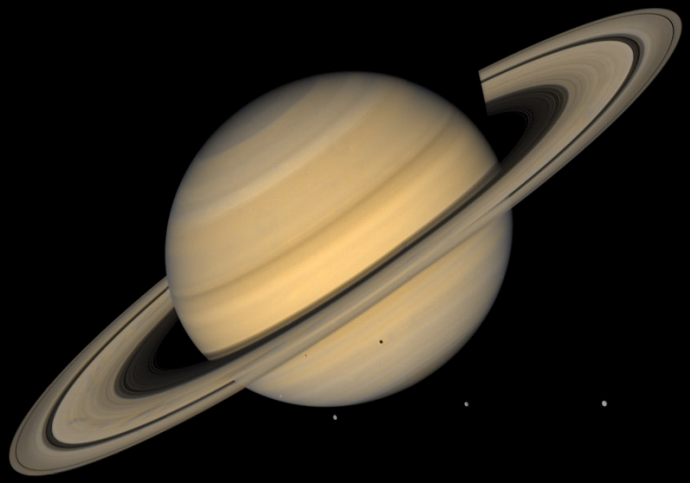
Where is Saturn's Deuterium Hiding?



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Outline

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

CASSINI
INTERPLANETARY TRAJECTORY

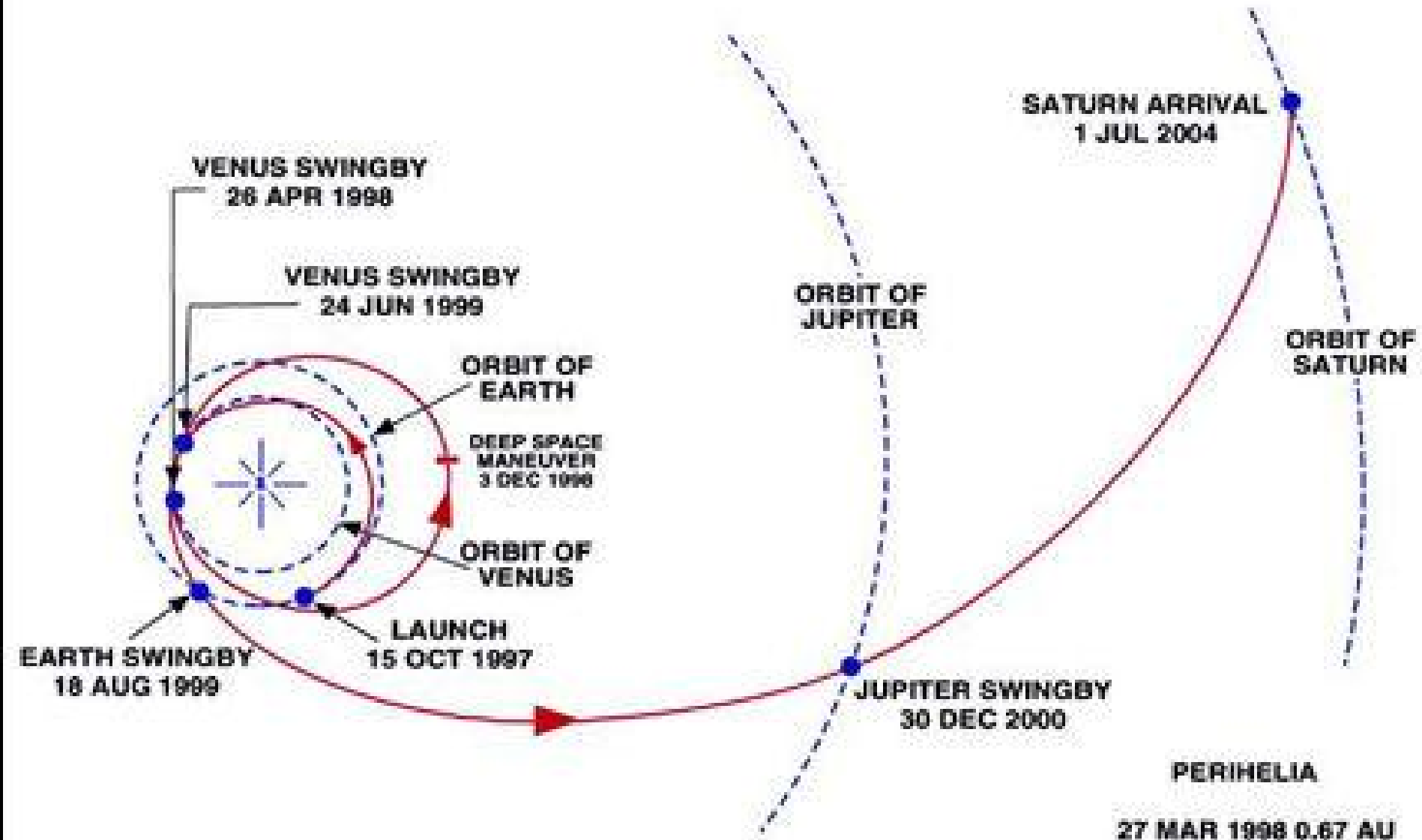


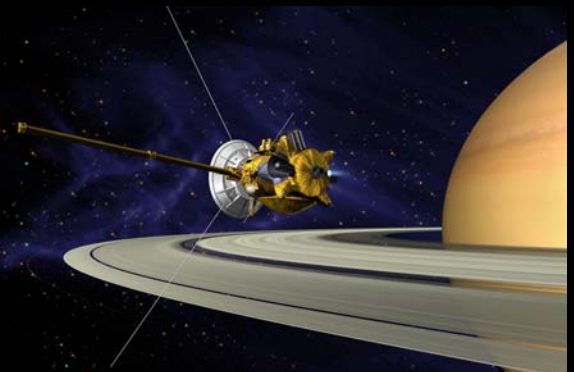
Image Credit: NASA JPL

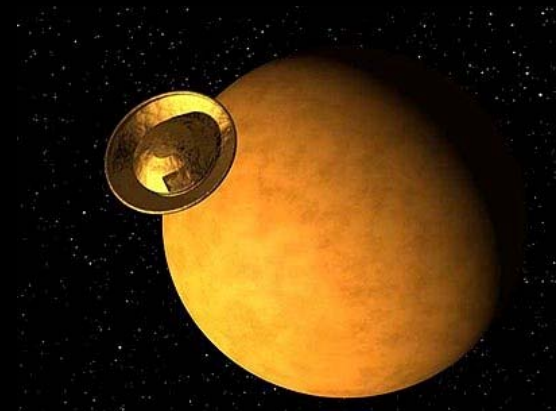
Cassini-Huygens Timeline

- 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

Specifications

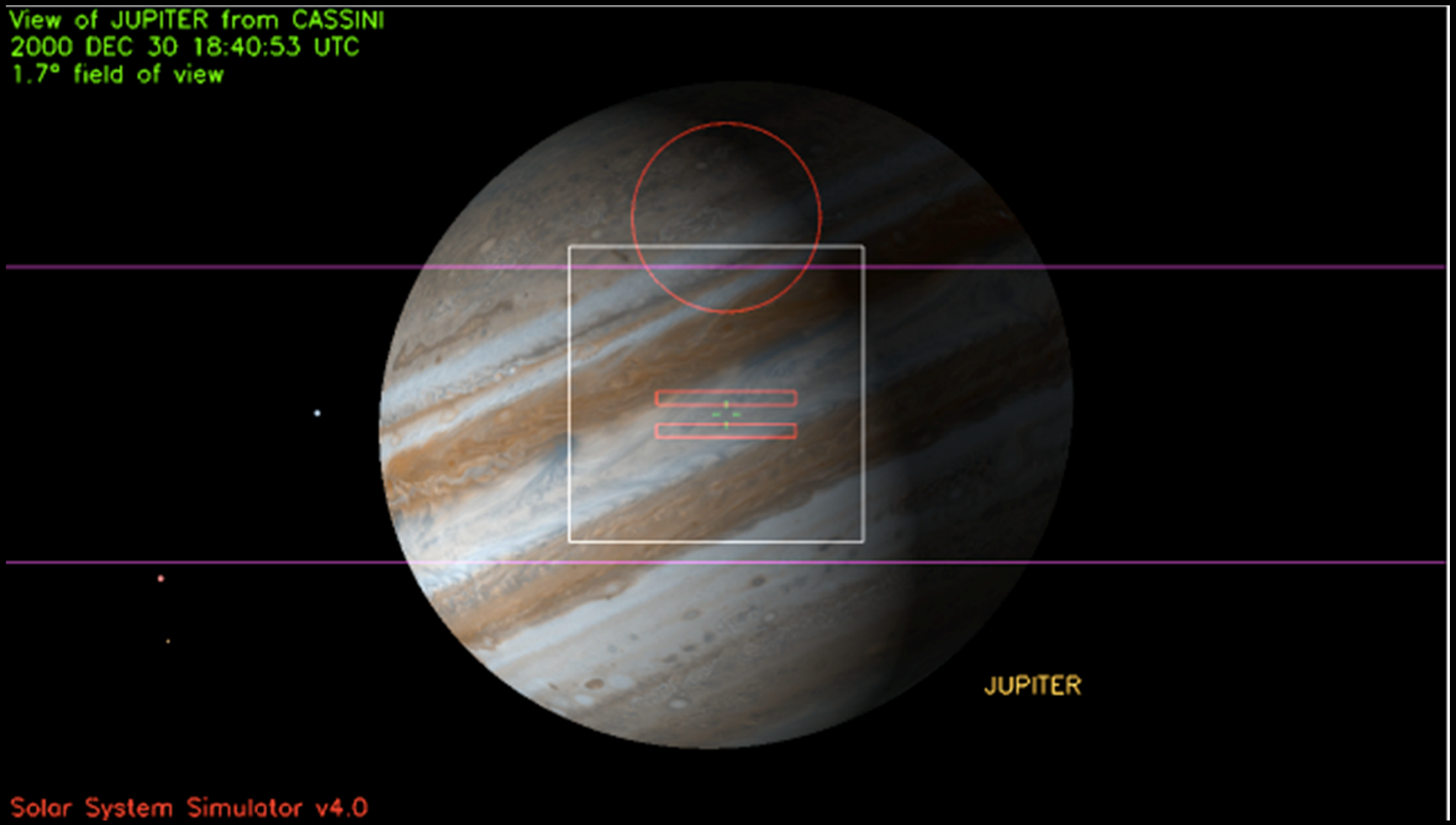
- 700 Watts of power
  - Radioisotope Thermoelectric Generators (RTGs)
- Cassini: 12 science instruments
- Huygens: 6 science instruments
- 27 science investigations

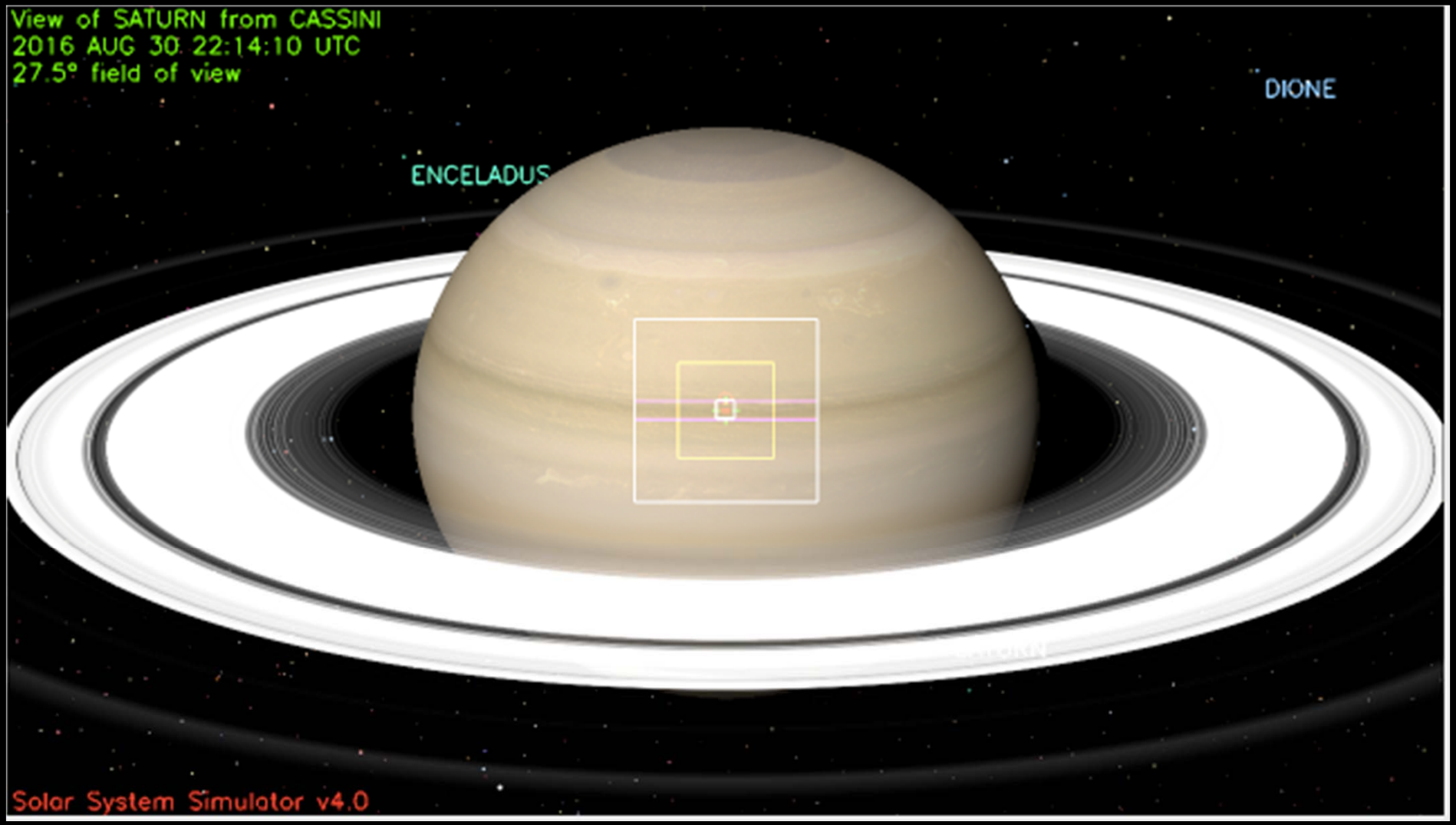


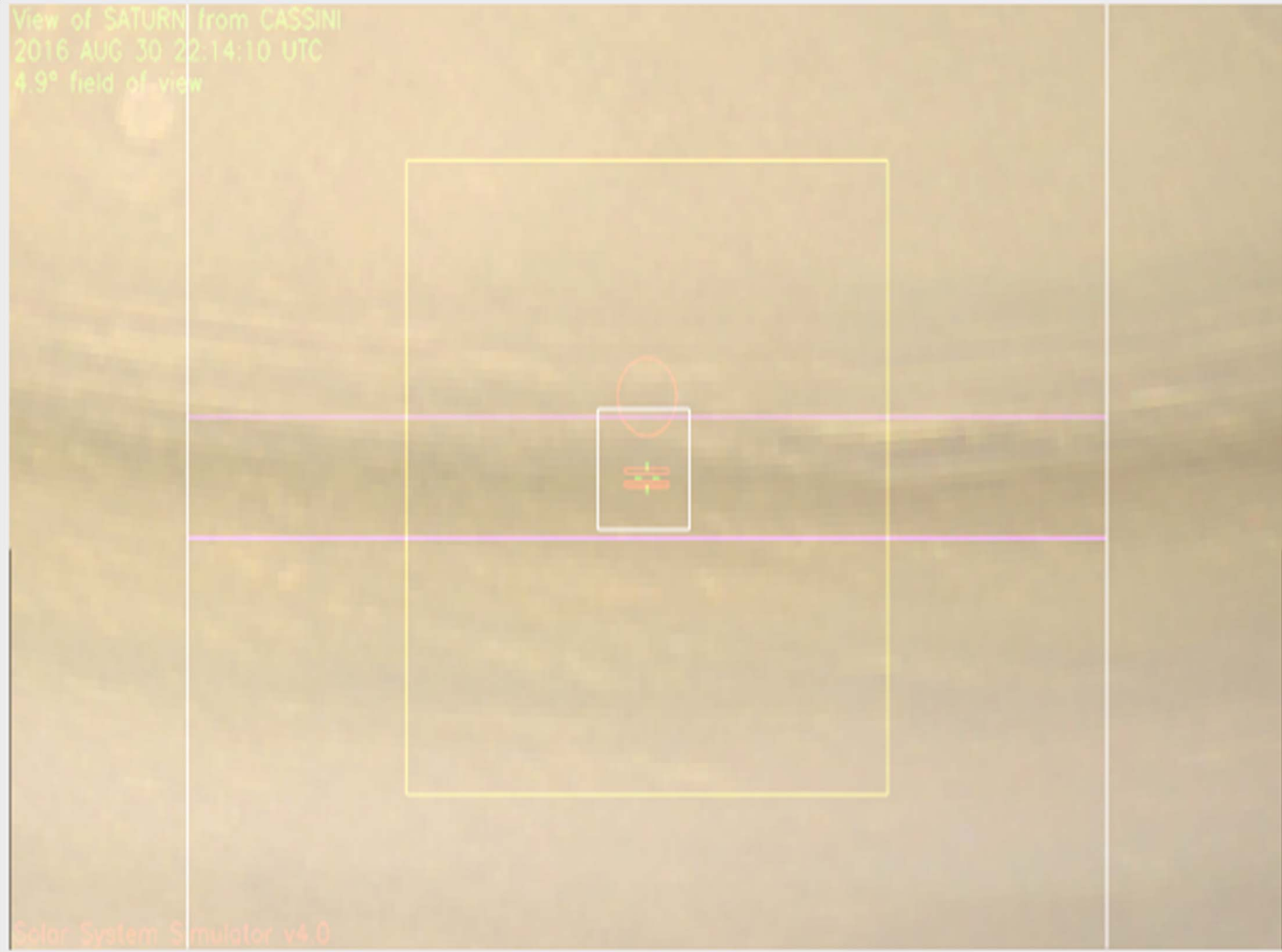


Composite Infrared Spectrometer (CIRS)

- 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

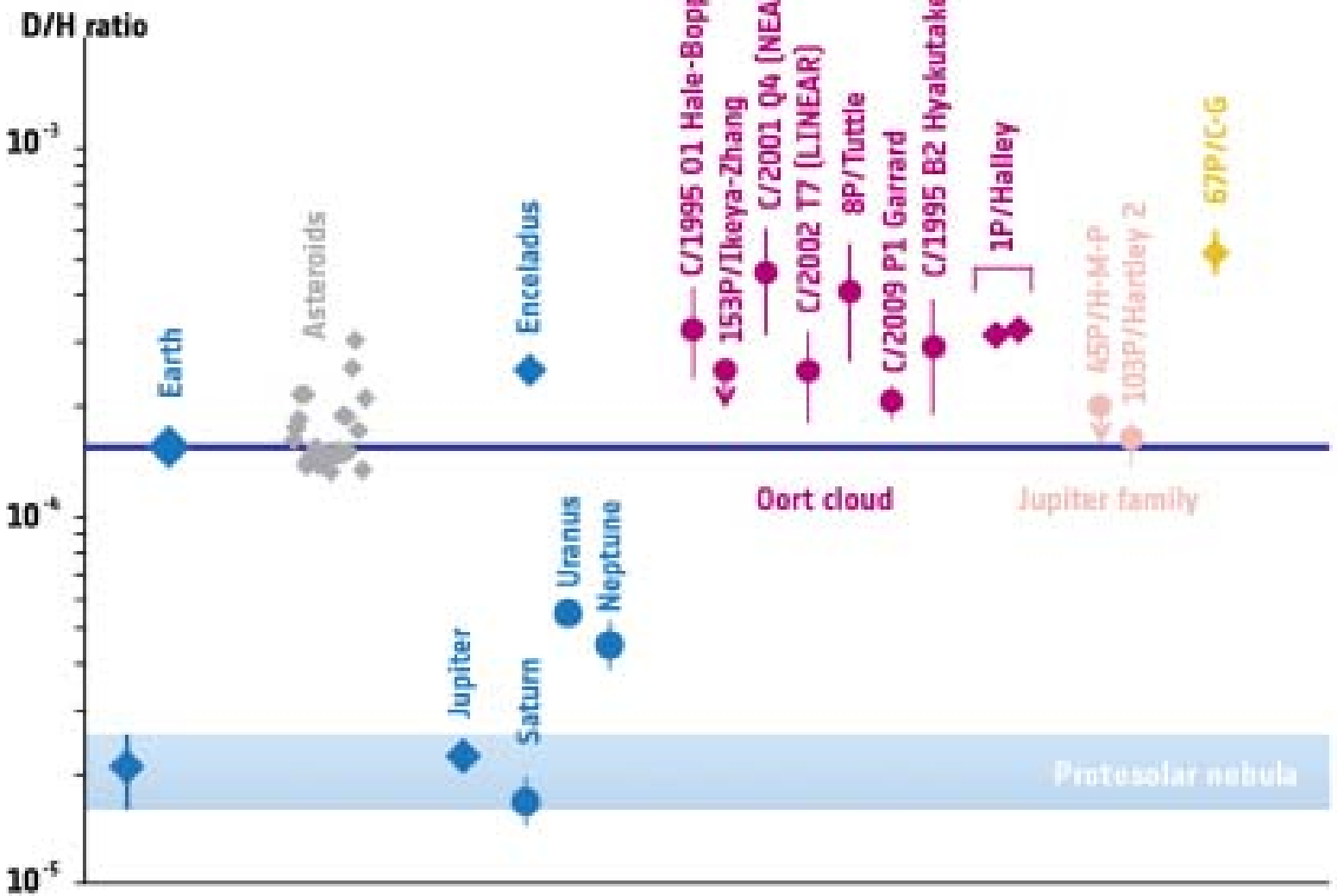
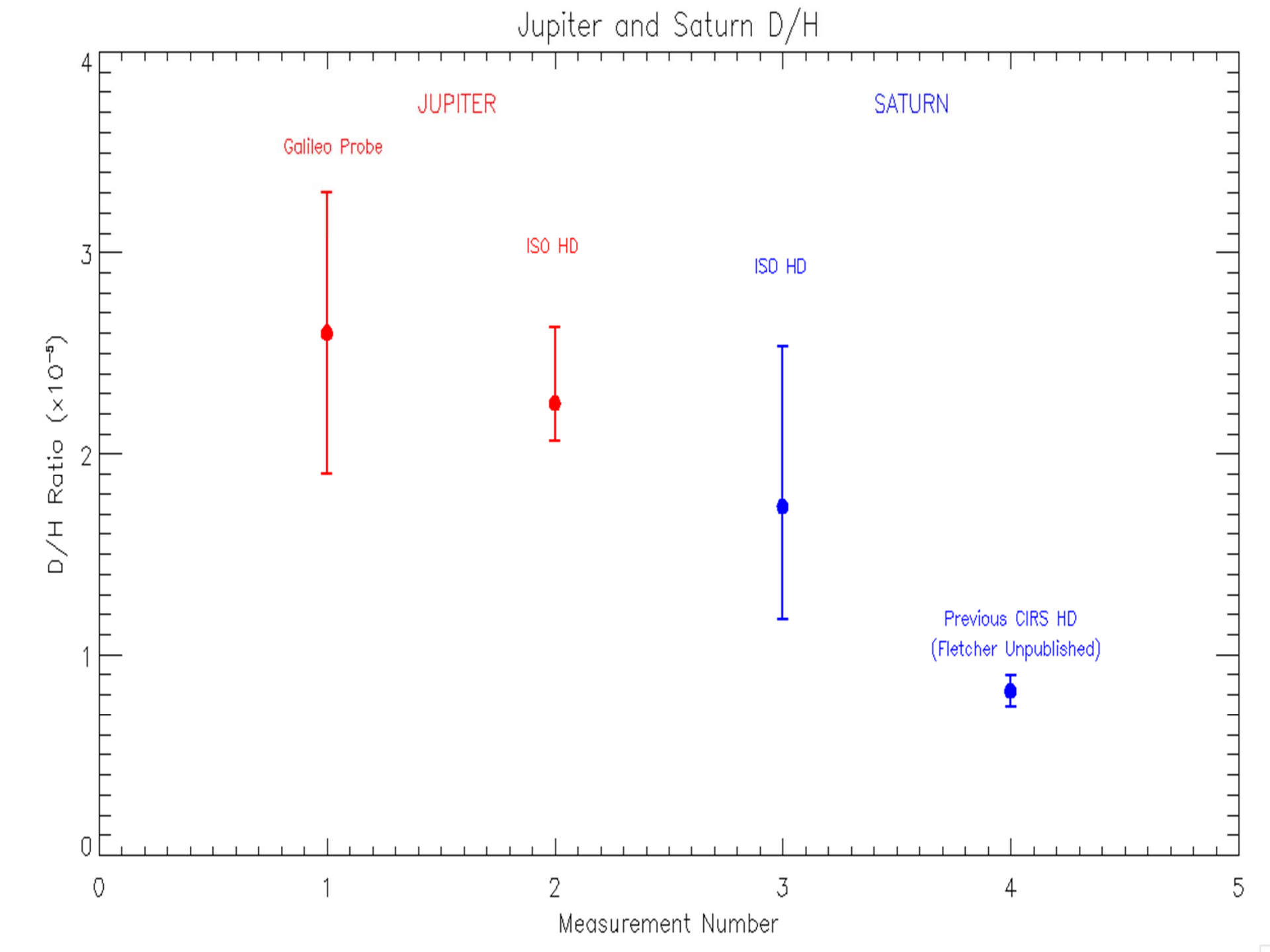


Image Credit: ESA


Jupiter and Saturn D/H
JUPITER
SATURN
Galileo Probe
ISO HD
ISO HD
Previous CIRS HD
(Fletcher Unpublished)
D/H Ratio (x10⁻⁵)
Measurement Number
0
1
2
3
4
5

Saturn Observations

- Time period: 2004-2009 (pre-storm)
- ~10-15° latitude bins 60°S to 60°N
- Emission angle < 30°
- Using apodized (.5 cm^{-1}) data ~35-400 cm^{-1} from FP1, 1250-1315cm^{-1} from FP4
- DS4000 Database (high S/N)
- > 1000 spectra per FP1 average

Spectral Modeling

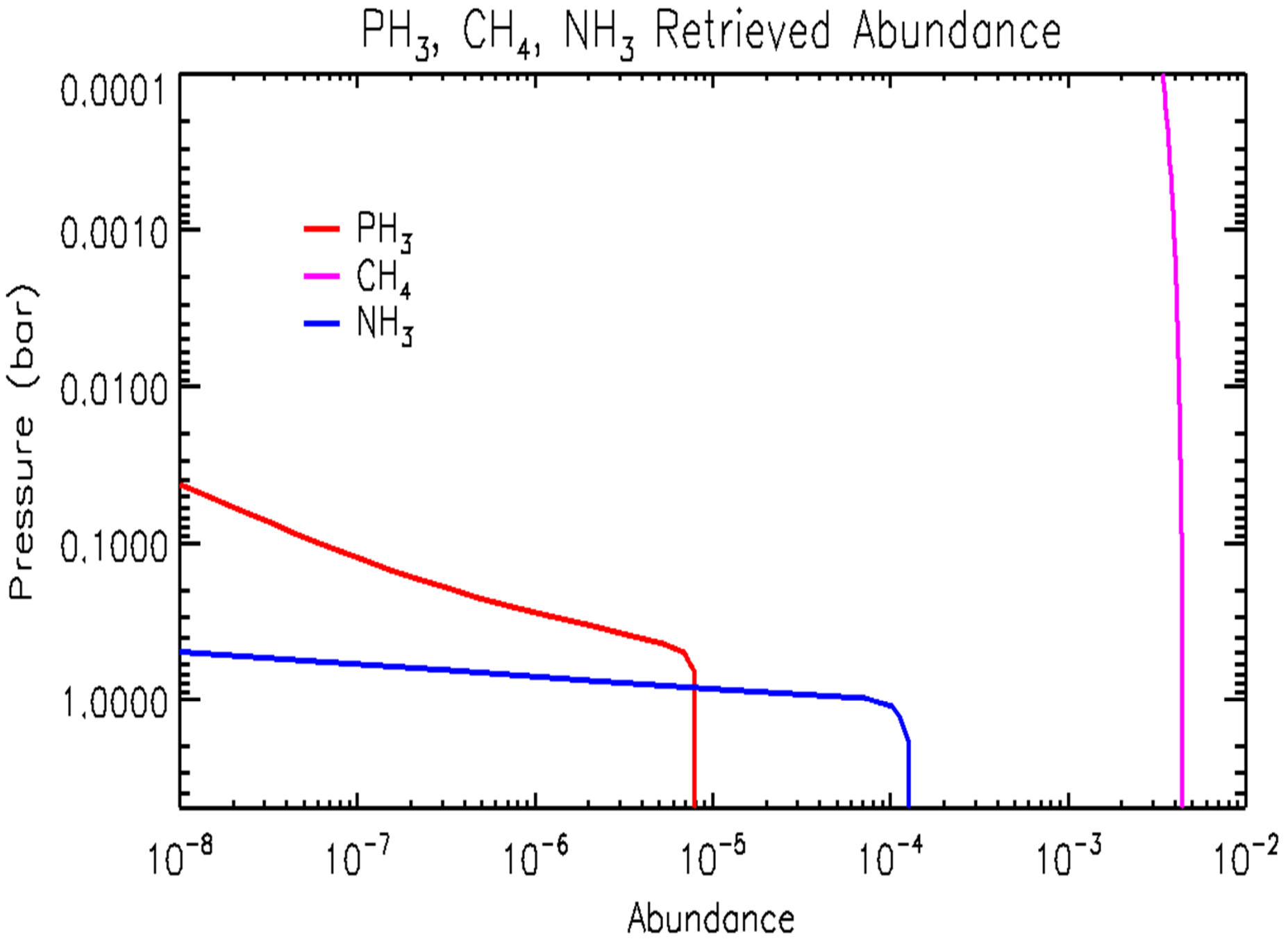
- Using NEMESIS retrieval model (Irwin et al.)
- Correlated-K used for line opacities
  - Construct line-by-line and band model based k distributions
  - Preserves monochromatic structure of the atmosphere at different pressures
  - Significantly faster than line-by-line retrievals

- HITRAN12 line data
- Used post HITRAN12 HD quadrupole lines
  - Previous R(1): 2.375 e-27 [cm-1/(molec cm-2)]
  - New R(1): 2.532 e-27 [cm-1/(molec cm-2)]
  - Recalculated 4^{th} order polynomial partition function

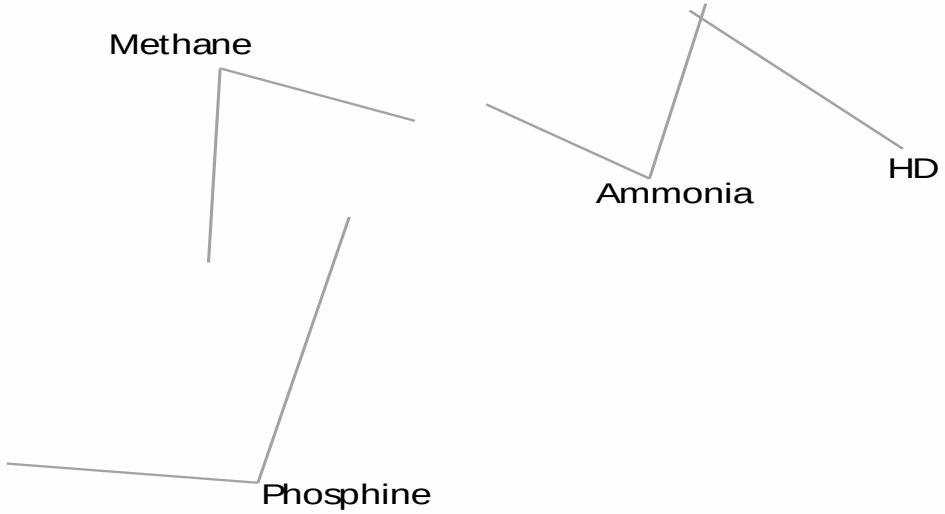
Initial NEMESIS Retrieval Conditions-No HD

- Temperature
  - Full vertical profile
  - Retrieve continuous profile
- Para-H_2 fraction
  - Calculate equilibrium Para-H_2 as a function of temperature
  - Retrieve continuous profile with equilibrium as a priori
- PH_3 3-parameter model
  - Knee pressure retrieved, starting at 550 mbar
  - Deep VMR retrieved, starting at 1E-6
  - FSH retrieved, starting at .25
- NH_3 3-parameter model
  - Knee pressure retrieved, starting at 1 bar
  - Deep VMR retrieved, starting at 1E-4
  - FSH retrieved, starting at .1
- CH_4 profile scaling
  - Retrieve a scalar for the a priori profile

$$\text{S1: } X = X_0 \left(\frac{p}{p_0}\right)^{1/f-1}$$


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

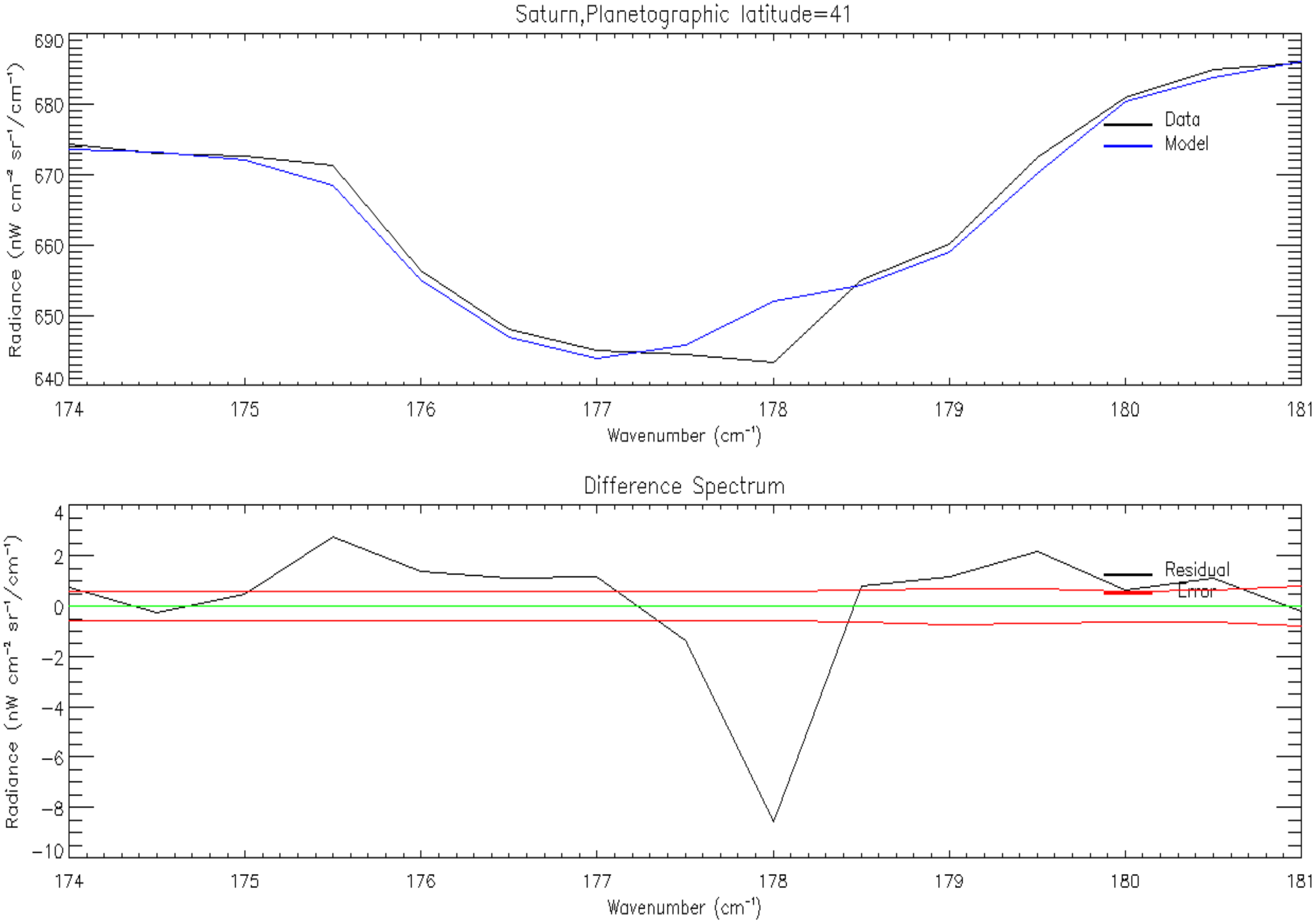
A



B

HD R(1) ⟶

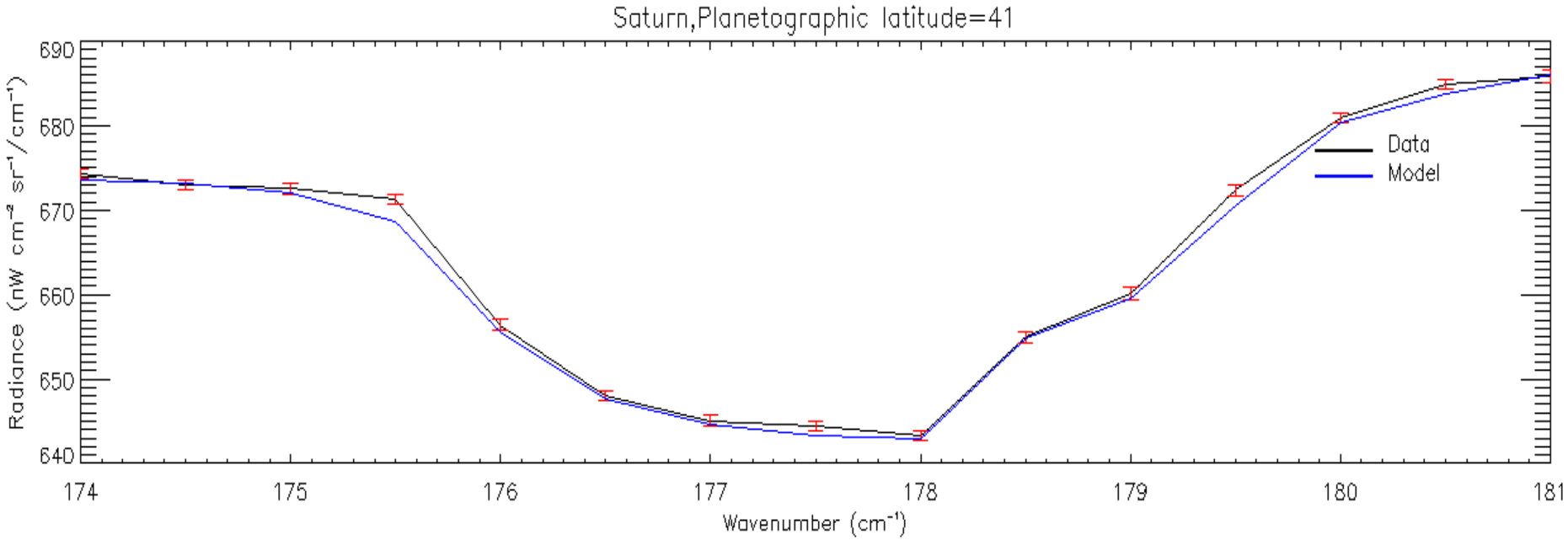
178 cm^{-1} R(1) line region

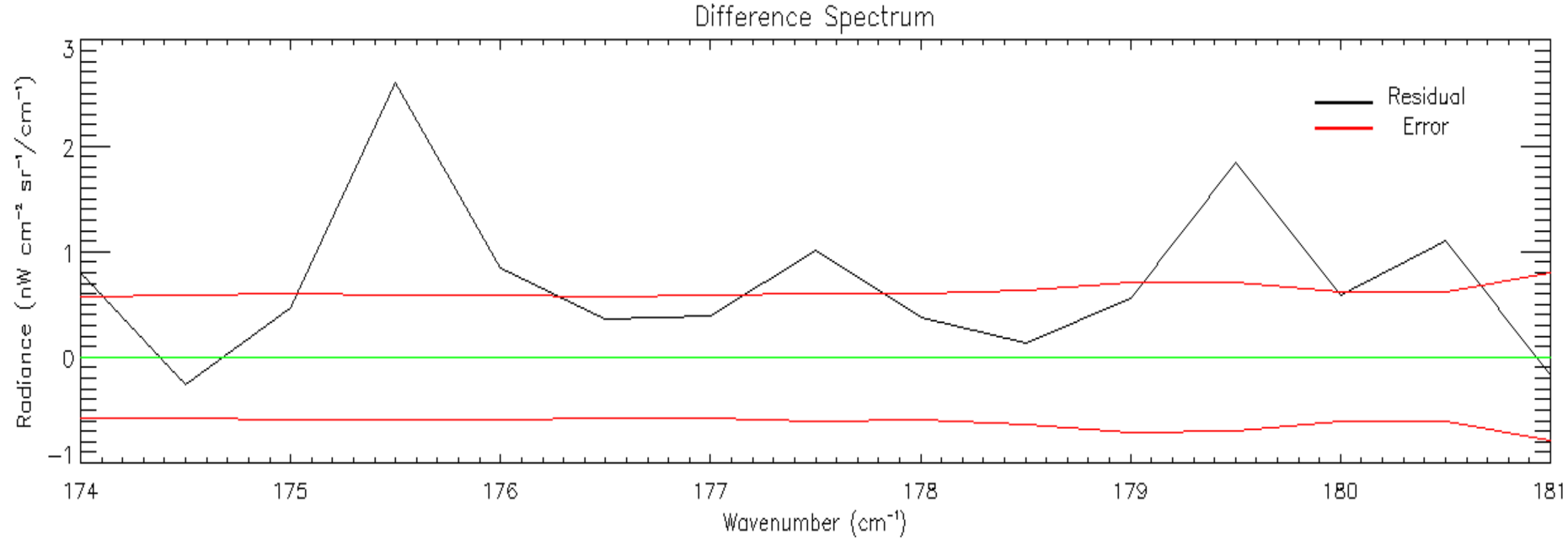


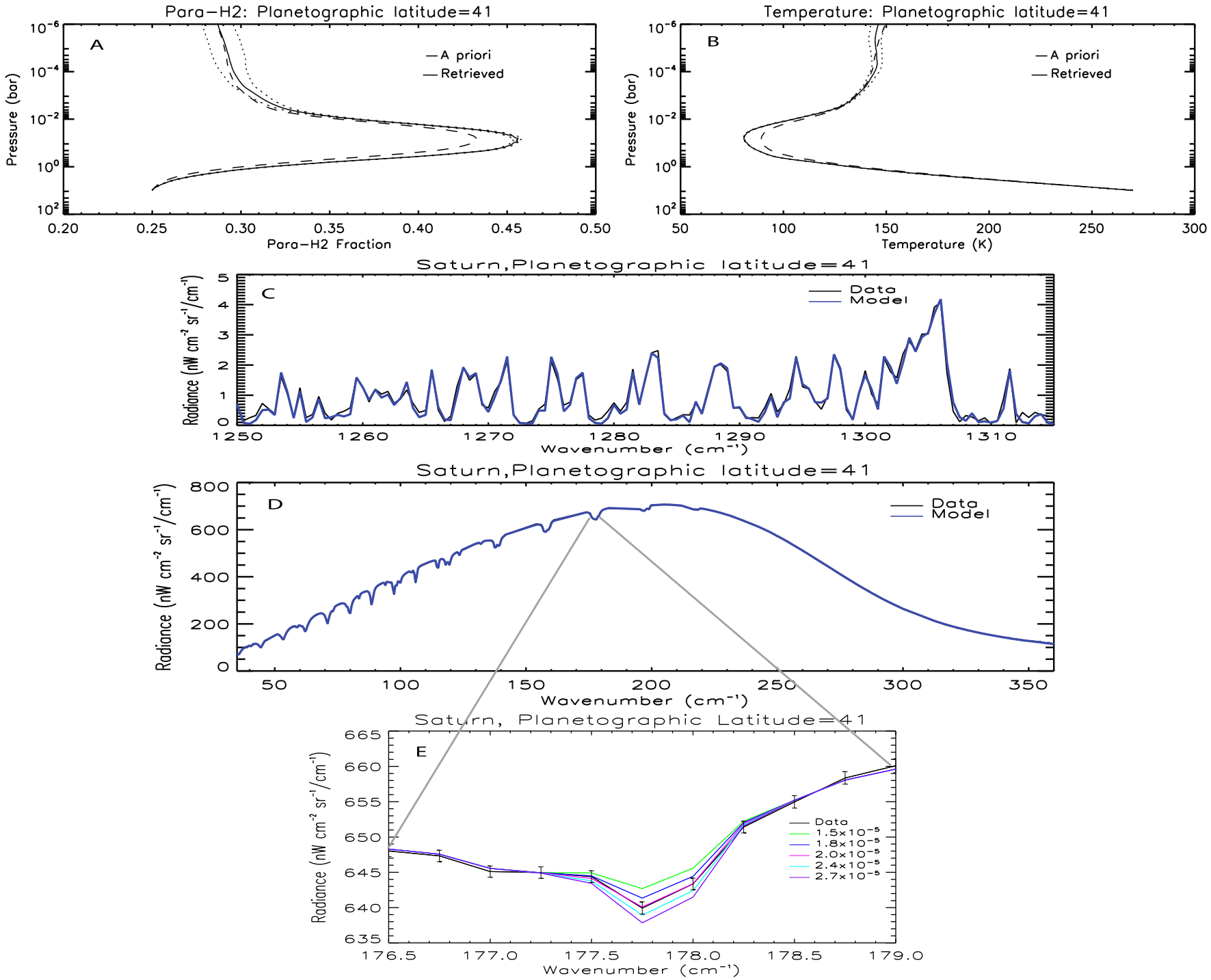
NEMESIS Retrieval-With HD

- All other retrieval parameters are the same
- HD
  - Line data from HITRAN12 update
  - K-table created from above data
  - Assumed well-mixed (constant VMR of $3x10^{-5}$)

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



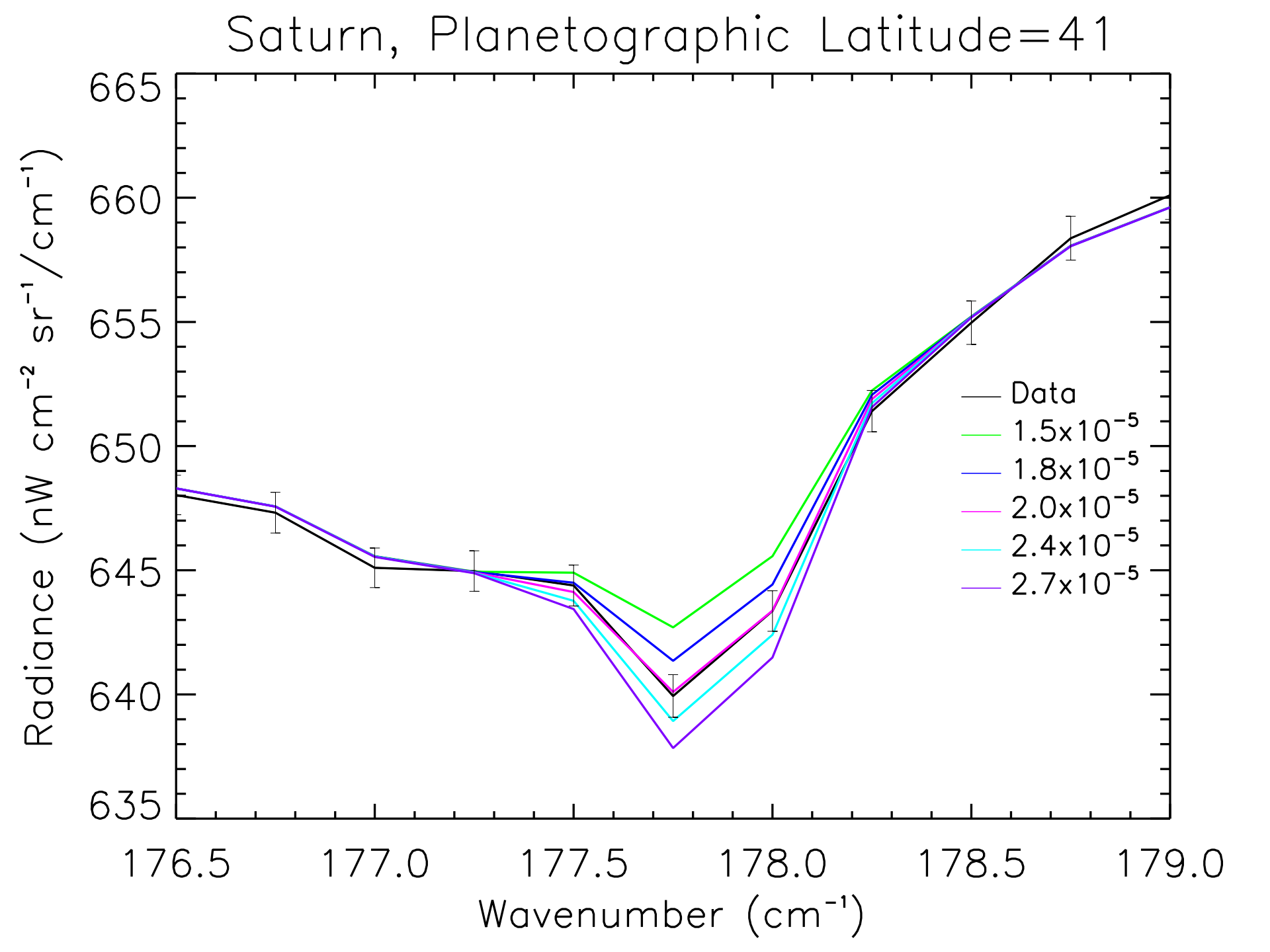


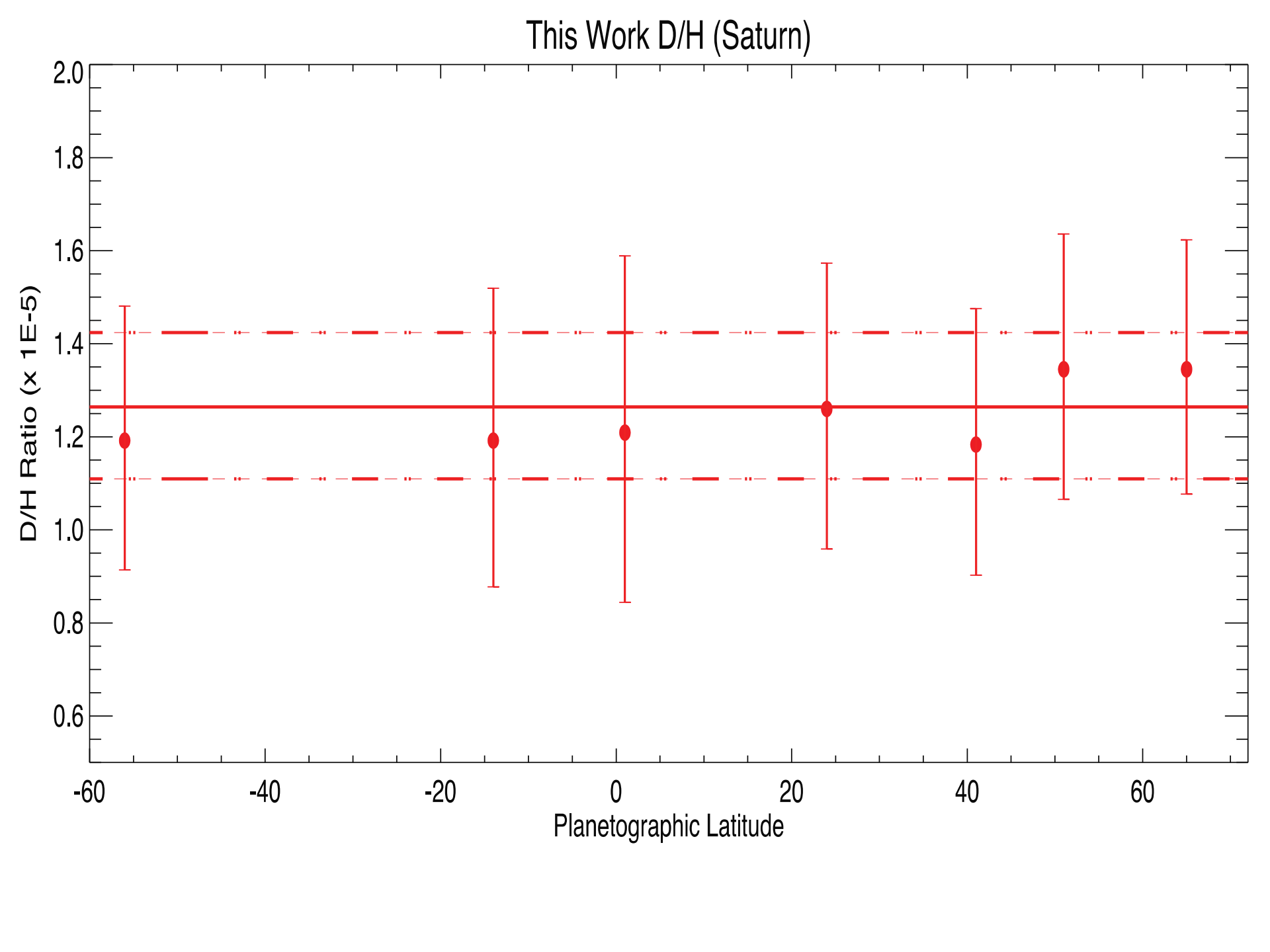

Para−H2: Planetographic latitude=41
A
A priori
Retrieved
Pressure (bar)
Para−H2 Fraction
Temperature: Planetographic latitude=41
B
Temperature (K)
Saturn,Planetographic latitude=41
C
Data
Model
Radiance (nW cm⁻² sr⁻¹/cm⁻¹)
Wavenumber (cm⁻¹)
D
Saturn, Planetographic Latitude=41
E
1.5x10⁻⁵
1.8x10⁻⁵
2.0x10⁻⁵
2.4x10⁻⁵
2.7x10⁻⁵

Forward Models

- Use all retrieved parameters (except HD) as a priori for series of forward models
- Use .5cm^{-1} data regridded to .25cm^{-1}(NESR scaled by $\sqrt{2}$)
- D/H calculated using qH_2=.882 (Conrath and Gautier)

$$D/H = \frac{1}{2} * \frac{[HD]}{[H_2]}$$

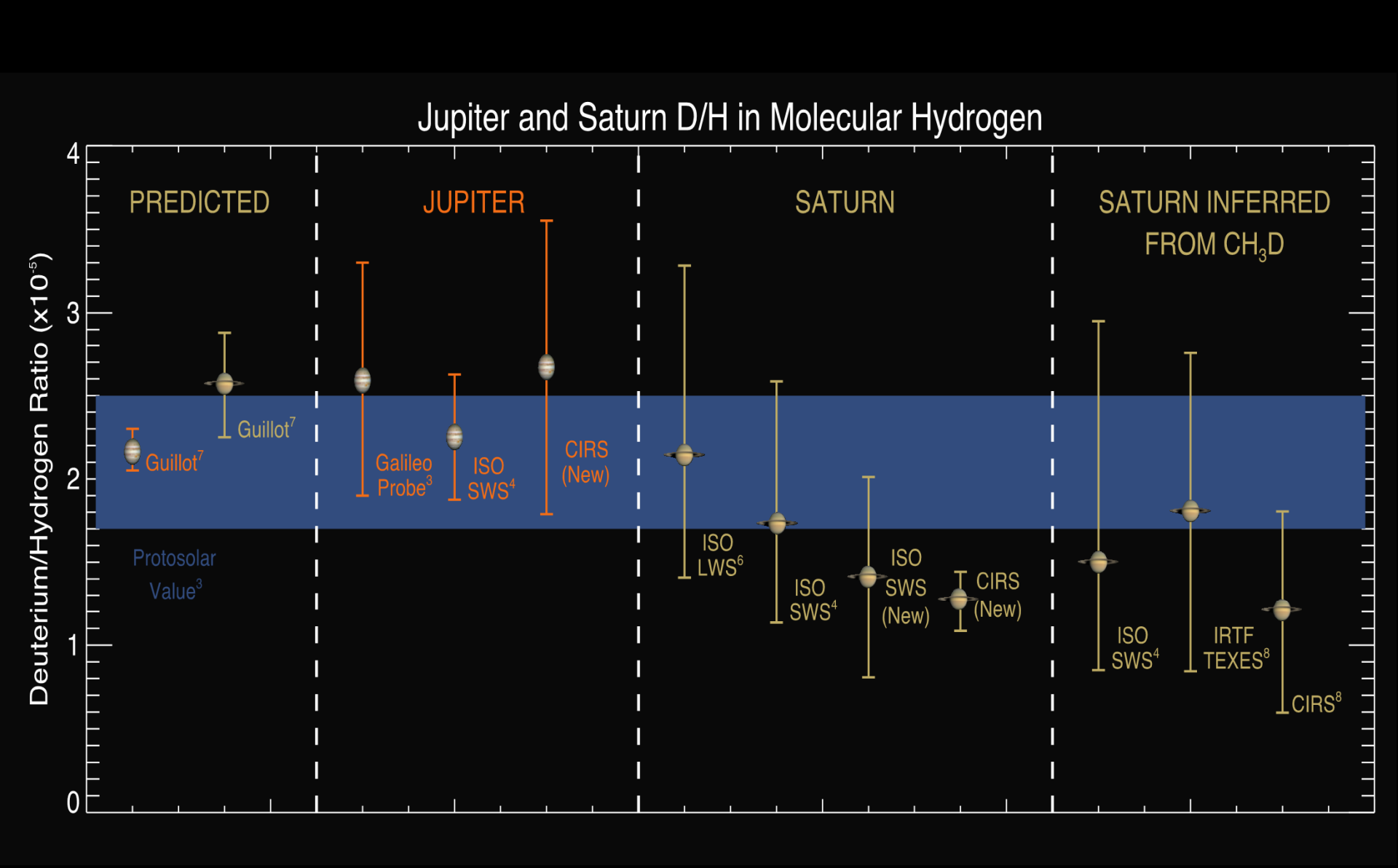

Saturn, Planetographic Latitude=41
Radiance (nW cm^{-2} sr^{-1}/cm^{-1})
665
660
655
650
645
640
635
176.5
177.0
177.5
178.0
178.5
179.0
Wavenumber (cm^{-1})
Data
1.5x10^{-5}
1.8x10^{-5}
2.0x10^{-5}
2.4x10^{-5}
2.7x10^{-5}


This Work D/H (Saturn)
D/H Ratio (x 1E-5)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
-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)
4
3
2
1
0
PREDICTED
JUPITER
SATURN
SATURN INFERRED FROM CH3D
Guillot7
Guillot7
Protosolar Value3
Galileo Probe3
ISO SWS4
CIRS (New)
ISO LWS6
ISO SWS4
ISO SWS (New)
CIRS (New)
ISO SWS4
IRTF TEXES8
CIRS8

Discussion

- We are able to model the HD R(1) line in the CIRS data accurately with NEMESIS
  - New measurement: $D/H=(1.26 \pm 0.20)x10^{-5}$
- 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