Modelling Infrared instrument performance and Science yield: the Ariel case study

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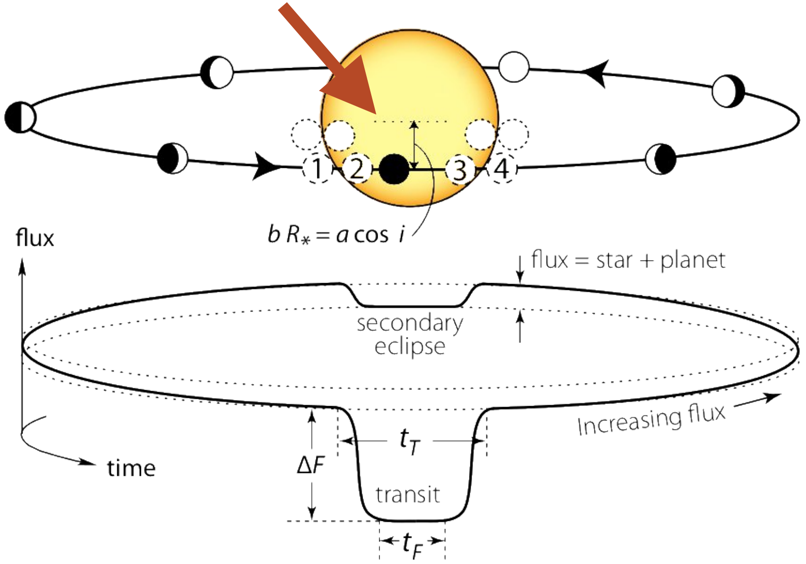
Characterisation: Transmission spectroscopy



When a planet transits in front of its host star, part of the star light is blocked, but part of the light passes through the planet atmosphere, and the flux drop depends on wavelength

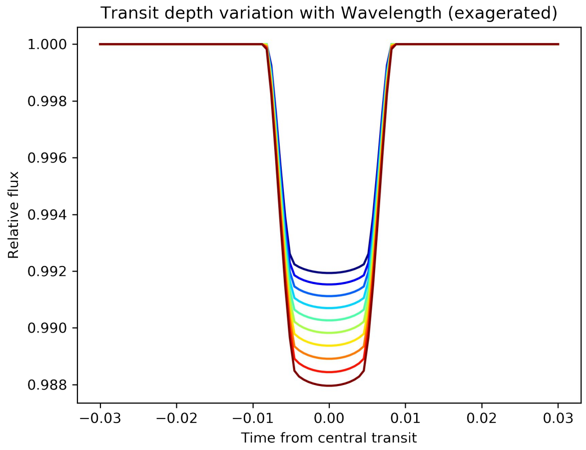
$$\frac{\Delta F}{F}(\lambda) = \left(\frac{R_p}{R_{star}}\right)^2 + A_b(\lambda)$$

(Seager, 2002)

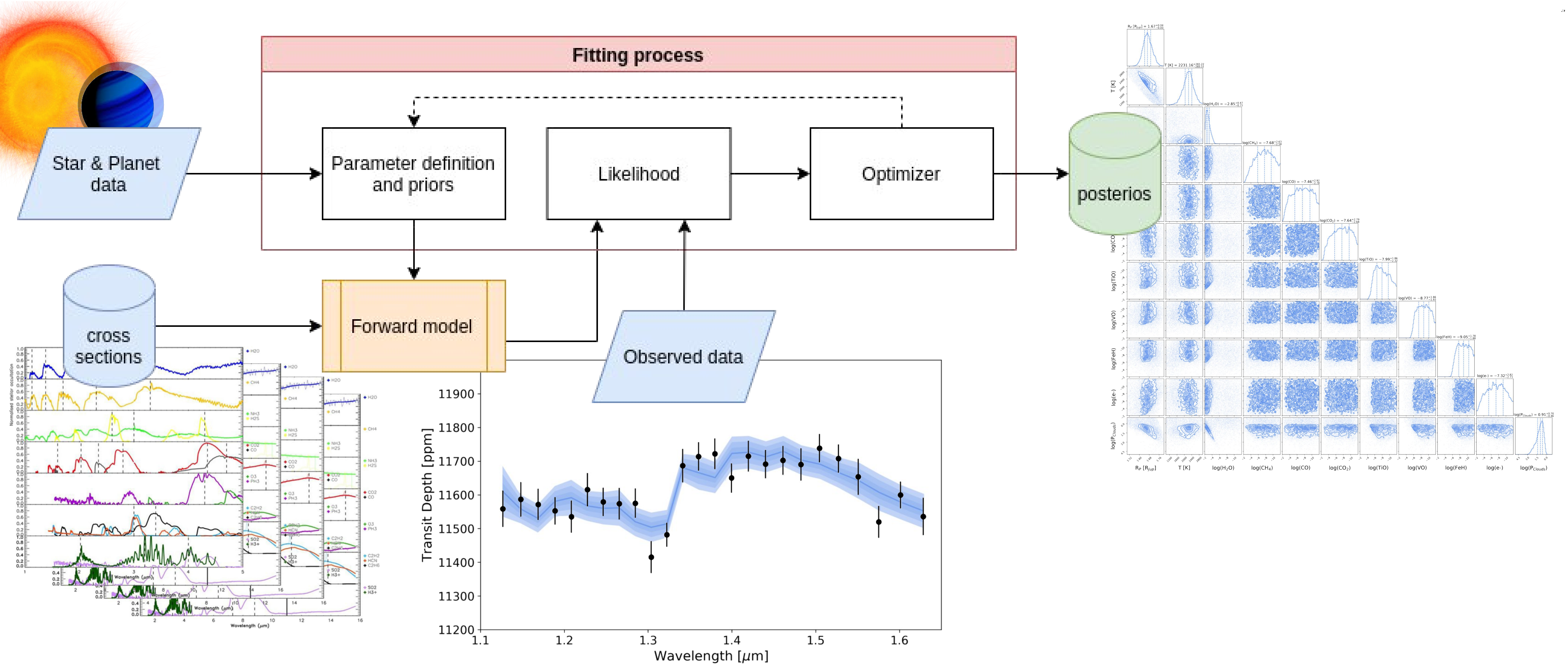
$A_b(\lambda)$ is the atmospheric absorption contribution.

$$A_b(\lambda) = \frac{2\pi R_p H}{R_{star}^2} ln\left(\frac{\chi_{ab}\sigma_{ab}(\lambda)\, P_0}{\tau_{eq}}\sqrt{\frac{2\pi R_p H}{k_B^2 T^2}}\right)$$

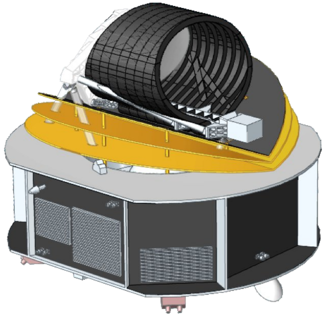
(Sing, 2018)



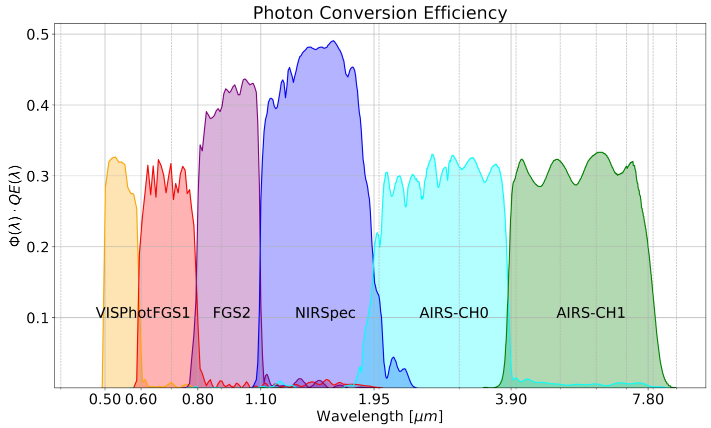
Spectral retrieval



Ariel space Mission

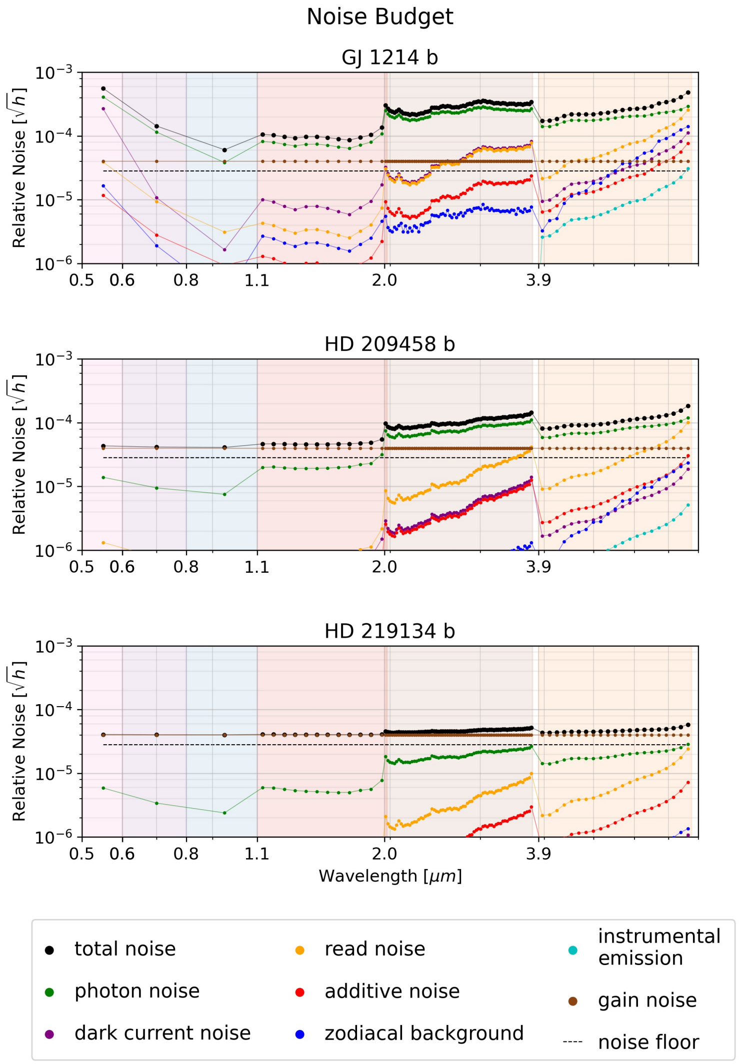


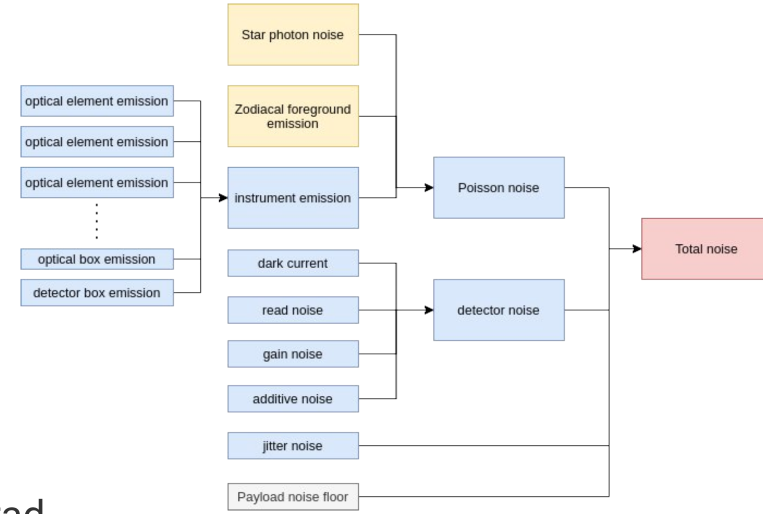
- Selected as ESA M4 mission in March 2018 (launch 2029)
- Payload consortium: 17 ESA countries + US, Japan and Canada
- 1m class Telescope, spectroscopy from VIS to IR
- Simultaneous coverage
  - 3 photometers (0.5-0.6, 0.6-0.8, 0.8-1.1 μm)
  - 3 spectrometers (1.1-1.95, 1.95-3.9, 3.9-7.8 μm)
- ~1000 exoplanets observed (rocky + gaseous)



Radiometric simulations

Radiometric models can help with fast estimation of telescope performance, helping mission design, strategy and preparing the science.





(Mugnai et al. 2020)

pip install exorad

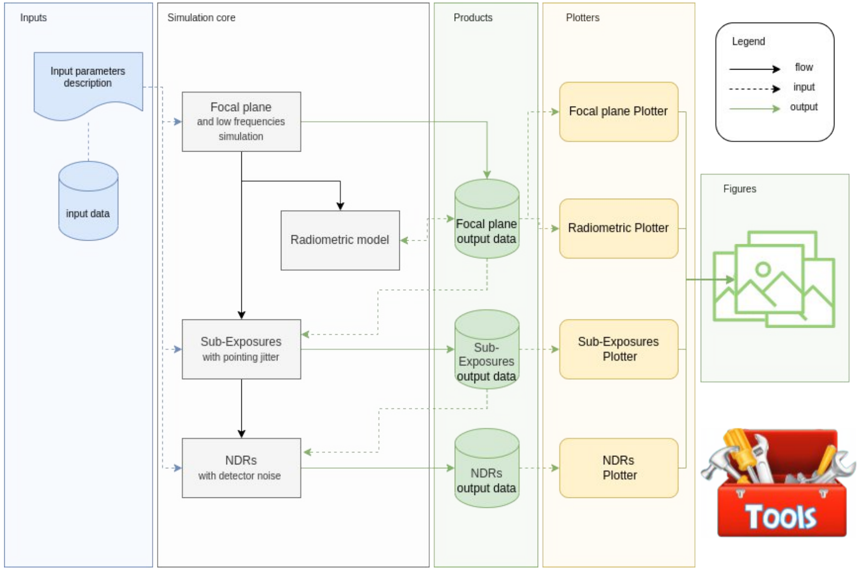
Observation simulations

To optimise observational strategies and validate pipelines, we can use observation simulators.

Try ExoSim2

- completely written in Python
- tested against Python 3.12+,
- Multi-Paradigm Architecture
- fast (~3 min for a 10h simulated observation… on 40 cores)

It comes with
- an installer
- documented examples
- a comprehensive guide

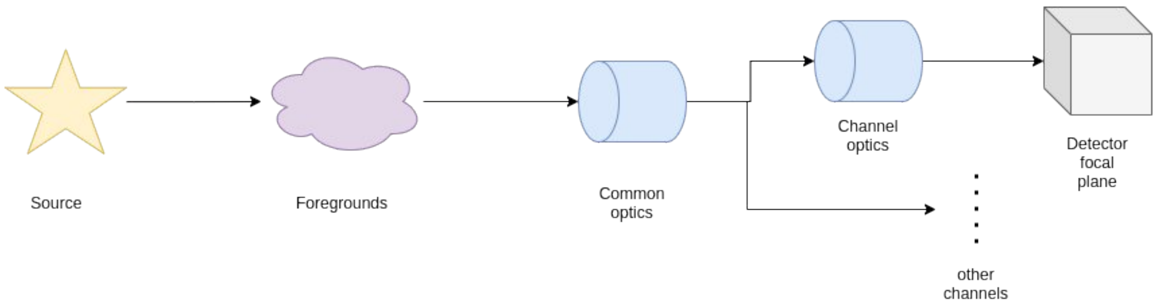


pip install exosim

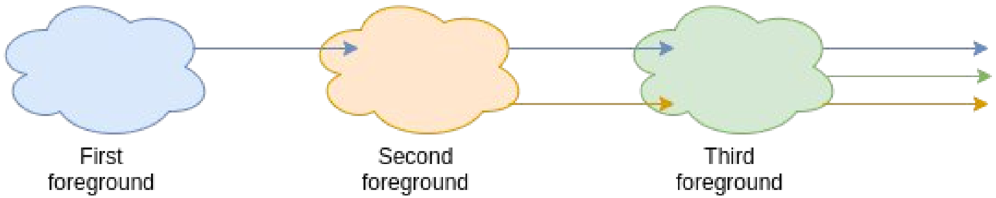
and almost every part of the code can be replaced by a user-defined function, which allows the user to include new functionalities to the simulator

(Mugnai et al. 2025)

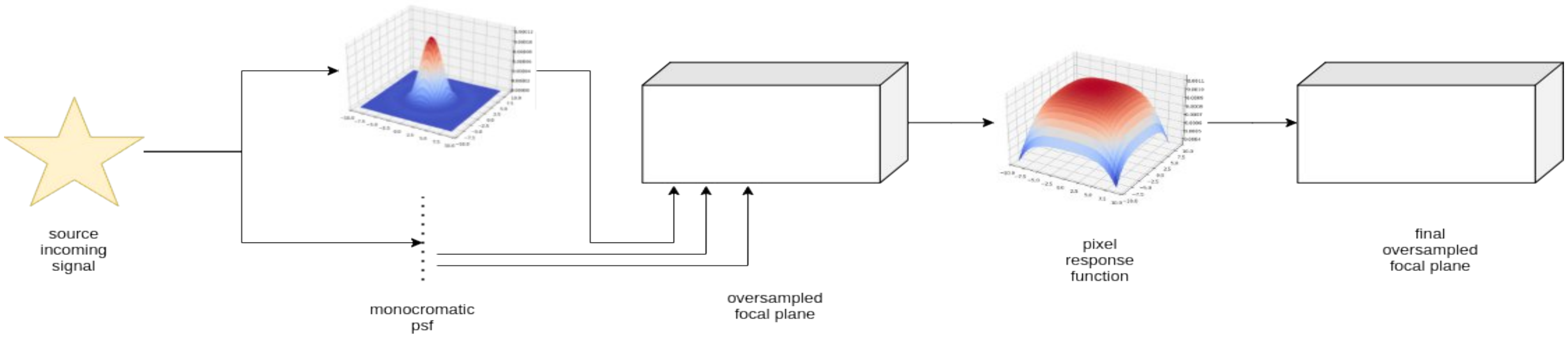
Road to focal plane



The light from the source is propagated through the foregrounds and optical path for each channel before reaching the focal plane.



Populate focal plane



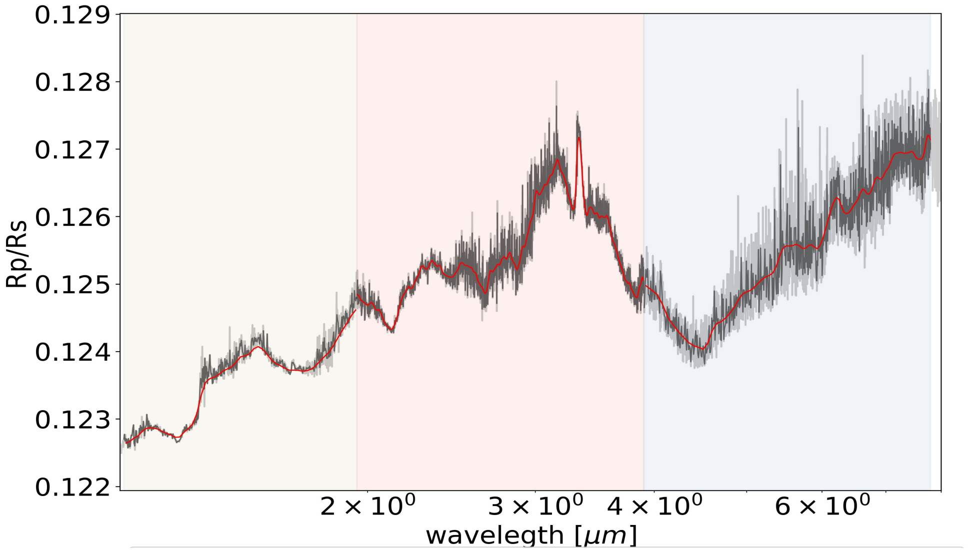
The focal plane is built considering

- The wavelength and time dependent efficiency
- The wavelength and time dependent signals from the sources
- The wavelength and time dependent PSFs
- The intra-pixel response function

Layers of details

Several layers of details are involved in the simulation, down to the **calibration products**.

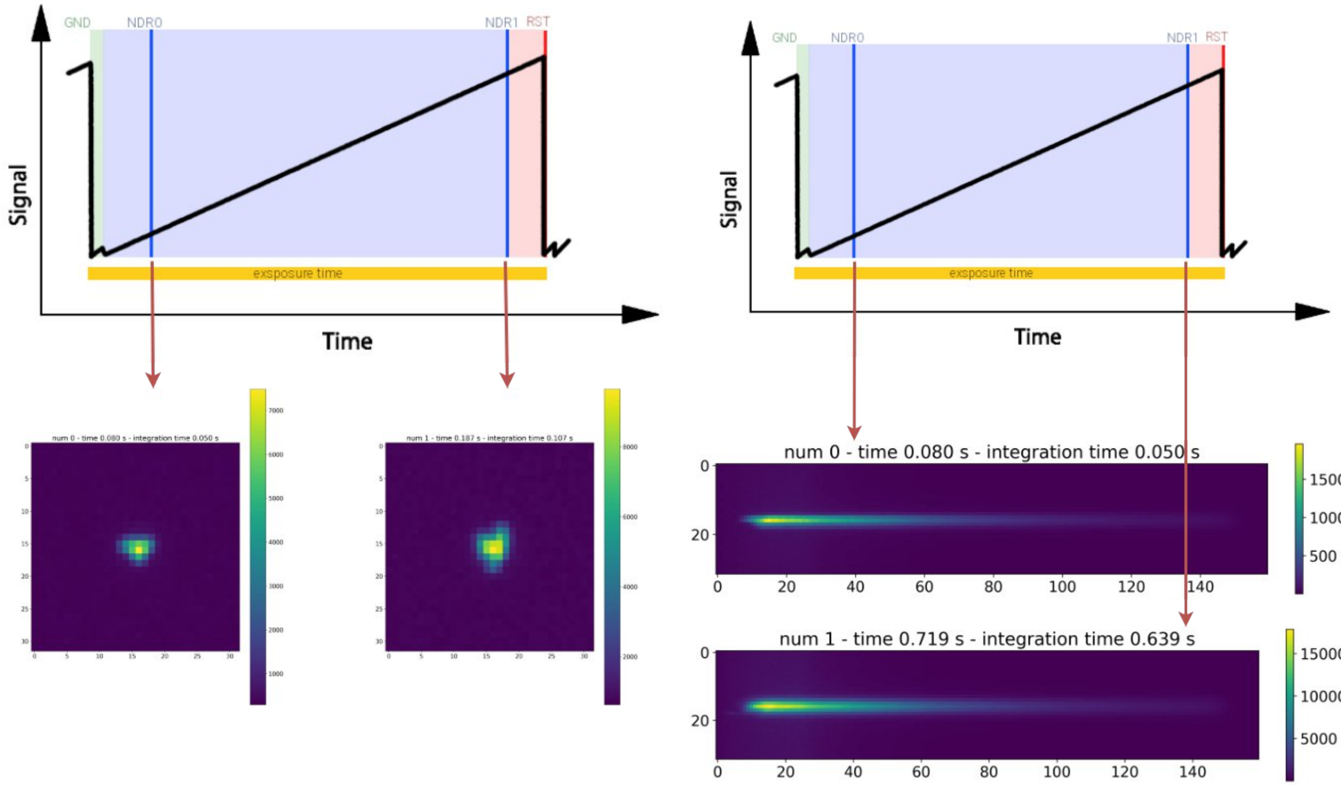
Time and wavelength dependent **astronomical signals** (as transit light curves) can be injected in ExoSim and recovered with a data reduction pipeline.



Sampling the ramp with Sub-Exposures

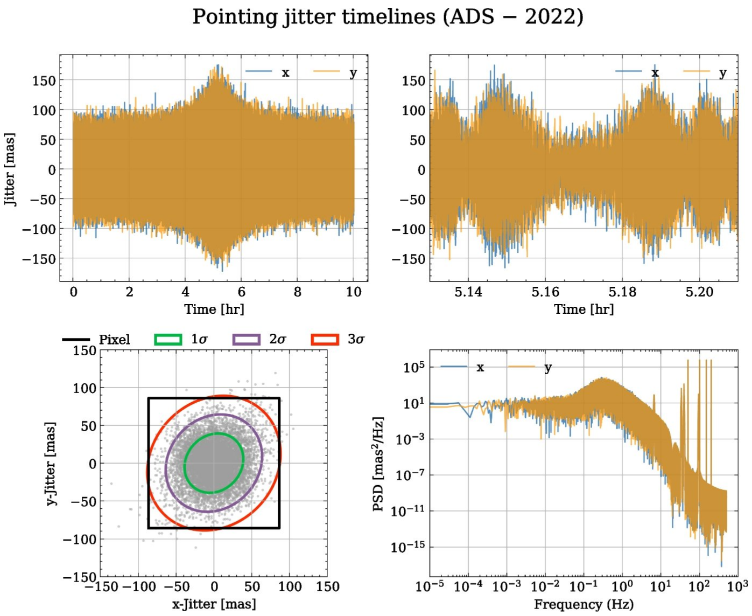
ExoSim2 includes a module for the ramp sampling.

Here, given the static focal planes, we can introduce the high frequency time effects, as the pointing jitter or astronomical signal.

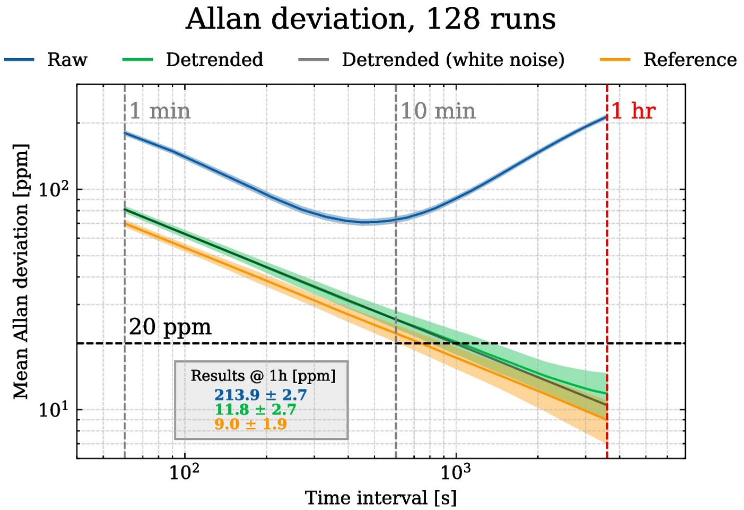


Preparing and testing pipelines

Simulations can be used to develop algorithms for the data reduction pipeline.

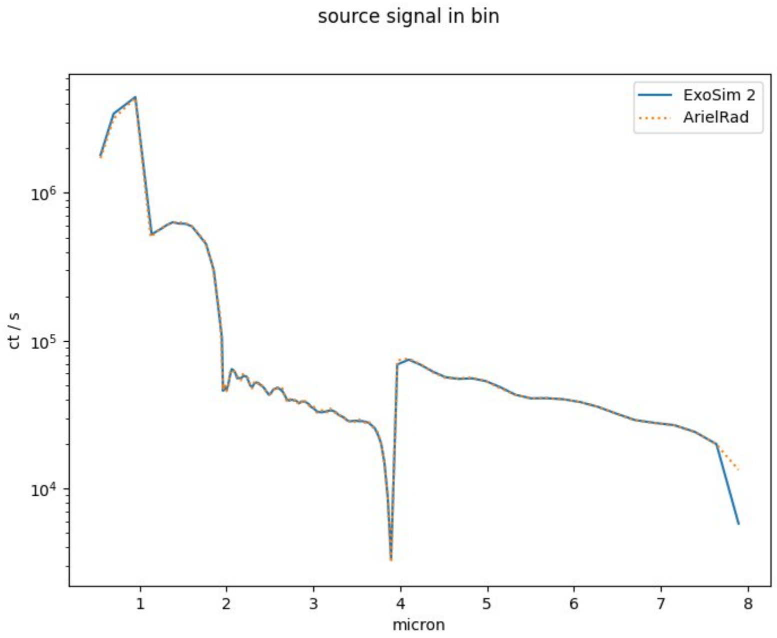


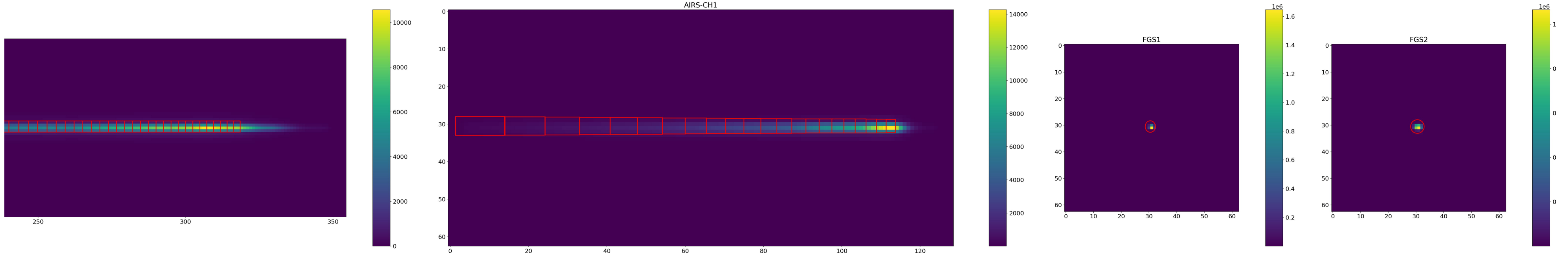
(Bocchieri et al. 2025)



One code to rule them all

Exosim 2.2 (*in prep*) now includes a radiometric model for consistent simulations

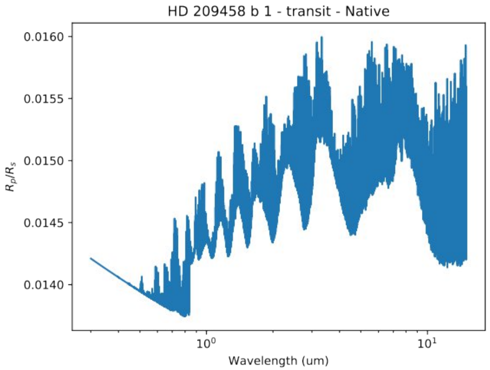


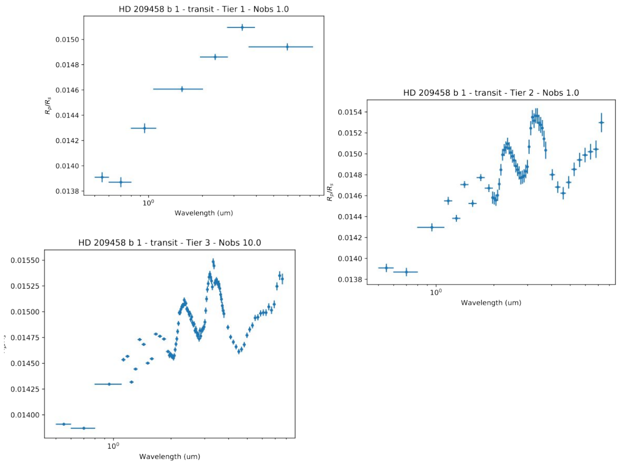


Enabling population studies

Combining simulators with an atmospheric retrieval code we can simulate observed planetary spectra.

Here we use TauREx3.





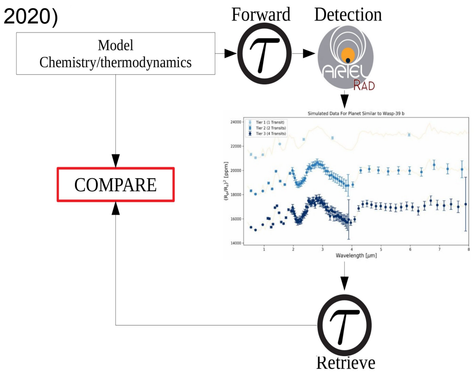
HD 209458b-like planet high resolution spectra binned according to ARIEL three tiers strategy.

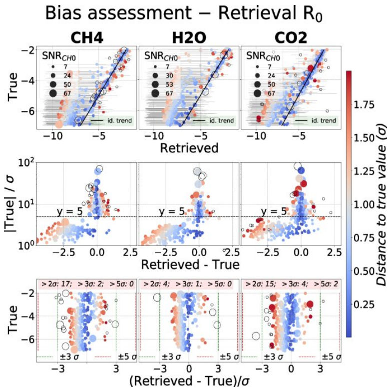
(Al-Refaie et al. 2020)

Population studies for Ariel

Molecular detection limits

(Changeat et al. 2020)



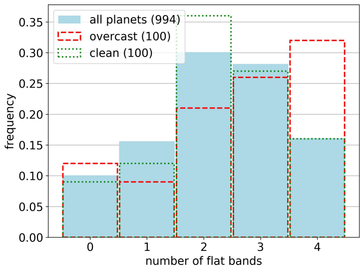


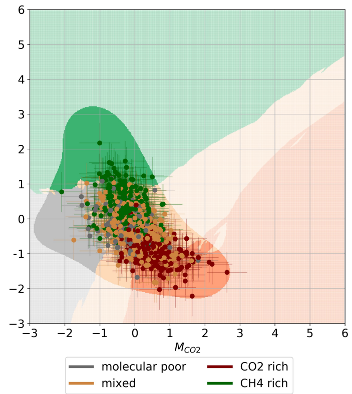
Detecting molecules in Ariel low resolution transmission spectra

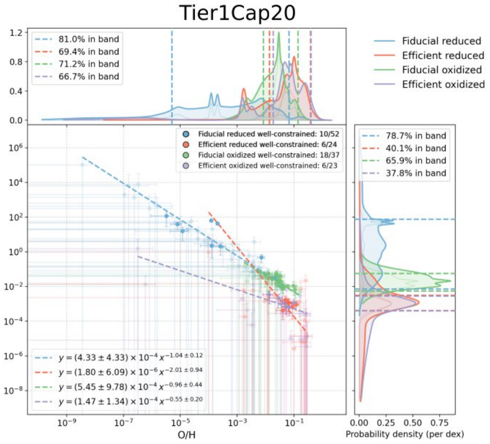
(Bocchieri, Mugnai et al. 2023)

Low resolution spectra information content

(Mugnai et al. 2021)







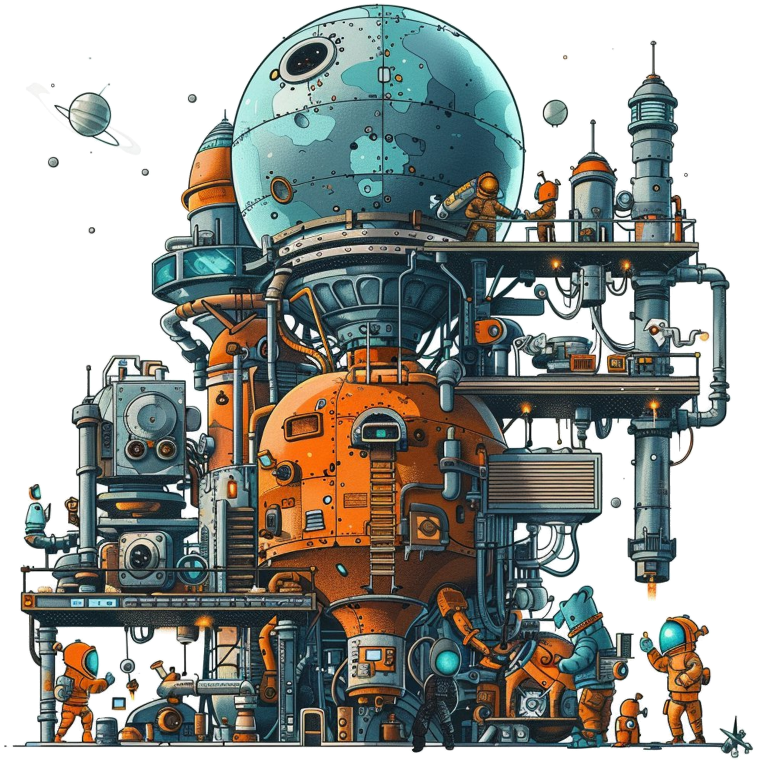
Connecting observations to formation scenarios

(Mugnai et al. *in prep*)

Investigating other strategies

Maybe we can do it alone, but we don't have to.

- Challenging the ML community with the problems we are dealing with can open new roads
- We prepared the Ariel Data Challenge 2024 and 2025 on Ariel data reduction: from RAW to transmission spectra.
- Accepted in NeurIPS2024 and NeurIPS2025, hosted and sponsored by Kaggle-Google.
- Attracted over 2,5k participants and 36k tentative solutions



Conclusions

- Realistic simulations are essential to understand the performance of future exoplanet missions.
- Radiometric and end-to-end observation simulators allow us to explore instrument design, optimise observing strategies, and prepare data analysis pipelines before launch.
- Tools such as ExoRad and ExoSim2 enable consistent simulations from photon noise to calibrated data products.
- Combining instrument simulations with science simulators (atmospheric retrievals) allows us to predict the science return of missions such as Ariel.

Thank you

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