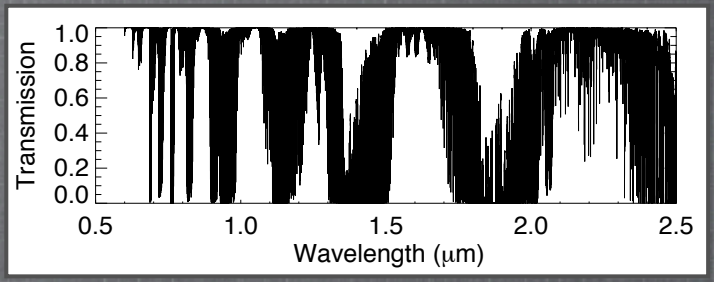
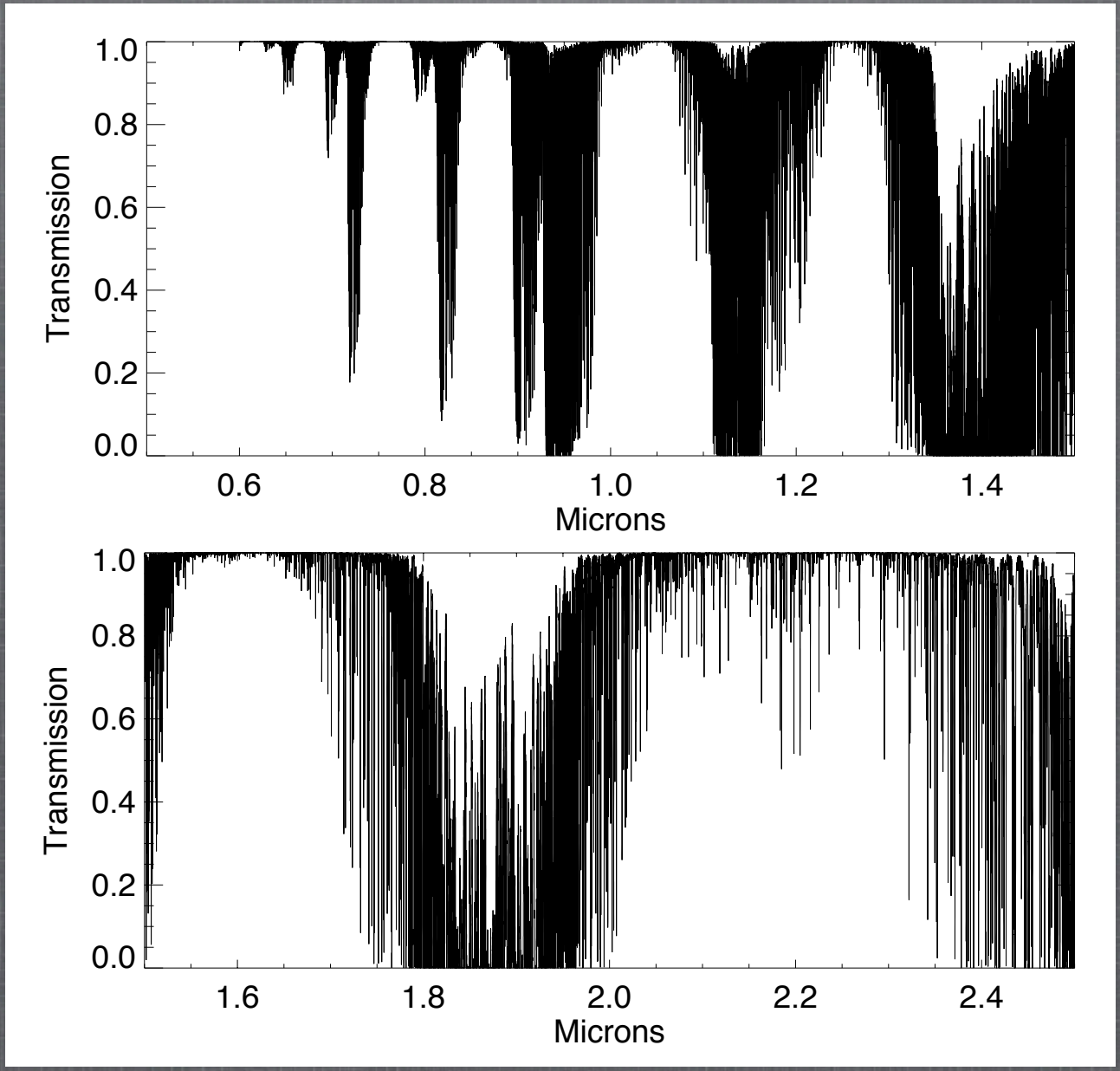
Measuring NIR Extinction with GPS



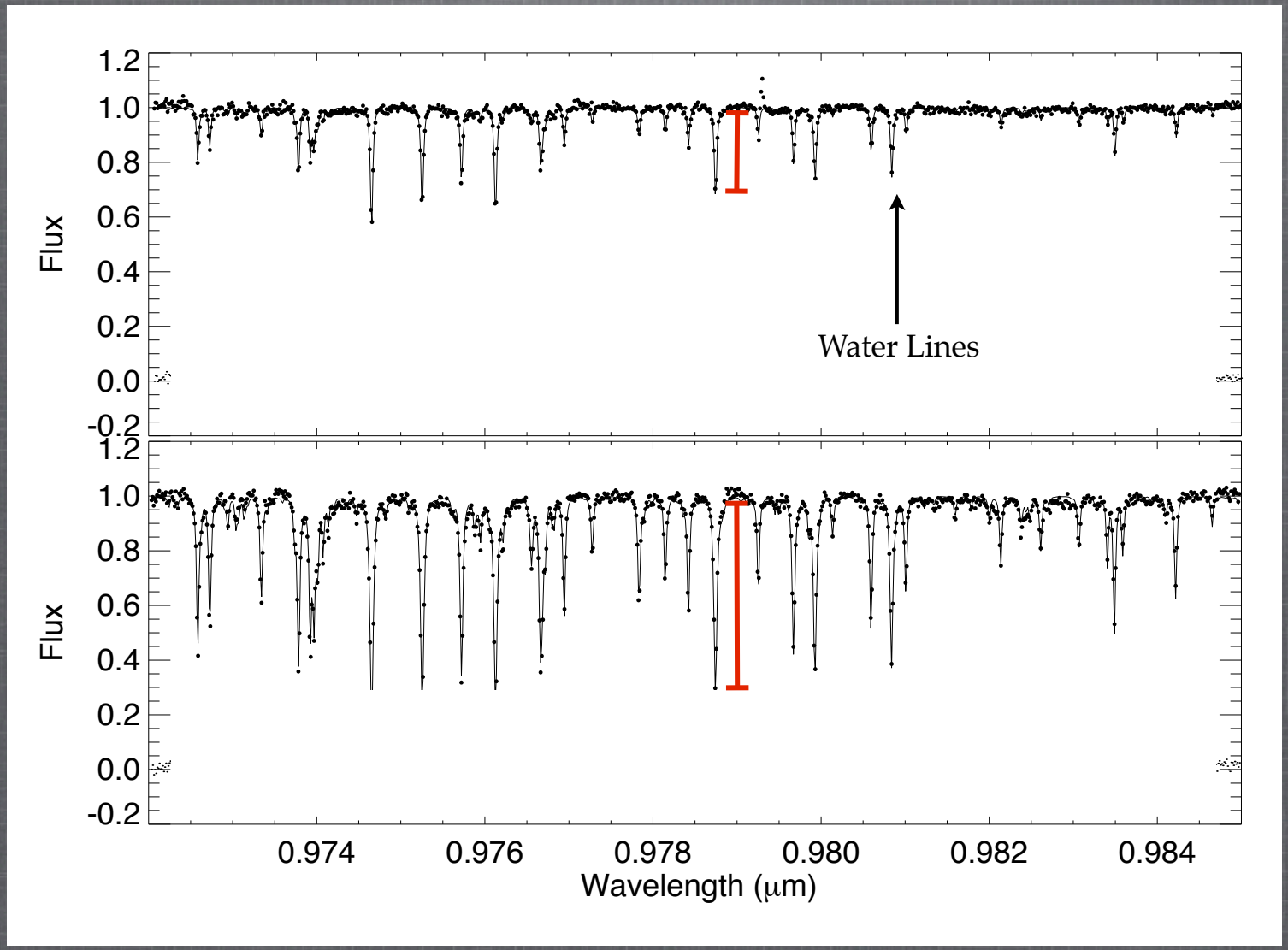
Cullen Blake & Margaret Shaw
Princeton University

Water, Water Everywhere!



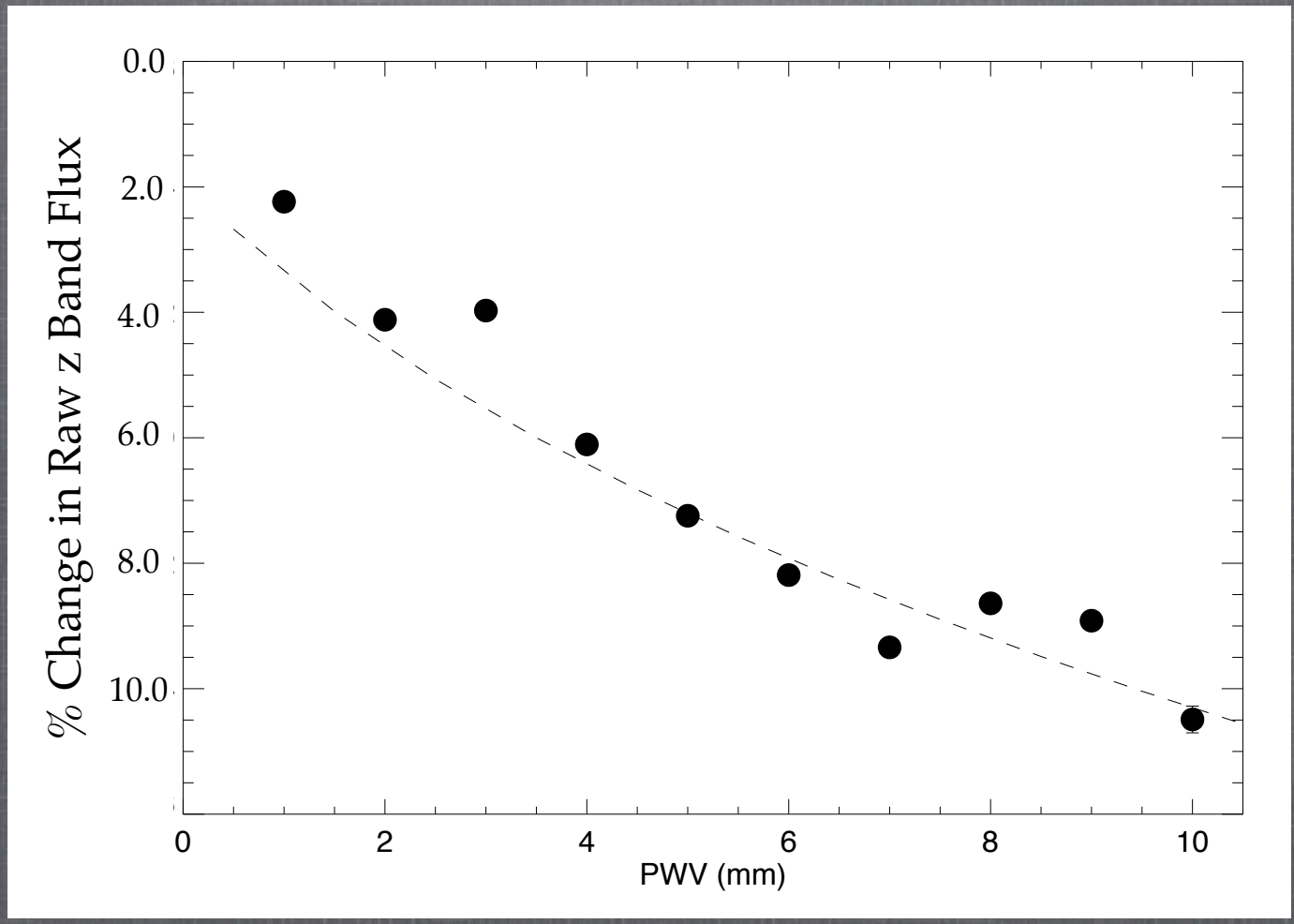
Typical Transmission: Apache Point Observatory

Water Absorption: Highly Variable



Two Echelle Spectra of an A Star
Same Airmass, 300% Change in Optical Depth

Broadband NIR Photometry

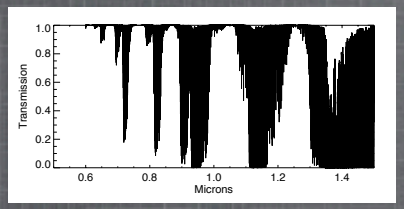


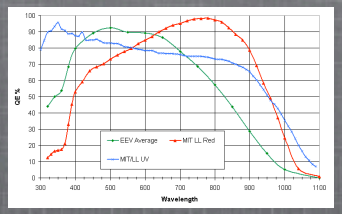
Change In Uncalibrated Flux:
Repeat SDSS z Band Observations of F Stars

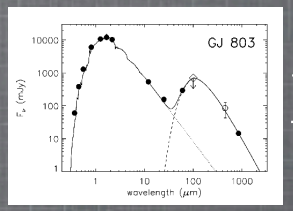
PWV = Precipitable Water Vapor

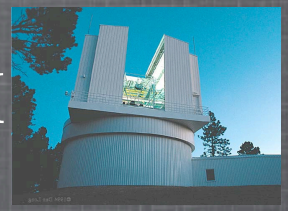
Differential Photometry

Detected Photons =

$\int$ Earth Atmosphere 

X Filter
X Detector 

X Source SED 

X Telescope  $d\lambda$

$$\frac{\int \text{Star A} \times \text{Filter}\, d\lambda}{\int \text{Star B} \times \text{Filter}\, d\lambda} \sim \text{Constant}$$

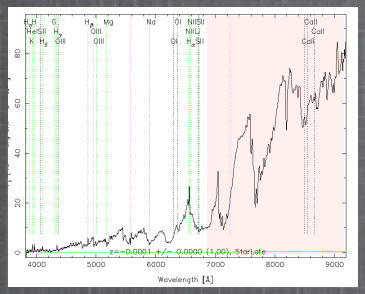
mmag Ground-based Differential Photometry Possible (Even in z Band)

Assumptions

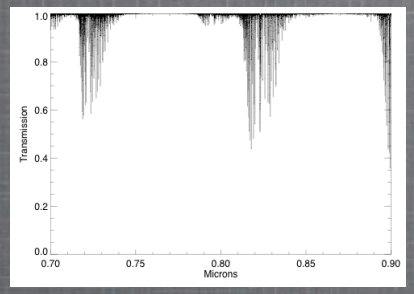
1) Contemporaneous observations of both stars
2) Perfectly calibrated 2D detector
3) Small angular separation between stars
4) Stellar SEDs same across filter bandpass

Differential Photometry of Cool Stars

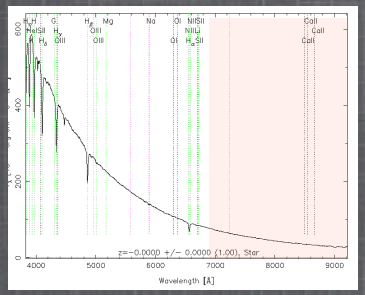
M Star



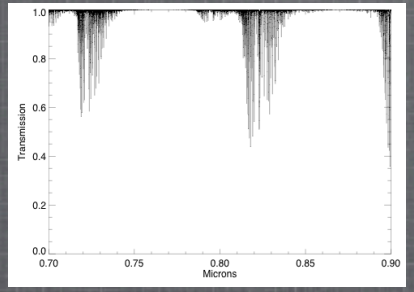
700-900nm (i+z)



A Star

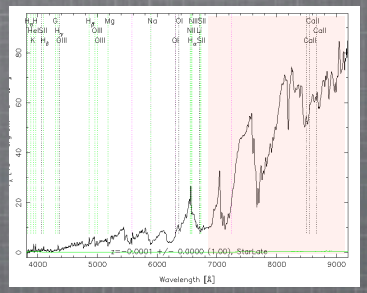


Low PWV

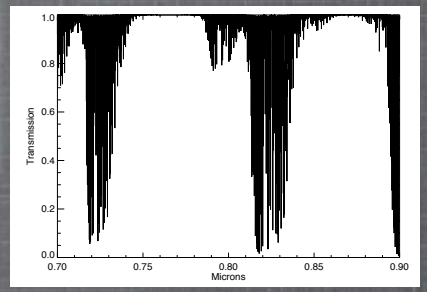


≠

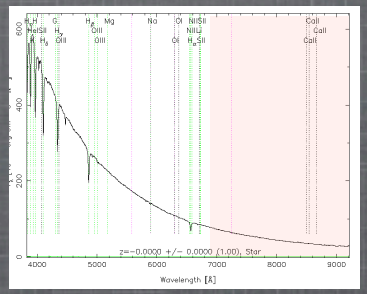
M Star



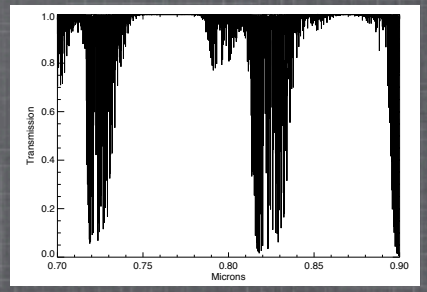
700-900nm (i+z)



A Star



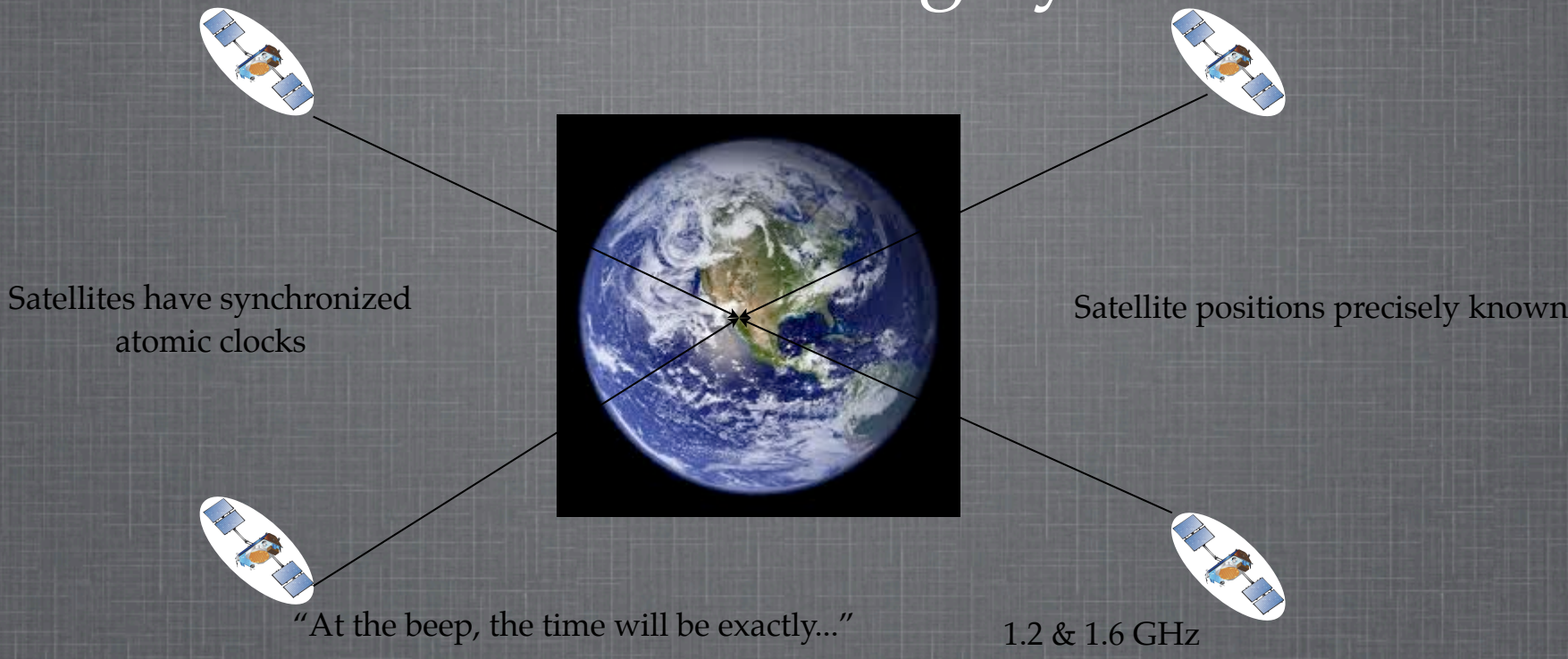
High PWV



Up to 1% Effect in *Differential* Photometry of Cool Stars

<u>Precise Telluric Models Can Help</u>

Global Positioning System



GPS measures light travel time: satellites to receiver

If Speed of Light (Index of Refraction) is Known:

Signals From Four Satellites Get You:

- Absolute X,Y,Z Position of Receiver
- Time Offset Between Receiver Clock and Satellite Clocks

GPS Timing Delays (Fixed Receiver)

Ionospheric Delay: 10 m +/- 1 mm

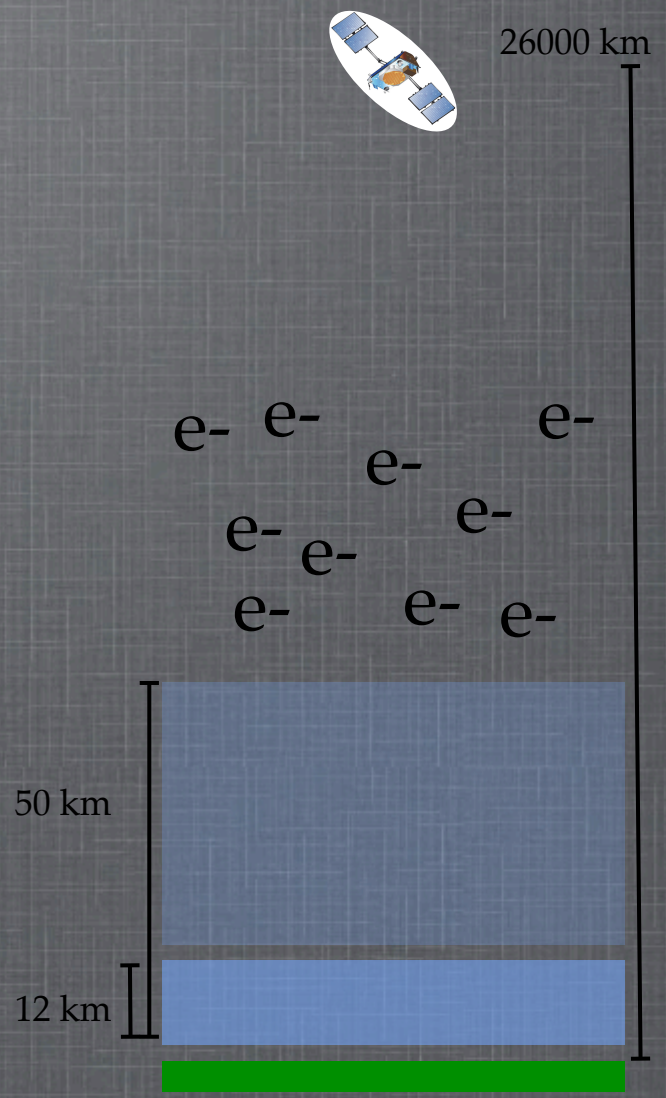
Frequency Dependent: Precisely Measured Using Dual Frequency GPS Data

"Dry Air": 2 m +/- 1 mm
"Hydrostatic Delay"

Water Vapor: 0.03 to 0.3 m
"Wet Delay"

Many Sources of Error Eliminated By *"Double Differencing"* - Network of GPS

"Pseudo Range" 10m = 3 ns Timing Delay



Measurements: GPS, Temperature, Pressure

$$\text{Dry Delay} = (2.2779 \pm 0.0024) P / F(Lat, Alt) \text{ (mm)}$$

Barometric Pressure +/- 0.3 mbar

Function of Position on Earth (constant)

Calculated From Raw GPS Data
Commercial Software (e.g. Bernese)

Wet Delay = Total Delay - (Ionospheric Delay+Dry Delay)

PWV ∝ F(T) x Wet Delay → Relative PWV +/- < 0.2 mm

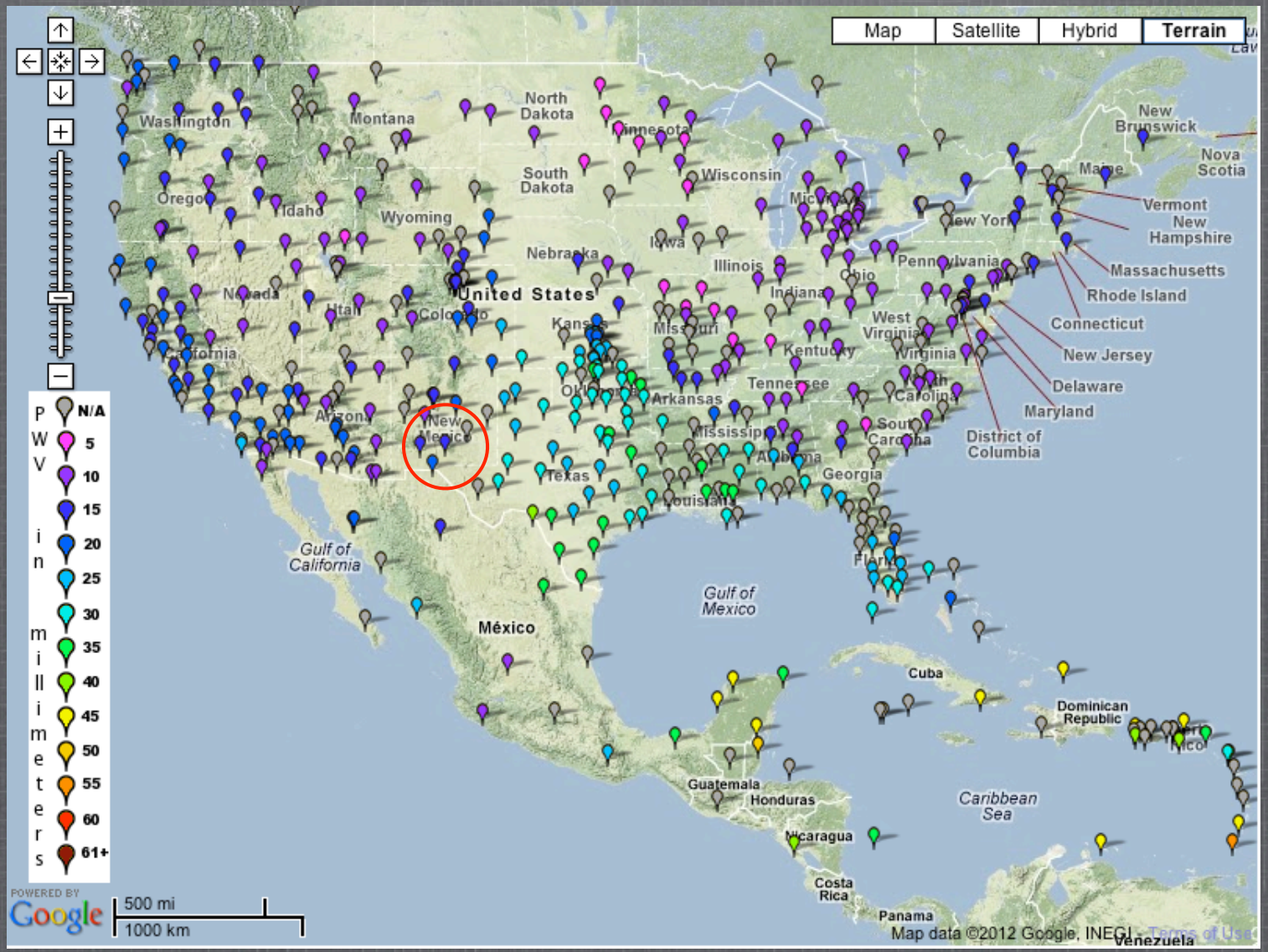
Approx. Linear Function of Surface Temperature

References: Bevis et al. 1992, 1994

Caveat: These are Estimated Zenith Quantities
Azimuthal Symmetry Assumed

GPS Monitoring Networks

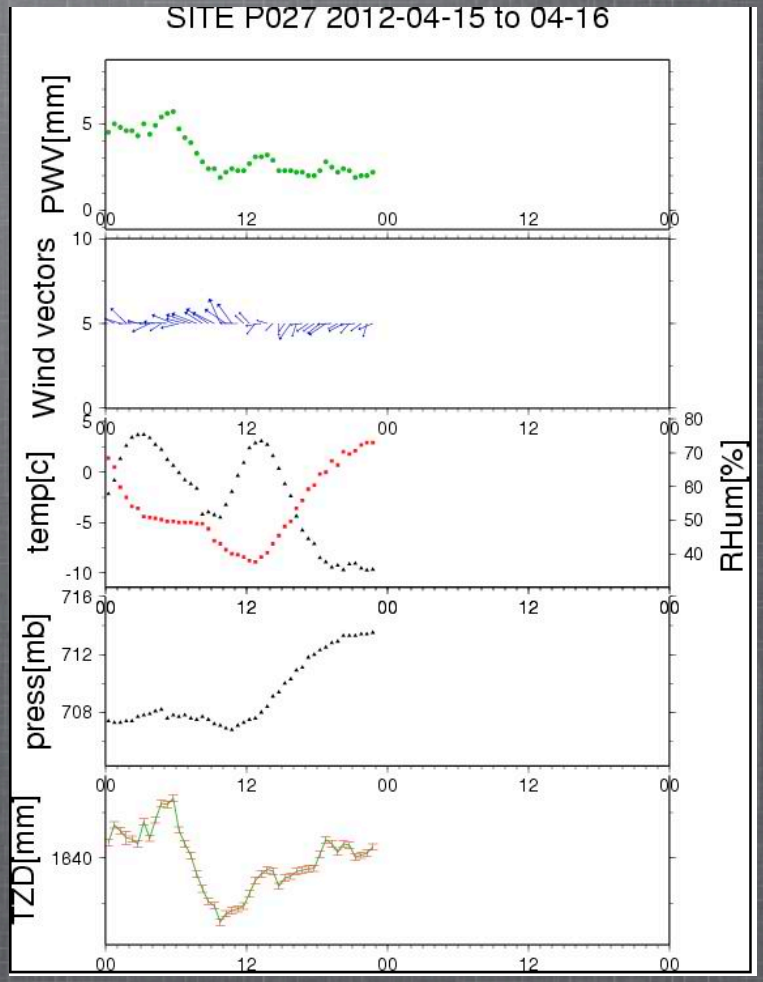
Suominet Network



http://www.suominet.ucar.edu/

Ware et al. 2000

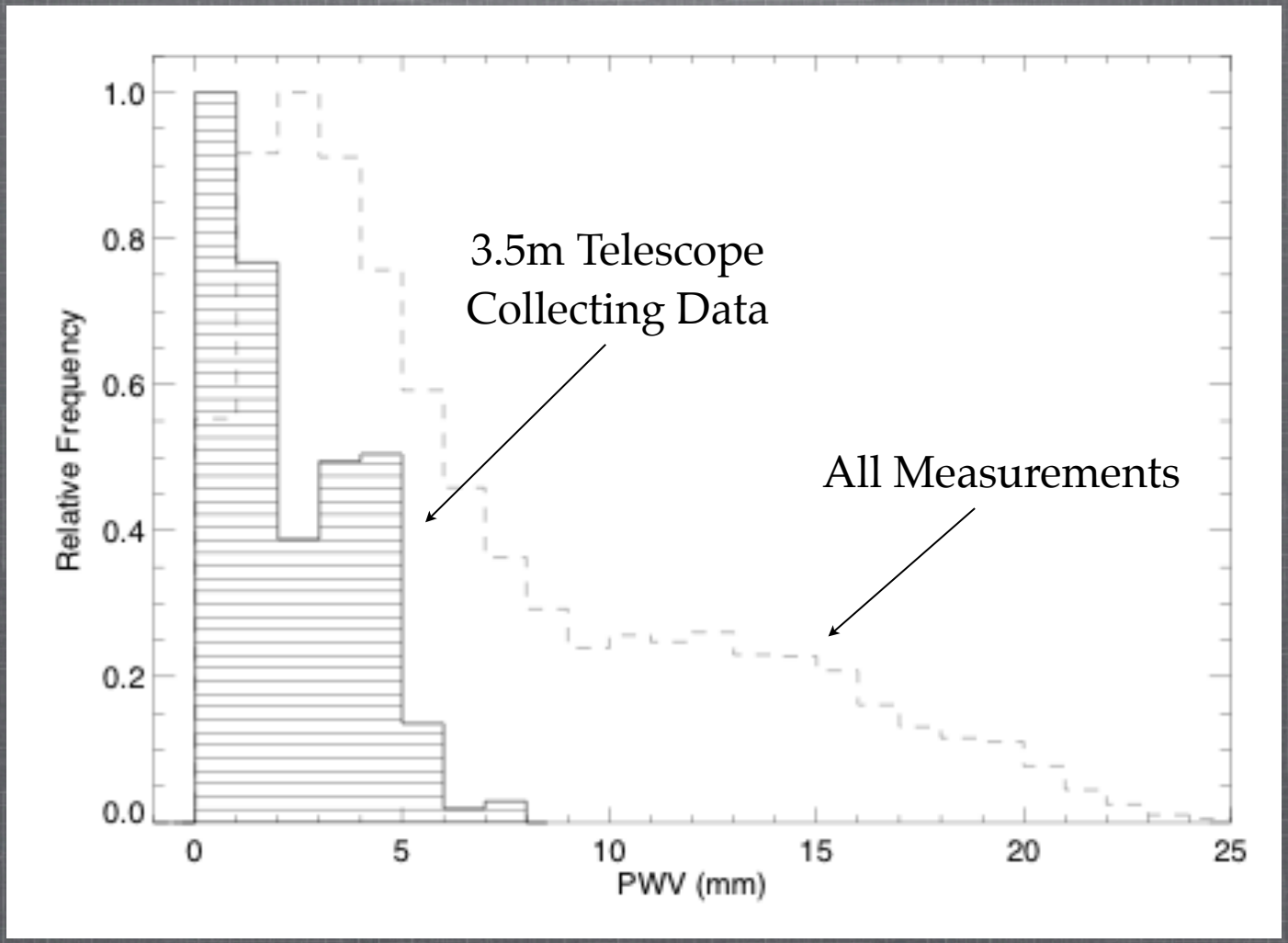
PWV Monitor at Apache Point



Data Processed in Real Time by Suominet Project
PWV Estimates Every 30 Minutes

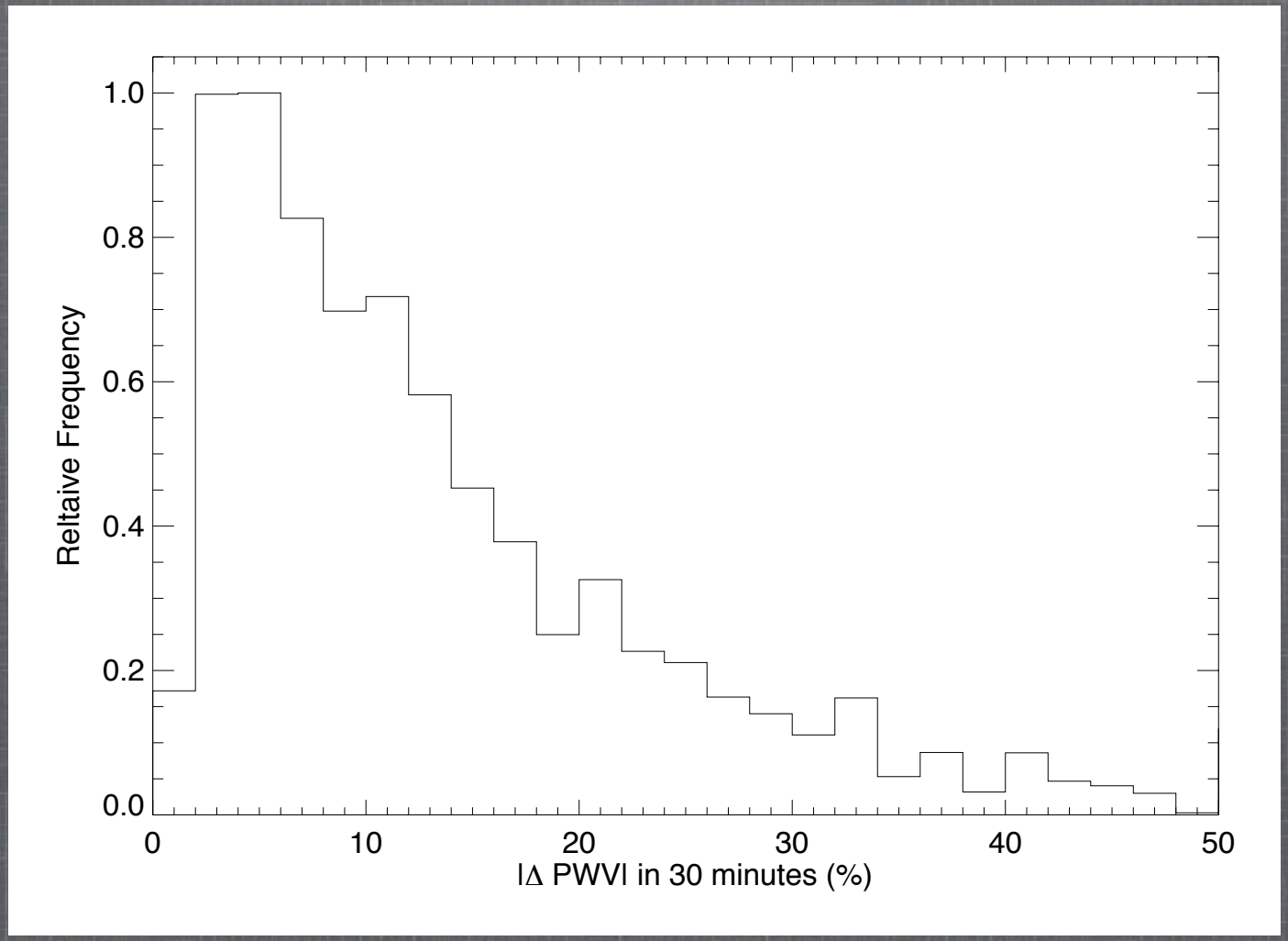
Lots of Great Work on Astronomical Applications of PWV Monitors:
Talk by Kerber; Kerber 2010, Thomas-Osip 2007, Querel 2008,2011, Otarola 2011, Seifahrt 2010

Water Vapor: Highly Variable



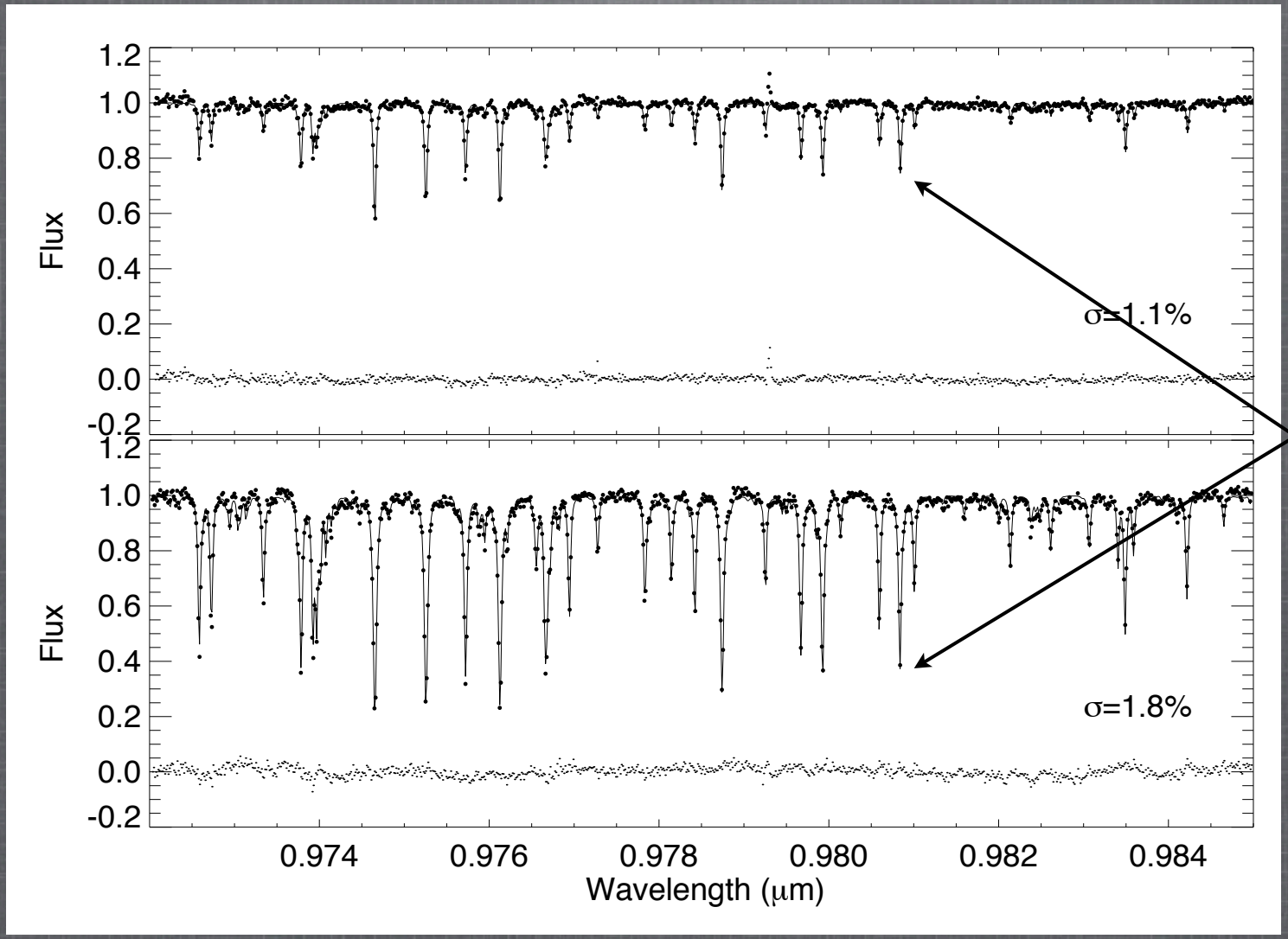
PWV at Apache Point Observatory

Water Vapor: Highly Variable



Histogram of Change in PWV Over 30 min Intervals
Two Years of "Good" Observing Conditions at APO

A Star Observations



ARCES on 3.5m at APO

100 Observations Over 1 Year, R=30,000 S/N~150

Forward Modeling of Spectra

Theoretical Telluric Templates

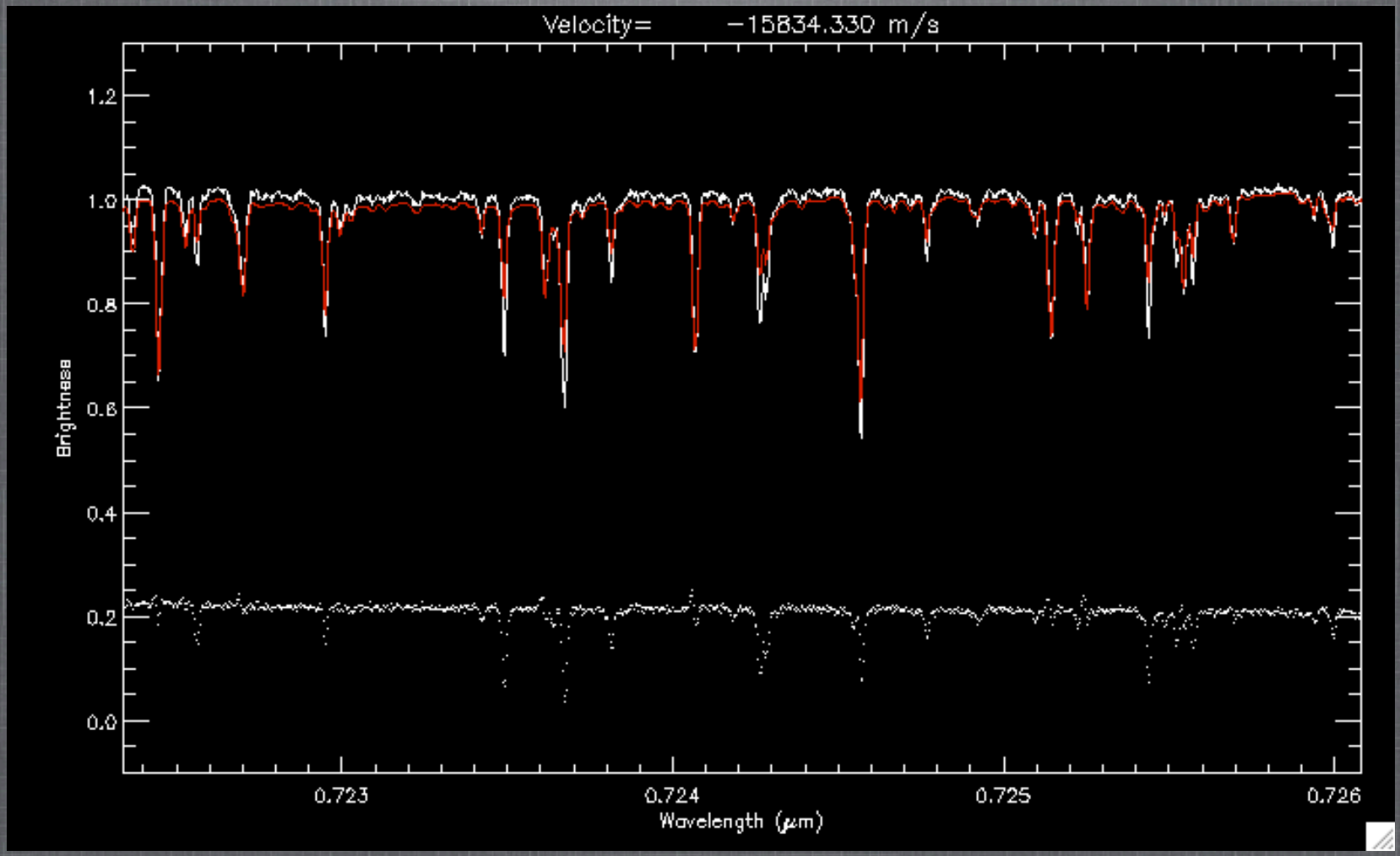
Custom Line-by-Line Radiative Transfer Code:

Fitting Telluric Templates to A Star Spectra

Free Parameters:

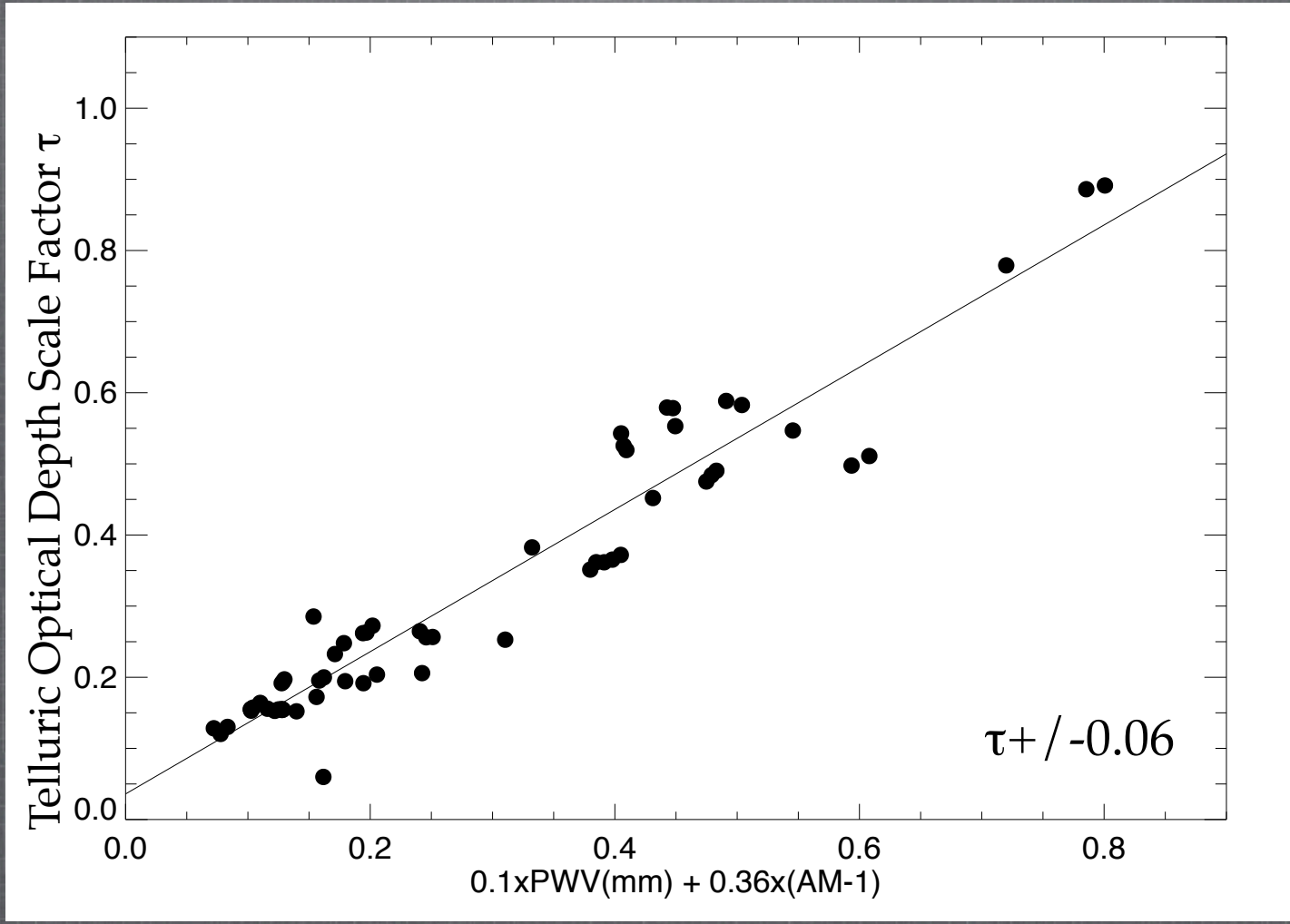
- Pixel-to-Wavelength Solution
- Spectrograph Line Spread Function
- Relative Water Vapor Optical Depth (τ)

Forward Modeling



Fit RMS Typically 1% for Unsaturated Lines

GPS-based PWV vs. Observed Line Depths

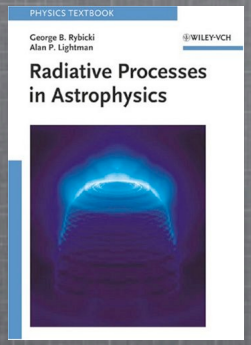


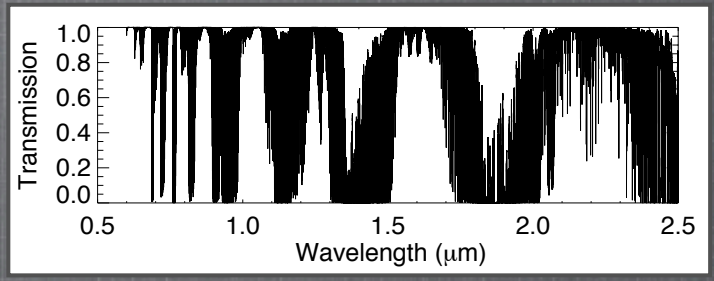
Strong Correlation Between Best-fit Scale Factor and PWV
Also Depends on Airmass

Blake & Shaw, 2011,PASP, 123, 1302

Applications

Precise Telluric Models:

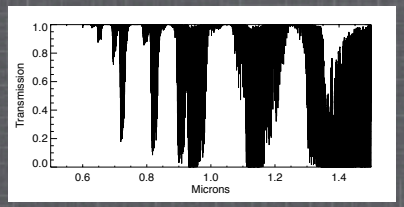


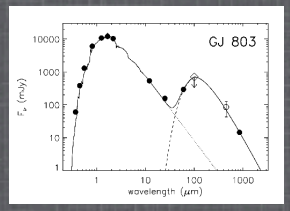


No Free Parameters
Match Observed (Unsaturated)
Lines to ~1%

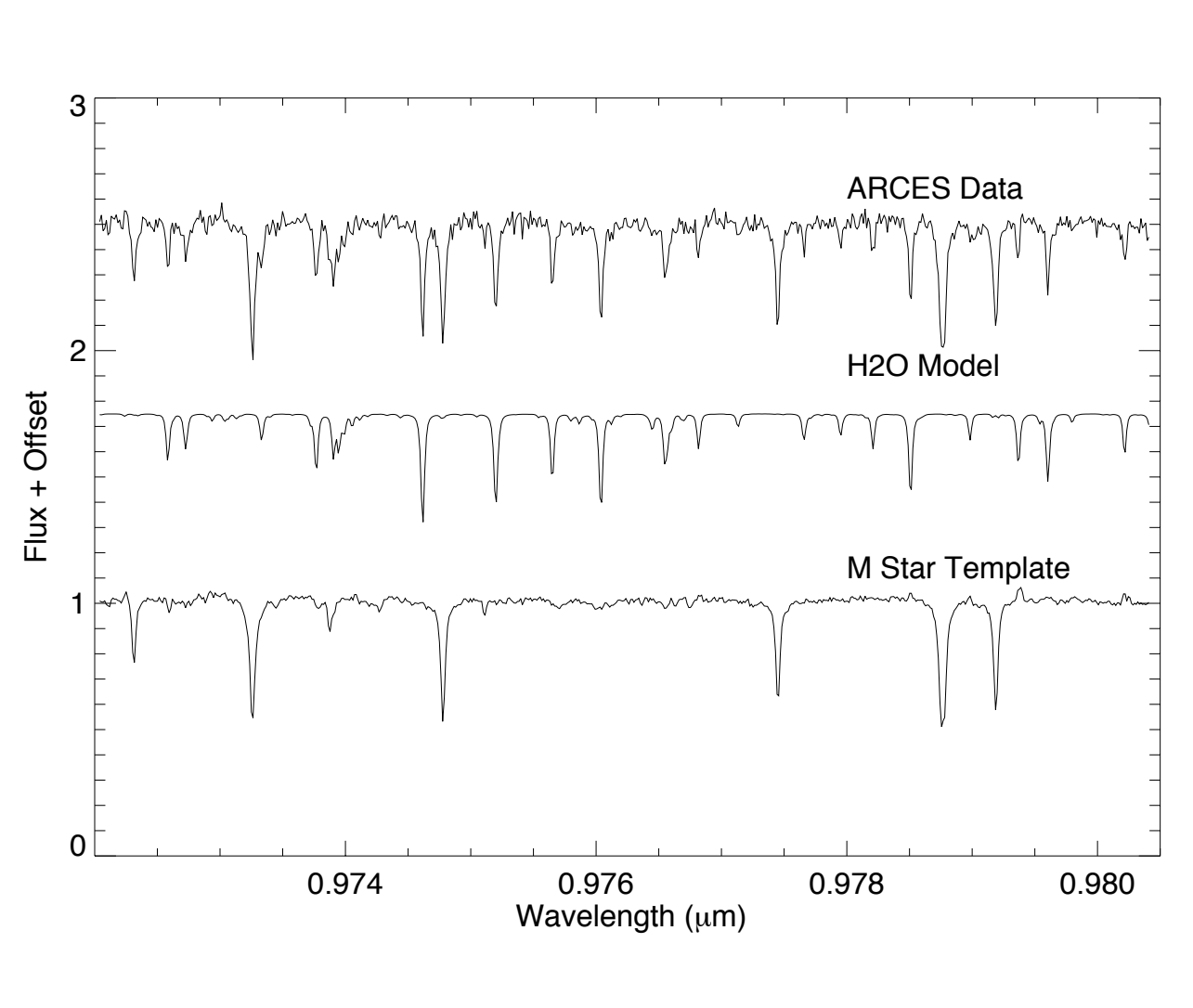
Correcting NIR Photometry:

$$\int \text{Earth Atmosphere} \times \text{Filter} \times \text{Source SED}\, d\lambda$$



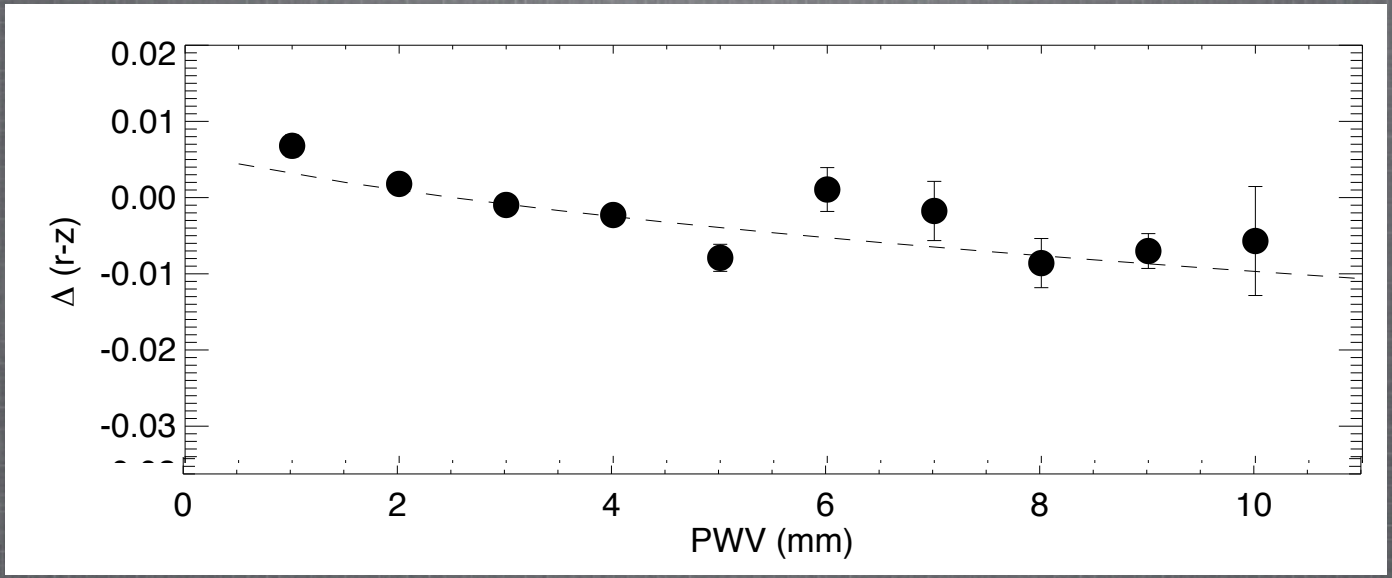


NIR Radial Velocity Measurements



Telluric Lines as a Simultaneous Absorption Reference

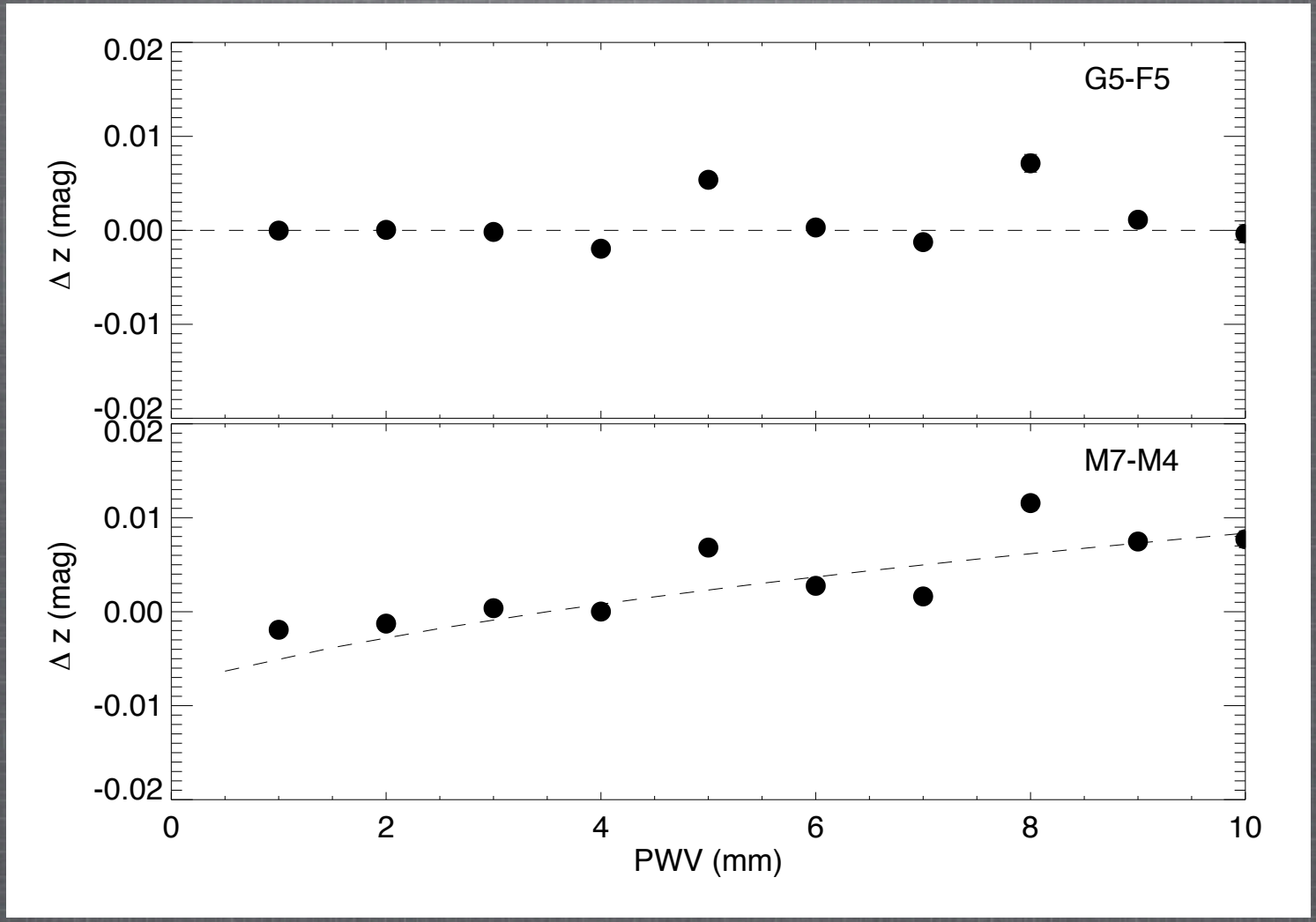
SDSS Photometry of Cool Stars



Points: *Calibrated* r-z Colors of SDSS M Dwarfs Relative to Stellar Locus

Dashed Line: Estimate of PWV Bias
Assumes SDSS Photometric Solutions Based on an F star

SDSS Photometry of Cool Stars



Calibrated Photometry of G-F and mid-M stars from Stripe 82
Important for Transiting Planet Searches Targeting M Stars

Conclusions

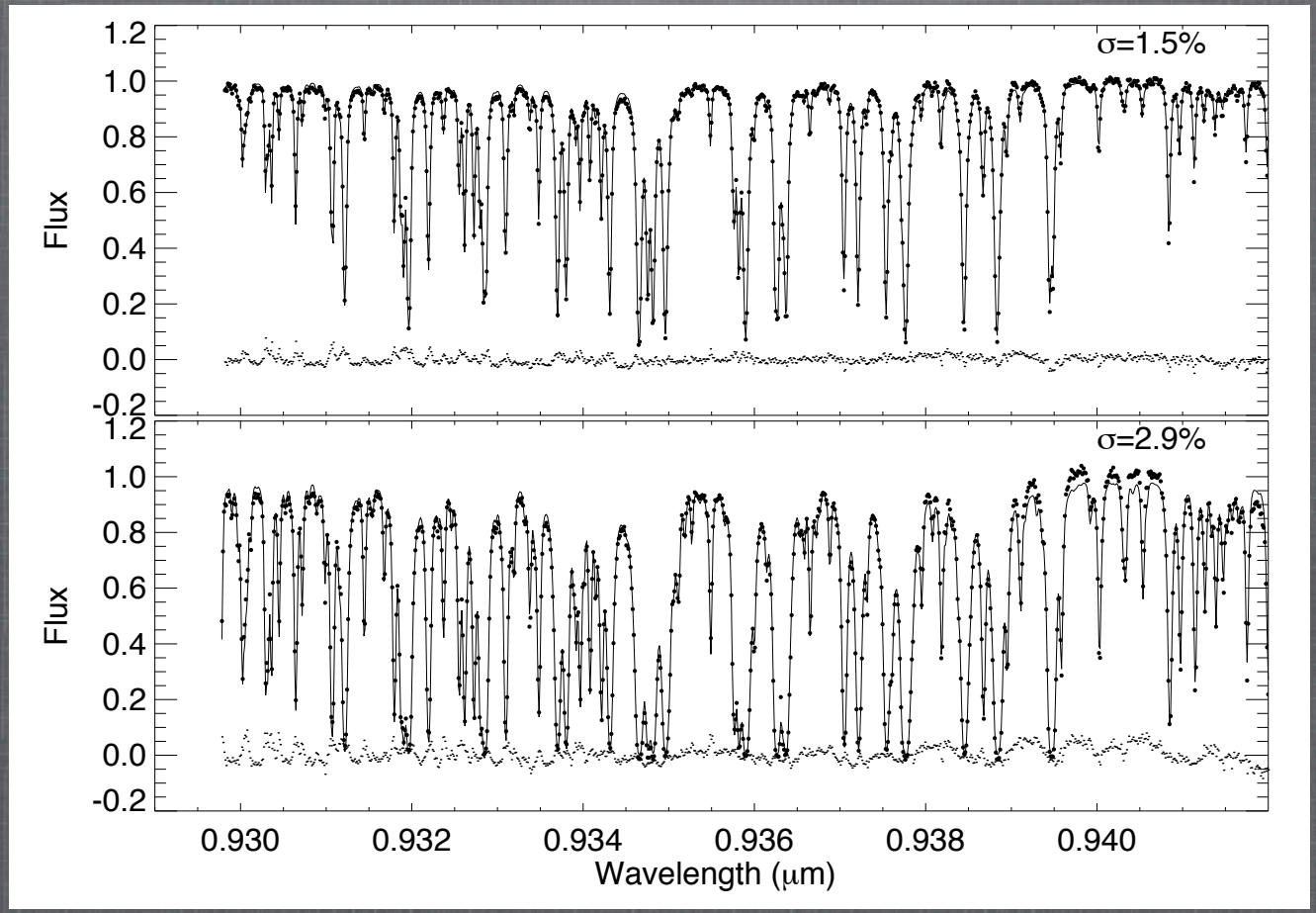
GPS-based PWV Estimates are Useful for Astronomy!

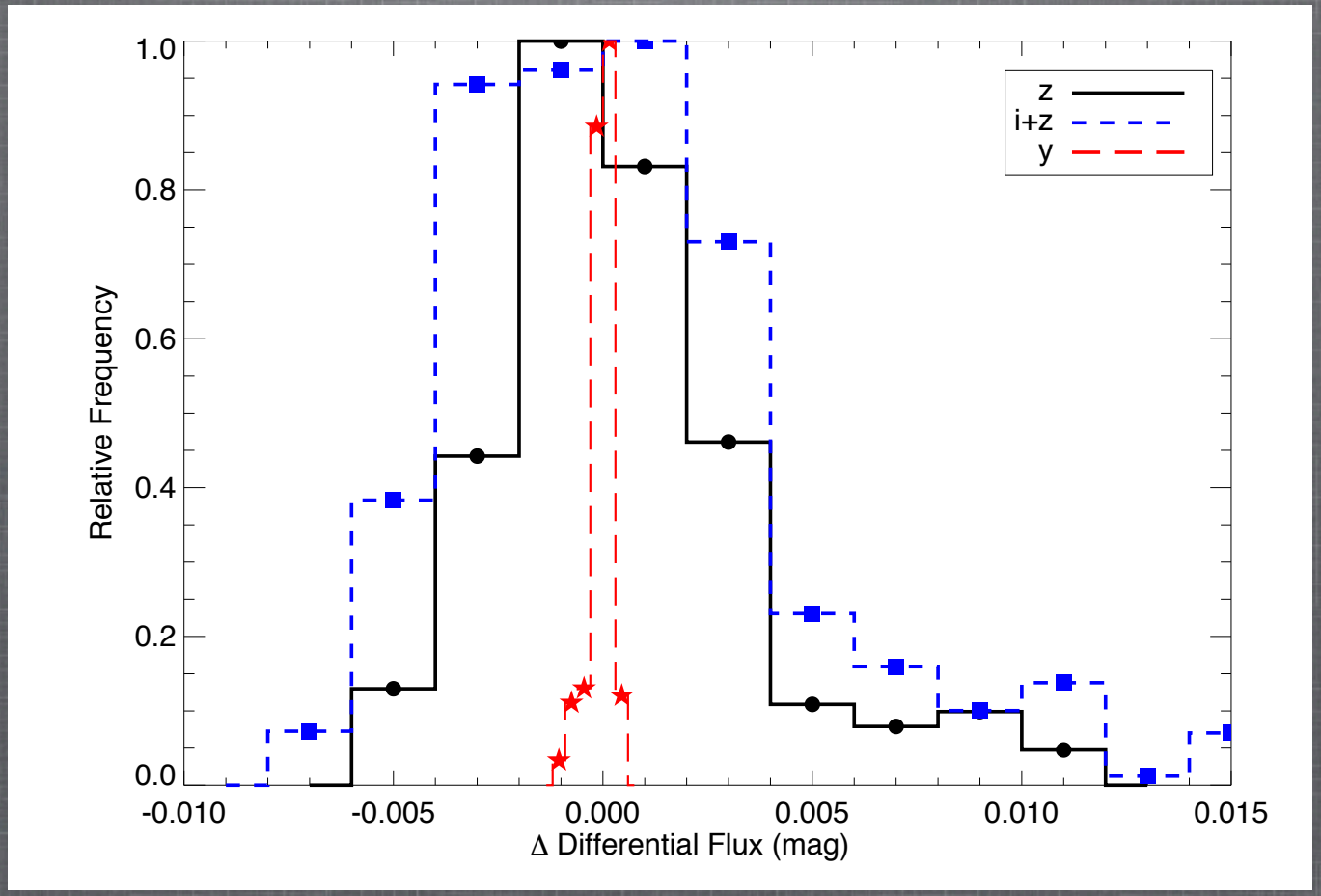
These Measurements Can Be Used to Generate Excellent Telluric Templates

These Templates Have Many Uses:

- Correct Relative Photometry of Cool Stars
- Radial Velocities and High-resolution NIR Spectroscopy

Future: A Network of Stations to Measure 3D Water Distribution in Real Time?


σ=1.5%
σ=2.9%
Flux
Flux
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
0.930
0.932
0.934
0.936
0.938
0.940
Wavelength (μm)


1.0
0.8
0.6
0.4
0.2
0.0
Relative Frequency
-0.010
-0.005
0.000
0.005
0.010
0.015
Δ Differential Flux (mag)
z
i+z
y