HOPS

HOlomon **P**hotometric **S**oftware

v3.3.3

USER MANUAL

Prerequisites

To be able to run HOPS on your computer you need the below requirements:

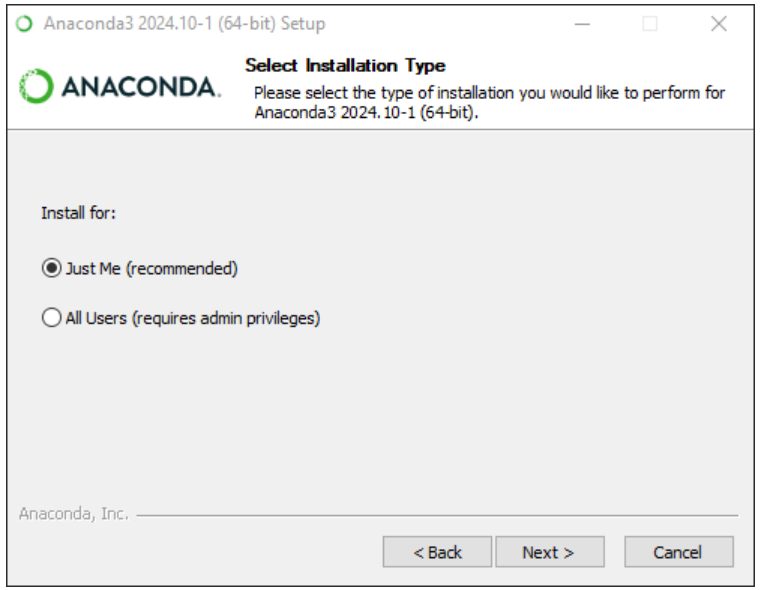
- Windows, MacOS or Linux
- 4 GB or more available RAM
- 4 GB or more free disk space
- Python version 3.7 or later (version 3.8 or later is recommended)

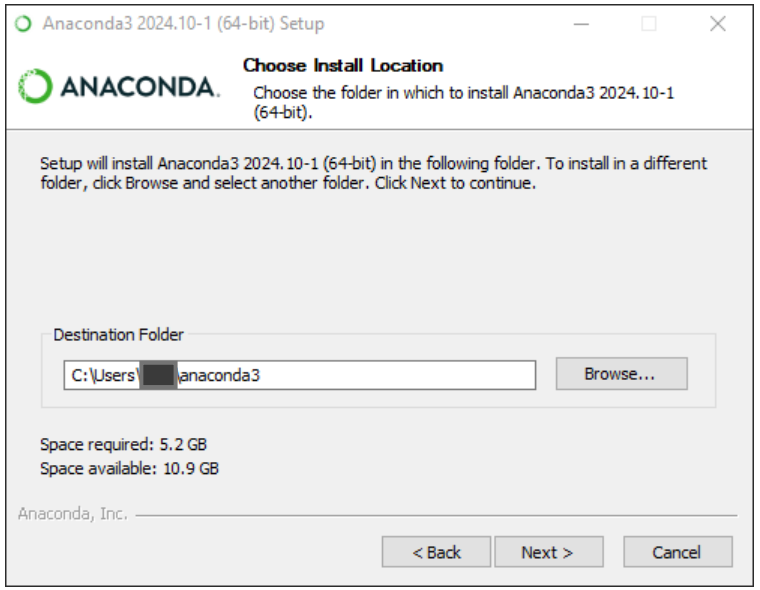
!!!If you have not installed in your computer Python, refer to the following slides.

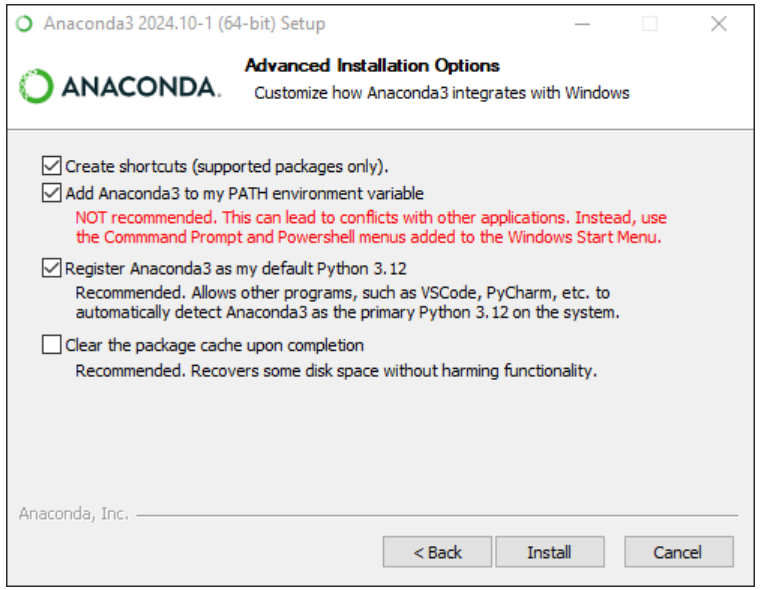
If you have already installed Python, you may skip them.

Python Installation

- Download Python from www.anaconda.com/products/individual#download-section
  - Choose the version you want to download depending on your operating system
  - Follow the on-screen installation instructions
- **For Windows** users:
  - Install Python for you only (as recommended)
  - Use any destination you prefer (or the default)
  - Add python as a system variable







Python Installation Verification

➢ **For Windows** users!

- Open a Terminal (Command Prompt for Windows)
- Type **python**
- Check that the Terminal enters a python environment like this: **Python 3.8.5 (default, Sep 4 2020, 02:22:02) [Clang 10.0.0] :: Anaconda, Inc. on darwinType "help", "copyright", "credits" or "license" for more information. >>>**
- **Or** before this step run the commands
    - **python –version** (verifies the Python version)
    - **conda ––version** (verifies the Anaconda itself)
    - **conda list** (verifies the packages installation)

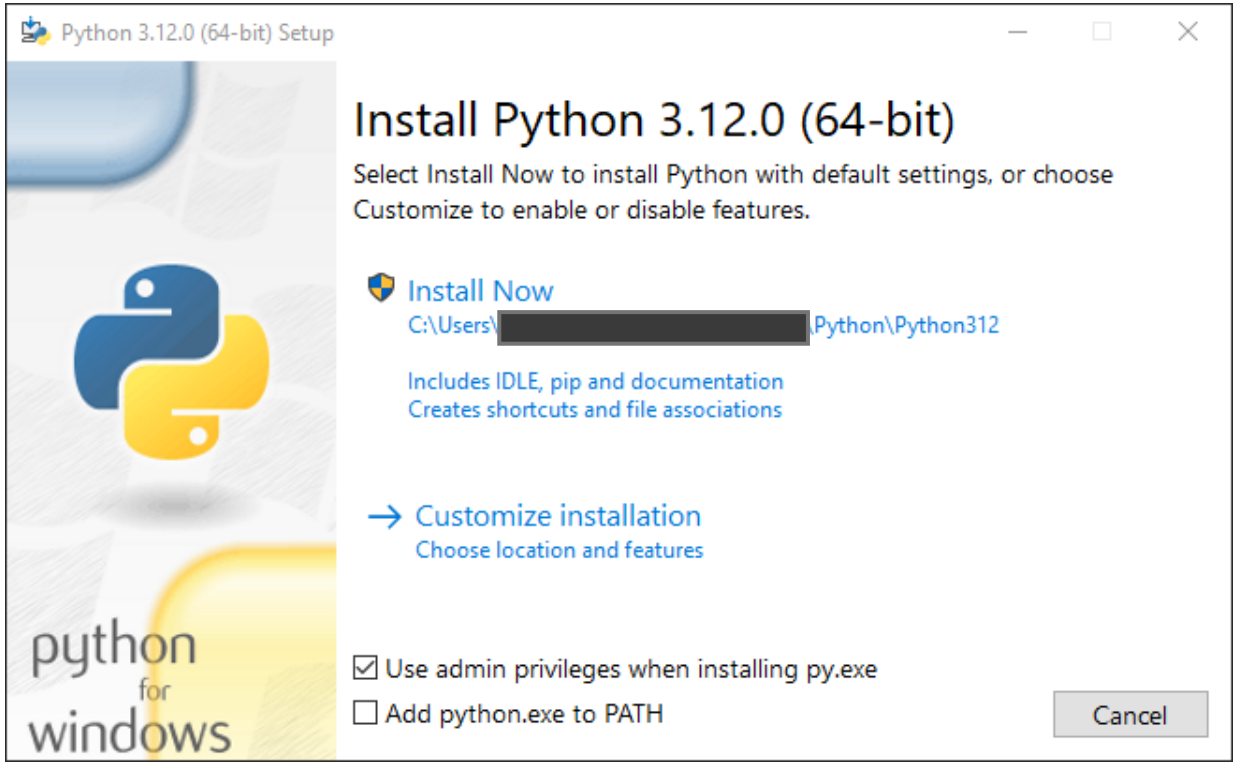
➢ If the command is not recognized:

- Close Command Prompt
- Add Python to the system variables manually (refer to this site: https://geek-university.com/add-python-to-the-windows-path/
- Start the verification process again

Python Installation

- **Alternatively**, download Python from https://www.python.org/downloads/
- Choose the Release version you want with a maintenance status "***security***"
- Choose to download the file "Windows Installer (64-bit) if your operating system is Windows.

- You can press the "Install Now" to install Python using a predetermined path to your computer
- For customizing the path or some of its features' press "Custom installation"



HOPS Installation

- Visit https://www.exoworldsspies.com/en/software/
- Click of the download button for the latest version
- Unzip the file “hops-master.zip”
- Double click on the “installer” files inside the extracted folder depending on your operating system
- A new file named “hops” will be created on your computer desktop
- Double click on it to start HOPS

➢ Known issues for **MacOS Mojave 10.14.6** users:

TkIner, the GUI backend used by HOPS, is not working properly on this MacOS version, causing a user log out. To solve this issue, you will need to either upgrade your MacOS to Catalina or downgrade your Python to 3.7.0

Before running HOPS

- Secure your Reduction frames!

- Use the same **camera temperature**, **binning** and **subframe** as the science frames.
- Obtain at least five bias frames (**zero exposure**, **using a cover**), and check that there is no external light contaminating them.
- Obtain at least five dark frames (**same exposure time as the science frames**, **using a cover**), and check that there is no external light contaminating them.
- Obtain at least five flat frames (**pointing to a uniformly illuminated surface, with the counts at 2/3 of the full well-depth of your camera**), if you are using the sky, check that stars are not visible in your frames.
- **Do not apply any pre-processing** (for example do not create master frames) HOPS will create the master frames on the fly and use them appropriately.

Before running HOPS

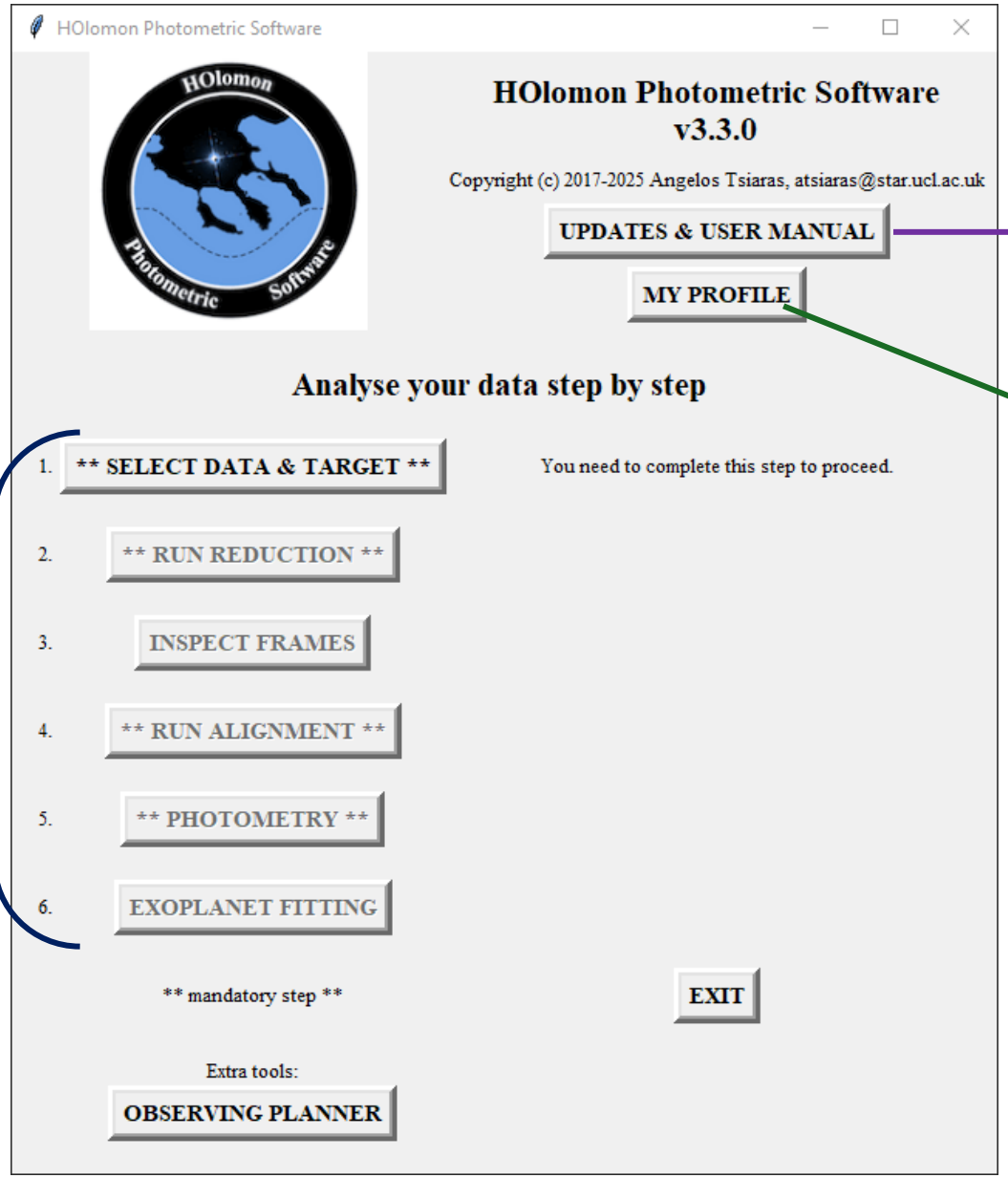
- Organize your data for easy access!

- Keep all scientific and reduction frames in one folder without subfolders.
- Use a specific identifier for the scientific frames,
  for example: "WASP-10b-001.fits", "WASP-10b-002.fits", etc...
- Use a specific identifier for the bias frames,
  for example: "bias-001.fits", "bias-002.fits" etc...
- Use a specific identifier for the dark frames,
  for example: "dark-001.fits", "dark-002.fits" etc...
- Use a specific identifier for the flat frames,
  for example: "flat-001.fits", "flat-002.fits"etc...

- Make sure each category of frames have its own distinct, different name!

- For practice you can also use existing data: https://www.exoworldsspies.com/en/observers/

Running HOPS - Main control window



Easy access to the user manual

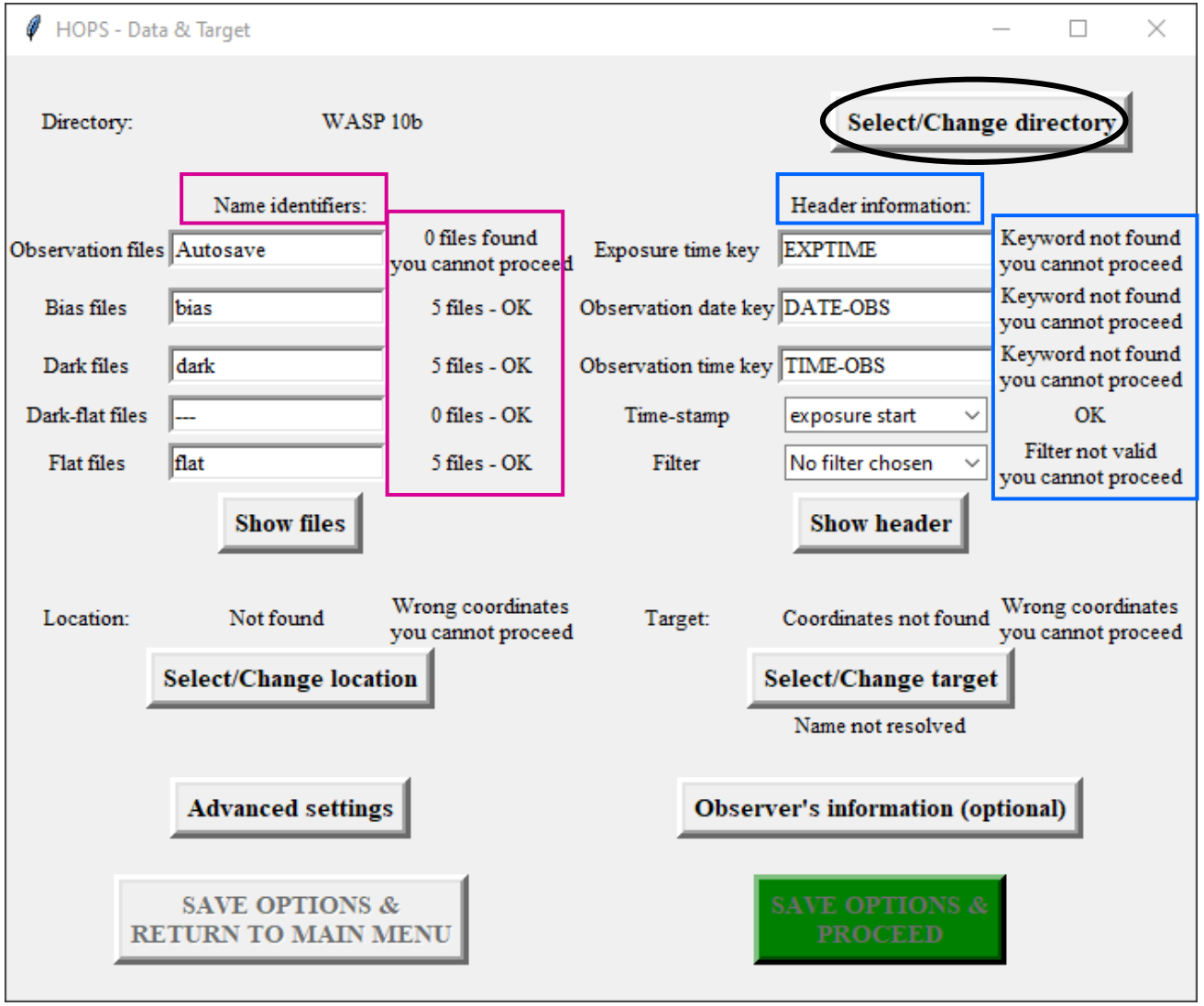
Personalize parameters for processing personal data

The 6 steps one can follow for analyzing the data.

The steps 1,2,4,5 are mandatory

Step 1: Select Data & Target

Begin by clicking on STEP 1: Select Data & Target



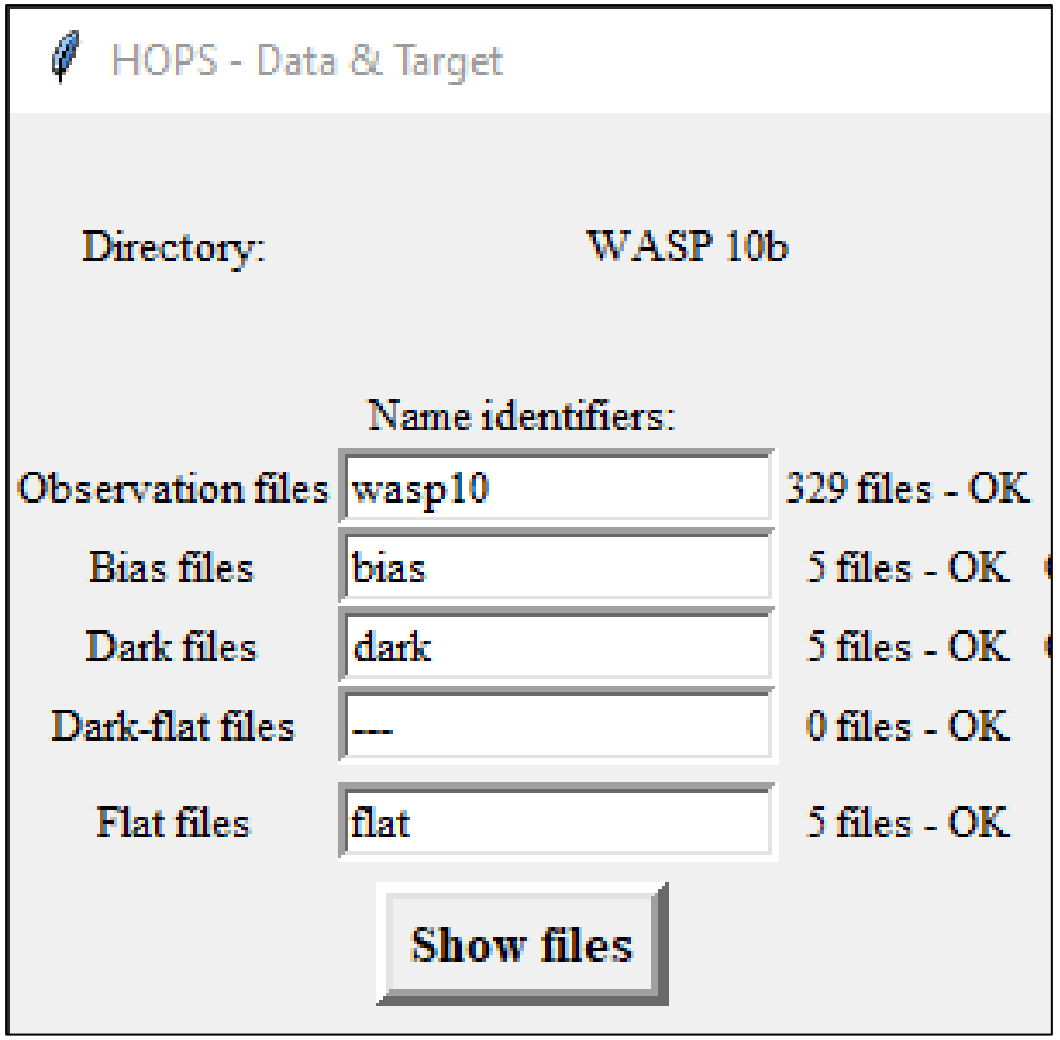
- **Select Directory**: select the file on your computer that contains all your frames.

As an example, WASP – 10b is used

- Next the "Name identifiers" and "Header information" must be checked.

Step 1: Select Data & Target

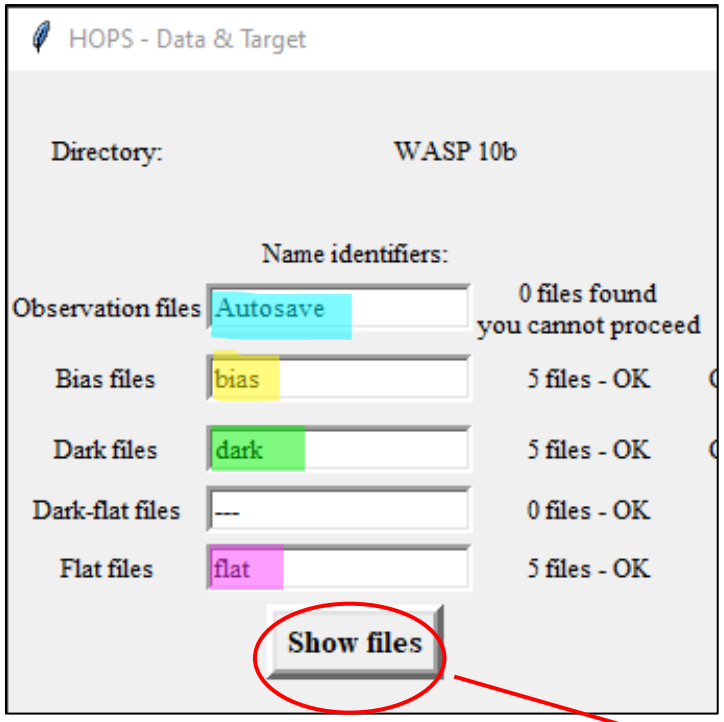
Name Identifiers



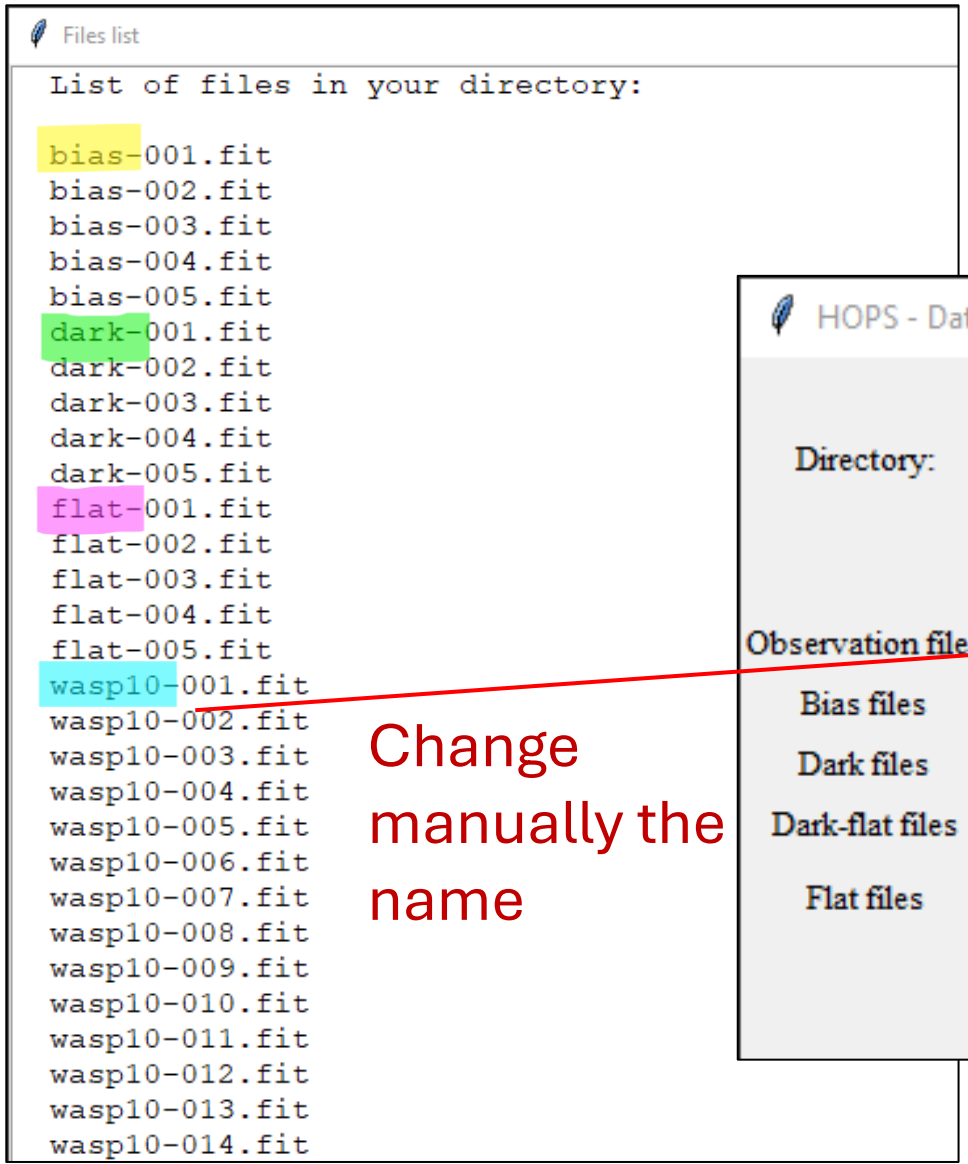
- The “Show files” button opens a second window showing all your files in your data directory.
- You cannot proceed with 0 observation files
- If you want to change the automatic name identifier, type your own name identifier.
- To show the message “OK” the name identifier for its of the files must be **the same** as in the file list.

Step 1: Select Data & Target

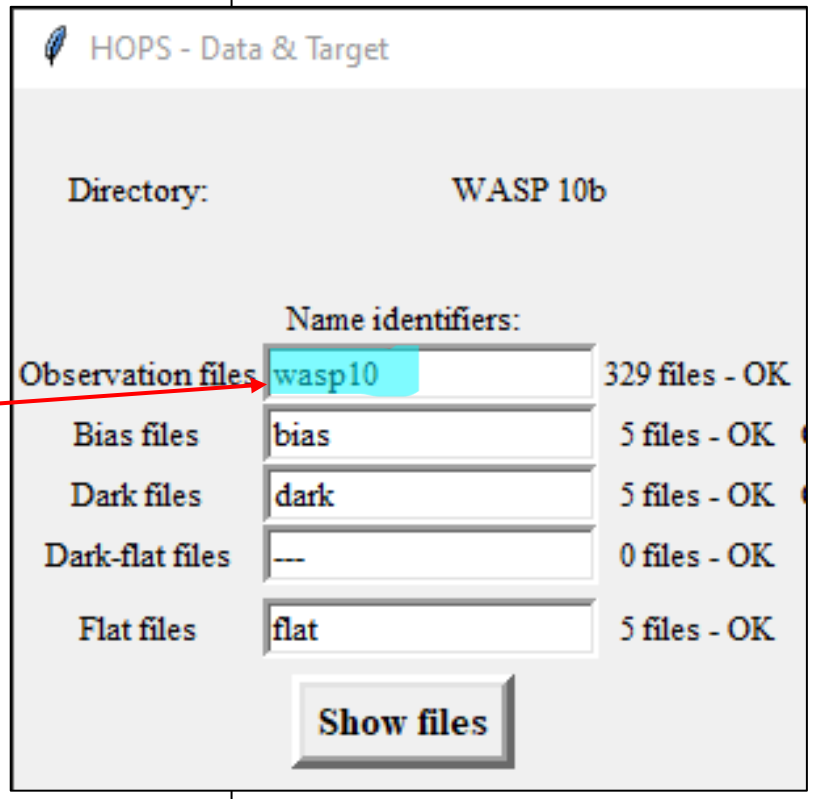
Name Identifiers



Click on



Change manually the name



Step 1: Select Data & Target

Tips for Reduction Frames

- It is suggested to not proceed without any reduction frames, but in some cases is unavoidable.
  - If your observatory provides fully reduced data, you can safely proceed without any bias, dark, or flat frames.
  - If your observatory provides bias-subtracted data, you can safely proceed without any bias frames.
  - If your observatory provides bias- and dark-subtracted data, you can safely proceed without any bias or dark frames.
- Do not proceed if:

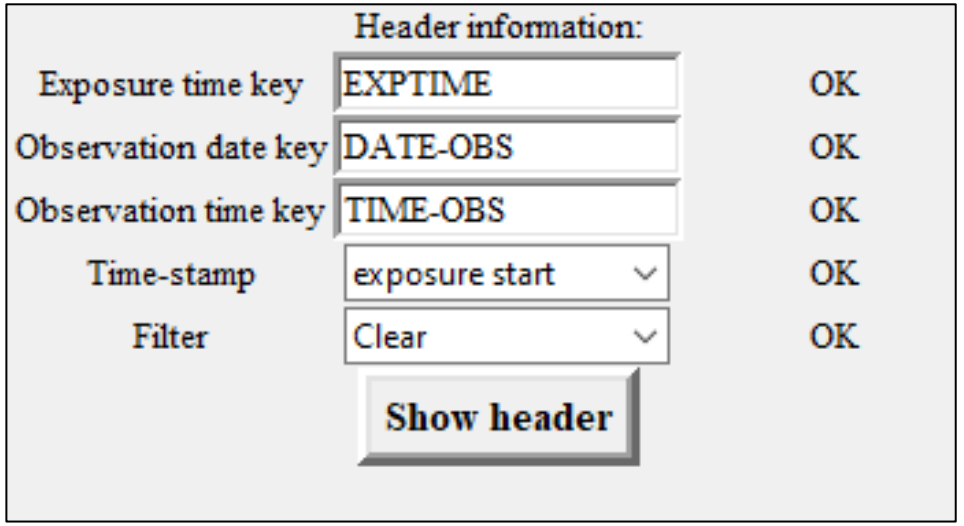
- you have raw data, dark and flat frames only. In absence of bias frames your reduced images will be distorted.
- you have raw data and flat frames only. Flat frames not corrected for bias and dark will cause problems to your reduced frames.

Step 1: Select Data & Target

Header Information

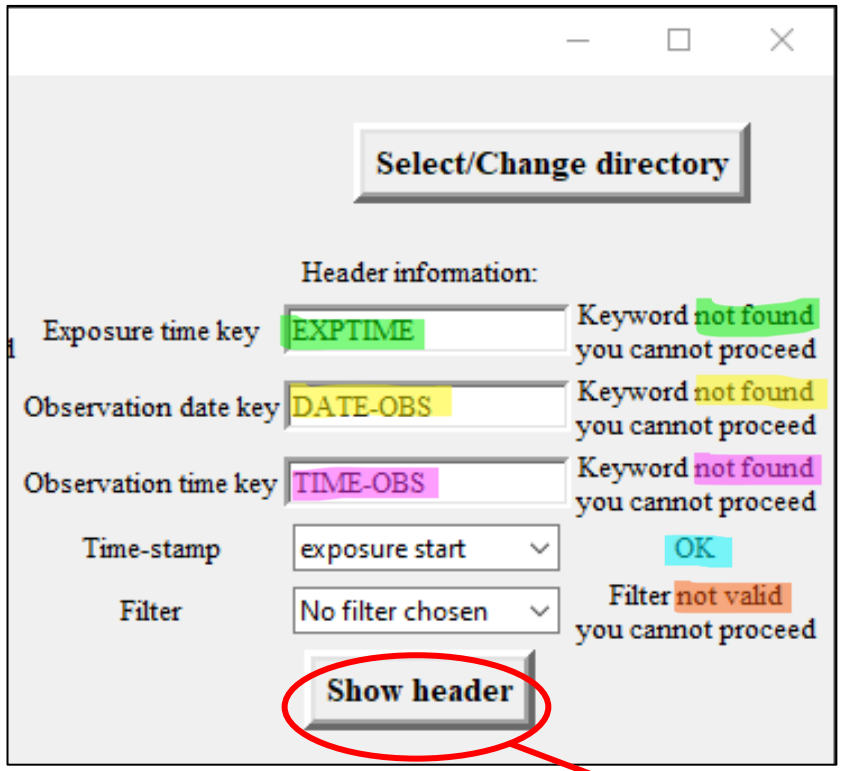
- The “Show header” button opens a second window showing the header for your observational files.
- To proceed, the message “**OK**” must be shown everywhere.
- You can check and type the names for *“Exposure time key”*, *“Observation date key”*, *“Observation time key”* from the ‘Header keywords list’.
- Select the time-stamp of your data from the *“Time-stamp”* drop-down menu.

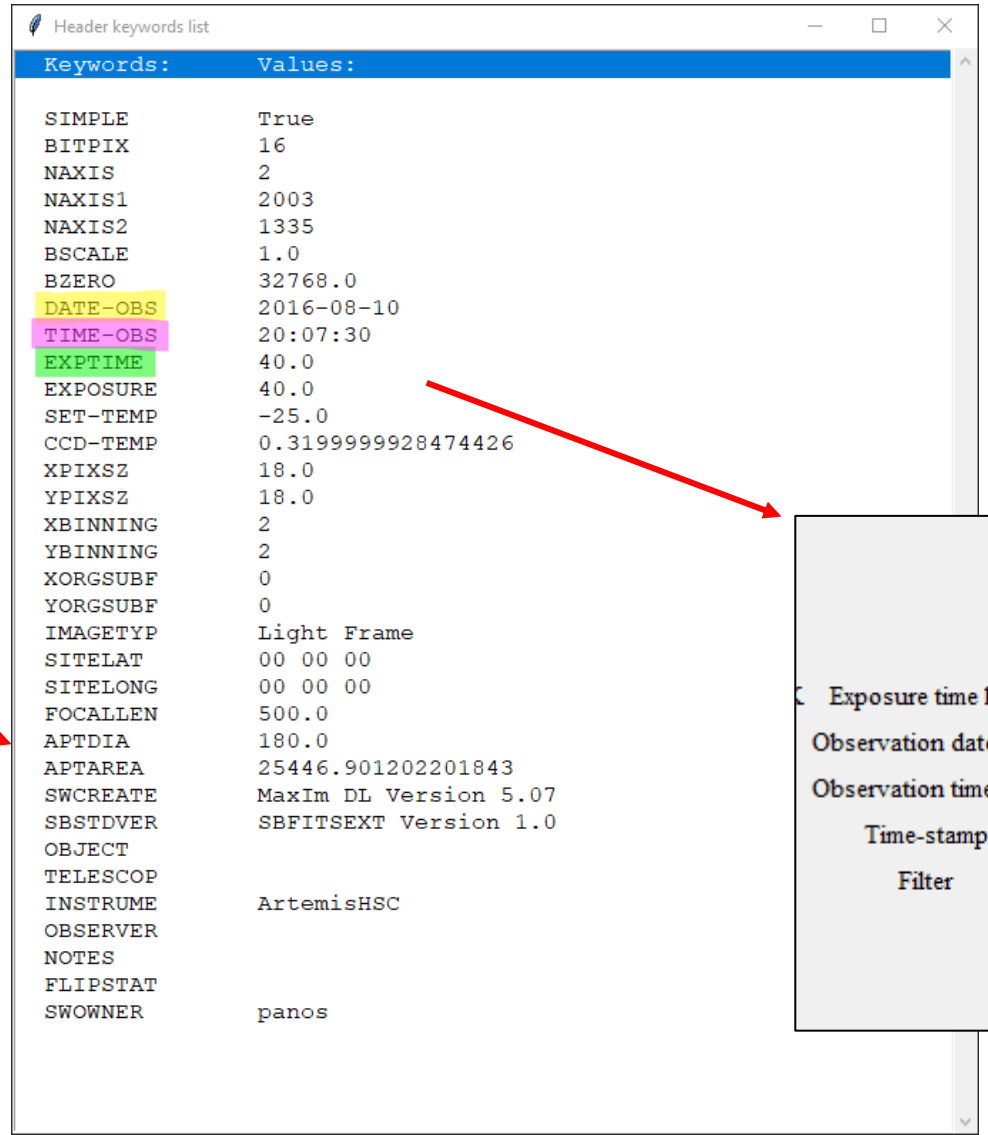
  Usually, the time saved in the *fits* header represents the exposure start time, but this may not be the case for you. Be careful to choose the correct time stamp!
- Select the filter used for your data from the *“Filter”* drop-down menu.

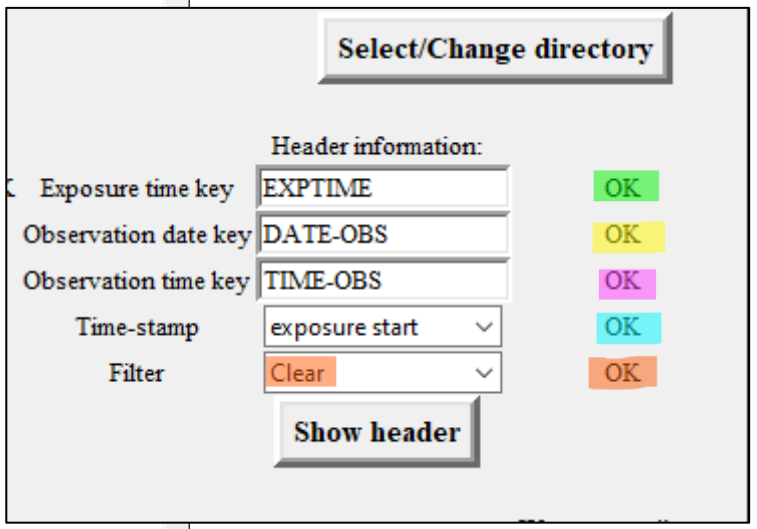


Step 1: Select Data & Target

Header Information







Step 1: Select Data & Target

Choose Target

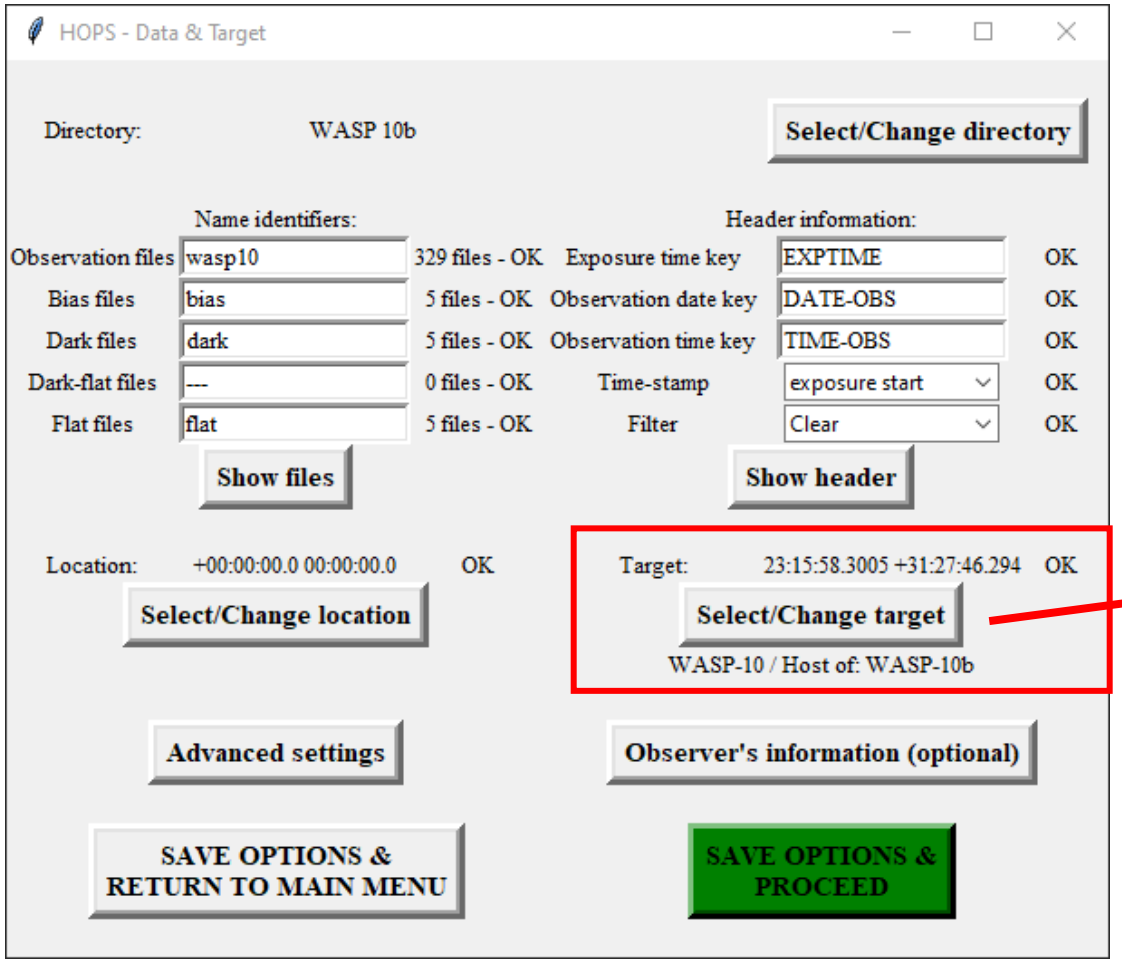
- Click on the “Select/Change target” button to choose your target.
- There are 3 options, and you can select any of those.

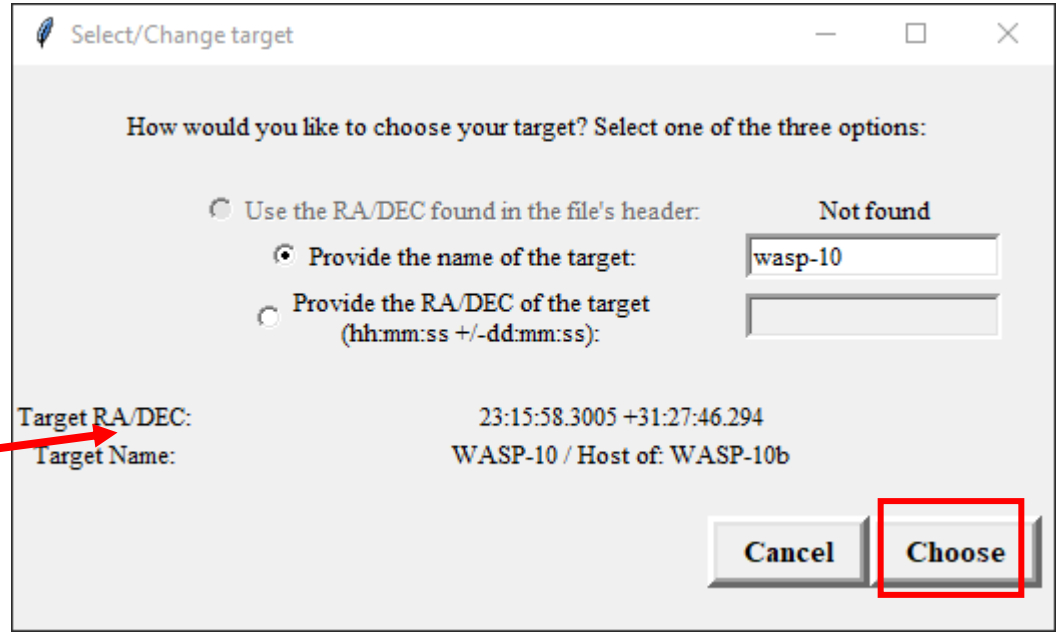
  - Option 1: is available only if the RA/DEC are included in the header of your images
  - Option 2: is available only if you have an internet connection as it utilizes coordinates from the SIMBAD database. To access these coordinates, provide the name of your chosen target.
  - Option 3: is always available, but you have to provide the RA/DEC in the appropriate format (+hh:mm:ss +/- dd:mm:ss)

Step 1: Select Data & Target

Choose Target

- Click on the “Select/Change target” button to choose your target.
- There are 3 options, and you can select any of those.

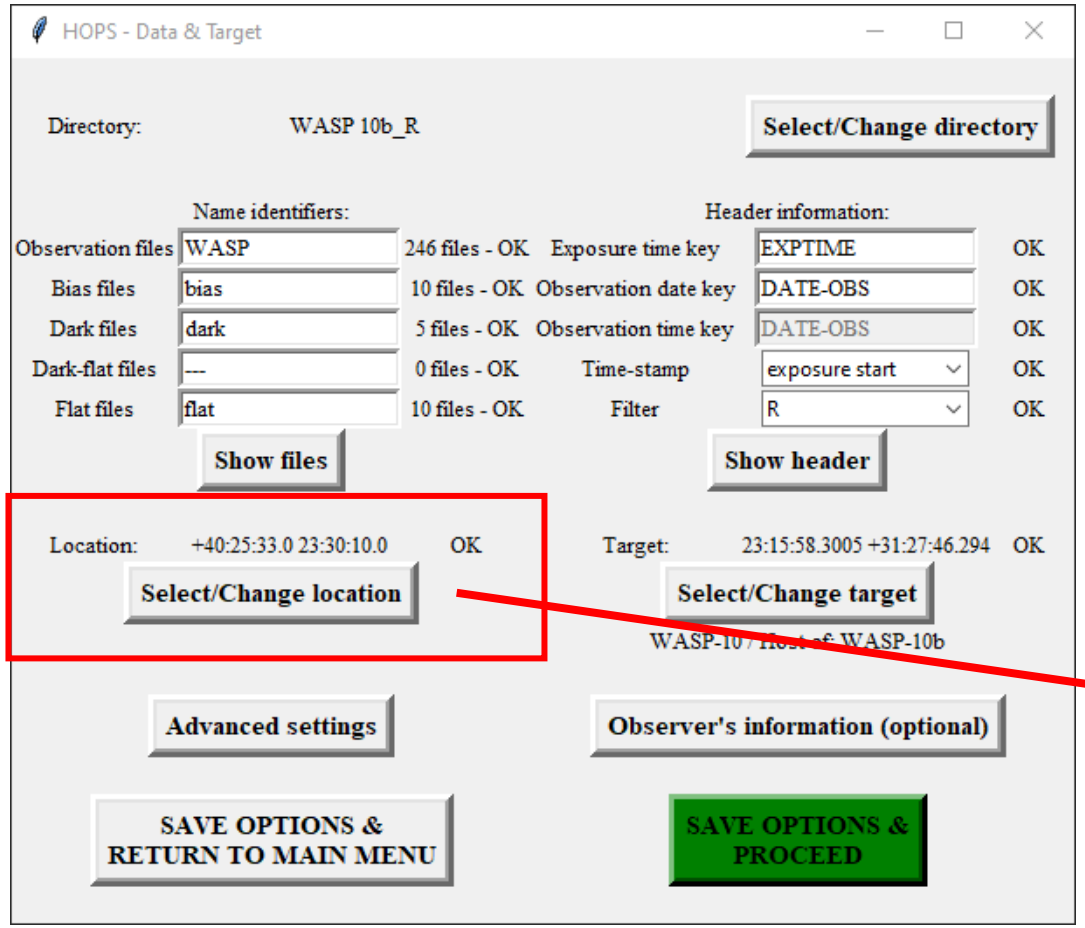


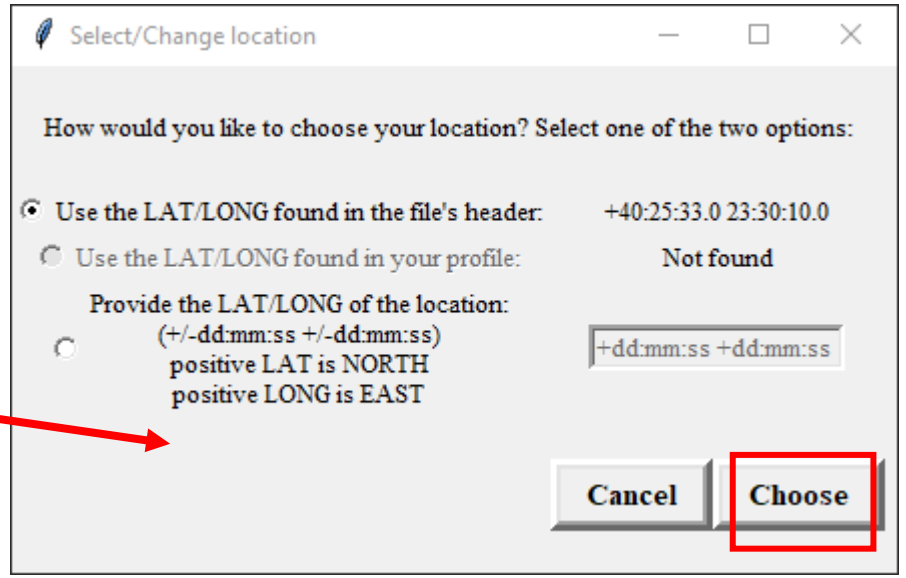


Step 1: Select Data & Target

Choose location

- Optional
- You can use the LAT/LONG provided in the file's header or choose differently



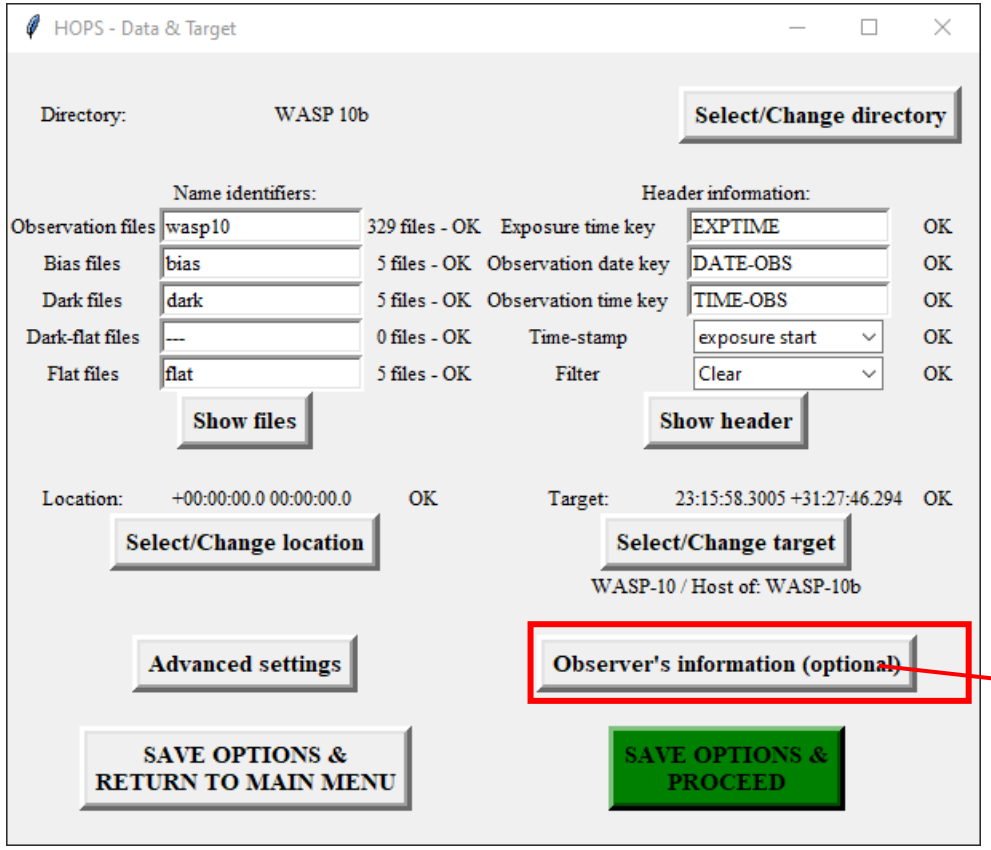


Step 1: Select Data & Target

Observer's information

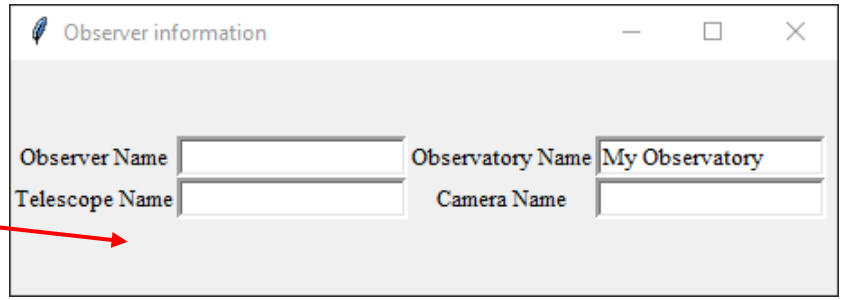
- Optional

- You can enter your personal information: your name, your observatory, telescope and camera name. They are not necessary for the analysis; however, they will be printed on the image with the final results.



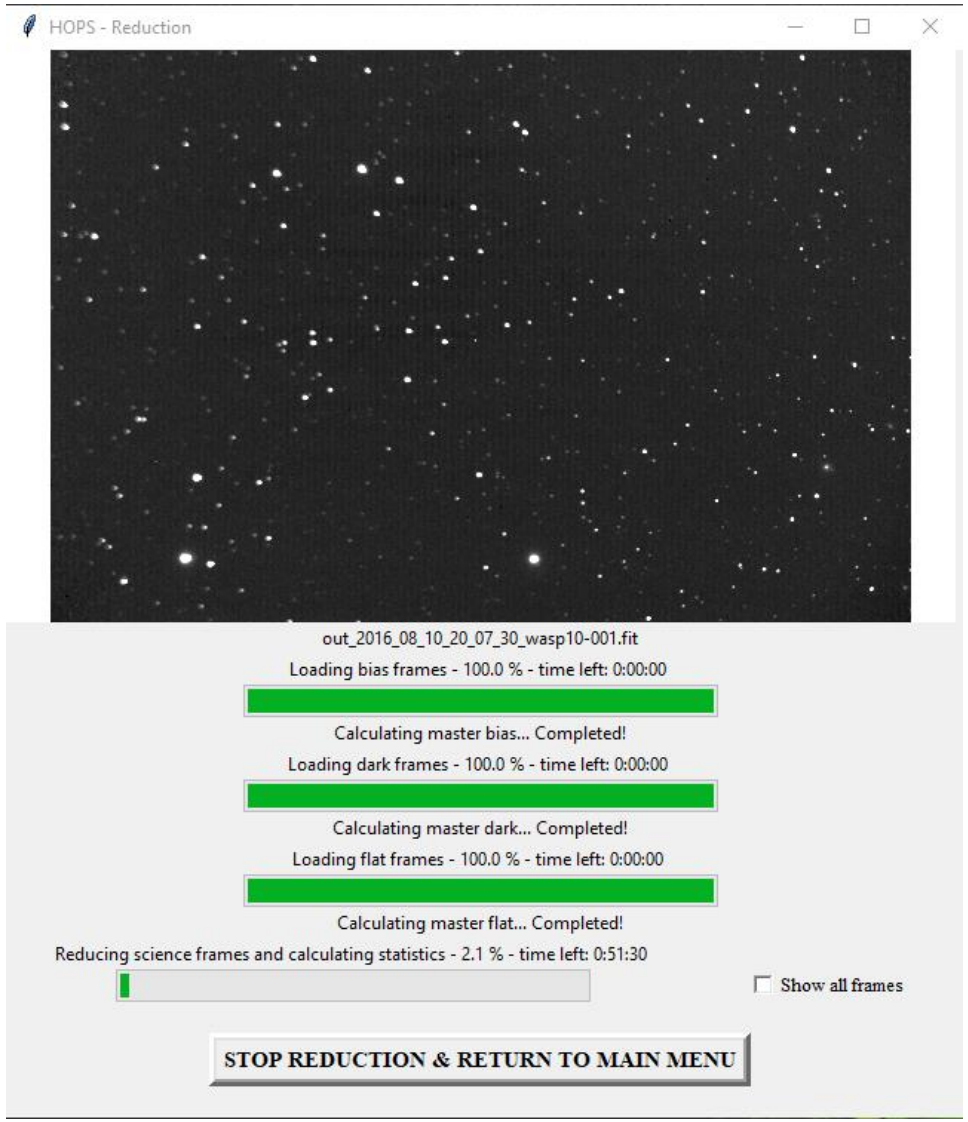
- **Now you can move on Step 2** by clicking "Save options & proceed"

- By clicking on "Save options & return to main menu", you can save your progress and return later.



Step 2: Run Reduction

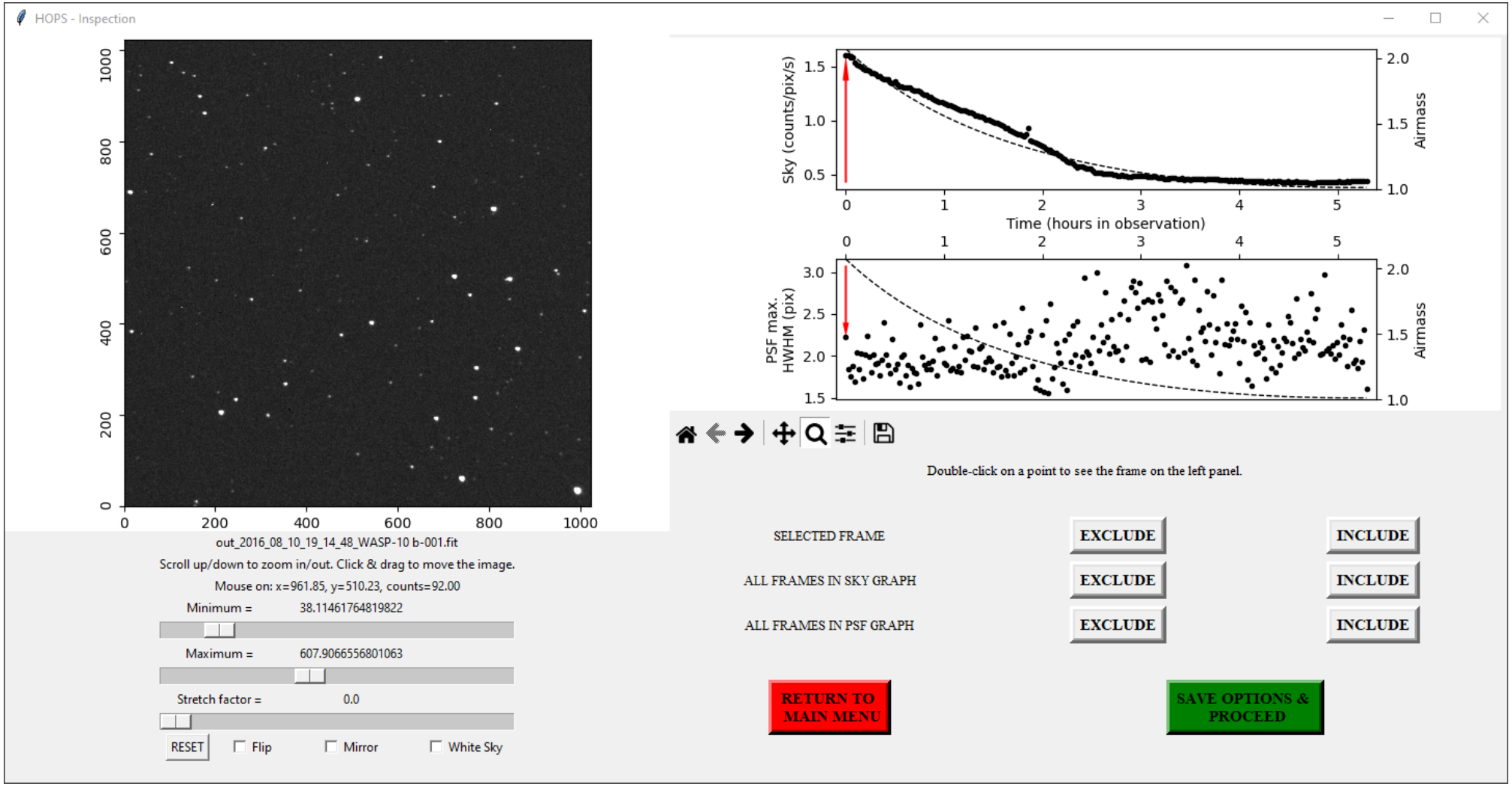
The process starts automatically after step 1



- For this step you just have to wait HOPS finish the reduction process.
  - *It might take some time!*
- Upon completion, automatically, you will advance on step 3.
- "Show all frames", displays all the images, if you prefer to visually inspect them.
  - *However, it will slow down the process.*
- To interrupt and stop the process, press "Stop reduction & return to main menu".

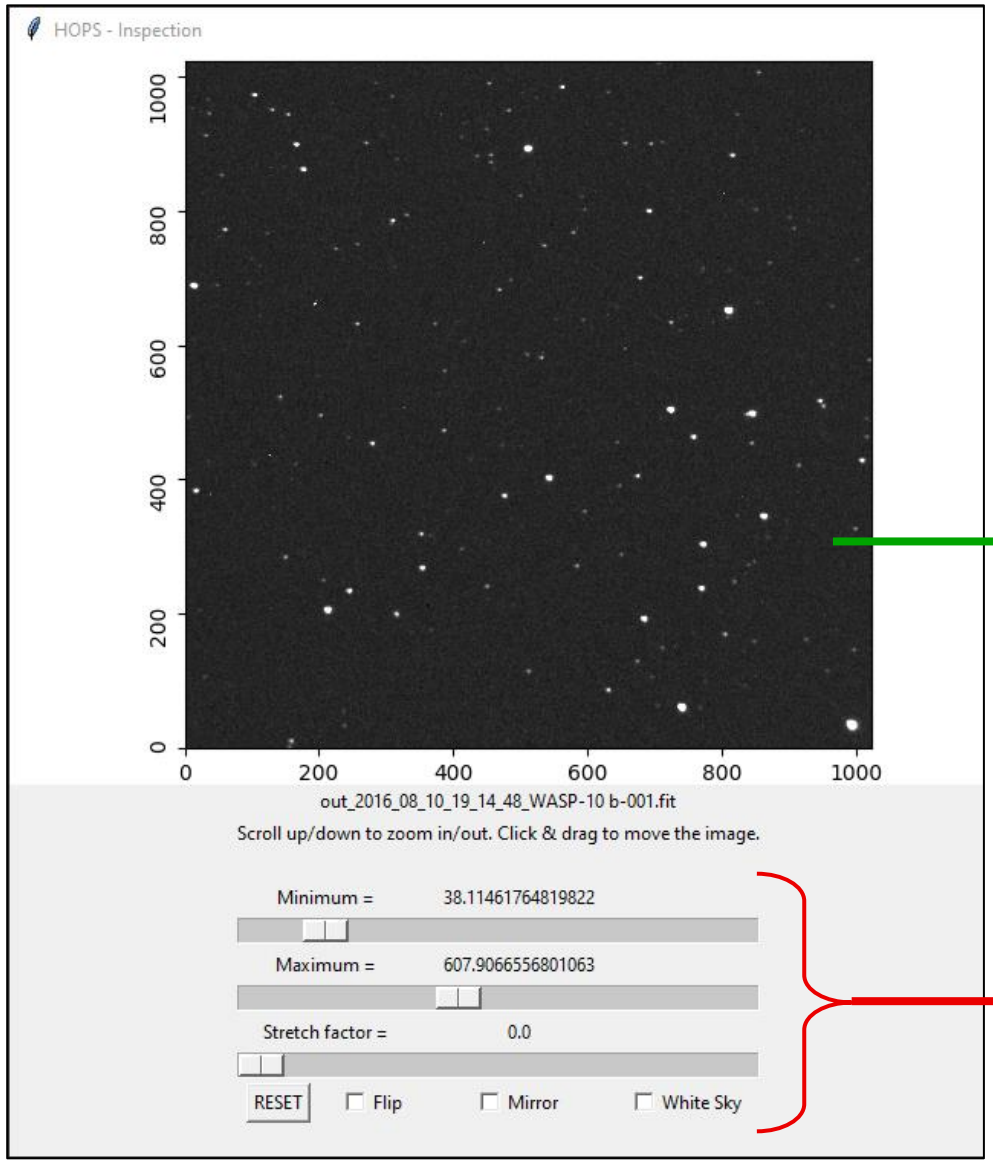
Step 3: Inspect Frames

This step is not mandatory however it operates as a filter for faulty images



Step 3: Inspect Frames

A filter for faulty images



➢ **Why filter out faulty images?**

Purpose of this inspection is to help you identify frames that have been affected by:

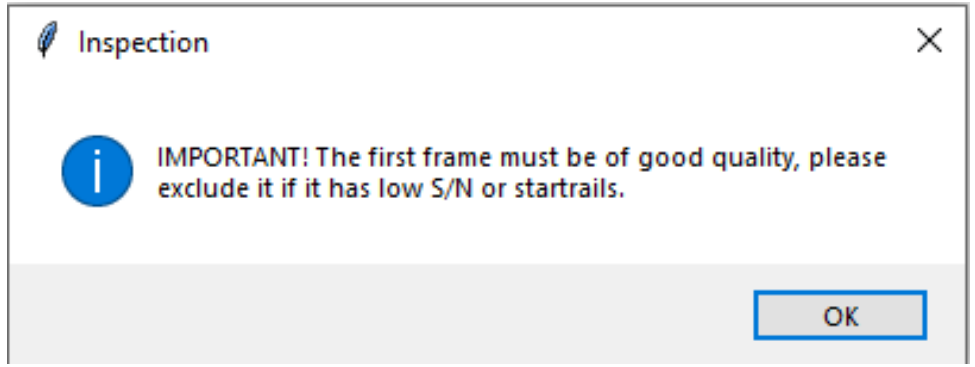
- Clouds or twilight (high SKY values)
- Pointing issues (high PSF values)

Visualization of an image. To pick an image double click on any point in the SKY or PSF graph. The selected image is shown with a red arrow.

You can adjust the contrast, zoom, move, flip, mirror, use a negative filter or reset your image

Step 3: Inspect Frames

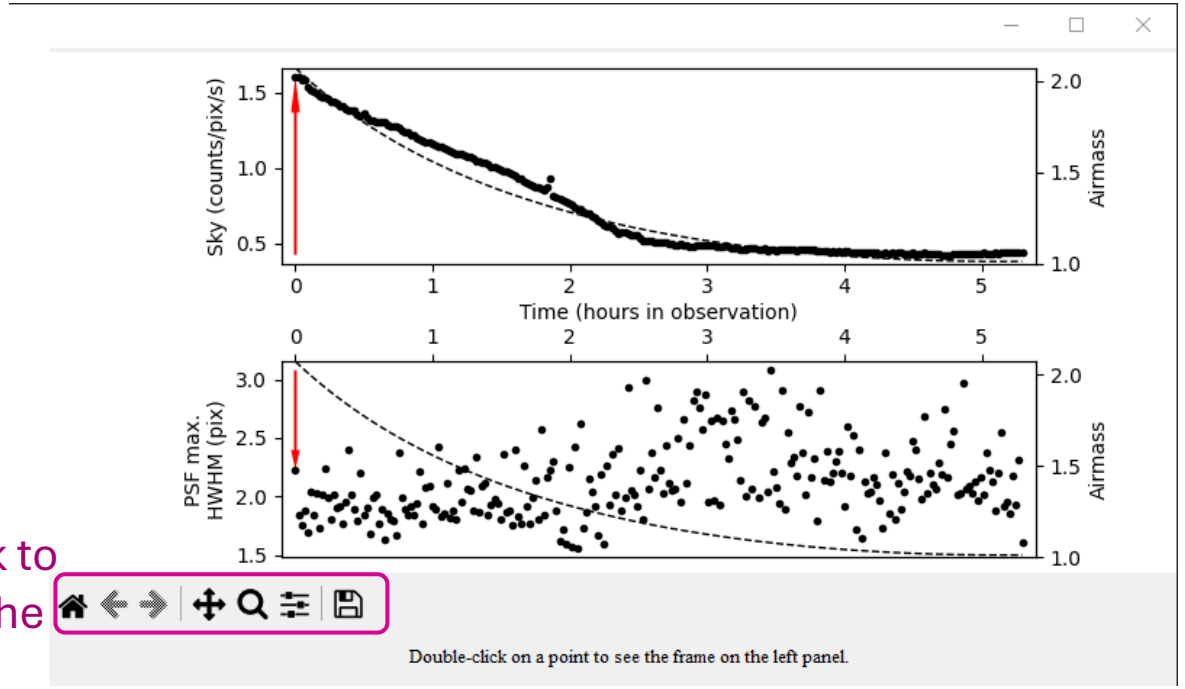
A filter for faulty images



- The next steps heavily relies on the first image. For this reason, the first image must be checked for overexposing and for the tracking be representative of your observation in total.

- **How to filter out faulty images?**

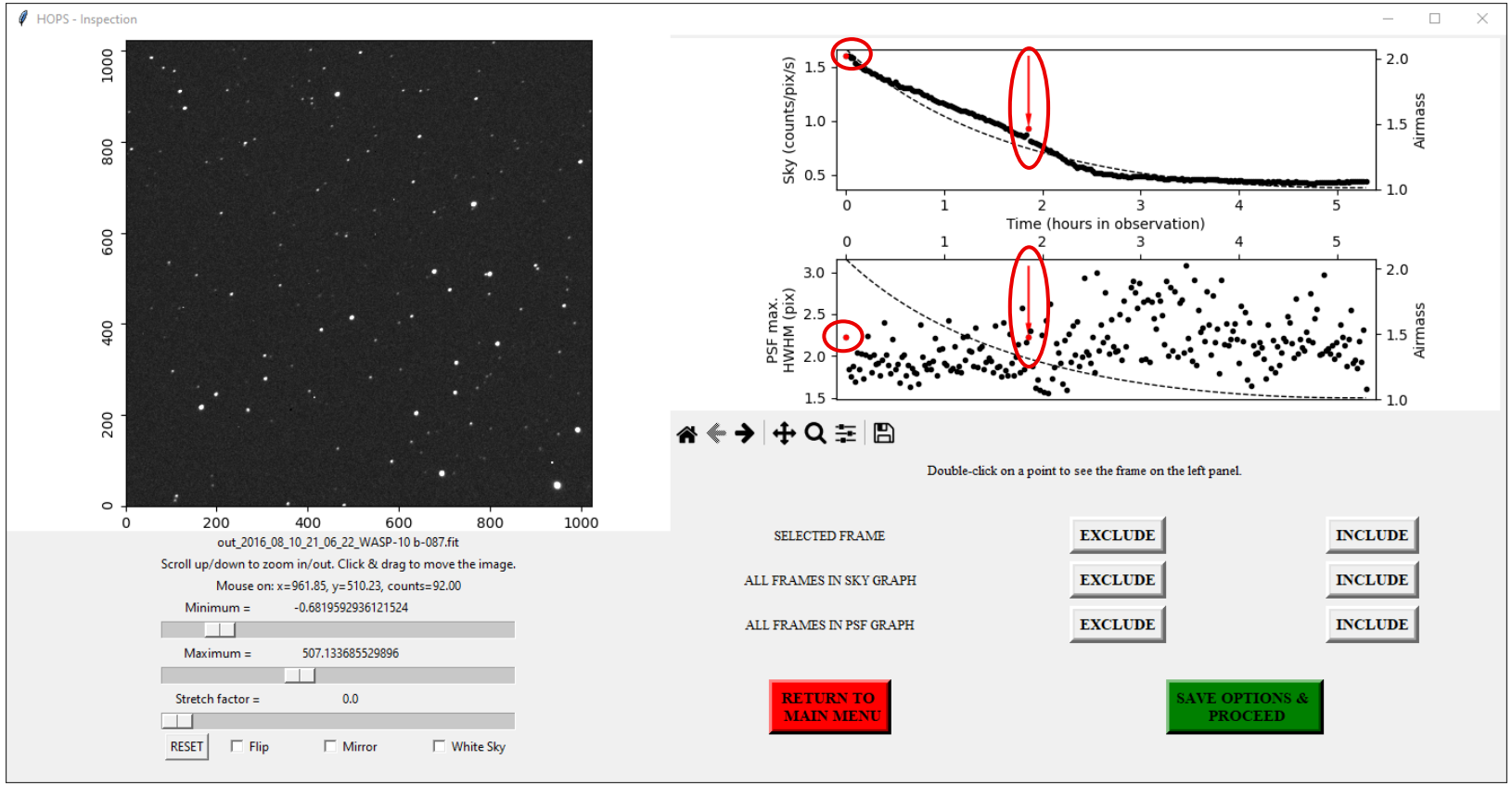
From the 2 graphs (SKY graph and PSF graph) you can select which images to be excluded for the process.



You can (from left to right): reset to original, back to previous, forward to next, move, zoom, change the dimensions, save the plot

Step 3: Inspect Frames

Using the SKY graph to filter out images

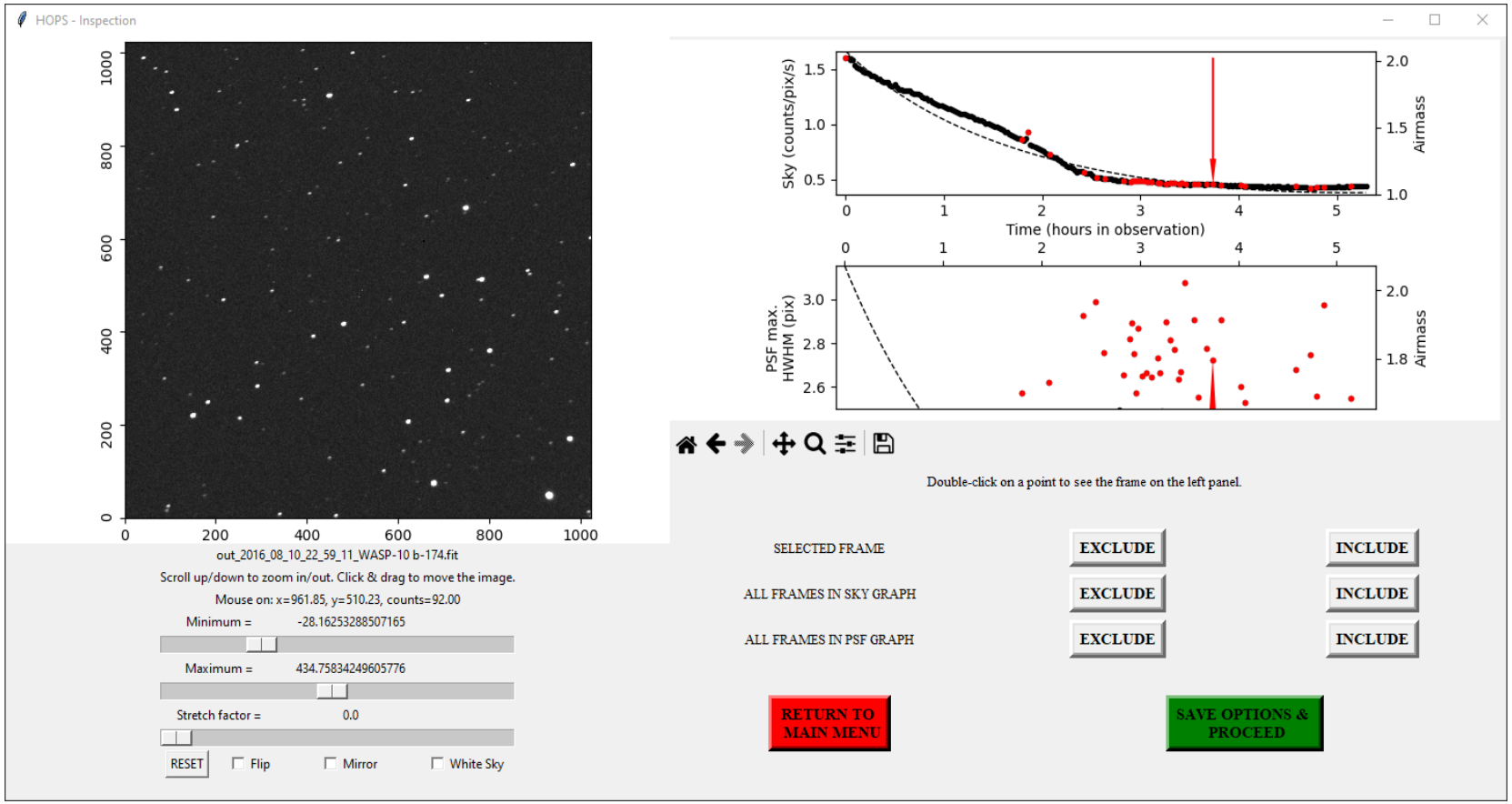


- In the SKY plot an indication for image, faulty image is a point's values and airmass in correlation to other points.
- <u>Double click</u> on a point to view the image.
- To exclude an image, press the button "EXCLUDE" next to the "SELECTED FRAME".
- To include an image back, press "INCLUDE".

- To exclude or include many images at the same time, zoom your plot in the area they are located, and press "EXCLUDE" for the "ALL FRAMES IN SKY GRAPH"

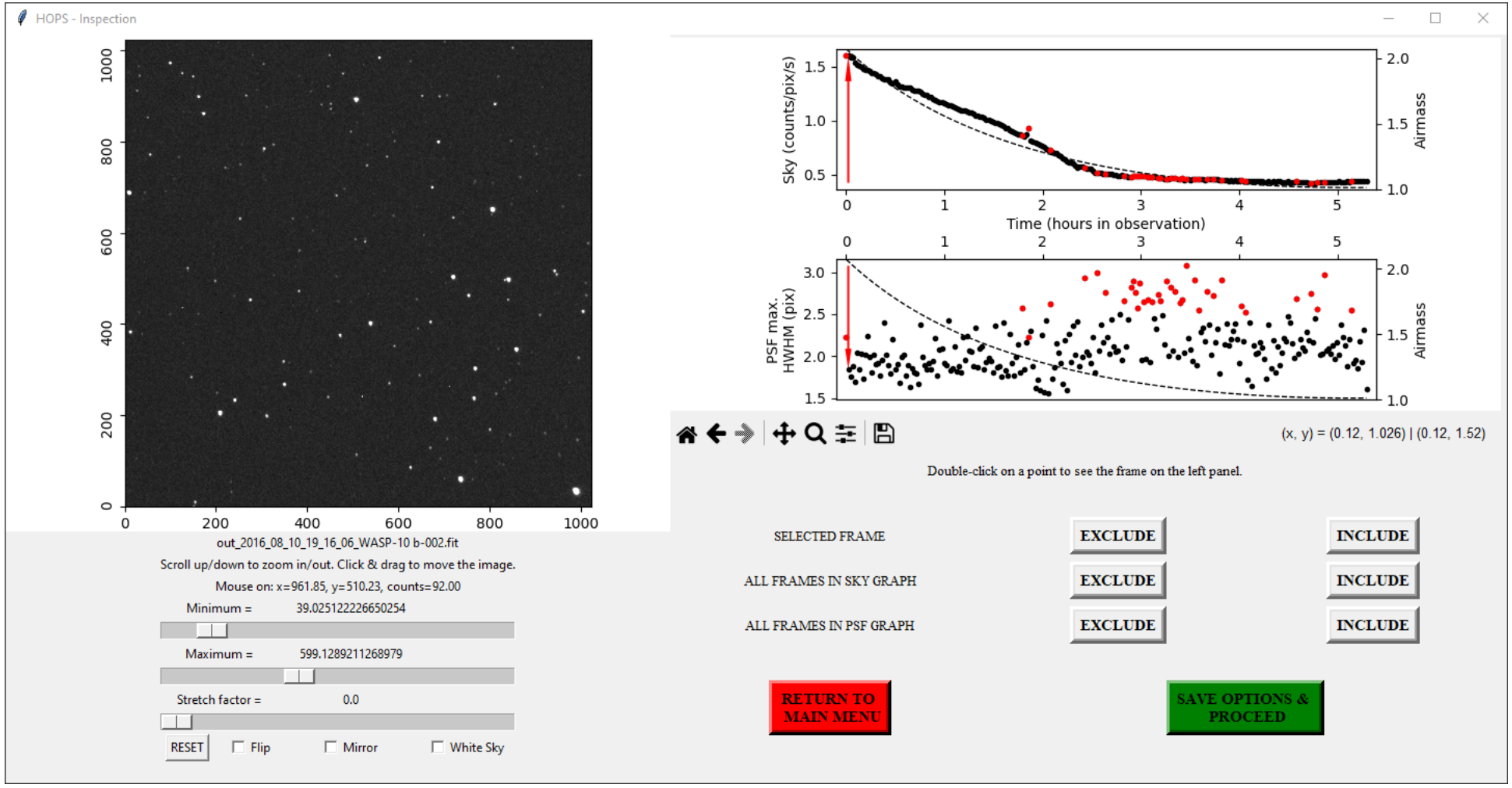
Step 3: Inspect Frames

Using the PSF graph to filter out images



- You can choose a PSF value as an upper limit that will define with frames to include or exclude. A value of 2.5 is appropriate.
- To exclude or include many images at the same time, zoom your plot in the area they are located, and press “EXCLUDE” for the “ALL FRAMES IN PSF GRAPH”

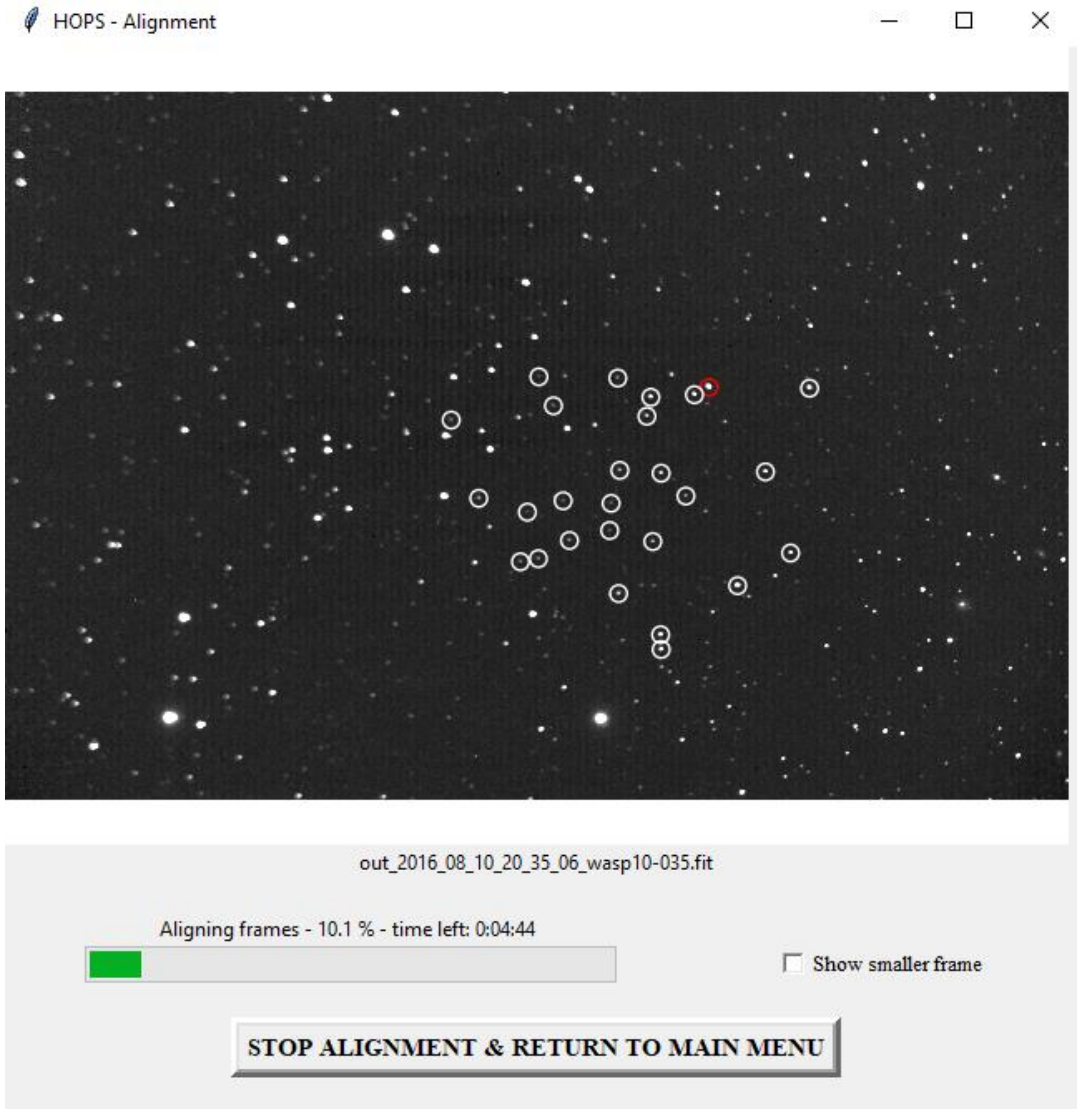
Step 3: Inspect Frames



- "RETURN TO MAIN MENU": all your progress will not be saved.
- "SAVE OPTIONS &PROCEED": your progress is saved, and you can proceed to step 4.

Step 4: Run Alignment

The process starts automatically after step 3



- To interrupt the process press “STOP ALIGNMENT & RETURN TO MAIN MENU”

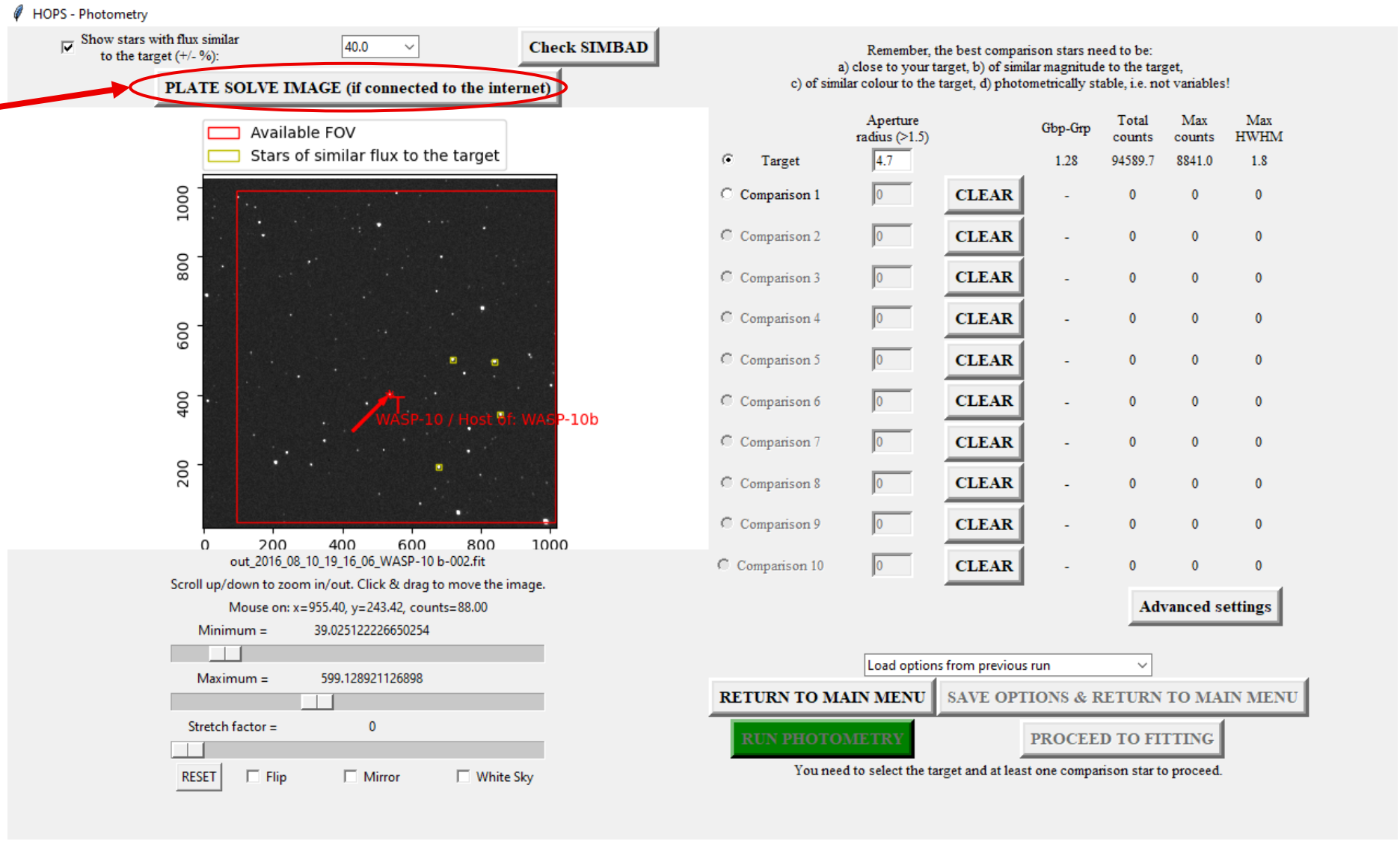
- If in the image the stars cannot be detected this message will be shown:

- Press “YES” if the image is faulty
- Press “NO” if the image is shifted or flipped

Step 5: Photometry

Select your target

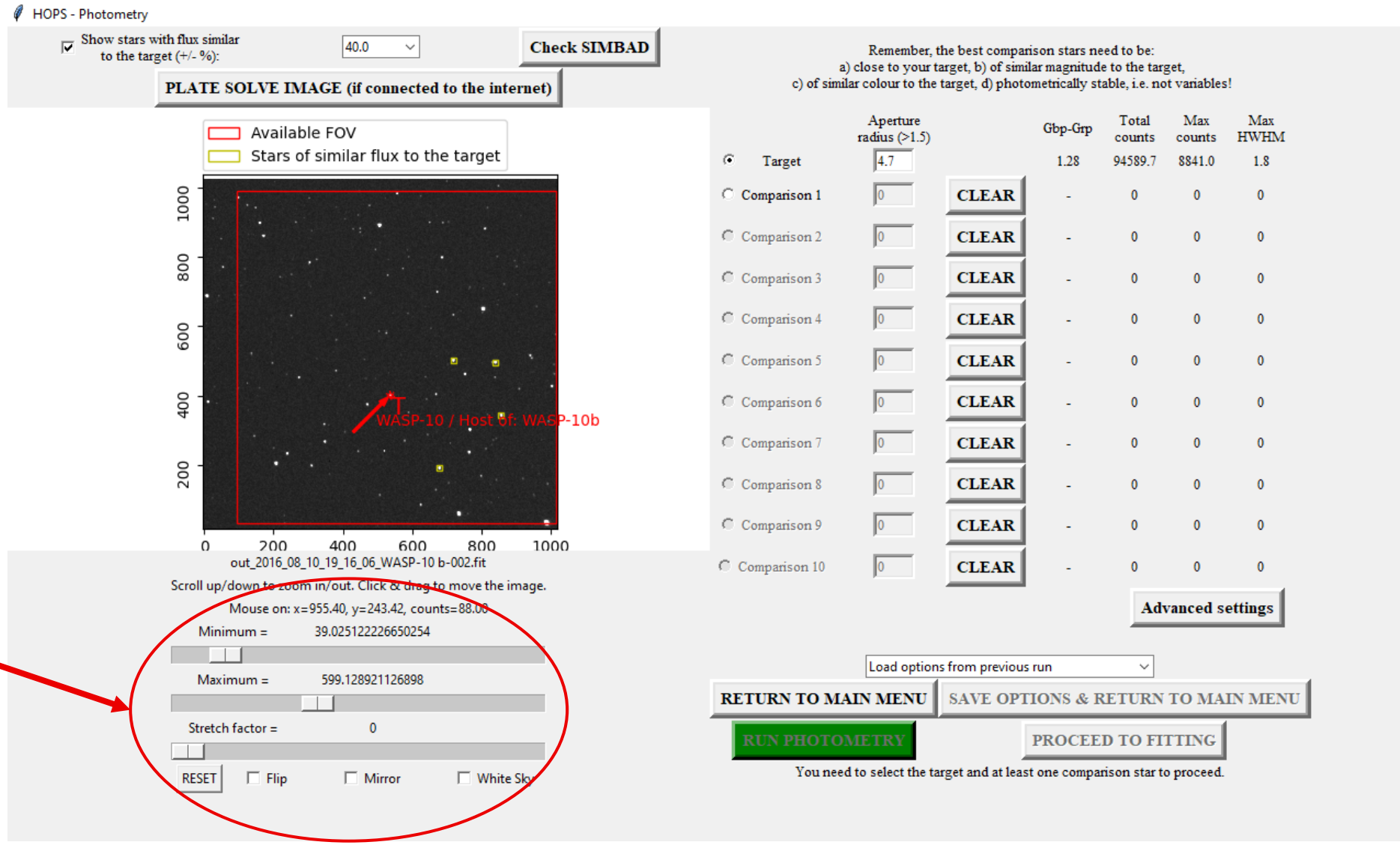
Use this button to automatically resolve your target. Alternatively press “Check SIMBAD” to find the target manually using its coordinates from SIMBAD.



Step 5: Photometry

Select your target

Use these to configurations to adjust the contrast, flip or mirror the image. They will be helpful when you will have to choose the comparison stars for your target.

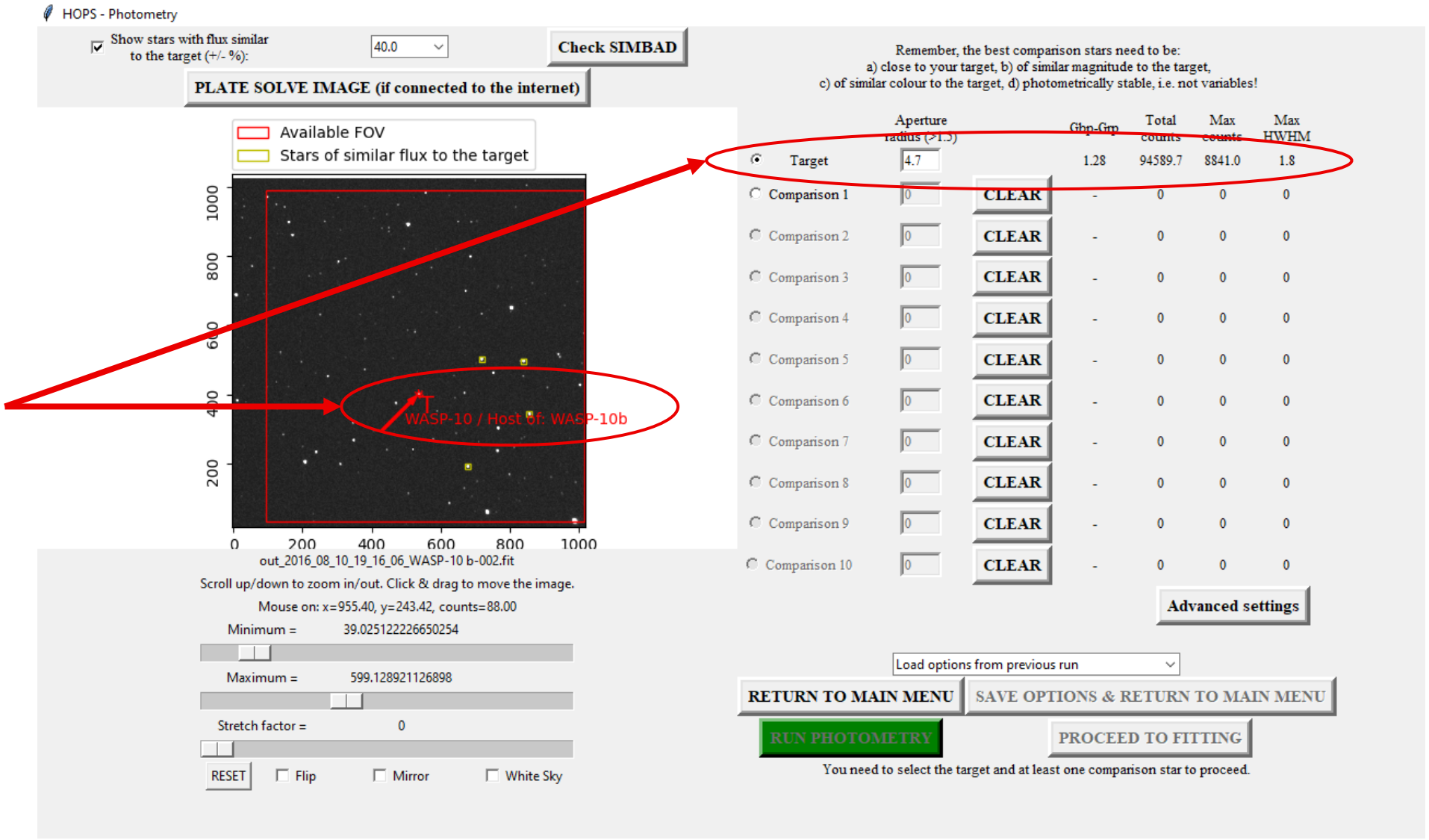


Step 5: Photometry

Select your target

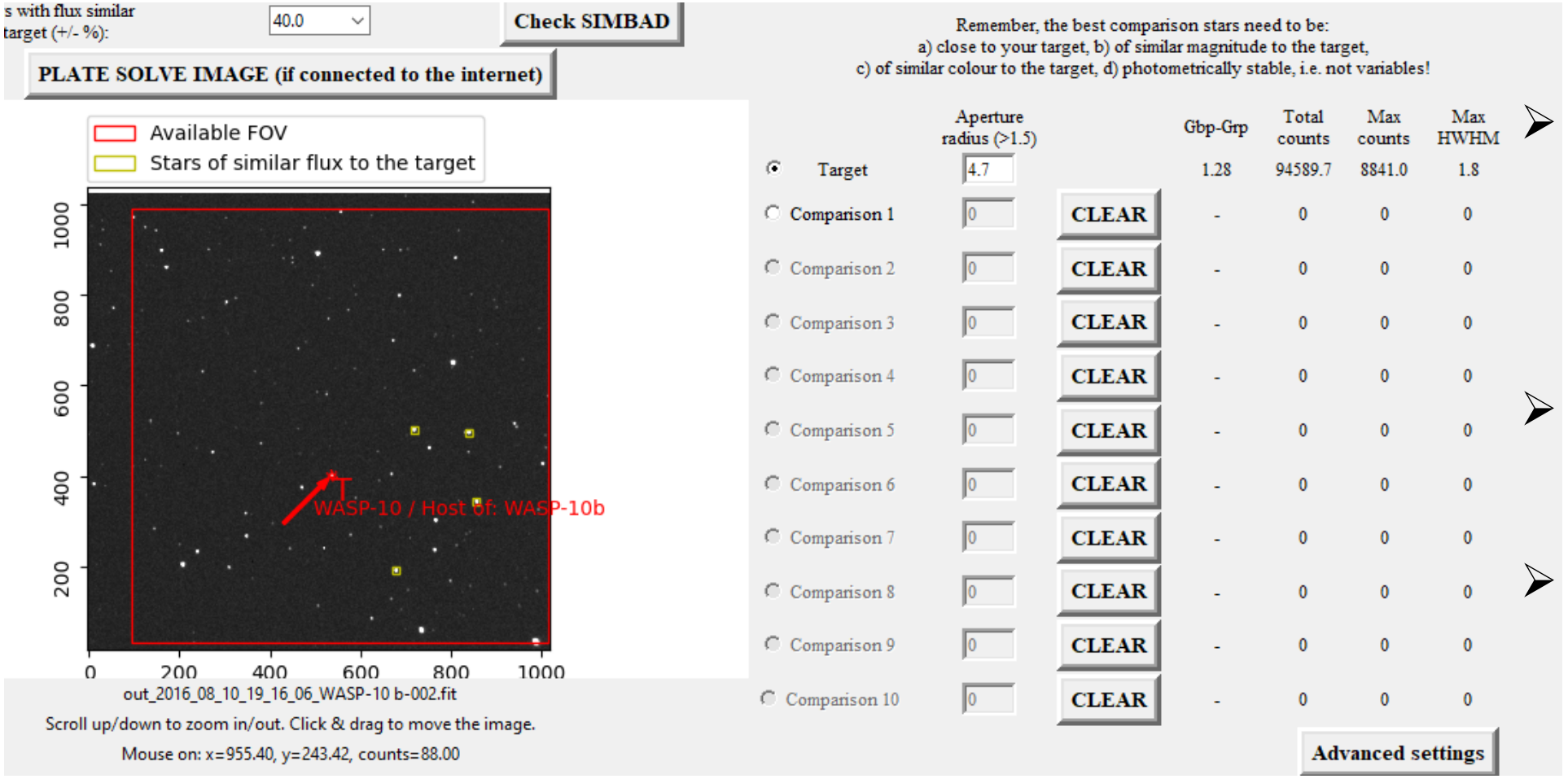
In the table (on the right), the option “Target” is selected. This means that the photometric data of identified target are configured.

!!! To identify these data for the stars double click on them on the image



Step 5: Photometry

Select your companion stars



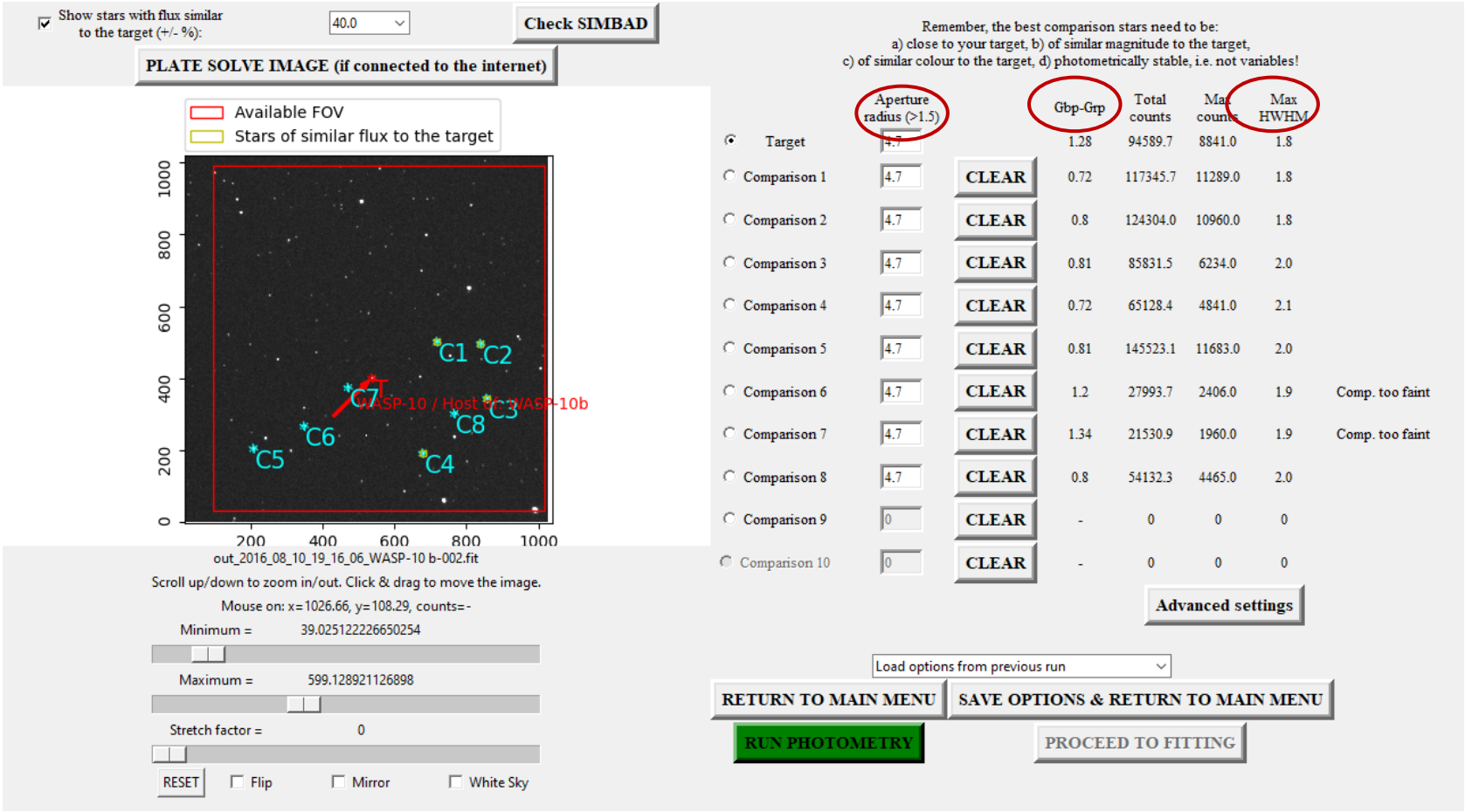
- Choose stars that are within the red square (it contains all the stars constantly inside your FOV)
- With yellow, stars of similar flux are shown
- To proceed you need **at least 2** companion stars.

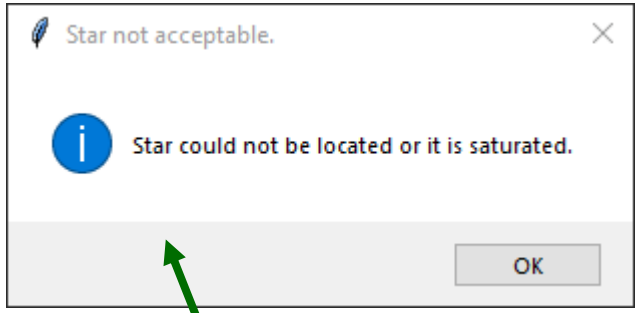
- When you have selected a star for “Companion 1”, you can proceed selecting a star for “Companion 2” etc.

Step 5: Photometry

Step 1: select possible candidates for your comparison stars

- Some eligibility criteria the selected comparison stars should cover are: similar (i) aperture, (ii) Gbp-Grp, (iii) HWHM.





If this error message is shown, zoom in the image and try again selecting a star.

Step 5: Photometry

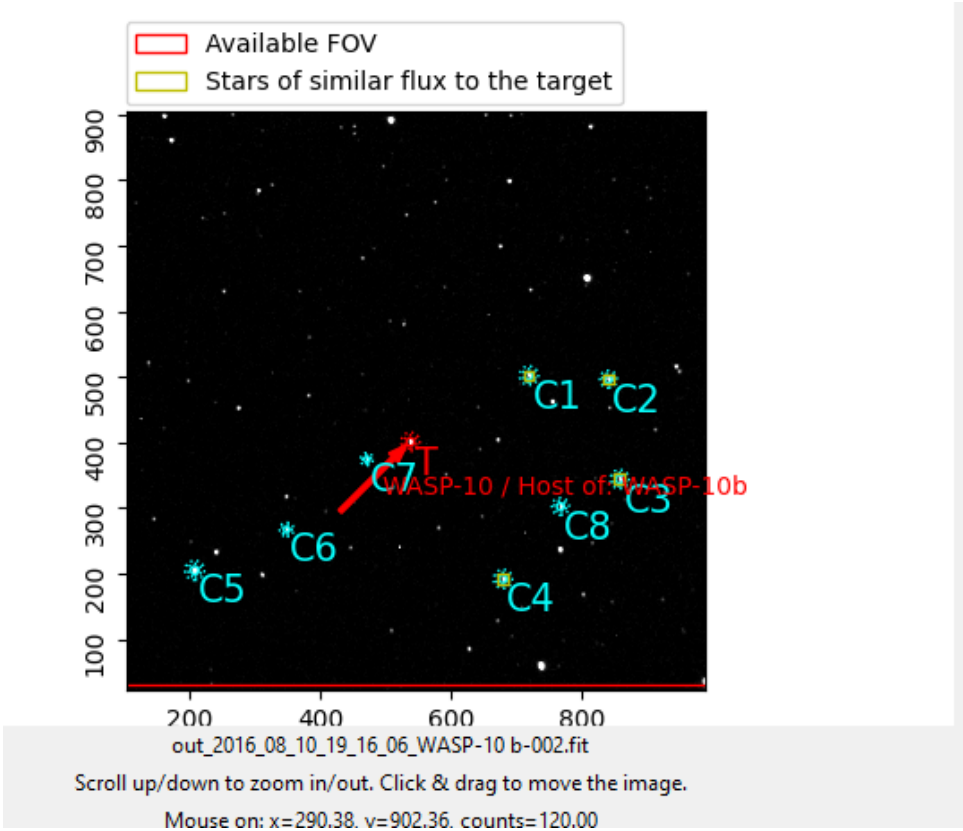
How to select the most compatible stars?

- Choose your comparison stars carefully, as they affect significantly the quality of the final result. The general rules are that the comparison stars need to be:
    1. close to the target star;
    2. of similar magnitude to the star;
    3. of similar color to the target star, Gbp-Grp (check with SIMBAD of GAIA);
    4. stable, i.e. not variables (check with SIMBAD or AAVSO or from the comparison light curves on a few pages later).
- There is always the possibility that no good comparison stars exist. In this case you have to proceed with on-ideal comparison stars (very faint or very bright).

Step 5: Photometry

Step 2: correct the aperture radius

- From the 8 stars we tried out, let's select the 4 with the characteristics most similar to our target. Those stars can form a first checkpoint for our photometry analysis



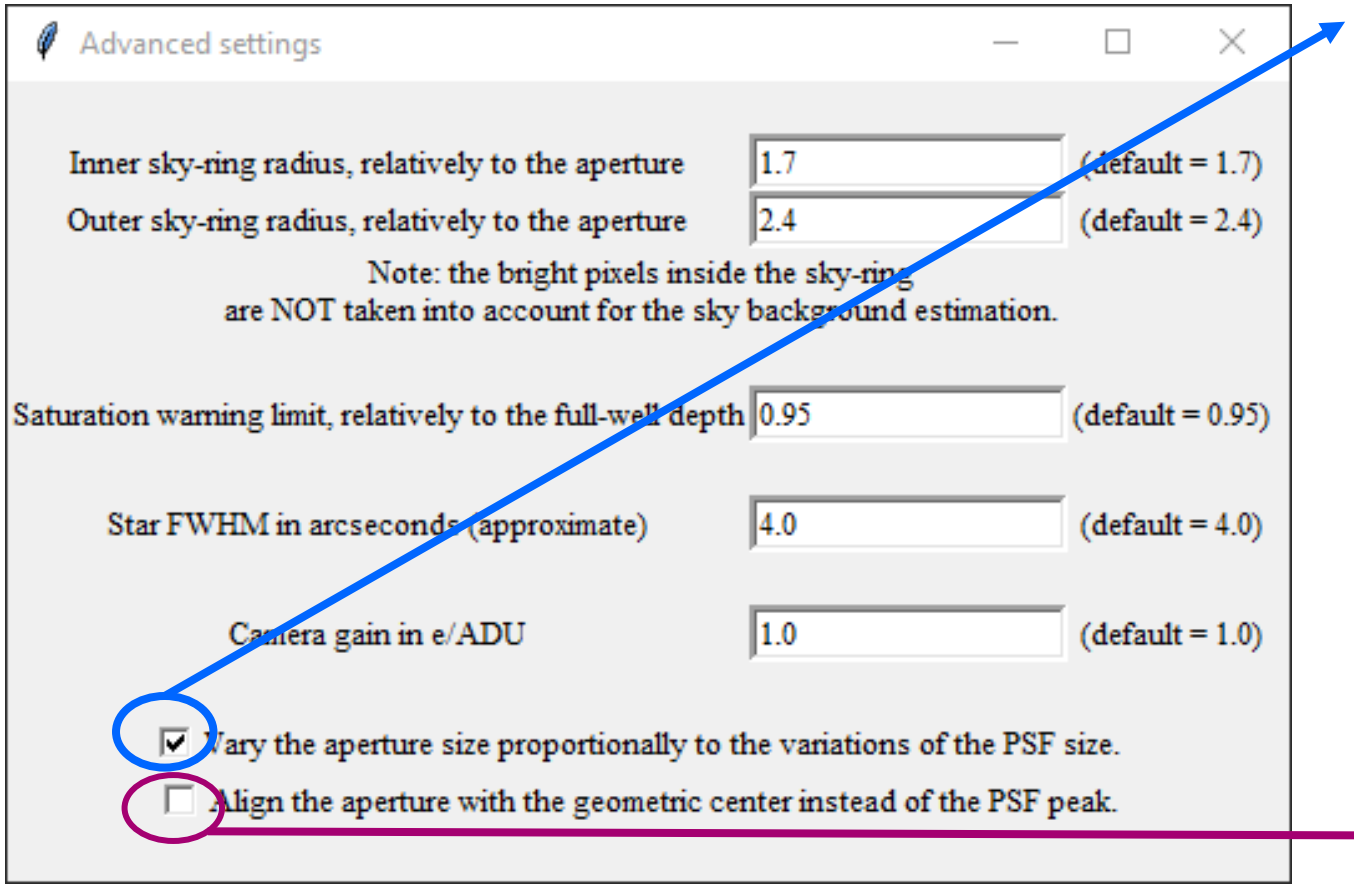
	Aperture radius (>1.5)		Gbp-Grp	Total counts	Max counts	Max HWHM	
Target	6.0		1.28	94589.7	8841.0	1.8	
Comparison 1	6.0	CLEAR	0.72	117345.7	11289.0	1.8	
Comparison 2	5.5	CLEAR	0.8	124304.0	10960.0	1.8	
Comparison 3	6.0	CLEAR	0.81	85831.5	6234.0	2.0	
Comparison 4	6.0	CLEAR	0.72	65128.4	4841.0	2.1	
Comparison 5	6.2	CLEAR	0.81	145523.1	11683.0	2.0	
Comparison 6	4.5	CLEAR	1.2	27993.7	2406.0	1.9	Comp. too faint
Comparison 7	4.0	CLEAR	1.34	21530.9	1960.0	1.9	Comp. too faint
Comparison 8	5.5	CLEAR	0.8	54132.3	4465.0	2.0	
Comparison 9	0	CLEAR	-	0	0	0	
Comparison 10	0	CLEAR	-	0	0	0	

Advanced settings

- If you want to select another star, select an "Comparison X" and double click to a new star. All the photometric data of the previous option will be replaced.

Step 5: Photometry

Advanced settings



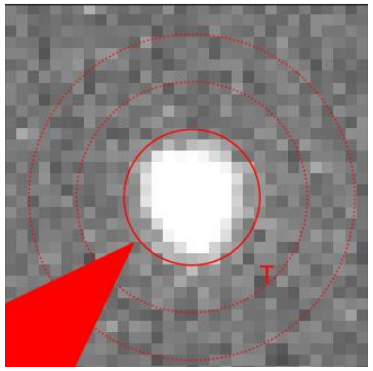
- If you believe that the PSF size is changing considerably during the observation you may wish to select the option to vary the aperture size proportionally to the variations of the PSF size. As this option is currently selected you can change the parameters to accommodate the PSF size.

- If your PSF suffers from strong asymmetries, you can select the option to align the aperture with the geometric center of the star instead of the PSF peak by clicking on this option.

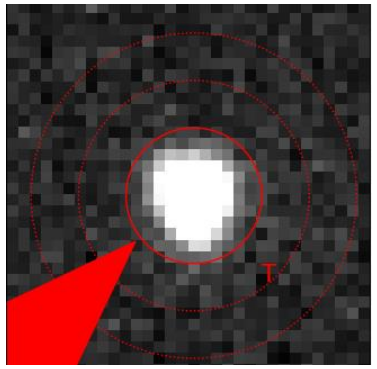
Step 5: Photometry

How to select the aperture radius?

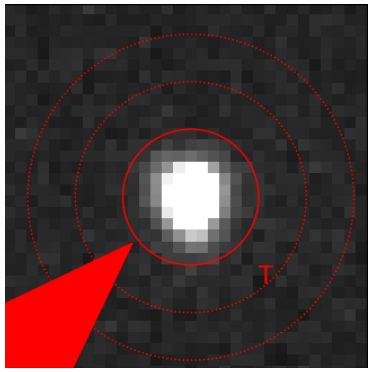
- The aperture should close completely the star and avoid nearby stars.
- Adjust the contrast in a way the star become more apparent.



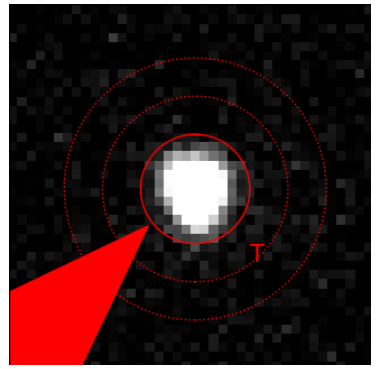
Too low contrast



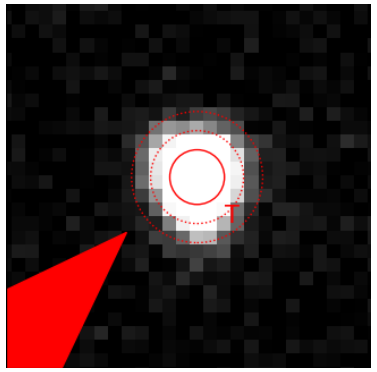
Original contrast



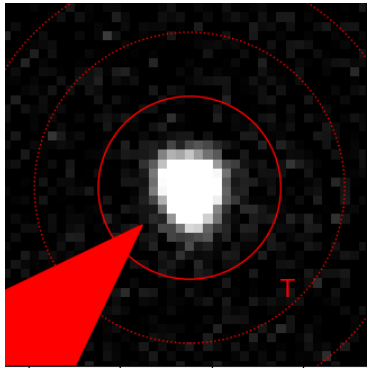
High contrast



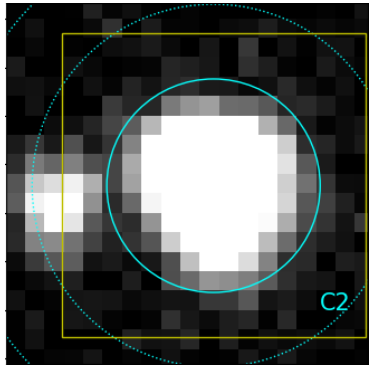
Too high contrast



Too small aperture



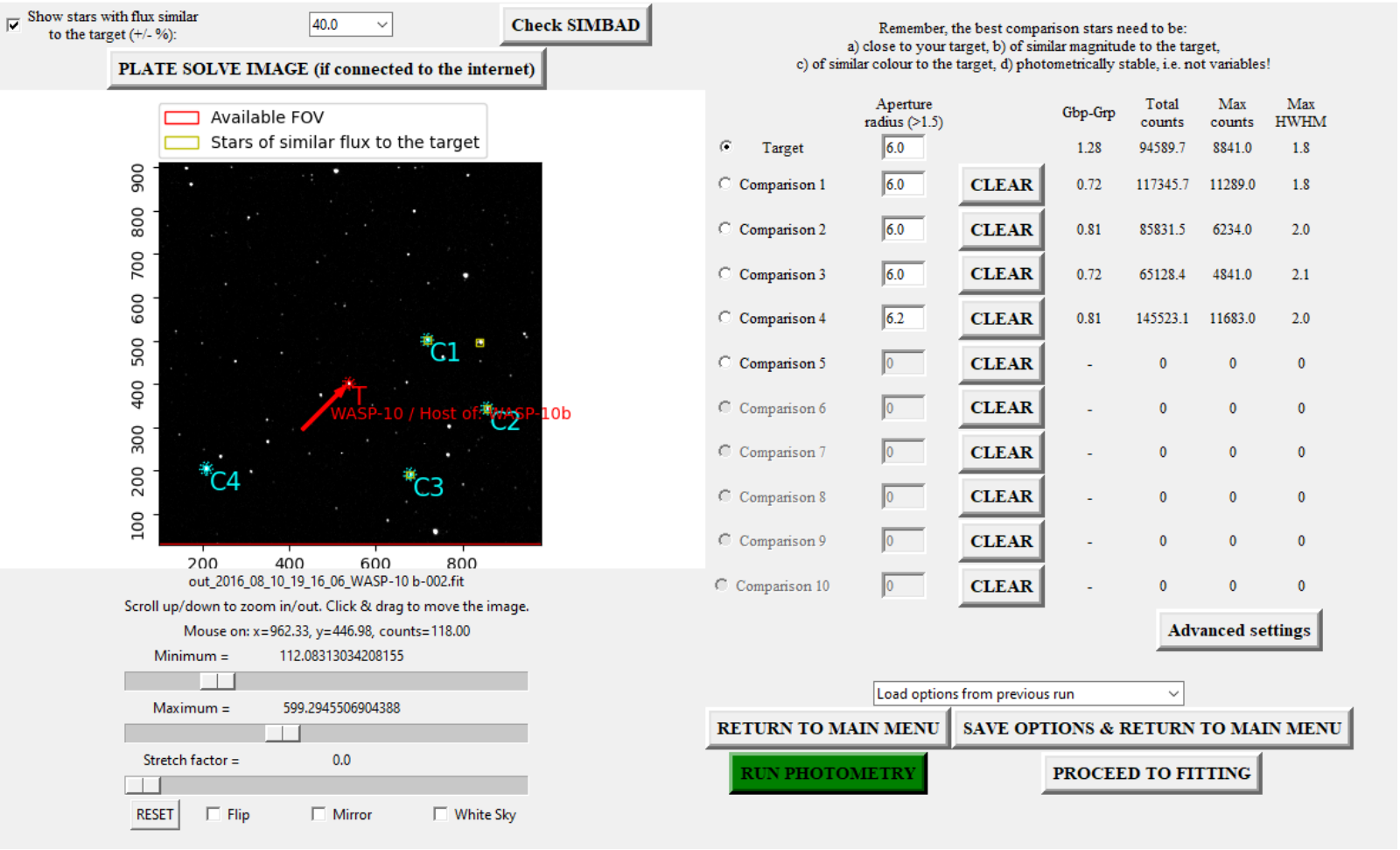
Too big aperture



Aperture with nearby star

Step 5: Photometry

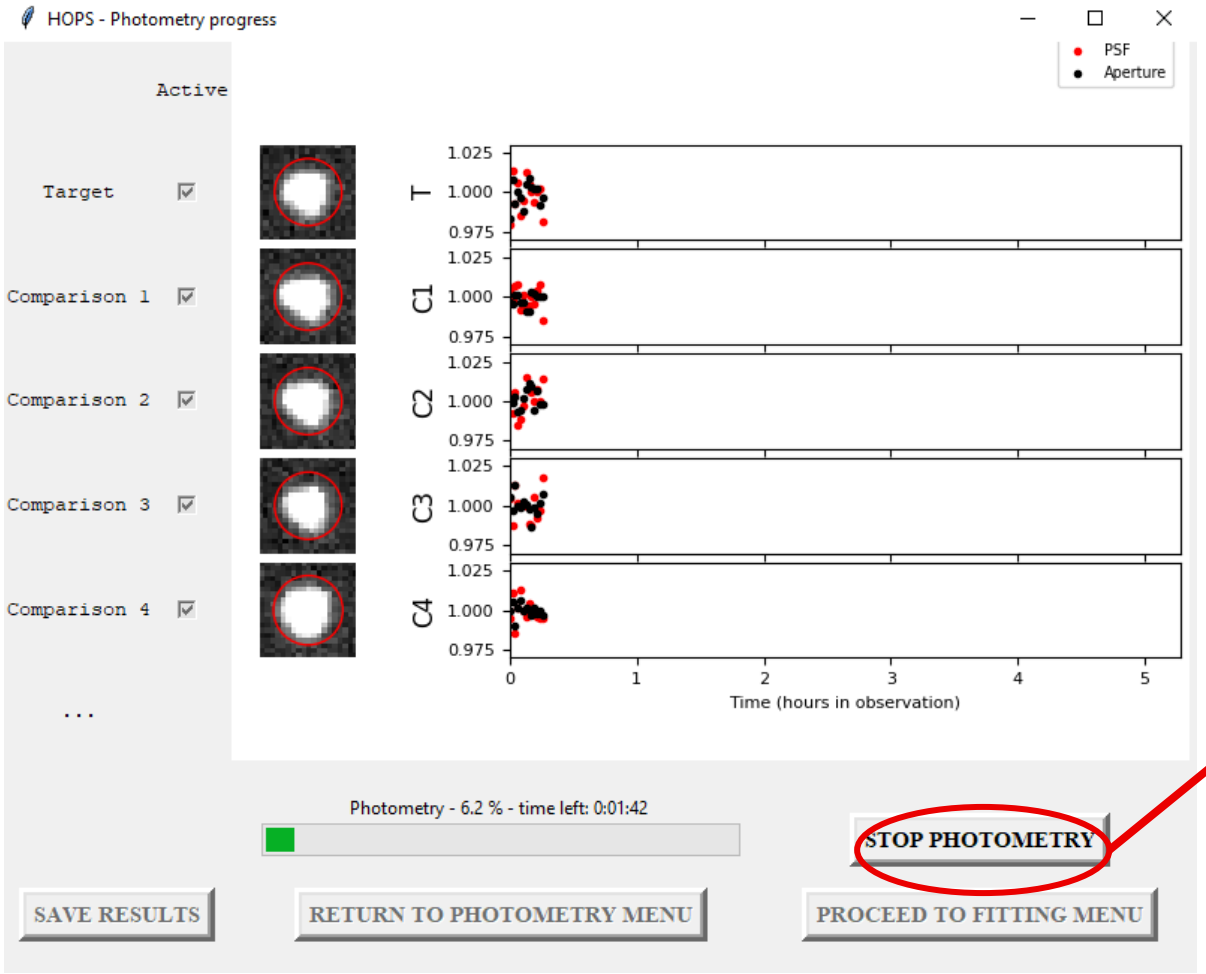
Step 3: the final selection



- Keep only the most compatible comparison stars.
- To delete all the other stars, press "*CLEAR*"
- To save your work but not proceed to the next level press "*SAVE OPTIONS & RETURN TO MAIN MENU*"
- To discard your work press "*RETURN TO MAIN MENU*"
- To proceed press "***RUN PHOTOMETRY***"

Step 5: Run Photometry

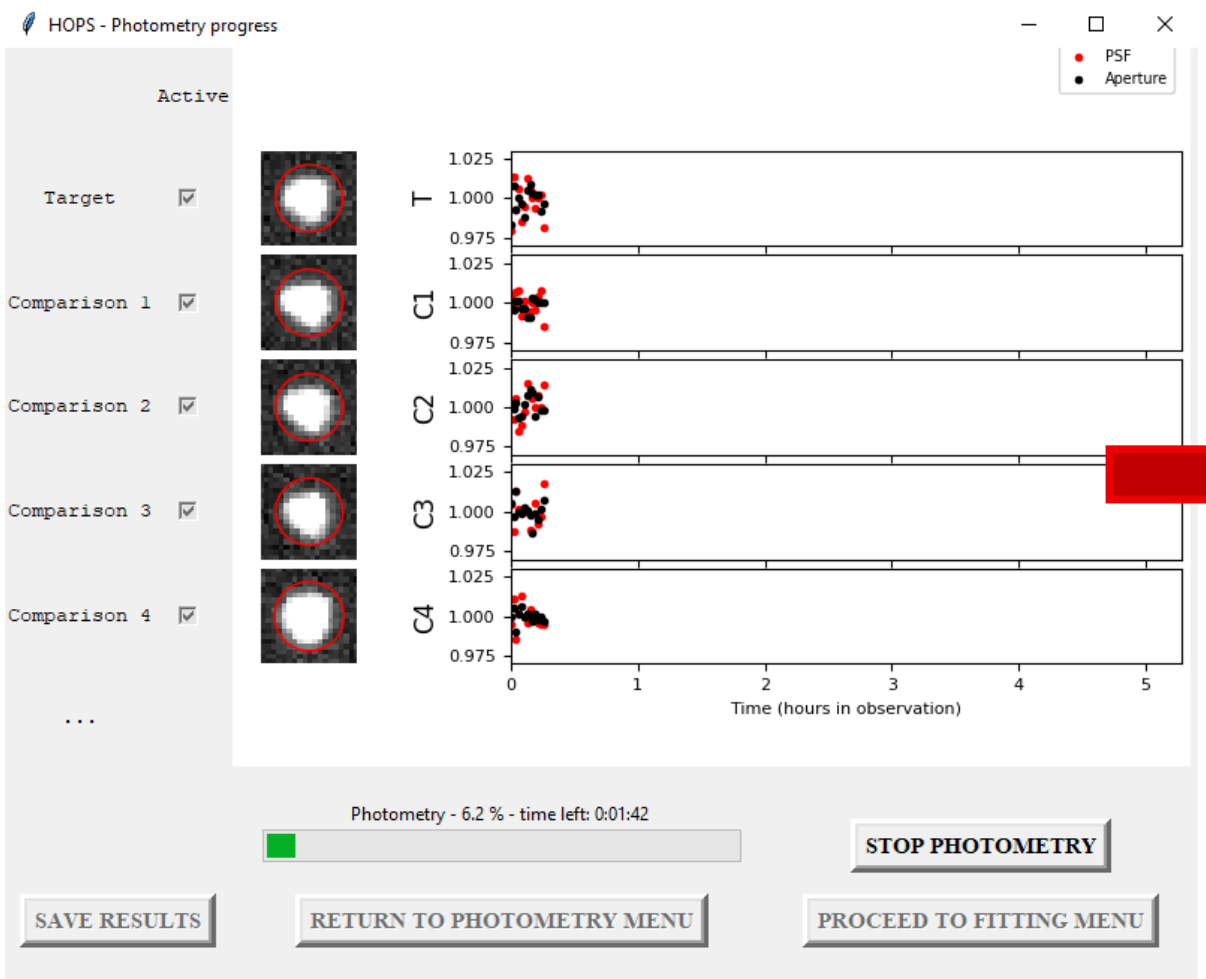
Starts automatically to process the photometric data of the selected target and comparison stars.

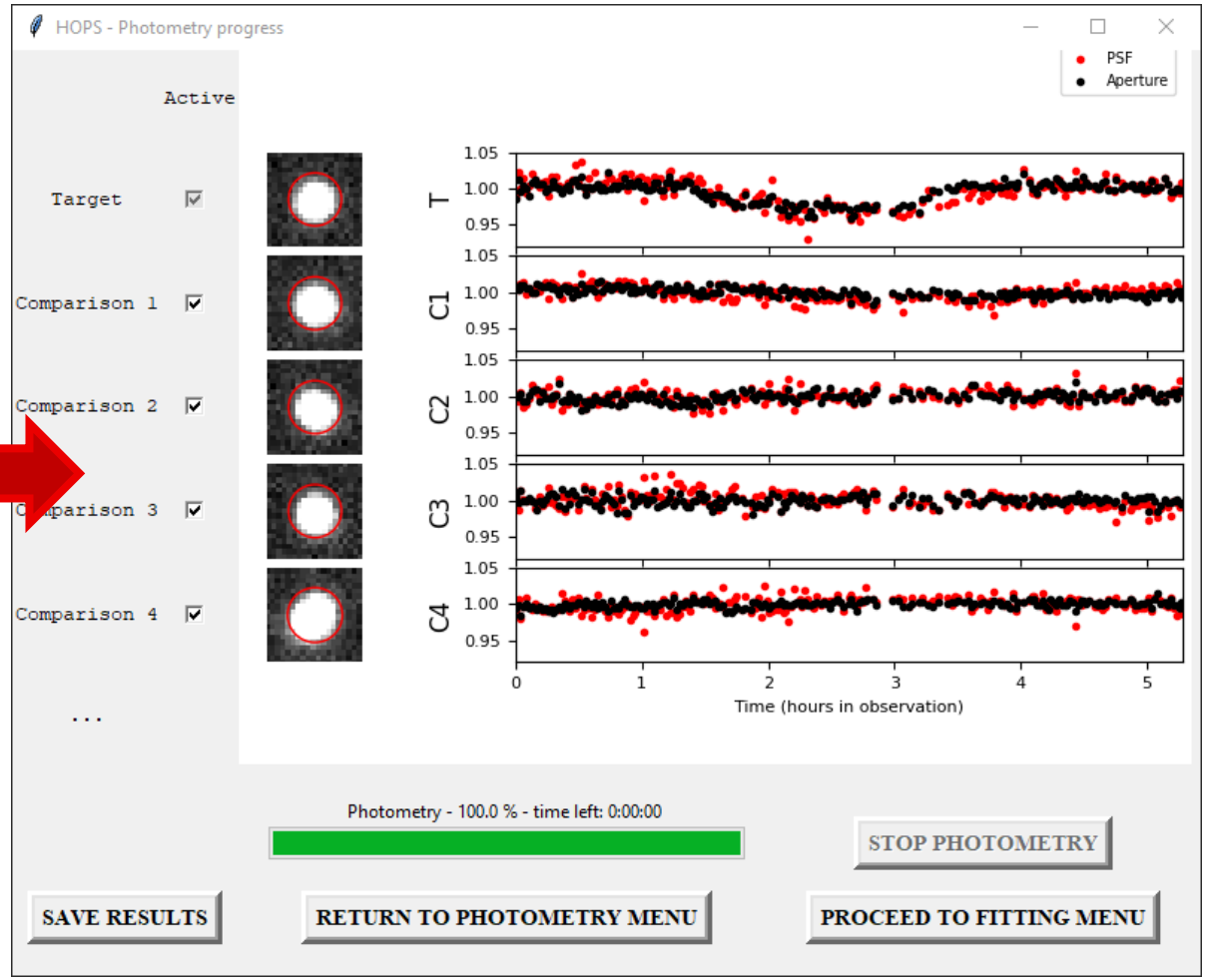


To stop the process and return to the main menu of photometry for selecting the target and comparison stars.

Step 5: Run Photometry

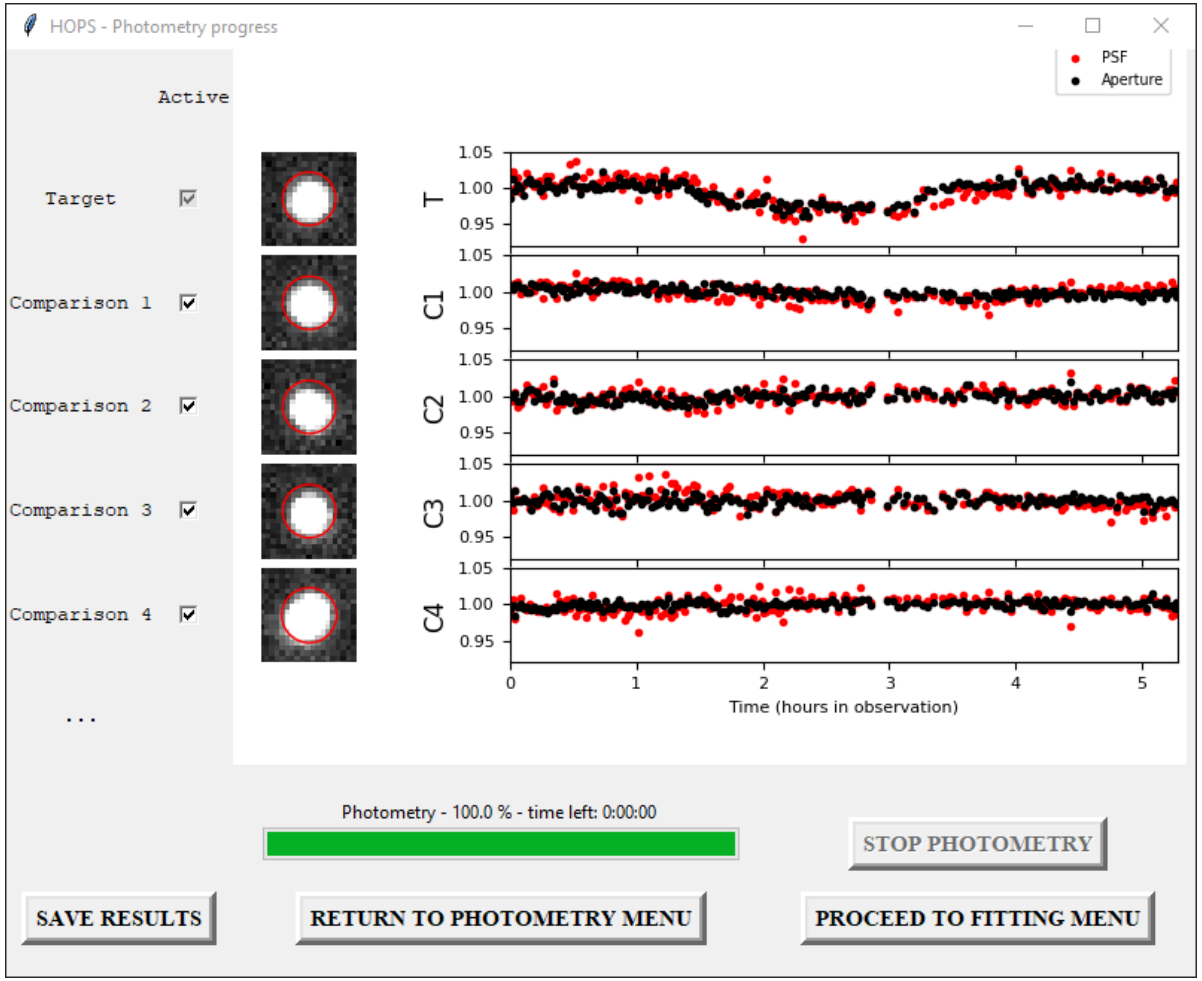
Starts automatically to process the photometric data of the selected target and comparison stars.





Step 5: Run Photometry

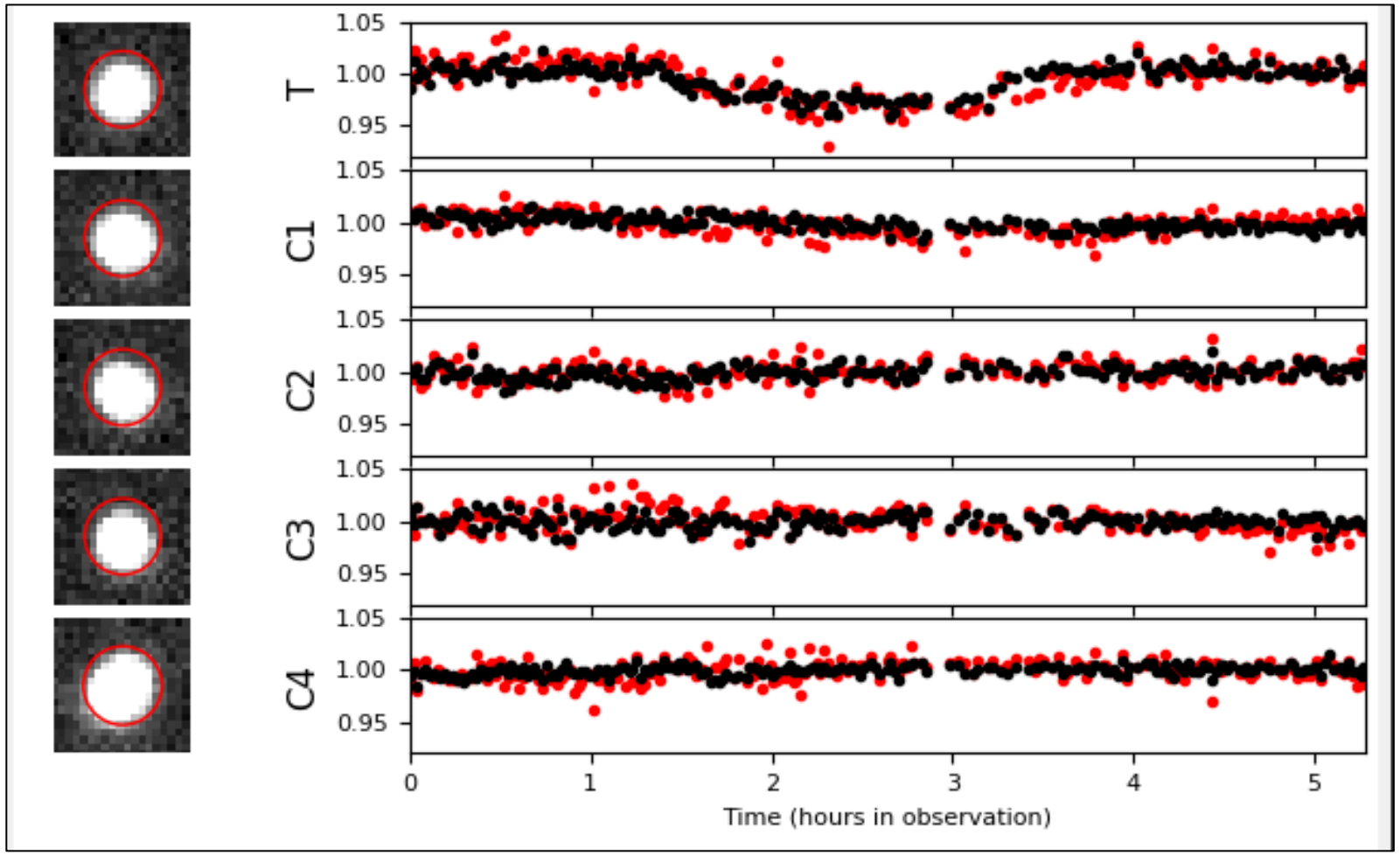
Inspection of the light curves



- By inspecting the light curves, we can determine if one or more stars have a negative impact to our target's light curve.
- Those light curves can be removed by clicking in the boxes next to the stars' names to deactivate them (or activate them back).
- You need at least 2 comparison stars because these curves are produced in relation to all the others.

Step 5: Run Photometry

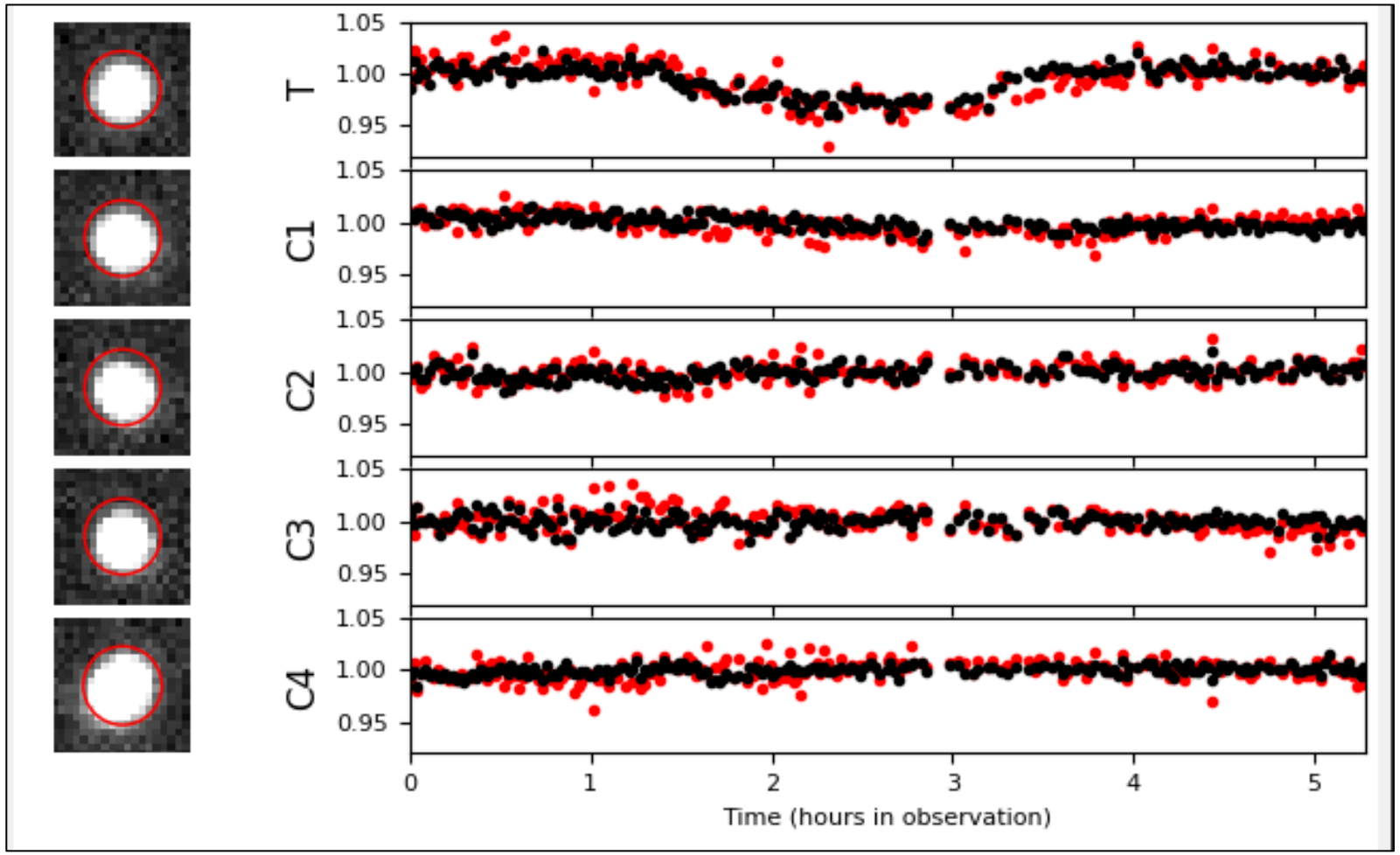
Inspection of the light curves



- The light curve of the target is divided by the sum of all the comparison stars.
- The light curve of its comparison star is divided by the sum of all the other comparison stars.

Step 5: Run Photometry

Inspection of the light curves



$$\frac{Target}{Comp1 + Comp2 + Comp3 + Comp4}$$

$$\frac{Comp1}{Comp2 + Comp3 + Comp4}$$

$$\frac{Comp2}{Comp1 + Comp3 + Comp4}$$

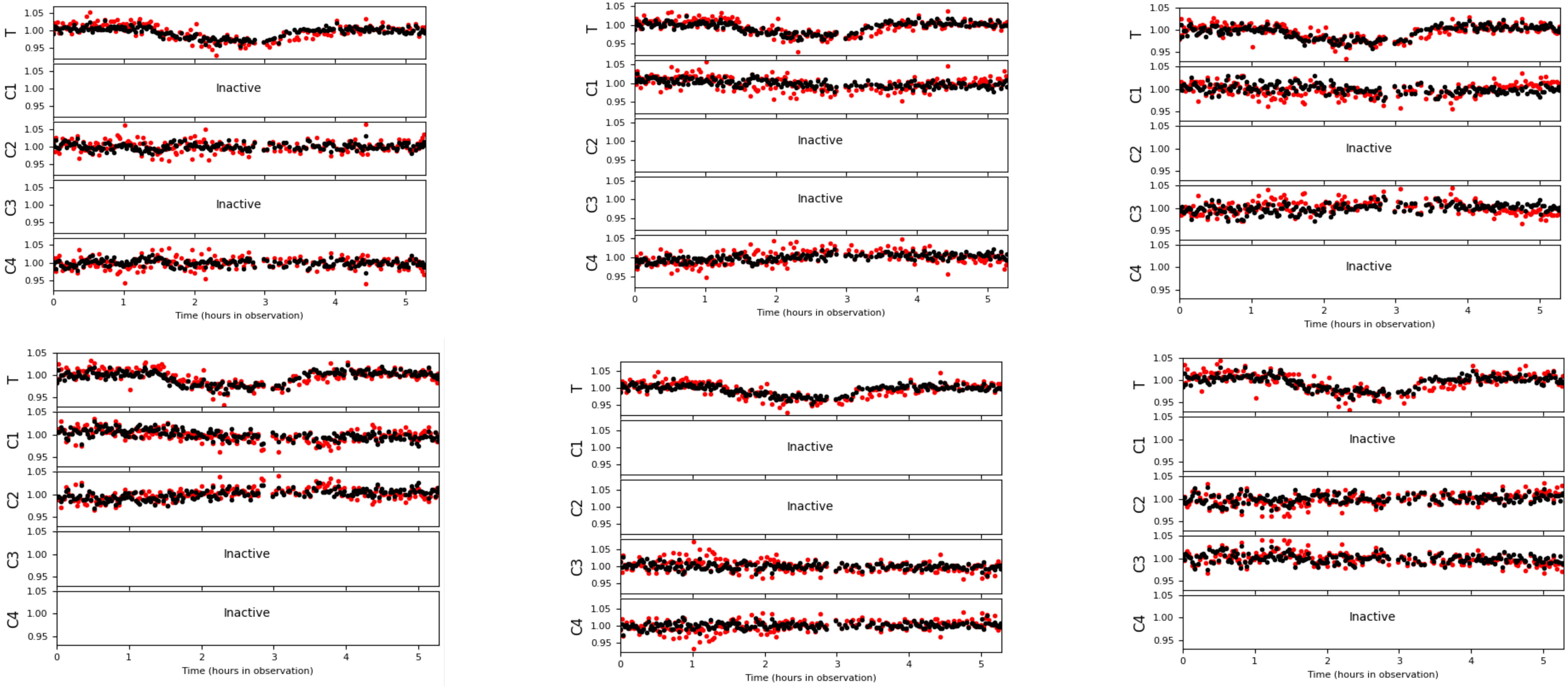
$$\frac{Comp3}{Comp1 + Comp2 + Comp4}$$

$$\frac{Comp4}{Comp1 + Comp2 + Comp3}$$

Step 5: Run Photometry

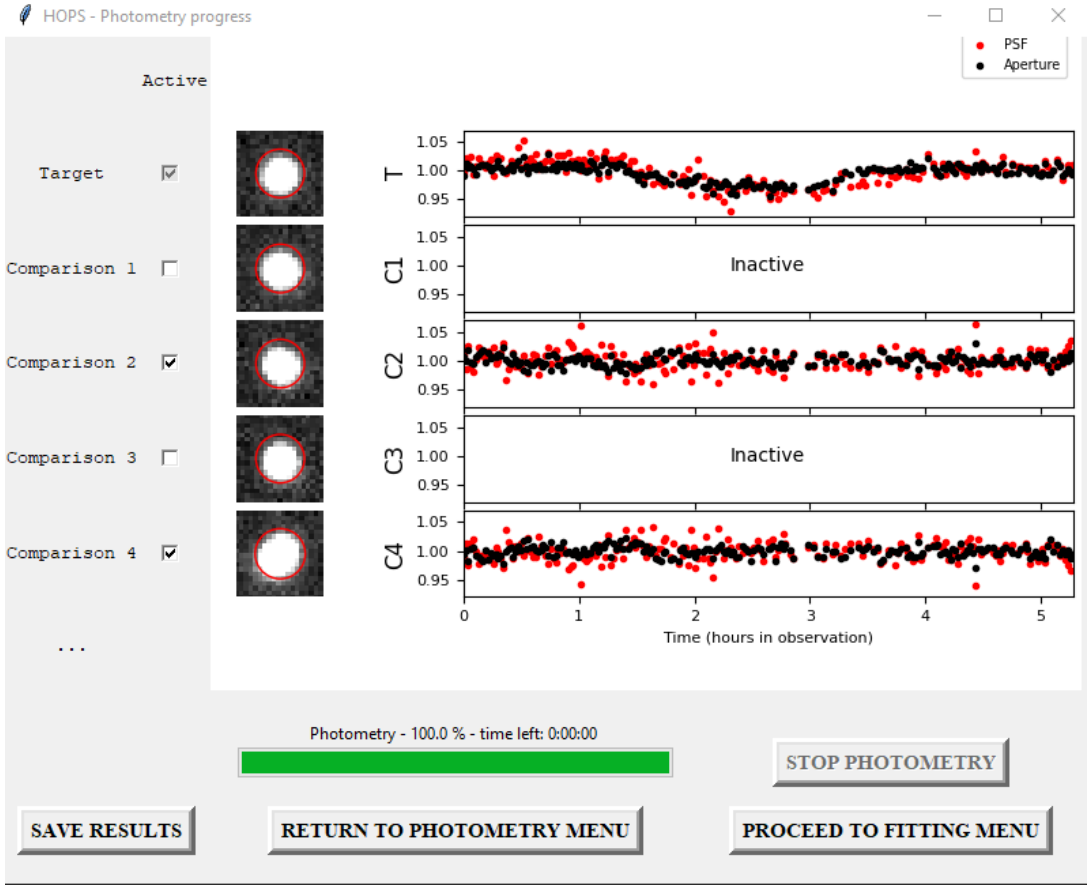
- Let's examine the scenario that we want only two comparison stars for our final fitting.

How can we pick which two comparison stars to keep?



Step 5: Run Photometry

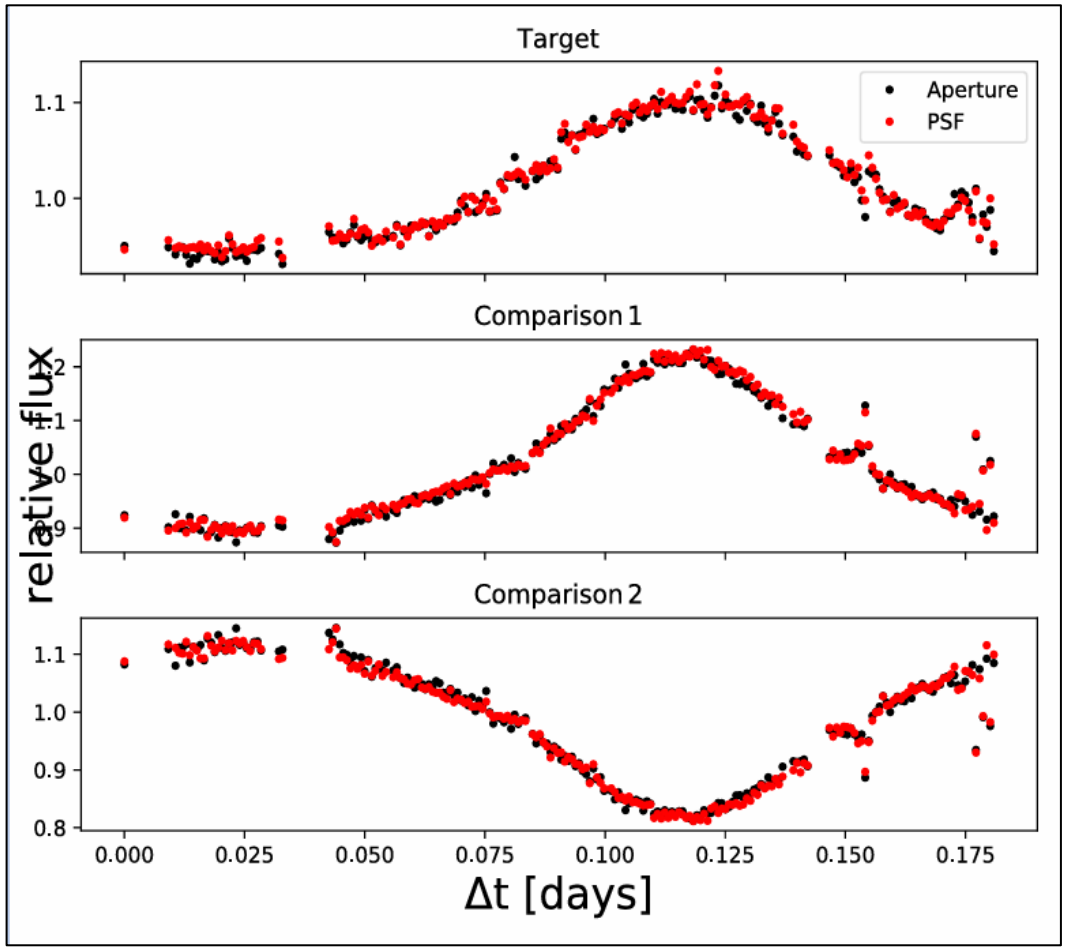
- The scenario we have picked is with the Comparison 2 and 4 because we can approximately evaluate it as the most symmetrical.



- Do not forget to save your work by pressing "**SAVE RESULTS**". You can utilize this as many times as you want if you want to export results for different scenarios.

Step 5: Run Photometry

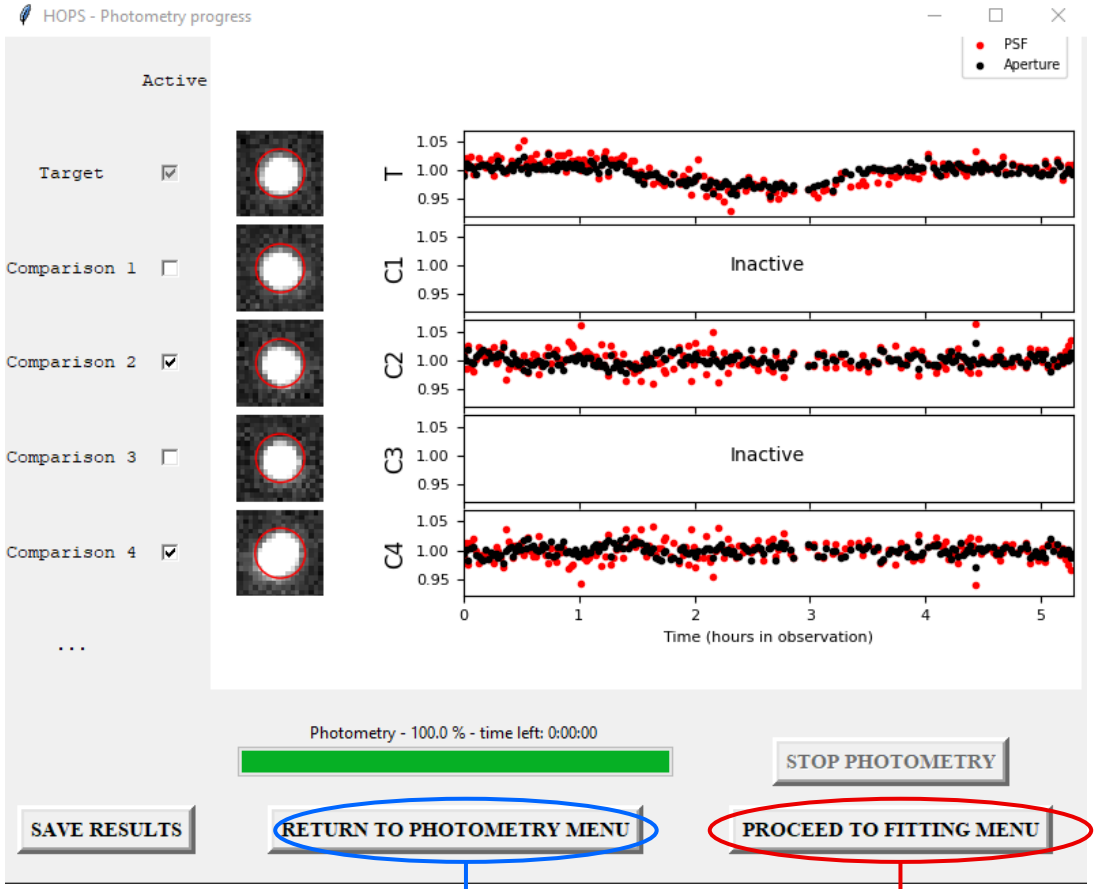
Variable stars as comparison stars.



- If one comparison star is variable, you will see its light curve is **anti-corelated to all the other light curves**, including the target's light curve.

Step 5: Run Photometry

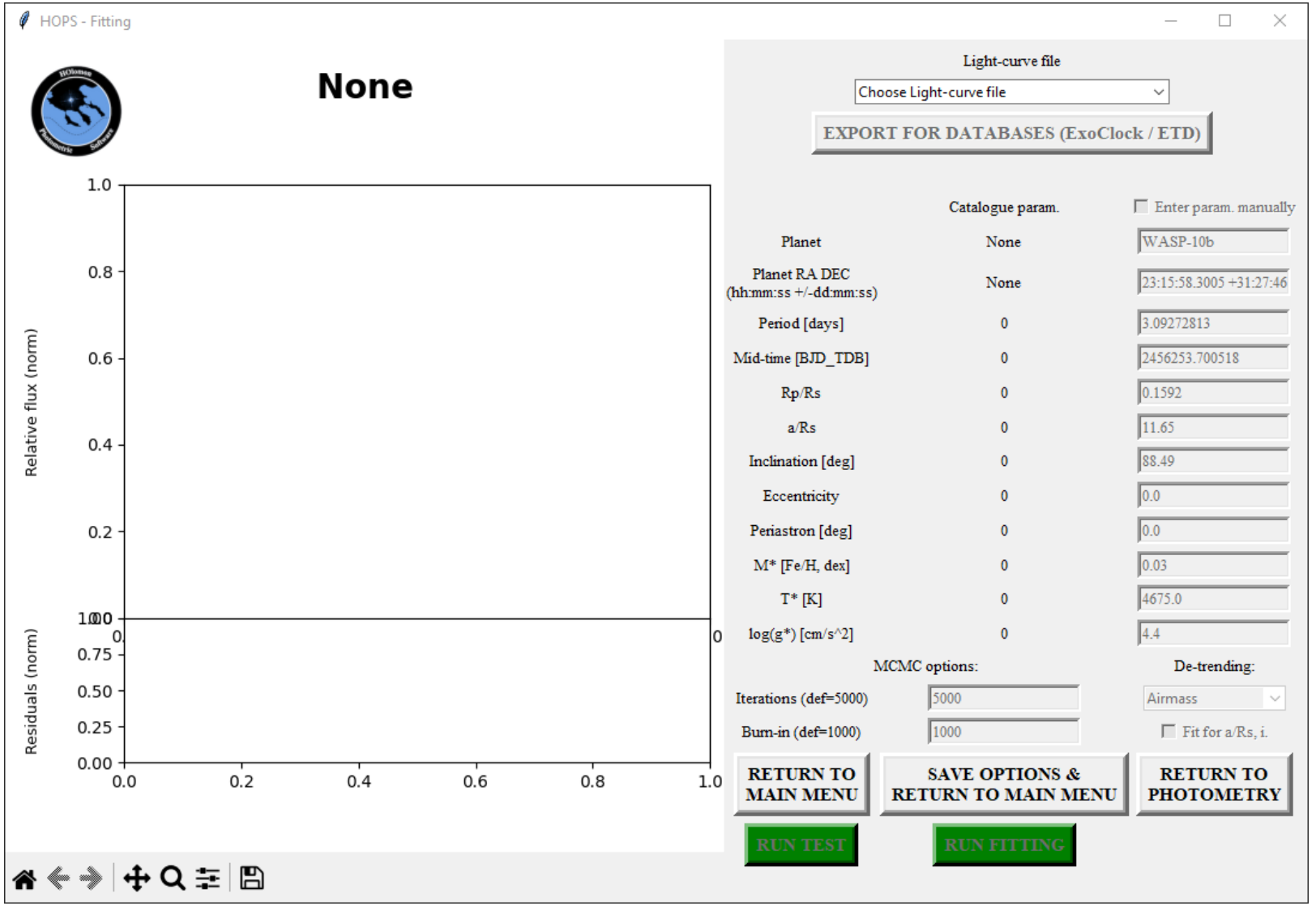
➢ When you are ready you can proceed to the next step: the *EXOPLANET FITTING*



Return to the main photometry result. **If you have saved your results**, you can see that previous work by clicking in the **"Load options from previous runs"** drop-down menu.

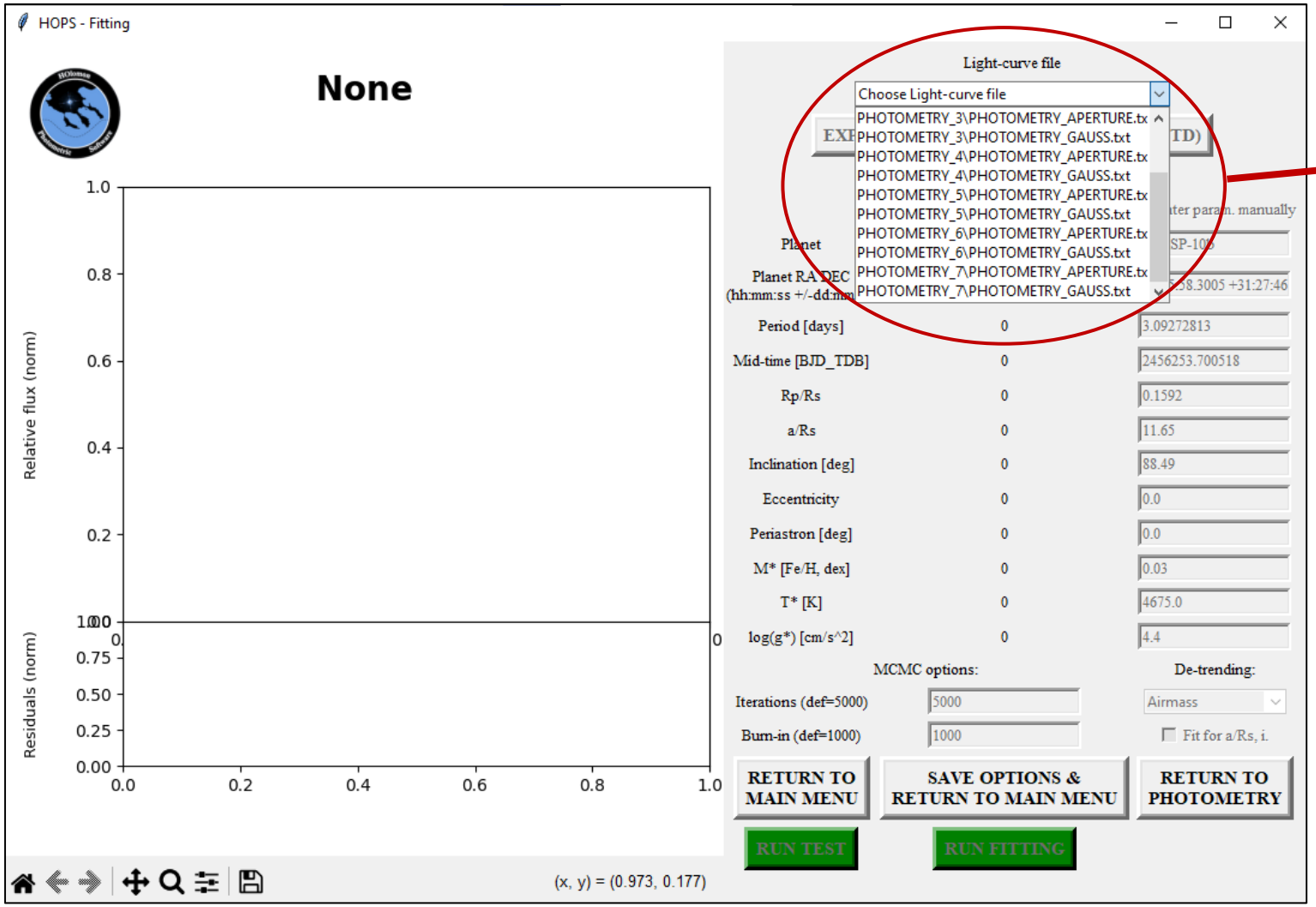
Proceed automatically to the next step.

Step 6: Exoplanet Fitting



Step 6: Exoplanet Fitting

Select a file

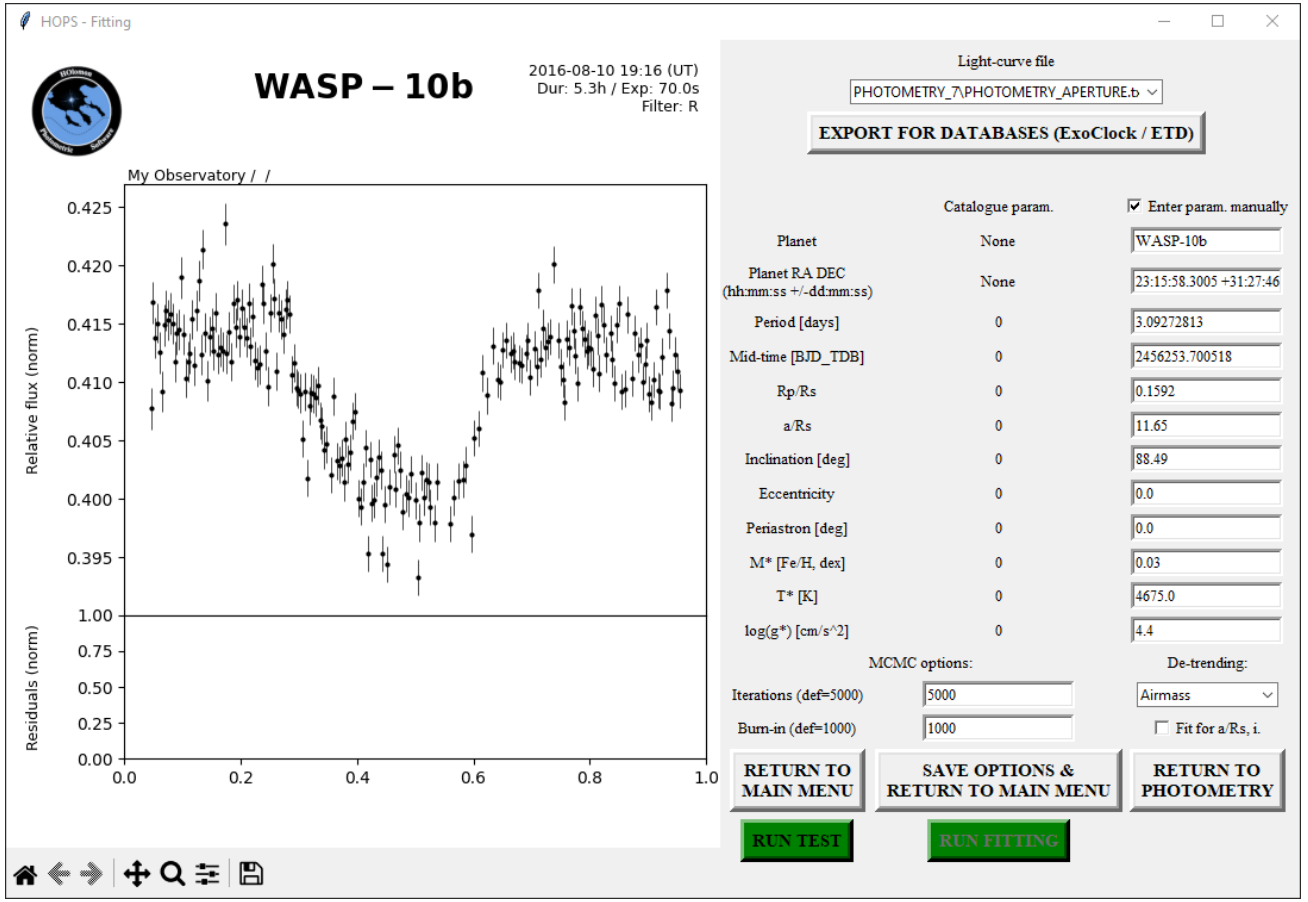


- Utilize the drop-down menu to pick which file you want.
- You have 2 options for its of your photometry attempts: APERTURE or GAUSS (PSF) fitting.

Step 6: Exoplanet Fitting

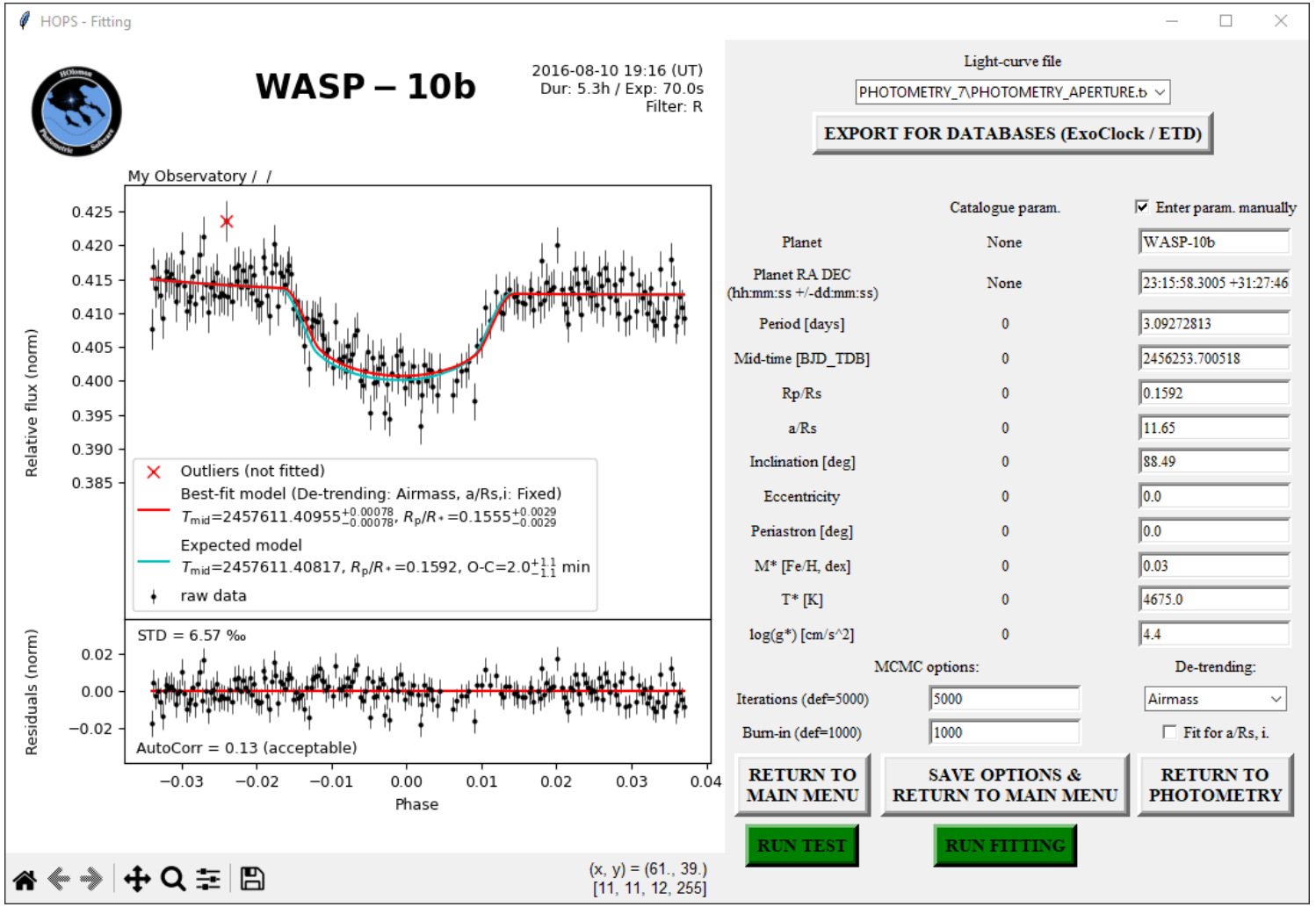
Enter the planets parameters

- The parameters of the exoplanet that is the closest to your coordinates will be chosen from a built-in catalogue. This catalogue contains about 400 exoplanets but not all of them.
- If this is not your target, or if you want to change the default values, select the "*Enter param. Manually*" option to activate the manual entries.
- When it is ready press **"RUN TEST"**



Step 6: Exoplanet Fitting

Run test

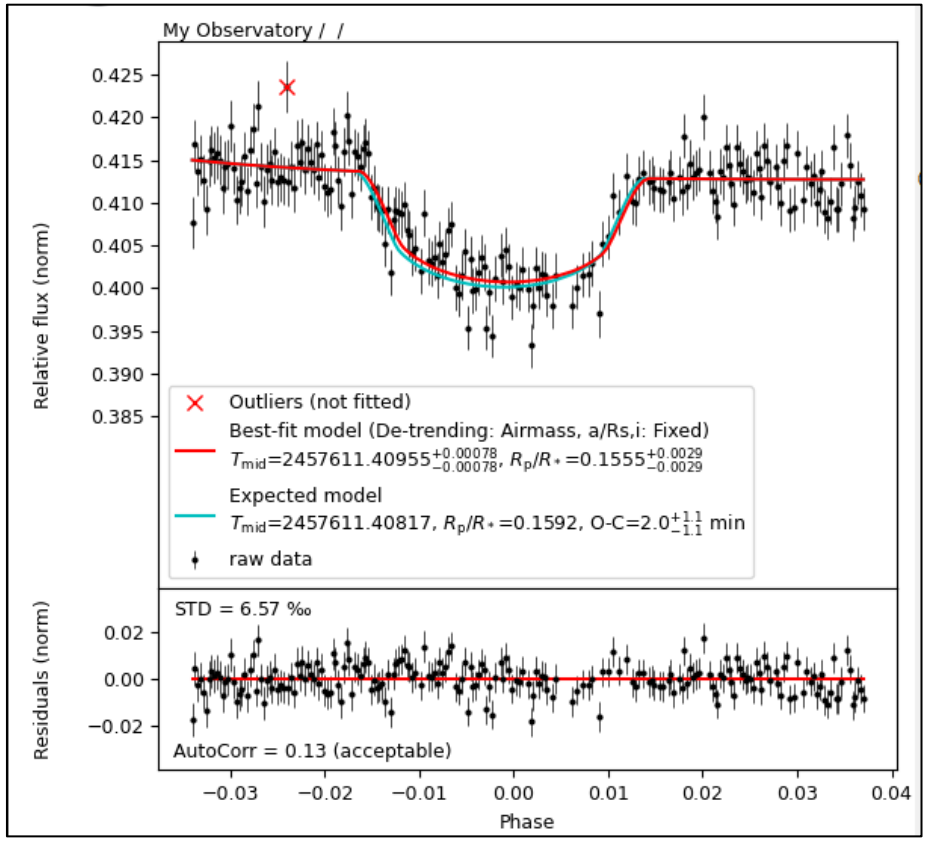


- This is a fitting preview. In this graph, the data have been corrected for a quadratic term (de-trended).
- The model plotted with red represent the best-fit model on the data (not MCMC).
- the expected model based on the parameters you have provided with cyan.
- This graph also shows the fitting residuals and some diagnostics on them (STD and autocorrelation).

Step 6: Exoplanet Fitting

Evaluation of test run

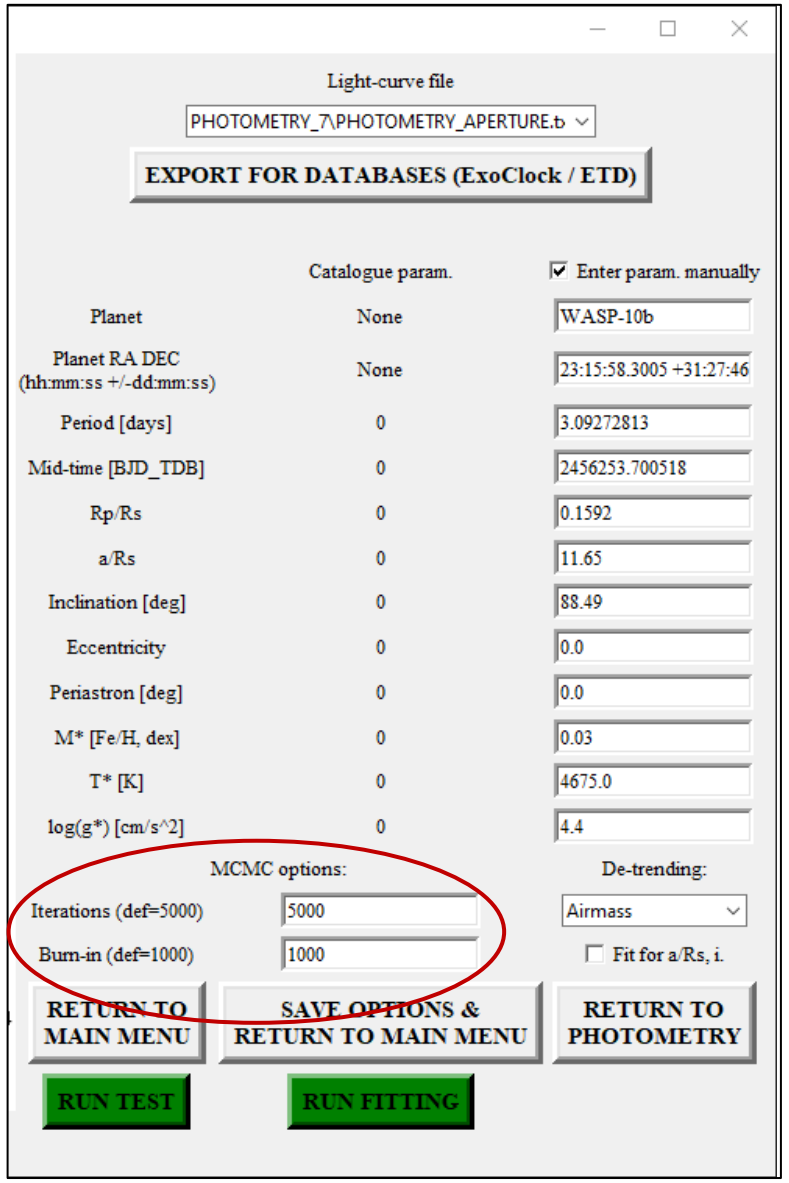
- Evaluate the fitting preview before hitting the **“RUN FITTING”** button. This is an important part of the process. It will tell you if your data are good to a level that results can be extracted.
- First check the compatibility with the expected model, especially the **transit depth**. If you find large inconsistencies you may need to go back to photometry and pick deferent comparisons or go back to reduction and check your flat frames.
  - You will realize that changing comparisons can affect your final results a lot! This is usually due to airmass effects caused by comparison stars of different spectral types. A way to be safe is to:
    i. get good flat fields
    ii. observe long before and after the transit
    iii. keep your stars within the linear response range of your camera.
- The residuals are the difference between your data and the best model. *STD* and *AutoCorr* are the standard deviation and autocorrelation of the residuals, respectively. The smaller these numbers, the better the fitting.



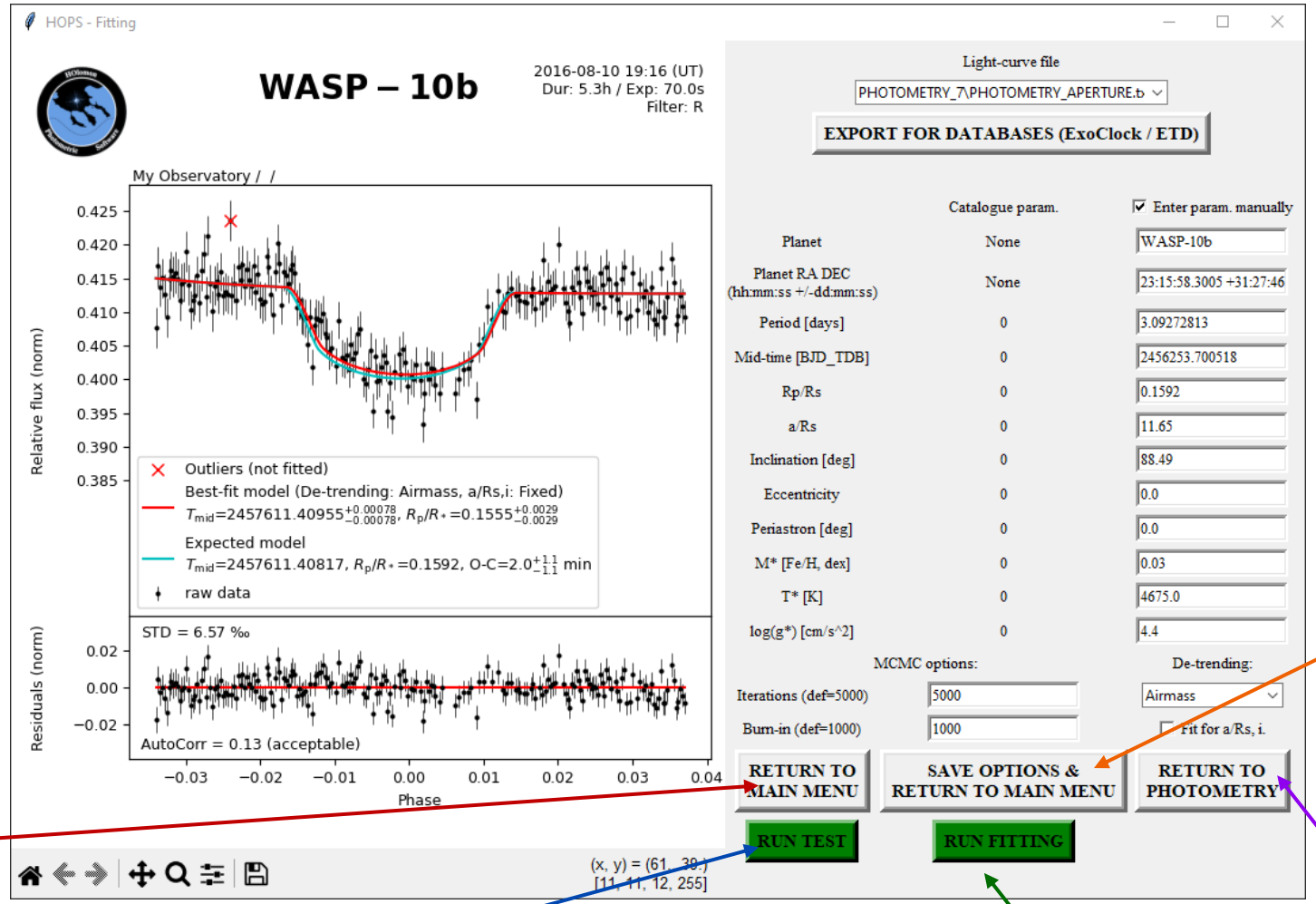
Step 6: Exoplanet Fitting

Adjust the MCMC parameters

- HOPS uses MCMC fitting, which is a process that tries to obtain the best result by approaching it in small steps.
- The number of steps is indicated by the MCMC iterations. The default value of 5000 should be sufficient but if the result is not good (very noisy light curve) you may need to increase it to 10000.
- The MCMC burn-in parameter states how many of the initial steps should be ignored and the default value is 1000. This is because in the beginning the algorithm is trying to “find its way towards the best solution” and the results are still unstable.
- If you increase MCMC iterations, increase MCMC burn-in accordingly, but do not exceed The MCMC iterations value!
- If the fitting preview is approved press “**RUN FITTING**”



Step 6: Exoplanet Fitting



Return to the main menu without saving your work

Run a fitting preview

Run a fitting

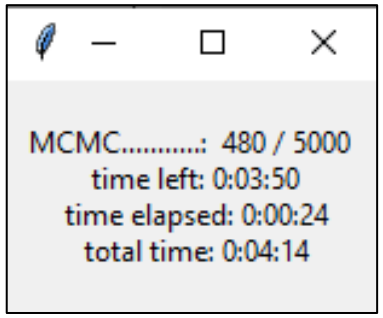
Save the current work and return to the main menu

Save the current work and return to the photometry menu

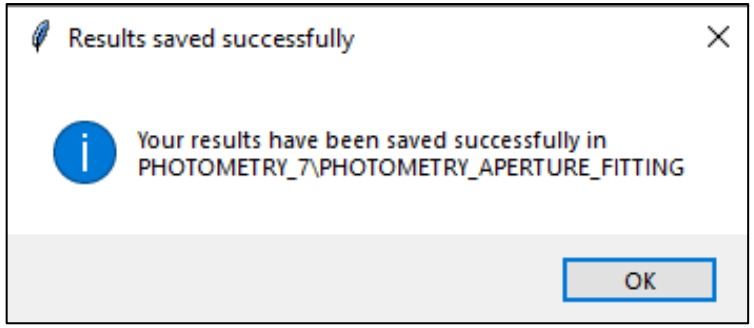
Step 6: Exoplanet Fitting

Run fitting

- During the process, the window below opens:



- When the process is finished a message is shown, that informs you about the name of the folder your files have been saved:



Step 6: Exoplanet Fitting

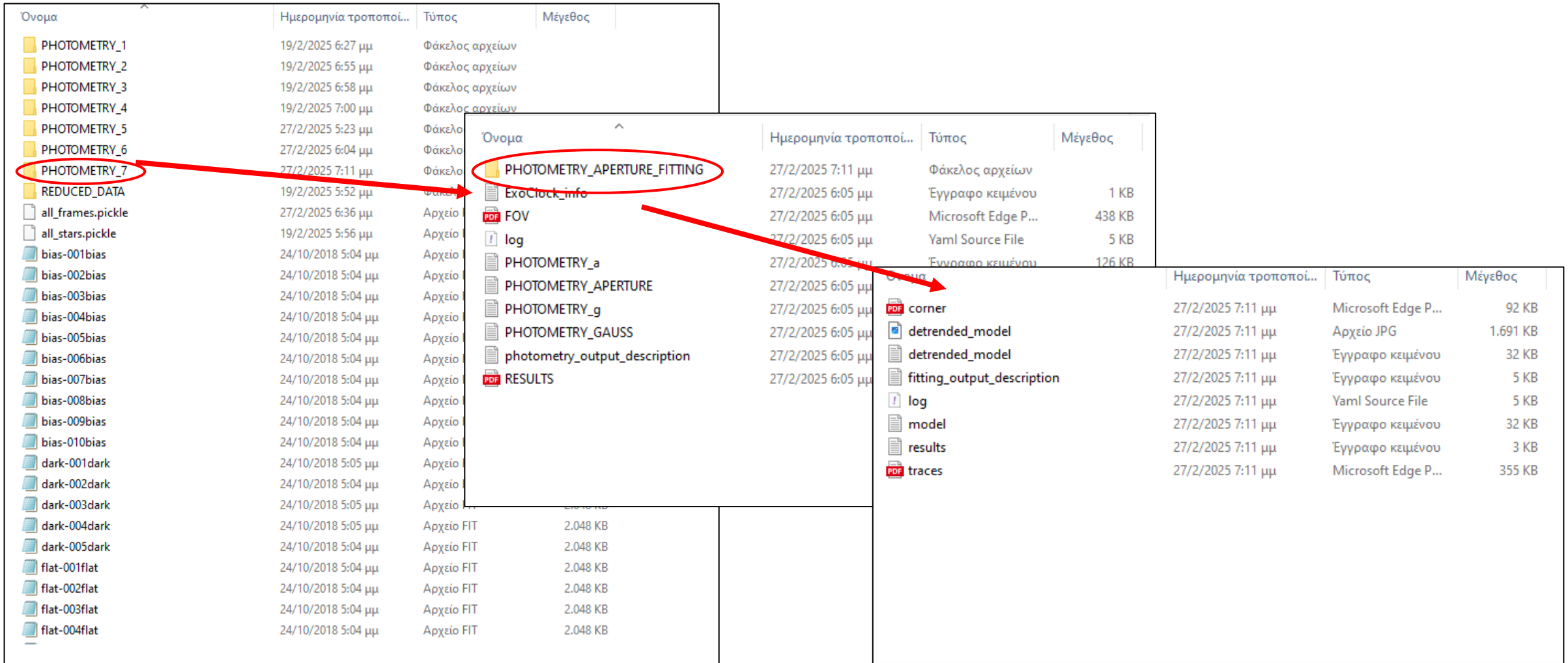
Output

- HOPS will create 3 new files and at least 2 new folders inside your initial data directory:
- ***log.yaml, all_frames.pickle, all_stars.pickle***: supporting files (**DO NOT DELETE THEM**!)
- ***REDUCED_DATA***: folder that contains the reduced data (**DO NOT DELETE OR ANOTATE DATA** in this folder, if you want to do so, work with the raw data and perform reduction again)
- ***PHOTOMETRY***: folder that contains the photometry results, one for each time you run photometry or saved the photometry results.
- ***PHOTOMETRY_APERTURE_FITTING*** or ***PHOTOMETRY_GAUSS_FITTING*** (included in the photometry folder): folders that contains the fitting results on the aperture or gauss light curves, respectively, one for each time you run fitting on this specific light curve.
- Included in the ***PHOTOMETRY*** and the ***FITTING*** folders you will find .txt files with more detailed descriptions of the output. files of your final fitting.

Step 6: Exoplanet Fitting

Output

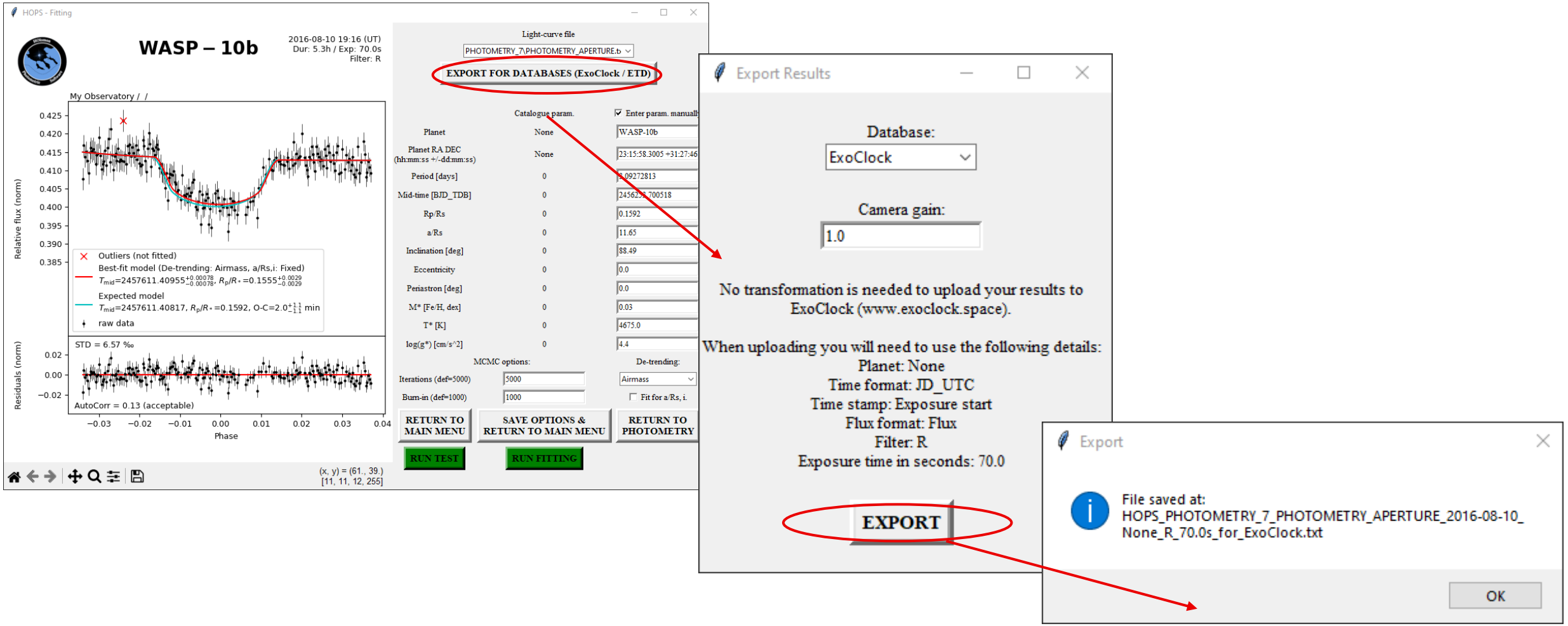
- In the folder in which your data are stored, new folders containing the results of its of your attempts are created. There you can find the files of your final fitting.



Step 6: Exoplanet Fitting

Export for databases

- Produce a .txt file which contains information of your observation and indicates which file to upload to keep the ExoClock's project database up to date.



My profile

set default values for some parameters to save time for future use of HOPS