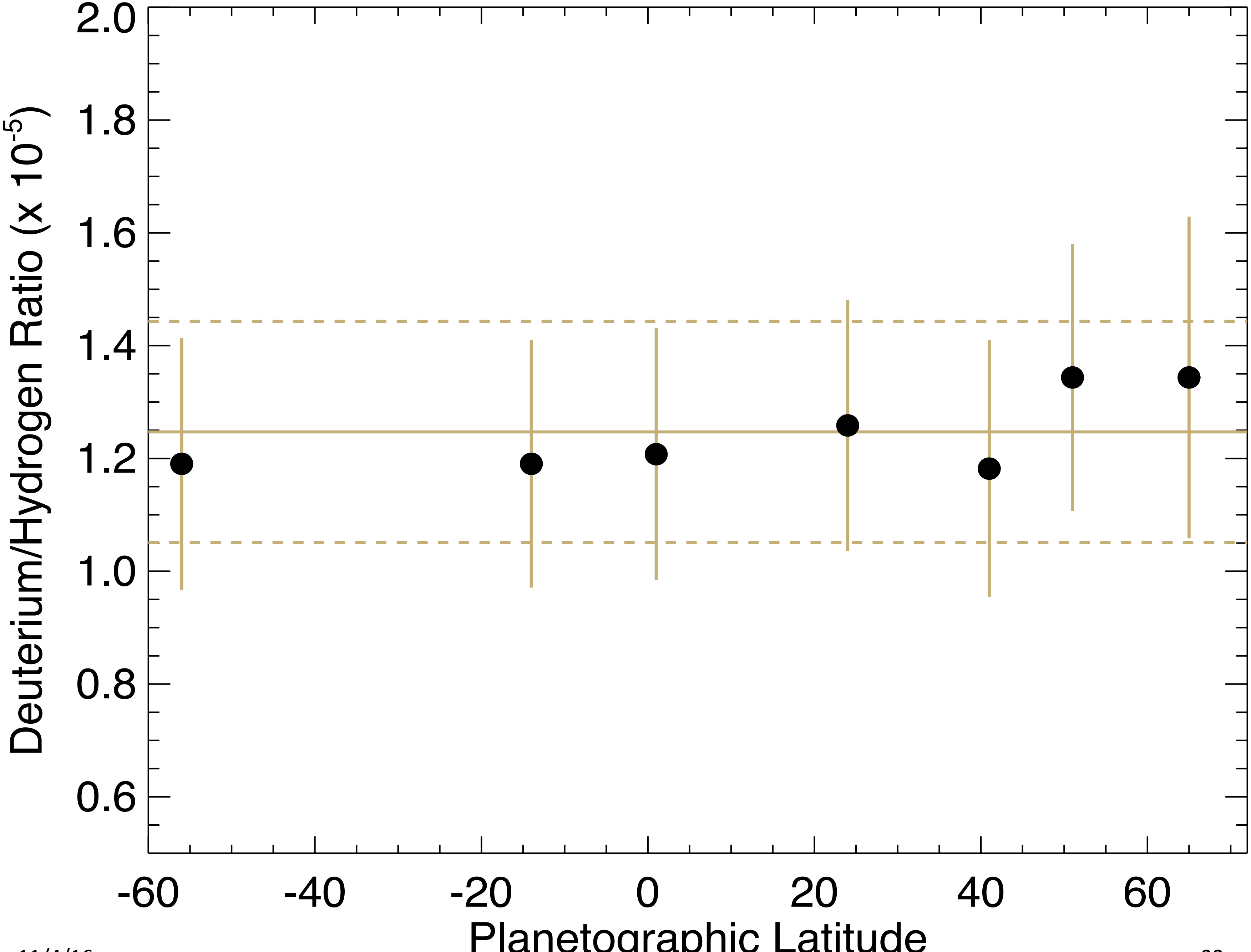

A
Data
Model
Methane
Ammonia
HD
Phosphine
Radiance (nW cm^{-2} sr^{-1}/cm^{-1})
Wavenumber (cm^{-1})
800
600
400
200
0
50
100
150
200
250
300
350
B
Residual
Error
HD R(1)
5
0
−5
−10

178 cm^{-1} R(1) line region



Saturn R1 HD Foward Models, Latitude=41°N



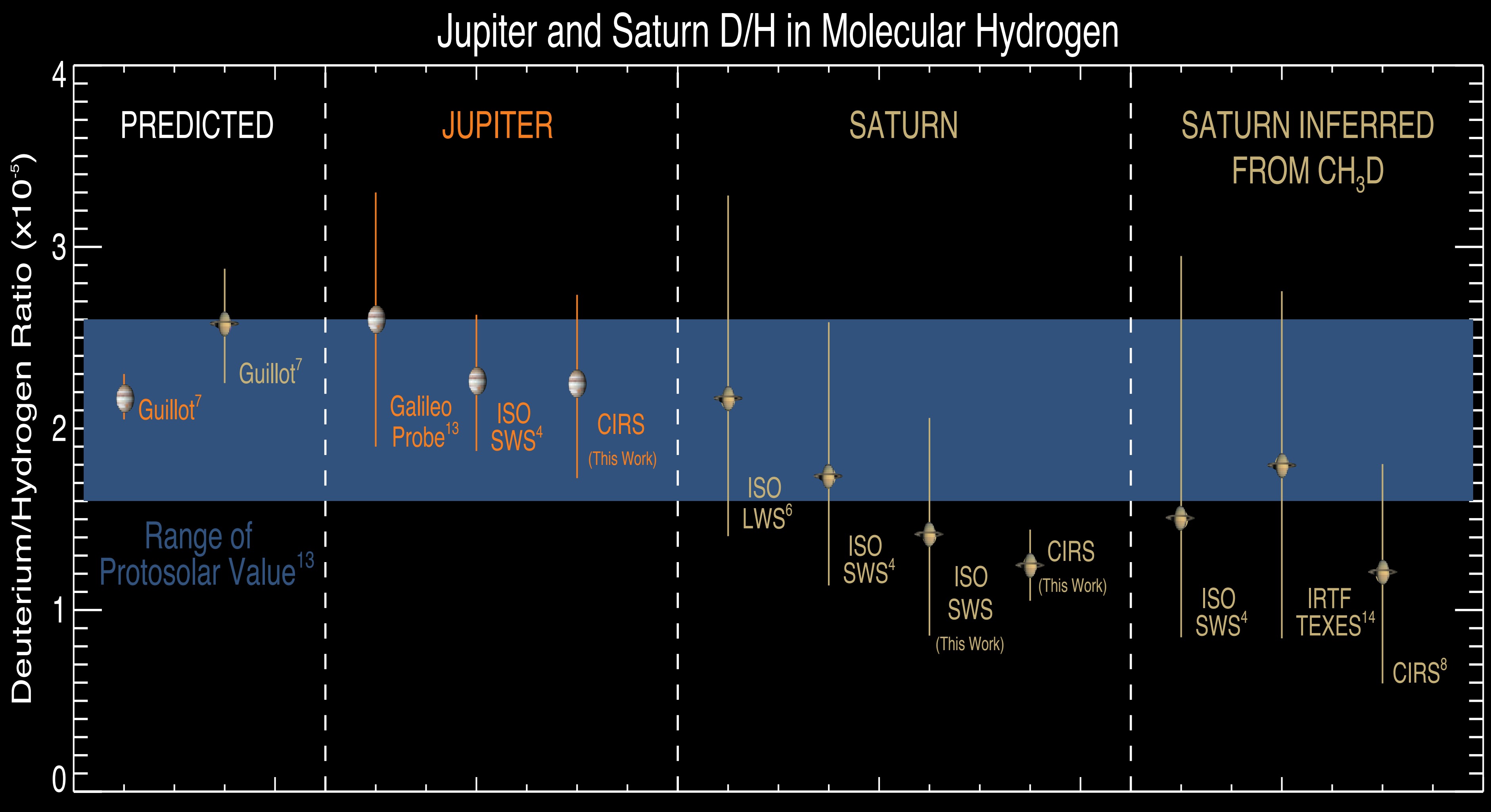


2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
Deuterium/Hydrogen Ratio (x 10-5)
-60
-40
-20
0
20
40
60
Planetographic Latitude

Model Assurances

- ISO/SWS
  - Reproduced the modeling efforts of Lellouch 2001
  - Were able to achieve the same result to within 8%
  - Utilized an improved method and found a lower result
- Galileo Probe
  - Measured D/H in Jupiter in-situ
  - CIRS result in excellent agreement

Conclusion: No systematic modeling errors contributed to this result.


Jupiter and Saturn D/H in Molecular Hydrogen
Deuterium/Hydrogen Ratio (x10-5)
0
1
2
3
4
PREDICTED
JUPITER
SATURN
SATURN INFERRED FROM CH3D
Guillot7
Guillot7
Range of Protosolar Value13
Galileo Probe13
ISO SWS4
CIRS (This Work)
ISO LWS6
ISO SWS4
ISO SWS (This Work)
CIRS (This Work)
ISO SWS4
IRTF TEXES14
CIRS8

Discussion

- We are able to measure D/H ratio in the CIRS data accurately with NEMESIS
- Current models do not accurately predict Saturn's D/H ratio
  - Predicted Saturn/Jupiter D/H ratio ~1.05-1.15
  - Measured Saturn/Jupiter D/H ratio: $0.48^{+0.29}_{-0.16}$
- Potential explanation: Deuterium Rain