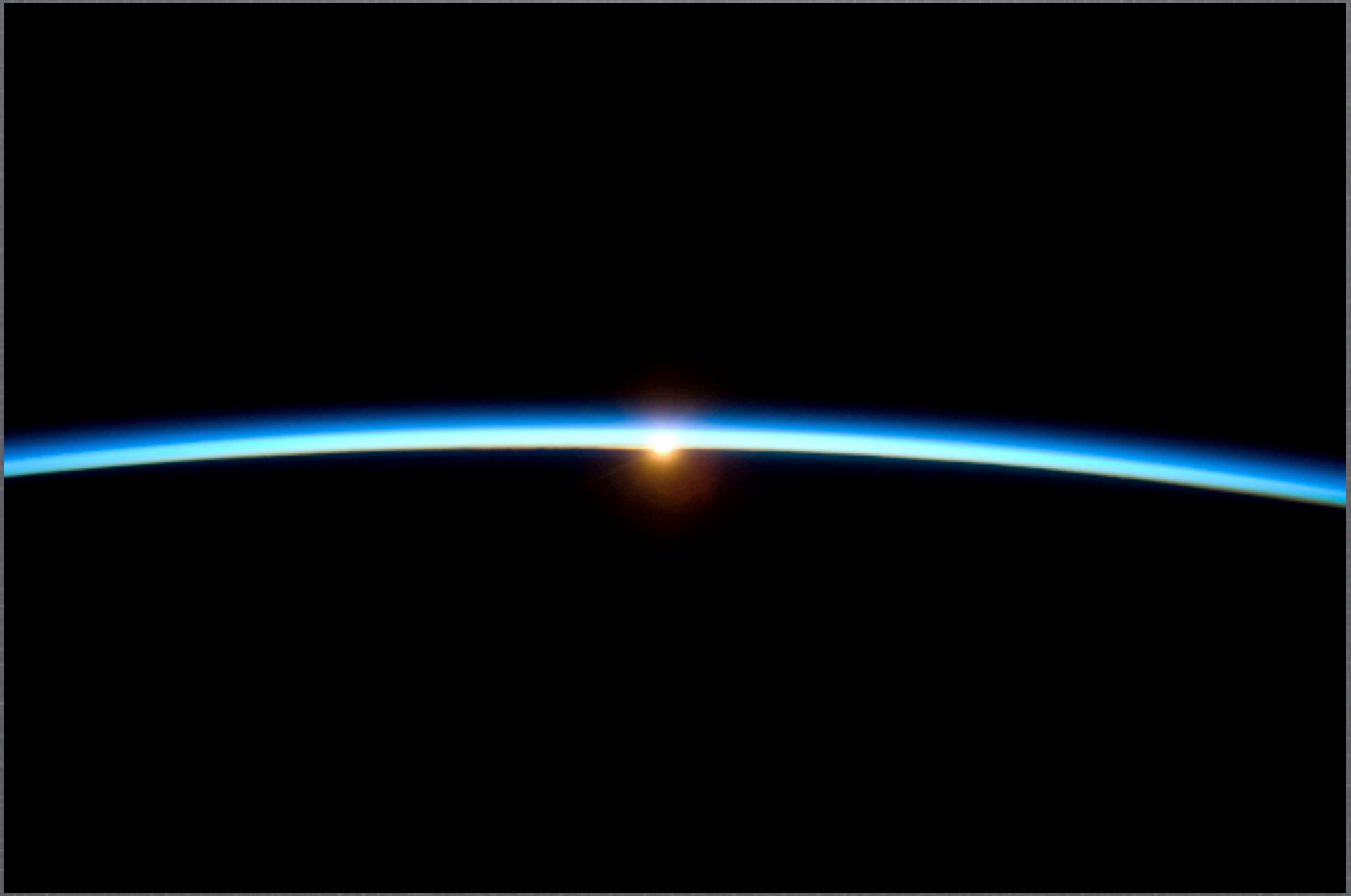
Telluric Lines as a Wavelength Reference at Deep Red and Near Infrared Wavelengths



Credit: NASA

Cullen Blake - Princeton University

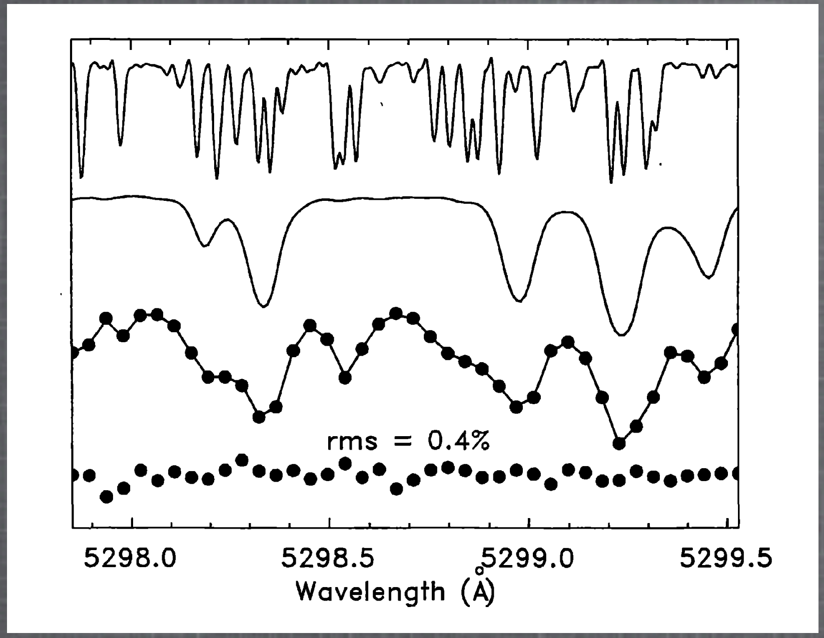
August 18, 2010

Absorption Cells:
A Superimposed Wavelength Reference

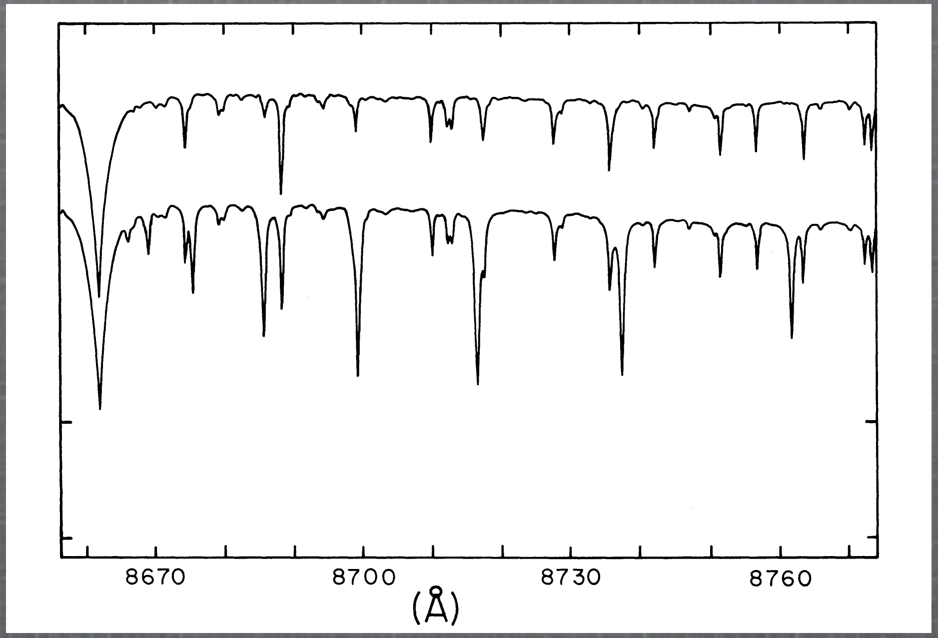
Ammonia

Iodine

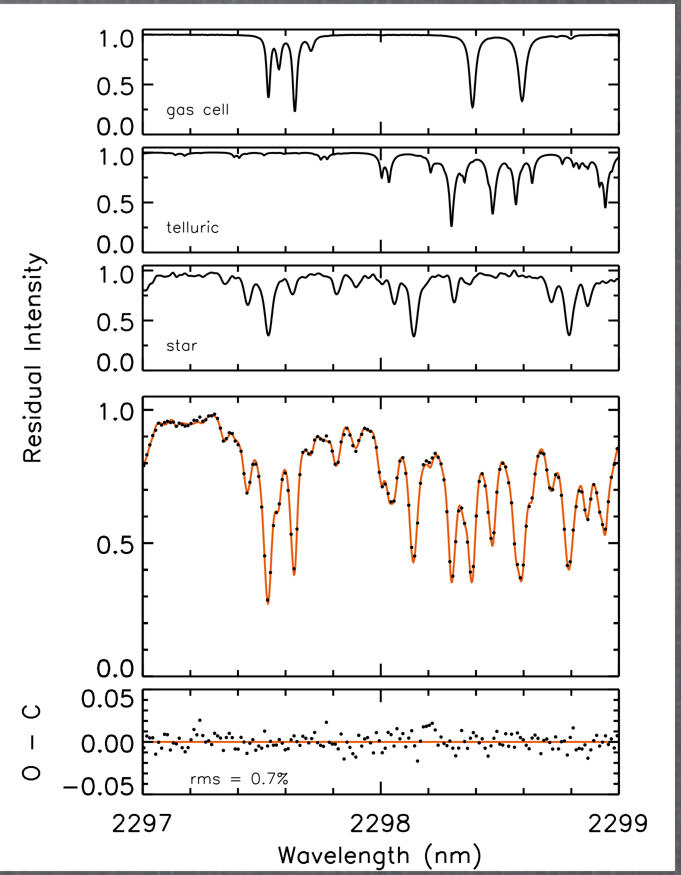
Hydrogen Fluoride



Marcy & Butler 1992
Butler et al. 1996



Campbell & Walker 1979



Bean et al. 2010

Advantages of "Deconvolution" Technique:

- Same light path for star and wavelength reference
- Very stable wavelength reference

Our Atmosphere: A Big Absorption Cell

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

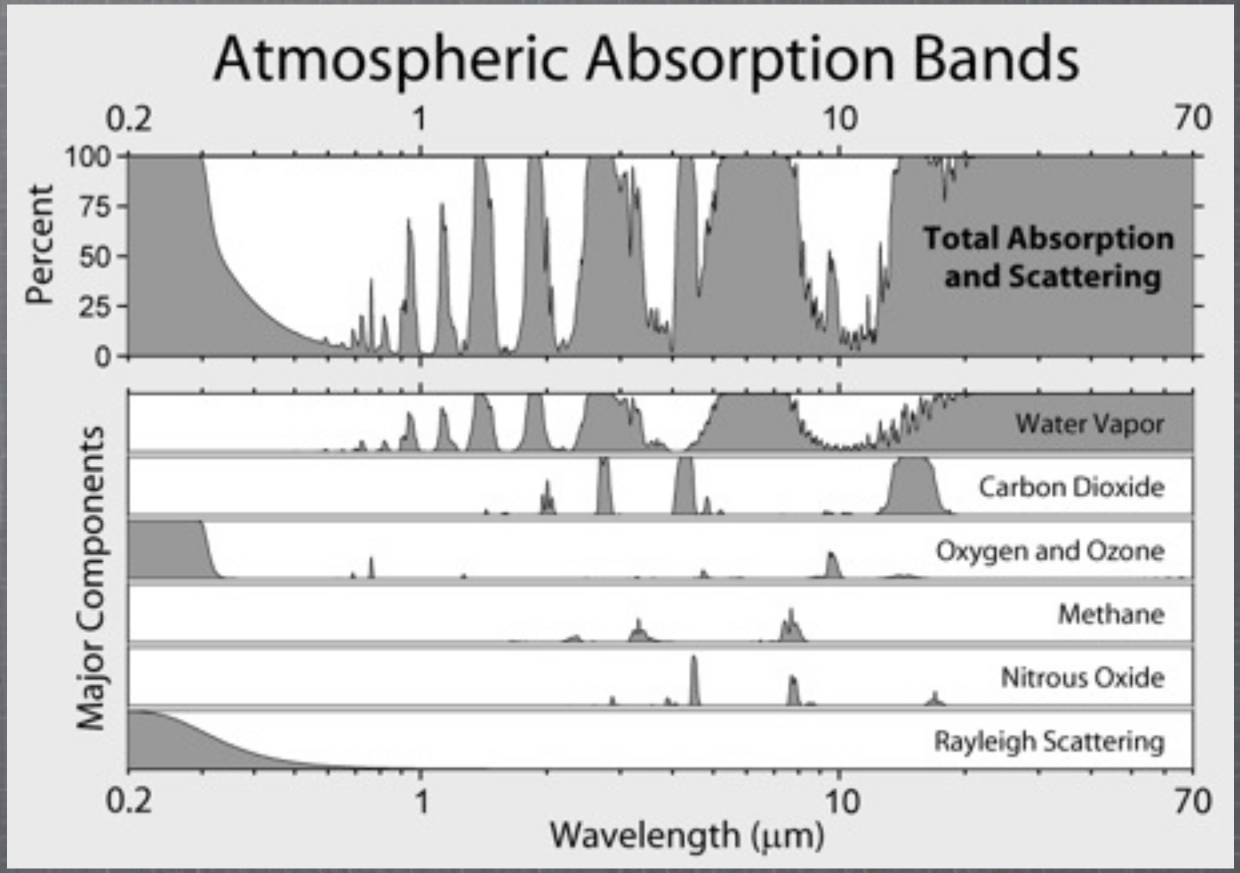
R. and R. Griffin

(Received 1972 December 20)

SUMMARY

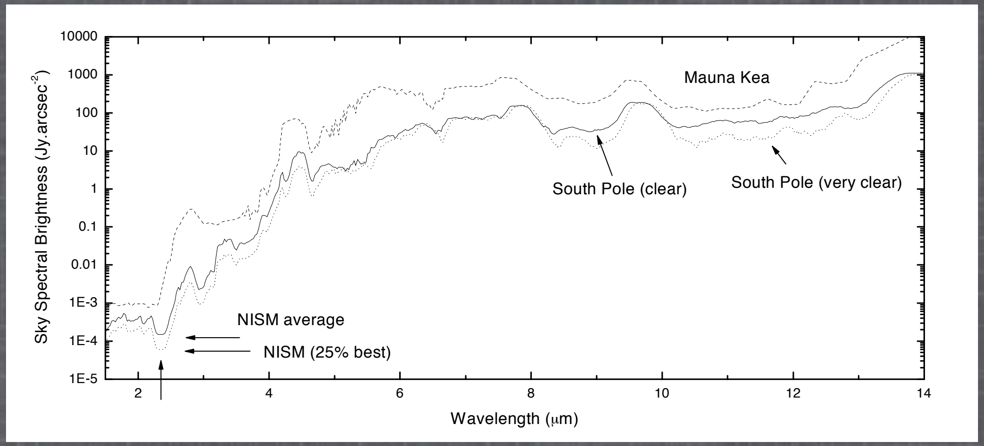
Dissimilarities in the illumination of spectrographs by star light and by comparison sources, respectively, normally prevent the realization of radial-velocity accuracies anywhere near those which high-resolution spectrographs ought to provide. These difficulties can be entirely circumvented by the use 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.

Griffin & Griffin, 1973, MNRAS,162, 243



Atmosphere Usually Considered A Major Obstacle!

Beales

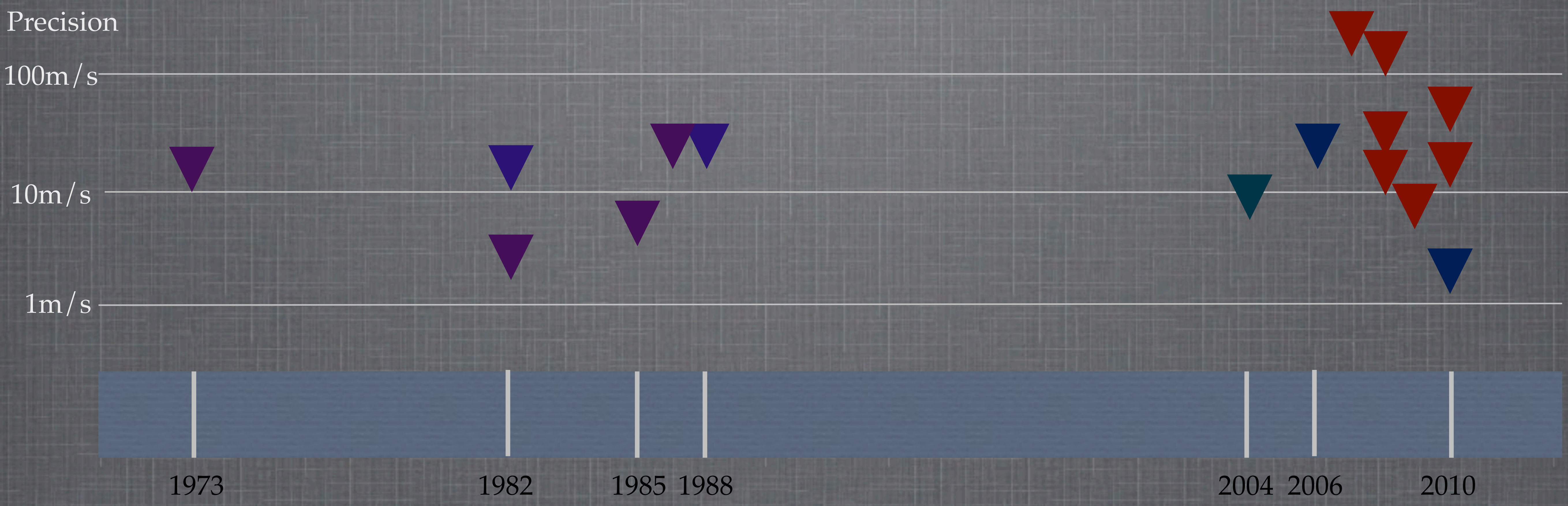


Telluric Lines: Friend or Foe?

	Absorption Cell*	Telluric Lines
Stable in Pressure, Temperature, Velocity	✔	✖
Laboratory Line Measurements	✔	✖
Wavelength Coverage	~150 nm	~1500 nm
No Additional Extinction	✖	✔
Number of “Good” Lines	20/nm	4/nm

*Numbers for I_2. Other Examples include: HF, N_2O, NH_3, $^{13}CH_4$

RV Measurements Using Telluric Lines



Theory or Solar Experiment: Griffin & Griffin (1973), Balthasar et al. (1982), Caccin et al. (1982), Demming et al. (1987)

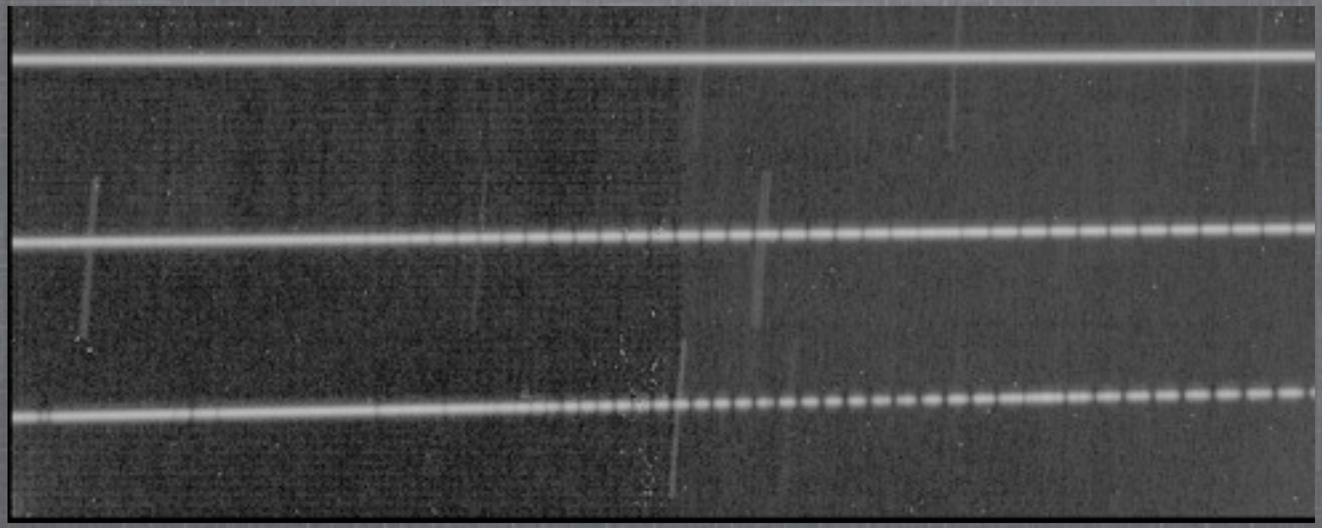
Optical Measurement (O_2): Smith (1982), Cochran(1998), Gray & Brown (2006), Figueira et al. (2010)

Optical Measurement (H_2O): Snellen (2004)

NIR Measurement (CH_4, N_2O, CO_2): Blake et al. (2007), Prato et al. (2008), Huélamo et al. (2008) Seifahrt & Käufl (2008), Figueira et al. (2009), Blake et al. (2010), Bean et al. (2010)

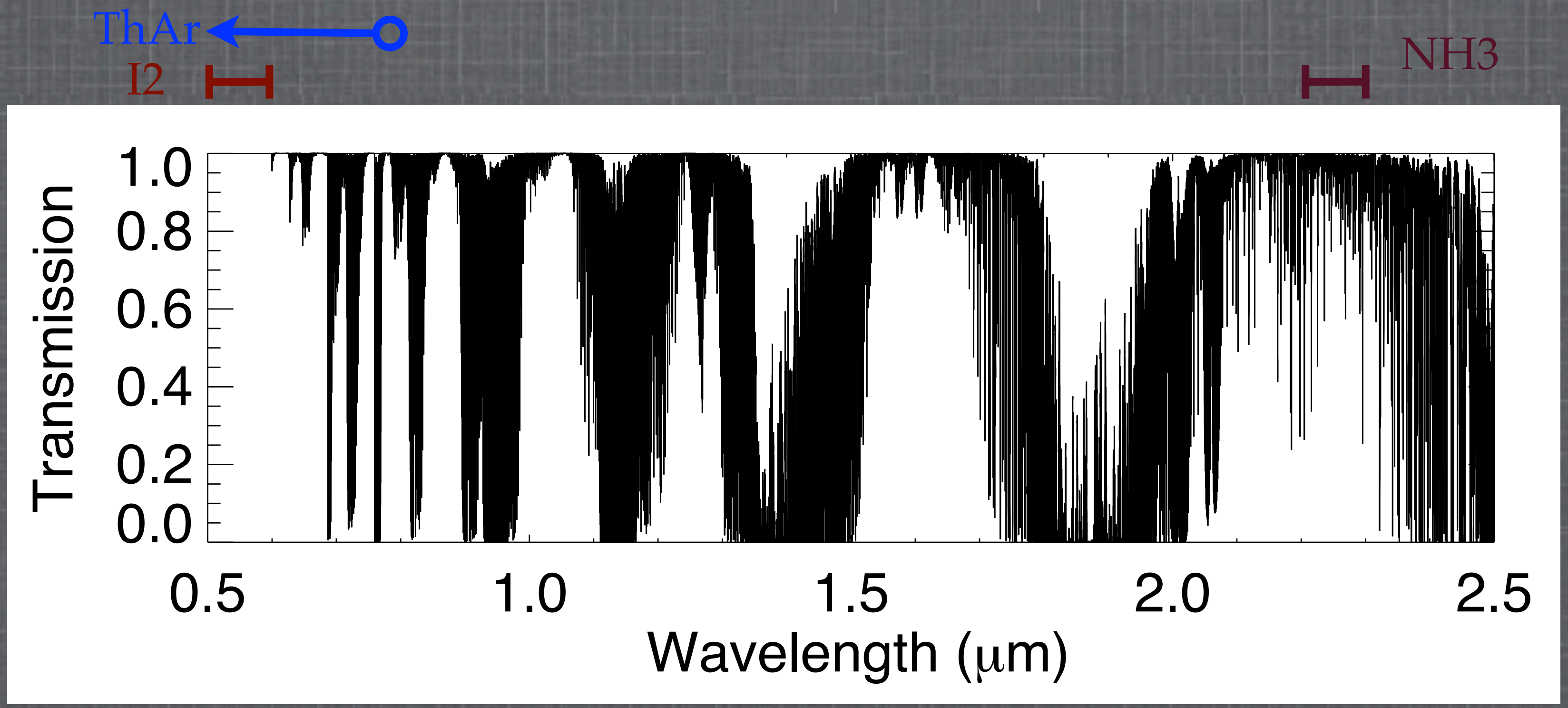
Why Use Telluric Lines Today?

- Require no modification of spectrograph



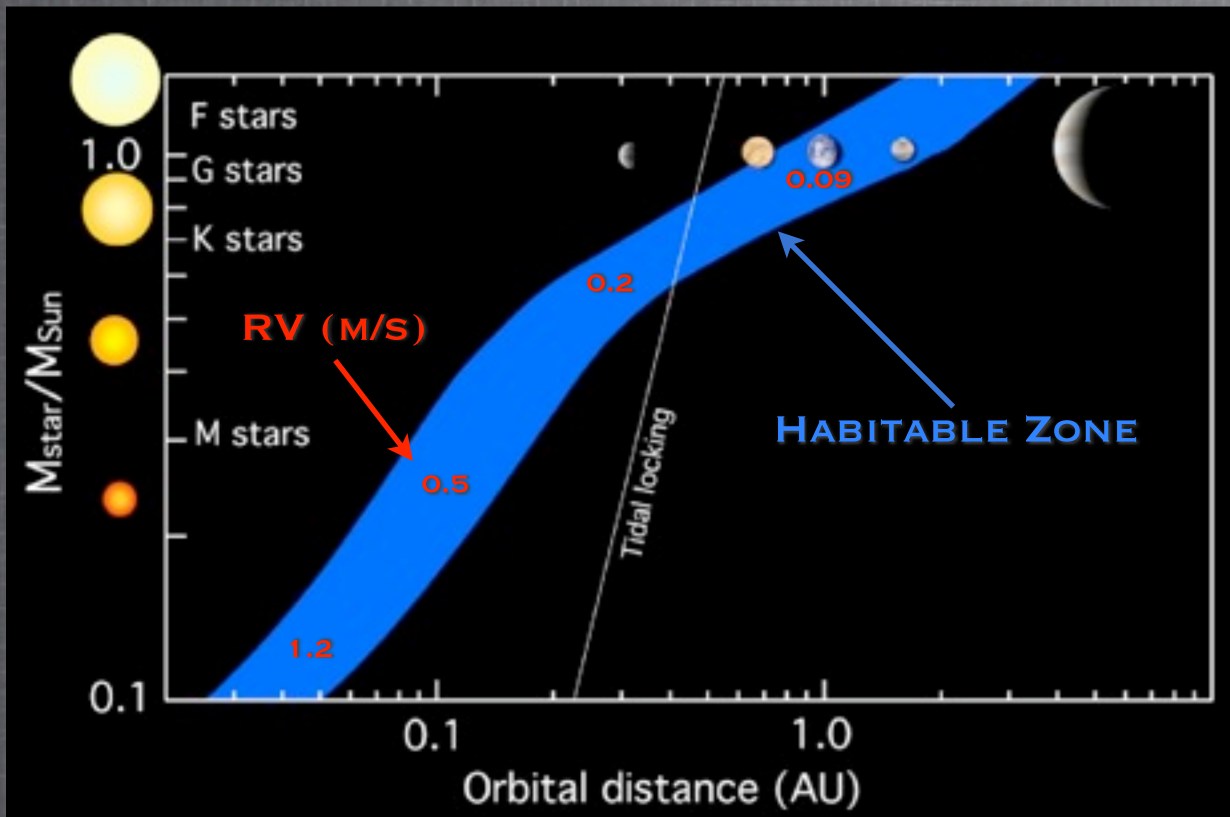
Free Wavelength Reference!

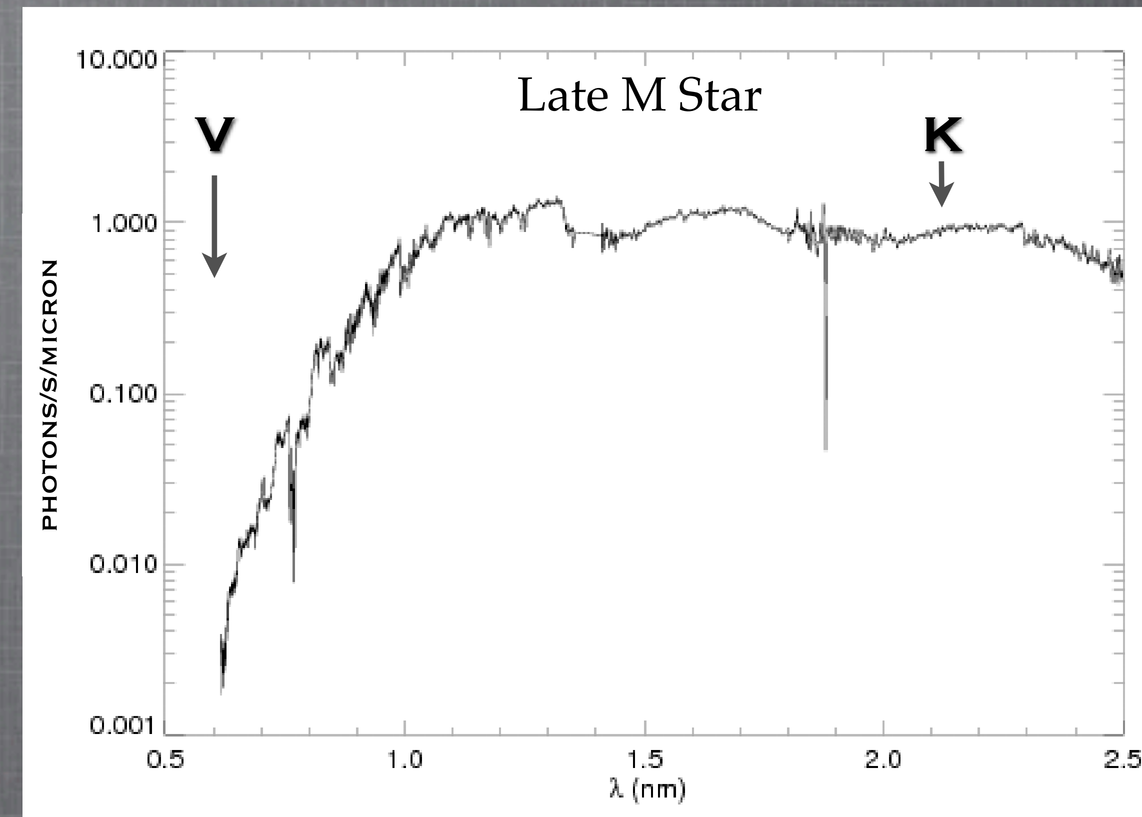
- Measurements in new wavelength regimes:
  - Deep Red and Near Infrared

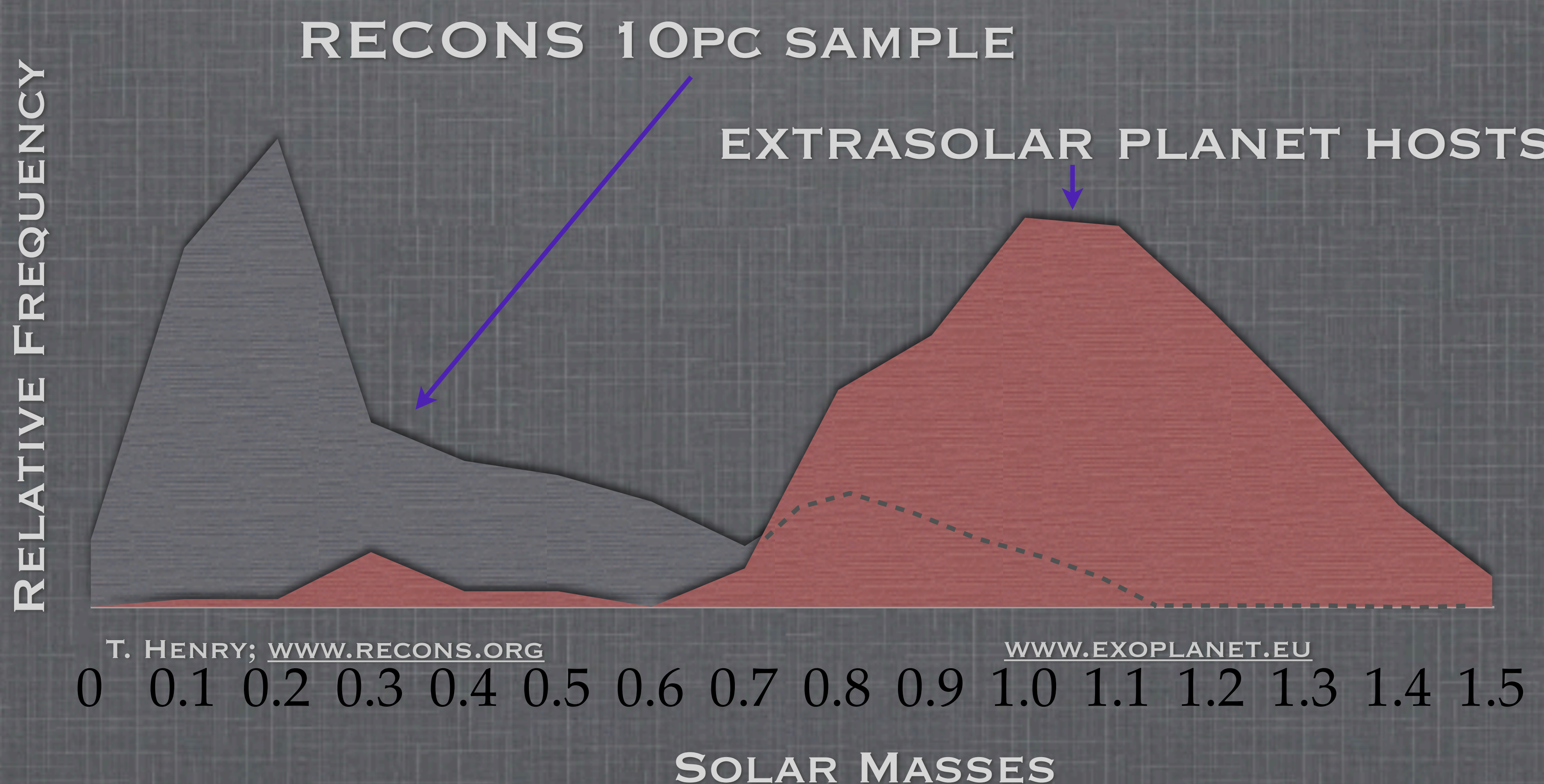


See Poster by Sara Gettel

Planets Orbiting Low-mass Stars





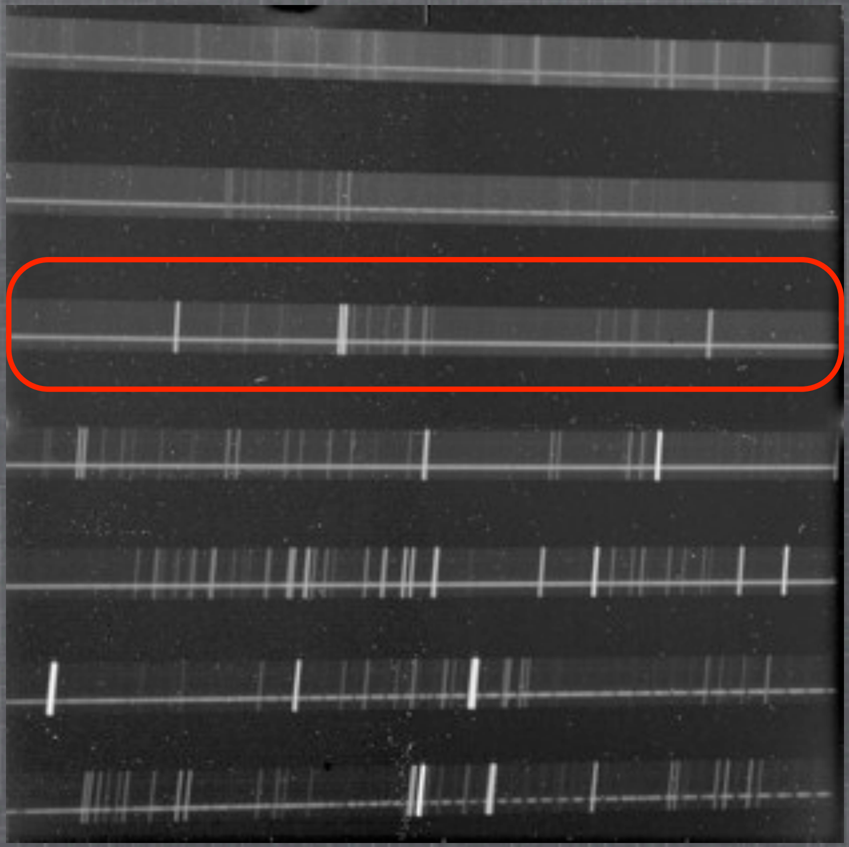


NIRSPEC Ultracool Dwarf RV Survey

Targets:	65 L dwarfs, K<13.0, Dec>-30
	600 individual spectra, S/N~75
	55 objects with 2+ epochs
Time span:	2004-2009
Team:	C. Blake, D. Charbonneau, R. White
	M. Marley, D. Saumon

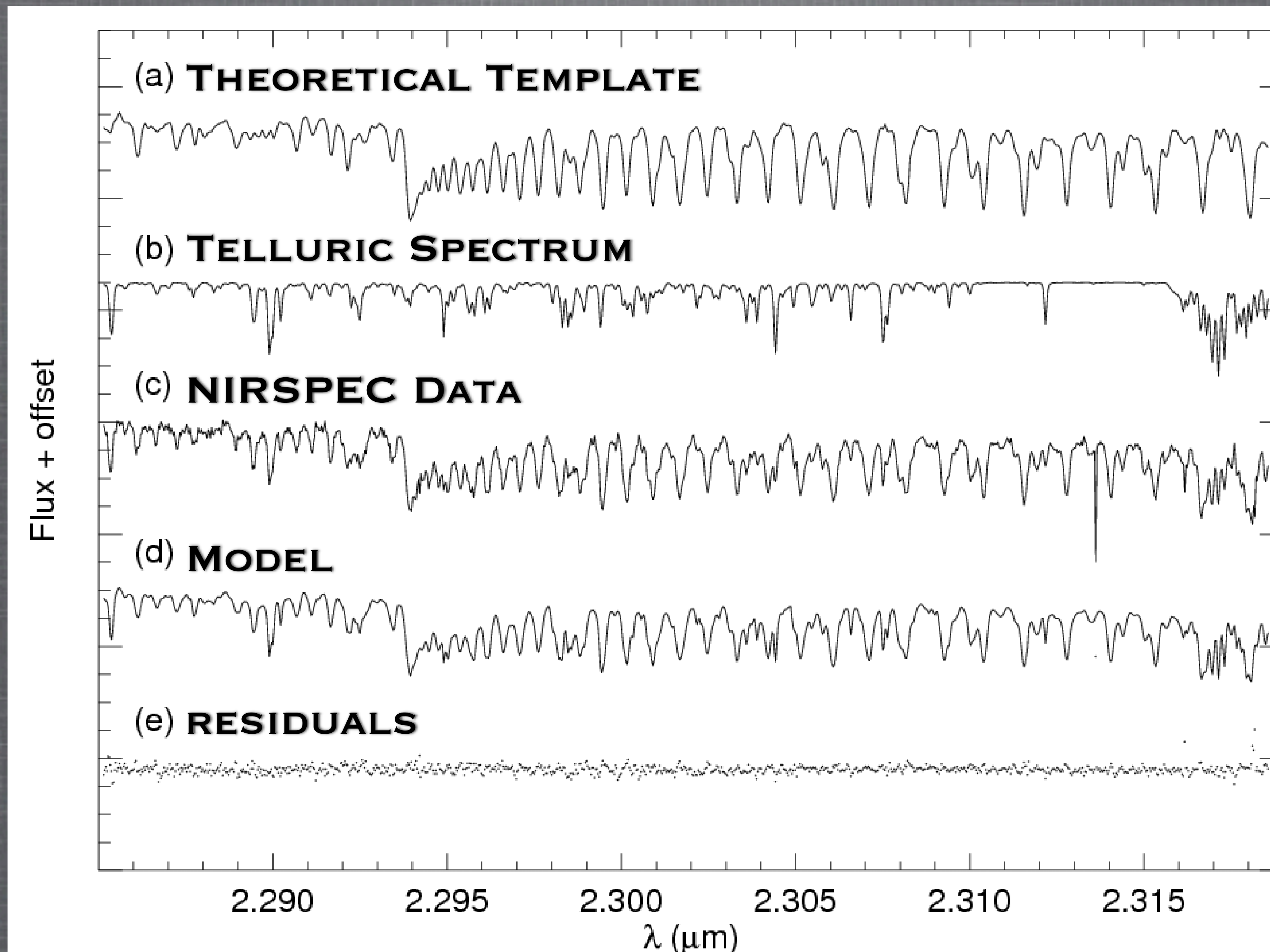
Includes NASA/NExSci Keck Time

NIRSPEC Spectrum, K band, R~25,000



See talk by Tanner and posters by Deshpande and White about NIRSPEC RV work

Radial Velocities with Telluric CH_4



CO

CH_4

[axb]⊗LSF

Modeling Process: Vsin(i) and RV

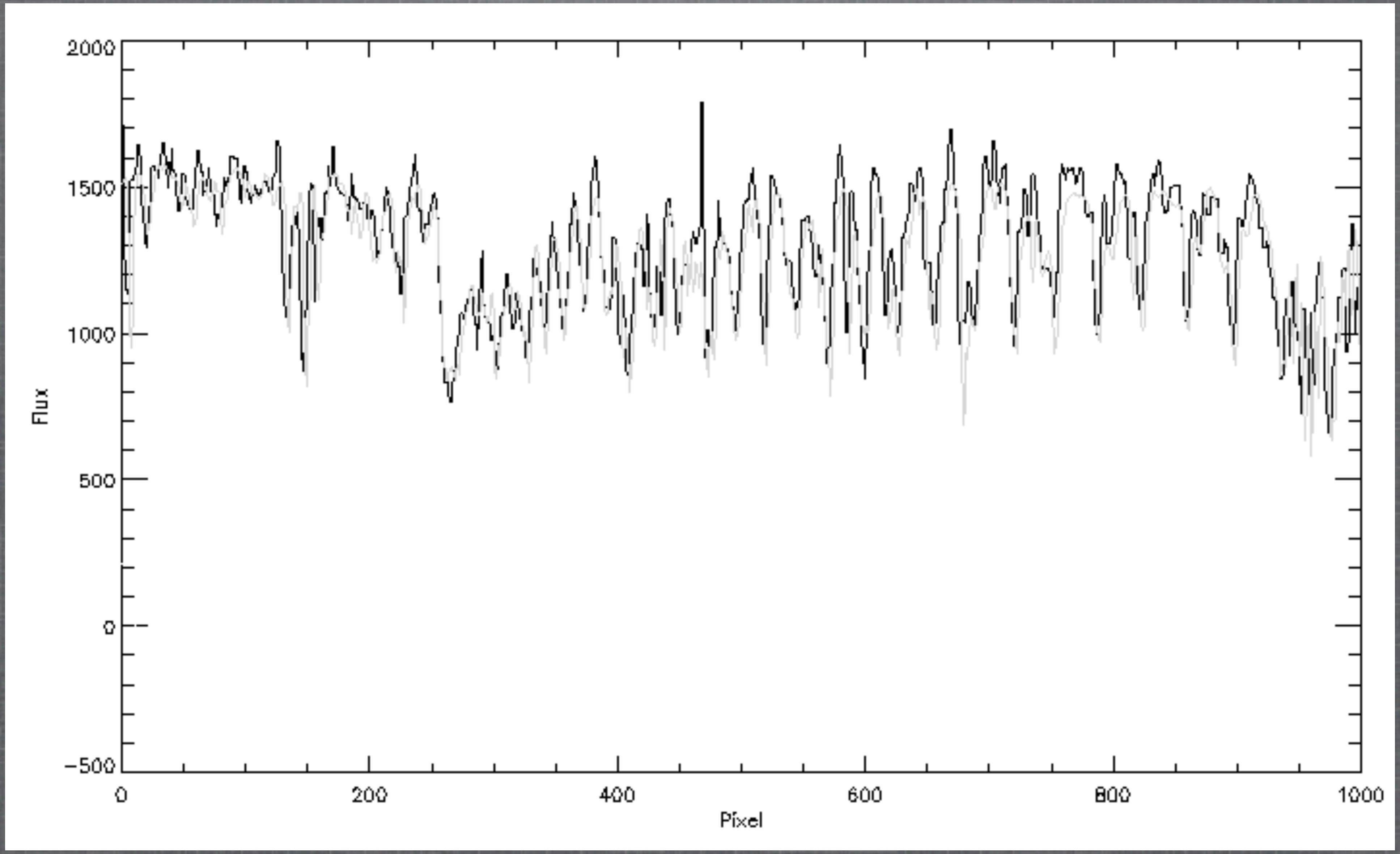
Blake et al. 2007, 2008, 2010

Fitting Process

Data

Model

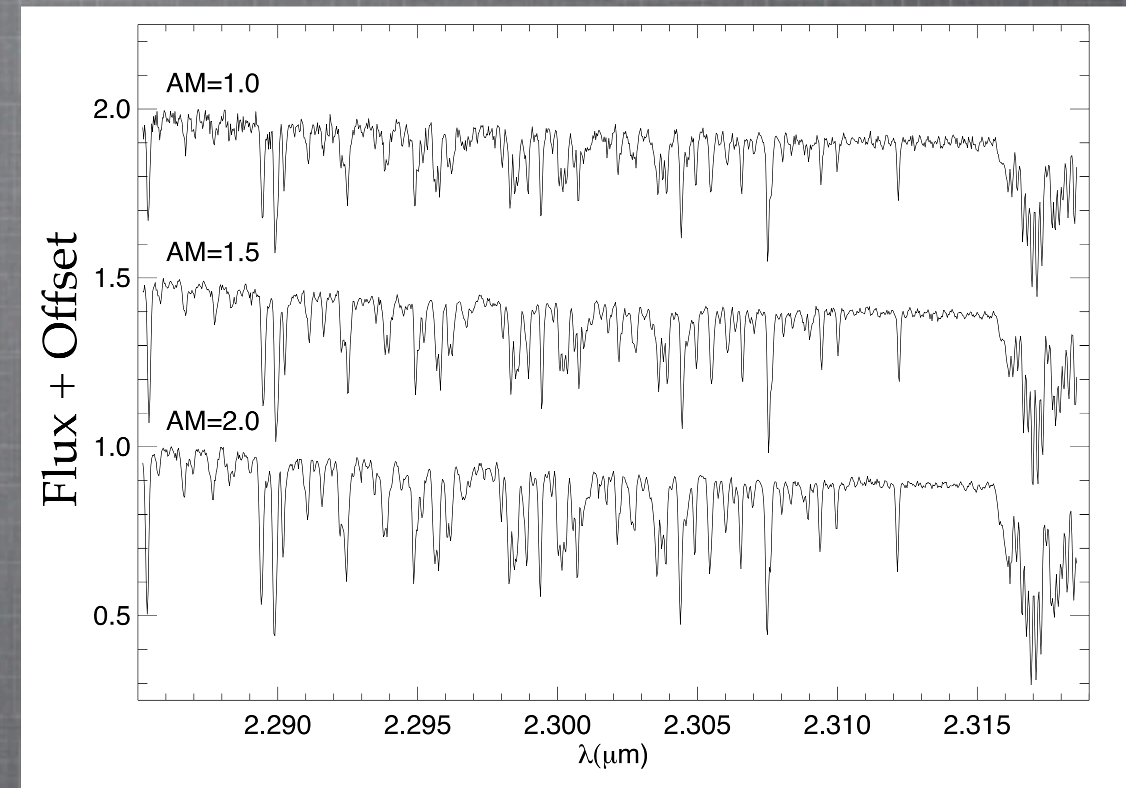
residuals



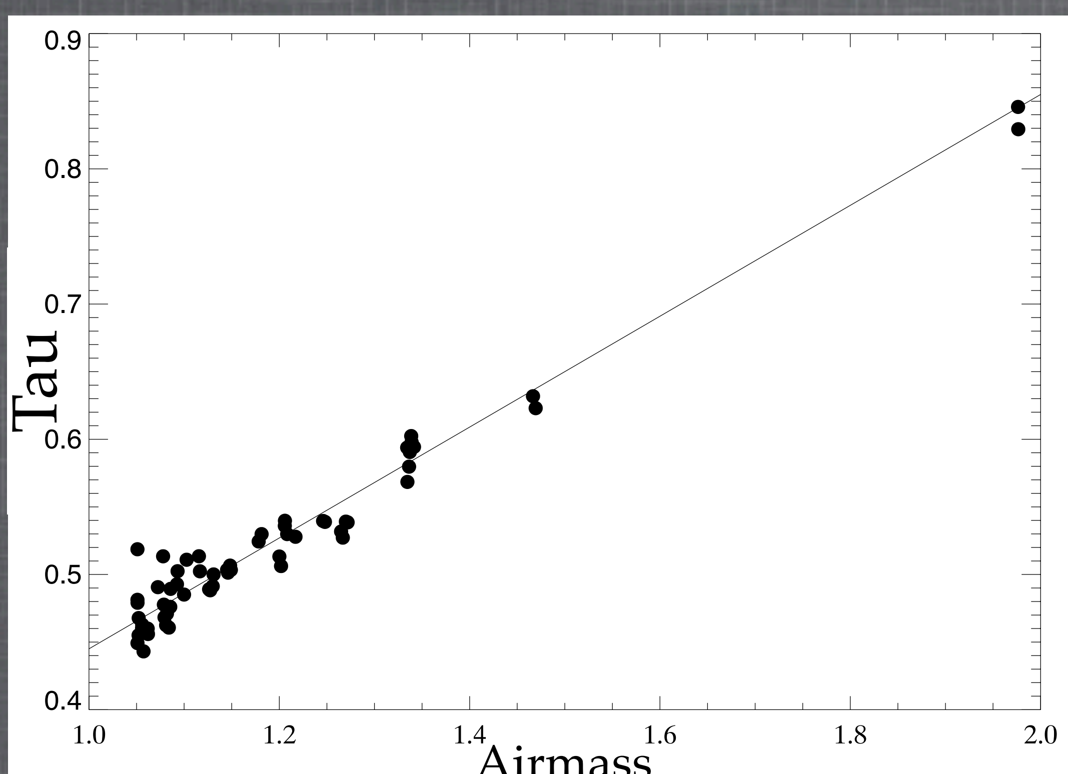
χ^2 minimization using simplex method

Telluric Spectrum Near 2.3 μm

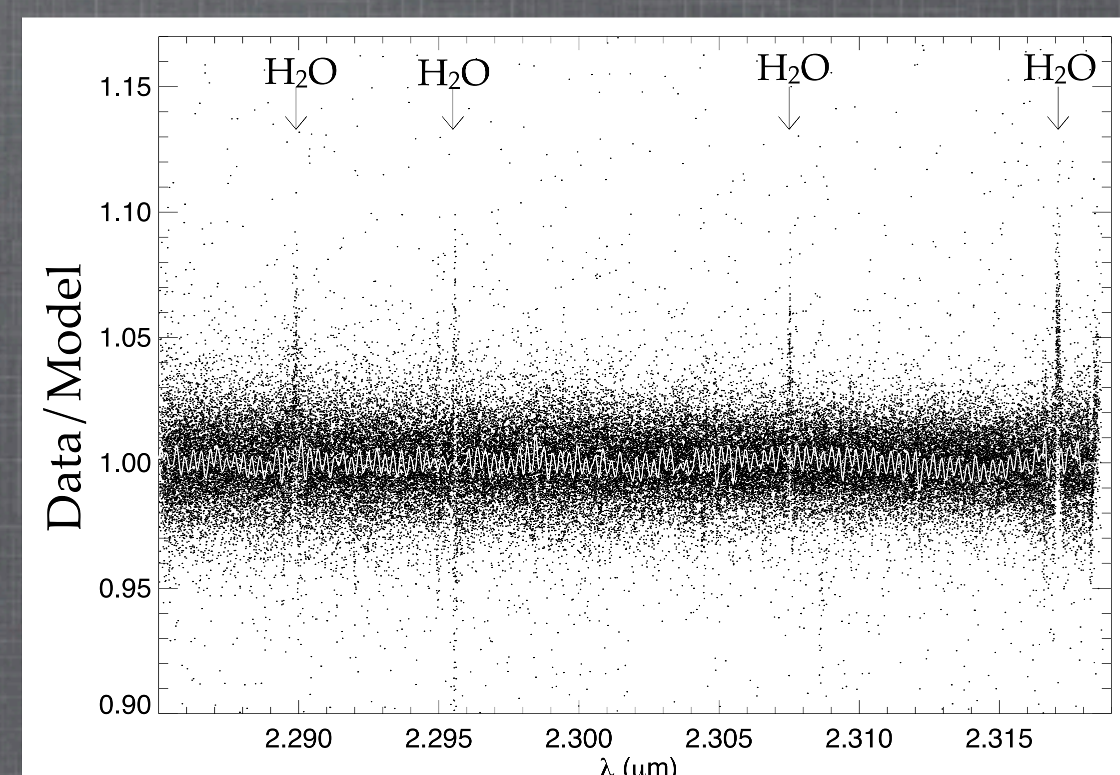
“An atlas of the solar spectrum in the infrared from 1850 to 9000 cm-1 (1.1 to 5.4 μm)”
Livingston & Wallace, R>300,000



Observed Telluric Spectrum

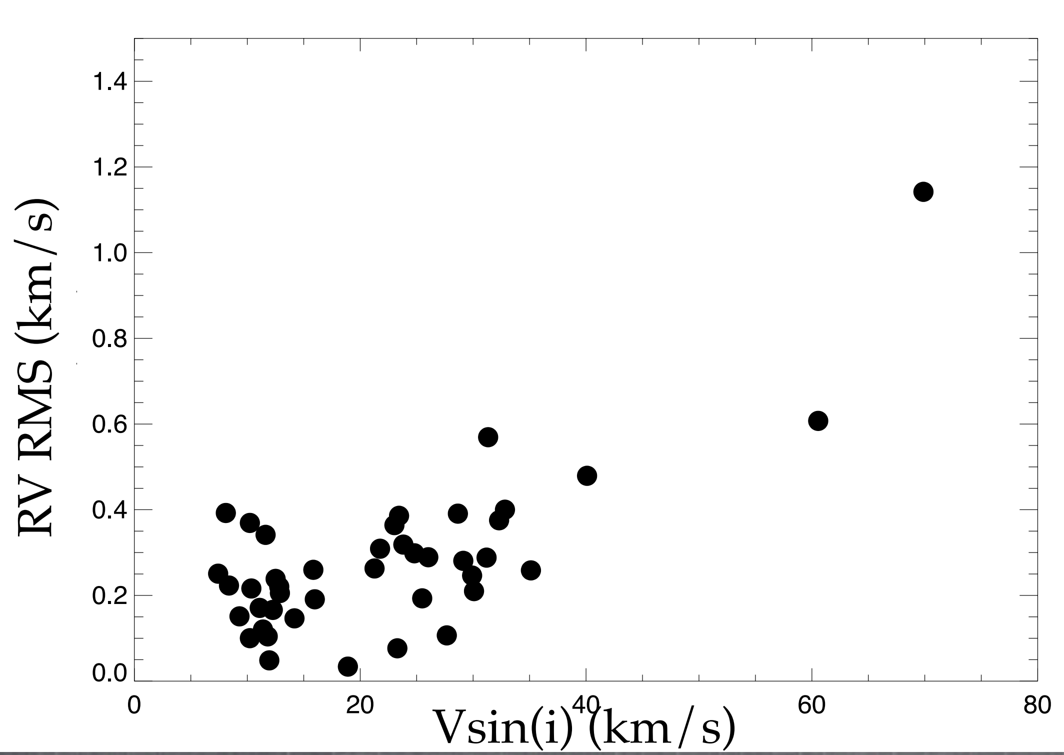


Scale for Airmass: $Model = Model_0^{\tau}$

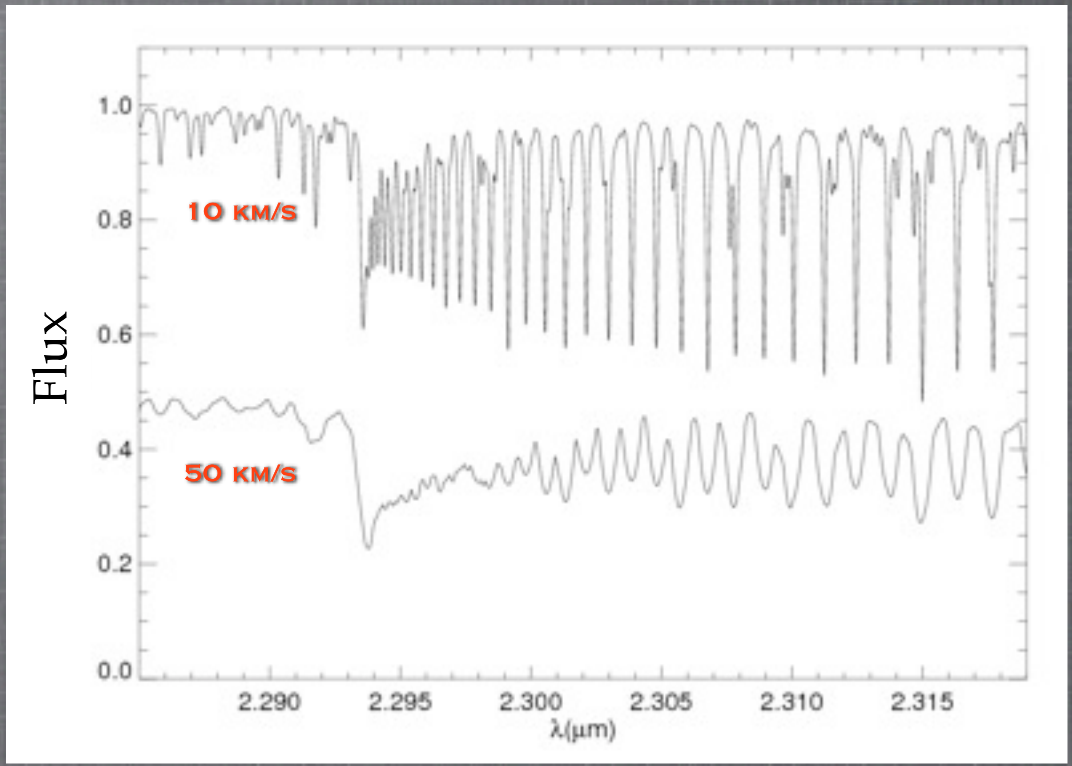


Residuals of 200 A star fits

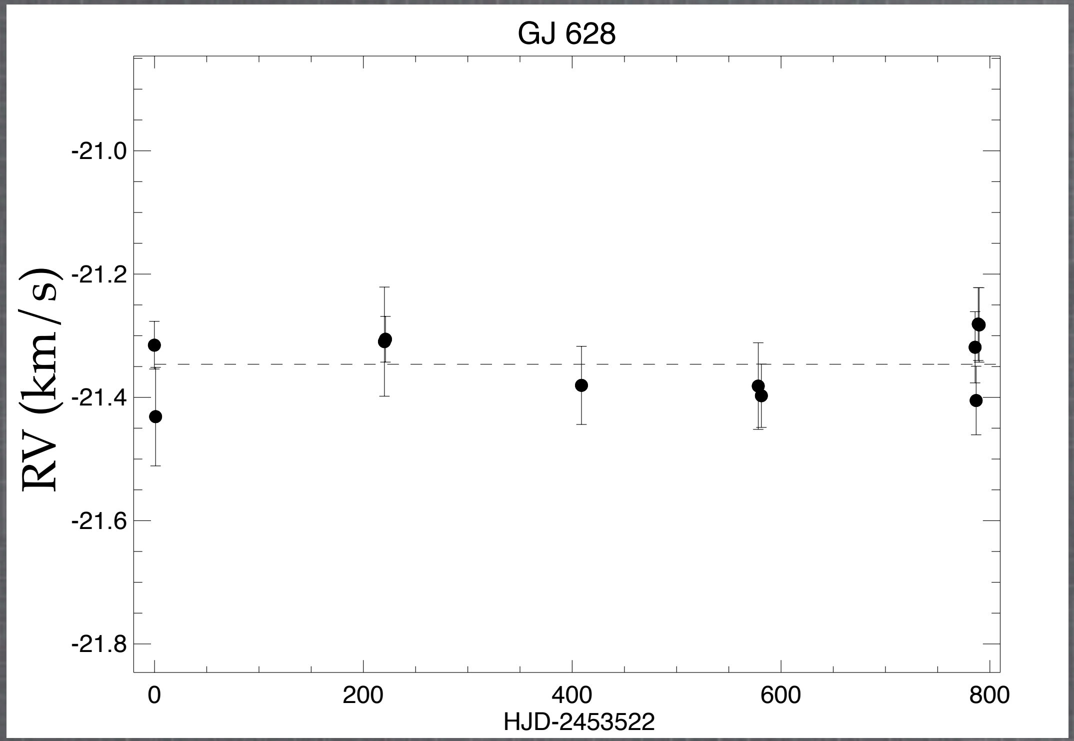
NIRSPEC RV Precision



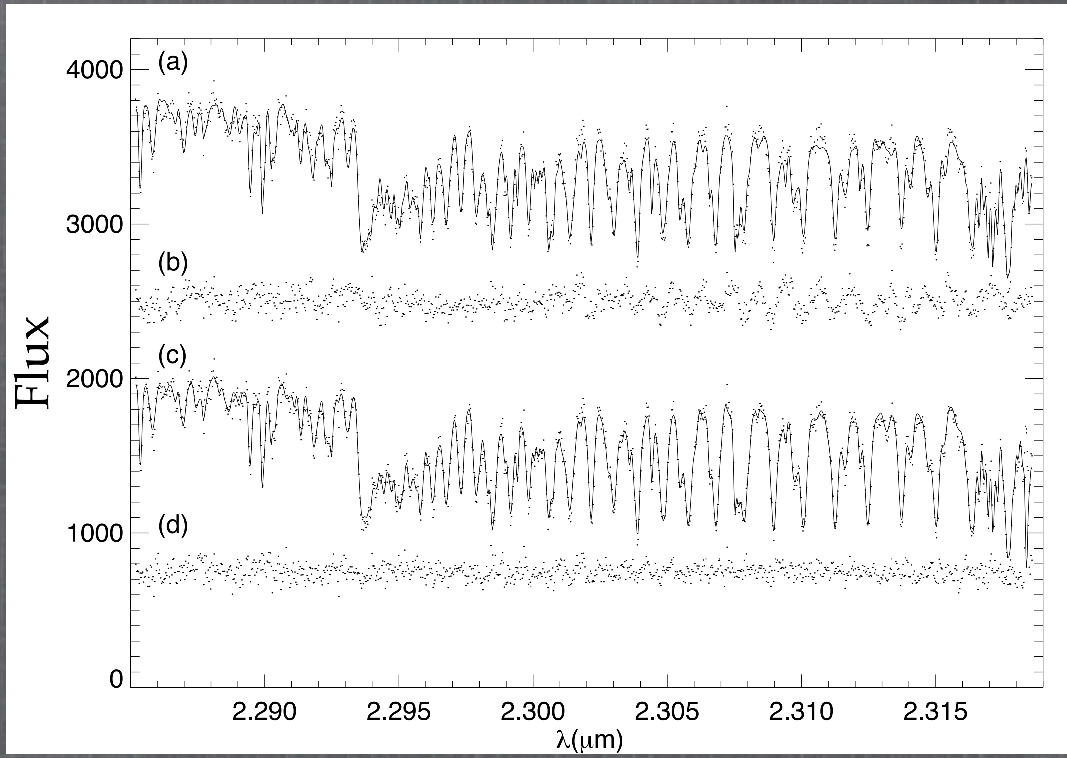
L Dwarfs 100-300 m/s, twice photon limit



Impact of Rapid Rotation

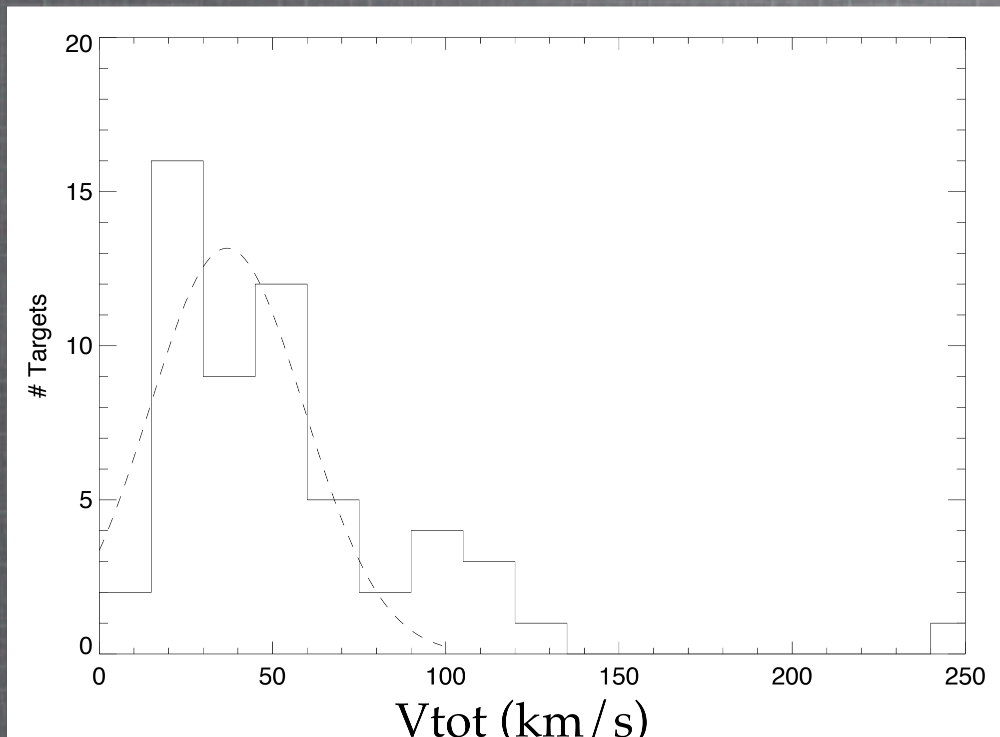


Bright M star 50 m/s, photon limit?

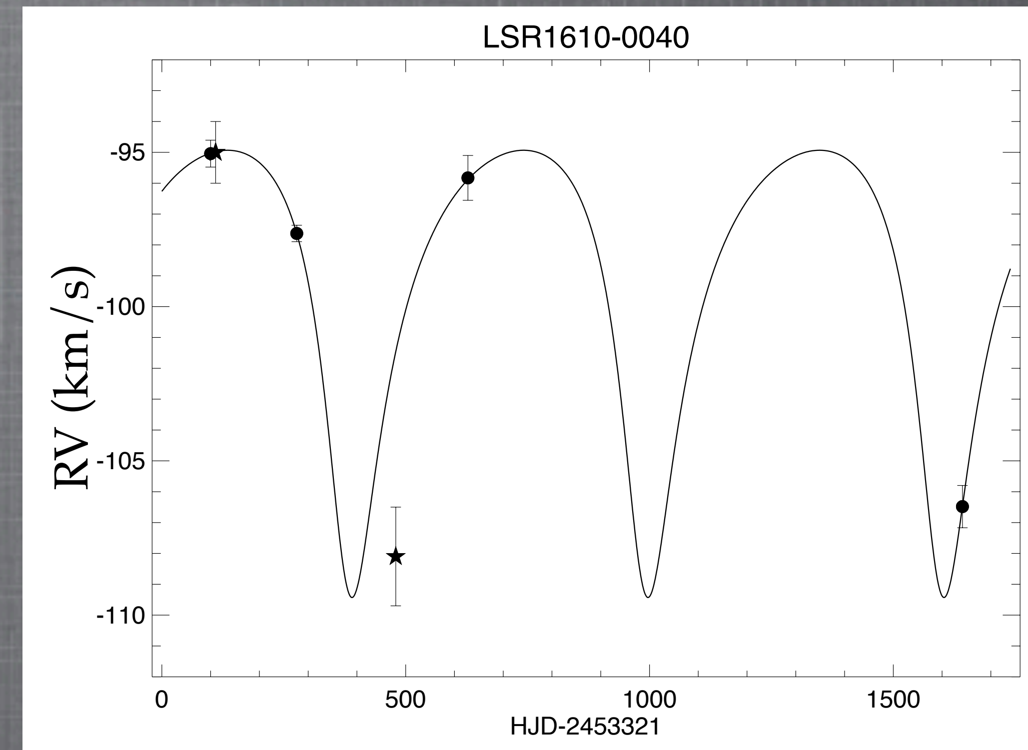


Theoretical Template vs. Empirical Template

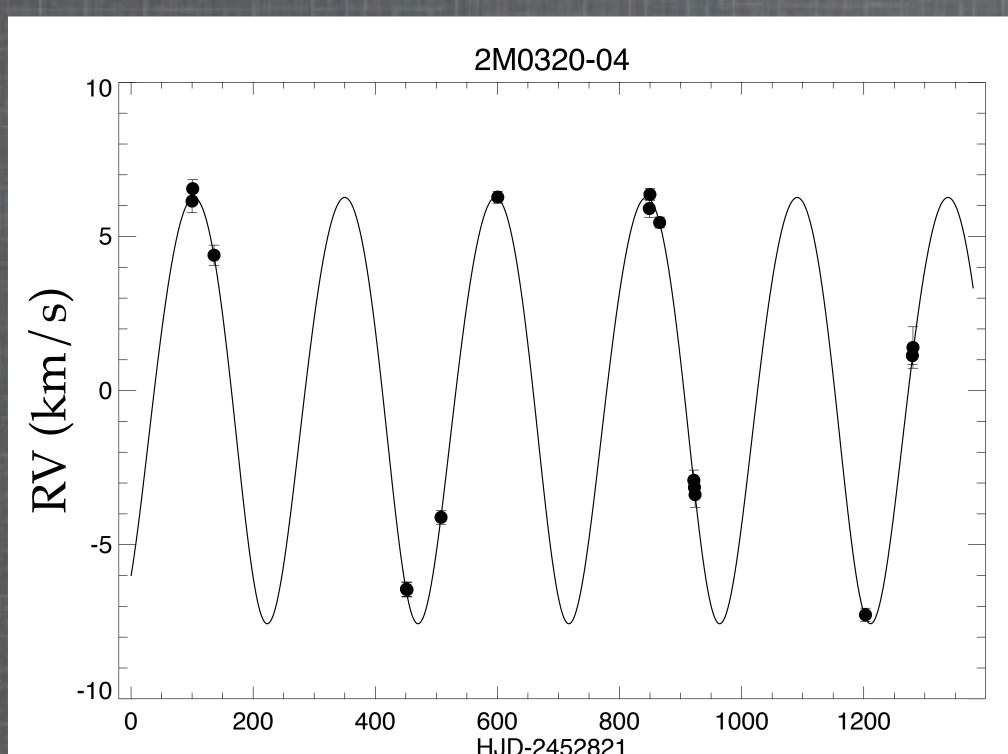
Ultracool Dwarf Results



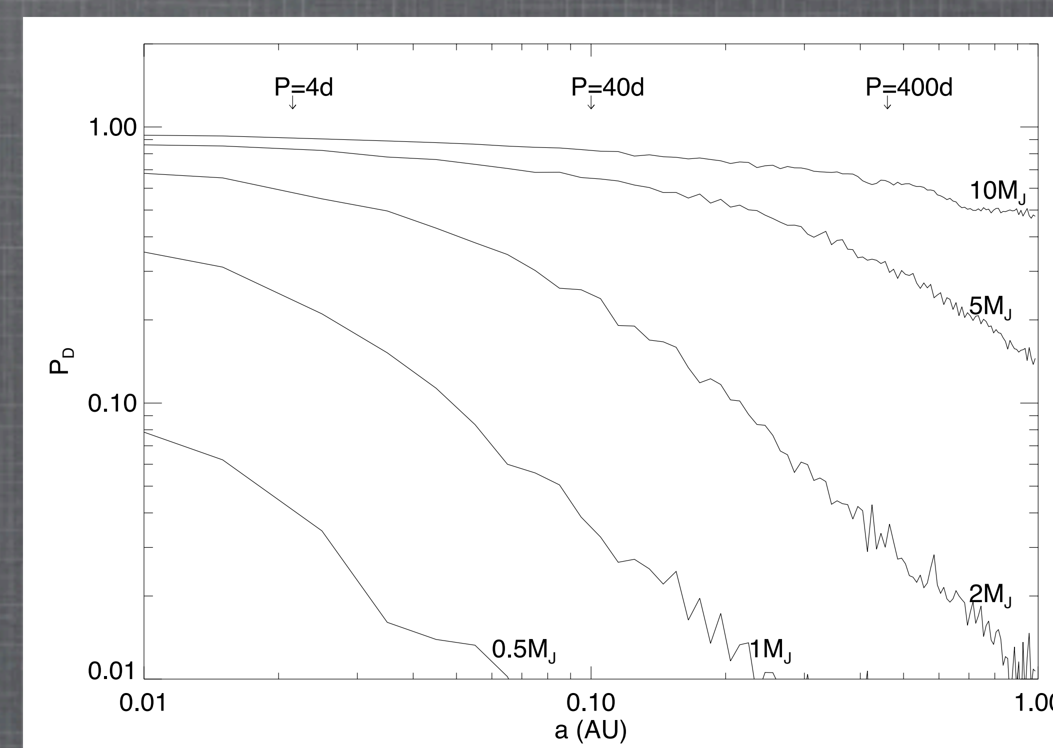
Kinematics: Average Age, Halo Objects?



M Subdwarf Spectroscopic Binary



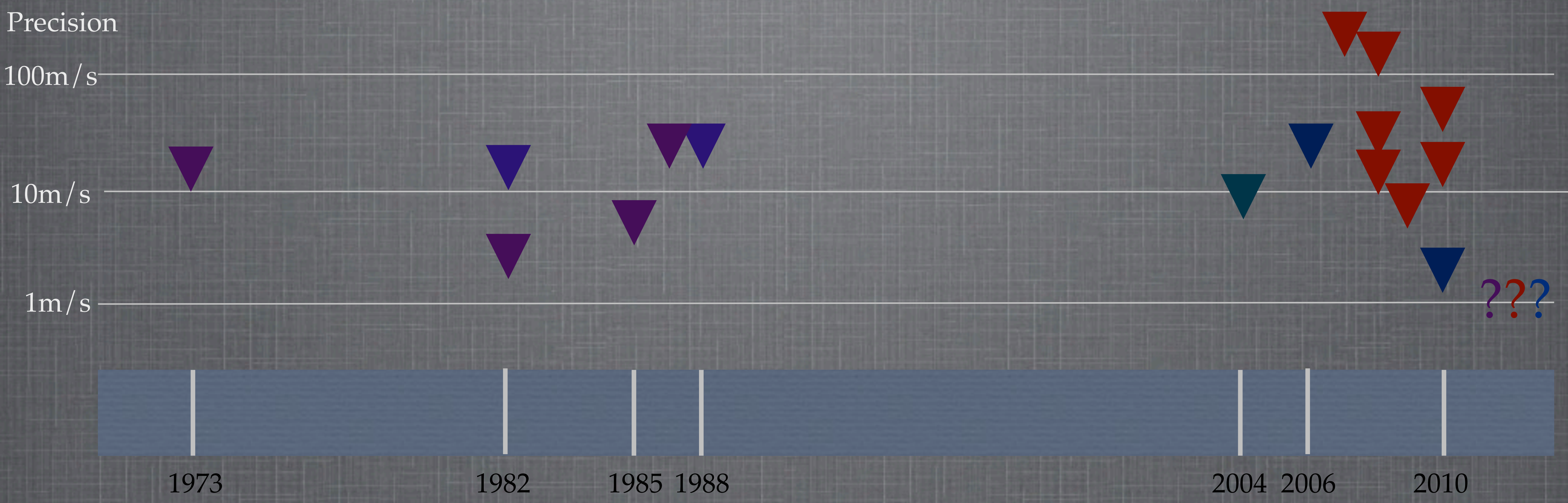
M/T Spectroscopic Binary



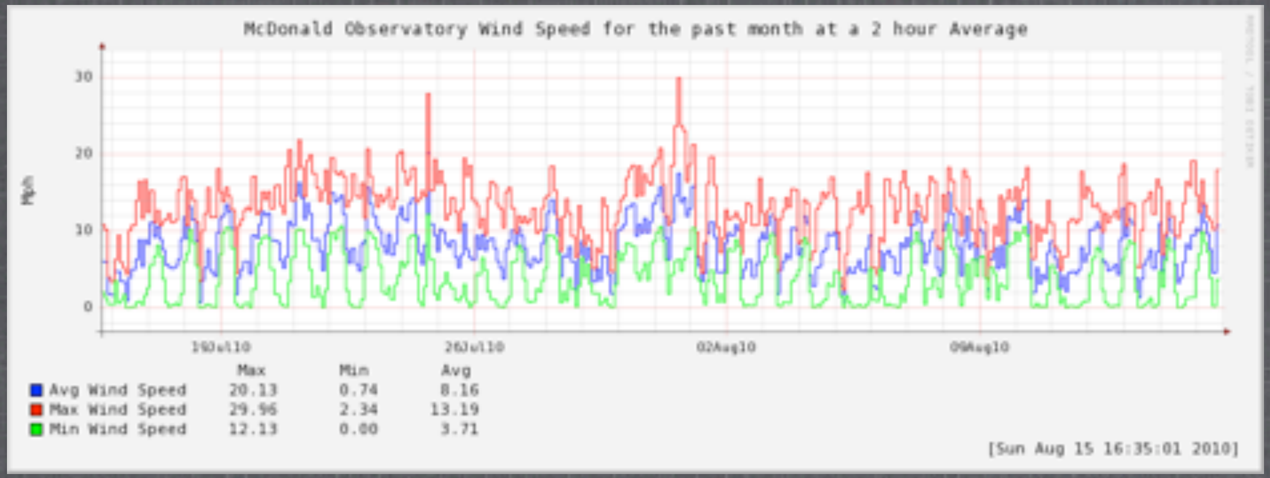
Upper Limits on Giant Planet Occurrence

From Blake, Charbonneau, & White, 2010, ApJ (accepted)

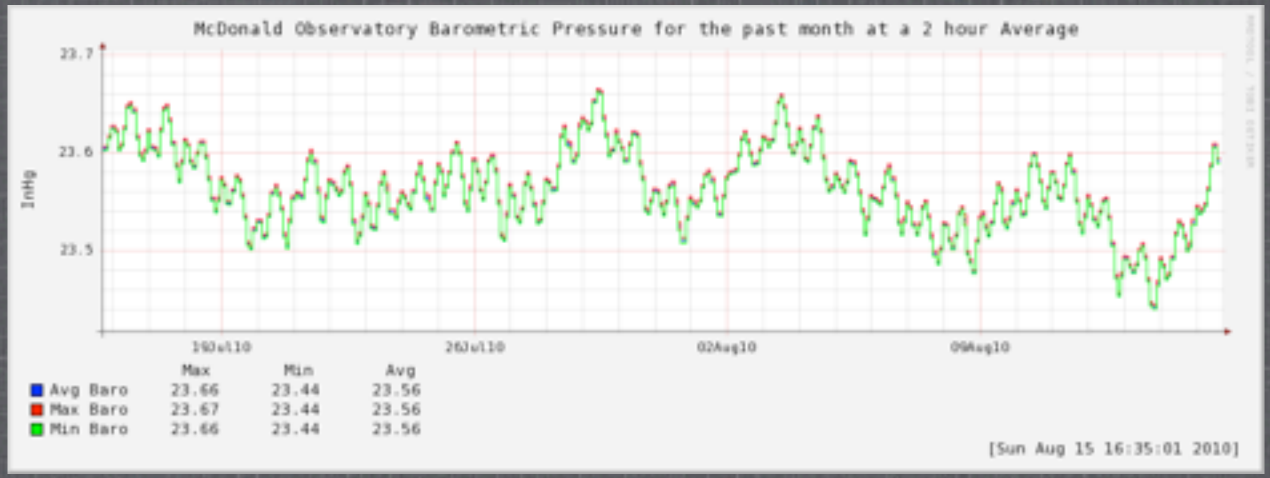
What Are The Fundamental Limits?



Winds



Pressure



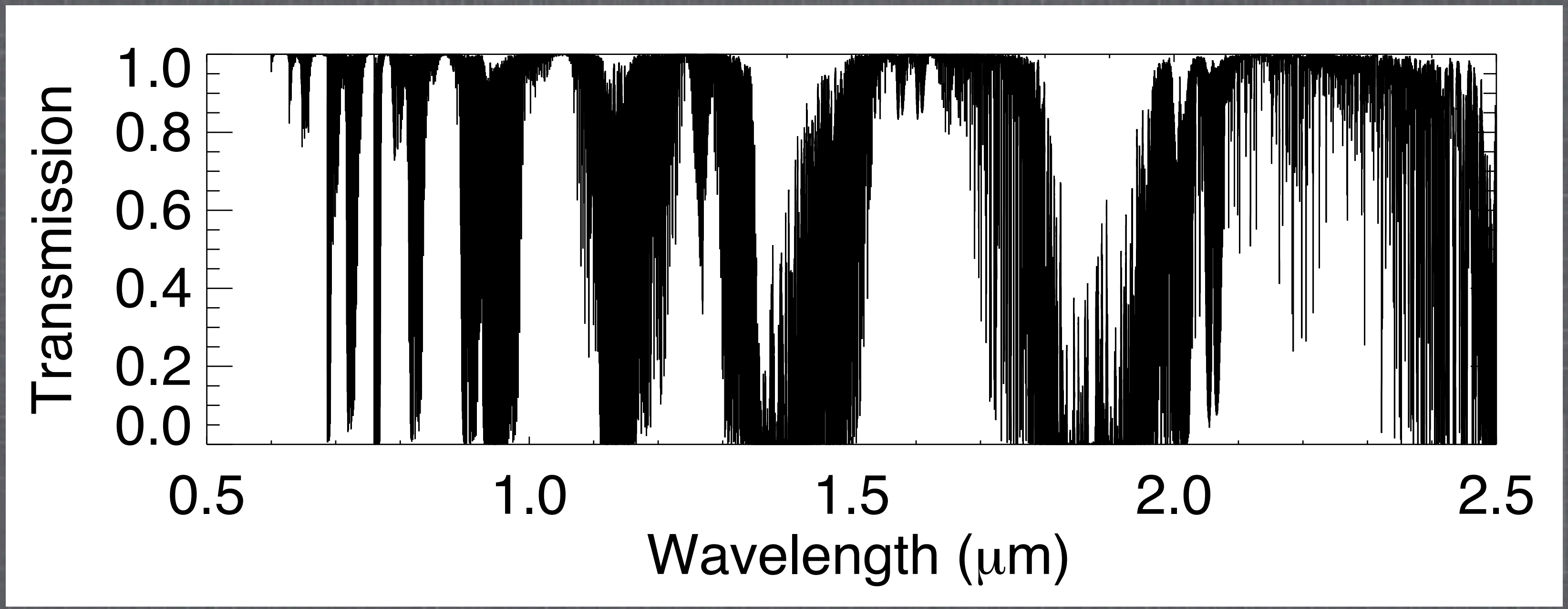
Calculating Telluric Models

Line Parameters

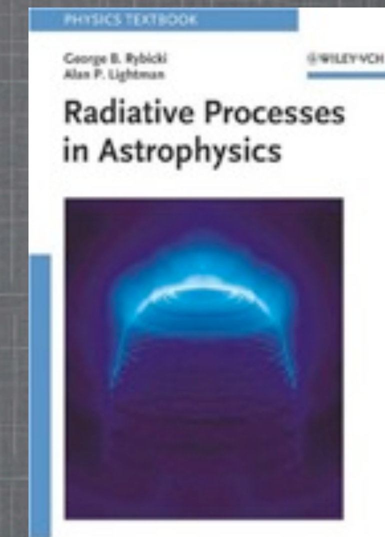
Center, Intensity, Pressure Shift, Temperature Shift, Energy, Width from Theory and Experiment

Climatology

Winds, Temperature, Pressure, Composition



Radiative Transfer

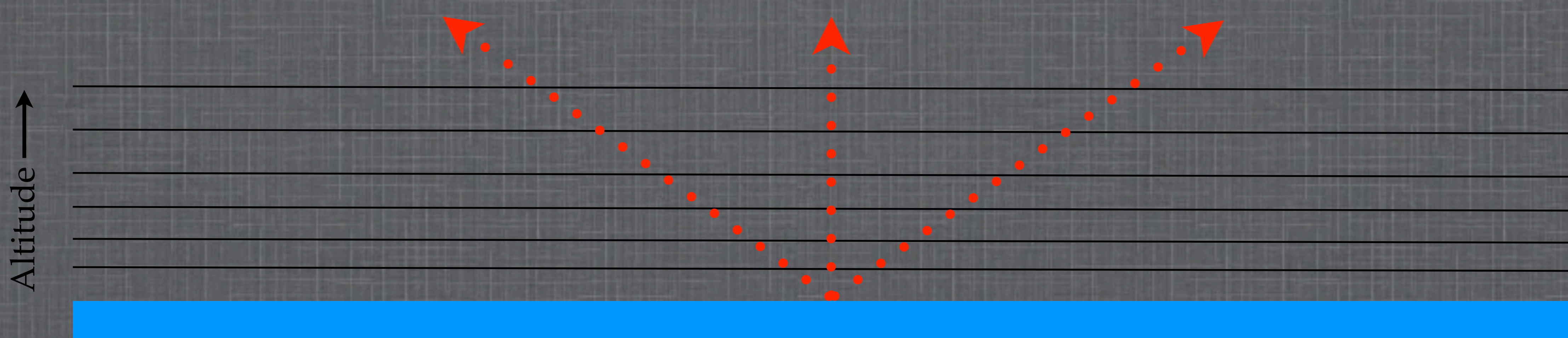


Transmission: $T_\nu = e^{-\tau_\nu}$

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

Line Shape

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



Assumptions: No line mixing, Neglecting refraction

Climate Model

- NASA Earth Global Reference Atmospheric Model (GRAM)

- Semi-empirical model of atmosphere for date and location

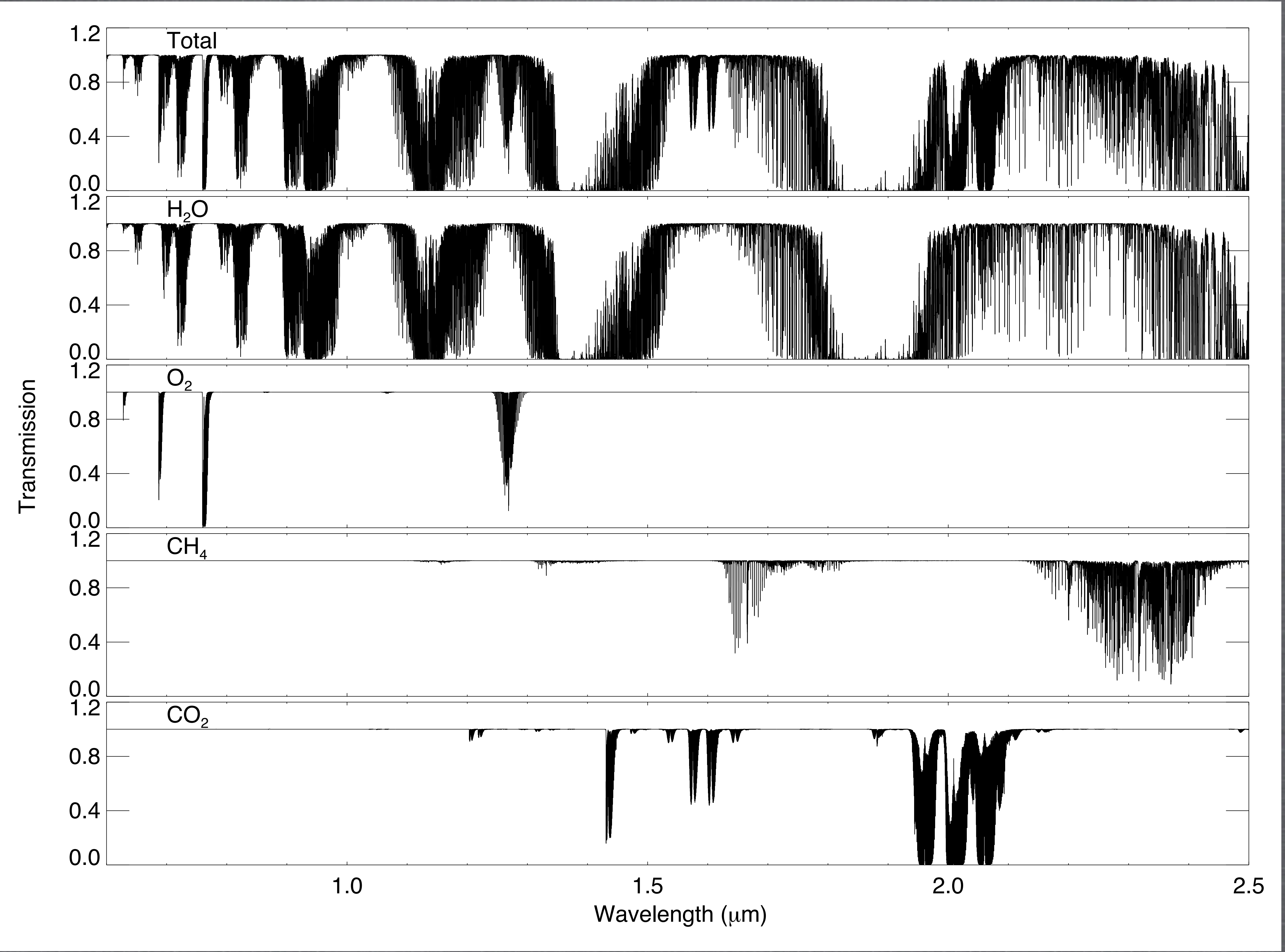
- GRAM model is based on:
  - Extensive observational data
  - Models for long- and short-term perturbations
  - Includes model of boundary layer

- Predicts over 0 to 120 km altitude:
  - Wind profiles and shear
  - Chemical composition
  - Pressure
  - Temperature

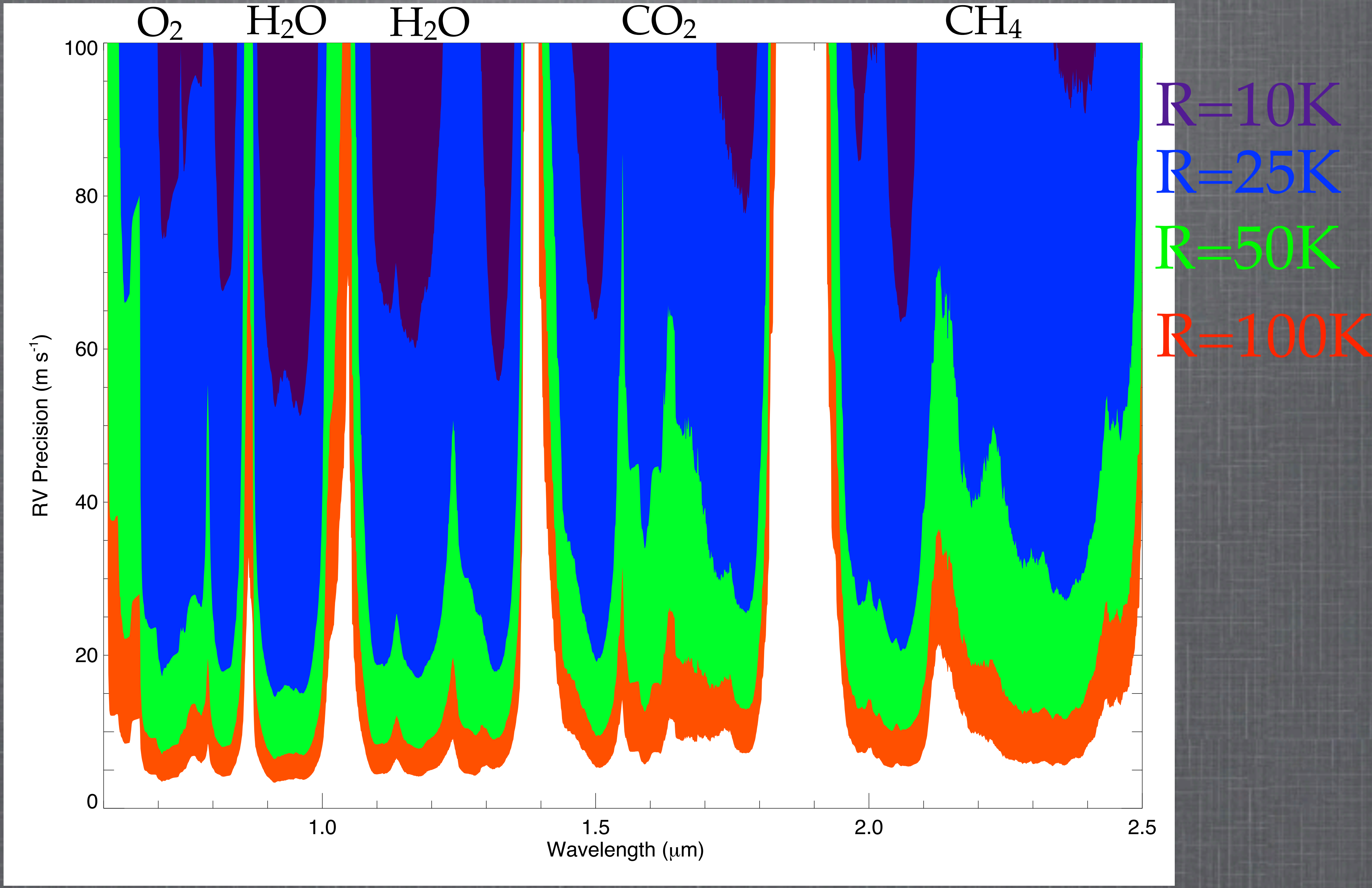
White Sands, NM

GRAM has been developed and maintained by C.G. Justus and F.W. Leslie (Marshall SFC)

Theoretical Telluric Spectrum

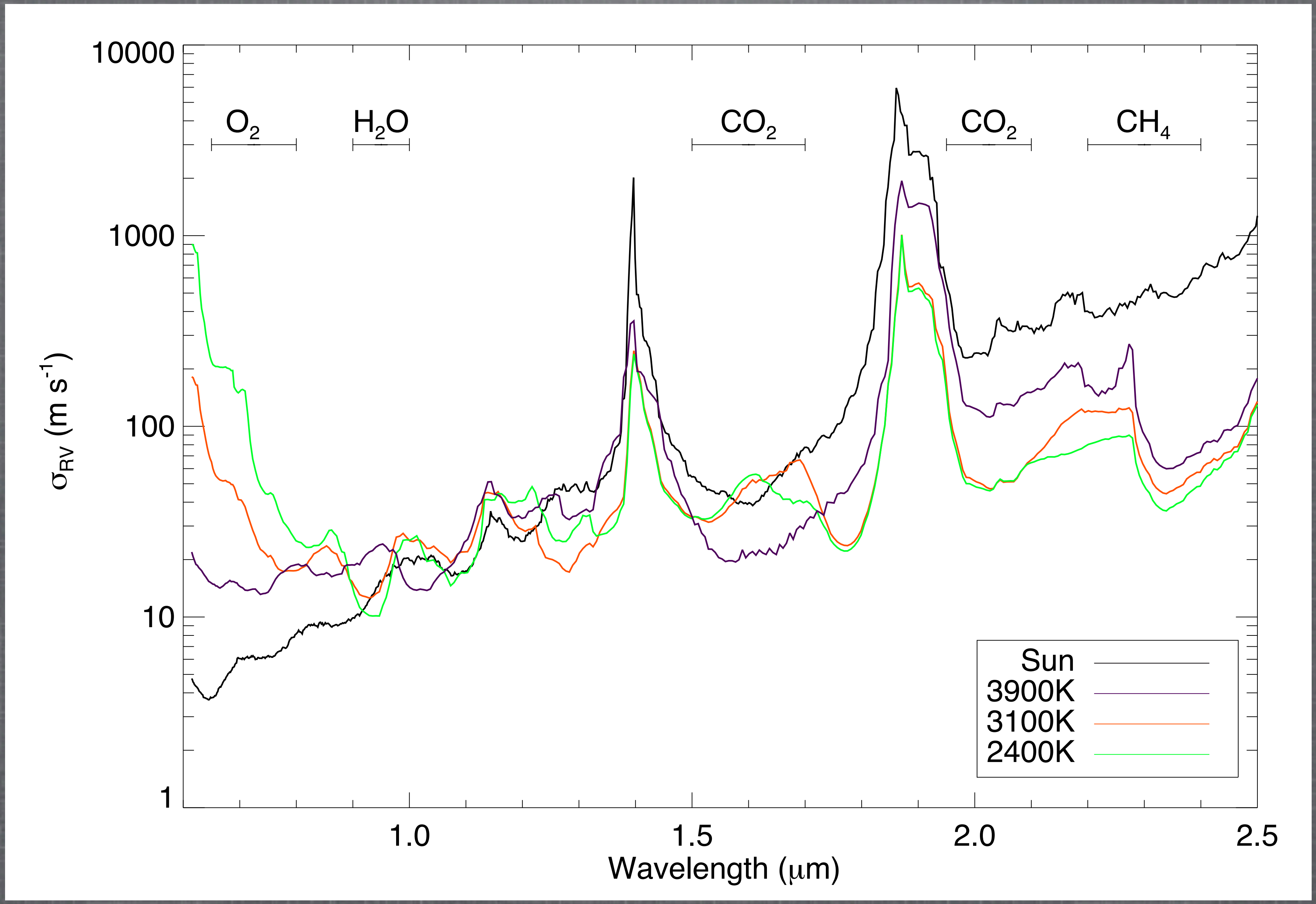


Telluric Photon Limits



- Photon-limited Doppler Precision (Butler et al. 1996 or Bouchy et al. 2001):
  - S/N=100 pixel at 500nm
  - 20 nm chunks

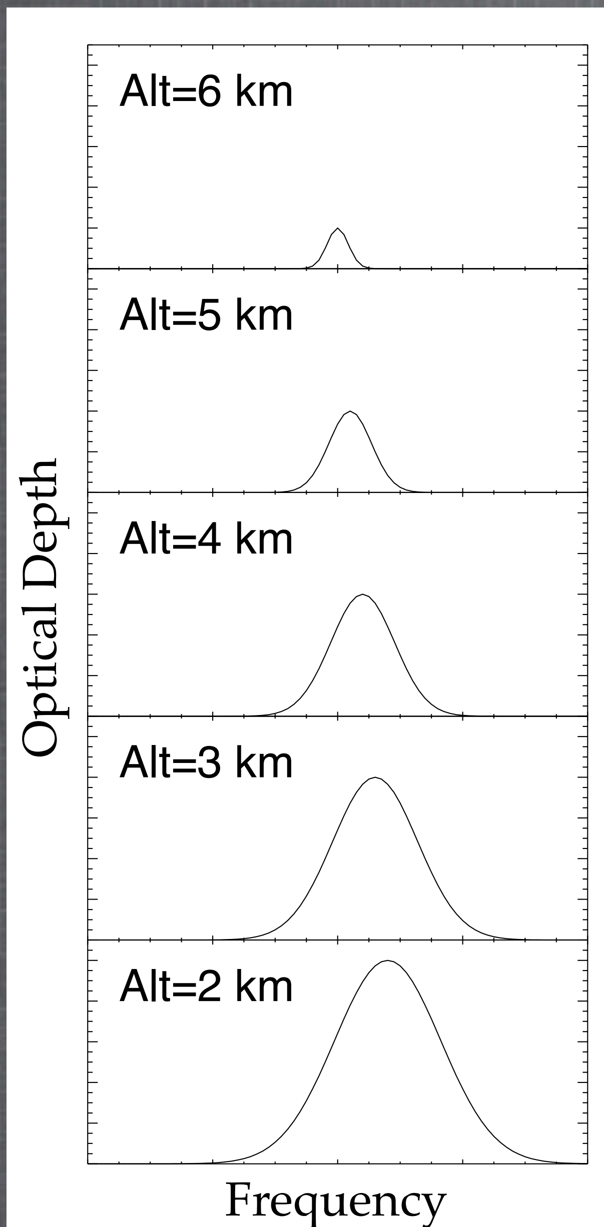
Stellar Photon Limits



- Photon-limited Doppler Precision:
  - Fixed J magnitude and integration time, Vsin(i) = 3 km/s
  - R=50,000, S/N=100 at 1 micron, 30 nm chunks
  - Includes Telluric absorption in S/N of each chunk

Telluric Line RV Shifts

Telluric Lines are Asymmetric!



$$T_\nu = e^{\left(-\sum_{Alt} \tau_\nu\right)}$$

Pressure Shifts: $\Delta RV < 10$ m/s

$$\nu_c^{'} = \nu_c^0 + \delta \frac{P}{P_0}$$

Winds: $\Delta RV < 20$ m/s

$$W_{RV} = \cos(\theta)\sin(\phi)W_{EW} + \sin(\theta)\sin(\phi)W_{NS} + \cos(\phi)W_V$$

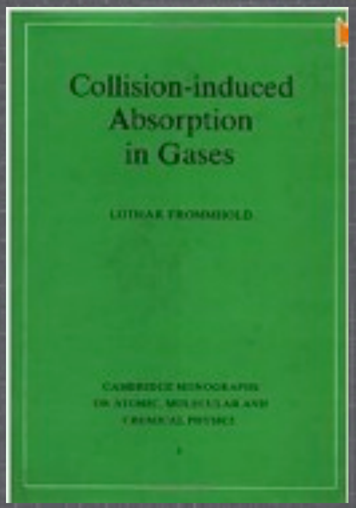
Intrinsic Asymmetry: $\Delta RV < 1$ m/s

$$G(\nu) \propto F[h\nu/kT] \int \frac{e^{-t^2}}{[\nu - \nu_c]^2 - [a]^2} dt$$

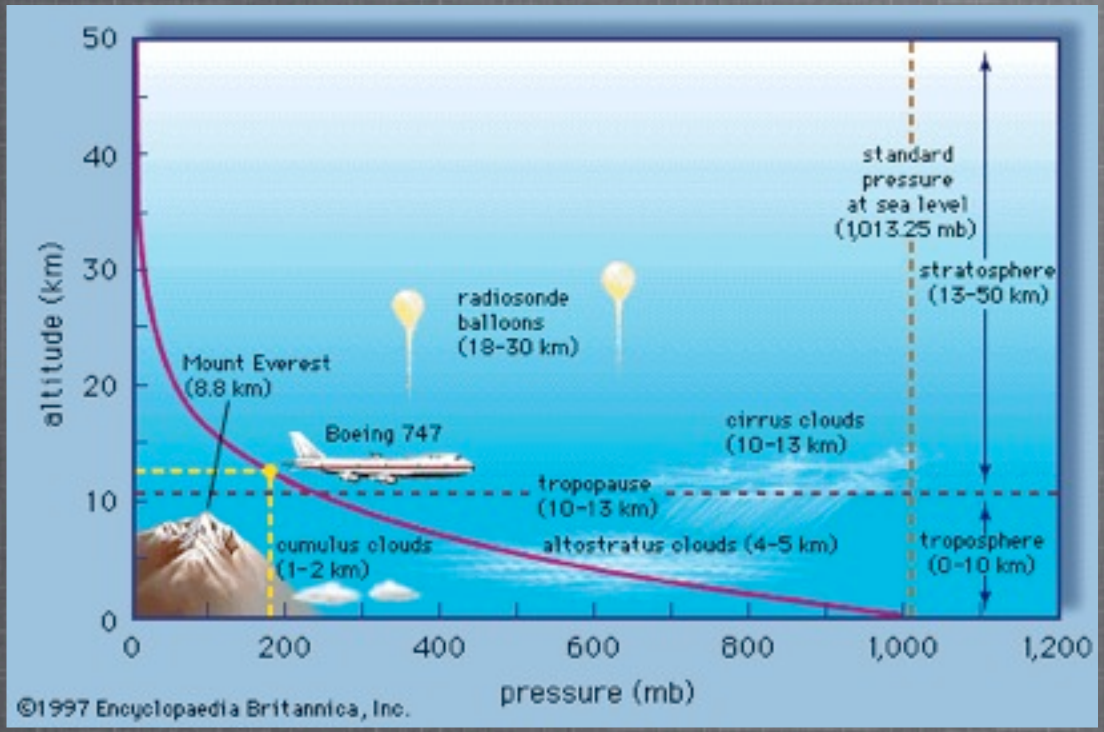
Line Shape

Asymmetric Function

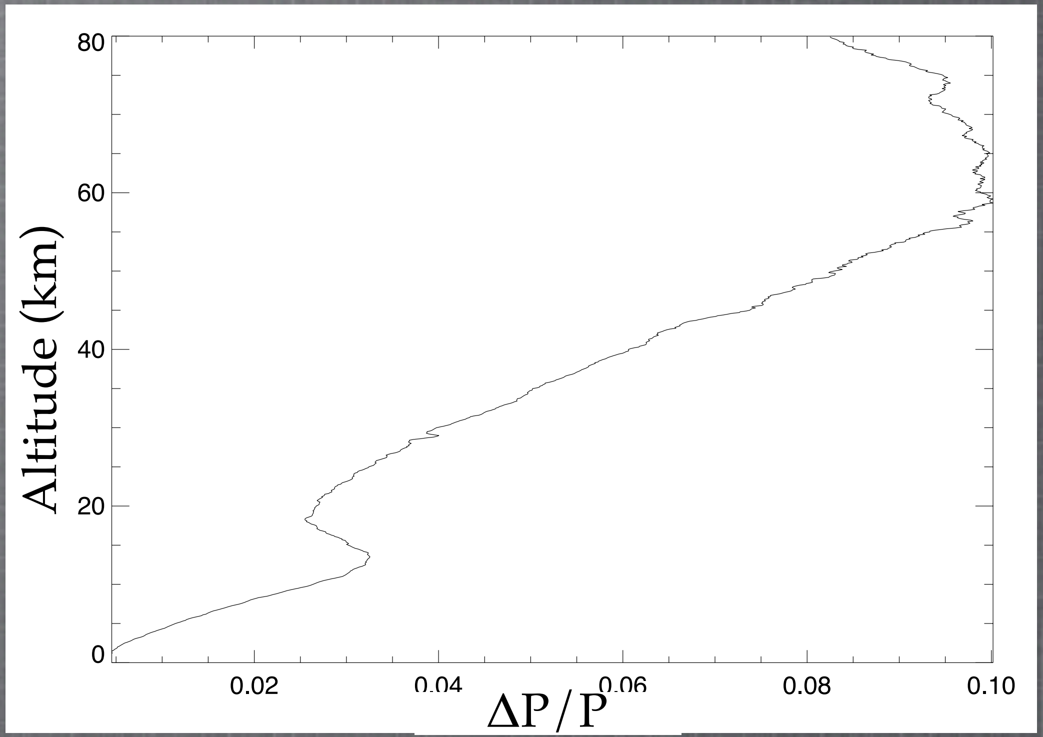
Voigt Profile



Atmospheric Pressure



Pressure with Altitude



1σ Variation in Pressure

$$\nu_c' = \nu_c^0 + \delta \frac{P}{P_0}$$

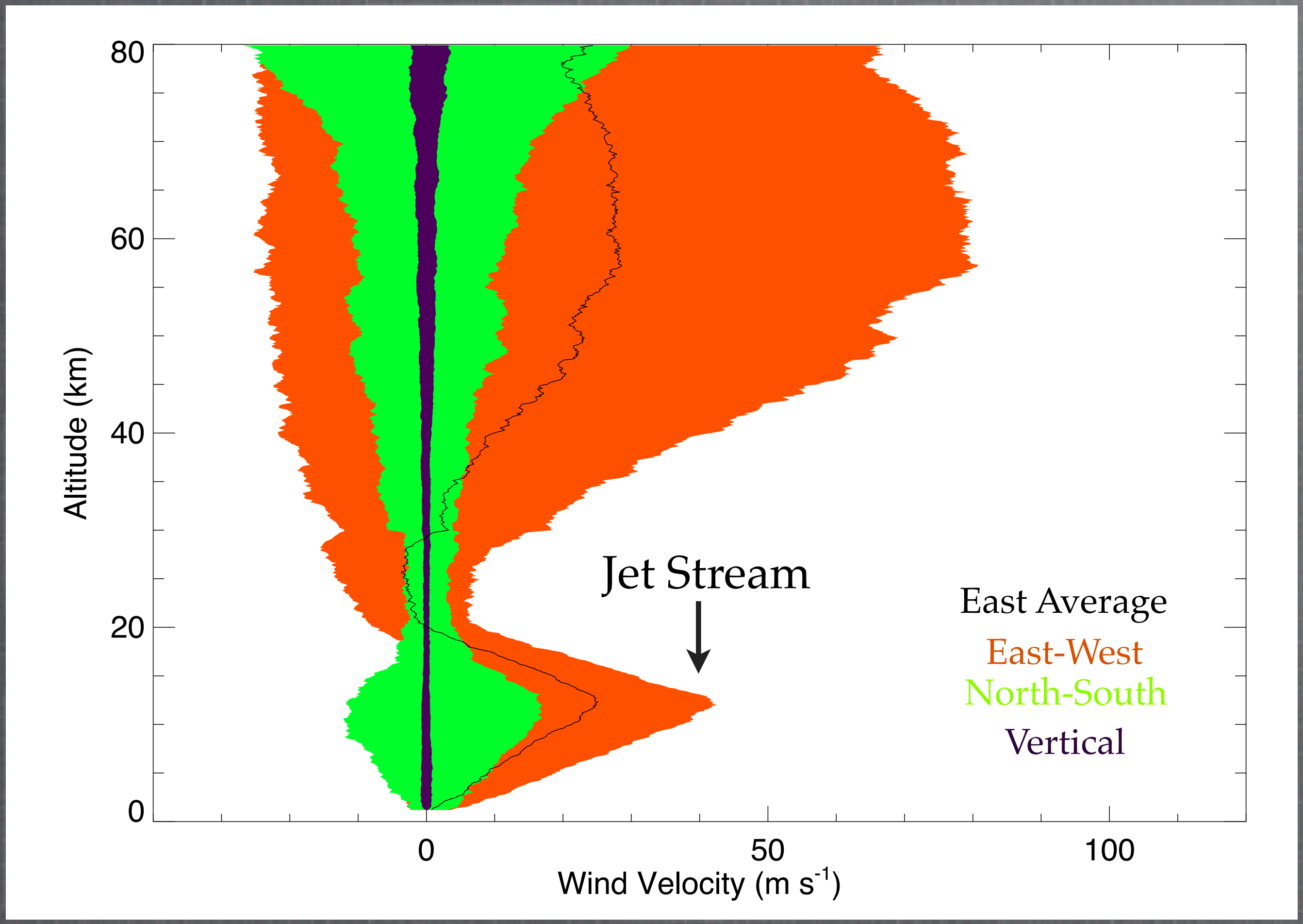
$\delta \sim -0.01$ For H_20, CO_2, CH_4, O_2

- 1% Pressure Change is ΔRV=3 m/s at 1 μm
- Depends on Altitude and Zenith Angle ϕ:

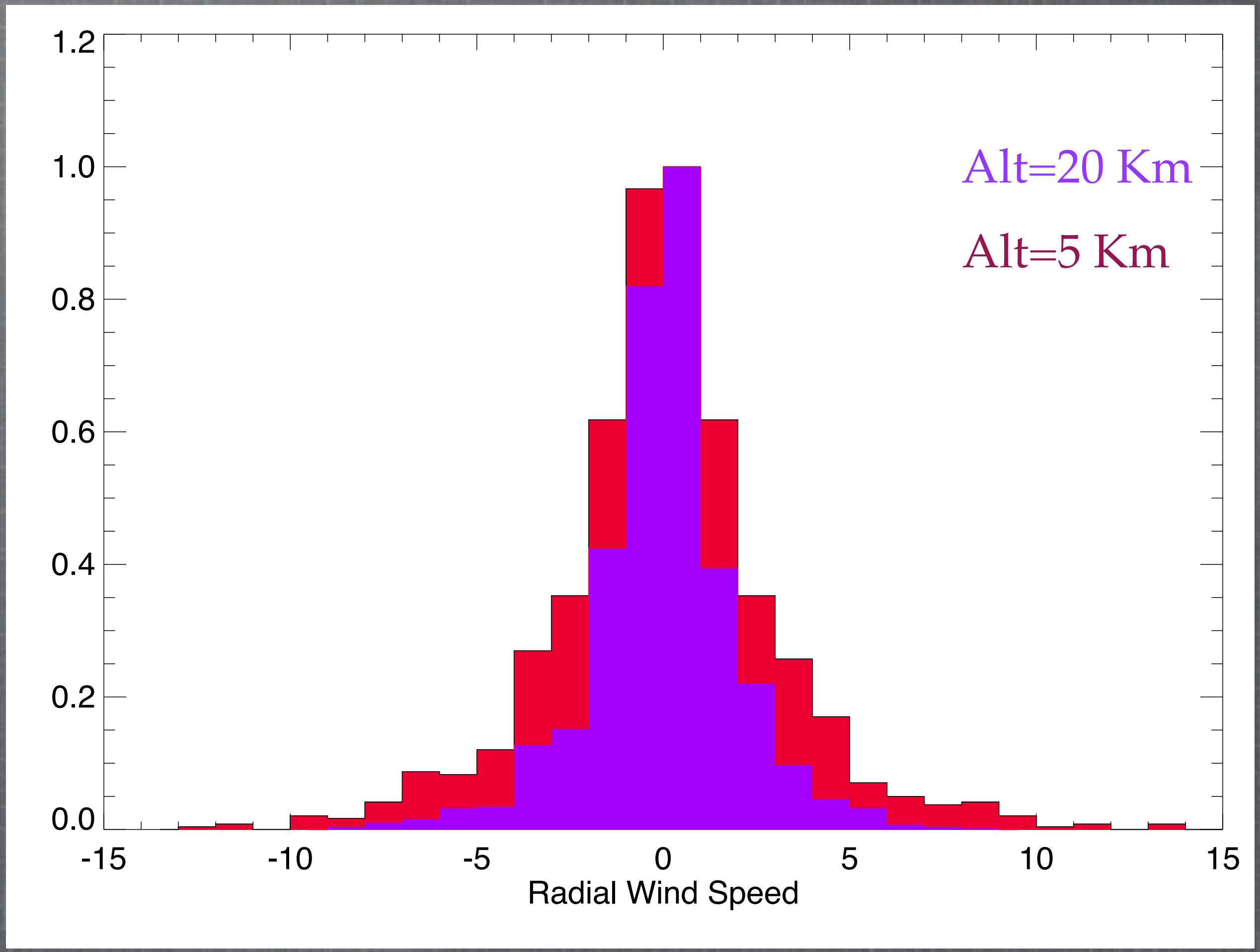
$$\frac{d(RV)}{dh} \approx 20m/s/km$$

$$\frac{d(RV)}{d(\sec(\phi))} \approx 20m/s/AM$$

Atmospheric Winds

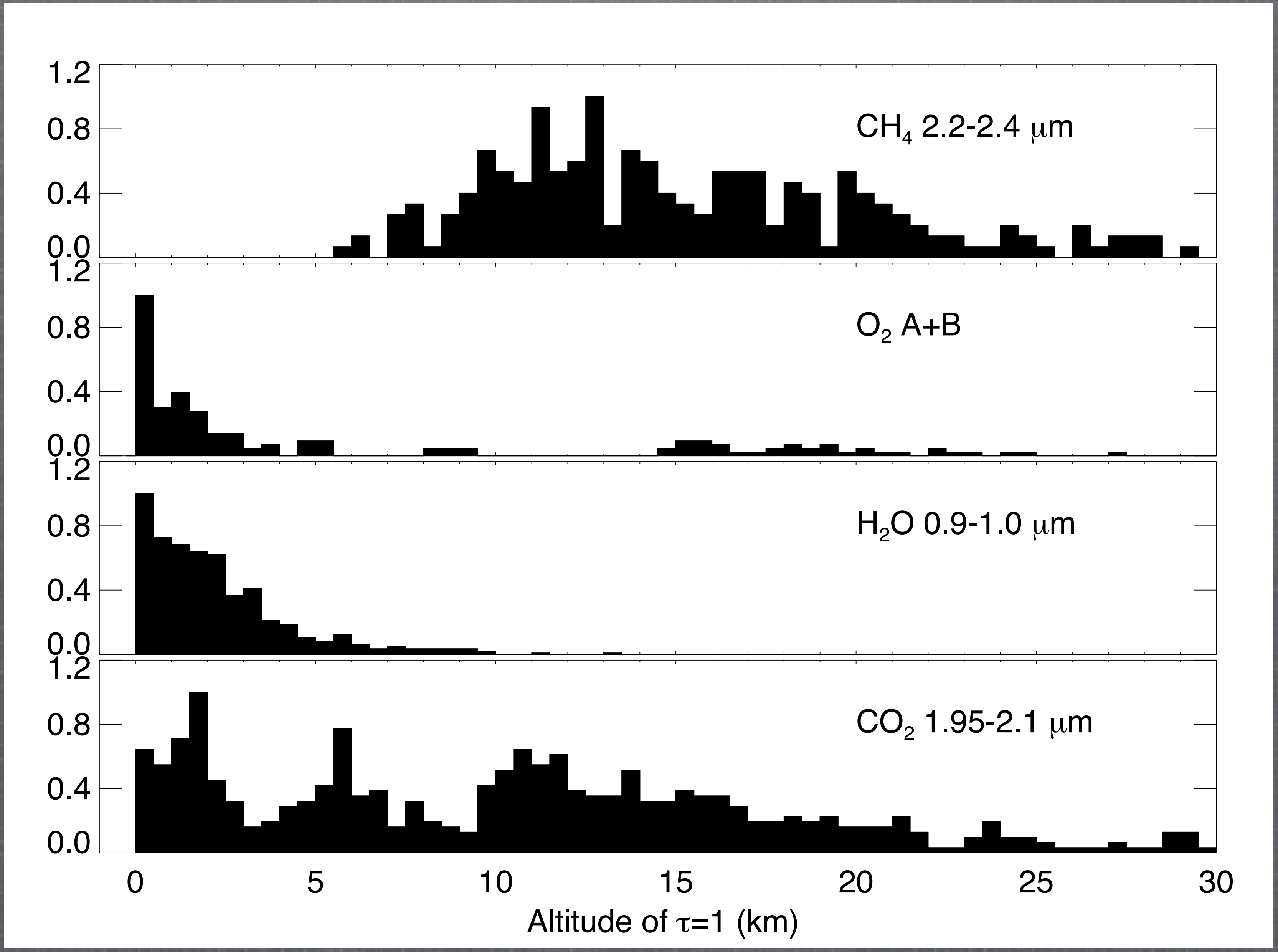


1σ Wind Region and Average E-W Wind



Radial Wind Speed
Random pointings AM<1.2
Difference from yearly average for given pointing

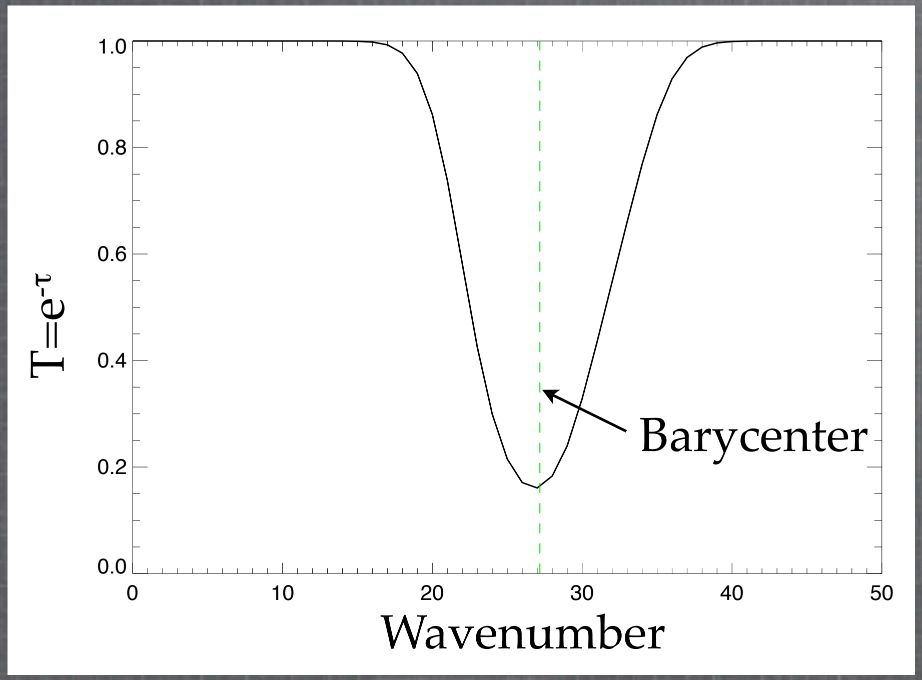
Altitude of Line Formation



Histograms of altitudes at which lines reach optical depth 1

Monte Carlo Simulations

- 100 night atmosphere models over 12 months
- Models for 1.2 km site in New Mexico
- 10 random sight lines each night, AM<1.2



Telluric Regions

O_2	0.685-0.695μm
H_2O	0.9-1.0 μm
CO_2	1.59-1.62μm
CH_4	2.28-2.3μm

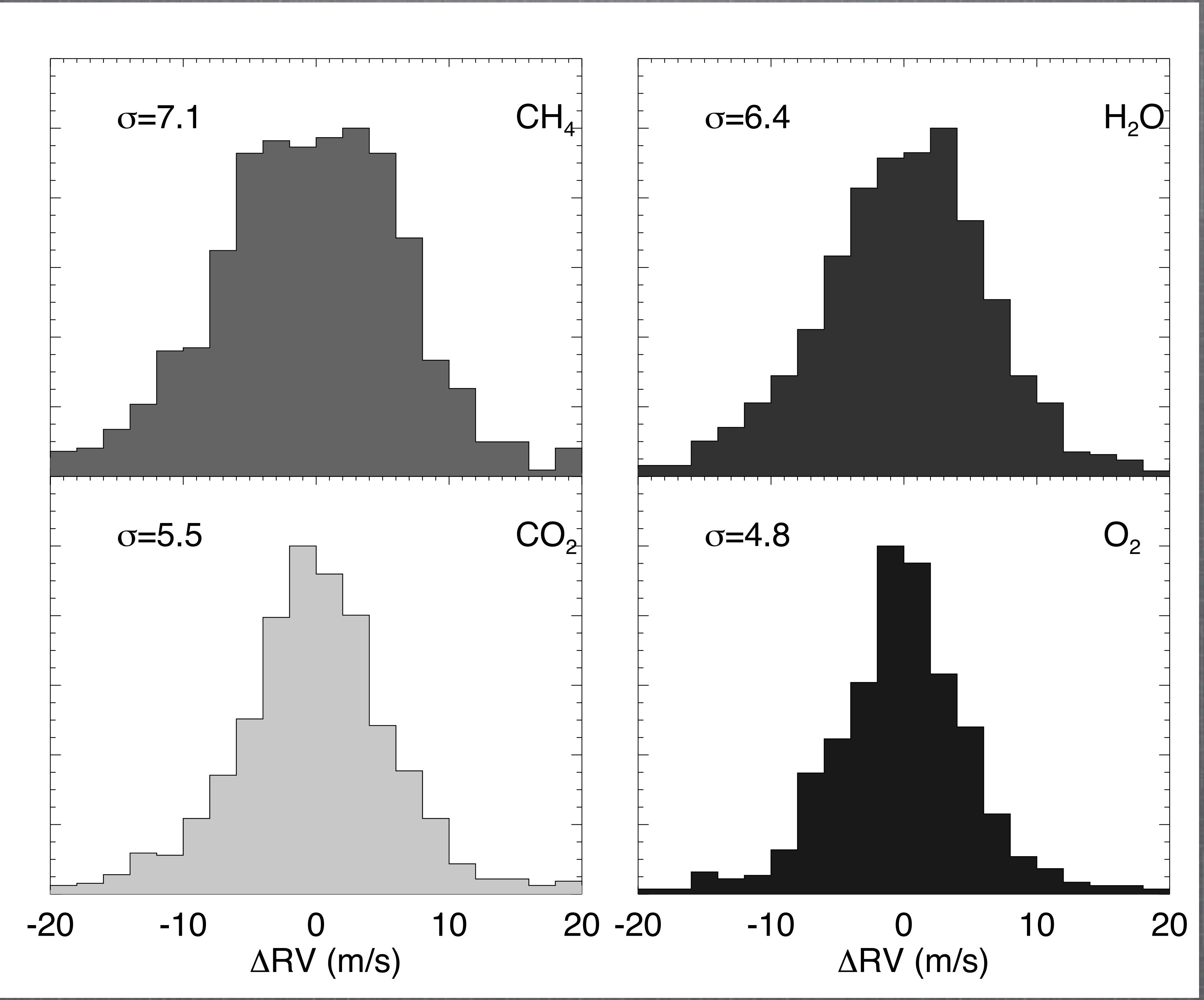
Approximation: Weighted Average of Lines in Region

$$\Delta\nu = \frac{\sum_i (1-T_i)(\nu_i - \nu_i^0)}{\sum_i (1-T_i)}$$

ν^0 derived from zenith observation in average atmosphere

Assumption: H_2O well-mixed

Simulation Results



RV residuals after correcting for zenith angle and yearly-average wind profile

Best Telluric RV Results

Radial Velocities with CRIRES★

Pushing precision down to 5-10 m/s

P. Figueira[1], F. Pepe[1], C. H. F. Melo[2], N. C. Santos[3], C. Lovis[1], M. Mayor[1], D. Queloz[1], A. Smette[4], and S. Udry[1]

A&A, 2010, 511, 55

Using CO_2 lines around 1.6 μm

Simulations predict ~6 m/s

Evaluating the stability of atmospheric lines with HARPS★

P. Figueira, F. Pepe, C. Lovis, and M. Mayor

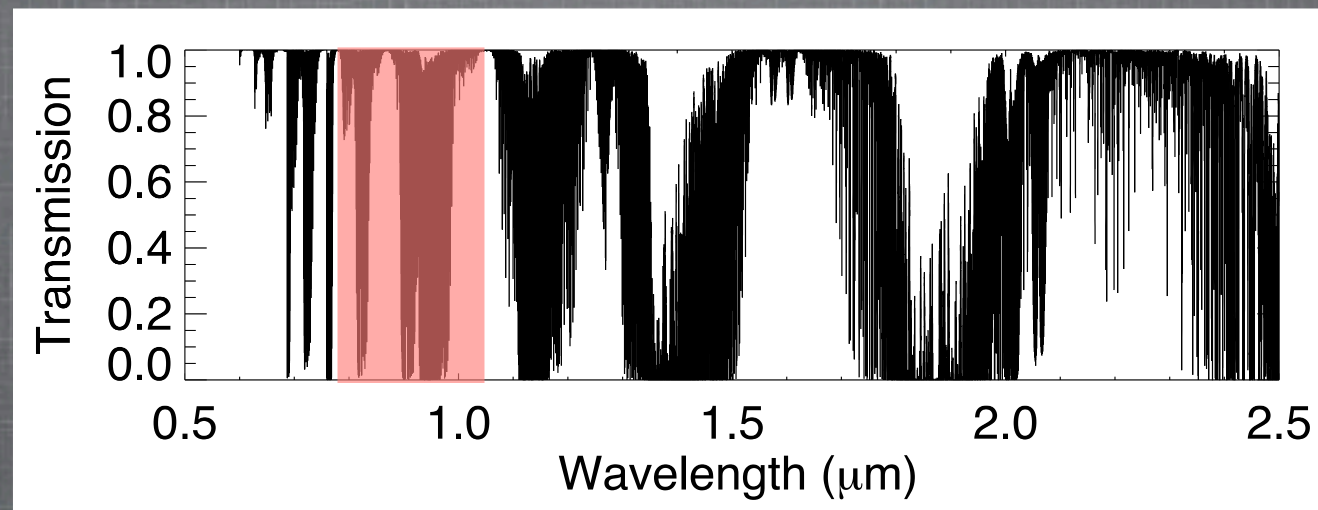
A&A, 2010, 515, 106

2 m/s using O_2 B and γ bands

Simulations predict ~5 m/s

Future Work

- What site characteristics result in the most stable RVs?
- Incorporate realistic motions of water vapor



Deep Red: Thick CCDs, many stellar lines (FeH), many water lines

- How best to incorporate real-time weather metrology




- How best to make RV measurements using telluric lines
  - We would like an "FTS spectrum" of our "gas cell"
  - Chad Bender's models are just what we need!

Conclusions

- Some 1980s technologies should not be brought back

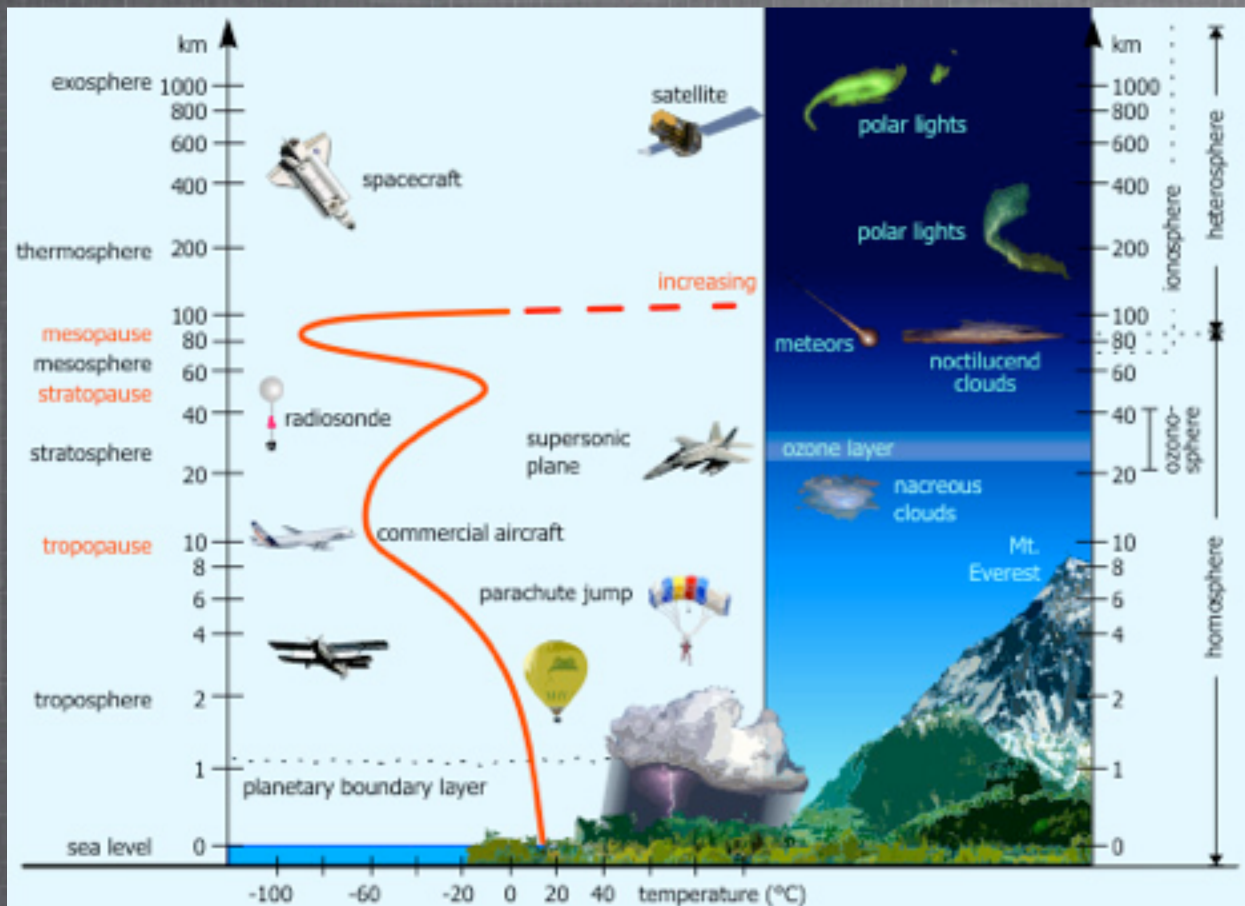
 

- Some should: RV precision of 5 m/s or better has been demonstrated across optical and NIR using telluric lines

- The atmosphere imposes fundamental limitations:
  - Wind and pressure variations
  - Expected to be less than 5 m/s with weather modeling

- Telluric lines as an RV reference are particularly appealing:
  - As an alternative in certain spectral regions (deep red)
  - When 5 m/s is interesting (late-M stars)

Earth's Complex Atmosphere



Dry Air Expressed in Volumes	
Nitrogen (N_2)	78.1%
Oxygen (O_2)	20.9%
Argon (A)	0.9%
Carbon dioxide (CO_2)	0.035%
Others	0.065%

Others : Neon (Ne)
Helium (He)
Krypton (Kr)
Hydrogen (H_2)
Xenon (Xe)
Ozone (O_3)
Radon (Rn)