Atmospheric transparency determination
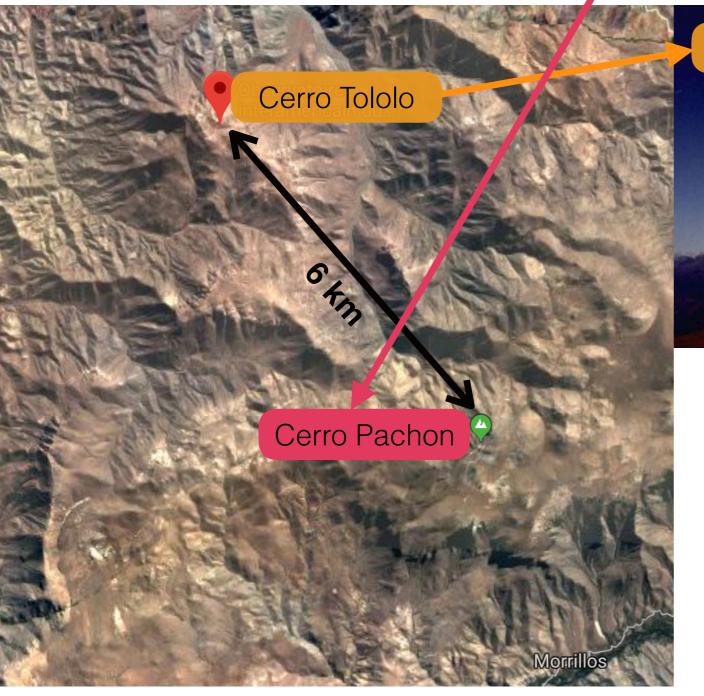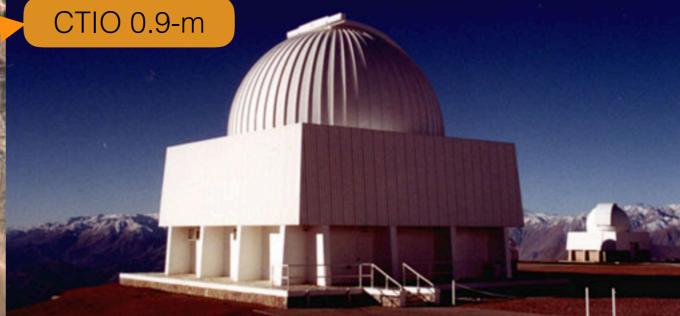# From slitless spectroscopic observations

Survey Calibration Workshop - May 2018

Augustin Guyonnet   Harvard University

May 17th, 2018

LSST

Auxiliary telescope (Aux.Tel.)

CTIO 0.9-m

Cerro Tololo

6 km

Cerro Pachon

Morrillos

Observations campaign	
2016	March
2016	August
2016	November
2016	December
2017	January
2017	June
2017	October
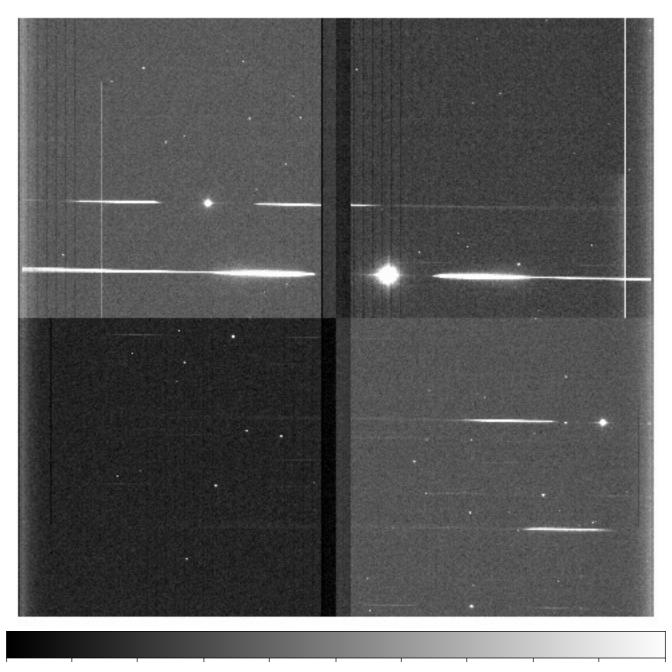
LSST Auxiliary telescope. And CTIO 0.9-m characteristics

	Aux. Tel.	CTIO 0.9-m
Diameter (m)	1.2	0.9
f/#	18	14
Focal Length (m)	21.6	12.6
Pixel (μm)	15	24
Arcsecond per pixel	0.15	0.40
FoV (arcmin)	13.6	30
Camera	ITL STA 3800	2048 x 2048 24 micron Tek2
Filters	2 wheels, 3x3 inches	2 wheels

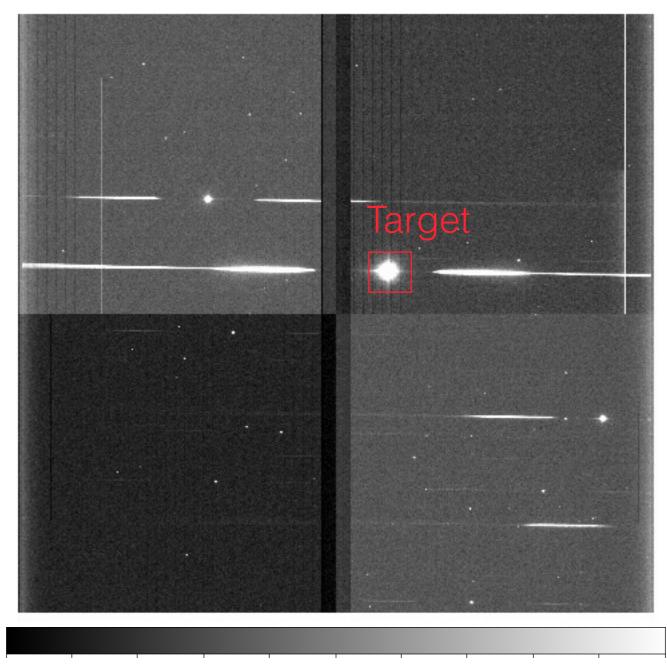# Talk outline

Report on the main findings :
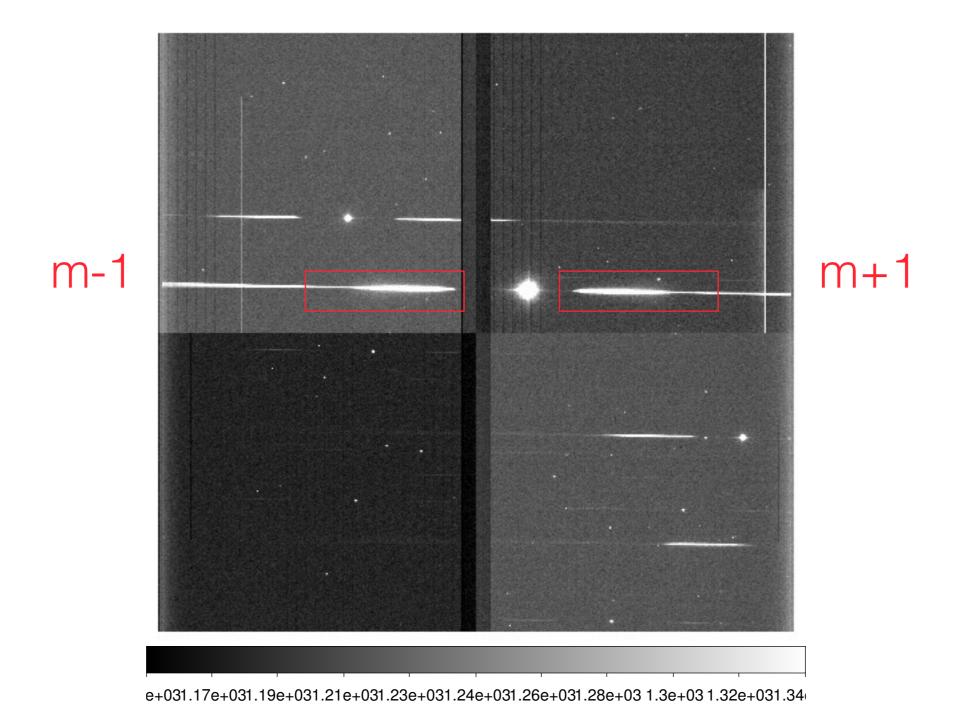
1. Key steps in image reduction,

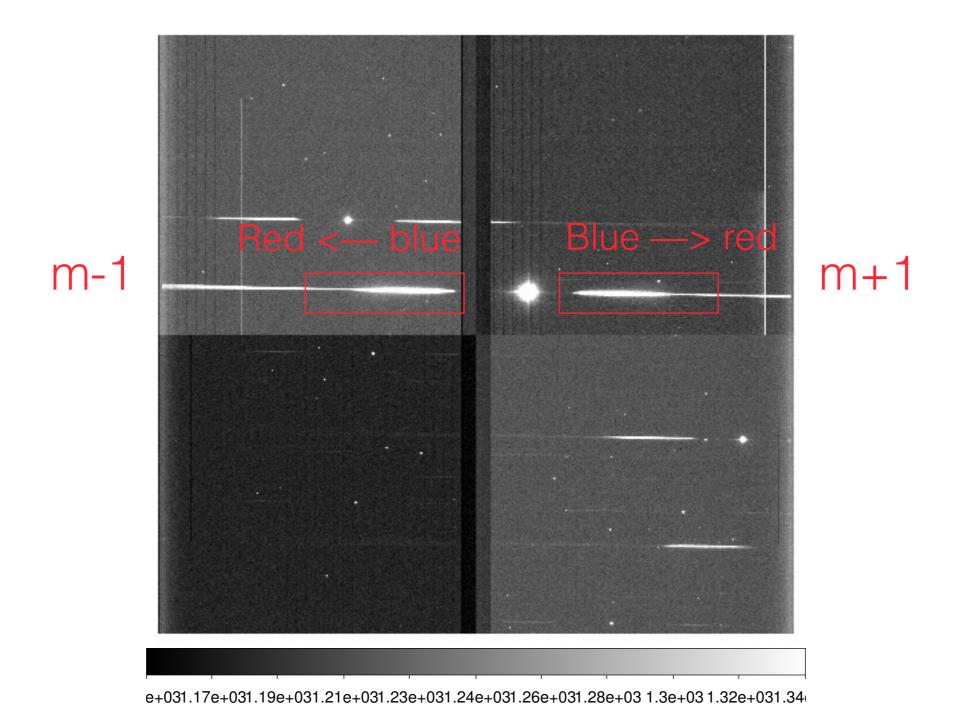2. Radiative transfer simulation,

3. Satellite data.

Dispersed image from slitless spectrometry
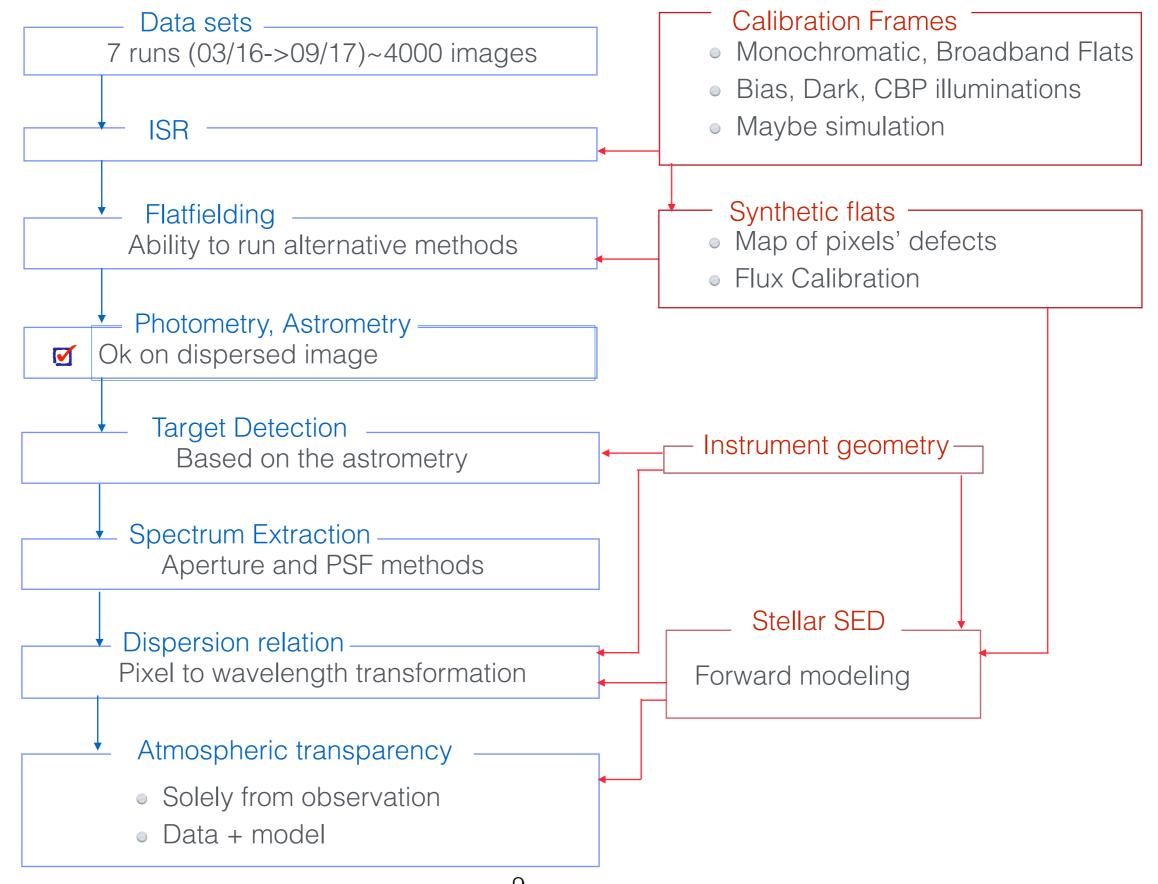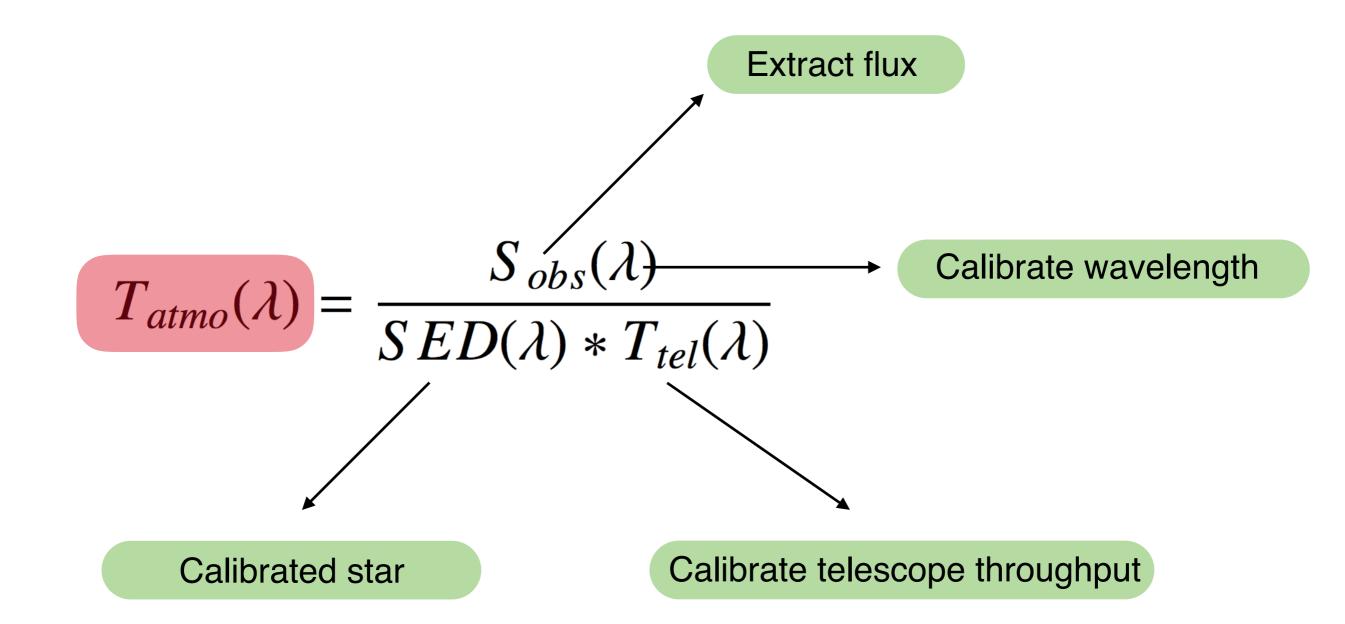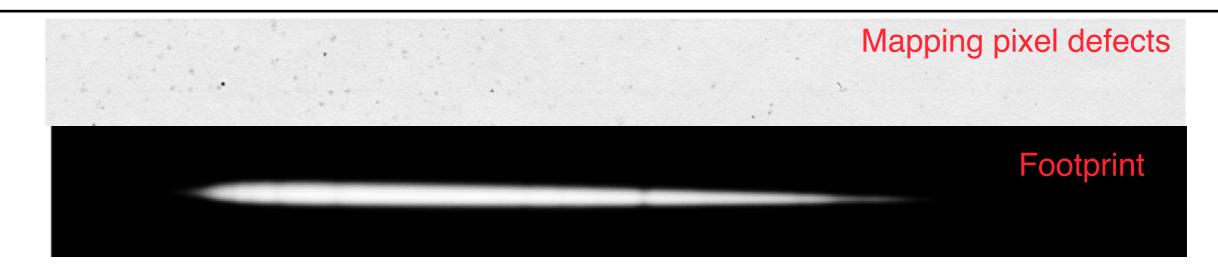
Processing Pipeline Flowchart

Data sets
7 runs (03/16->09/17)~4000 images

Calibration Frames
- Monochromatic, Broadband Flats
- Bias, Dark, CBP illuminations
- Maybe simulation

ISR

Flatfielding
Ability to run alternative methods

Synthetic flats
- Map of pixels' defects
- Flux Calibration

Photometry, Astrometry
☑ Ok on dispersed image

Target Detection
Based on the astrometry

Instrument geometry

Spectrum Extraction
Aperture and PSF methods

Dispersion relation
Pixel to wavelength transformation

Stellar SED
Forward modeling

Atmospheric transparency
- Solely from observation
- Data + model

9

Extract flux

$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$

Calibrate wavelength

Calibrated star

Calibrate telescope throughput

spectrum footprint

spectrum footprint

Mapping pixel defects

Footprint

no background subtraction

/ map of defects
raw

(Checked on other images
That the feature is not there)

Spurious spectral features
Due to pixel-to-pixel
Sensibility variation *

Flux

Pixel

Extracting the flux

Mapping pixel defects

Footprint

80 pixel Aperture

hd14943 clear RONCHI400

Aperture flux Vs aperture

Ratios, from 40 pixels to 160
20 pixels steps

ratio 40/100
ratio 60/100
ratio 80/100
ratio 120/100
ratio 140/100
ratio 160/100

Extracting the flux

Mapping pixel defects

Footprint

PSF

Residuals

$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$
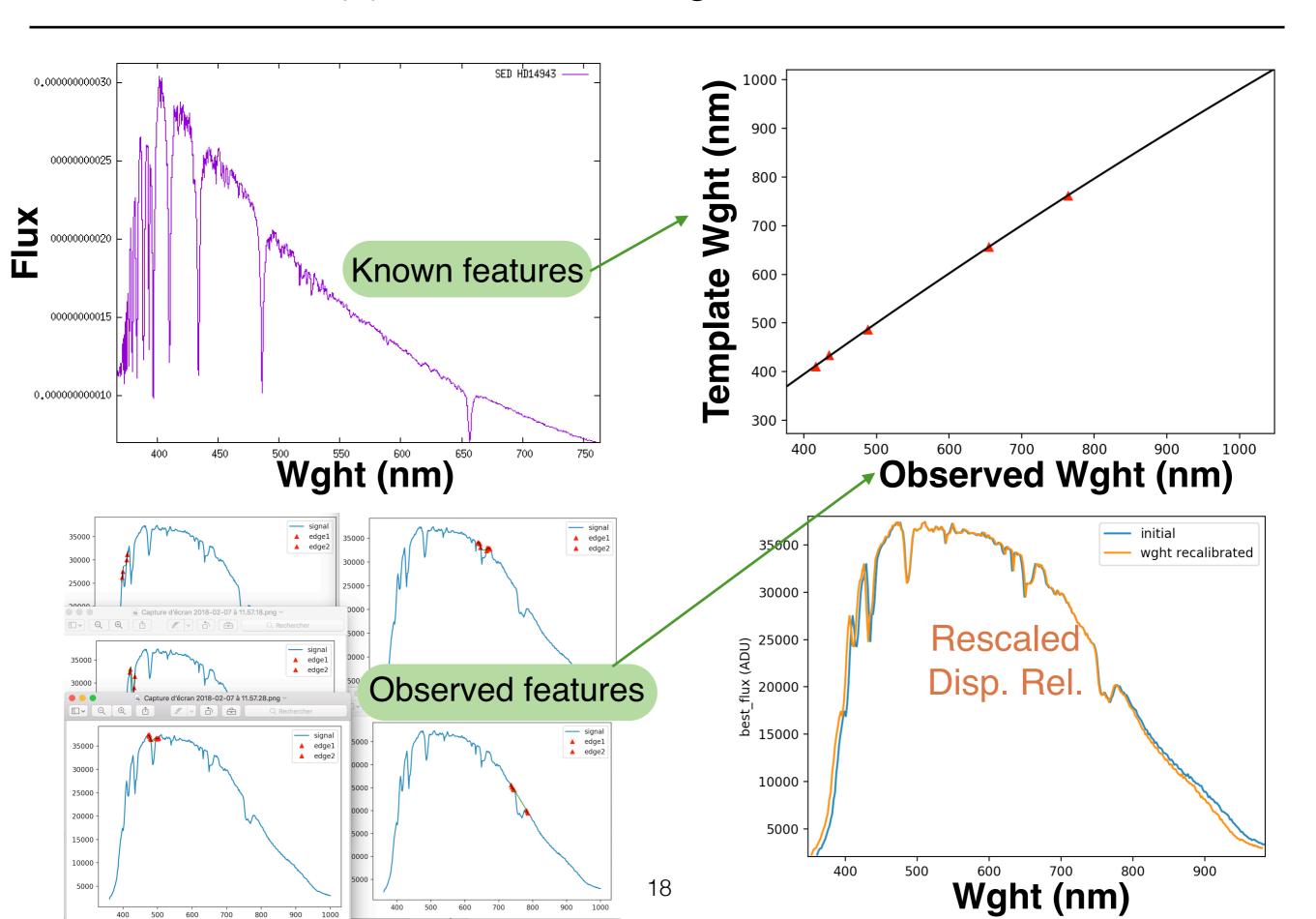
Determination of dispersion relation

(2). Pixel-to-wavelength transformation

$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$

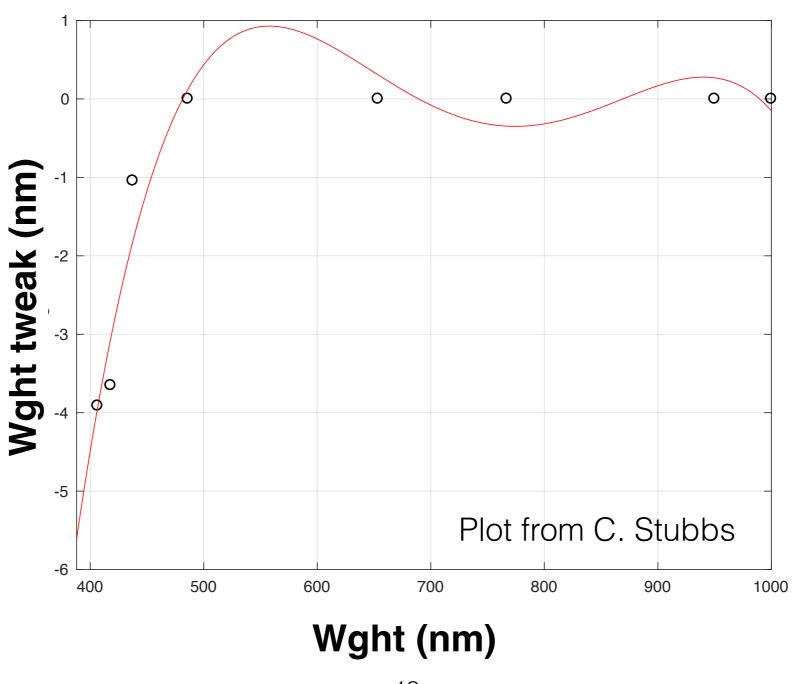Determination of dispersion relation

I - First estimate using the geometry :

distance between the focal plan and the grating.   grating spacing

$$Pixel = d \times \left(\frac{\lambda/a}{\sqrt{1 - (\lambda/a)^2}} \right)$$

II - Fit observed spectral features against a template of SED * Tatmo

(2). Pixel-to-wavelength transformation

Known features

Observed features

Rescaled Disp. Rel.

18

- The correction is several nm on the blue side

- Extrapolation of the solution at lower/higher wght is unreliable

Plot from C. Stubbs

19

$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$

Calibrate telescope throughput

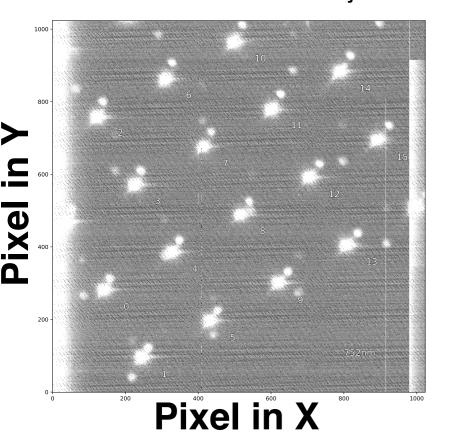# Telescope throughput calibration

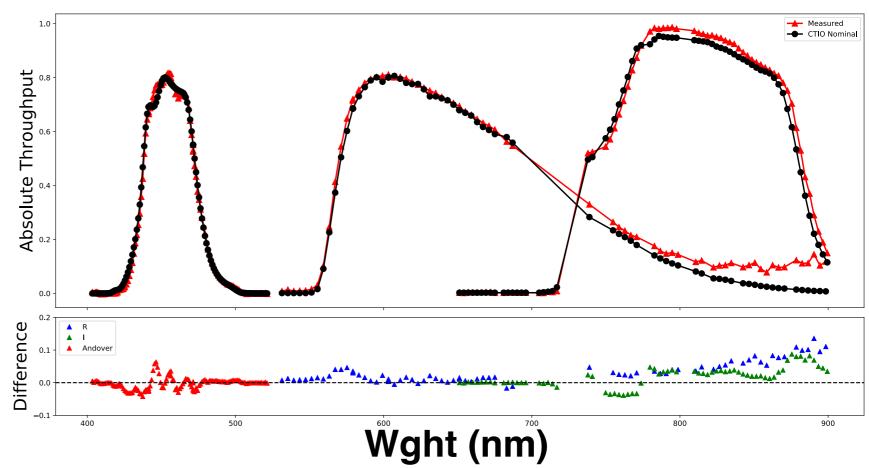$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$

Calibrate telescope throughput

$$N_{ADU}(\vec{r}, \lambda) = B(\vec{r}, \lambda) \cdot T(\vec{r}, \lambda) \cdot QE(\vec{r}, \lambda)/g$$

Collimated Beam Projector

Pixel in Y / **Pixel in X**

Filters Transmission curves

Wght (nm)

$$T_{atmo}(\lambda) = \frac{S_{obs}(\lambda)}{SED(\lambda) * T_{tel}(\lambda)}$$

Calibrate telescope throughput

$$N_{ADU}(\vec{r}, \lambda) = B(\vec{r}, \lambda) \cdot T(\vec{r}, \lambda) \cdot QE(\vec{r}, \lambda)/g$$

Based on lessons learned from previous attempts,

The elected method to determine Ttel will be to use the collimated beam projector (CBP) with a rectangular slit mounted in front of it, instead of circular pinholes. The resulting image fulfill all the requirements for proper flatfielding of dispersed images :

- It probes the same light-path as in a science exposure,

- the illuminated patch of the focal plane will be large enough to isolate an area of uniform intensity, and small enough so that orders do not overlap.
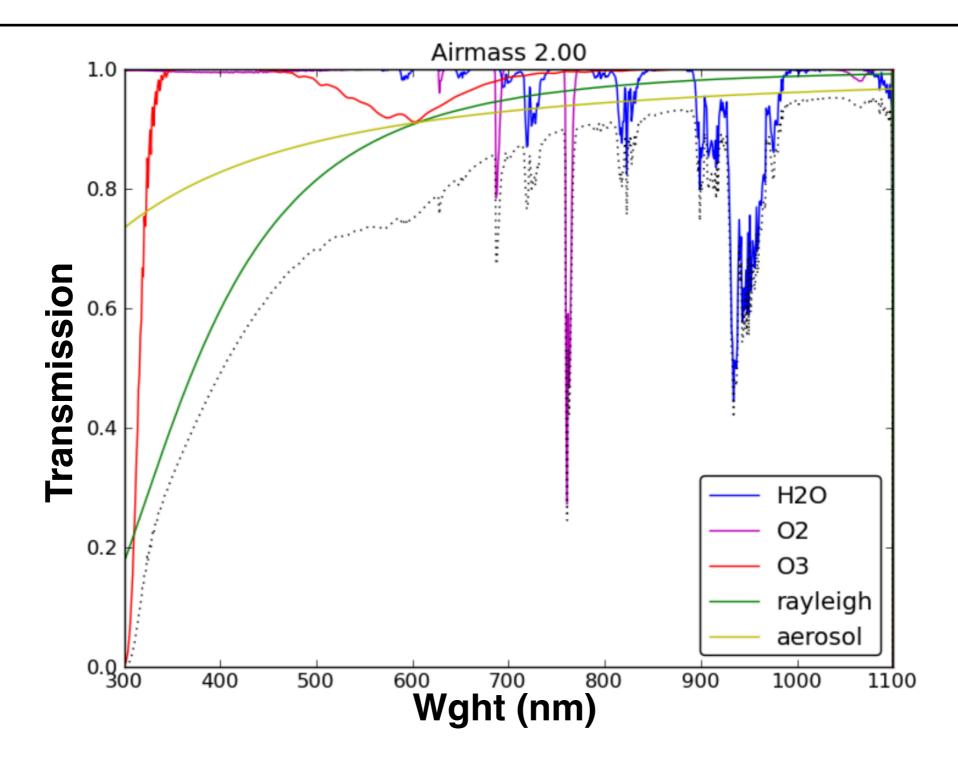
It is possible to extract informations about the atmospheric transparency

without knowledge of the telescope throughput,

provided that :

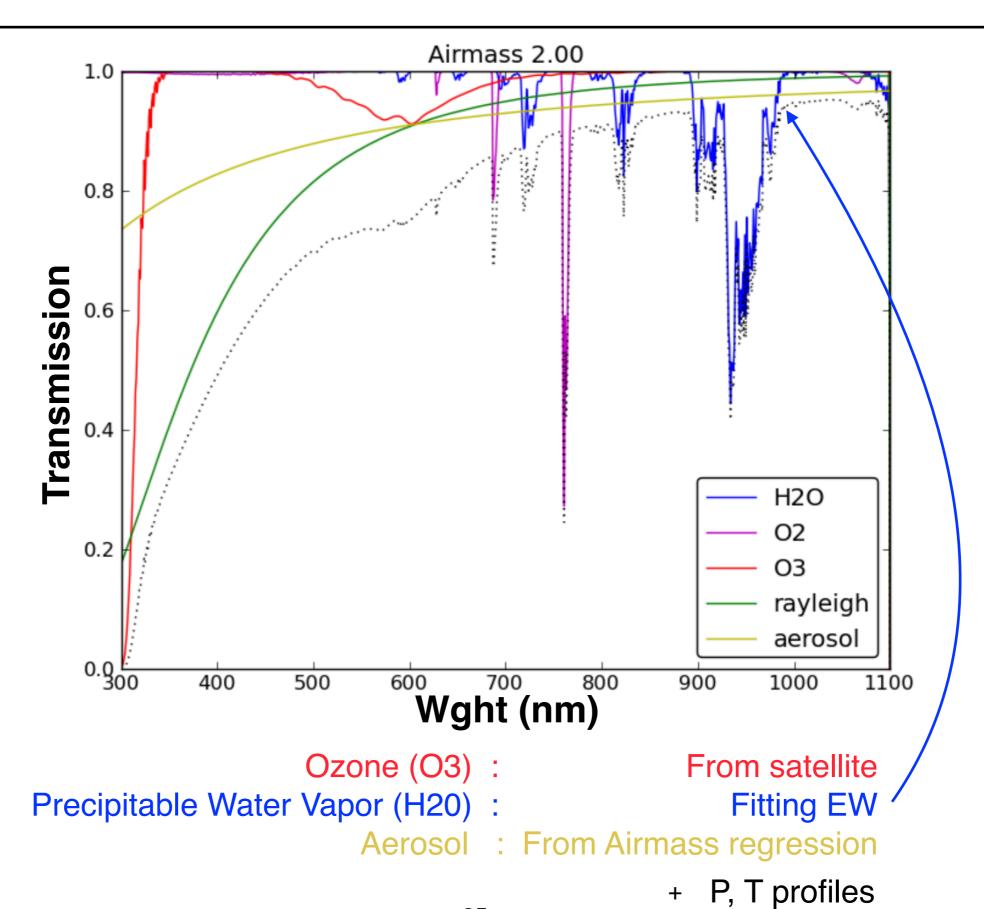- The instrument response function is stable,

And associated with :

- A radiative transfer simulation,

- and satellite data.

Airmass 2.00

Atmospheric Transparency Parametrization

Ozone (O3) :   From satellite

Precipitable Water Vapor (H20) :   Fitting EW

Aerosol : From Airmass regression
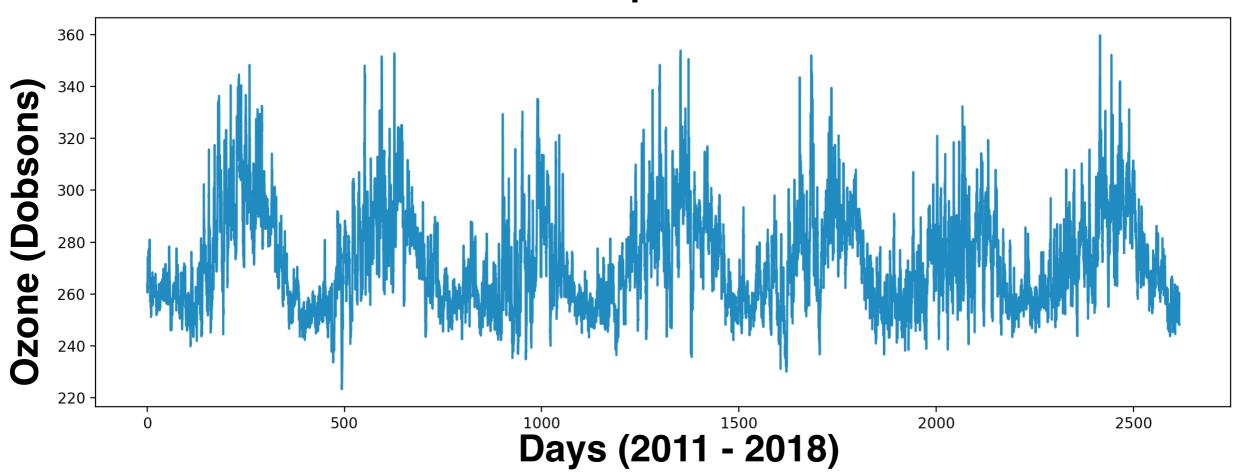
+   P, T profiles
+   Airmass
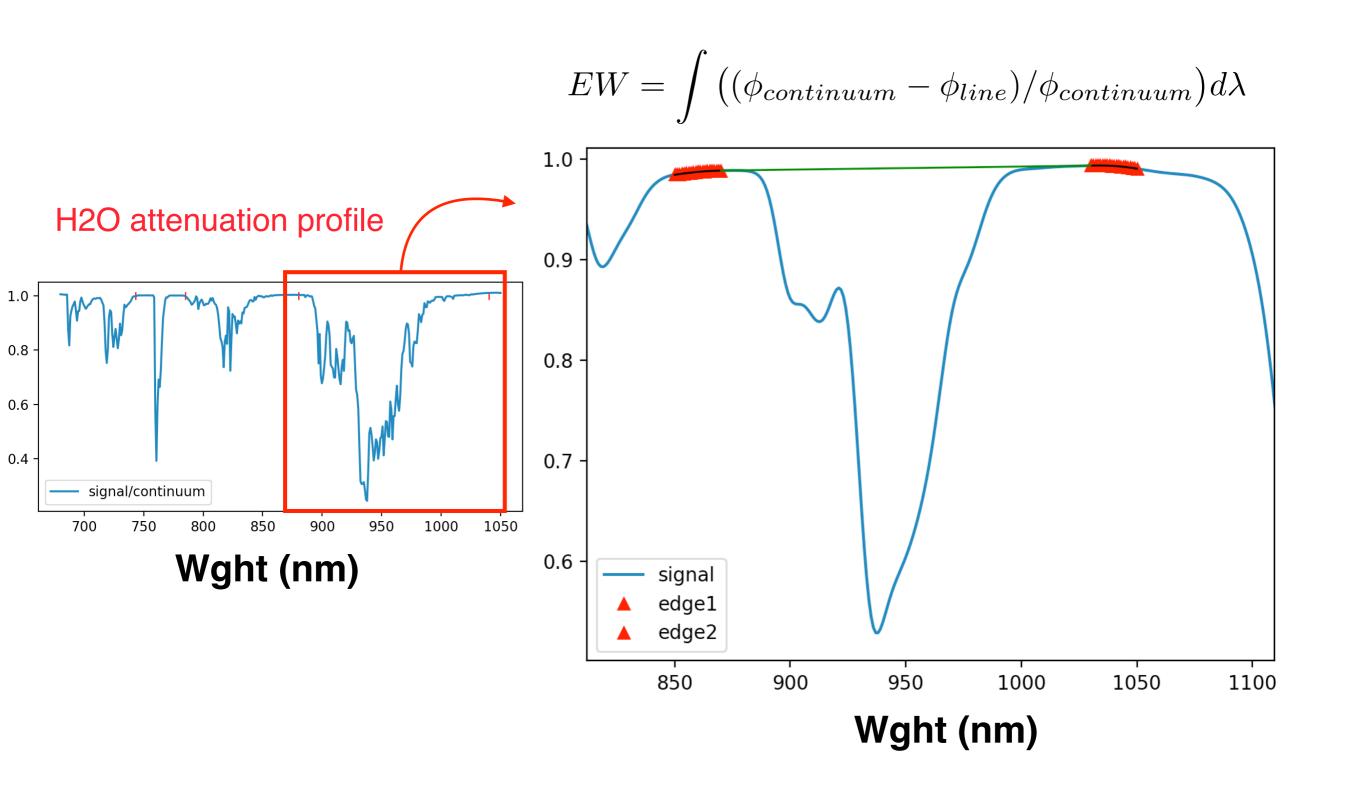
Ozone Column depth
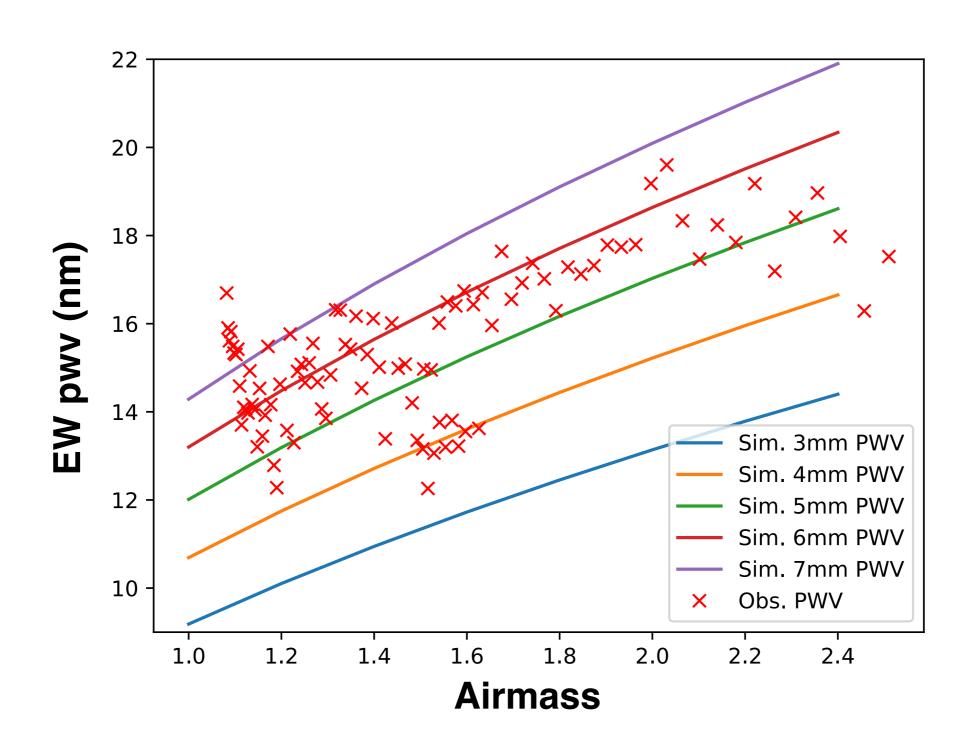
MERRA2 data interpolation at CTIO lat-lon

➡ **Ozone follows both an annual and a circadian variations**
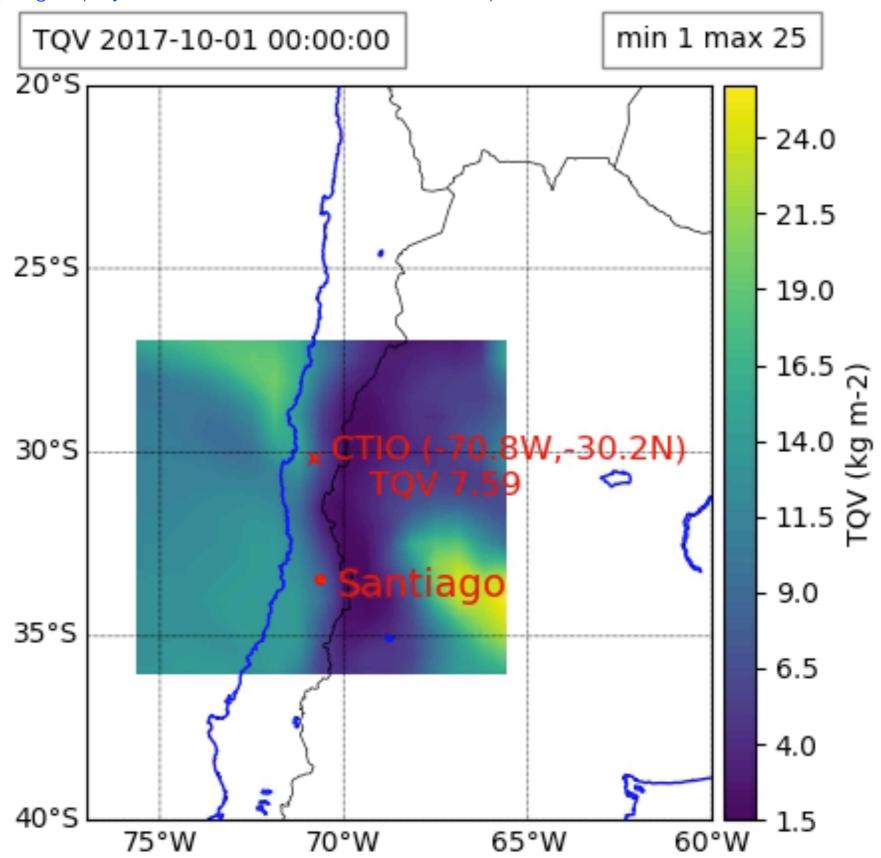
Equivalent Width - Reminder
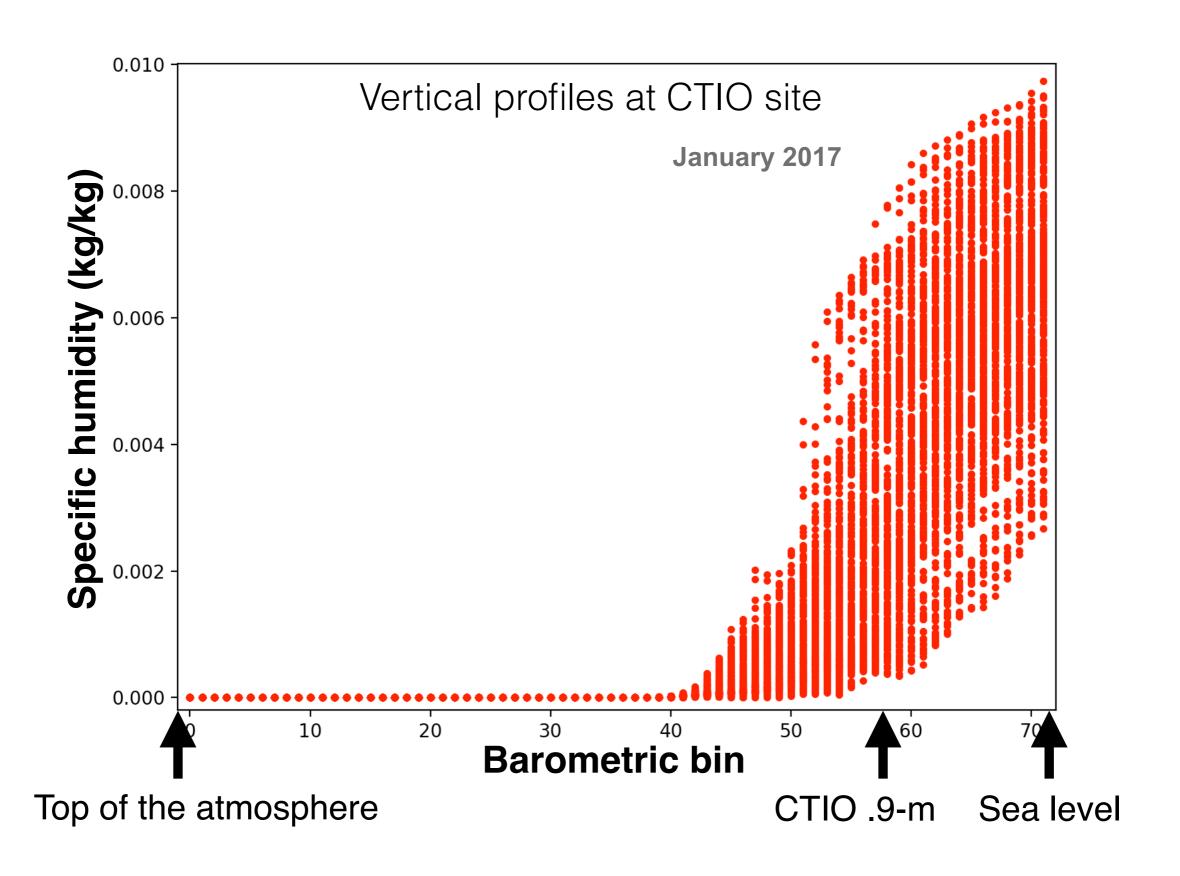
$$EW = \int \left((\phi_{continuum} - \phi_{line})/\phi_{continuum} \right) d\lambda$$

H2O attenuation profile

Precipitable Water Vapor (PWV)

Precipitable Water Vapor

Vertical profiles at CTIO site

January 2017
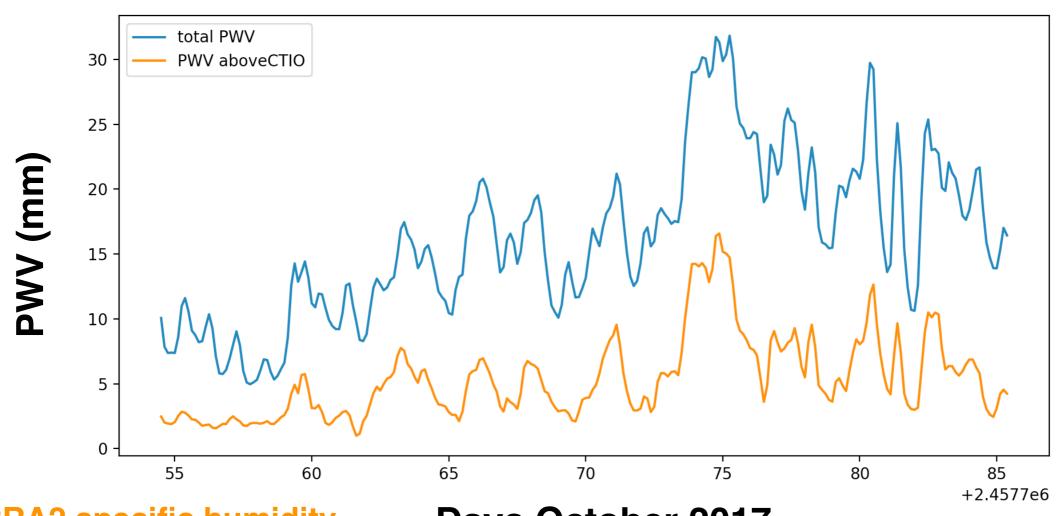
PWV : comments on the analysis (1)

MERRA2 data interpolation at CTIO lat-lon

Days October 2017
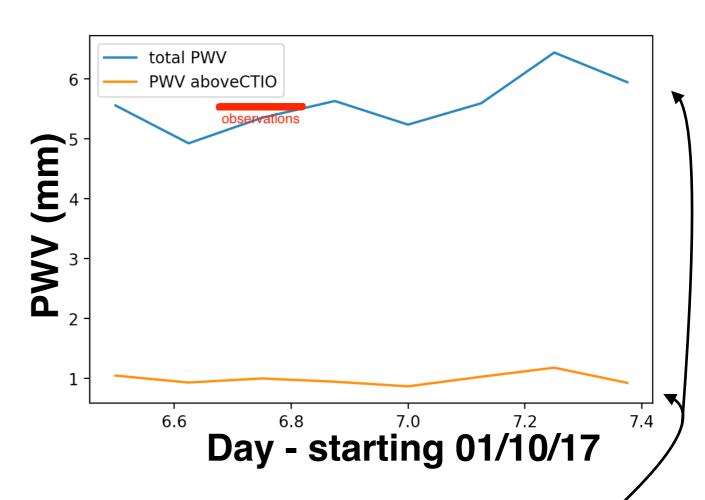
MERRA2 specific humidity interpolation at CTIO lat-lon, Then integrated from 2200m to top of the atmosphere
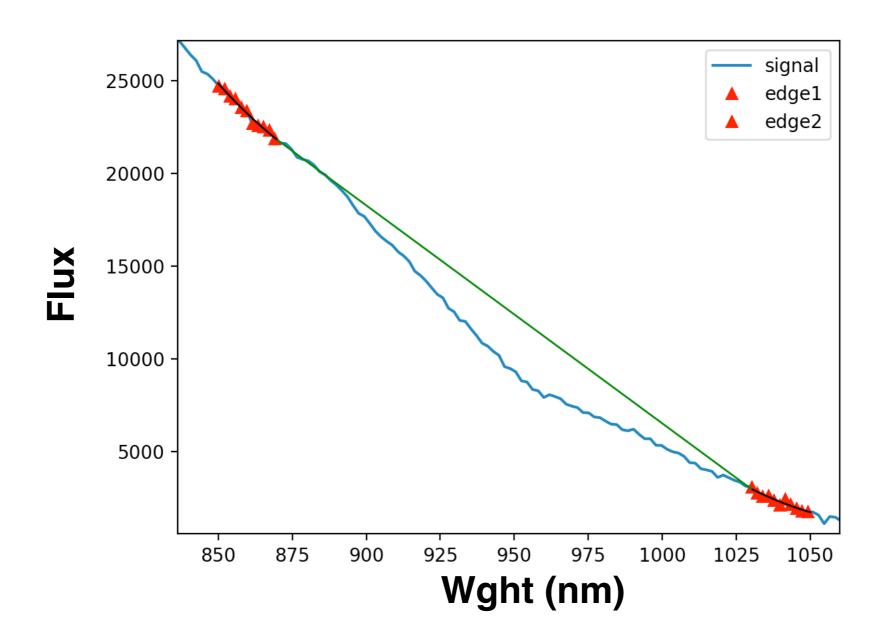
01/10/17

- From Satellite data, correct answer could be in between these two
- Hourly variations are most often sub-mm.

Currently, systematics are introduced by :

- The definition of the position of the edges (seeing matters)
- The model for the continuum (SED*Ttel)

Determination of the Aerosol Optical Depth

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

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

$$\frac{S_{z1}(\lambda)}{S_{z2}(\lambda)} = \frac{T_{atmo}^{z1}(\lambda)}{T_{atmo}^{z2}(\lambda)} \qquad (1)$$

It is common in astronomy to express the extinction in magnitudes,
such that the transmission, Tatm(λ,zˆ), is given by (Buton et al. 2012):

$$T_{atmo}^{z}(\lambda) = 10^{-0.4 K_{atmo}(\lambda, z)} \qquad (2)$$

With :

$$K_{atmo}(\lambda, \hat{z}) = \sum_{j} X^{\rho_j}(\hat{z}) \times k_j(\lambda)$$

X denotes airmass

the different components k_j are:
- Rayleigh scattering, kR,
– aerosol scattering, kA,
– ozone absorption, kO3 ,
– telluric absorption, k⊕.

In a region free of telluric lines (**ρ**j = 1):

$$K_{atmo}(\lambda, z) = zk_r + zk_A + zk_{O_3}$$

Using an inverse power law for the chromaticity of the aerosol scattering:
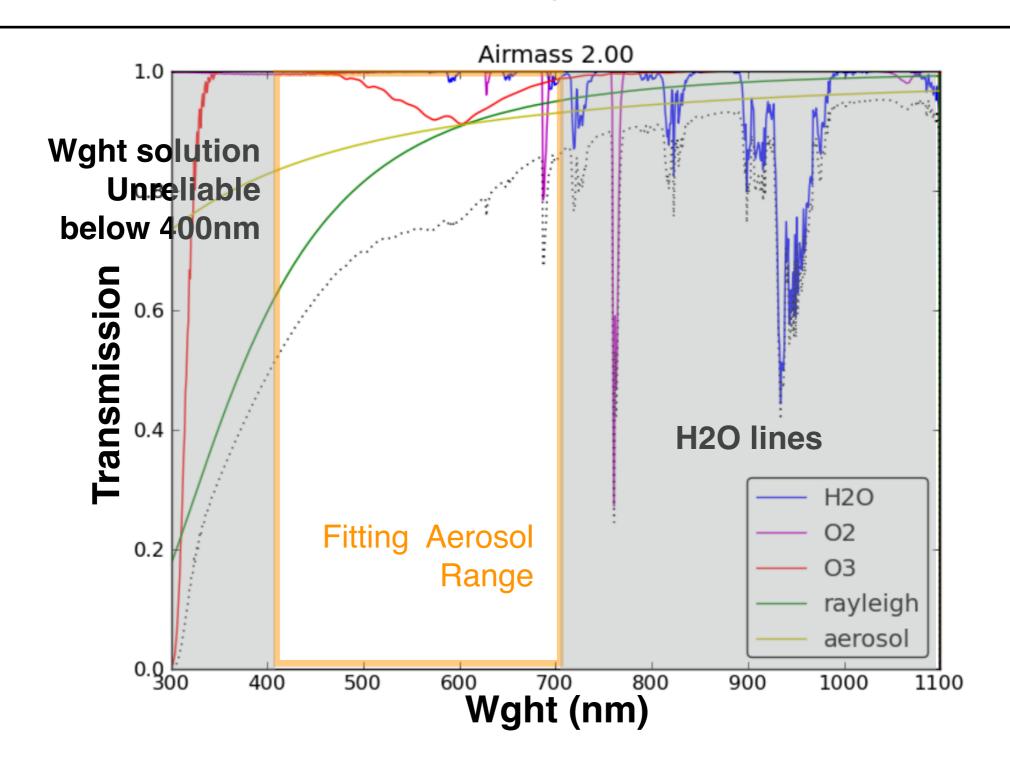
$$k_A(\lambda) = \tau \lambda^{-\alpha}$$

Rewritting Equation (1) :

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

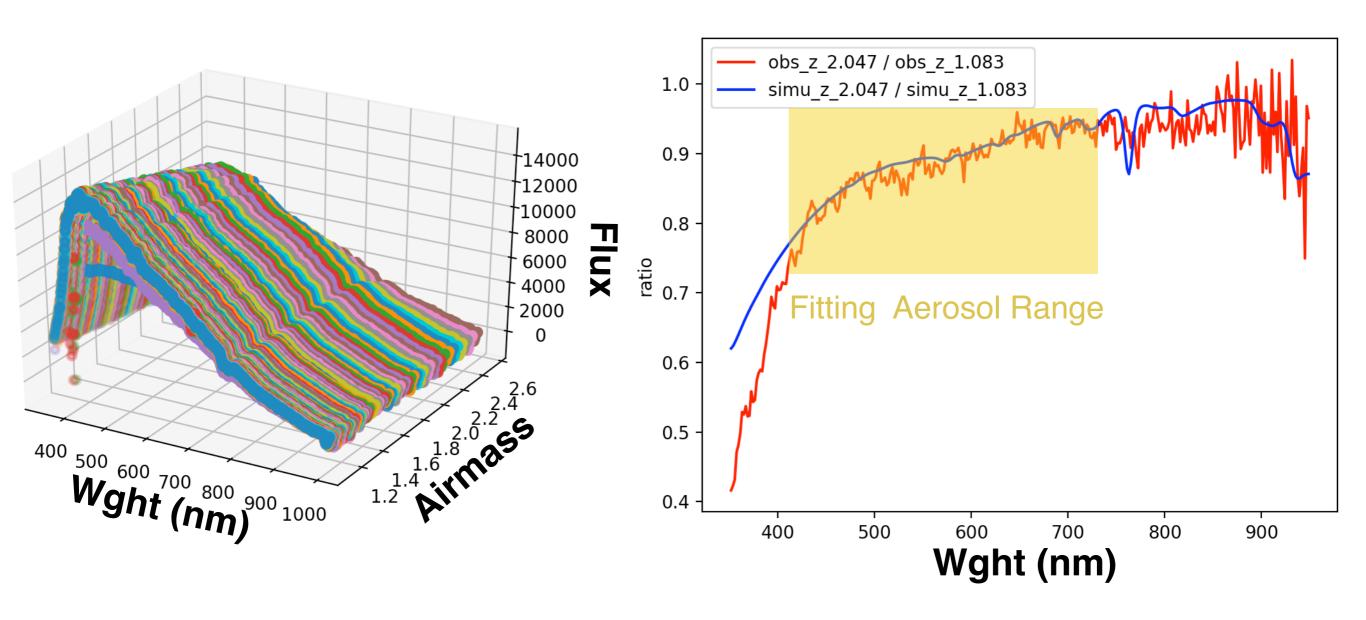Using radiative transfer simulation of the observations without aerosols :

$$\frac{\left(S_{z_1}(\lambda)/(S_{z_2}(\lambda) \right)}{\left(T_{atmosim}^{z_1 \quad noA}(\lambda)/(T_{atmosim}^{z_2 \quad noA}(\lambda) \right)} = 10^{-0.4(z_2 - z_1)\tau \lambda^{-\alpha}}$$

AOD Fitting interval
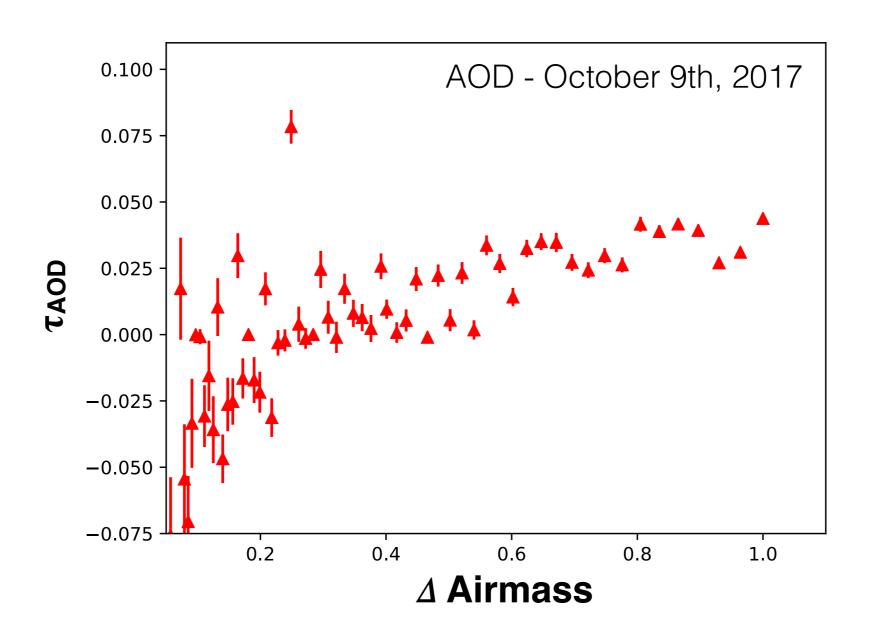
LamLep in a time series - October 9th, 2017

AOD - October 9th, 2017
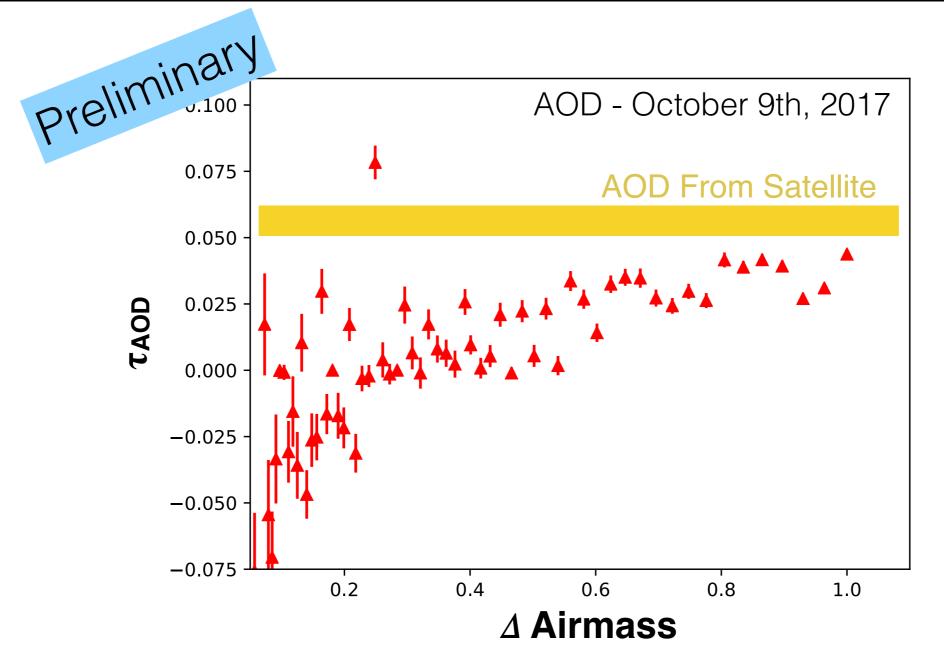
Aerosol Optical Depth

- ◉ What about the offset ?
  - ‣ 3-D MERRA-2 table for the aerosols.
- ◉ What about the drift with airmass?
  - ‣ Other single target observations in a timeseries.

Summary and Perspective

We have been conducting on-site campaigns to prepare for the integration of the LSST calibration sub-system.
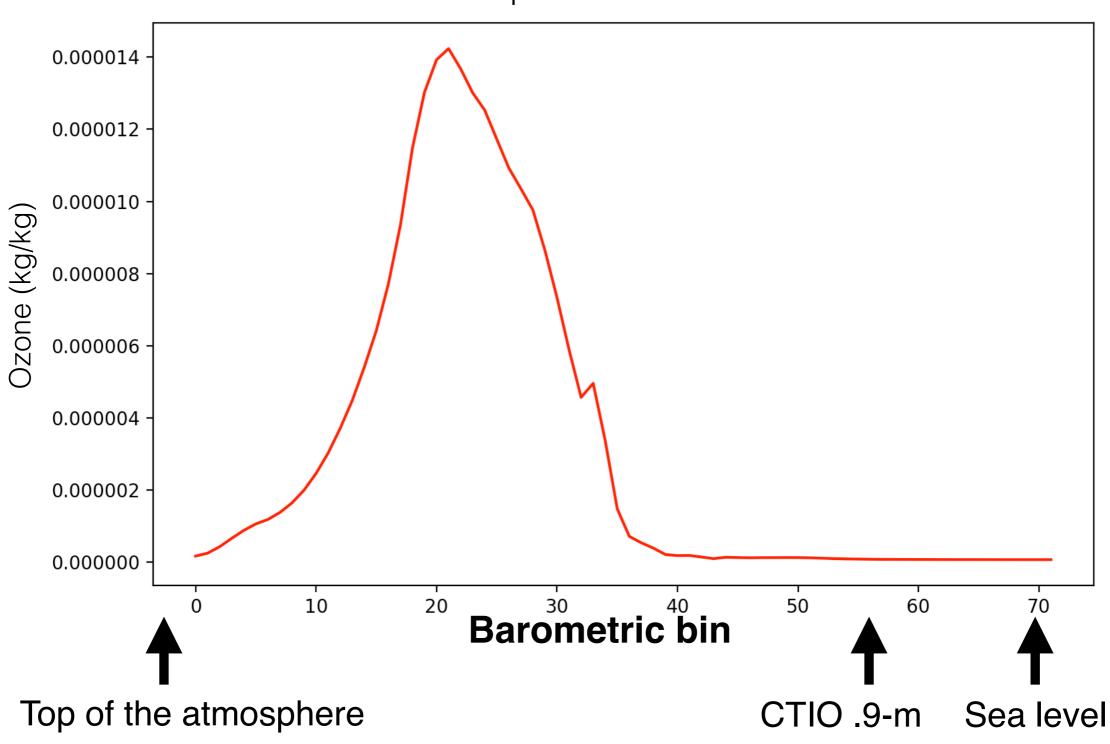
➡ We have learnt that CTIO 0.9m has a poor detector :(

➡ We have prototyped an image reduction pipeline :)

Which goes from the raw image, up to the determination of atmospheric parameters.

The current approach uses a radiative transfer simulation, associated with satellite data.

➡ There is a lot more to learn from satellite data *

➡ AuxTel coming online soon !

* Broadband observations versus synthetic photometry using satellite data.

Back-up slides

* The informations that we extract from satellite data are the followings :

- CTIO seats on a large east-west PWV gradient.

- PWV and Ozone follow circadian variations.

- PWV and Ozone are somewhat anti-correlated on an annual basis.

- Large variations of AOD, PWV and Ozone can sometimes occur within a few hours timespan.

- O3 and PWV gradients go along the same direction, both at CTIO and Mauna Kea.

Precipitable Water Vapor

Vertical profiles at Mauna Kea

Precipitable Water Vapor

Precipitable Water Vapor @s CTIO

➡️ **PWV follows both an annual and circadian variations,**
➡️ **CTIO seats on a large east-west PWV gradient.**

Ozone

Vertical profile at CTIO site

HD14943_2

Legend:
- Obs ctio 0.9-m (blue)
- SED forward modeling (black)

Tatmo from simulation using input parameters from satellite data

X-axis: wavelength (nm)
Y-axis: flux (norm@max)

.9-m CCD calibration from monochromatic flats, ronchi =off

Method using radiative transfer simulation + Satellite data

Aerosol determination

LamLep in a time series - October 9th, 2017
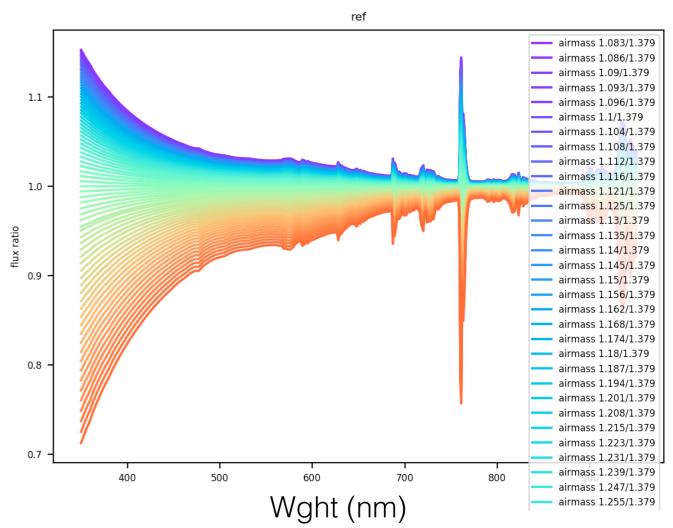
Aerosol determination

Ratio of observations
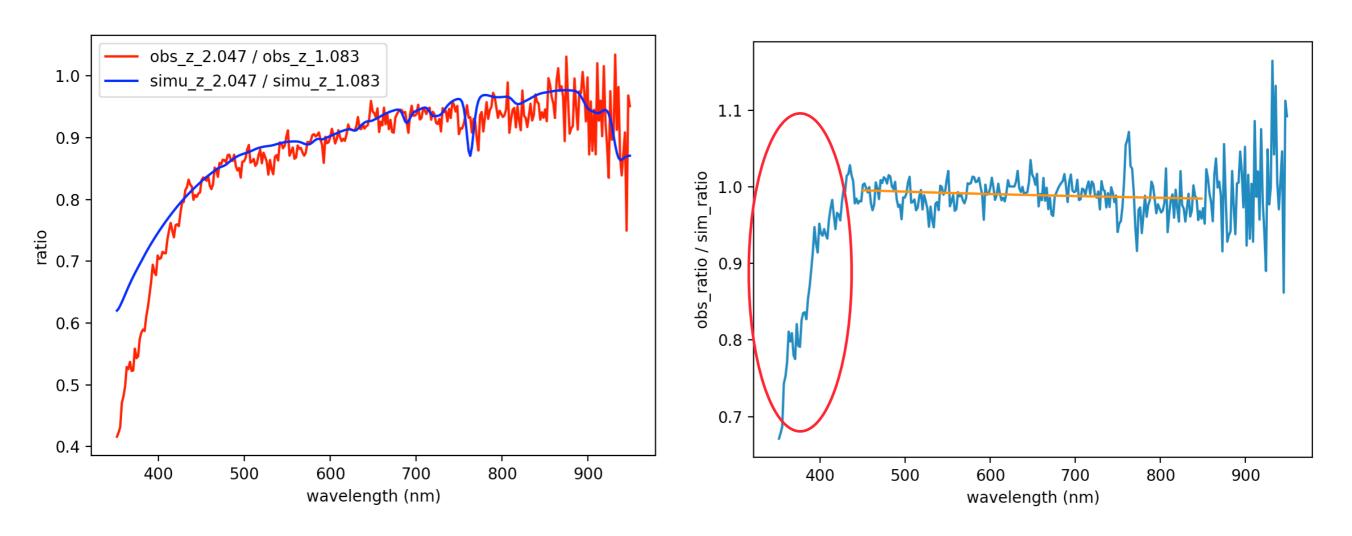
Ratio of Simulations

altitude   2.241
mol_modify H2O   4. MM
aerosol_angstrom 1. 0.02
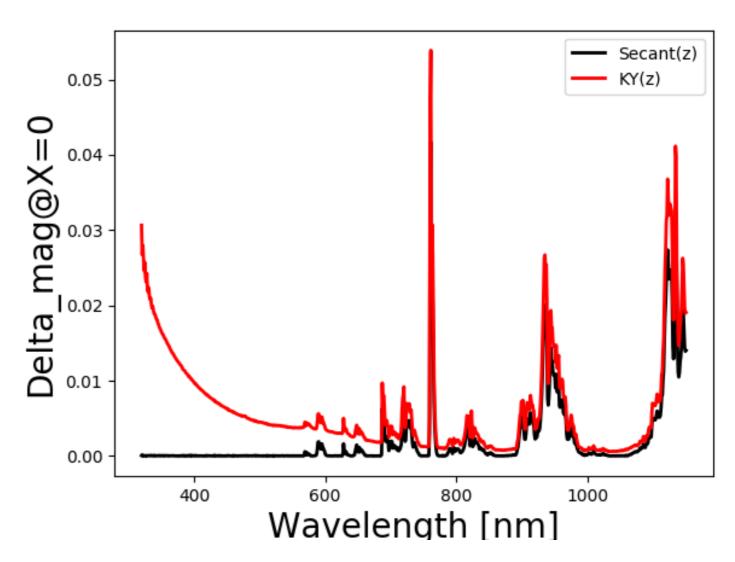mol_modify O3   270 DU

Aerosol determination

What is going on here ?

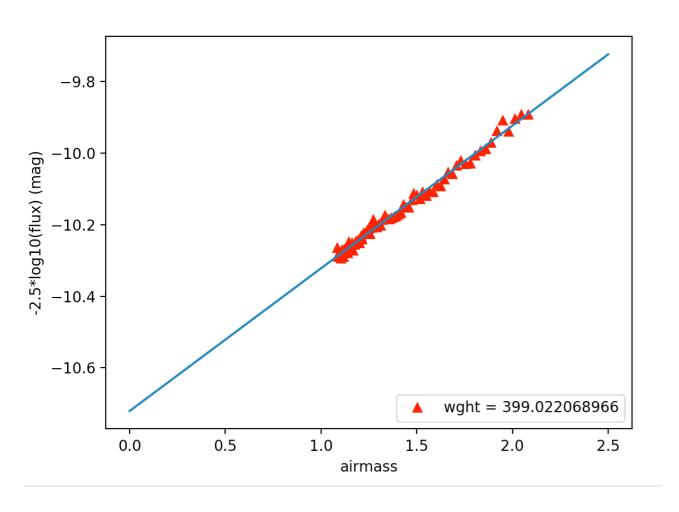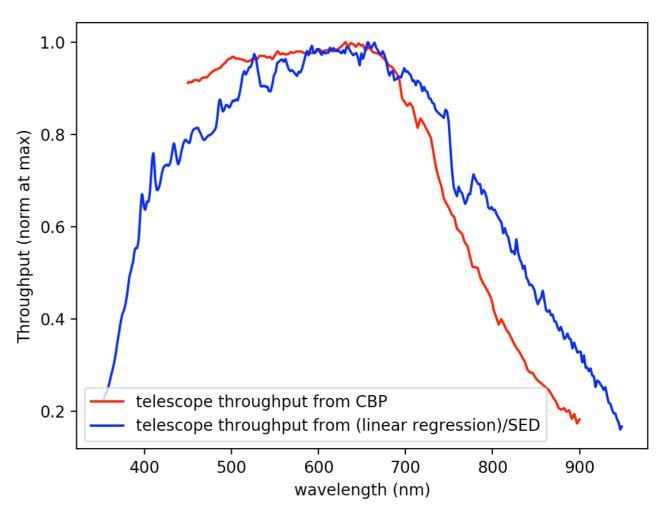https://arxiv.org/pdf/1011.6156.pdf
fig. 4 + AppendixA ?

Patat 2010

Deviations of the derived extinction curve
from the LBLRTM simulation for Cerro Paranal
(observed minus model).

Regression to 0 airmass
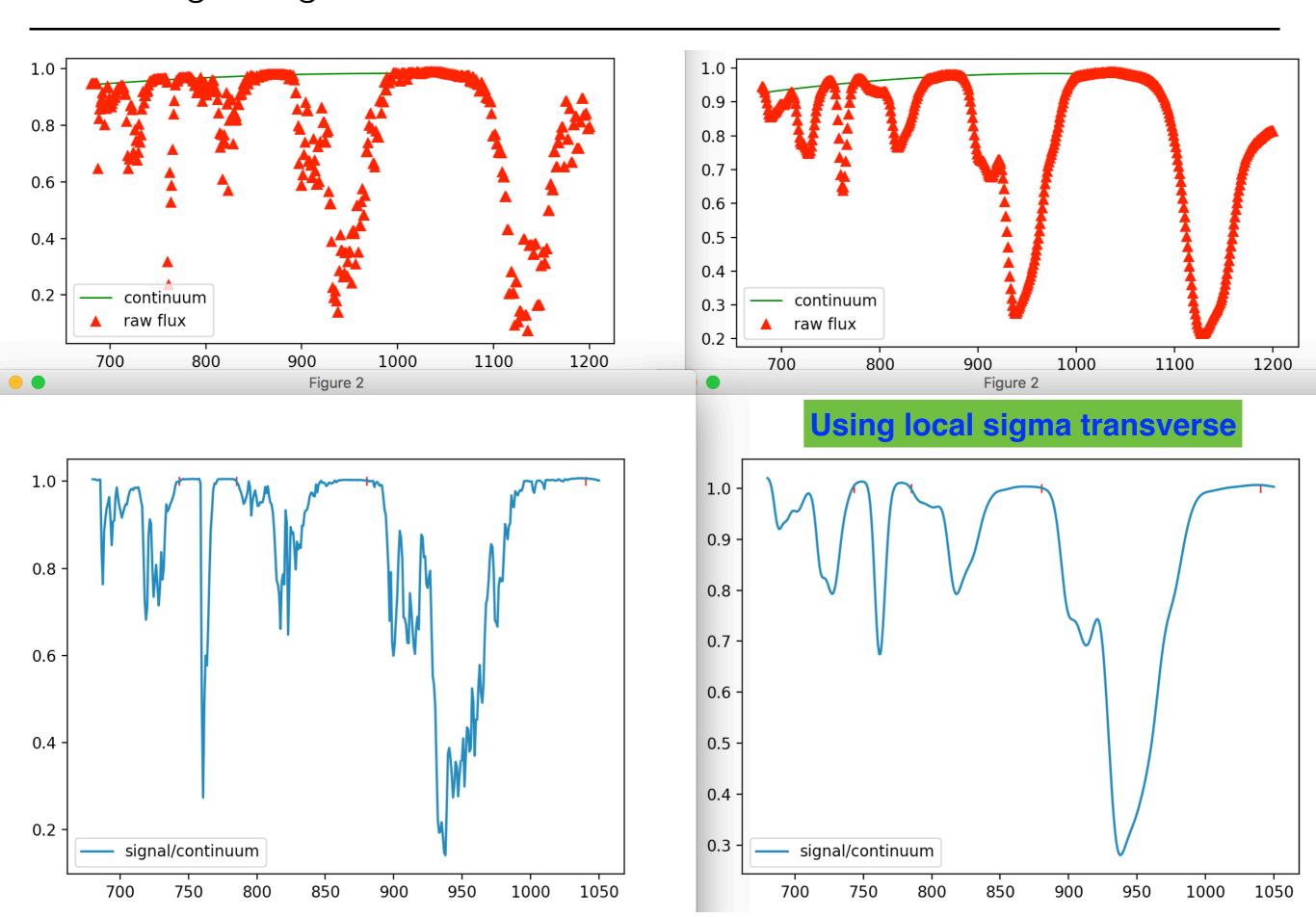Using 2 different zenith angle-to-airmass conversion
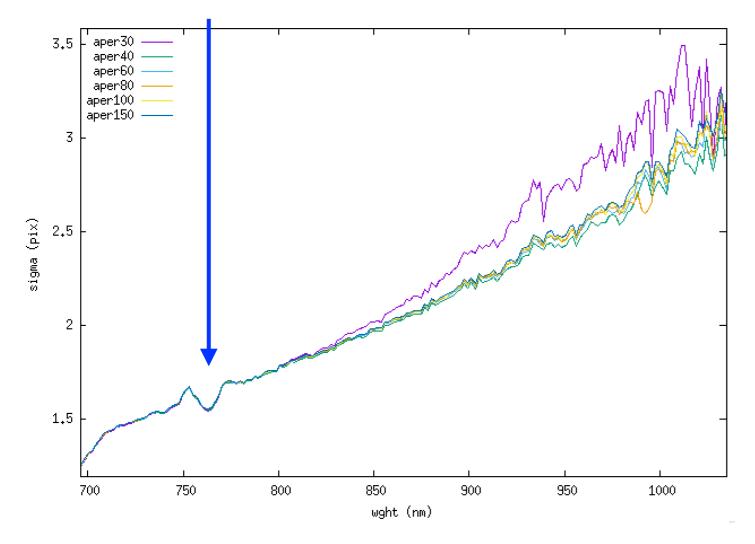
Result of the regression to 0 airmass

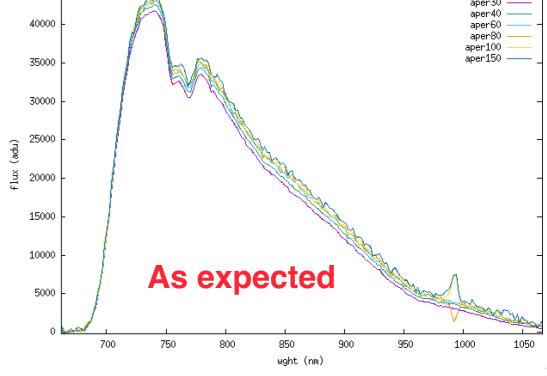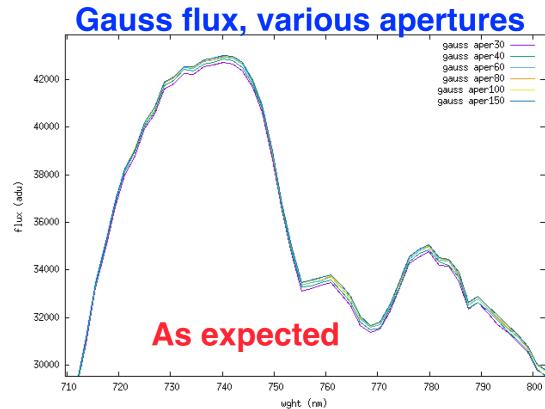# Downgrading the resolution of the simulation to match observations

Using local sigma transverse

The spike does not change -> it's coming from the core of the profile, not the wings

Aperture flux, various apertures

As expected

Gauss flux, various apertures

As expected

55

Impact on transparency curve from Varying Ozone level

From 0 Dobson to 900 Dobson

oz=0 (DU)
oz=10 (DU)
oz=100 (DU)
oz=300 (DU)
oz=400 (DU)
oz=500 (DU)
oz=900 (DU)

Wavelength

Abrupt threshold in Huggins band

Linear in Chappuis band
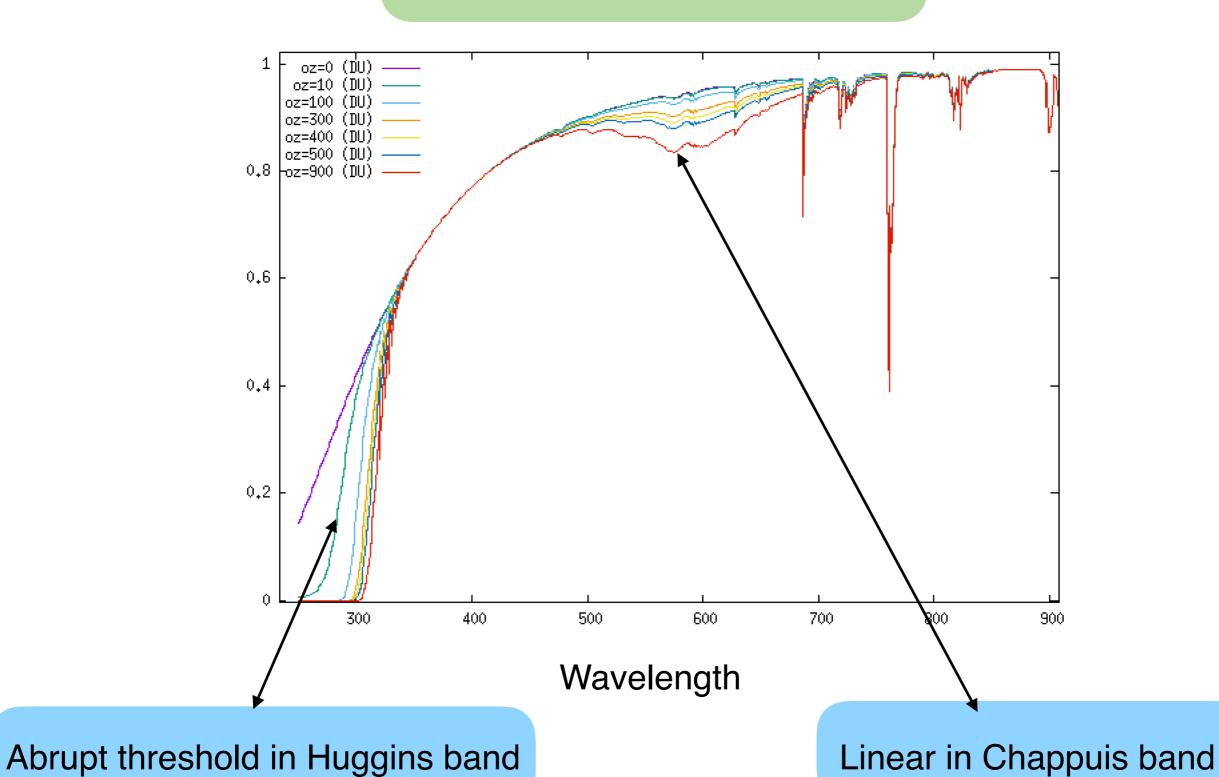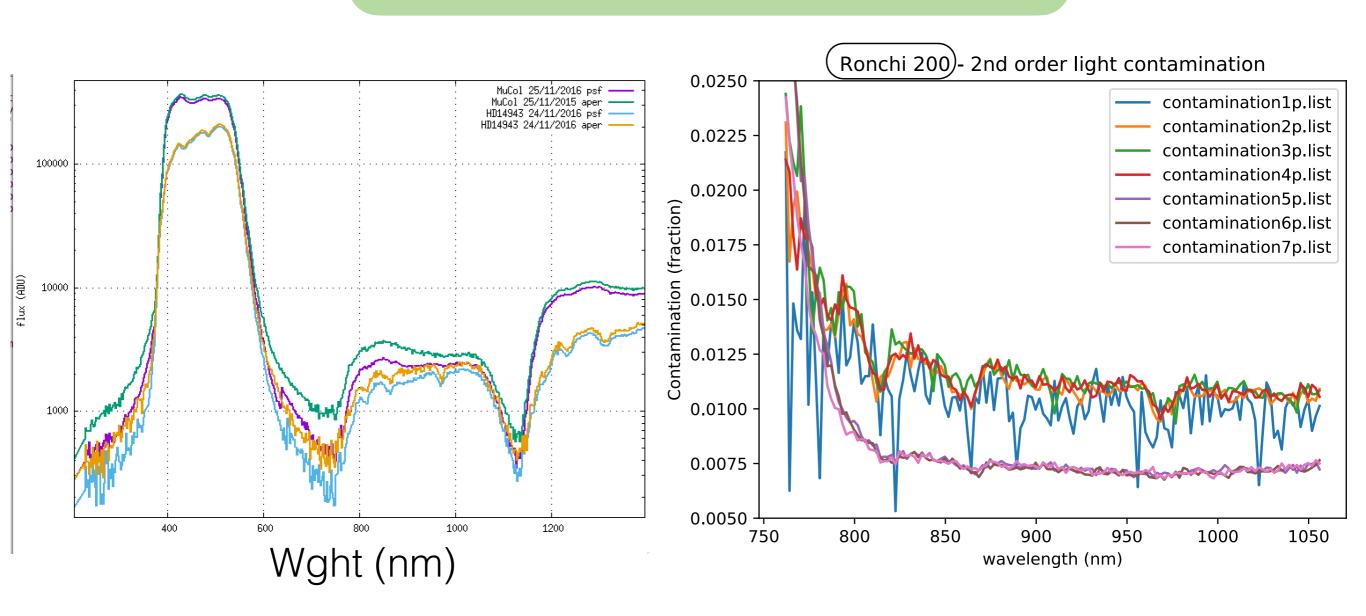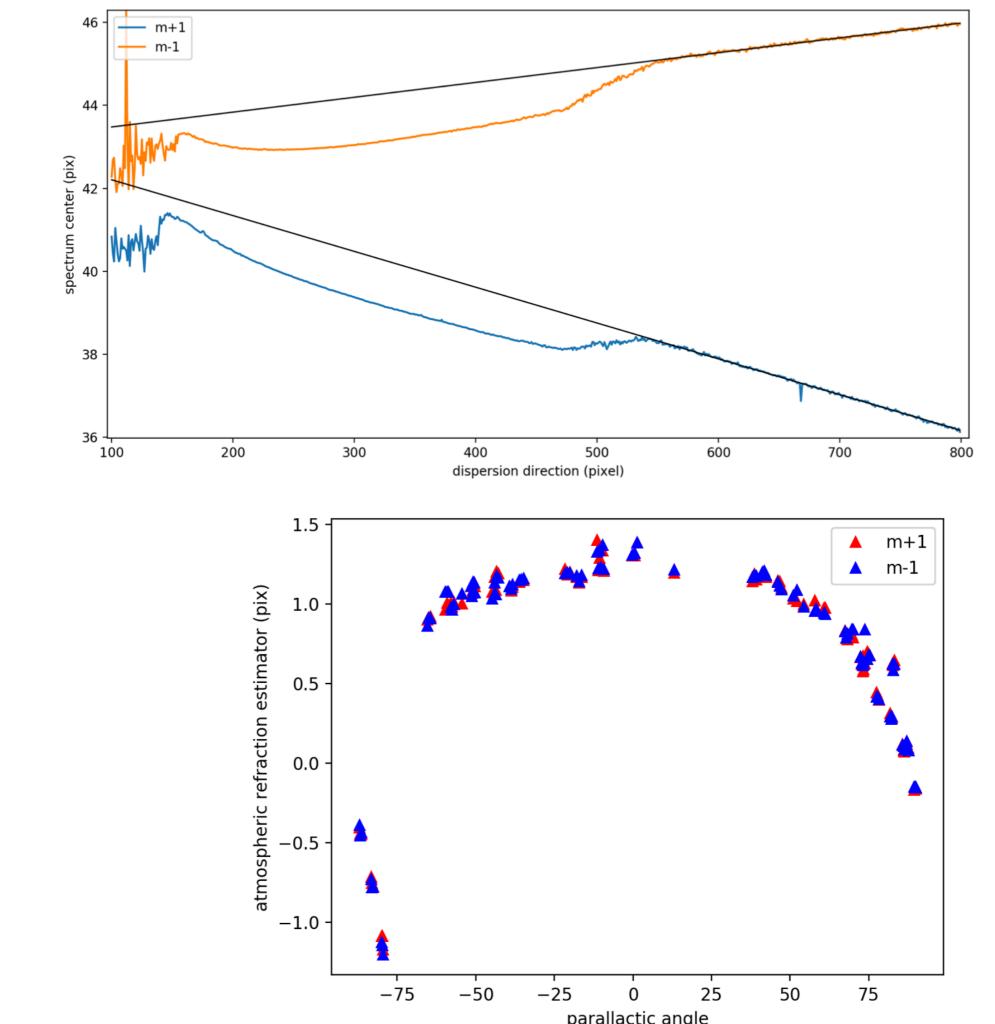
56

Determination of 2nd order light contamination

Red blocking filter
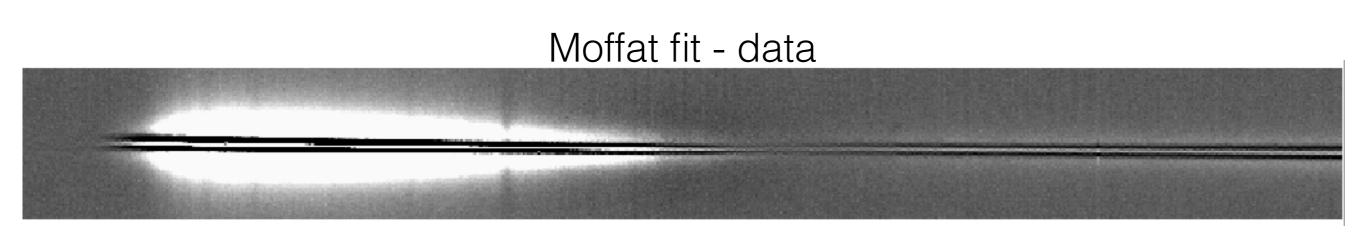

Contamination =Flux(w) / Flux(w/2) ~ 1% cst
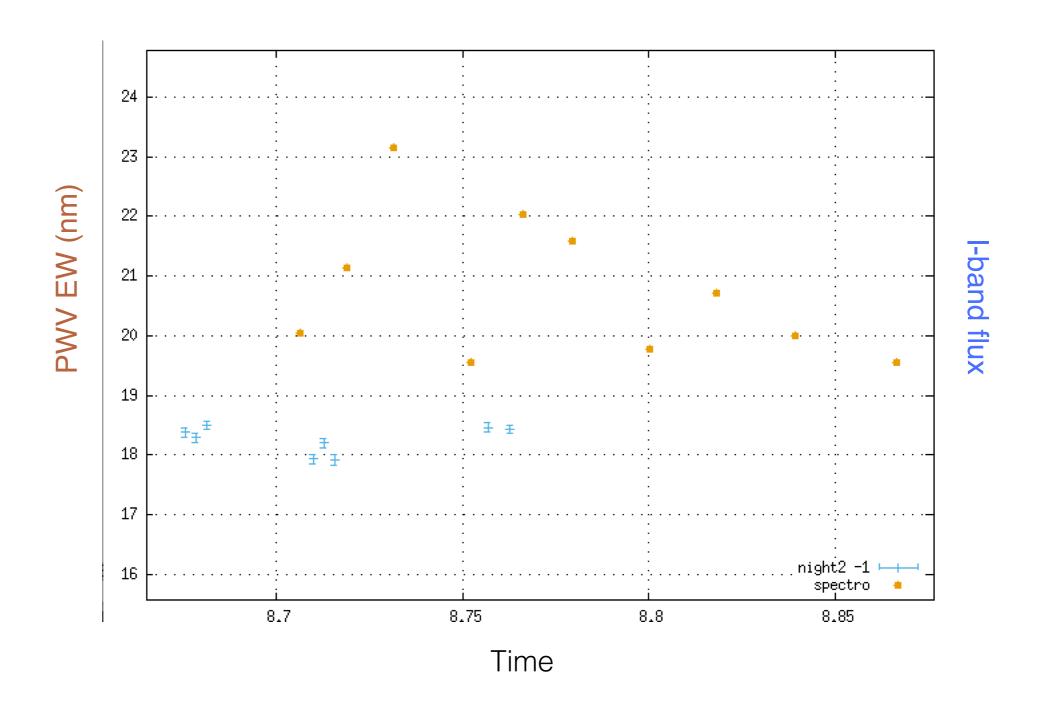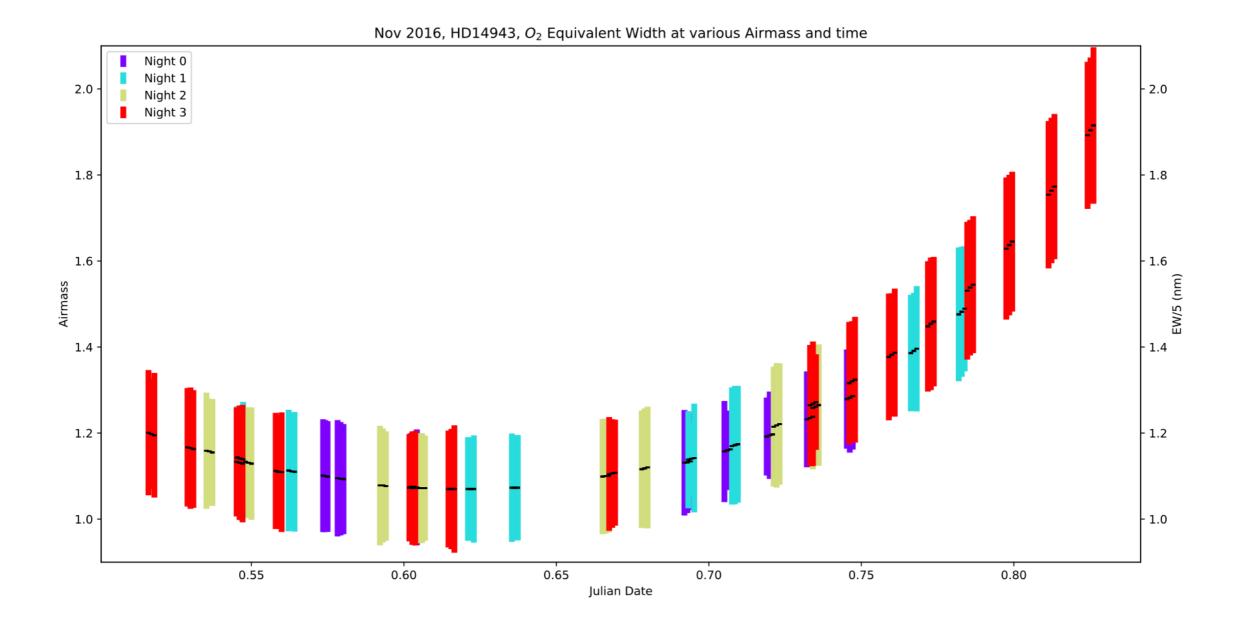
Signal extraction from fitting profile : Residuals
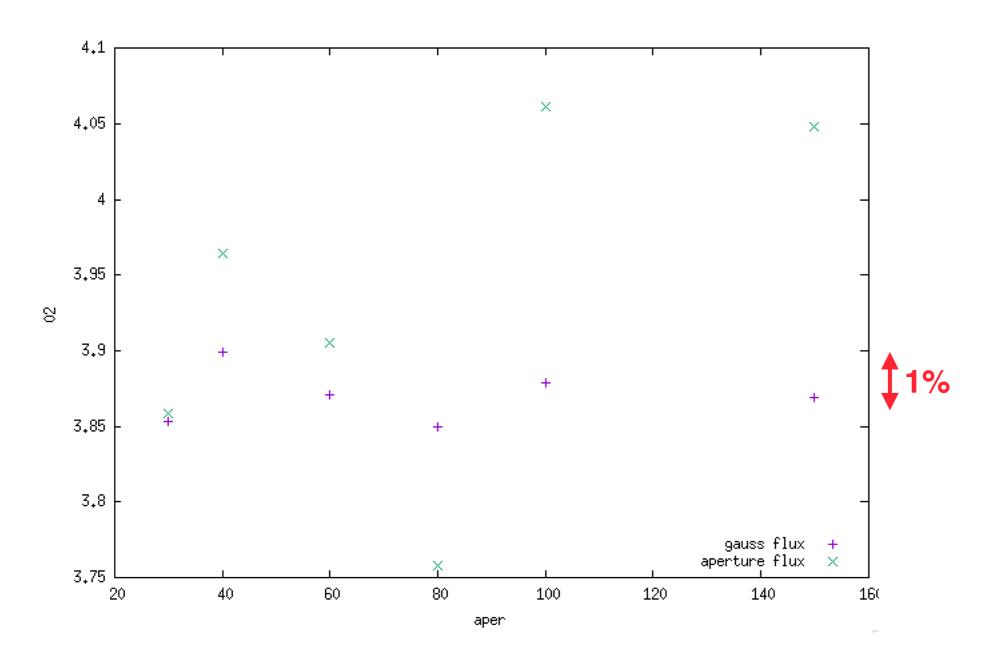
Gaussian fit - data

Moffat fit - data

(Gaussian+Moffat) fit - data

Realtime Spectrometry VS photometry

Nov 2016, HD14943, O_2 Equivalent Width at various Airmass and time

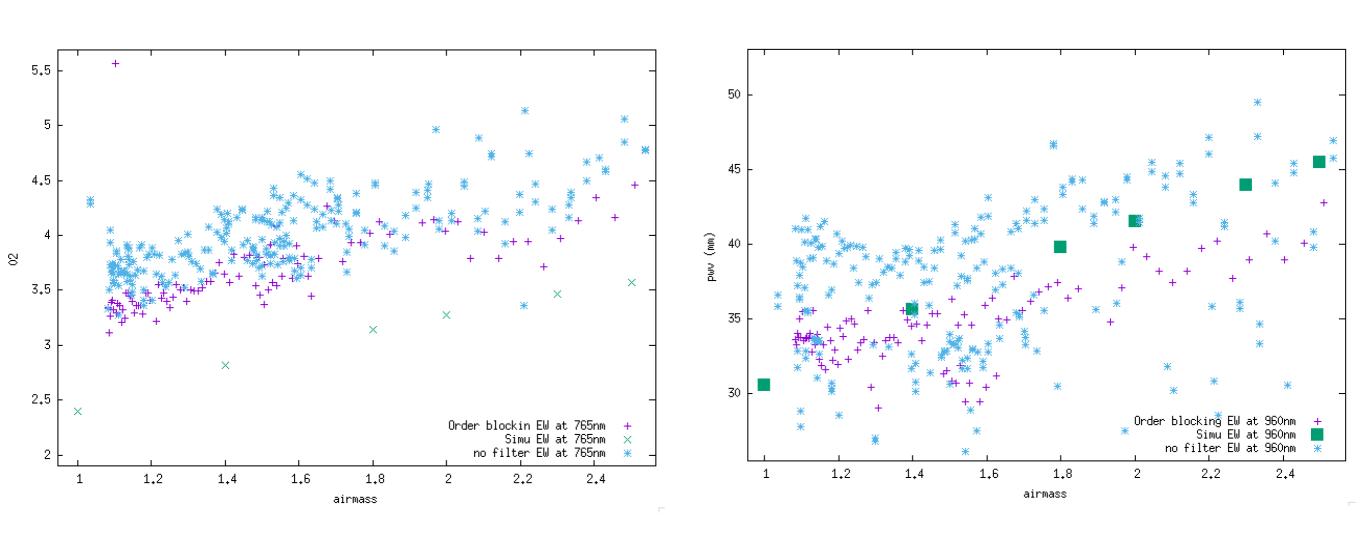# O2 EW VS aperture, for both Gaussian profile model and aperture flux

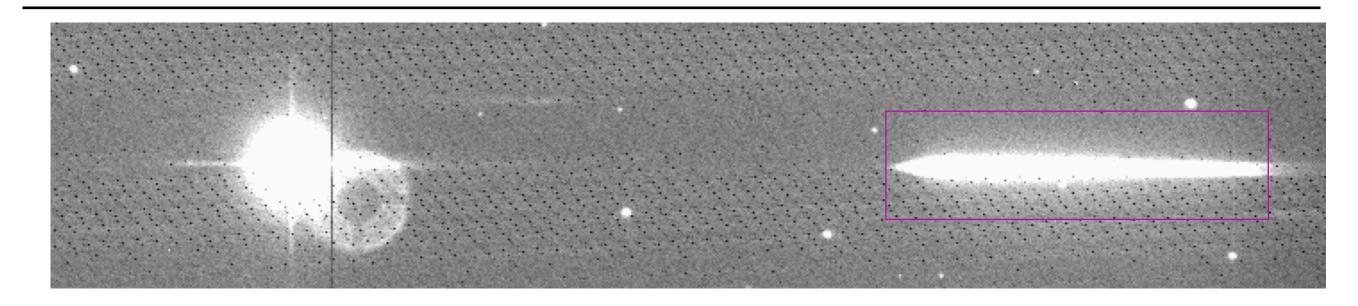**The O2 EW does not correlated with the aperture —> good !**

The impact on the O2 EW from varying the aperture
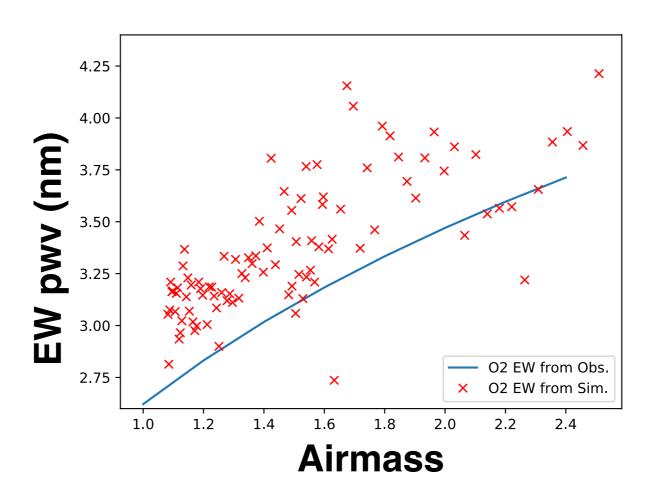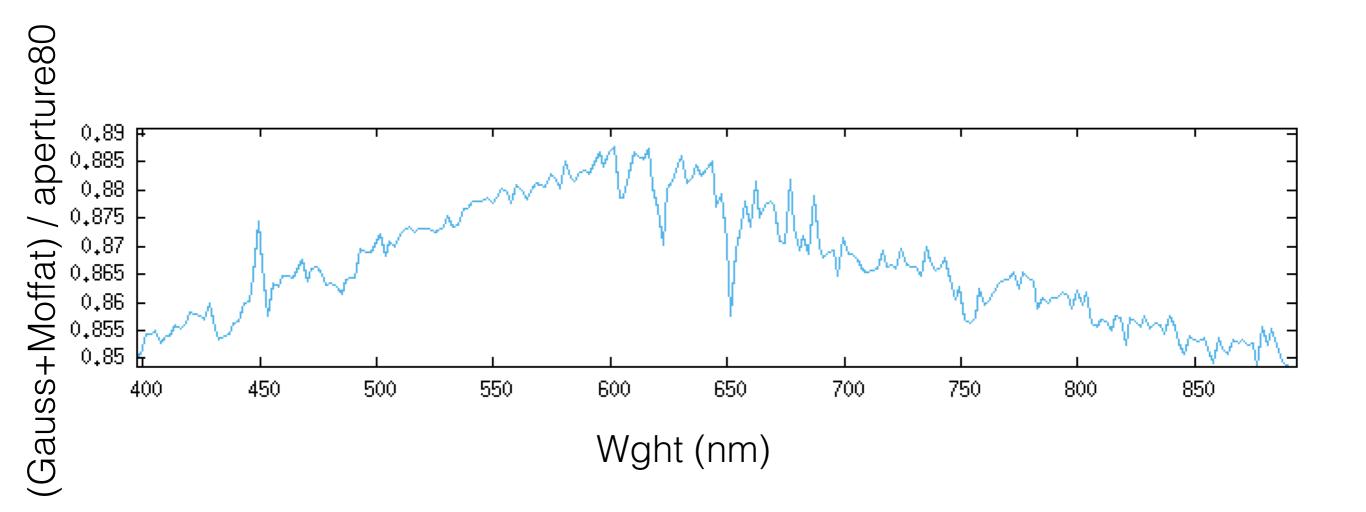**is sub-percent when using Gauss flux —> Good also**

The EW is ~20% higher in no filter images

Dispersion relation re-calibration

res=((1.922*pix+34)-wght)/wght

Our initial linear solution are compatible within 1%

To go from pixels to wavelength I
1) started with lambda=1.922*pixel + 34
2) I then made an interpolated flux vector at the Calspec wavelengths
3) The wavelength shift vs. calspec lambda

3rd order poly. fit
fitting a parabola

Our recalibration both reveal
the large non linearity of the dispersion relation in the blue