# Telescópios - Trabalho prático

## High-precision photometry with the ESA-CHEOPS space telescope

**Olivier Demangeon - 18 March 2021**

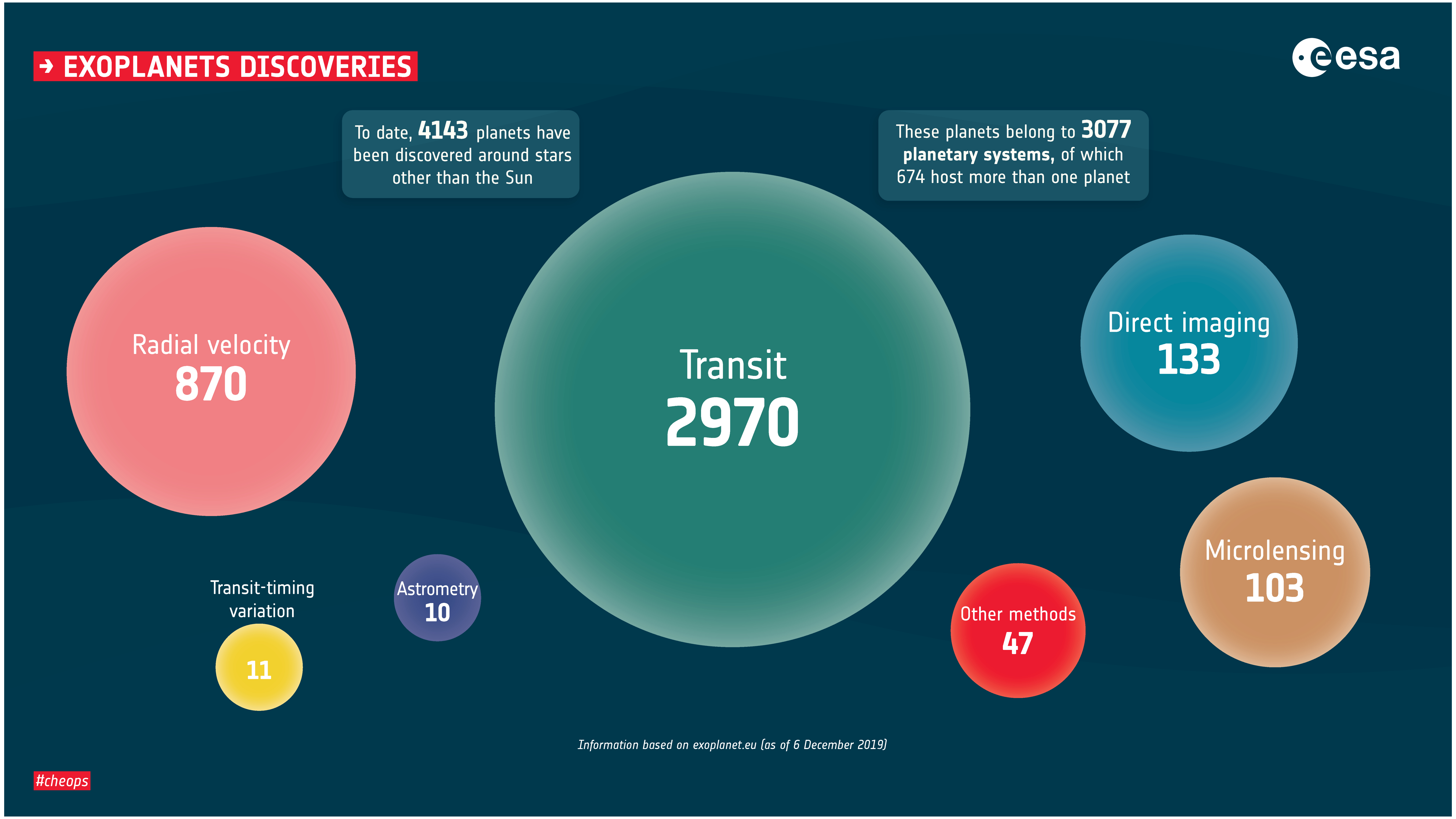
# Exoplanetology a (very) short introduction

ESO/M. Kornmesser

# Exoplanets:

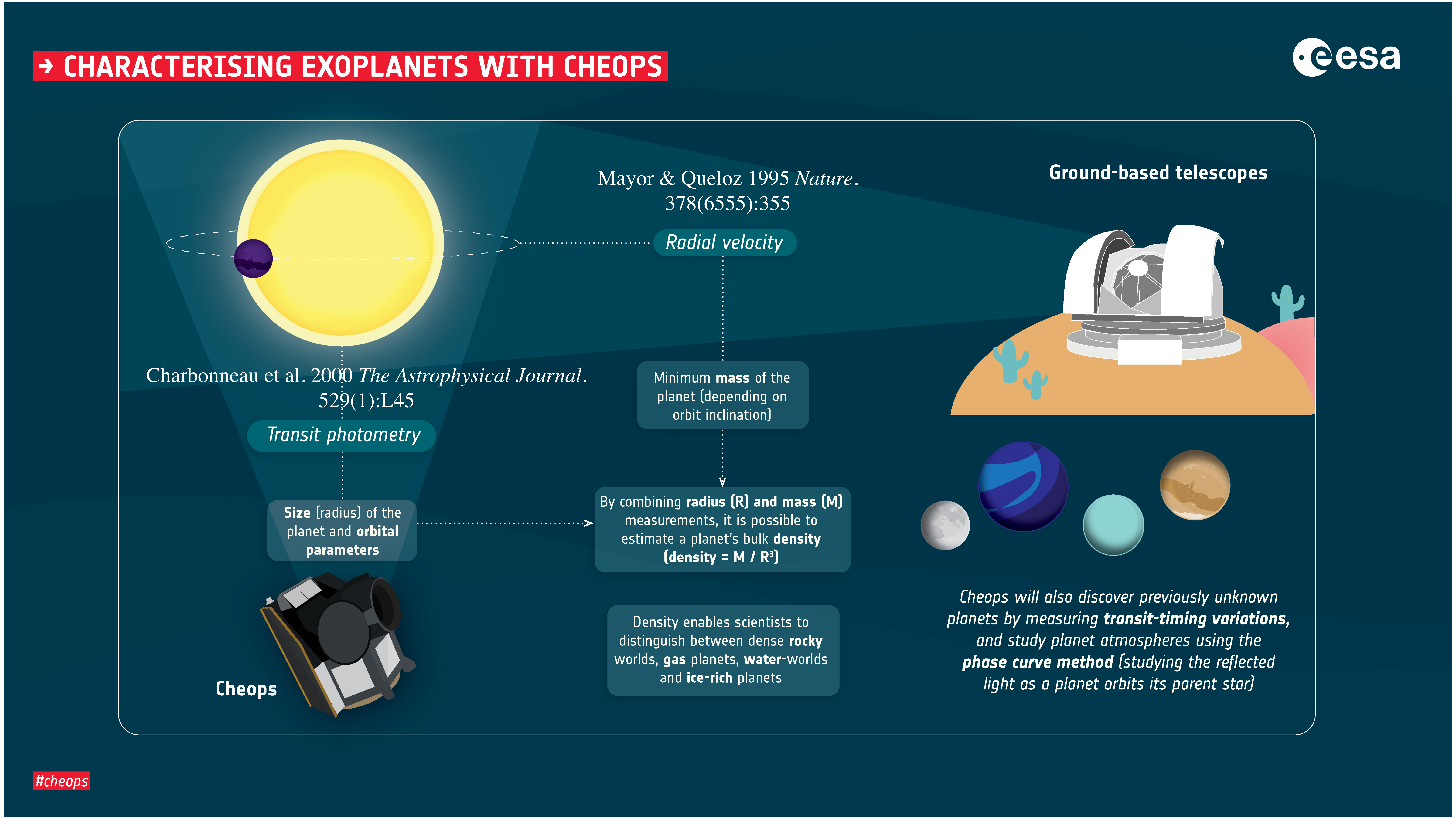
## What are they and how many do we know?

An exoplanet is a planet which doesn't belong to the Solar System



# Exoplanets

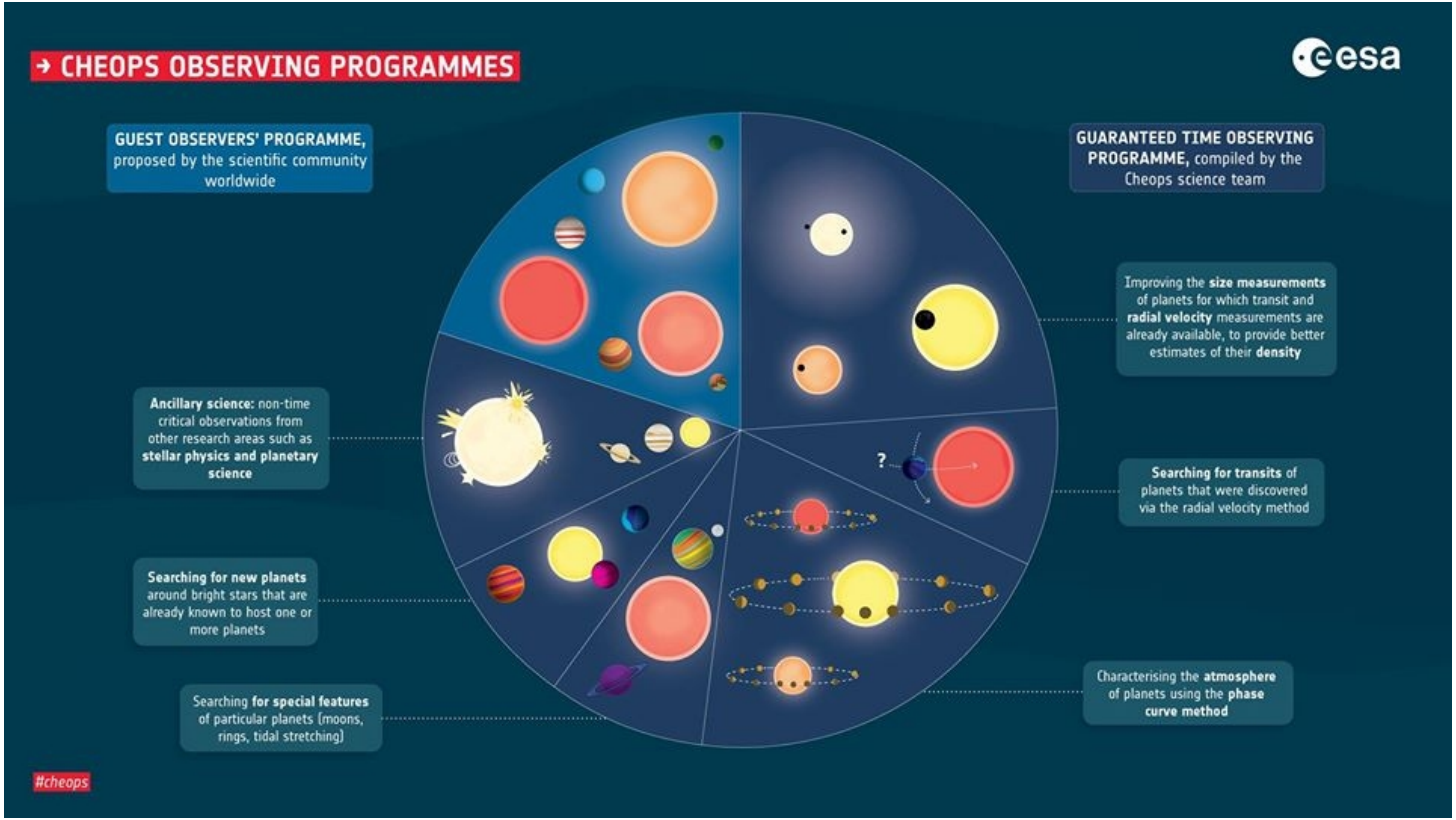
## How do we study them ?




CHEOPS: A space telescope to characterize exoplanets

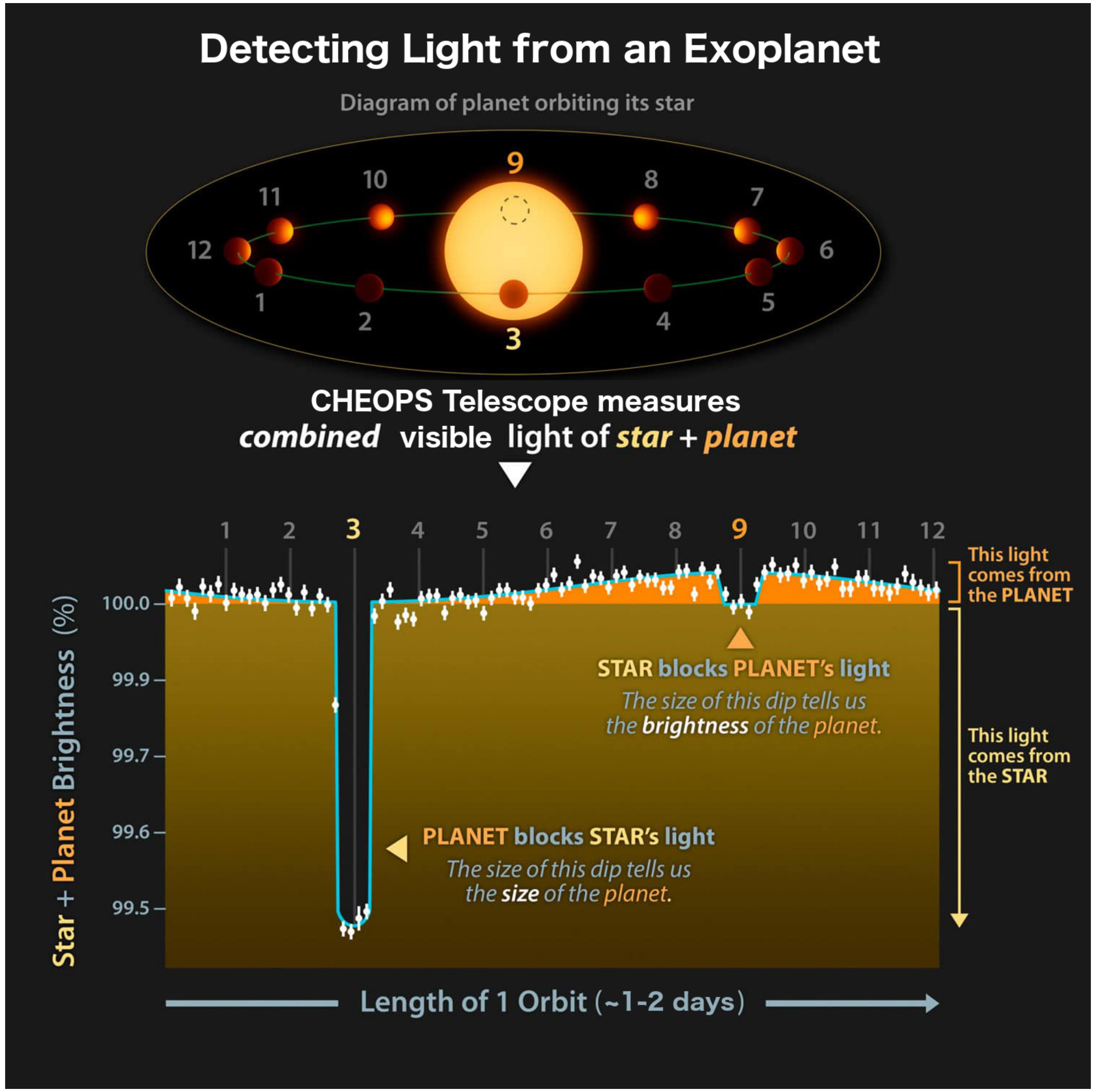
# CHEOPS: A space telescope to characterize exoplanets

## The Science of CHEOPS



# CHEOPS: A space telescope to characterize exoplanets

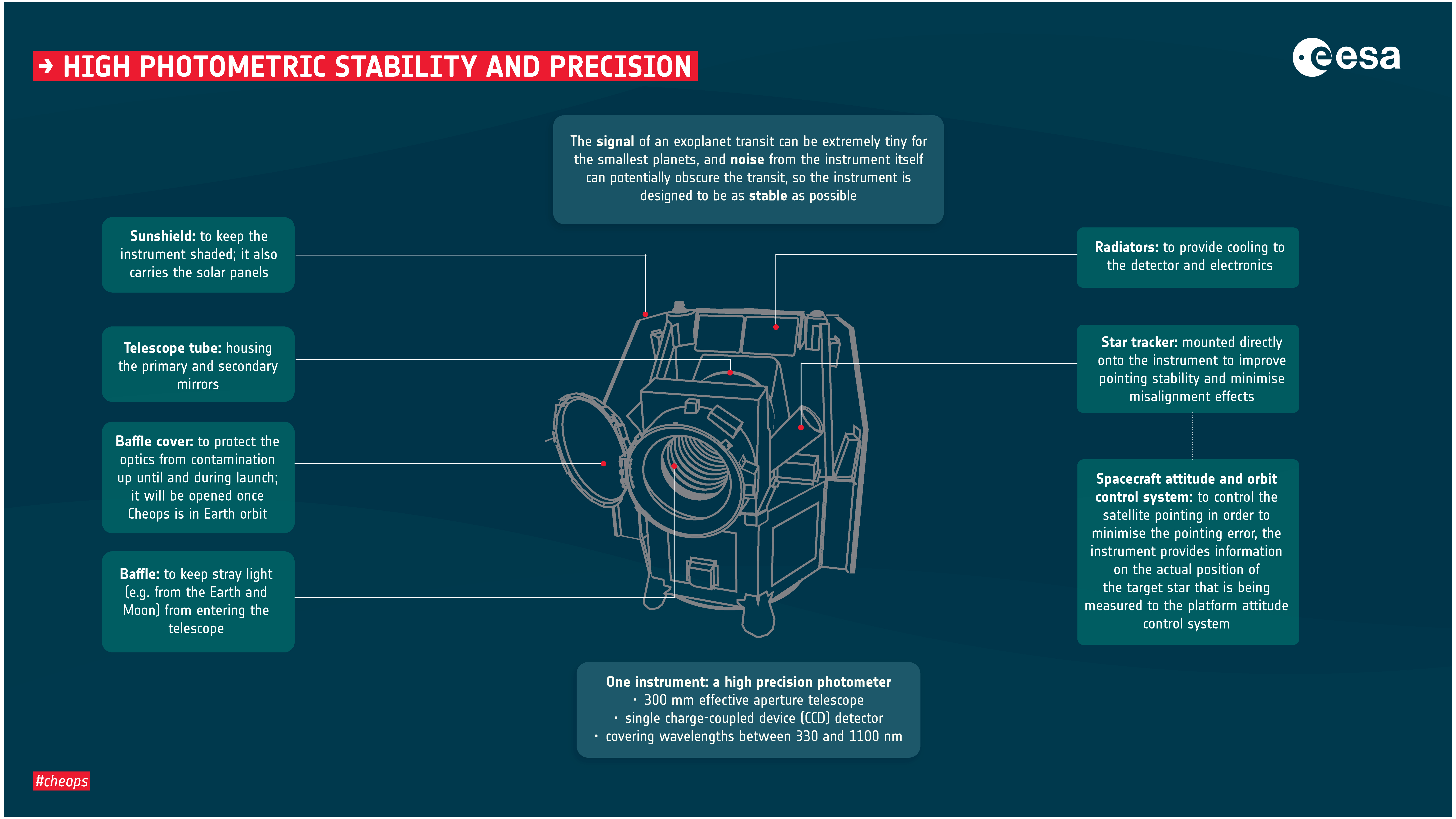
## High precision photometry (alias transit photometry)




Credit NASA/JPL-Caltech
L. Kreidberg/Harvard-Smithsonian CfA

# CHEOPS: A space telescope to characterize exoplanets

## The satellite and the instrument



# CHEOPS: A space telescope to characterize exoplanets

## The satellite and the instrument

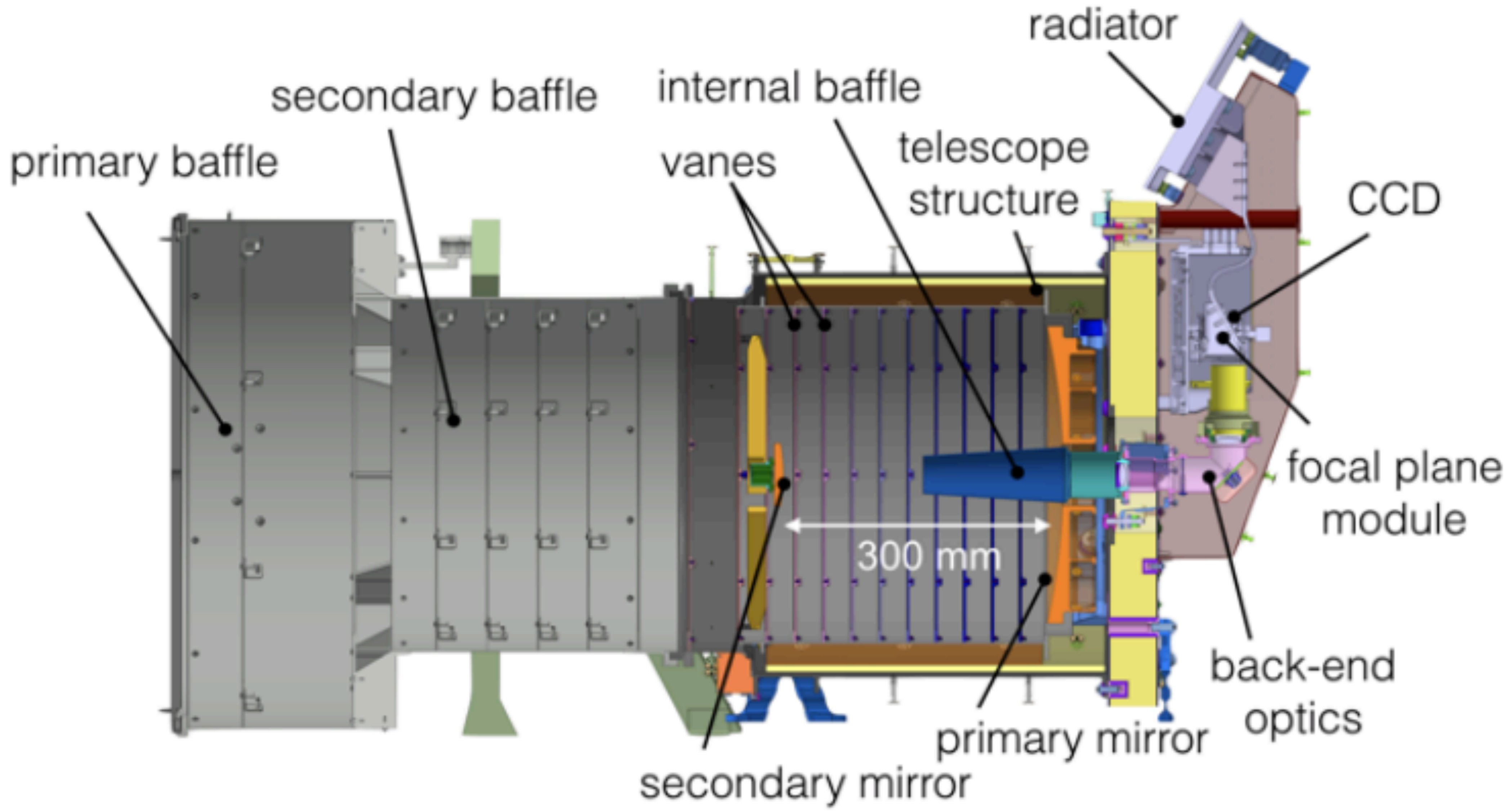



**Fig. 5** CAD/CAM view of the OTA and BCA assemblies as mounted on the spacecraft. The primary and secondary baffle constitute the BCA. It is a separate unit mounted on the spacecraft independently of the OTA. The remaining items resemble the OTA.

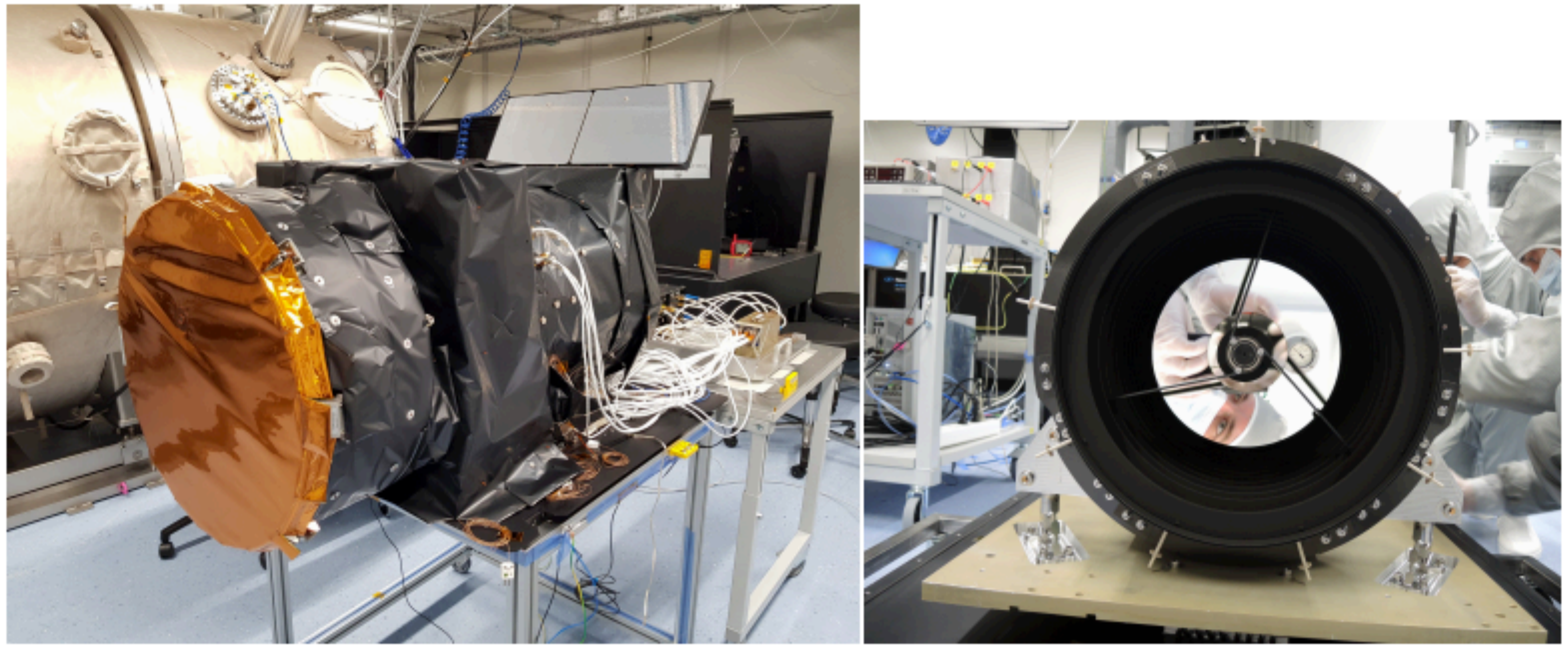


**Fig. 6** Left: The CHEOPS payload fully assembled before delivery. Right: The telescope with mirrors installed and cover open before full OTA assembly.

Benz et al. 2021 *Exp. Ast.* 51(1):109–51 - https://arxiv.org/pdf/2009.11633.pdf

# CHEOPS: A space telescope to characterize exoplanets

## The CCD

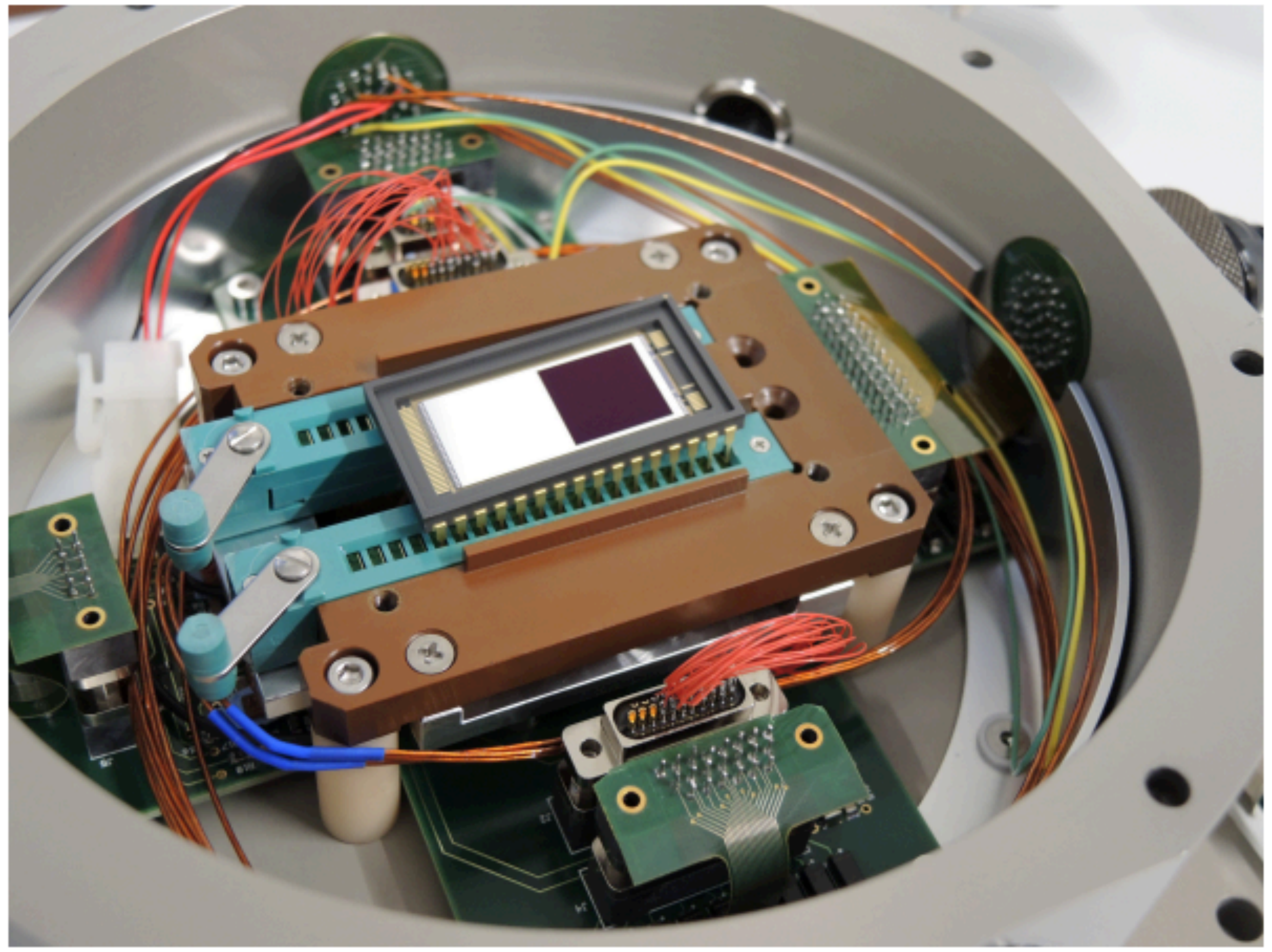


Fig. 9 CHEOPS CCD mounted in the cryostat of the University of Geneva.

Benz et al. 2021 *Exp. Ast.* 51(1):109–51 - https://arxiv.org/pdf/2009.11633.pdf

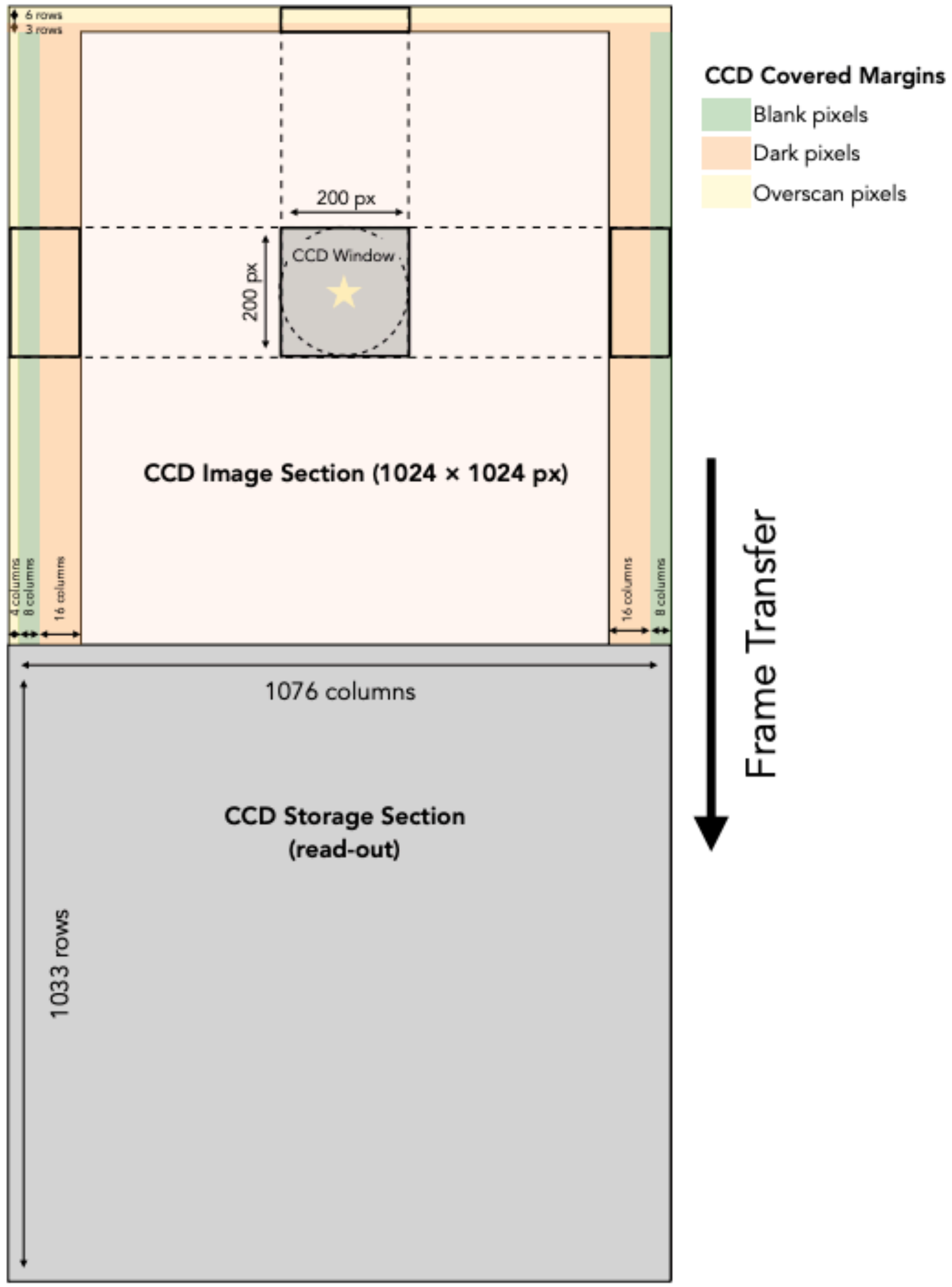
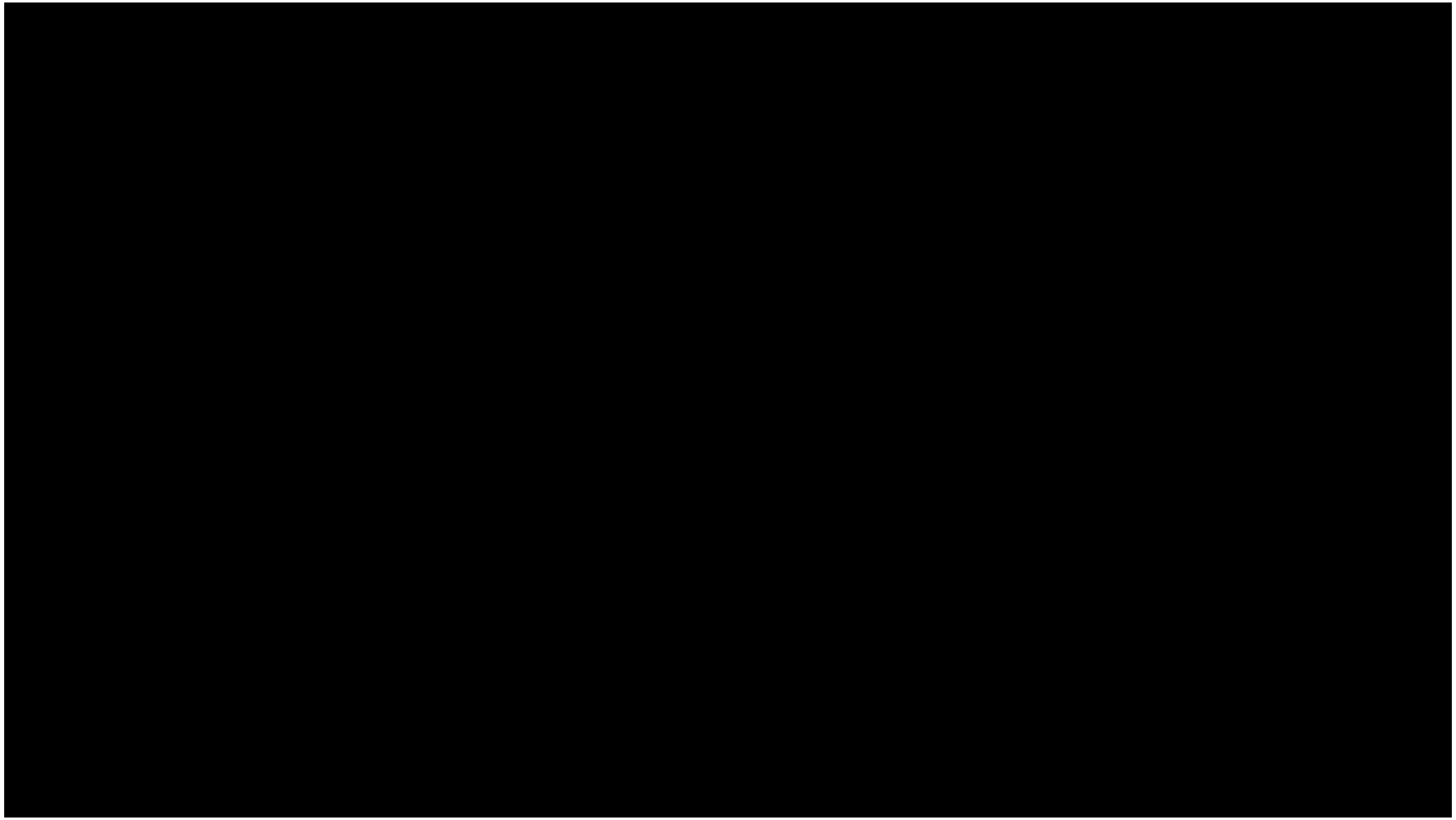



Fig. 8 Schematic view of the CCD elements.

# CHEOPS: A space telescope to characterize exoplanets

## CHEOPS’ orbit



# The CHEOPS Data Reduction Pipeline

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## The Data Products: From images to light-curve

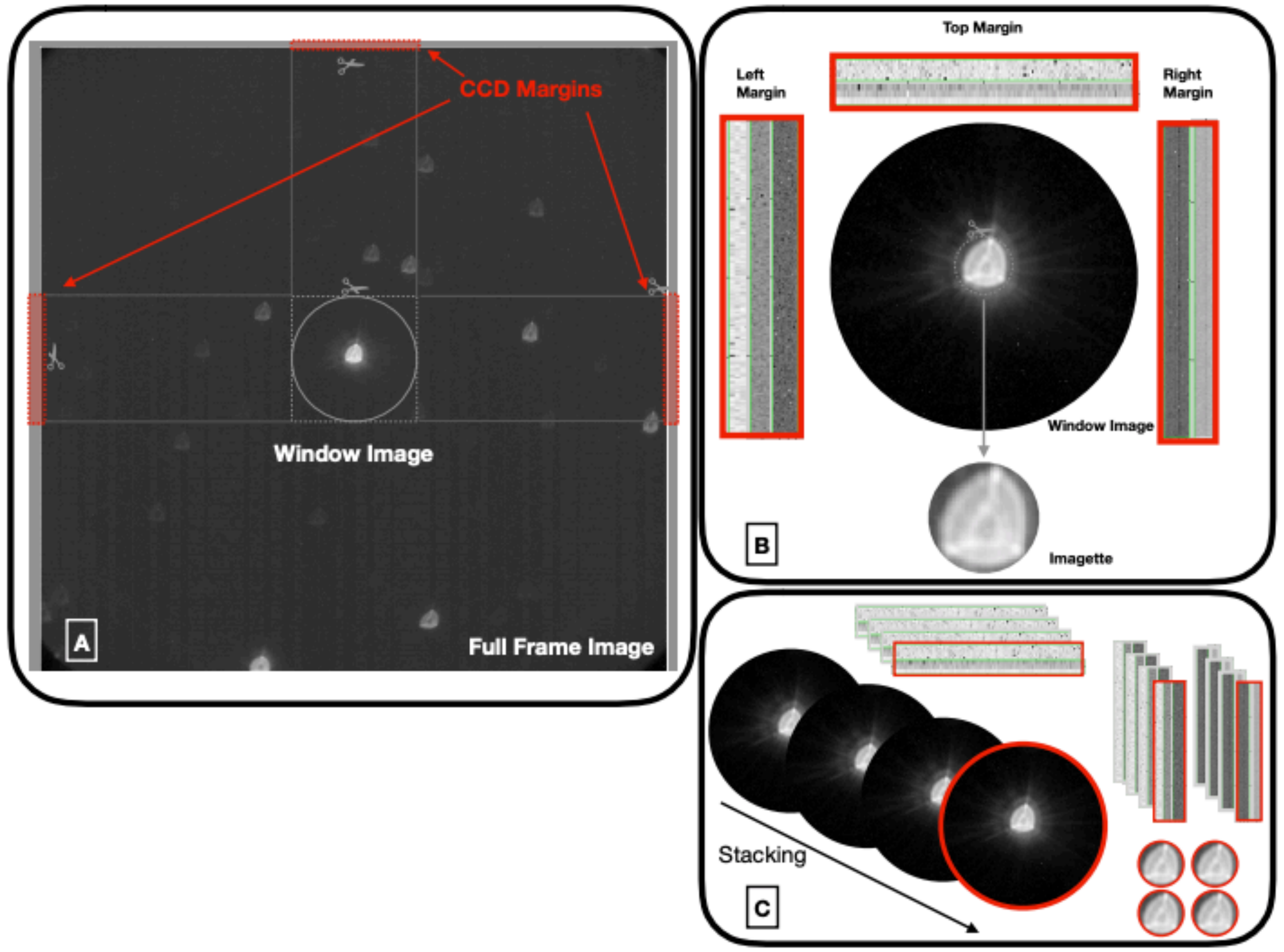



**Fig. 10** This figure illustrates the on-board data processing. Panel A shows a full-frame image (1024x1024 plus CCD margins). Due to the limited bandwidth capabilities, all full-frame images cannot be down-linked to the ground. Therefore, circular window images with the target on their centre are cropped. The same is done to the corresponding section of the margins (details in panel B). If the exposure time of the image is longer than 30 seconds, all window images and margins are sent to the ground without any further on-board manipulation. However, if the exposure time is shorter than 30 seconds images have to be stacked on-board. In that case, small "imagettes" containing only the PSF of the target star, are also cropped but they are down-linked to the ground without stacking. For example, as illustrated in panel C, if the exposure time is 15 seconds, one stacked window image resulting from co-adding four images will be down-linked, together with the corresponding stacked margins and the four "imagettes".

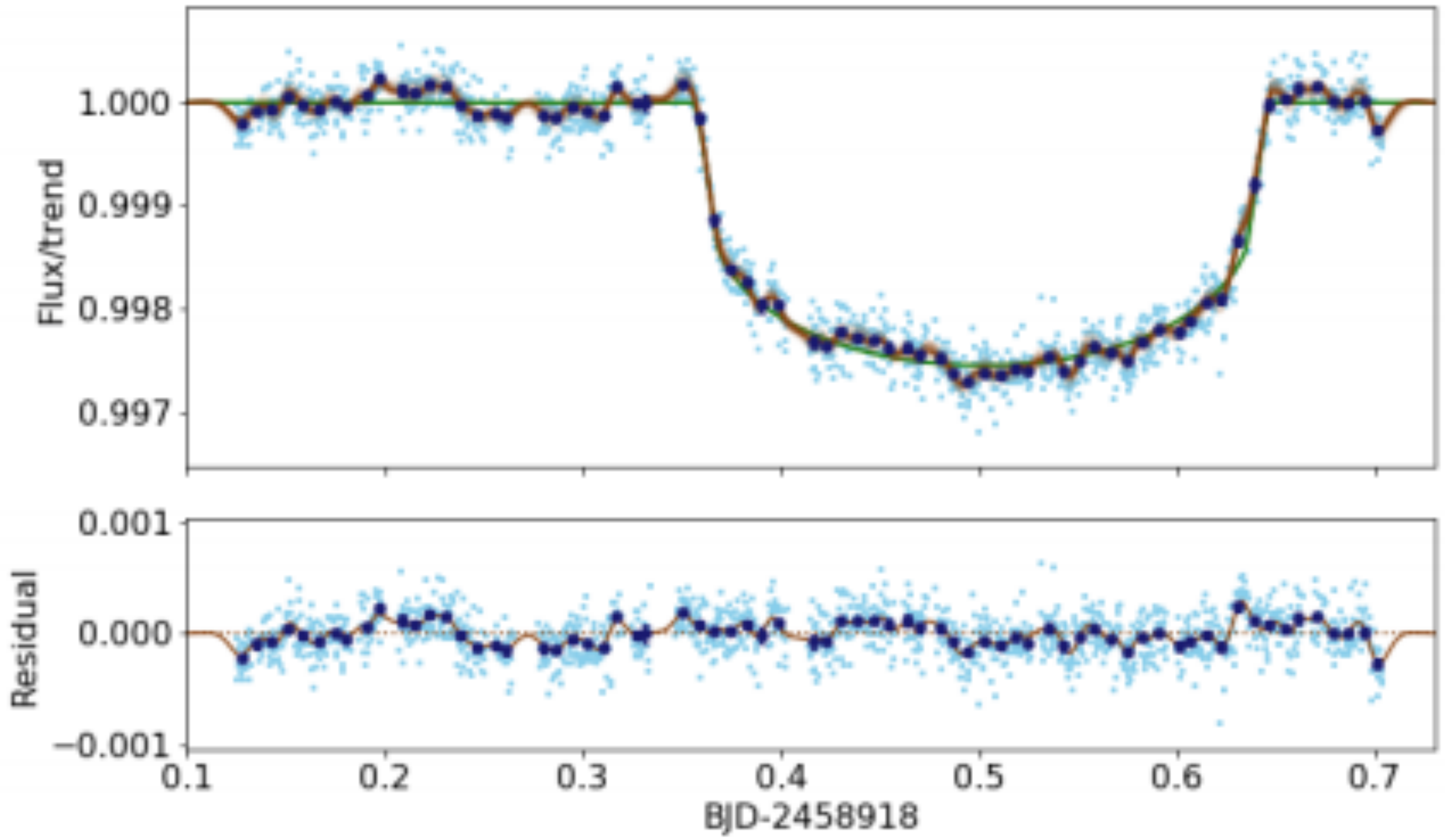
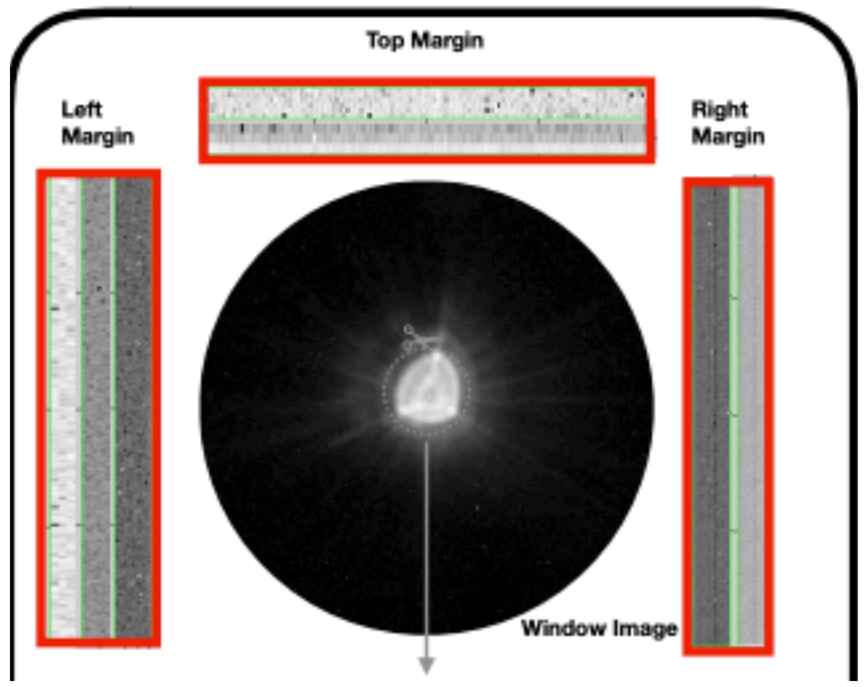


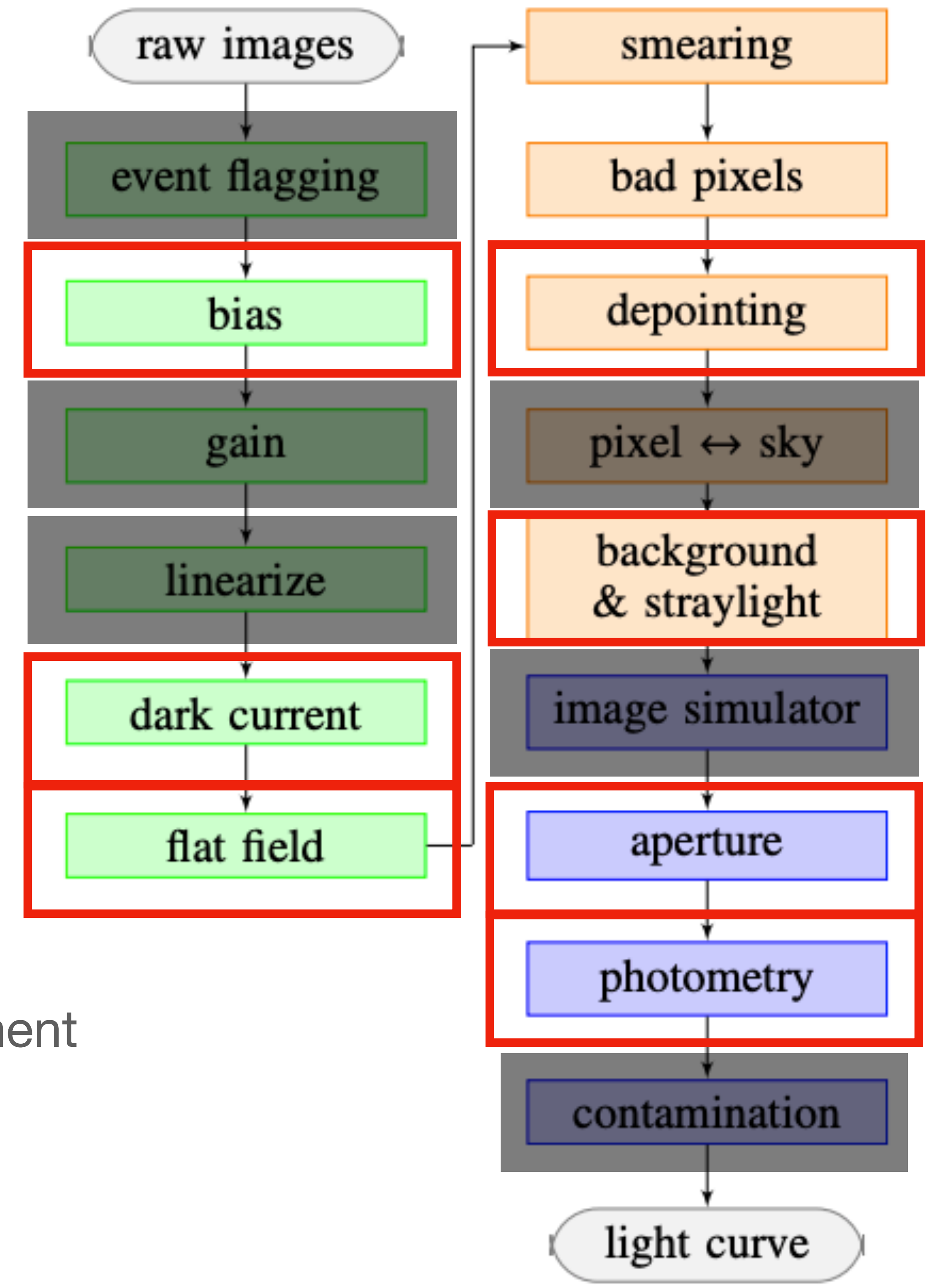

**Fig. 15** Observed light curve of KELT-11 and model fit from pycheops. The measured fluxes (light blue points) are also shown binned in time (dark blue points). The transit model (green line, barely visible) is shown in the upper panel together with the several realisations of our complete model including stellar noise sampled from the PPD. The lower panel shows residuals from the transit model plus instrumental effects (blue points) together with the best-fit stellar noise model (brown line).

Benz et al. 2021 *Exp. Ast.* 51(1):109–51 - https://arxiv.org/pdf/2009.11633.pdf

# The CHEOPS Data Reduction Pipeline

## The software architecture




Step that you should try to implement

**Fig. 1.** Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

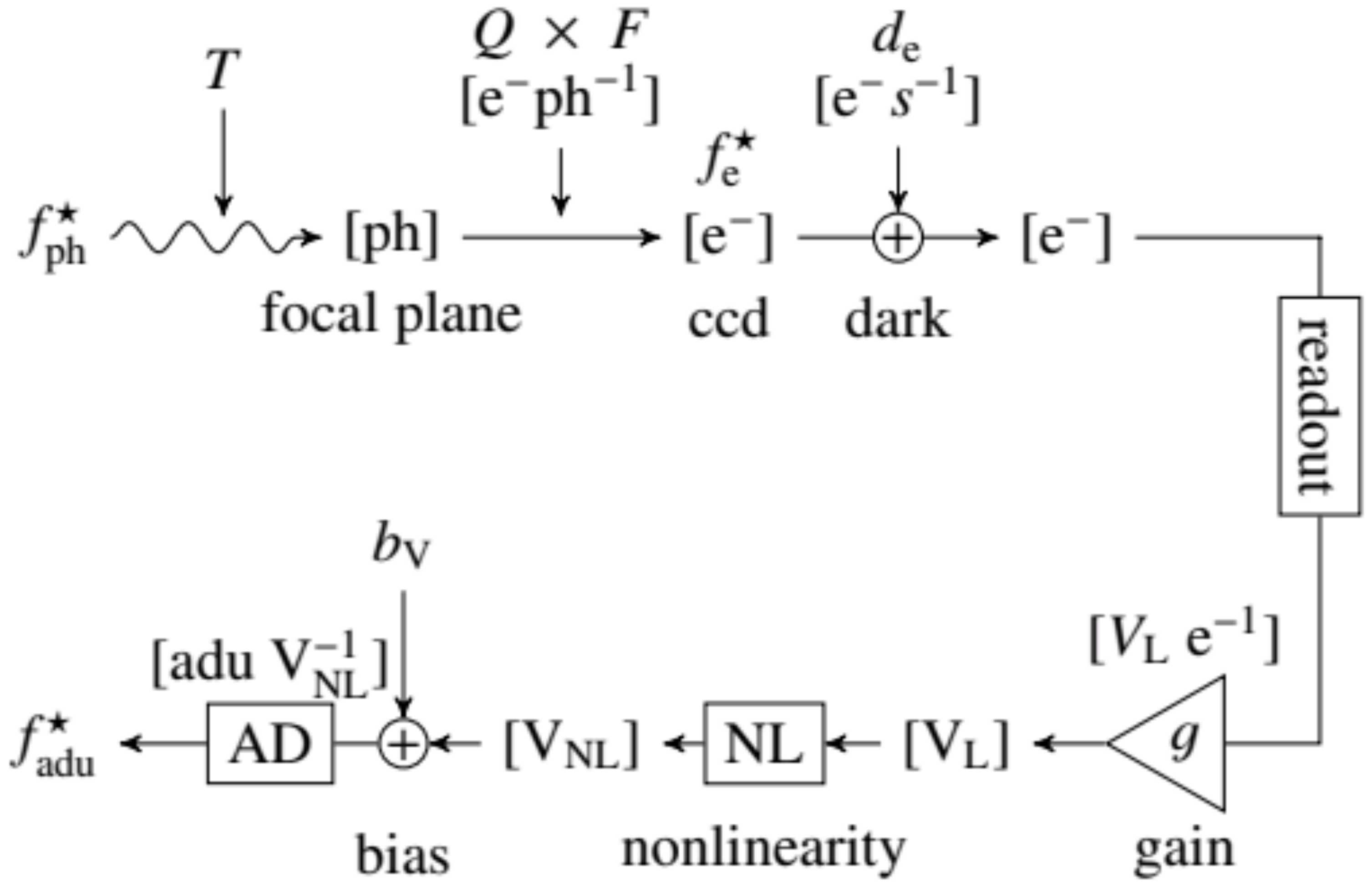



**Fig. 2.** Signal chain. Following the main arrow, $f^{\star}_{\rm ph}$ is the input photon flux. The units of successive transformations are given in brackets: [ph] photons, [e$^-$] electrons, [V$_{\rm L}$] and [V$_{\rm NL}$] linear and nonlinear volts, and [adu] the analog-to-digital units. $T$ is the optical throughput, $Q$ is the quantum efficiency, $F$ the flat field, $d_{\rm e}$ is the dark current. The readout label is the frame transfer, the triangle represents the analog amplifier with its gain $g$, its nonlinearity NL and its bias voltage $b_{\rm V}$. AD is the analog to digital converter. The output is the raw image $f^{\star}_{\rm adu}$.

Hoyer et al. 2020 *A&A*. 635, A24:14 pp. , https://arxiv.org/pdf/1909.08363.pdf

# The CHEOPS Data Reduction Pipeline

## Accessing at the data

- Quick look with DS9 and fv
- How to read the data with Python

  https://github.com/odemangeon/pw_cheops

# Instructions for this practical work

# Extract CHEOPS photometry

- We have seen how the CHEOPS Data Reduction pipeline processes the data to extract the light curve.
- You have been given the RAW data of two CHEOPS observations:
  - The transit of KELT-11 b published in Benz et al. 2021, *Exp. Ast.*, 51(1):109–51 - https://arxiv.org/pdf/2009.11633.pdf
  - On occultation of WASP-189 b published in Lendl et al. 2020 A&A. 643:A94 - https://arxiv.org/pdf/2009.13403.pdf
- Objective: Extract the “best” light-curve of at least one of these datasets
  - Write a report about your extraction of at least 1 dataset on Thursday 27/05.
  - For each step of your data reduction: Explain what you did, and why you did it like that. Explore different possibilities and show the scientific procedure that you used to decide which one is the best.
  - The report will be in english and for the report use the A&A article LaTeX template.

# Second class

# Status of your pipeline

- Describe what you did for the bias correction:
    - Which steps did you implement ?
    - What are the issues that you encountered if any ?
    - Show me what you managed to achieve and why do you think your correction is good ?

# The other steps: Bias correction

Step that you should try to implement

Let's look at one way to do it

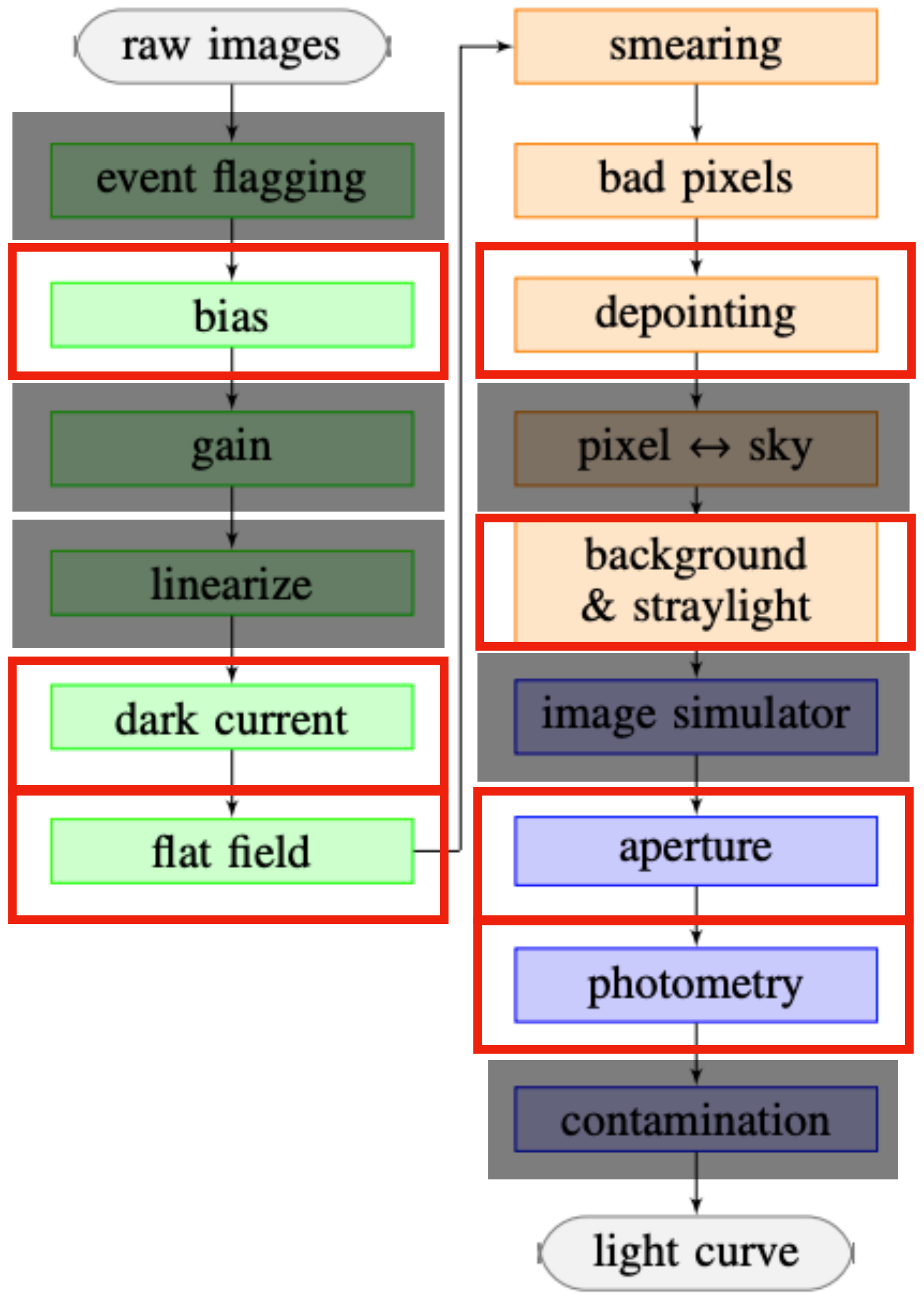



**Fig. 1.** Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

# The other steps: Dark current correction

Step that you should try to implement

The same principles can be applied to the dark current correction but the dark current correction is a bit more challenging:
The are dark left, right and top and due to the fact they are real pixels, they are affected by cosmic rays and hot/dead pixels or columns .
You will need to find a way to remove these “outliers” bad pixels/column manually or with an automatic routine(astropy.sat)

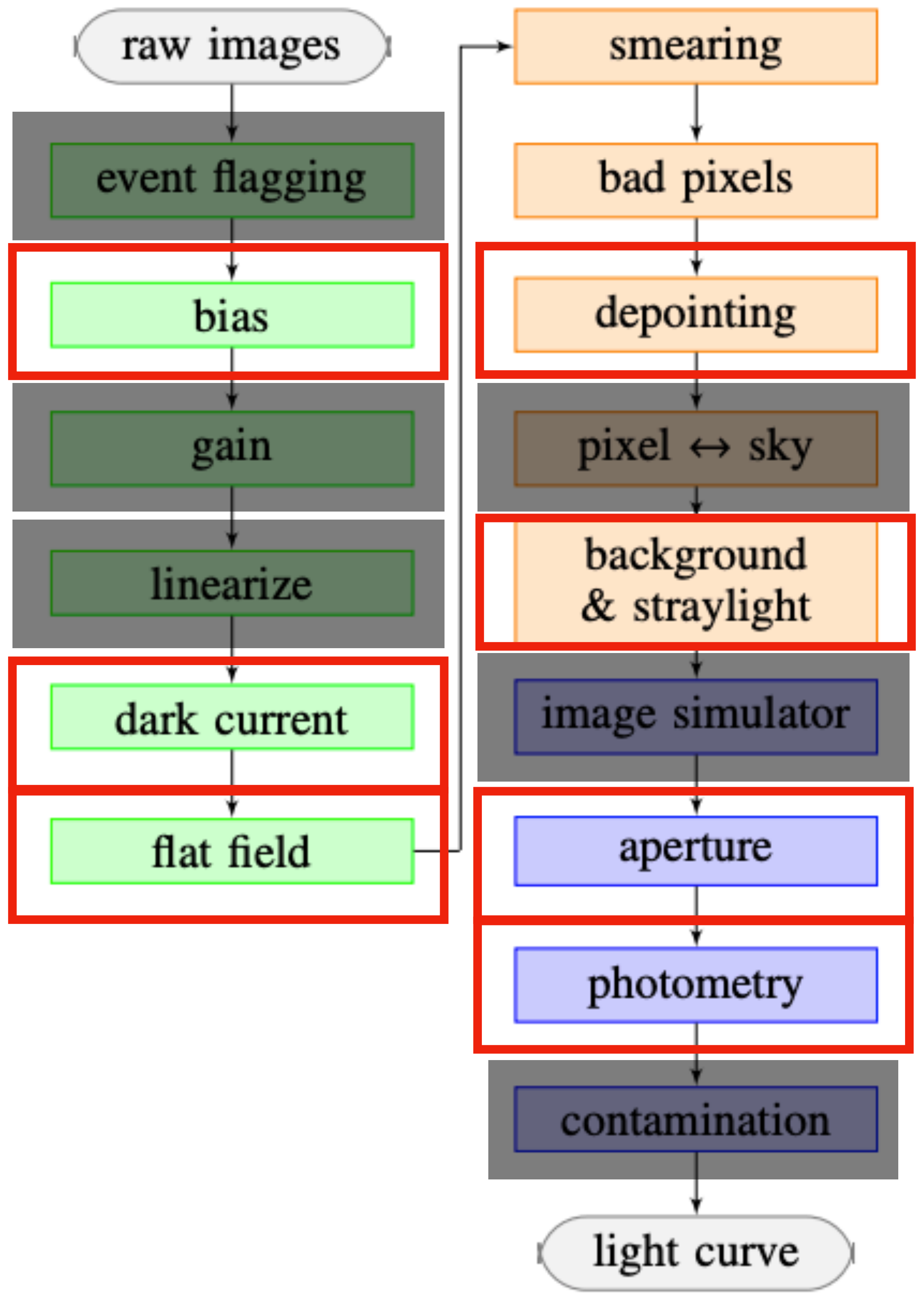



**Fig. 1.** Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

# The other steps: Flat-field correction

Step that you should try to implement

You can find on the github repository the flat-field for each observation

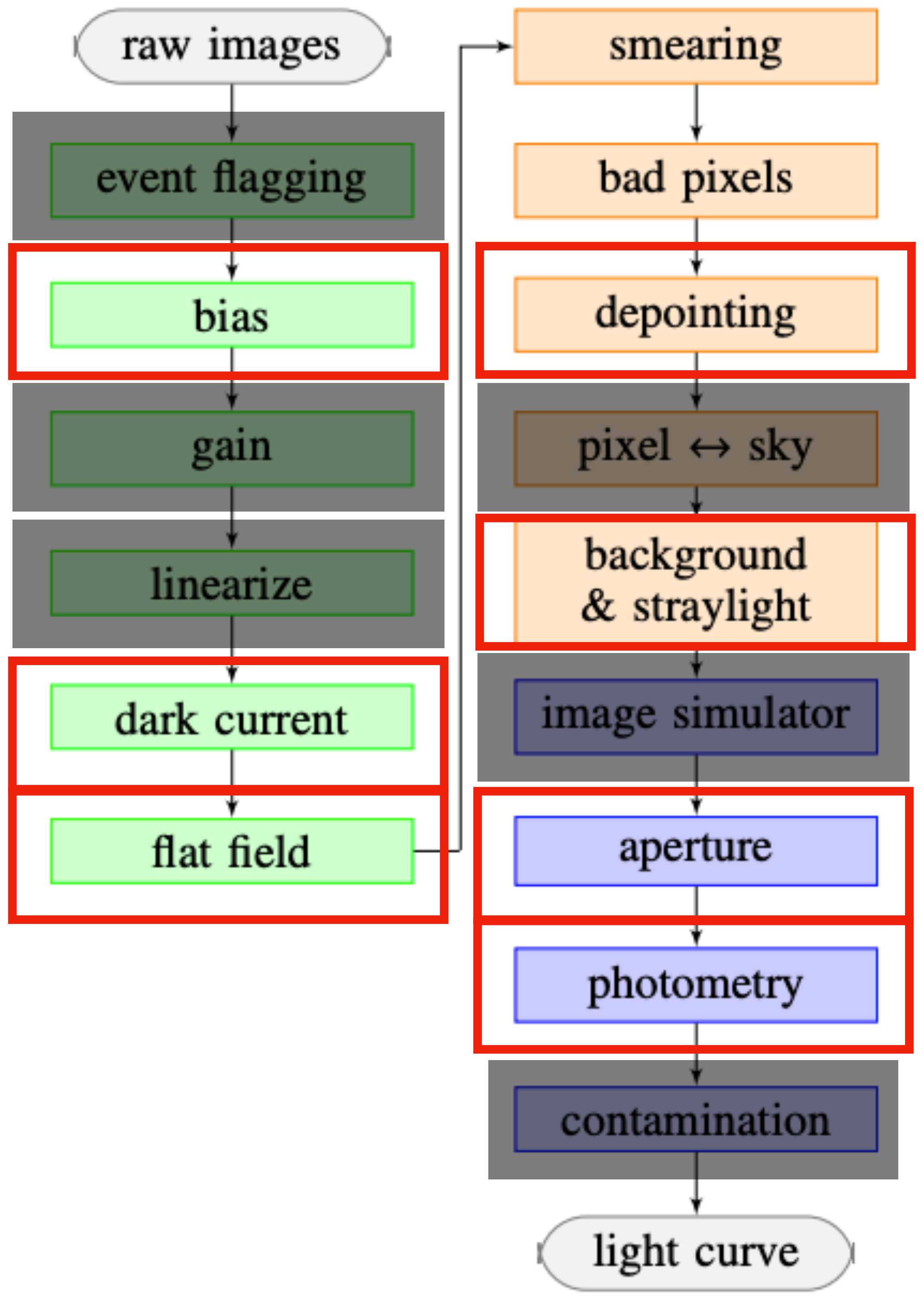



**Fig. 1.** Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

# The other steps: Depointing, background and stray-light, aperture definition, photometry

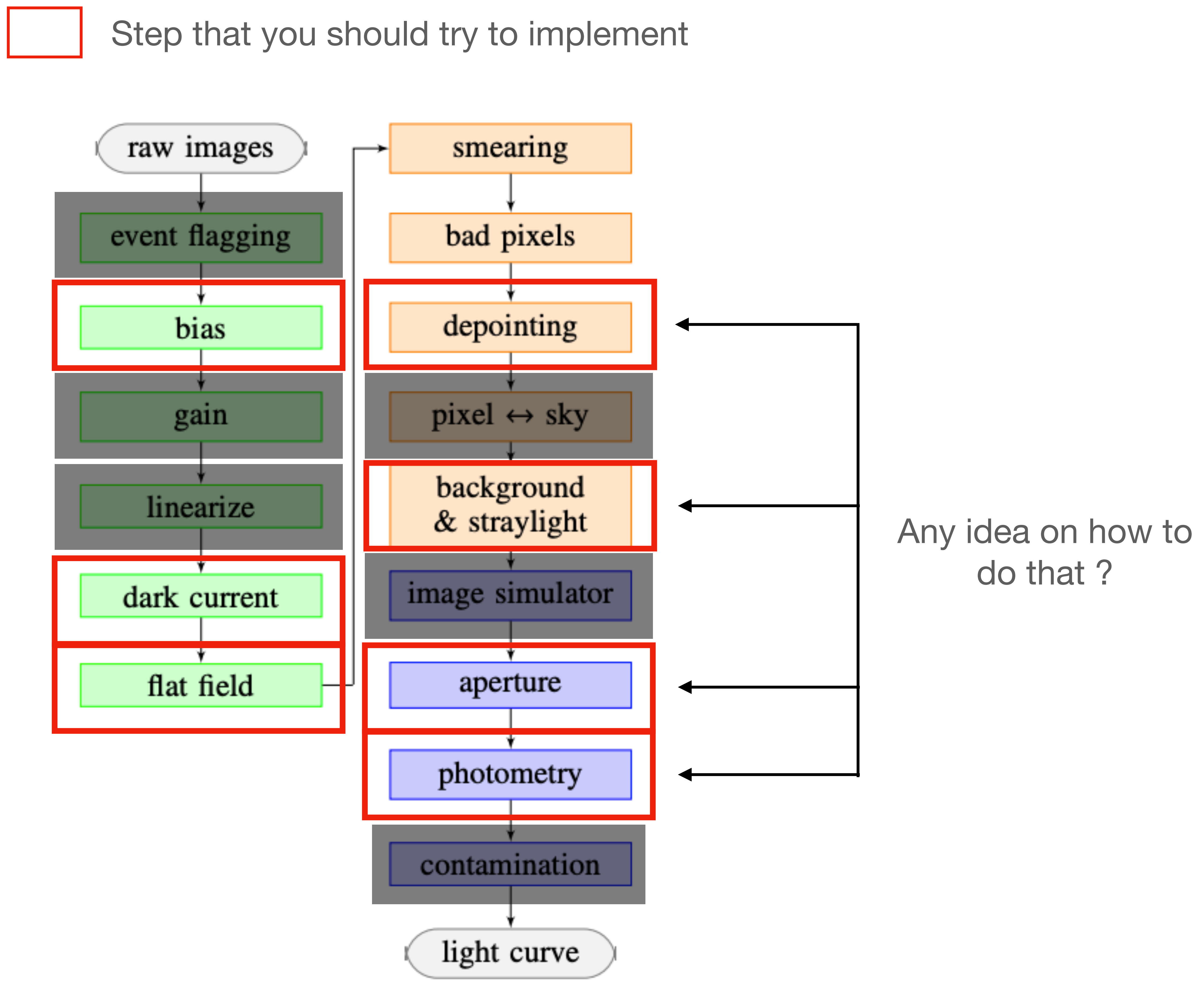



**Fig. 1.** Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

# What is expected of you ?

- Show that you understood:
    - Implement at least one method for each step. The one shown are another that seems more promising to you.
    - Explain the reason for the different steps of the method you are implementing ?
    - What are the hypothesis if there is any ?
    - Why are we implementing each step like this ? Is there other ways to do it ? What are the pros and cons of your method ?
    - Even if you could not or didn't have time to implement you can propose ways to improve
- How to estimate the precision of your light-curve ?