

# Jakob Vinther ESO

## Innsbruck ESO In-Kind Projects

Institute for Astro- and Particle Physics, University of Innsbruck  
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S. Kimeswenger, S. Noll, W. Kausch, A. Jones, C. Szyszka, M. Barden

1. Sky Model - The Cerro Paranal Advanced Sky Model
2. Molecfit - Correcting observations for telluric absorption
3. Skycorr - Sky emission subtraction without plain sky information

Codes, manuals, tutorials, links, references:

[www.eso.org/pipelines/skytools](http://www.eso.org/pipelines/skytools)

# Sky Model - Motivation

- The expensive telescope time at large astronomical observatories has to be efficiently used
- S/N prediction of proposed astronomical observations with exposure time calculators (ETCs)
- Realistic model of the sky, including emission, absorption, and scattering processes in the Earth's atmosphere
- Development of sky brightness model for ETCs

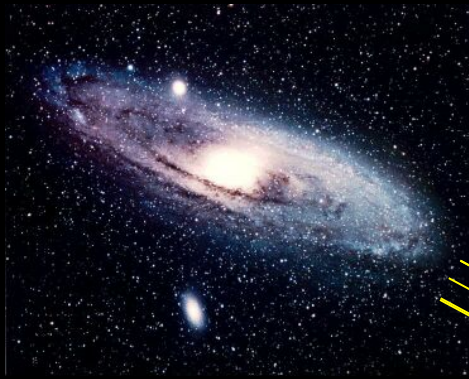
Sky transmission curves [0-1] +/-sigma

Sky radiance spectra (phot/s/m<sup>2</sup>/μm/arcsec<sup>2</sup>) +/-sigma

Range: 0.3 – 30μm.

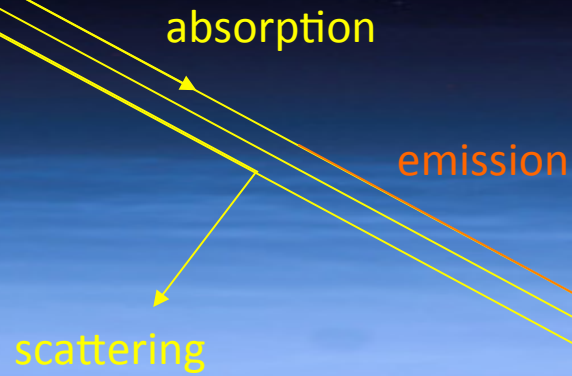
Resolution up to 10<sup>6</sup>

# Earth's atmosphere interacts with light



Additional influences:

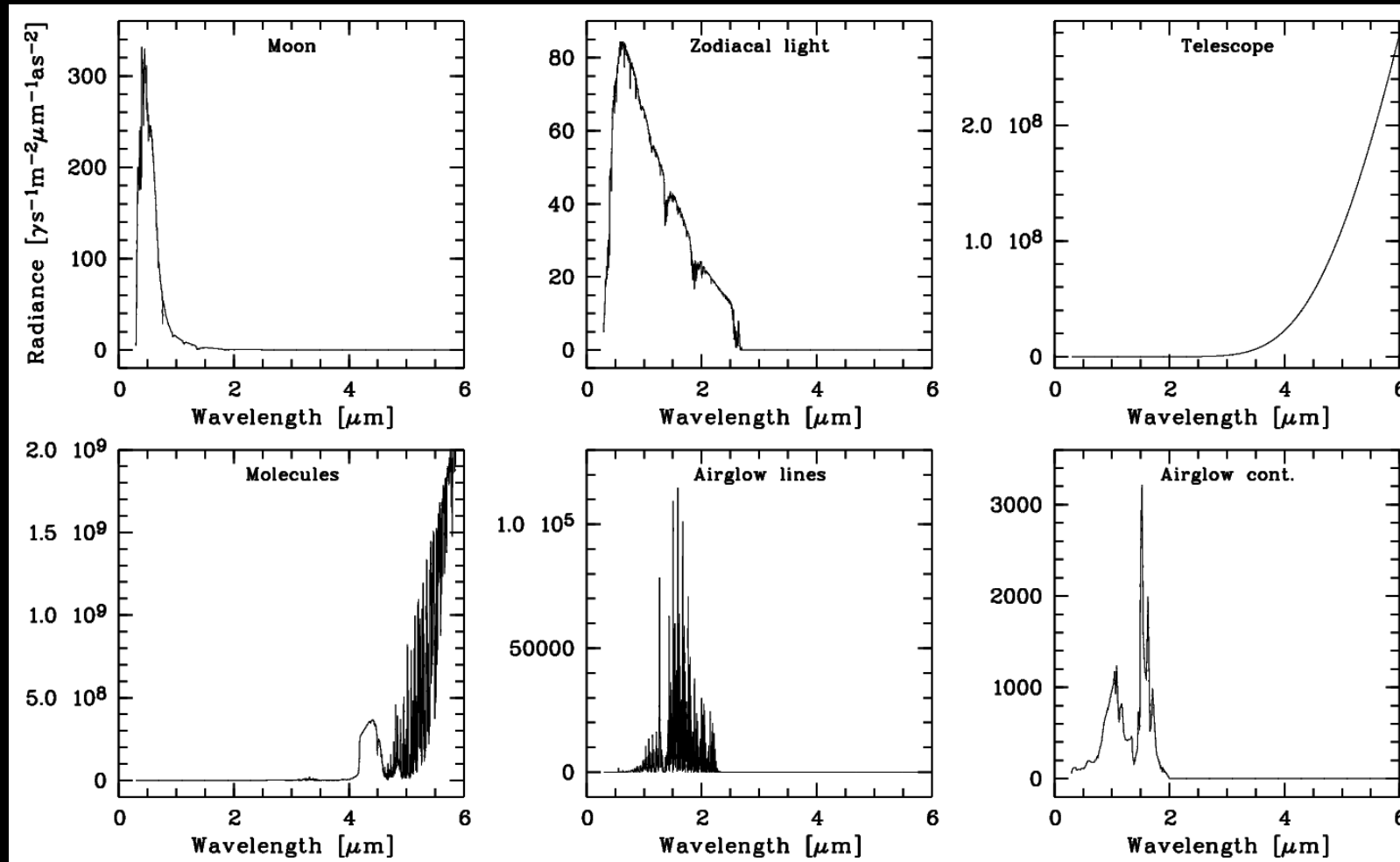
- Moon
- Zodiacal light
- Telescope emission



**sky background**

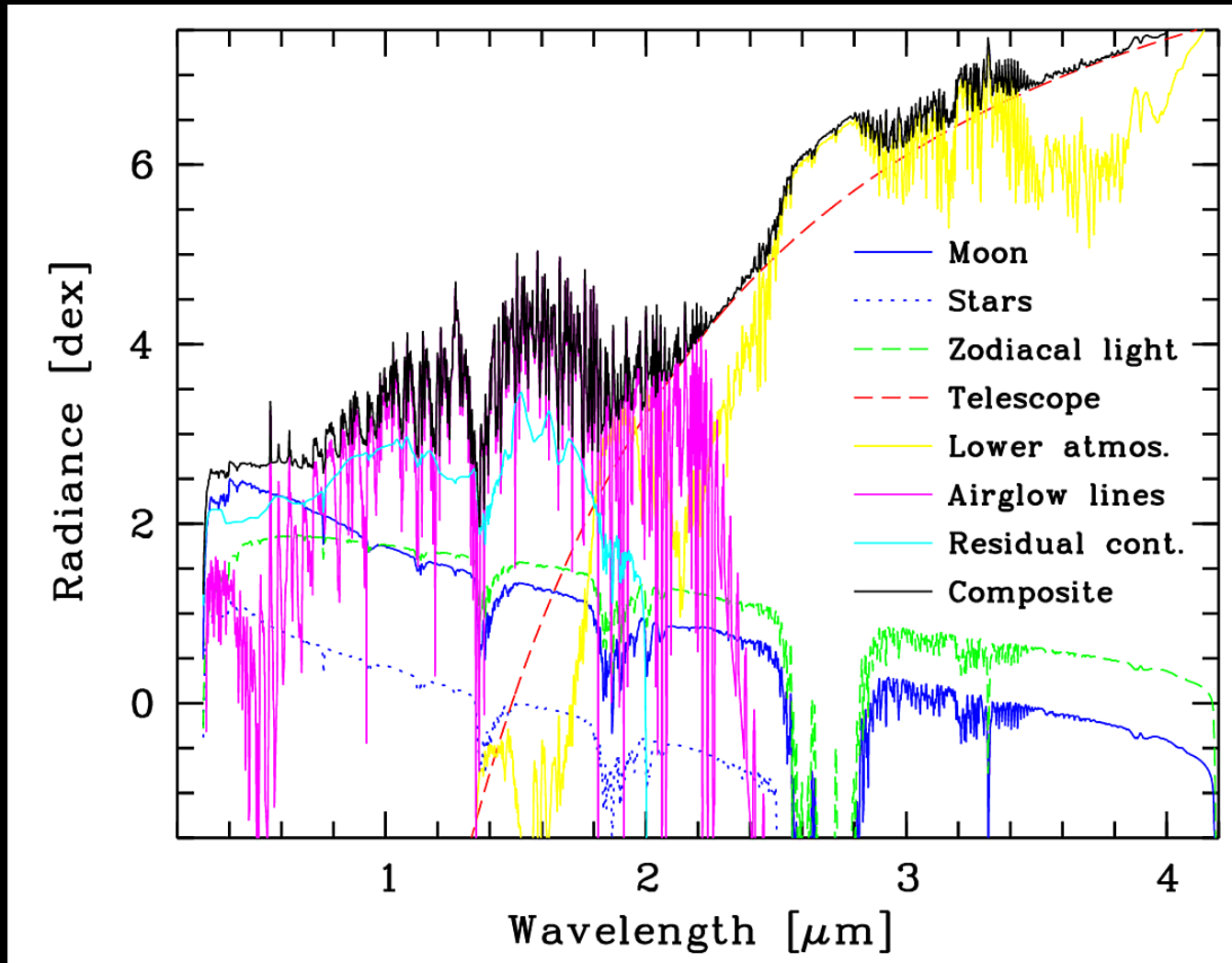


# Sky Model Radiation Components



General description (optical): Noll et al. 2012, A&A, 543, A92  
Scattered moonlight model: Jones et al. 2013, A&A 560, A91

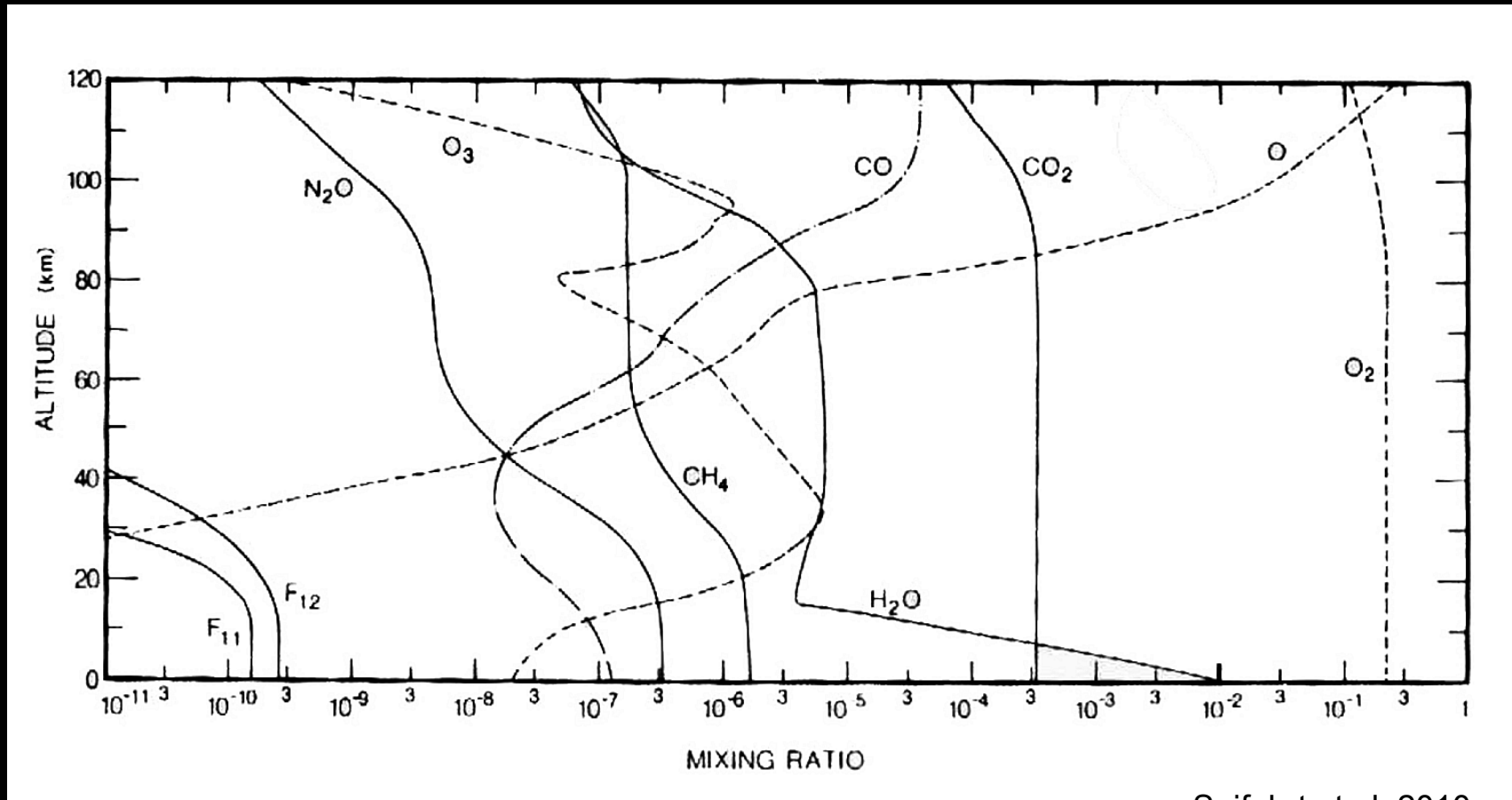
# Sky Model Radiation Components



# Processes in the lower atmosphere

- Scattering, absorption, and thermal radiation by molecules in the troposphere and stratosphere
- Calculation of spectra by atmospheric radiative transfer code LBLRTM (Line-By-Line Radiative Transfer Model)
- Required input:
  - HITRAN line data base (39 molecules and > 2.7 million lines)
  - Profiles of pressure, temperature, and molecular abundances

# Atmospheric profiles



**Optimisation for Cerro Paranal:** standard profiles (MIPAS@ENVISAT) + weather-dependent pressure, temperature, and humidity ( $H_2O$ ) from GDAS weather models (profiles up to 26 km;  $1^\circ \times 1^\circ$  and 3 h resolution), and ESO meteo monitor at 2.6 km

# Module 1 (slow) generating library (once)

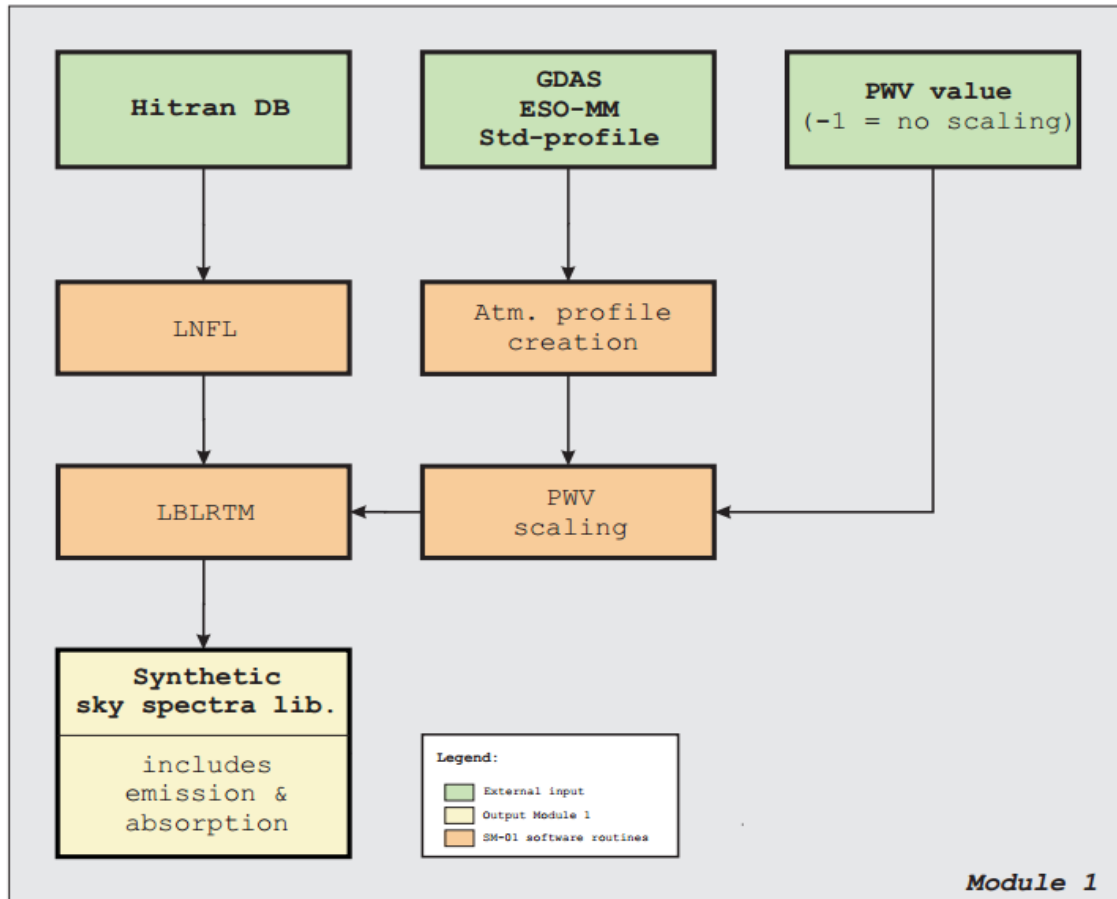


Figure 1: *Module 1*: This module creates a library of synthetic sky spectra on the basis of the HITRAN 2008 database and an atmospheric profile. The profile is created by merging the standard profile `equ.atm` (<http://www.atm.ox.ac.uk/RFM/>) and GDAS data (see [5] and Section 5), which provide information on temperature, pressure, and humidity of the selected observing site. Both, the HITRAN 2008 and the atmospheric profile, are used as input for the radiative transfer code LNFL/LBLRTM in order to calculate the sky spectrum.

Transmission

Emission

+ $\pm$ -sigma

Parameter Grid:

- Airmass (5)
- Season (6+1) or
- PWV (8)



# Module 2 (fast) at ETC runtime

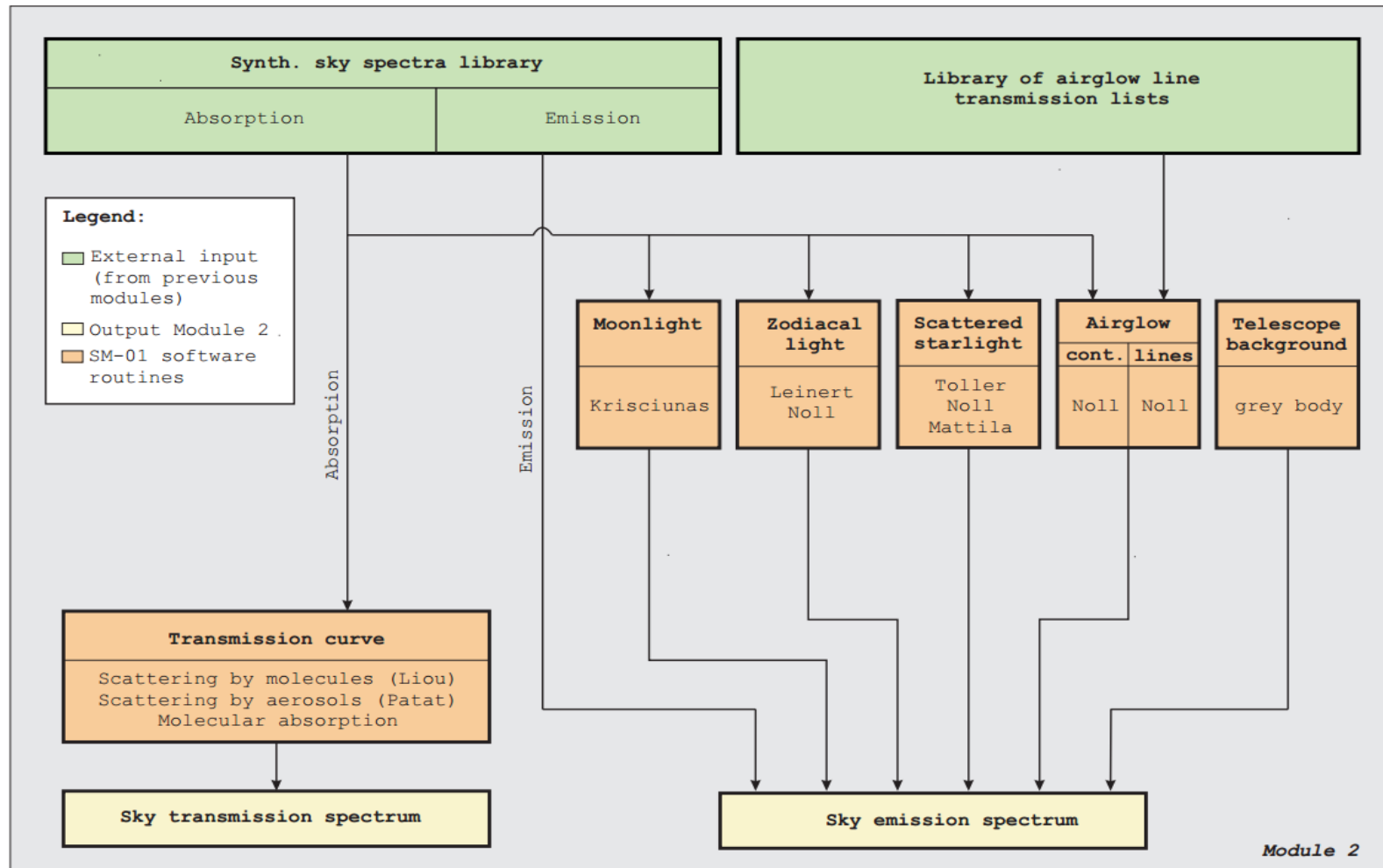
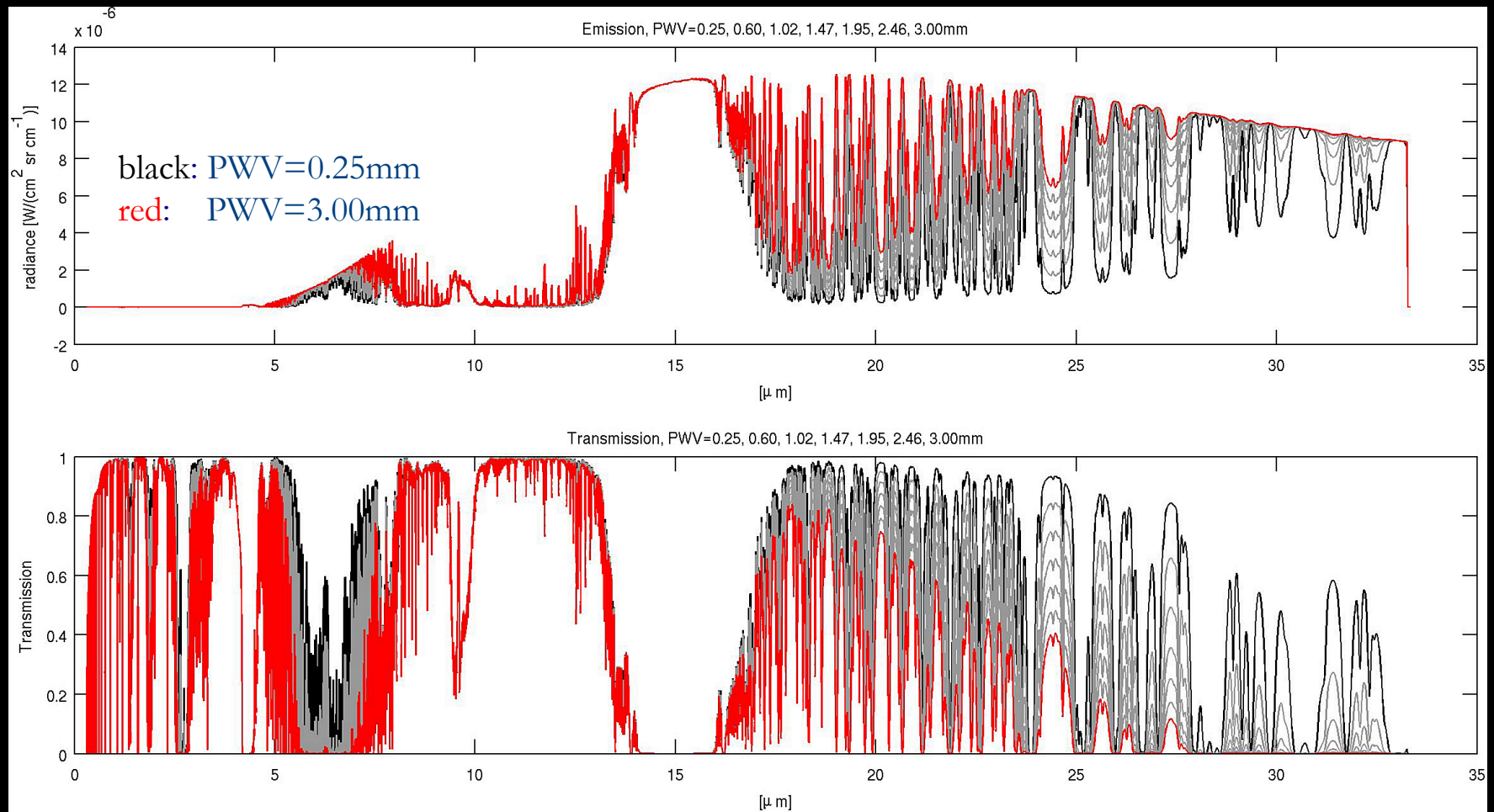


Figure 3: *Module 2* calculates the components, which need only minimal computing time. Hence, these components are computed during every ETC call. The final sky background spectrum is obtained by merging the appropriate synthetic sky spectrum from *Module 1* (selected by user defined input) with these "fast" components.

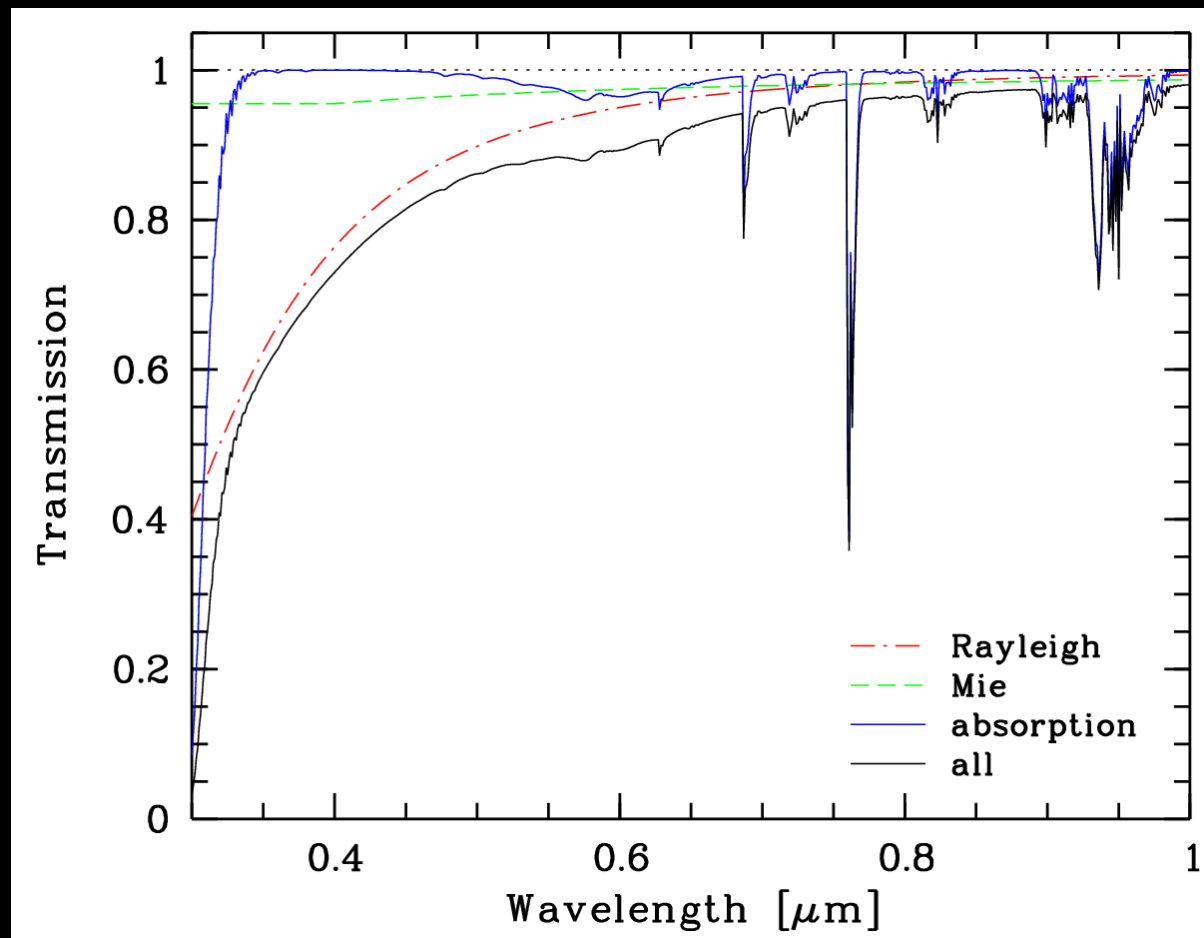
# Emission and transmission spectra



Changes in the water vapour content PWV of the atmosphere strongly affect sky emission and transmission spectra (especially in the thermal IR)

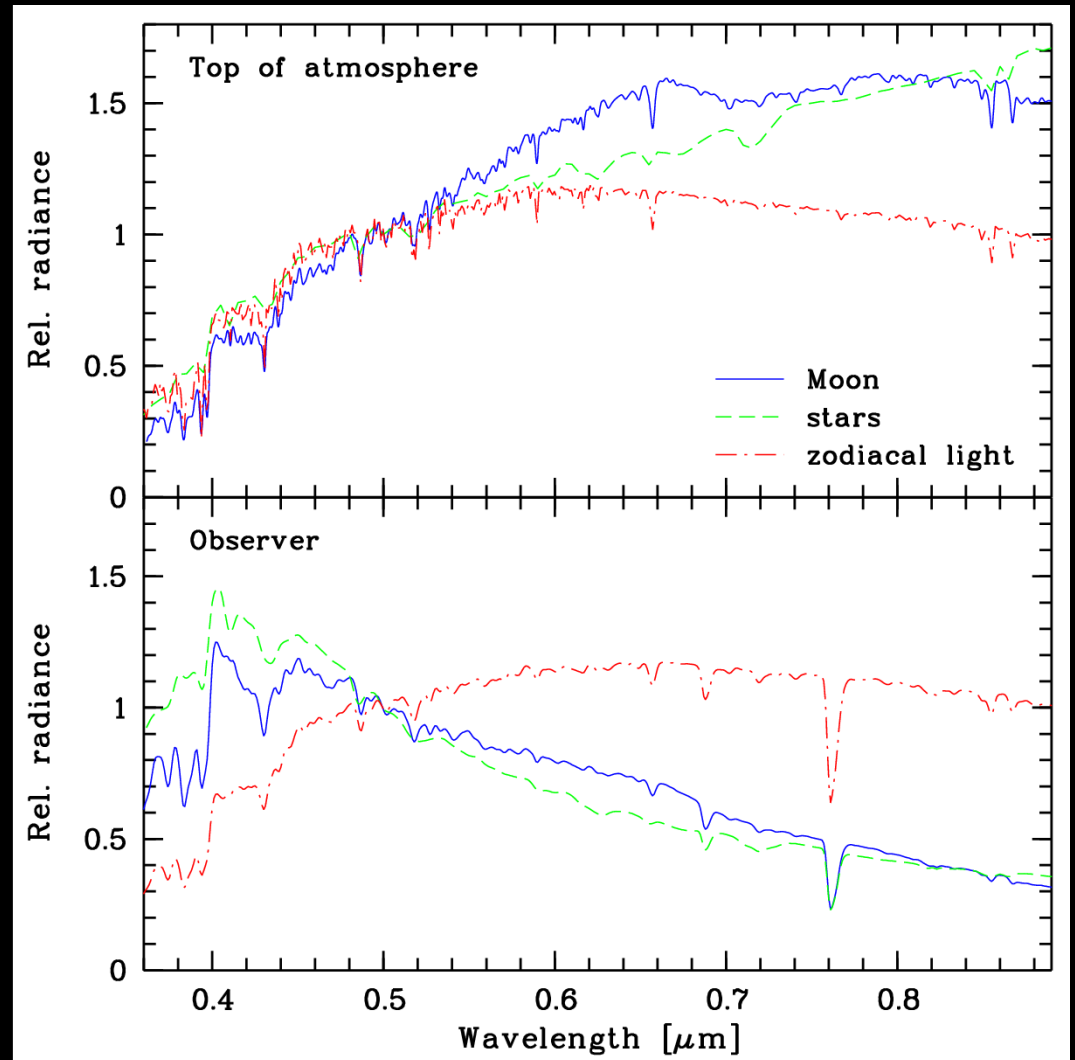
# Atmospheric extinction

- **Molecular absorption:** LBLRTM calculations depending on season
- **Rayleigh scattering (molecules):** parametrisation by Liou (2002)
- **Aerosol extinction:** Ångström-law fit by Patat et al. (2011) for Paranal



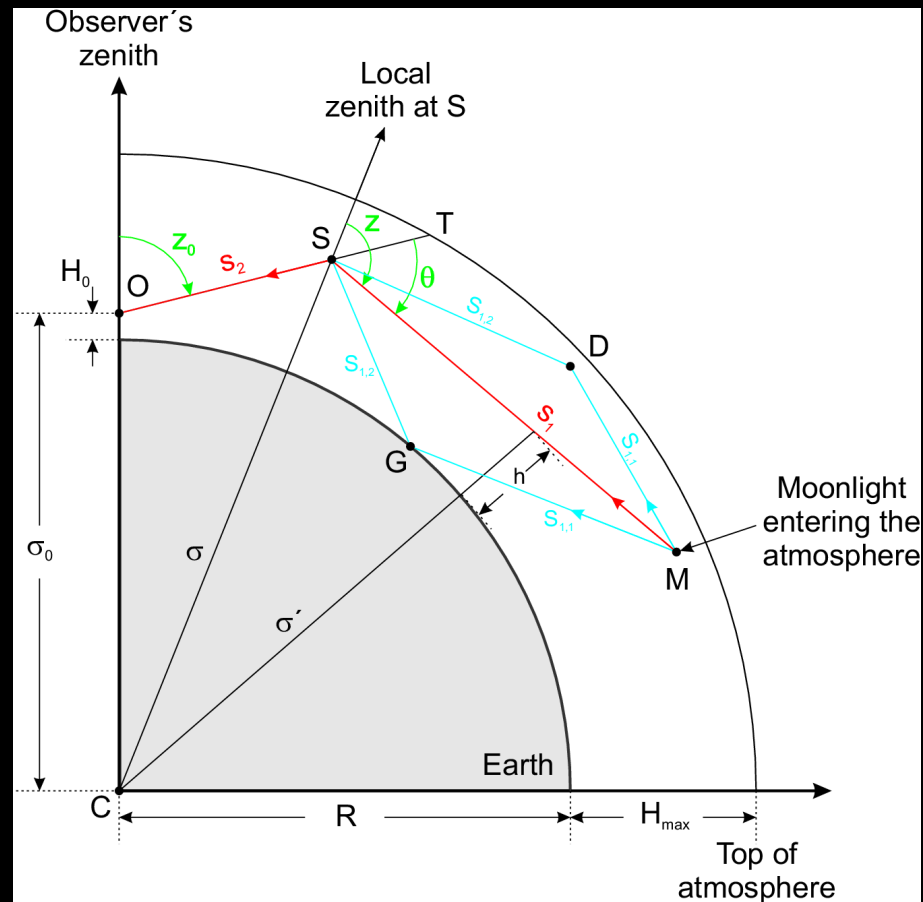
# Moon, stars, and interplanetary dust

- **Zodiacal light and integrated starlight:** Leinert et al. (1998)
- **Starlight spectrum:** Mattila (1980)
- **Moon albedo:** ROLO (Kieffer & Stone 2005)
- **Radiative transfer:** own 3D scattering calculations (Noll et al. 2012; Jones et al. 2013)



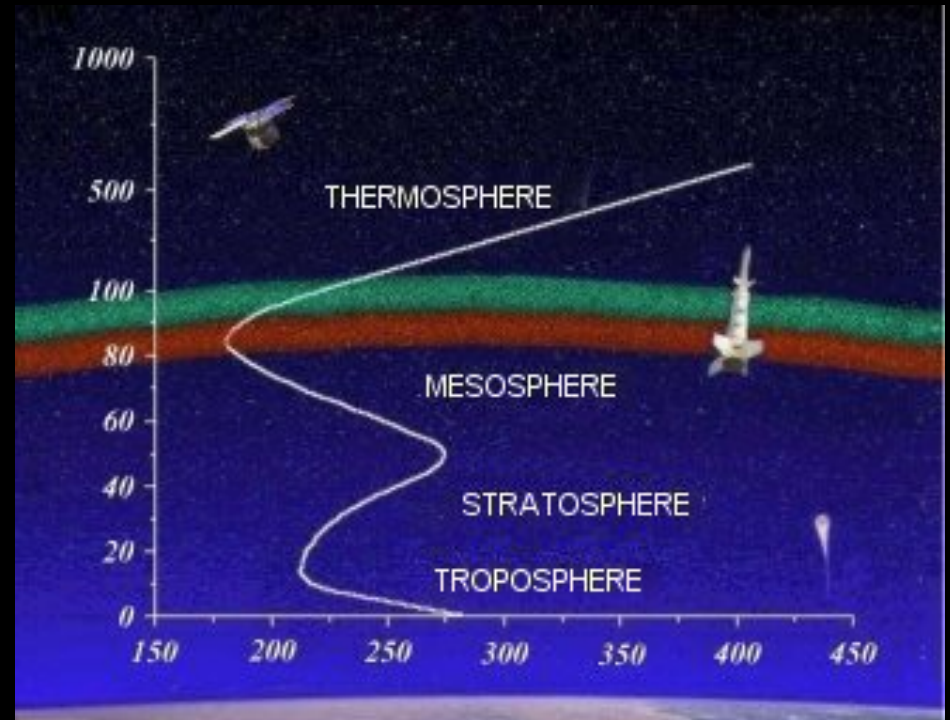
# Radiative transfer of moonlight

- Single and double scattering at molecules, aerosols, and the ground with multiple scattering correction (Jones et al. 2013, A&A 560, A91)



# 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 region (P < 0.01 mbar [?] thin gas)
- Usually very thin emission layers of a few km thickness only



[www.laser.inpe.br/lume/](http://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
- Gravity waves ( $P > 5$  min; caused by mountains / weather fronts)
- Longterm trend ( $\rightarrow$  climate change)



MASCOT/Paranal/ESO

**Site-dependent semi-empirical  
airglow model required!**

**“The Dancing Sky”**

# SkyCalc: Web interface to the Sky Model

[www.eso.org/observing/etc/skycalc](http://www.eso.org/observing/etc/skycalc)

SKYCALC Sky Model Calculator

Sky Model Mode Version 1.4.2 [Description](#) [FAQ](#)

## SkyCalc Sky Model Calculator

Optional Parameter Initialisation using Almanac Service

All sky model parameters in the input form below can be set manually, but the time/coordinate dependent ones can be automatically initialised using this almanac service corresponding to a given time and sky position at the Paranal Observatory at geographic latitude  $-24^{\circ}37'38''.64$ , longitude  $-70^{\circ}24'17''.64$ .

Date and UT time:

Target equatorial coordinates: R.A.  dec

### The Cerro Paranal Advanced Sky Model

Altitude of Target above Horizon:  [19.5, 90]<sup>o</sup>

Airmass:  [1, 3]

Season and Period of Night: Season:  Night Period:

Precipitable Water Vapor PWV:  mm [Paranal median = 2.5mm]

Monthly Averaged Solar Flux:   $\mu\text{W}/\text{m}^2$

Select Components to Include in the Radiance Model:

- Scattered Moon Light**  
Note the following moon coordinate constraints:  $|z - z_{\text{moon}}| \leq p \leq |z + z_{\text{moon}}|$   
where  $p$ =moon target separation,  $z=90^\circ$ =target altitude and  $z_{\text{moon}}$ =90°-moon altitude.  
Separation of Sun and Moon as seen from Earth:  [0.5607, 180]<sup>o</sup>,  $\text{sun}=\text{0}^\circ$ ,  $10^\circ$ 180°=vertical, full=180°, 118°-300°=rising
- Zodiacal Light**  
Heliocentric Ecliptic Longitude of Target:  [-180, 180]<sup>o</sup>  
Ecliptic Latitude of Target:  [-90, 90]<sup>o</sup>
- Molecular Emission of Lower Atmosphere**
- Emission Lines of Upper Atmosphere**
- Airglow Continuum (Residual Continuum)**
- Thermal Emission**  
This radiance component represents an instrumental effect. The emission is provided relative to the other model components. To obtain the correct absolute flux, an instrumental response curve must be applied to the resulting model spectrum (see section 6.2.4 in the documentation).

Wavelength Grid (in Vacuum):   $\mu\text{m}$  [ $\geq 300$  nm]   $\mu\text{m}$  [ $\leq 30,000$  nm]

Convolution Line Spread Function:

- None
- Gaussian FWHM:  bins
- Boxcar Width:  bins

SkyCalc is based on the Cerro Paranal Advanced Sky Model, which was developed in particular to be used in the ESO Exposure Time Calculators, by a team of astronomers at the Institute for Astro- and Particle Physics at the University of Innsbruck, as part of an Austrian in-kind contribution to ESO.

The in-kind contribution also includes two tools to correct observations for telluric absorption and emission (Molecfit and Skycorr), which can be found here.

The citations for the Cerro Paranal Sky Model are Noll et al. (2012, A&A 543, 492) and Jones et al. (2013, A&A 560, 491).

A library of telluric transmission spectra with various resolutions and atmospheric conditions has been calculated with the Cerro Paranal Advanced Sky Model. A description of the usage of the spectra can be found in the article Mosser et al. (2014, A&A 568, 49).

[Send questions and comments to \[ask@skycalc.eso.org\]\(mailto:ask@skycalc.eso.org\) and \[ask@kep.eso.org\]\(mailto:ask@kep.eso.org\)](#)

SKYCALC Sky Model Calculator

Sky Model Mode Version 1.4.2 [Description](#) [FAQ](#)

### Input Configuration

Altitude: 90.00  
Airmass: 1.00

Season: Entire Year  
Time Period: Entire Night

PWV: Seasonal Average  
Monthly Averaged Solar Flux: 130.00  $\mu\text{W}/\text{m}^2$

Components included in the radiance model:

- Scattered Moon Light**  
Separation of Sun and Moon: 50.00 degrees  
Separation of Moon and object: 45.00 degrees  
Altitude of Moon above horizon: 41.00 degrees  
Distance to Moon: 1.0000
- Star Light**
- Zodiacal Light**  
Heliocentric ecliptic longitude of object: 135.00 degrees  
Ecliptic latitude of object: 00.00 degrees
- Molecular Emission of Lower Atmosphere**
- Emission Lines of Upper Atmosphere**
- Airglow Continuum**

Wavelength grid:  
Range: 200.00 nm - 2000.00 nm  
Fixed spectral resolution R=1000  
LSF convolution kernel: none

### Output

Download the resulting model spectra as FITS table: [skytable.fits](#)

Radiance

ASCII data [Java applet plot](#) [PDF file](#) [log\(y\) plot](#) [log\(y\) PDF](#)

Transmission

ASCII data [Java applet plot](#) [PDF file](#) [log\(y\) plot](#) [log\(y\) PDF](#)

[Send questions and comments to \[ask@skycalc.eso.org\]\(mailto:ask@skycalc.eso.org\) and \[ask@kep.eso.org\]\(mailto:ask@kep.eso.org\)](#)



# SkyCalc numerical output

## skytable.fits

```
jvinther@pc017890:~$
jvinther@pc017890:~$
jvinther@pc017890:~$ dfits skytable.fits
====> file skytable.fits (main) <====
SIMPLE = T / file does conform to FITS standard
BITPIX = 16 / number of bits per data pixel
NAXIS = 0 / number of data axes
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
DATE = '2015-09-22T14:33:31' / file creation date (YYYY-MM-DDThh:mm:ss UT)
COMMENT
COMMENT ESO SkyCalc www.eso.org/observing/etc/skycalc/skycalc.htm
COMMENT Documentation www.eso.org/observing/etc/doc/skycalc/helpskycalc.html
COMMENT References: Noll et al. (2012, A&A 543, A92)
COMMENT and Jones et al. (2013, A&A 560, A91)
COMMENT
COMMENT column lam: vacuum wavelength in micron
COMMENT column flux: sky emission radiance flux in ph/s/m2/micron/arcsec2
COMMENT column dflux1: sky emission -1sigma flux uncertainty
COMMENT column dflux2: sky emission +1sigma flux uncertainty
COMMENT column dtrans: sky transmission
COMMENT column dtrans1: sky transmission -1sigma uncertainty
COMMENT column dtrans2: sky transmission +1sigma uncertainty
COMMENT
COMMENT Web application input parameters:
COMMENT INS.NAME=SKYCALC
COMMENT INS.MODE=swspectr
COMMENT POSTFILE.FLAG=0
COMMENT COORD.DAY=
COMMENT COORD.MONTH=1
COMMENT COORD.YEAR=
```

## ASCII (plots)

```
1000 561.866
1000.05 561.163
1000.1 561.813
1000.15 561.438
1000.2 559.054
1000.25 10568.8
1000.3 10569.3
1000.35 626.353
1000.4 562.096
1000.45 562.056
1000.5 616.288
1000.55 616.427
1000.6 562.225
1000.65 562.256
1000.7 562.287
1000.75 562.318
1000.8 562.349
1000.85 562.379
1000.9 562.41
1000.95 562.441
1001 562.472
1001.05 562.502
1001.1 562.532
1001.15 562.562
1001.2 562.587
1001.25 562.582
1001.3 561.926
1001.35 561.764
1001.4 13797.4
1001.45 561.619
1001.5 562.054
1001.55 125607
1001.6 562.827
1001.65 21885.7
1001.7 21884.5
```

# Sky correction tools

**Molecfit** - Correcting observations for telluric absorption

**Skycorr** - Sky emission subtraction without plain sky information

[www.eso.org/pipelines/skytools](http://www.eso.org/pipelines/skytools)

## Correcting for

### absorption

**Required:** transmission spectrum

#### ***Telluric standard stars:***

- hot stars without/with few, well known intrinsic spectral features (B-type)
- observation in the vicinity, at least same airmass than science target
- observation directly before/after the science target

**molecfi**

### emission

**Required:** airglow spectrum

#### ***Plain sky observations:***

- LSS: portion of the slit w/o object
- specific sky spectrum taken before/after the science target and
- taken in the very vicinity of the science target
- same exposure time

**skycorr**

# Telluric Absorption Correction with molecfit

## Basic idea ([1],[2]):

- derive the atmospheric state from its fingerprint in the science spectra
- calculation of synthetic transmission spectra corresponding to this state by means of a radiative transfer code
- iteratively fitting these spectra to absorption features in science spectra
- use the best-fit transmission for the telluric absorption correction

## Features:

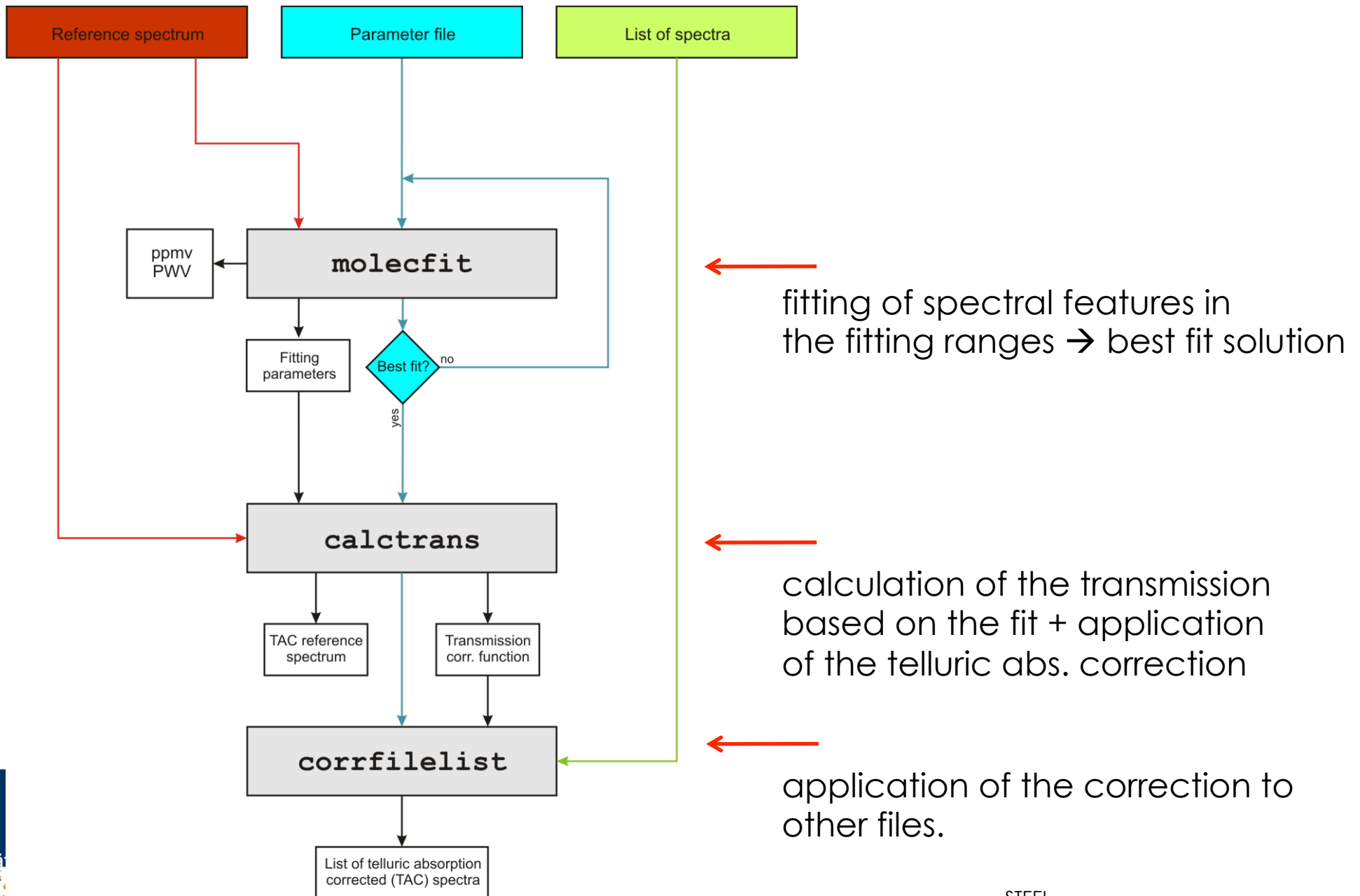
- comprehensive software suite for telluric absorption correction
- instrument independent
- world-wide use
- based on Ansi-C → high compatibility (Linux+MacOS)
- freely available\*

[1] Smette et al. 2015, A&A, 576, A77

[2] Kausch et al. 2015, A&A, 576, A78

\*<http://www.eso.org/pipelines/skytools>

# Telluric Absorption Correction with molecfit



# Molecfit Limitations

## **External:**

- Accuracy of the line database
- Radiative transfer code accuracy
- Initial atmospheric profile

## **Internal:**

- Low S/N spectra cannot be fitted reliably
- Number of fitting parameters (l-fit, continuum, LSF,...)
- Intrinsic spectral features of the object
- Resolution

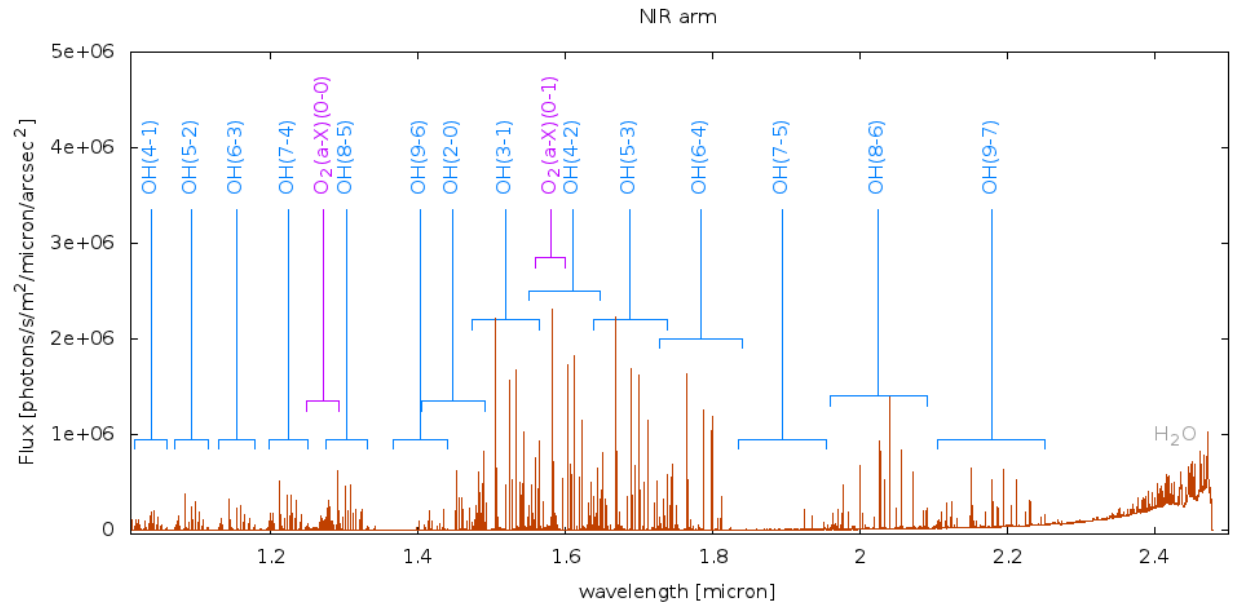
# Sky emission removal with skycorr

## Basic idea ([1], [2]):

- Use an arbitrary plain sky spectrum of the same instrument/setup (archive)
- Iteratively fitting OH line groups individually to corresponding OH emission features in science spectra
- Use the best-fit sky spectrum for the sky emission removal

## Features:

- Comprehensive software suite for sky emission removal
- Instrument independent
- world-wide use
- based on Ansi-C
- freely available\*

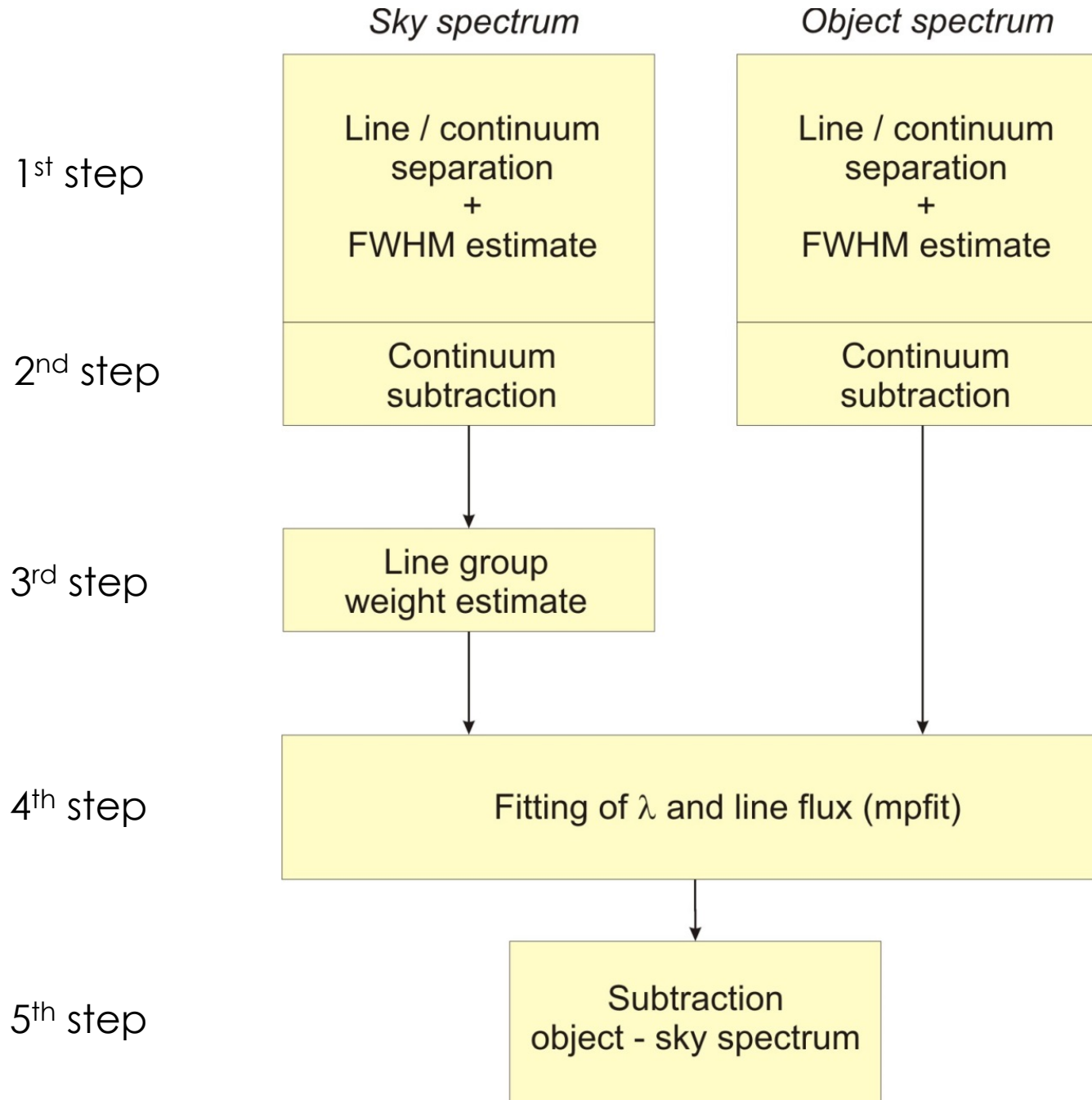


[1] Davies, 2007, MNRAS, 375, 1099

[2] Noll et al., 2014, A&A, 576, 25

\*<http://www.eso.org/pipelines/skytools>

# Sky emission removal with **skycorr**





# Skycorr Limitations

- Accuracy of the incorporated line lists
- Airglow model
- Atmospheric conditions (transparency)
- Instrumental calibration
- Number of fitting parameters ( $\lambda$ , line groups,...)
- Spectral resolution
- Intrinsic spectral features of the object