Telescópios - Trabalho prático

Photometry applied to exoplanetology with the ESA-CHEOPS space telescope

Olivier Demangeon - 28 April 2023

Overview for the next 4 classes

Photometry and its application in exoplanetology

- What is photometry ?
- What is it used for ?
- How to perform photometry ?
- How to use photometry to characterize exoplanets ?

Project: You will make your own analysis of the data from a professional satellite (ESA-CHEOPS)

Overview for the next 4 classes

Photometry and its application in exoplanetology

- 1st class (28/04): Introduction to photometry, exoplanetology and study of exoplanets with the ESA-CHEOPS satellite.

- 2nd class (05/05): Detailed presentation of the analysis of the data taken with CHEOPS.

- 3rd class (19/05): Introduction to exoplanet transit fitting and work on your analysis of the data.

- 4th class (26/05): Oral presentations of your analysis of the CHEOPS data (~10-15 minutes presentations followed by questions).

  Written report of your analysis of the CHEOPS data to be submitted by the 28/05.

Overview for the next 4 classes

Evaluation

- Your final grade for the course is the combination of the exam, the optics labs and these data analysis labs.
- You grades for the data analysis labs is divided into 3 components:
    - 20% Attendance and participation;
    - 40% Oral presentation and questions;
    - 40% Written report.

Photometry

What is photometry ?

- Astronomy and astrophysics are the study of the universe. Traditionally astronomy is the observational/instrumental side of this study and astrophysics the more theoretical side.
- Astronomy relies mostly on the measurement of the electromagnetic radiations (light).

What is photometry ?

We can measure different properties of the light:

- Its spatial distribution: imaging measurements

Credits: NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Anton M. Koekemoer (STScI), Alyssa Pagan (STScI). Source: https://www.nasa.gov/feature/goddard/2022/nasa-s-webb-takes-star-filled-portrait-of-pillars-of-creation

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- Its spectral distribution (how much light we receive at different wavelength): spectroscopic measurement

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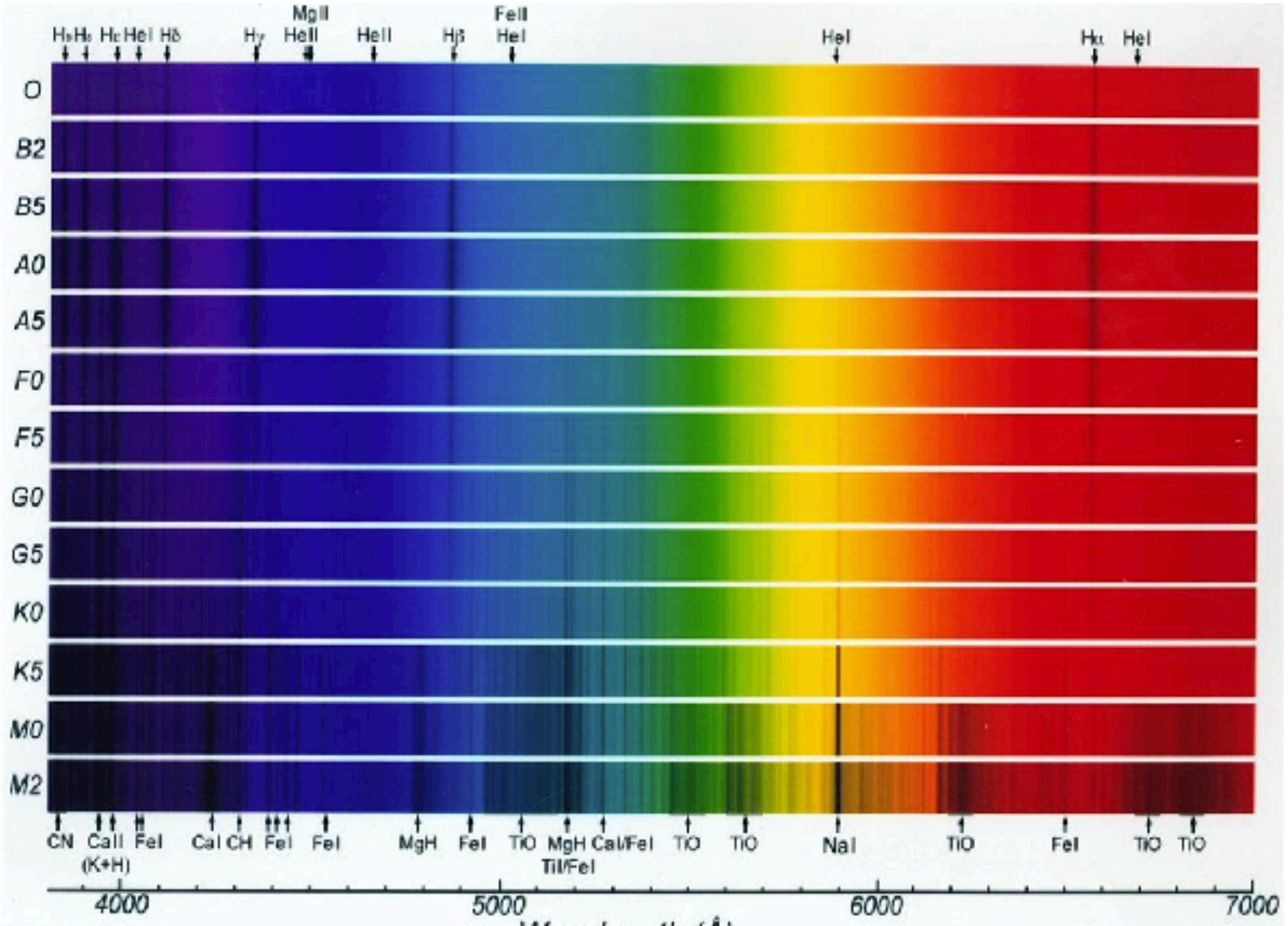
Source: https://www.nasa.gov/feature/goddard/2022/nasa-s-webb-takes-star-filled-portrait-of-pillars-of-creation

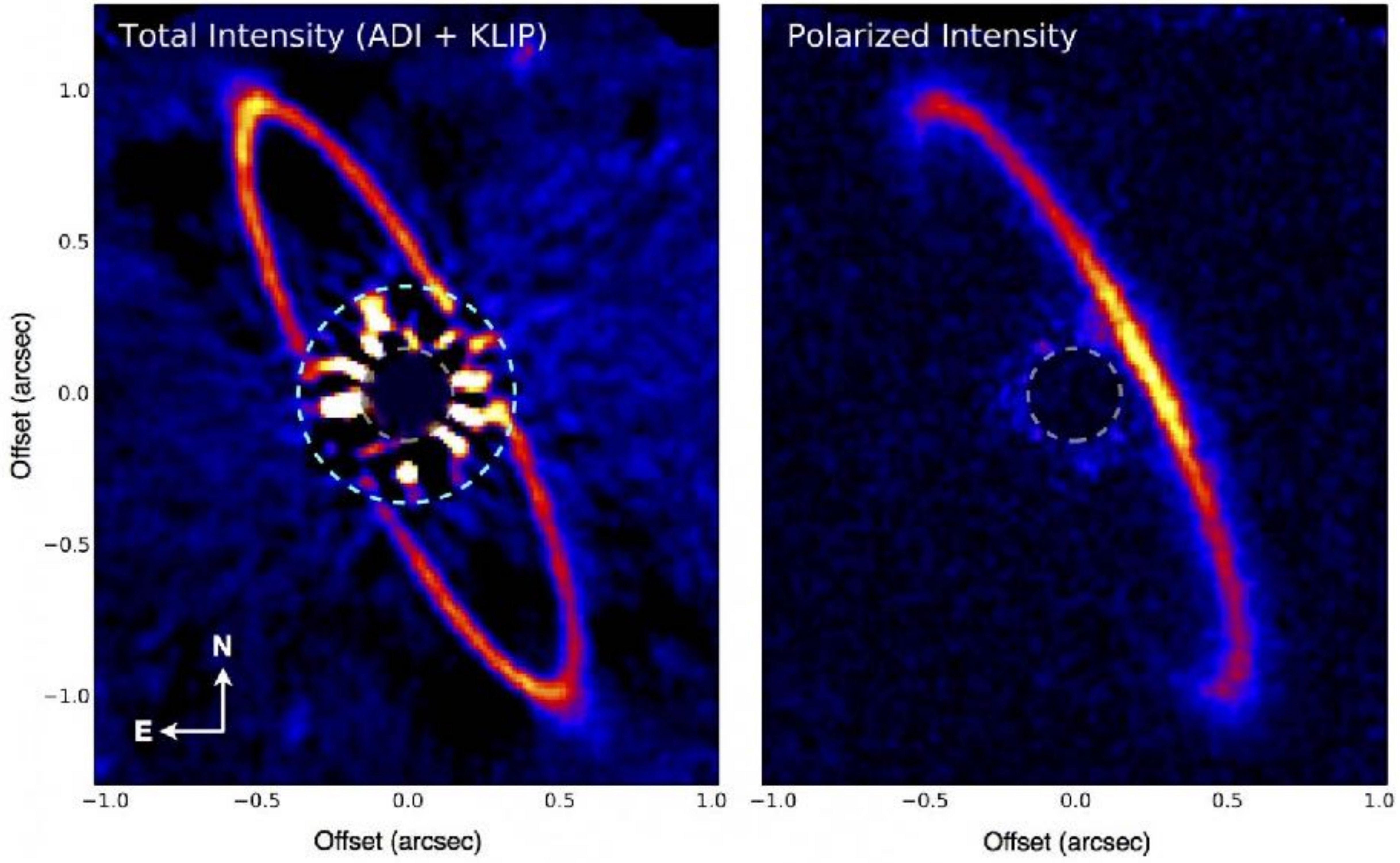


crédit: Adam Burrows
link

What is photometry ?

We can measure different properties of the light:

- Its spatial distribution: imaging measurements
- Its intensity (how much light we receive from a given object): photometry measurements
- Its spectral distribution (how much light we receive at different wavelength): spectroscopic measurement
- Its polarization (how the magnetic and electric fields are oriented): polarimetric measurements (a bit more info here)



GPI images taken at the Gemini observatory (source)

What is photometry ?

- Photometry is the measurement of the quantity of light that we receive from an object.
- We distinguish absolute photometry and relative photometry
  - Absolute photometry aims at measuring the exact quantity of energy received from on object and is often expressed as a flux (F) which is the energy that passes through a surface per unit of surface, per second and Hertz (frequency of the light that passes through) expressed in J.m-2.s-1.Hz-1. Another common unit to express the flux is the magnitude.

    $$m = -2.5 \ \log(F/F0)$$

    F0 is the flux at magnitude = 0.
  - Relative photometry focuses only on the relative difference between measurements. We are not interested the exact flux received, but by which fraction it varies from measurement to measurement.
- Relative photometry requires less calibrations than absolute photometry.

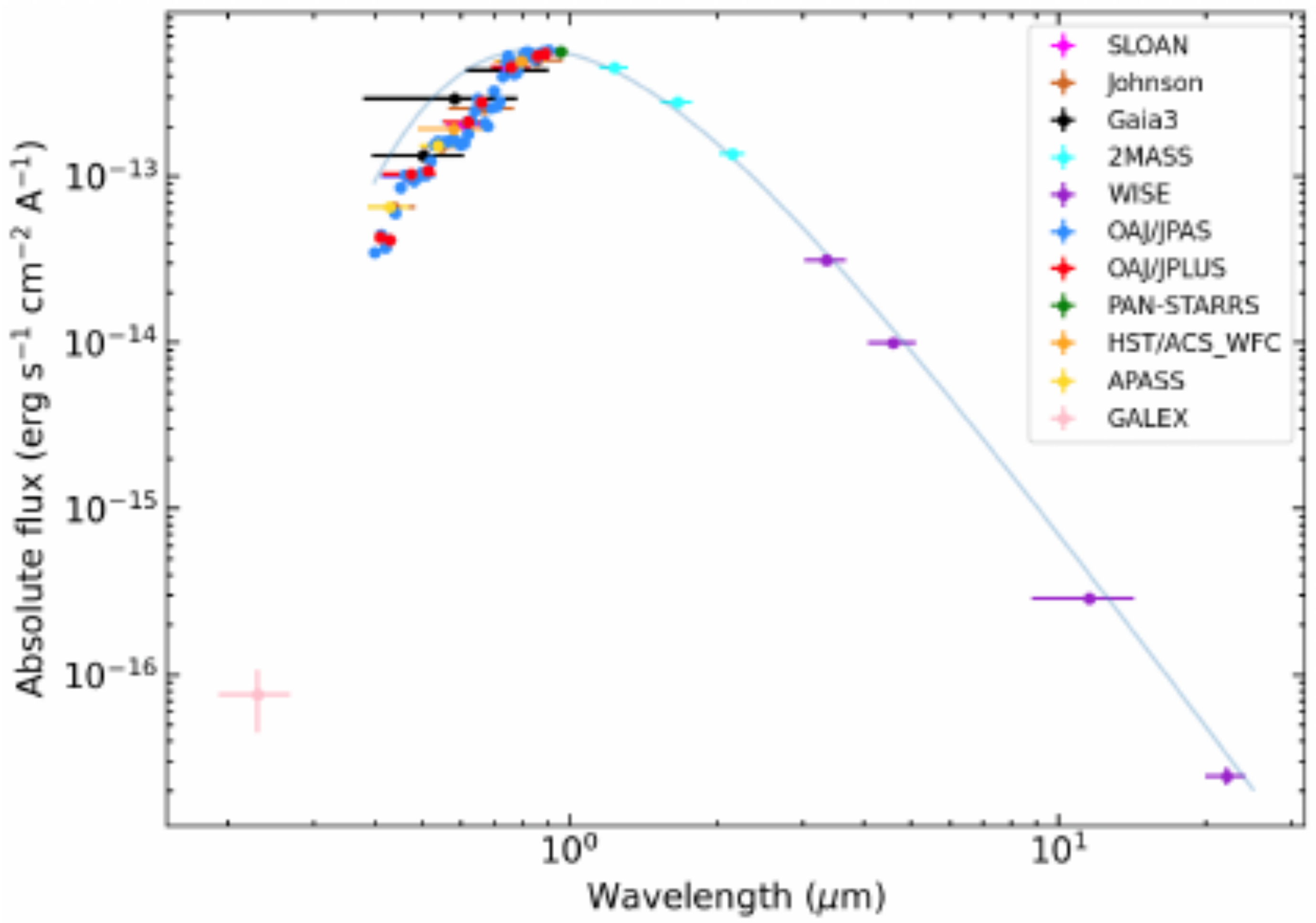
What is photometry used for ?

- Absolute photometry combined with a measurement of the distance (throught parallaxe measurement for ex.) provides information on the total energy emitted by an object (luminosity);

- If absolute photometry is acquired is acquired at several wavelength (banpasses). We can sample the spectral energy distribution (SED) of an object and infer its size and temperature (see for example the vosa tool for more info);

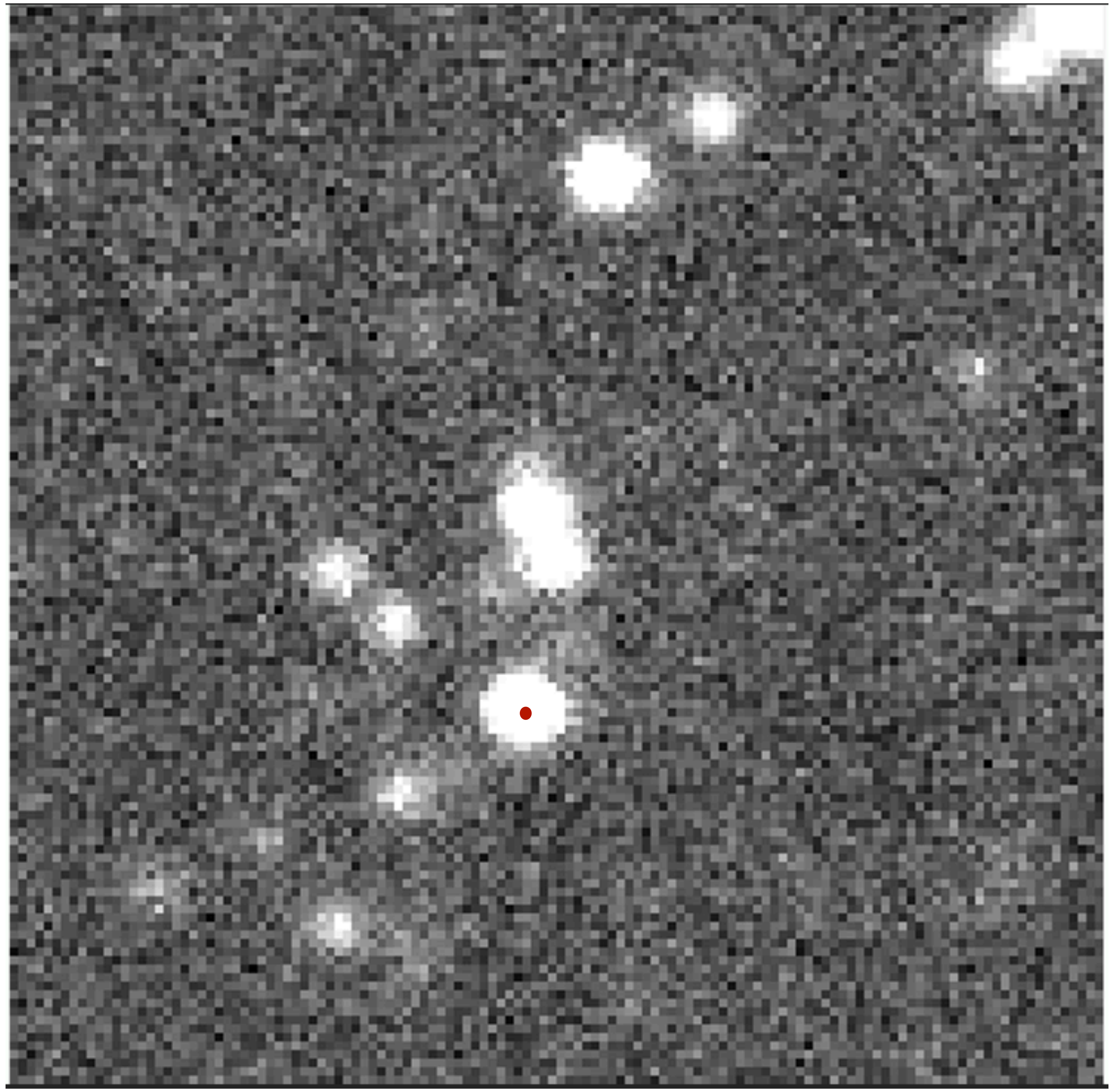
- One application of relative photometry is the detection of exoplanets in transit;

- This is not an exhaustive list.



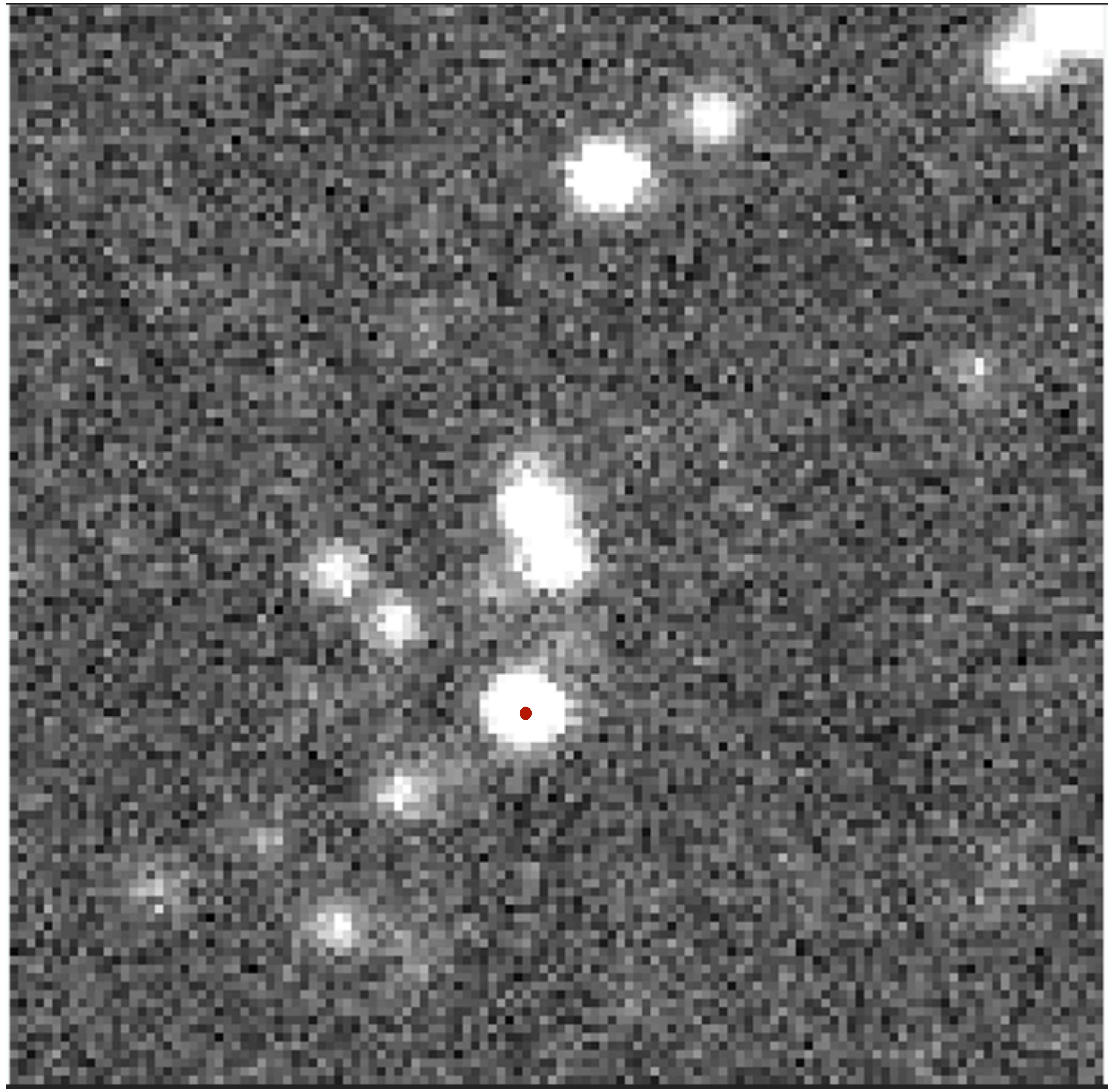
Castro, Demangeon et al 2023 (TOI 244)

How do you measure photometry ?



How do you measure photometry ?

- There is two main method to measure the photometry of a non-resolved object:
  - Aperture photometry



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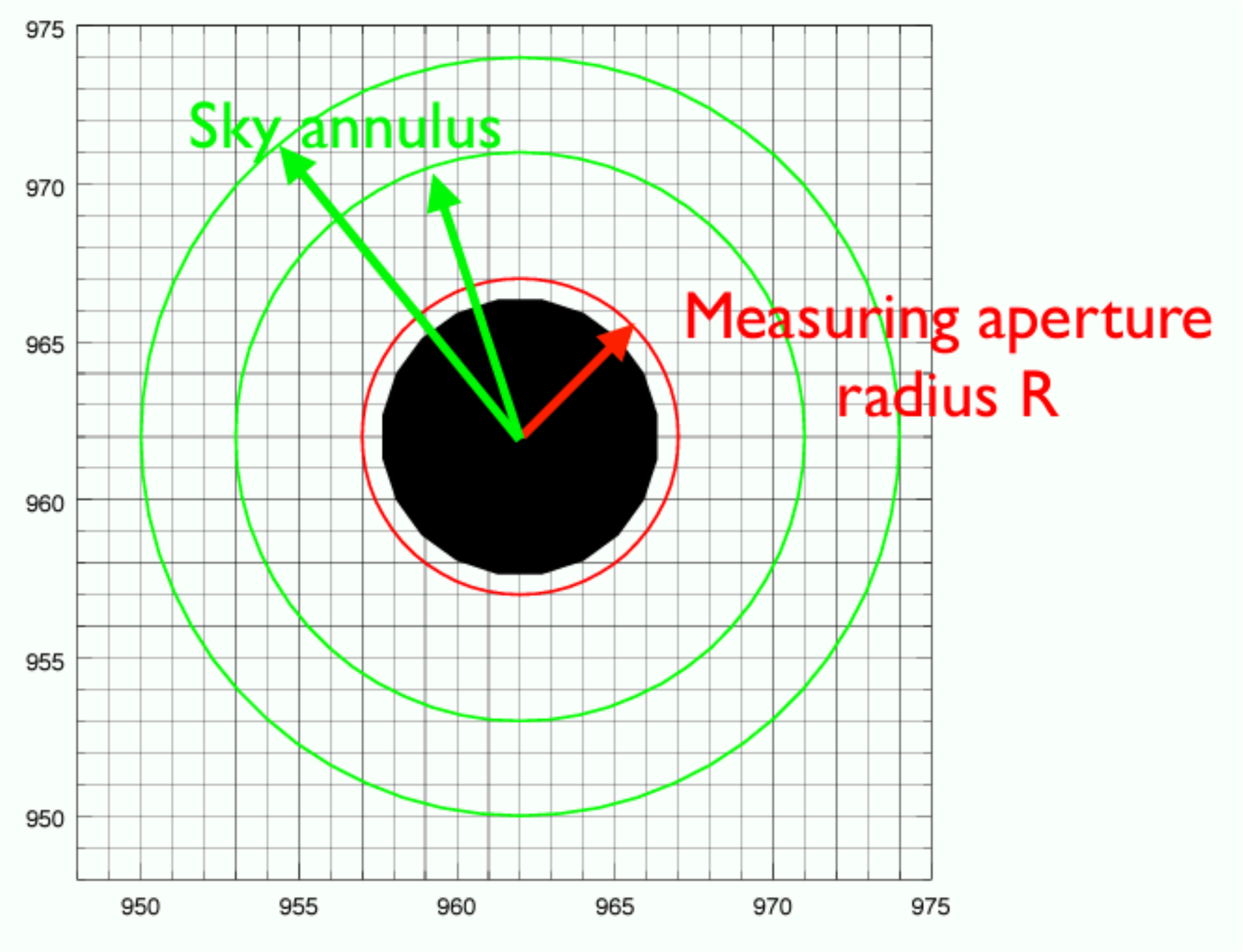

How do you measure photometry ?

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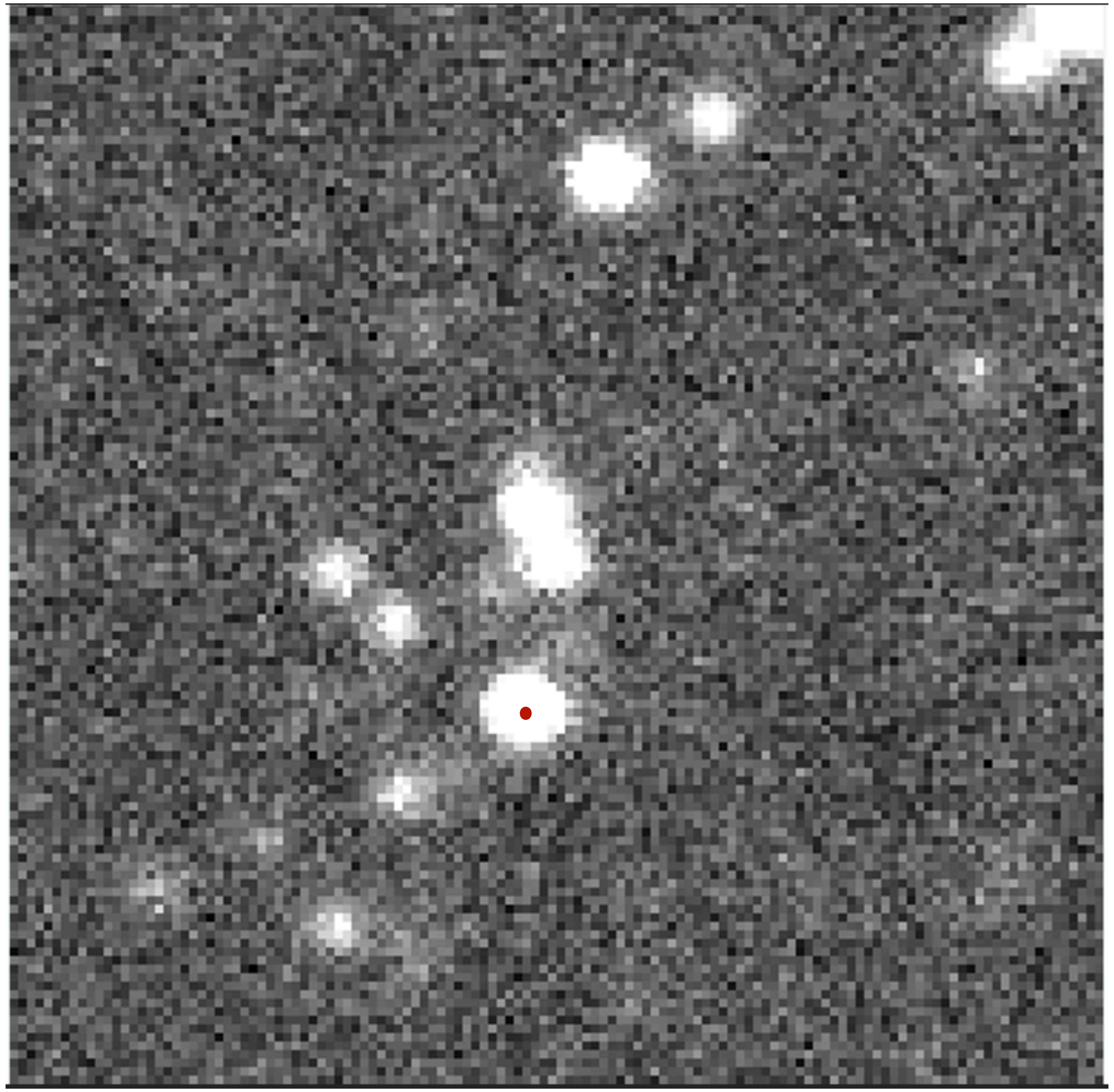
    - Aperture photometry (more info see for example Hoyer et al. 2020 *A&A*. 635, A24:14 pp. , https://arxiv.org/pdf/1909.08363.pdf)
    - PSF fitting



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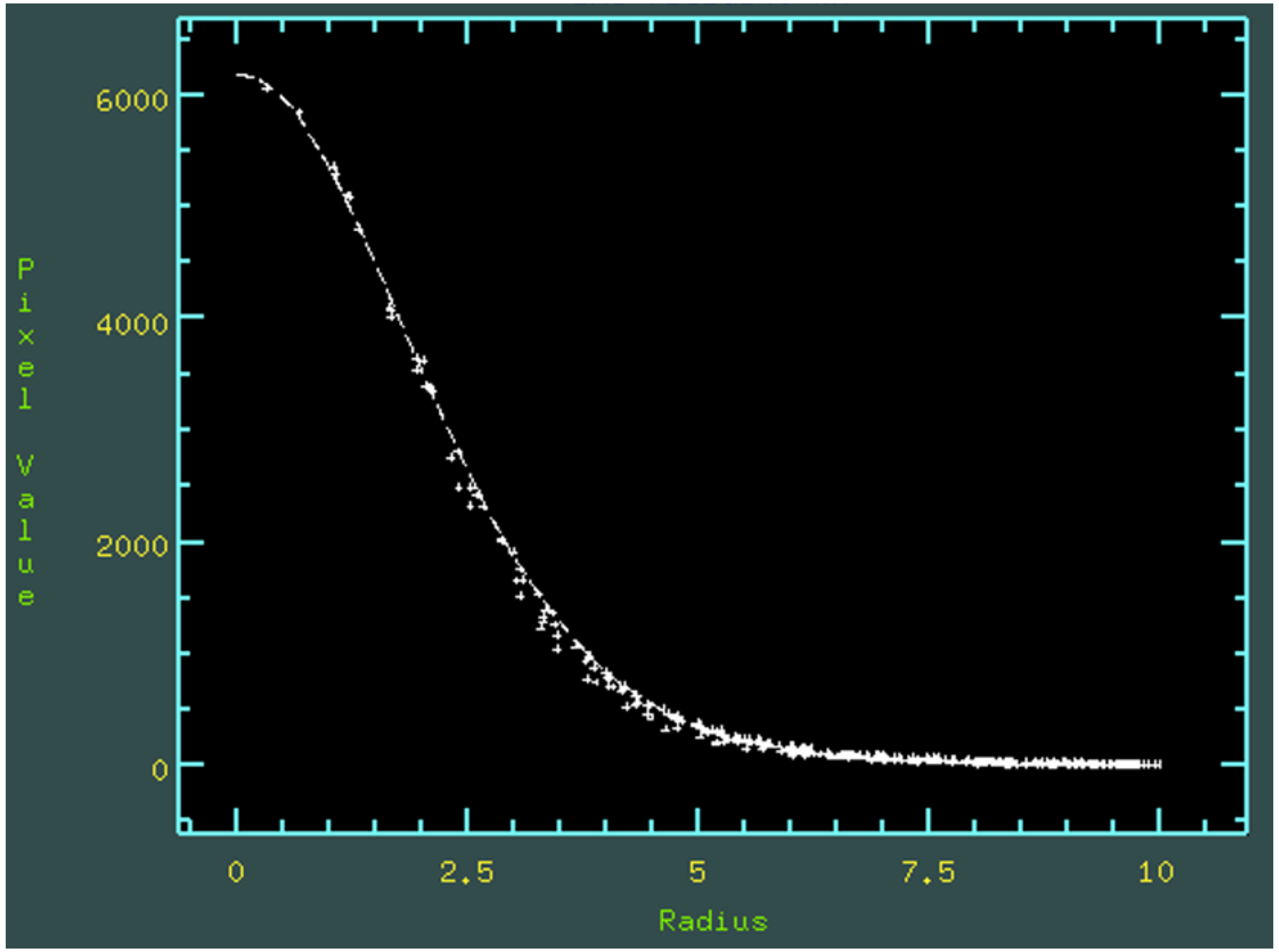
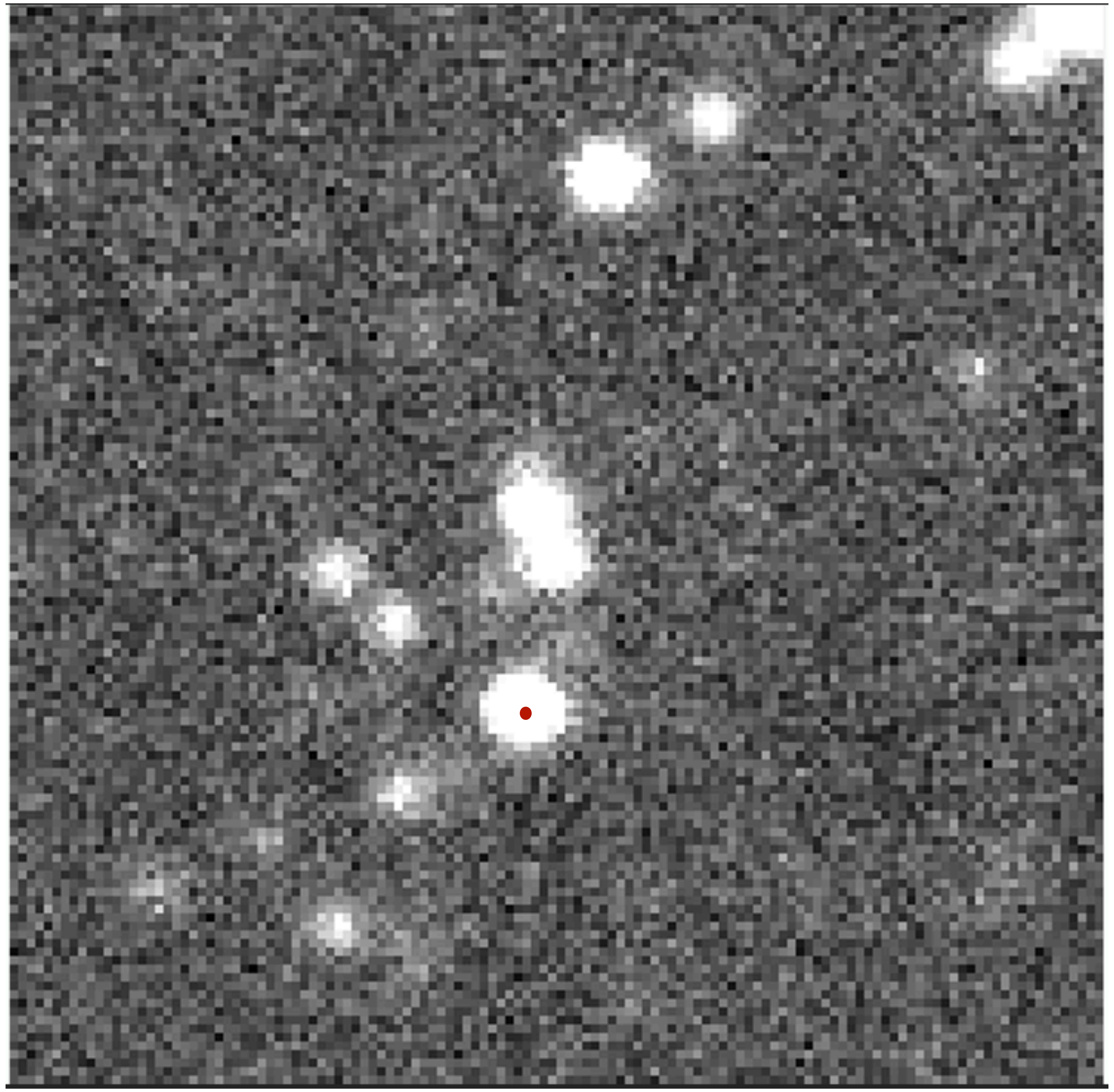


How do you measure photometry ?

- There is two main method to measure the photometry of a non-resolved object:
  - Aperture photometry
  - PSF fitting (for more info see for ex. https://photutils.readthedocs.io/en/stable/psf.html)
- PSF fitting is in theory more accurate has it takes into account more information (PSF) and allows to mitigate the impact of nearby star. However it requires a good knowledge of the PSF and a fitting procedure which usually required supervision.



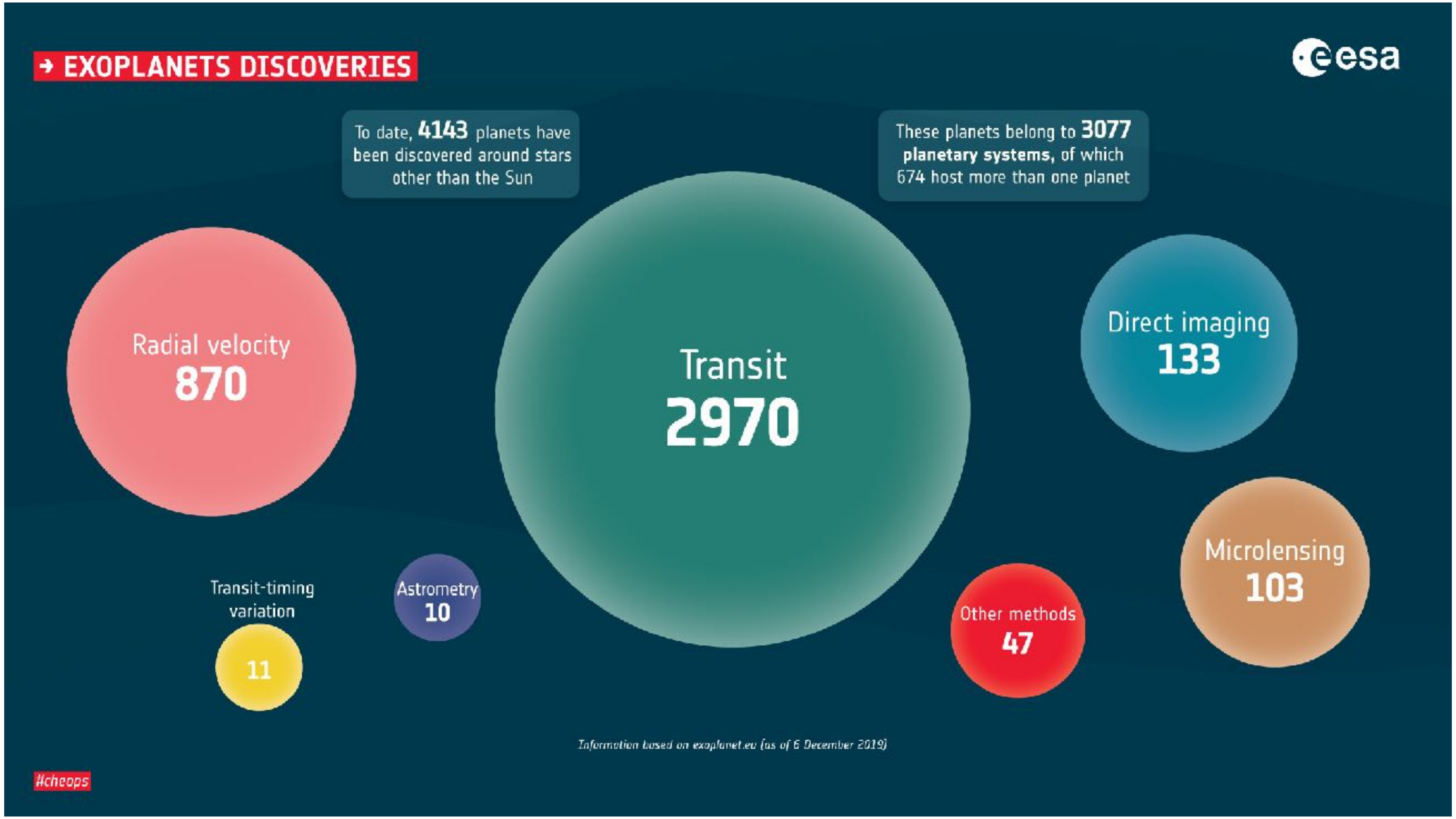
Exoplanetology a short introduction

ESO/M. Kornmesser

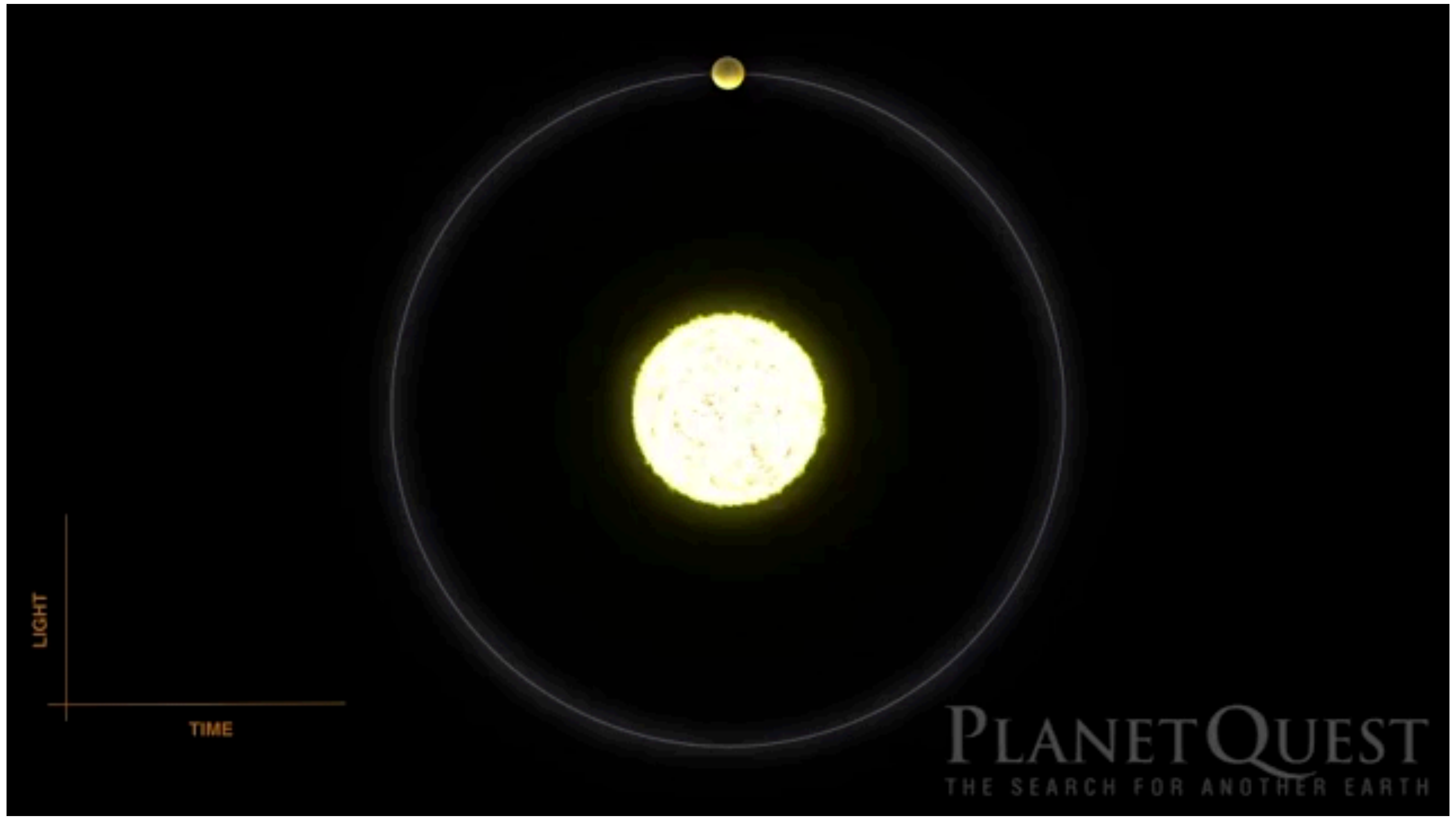
Exoplanets:

What are they and how many do we know?

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

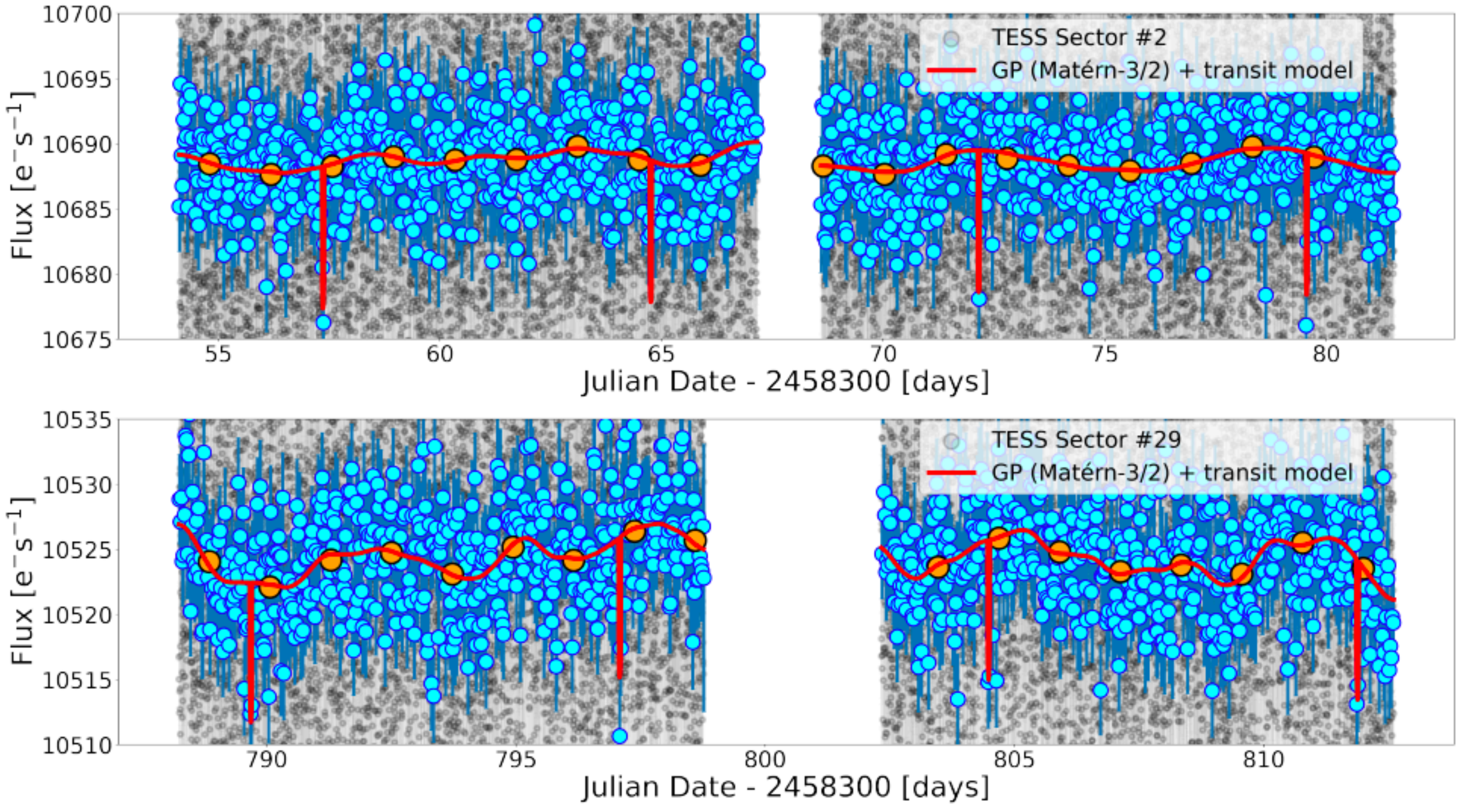


Transit photometry



source: https://exoplanets.nasa.gov/faq/31/whats-a-transit/

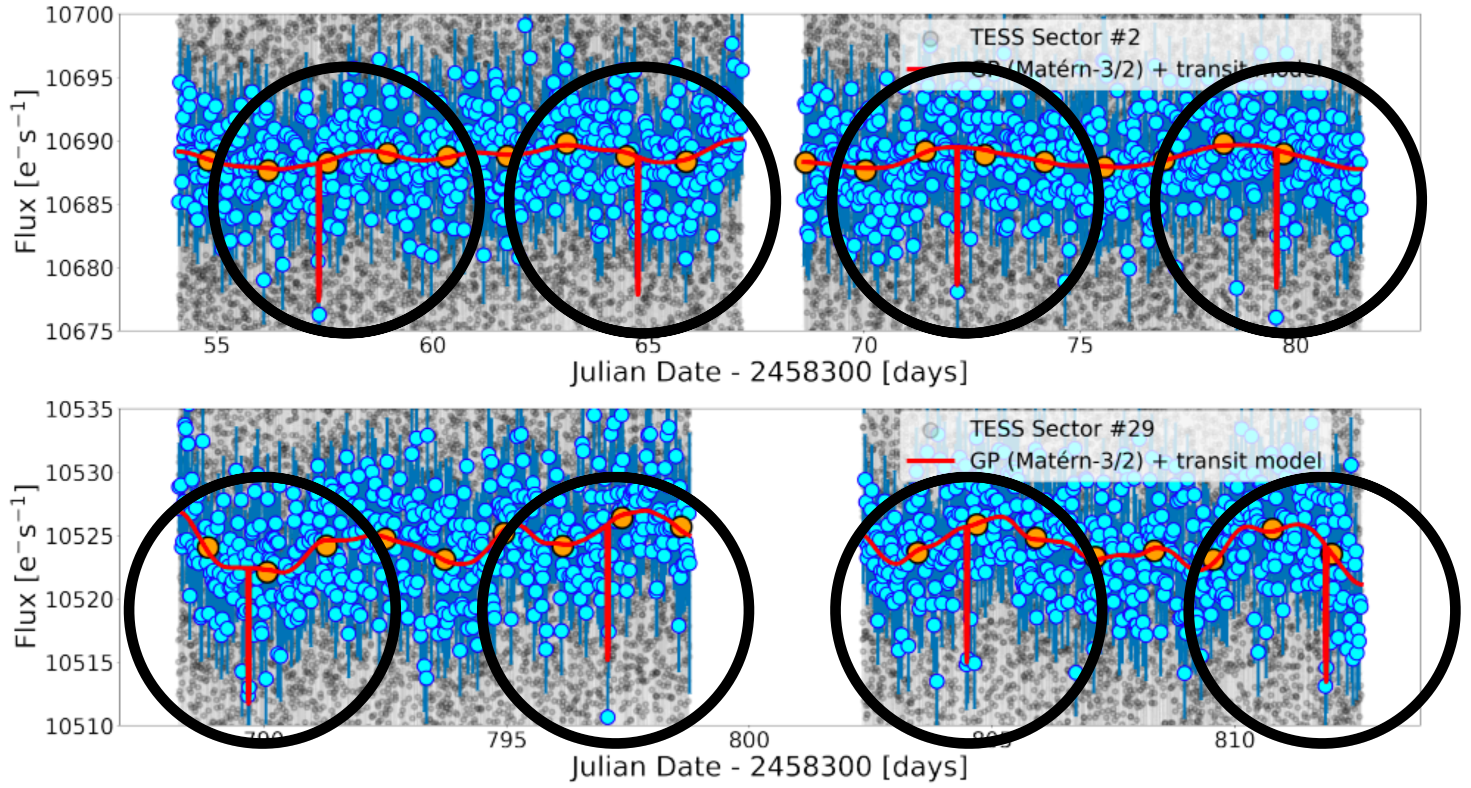
Transit photometry



Castro, Demangeon et al 2023 (TOI 244)

- Exoplanetary transit are periodic events.
- The depth of the transit provides a measure of the radius ratio planet over star.

Transit photometry



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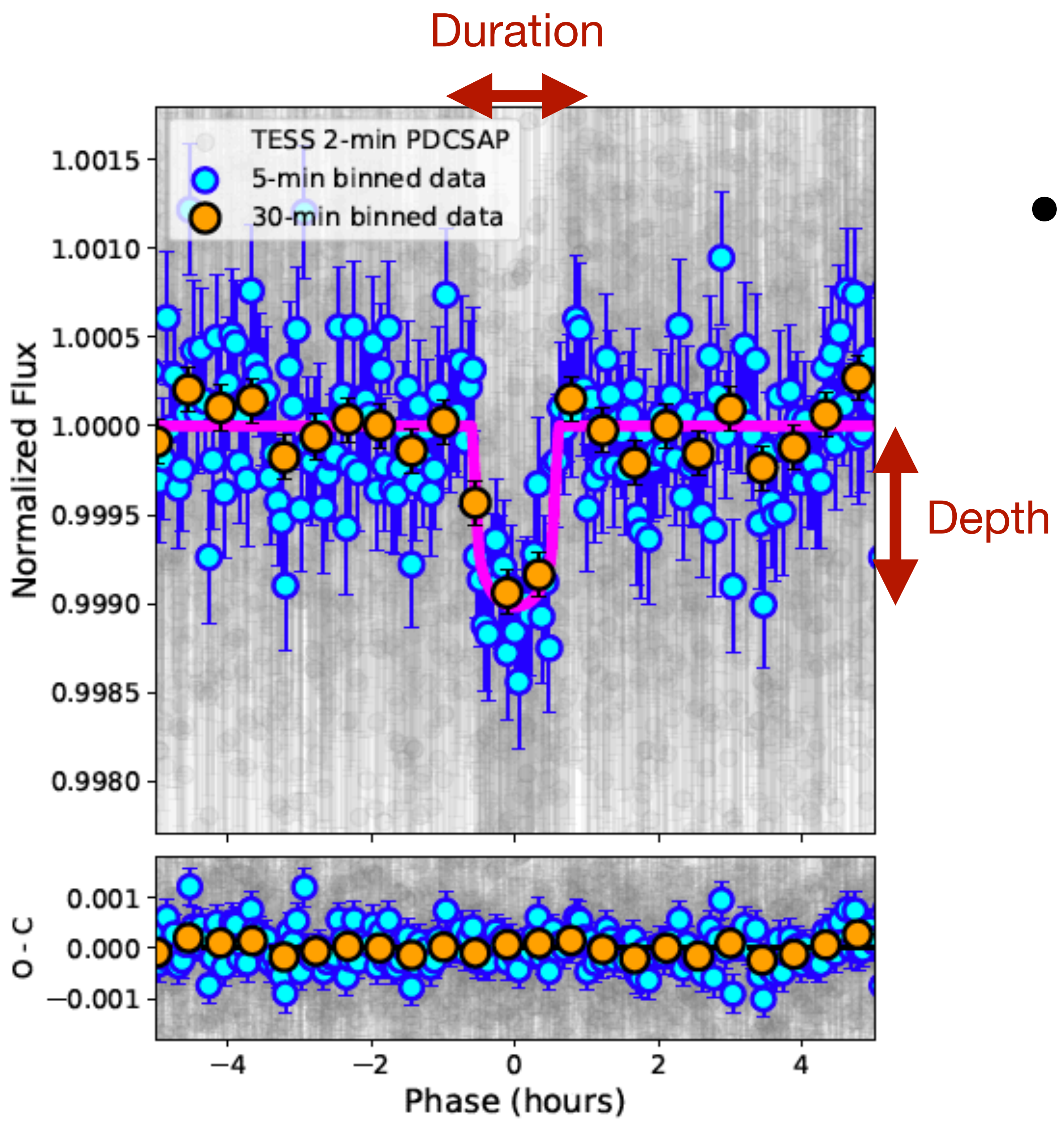
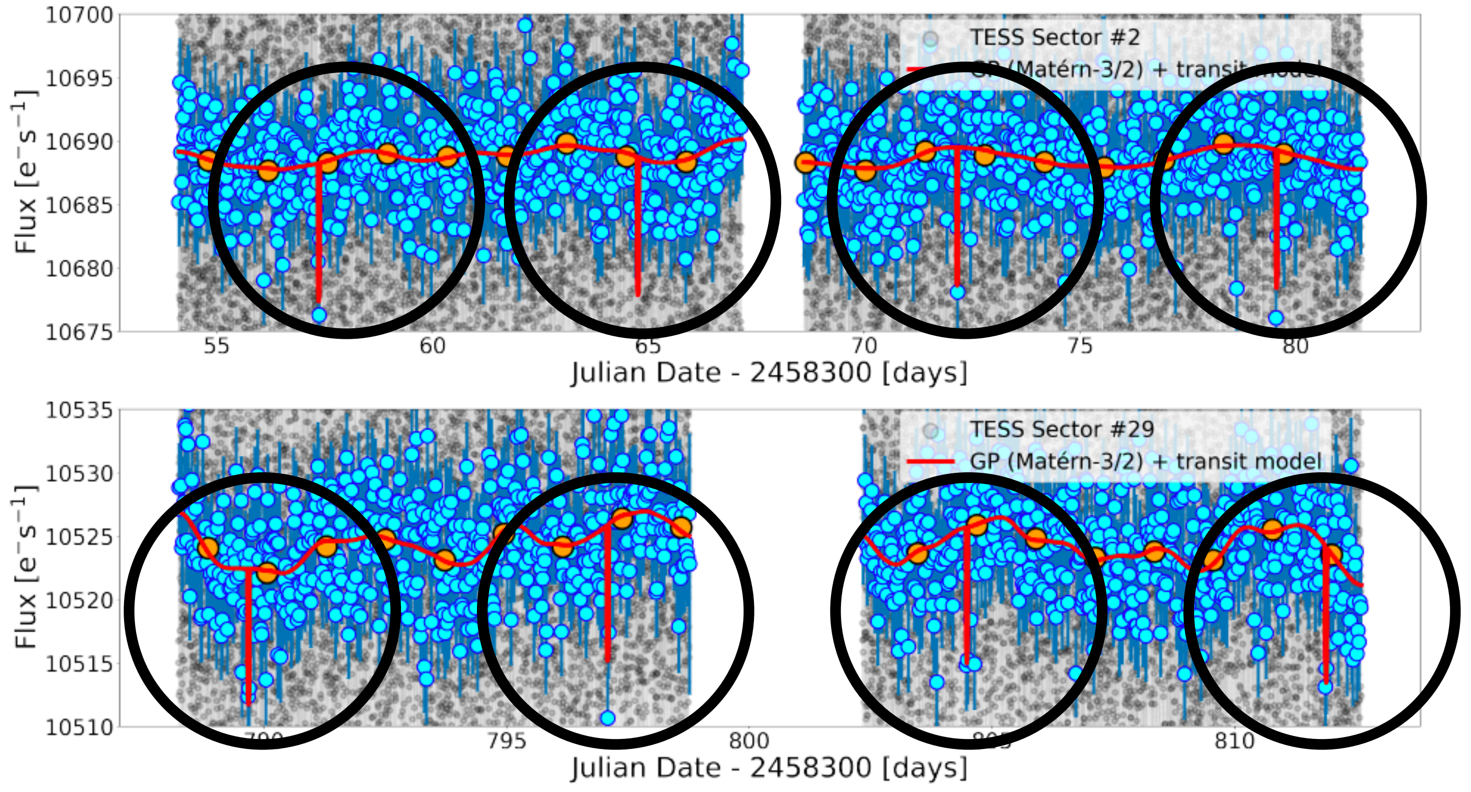


- Exoplanetary transit are periodic events.
- The depth of the transit (DeltaF/F) provides a measure of the radius ratio planet over star.

$$\Delta F \ \alpha \ \left(\frac{Rp}{Rs}\right)^2$$

Transit photometry



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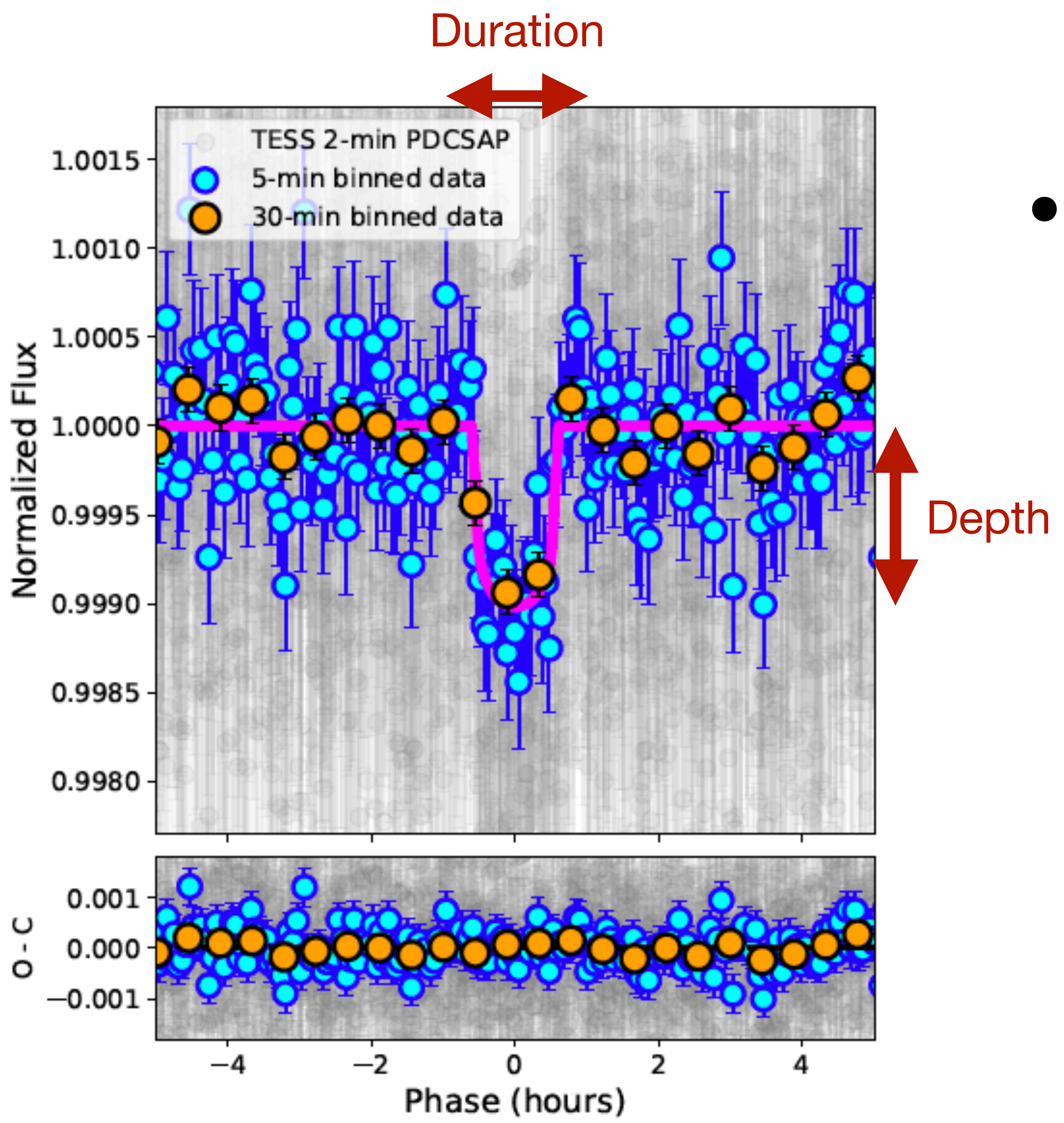

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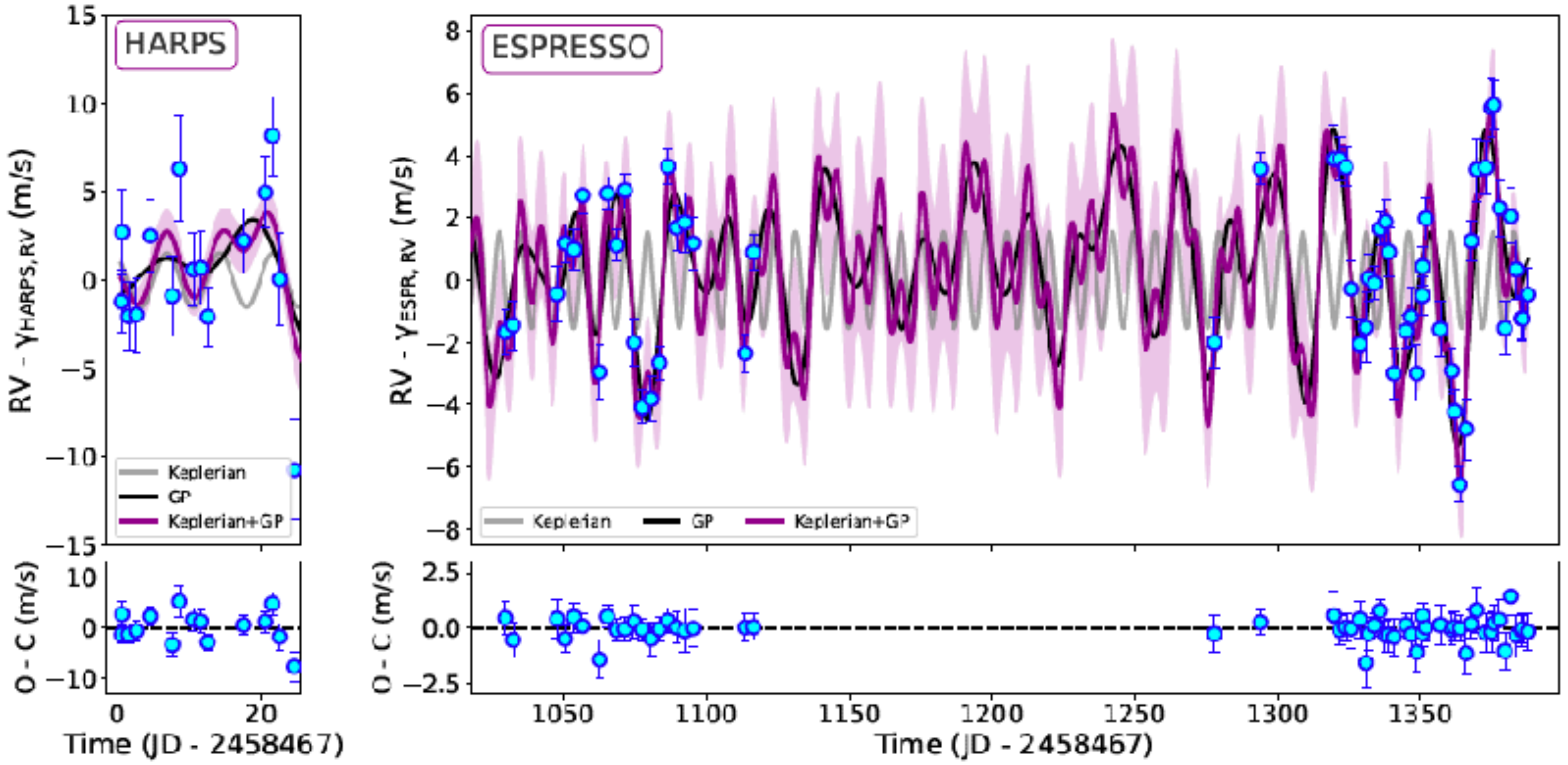
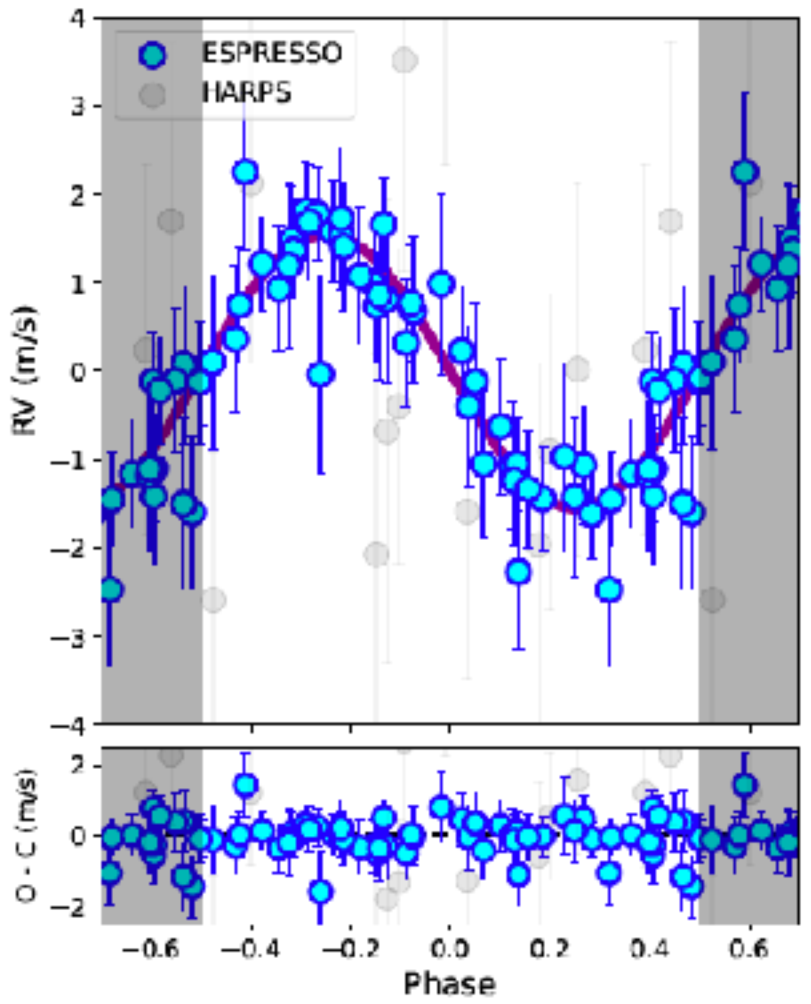
Radial velocity

source: https://exoplanets.nasa.gov/resources/2337/exoplanet-detection-radial-velocity-method/

Radial velocity





K = RV semi-amplitude

Castro, Demangeon et al 2023 (TOI 244)

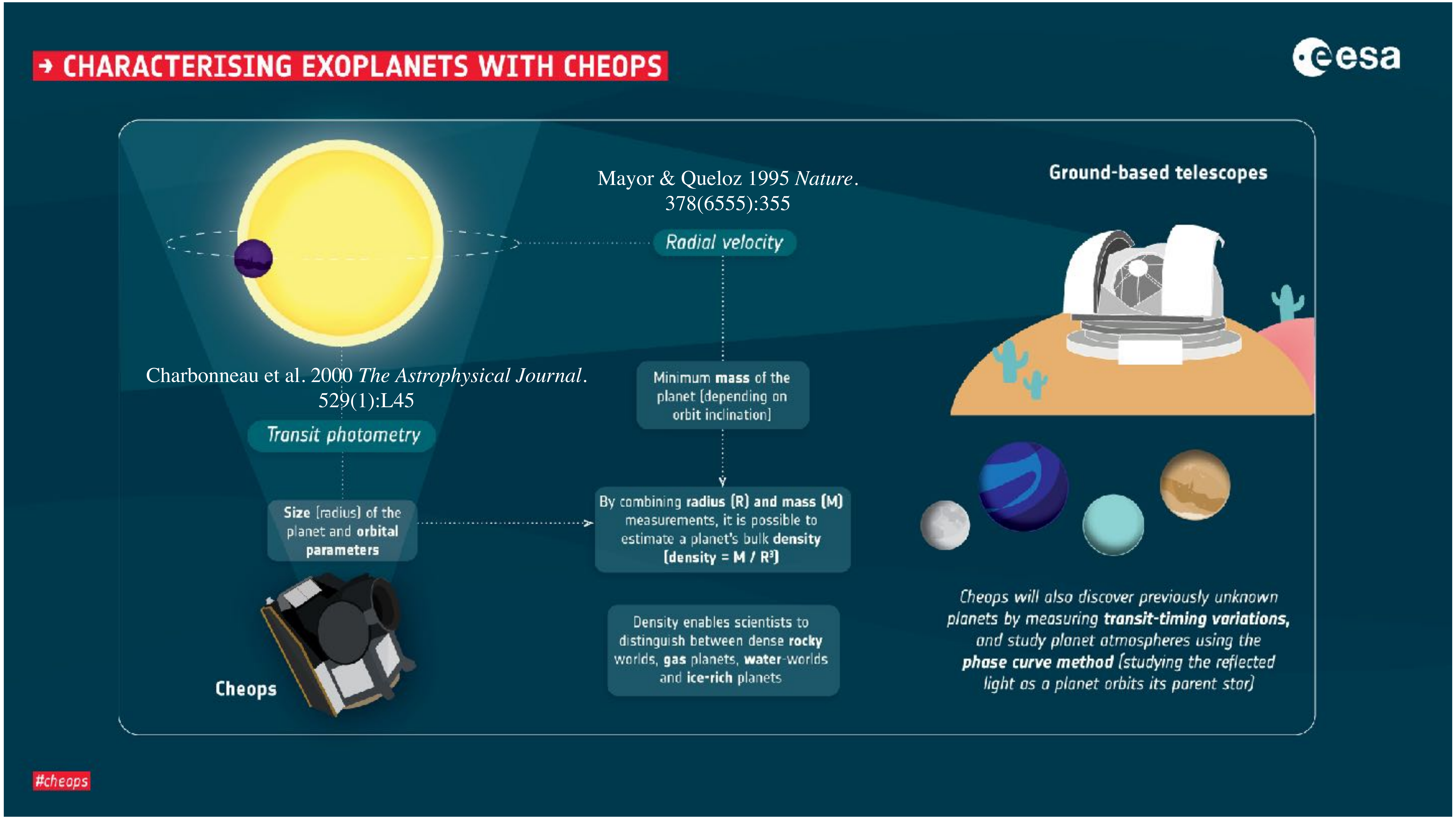
- Exoplanetary radial velocity curves are periodic.
- The amplitude of the wobble informs

$$K_1 = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_2 \sin i}{(M_1+M_2)^{2/3}} \frac{\sin i}{\sqrt{1-e^2}}$$

see for example Perryman, M. (2018). The Exoplanet Handbook or Santos, Barros, D.S. Demangeon, Faria 2020

Exoplanets

How do we study them ?



Exoplanets

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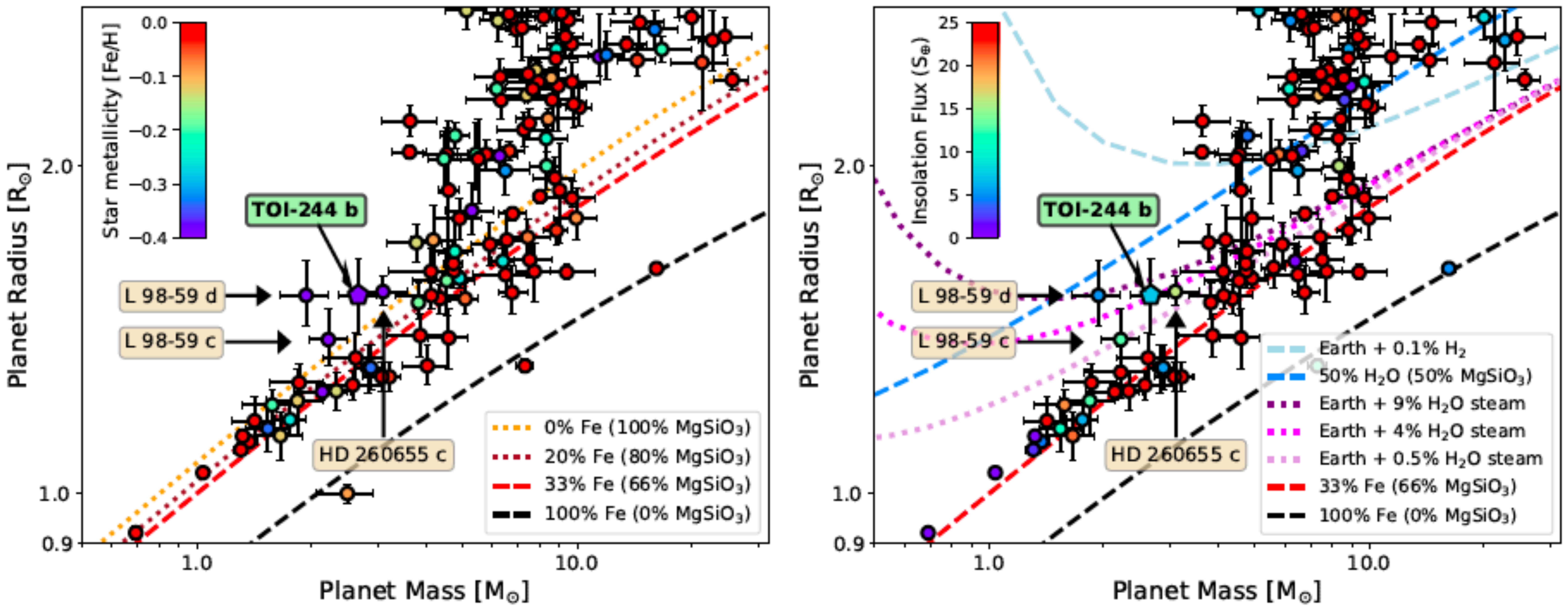

Fig. 10. Mass-radius diagrams for the small planet sample with measured dynamical masses with a precision better than 20%. **Left:** Colour coding indicates the stellar host metallicities. The dashed and dotted lines correspond to theoretical interior models that consider different mass percentages of Fe and $MgSiO_3$ (Zeng et al. 2016, 2019). **Right:** Color coding indicates the stellar insolation received by the planets. The dashed lines correspond to theoretical models from Zeng et al. (2019), which consider planets without a significant amount of volatiles (back and red lines), planets with condensed water (dark blue), and planets with H_2 atmospheric envelopes (light blue). The dotted lines correspond to the Turbet et al. (2020) theoretical models for Earth-like planets with H_2O-dominated atmospheres.

Castro, Demangeon et al 2023 (TOI 244)

CHEOPS: A space telescope to characterize exoplanets

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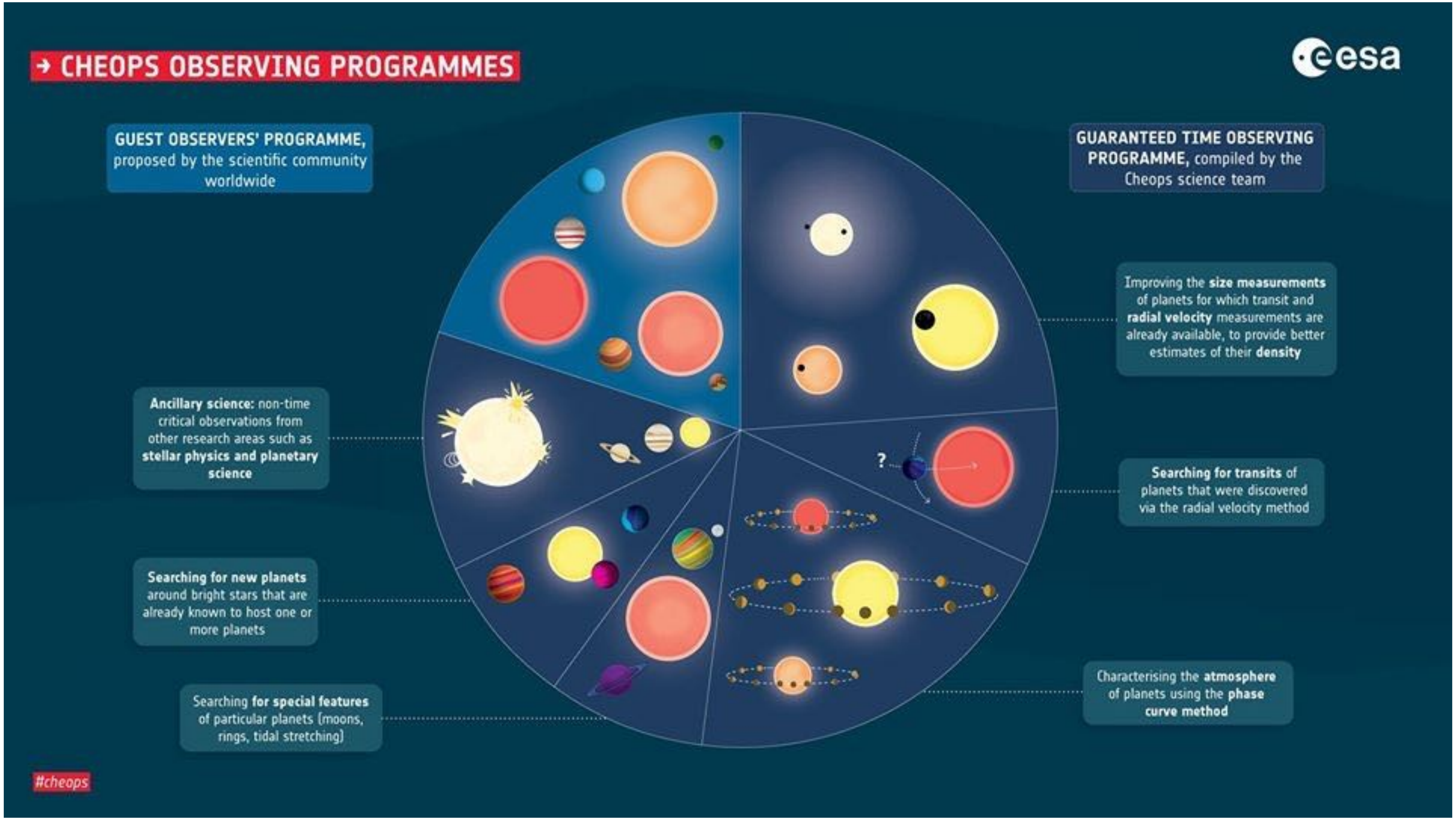
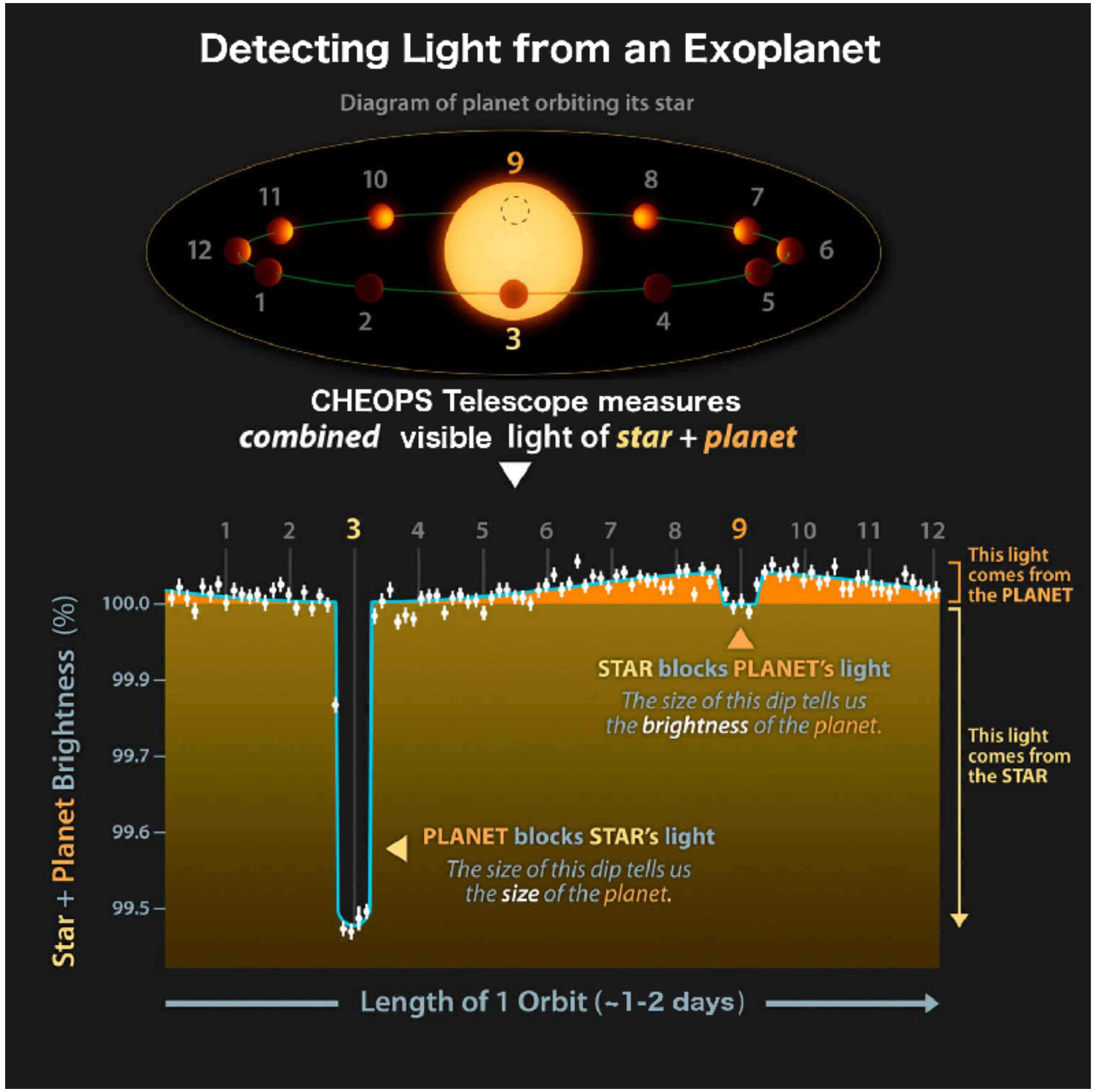
The Science of CHEOPS



CHEOPS: A space telescope to characterize exoplanets

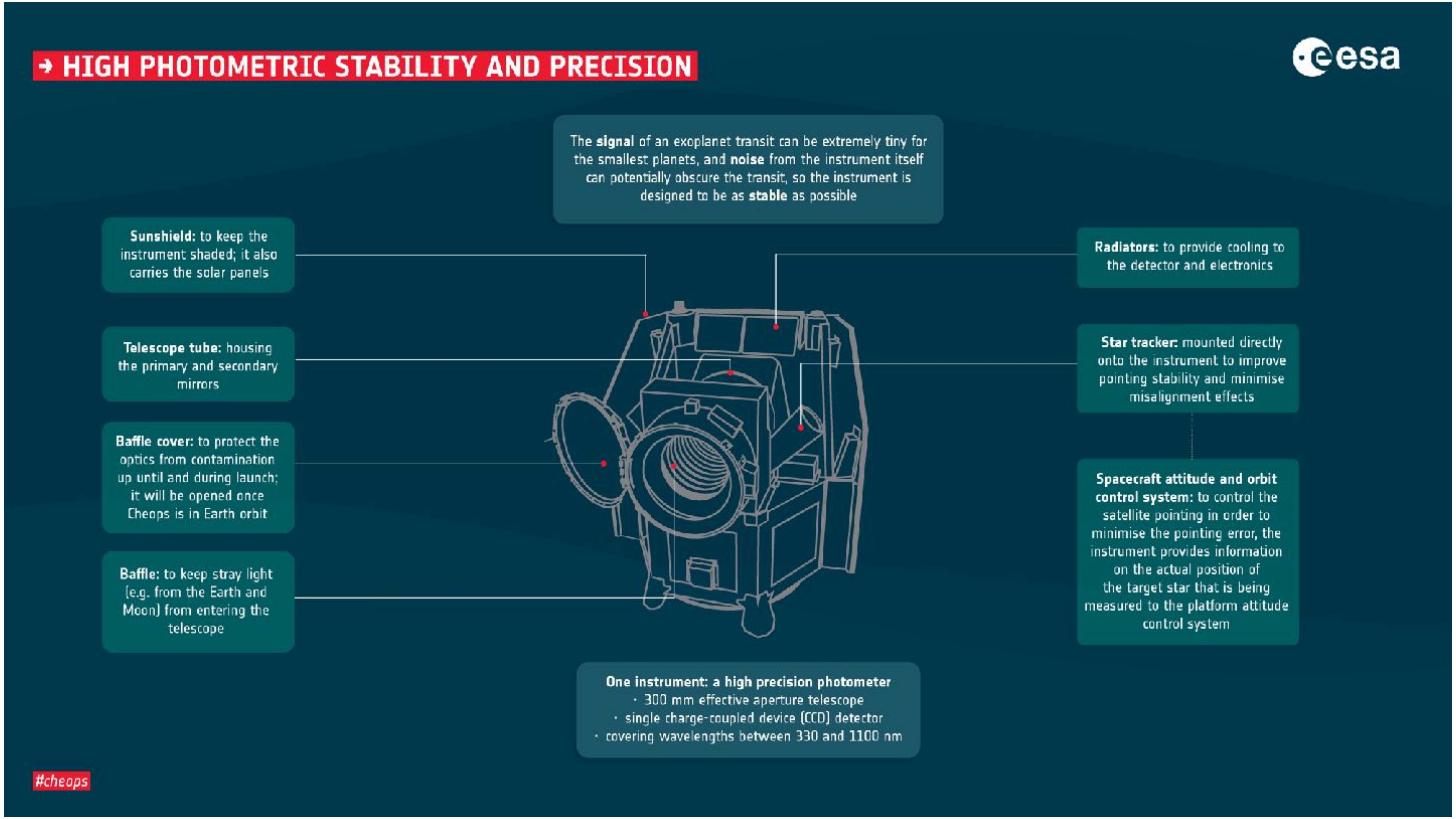
High precision photometry (alias transit photometry)



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

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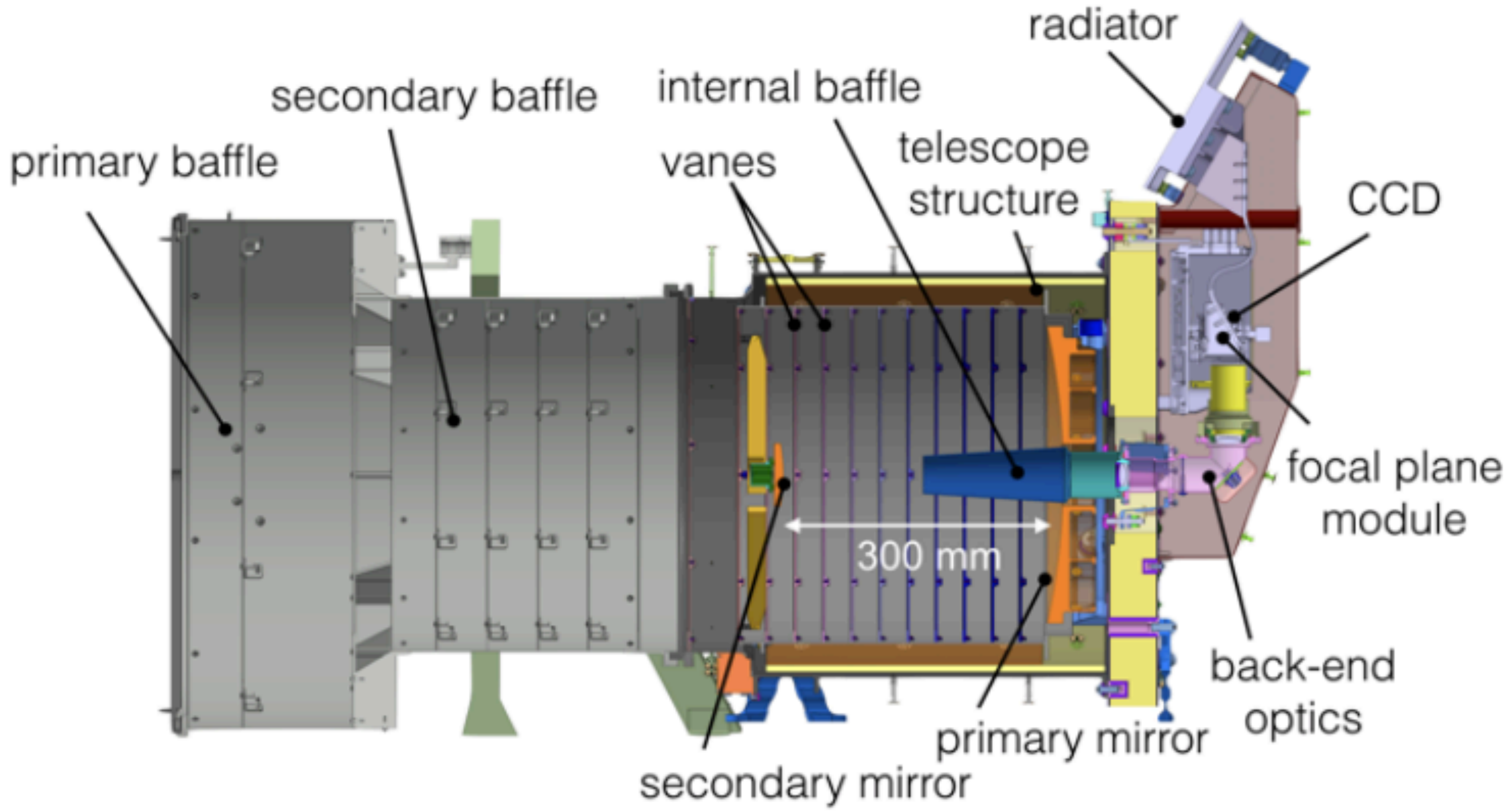


Fig. 5 CAD/CAM view of the OTA and BCA assemblies as mounted on the spacecraft. The primary and secondary baffle constitute the BCA. It is a separate unit mounted on the spacecraft independently of the OTA. The remaining items resemble the OTA.

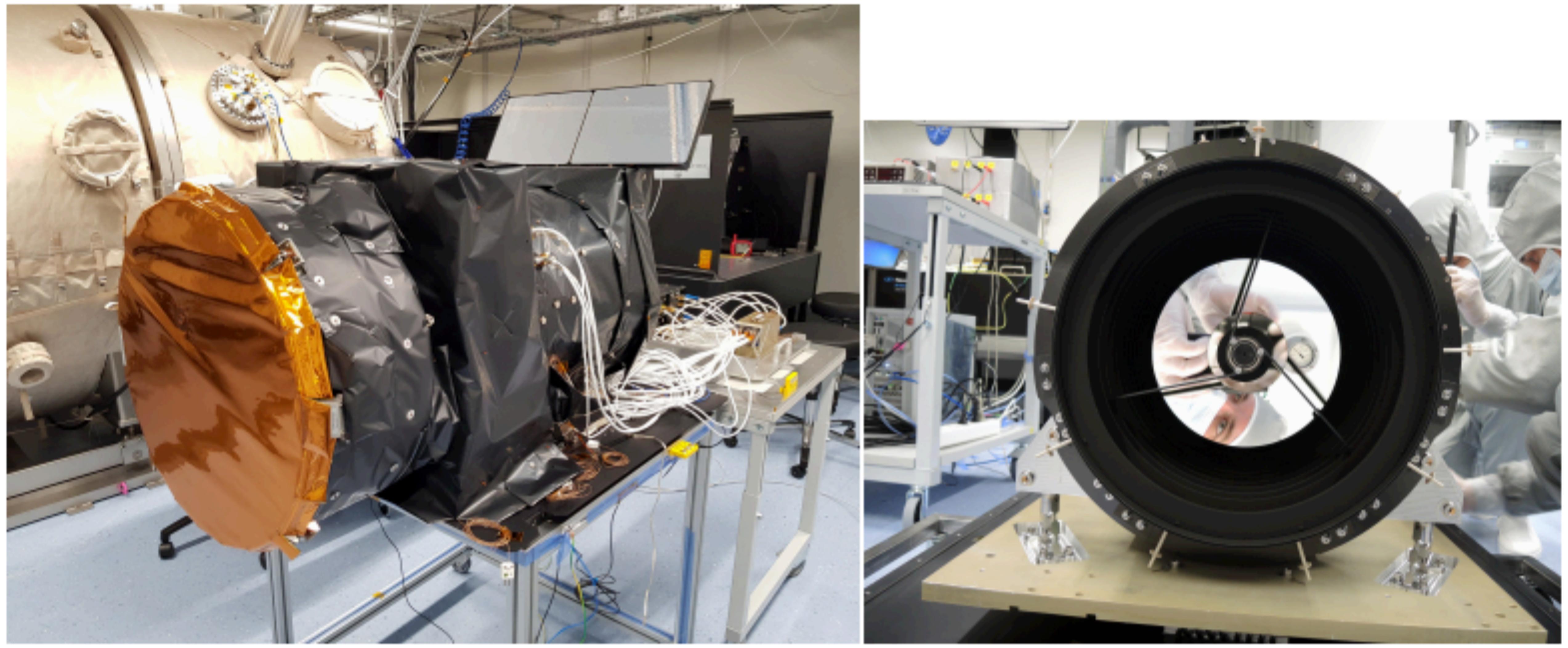


Fig. 6 Left: The CHEOPS payload fully assembled before delivery. Right: The telescope with mirrors installed and cover open before full OTA assembly.

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

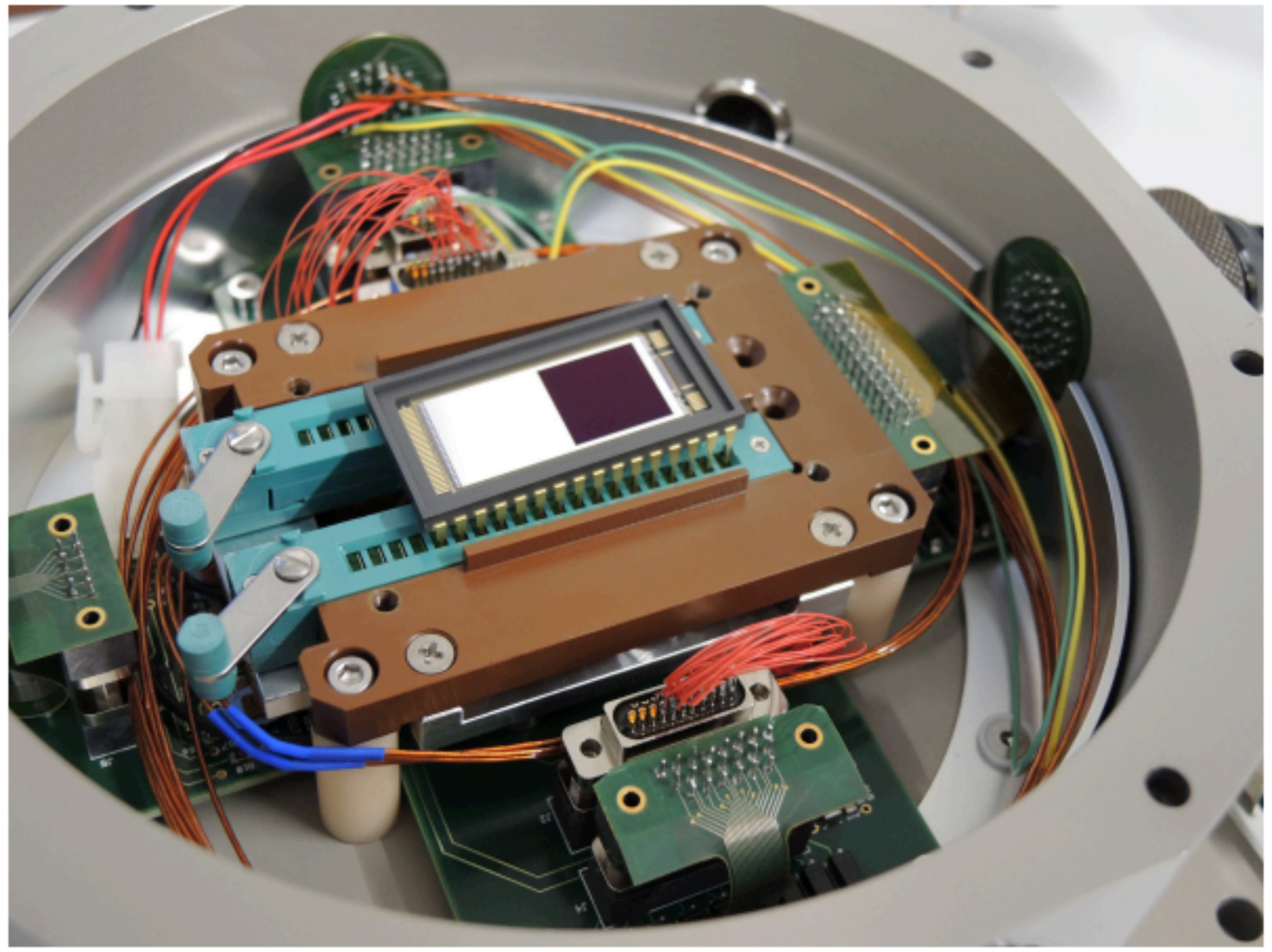


Fig. 9 CHEOPS CCD mounted in the cryostat of the University of Geneva.

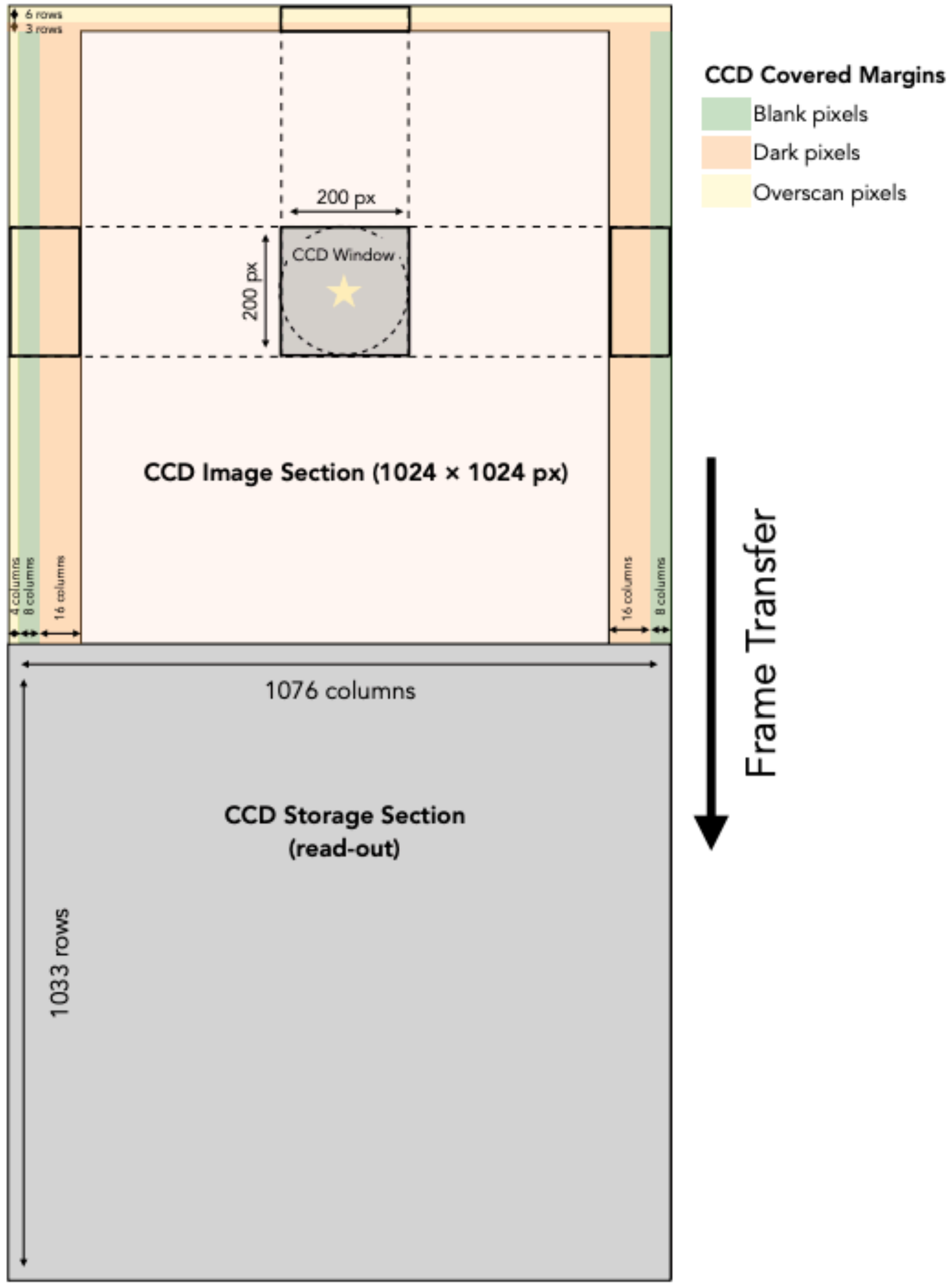
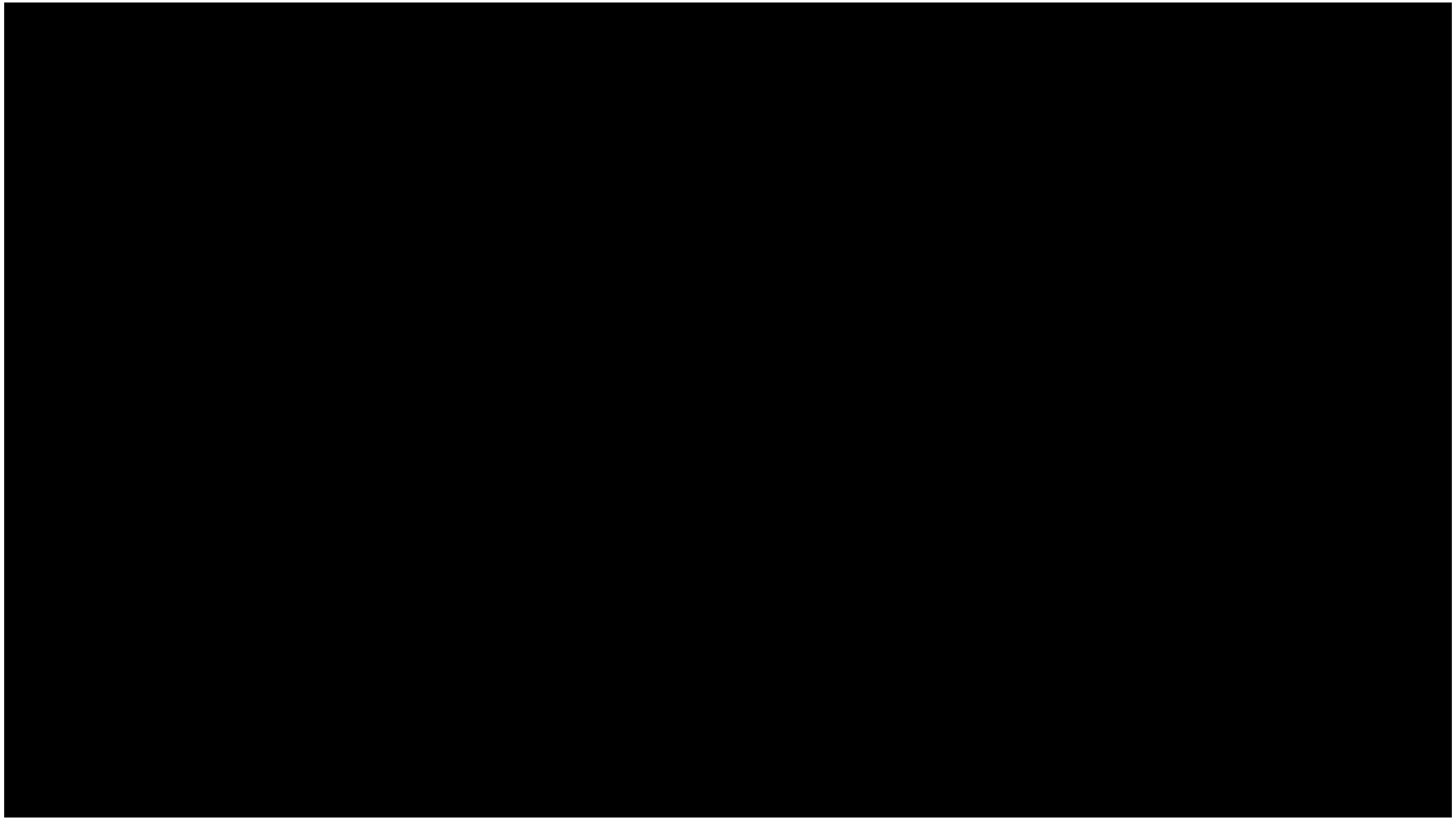


Fig. 8 Schematic view of the CCD elements.

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

CHEOPS: A space telescope to characterize exoplanets

CHEOPS’ orbit



The CHEOPS Data Reduction Pipeline

The CHEOPS Data Reduction Pipeline

The Data Products: From images to light-curve

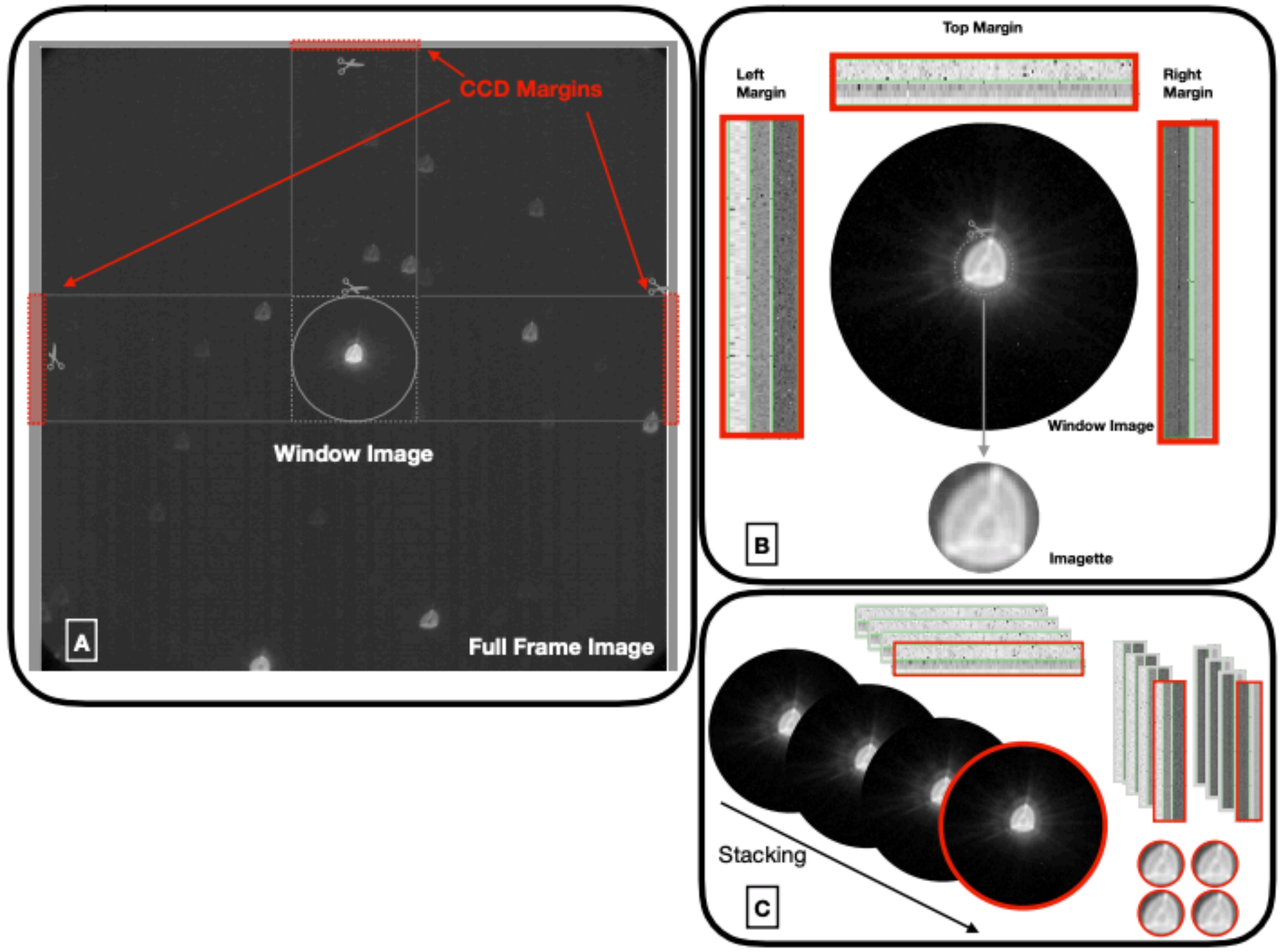


Fig. 10 This figure illustrates the on-board data processing. Panel A shows a full-frame image (1024x1024 plus CCD margins). Due to the limited bandwidth capabilities, all full-frame images cannot be down-linked to the ground. Therefore, circular window images with the target on their centre are cropped. 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".

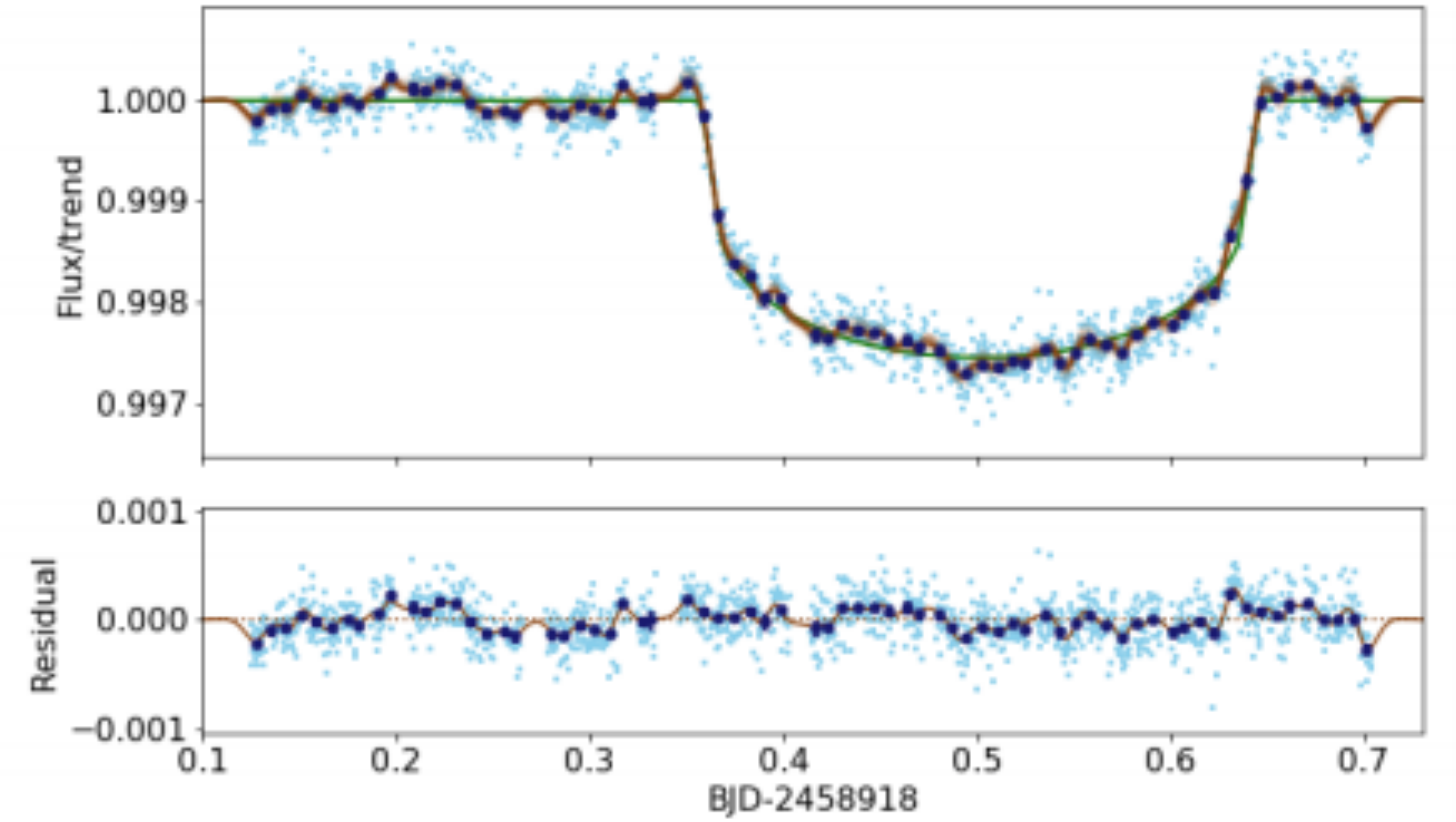
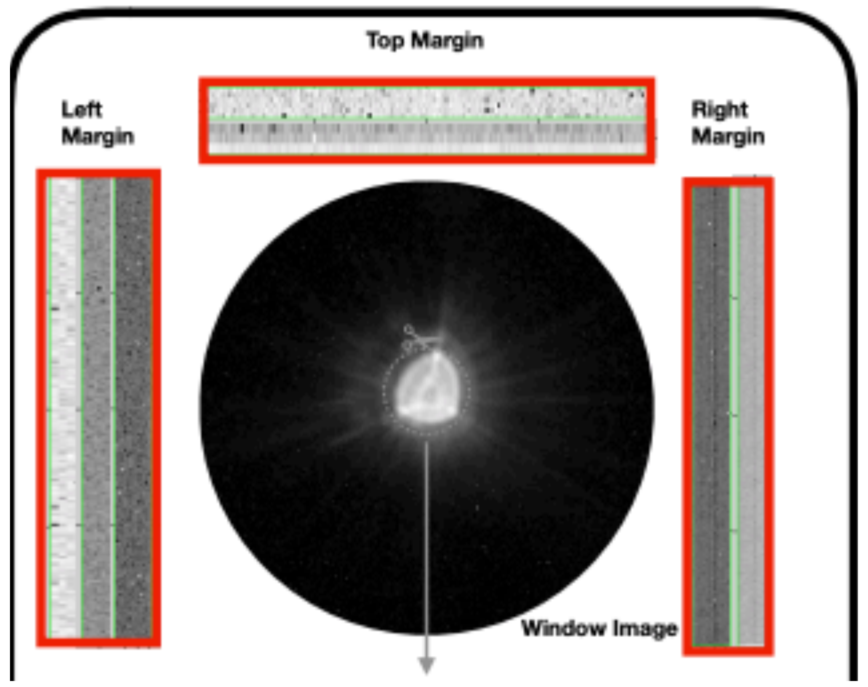


Fig. 15 Observed light curve of KELT-11 and model fit from pycheops. The measured fluxes (light blue points) are also shown binned in time (dark blue points). The transit model (green line, barely visible) is shown in the upper panel together with the several realisations of our complete model including 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



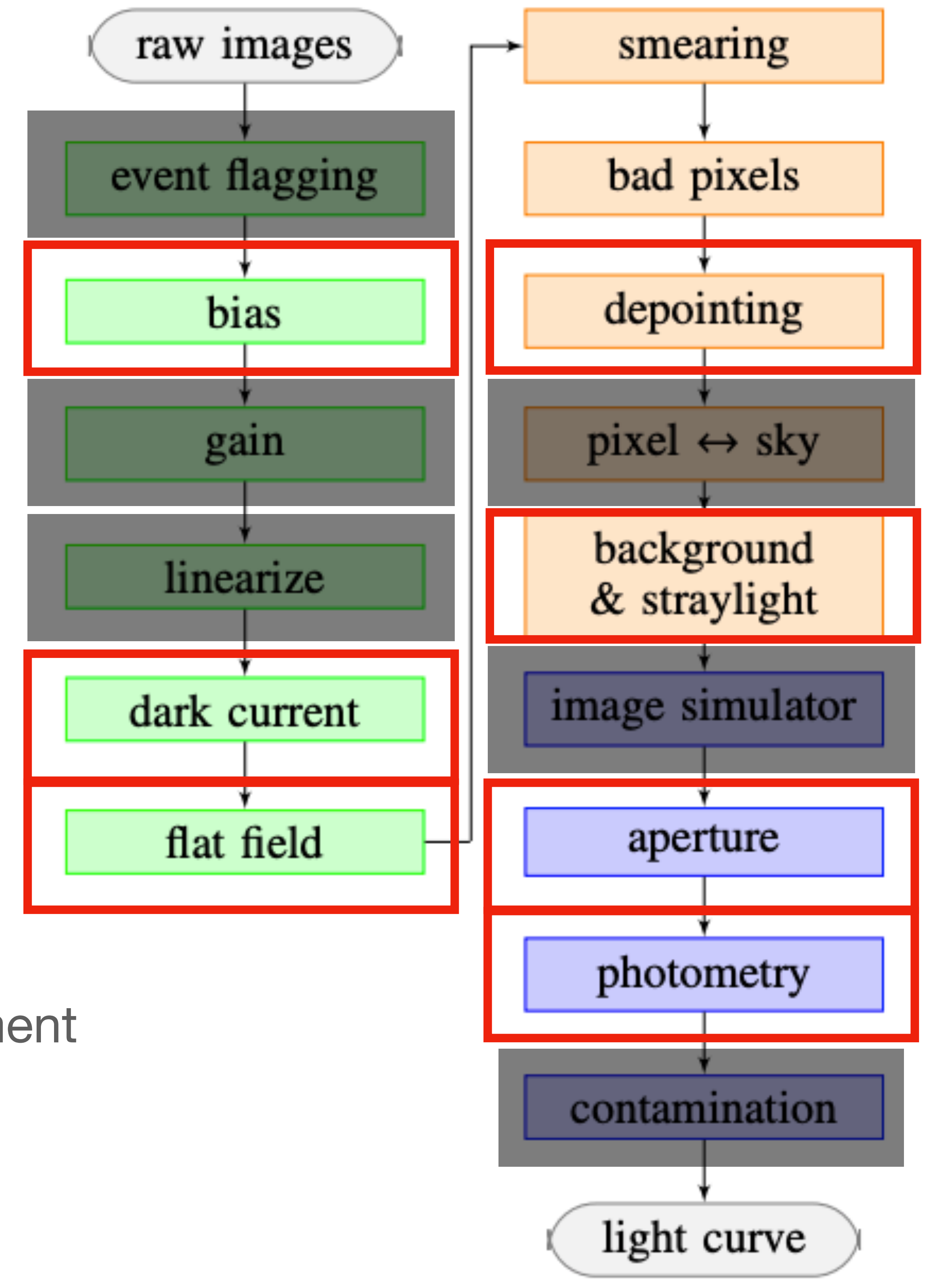


Fig. 1. Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

Step that you should try to implement

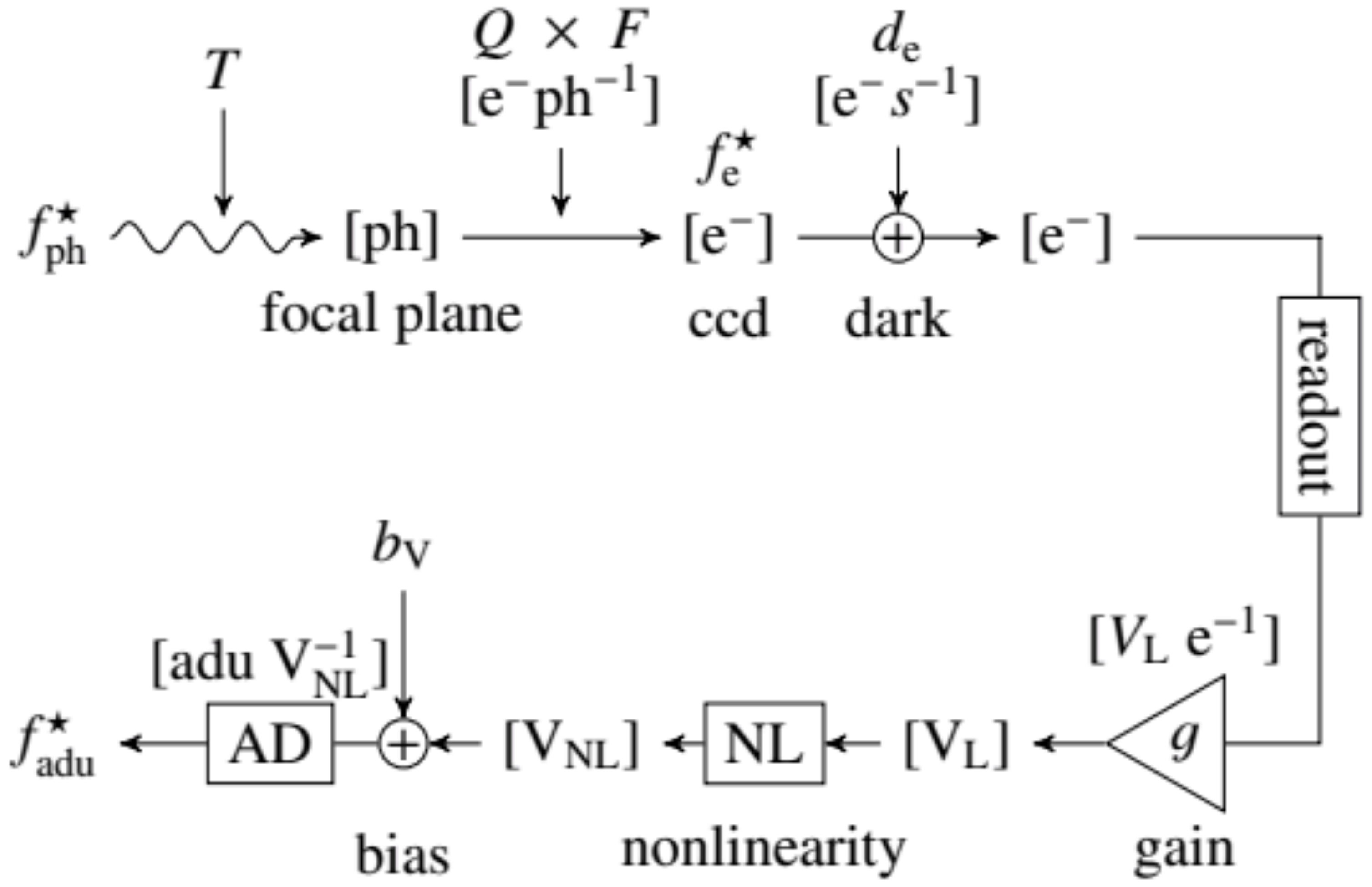


Fig. 2. Signal chain. Following the main arrow, $f^{\star}_{\mathrm{ph}}$ is the input photon flux. The units of successive transformations are given in brackets: [ph] photons, [e$^-$] electrons, [V$_{\mathrm{L}}$] and [V$_{\mathrm{NL}}$] linear and nonlinear volts, and [adu] the analog-to-digital units. T is the optical throughput, Q is the quantum efficiency, F the flat field, d_{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_{V}. AD is the analog to digital converter. The output is the raw image $f^{\star}_{\mathrm{adu}}$.

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 (https://sites.google.com/cfa.harvard.edu/saoimageds9) and fv (https://heasarc.gsfc.nasa.gov/ftools/fv/)
- How to read the data with Python (jupyter notebook)
  Anaconda (https://www.anaconda.com/products/individual) one way to install Python and the required
- 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
  - Presentation of your work on 26/05 and report due by the 28/05.
  - 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 and presentation will be in english and for the report use the A&A article LaTeX template.

Second class

The other steps: Bias correction

Step that you should try to implement

Let's look at one way to do it

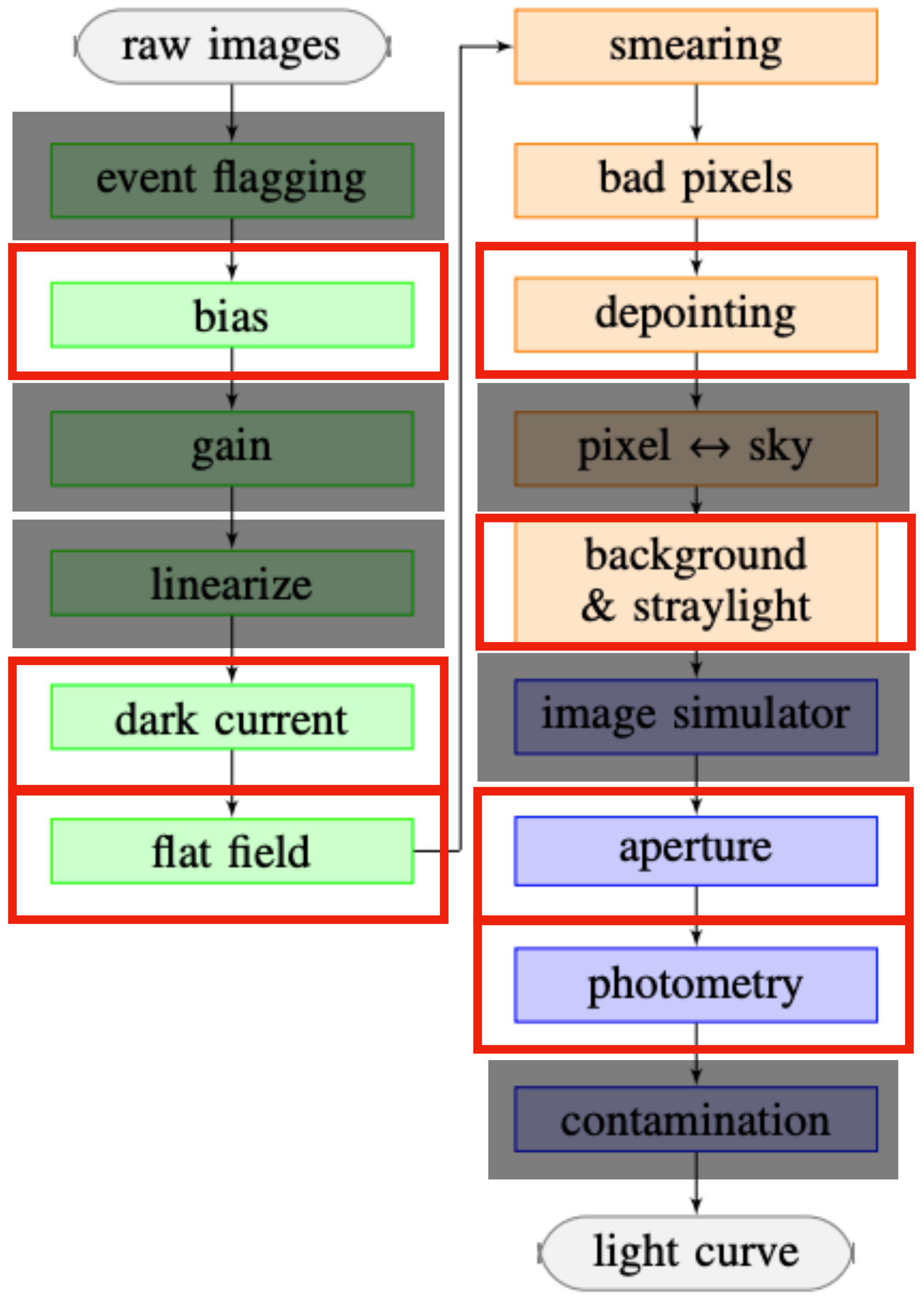


Fig. 1. Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

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)

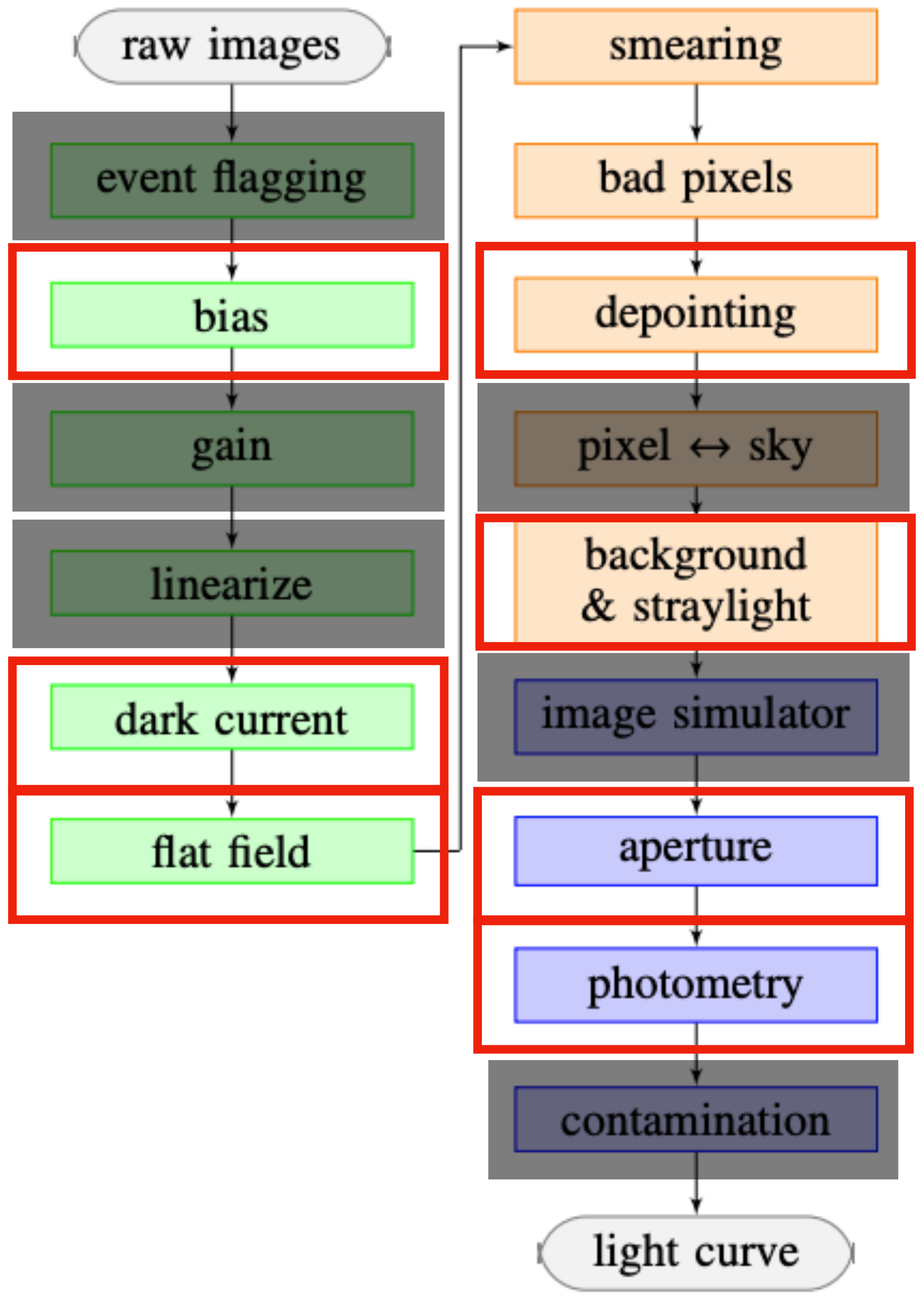


Fig. 1. Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

The other steps: Flat-field correction

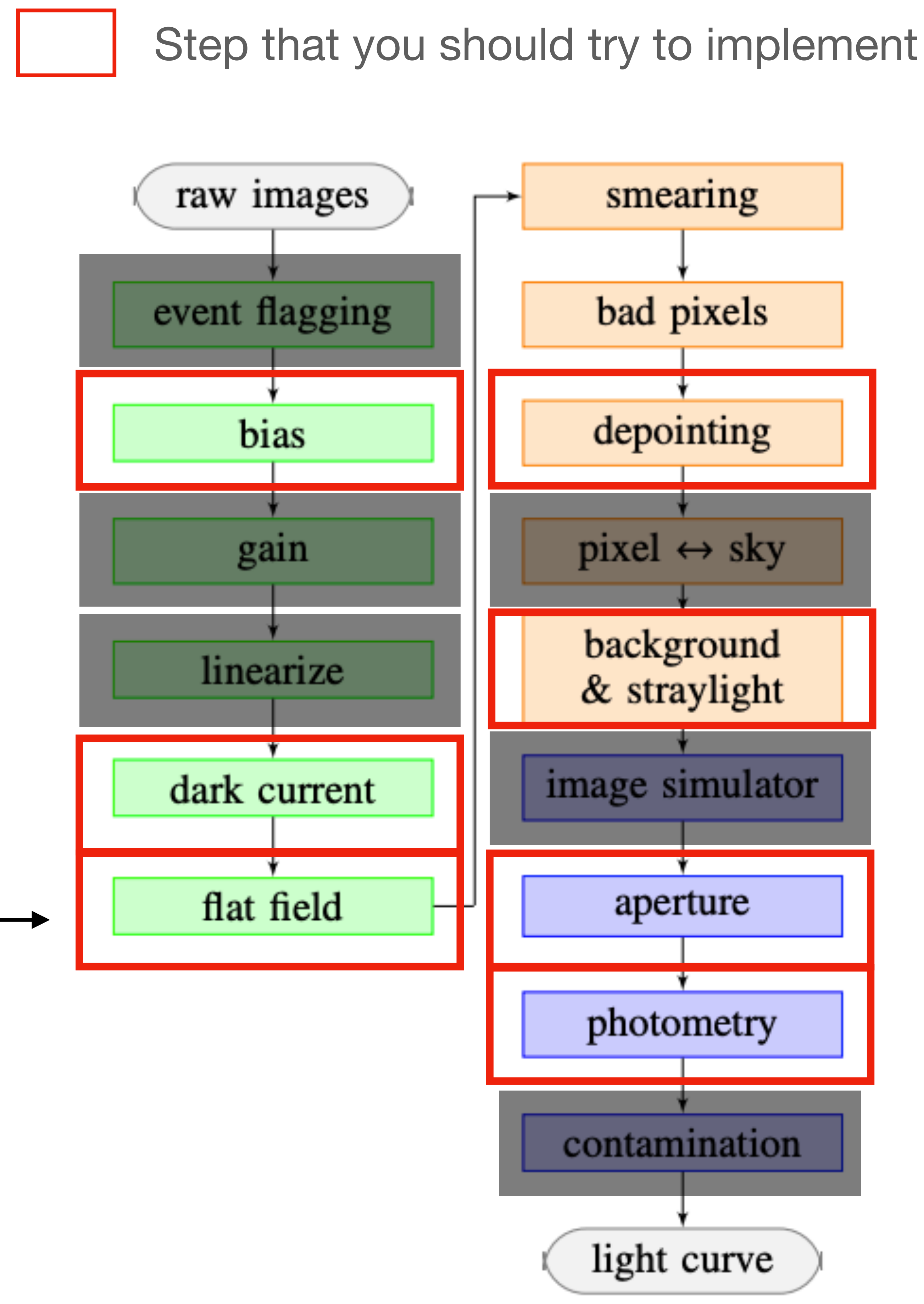


Fig. 1. Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

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

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

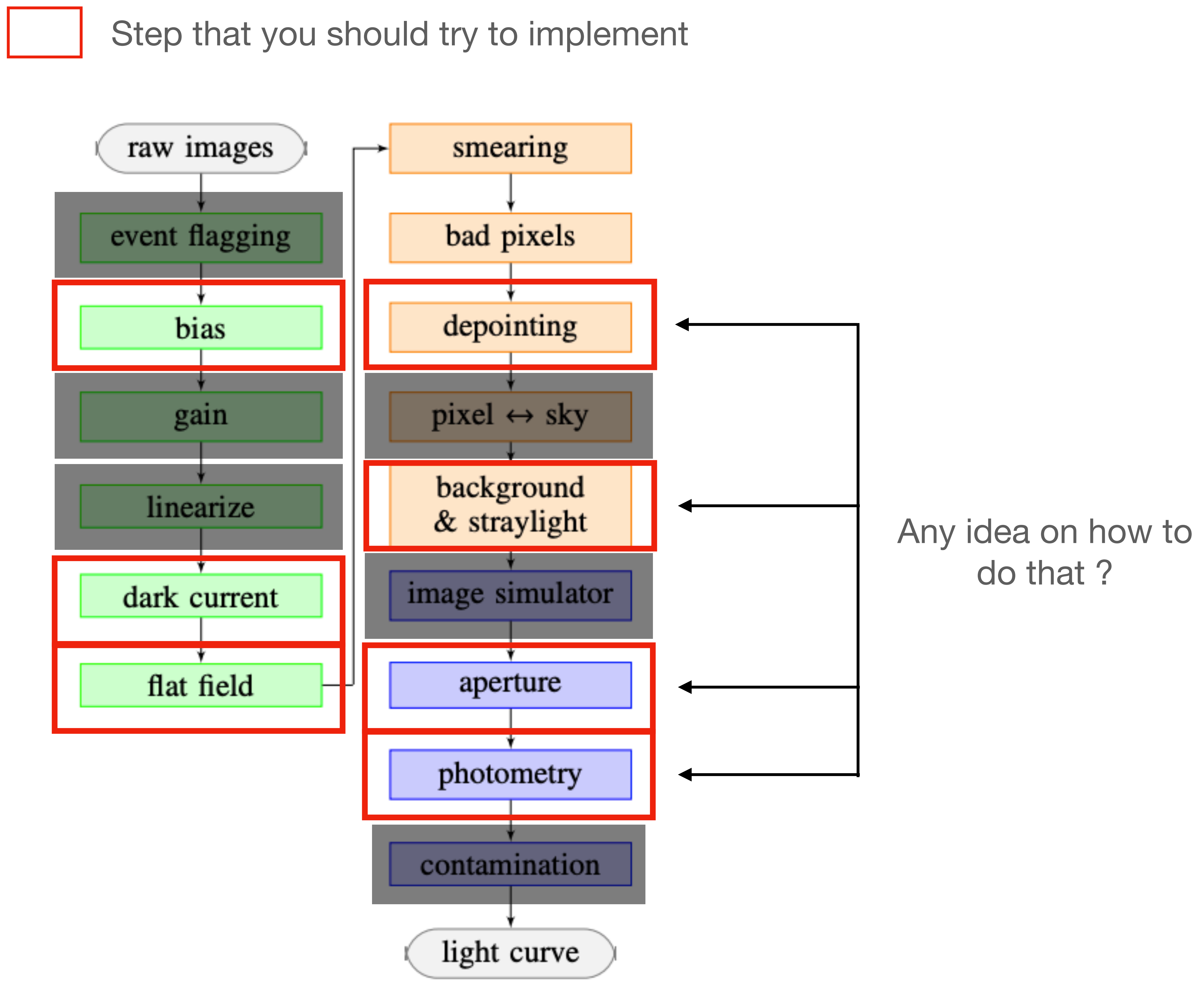


Fig. 1. Data reduction flowchart. Green, orange and blue color are calibration, correction and photometry main modules, respectively.

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 correction and when is it not necessary to improve further ?
- How to estimate the precision of your light-curve ?

Third class

Model for the transit of an exoplanet

- Reference paper: Seager & Mallén Ornelas 2003: https://ui.adsabs.harvard.edu/abs/2003ApJ...585.1038S/abstract

- One commonly used model for thre representation of a exoplanetary transit: batman package: https://lkreidberg.github.io/batman/docs/html/index.html
Reference paper: Kreidberg 2015: http://adsabs.harvard.edu/abs/2015PASP..127.1161K

- Let's have a look with a notebook on the github repository: https://github.com/odemangeon/pw_cheops

What is fitting ?

A very brief introduction

- Fitting is the action to adjust to parameter of model to find the best agreement between the model and a set of data.

- The best agreement is found by minimizing a cost function. One common type of cost function is the Chi-square.

$$\chi^2 = \sum_i^N \frac{\left[y_i^{\text{meas}} - y_i^{\text{model}}(\mathbf{v})\right]^2}{\epsilon_i^2}$$

  and the associated reduced chi-sc ed by the number of degrees of freedom in the model (~ number of parameter that are adjusted). The closer the reduced chi-square is to 1, the better is the fit. Values below one indicate over-fitting

- There are different procedure to explore the parameter space and find the minimum (minima) of the cost function. Two of the most common ones are gradient based methods and Monte-Carlo Markov Chain.

- The package lmfit implements different fitting procedure we are going to see how it works in the notebook.

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