CHARACTERIZATION OF EXOPLANET ATMOSPHERES

FROM RAW DATA TO PLANET PARAMETERS

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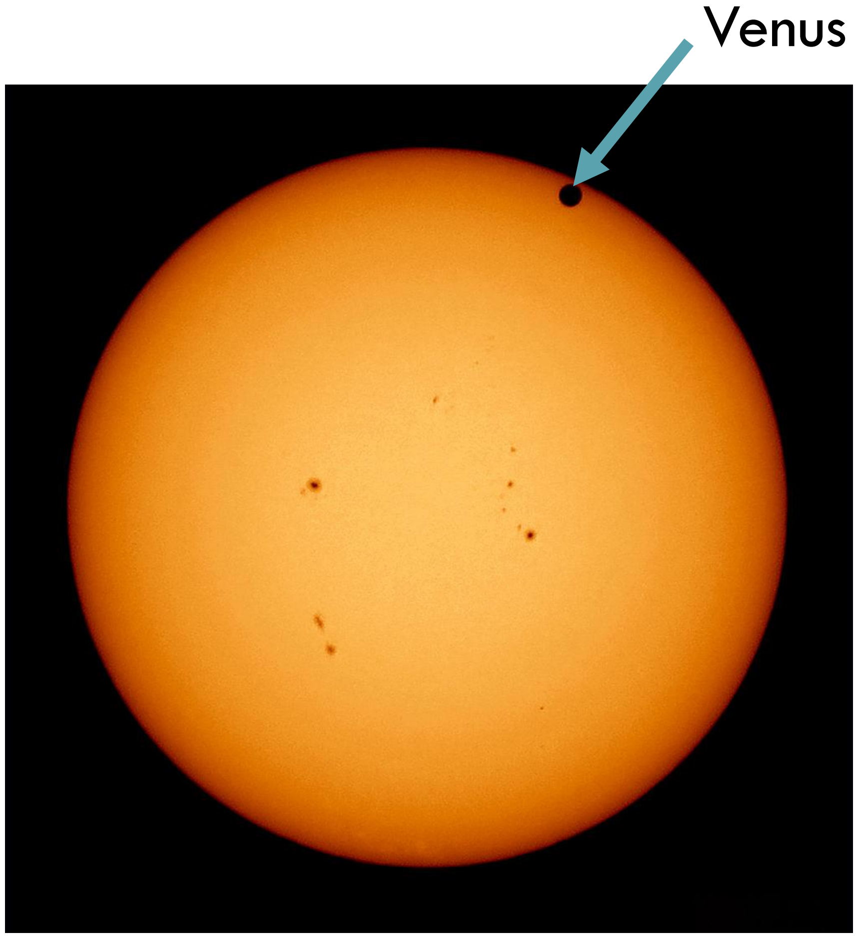
6 Month Seminar
22. September 2022

EXOPLANET CHARACTERIZATION

- Exoplanets are small
  - very difficult to observe
  - <1% of area of star
- Atmospheres are even smaller
- Characterization requires accurate:
  - Spectra
  - Stellar parameters



Credit: Wikipedia/Brocken Inaglory

ATMOSPHERES

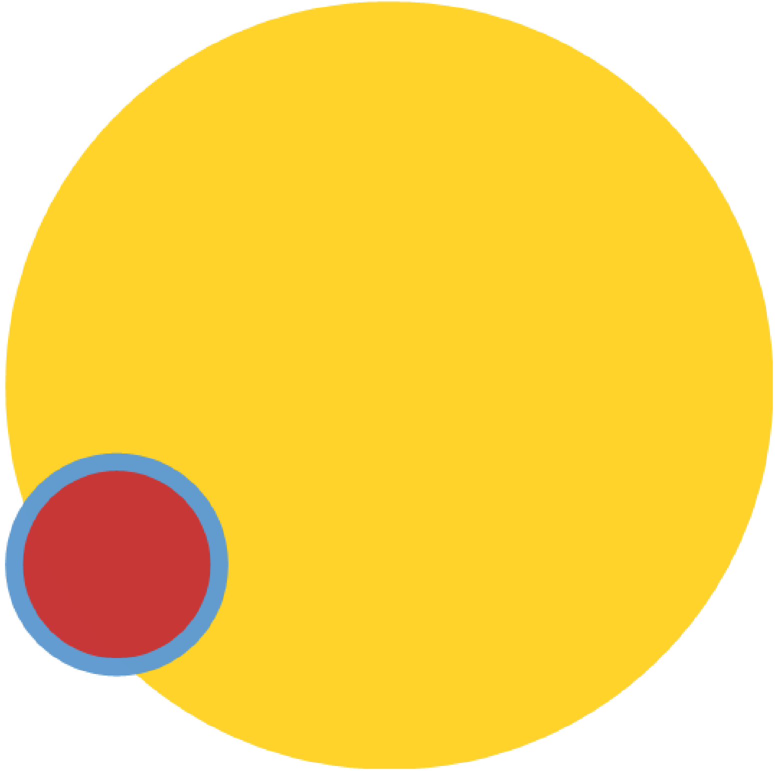
Informative about:

- Chemical composition (H2O, CO, CO2, etc.)
- Formation history
- Habitability

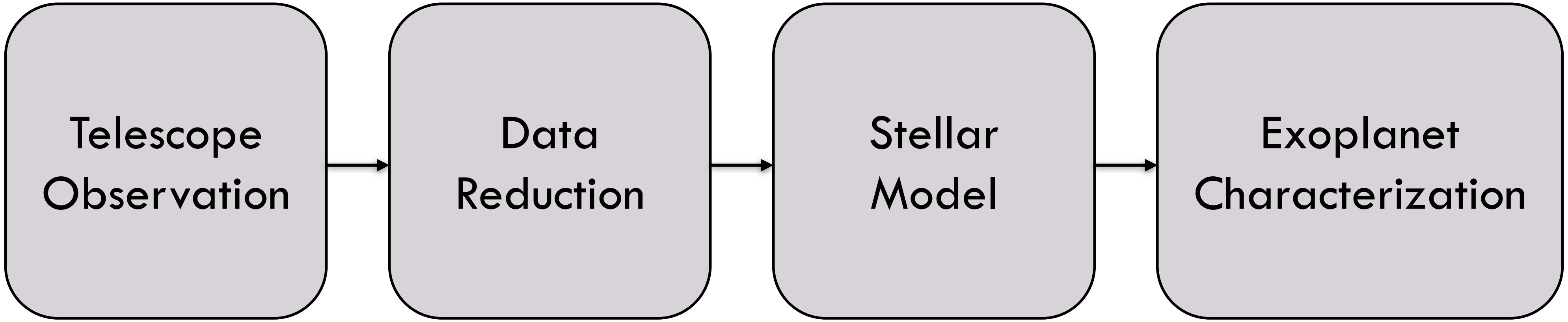
Currently only detections in gas giants

- Goal: detect weaker signals

(e.g. Smaller planets, different molecules)



ANALYSIS PIPELINE



Telescope Observation

Raw Data
Calibrations

PyReduce
Paper 1

Data Reduction

1D Spectrum

PySME
Paper 2

Stellar Model

Stellar
Parameters

ChEATS
Paper 3

Exoplanet Characterization

Planet
Atmosphere
Composition

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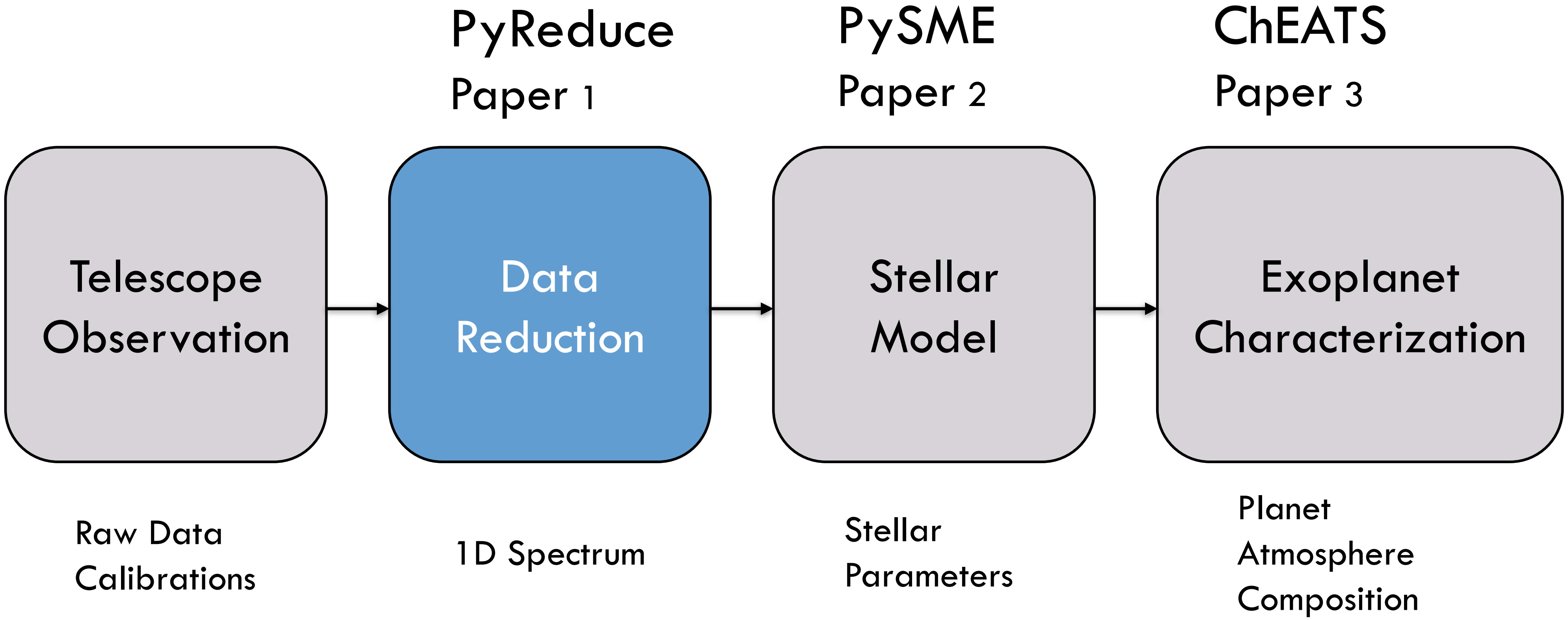

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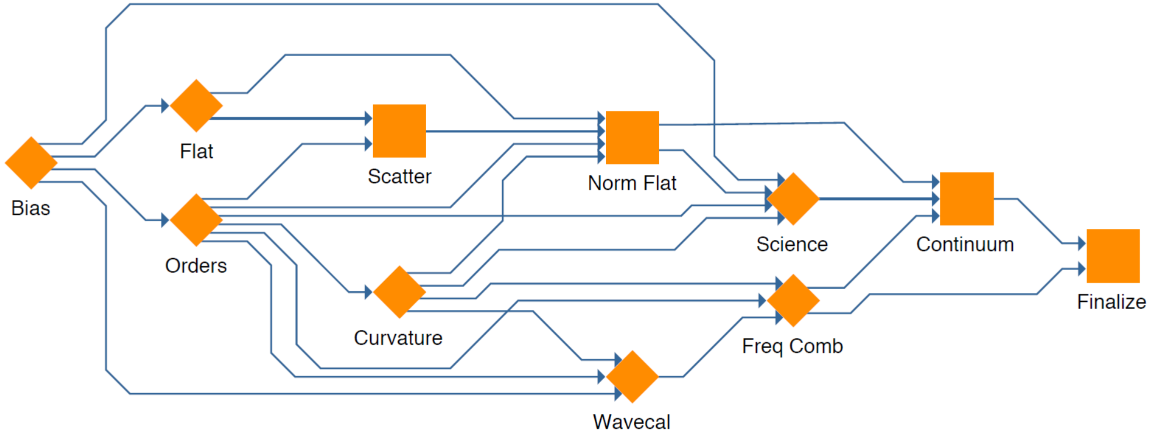
PYREDUCE (PAPER 1, PISKUNOV ET AL. 2021)

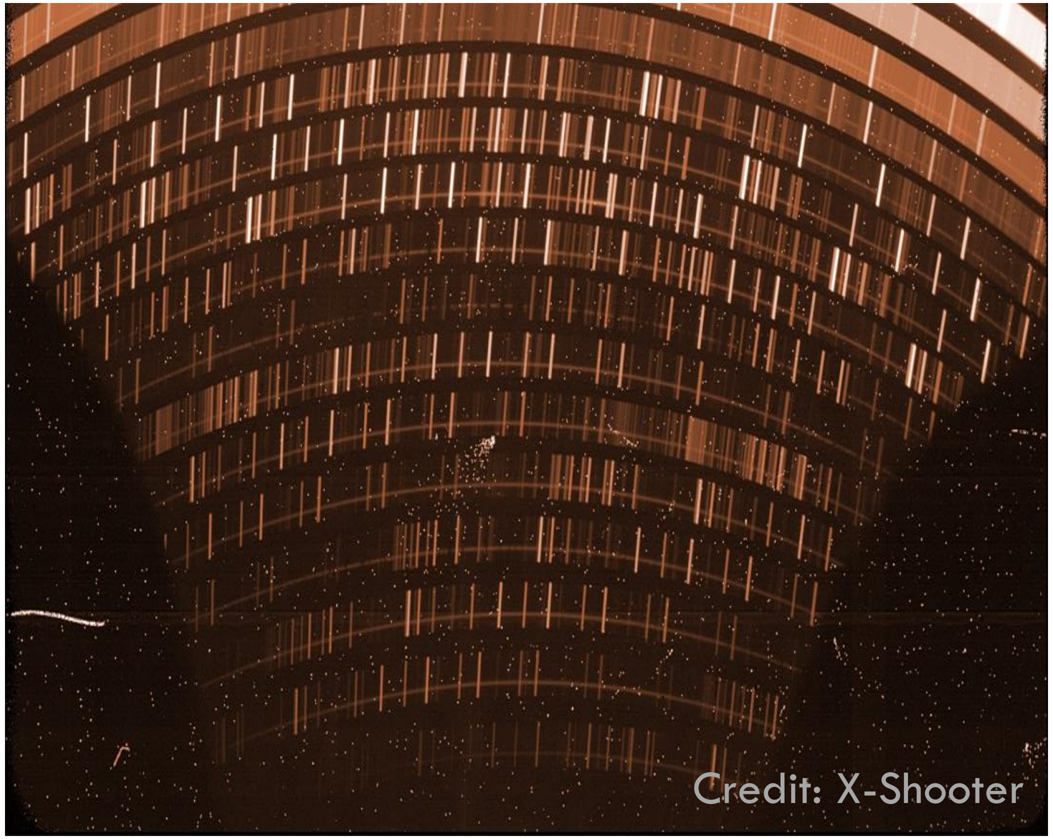
- Python package
- REDUCE (Piskunov & Valenti 2002) translated to Python with improvements
- Takes raw data + calibrations and turns them into a wavelength calibrated spectrum
- Instrument independent
- Specialised for echelle spectrographs



PYREDUCE (PAPER 1, PISKUNOV ET AL. 2021)

Echelle Spectrographs

- PROS:
  - High Resolution
  - Efficient use of the Camera Area
- CONS:
  - Optical distortions
  - Detector defects
  - Cosmic rays


Credit: X-Shooter

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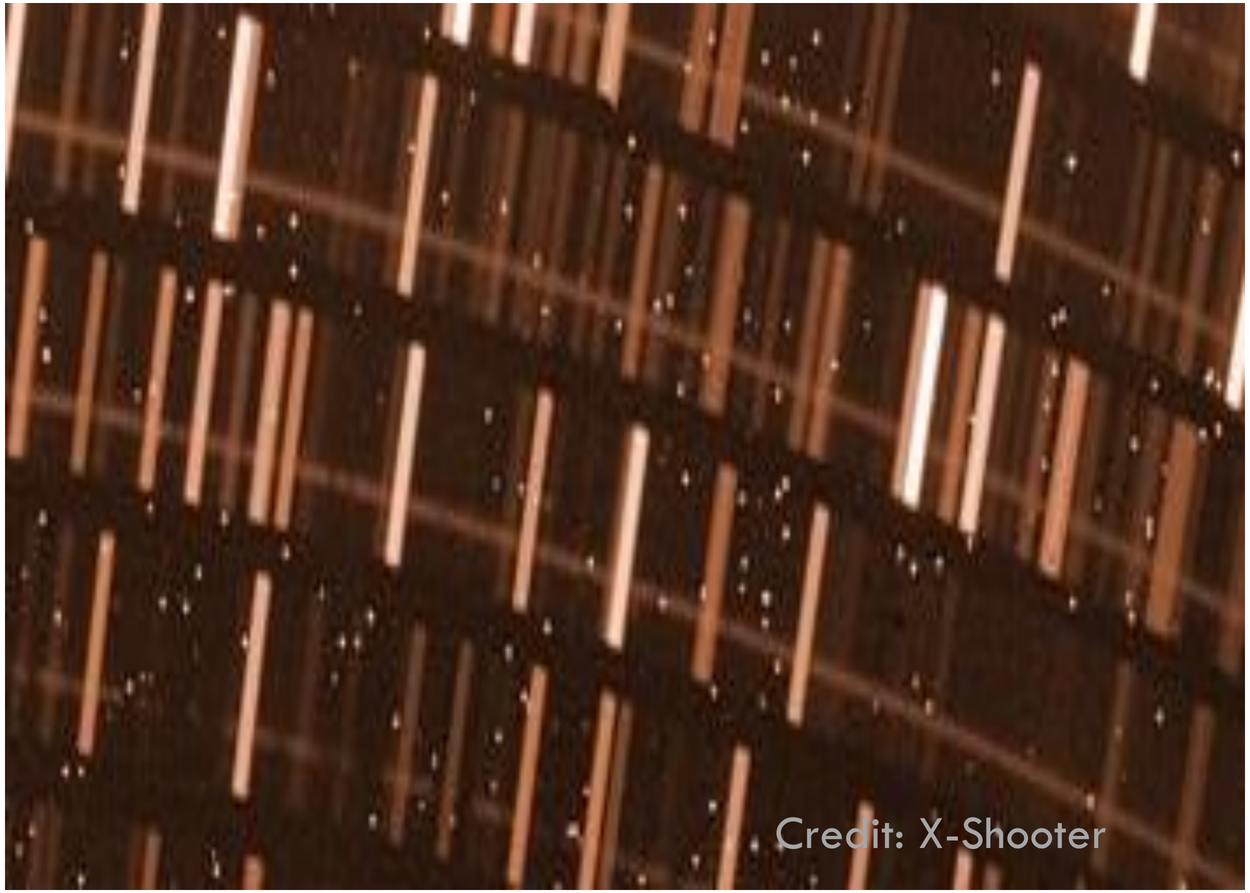

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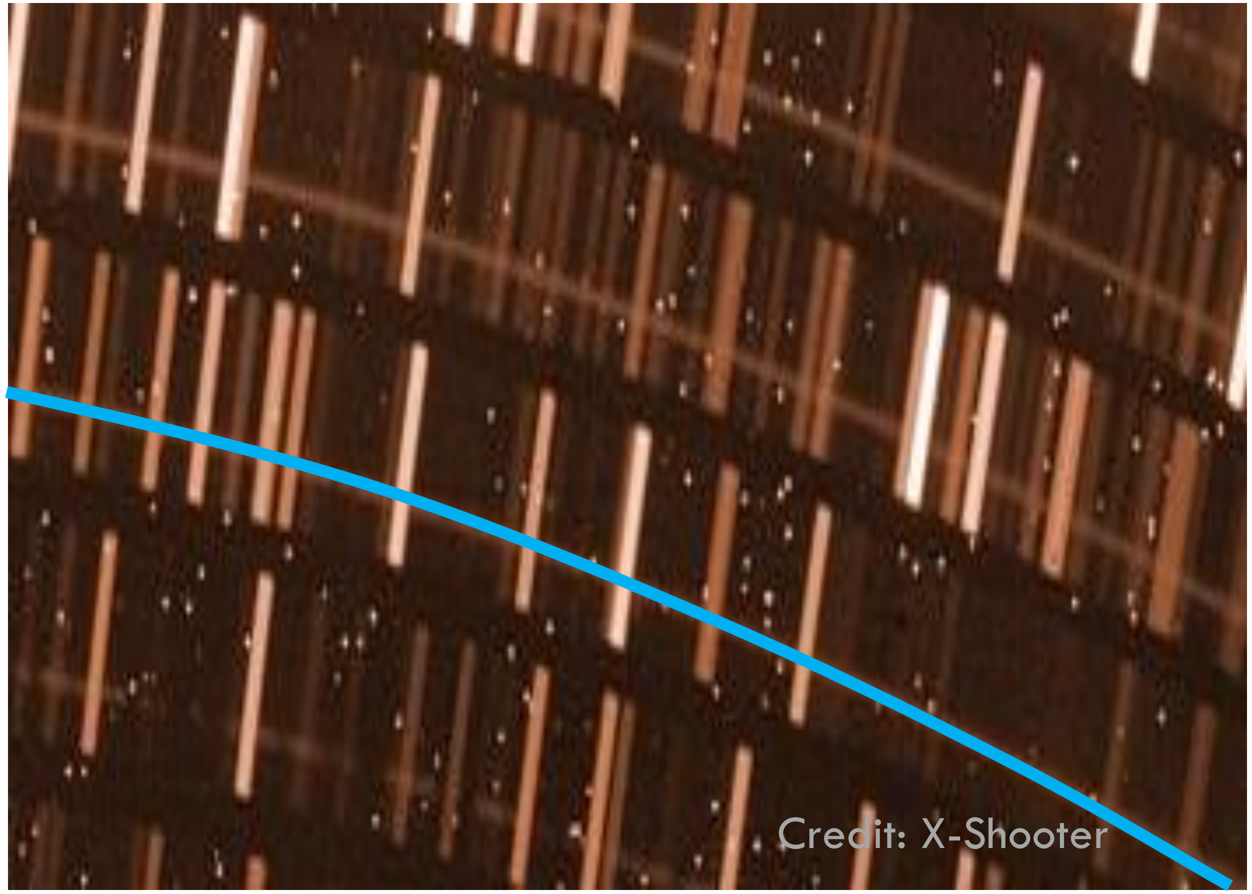

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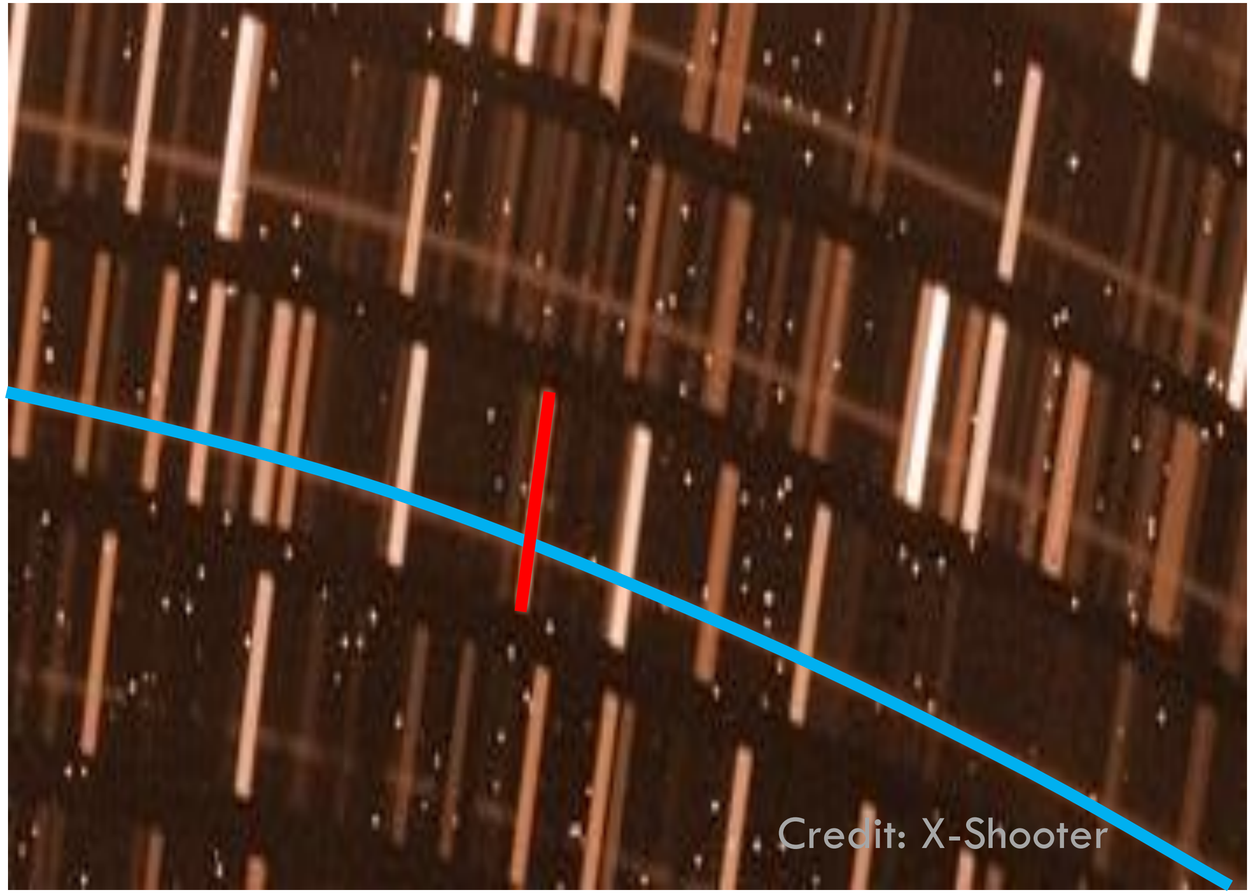
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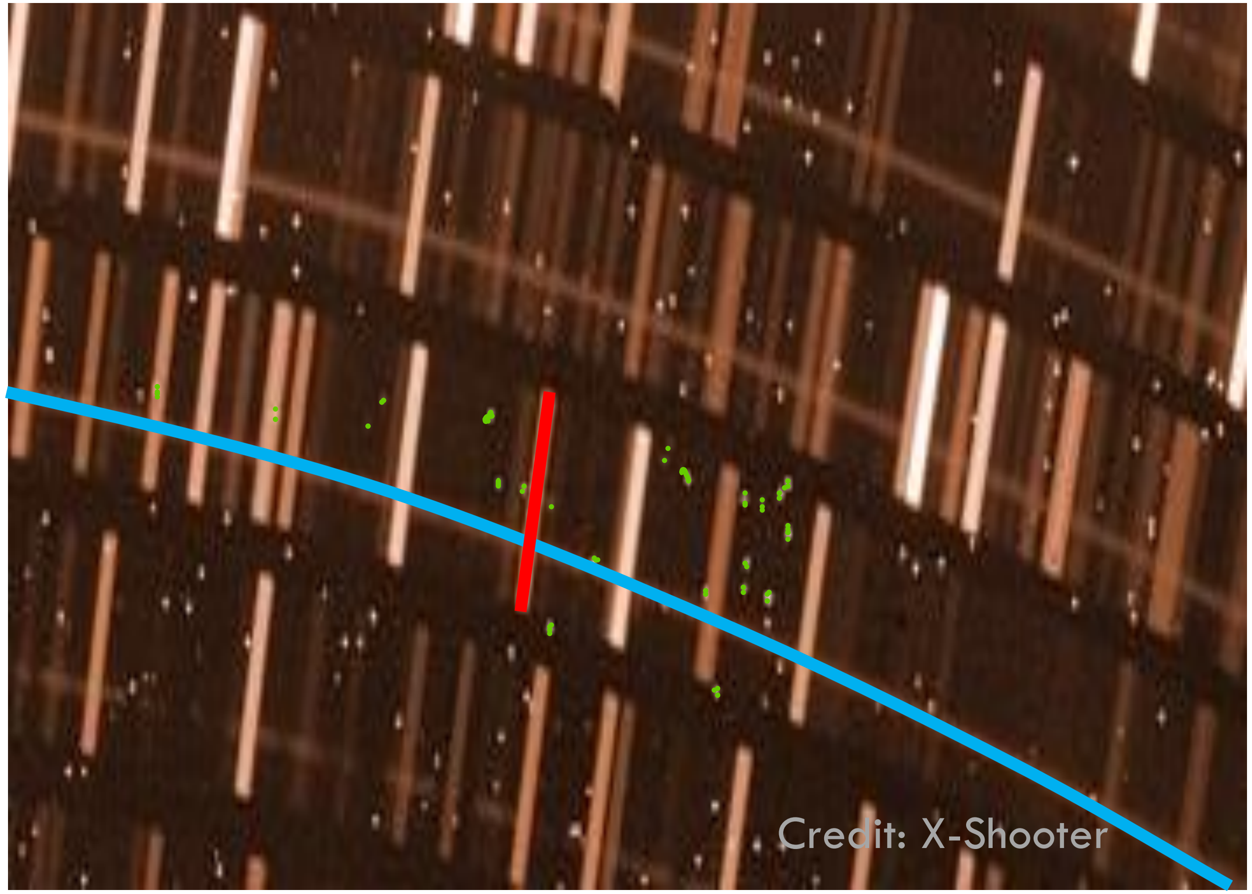


Credit: X-Shooter

PYREDUCE

Optimal extraction for model S:

$$S(x,y) = P(x)\Omega_x L(y)$$

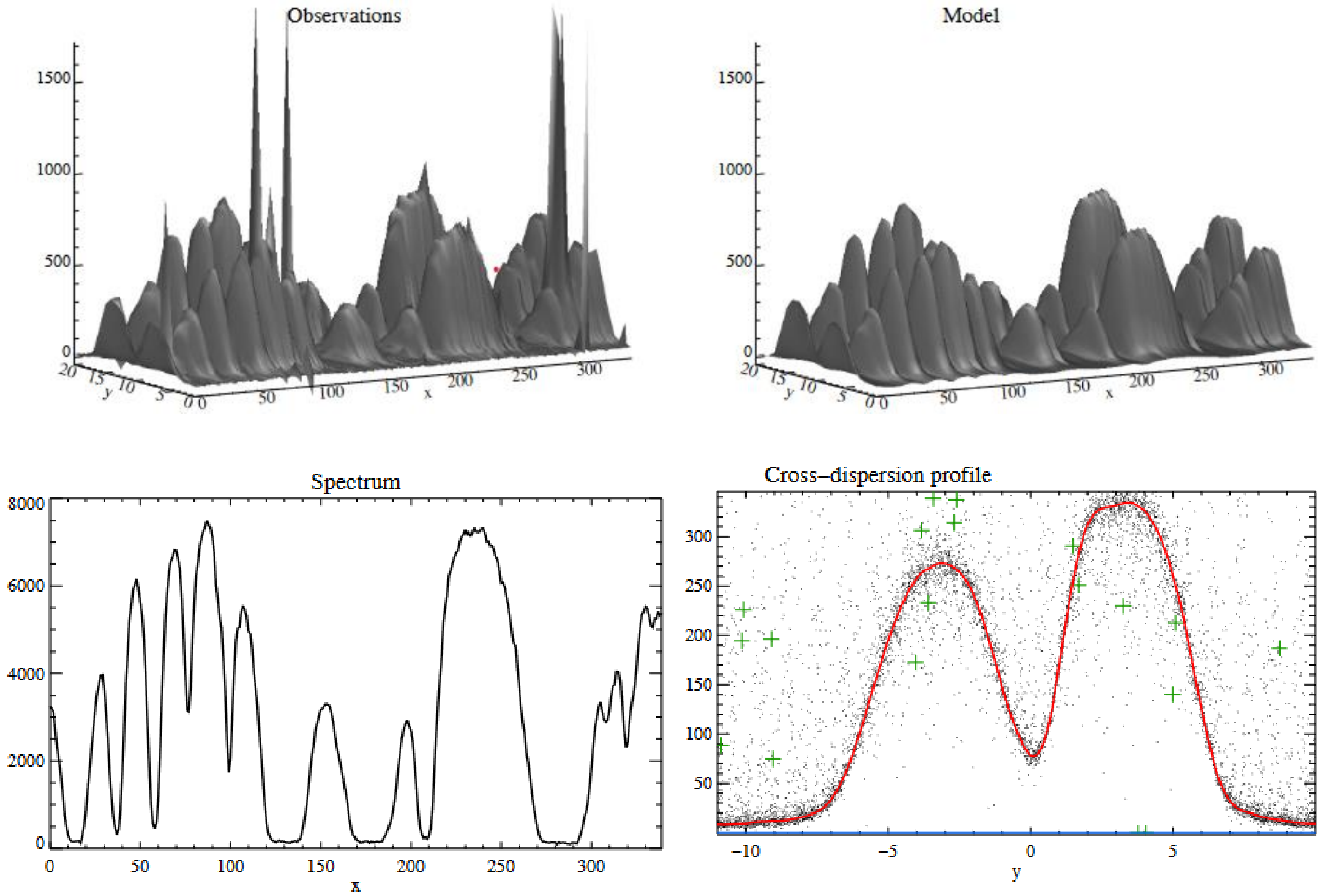
Where:

$L(y)$ is the slit illumination function

$P(x)$ is the spectrum

Ω_x is the geometry matrix describing:

- Curvature, i.e. the contribution of each pixel to the wavelength bin



PYREDUCE IMPROVEMENTS

Open source

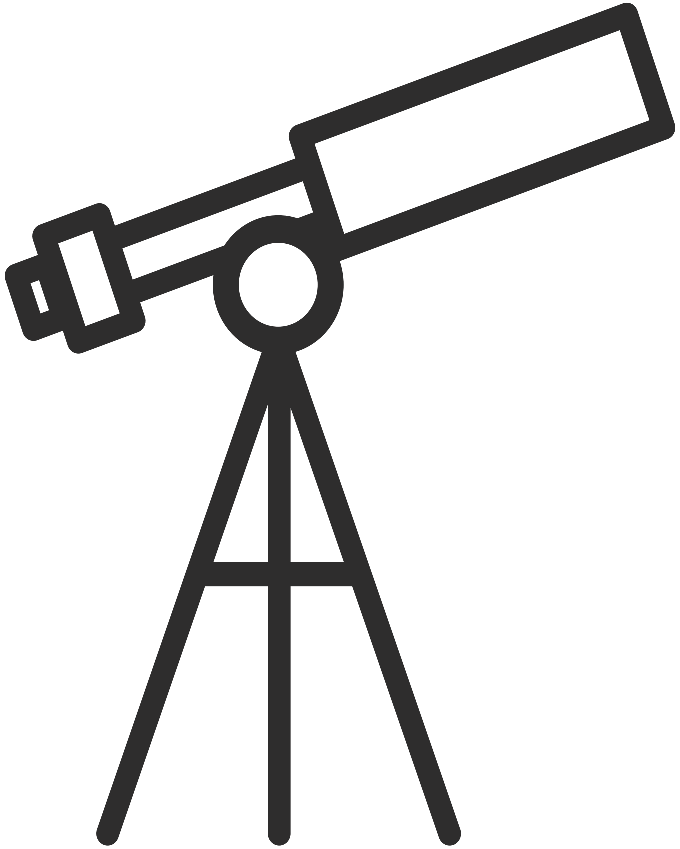
- formerly IDL (proprietary)
- now in Python (free)

Wavelength calibration

- More accurate using data from:
  - Laser Frequency Comb
  - Fabry Perot Interferometer

Curved slit corrected for

- Optimal extraction algorithm



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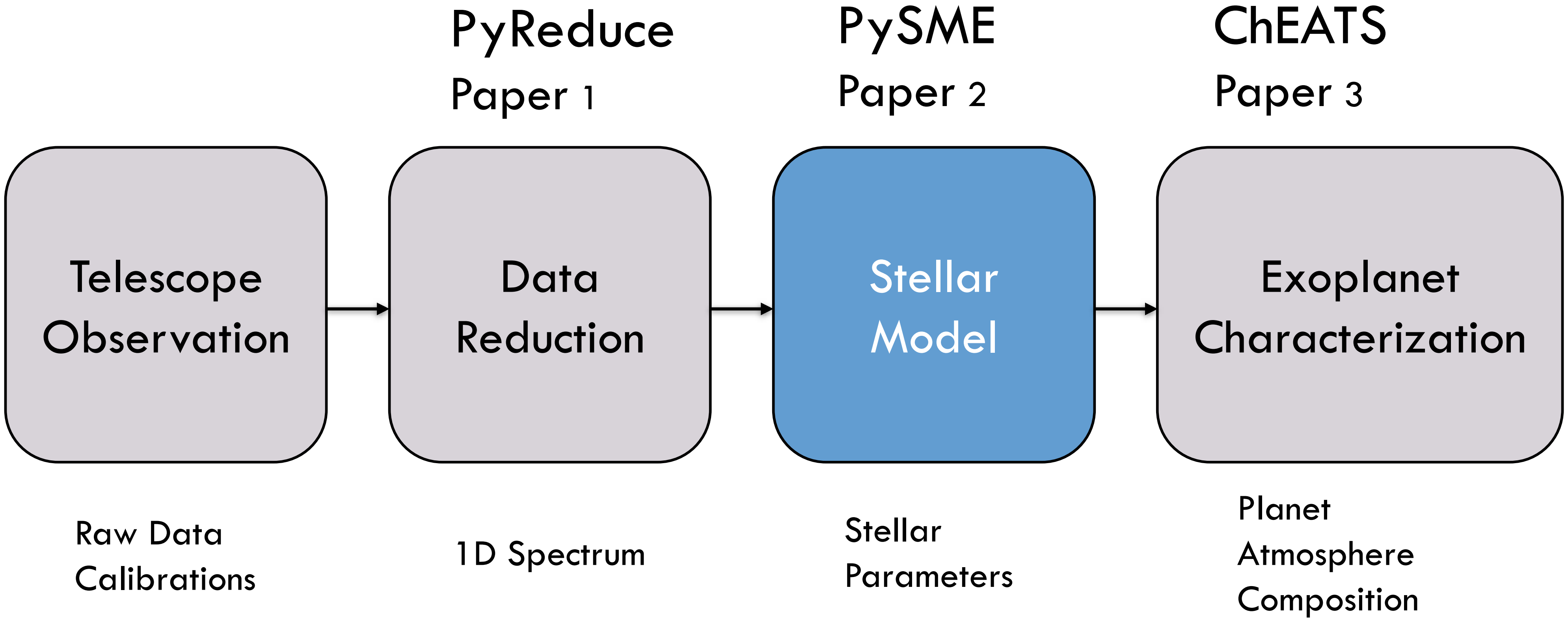

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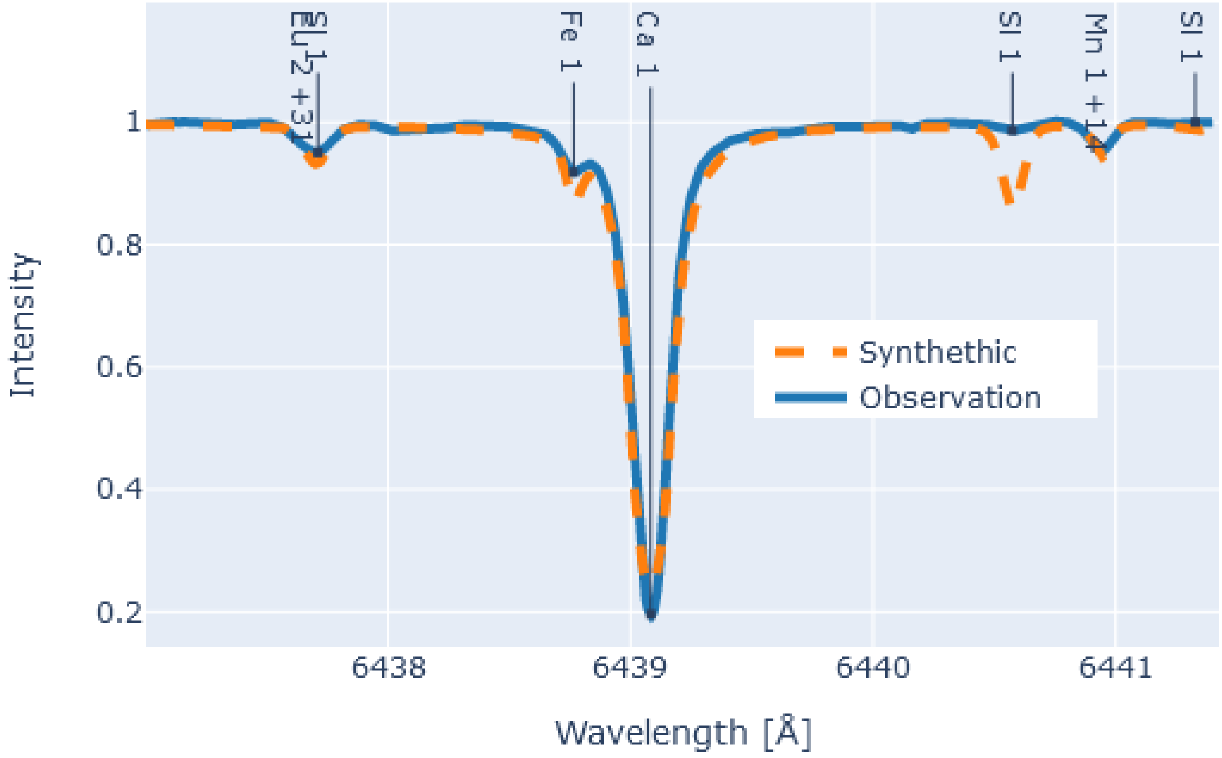
PYSME (PAPER 2, SUBMITTED)

- Python Spectroscopy Made Easy
- SME (Piskunov & Valenti 2017) translated to Python with improvements
- Calculates model stellar spectrum based on stellar parameters
- Determines best fit stellar parameters based on spectrum
- 1D LTE radiative transfer
- Non-LTE corrections available (for common elements)

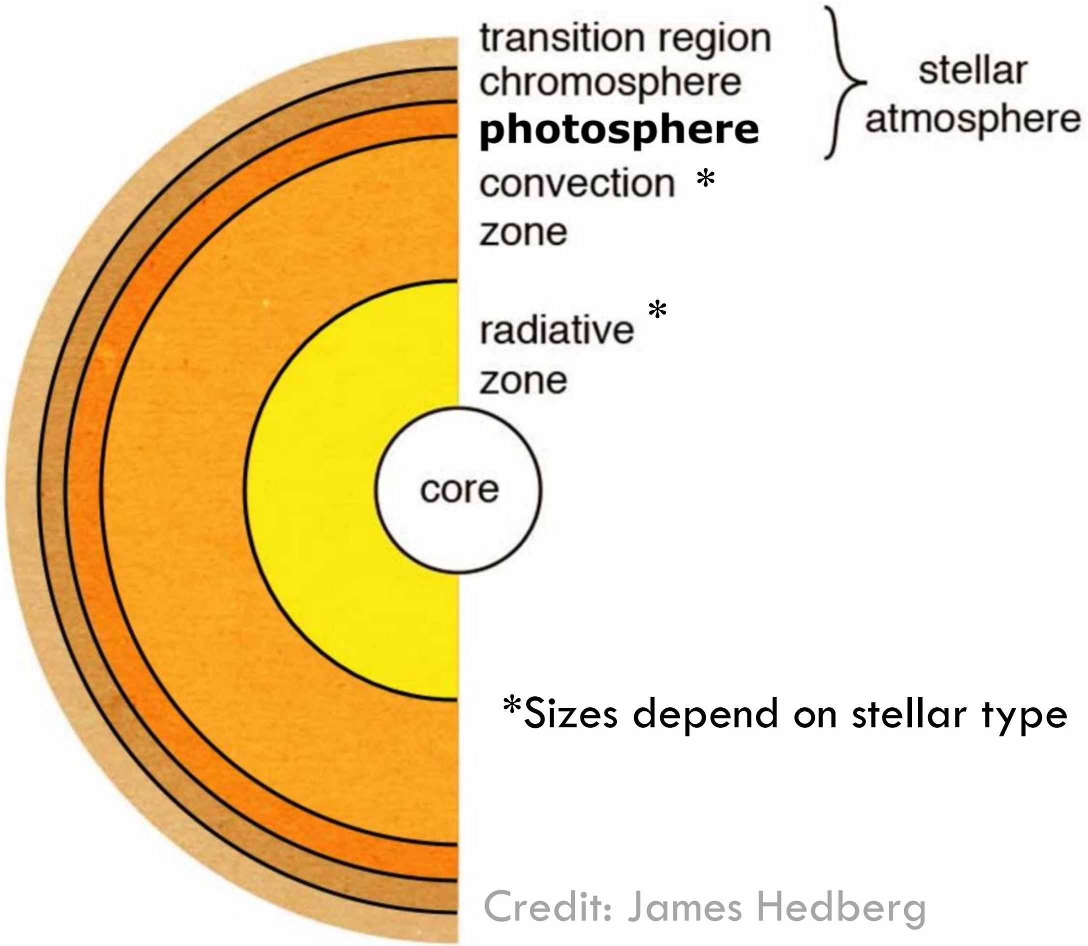


- Uses MARCS atmospheres (Gustafsson et al. 2008) and VALD linelists (Ryabchikova et al. 2015)

PYSME

Stellar flux (in Optical/NIR) is determined in the photosphere

- Lowest layer of the atmosphere
- Characterized by a few stellar parameters
  - Effective Temperature T_{eff}
  - Surface gravity $\log(g)$
  - Metallicity [M/H]
  - Turbulence parameters v_{mic}, v_{mac}
  - Rotation velocity $v \sin(i)$



*Sizes depend on stellar type

Credit: James Hedberg

PYSME IMPROVEMENTS

New optimization algorithm

- Bounds on the parameter space

New Non-LTE departure coefficient grids (Amarsi et al. 2020)

Improved radial velocity determination

Expanded continuum options

Easier installation and setup

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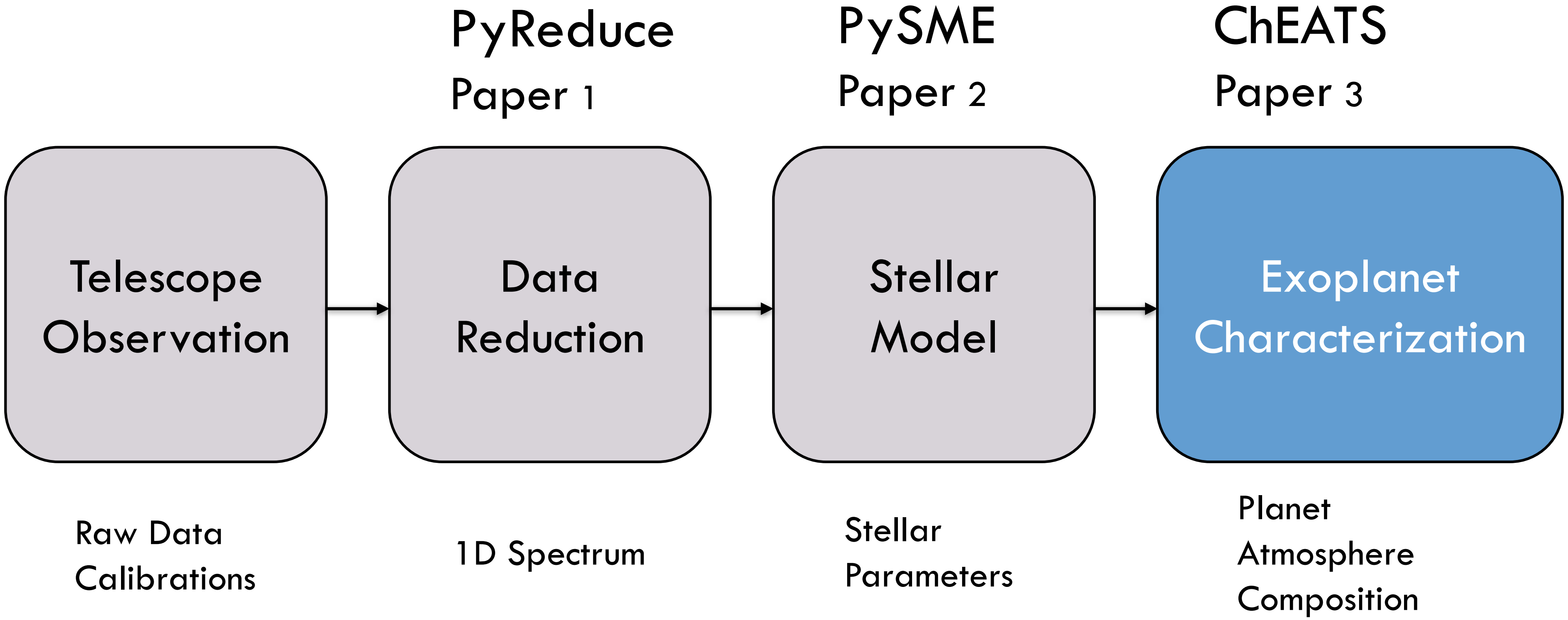

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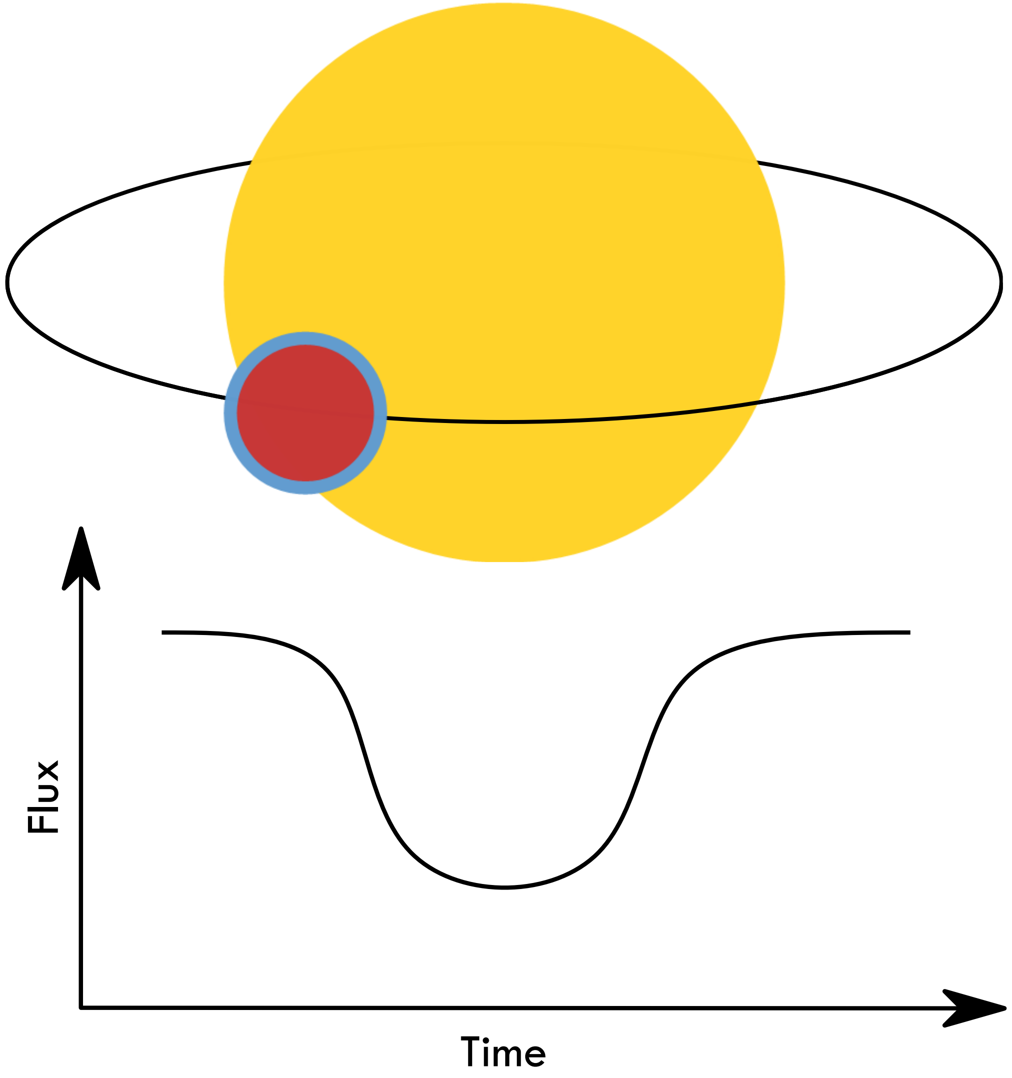
CHEATS (PAPER 3, IN PREP)

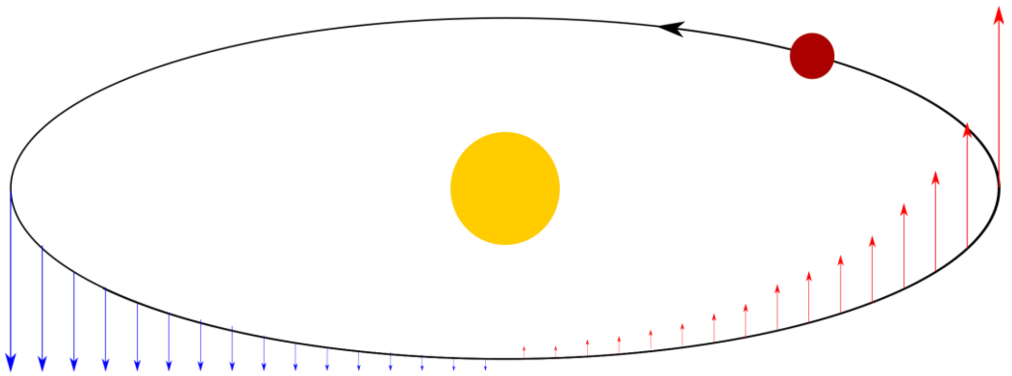
Characterization of Exoplanet Atmospheres Using Transit Spectroscopy

Use high resolution spectra of transit observations to determine atmosphere composition



EXOPLANET CHARACTERIZATION

- Planet spectrum has Doppler shift
- Stellar spectrum shift is small
- Telluric spectrum does not shift
- Separate the stellar and telluric signal from the planet



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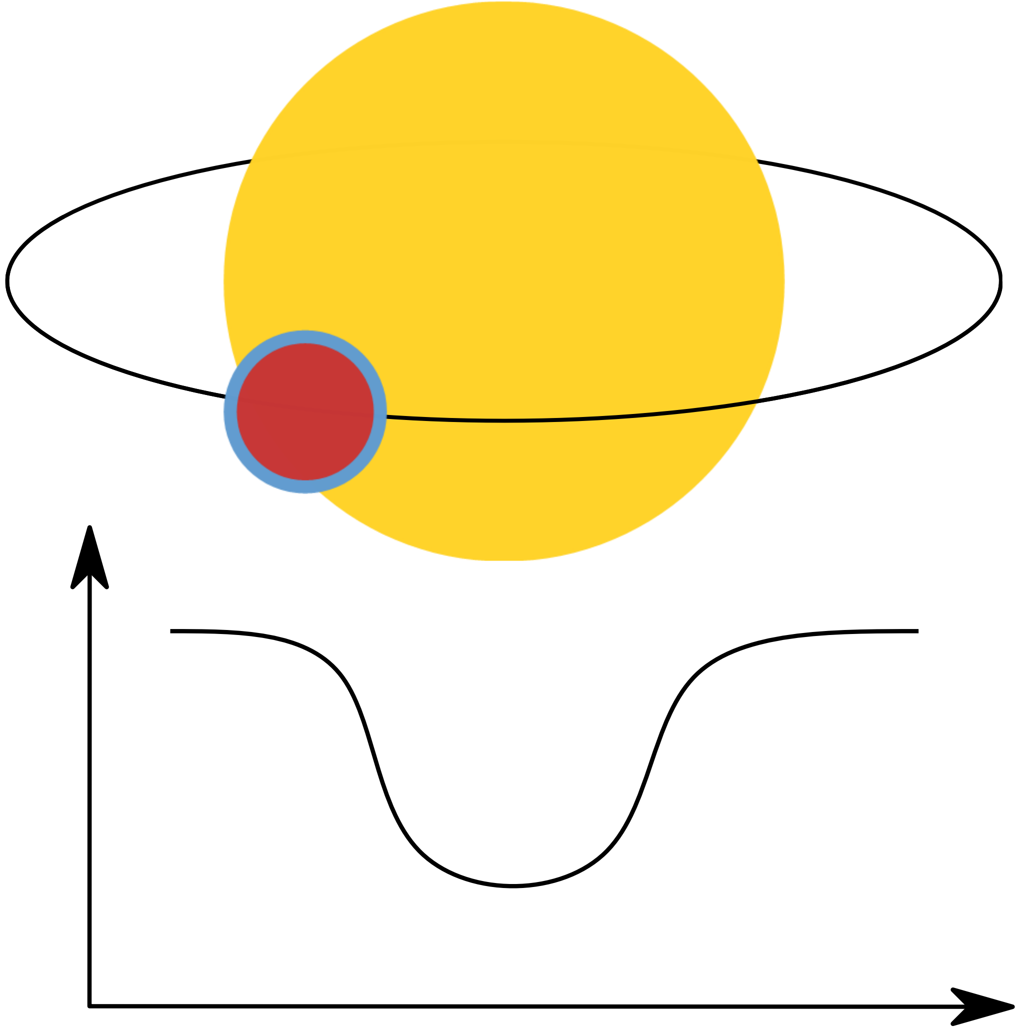


Cross-Correlation Method:

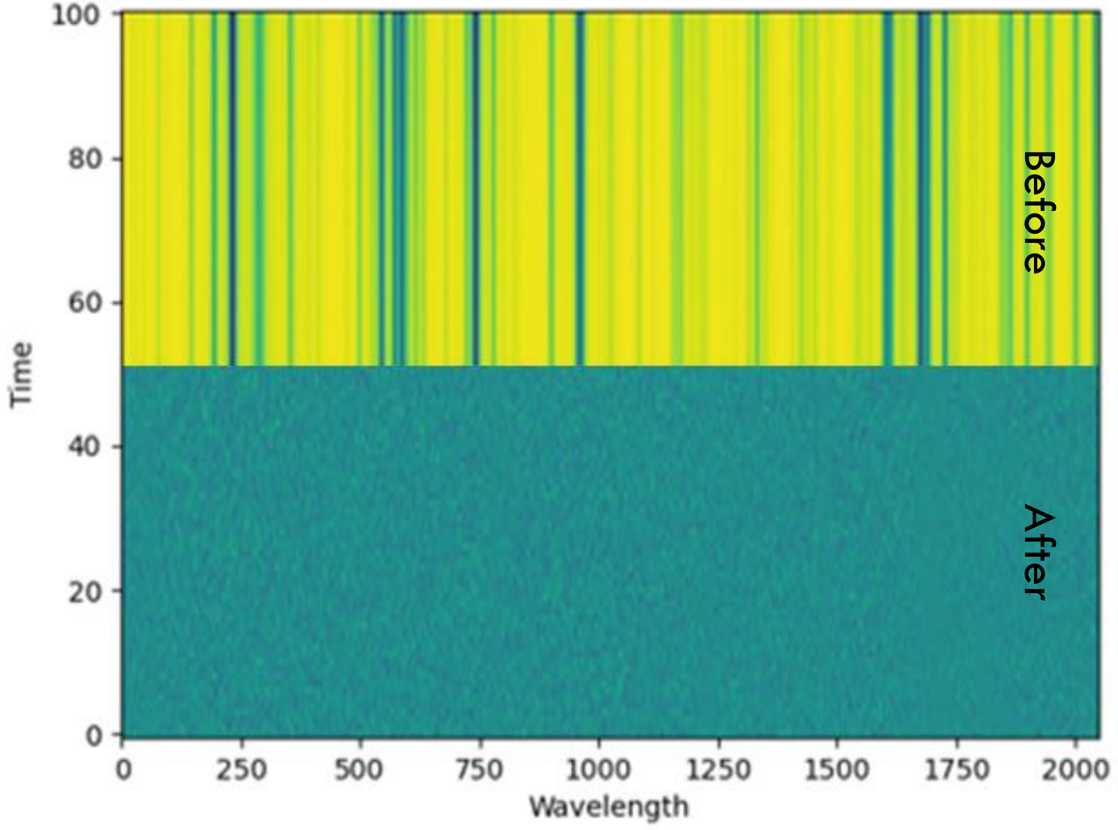
- Remove stellar and telluric signal (SYSREM)
- Model transmission spectrum of the planet (petitRADTRANS)
- Calculate cross-correlation between residuals and model at different radial velocity offsets

SYSREM

- Model the observation:

$$Obs(\lambda, t) = c(\lambda)\, a(t)$$

  - Where c is the spectrum
  - And a is the "airmass", i.e. the variation with time
- Subtract the model from the observation
- Repeat several times (~10 times)
- Planet signal changes both in time and wavelength, is not removed
- Residual looks like noise, but contains planet signal



petitRADTRANS

Python package

Models the planet atmosphere

High resolution (R~1 000 000)

Molliere et al. 2019

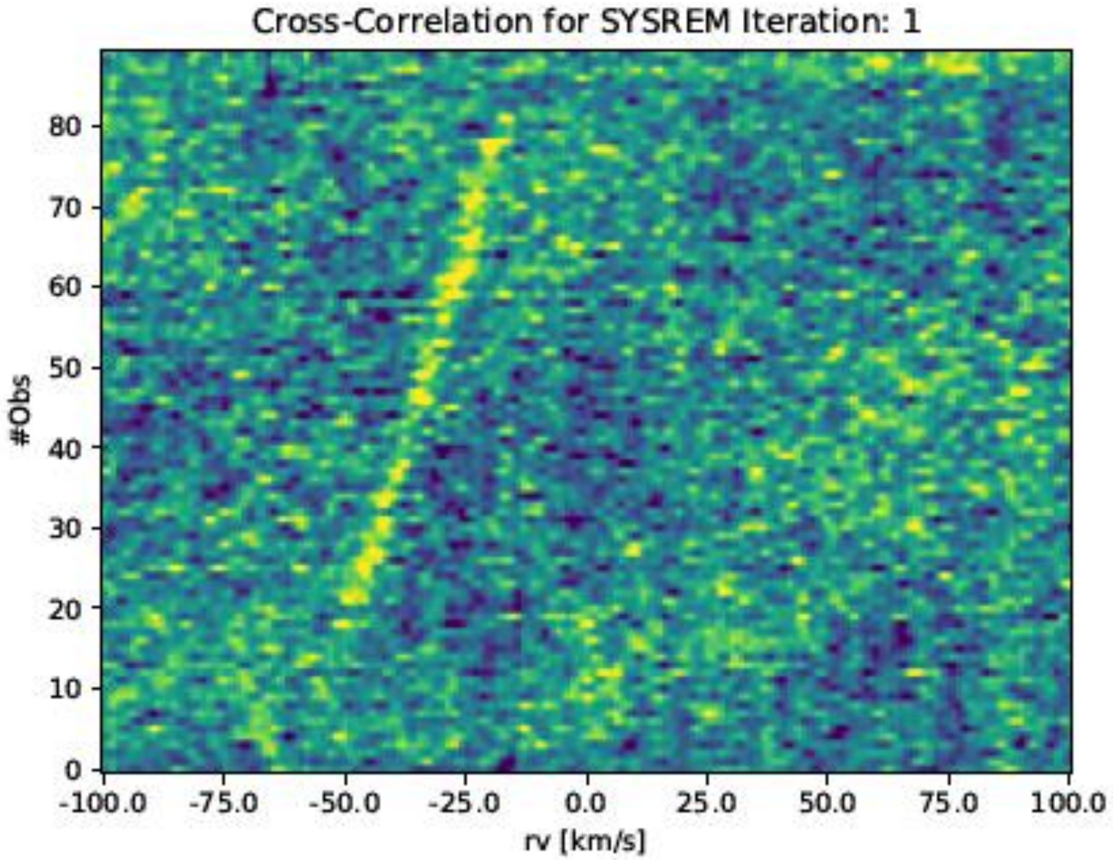
ChEATS

Atmosphere signal is still very small

Combine signal from all lines of the planet atmosphere

Cross Correlation technique

- $CCF = \sum_{\lambda} R(\lambda)\, M(\lambda, rv)$
- Where R is the residual of the observation after the stellar and telluric signal has been removed
- And M is the model of the planet transmission spectrum with doppler shift of velocity rv



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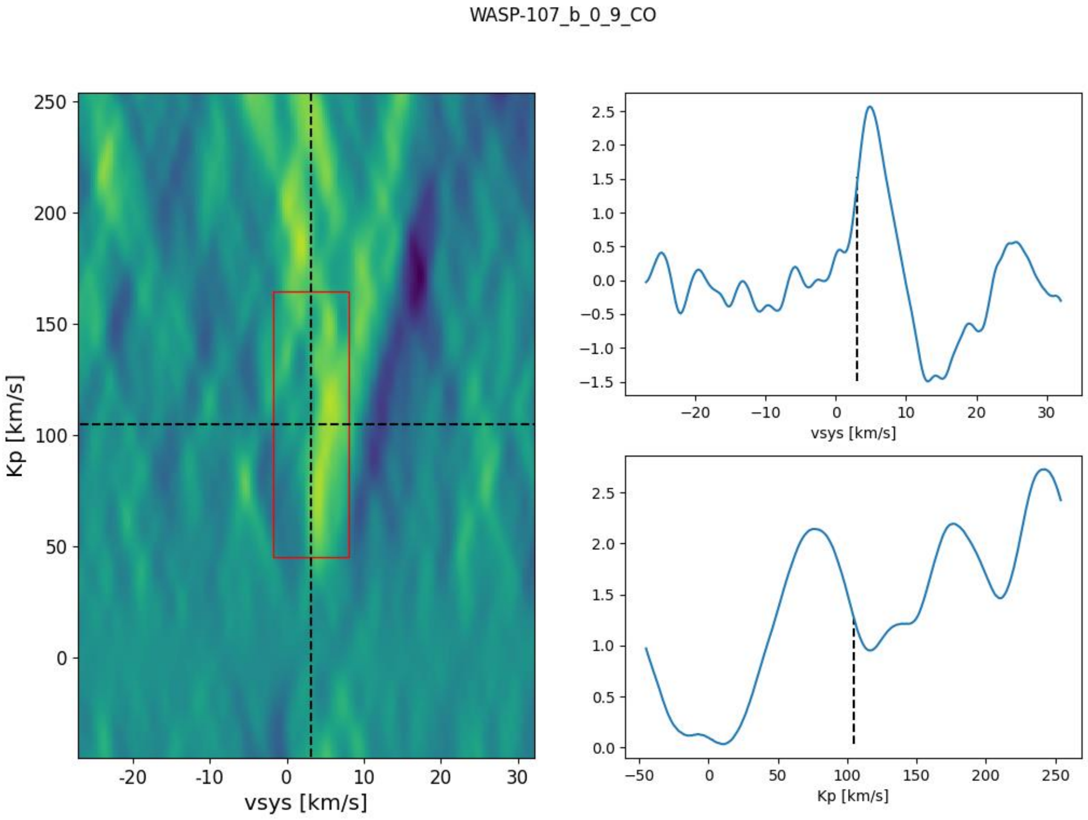


CRIRES+

Near Infrared (Y, J, H, K, L, M) Spectrograph

High resolution, $R = \frac{\lambda}{\Delta\lambda} \sim 100\ 000$

Very Large Telescope (VLT), 8m telescope

Science operation since 1 year ago

Already observed several transits of gas giants

Not enough data for rocky planets yet

WASP-107 B

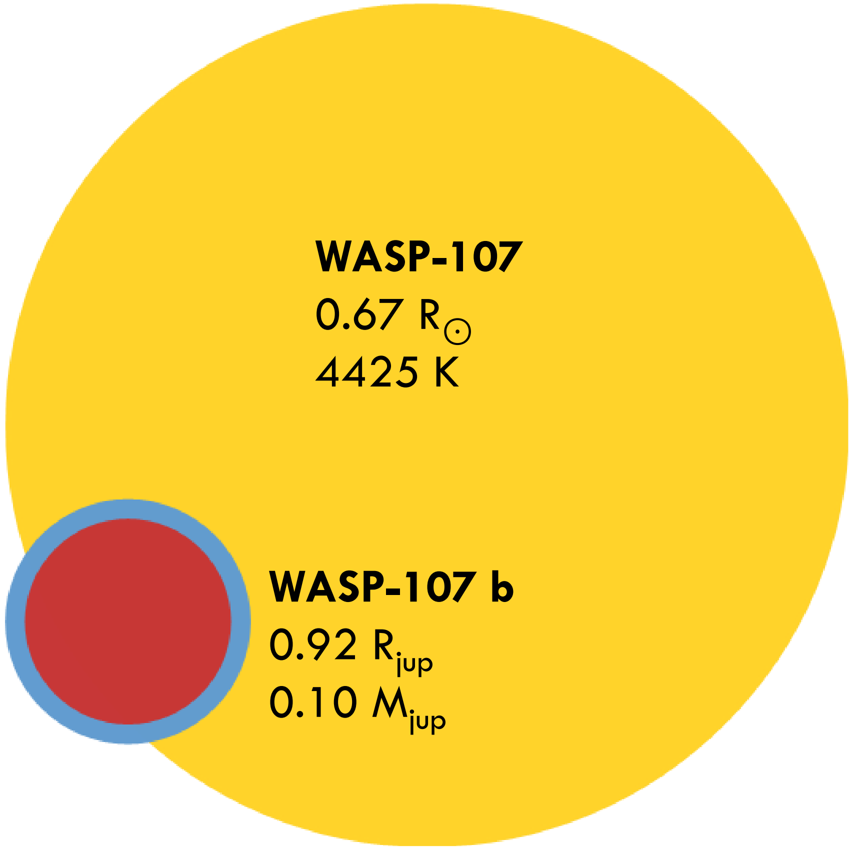
Use ChEATS on real observations

One of the lowest density planets

He trail detected by previous observations

Our observations:

- 64 observations
- 5.5 hours
- Average SNR 72
- K band



WASP-107
$0.67\ R_\odot$
4425 K

WASP-107 b
$0.92\ R_{\mathrm{jup}}$
$0.10\ M_{\mathrm{jup}}$

WASP-107 B

Detect CO

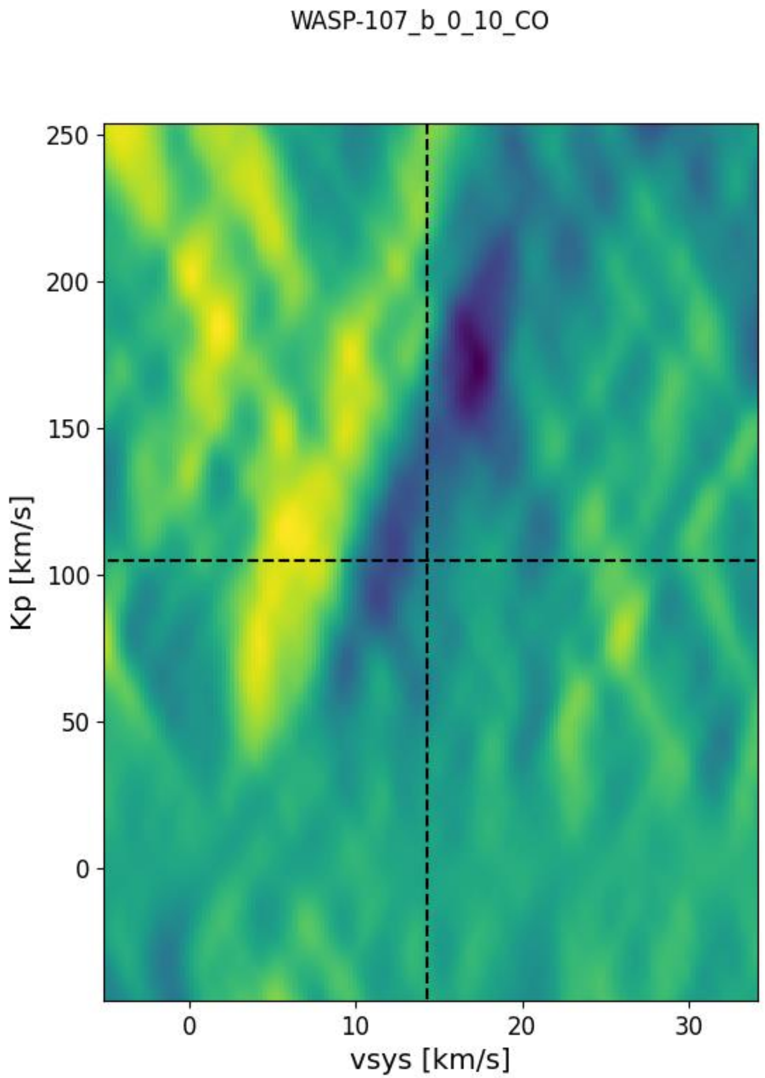
but not H2O

H has evaporated? (Hu et al. 2015)

Strong X-ray and EUV irradiation (Poppenhäger 2022)

H2O was detected in low resolution transits (Kreidberg et al. 2018)

Wrong temperature for clouds (Yu et al. 2021)



CONCLUSION

- Reduce observations to spectra
- Determine stellar parameters
- Detect molecules in exoplanet atmospheres
- Detected CO in WASP-107 b