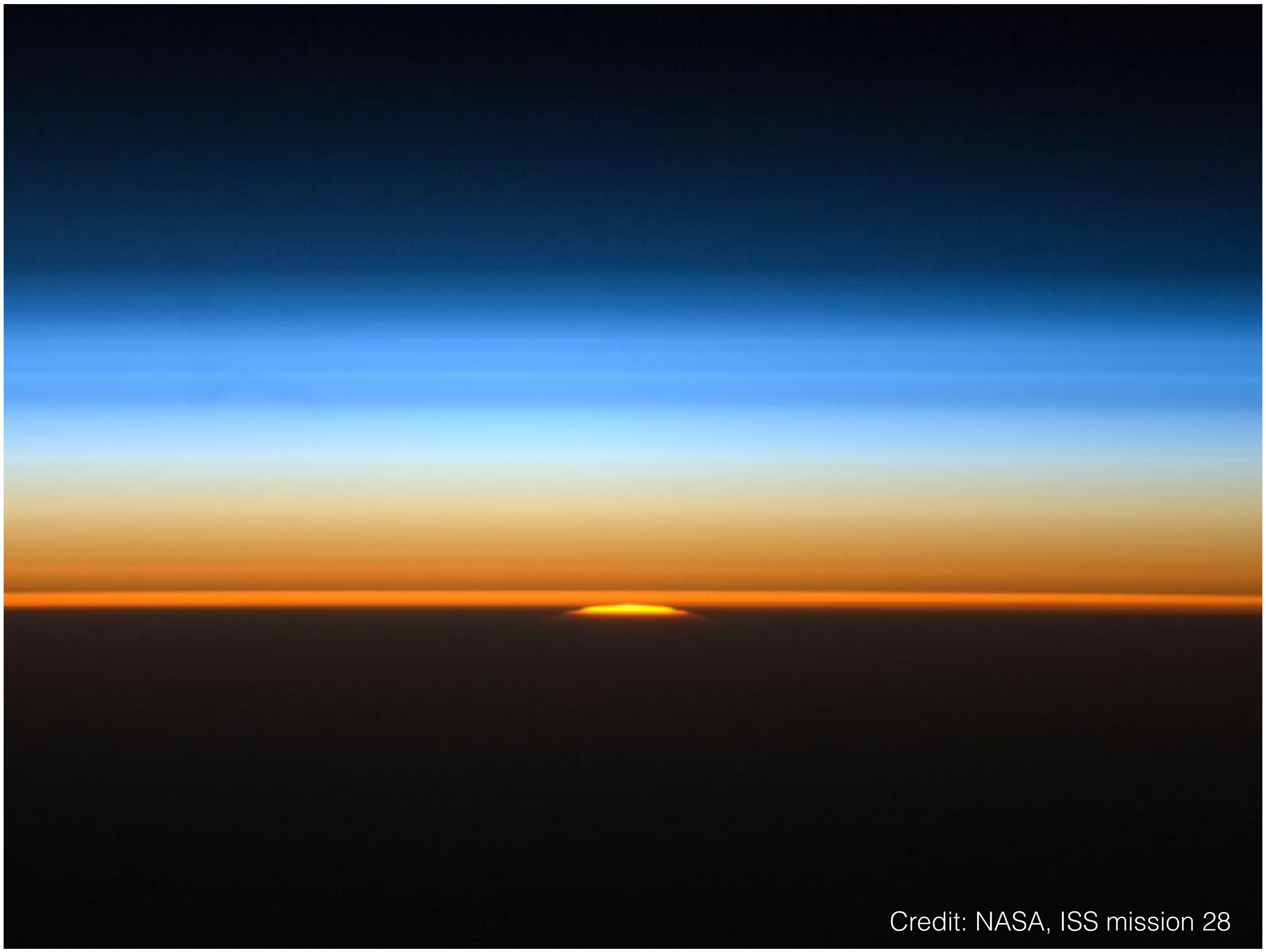
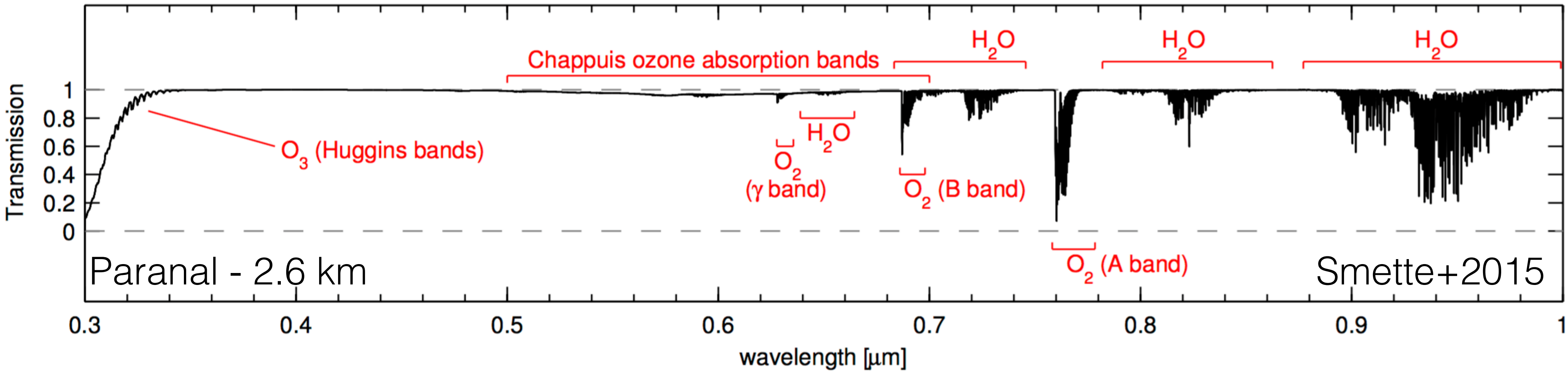
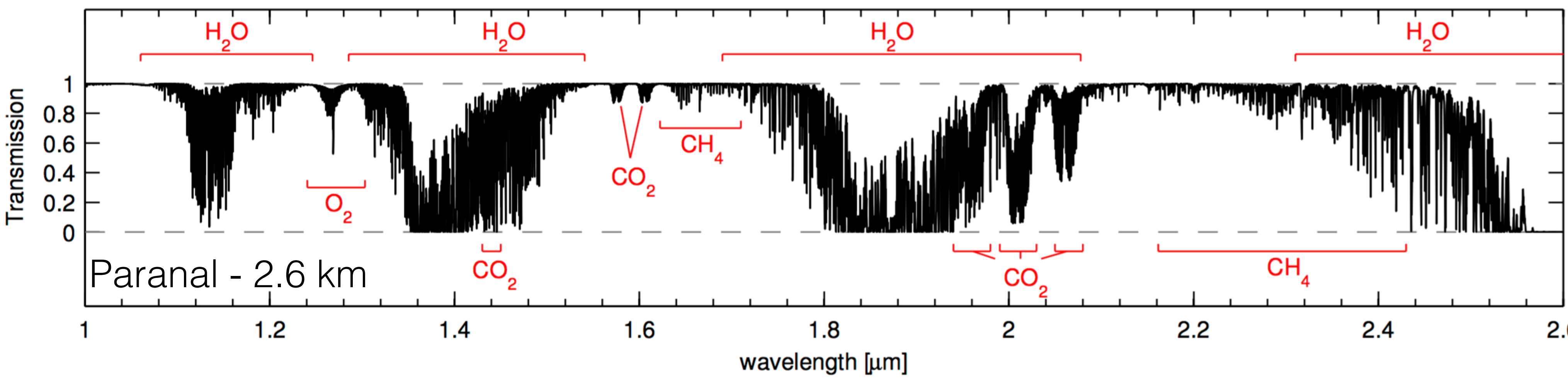
The Impact of Telluric Lines on EPRV Measurements



Cullen Blake - University of Pennsylvania

Telluric Absorption: Optical and NIR

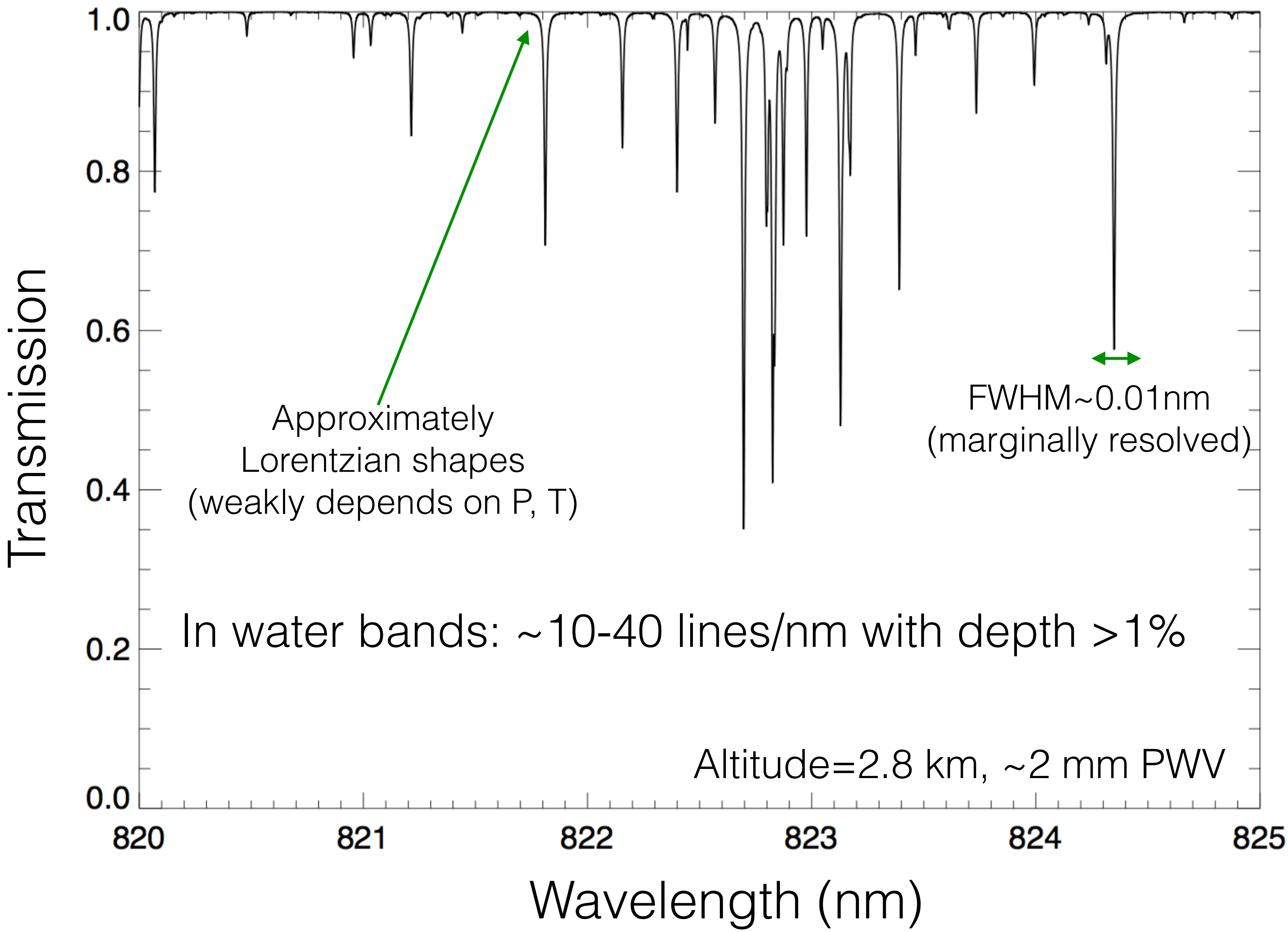




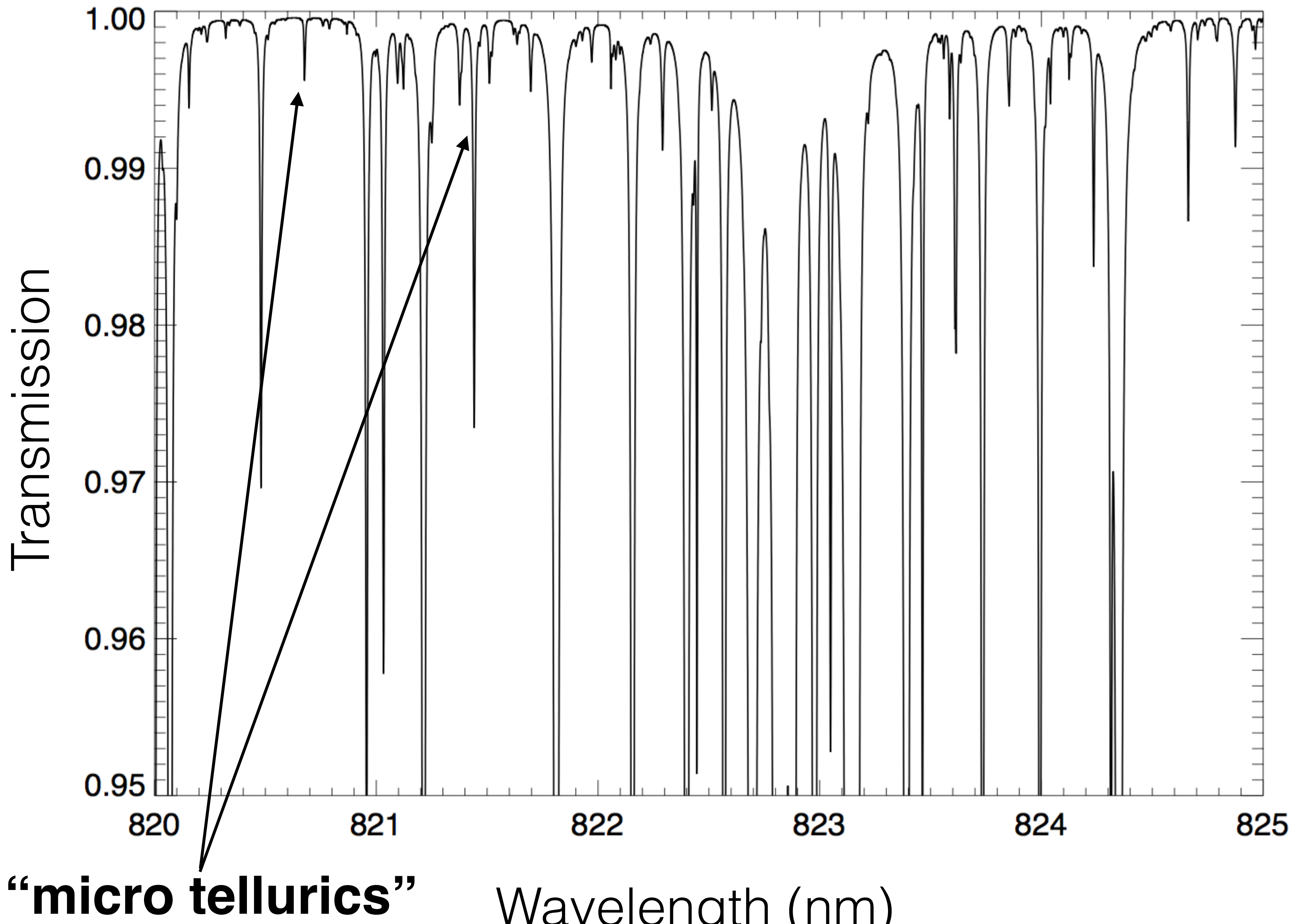
The primary offenders: H_2O, O_2, O_3, CO_2, CH_4

Broad O_3 features can make continuum normalization hard

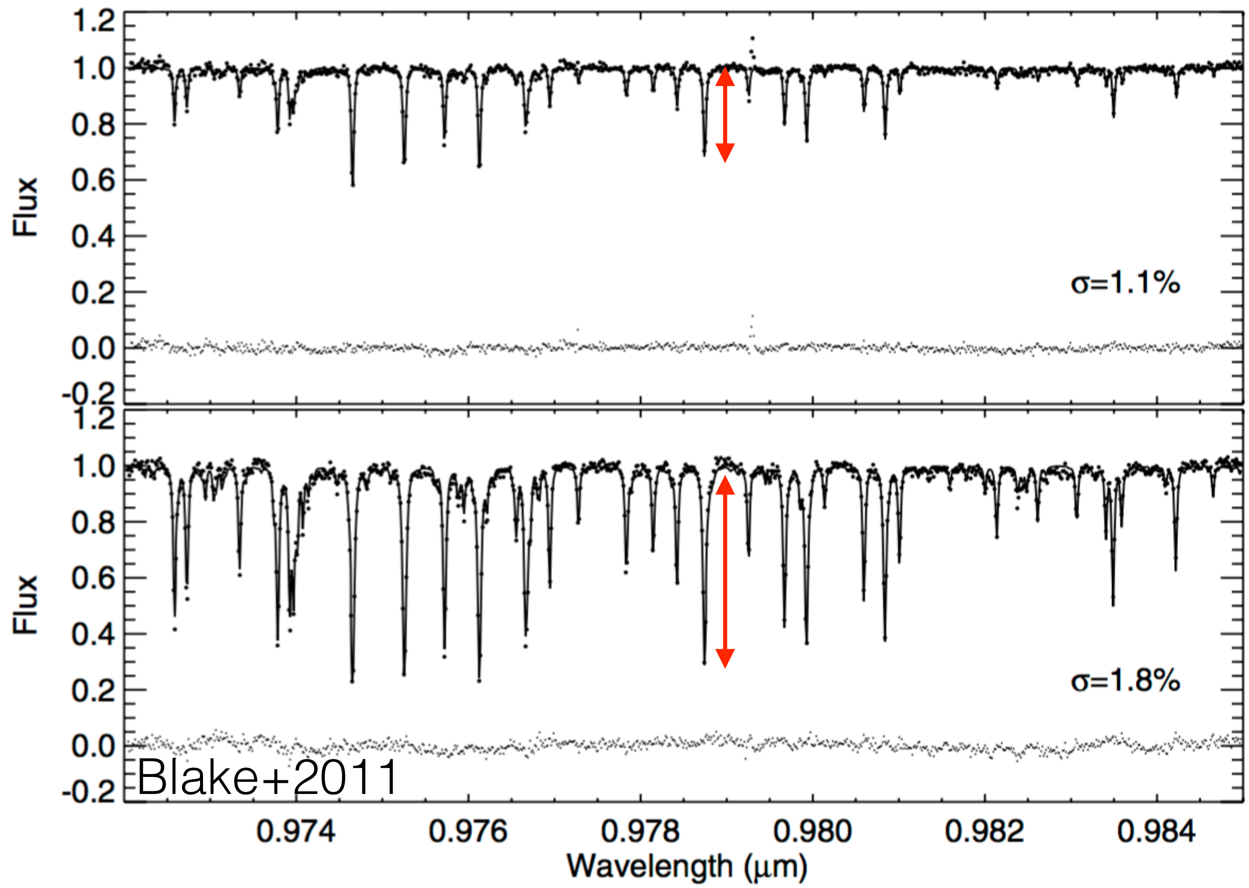
Water, Water Everywhere…



Water, Water Everywhere…



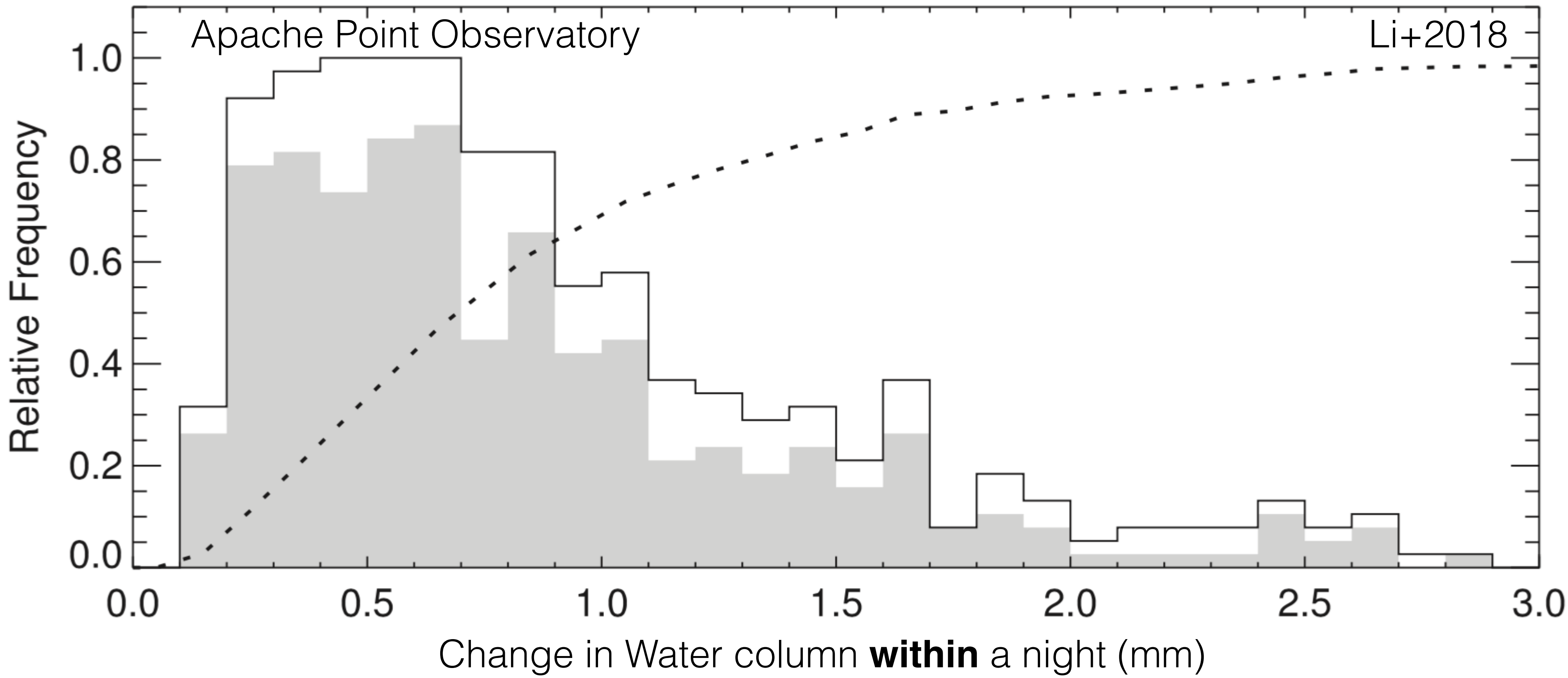
Water is Highly Variable



Line depths depend strongly on airmass and Precipitable Water Vapor (PWV)

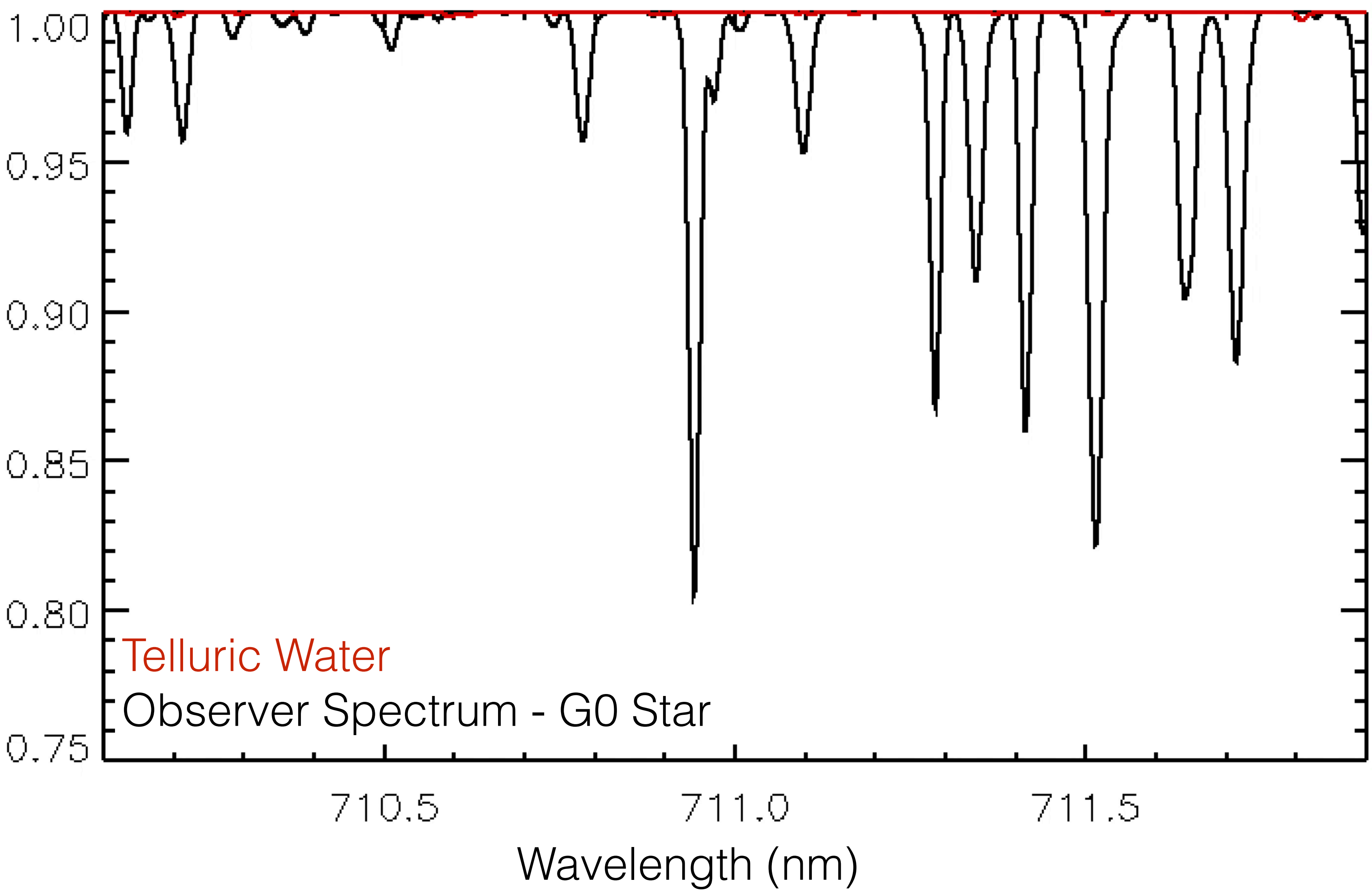
Water vapor varies a lot, other species are relatively stable

Water is Highly Variable



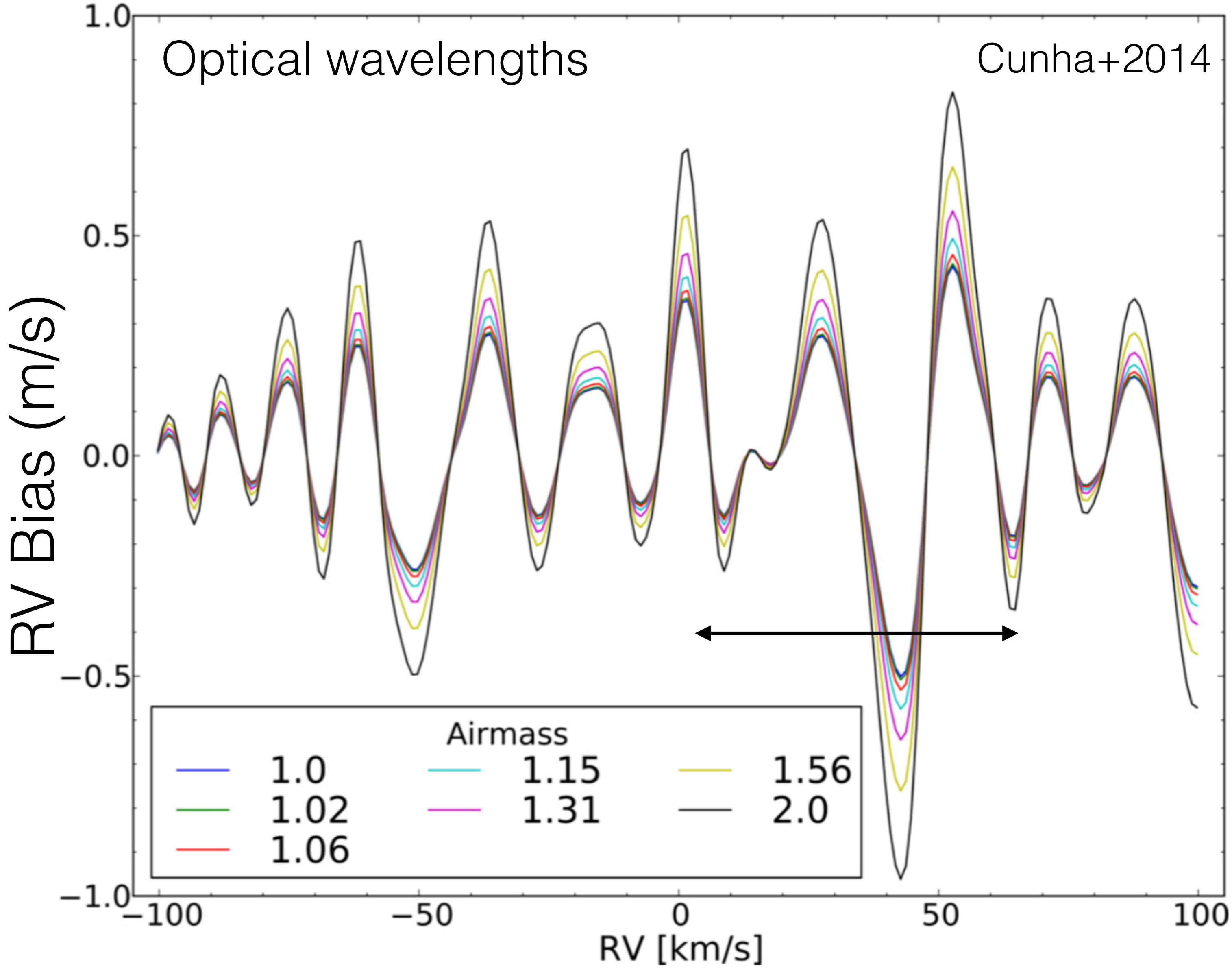
- Distribution of **change** in PWV **within** a night
- 25% changes in water line depths within a night are **common**

Water, Water Everywhere…



In rest frame of star - barycentric motion applied to tellurics

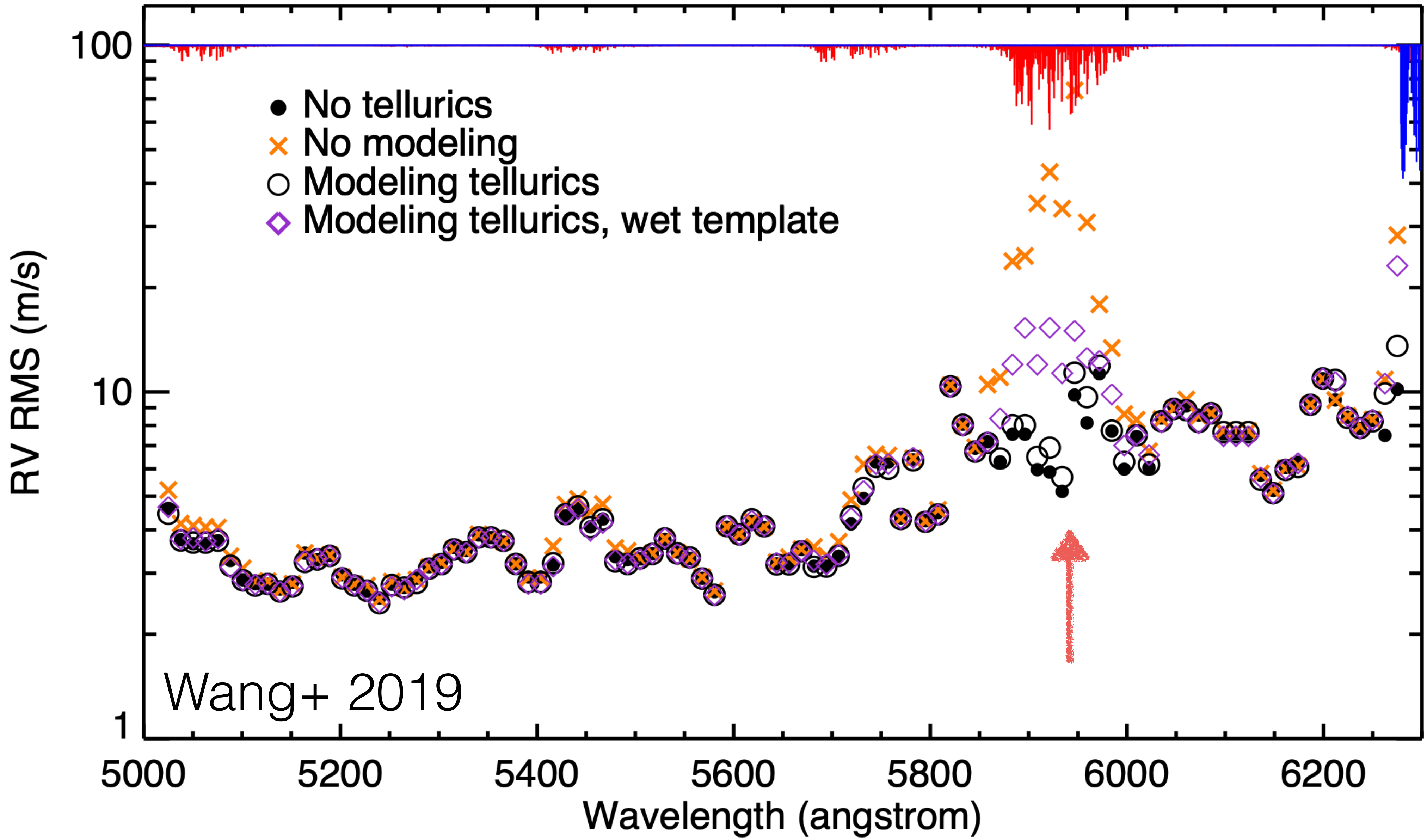
Simulated RV Impact - Masking



Sun-like star, observations at fixed PWV, different airmass

Deep lines already masked out

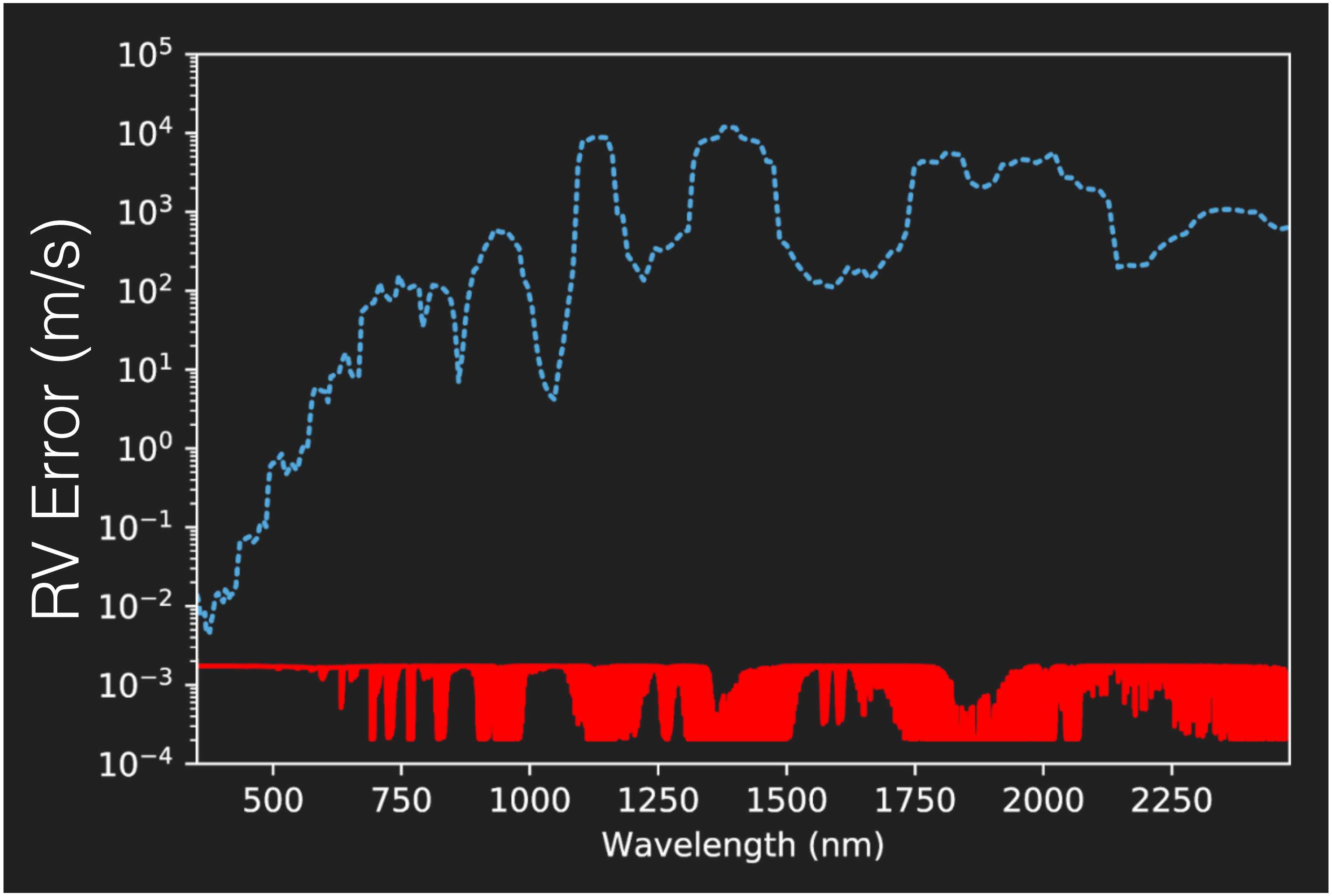
Simulated RV Impact - I_2 Region



Telluric important below 2 m/s in I_2 region

Modeling them out works

Simulated RV Impact - No Mitigation



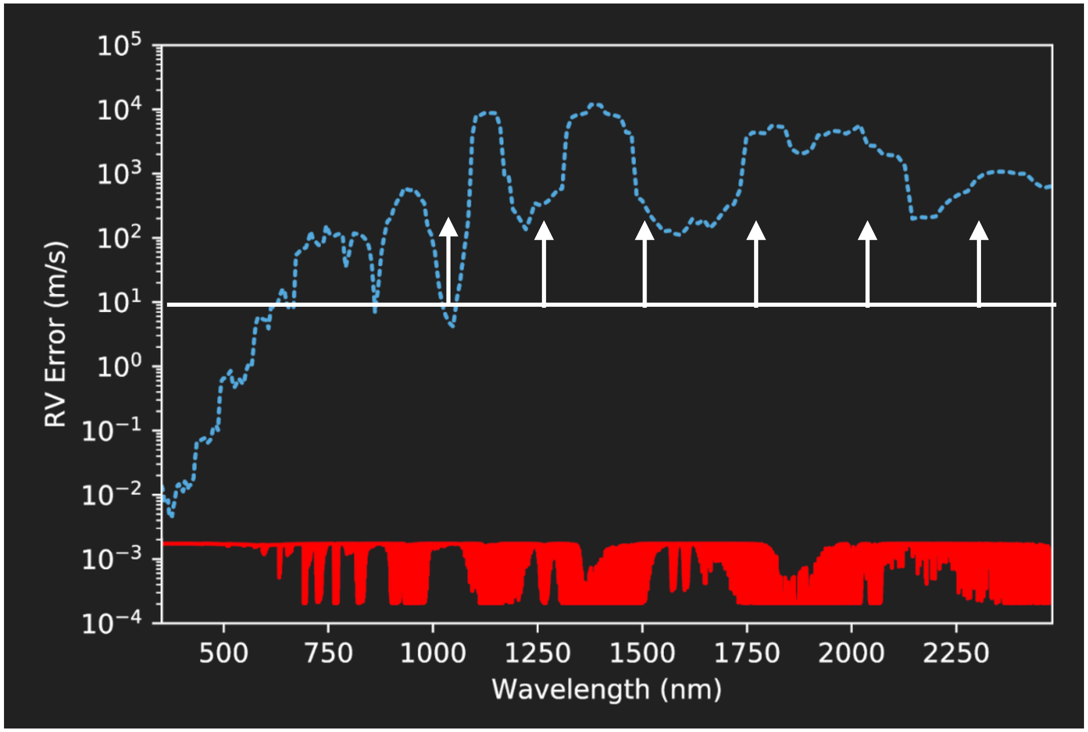
- Simulations from Natasha Latouf for EarthFinder Probe study
- Realistic distribution of atmospheric parameters (PWV, airmass, etc)

So, What Are We Going to do About It?

Option 1: Nothing

- Telluric lines may limit precision to 50 cm/s in optical (<600 nm), <10 (?) m/s in the "red optical" (700 - 900 nm)

- PRVs in the infrared (>1000 nm) probably not possible



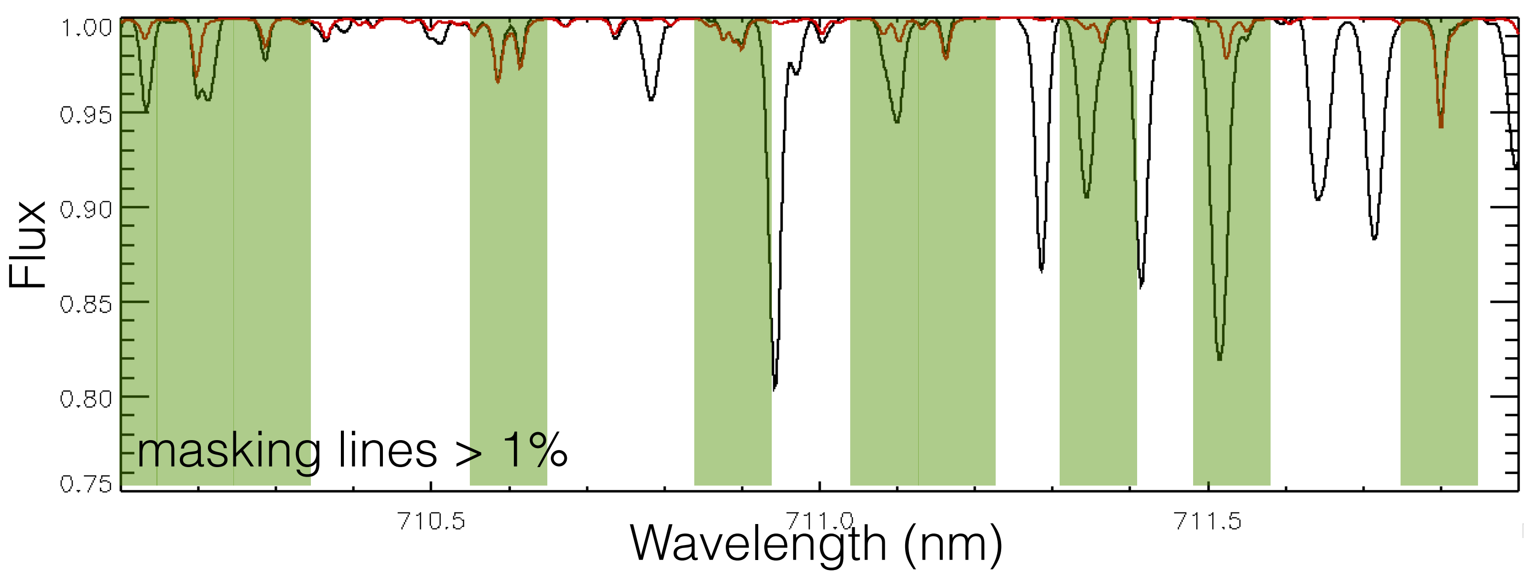
So, What Are We Going to do About It?

Option 2: Mask Telluric Lines During Analysis

- Viable in parts of optical, problematic in NIR

- To account for barycentric motion, each masked line removes ~0.1 nm of spectrum

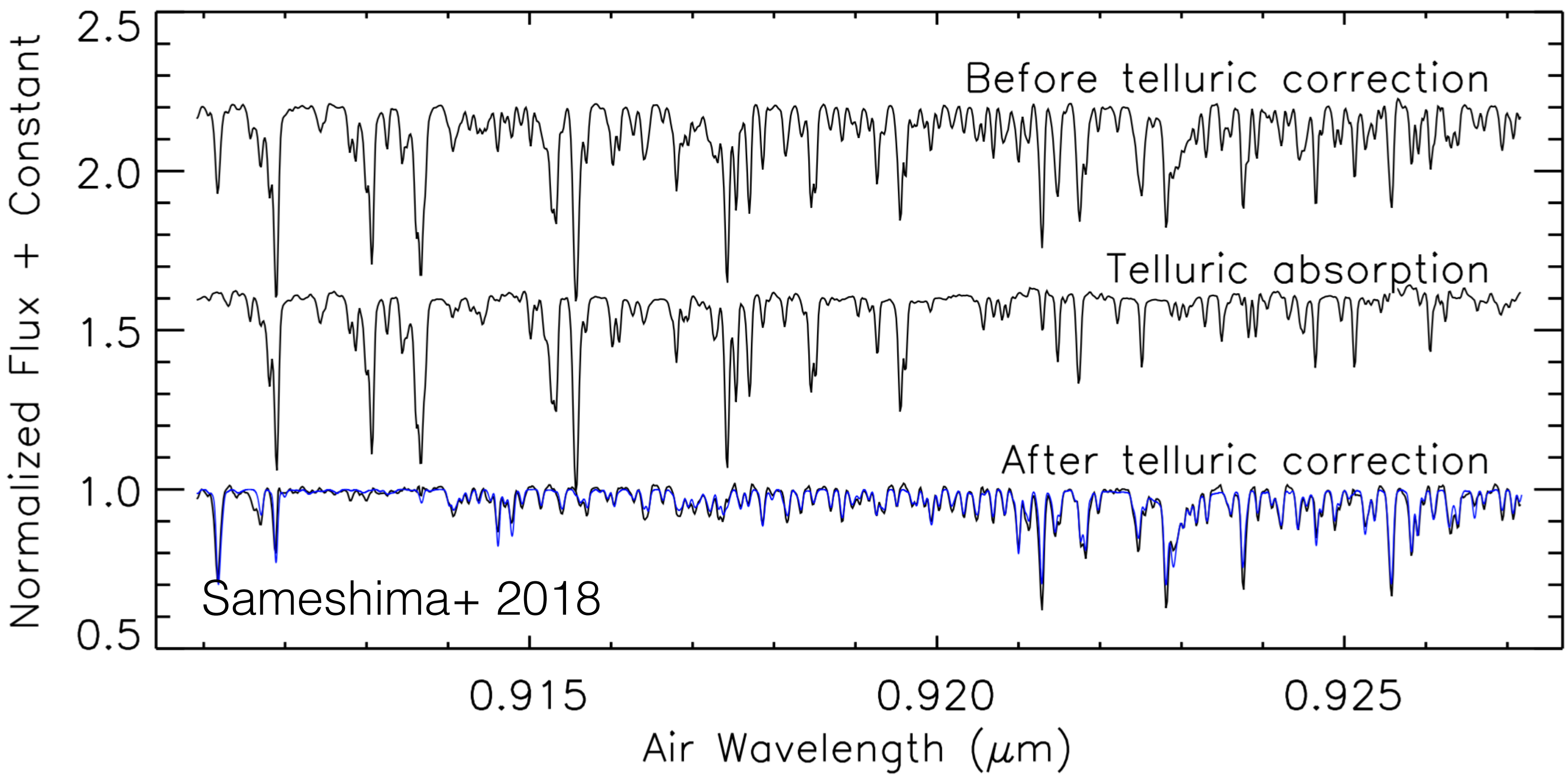
- See, for example, Artigau+2014, Reiners+2010 for a discussion of more efficient masking strategies



So, What Are We Going to do About It?

Option 3: "Correct" the spectra

- Divide the spectrum by telluric model (e.g. Vacca+2003)
- Model may be calculated or empirical (but, hot star observations are expensive)

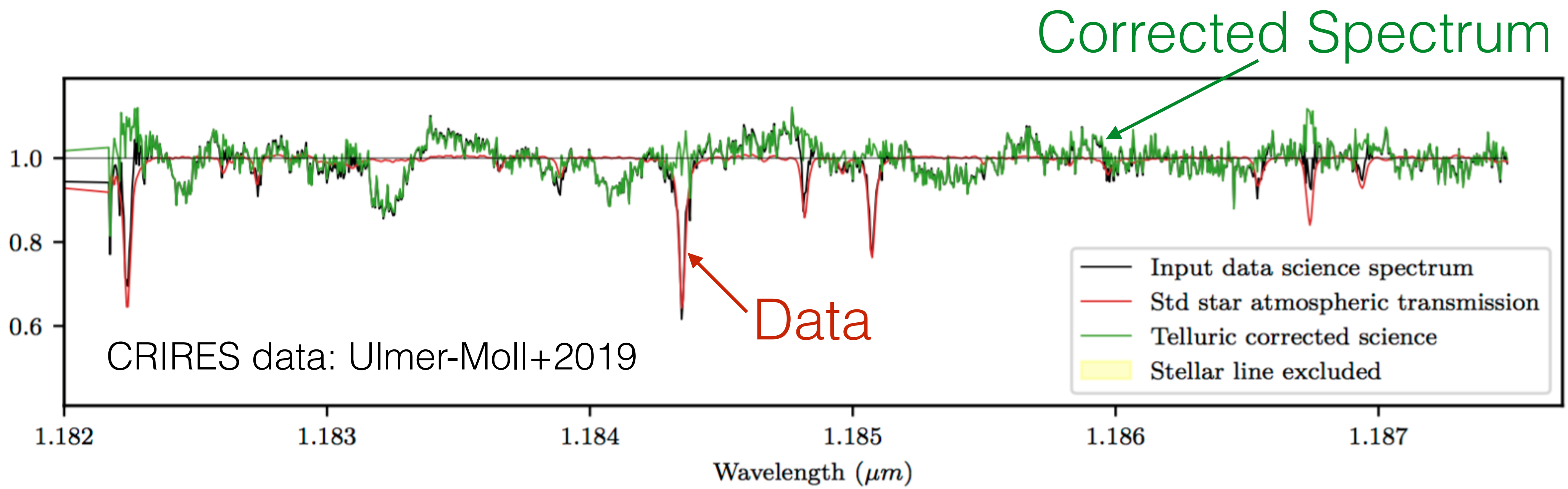


So, What Are We Going to do About It?

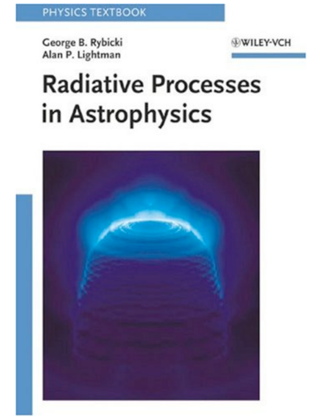
Option 3: "Correct" the spectra

- Divide the spectrum by telluric model (e.g. Vacca+2003)

- Model may be calculated or empirical (but, hot star observations are expensive)



Radiative Transfer Calculations

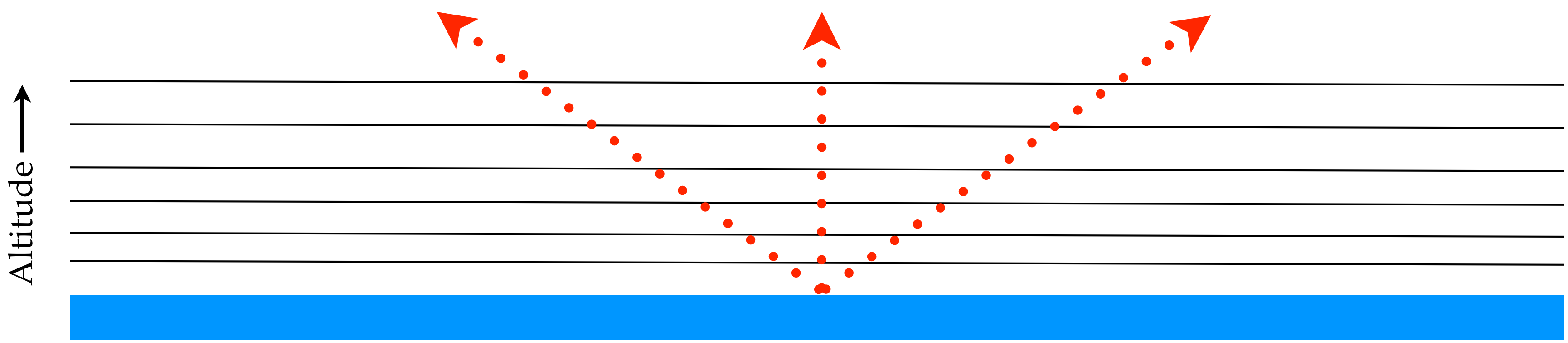


Transmission: $$T_\nu = e^{-\tau_\nu}$$

Line by Line: $$\tau_\nu = \sum_{Altitude} \sum_{Species} \sum_{Line} \tau_{\nu,L,S,A}$$

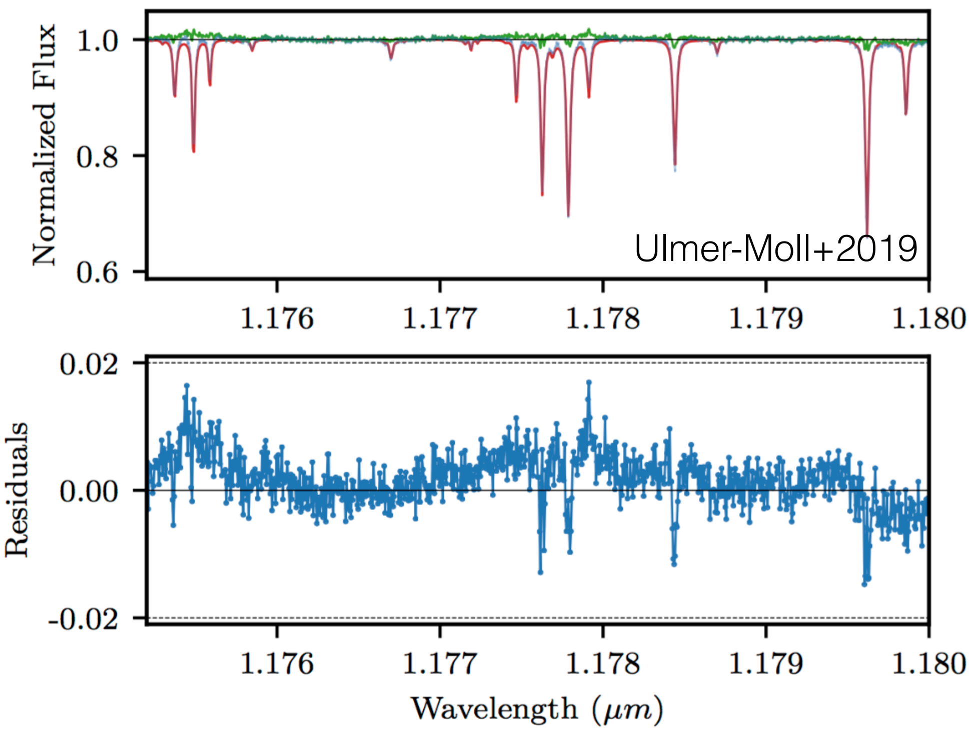
Line Shape

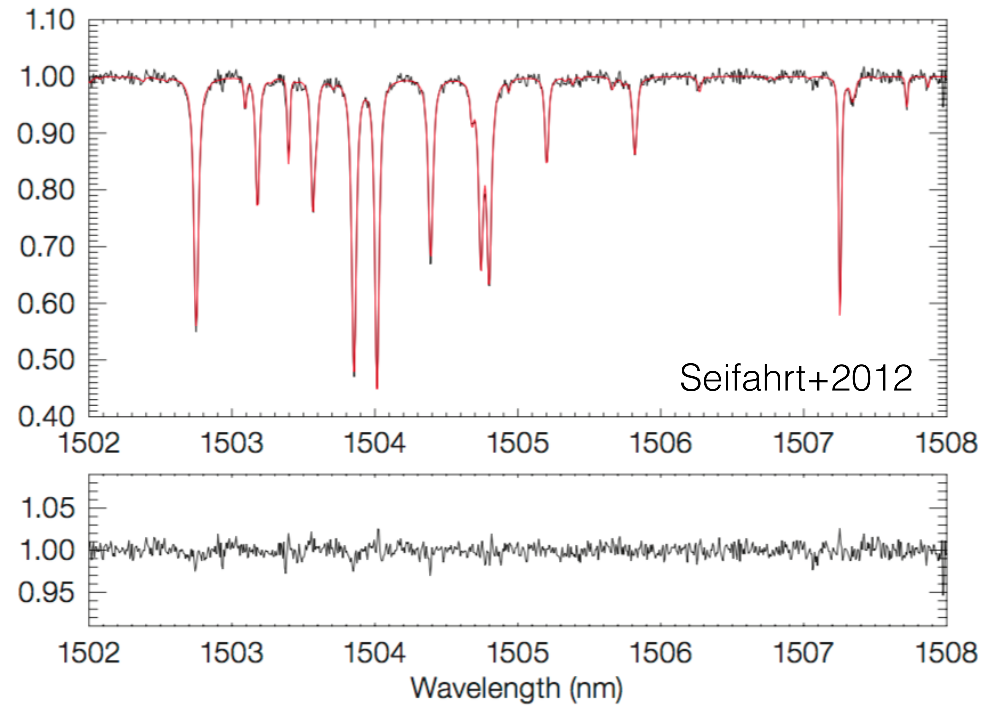
Line Shape and Depth: $$\tau_{\nu,L,S,A} = F[\underline{HITRAN}, P, T, Wind, G]$$



Theoretical Templates vs. Spectra of Hot Stars

Codes include: TAPAS (Bertaux+2014), TERRASPEC (Bender - see Lockwood+2014), LBLRTM (Clough+2015), Telfit (Gullickson2014), Molecfit (Smette+2015), many others



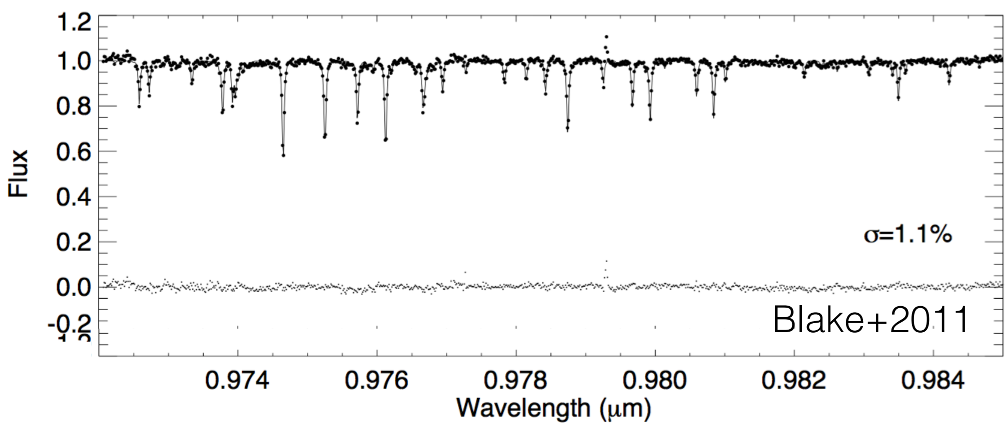


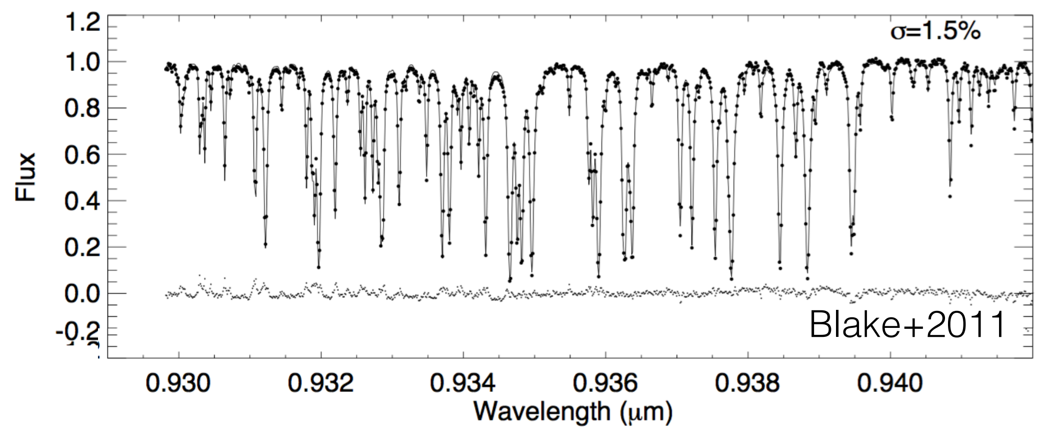
<u>Agreement is quite good for moderate line depths</u>

For example, see Ulmer-Moll+ 2019

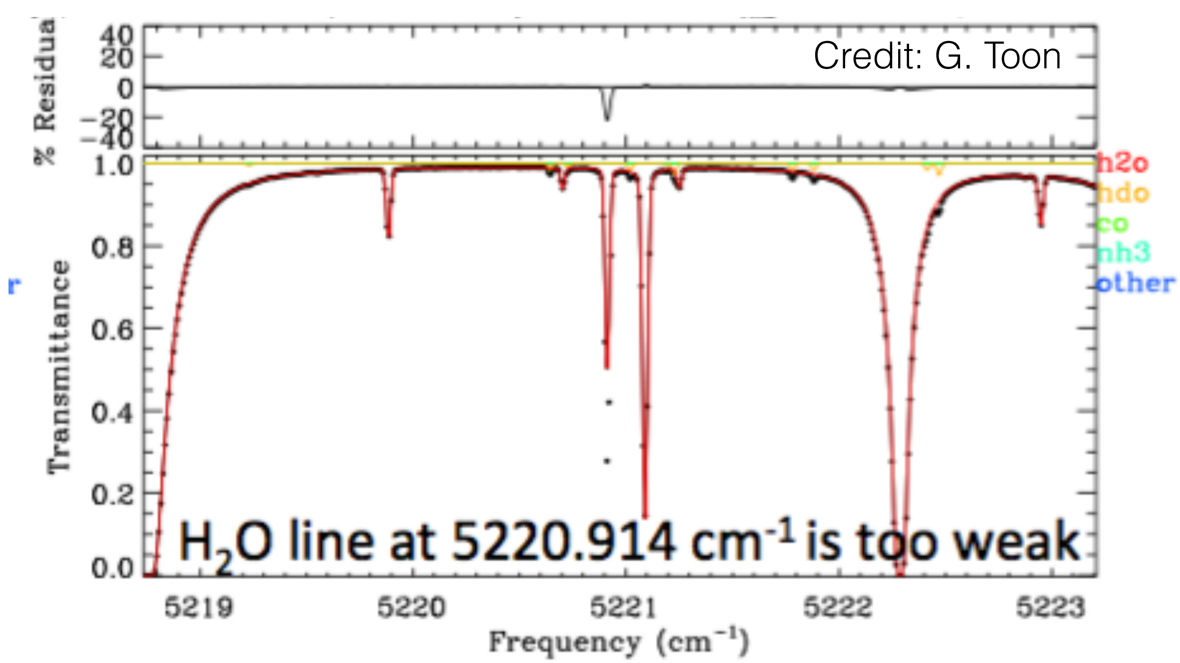
Bean+ 2010 - example of tweaks to HITRAN (older line list)

Theoretical Templates vs. Spectra of Hot Stars





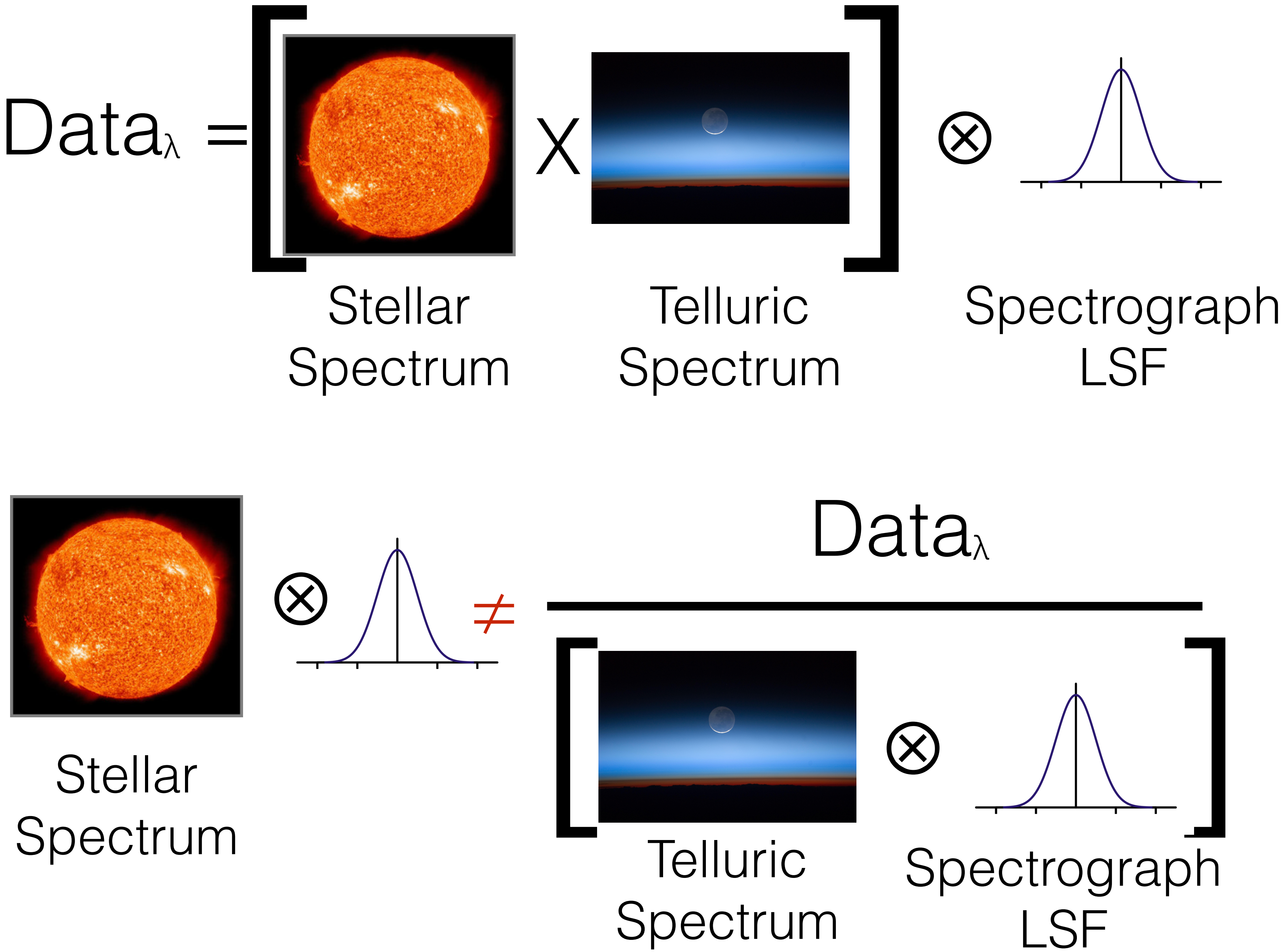
Agreement is worse for stronger lines…



FTS Spectrum of Sun - TCONS Project

HITRAN line values are VERY GOOD and VERY CLOSE TO COMPLETE for the line strengths we care about

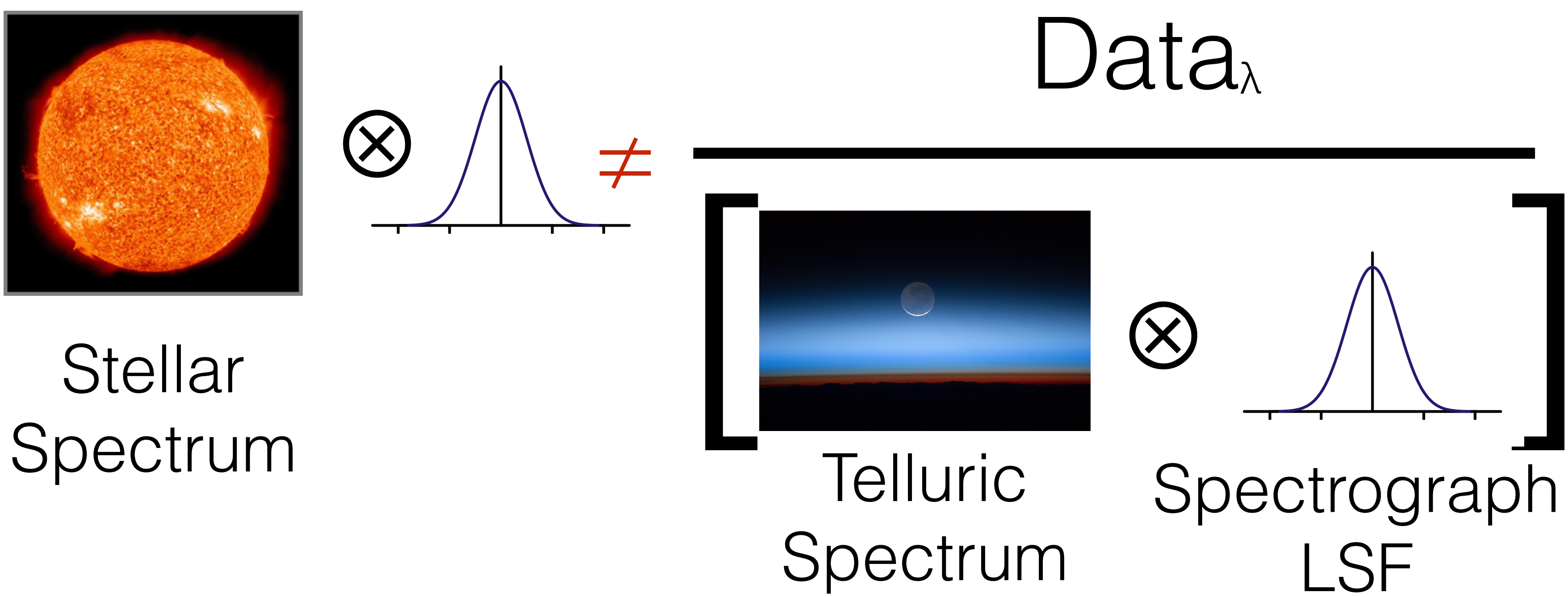
Correcting Telluric Absorption



Correcting Telluric Absorption

This approximation is "less bad" at higher spectral resolution

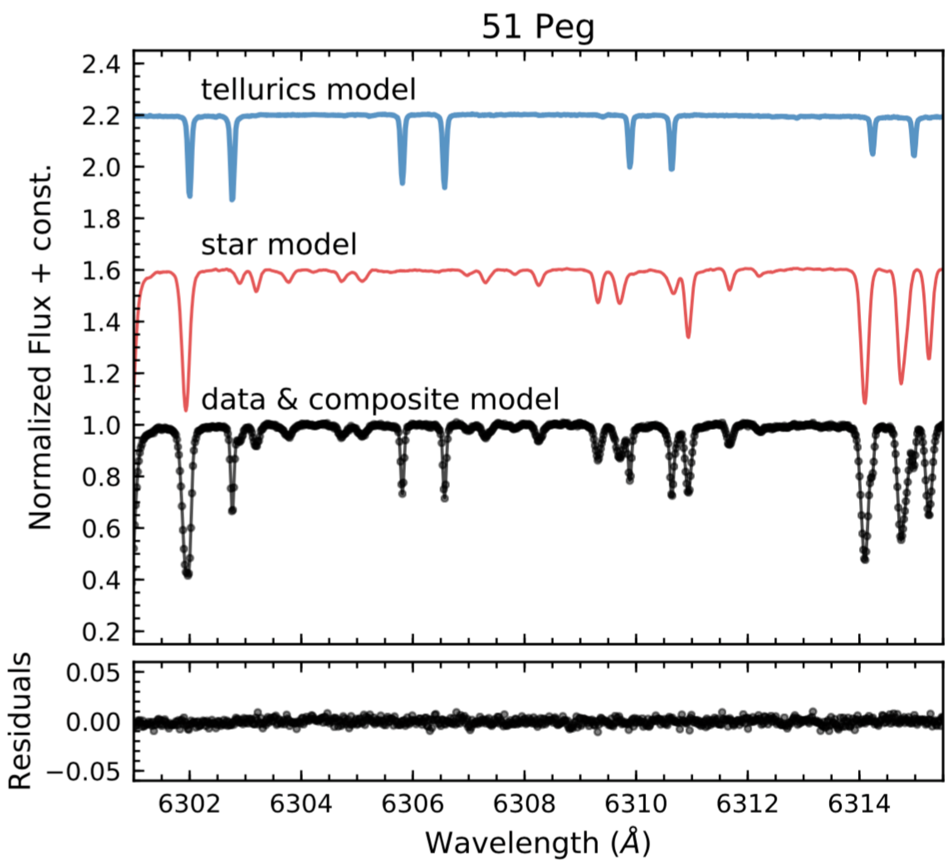
This approximation is worse when telluric line density is higher (many lines per nm in NIR)



So, What Are We Going to do About It?

Option 4: Modeling

- It should be possible to simultaneously model stellar spectrum, telluric spectrum, while *inferring* RV



wobble
(pronounced like Michael Bublé)
Empirical
Bedell+ 2019

Semi-empirical
Full forward model
Baker+ 2019

Probably requires wide coverage in barycentric velocity

Three Questions

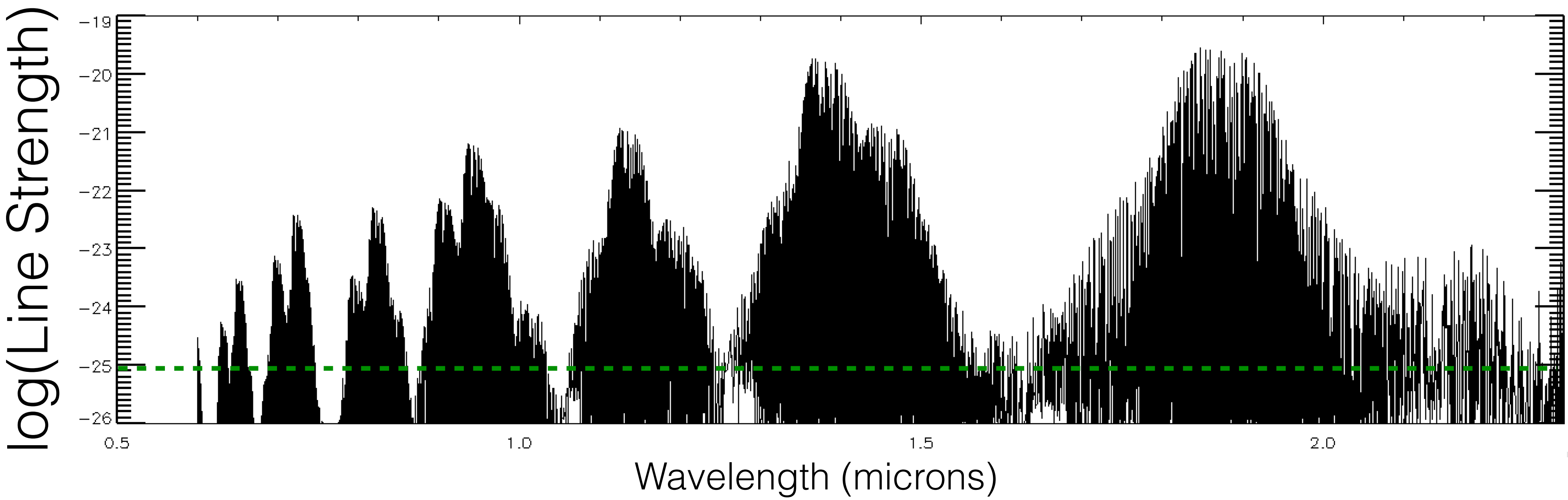
1) How to determine the spectrum of telluric water absorption in ground-based stellar spectra?
   Theoretical models, machine learning approaches, on-sky calibration data…

2) What are we going to do with that information to improve RV precision?
   "Correct" the stellar spectra, mask telluric lines, just work in very clean atmospheric windows…

3) Should we be forward modeling all of our spectra?
   Is this computationally tractable? What simplifications can we make to the model while still getting good RV precision?

Some Takeaways

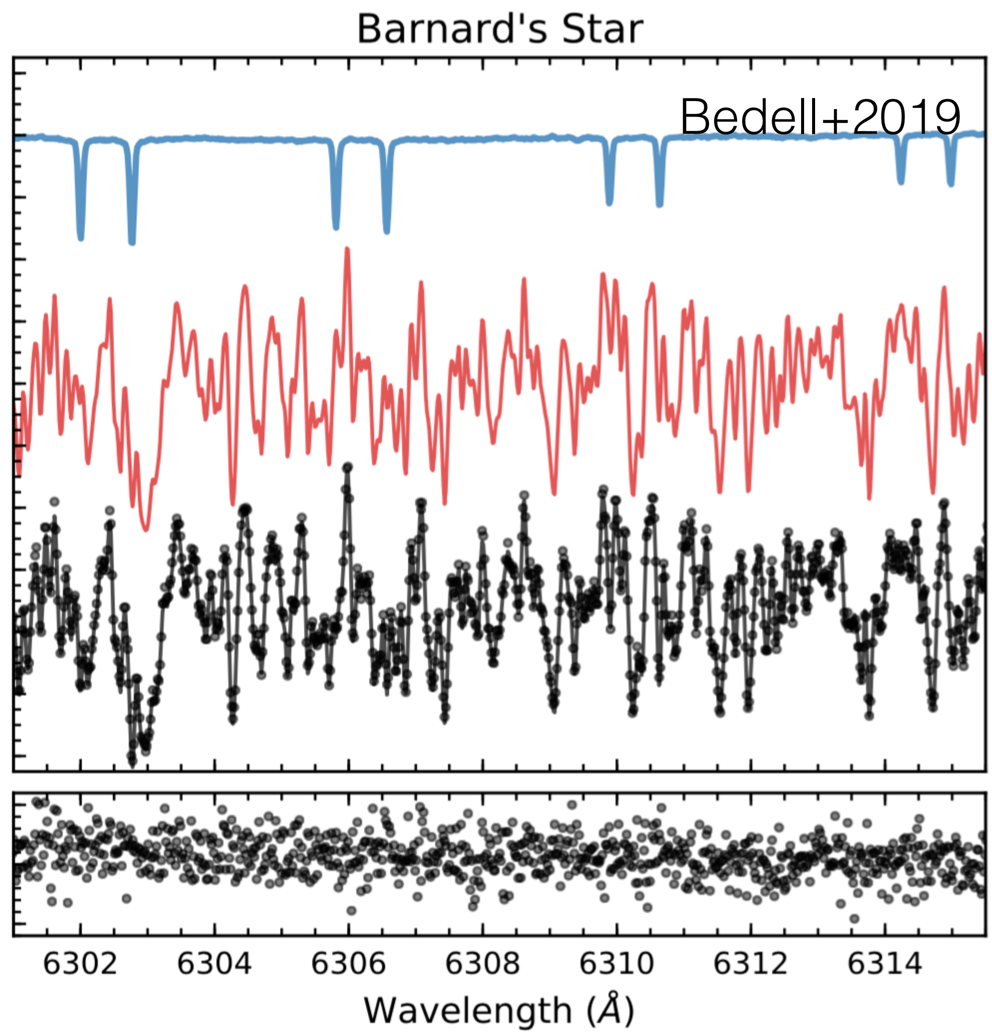
<u>A lot</u> of knowledge/data that we can use related to molecular transitions and Earth's atmosphere



•HITRAN database is expected to essentially be complete and accurate for water at the intensities we care about [1%~10^{-25} $cm^{-1}/(mol. \times cm^{-2})$]

<u>Use the most recent version of HITRAN (constantly updated)</u>

Some Takeaways

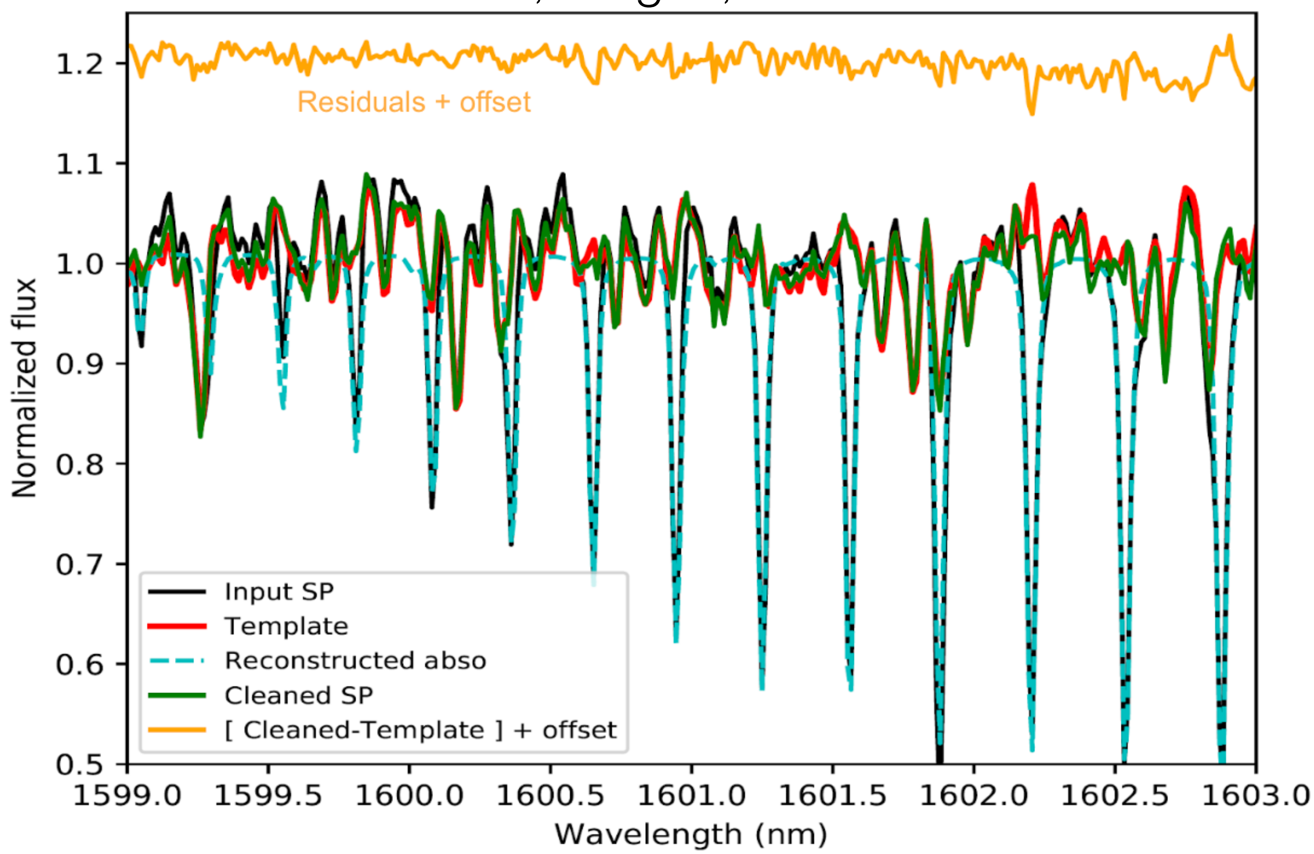


- Lots of enthusiasm for "full up" modeling (like *wobble*)
- Are hybrid approaches involving empirical and physics-based model components the way forward?
- How well do these techniques extend to the NIR?

Some Takeaways

- Completely empirical approaches to determining telluric absorption spectrum are powerful
- Are *linear* (in optical depth?) models sufficient?

Credit: Cook, Artigau, and SPiRou team

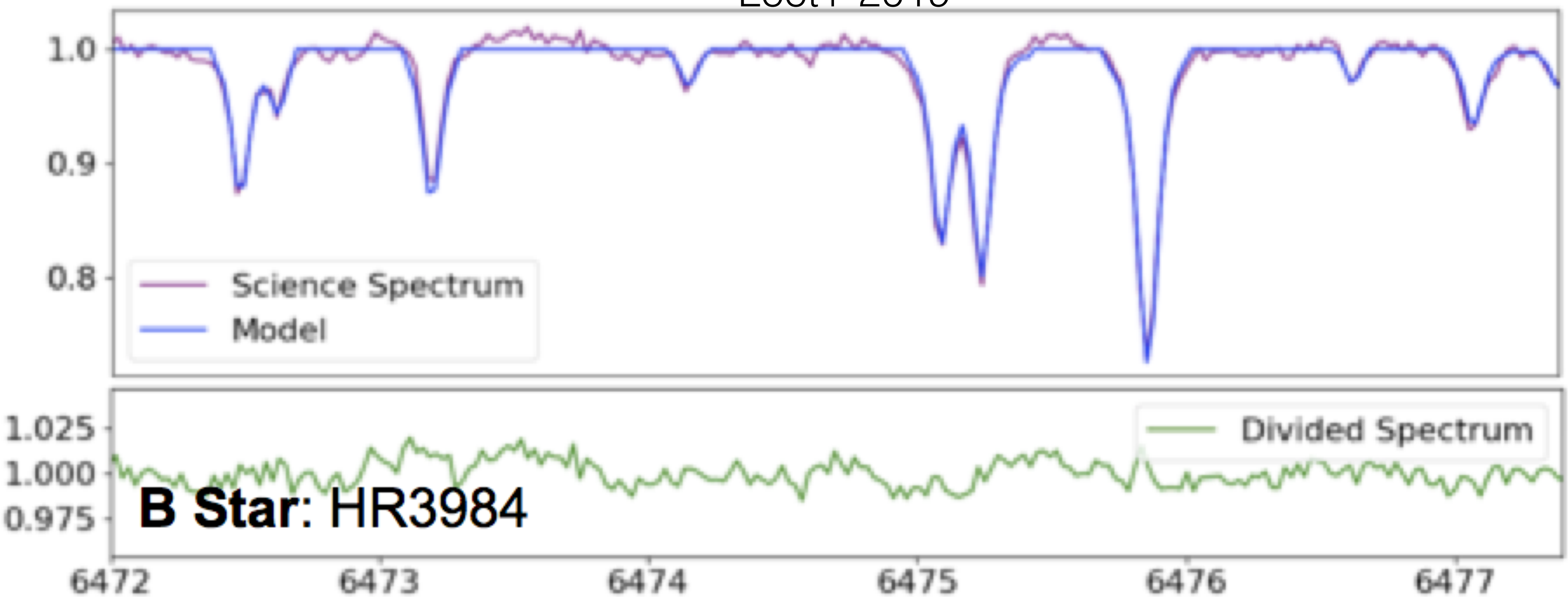


Principle Component Analysis (PCA) - SPiRou Pipeline

See also Artigau+2014

Some Takeaways

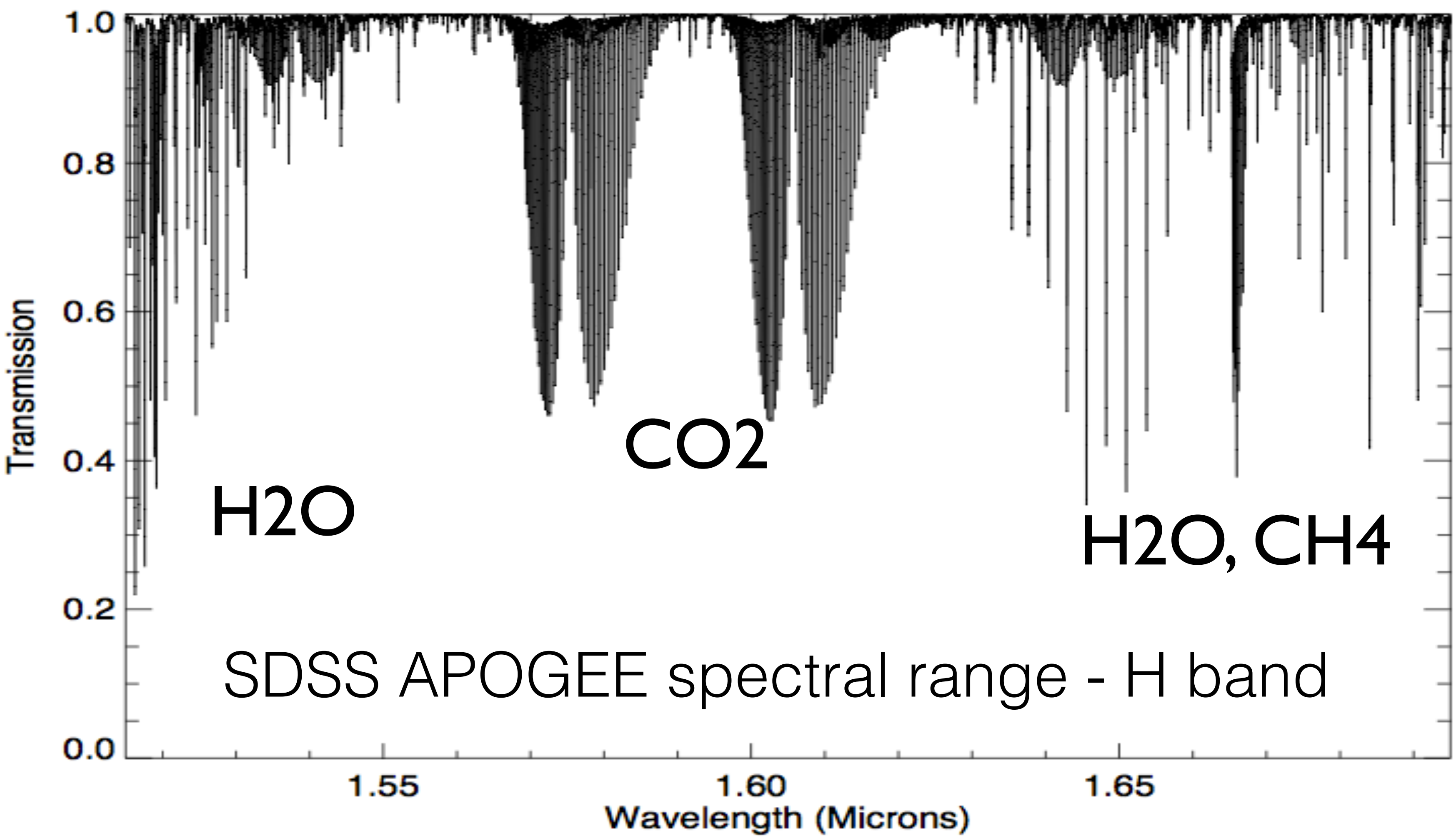
Leet+ 2019



- SELENITE: A linear approach to deriving telluric templates from sets of stellar observations
- Fast and totally empirical, naturally handles different absorbing species

Some Takeaways

- Problem is *much* harder in NIR
- Multiple species, high line density, line mixing, CH_4 line parameters not as good as those for CO_2 and H_2O
- Strong sky *emission*



Some Takeaways

- *Optimism* - people feel like tellurics *should* be a solvable problem for EPRVs

- Lots of well understood physics related to Earth's atmosphere and molecular transitions

- Array of sophisticated analysis techniques that we are *just* starting to explore

ON THE POSSIBILITY OF DETERMINING STELLAR RADIAL VELOCITIES TO 0·01 KM S^{-1}

R. and R. Griffin

MNRAS, 1973, 162, 243

SUMMARY

Dissimilarities in the illumination of spectrographs by star light and by comparison sources, respectively, normally prevent the realization of radial-velocity accuracies anywhere near those which high-resolution spectrographs ought to provide. These difficulties can be entirely circumvented by the use of telluric absorption lines as the stationary comparison source. There seems to be no reason, if the appropriate and possible precautions enumerated in this paper are taken, why radial velocities accurate to 10 m s^{-1} should not be achieved for a restricted selection of stars. Existing spectrograms, taken for other purposes and without the benefit of any special precautions, already show an accuracy well in advance of normal standards.

Today we are aiming for 100x better!

Conclusions

- Telluric lines may be a leading source of systematic RV error in the optical below 50 cm/s (and maybe even a few m/s in NIR)
- We have tools at our disposal to deal with this problem
- Given all the talented students+postdocs working on this topic, fully expect problem to be solved (hopefully before I retire)

Thanks!