CHEOPS
CHARACTERISING EXOPLANET SATELLITE

# CHEOPS Science Performance

## Examples of CHEOPS precision using in-flight data

**CHEOPS Consortium, 3rd November 2020**

# Introduction

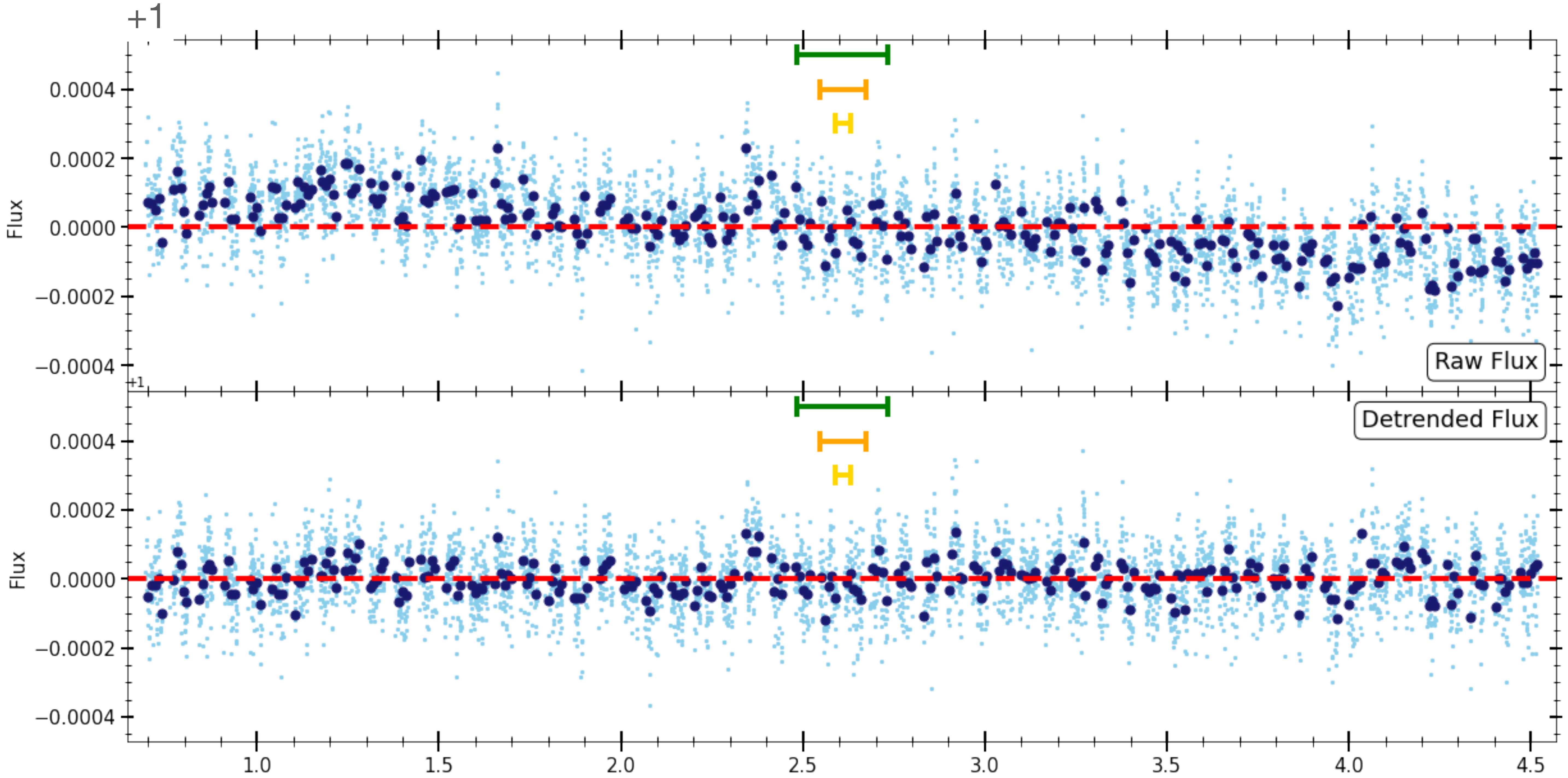
## Data, tools and brief description

- In the next slides, six visits whose targets cover the nominal CHEOPS magnitude range ($6<G_{mag}<12$), illustrate CHEOPS performances
- Three of these targets were observed as part of the GTO programme. For two of them the identities are not provided and therefore referred as “Anonymous”
- All the visits were processed with the latest version of the Data Reduction Pipeline (v12.0, see Hoyer et al. 2020)
- Some light curves show instrumental features. Discussing them is beyond the scope of this document
- The light curves shown were obtained using the DEFAULT photometric aperture (circular aperture, radius = 25 px)
- All light curves were analysed with `pycheops` (V0.9.3) ➪ https://github.com/pmaxted/pycheops
- The science performance is quantified calculating the light curve’s noise (in ppm) for six timescales: 1 minute, 10 minutes, 30 minutes, 1 hour, 3 hours and 6 hours The idea behind the noise definition is to determine the transit depth that can be detected with a signal-to-noise ratio (SNR) of 1
- Noise estimations are reported for the raw light curve (output of the DRP) and the detrended lightcurve (detrending done using `pycheops`). The noise estimation corresponds to the Scaled Errors Method, if the scaling factor is lower than 2, or to the Minimum Errors Method otherwise (see the Method description at the end of the slides). Both methods are implemented in `pycheops`
- A comparison with the noise estimation from the ETC (V2.0) is given for reference. Note that for the very bright stars the real performance is in general better than expected, for medium bright stars the ETC agrees well with the measured performance and for faint stars the ETC is reliable only for long time scales (beyond 3 hours). Future versions of the ETC will try to solve the discrepancies between “real” and “expected” performances

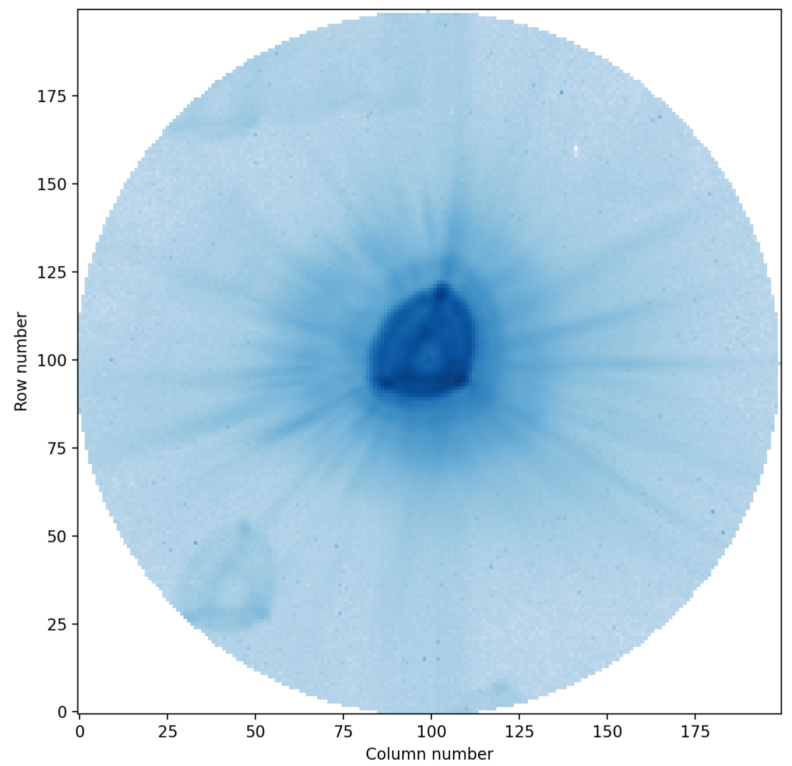
# Anonymous 1

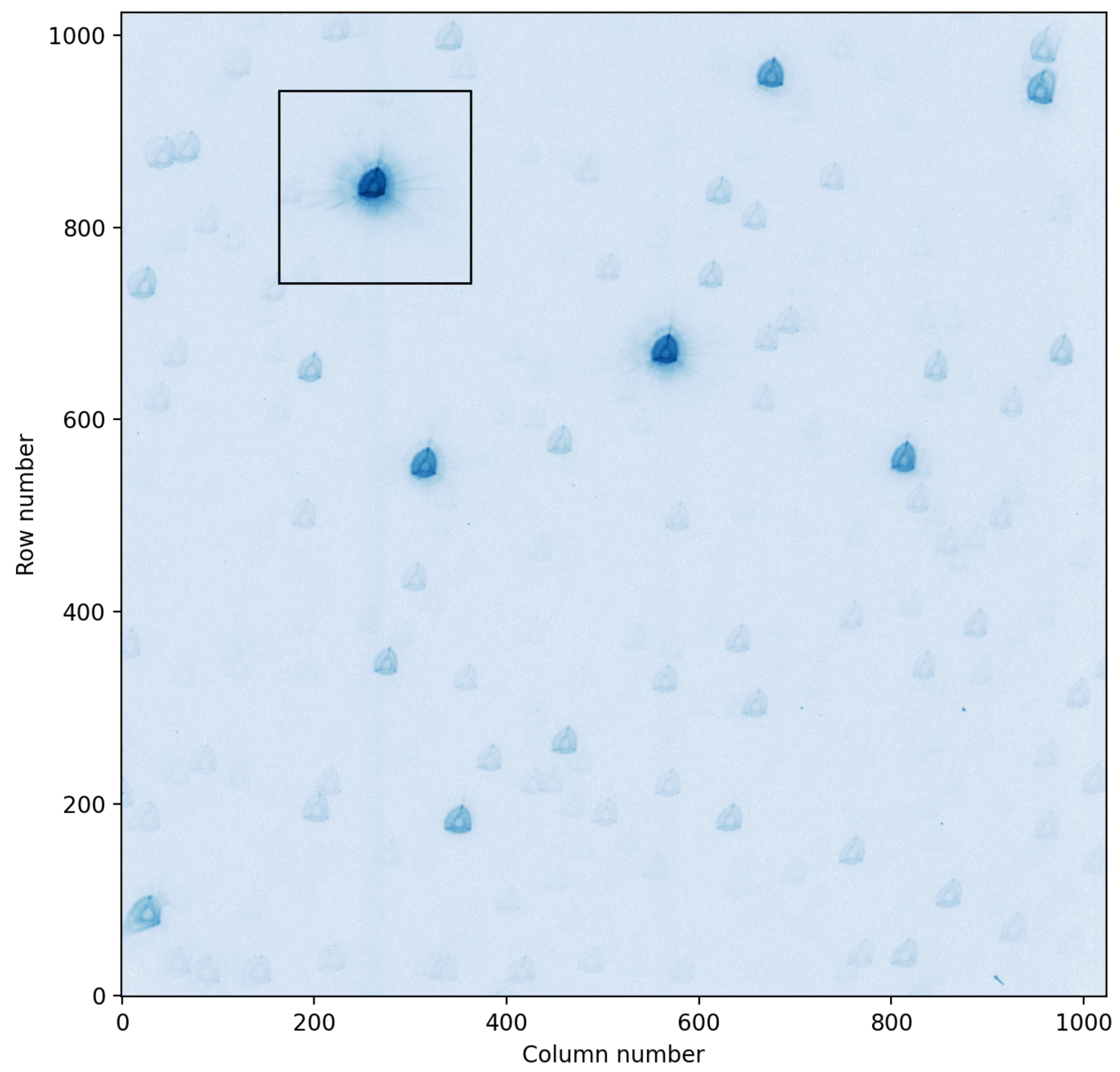
## $G_{mag}$ ~ 5, $T_{eff}$ ~ 5500 K

- Exposure time: ~1.8 s




6 hours
3 hours
1 hour



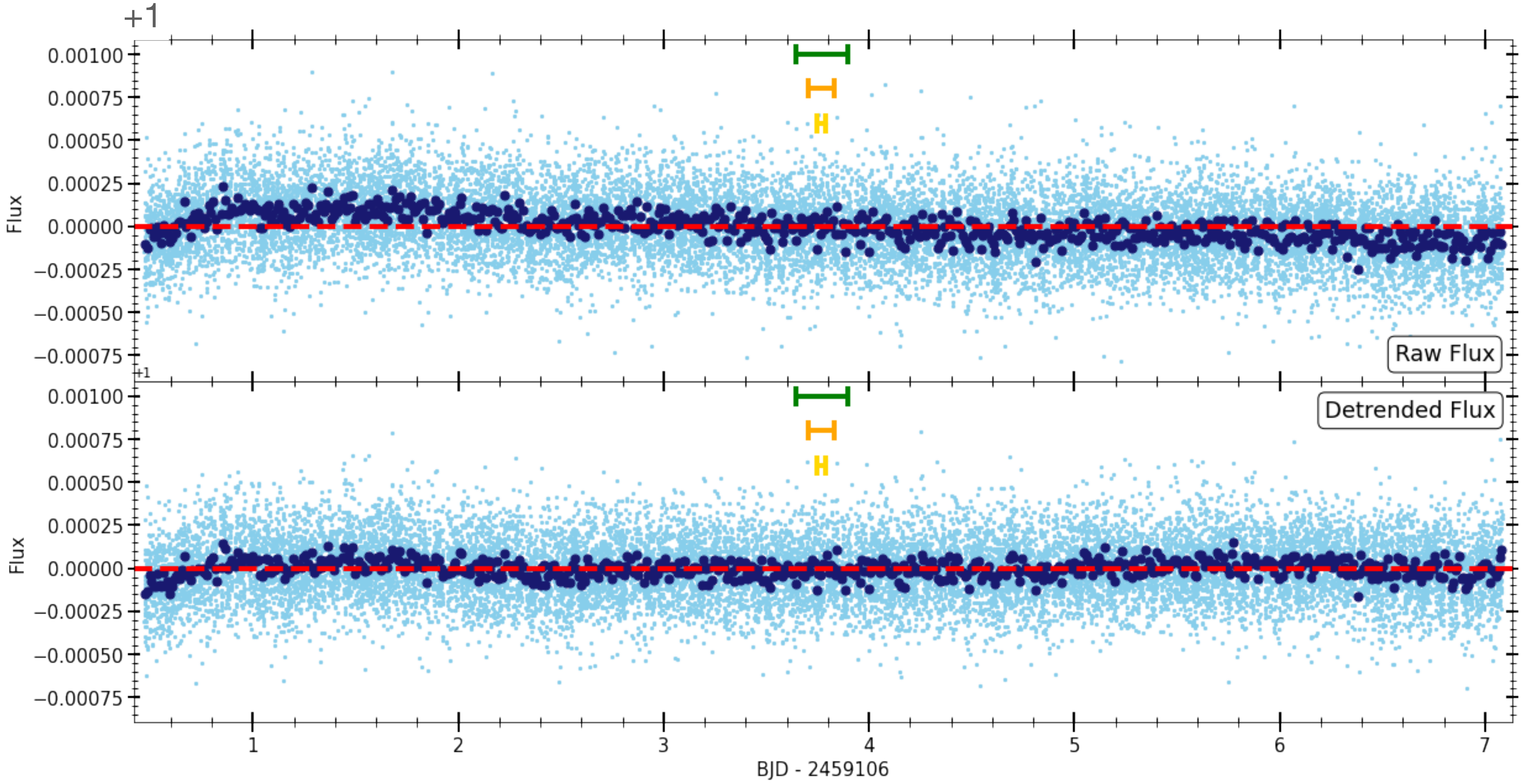

[2]Noise calculated using the Minimum Error Method

| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| Raw LC[2] | 60 | 27 | 21 | 15 | 8 | 6 |
| Detrended LC[2] | 58 | 24 | 19 | 13 | 7 | 5 |
| ETC | 145 | 60 | 35 | 21 | 14 | 10 |

# HD 215152

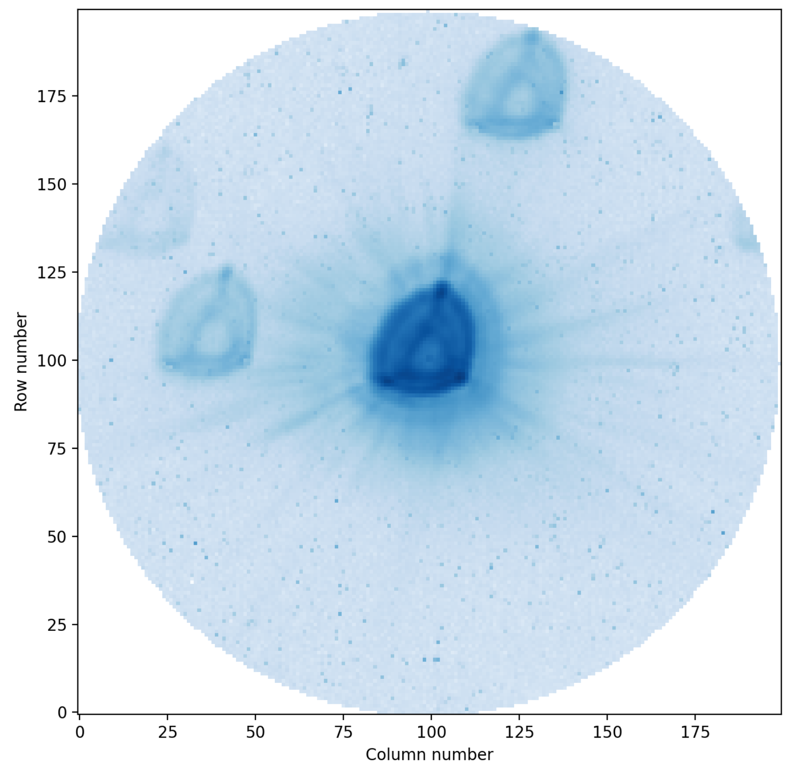
## $G_{mag}$ = 7.8, $T_{eff}$ = 4803 K

- Exposure time: 15.12 s
- Visit Duration: 6.6 days
- Observation Date: 13/09/2020

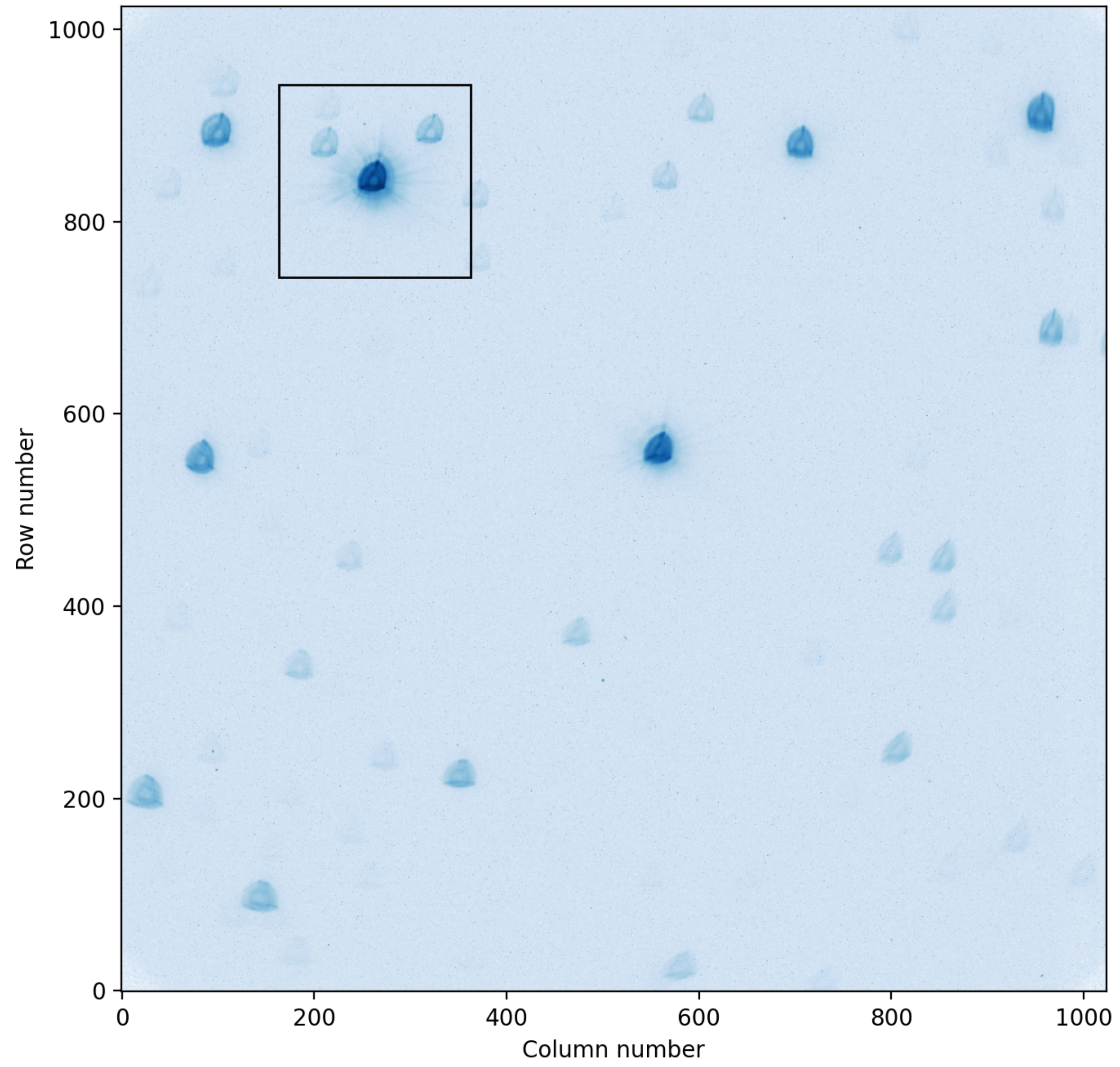



6 hours
3 hours
1 hour

**Window Image**




**Full Field of View**



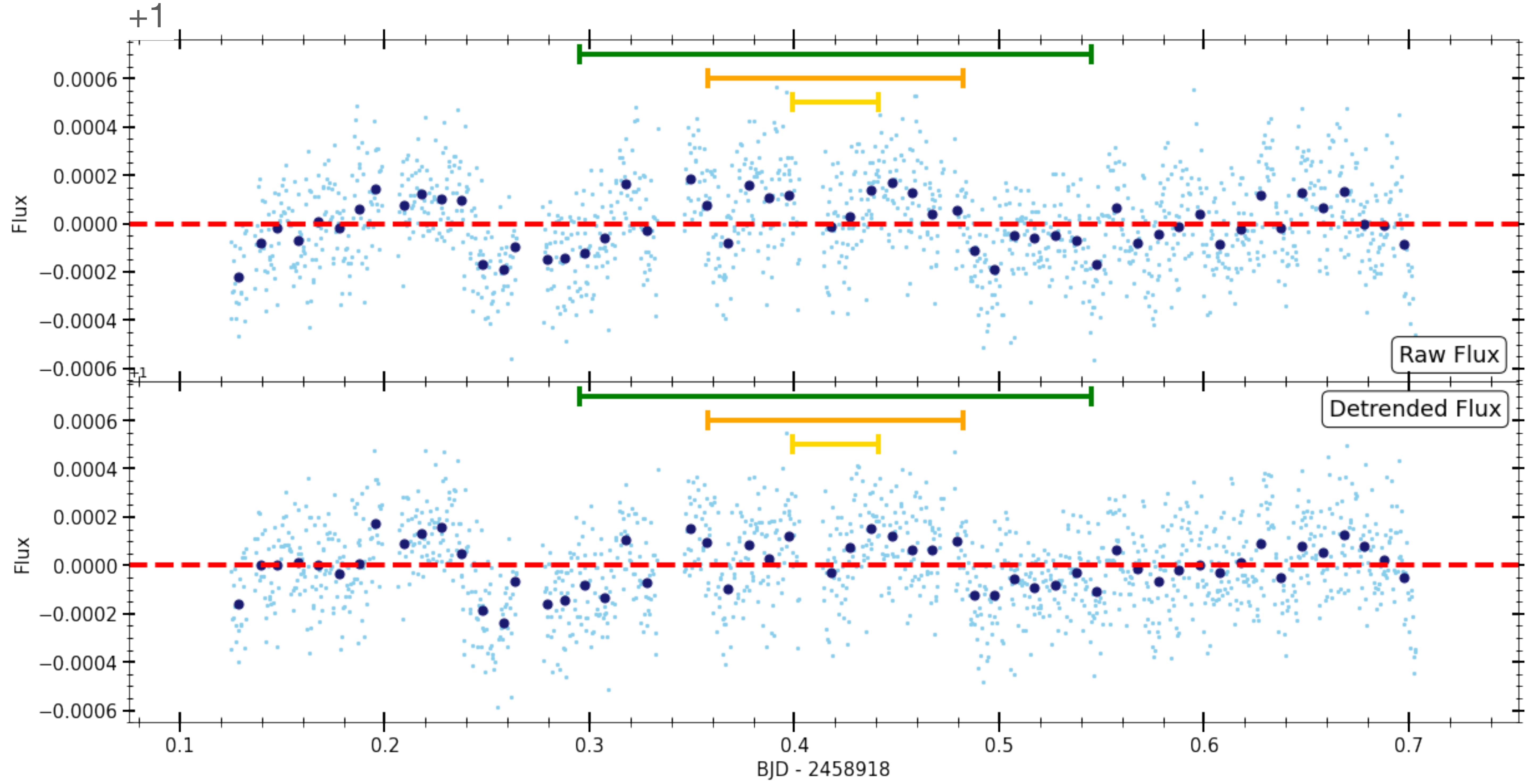

[1]Noise calculated using the Scaled Error Method

| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| **Raw LC[1]** | 147 | 50 | 29 | 20 | 12 | 8 |
| **Detrended LC[1]** | 103 | 34 | 20 | 14 | 8 | 6 |
| **ETC** | 178 | 68 | 40 | 24 | 16 | 12 |

# KELT-11b*

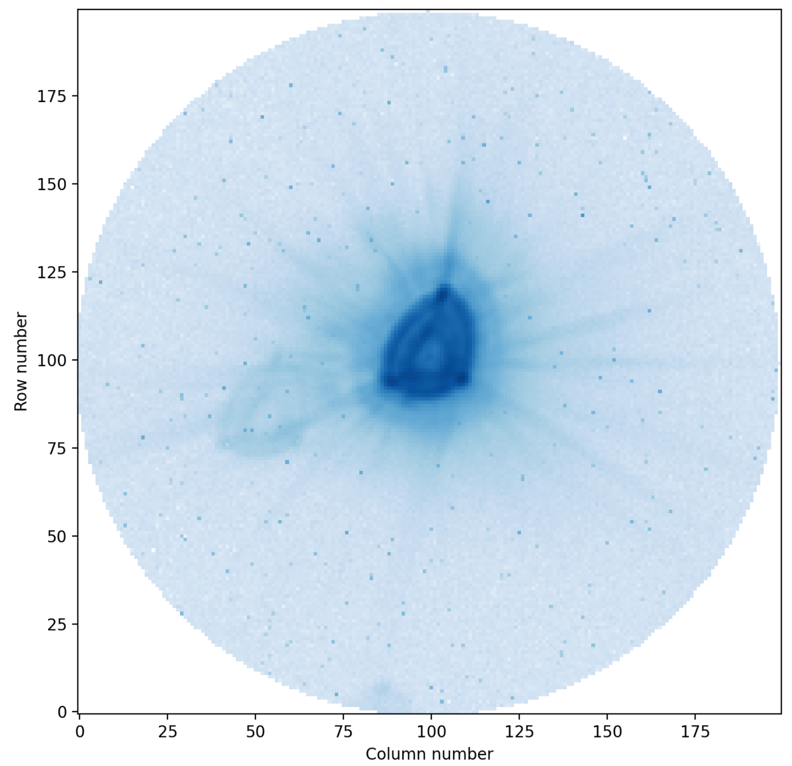
## $G_{mag}$ = 7.83, $T_{eff}$ = 5414 K

- Exposure time: 15 s
- Visit Duration: 14 h
- Observation Date: 09/03/2020

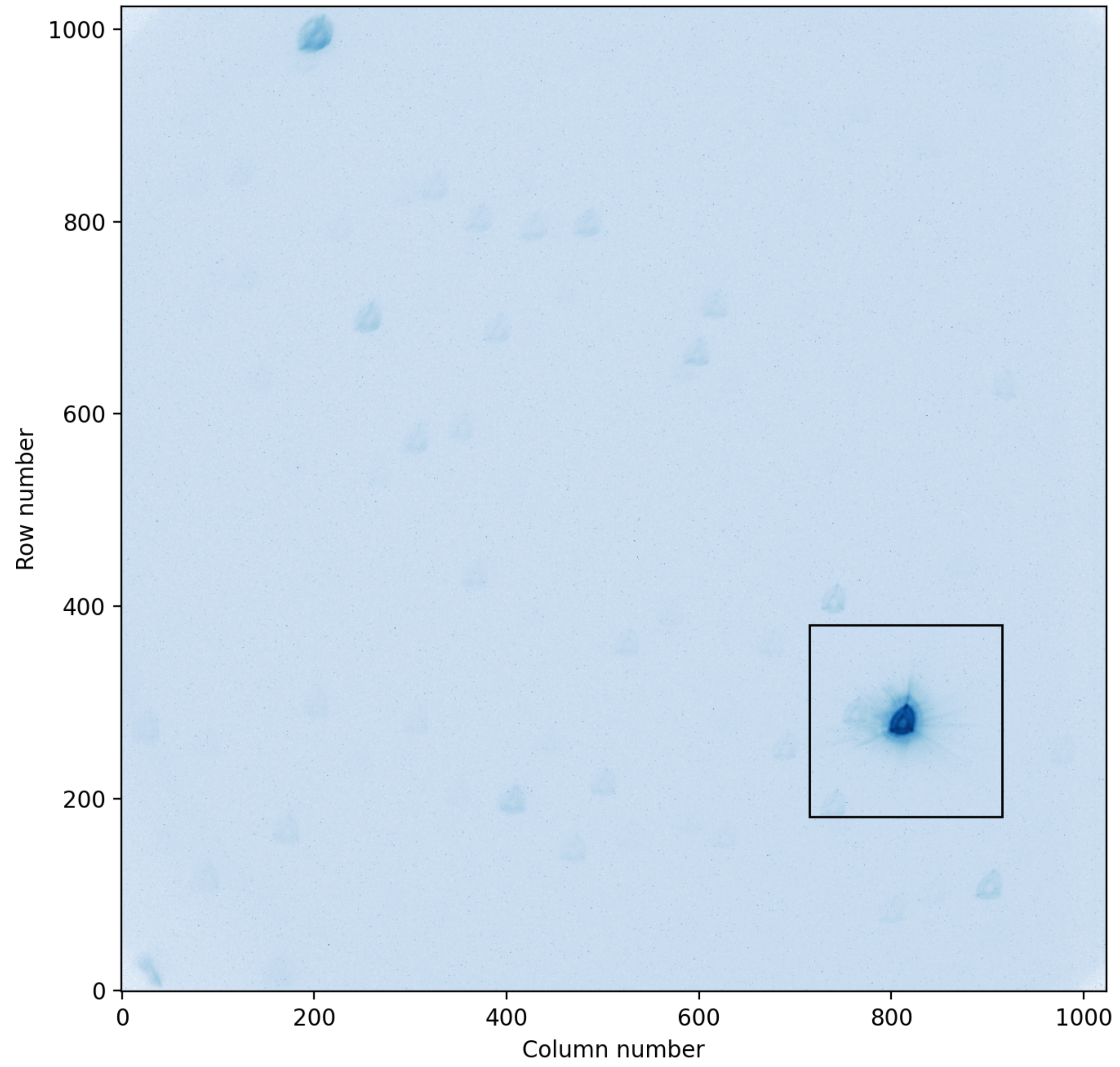



6 hours
3 hours
1 hour

Window Image




Full Field of View




[1]Noise calculated using the Scaled Error Method

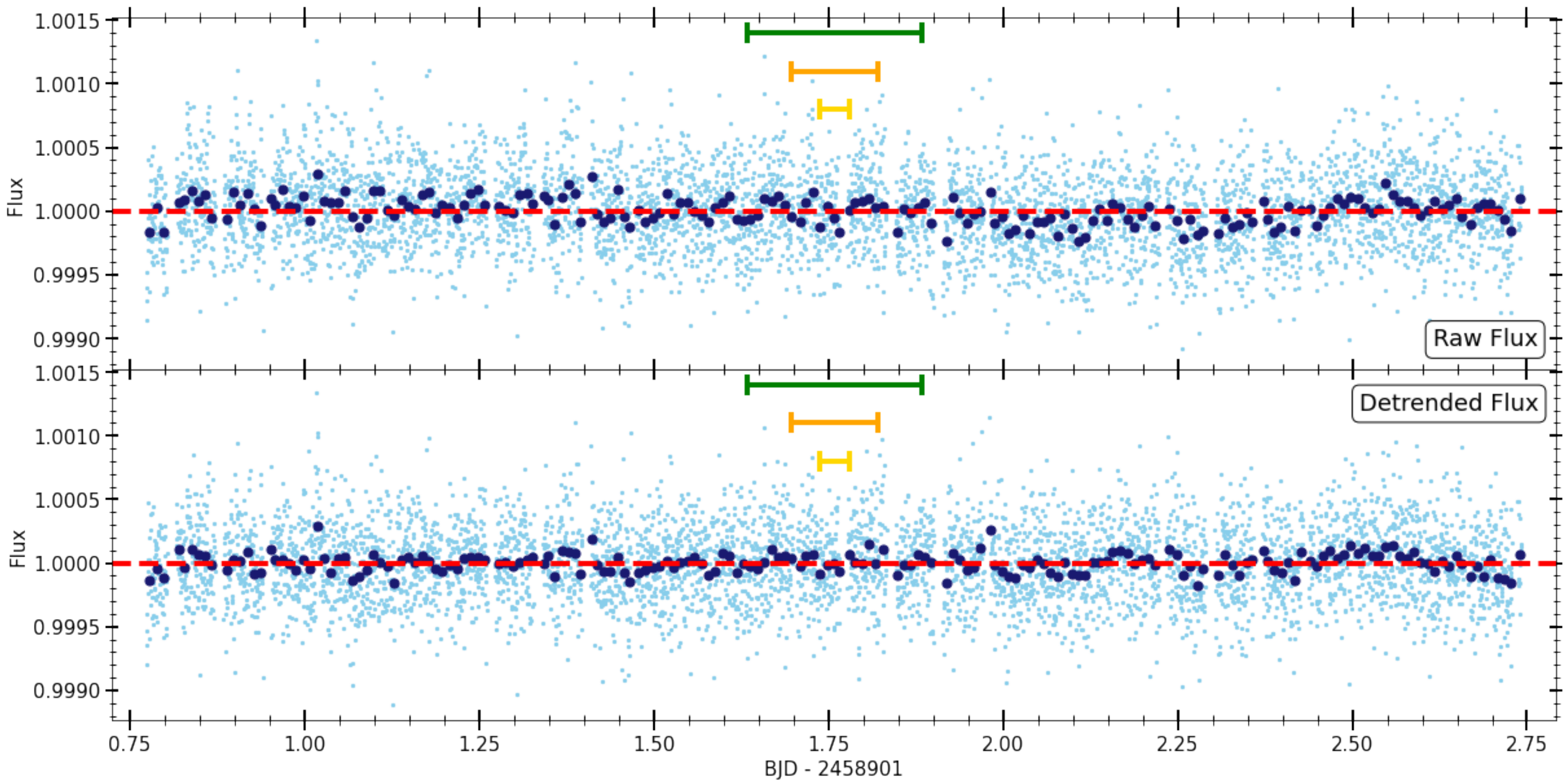
| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| **Raw LC[1]** | 125 | 41 | 24 | 17 | 10 | 7 |
| **Detrended LC[1]** | 111 | 42 | 25 | 17 | 10 | 7 |
| **ETC** | 179 | 69 | 40 | 25 | 16 | 12 |

* Transit of Kelt-11b removed. See Benz et al. (2020) for more details.
All data publicly available.

# HD88111*

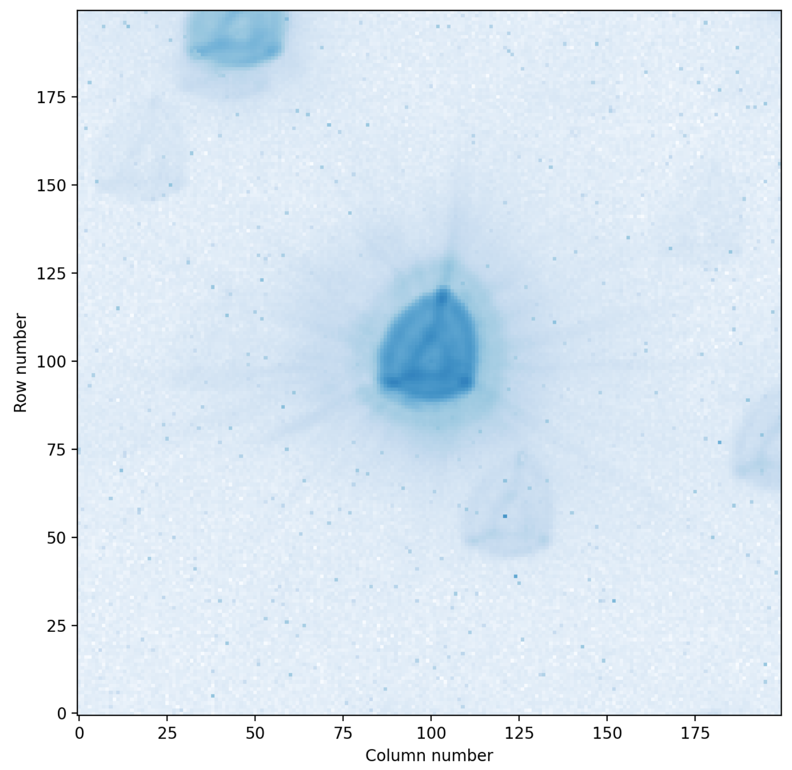
## $G_{mag}$ = 8.97, $T_{eff}$ = 5330 K

- Exposure time: 30 s
- Visit Duration: 47 h
- Observation Date: 22/02/2020

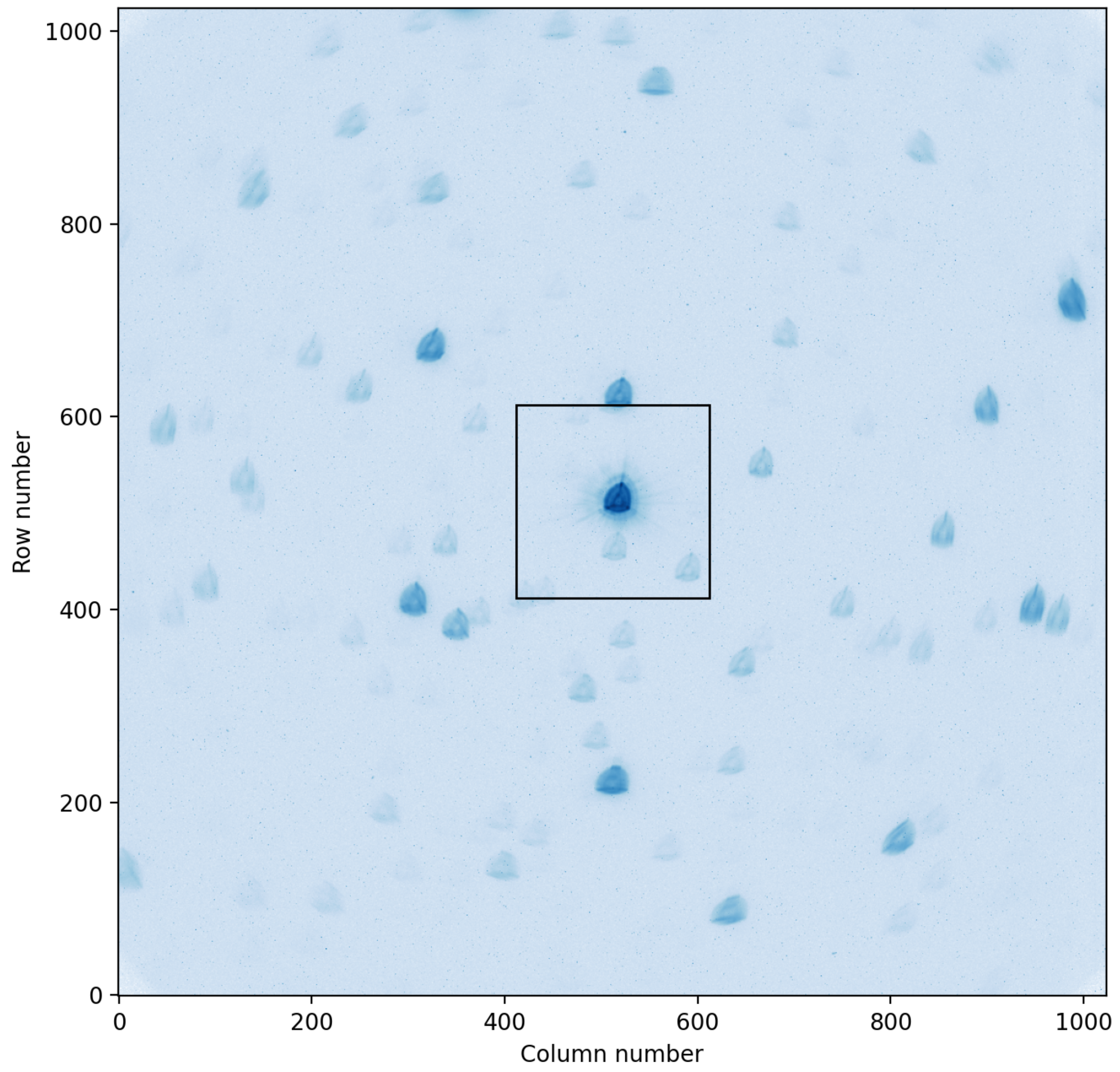



6 hours
3 hours
1 hour

Window Image




Full Field of View




[1]Noise calculated using the Scaled Error Method

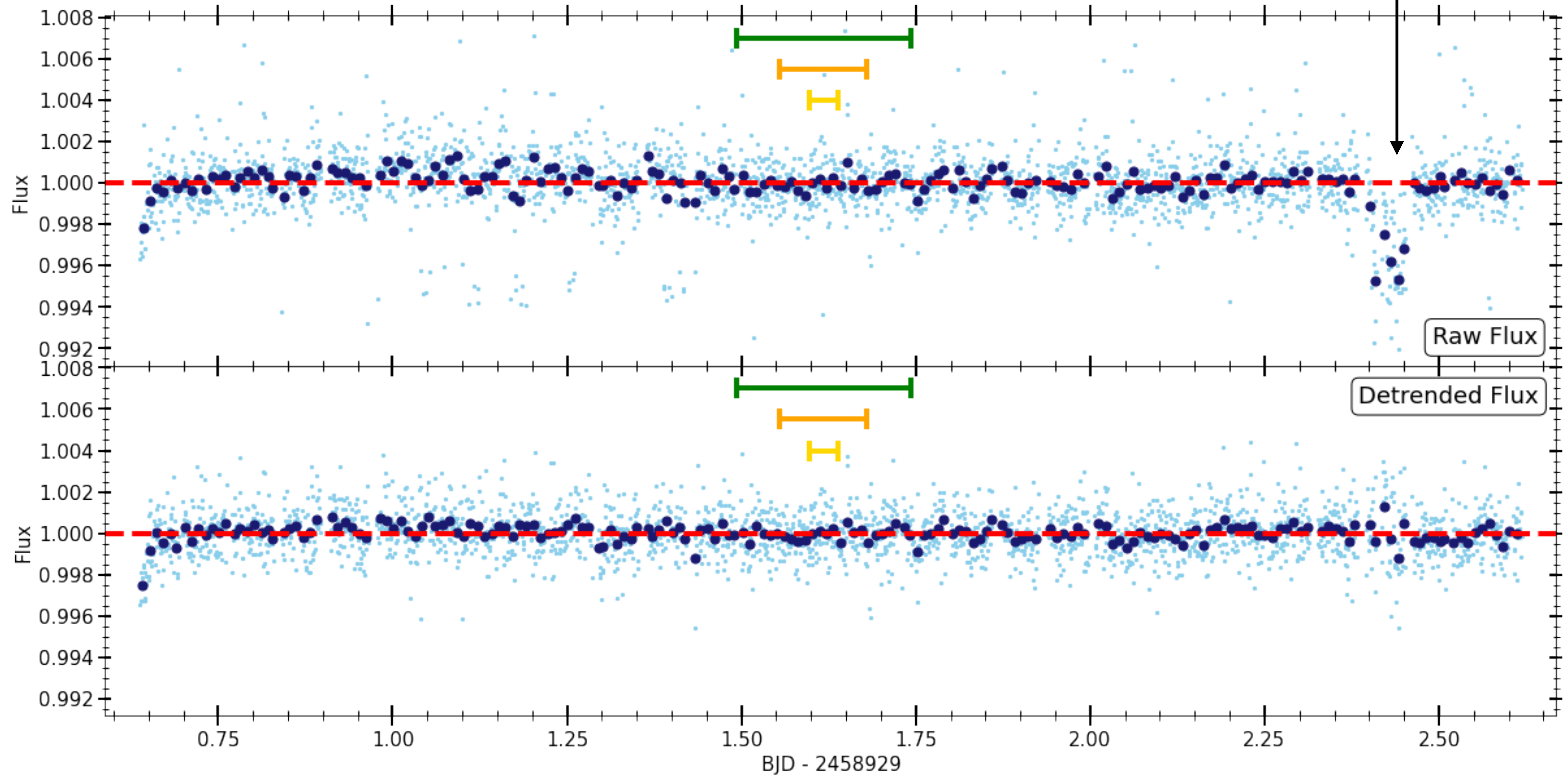
| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| Raw LC[1] | 202 | 75 | 45 | 31 | 18 | 12 |
| Detrended LC[1] | 193 | 62 | 36 | 27 | 15 | 11 |
| ETC | 235 | 84 | 49 | 32 | 20 | 15 |

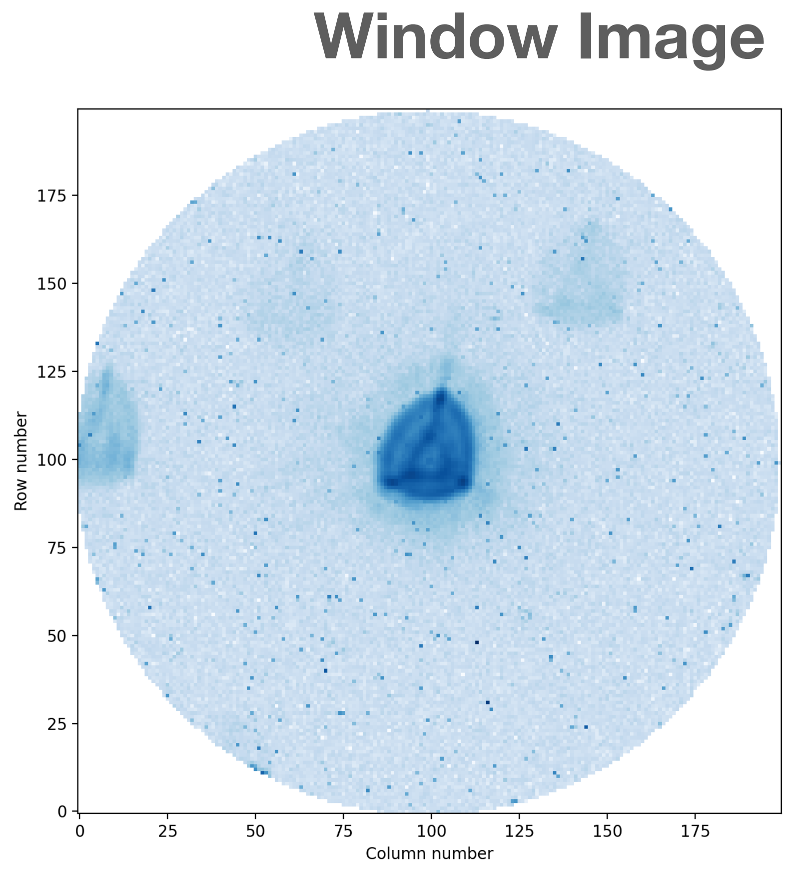
* See Benz et al. (2020) for more details. All data publicly available.

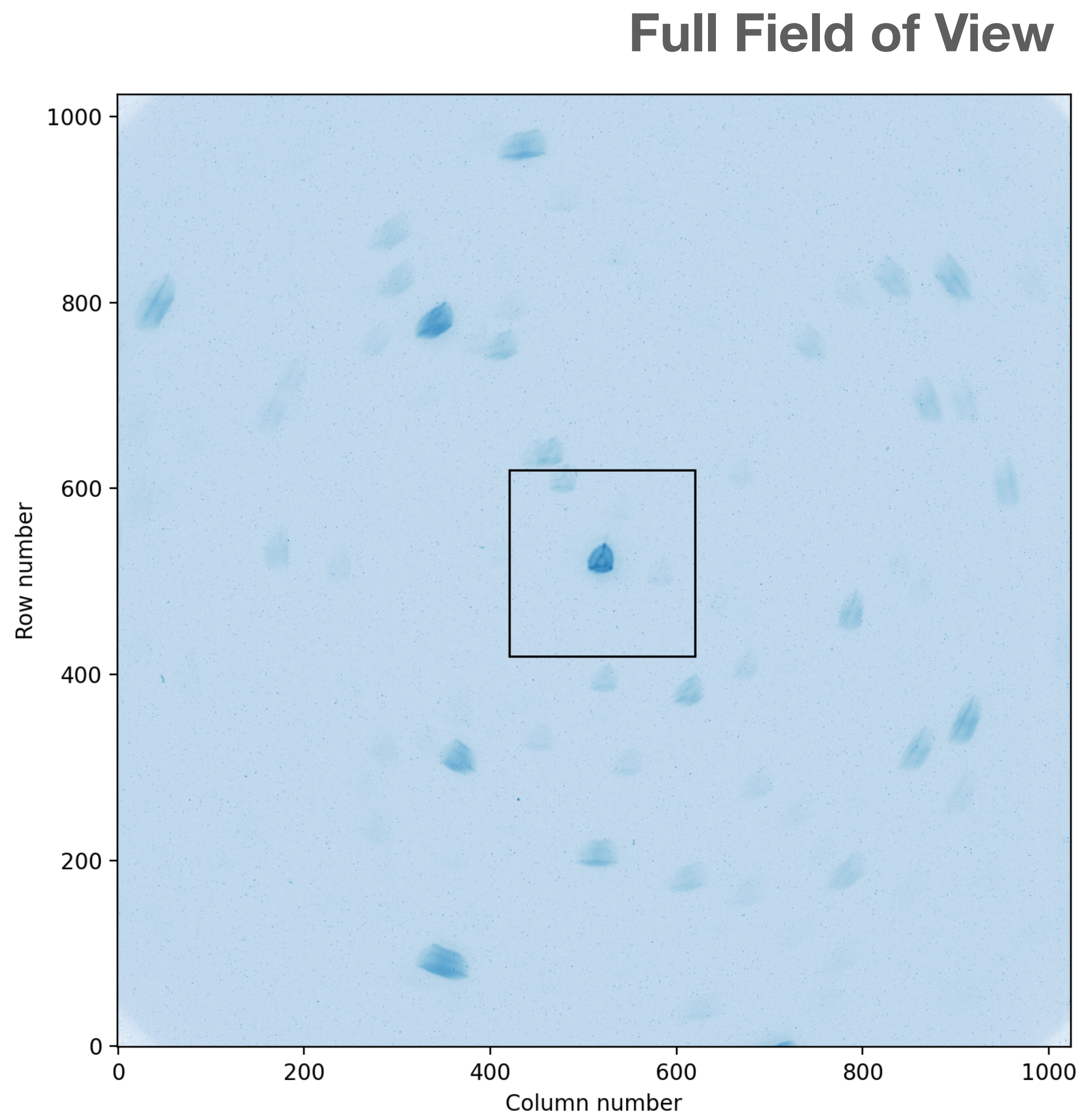
# TYC5502-1037-1*

## $G_{mag}$ = 11.98, $T_{eff}$ = 4750 K

- Exposure time: 60 s
- Visit Duration: 48 h
- Observation Date: 21/03/2020




6 hours
3 hours
1 hour

[1]Noise calculated using the Scaled Error Method
[2]Noise calculated using the Minimum Error Method

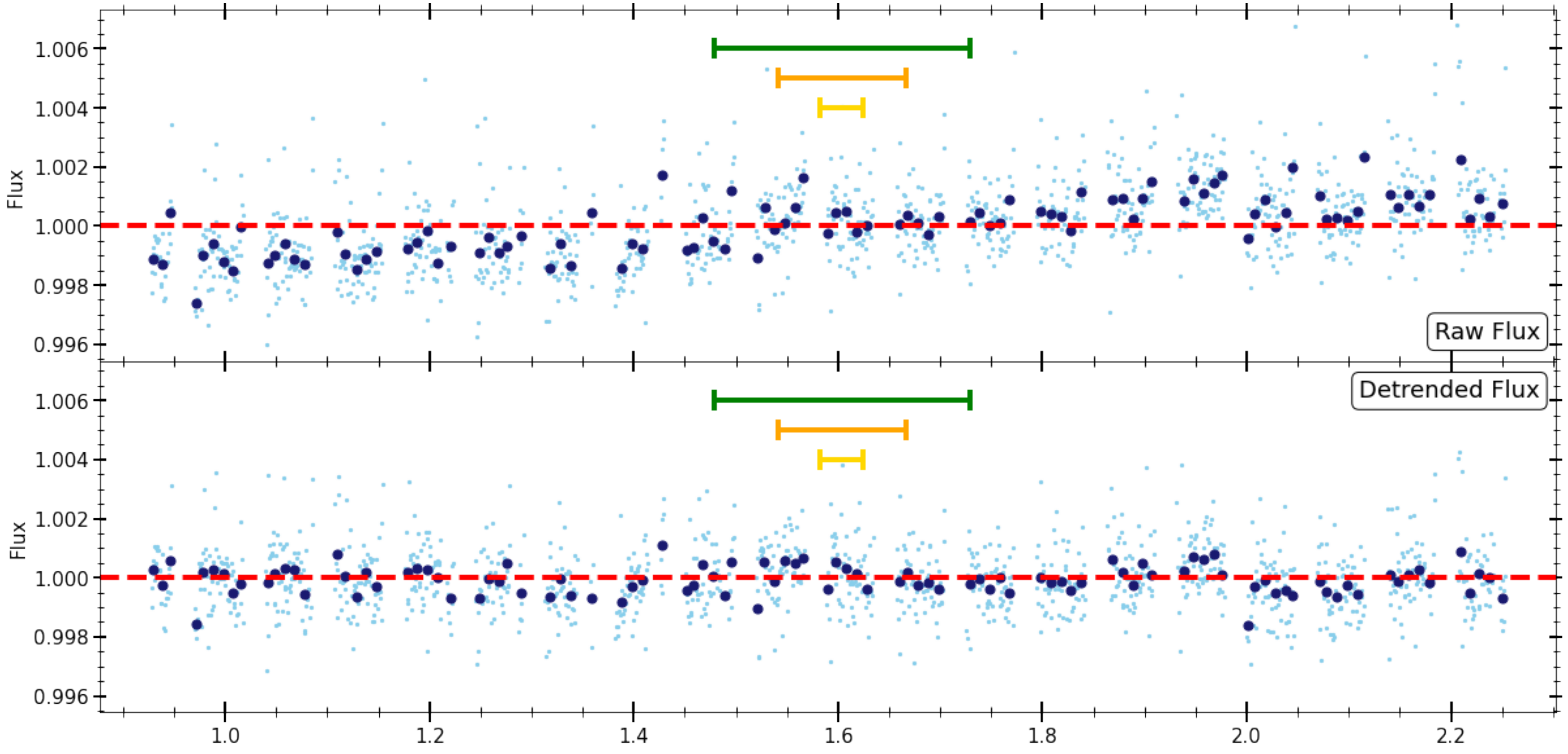
| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| Raw LC[2] | 1100 | 440 | 269 | 188 | 108 | 76 |
| Detrended LC[1] | 669 | 348 | 209 | 145 | 83 | 59 |
| ETC | 799 | 265 | 164 | 126 | 94 | 84 |

* See Benz et al. (2020) for more details. All data publicly available.

# Anonymous 2

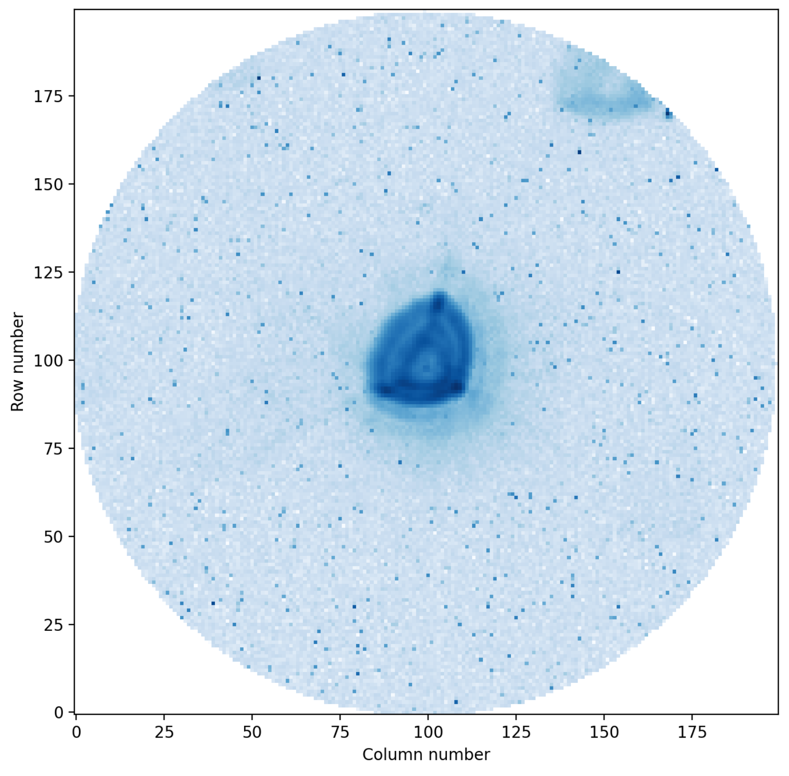
## $G_{mag}$ ~ 12, $T_{eff}$ ~ 3200 K

- Exposure time: 60 s

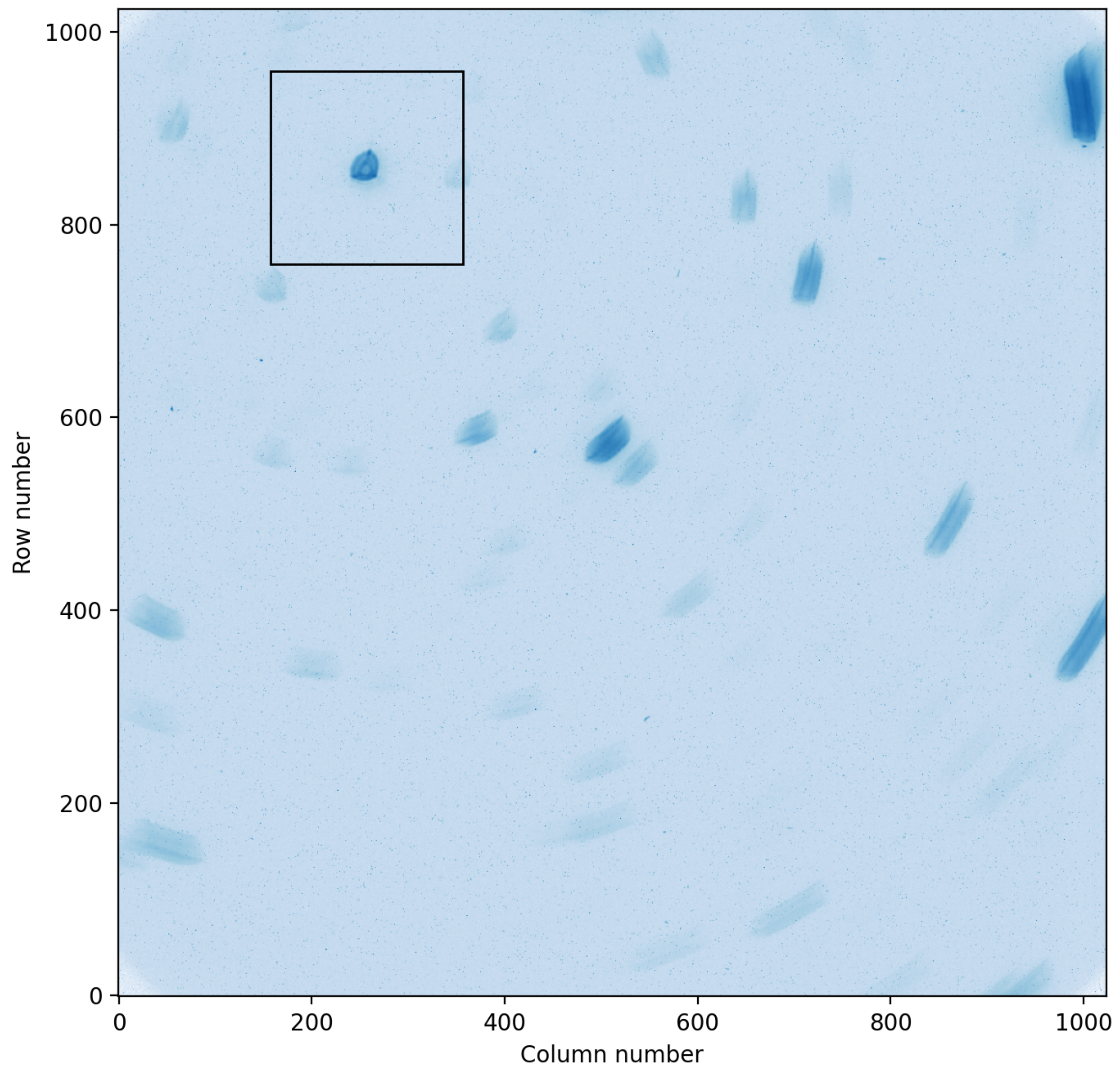



6 hours
3 hours
1 hour

Window Image




Full Field of View




[1]Noise calculated using the Scaled Error Method
[2]Noise calculated using the Minimum Error Method

| Noise [ppm] | 1 min | 10 min | 30 min | 1 h | 3 h | 6 h |
|---|---|---|---|---|---|---|
| **Raw LC[2]** | 1103 | 352 | 232 | 203 | 108 | 77 |
| **Detrended LC[1]** | 1137 | 307 | 200 | 157 | 91 | 63 |
| **ETC** | 683 | 225 | 137 | 103 | 74 | 65 |

# Noise estimation methods

**Method**

The photometric precision on the timescale of the transit is estimated by finding the transit depth that can be detected with a signal-to-noise of 1. This is essentially the same method used to calculate the Kepler CDPP noise value.

We can use a factor $s$ to modify the transit depth in a nominal model $\mathbf{m}_0$ calculated with approximately the correct depth that is scaled as follows ...

$$\mathbf{m}(s) = 1 + s \times (\mathbf{m}_0 - 1).$$

The nominal model is calculated assuming an impact parameter $b = 0$ and includes limb-darkening appropriate for the star observed.

The data are normalised fluxes $\mathbf{f} = f_1, \ldots, f_N$ with nominal errors $\boldsymbol{\sigma} = \sigma_1, \ldots, \sigma_N$.

Two different methods are used to perform the least-squares fit to the simulated transits that differ in their assumptions concerning the true standard errors on the data.

**Scaled errors method** The "scaled" method assumes that the actual standard errors are underestimated by some factor $b$, and that these are normally distributed and uncorrelated, so that the log-likelihood is

$$\ln \mathcal{L} = -\frac{1}{2b^2}\chi^2 - \frac{1}{2}\sum_{k=1}^{N} \ln \sigma_k^2 - N \ln b - \frac{N}{2}\ln(2\pi),$$

where

$$\chi^2 = \sum_{k}^{N} \frac{(f_k - 1 - s(m_{0,k} - 1))^2}{\sigma_k^2}$$

The maximum likelihood occurs for parameter values $\hat{s}$, and $\hat{b}$ such that

$$\left.\frac{\partial \ln \mathcal{L}}{\partial s}\right|_{\hat{s},\hat{b}} = 0$$

and

$$\left.\frac{\partial \ln \mathcal{L}}{\partial b}\right|_{\hat{s},\hat{b}} = 0$$

from which we obtain

$$\hat{s} = \sum_{k=1}^{N} \frac{(f_k - 1)(m_{0,k} - 1)}{\sigma_k^2} \left[\sum_{k=1}^{N} \frac{(m_{0,k} - 1)^2}{\sigma_k^2}\right]^{-1}$$

and

$$\boxed{\hat{b} = \sqrt{\chi^2/N}}$$ Scaling factor

For the standard errors on these parameters we use

$$\sigma_s^{-2} = -\frac{\partial^2 \ln \mathcal{L}}{\partial^2 s^2}\Big|_{\hat{s},\hat{b}}$$

and

$$\sigma_b^{-2} = -\frac{\partial^2 \ln \mathcal{L}}{\partial^2 b^2}\Big|_{\hat{s},\hat{b}}$$

to derive

$$\sigma_s = b\left[\sum_{i=1}^{N} \frac{(m_i - 1)^2}{\sigma_i^2}\right]^{-1/2}$$

and

$$\sigma_b = \left[3\chi^2/b^4 - N/b^2\right]^{-1/2}.$$

This method is appropriate in cases where the noise scaling factor has a value $b \approx 1$, i.e. unknown sources of noise are small compared to the known sources of noise that are quantied in the flux error values provided.

**Minimum errors method** The "minerr" method is more appropriate where the nominal errors should be treated as a lower-bound to the true standard errors, i.e., where there is some additional noise source that is not well quantified (e.g., poor cosmic-ray rejection). As a result, this method tends to be more conservative, i.e., more pessimisitic. We assume that actual standard error on observation $k$ is $\sigma_k$ with probability distribution

$$P(\sigma_k|\sigma_{0,k}) = \begin{cases} 0 & \sigma_k < \sigma_{0,k} \\ \frac{\sigma_{0,k}}{\sigma_k^2} & \sigma_k \geq \sigma_{0,k} \end{cases}$$

Assuming independent measurements and uniform priors, the posterior probability distribution is then

$$\ln \mathcal{L} = C + \sum_{k=1}^{N} \ln\left[\frac{1 - \exp(-R_k^2/2)}{R_k^2}\right]$$

where $C$ is a normalising constant and $R_k = (m_k - f_k)/\sigma_{0,k}$ (Sivia & Skilling "Data Analysis", section 8.3.1).

Since this is a function of one parameter only we can be efficiently find the maximum likelihood using a numerical search (Brent's method). The standard error on the $s$ is then found from the value of $s$ that give a log-likelihood that is 0.5 less than the maximum log-likelihood, i.e., at 1-sigma assuming a Gaussian distribution.