Understanding the Atmospheres of Uranus and Neptune through Spectroscopy and Imaging of Thermal Emission

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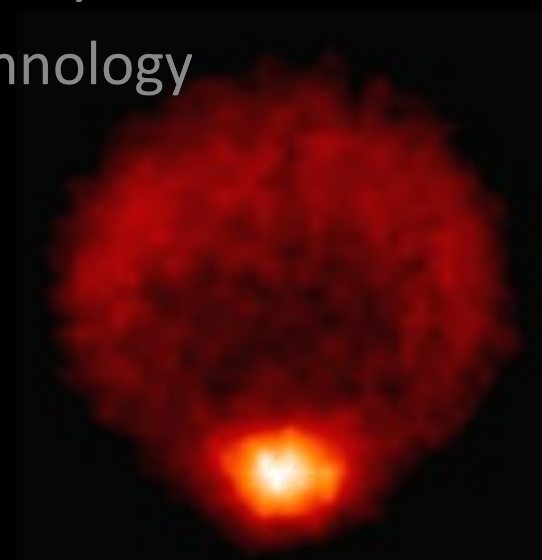

Acknowledgements

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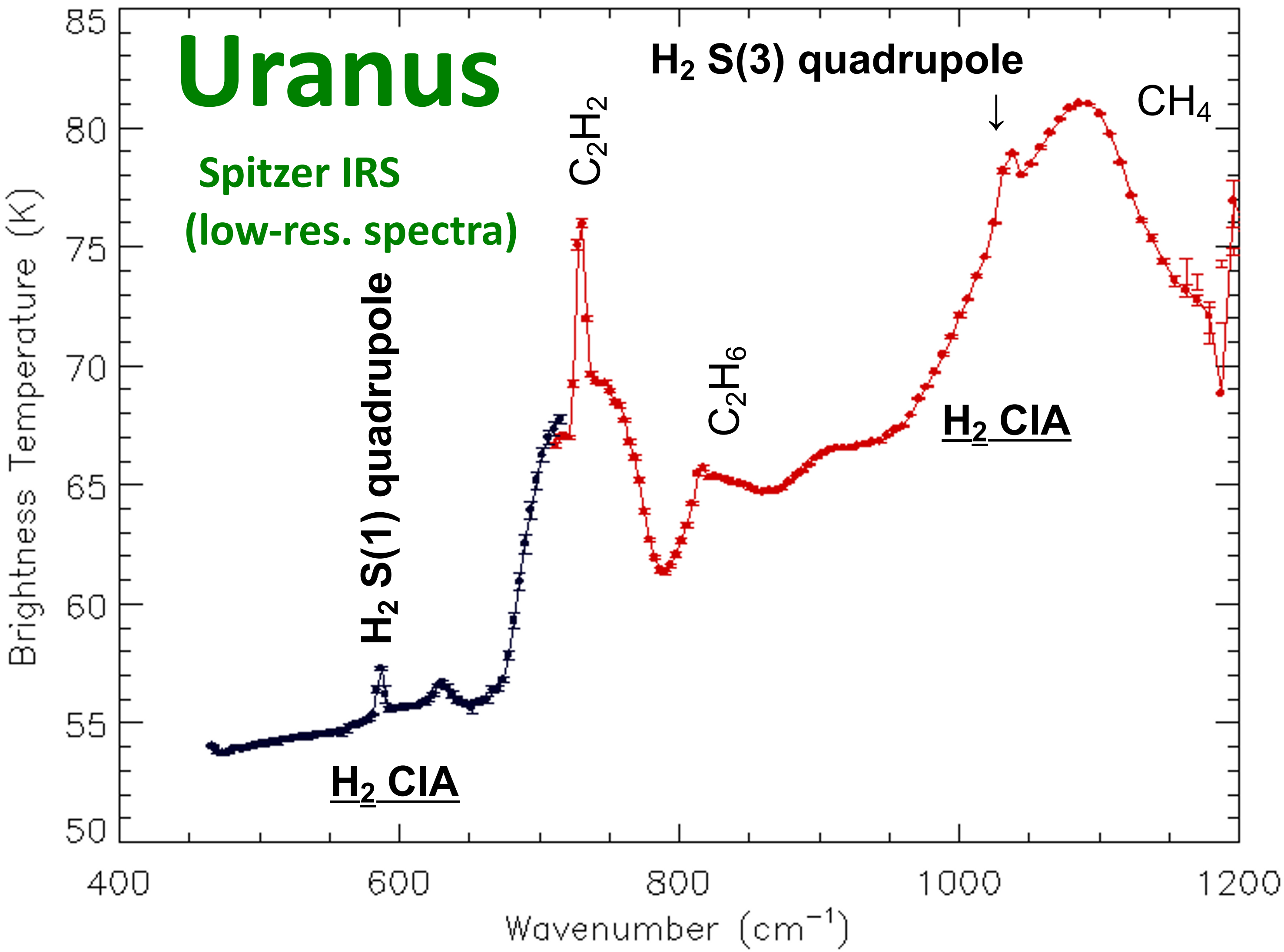
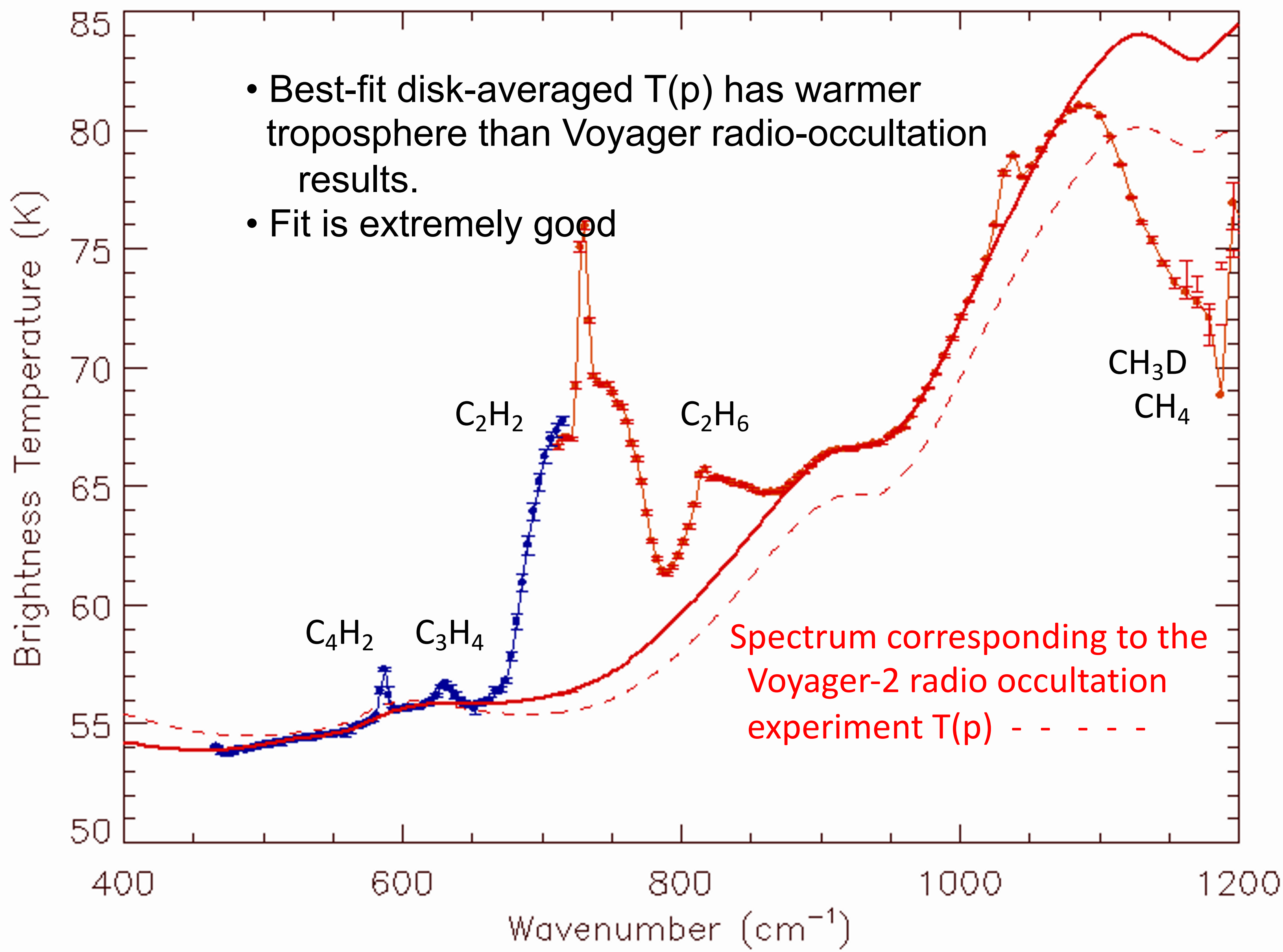
- Disk-averaged thermal spectroscopy
  - Spitzer IRS
  - Herschel PACS
  - ISO Short- and Long-Wavelength Spectrometers
  - Implications for the far IR & submm
- Spatially resolved thermal images
  - Uranus: possible zonal waves, seasonal changes
  - Neptune: stratospheric CH_4 distribution, possible near-polar waves
- Where we need to go from here?
  - Role of SOFIA FORCAST observations
  - Ideas for future SOFIA observations
- Applied physics experiments west of NASA Dryden – Willow Springs Raceway (Streets of Willow track)

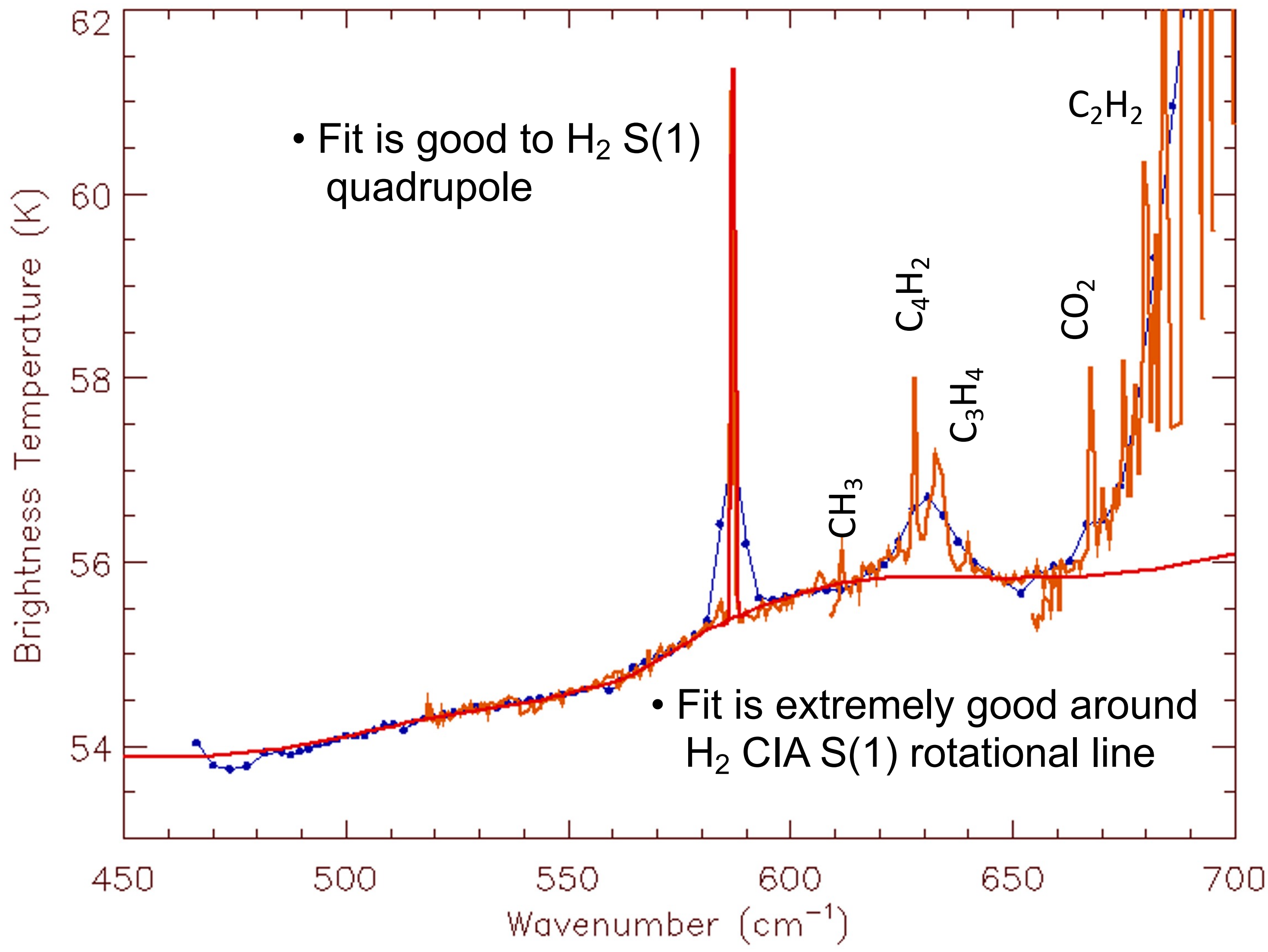
Spectral regions controlled by H_2 used to determine T(p):

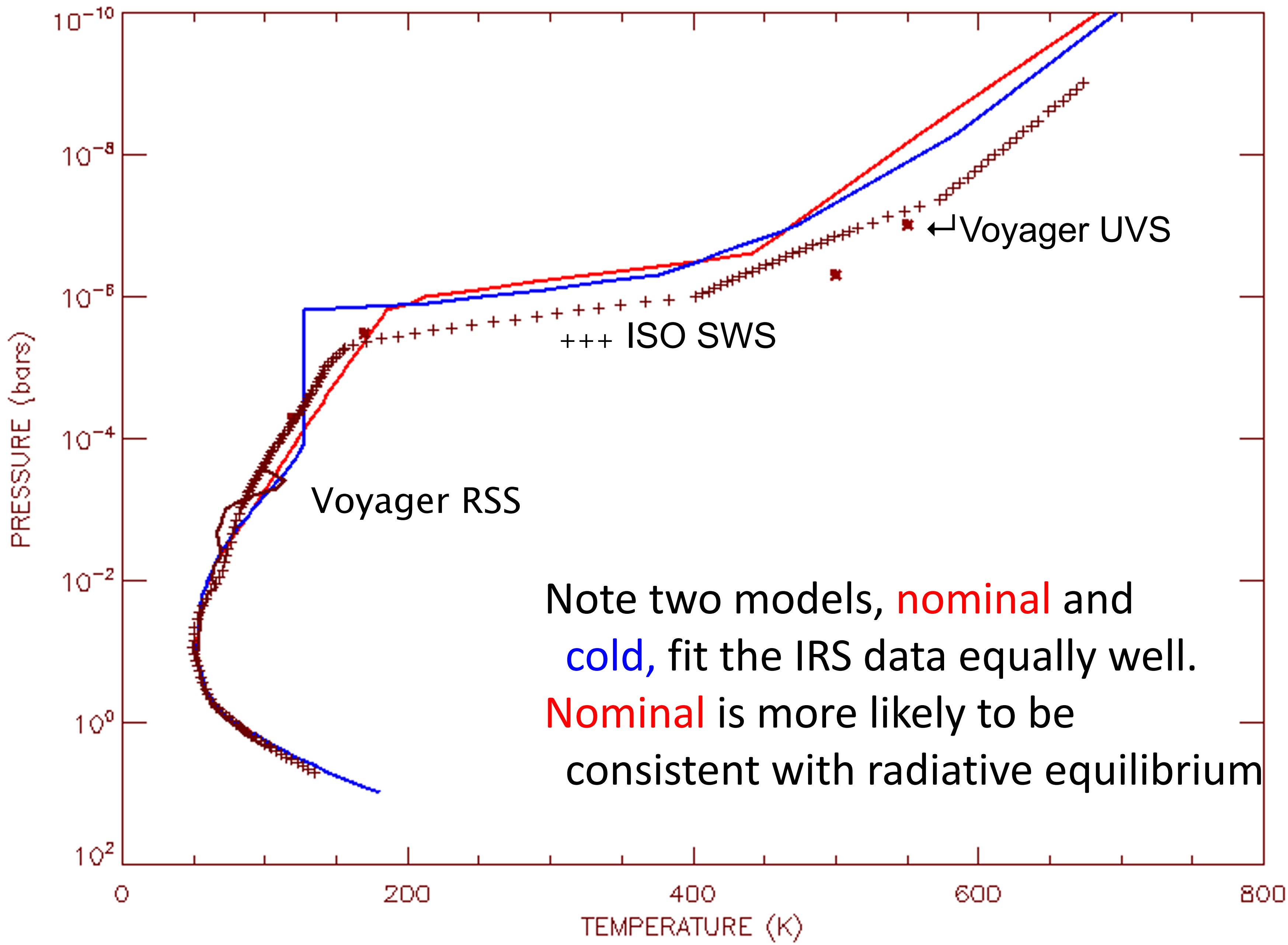
1. Collision-Induced Absorption (SL and LL modes only)
2. quadrupole lines (S(1) and S(2) in SH mode, scaled to the SL continuum)




• Best-fit disk-averaged T(p) has warmer troposphere than Voyager radio-occultation results.
• Fit is extremely good
C_4H_2
C_3H_4
C_2H_2
C_2H_6
CH_3D
CH_4
Spectrum corresponding to the Voyager-2 radio occultation experiment T(p) - - - - -
Brightness Temperature (K)
Wavenumber (cm^{-1})
85
80
75
70
65
60
55
50
400
600
800
1000
1200

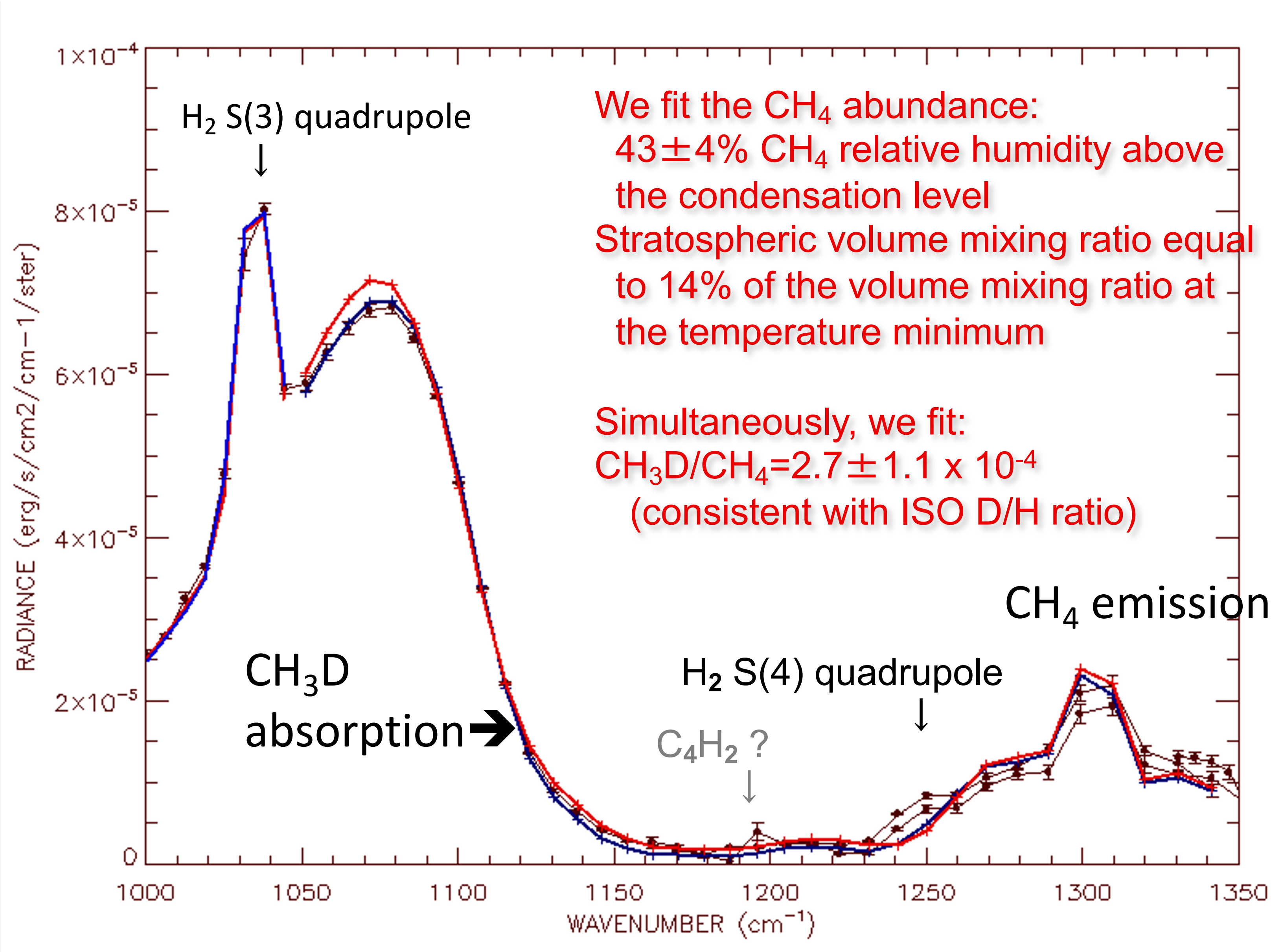
Quadrupole lines S(1) and S(2) in SH mode R~600, scaled to the SL continuum, constrain stratospheric and mesospheric temperatures

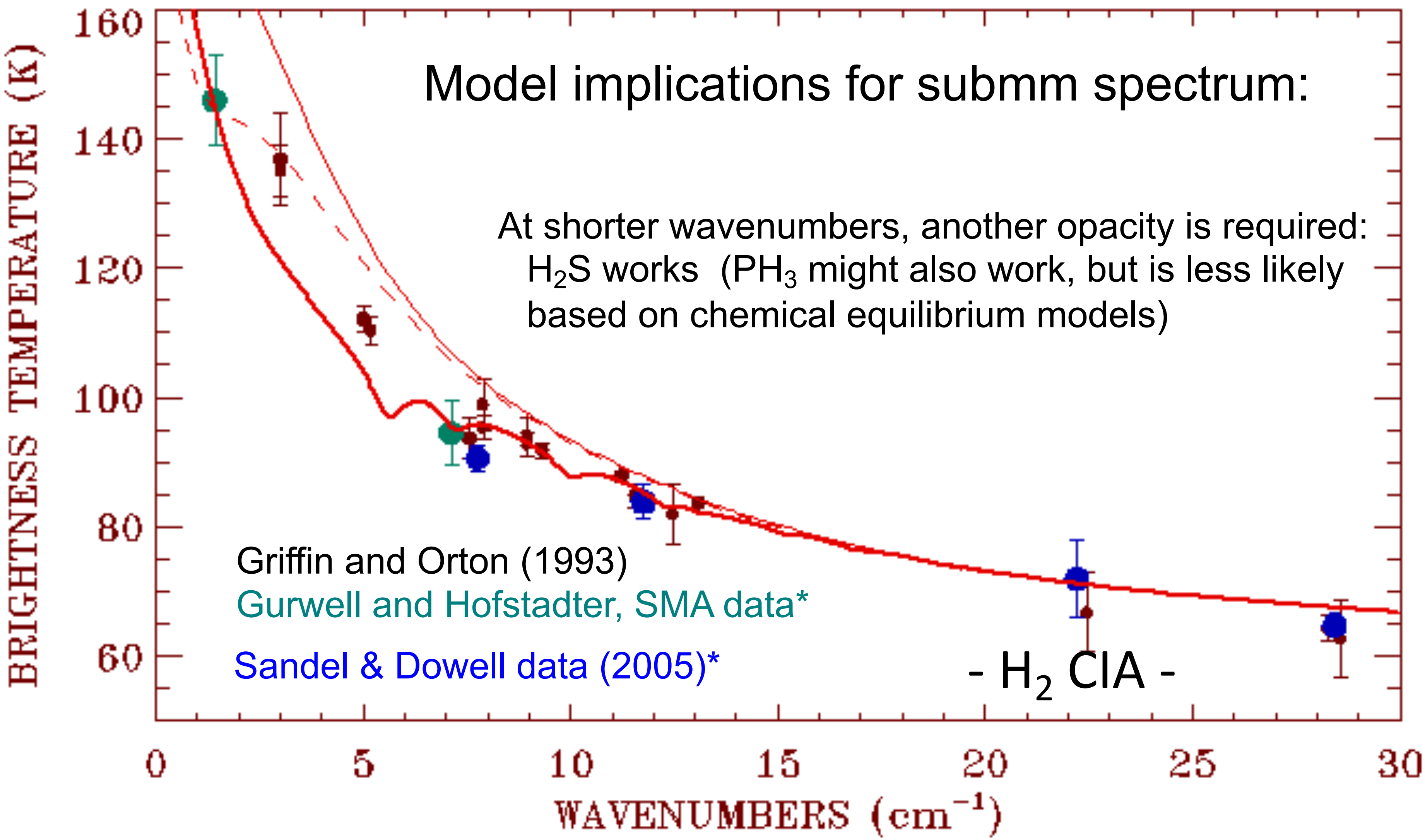




Note two models, nominal and cold, fit the IRS data equally well. Nominal is more likely to be consistent with radiative equilibrium

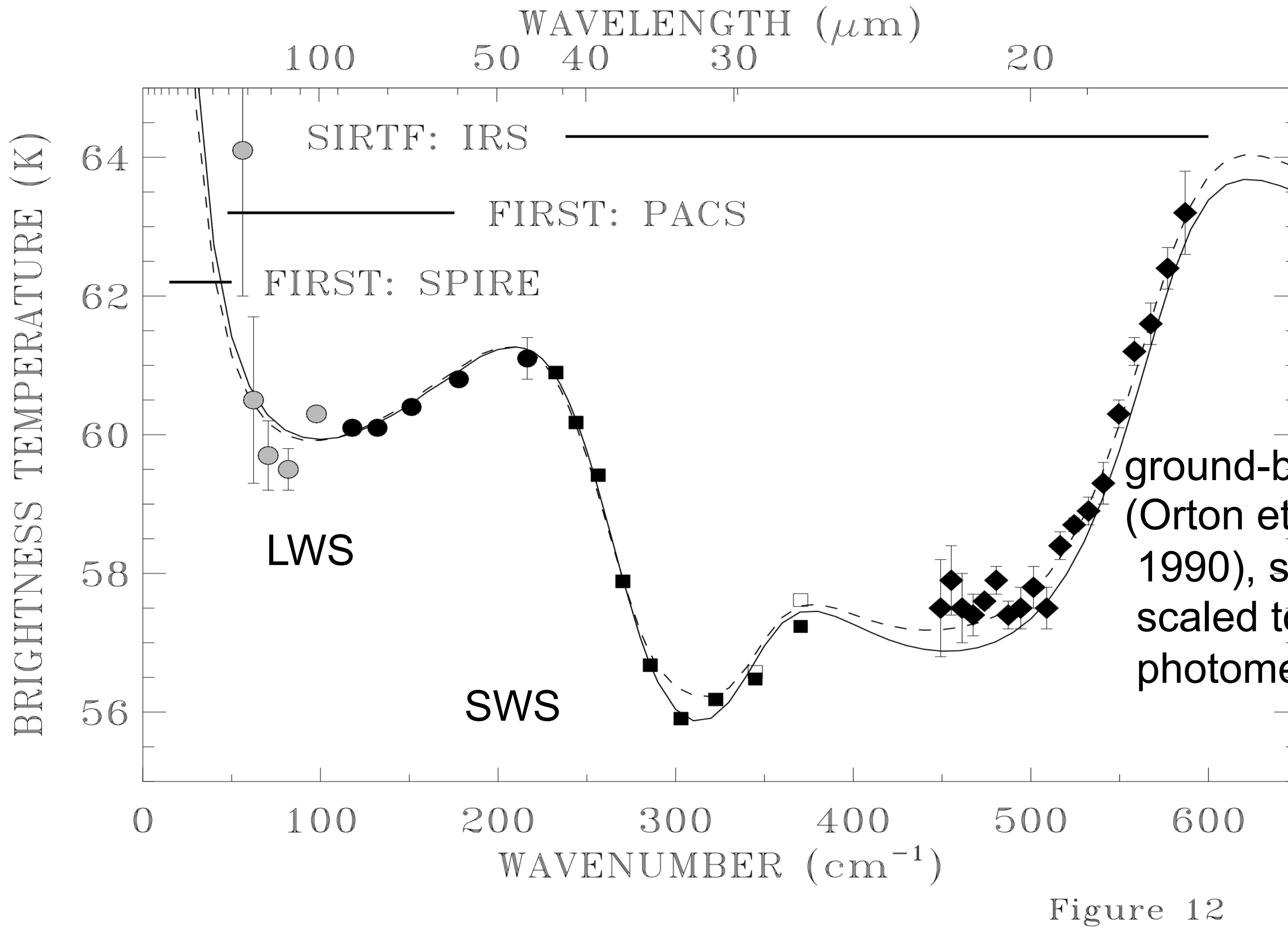
7 – 10 µm region: matching CH_4 and CH_3D





*with WMAP-based recalibration of Mars standard model (1.9% decrease from Rudy)

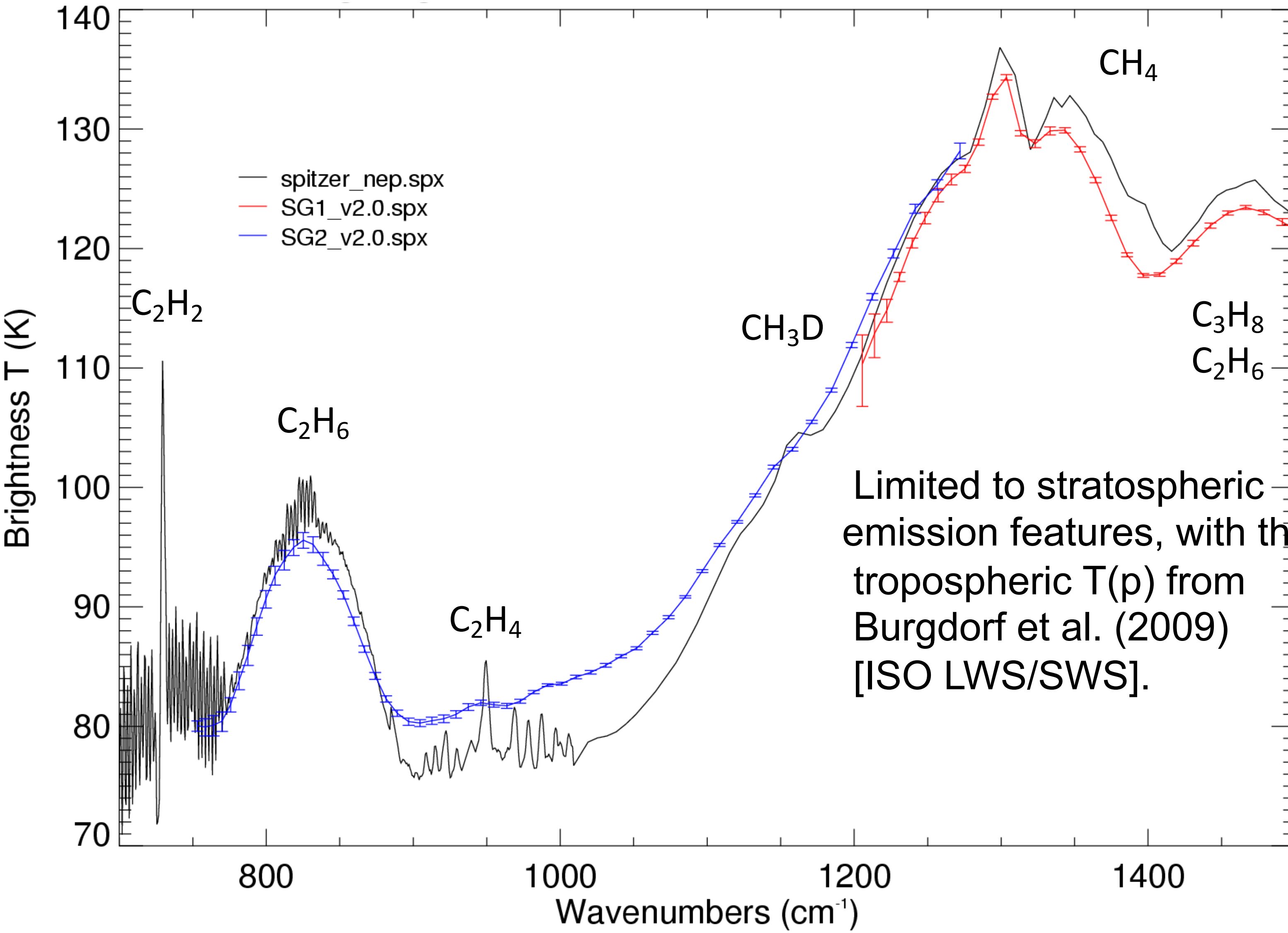
ISO Heritage: LWS and SWS studies of **Neptune**: application to ~~FIRST~~ Herschel (Burgdorf et al. 2003)



ground-based: IRTF (Orton et al. 1989, 1990), spectrum scaled to two photometric points

calibration based on the Griffin & Orton + 3 K "standard model" for Uranus

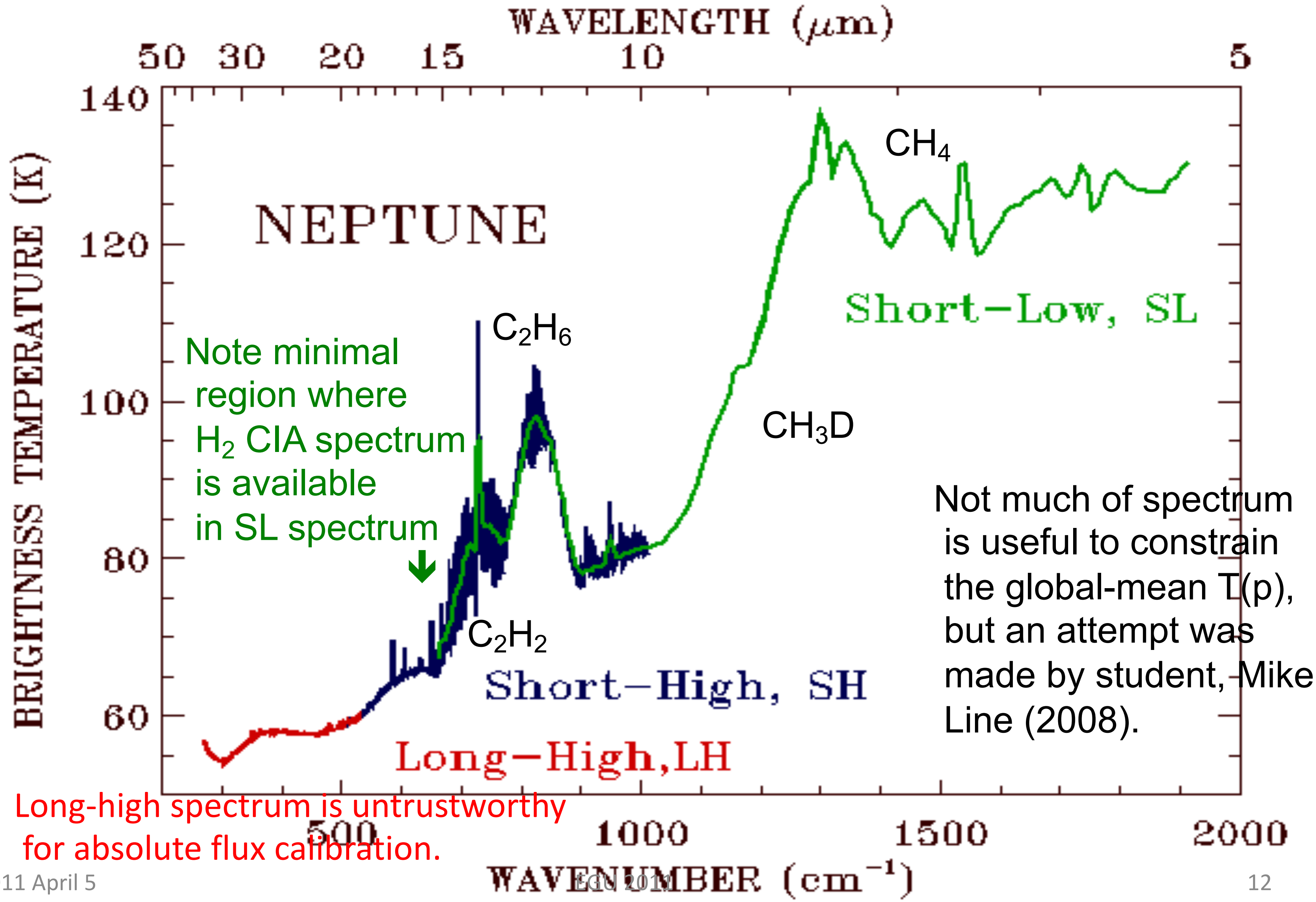
Akari Neptune data analysis (Fletcher et al. 2010)



Limited to stratospheric emission features, with the tropospheric T(p) from Burgdorf et al. (2009) [ISO LWS/SWS].

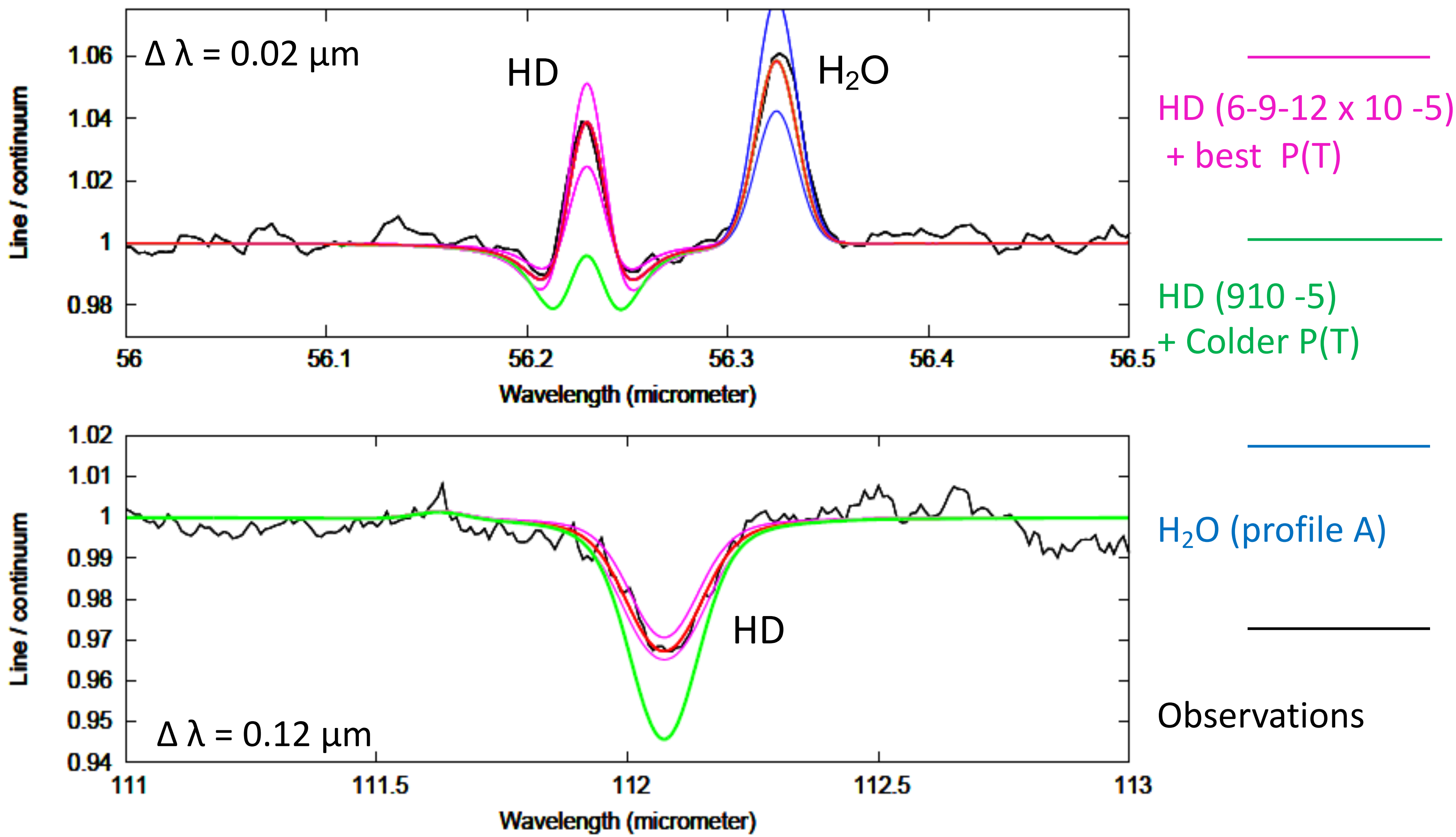
Spitzer IRS Spectrum of Neptune:

(modeling is less mature)



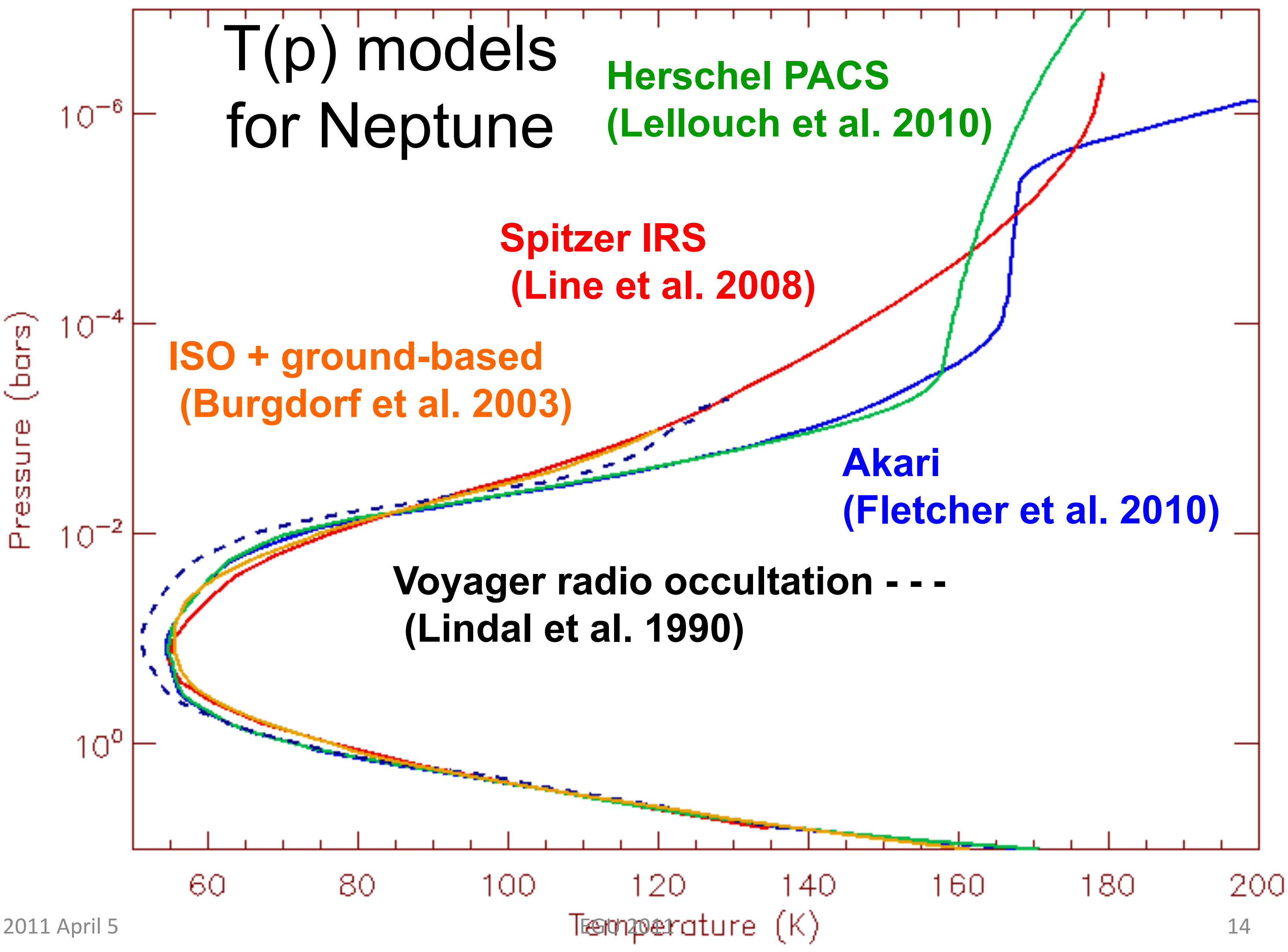
Long-high spectrum is untrustworthy for absolute flux calibration.

Neptune: Herschel PACS line/continuum ratio spectrum: HD & T(p) - Lellouch et al. (2010)



D/H = (4.5±1) x 10-5

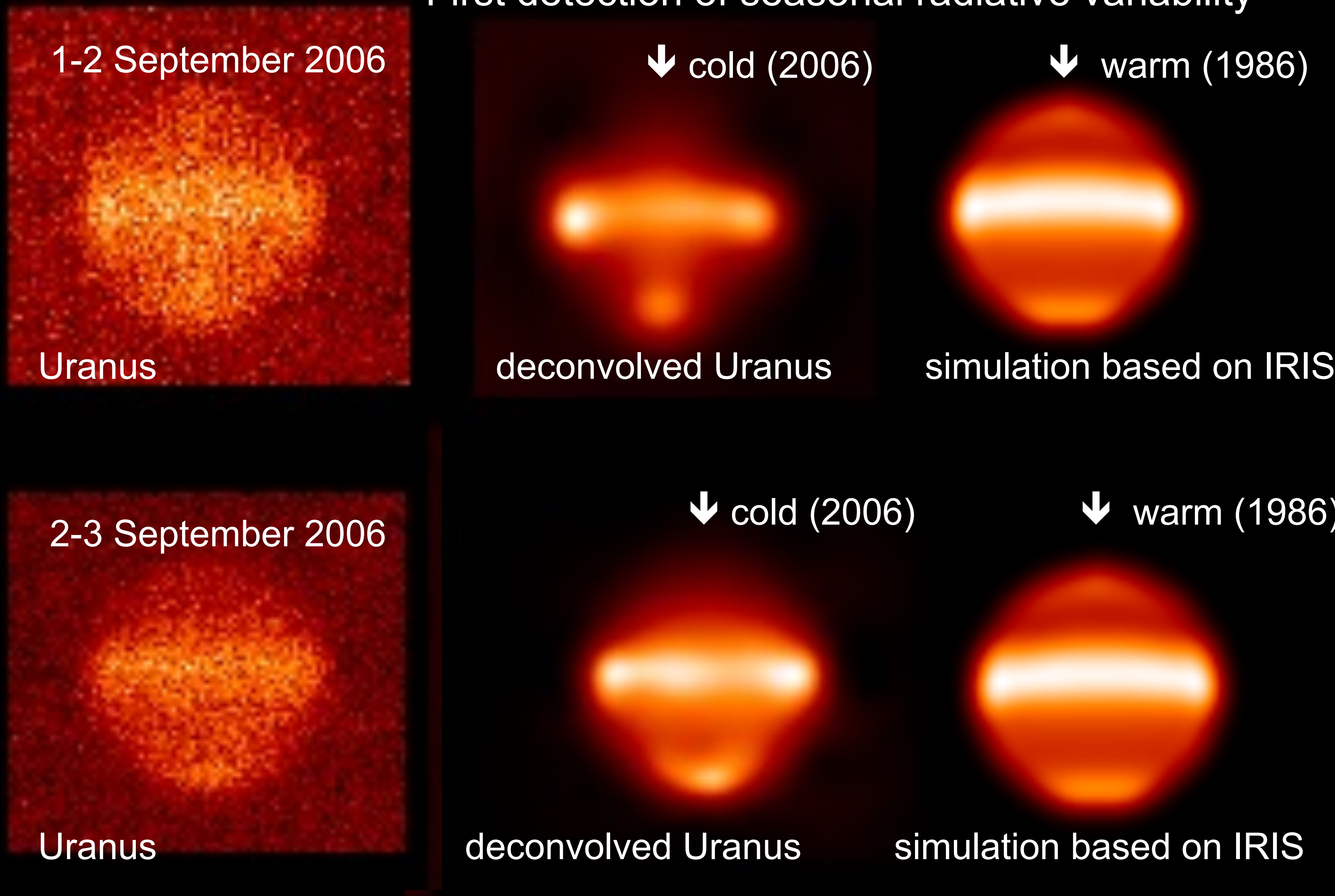
Nominally smaller but consistent with ISO value (D/H = (6.5±2) x 10-**5** , Feuchtgruber *et al* 1999)



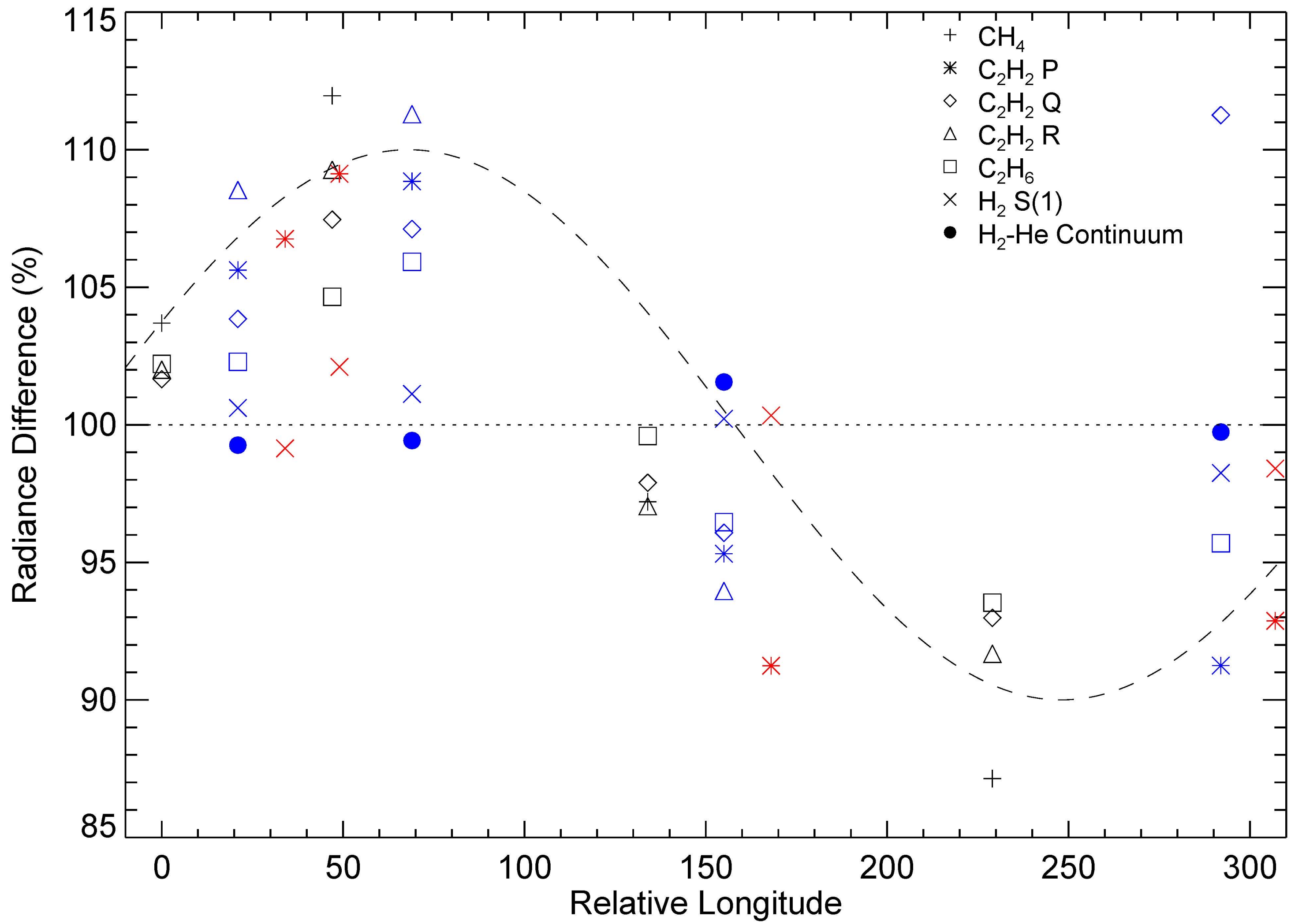
T(p) models
for Neptune
Herschel PACS
(Lellouch et al. 2010)
Spitzer IRS
(Line et al. 2008)
ISO + ground-based
(Burgdorf et al. 2003)
Akari
(Fletcher et al. 2010)
Voyager radio occultation - - -
(Lindal et al. 1990)
Pressure (bars)
10^{-6}
10^{-4}
10^{-2}
10^{0}
60
80
100
120
140
160
180
200
Temperature (K)

VLR / VISIR image of **Uranus** at 18 μm compared with model based on Voyager IRIS T(p,lat.): generally consistent, but north pole is colder:

First detection of seasonal radiative variability



Uranus: Spitzer data show a variability in hydrocarbon emissions that is clearly a function of the longitude, which is observed as the planet rotates.

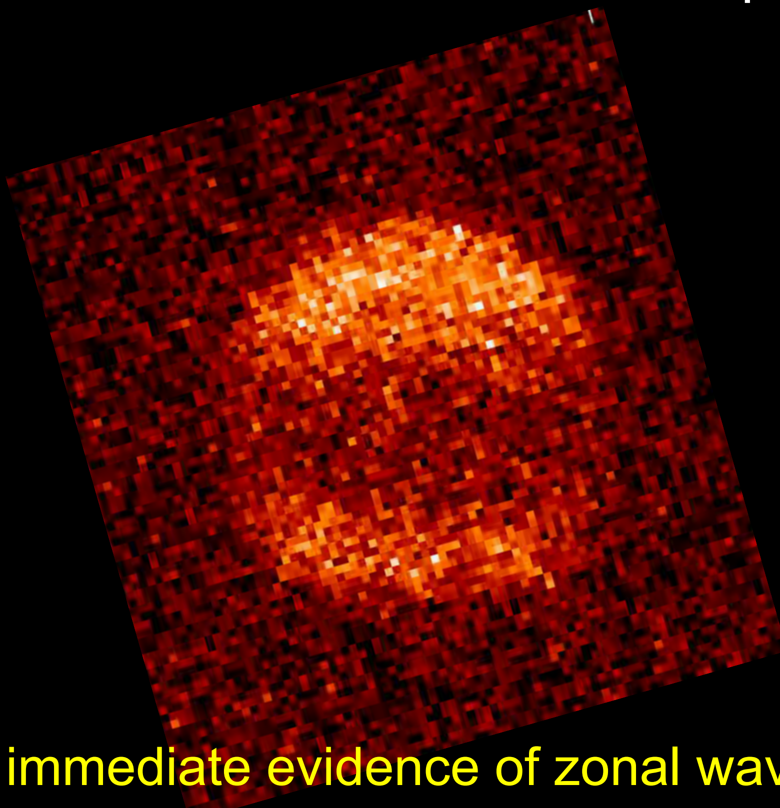


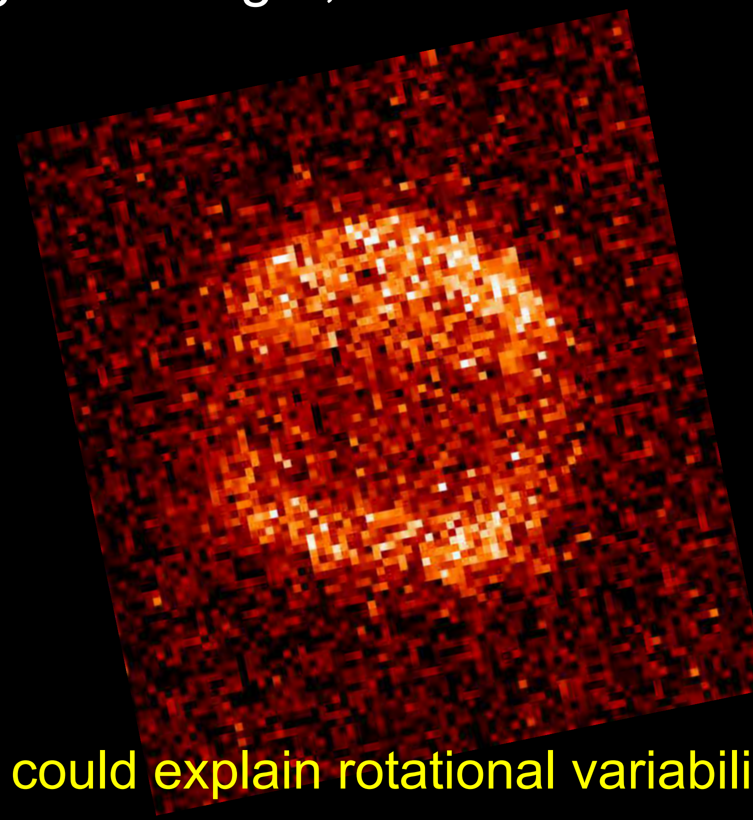
2009 Thermal Images of Uranus

FIRST IMAGES OF STRATOSPHERIC (acetylene) EMISSION

Gemini-S/T-Recs 13.2-μm images on Aug 29; Sep 18, 19, 20, 21, 22

VLT/VISIR 13.2 μm images on Aug 5, 6:

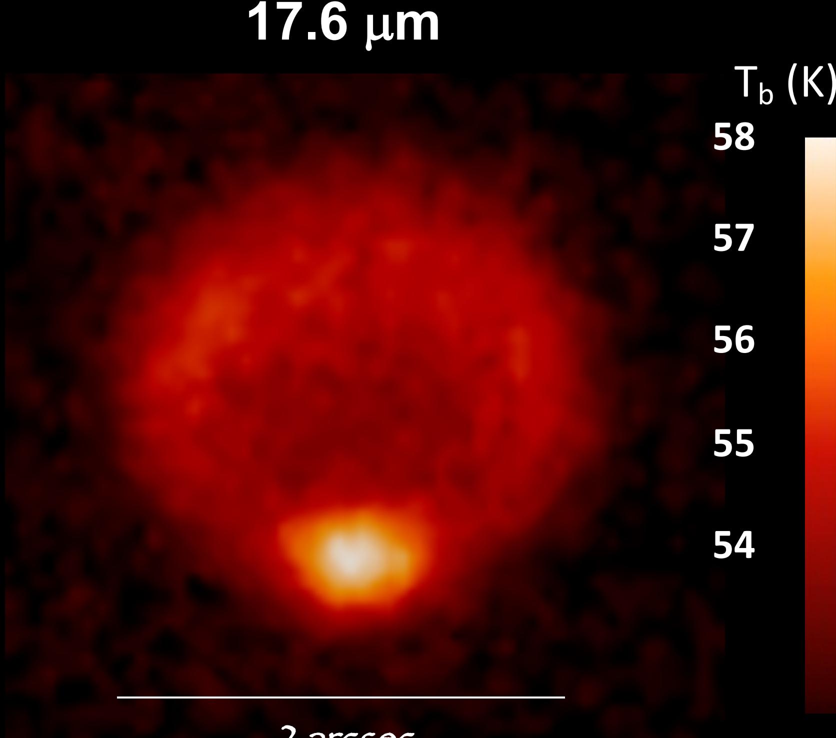




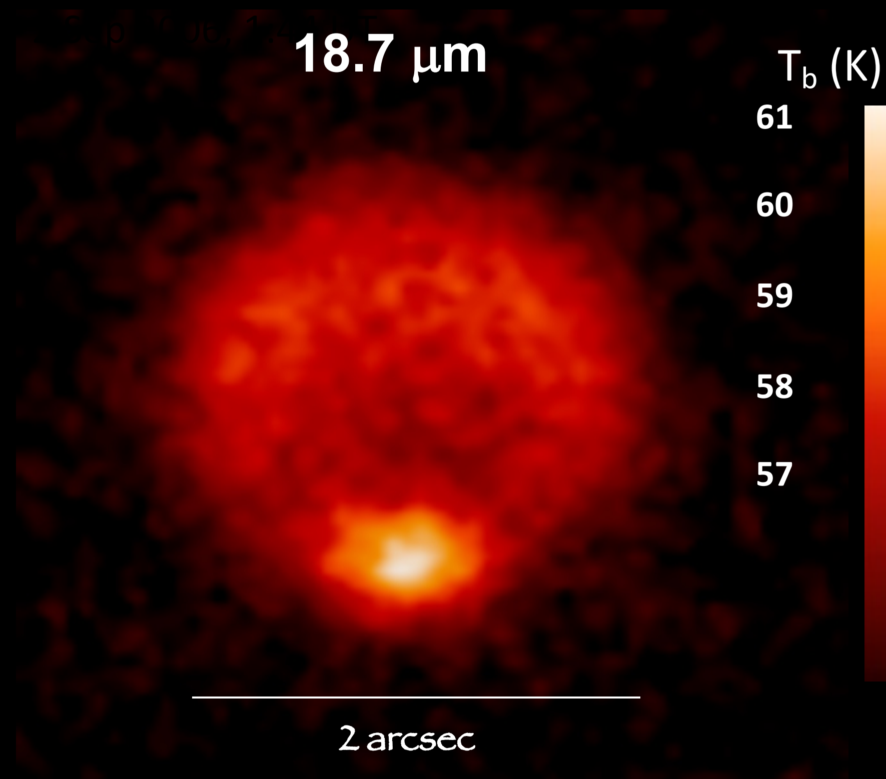
No immediate evidence of zonal waves that could explain rotational variability in the Spitzer spectra

Neptune

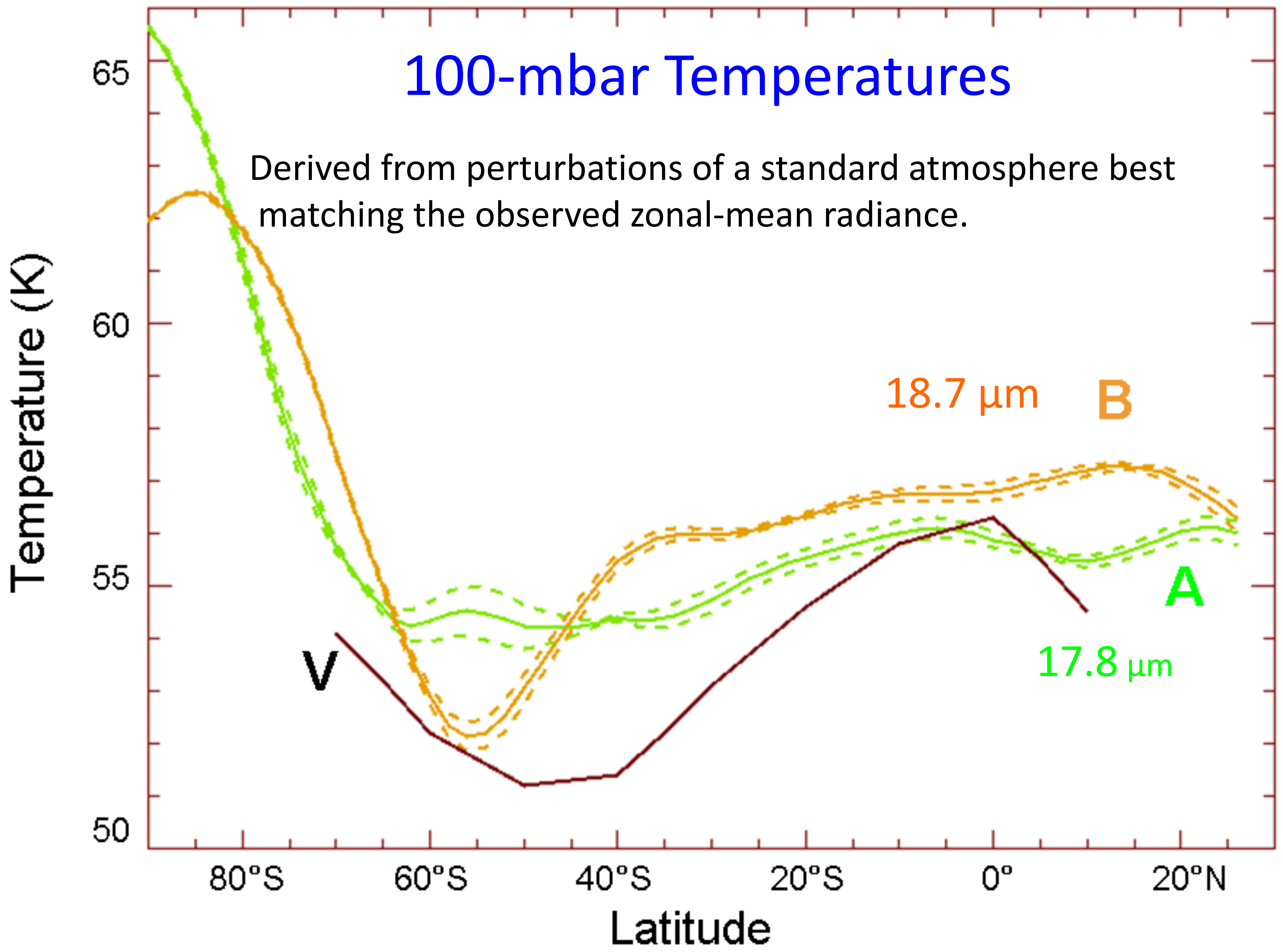
VISIR - ESO/VLT, 2006 Sept. 1

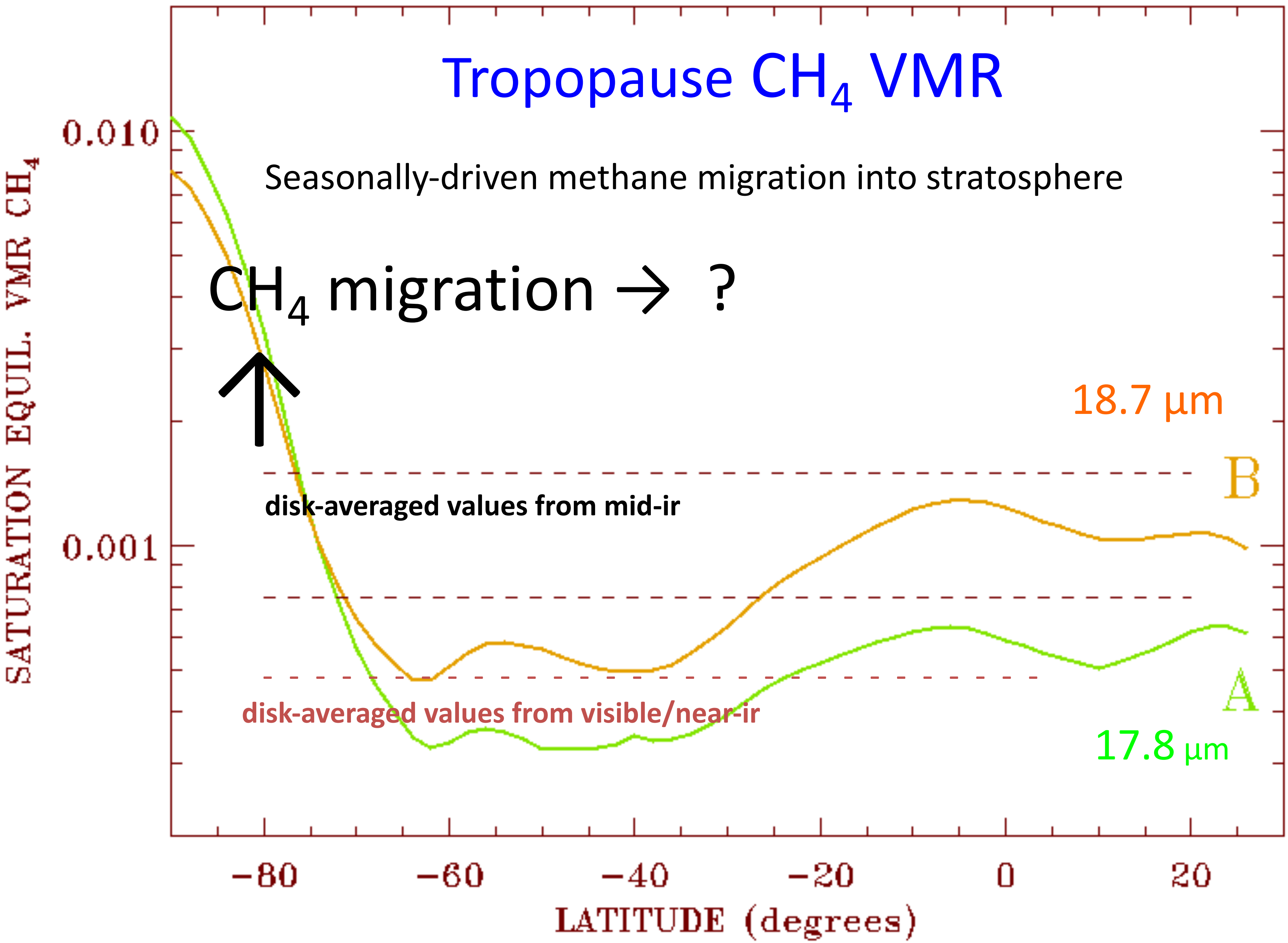


Probed level: about 80 mbar



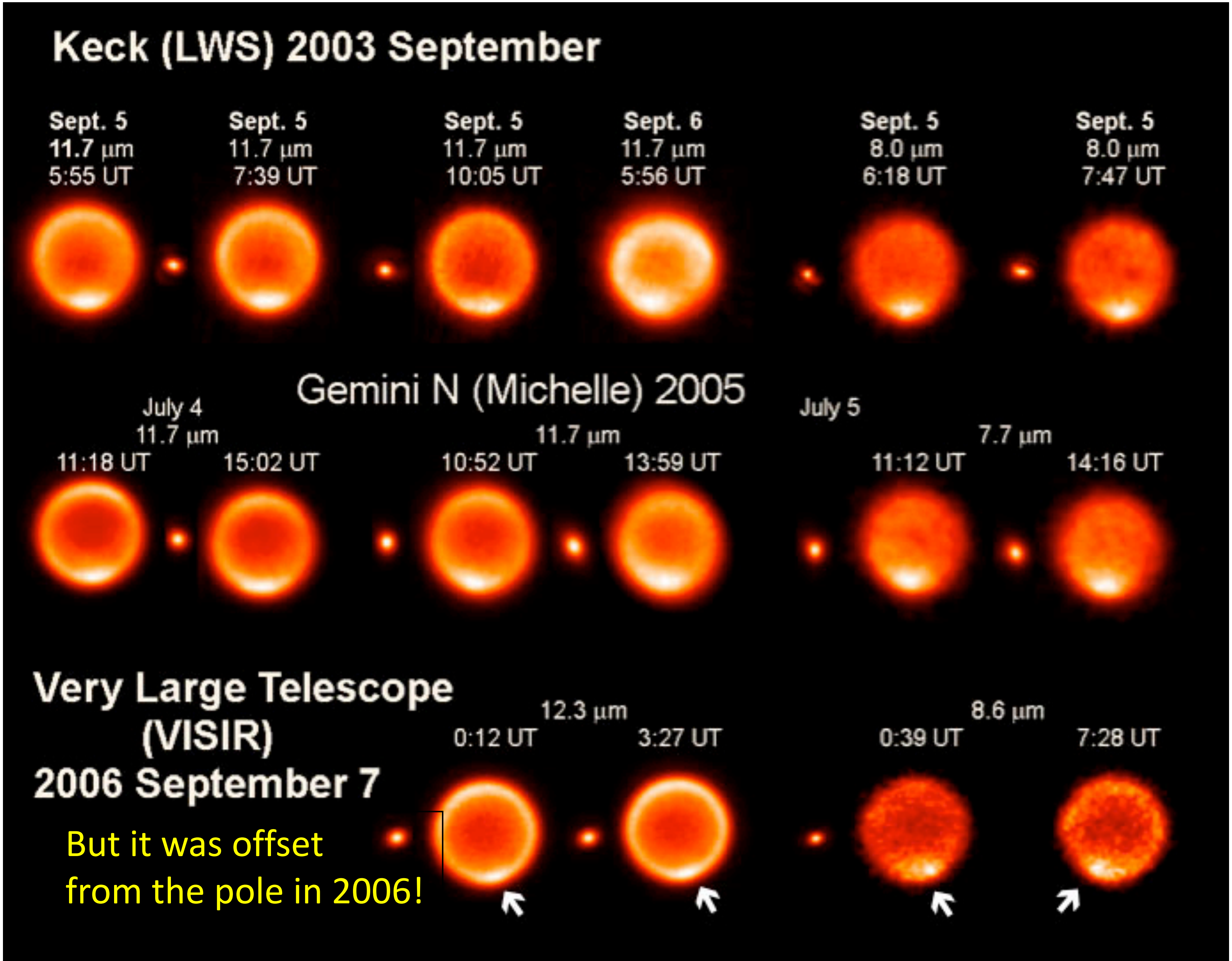
Probed level: about 110 mbar


100-mbar Temperatures
Derived from perturbations of a standard atmosphere best matching the observed zonal-mean radiance.
65
60
55
50
Temperature (K)
18.7 μm
B
A
17.8 μm
V
80°S
60°S
40°S
20°S
0°
20°N
Latitude

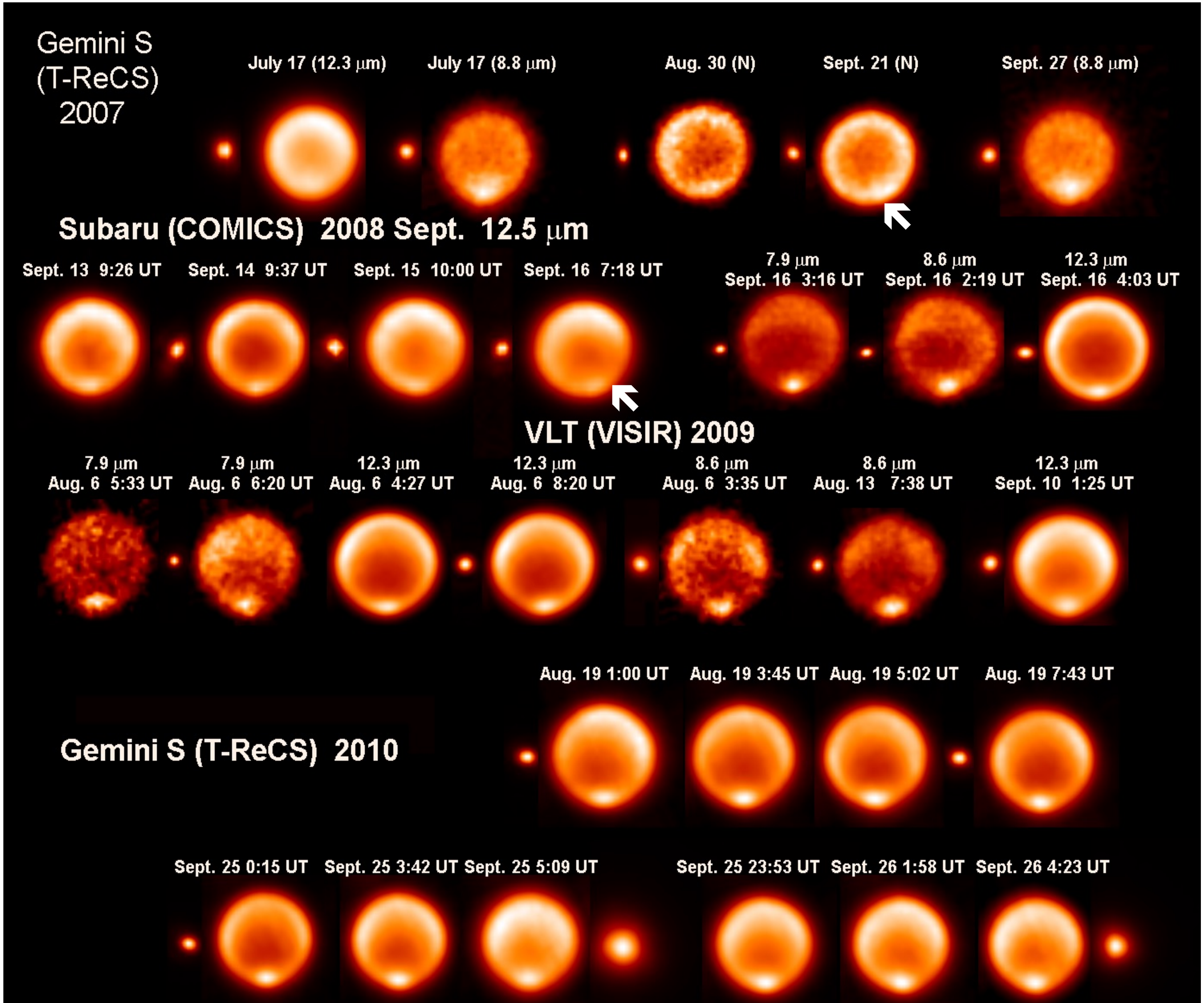


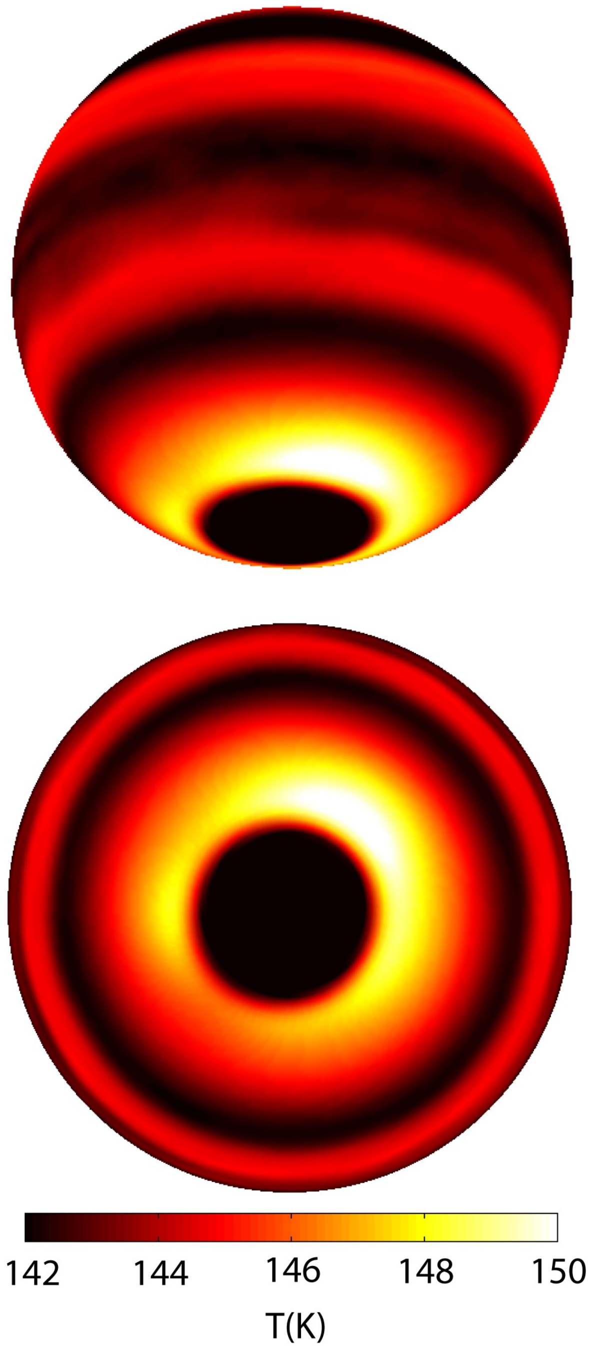
Tropopause CH_4 VMR
Seasonally-driven methane migration into stratosphere
CH_4 migration → ?
18.7 µm
B
disk-averaged values from mid-ir
A
disk-averaged values from visible/near-ir
17.8 µm
0.010
0.001
SATURATION EQUIL. VMR CH_4
−80
−60
−40
−20
0
20
LATITUDE (degrees)

Neptune also has a radiatively driven stratospheric polar hot spot



Offset hot spot survey: detected in 3 out of 13 epochs, 2003-2010



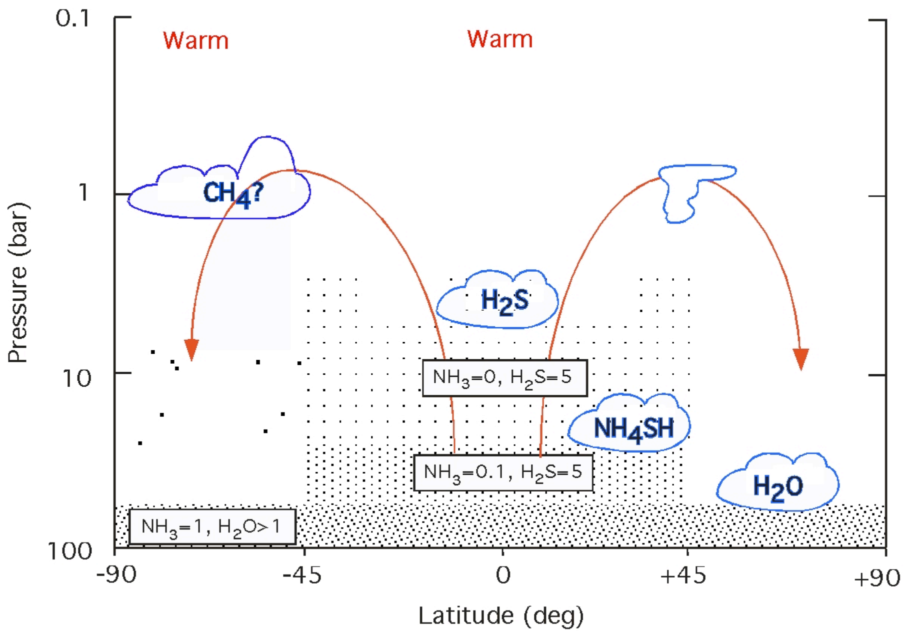


It is possible to model this feature as a wavenumber-1 zonal thermal wave.

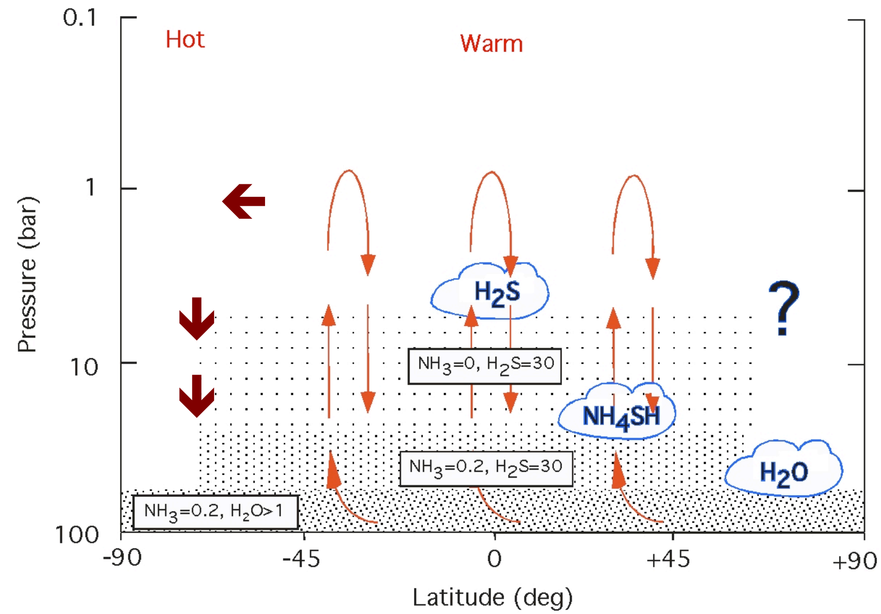
The model shown is based on GCM models by Liu and Schneider, showing 4-mbar temperatures.

What is the overall picture of organized flow?

Uranus



Neptune



From microwave, visible and near-infrared data (Hofstadter et al. 2008).

Migration of CH_4 into the stratosphere from the south pole seems inconsistent with possible downwelling at the pole.

Conclusions – Uranus

- A T(p) that fits the Spitzer IRS data has a wider tropopause and is warmer at depth compared with Voyager RSS results
- CH_4 can be distributed vertically in the low and middle stratosphere at a VMR determined by 14% of saturation equilibrium at the tropopause
- $[CH_3D]/[CH_4]$is consistent with ISO/SWS results.
- The submm-radio spectrum may be controlled by H_2S opacity (possibly PH_3; both are testable)
- Zonal thermal wave was present in 2005 and 2007, not evident in images
- Seasonal variability of upper troposphere has been detected at the N pole

Conclusions – Neptune

- A T(p) that fits the Spitzer IRS data is warmer than the Voyager RSS results
- CH_4 is distributed in the stratosphere with a mixing ratio significantly higher than saturation equilibrium
- [CH_3D]/[CH_4]is consistent with ISO/SWS results.
- Offset polar hot spot is not a rare condition; it can be explained by a dynamical phenomenon
- CH_4 could migrate up into the stratosphere at the south pole, but this must be reconciled with other evidence implying downwelling winds at the pole

Work Remaining - Uranus

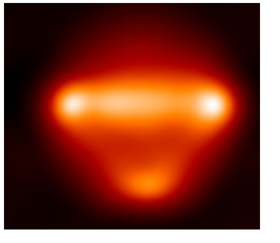
- Understand why hydrocarbon emission can vary, but not the quadrupole emission (assuming the zonal distribution of hydrocarbons must be uniform)

- Test the influence of disequilibrium *para- vs ortho*-H_2 in the stratosphere (Fouchet et al. 2003) on the quadrupole sensitivity

- Compare with older data sets and determining the consistency of observed variations with changing geometry

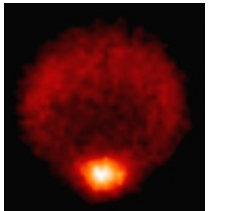
- Determine hydrocarbon abundances

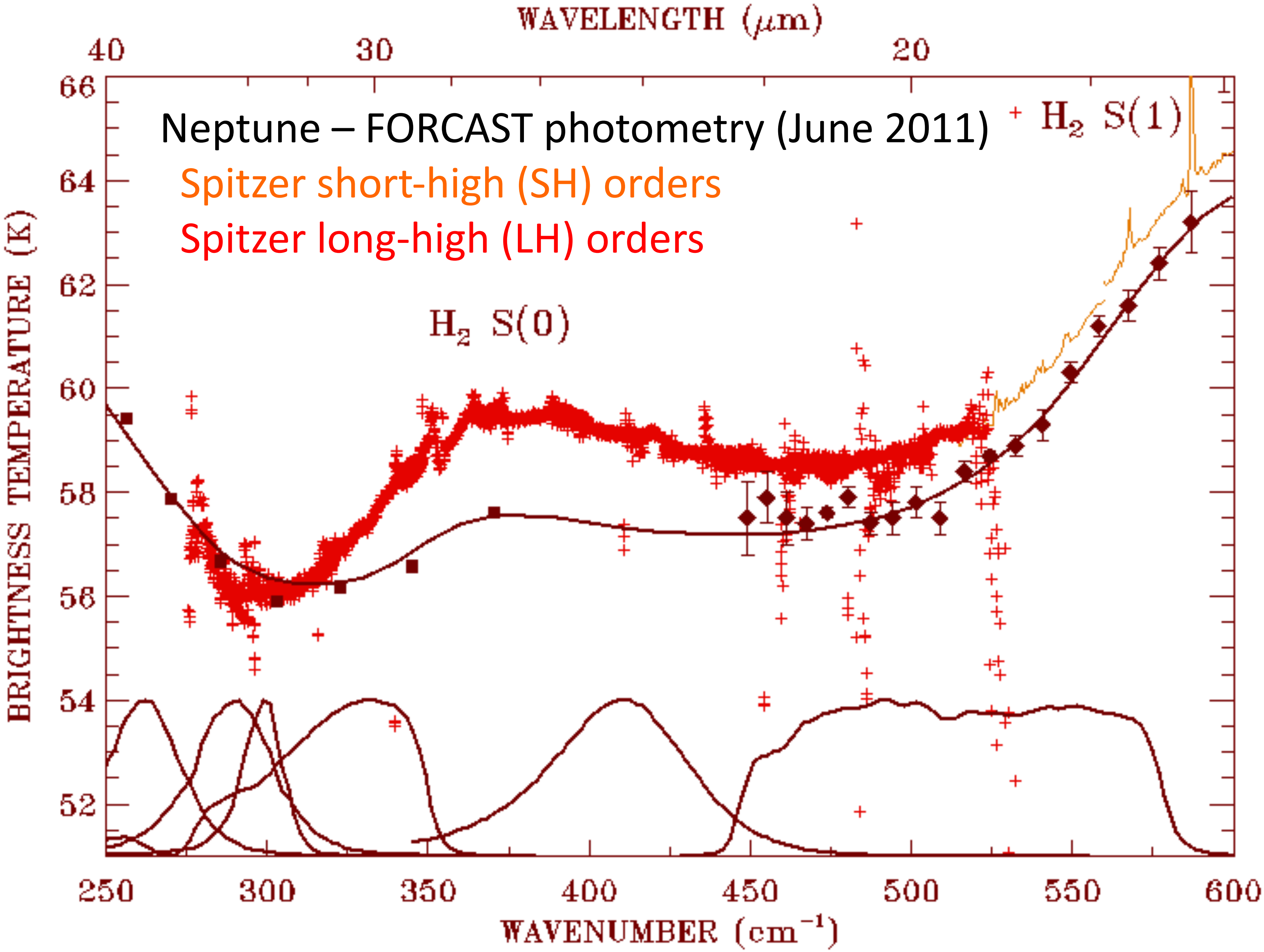
- Analyze the short-wavelength spectrum, which is a mixture of thermal and reflected solar radiation and radio images.



Work Remaining - Neptune

- Explore the implications of the derived T(p) for the far-infrared/submillimeter/millimeter spectral region, including the influence of uncertainties in the bulk composition
- Compare with older data sets and determining the consistency of observed variations with changing geometry
- Determine hydrocarbon abundances
- Analyze the short-wavelength spectrum, which is a mixture of thermal and reflected solar radiation
- Examine mid-IR, submm and radio images





Neptune – FORCAST photometry (June 2011)
Spitzer short-high (SH) orders
Spitzer long-high (LH) orders
H_2 S(0)
H_2 S(1)
WAVELENGTH (μm)
40
30
20
BRIGHTNESS TEMPERATURE (K)
66
64
62
60
58
56
54
52
250
300
350
400
450
500
550
600
WAVENUMBER (cm^{-1})

SOFIA – current (June 2011)

- Re-examine the global-mean temperature structure using the 15-35 μm spectrum
  - No long-low Spitzer spectrum was made because of saturation concerns
  - Long-high Spitzer spectrum was totally unusable
  - No grism spectroscopy on FORCAST was yet available, so
  - Start with multi-channel photometry

SOFIA - future

- Examine the chemical inventory of both planets, including isotopic constituents, using EXES, GREAT; use high spectral resolution to
  - Differentiate between various hydrocarbons
  - Determine the vertical distribution
  - Complete the chemical inventory of the planet
- Examine the longer-wavelength spectrum, to mitigate systematic uncertainties between the ISO SWS and LWS calibration systems
  - Requires a far-infrared spectrometer
  - Not necessarily high resolution; we're interested in the continuum for Uranus and Neptune

West of NASA Dryden

- *In situ* multi-temperature kinetic cohesion experiments


the STREETS of WILLOW SPRINGS
Paved Road Course & Skid Pad
TOYOTA
BALCONY

"Streets of Willow" track map
from Google maps.

The track video is from 2011 June 18, using an Android 2 camcorder app.

-I ran the track clockwise (the video excerpt starts with the "front straight".

-Note "the bowl" has a 20° bank

-The emphasis of high-performance driving is: SAFETY, then making all maneuvers SMOOTH, and only then on increasing speed.

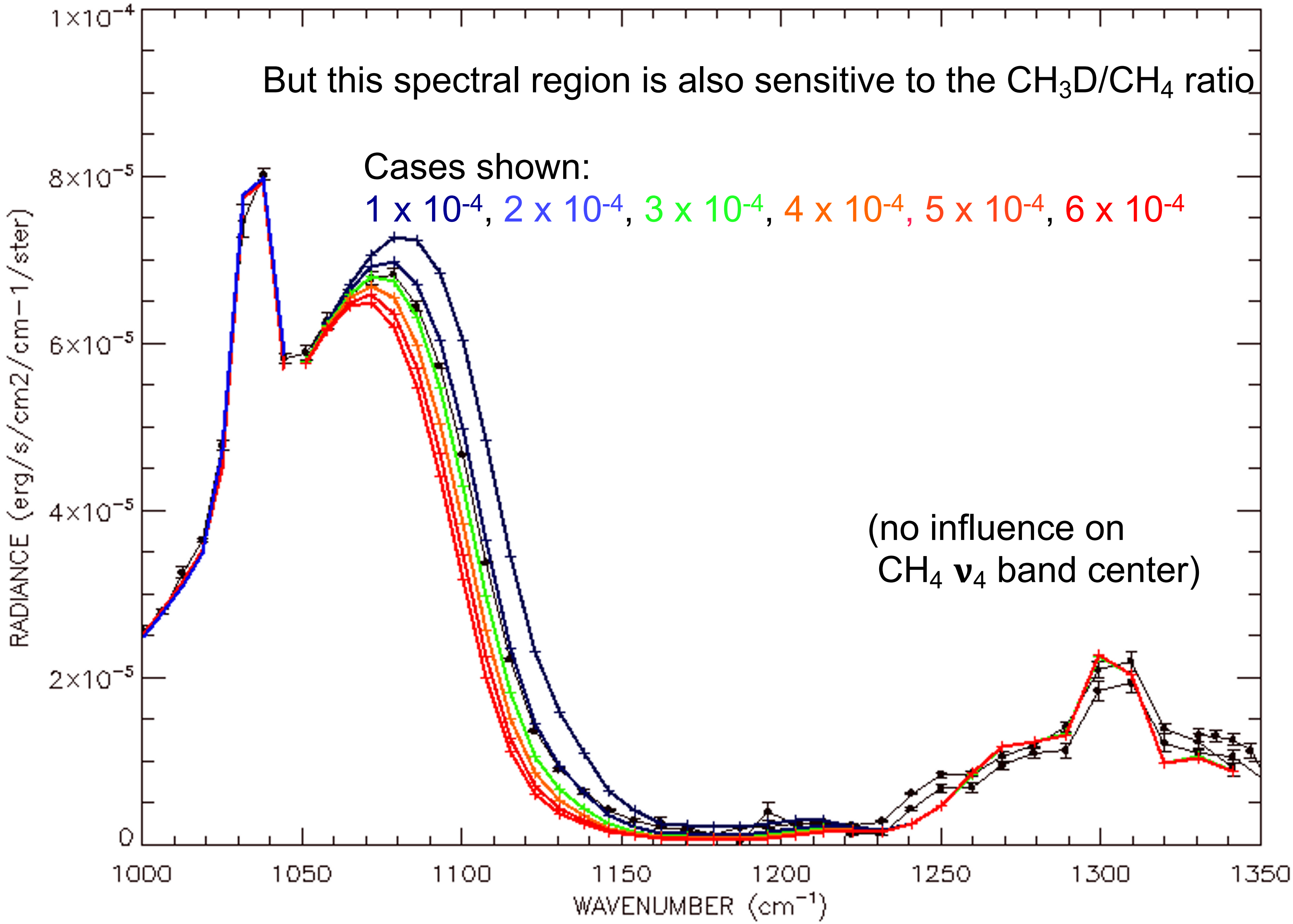
-This is all a matter of changes in momentum, while maintaining maximum car stability

-Note I slow the car down considerably for tight corners, turn only when not accelerating to move weight to the front tires, and try to approach the maximum forward and lateral acceleration the tires can tolerate.

Glenn driving his 2007 Porsche Cayman at Streets of Willow (CCW)
specs: 245 Hp, 2.7-liter displacement engine

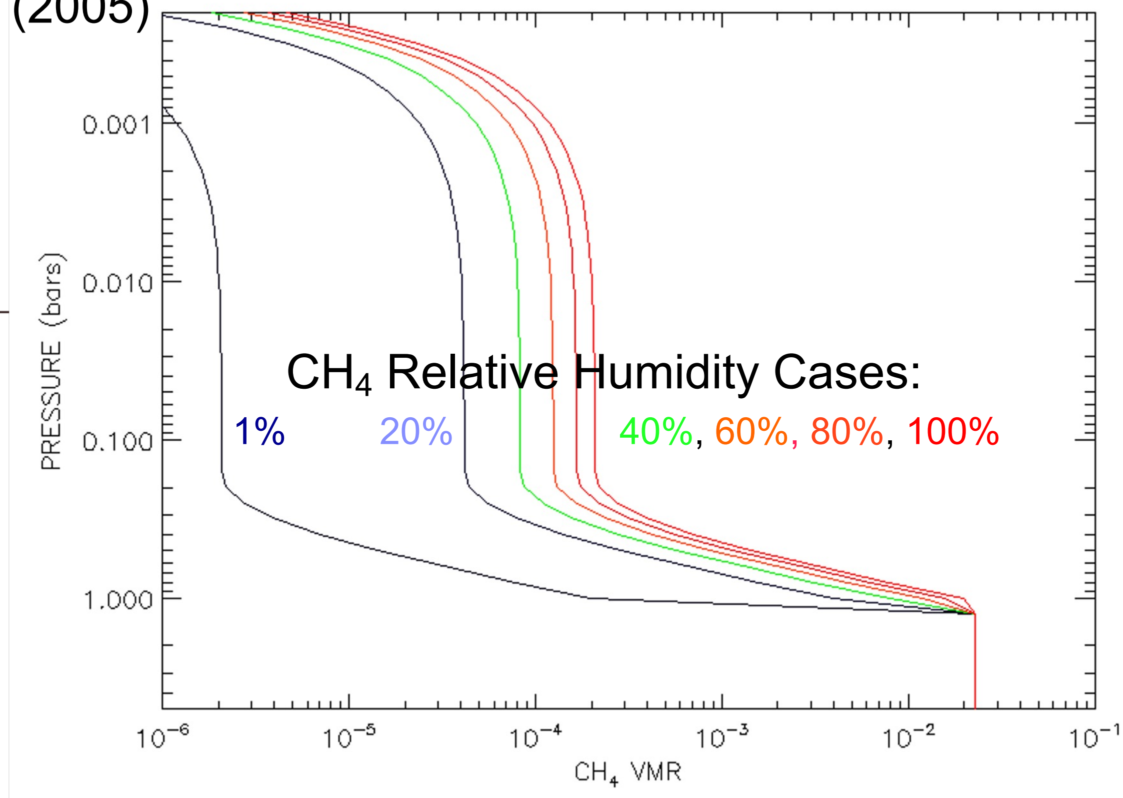
Video

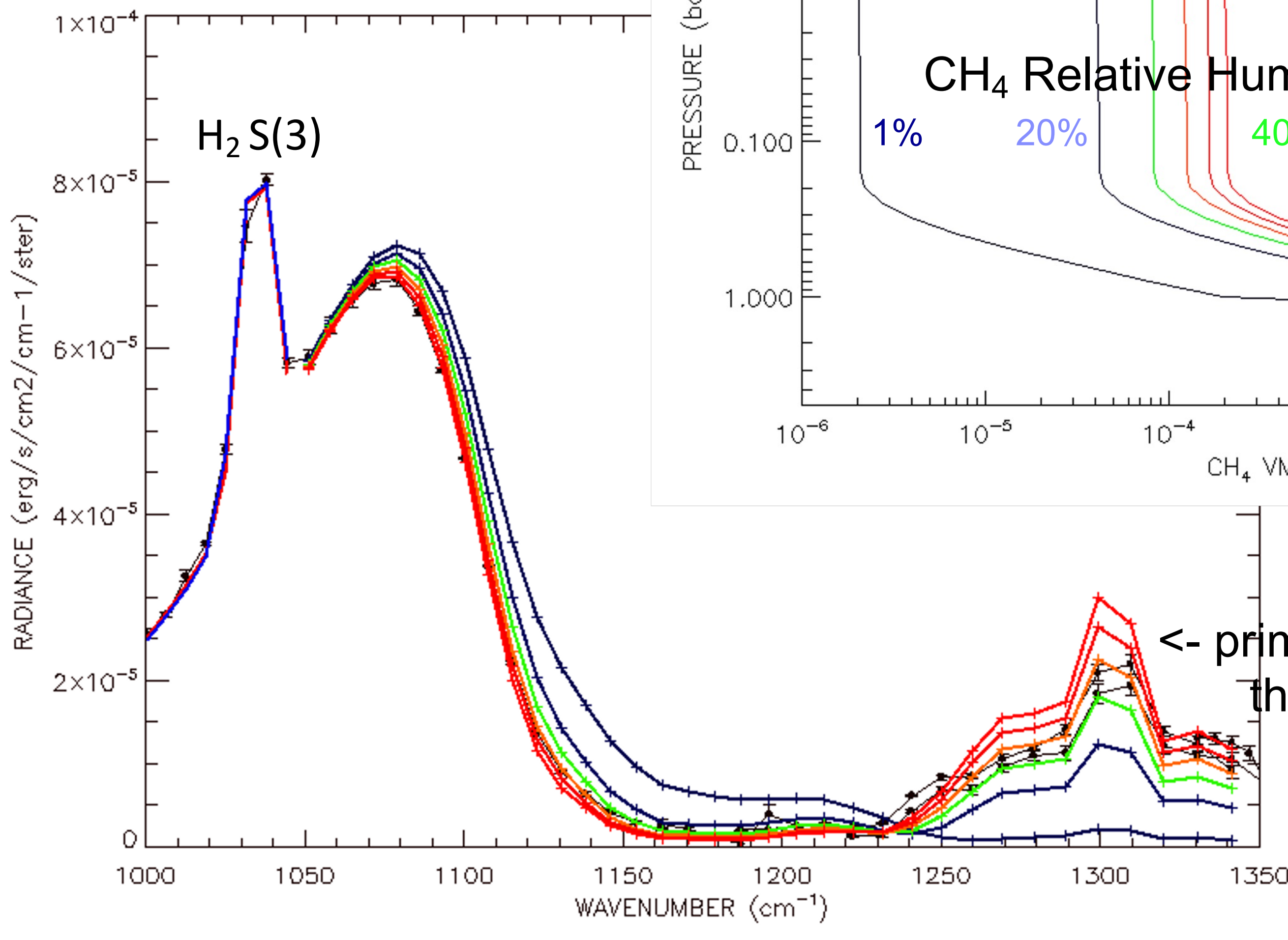
Additional Information



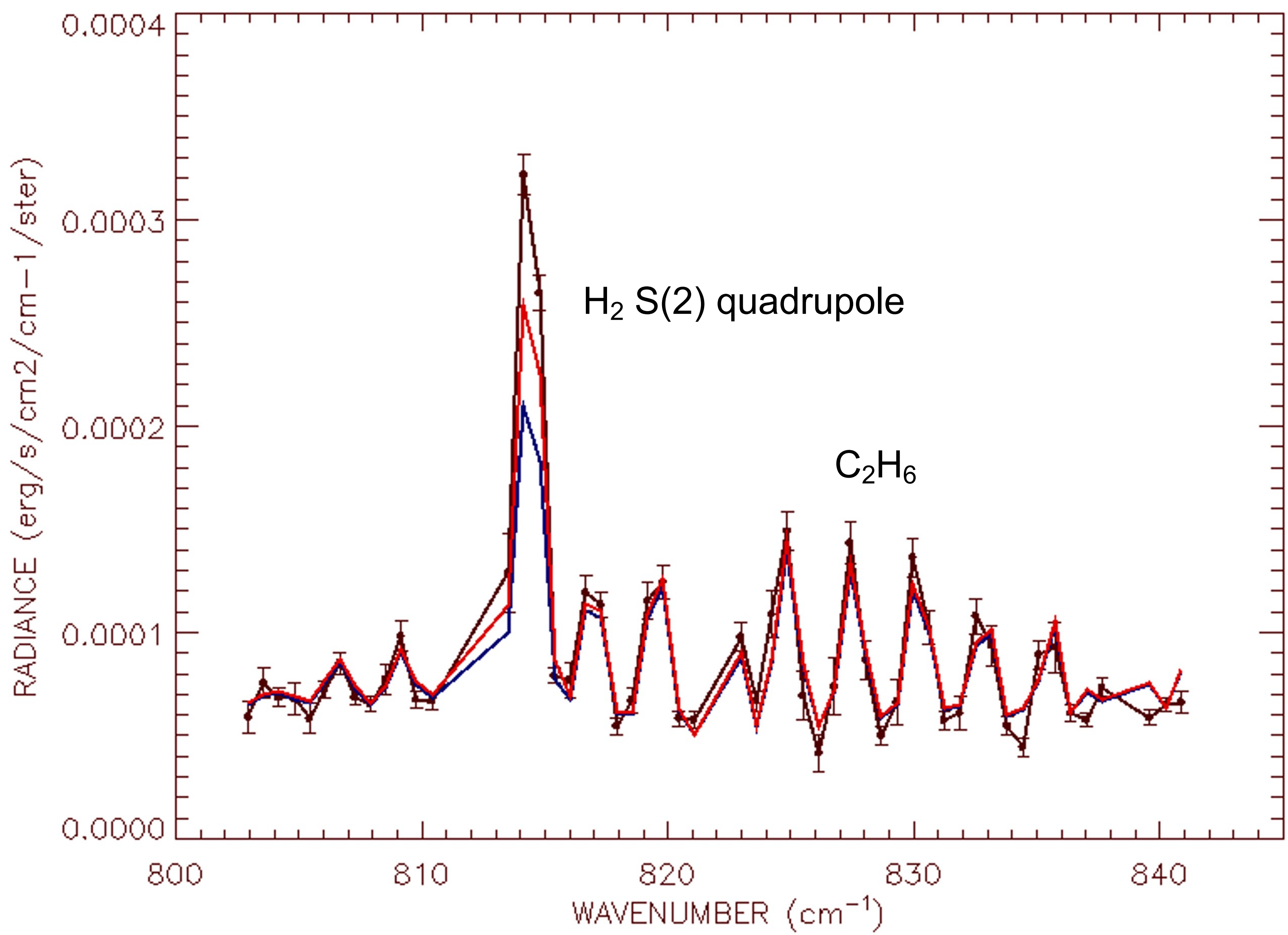
But this spectral region is also sensitive to the CH_3D/CH_4 ratio
Cases shown:
1×10^{-4}, 2×10^{-4}, 3×10^{-4}, 4×10^{-4}, 5×10^{-4}, 6×10^{-4}
(no influence on CH_4 $\boldsymbol{\nu}_4$ band center)
RADIANCE (erg/s/cm2/cm−1/ster)
1×10^{-4}
8×10^{-5}
6×10^{-5}
4×10^{-5}
2×10^{-5}
0
1000
1050
1100
1150
1200
1250
1300
1350
WAVENUMBER (cm^{-1})

Simple model: 2.2% CH_4 VMR below saturation level (~1 bar), adjustable relative humidity above saturation level, with photochemical rolloff in upper stratosphere scaled to model of Moses et al. (2005)

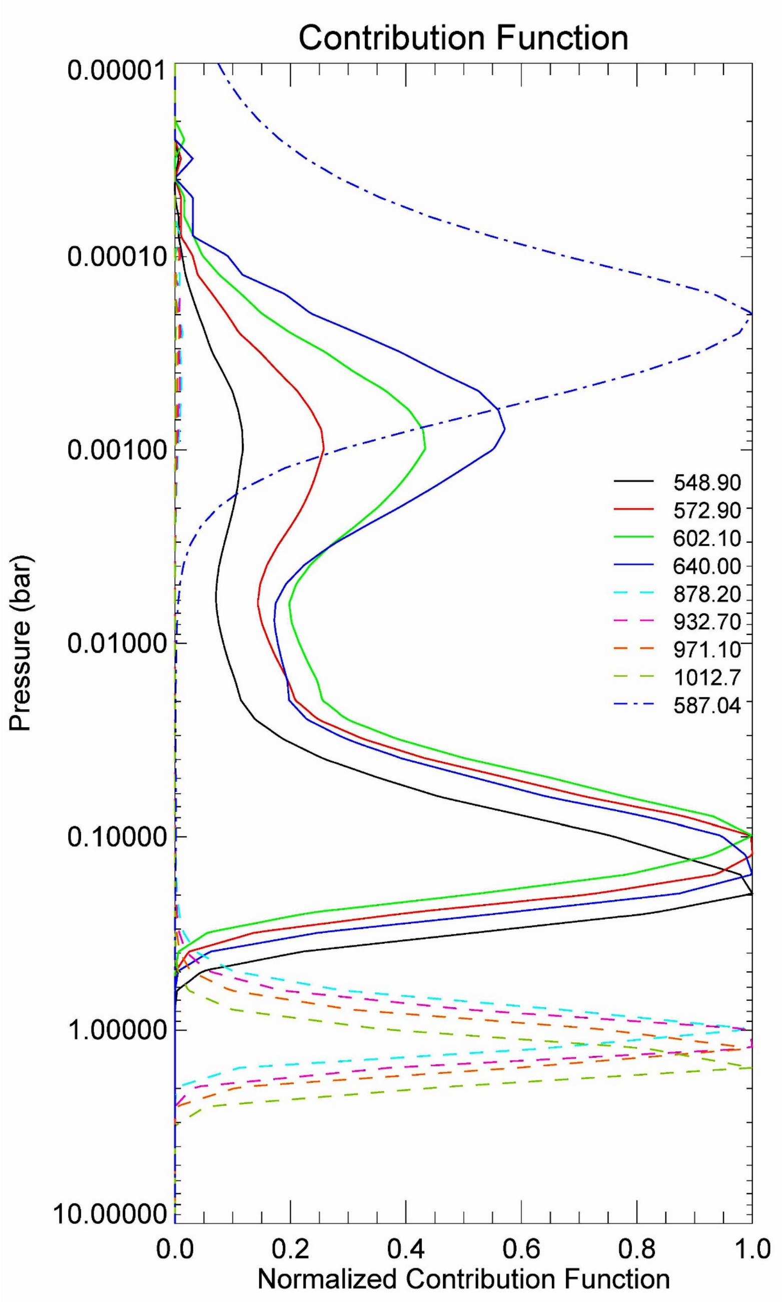




<- primary influence is on the CH_4 ν_4 band center



H2 S(2) quadrupole
C2H6
0.0004
0.0003
0.0002
0.0001
0.0000
RADIANCE (erg/s/cm2/cm-1/ster)
800
810
820
830
840
WAVENUMBER (cm-1)



Wide vertical range of sensitivity:

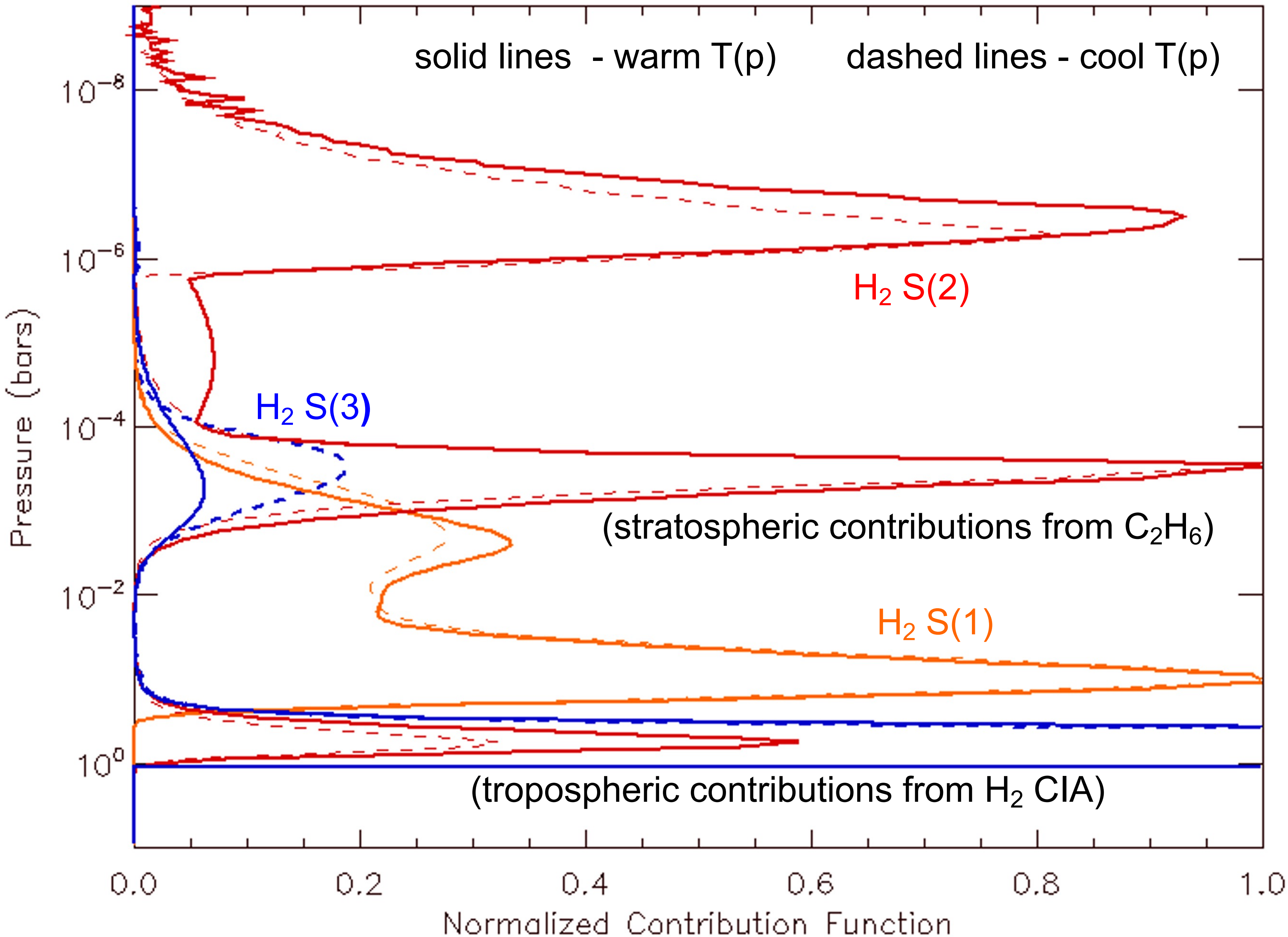
H_2 S(1) quadrupole senses much higher than H_2 CIA – pressures as low as *0.5 mbar*

(some vertical regions not covered well)

H_2 CIA continuum near quadrupole senses upper troposphere – *80-300 mbar*

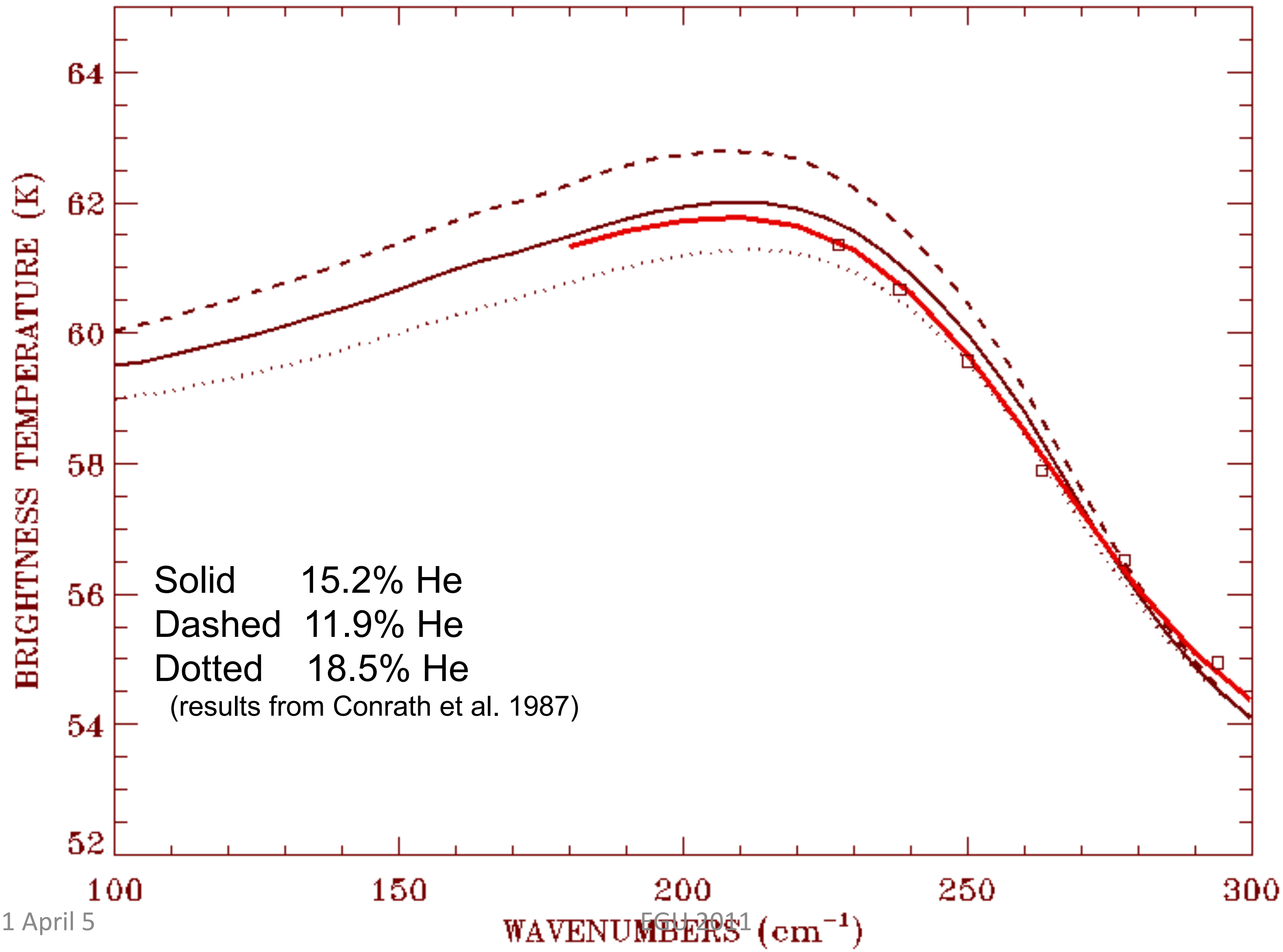
H_2 CIA continuum near 1000 – 1100 cm^{-1} senses deepest – down to *2 bars pressure*

Contribution functions for the upwelling radiance at the centers of H_2 quadrupole lines: substantial input from the hot thermosphere (~700 K)

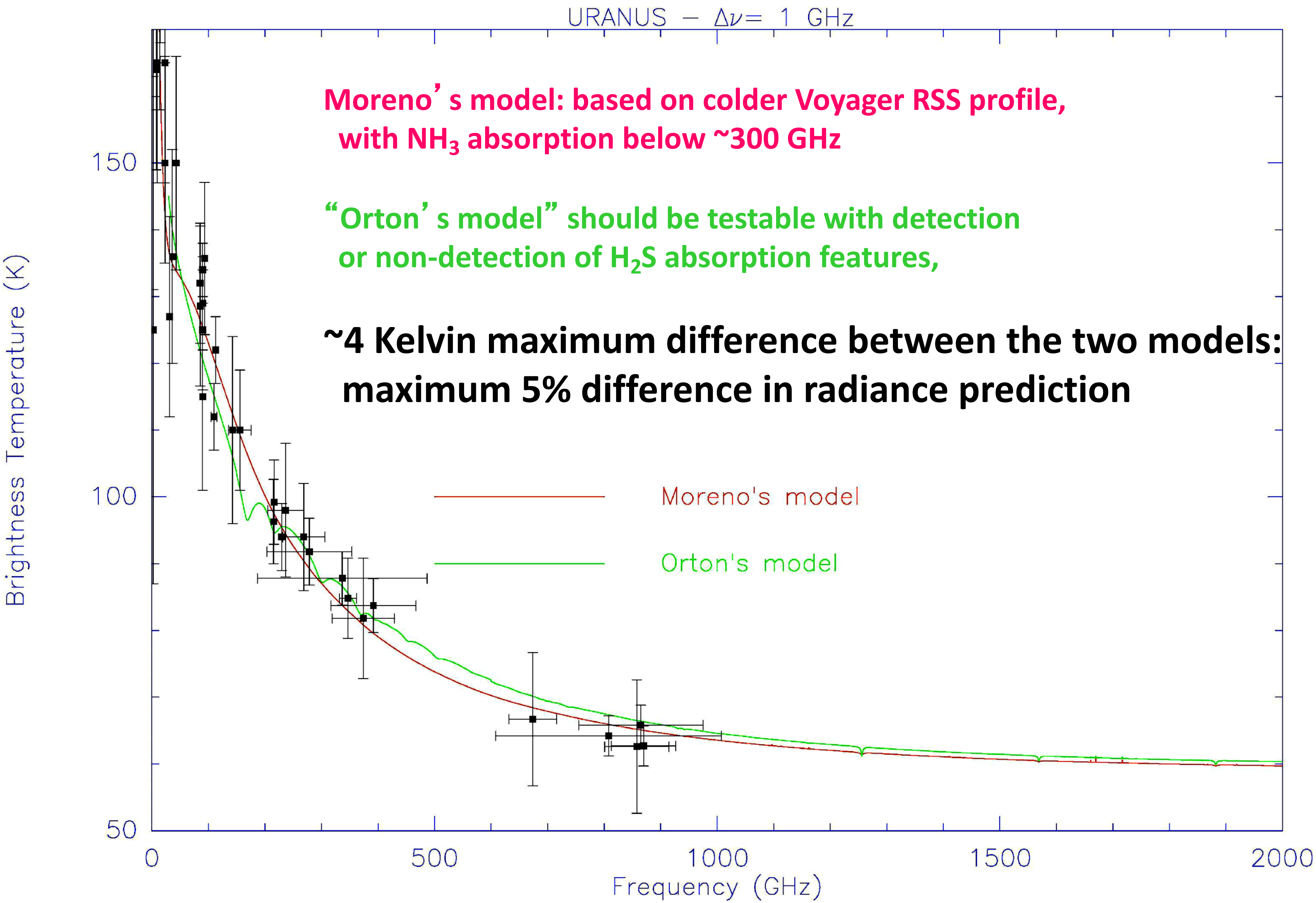


This spectrum of this model does come close to

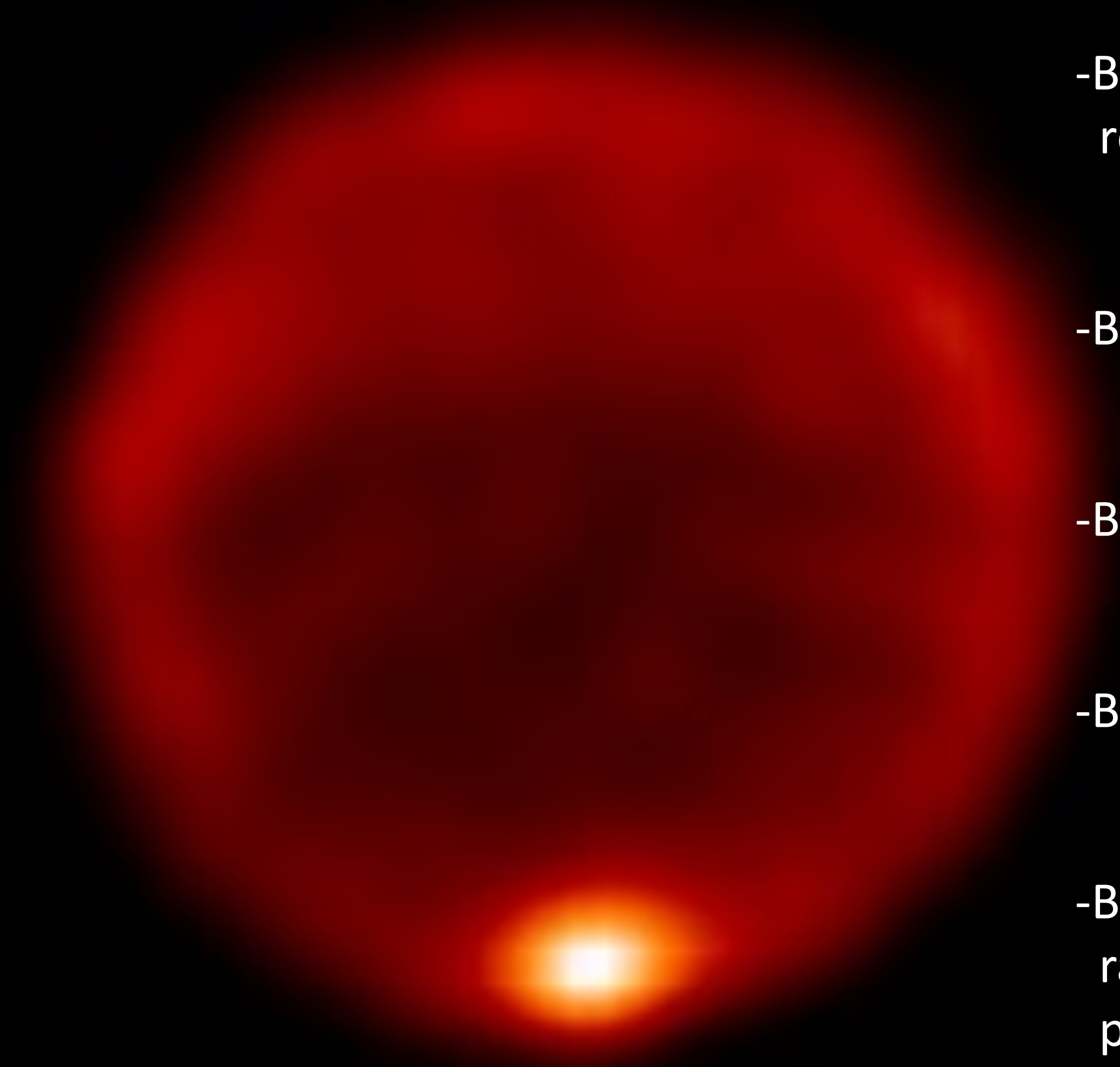
- Voyager-2 IRIS observations of the disk of Uranus (1986, pole-on geometry) ____
- ISO SWS spectrum, calibrated relative to Mars (Burgdorf et al., unpublished) □□□□



Uranus spectral models suggested for Herschel calibration:



One of these images: 2008 Sept. 16 (7.9 µm) CH_4 emission
- Modest deconvolution reveals first detection of banded stratospheric emission in Neptune



- -Bright northern temperate region
- -Bright equatorial region
- -Bright tropical band
- -Bright temperate band
- -Bright polar cap (seasonal radiative warming, or compact polar vortex, like Saturn?)