Jakob Vinther ESO

Innsbruck ESO In-Kind Projects

Institute for Astro- and Particle Physics, University of Innsbruck
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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

Sky Model - Motivation

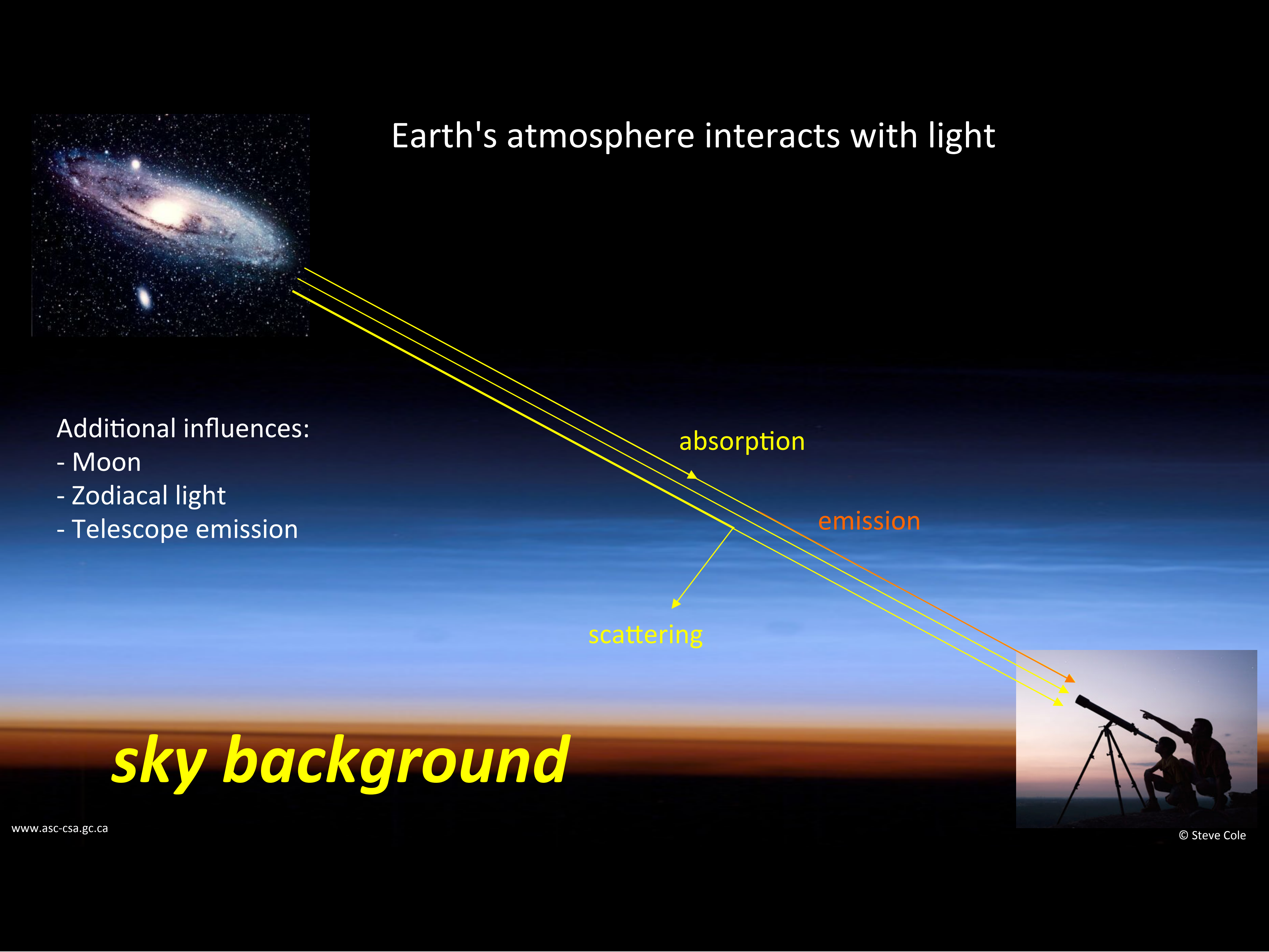
- The expensive telescope time at large astronomical observatories has to be efficiently used
- S/N prediction of proposed astronomical observations with exposure time calculators (ETCs)
- Realistic model of the sky, including emission, absorption, and scattering processes in the Earth's atmosphere
-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

Sky transmission curves [0-1] +-sigma

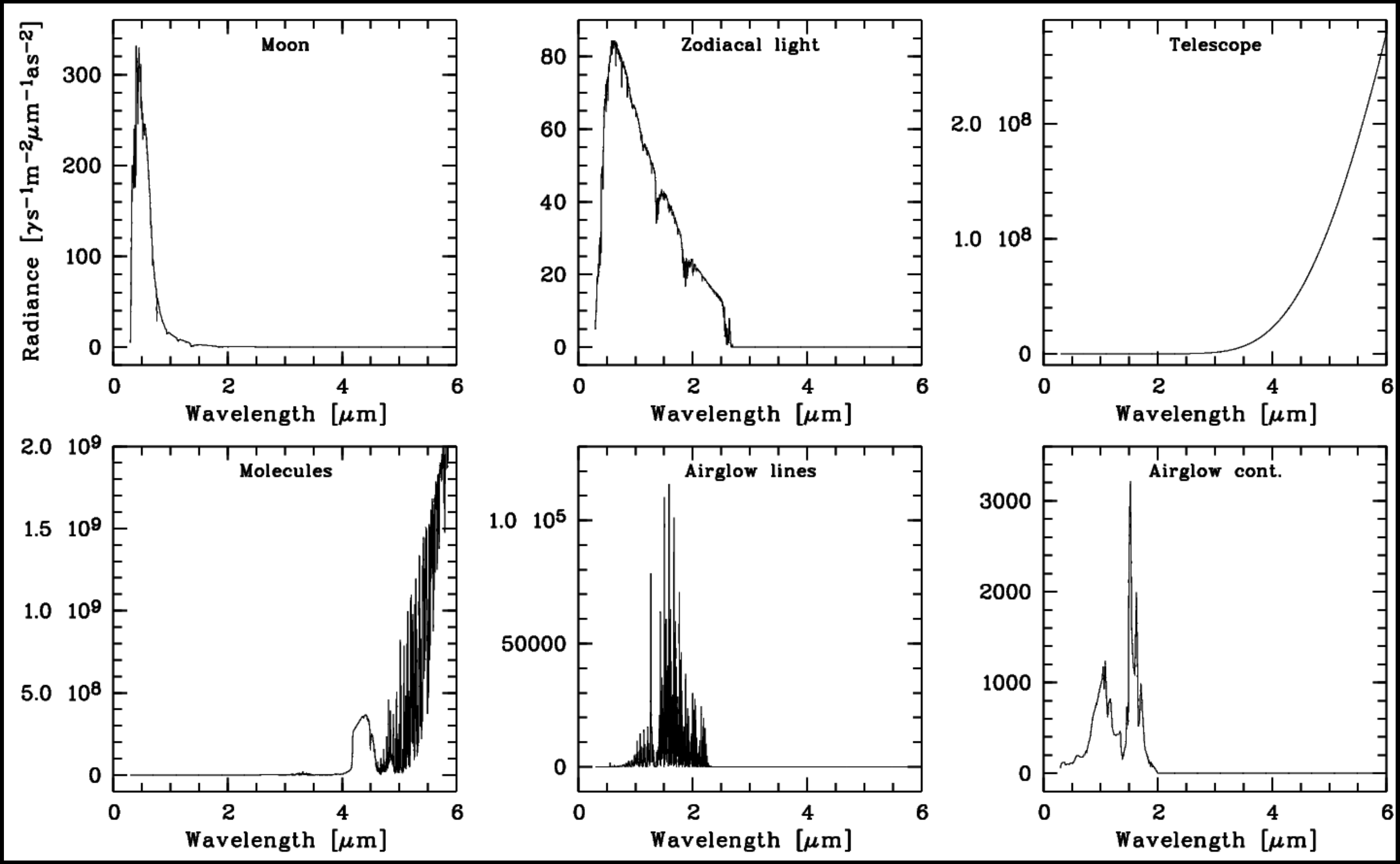
Sky radiance spectra (phot/s/m2/µm/arcsec2) +-sigma

Range: 0.3 – 30µm.

Resolution up to 10^6

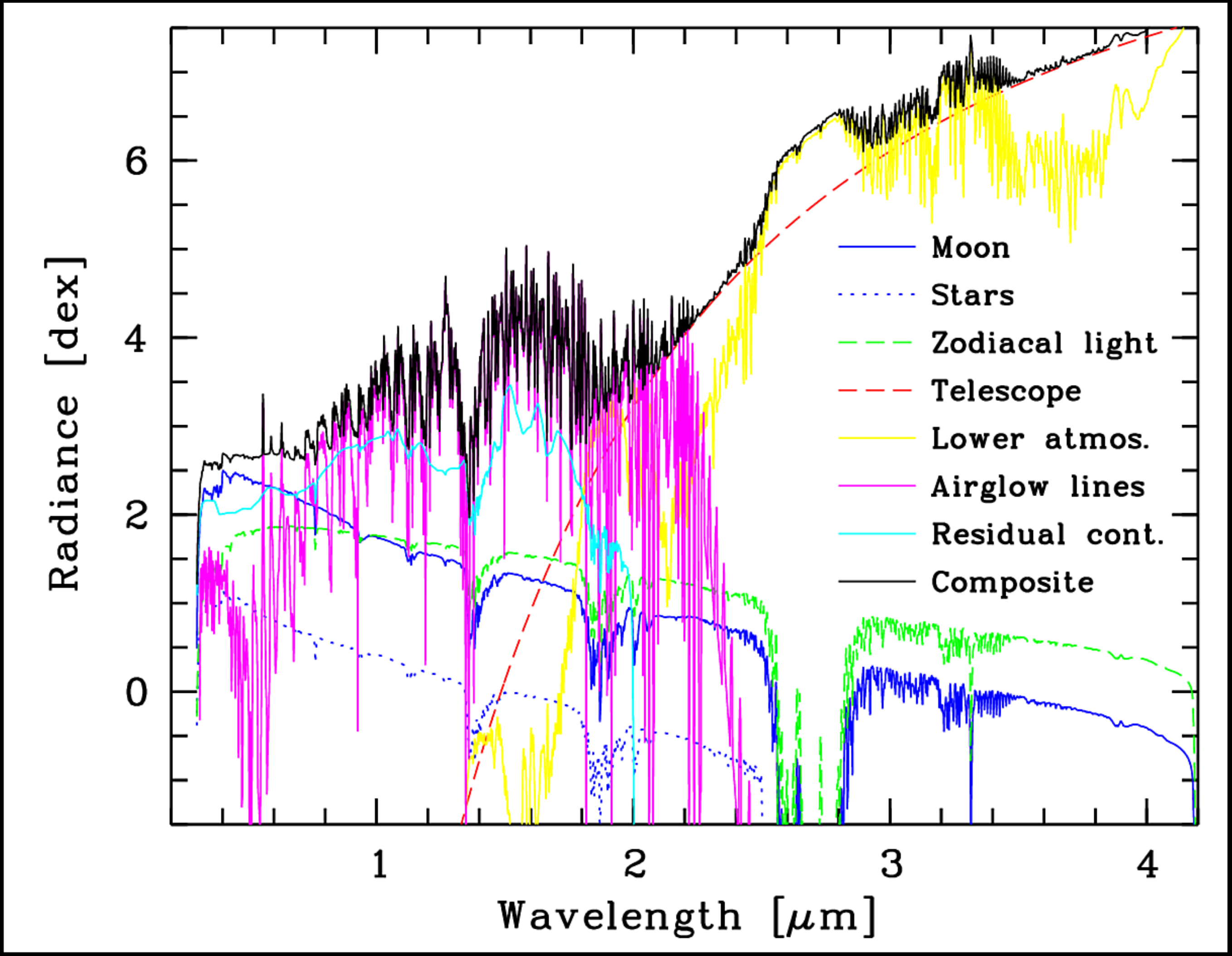

Earth's atmosphere interacts with light
Additional influences:
- Moon
- Zodiacal light
- Telescope emission
absorption
emission
scattering
sky background
www.asc-csa.gc.ca
© Steve Cole

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

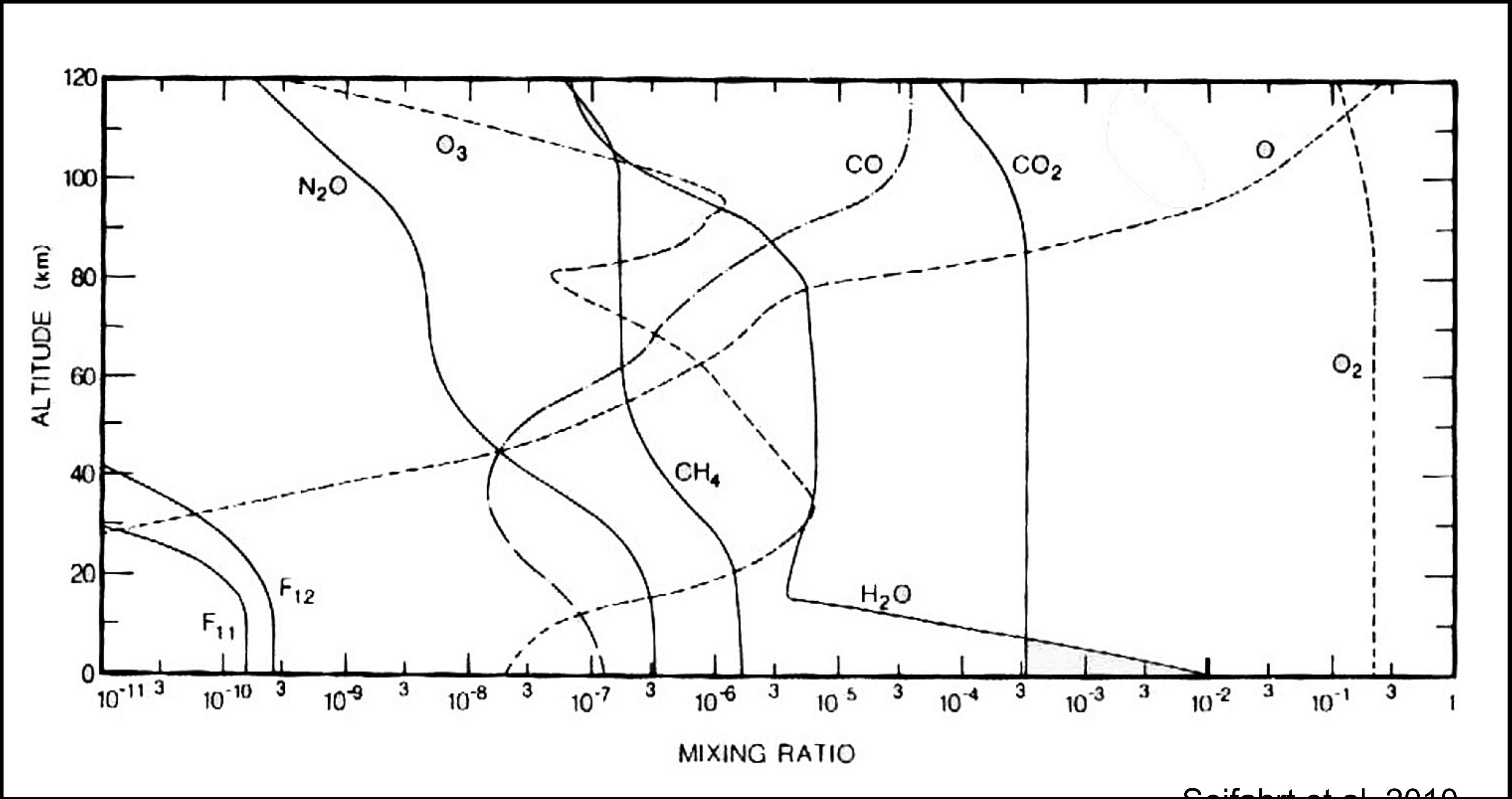
Sky Model Radiation Components



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° x 1° and 3 h resolution), and ESO meteo monitor at 2.6 km

Module 1 (slow) generating library (once)

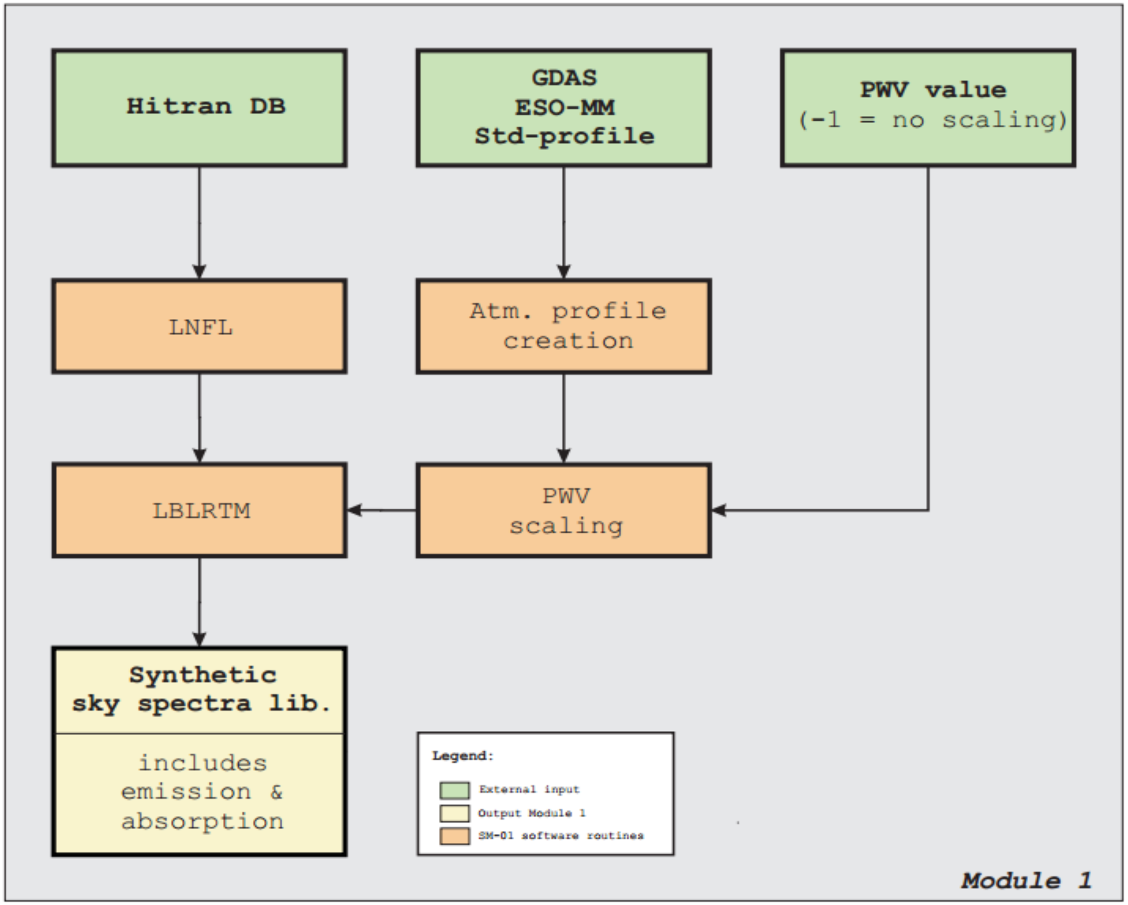


Figure 1: *Module 1:* This module creates a library of synthetic sky spectra on the basis of the HITRAN 2008 database and an atmospheric profile. The profile is created by merging the standard profile equ.atm (http://www.atm.ox.ac.uk/RFM/) and GDAS data (see [5] and Section 5), which provide information 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

+-sigma

Parameter Grid:

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

Module 2 (fast) at ETC runtime

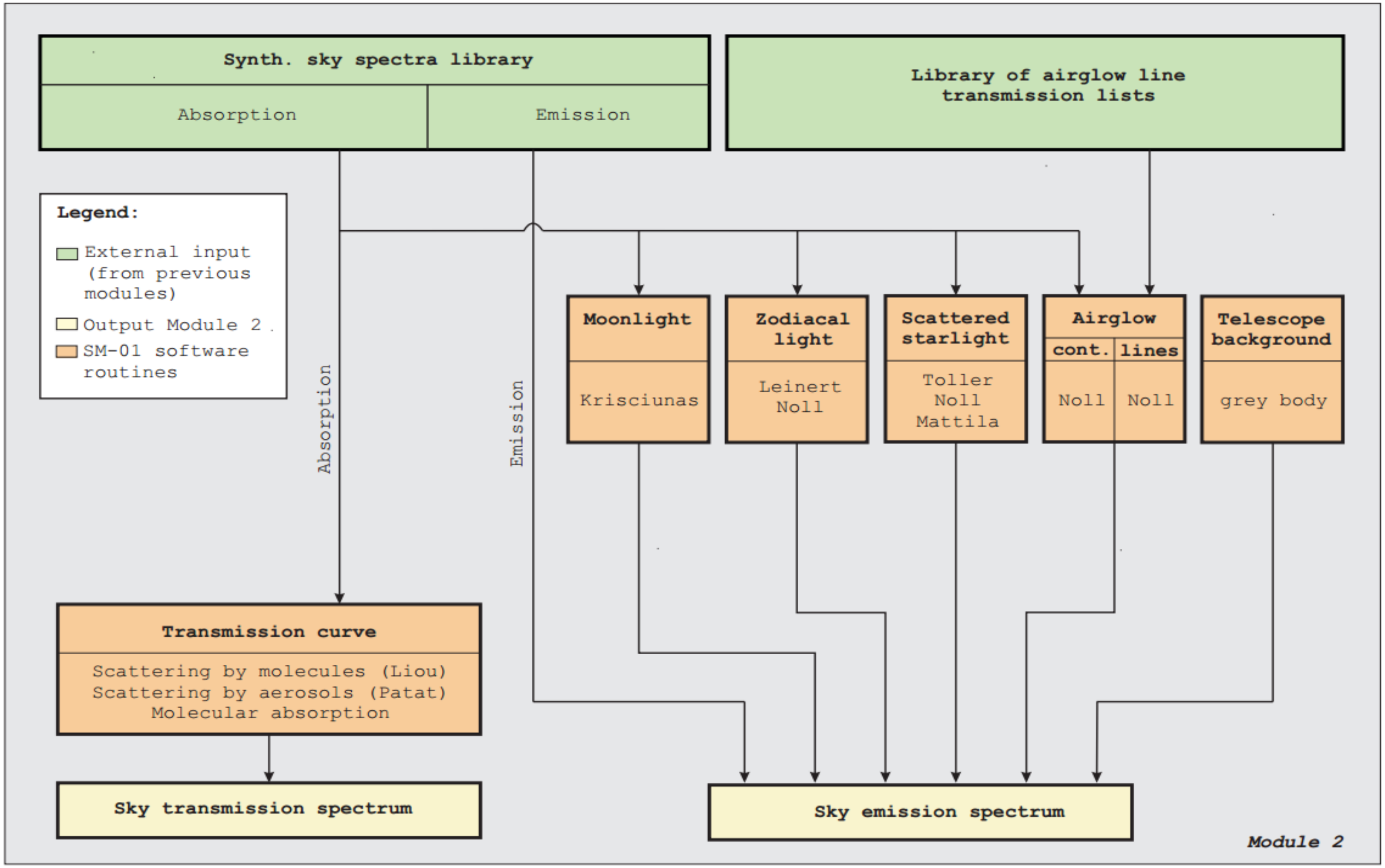
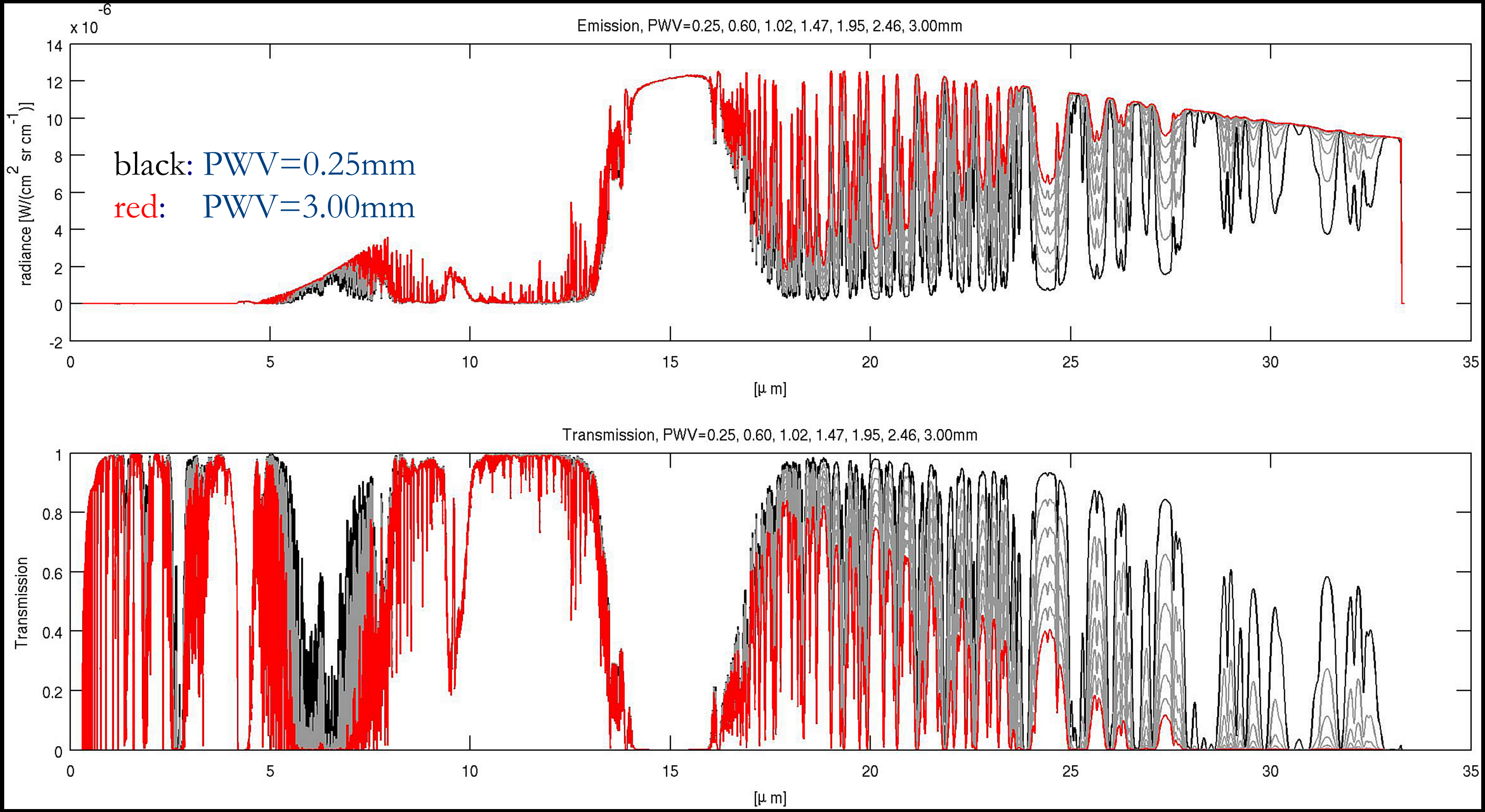


Figure 3: *Module 2* calculates the components, which need only minimal computing time. Hence, these components are computed during every ETC call. The final sky background spectrum is obtained by merging the appropriate synthetic sky spectrum from Module 1 (selected by user defined input) with these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

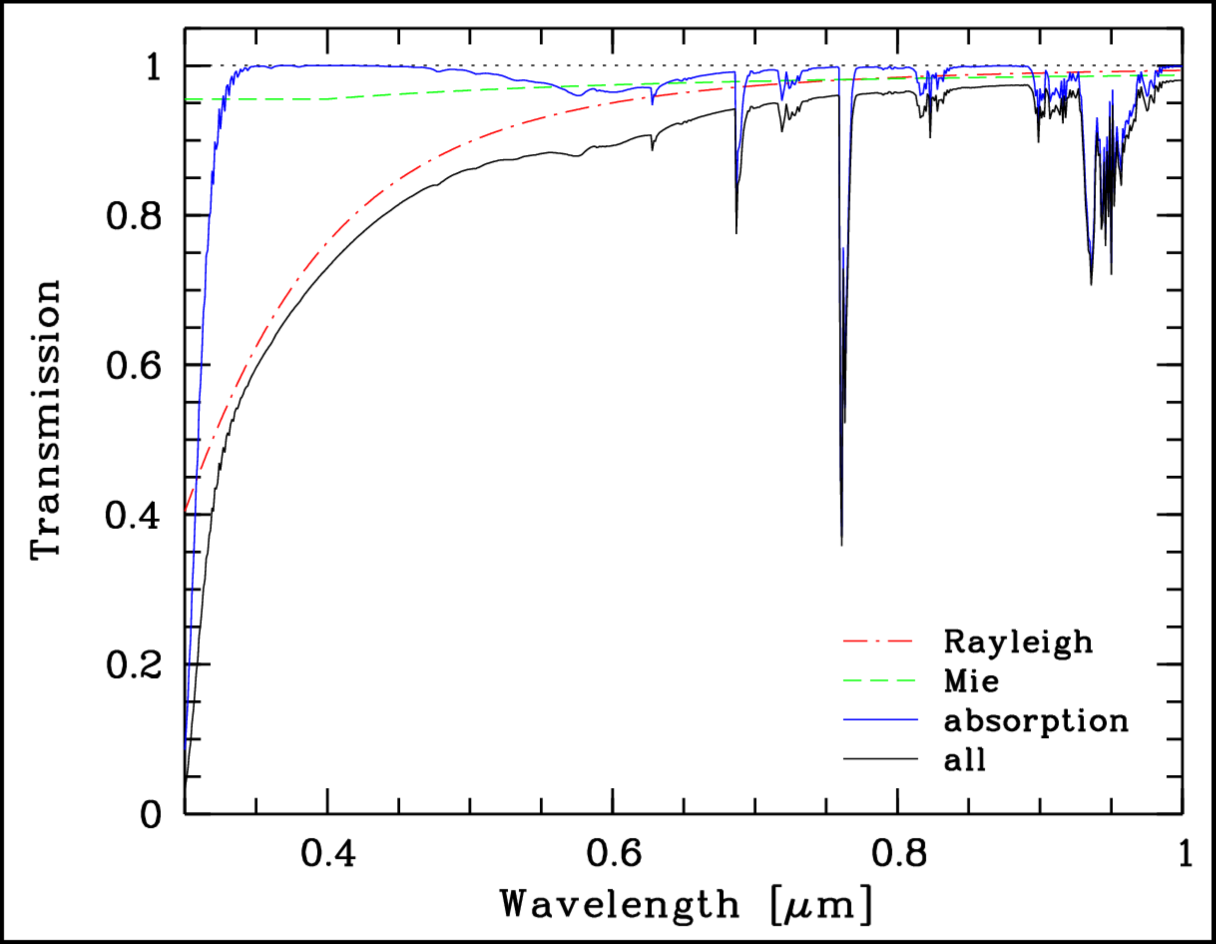
Emission and transmission spectra



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

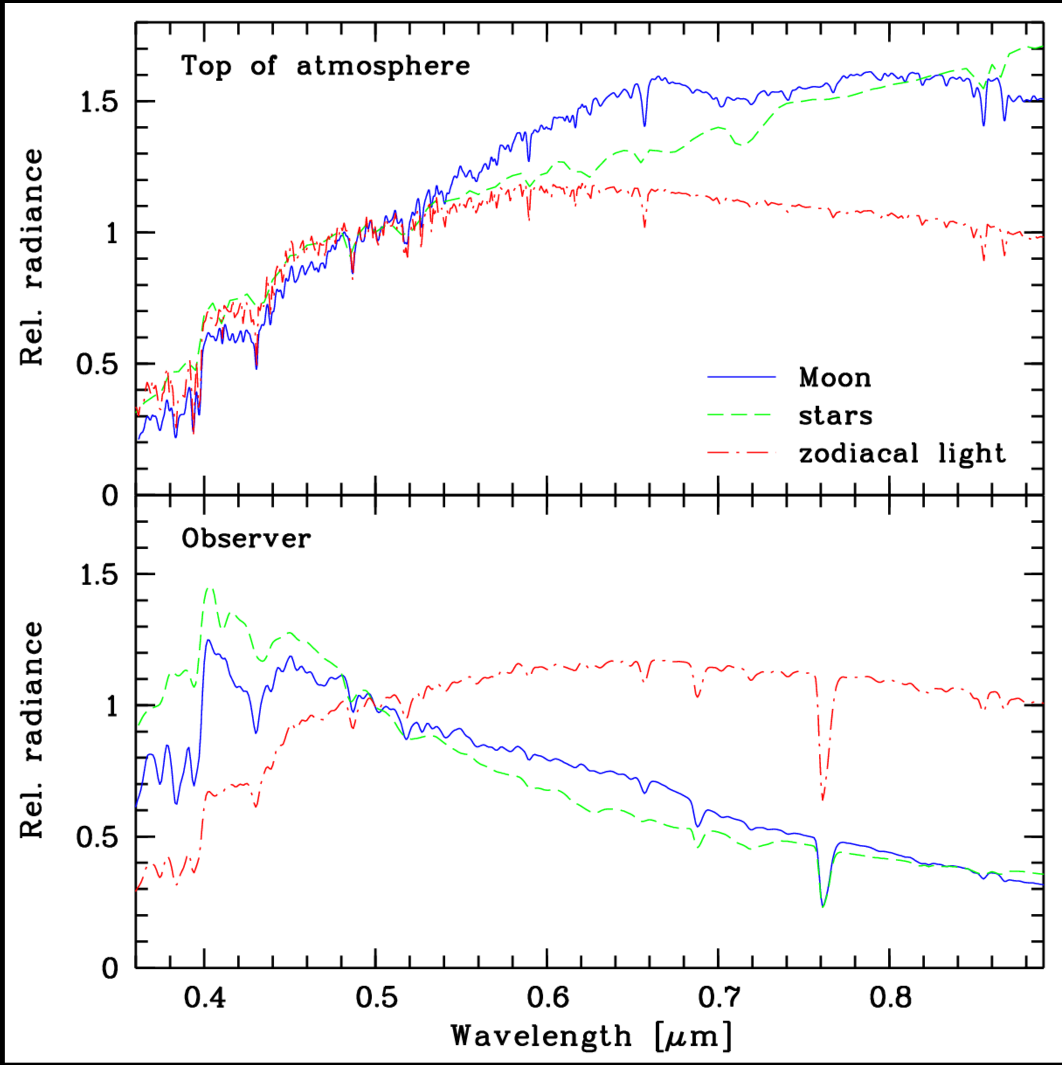
Atmospheric extinction

- **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



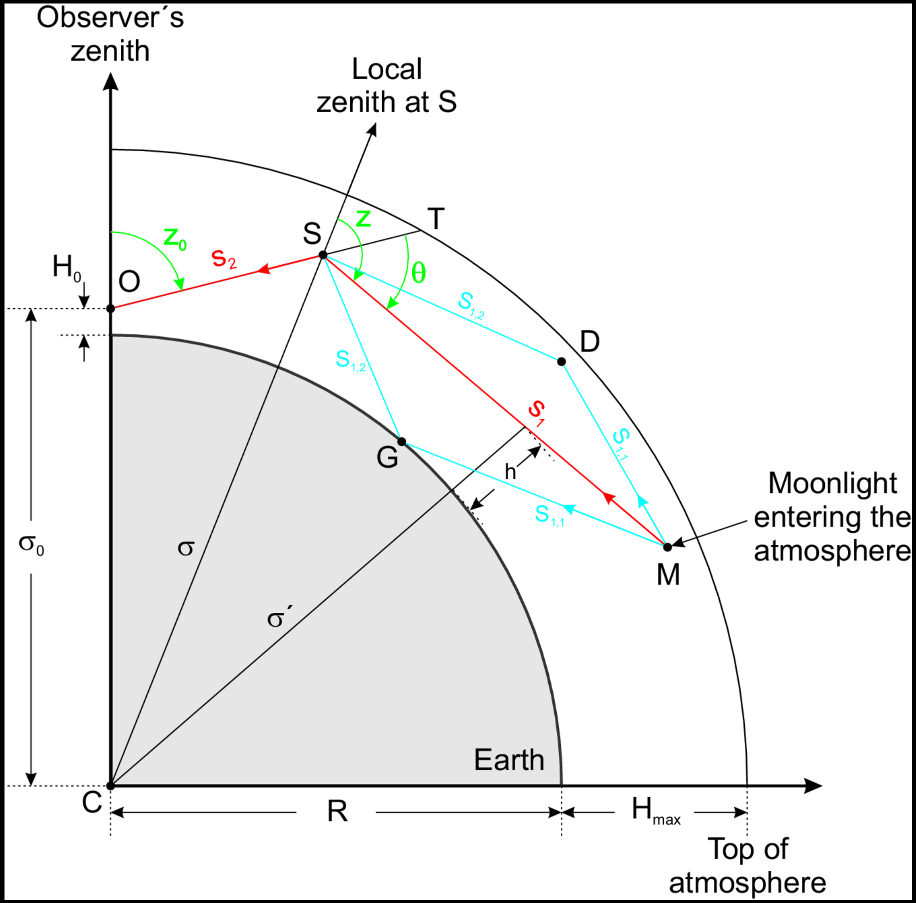
Moon, stars, and interplanetary dust

- **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)



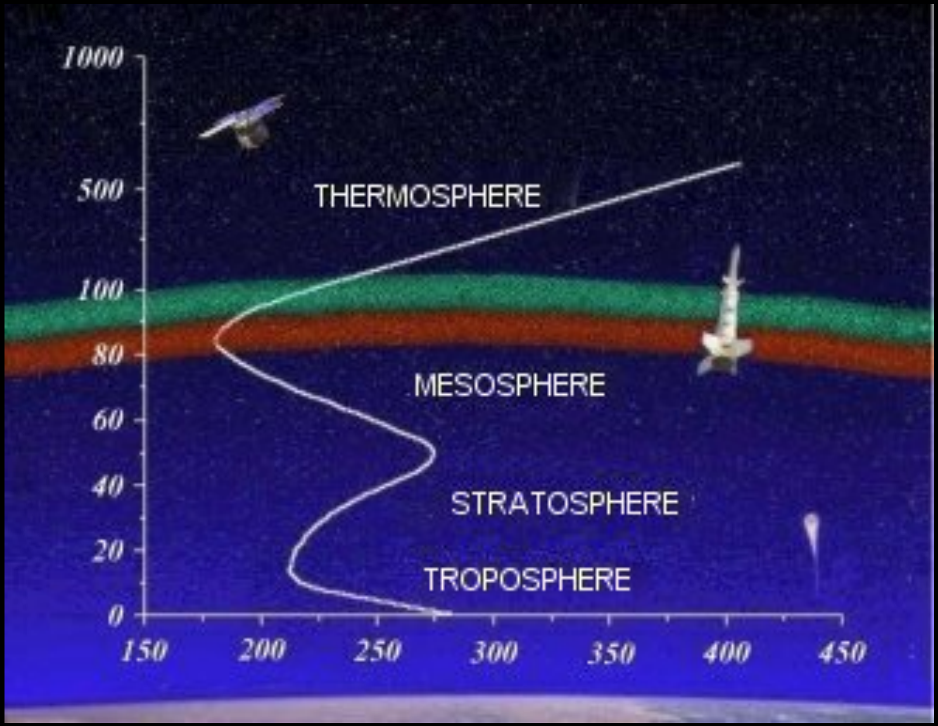
Radiative transfer of moonlight

– **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/

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 (→ climate change)

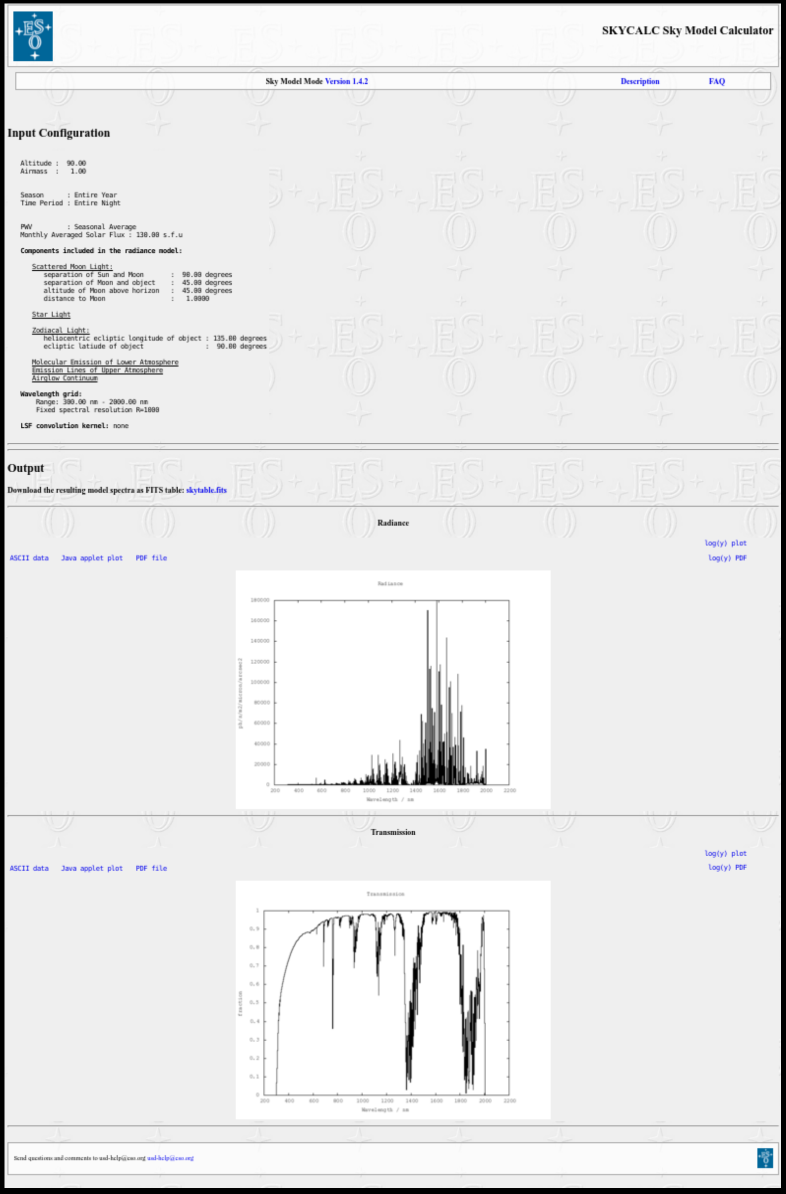
MASCOT/Paranal/ESO

Site-dependent semi-empirical airglow model required!

“The Dancing Sky”

SkyCalc: Web interface to the Sky Model

www.eso.org/observing/etc/skycalc



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`

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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

molecfit

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]):

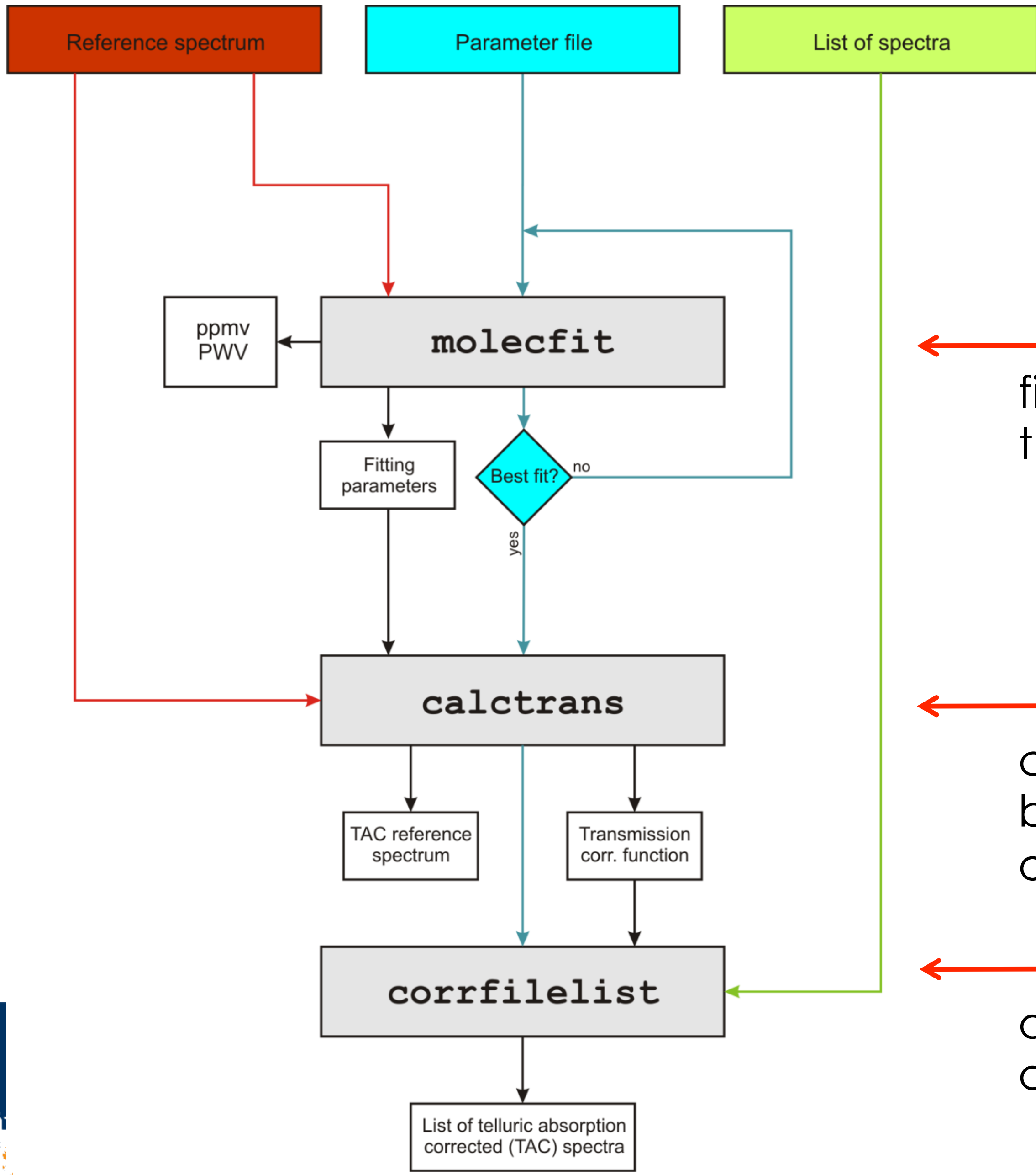
- derive the atmospheric state from its fingerprint in the science spectra
- calculation of synthetic transmission spectra corresponding to this state by means of a radiative transfer code
- iteratively fitting these spectra to absorption features in science spectra
- use the best-fit transmission for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



fitting of spectral features in the fitting ranges → best fit solution

calculation of the transmission based on the fit + application of the telluric abs. correction

application of the correction to other files.

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

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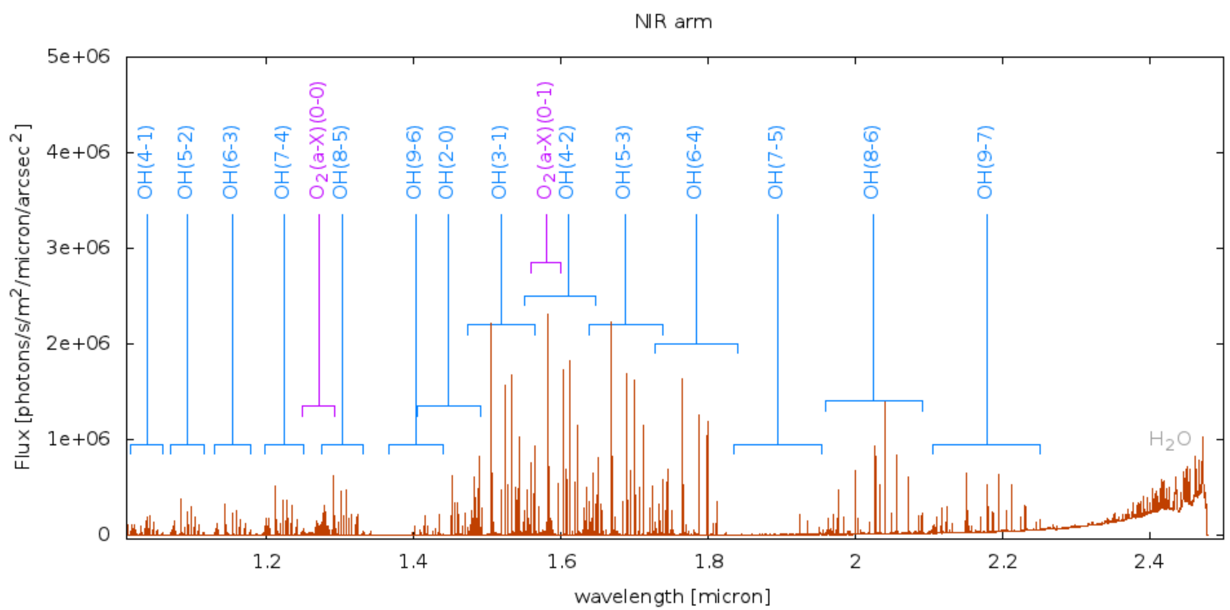
Sky emission removal with skycorr

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:

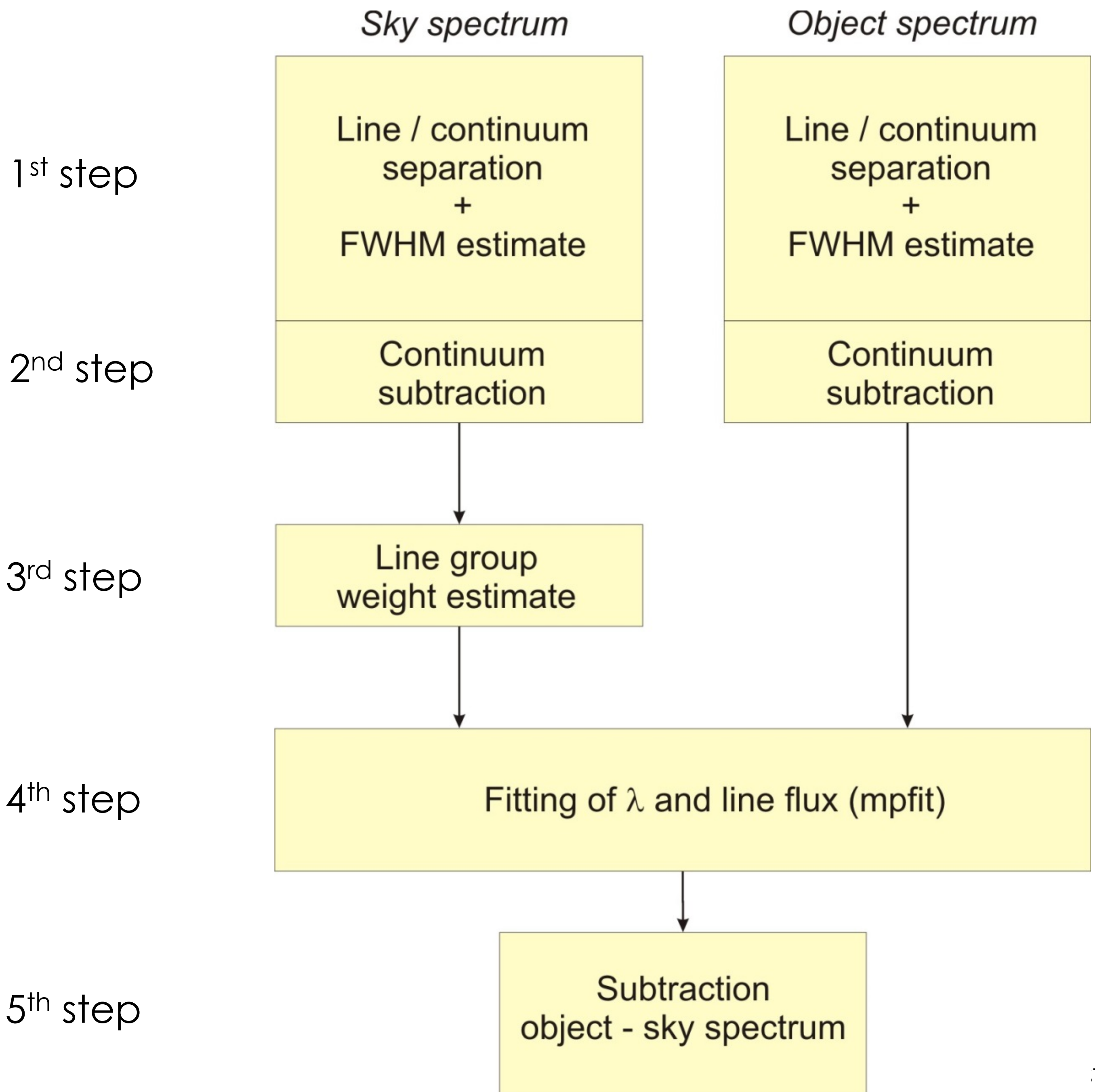
- Comprehensive software suite for sky emission removal
- Instrument independent
- world-wide use
- based on Ansi-C
- freely available*



[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`



Noll et al. 2014, A&A, 576, A25

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