Planetary Model Refinements and Verifications: Uranus and Neptune

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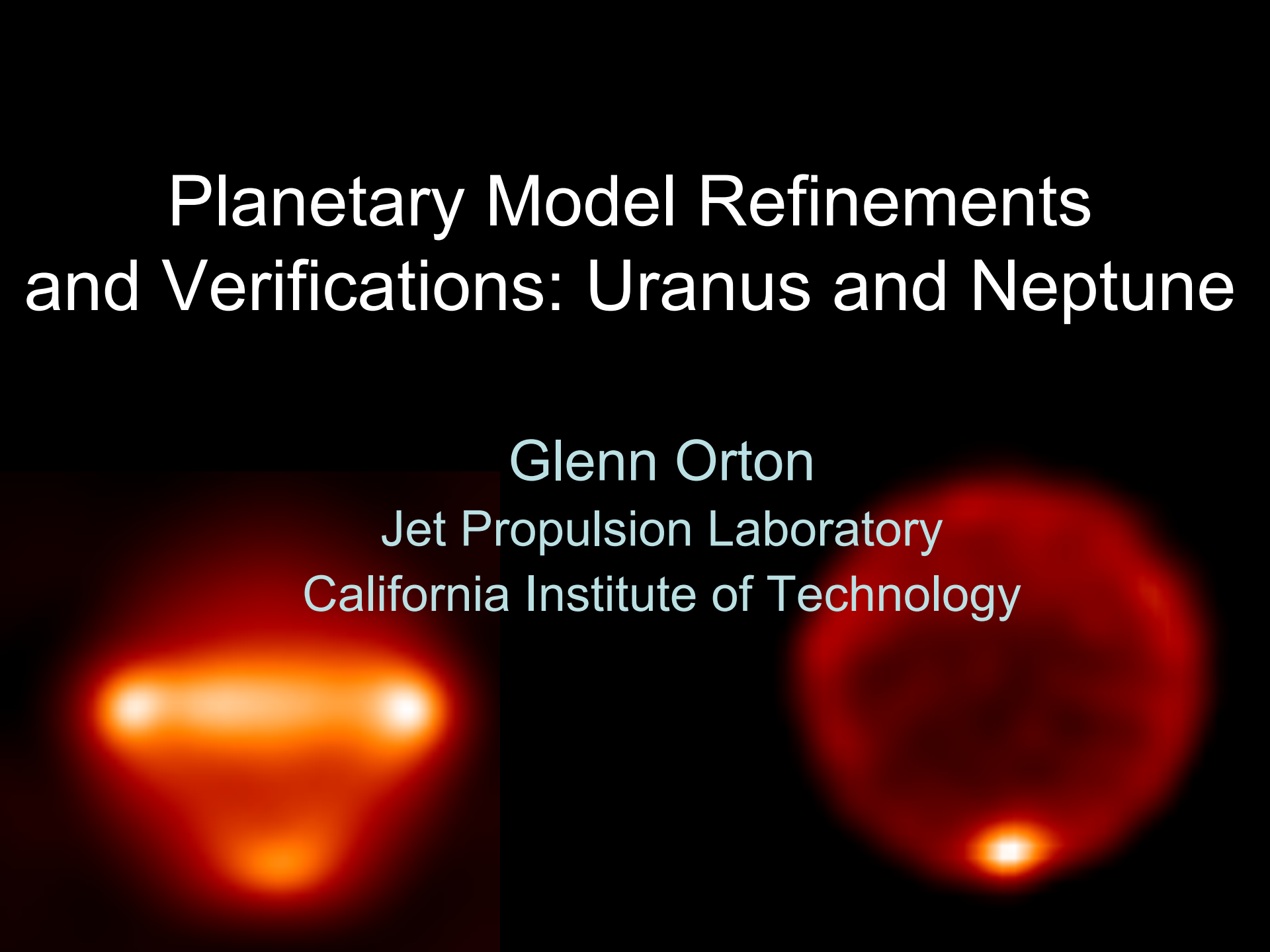
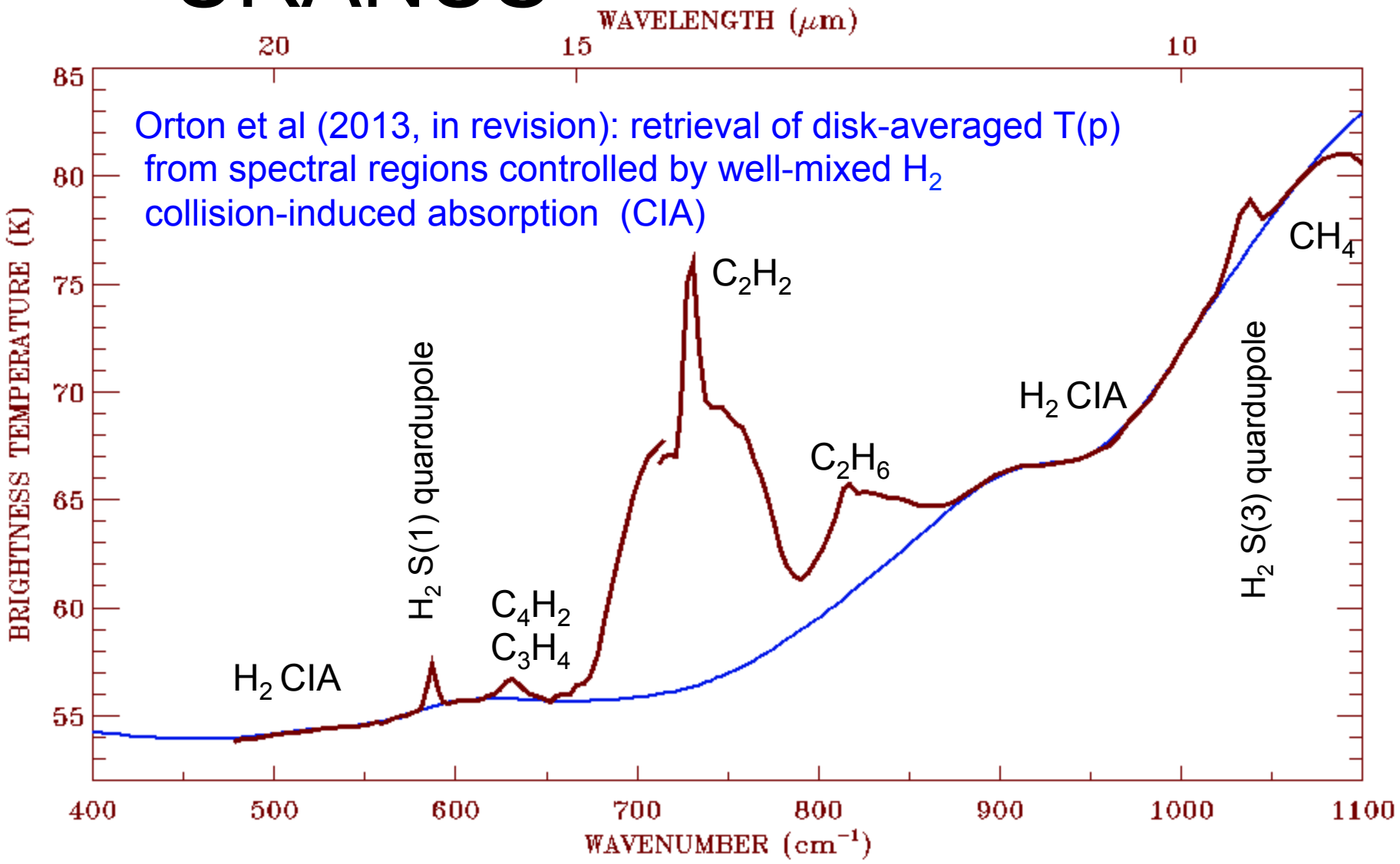
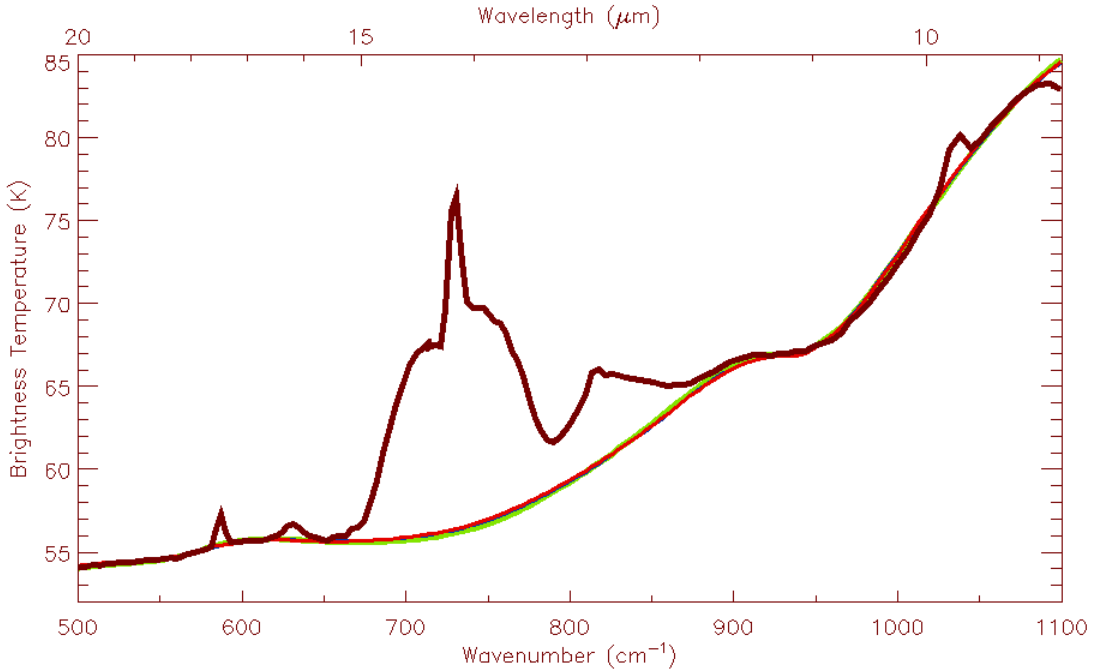


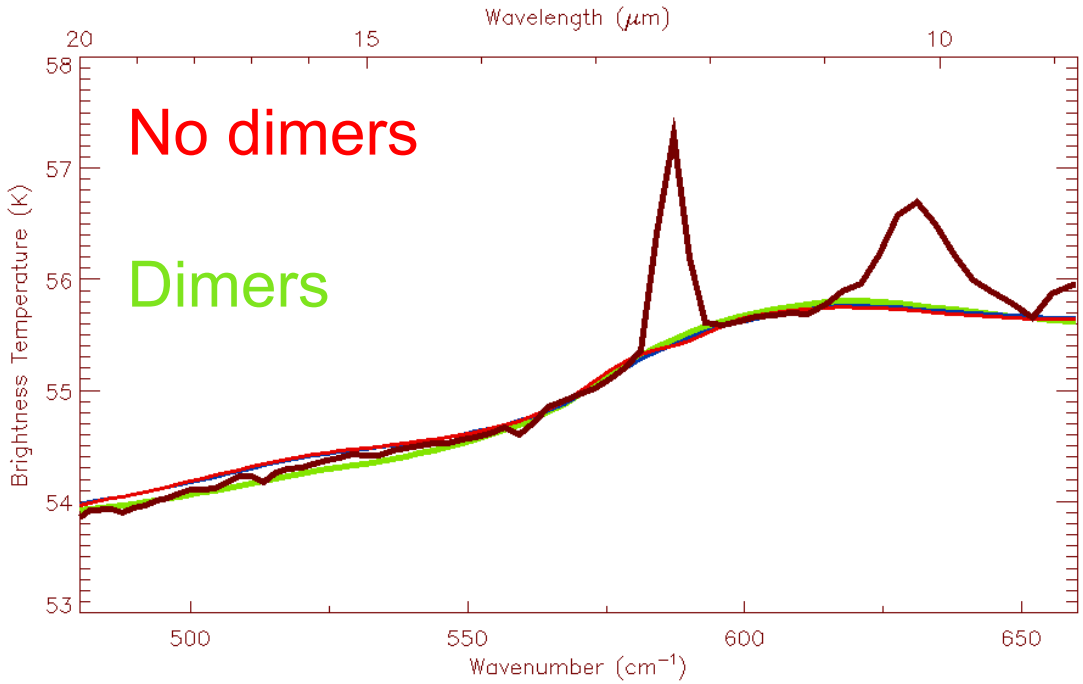
Roadmap

- Assessment of the Uranus model that is based on Spitzer IRS data analysis
  - Re-assessment of the Spitzer IRS radiances
  - Use of updated H_2 absorption model
  - Comparison with PACS photometry
  - Changes from the ESA4 model
  - Remaining problems and unassessed issues
- Assessment of the Neptune model that is based on ISO LWS/SWS data, using a PACS HD-derived profile as a first guess
  - Spitzer IRS constraints
  - ISO LWS/SWS constraints
  - Earth-based data constraints
  - Comparison with SPIRE results
  - Remaining problems
    - PACS photometry

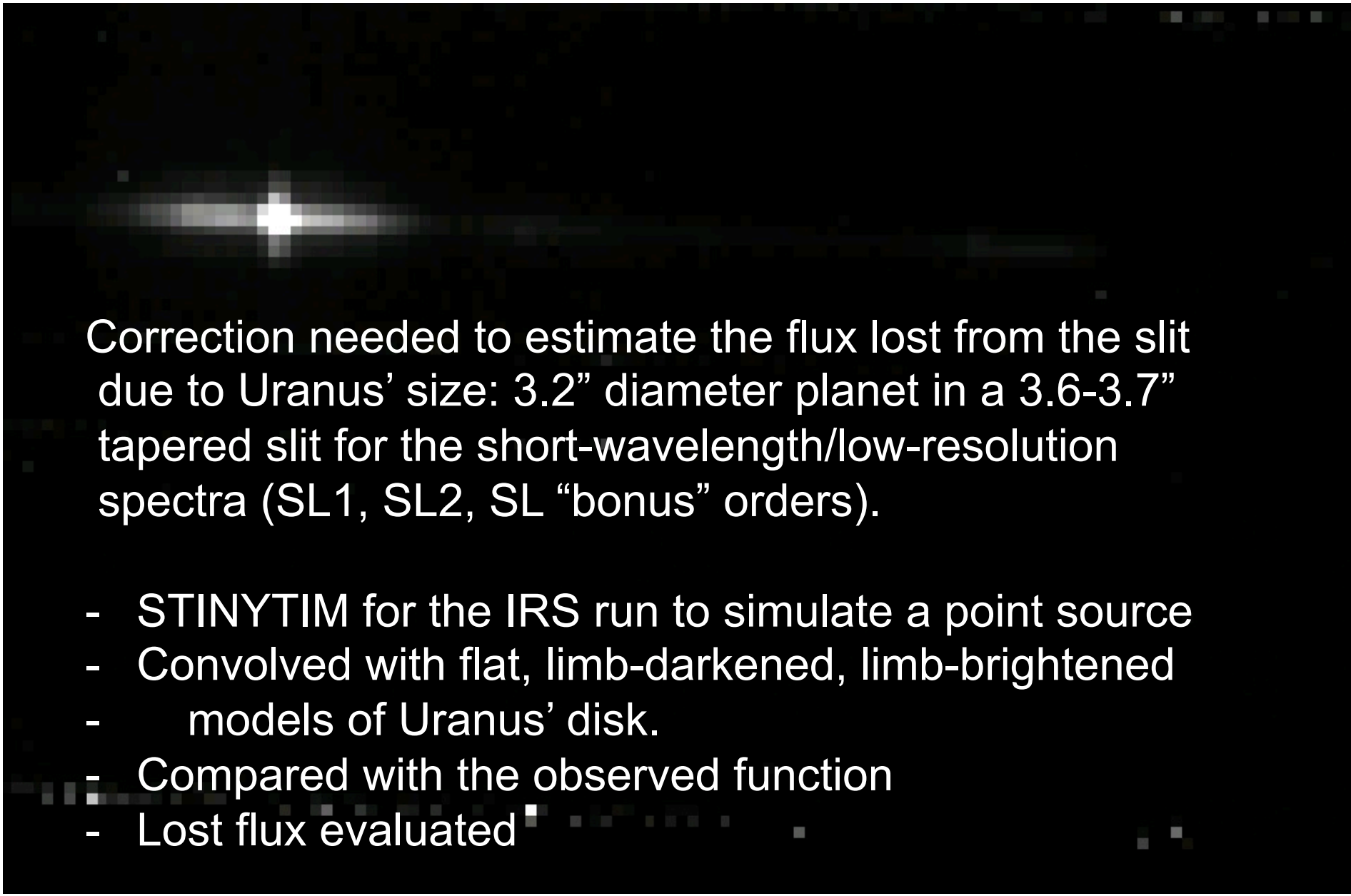
URANUS


WAVELENGTH (μm)
20
15
10
BRIGHTNESS TEMPERATURE (K)
85
80
75
70
65
60
55
Orton et al (2013, in revision): retrieval of disk-averaged T(p) from spectral regions controlled by well-mixed H2 collision-induced absorption (CIA)
H2 CIA
H2 S(1) quardupole
C4H2
C3H4
C2H2
C2H6
H2 CIA
H2 S(3) quardupole
CH4
400
500
600
700
800
900
1000
1100
WAVENUMBER (cm−1)





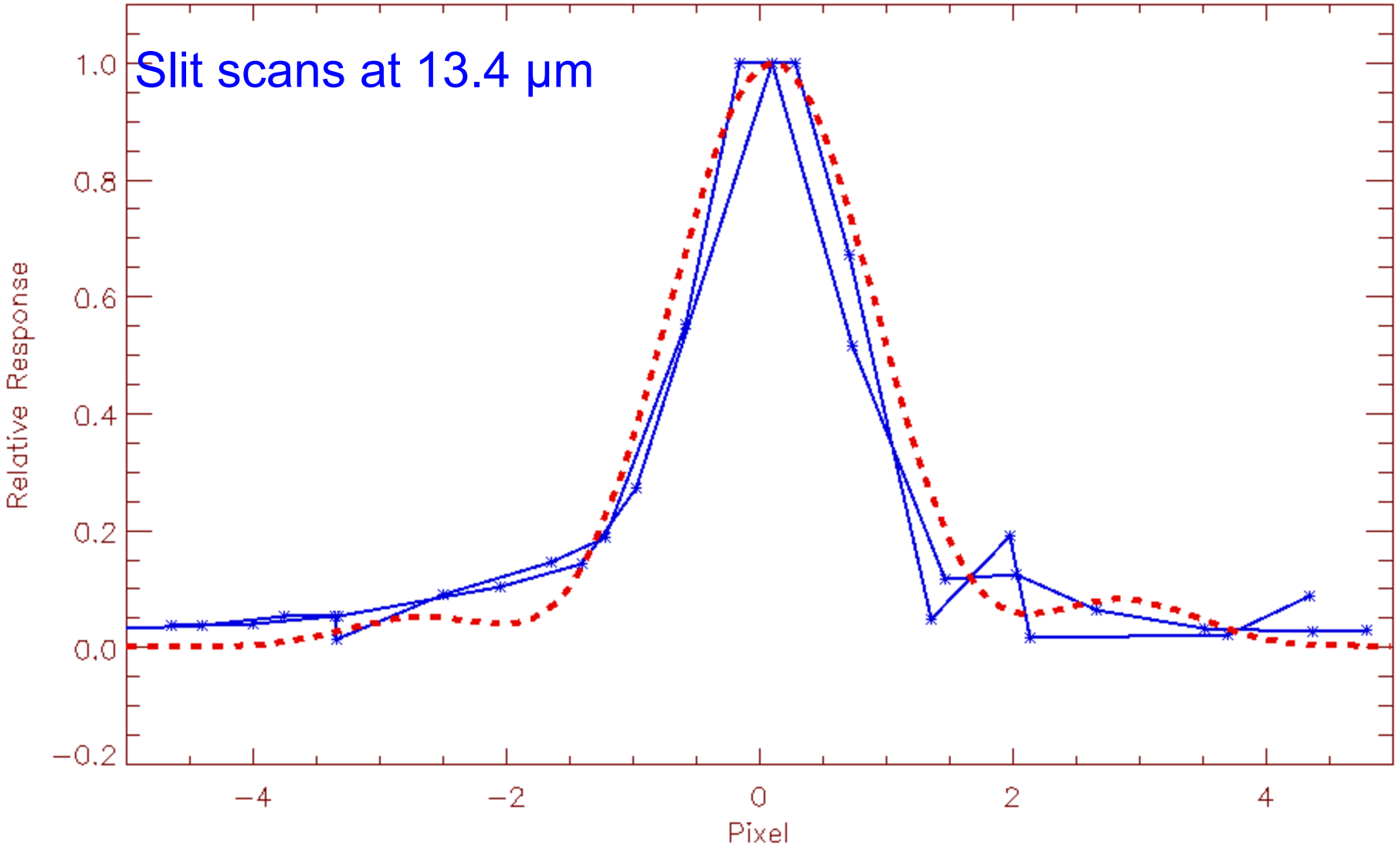
H_2 dimer absorptions added: not much different
– mostly around rotational lines, e.g. S(1) here at 587 cm^{-1}



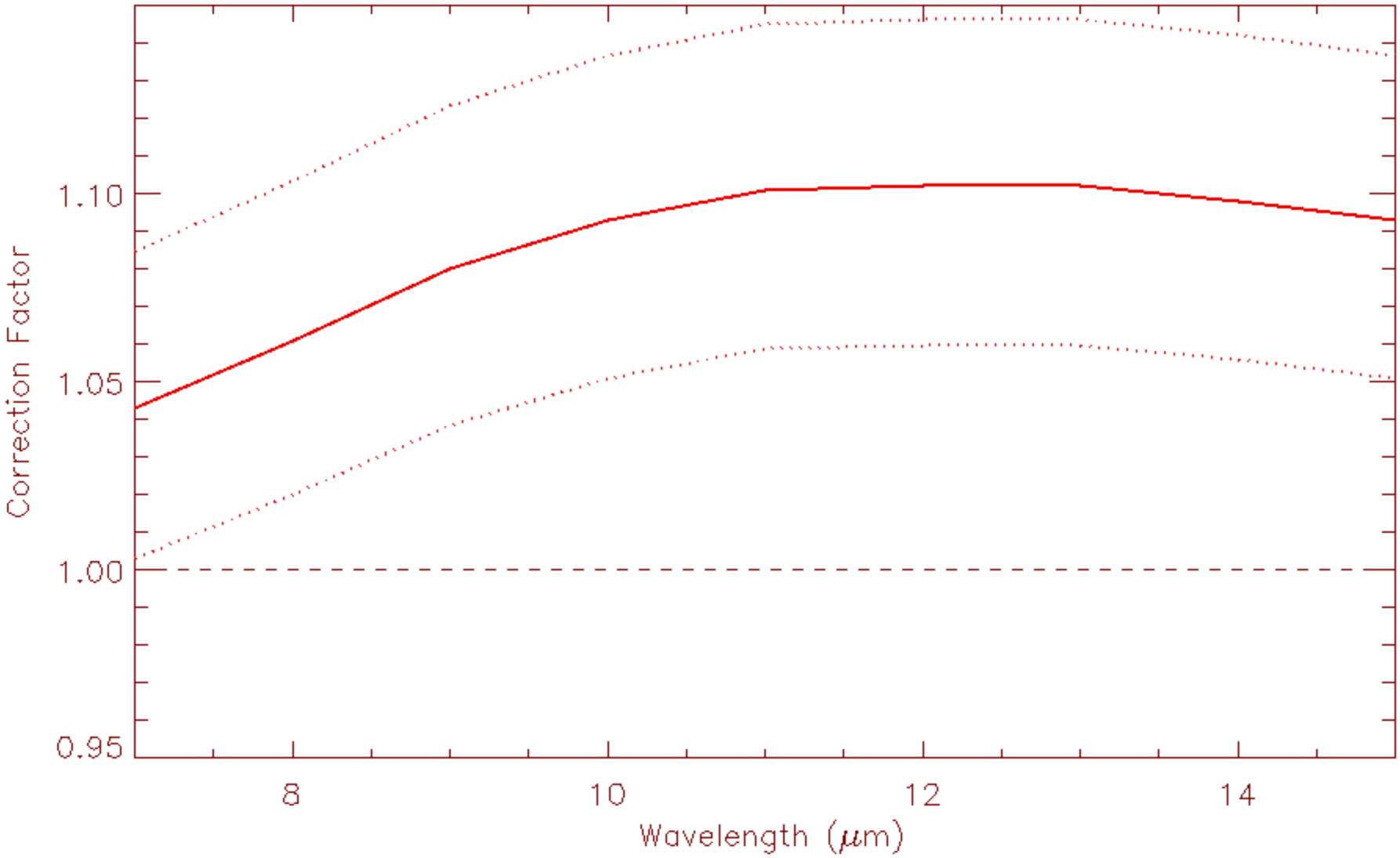
Correction needed to estimate the flux lost from the slit due to Uranus' size: 3.2" diameter planet in a 3.6-3.7" tapered slit for the short-wavelength/low-resolution spectra (SL1, SL2, SL "bonus" orders).

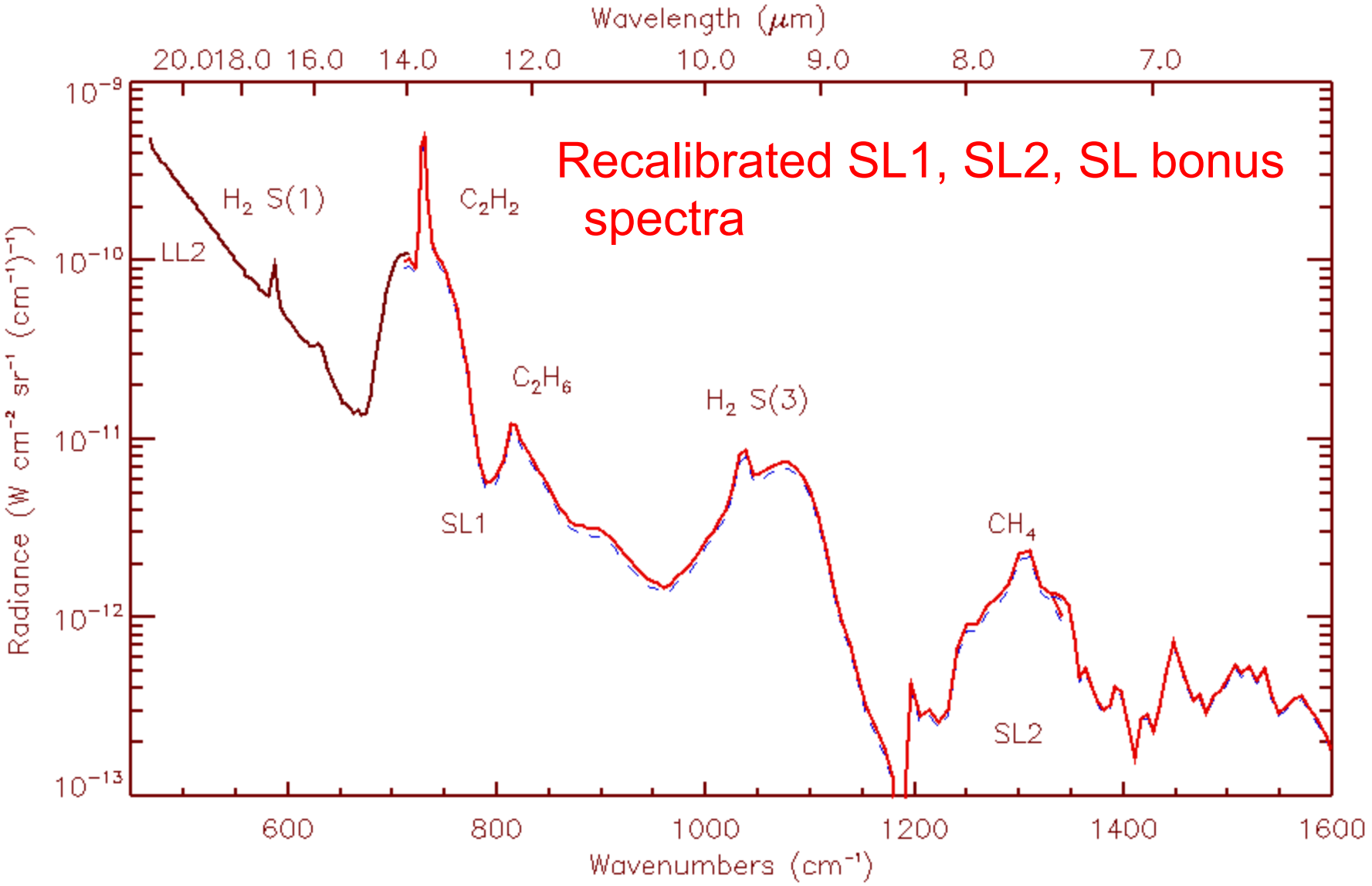
- STINYTIM for the IRS run to simulate a point source
- Convolved with flat, limb-darkened, limb-brightened
- models of Uranus' disk.
- Compared with the observed function
- Lost flux evaluated

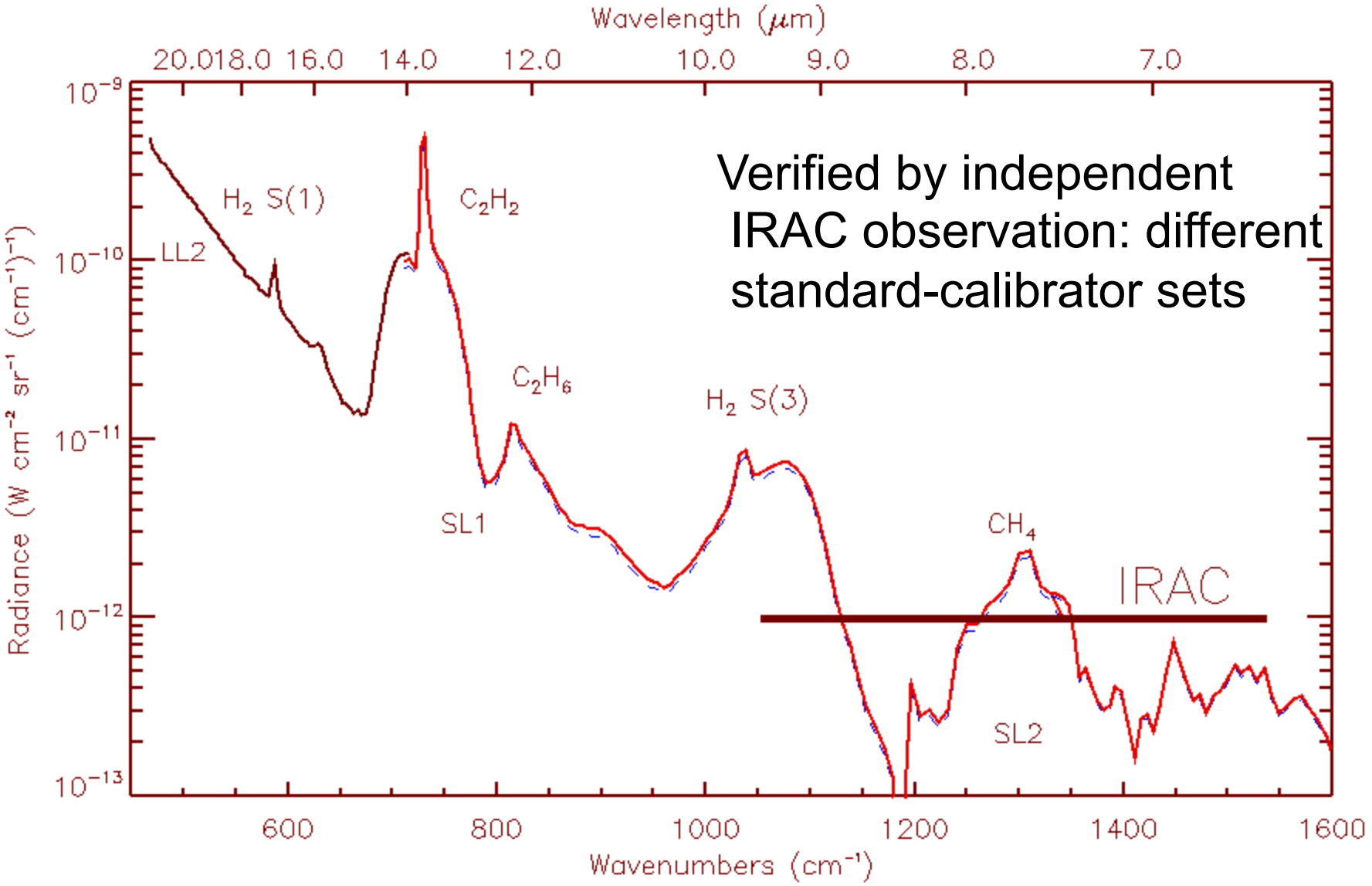
STINYTIM convolution with uniform disk at 13.4 μm



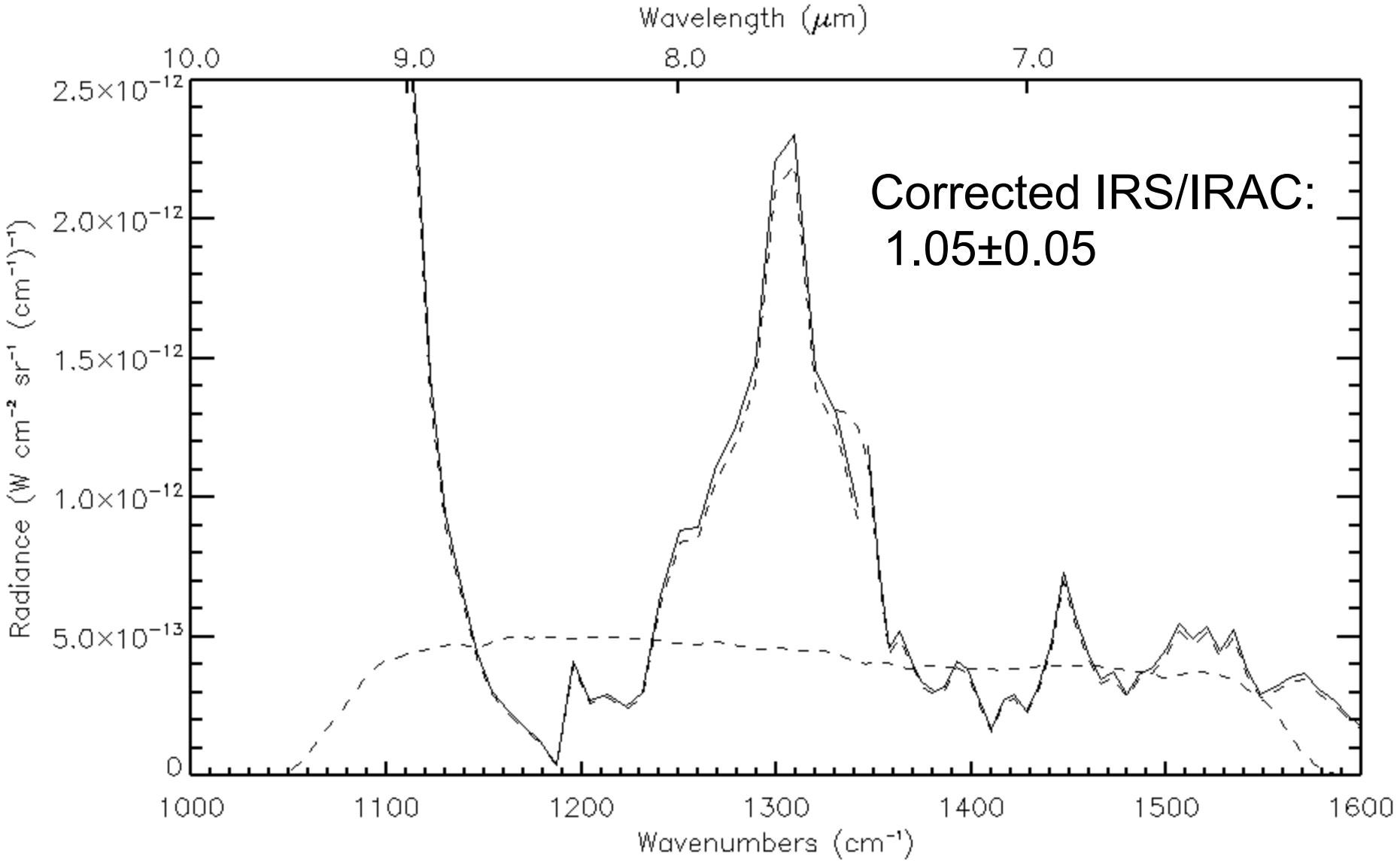
Correction factors: increase in flux of 5-9% for SL modes.



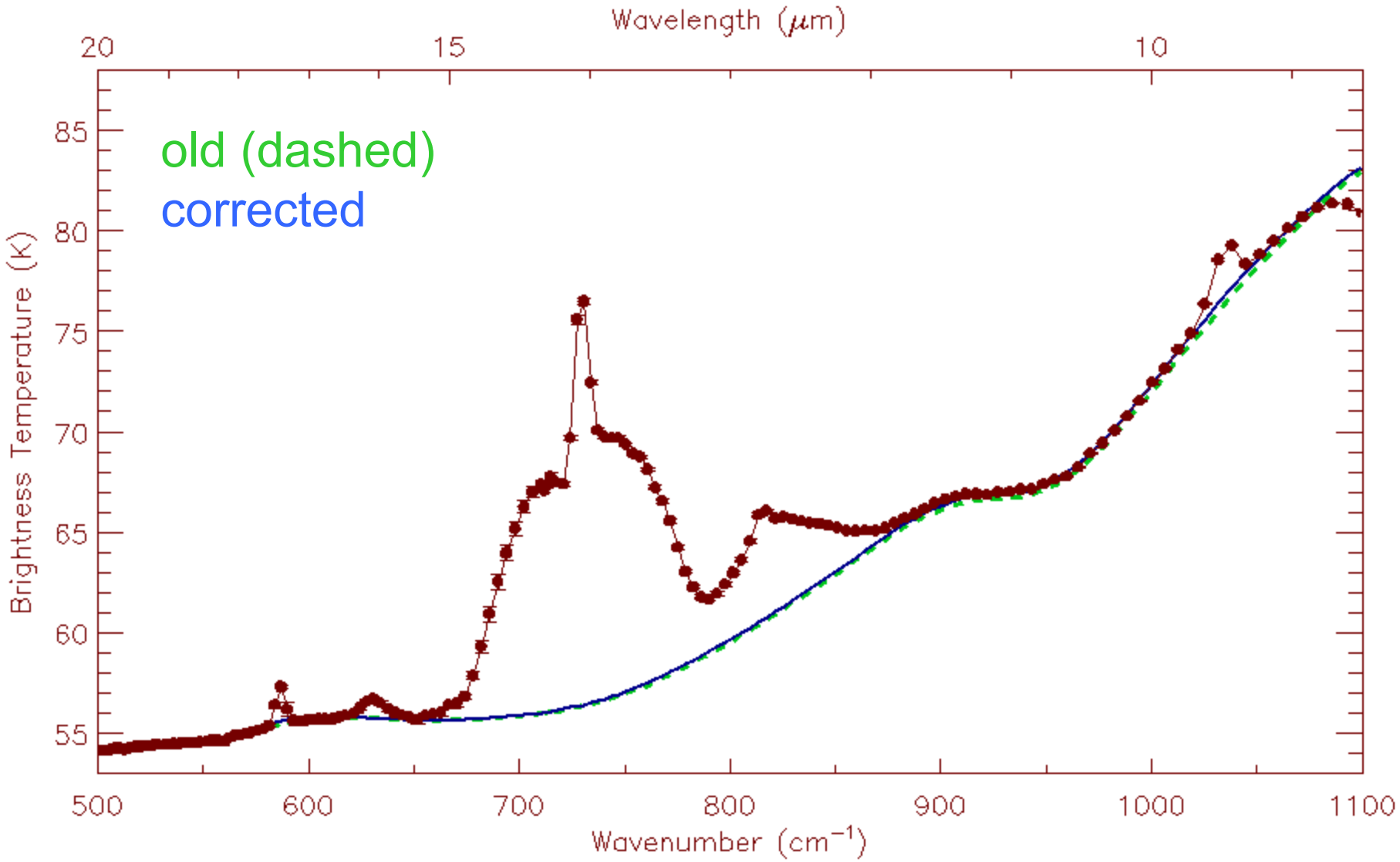

Recalibrated SL1, SL2, SL bonus spectra
Wavelength (μm)
20.0 18.0 16.0 14.0 12.0 10.0 9.0 8.0 7.0
Radiance (W cm⁻² sr⁻¹ (cm⁻¹)⁻¹)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻¹³
H₂ S(1)
LL2
C₂H₂
C₂H₆
H₂ S(3)
SL1
CH₄
SL2
600 800 1000 1200 1400 1600
Wavenumbers (cm⁻¹)

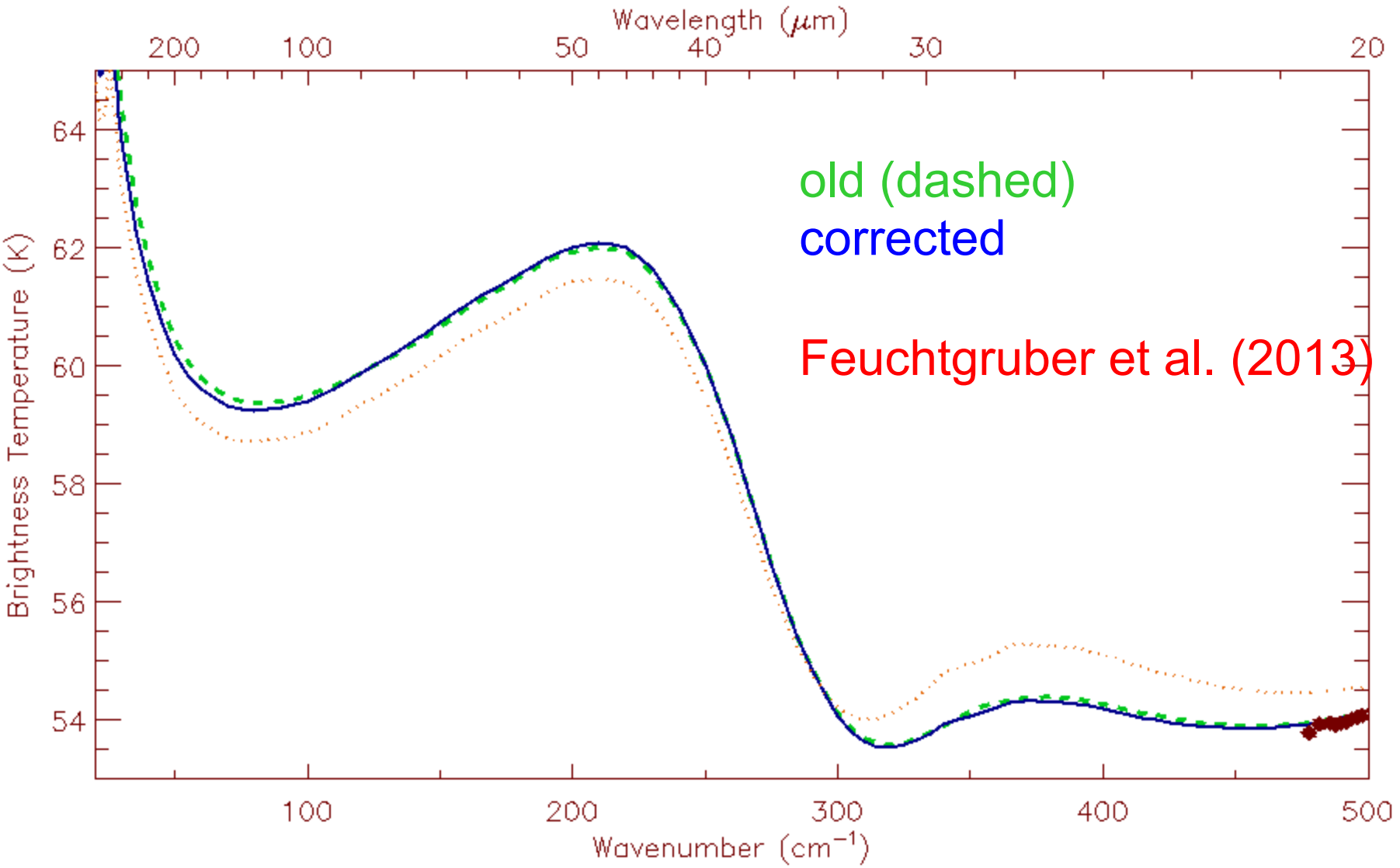


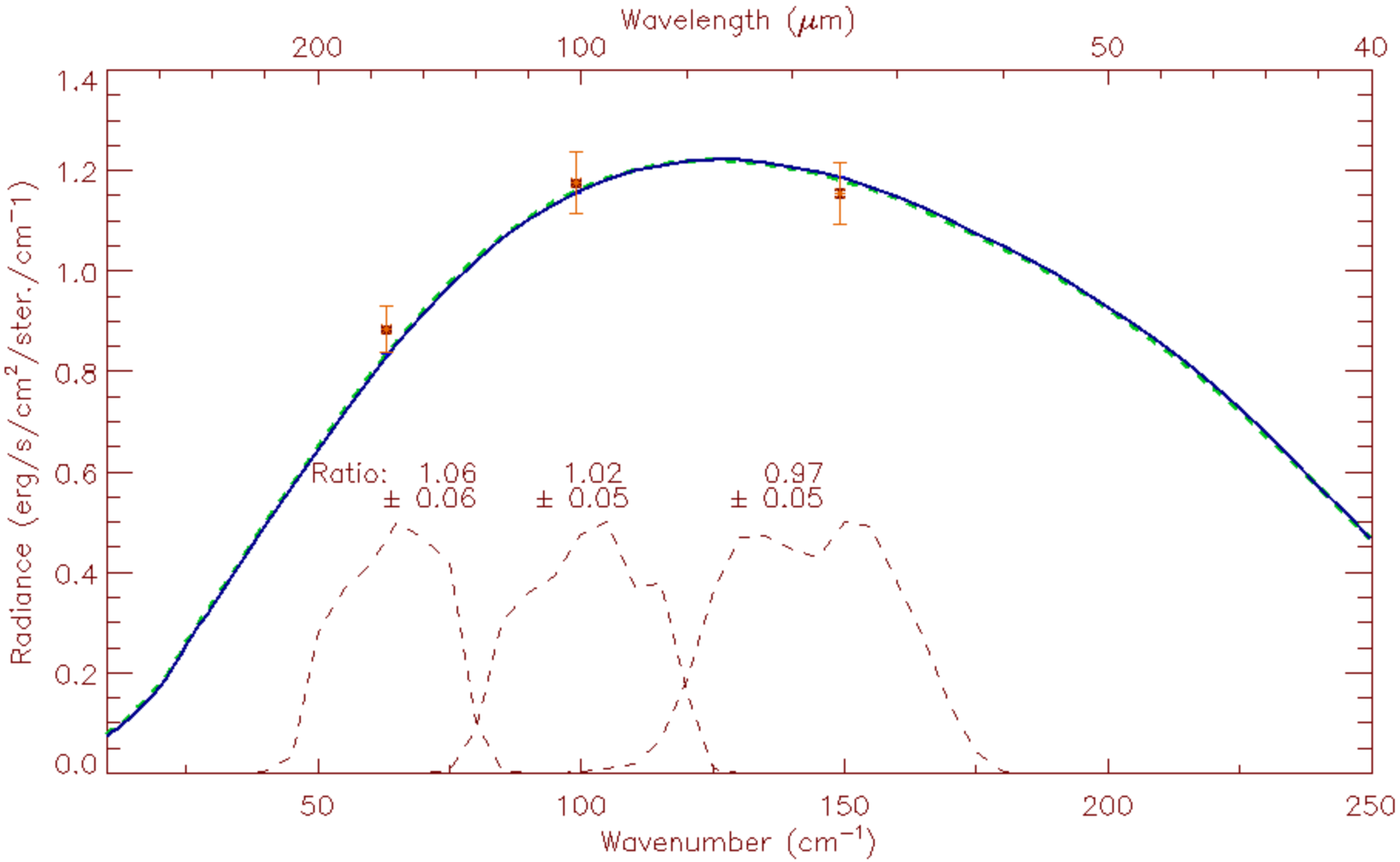
Verified by independent IRAC observation: different standard-calibrator sets

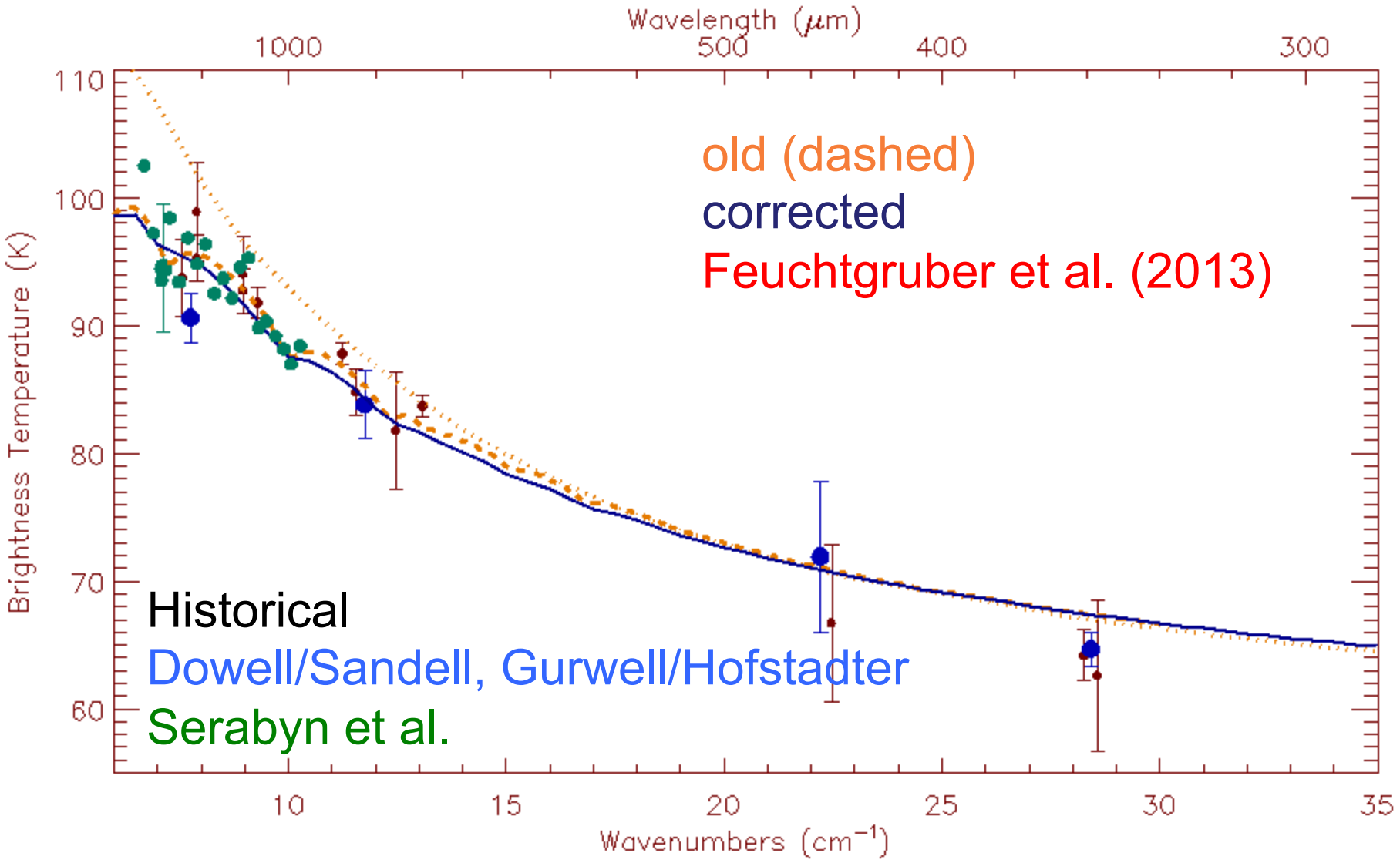

Wavelength (μm)
10.0
9.0
8.0
7.0
2.5×10⁻¹²
2.0×10⁻¹²
1.5×10⁻¹²
1.0×10⁻¹²
5.0×10⁻¹³
0
Radiance (W cm⁻² sr⁻¹ (cm⁻¹)⁻¹)
1000
1100
1200
1300
1400
1500
1600
Wavenumbers (cm⁻¹)
Corrected IRS/IRAC:
1.05±0.05

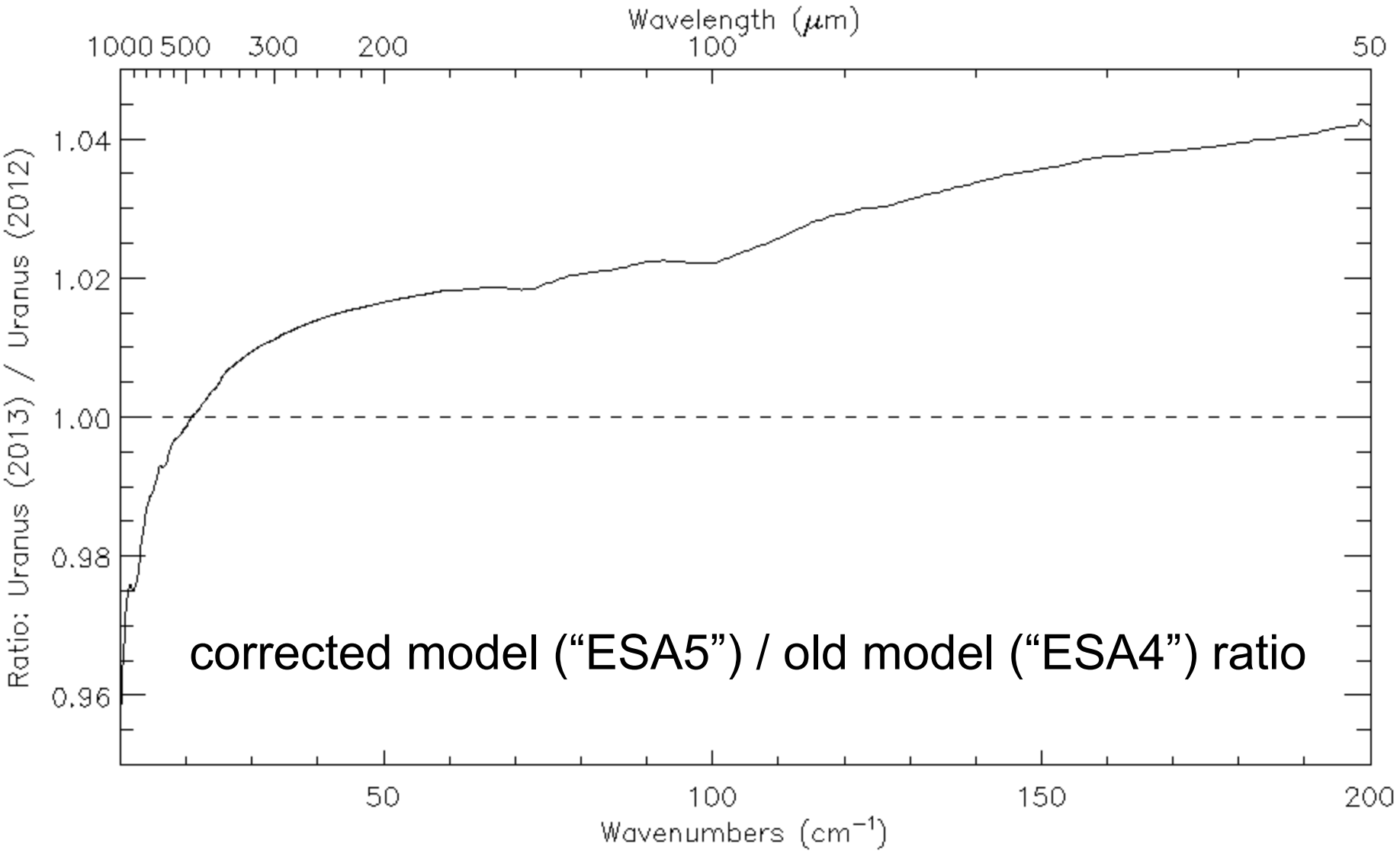
This moves temperatures up, but by a small amount.



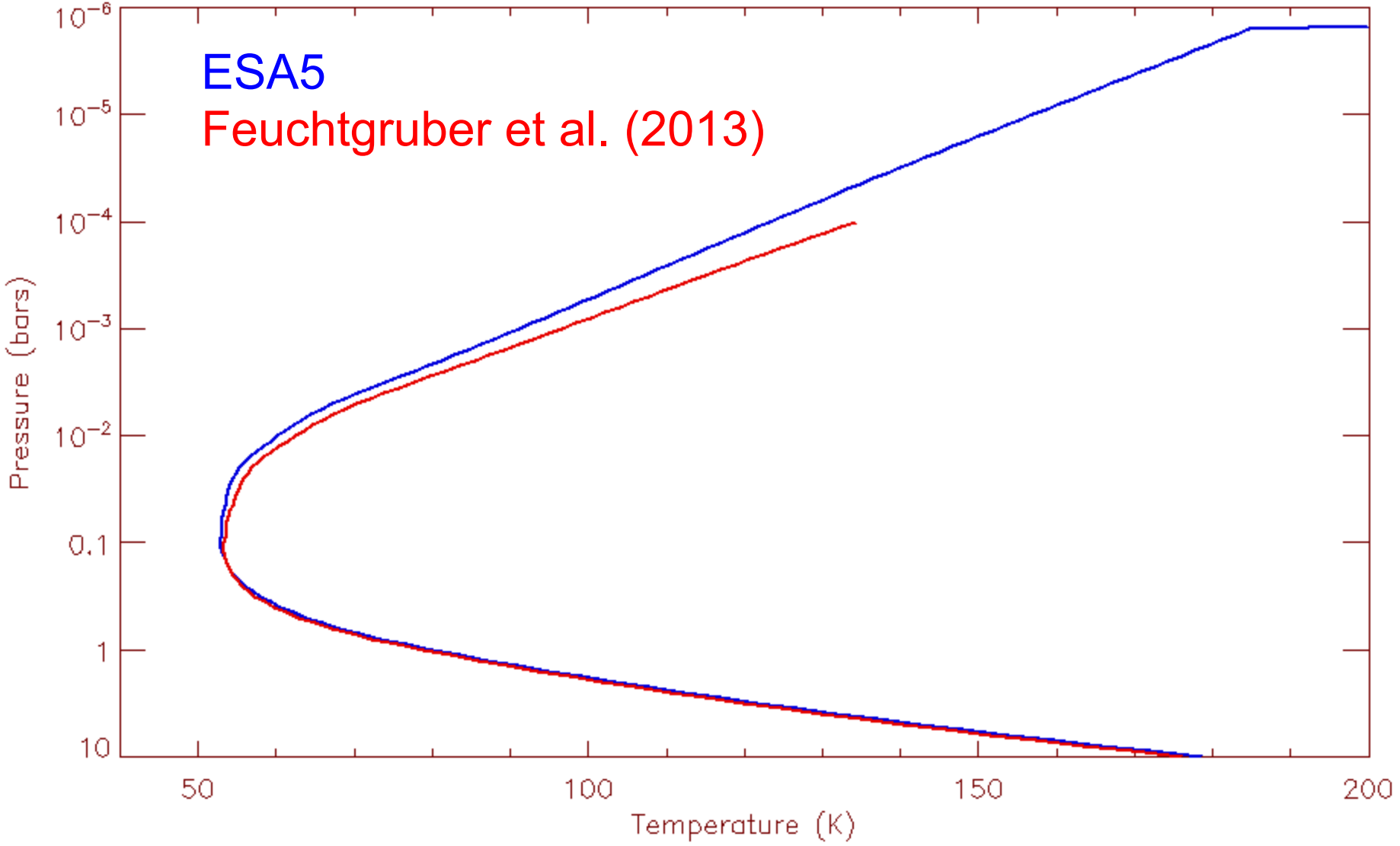

Wavelength (μm)
200
100
50
40
30
20
64
62
60
58
56
54
Brightness Temperature (K)
old (dashed)
corrected
Feuchtgruber et al. (2013)
100
200
300
400
500
Wavenumber (cm^{-1})


Wavelength (μm)
200
100
50
40
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Radiance (erg/s/cm²/ster./cm⁻¹)
Ratio: 1.06 ± 0.06
1.02 ± 0.05
0.97 ± 0.05
50
100
150
200
250
Wavenumber (cm⁻¹)

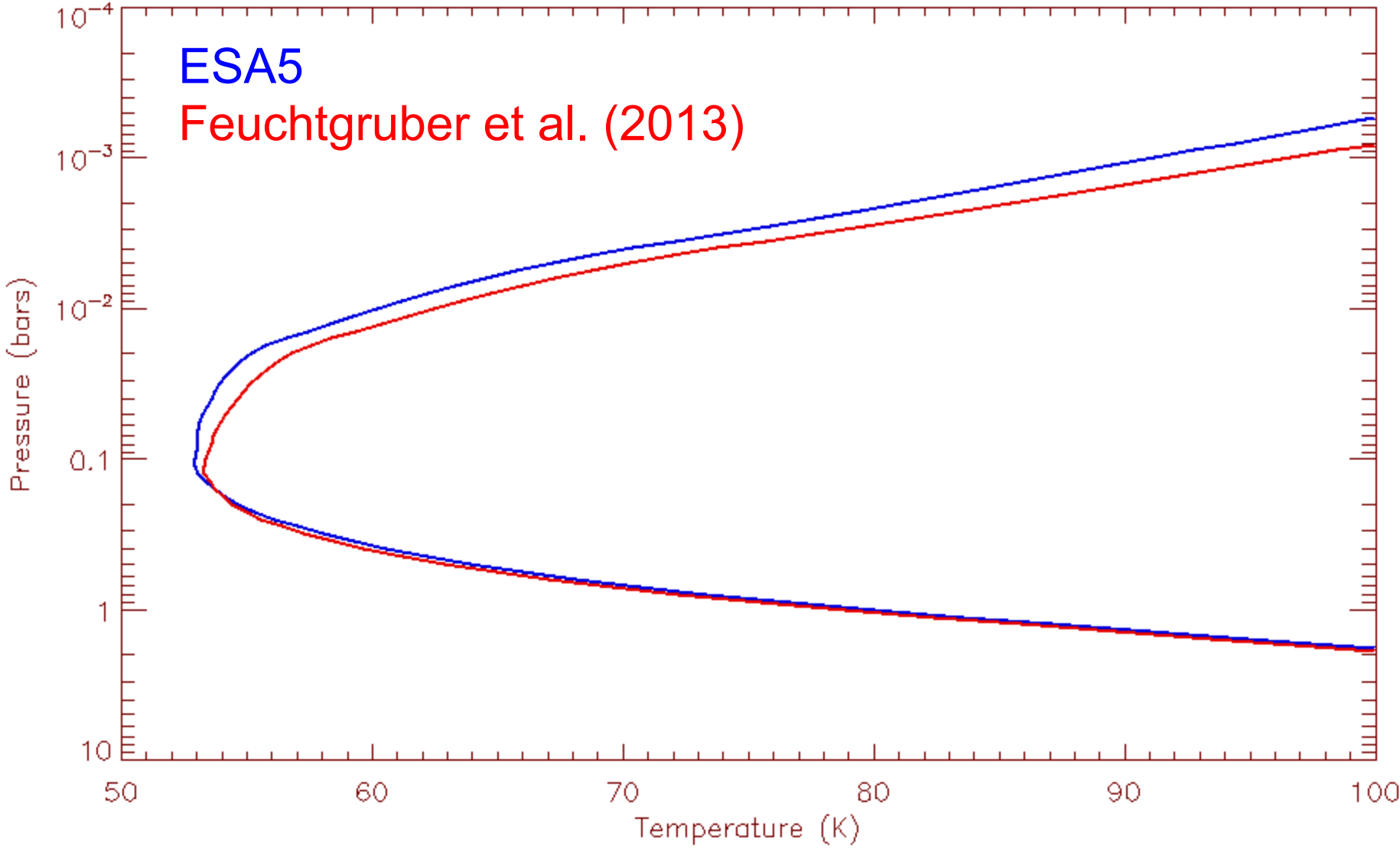

Wavelength (μm)
1000
500
400
300
110
100
90
80
70
60
Brightness Temperature (K)
old (dashed)
corrected
Feuchtgruber et al. (2013)
Historical
Dowell/Sandell, Gurwell/Hofstadter
Serabyn et al.
10
15
20
25
30
35
Wavenumbers (cm⁻¹)

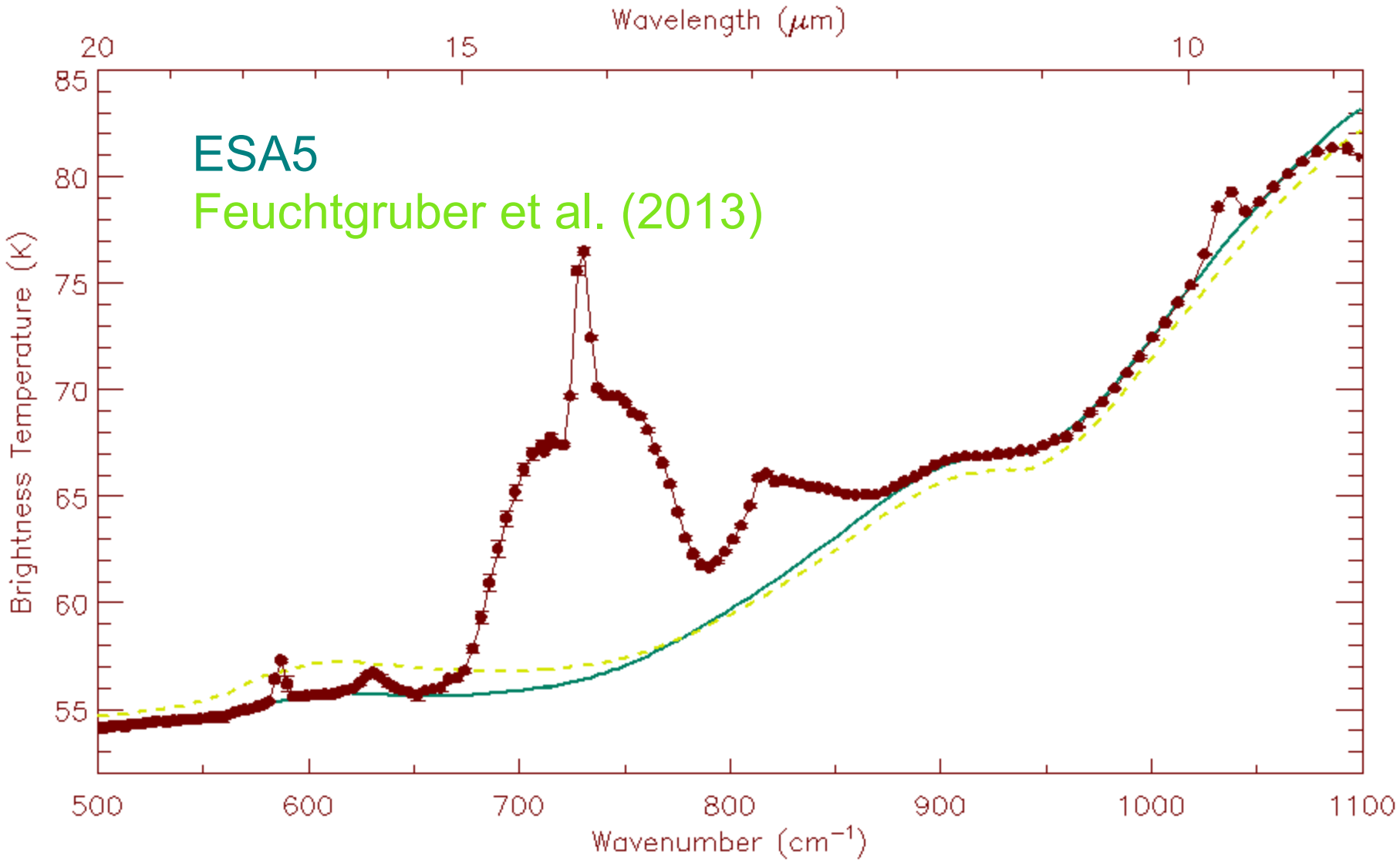

Wavelength (μm)
1000 500 300 200 100 50
Ratio: Uranus (2013) / Uranus (2012)
1.04
1.02
1.00
0.98
0.96
corrected model (“ESA5”) / old model (“ESA4”) ratio
50 100 150 200
Wavenumbers (cm⁻¹)

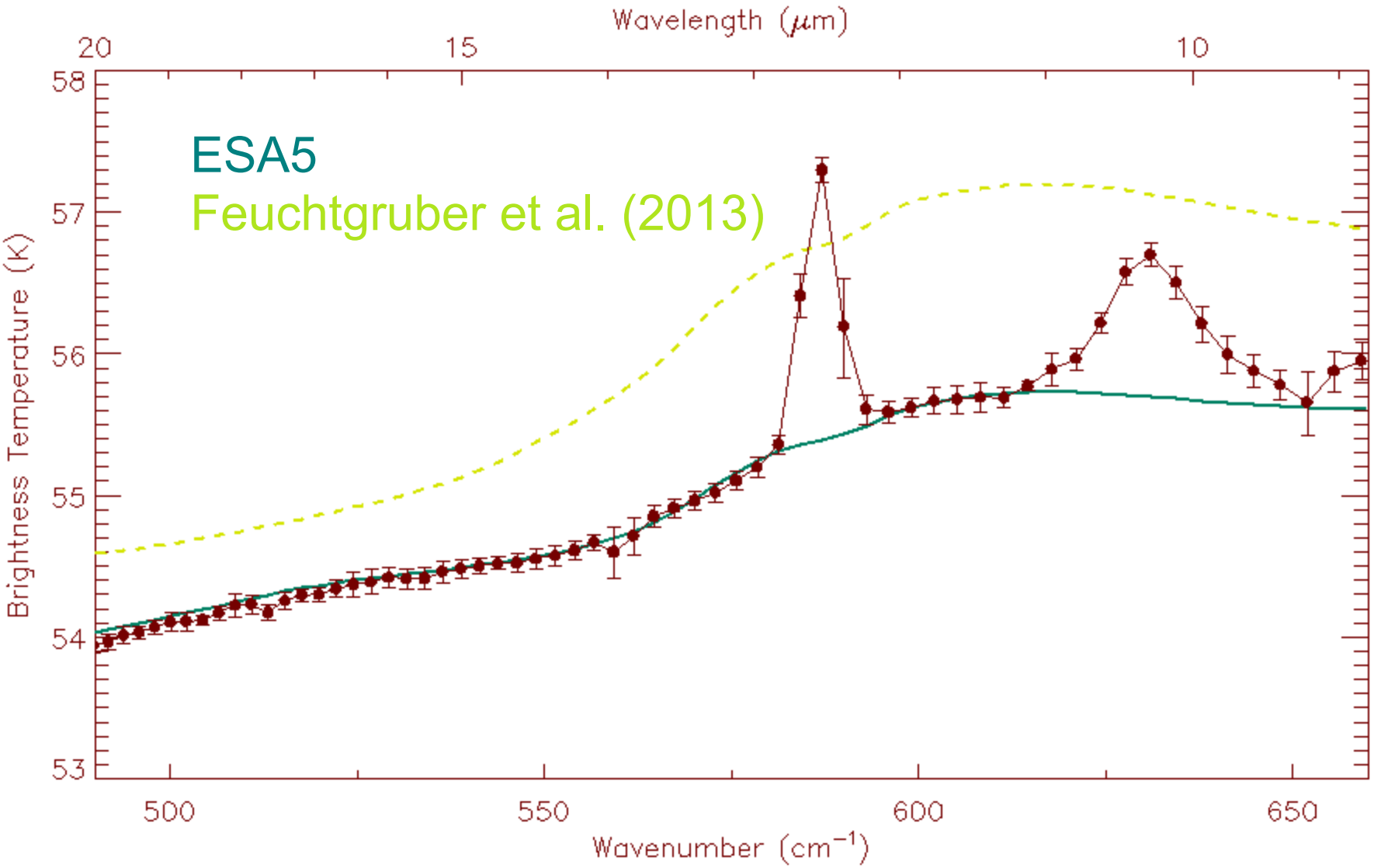
Problem: incompatibility of T(p) and PACS HD data



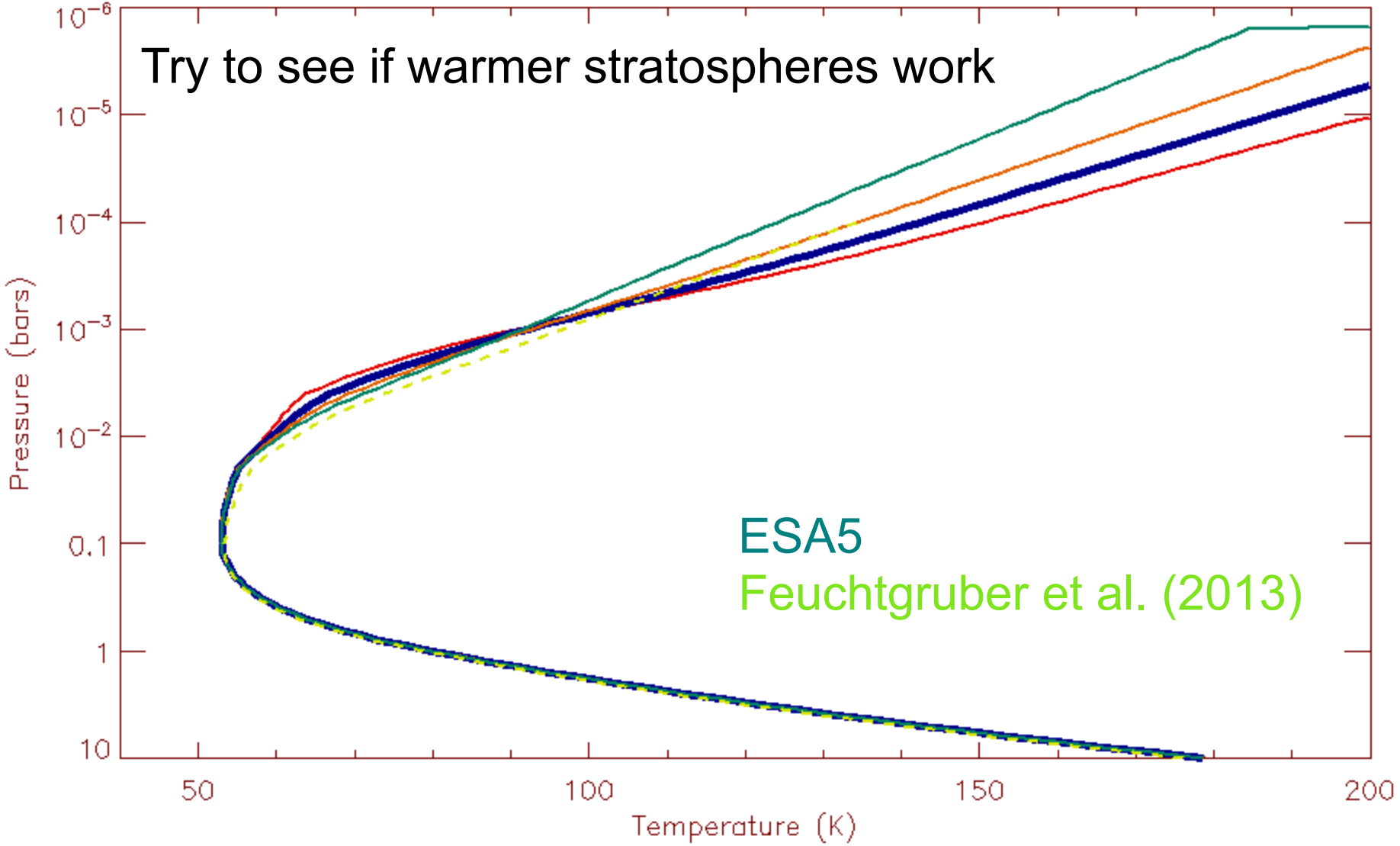
We are sensitive to small differences in temperature.

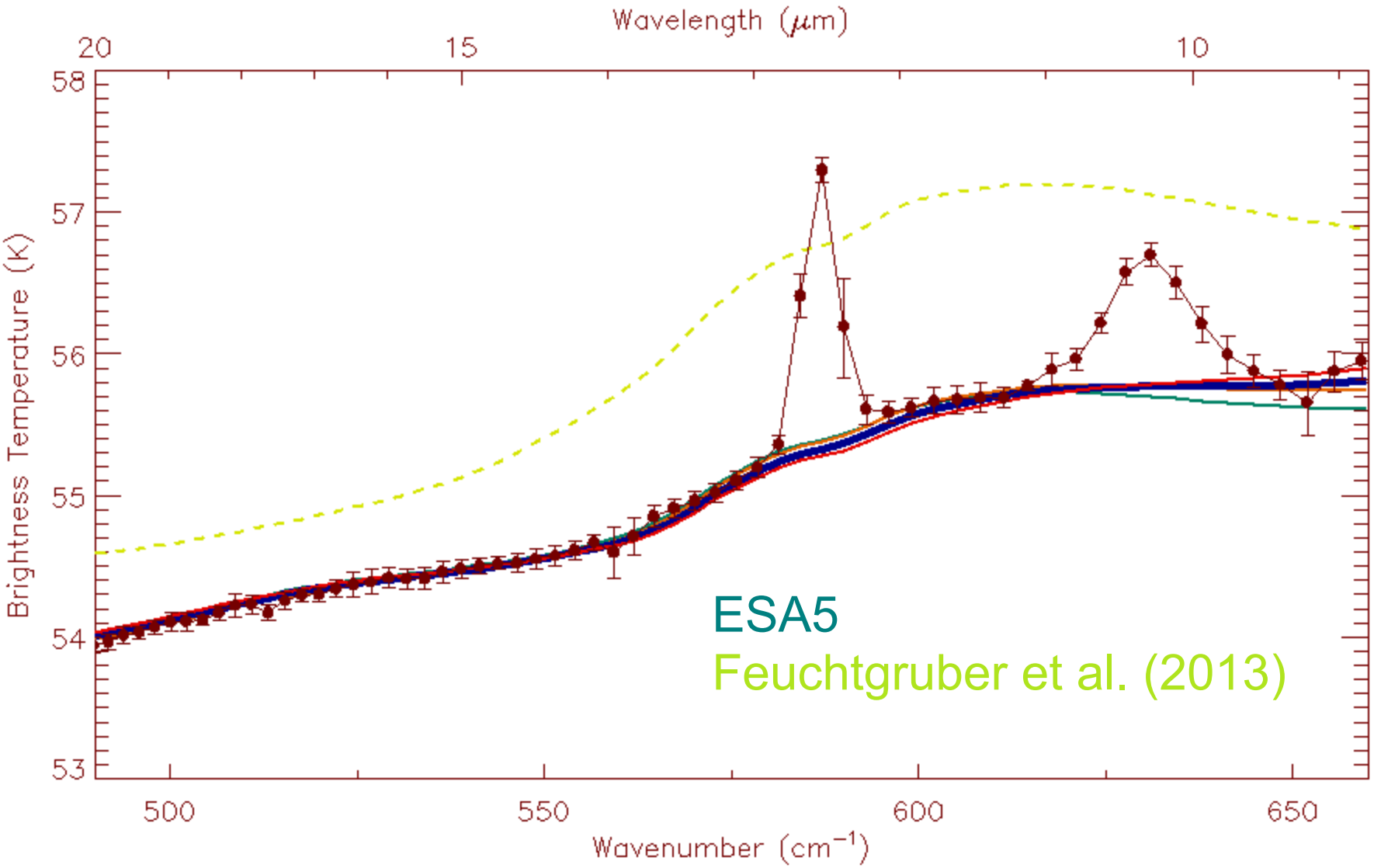


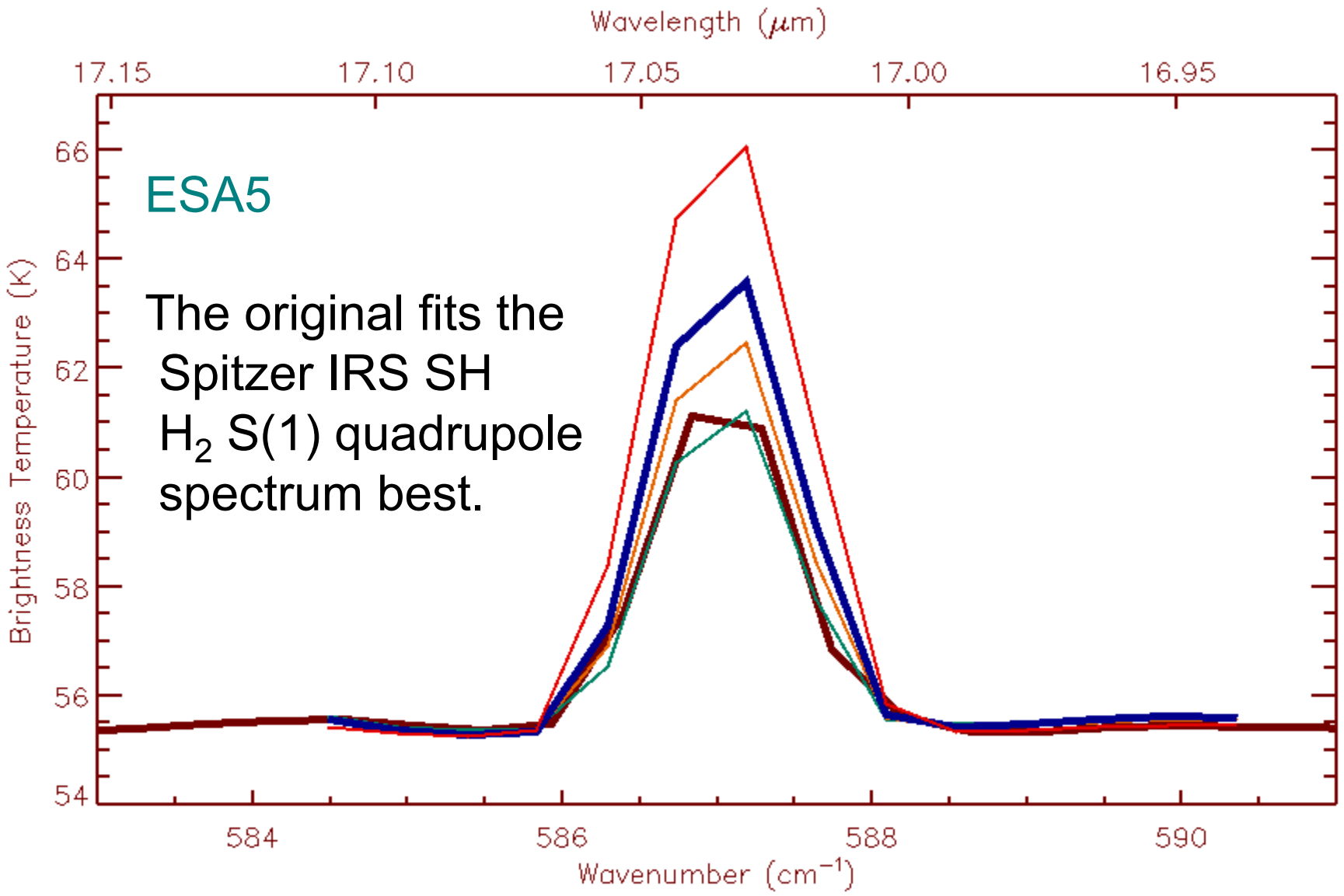

ESA5
Feuchtgruber et al. (2013)
Wavelength (μm)
20
15
10
Brightness Temperature (K)
85
80
75
70
65
60
55
500
600
700
800
900
1000
1100
Wavenumber (cm⁻¹)


ESA5
Feuchtgruber et al. (2013)
Wavelength (μm)
20
15
10
58
57
56
55
54
53
Brightness Temperature (K)
500
550
600
650
Wavenumber (cm⁻¹)

“ESA5” stratosphere is too cold to match the HD lines:



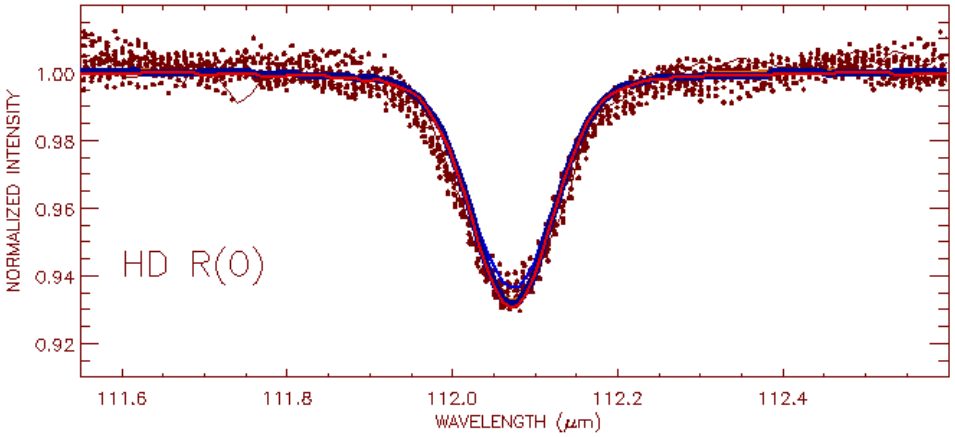

Wavelength (μm)
20
15
10
58
57
56
55
54
53
Brightness Temperature (K)
500
550
600
650
Wavenumber (cm⁻¹)
ESA5
Feuchtgruber et al. (2013)

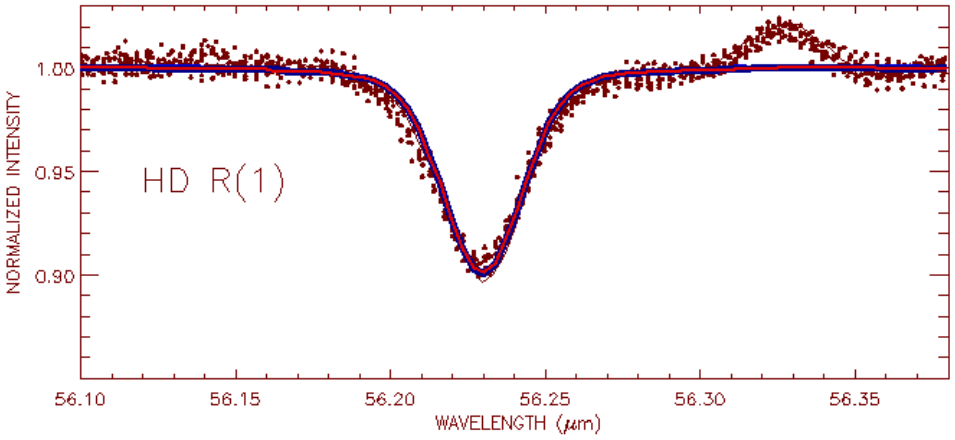

Wavelength (μm)
17.15
17.10
17.05
17.00
16.95
ESA5
The original fits the Spitzer IRS SH H_2 S(1) quadrupole spectrum best.
Brightness Temperature (K)
66
64
62
60
58
56
54
584
586
588
590
Wavenumber (cm^{-1})

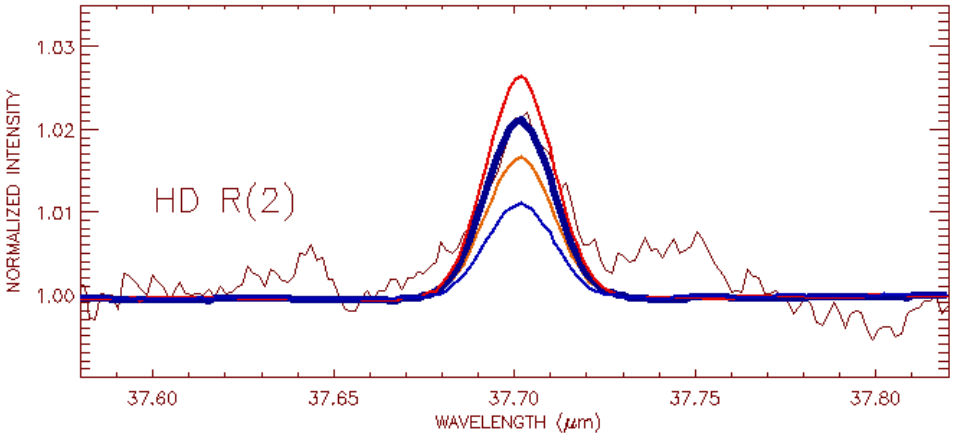
Changing the stratospheric T(p) has little effect on the HD R(0) and R(1) line fits, so the D/H ratio can be fitted independently.

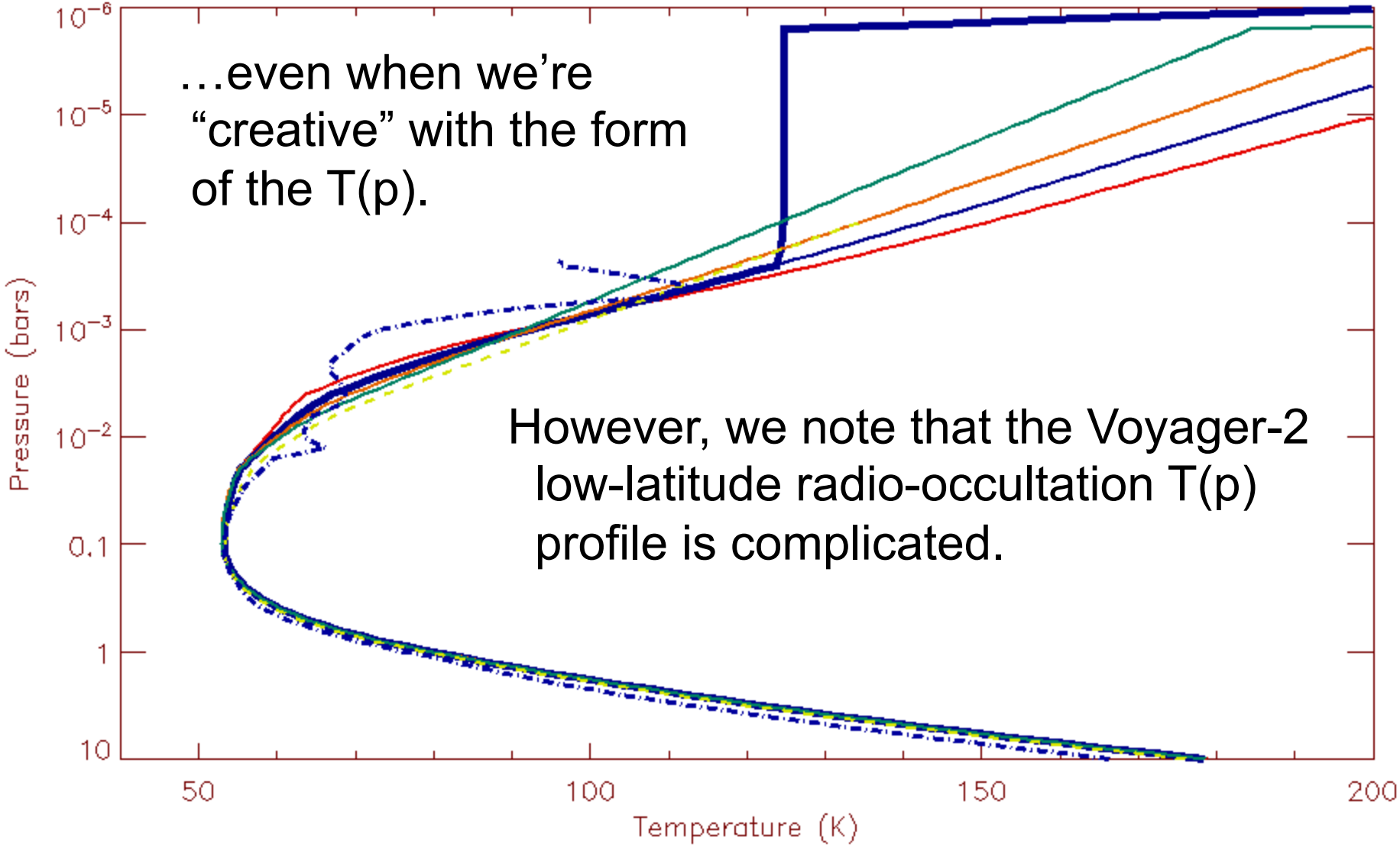
But the ESA5 profile (coldest) is not compatible with these, i.e. for the moment, we haven't found a way to fit the Spitzer IRS H_2 S(1) and the ISO HD R(2) line simultaneously.

NB: The IRS H_2 S(1) and ISO H_2 S(1) are compatible.





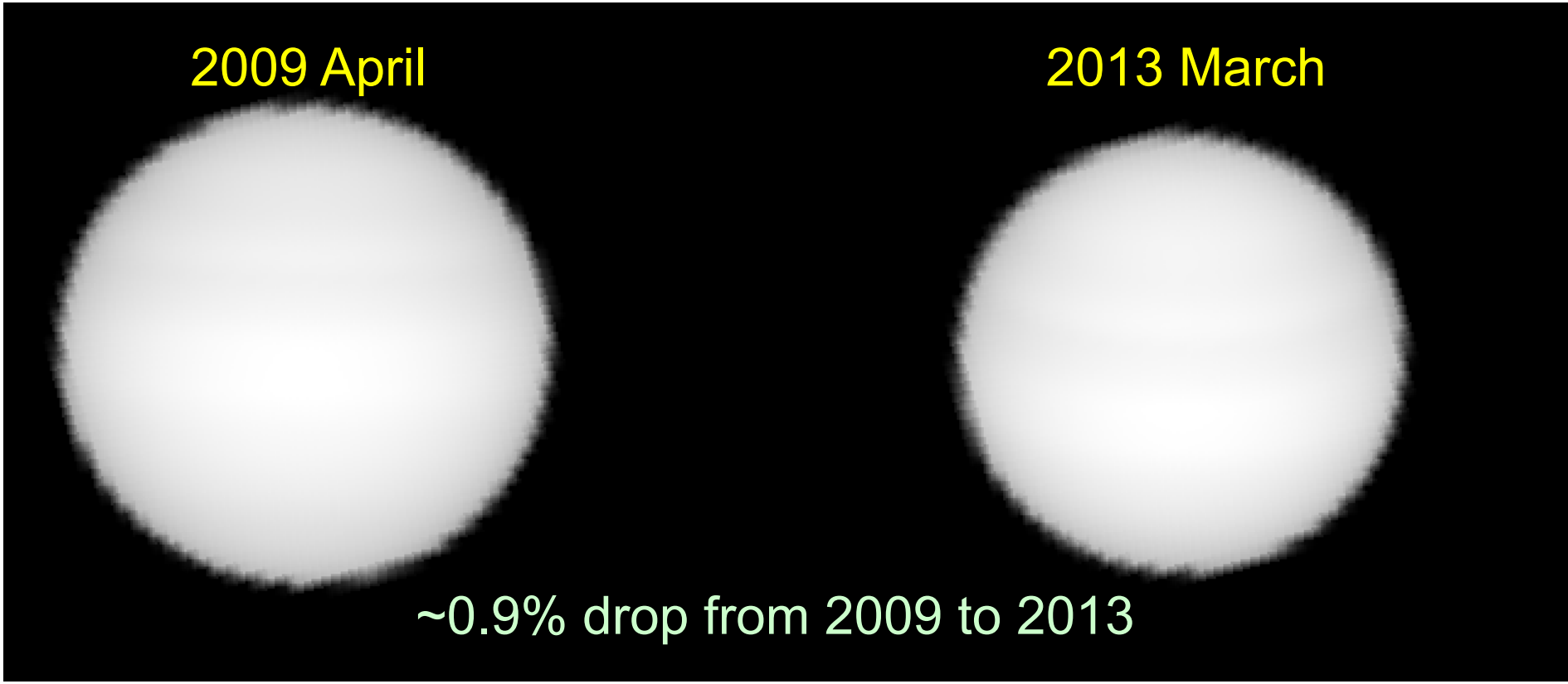



…even when we're "creative" with the form of the T(p).
However, we note that the Voyager-2 low-latitude radio-occultation T(p) profile is complicated.
Pressure (bars)
Temperature (K)
10^-6
10^-5
10^-4
10^-3
10^-2
0.1
1
10
50
100
150
200

Time Variability?

Seasonal variations show a different perspective of Uranus as a strong function of time

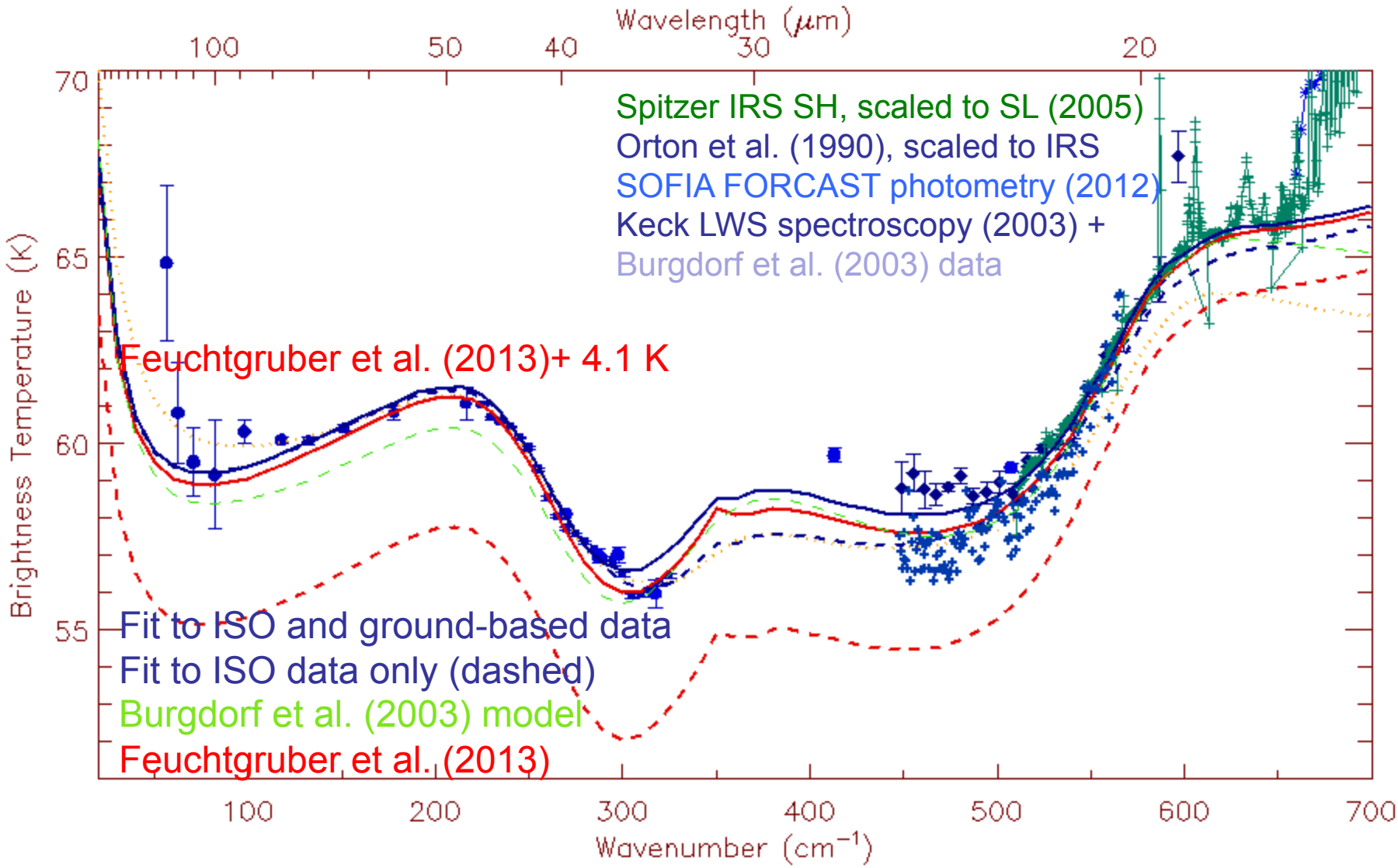
Pseudo-images below show a simulation of 0.5-mm images of Uranus extrapolated from Voyager-2 IRIS T(p) retrievals, extrapolated downward (oriented so north is up)

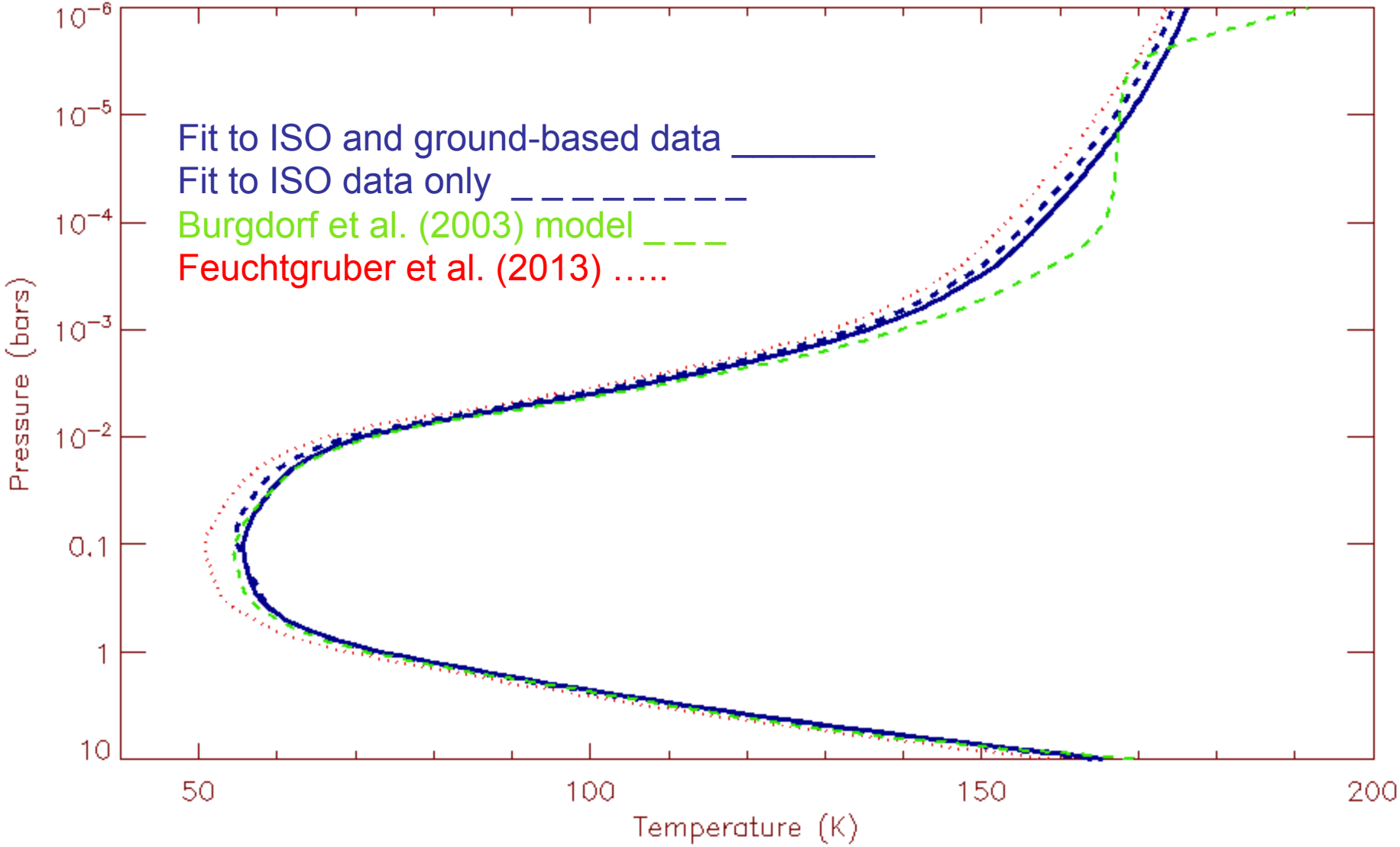


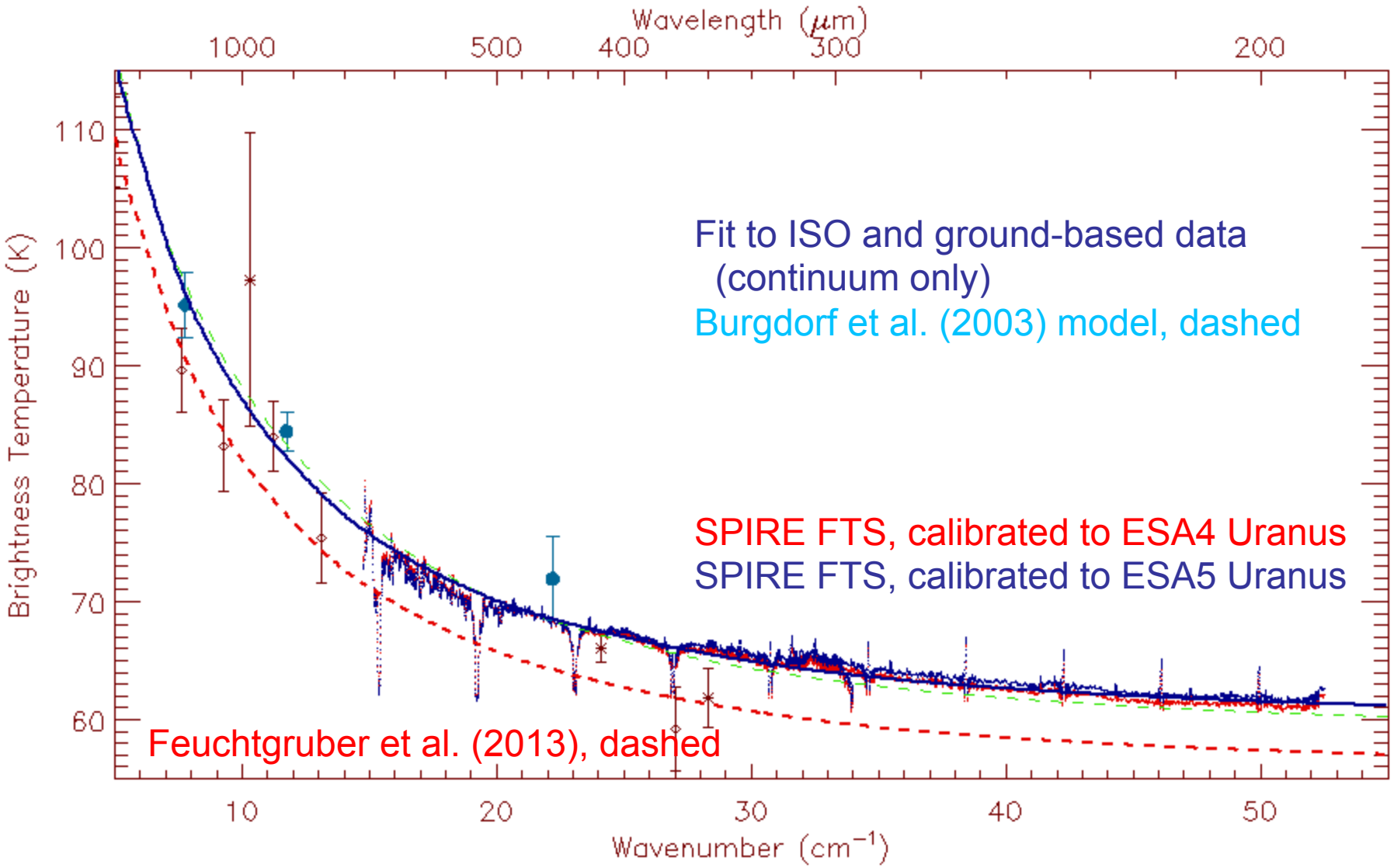
PACS Photometry vs. Time

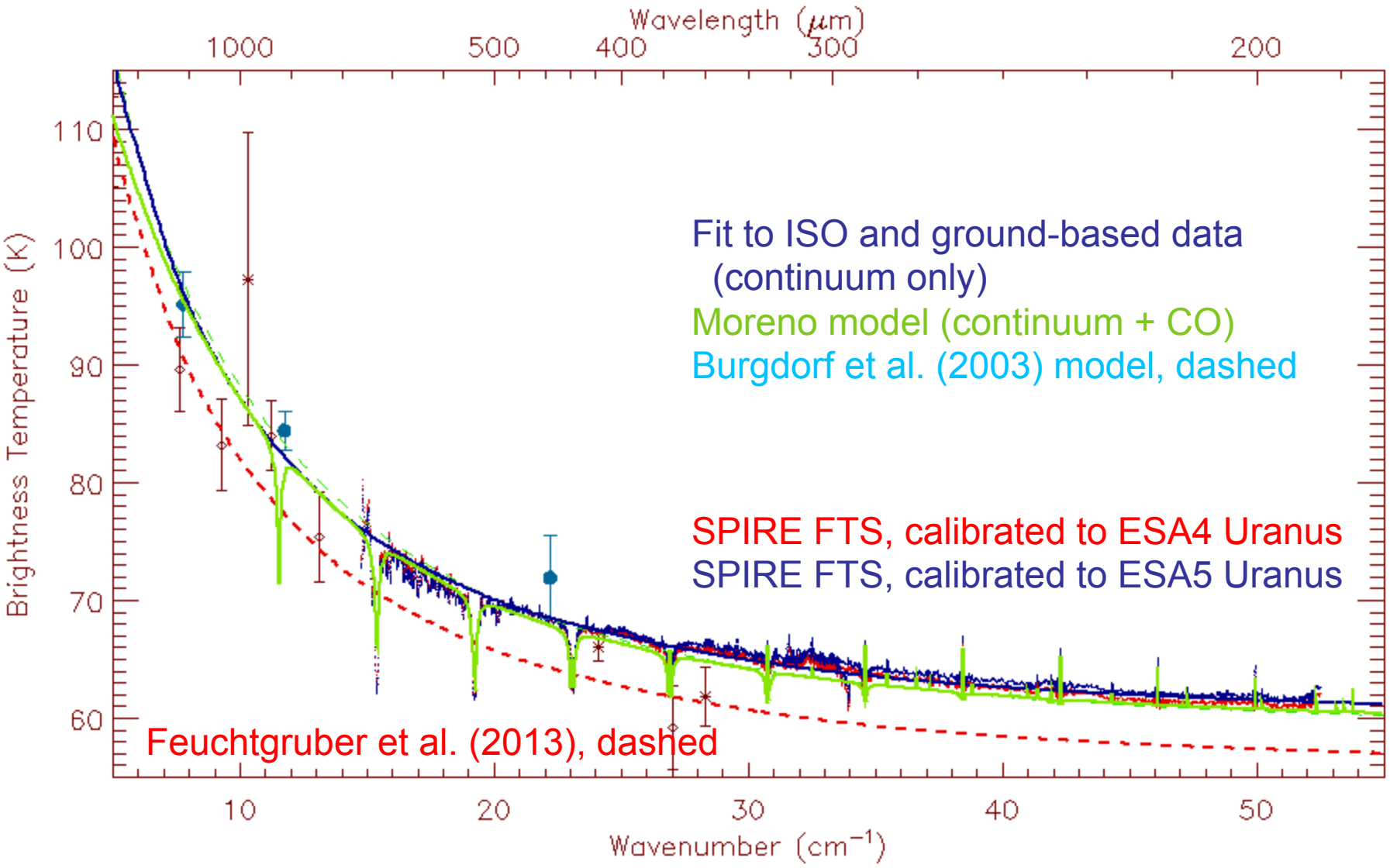
- Ratio of PACS photometry of Uranus vs. Neptune
- Observations span 2010 Dec. – 2012 June
- Uranus/Neptune radiance ratio changes by < 0.3%

NEPTUNE


Wavelength (μm)
100
50
40
30
20
70
65
60
55
Brightness Temperature (K)
Spitzer IRS SH, scaled to SL (2005)
Orton et al. (1990), scaled to IRS
SOFIA FORCAST photometry (2012)
Keck LWS spectroscopy (2003) +
Burgdorf et al. (2003) data
Feuchtgruber et al. (2013)+ 4.1 K
Fit to ISO and ground-based data
Fit to ISO data only (dashed)
Burgdorf et al. (2003) model
Feuchtgruber et al. (2013)
100
200
300
400
500
600
700
Wavenumber (cm^{-1})

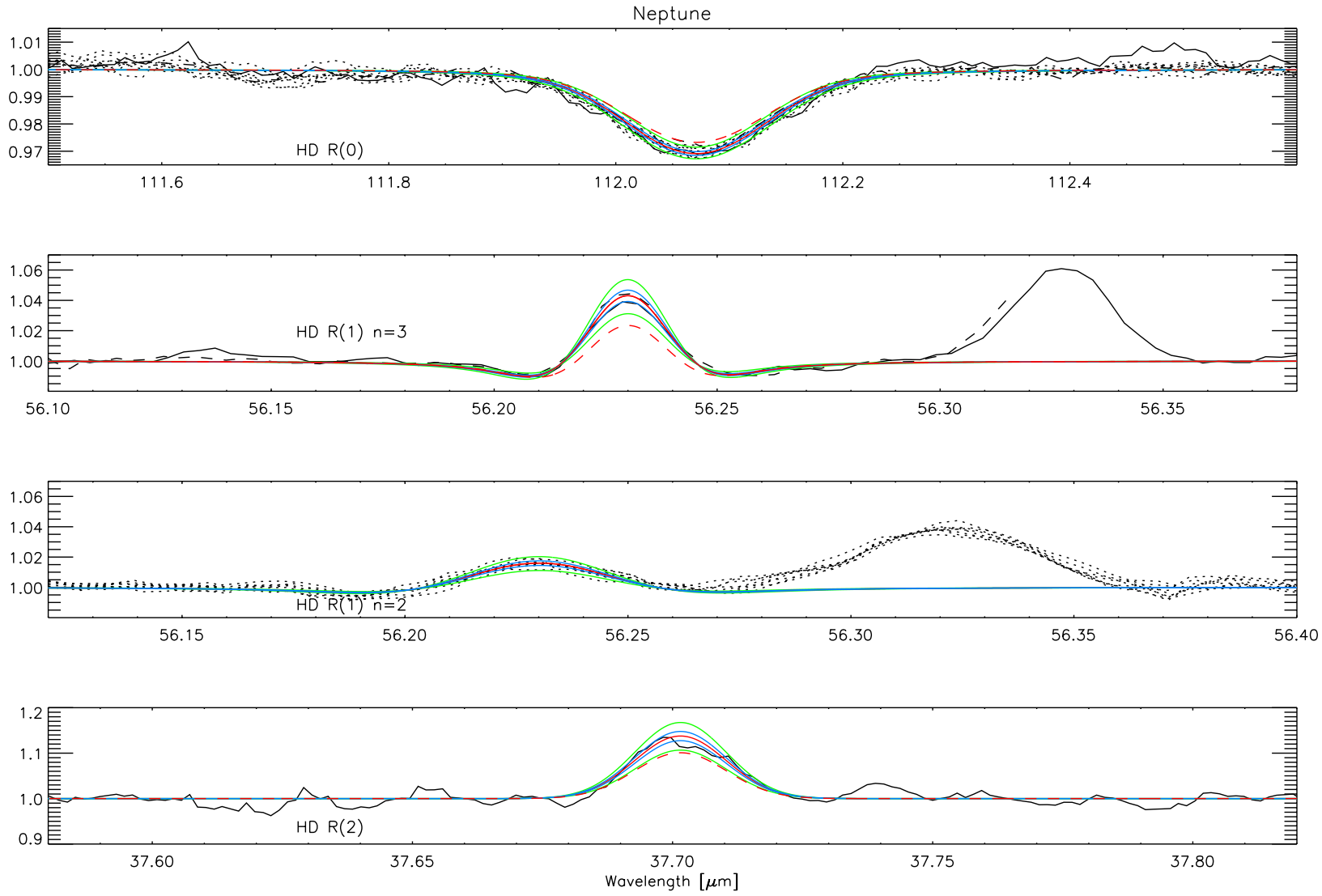

Fit to ISO and ground-based data
Fit to ISO data only
Burgdorf et al. (2003) model
Feuchtgruber et al. (2013) .....
Pressure (bars)
10^-6
10^-5
10^-4
10^-3
10^-2
0.1
1
10
50
100
150
200
Temperature (K)


Wavelength (μm)
1000
500
400
300
200
110
100
90
80
70
60
Brightness Temperature (K)
10
20
30
40
50
Wavenumber (cm^{-1})
Fit to ISO and ground-based data
(continuum only)
Burgdorf et al. (2003) model, dashed
SPIRE FTS, calibrated to ESA4 Uranus
SPIRE FTS, calibrated to ESA5 Uranus
Feuchtgruber et al. (2013), dashed

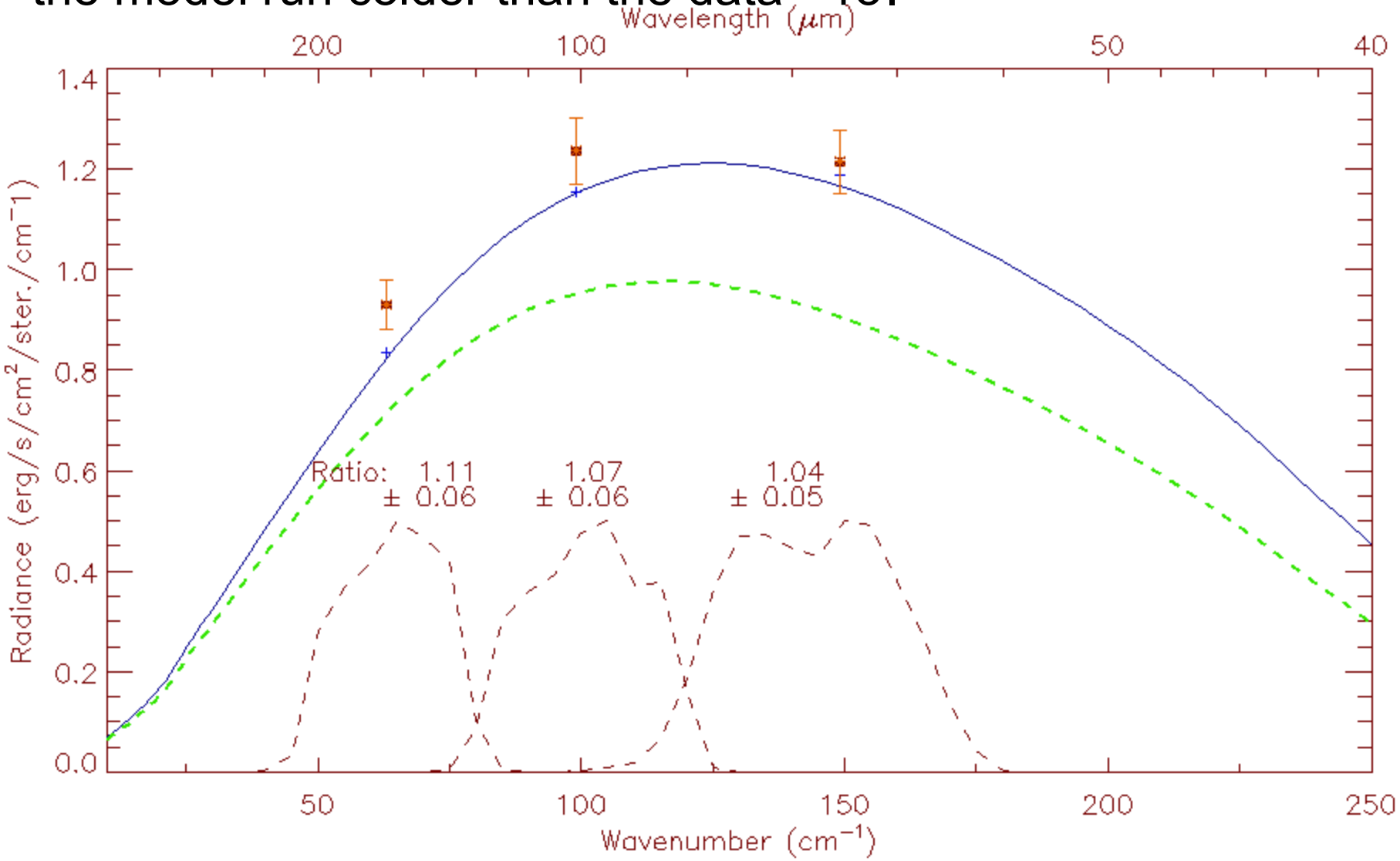

Wavelength (μm)
1000
500
400
300
200
110
100
90
80
70
60
Brightness Temperature (K)
10
20
30
40
50
Wavenumber (cm⁻¹)
Fit to ISO and ground-based data
(continuum only)
Moreno model (continuum + CO)
Burgdorf et al. (2003) model, dashed
SPIRE FTS, calibrated to ESA4 Uranus
SPIRE FTS, calibrated to ESA5 Uranus
Feuchtgruber et al. (2013), dashed

Issues: adding 4.1 K to the Feuchtgruber et al. (2013) profile (red dashed) doesn't quite preserve the shape of HD lines

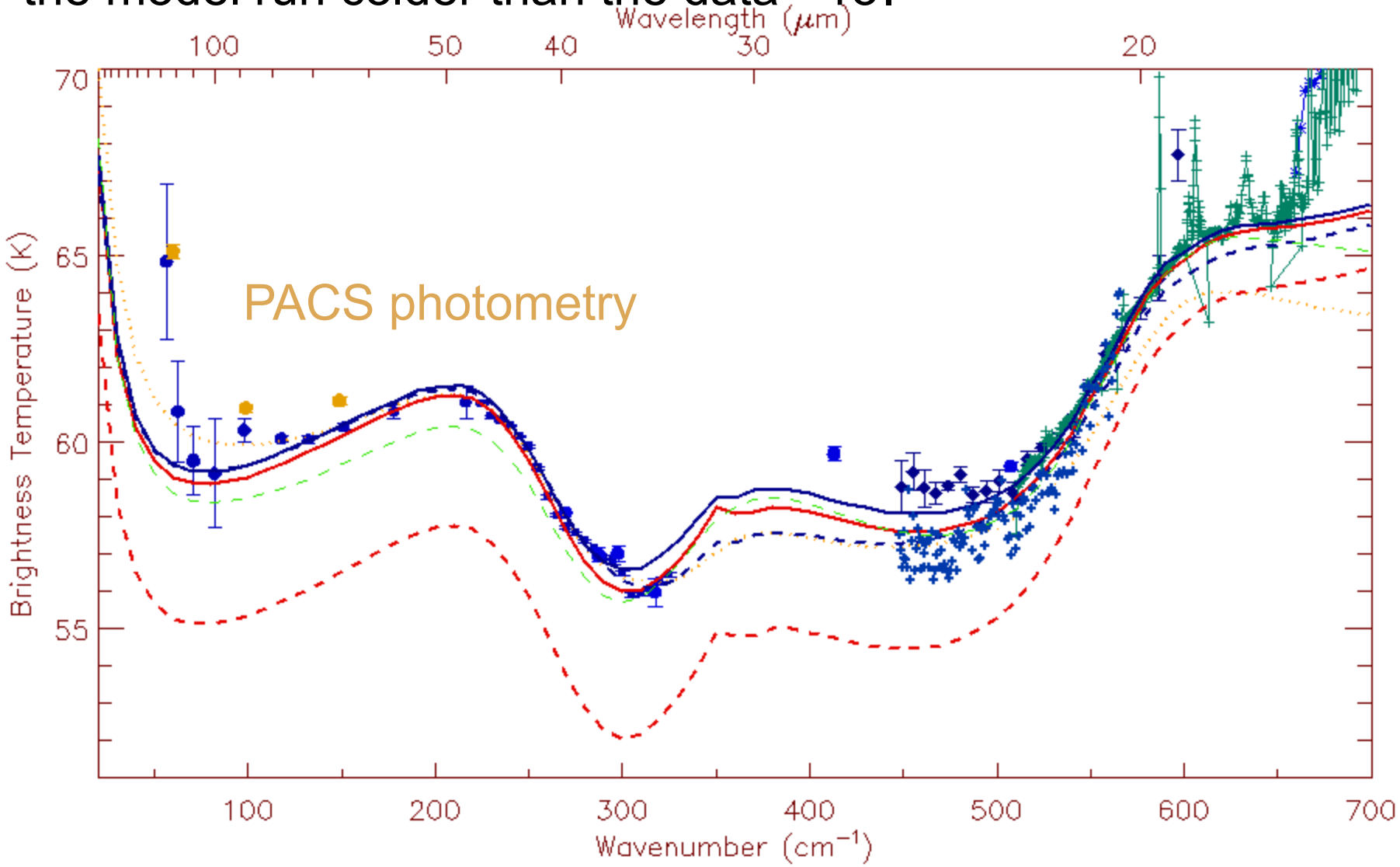
At very least, some "tweaking" of the profile is required.



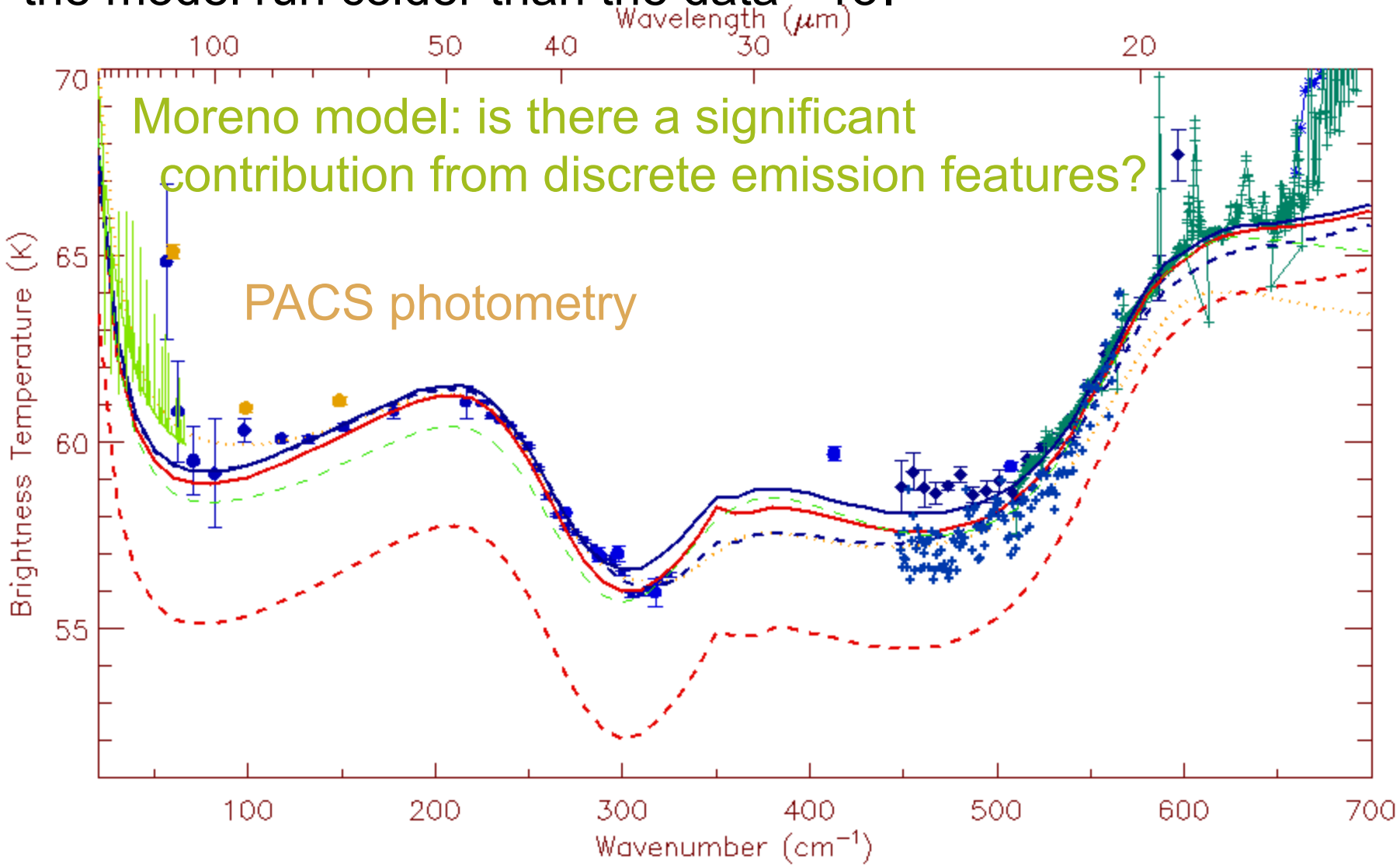
Issues: the continuum model doesn't fit the PACS photometry: the model run colder than the data - 1σ.



Issues: the continuum model doesn't fit the PACS photometry: the model run colder than the data - 1σ.



Issues: the continuum model doesn't fit the PACS photometry: the model run colder than the data - 1σ.

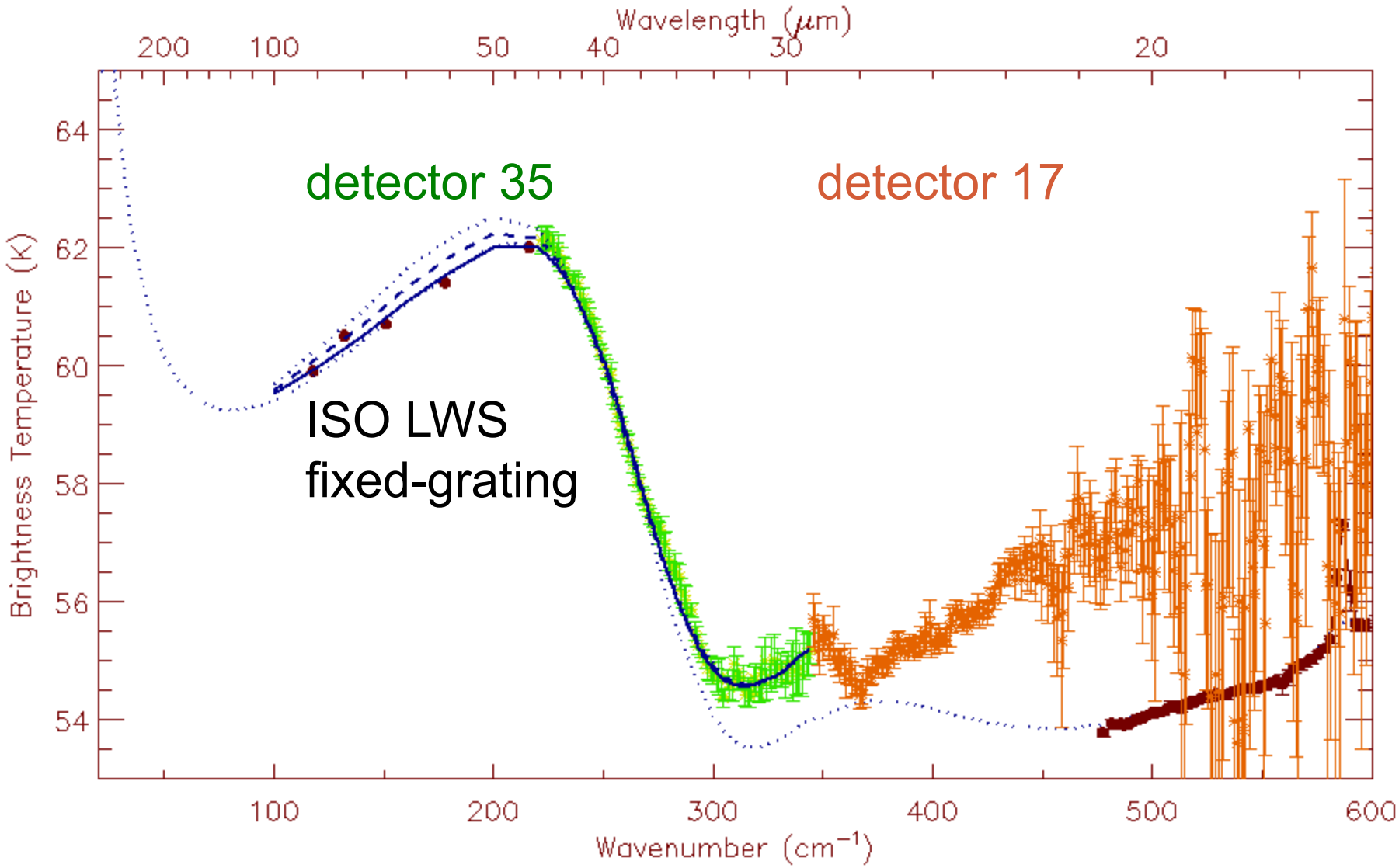


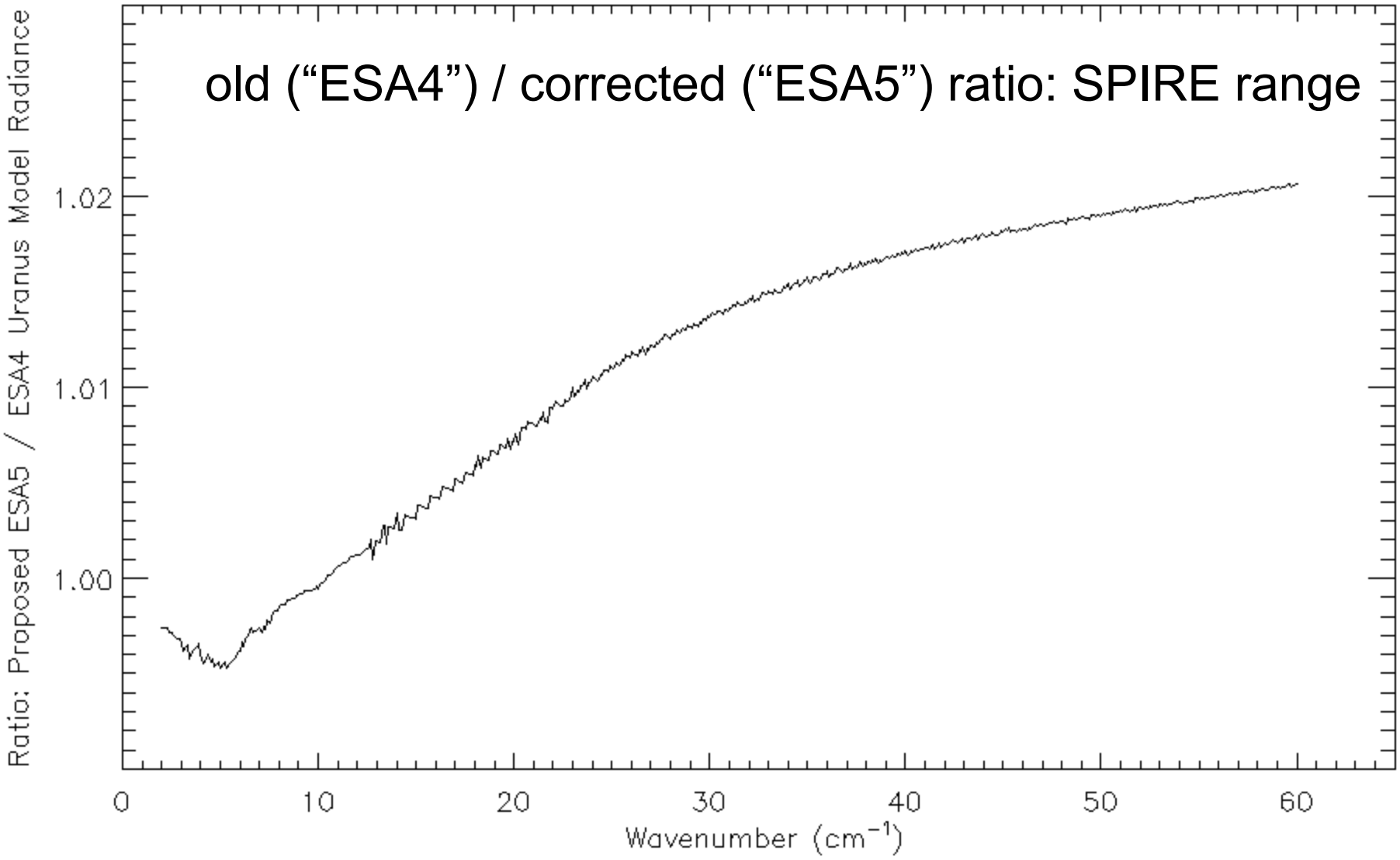
Summary

- Uranus
  - Small ‘tweaks’ to the ESA4 model, suggested as ESA5
  - Consistent within the PACS photometry (5%)
  - 0-4% differences from ESA4
  - Unresolved inconsistency with PACS HD measurements, but probably minimal impact on the spectral continuum in the Herschel range
  - Indications are that time variability over 2009-2013 is < 1%
- Neptune
  - Small changes to the Feuchtgruber et al. (2013) T(p)
  - Consistent with ISO LWS+SWS, Spitzer IRS spectrum
    - Also ground-based
  - Match to 1K or better with SPIRE FTS data based on revised Uranus model (suggested as ESA5)
  - Small inconsistencies with PACS HD need to be resolved
  - Inconsistency with PACS photometry: unmodeled discrete emission features?

Supplementary Material

Uranus spectrum: ISO SWS




old (“ESA4”) / corrected (“ESA5”) ratio: SPIRE range
Ratio: Proposed ESA5 / ESA4 Uranus Model Radiance
1.02
1.01
1.00
0
10
20
30
40
50
60
Wavenumber (cm^{-1})

Feuchtgruber et al. (2013) T(p) for Uranus with various D/H models