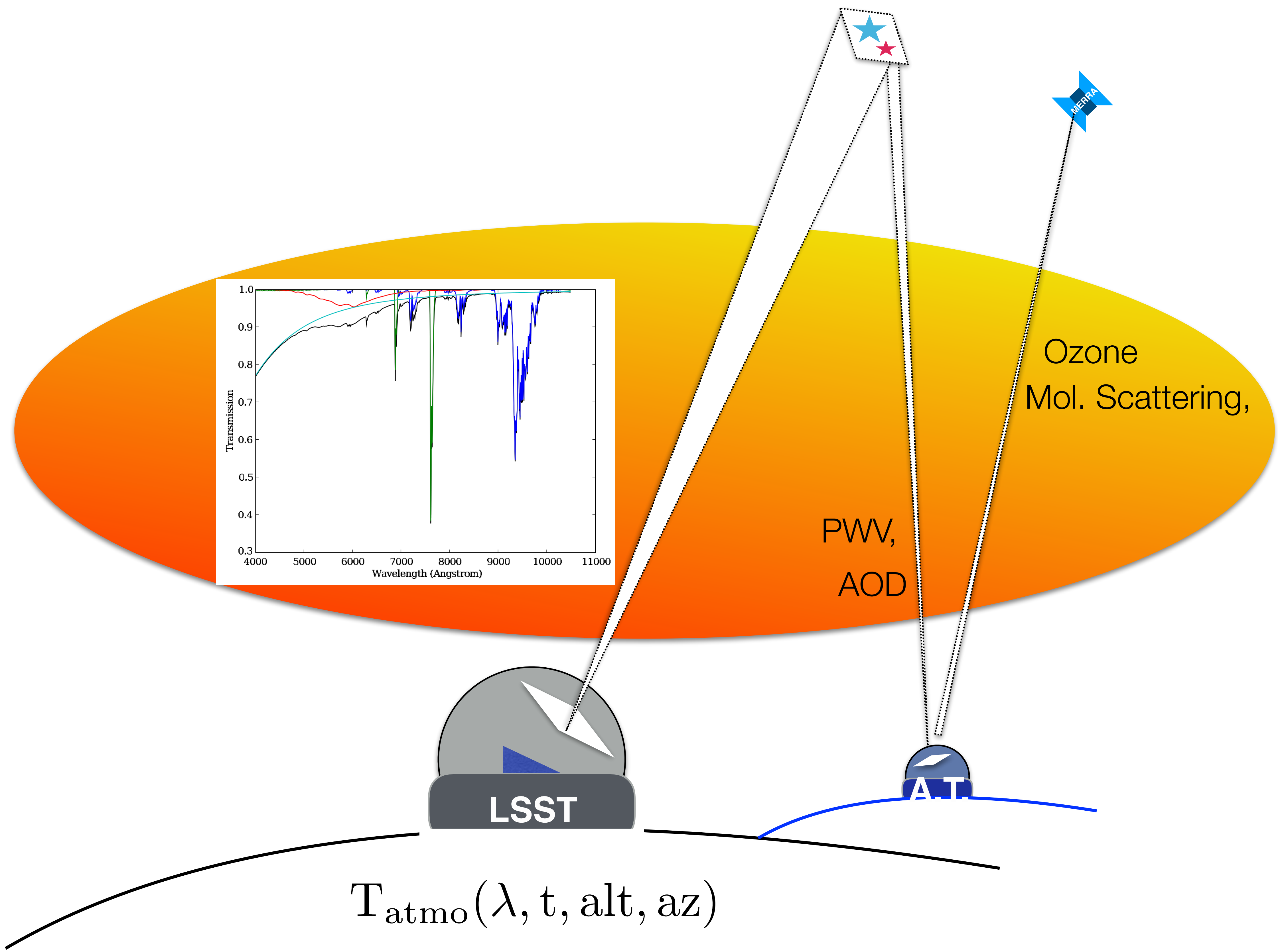
A.T. Observation strategy :

(Redundant) (Composite) Forward Atmospheric Modeling



$$T_{atmo}(\lambda, t, alt, az)$$

Strategies

To deliver a ‰ level monitoring of atmospheric transparency

10-4 electronic	Steady sources	MERRA-2	SED	Telescope Throughput	AOD+PWV+Mol.Scattering+Ozone Model from
✔	✔	✔	✔	✔	Global fit+priors
✔	✔	✔	✔		Global fit+priors+nuisance parameters
✔	✔	✔			Splitted fit
✔	✔				Hopeless global fit

Variability is introduced either by

The target
The atmosphere
The extraction

An holistic approach, that is, exploring all methods:

1) Global fit @ CTIO 0.9m

2) SNFactory @ Mauna Kea

3) Composite solution @ CTIO 0.9m

4) PCWG experts + data challenge

Global fit + priors + (nuisance parameters)

- CALSPEC SED and atmospheric transmission from Libradtran

$$\Phi(\lambda;\sigma,\mathrm{atm}) = [SED(\lambda) \times T(\lambda, \mathrm{PWV}, \mathrm{VAOD}, \mathrm{OZ})] * G(\sigma)$$

$$S(\lambda;\mathrm{params}) = A_1 \left[\Phi\left(\lambda(D_{CCD}, \alpha_{pix})\right) + A_2 \Phi\left(\frac{1}{2}\lambda(D_{CCD}, \alpha_{pix})\right)\right]$$

- 8 parameters to fit (3 atmospheric, 5 instrumental): python EMCEE

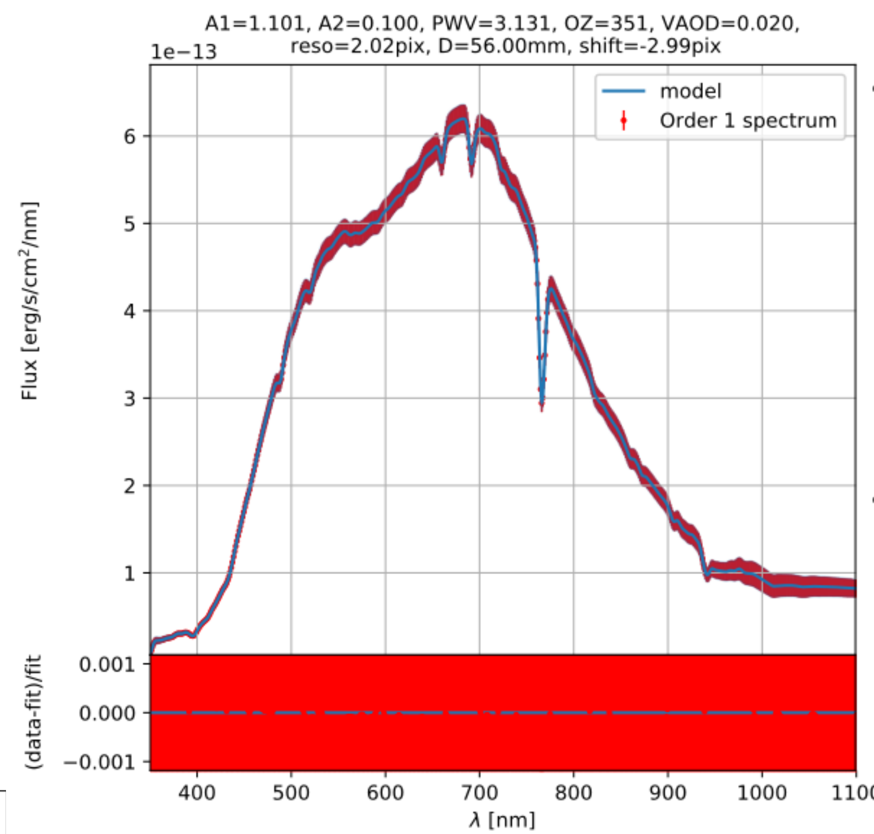
Atmospheric parameters:
PWV: water: VAOD: aerosols: OZ: ozone

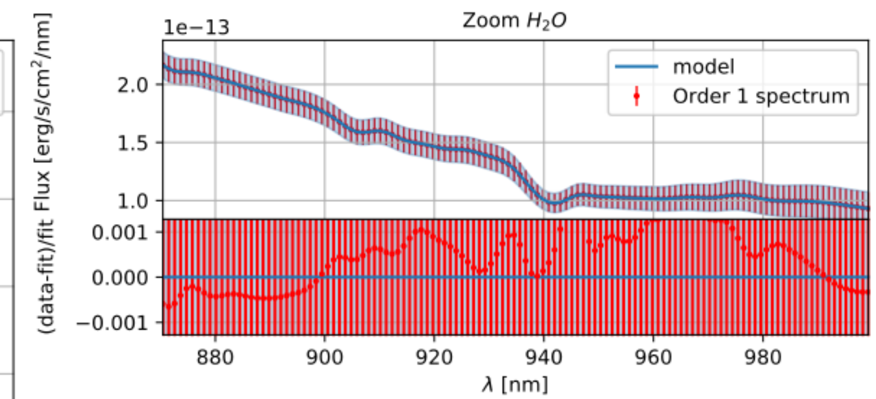
Instrumental effects:

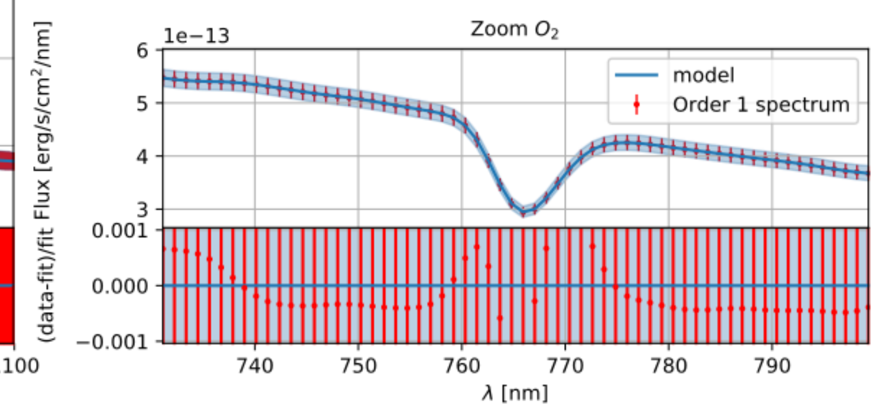
- A_1,: general amplitude of the spectrum
- A_2 : level of the order 2 contamination
- $G(\sigma)$: Gaussian convolution with σ modeling the resolution and the seeing
- D_{CCD}: the distance between the CCD and the disperser
- α_{pix}: shift in pixels on the order 0 position to calibrate the wavelengths

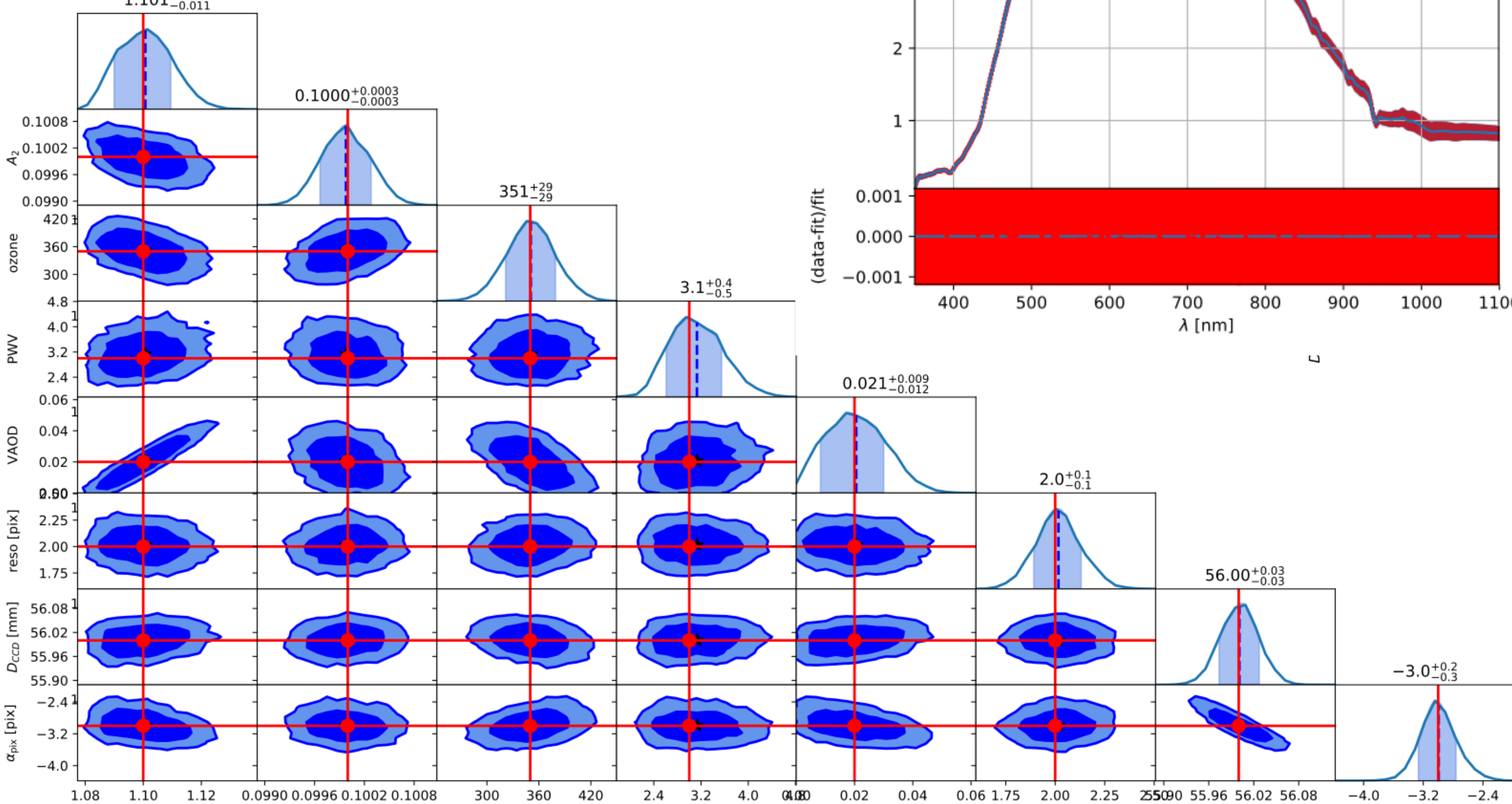
Test of the fitter on a simulated spectra

Target: HD111980









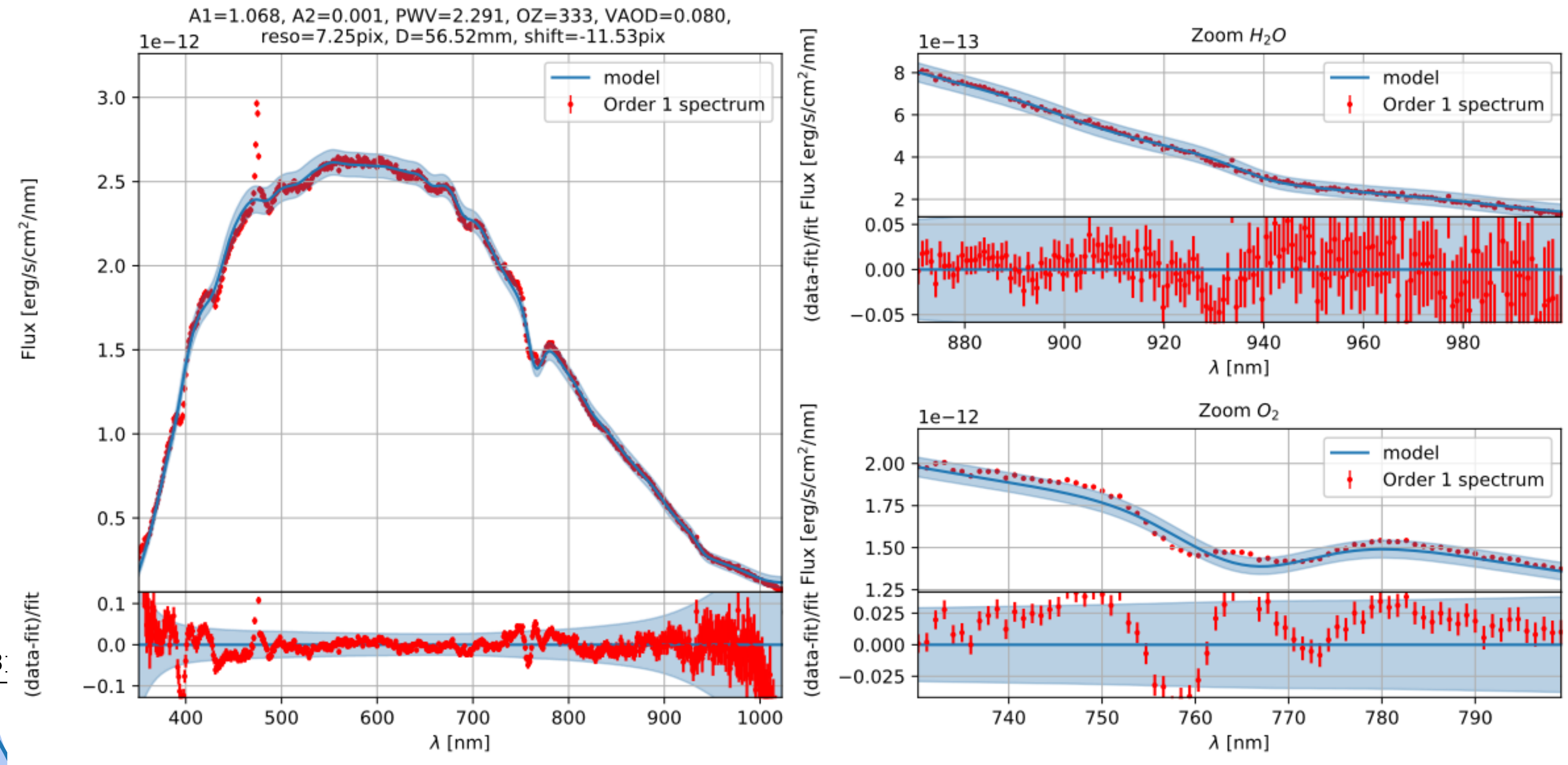
A1 **A2** **ozone** **PWV** **AOD** **reso (pix)** **Dccd (mm)** **α (pix)**

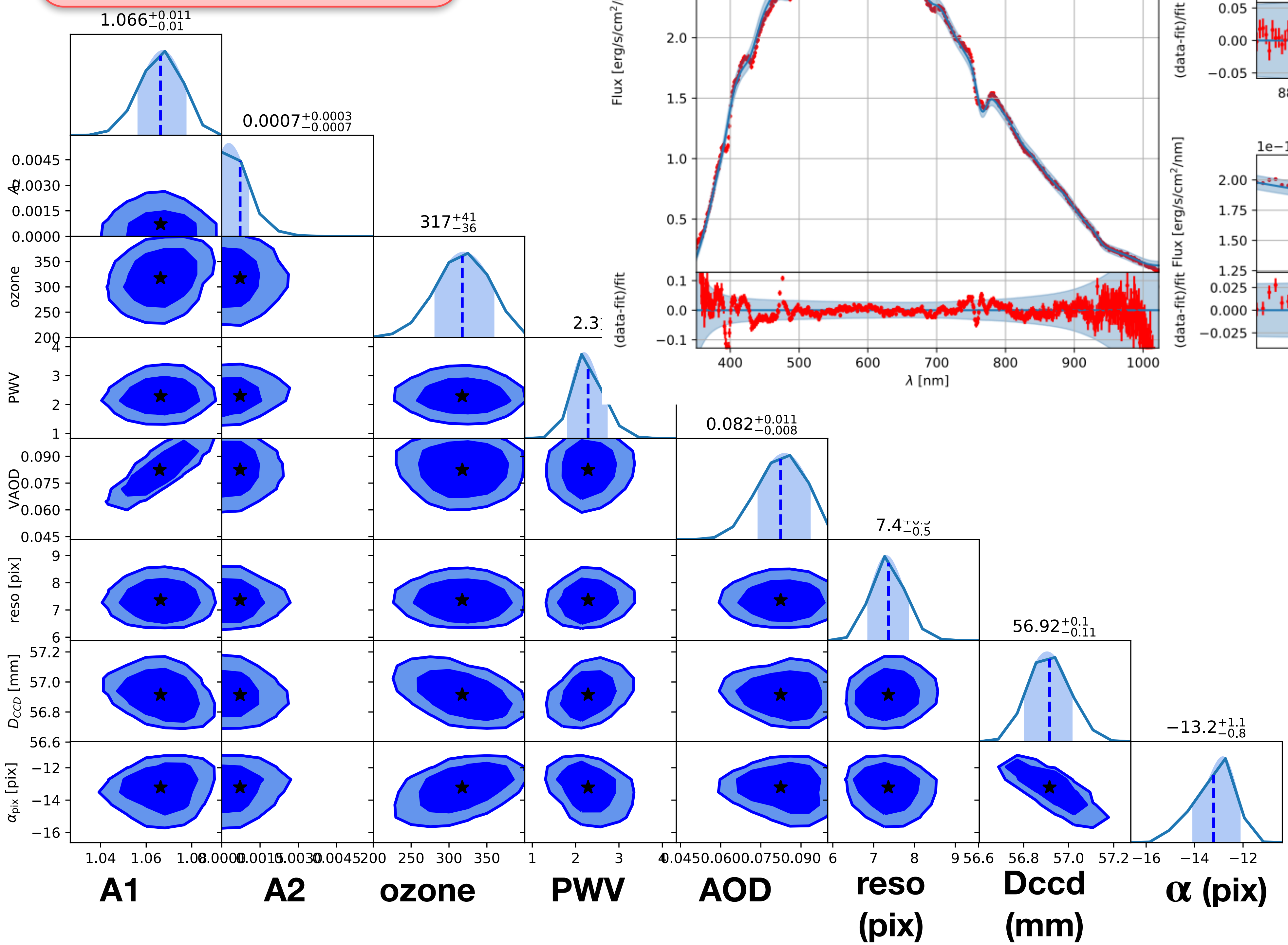
MCMC OK.

Global fit + priors + (nuisance parameters)

Ronchi 400: #130 2017/05/31 02h45 UTC

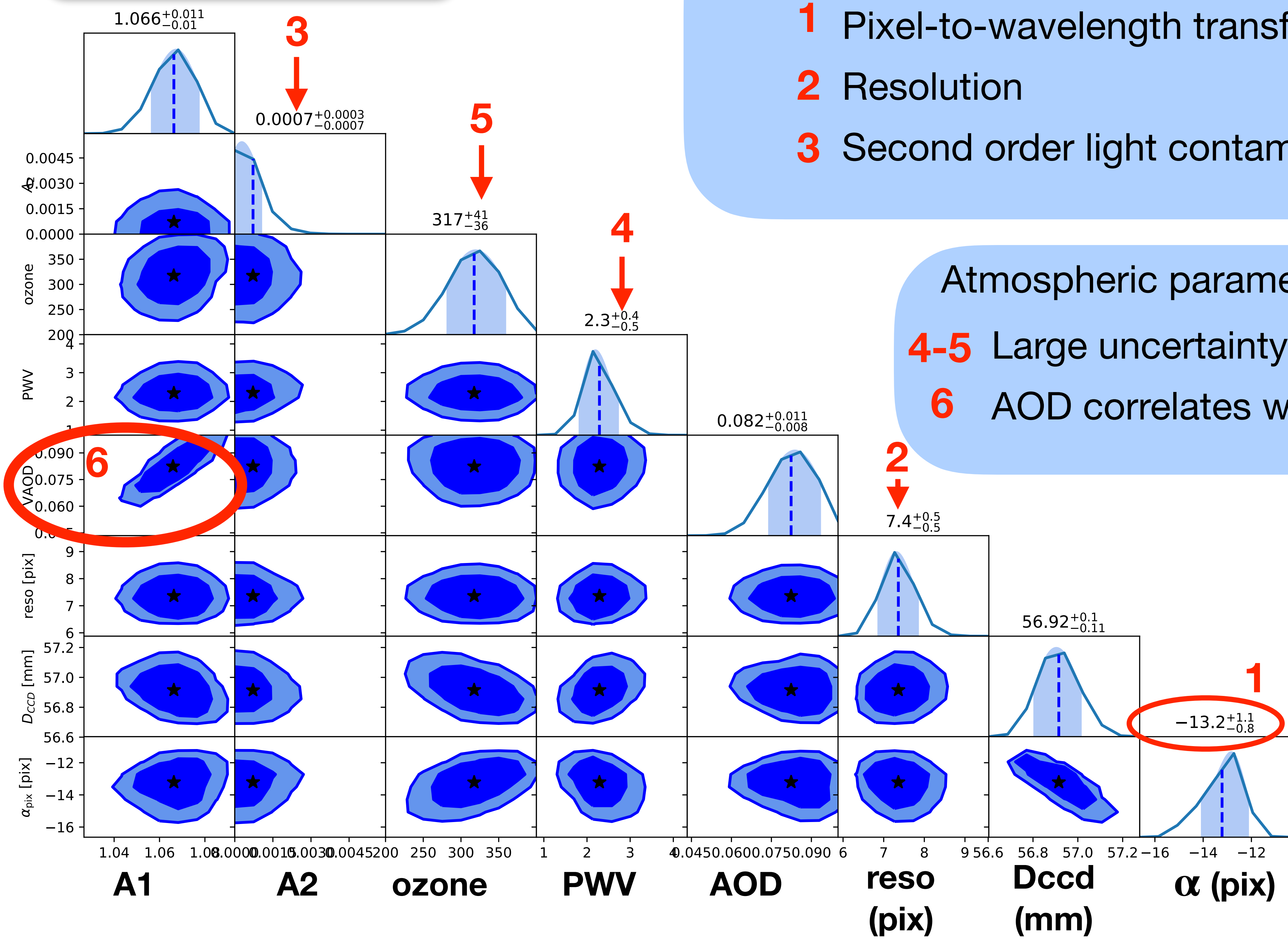
Target: HD111980





Ronchi 400: #130 2017/05/31 02h45 UTC

Target: HD111980



Nuisance parameters

1. Pixel-to-wavelength transformation
2. Resolution
3. Second order light contamination

Atmospheric parameters

4-5 Large uncertainty on PWV and ozone

6 AOD correlates with telescope throughput

Global fit - Lesson learnt from SNFactory

Atmospheric extinction properties above Mauna Kea from the Nearby Supernova Factory spectro-photometric data set

https://arxiv.org/pdf/1210.2619.pdf

- Snif instrument on the UH telescope at Mauna Kea has been routinely observing standard stars since 2006.
- 4285 spectra from 478 nights.
- Overnight instrument response stability much better than 1%.
- Spectra extraction based on a detailed optical model.
- Wavelength-calibrated using arc lamp exposures acquired immediately after the science exposures.
- Spectro-spatially flatfielded using continuum lamp exposures obtained during the same night.
- Chromatic semi-analytical PSF model (a constrained sum of a Gaussian and a Moffat function) fit over a uniform background.

Global fit - Lesson learn from SNFactory

Residuals of the $\chi 2$ for an individual observation *i* of the atmospheric extinction in mag/airmass :

$$\mathcal{R}_i = \log C(\lambda) - 0.4 \times K_{\mathrm{atm}}(\lambda, \hat{z}) + \log \delta T_i(\hat{z}, t) - \log \frac{S_i(\lambda, \hat{z}, t)}{\overline{S}_i(\lambda)}$$

Instrument calibration

Gray extinction

SED

O3, aerosols

Prior	Value	Scaling
$I^{\star}_{O_3}$	260 ± 50 DU	linear
$\tau^{\star}$	0.007 ± 80%	logarithmic
$å^{\star}$	1 ± 3	linear

(Gaussian) Bayesian priors

- Rayleigh scattering is not adjusted, it is determined from the surface pressure.
- Telluric lines are adjusted in a different step.
- There is a degeneracy between δT and $\tau \sim \lambda$ 0 on non-photometric nights,
- And between δT and C.

Global fit - Lesson learn from SNFactory

O2 lines fluctuations are remarkably small.

Rayleigh extinction

Peak-to-peak variation of 6 mbar around 616 mbar.

Dispersion of 2 mbar which translate into **2 mmag/airmass** at the blue edge.

Ozone Varying mostly on seasonal timescales.

60 DU uncertainty with no prior.

Difficult to detect 20 DU variation (**4 mmag/airmass** at 6000 Å.)

—> Better to use a dedicated probe.

H2O Has large fluctuations.

Aerosol Largest contributor to the variability of the extinction continuum from one night to another.

~10-40 mmag/airmass overnight—> the primary concern for extinction variations.

δT is degenerated with an aerosol extinction having an Ångstrom exponent of zero.

limited temporal sampling during each night —> difficult to detect extinction variability of less than 1%

Overall relative error of 2-3%

Going beyond the current limitations with a composite solution
Using MERRA-2 global modeling system:

Ozone MERRA-2 tables provides an accurate estimate.

Molecular scattering

MERRA-2 tables and weather balloons are in excellent agreement.

—> Impact LibRadTran transmission by < ‰.

PWV Smooth variation and axis-symmetry approximations are not valid.

—> H_2O EW [880 - 990] nm from single order blocking filter exposure.

AOD Degenerated both with telescope throughput and SED uncertainties

—> Pair of exposures method.

MERRA-2 ozone

< Oct. 1st. 2004

From Solar Backscatter Ultra Violet Radiometers (SBUV)

Assimilates partial column ozone on 21 layers, each ~3km deep.

> Oct. 1st. 2004

Stratospheric profiles from the Microwave Limb Sounder (MLS, Waters et al. 2006) instrument and total ozone column observations from the Ozone Monitoring Instrument (OMI), Onboard NASA's Earth Observing System Aura (EOS Aura) satellite.

Comparing OMI with ground-based measurements and with aircraft for four campaign missions. (McPeters et al. 2008) :

+ 0.4 % offset with respect to ground-baed measurements,

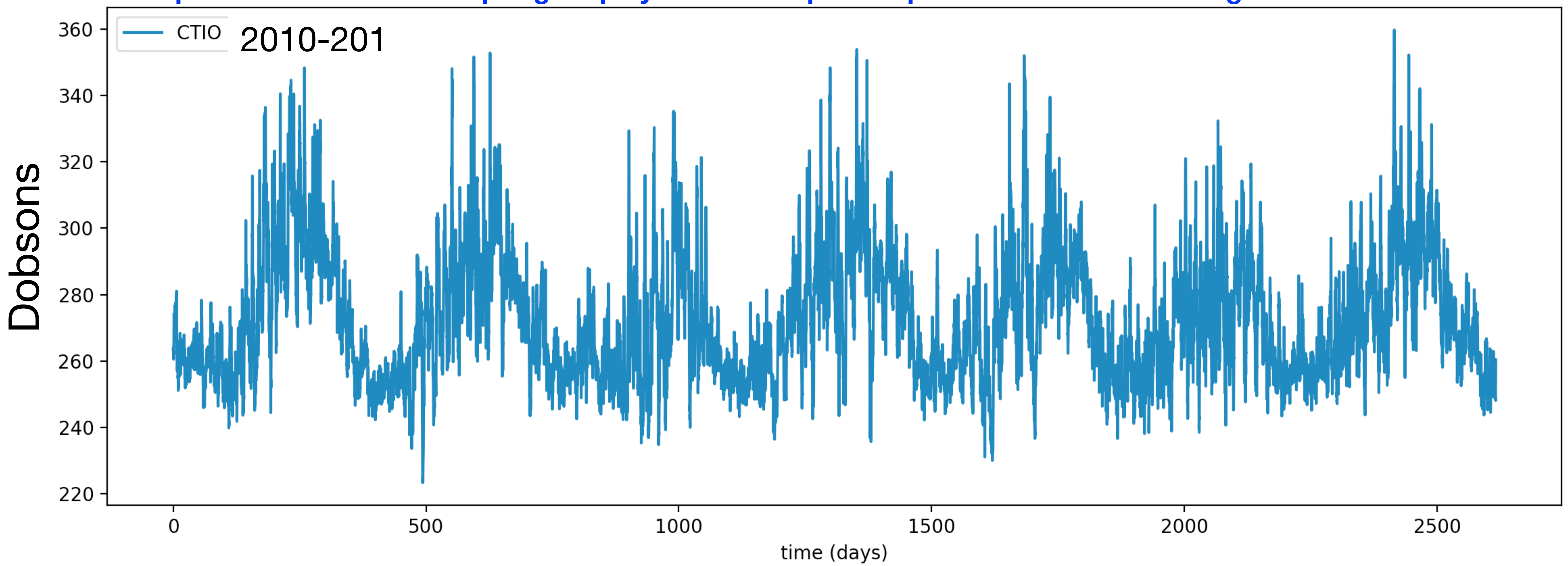
- 0.2 % offset with aircraft measurements and an RMS difference of 3%.

—>For 300 DU, these numbers indicate an offset of ~1 DU and RMS difference of 9 DU.

Chile, 8 years of ozone data above Cerro Pachon

1 Dobson E-W gradient

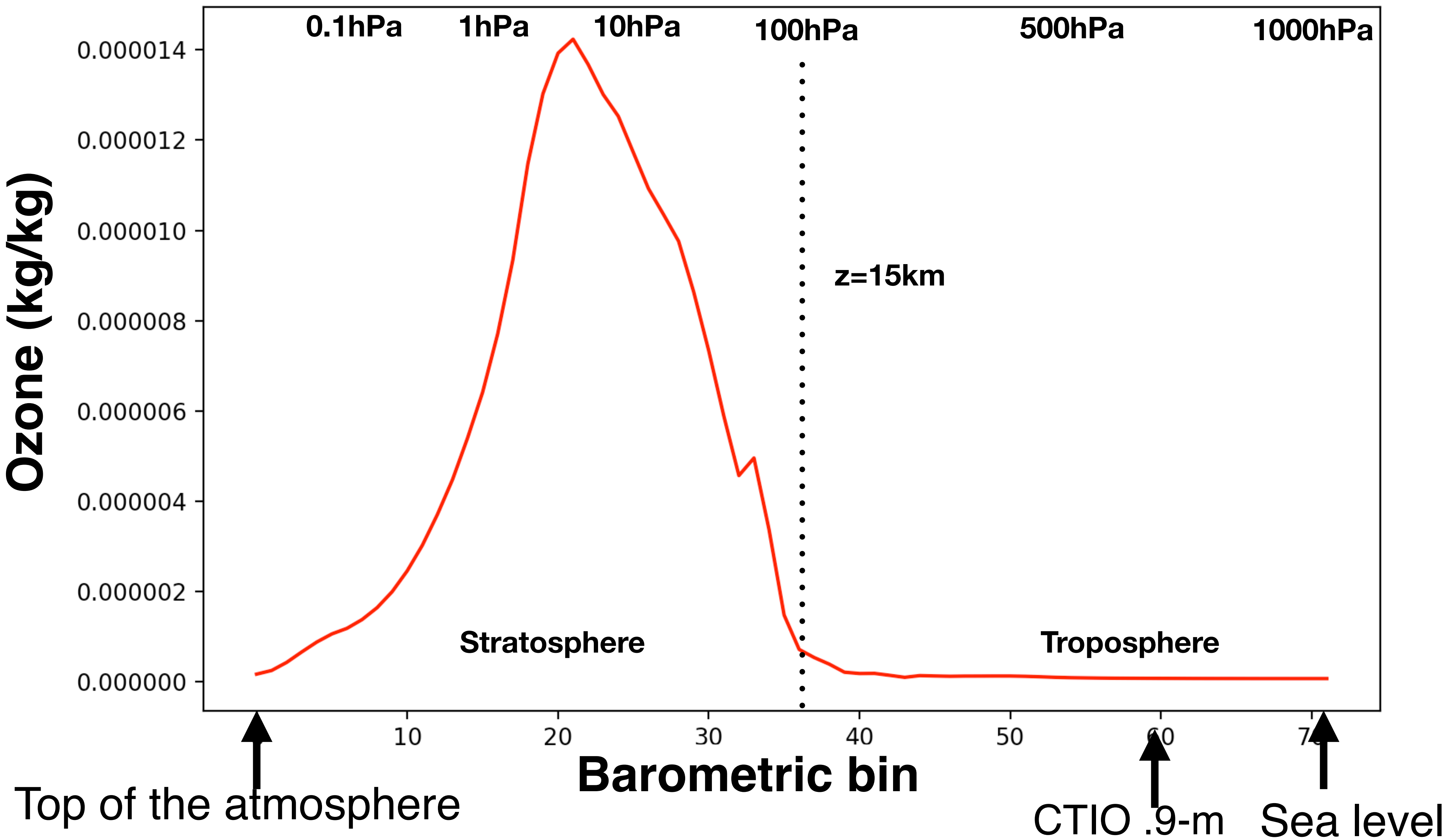
https://confluence.lsstcorp.org/display/DM/Atmospheric+parameters+horizontal+gradients+above+CTIO



—> ~10 DU uncertainty —> 2 mmag/airmass

Ozone above Cerro Pachon resides predominantly in the upper troposphere and lower stratosphere, and driven by jet stream winds, can vary 5%–10% day-to-day around average values that exhibit season variations of 25% or so.

Ozone Vertical profile at CTIO site



The ozone layer is well above the mountains, it is not much affected by local condition

—> 2-D interpolation of MERRA-2 table probably ok

Weather Balloons Vs. MERRA-2

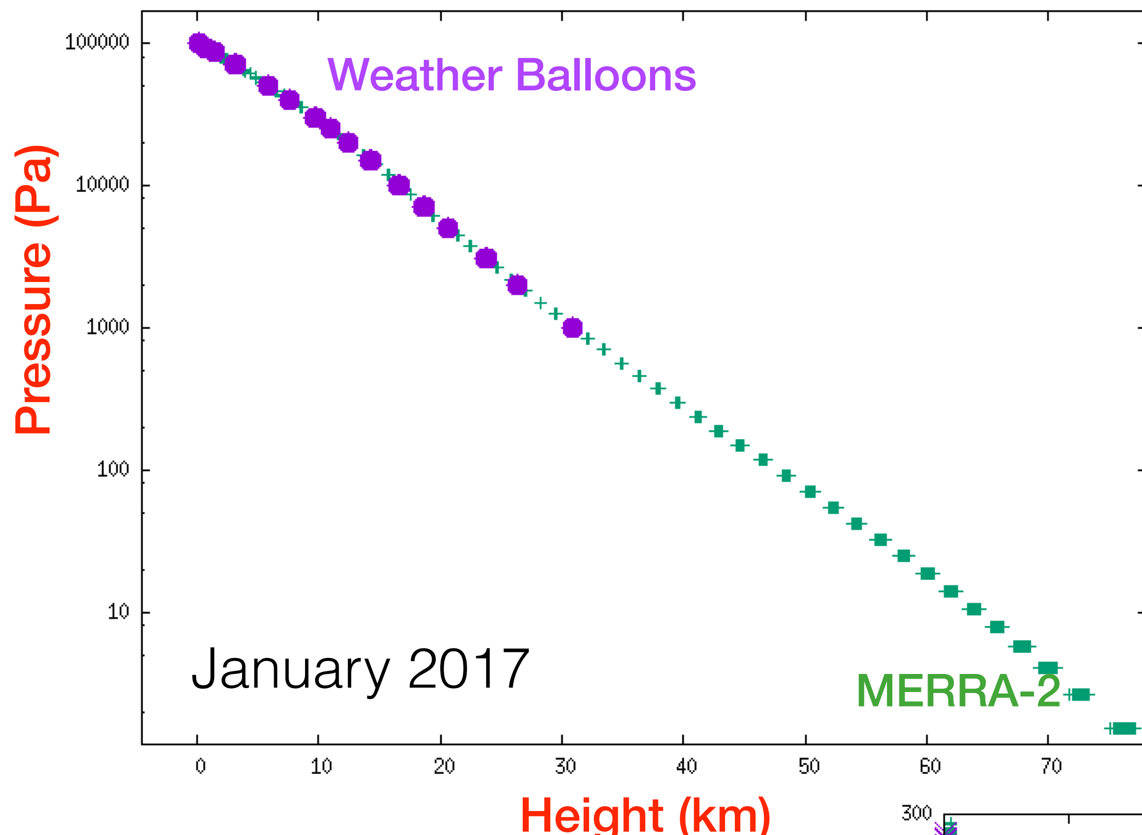
Temperature and barometric profile

Daily launch of weather balloons

Weather Balloons Vs. MERRA-2

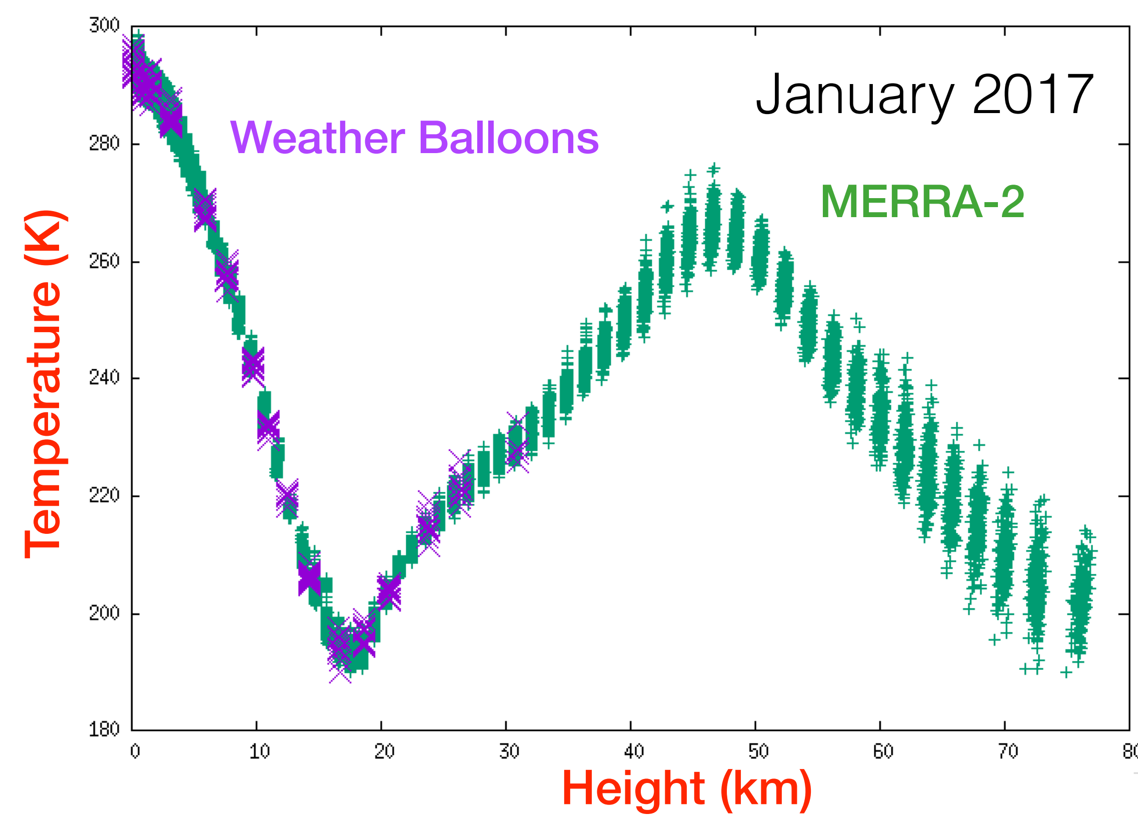
Temperature and barometric profile

Daily launch of weather balloons



excellent agreement…

😬



Weather Balloons Vs. MERRA-2

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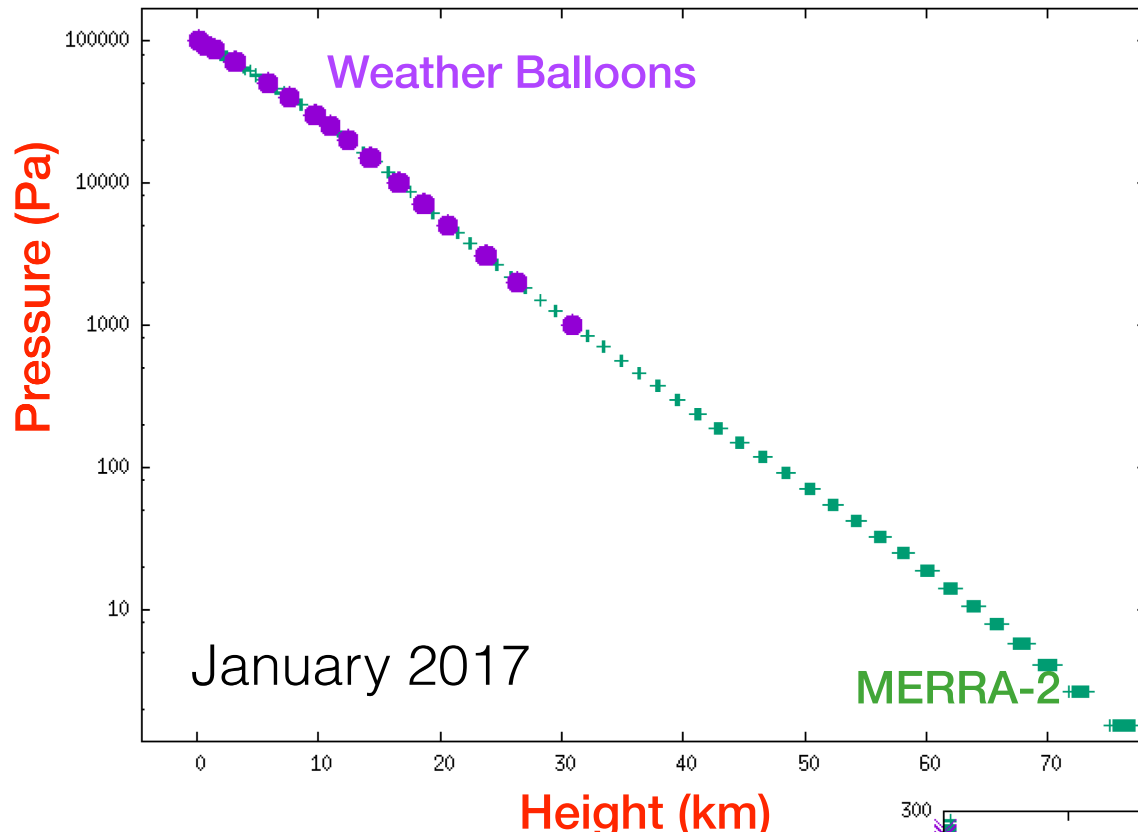
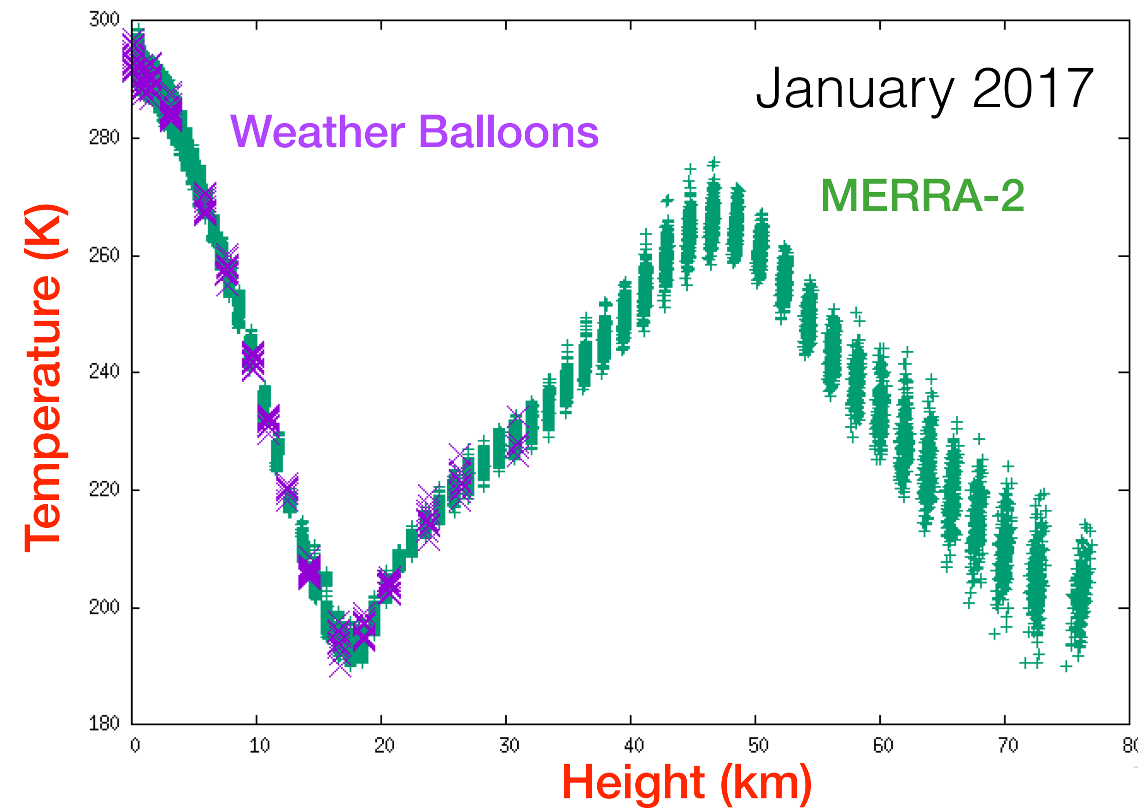


excellent agreement…

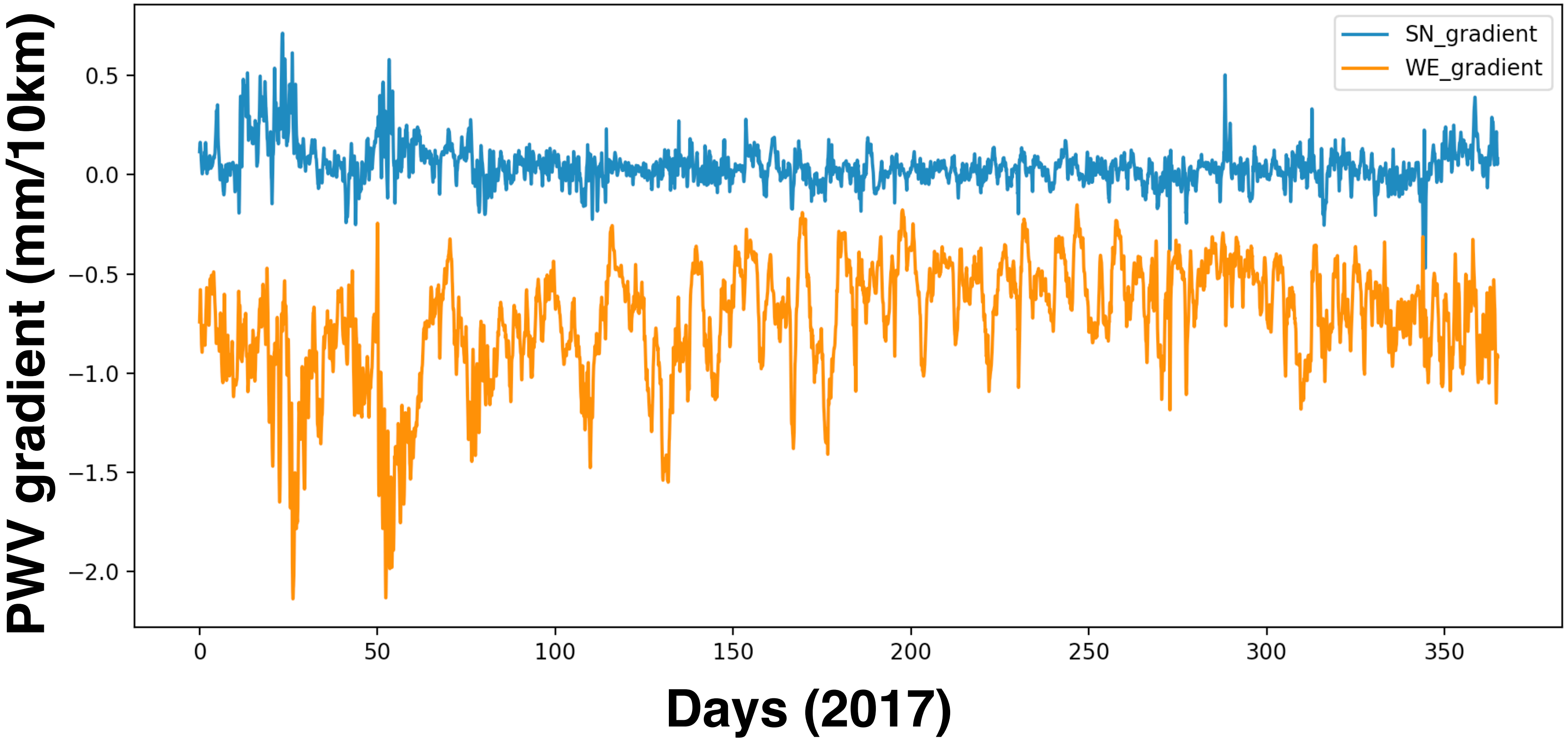
😬

Weather ballons above Cerro Pachon?

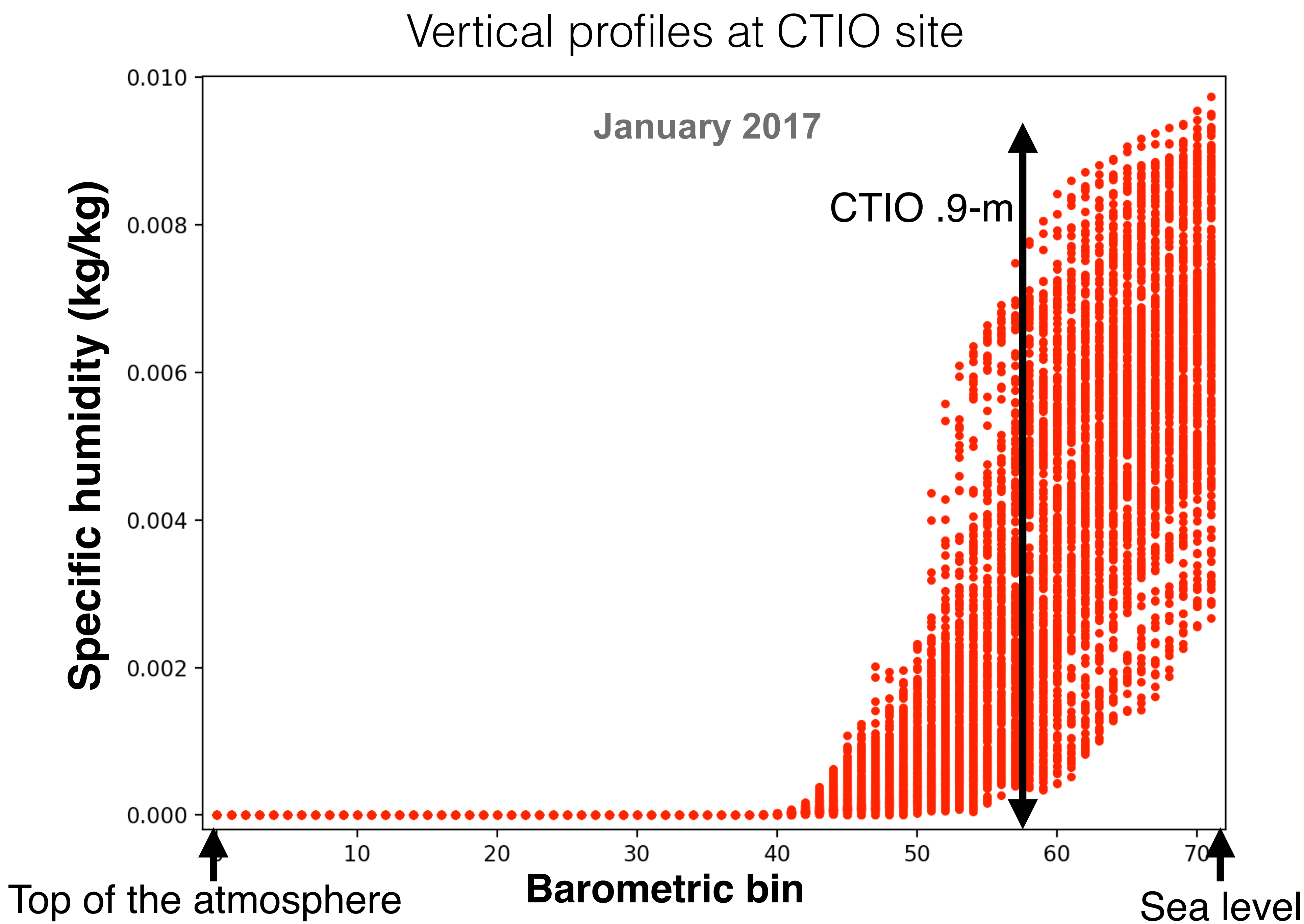


Steady non axis-symmetry of H2O component

- large east-west PWV gradient.



Strong variability near the ground layer

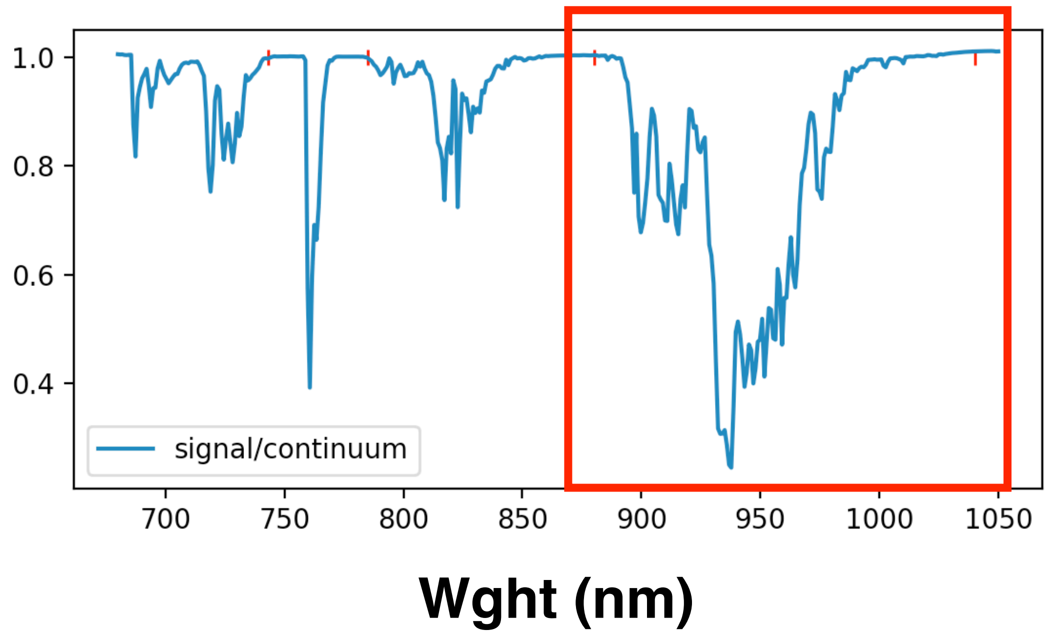


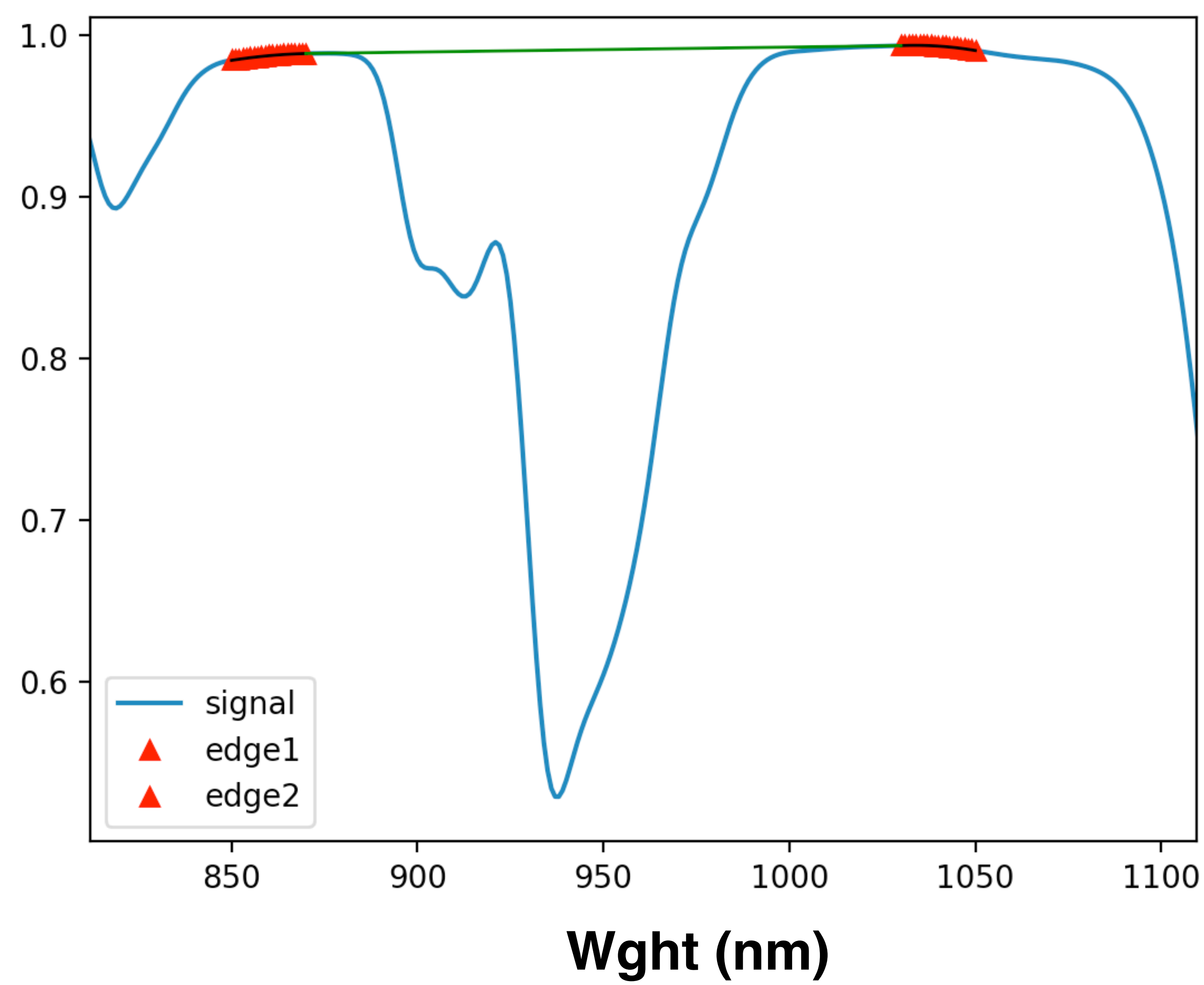
MERRA-2 PWV profiles may not represent the local atmospheric conditions of the geographical position and height of the observing site.

Measurement along the line-of-sight

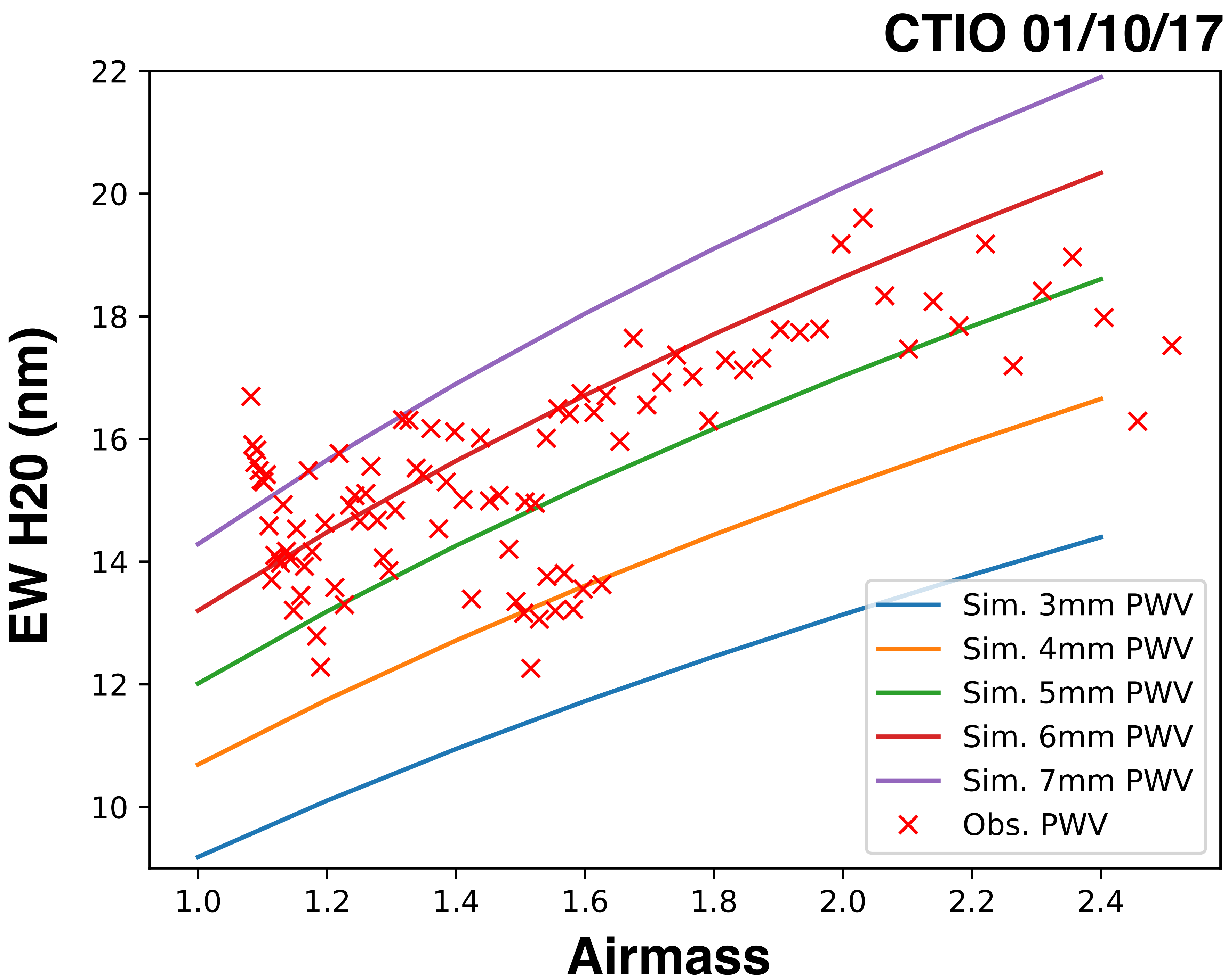
$$EW = \int ((\phi_{continuum} - \phi_{line})/\phi_{continuum}) d\lambda$$

H2O attenuation profile





Measurement along the line-of-sight



AOD determination

$$S(\lambda, z, t) = SED(\lambda) \times T_{tel}(\lambda, t) \times T_{atmo}(\lambda, z, t) \quad (1)$$

Examining the same target at two different airmasses z1, z2 :

$$\frac{S_{z1}(\lambda)}{S_{z2}(\lambda)} = \frac{T^{z1}_{atmo}(\lambda)}{T^{z2}_{atmo}(\lambda)}$$

Using an inverse power law for the chromaticity of the aerosol scattering:

$$k_A(\lambda) = \tau\lambda^{-\alpha}$$

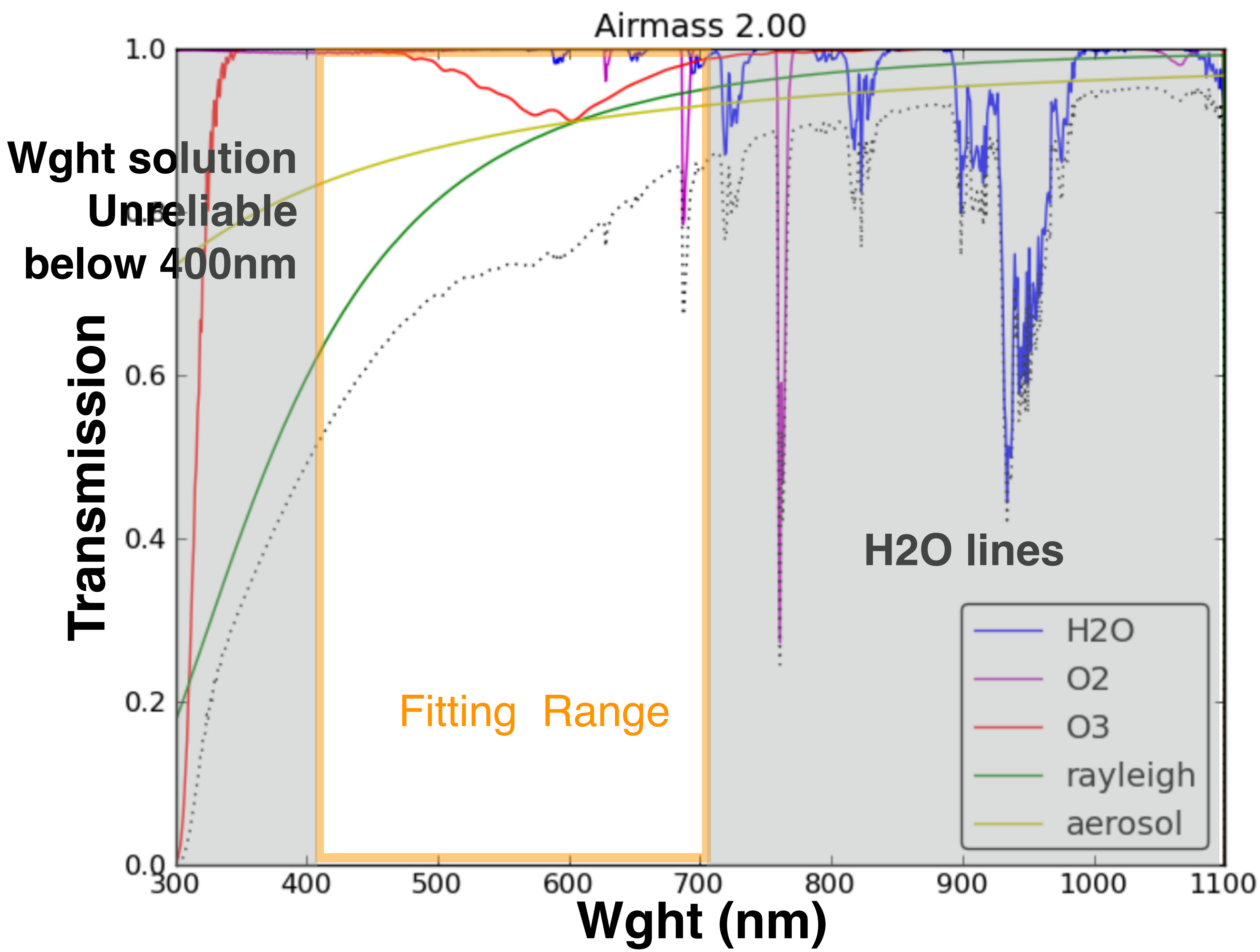
Rewriting Equation (1) :

$$\frac{S_{z_1}(\lambda)}{S_{z_2}(\lambda)} = \frac{10^{-0.4z_1(k_r(\lambda)+k_{o3}(\lambda))} \cdot 10^{-0.4z_1\tau\lambda^{-\alpha}}}{10^{-0.4z_2(k_r(\lambda)+k_{o3}(\lambda))} \cdot 10^{-0.4z_2\tau\lambda^{-\alpha}}}$$

Using radiative transfer simulation of the observations without aerosols :

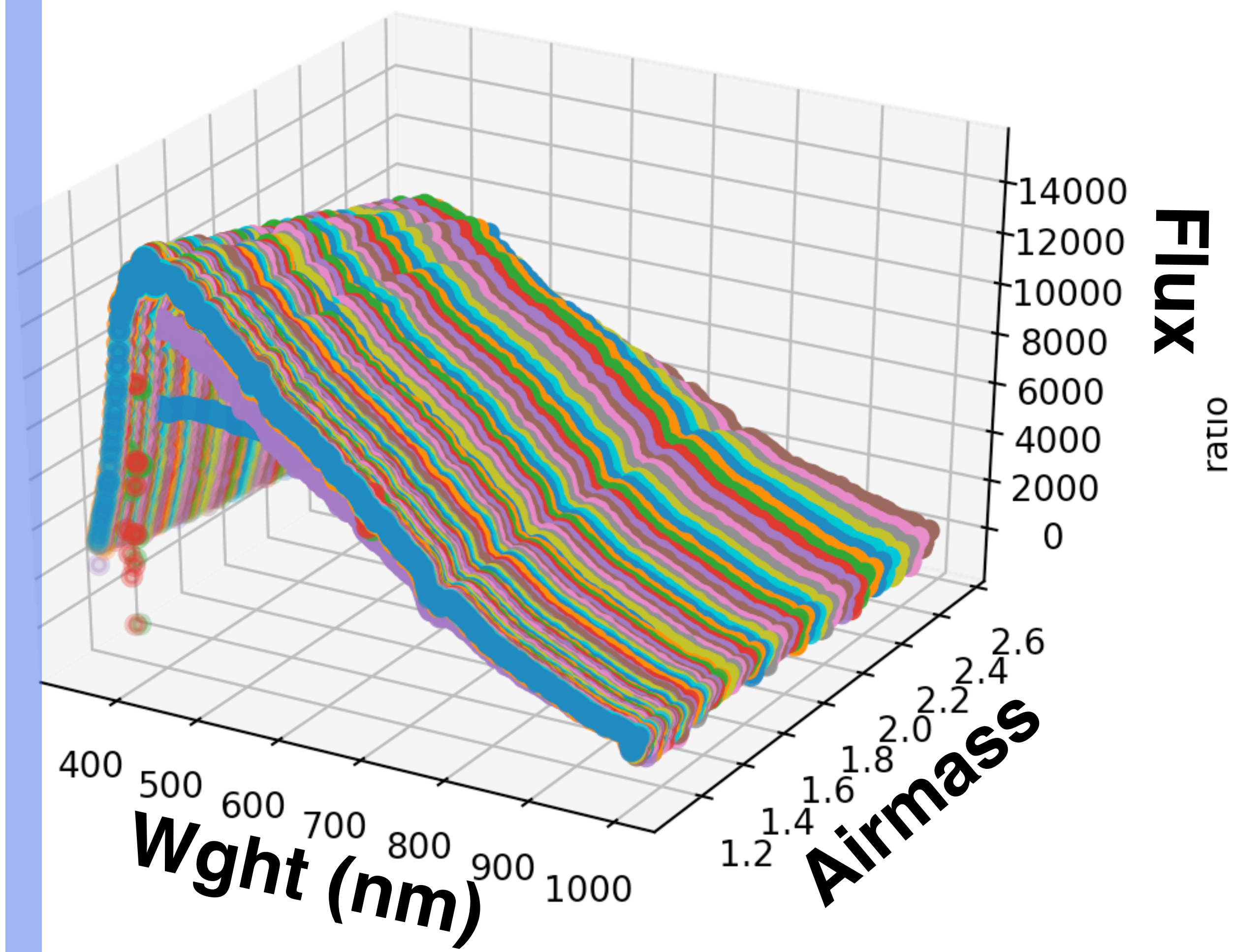
$$\frac{\left(S_{z_1}(\lambda)/(S_{z_2}(\lambda)\right)}{\left(T^{z_1}_{atmo}{}^{noA}_{sim}(\lambda)/(T^{z_2}_{atmo}{}^{noA}_{sim}(\lambda)\right)} = 10^{-0.4(z_2-z_1)\tau\lambda^{-\alpha}}$$

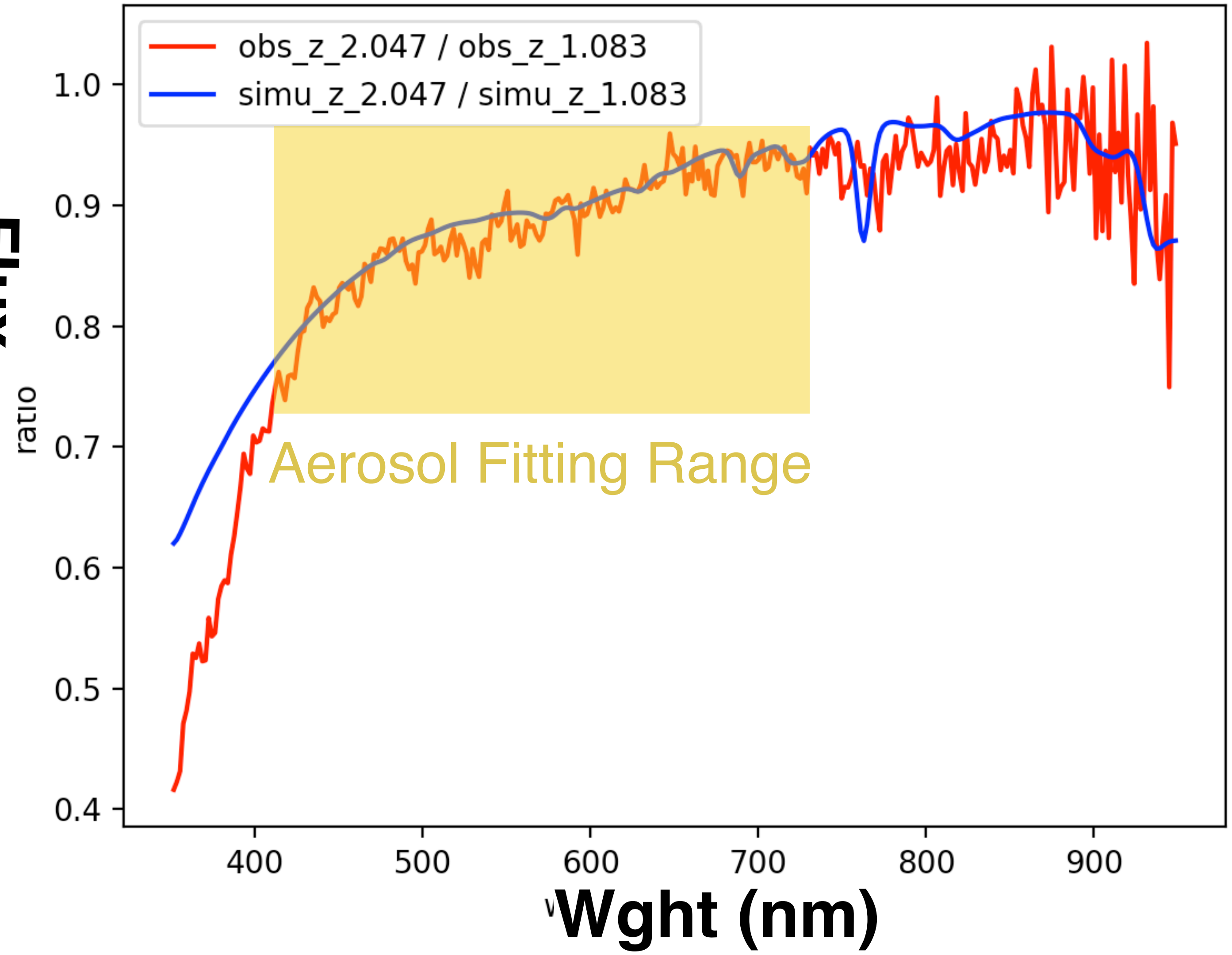
AOD Fitting interval



Practical test

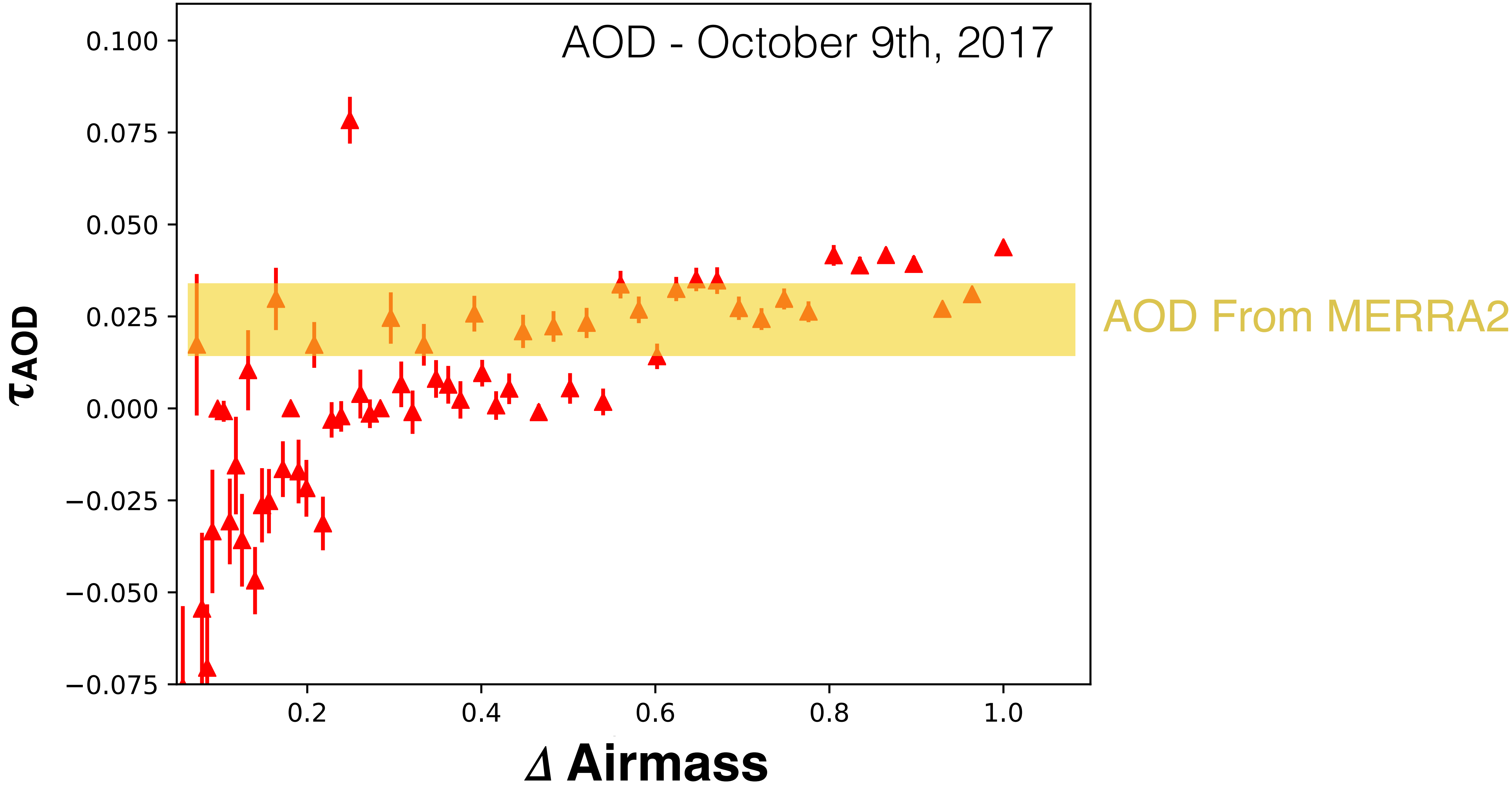
LamLep in a time series - October 9th, 2017





AOD pair of exposures method

ΔAOD 0.01→ ΔTatmo~1% @ 500nm



PCWG experts + data challenge

- What can we learn from LSST measurements themselves :

  ~ 10^4 i < 19 stars / exposure

  most often with good color diversity

  uniformized mags sensitive to Tatmo at the level of a few mmag

How can calibration residuals help constrain the variations of Tatmo ?

We will discuss tomorrow

How ancillary data could be further assimilated to improve our measurement

Discussion

Observation cadence ?

— Do we want a telescope throughput determination from airmass regression?

— Cadence for order blocking exposure in LSST field (ΔPWV~1mm/hour)?

— Broadband exposure in LSST field to align telescopes photometry and
Checks against synthetic photometry?

What else?

Atmospheric transparency at LSST : What we can expect

Parameter Variability	Impact on transmission	Achievable precision
Δ O3 ~ 20 Dobsons overnight	8% variation 4 mmag/airmass @ 6000 Å O3 peak Buton et al. 2012	σ_{O3} ~ 6 Dobsons From MERRA-2
Δ PWV ~ 1 mm hourly	ΔTtrans ~3% @ 900 nm	σ_{PWV} ~ 0.3 mm T. Li et Al. 2014
Δ AOD ~ 0.05 overnight	ΔAOD 0.01→ ΔTatmo~1% @ 500nm	σ_{AOD} ~ 0.02 From MERRA-2