Removing the signature of the Earth's atmosphere from astronomical spectra

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16/04/14, MPE

C. Malin/TWAN

The project

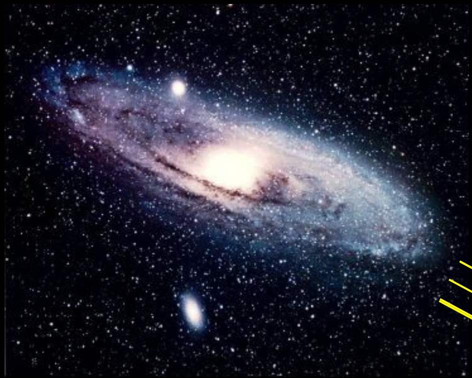
- In-kind projects related to Austria's accession to ESO in 2008 (software projects in Vienna, Linz, and Innsbruck)
- Topic of Innsbruck: The effect of the Earth's atmosphere on astronomical observations with the VLT (and E-ELT)
- Three subprojects (2009 – 2013):
  - Sky emission and transmission model for ESO's exposure time calculators (ETCs)
  - Tool for removal of telluric absorption features in astronomical spectra and water vapour abundance measurements
  - Tool for sky subtraction in the near-IR for observations without plain sky information

People involved

- **Innsbruck:**
  - Stefan Kimeswenger (professor, head of group)
  - Stefan Noll (postdoc, since 2009)
  - Wolfgang Kausch (postdoc, since 2009)
  - Marco Barden (postdoc, 2009 – 2011)
  - Cezary Szyszka (postdoc, 2011 – 2013)
  - Amy Jones (PhD student, since 2011)

- **ESO Garching** (selection)**:** Pascal Ballester, Jakob Vinther, Andrea Modigliani, Julian Taylor
- **ESO Santiago:** Alain Smette

Cerro Paranal Sky Model



Light propagates (billions of) light years widely unchanged. However, in the very last region the largest influences occur, mainly by the Earth‘s atmosphere:

Additional influences:
- Moon
- Zodiacal light
- Telescope emission

absorption

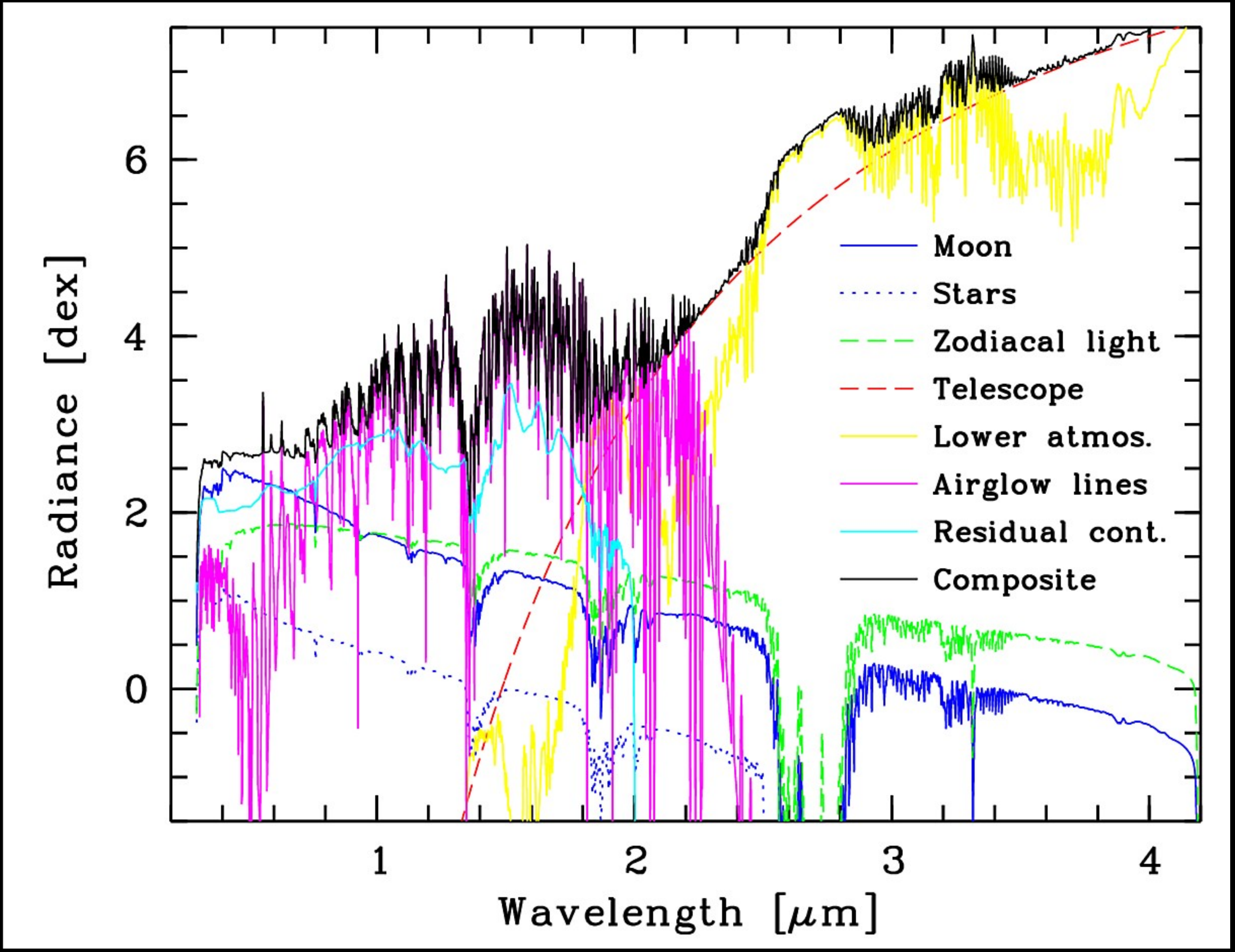
emission

scattering

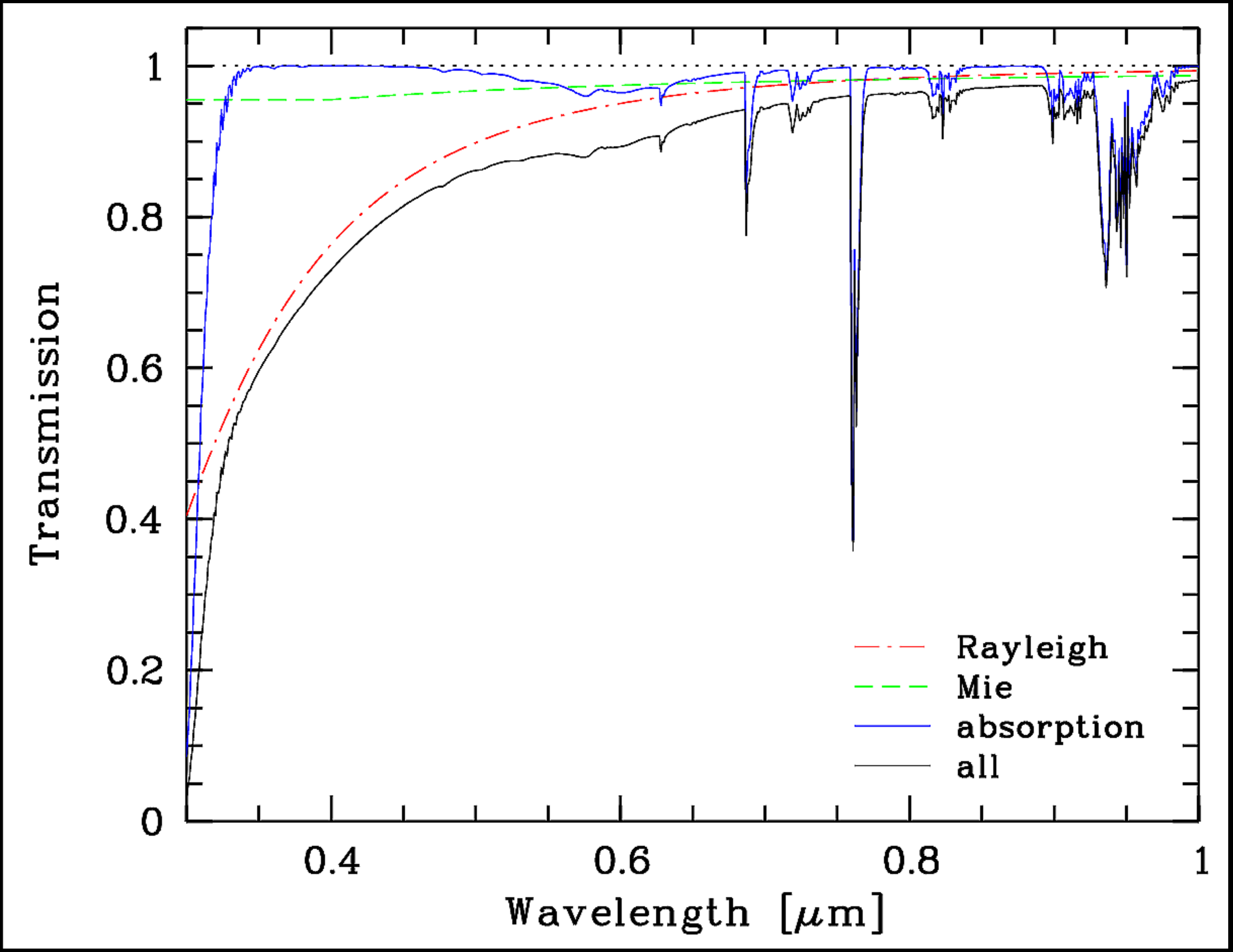
"sky background"

www.asc-csa.gc.ca

Cerro Paranal sky model: radiance

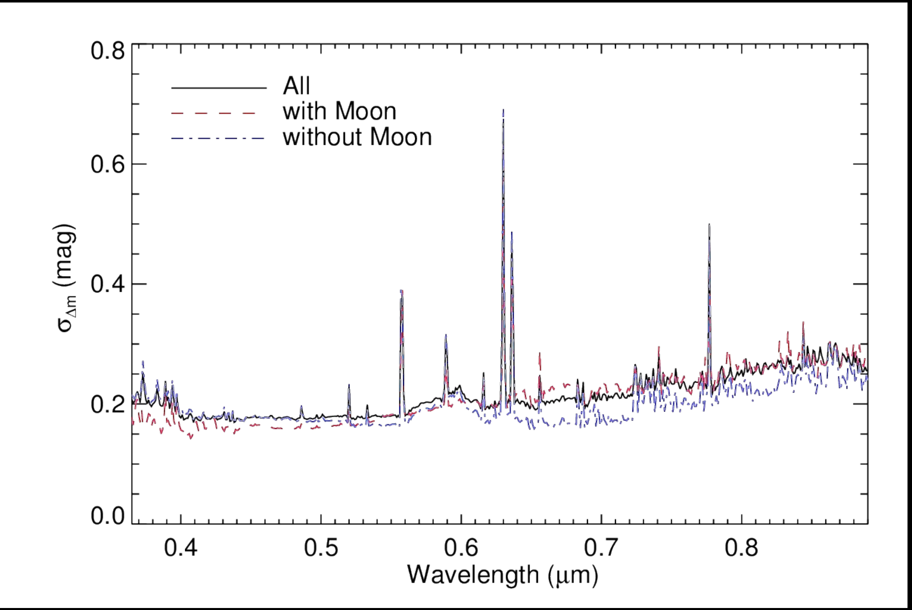


Cerro Paranal sky model: transmission

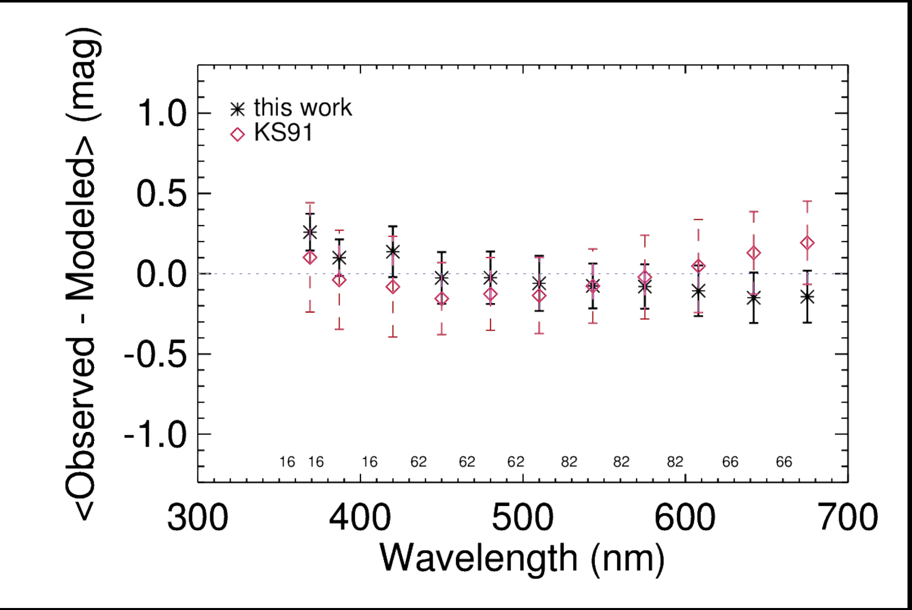


Evaluation of sky model

– Comparison to spectroscopic data (Patat 2008): accuracy ~ 20% in the optical



– New scattered moonlight model (Jones et al. 2013) significantly better than extended Krisciunas & Schaefer (1991) model (Noll et al. 2012)



Evaluation of model sky brightness

Source	Site	$S_{10.7cm}$ [sfu]	U	B	V	R	I	J	H	K
Advanced Sky Model	Cerro Paranal	180	21.9	22.6	21.6	20.9	19.6	16.5	14.4	12.8
Patat (2003)	Cerro Paranal	180	22.3	22.6	21.6	20.9	19.7			
Cuby et al. (2000)	Cerro Paranal	160						16.5	14.4	13.0
Mattila et al. (2003)	La Silla	150		22.8	21.7	20.8	19.5			
Advanced Sky Model	Cerro Paranal	130	22.1	22.8	21.8	21.0	19.7	16.7	14.4	12.8
Advanced Sky Model	Cerro Paranal	90	22.3	22.9	22.0	21.2	19.8	16.8	14.4	12.8
Walker (1987)	Cerro Tololo	90	22.0	22.7	21.8	20.9	19.9			
Benn & Ellison (2007)	La Palma	80	22.0	22.7	21.9	21.0	20.0	16.6	14.4	12.0

Magnitudes per $arcsec^2$, no Moon, faint zodiacal light, different solar radio fluxes

Sky model references

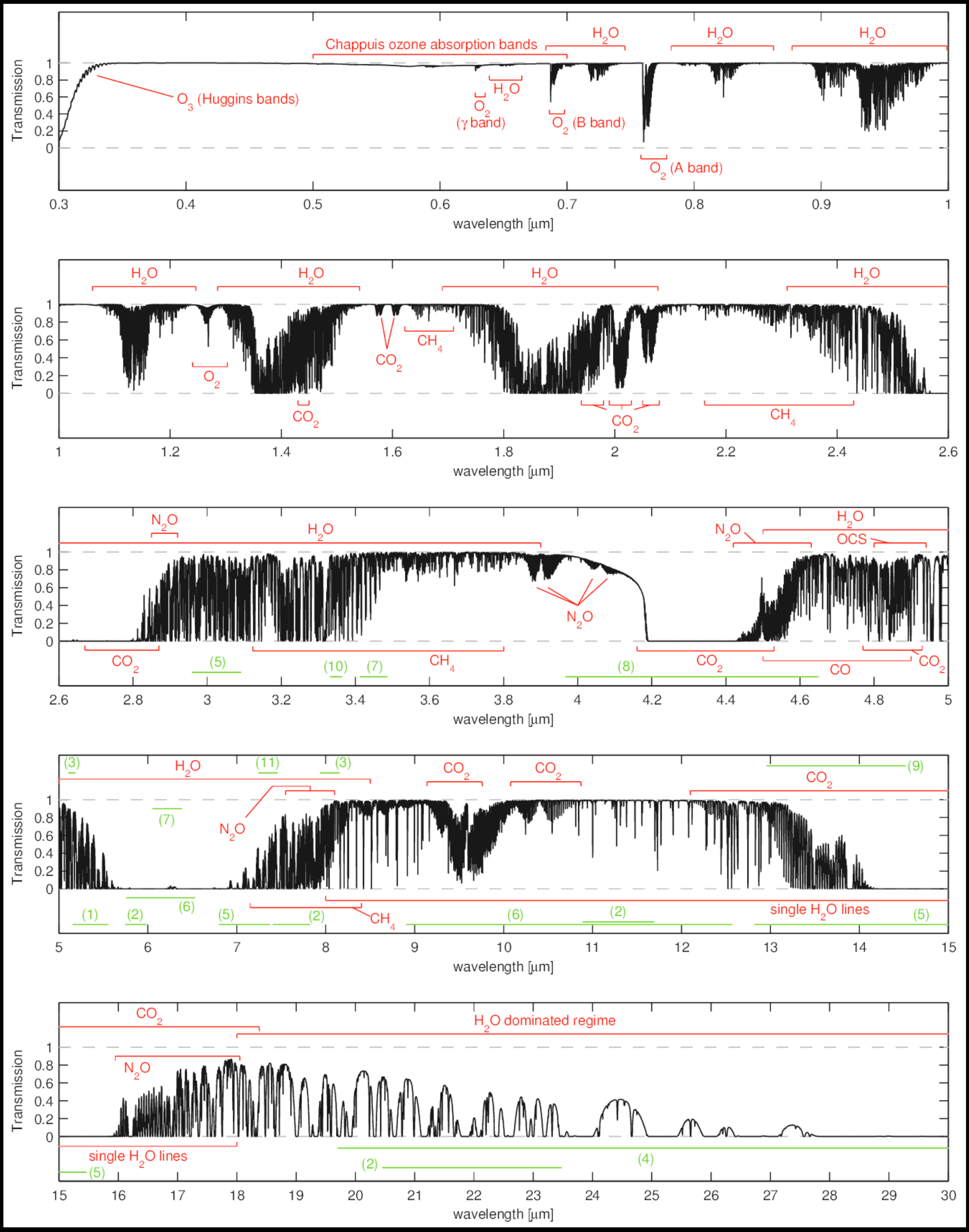
– S. Noll, W. Kausch, M. Barden, A.M. Jones, C. Szyszka, S. Kineswenger, J. Vinther, 2012, A&A 543, A92: “An atmospheric radiation model for Cerro Paranal. I. The optical range”

– A. Jones, S. Noll, W. Kausch, C. Szyszka, S. Kineswenger, 2013, A&A 560, A91: “An advanced scattered moonlight model for Cerro Paranal”

– SkyCalc web interface at `http://www.eso.org/observing/etc/skycalc/skycalc.htm`

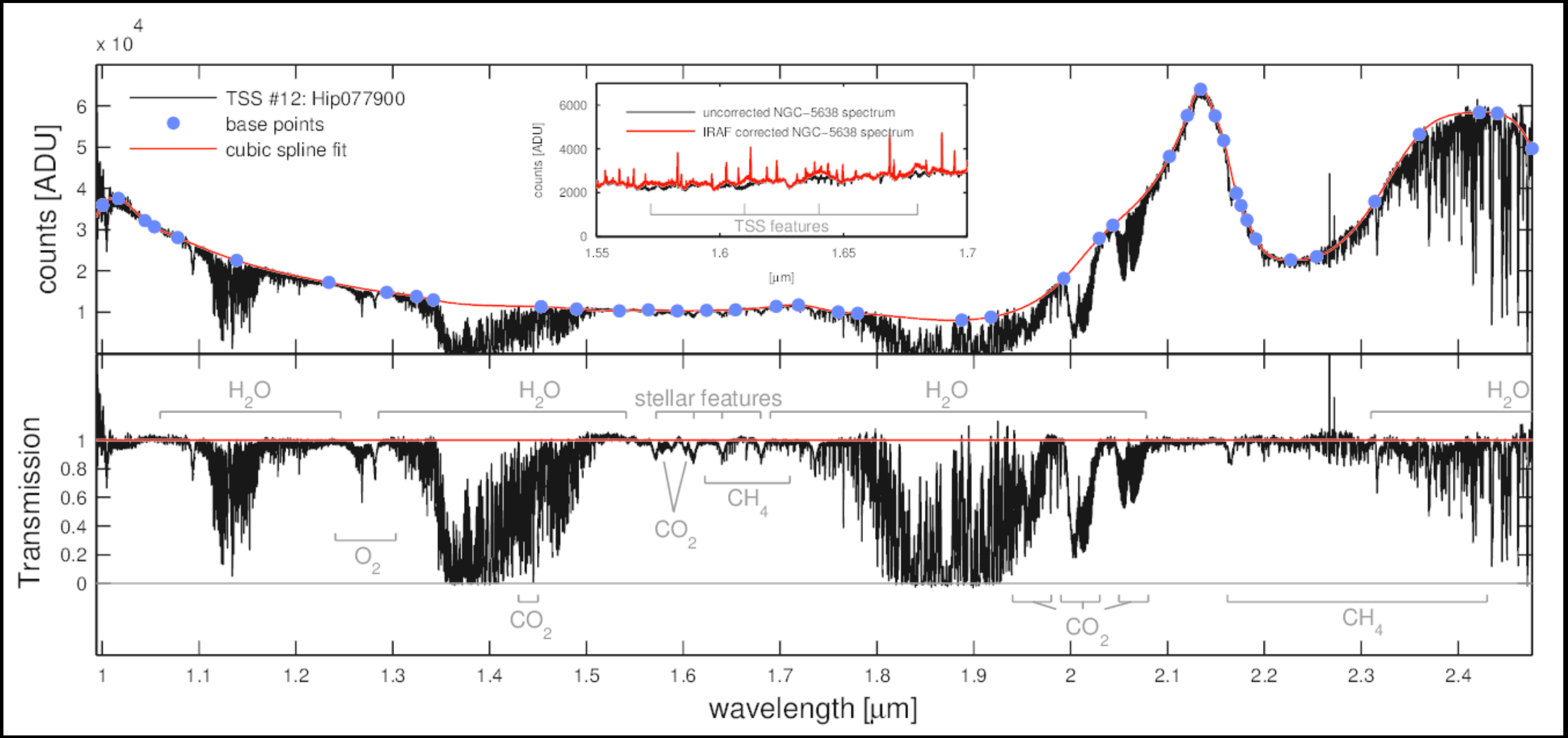
MOLECFIT

Molecular absorption in the atmosphere (Cerro Paranal mean conditions)



Telluric absorption correction: classical approach

- Transmission function from telluric standard star (TSS)
- Problems: interpolation over wide wavelength ranges, stellar features, time and line-of-sight differences between TSS and target



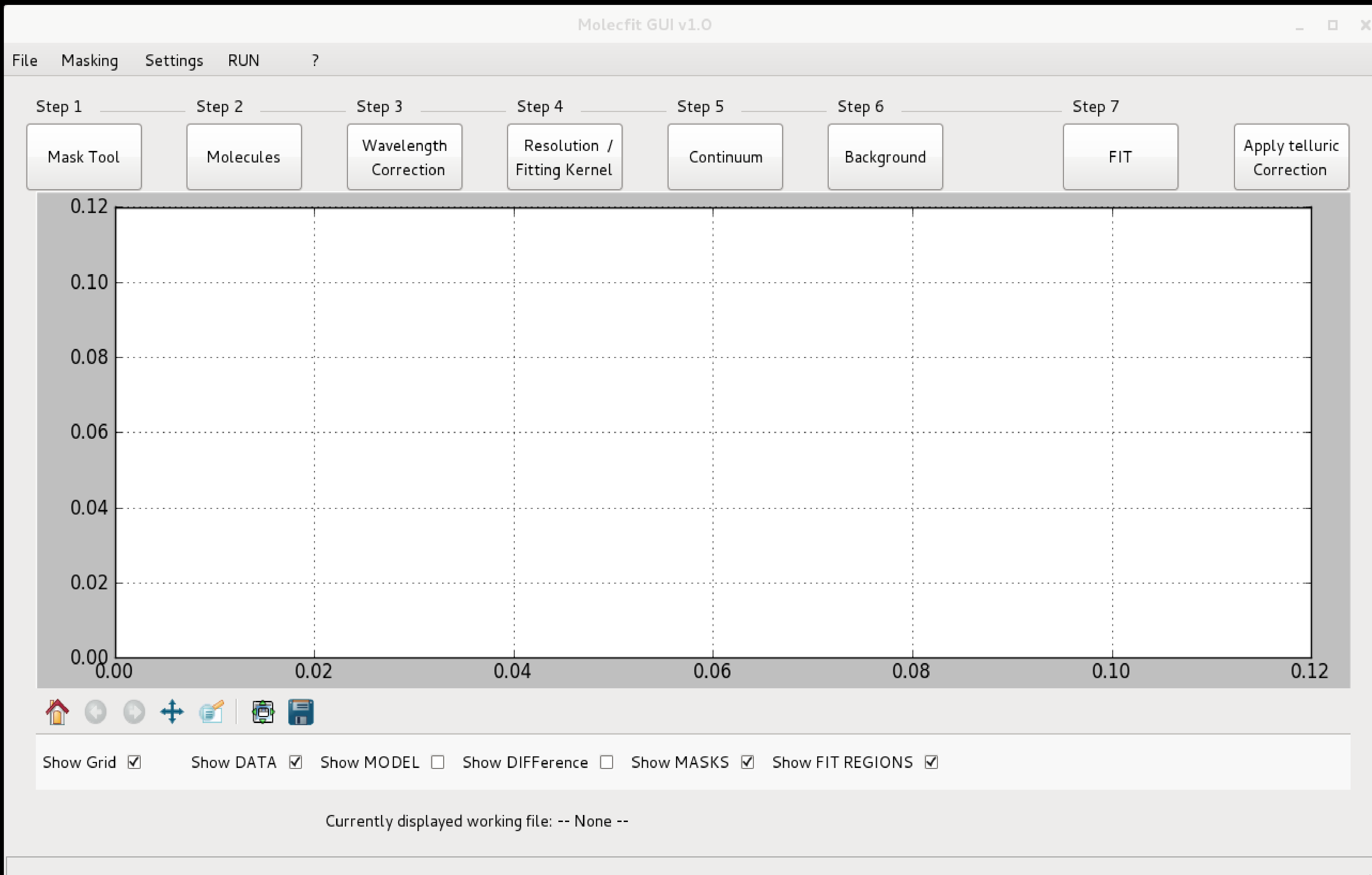
Telluric absorption corr.: calculated transmission

- Transmission function from radiative transfer code
- Method requires:
  - molecular line list (HITRAN)
  - pressure, temperature, and molecular abundances as a function of altitude for given time and line of sight
  - Adaptation of calculated spectrum to observed spectrum considering line profile, wavelength calibration, and continuum
- Advantages:
  - No requirement of regions without telluric features
  - Transmission curve without stellar features
  - Fitting of transmission curve directly to observed spectrum if S/N is sufficient (object features can be excluded by prudent setting of fitting ranges)

MOLECFIT

- Software package for telluric absorption correction (TAC) and fitting of molecular abundances based on the radiative transfer code LBLRTM (Clough et al. 2005)
- Instrument-independent and for world-wide use
- Programming language: C (involving ESO's CPL library)
- Command-line version and GUI (optimised for Cerro Paranal)
- First release was on 1st of April 2014 (see `http://www.eso.org/pipelines/skytools/`)
- Related papers:
  - A. Smette, H. Sana, S. Noll, et al. 2014, A&A, submitted
  - W. Kausch, S. Noll, A. Smette, et al. 2014, A&A, submitted

MOLECFIT GUI



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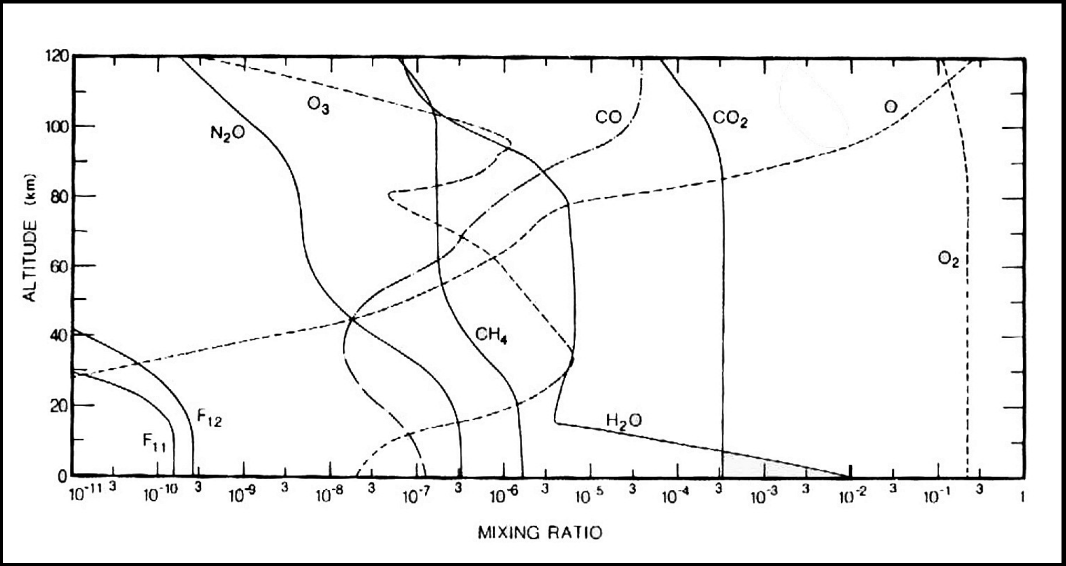
Building atmospheric profiles

– Static atmospheric standard profile (pressure, temperature, mixing ratios for many molecules)

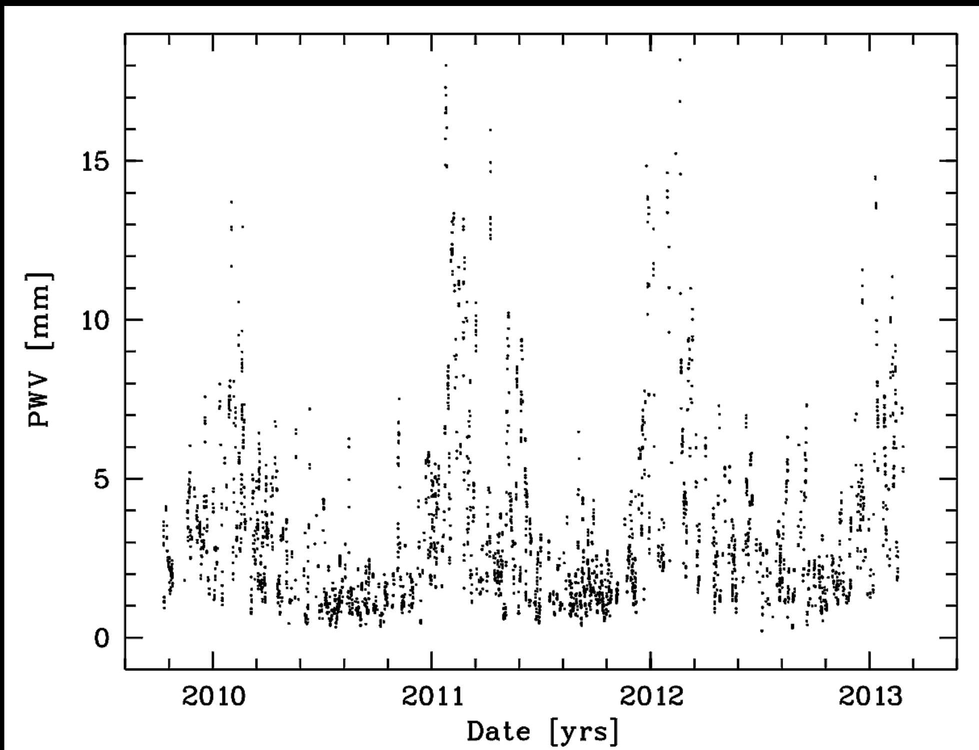
– Global GDAS weather model: 1° x 1° grid, every 3 h, profiles for pressure, temperature, and water vapour (automatic download by MOLECFIT or profile provide by user)

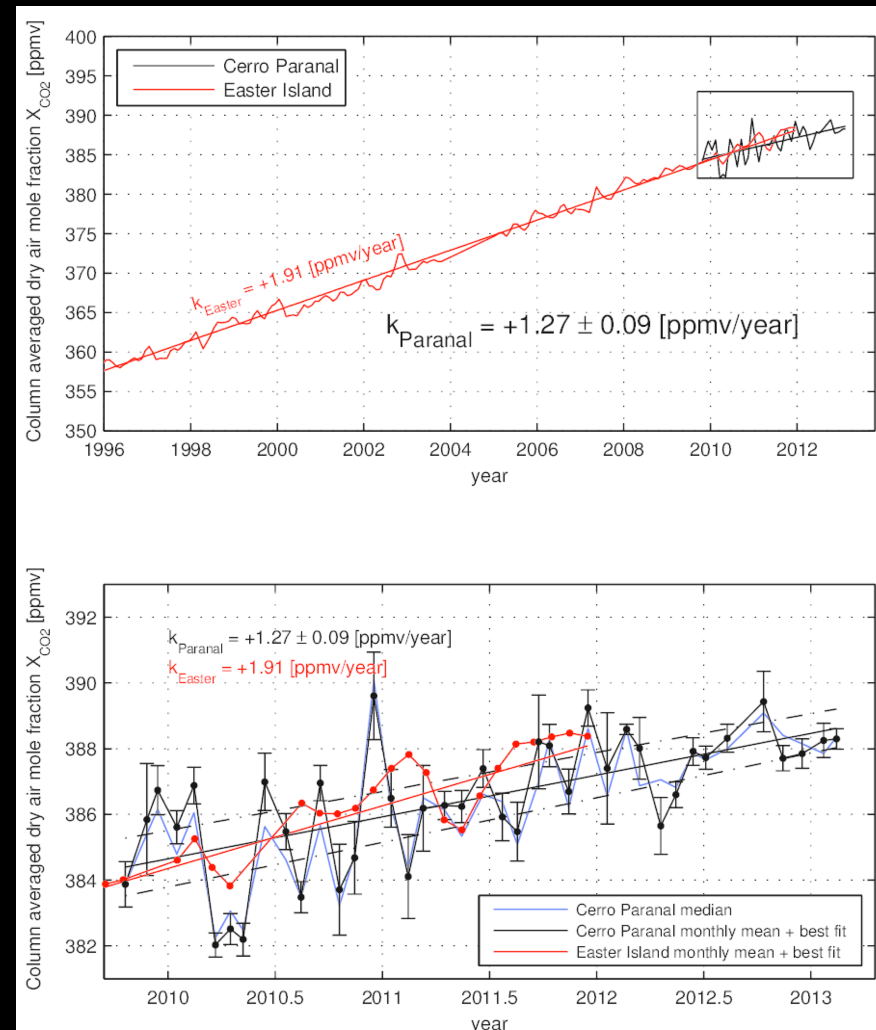
– Local meteorological data for height of site: pressure, temperature, and relative humidity (taken from FITS header if present)

– Scaling of merged profiles for molecules by a factor (fitting parameter)



Molecular abundances by MOLECFIT





PWV (precipitable water vapour):
Important for scheduling
observations in thermal IR
(see also ESO PWV monitor)

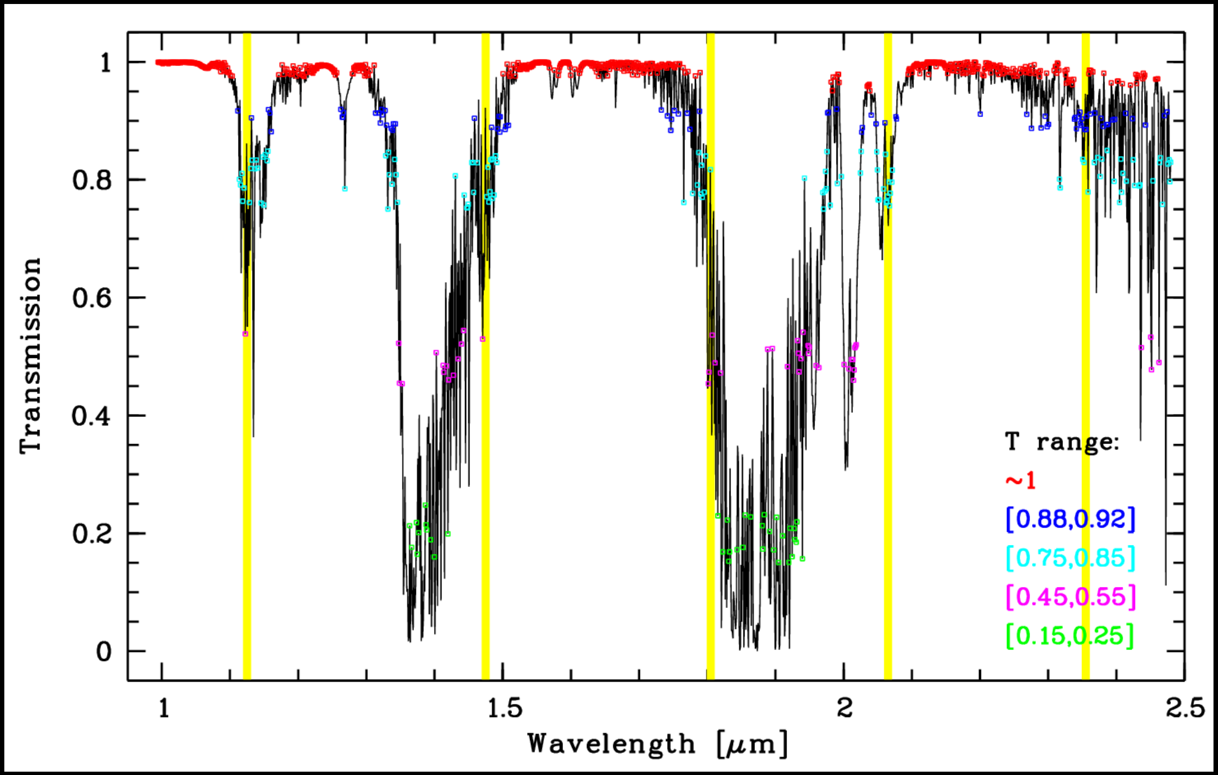
All measurements based on X-Shooter NIR-arm TSS spectra

Fitting procedure

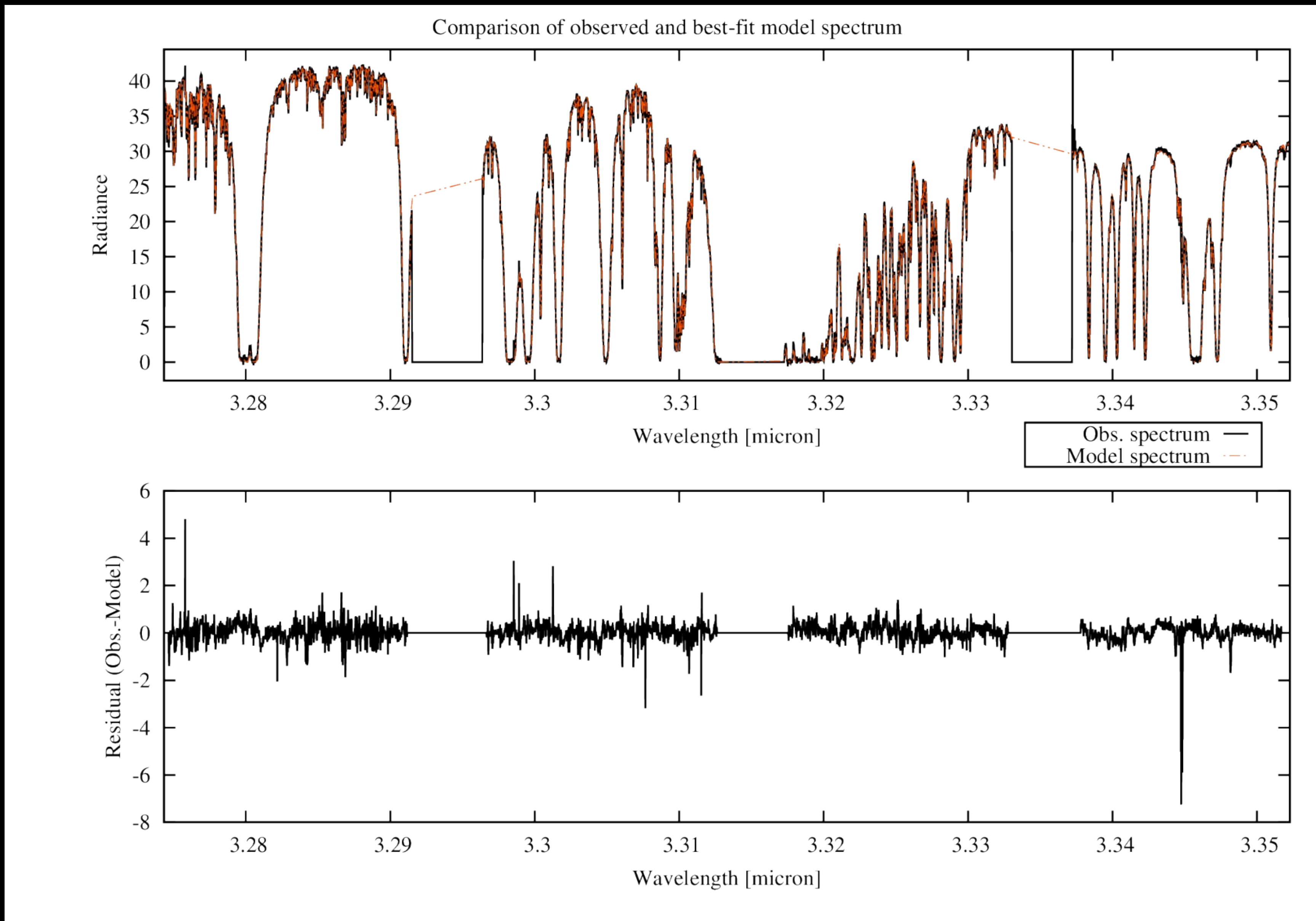
- χ^2 minimisation by a Levenberg-Marquardt technique (MPFIT)
- Fitting parameters:
  - Scaling factors for molecular profiles
  - Coefficients of polynomials for continuum fit
  - Coefficients of Chebyshev polynomials for modification of wavelength grid
  - Widths of boxcar, Gaussian, and Lorentzian for instrumental profile (alternative: user-provided kernel → no fit)
  - Emissivity of greybody (only for fit of sky emission spectra in the thermal IR)

Fitting ranges and exclusion regions

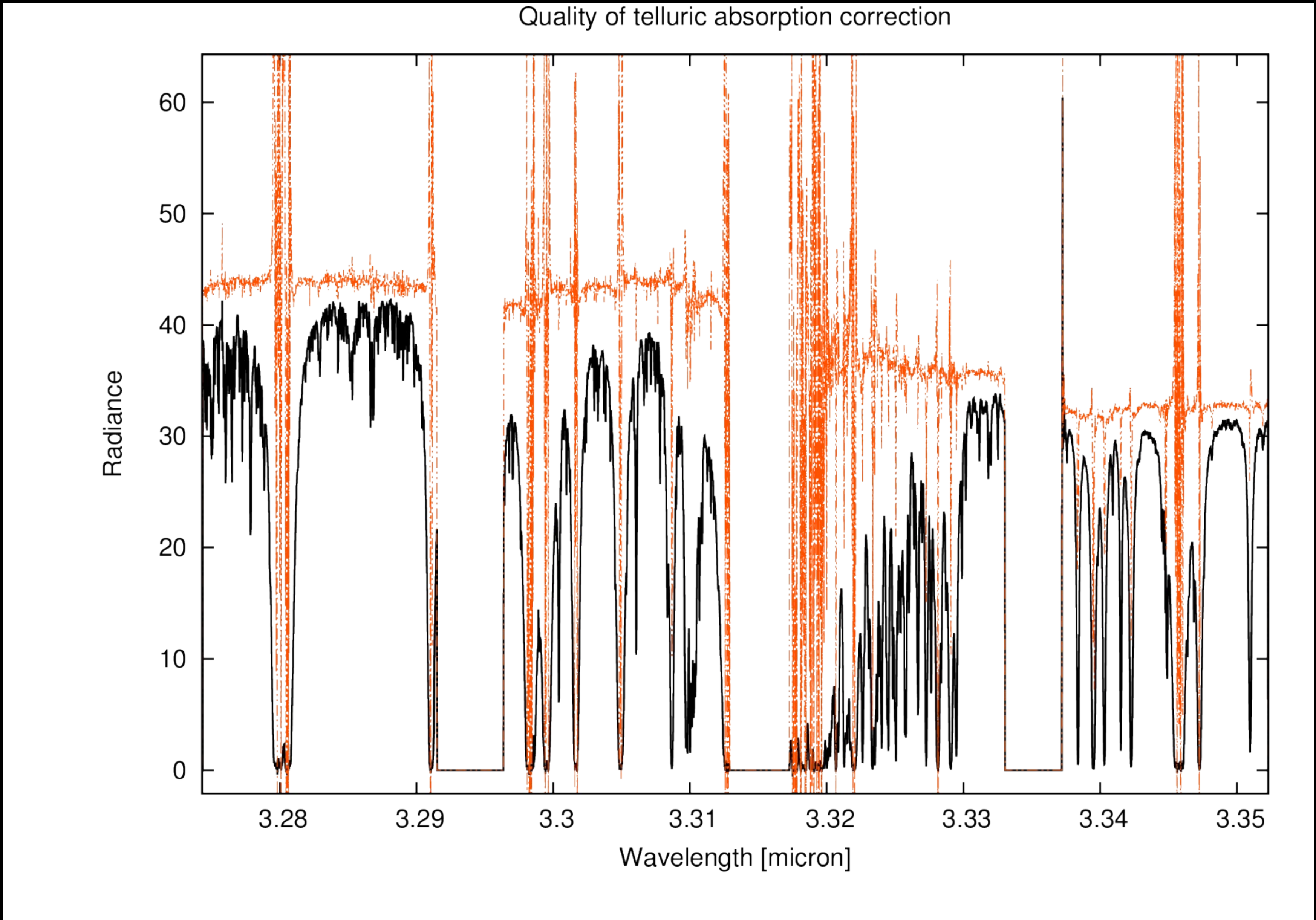
- **Fitting ranges:** lines of intermediate strength; good coverage of wavelength range; as narrow as possible (better continuum fit and shorter code run times)
- **Exclusion regions:** no fitting of bad pixels (or other instrumental defects) and object features



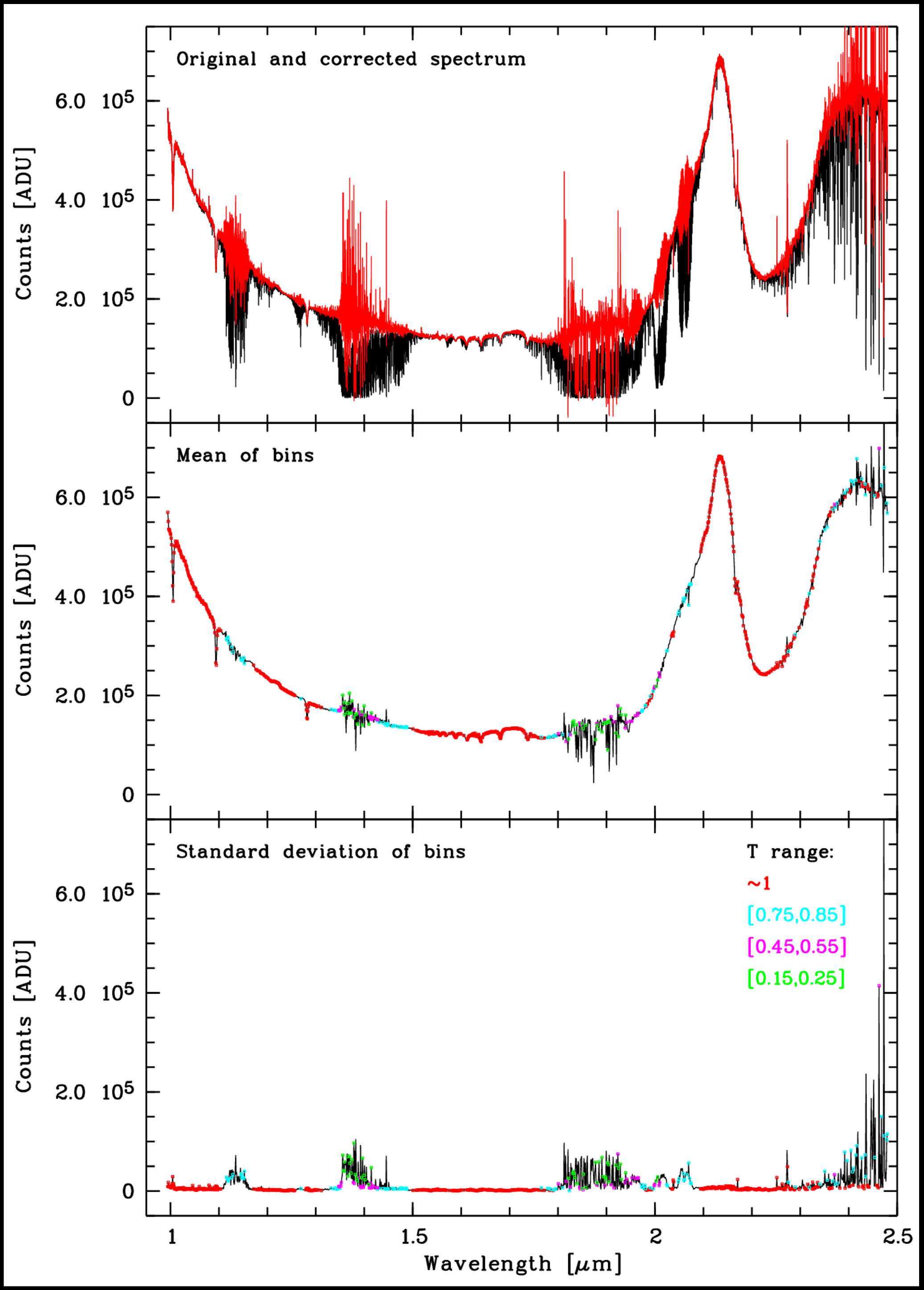
Fit for CRIRES example



TAC of CRIRES example



TAC of X-Shooter NIR-arm example

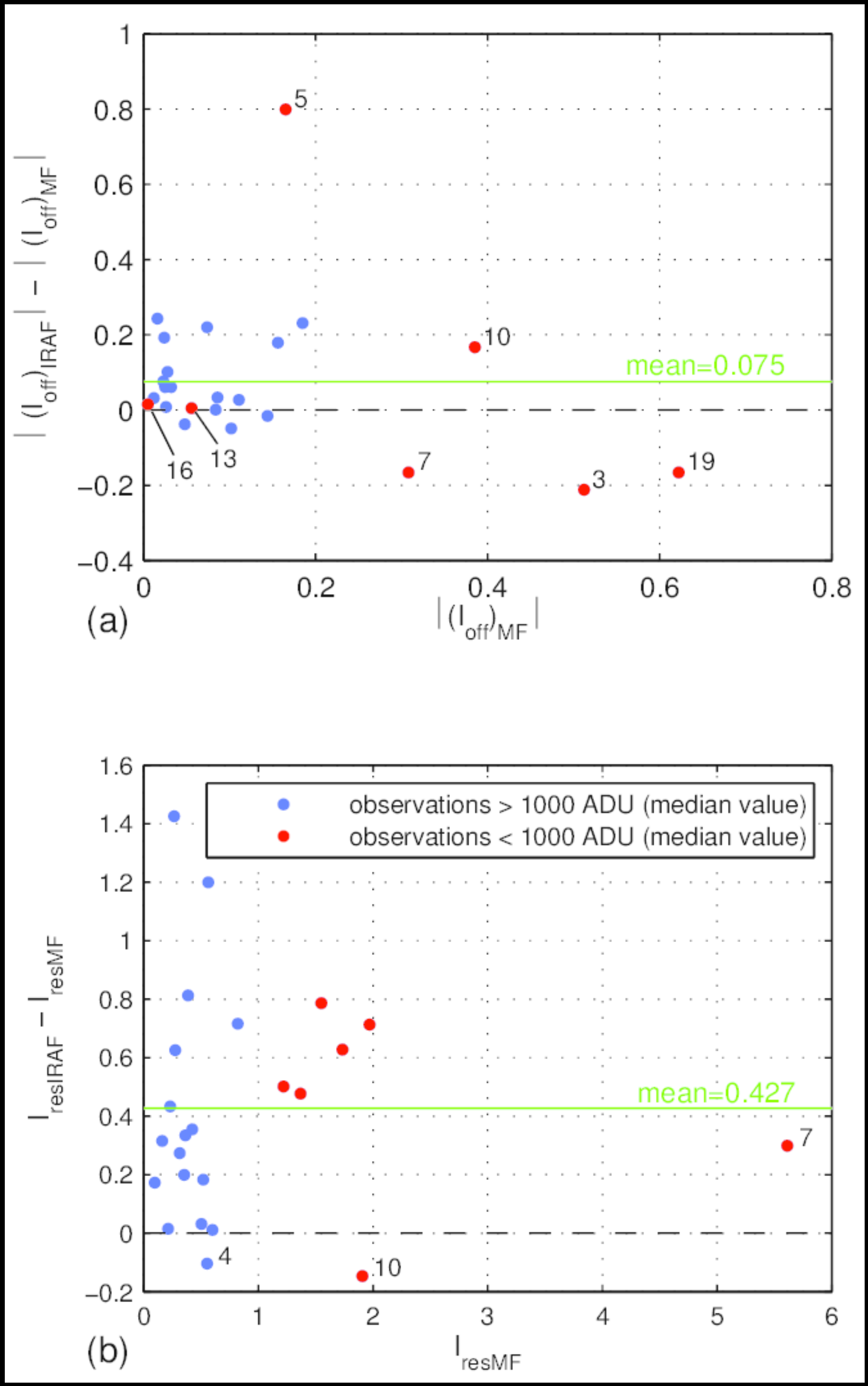


Comparison of MOLECFIT and classical approach

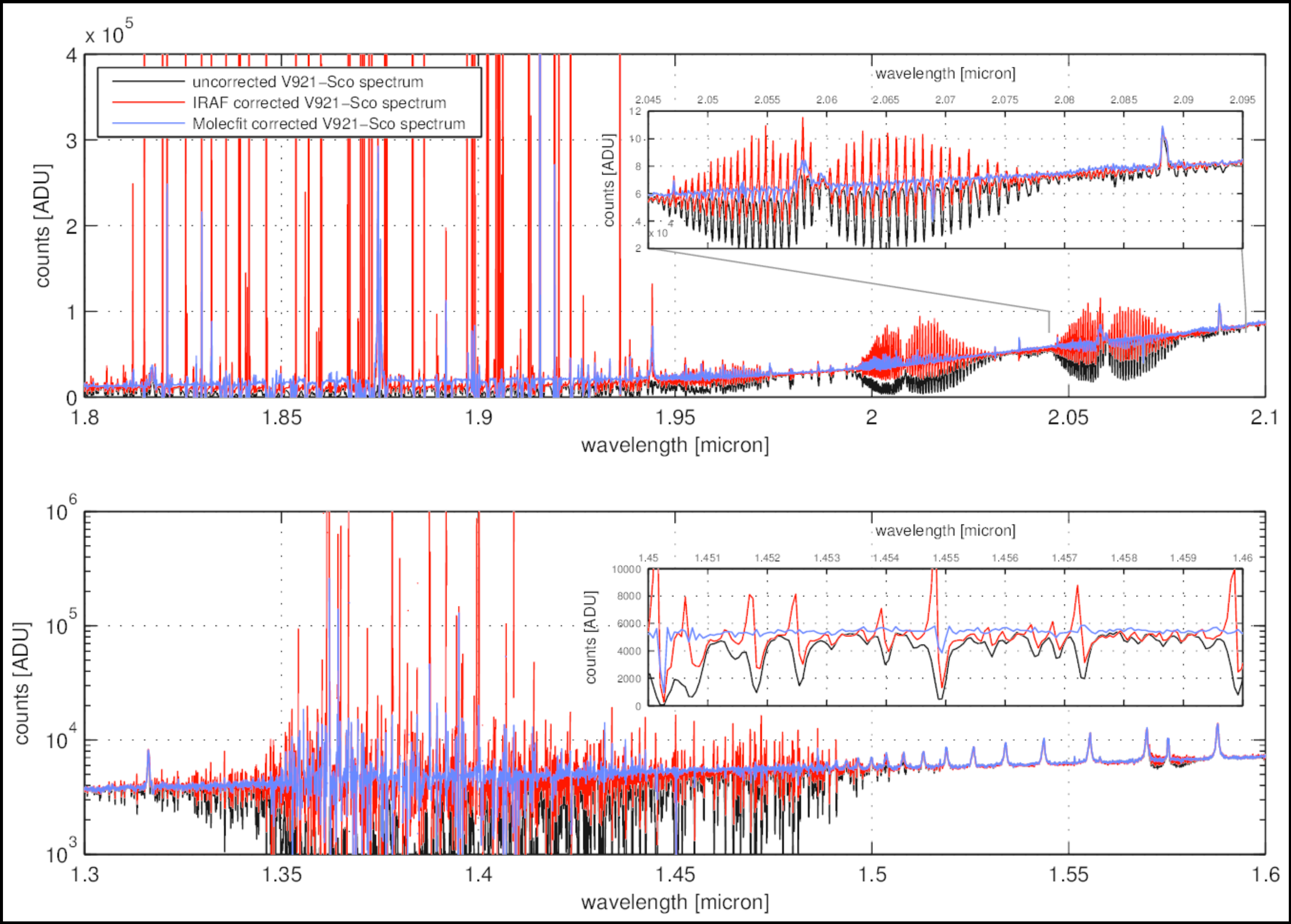
- **Test data set:** 24 X-Shooter NIR-arm science spectra covering a wide S/N range + a corresponding set of TSS
- **MOLECFIT:** direct fit of science spectra
- **Classical method:** transmission curve by interpolation of TSS spectra + IRAF task `telluric` for scaling and shifting of transmission curve

Comparison of MOLECFIT and classical approach

- **I_{off}:** large-scale residuals (systematic offsets; e.g. by wrong molecular abundance)
- **I_{res}:** small-scale residuals (e.g. by wrong instrumental profile or wavelength calibration)
- **Result:** MOLECFIT significantly better at least for moderate to high S/N data



Results for both methods for an X-Shooter example

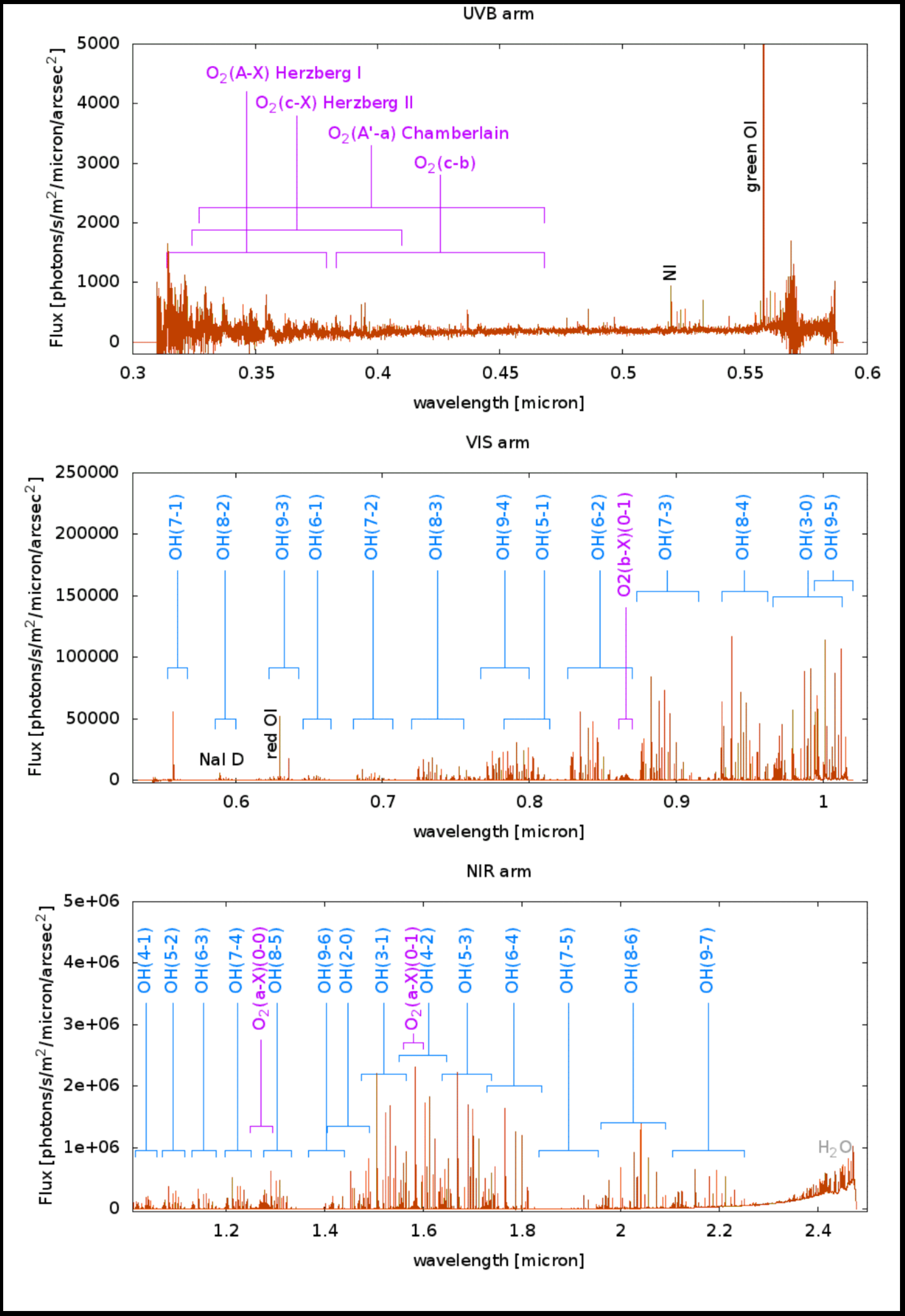


SKYCORR

Sky emission in the optical and near-IR

X-Shooter example spectrum:

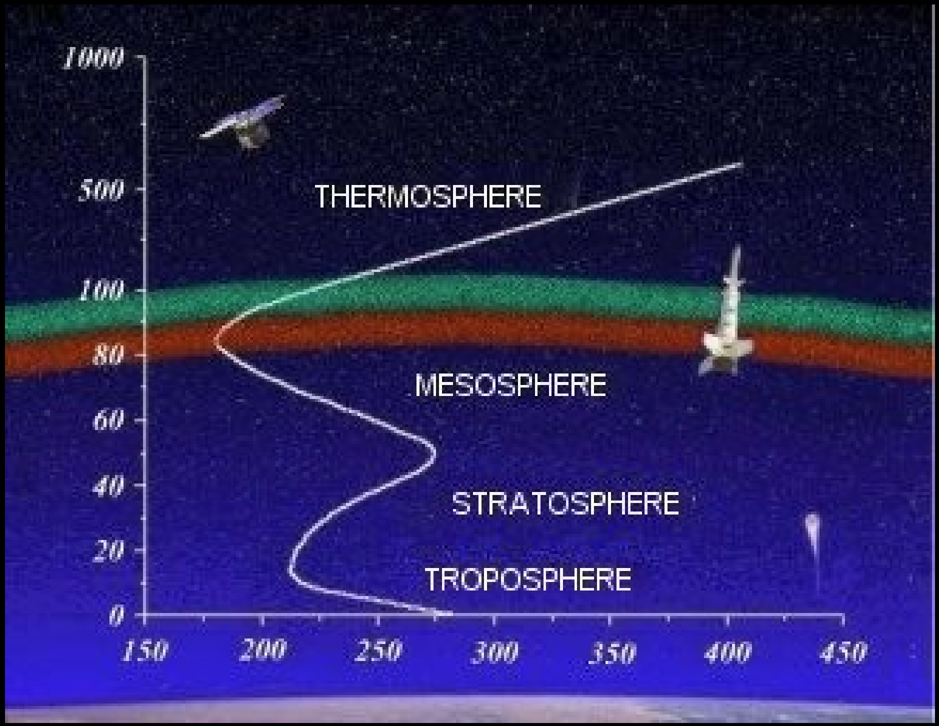
predominance of airglow emission lines in the near-IR



ISS/NASA

Airglow

- Chemiluminescence (light emission by chemical reactions)
- Solar UV radiation starts chain reactions by photochemical reactions (airglow reaction can be significantly delayed).
- Origin in mesopause / lower thermosphere (MLT) region ($P < 0.01$ mbar → thin gas)
- Usually very thin emission layers of a few km thickness only



www.laser.inpe.br/lume/

Airglow variability

- Diurnal variations (sun altitude)
- Seasonal variations
- 11-yr solar activity cycle
- Lunar variations (e.g. tides)
- Dependence on latitude
- Planetary (Rossby) waves (P typically a few days)
- Gravity waves (P > 5 min; caused by mountains / weather fronts)
- Longterm trend (→ climate change)

MASCOT/Paranal/ESO

Sky subtraction

- **Ideal situation:** 2D spectra with plain sky on both sides of the target (→ 2D interpolation method)
- **Challenging situation:** no plain sky (e.g. 1D data or object emission too extended) → sky exposure to be taken with same instrumental set-up at different time
- **Problem:** strong airglow variability
- **Solution:** Scaling of airglow lines in sky spectrum by means of physically motivated line grouping
- Only algorithm so far by Ric Davies (2007) for SINFONI data

SKYCORR

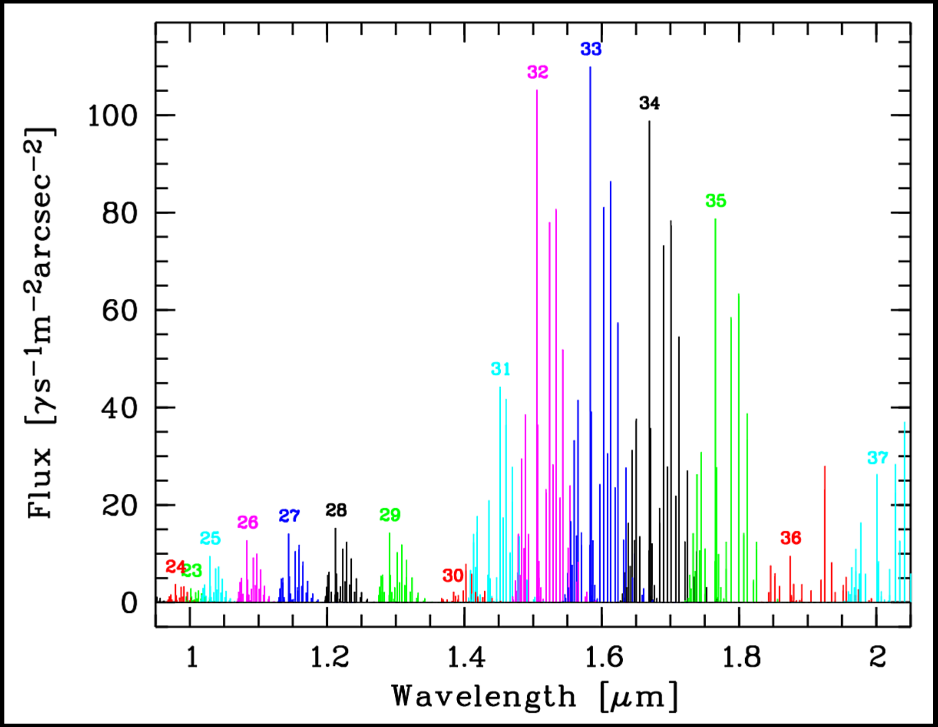
- Software package for sky subtraction (in the near-IR) based on 1D data
- Instrument-independent and for world-wide use (although optimised for Cerro Paranal)
- The code has been designed to minimise user interaction.
- Programming language: C (involving ESO's CPL library)
- First release was on 1st of April 2014 (see `http://www.eso.org/pipelines/skytools/`)
- Related paper:
  - S. Noll, W. Kausch, S. Kimeswenger, et al. 2014, A&A, submitted

Main properties of SKYCORR

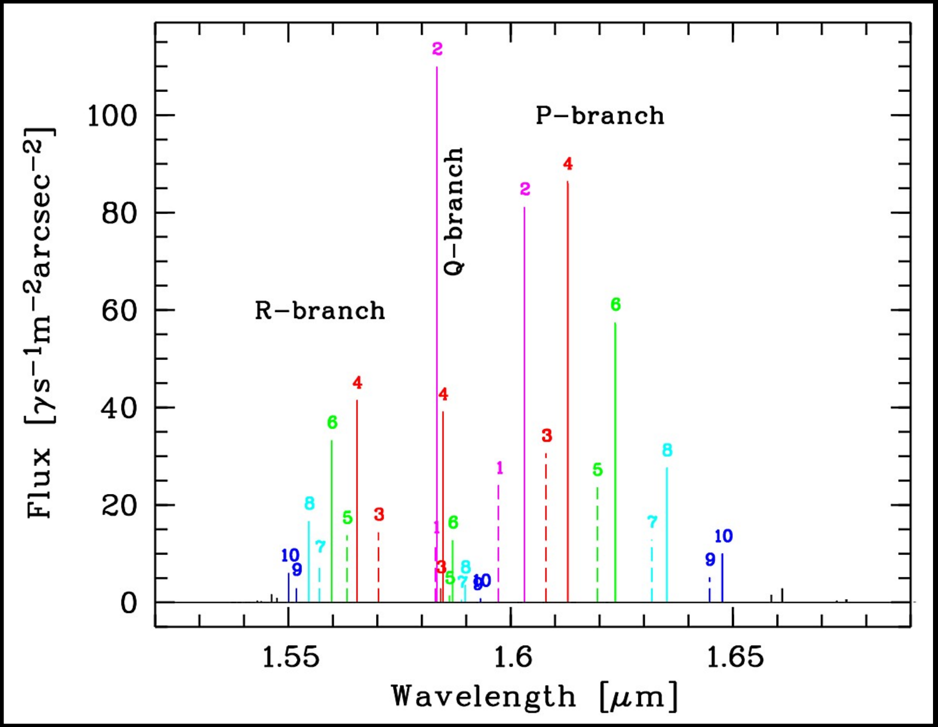
- Line finder for line and continuum identification
- Separation of lines and continuum by linear continuum interpolation
- Molecular bands of OH and O_2 as groups for line scaling (coverage from U to K band)
- Second group category for rotational transitions (same lines in similar bands)
- Initial weights for each group for each pixel from semi-empirical Cerro Paranal airglow model
- Polynomial fit of wavelength grid and advanced rebinning without line broadening
- Subtraction of best-fit sky line spectrum and unscaled sky continuum from input science spectrum

SKYCORR line grouping

Vibrational OH groups in the near-IR



Rotational OH groups



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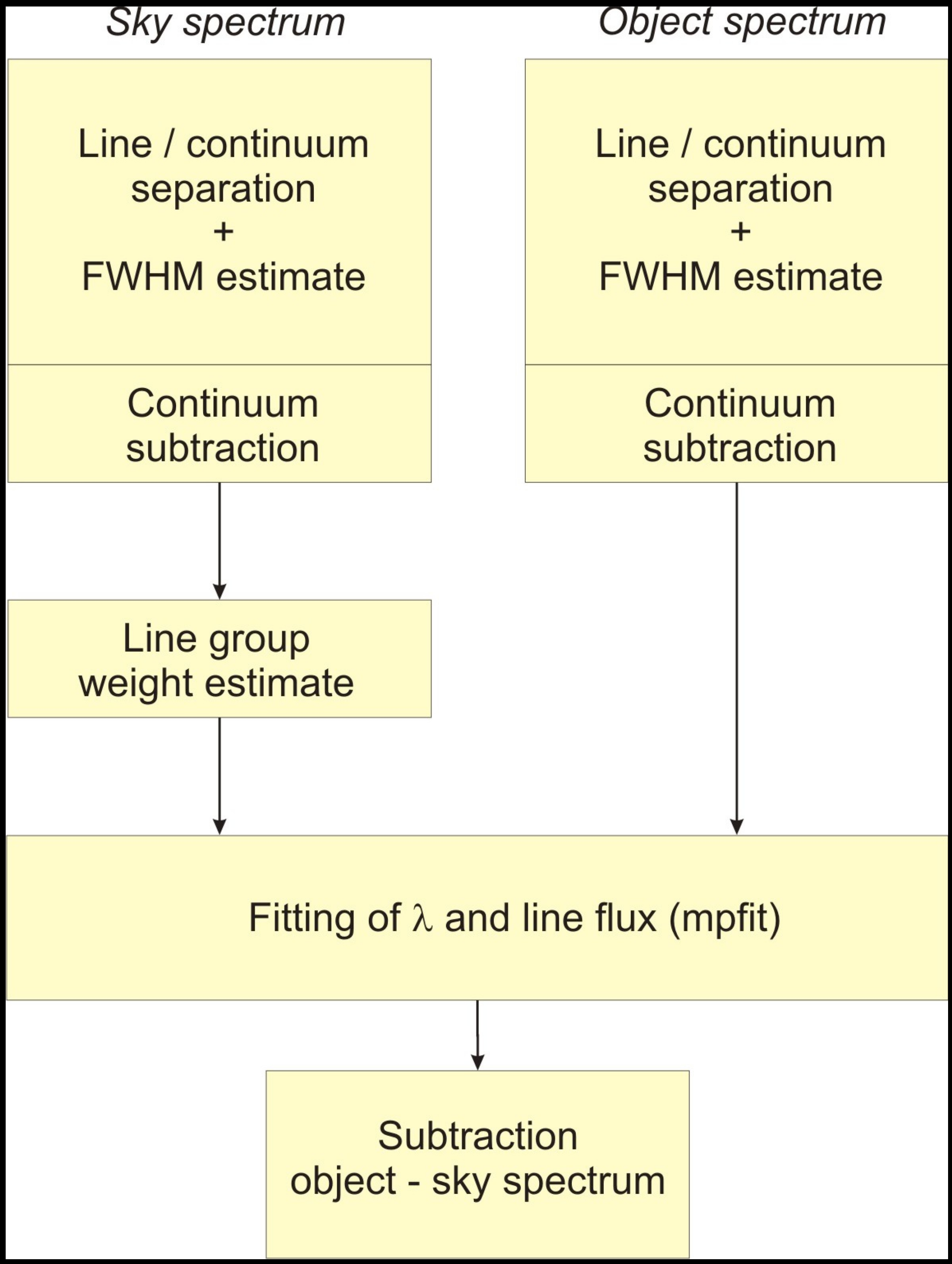
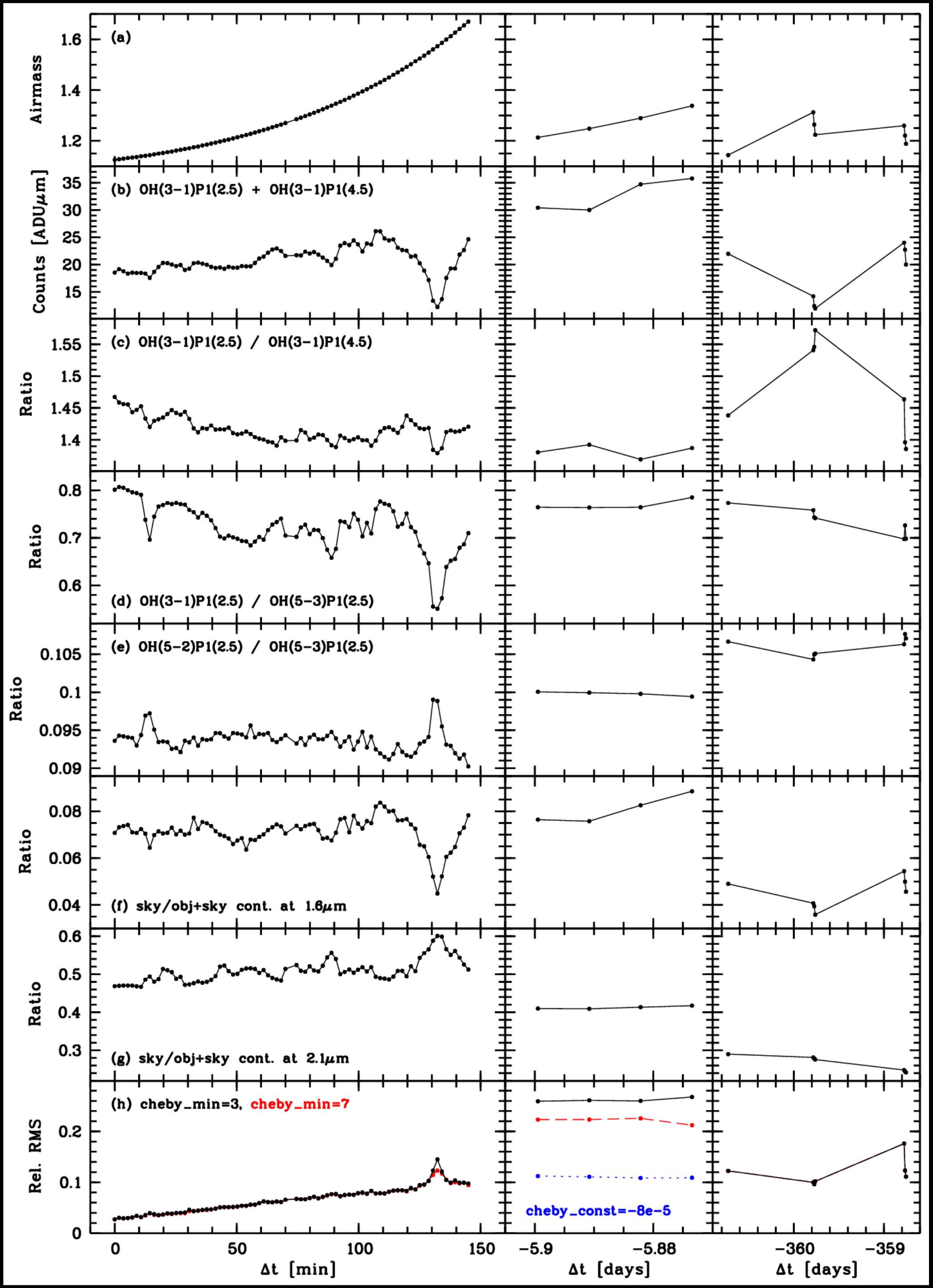
SKYCORR workflow

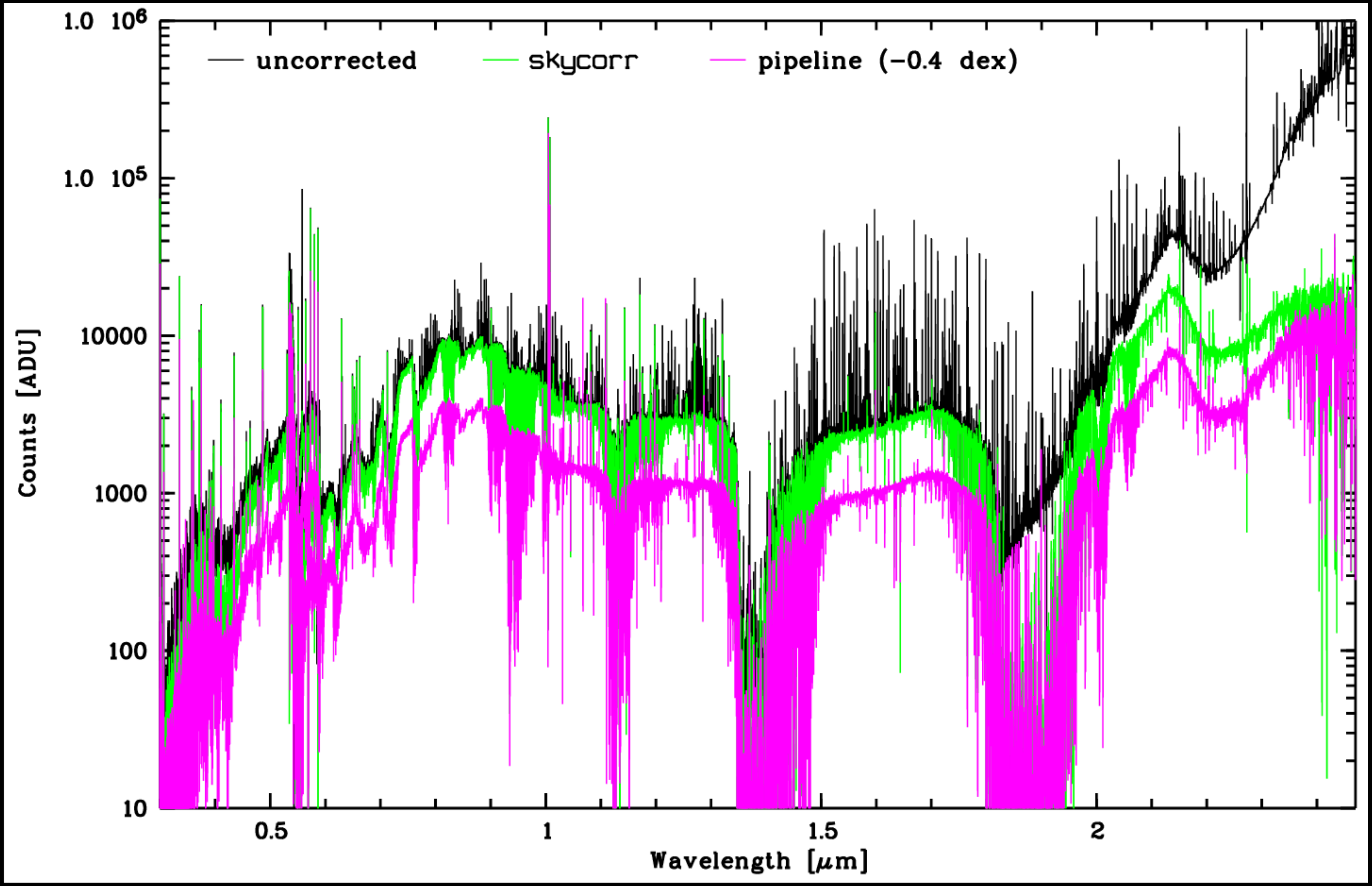


Evaluation of SKYCORR performance

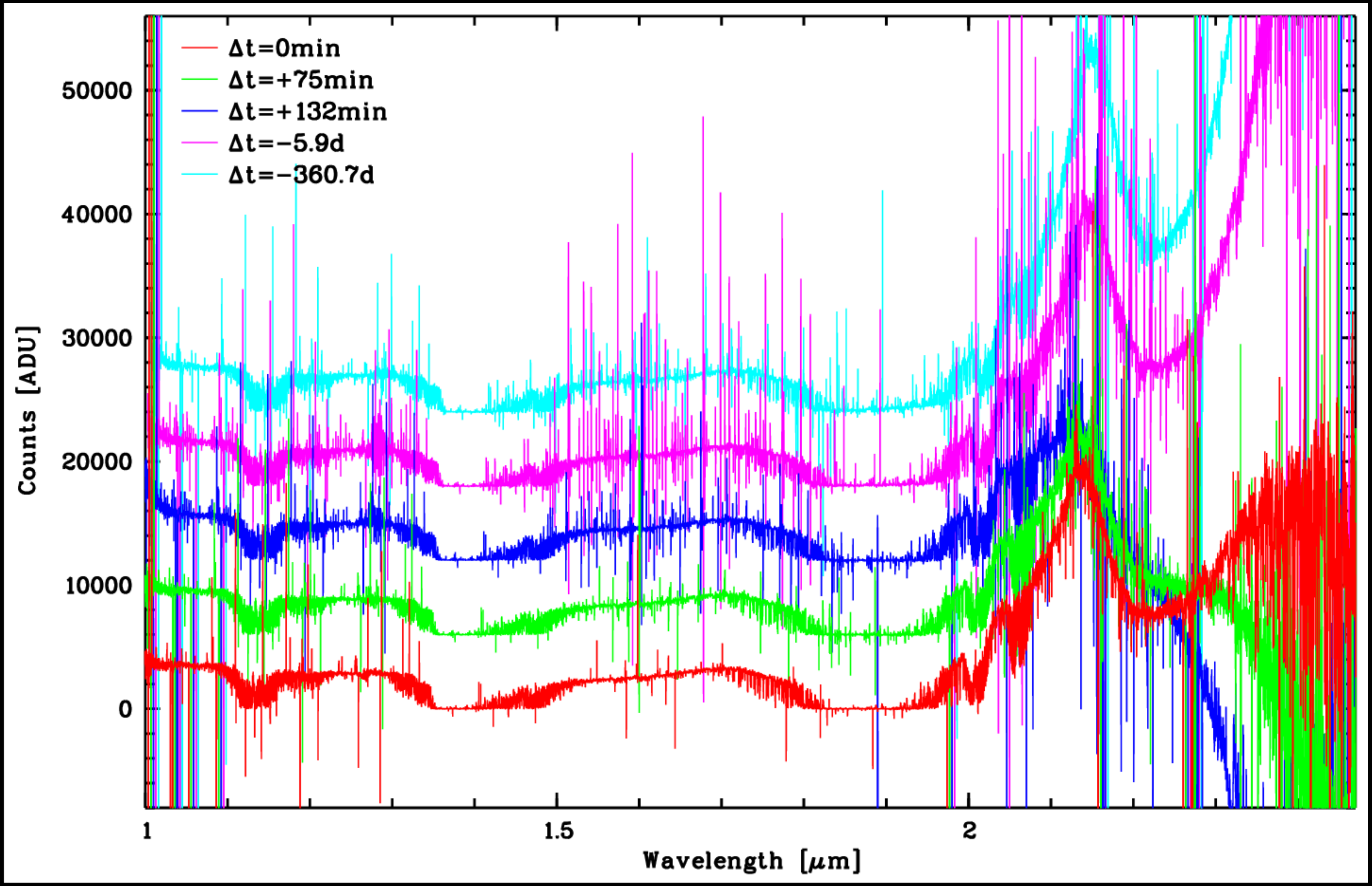
X-Shooter test data set for different time intervals between science and sky exposure (0 min to about 1 yr)



Comparison to 2D method for Δt = 0



SKYCORR results for different Δt = 0



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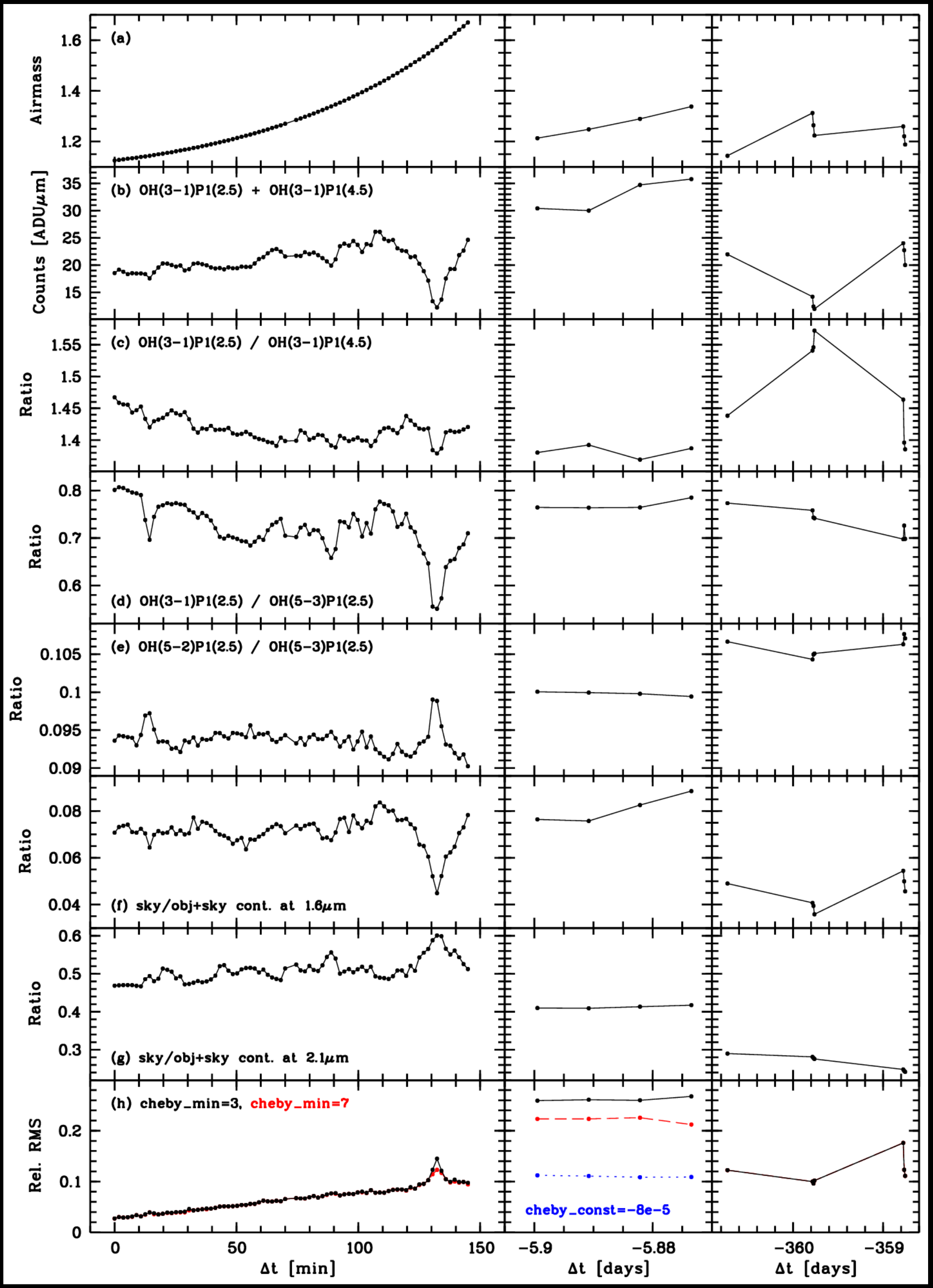
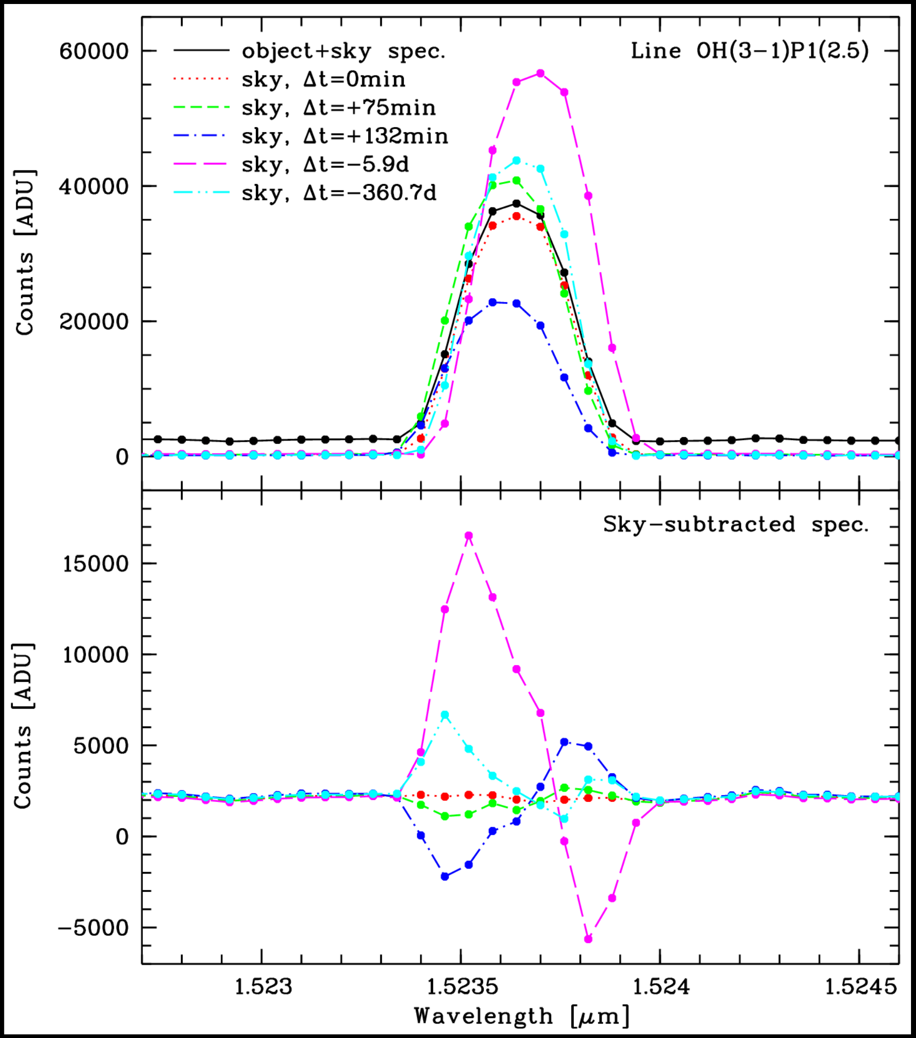
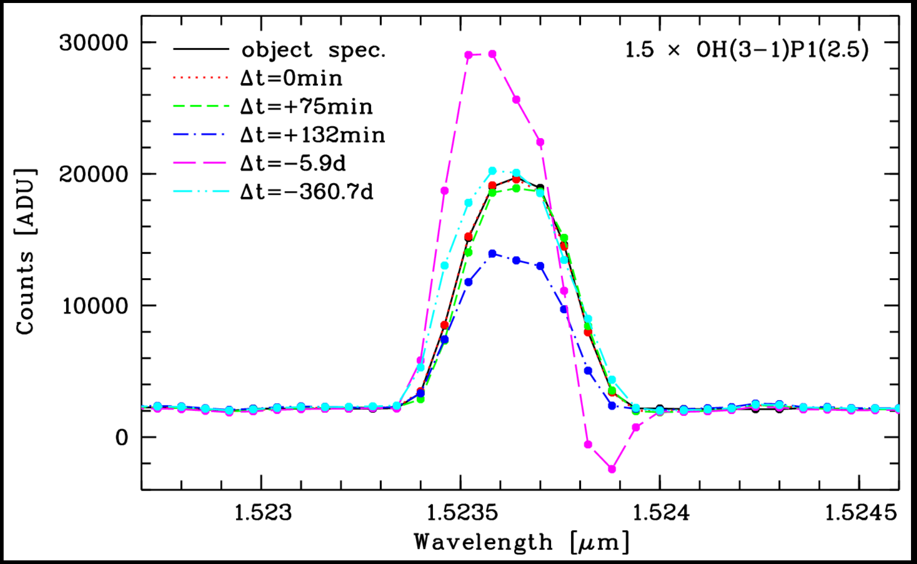


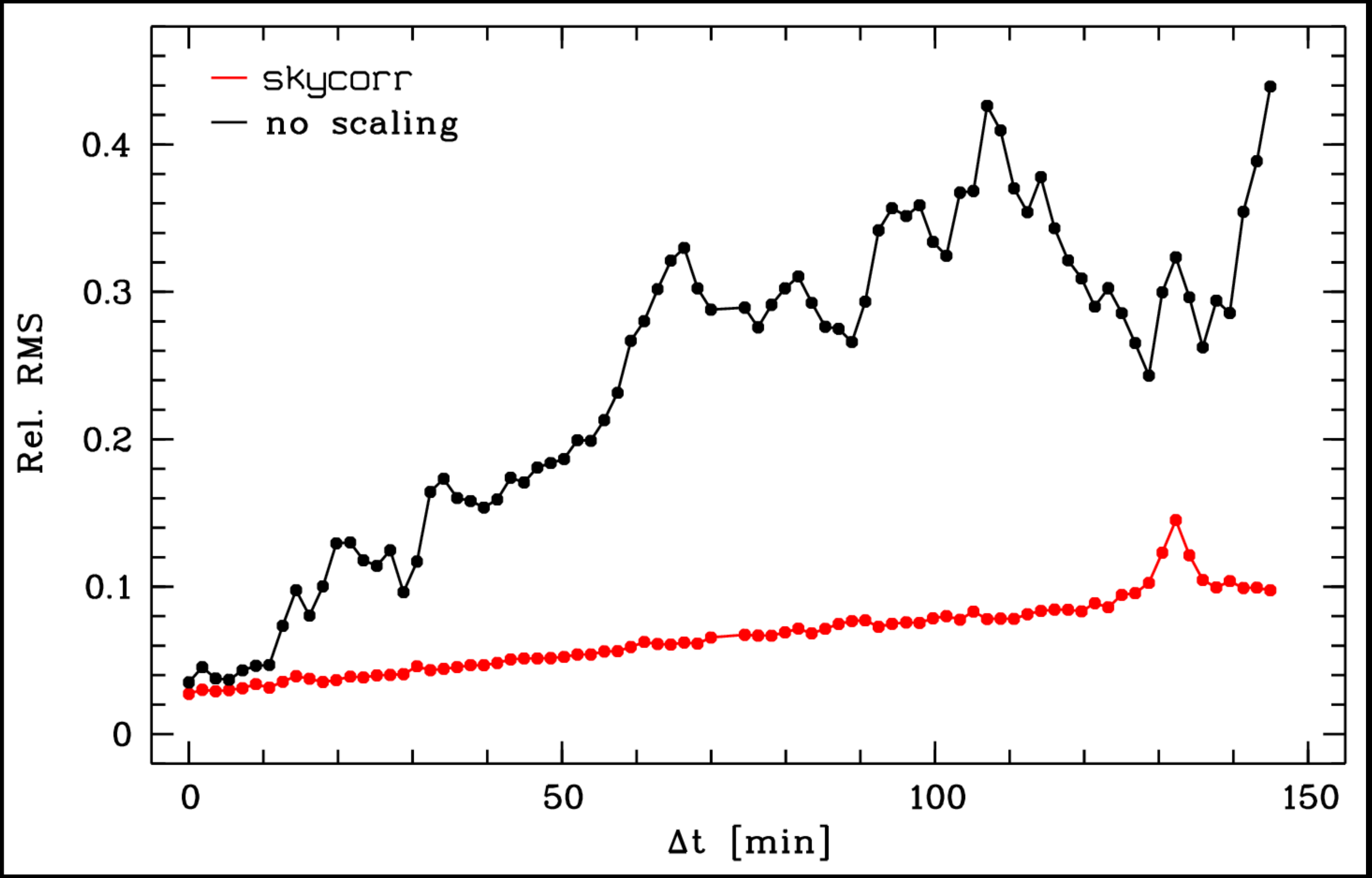
SKYCORR results for single line



Conservation of object line on top of strong airglow line:



Comparison to results without scaling

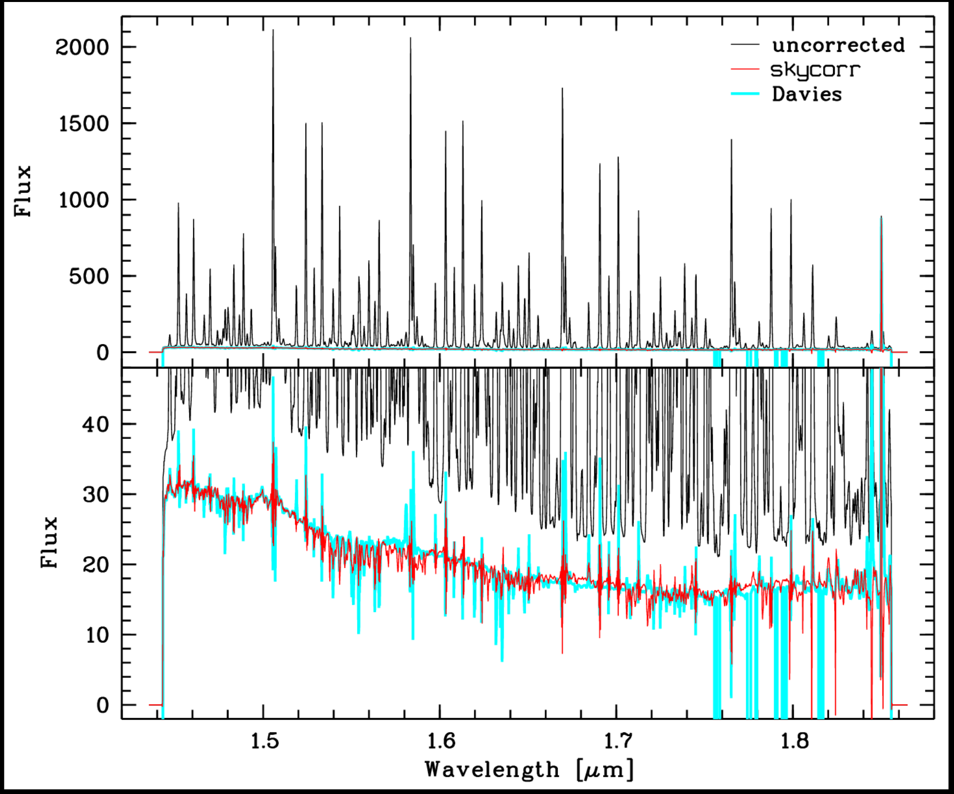


→ After about 10 min RMS ratios between 2 and 6

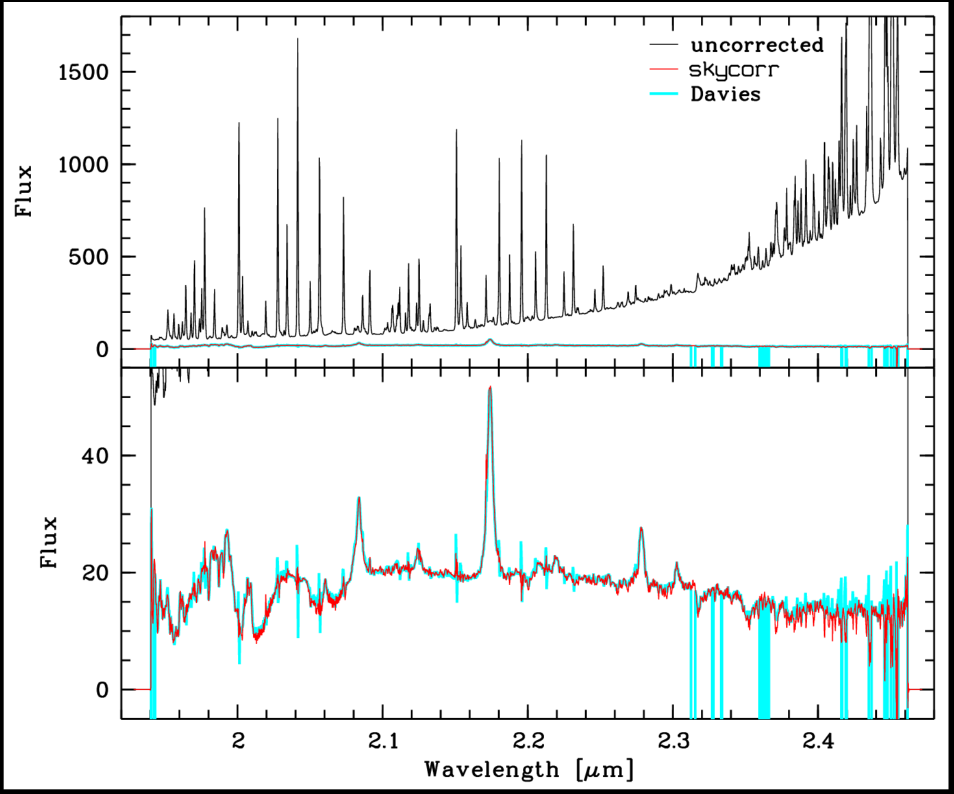
Comparison to Davies' method

X-Shooter: Davies' code too unstable for a fair comparison
(requires suitable IFU data cubes, as it was designed for SINFONI)

SINFONI H-band example
(Δt = 39 min):



SINFONI K-band example
(Δt = 11 min):



Conclusions

- The Innsbruck group of the Austrian ESO In-Kind project has worked on three software products:
  - An advanced sky model for Cerro Paranal used for ESO's ETCs and instrument simulators
  - The software MOLECFIT for telluric absorption correction and molecular abundance fitting
  - The software SKYCORR for sky subtraction in airglow-dominated wavelength regimes, which only requires 1D reference sky data
- The products indicate a convincingly higher accuracy and flexibility compared to previous developments.
- The software is available for everyone at `http://www.eso.org/pipelines/skytools/`