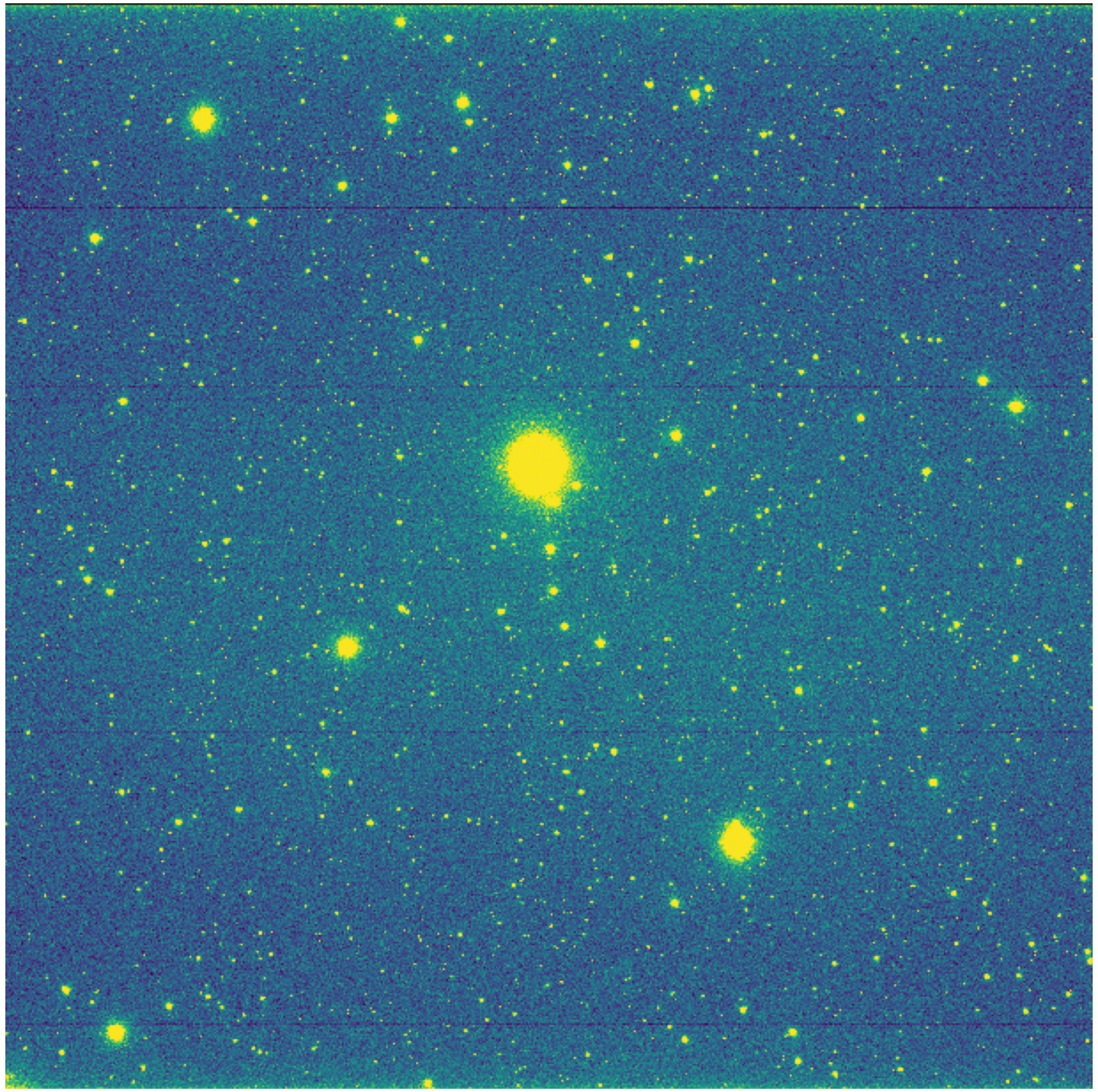
Photometric measurements

An example of final project images



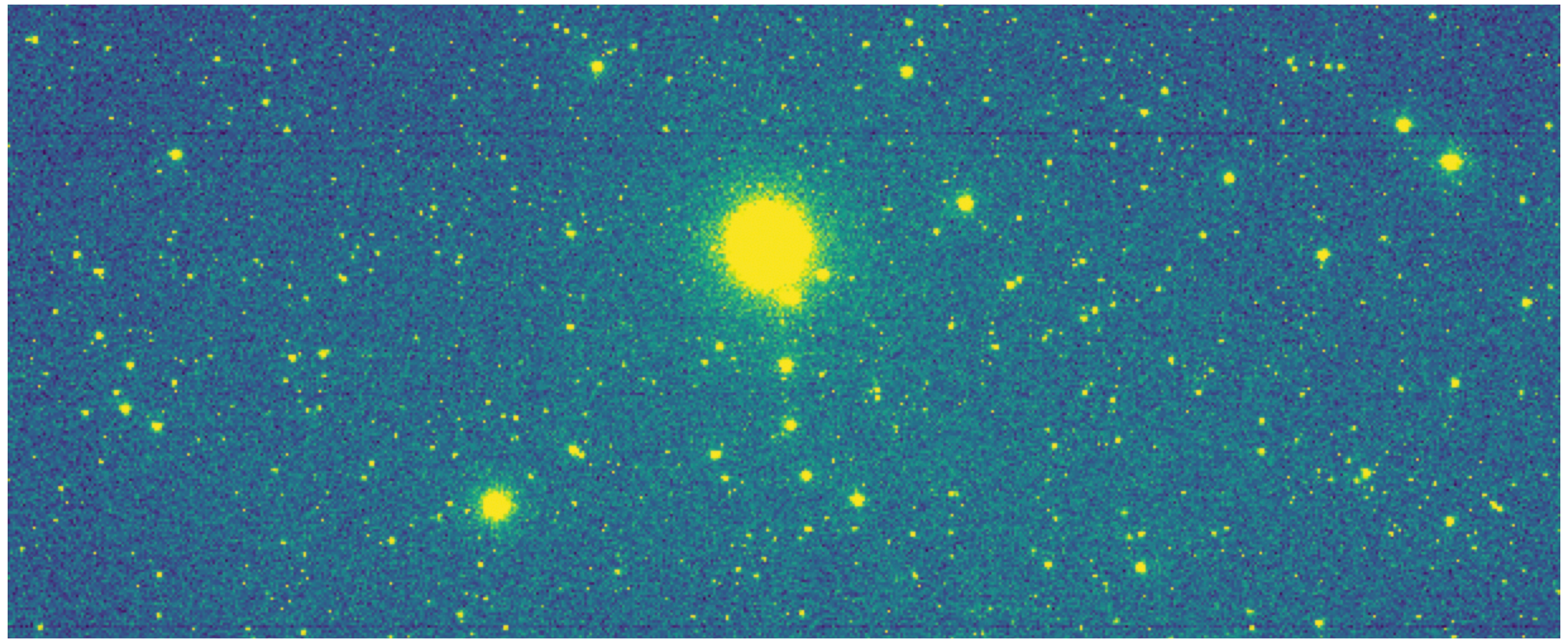
Observations: ARCSat time series oservations of transiting planet TOI-2046

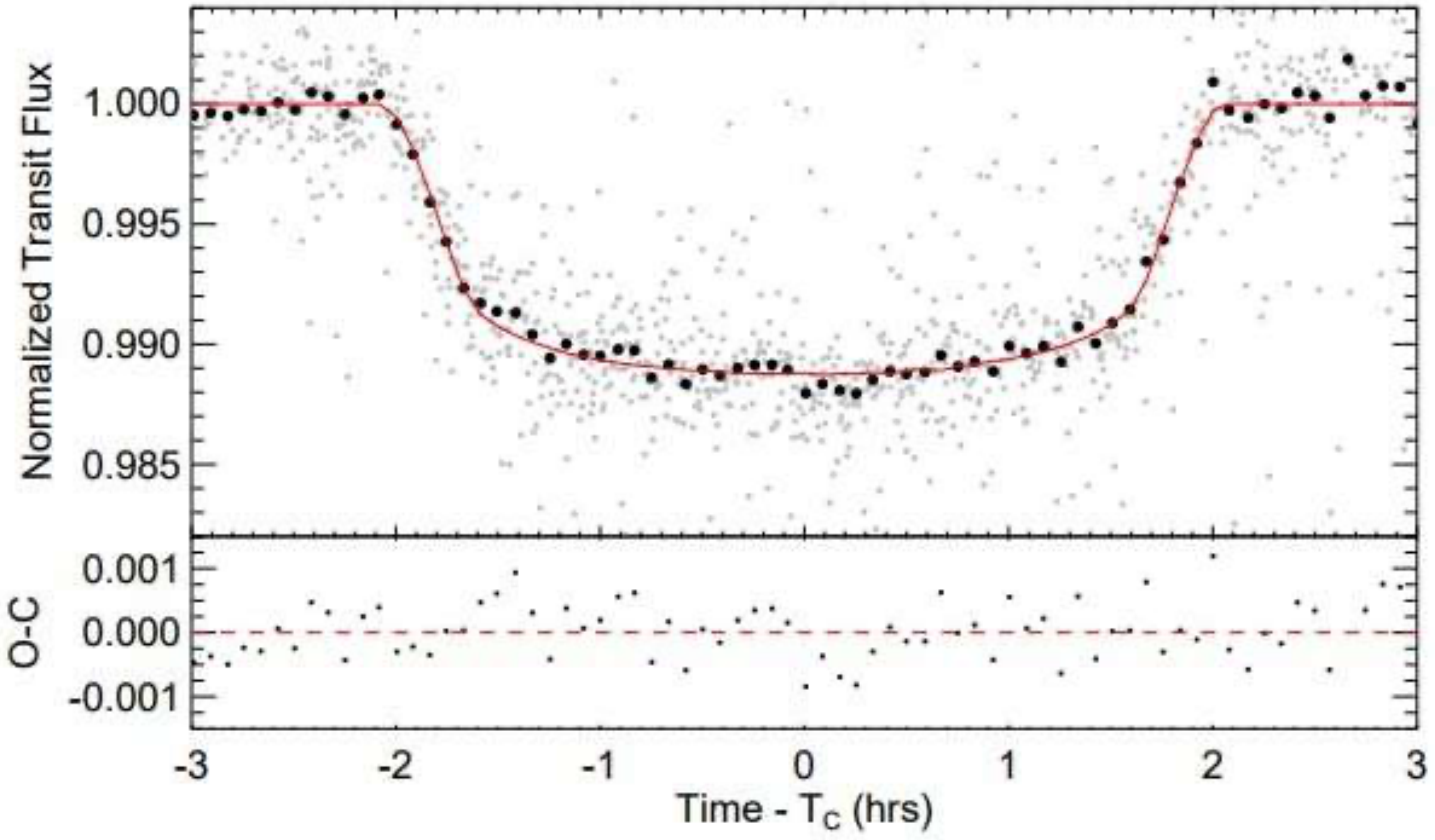
TOI-2046 b is a recently discovered massive hot Jupiter orbiting an F-type main sequence star (Kabáth et al. 2022).

It is among the youngest known hot Jupiter (age estimate: 100 to 400 Myr).

An interesting target for long-term transit monitoring.

Final project goals





* CCD data collection and reduction
* Error analysis
* High-precision relative photometric measurements
    * Photometric methods
    * Photometric data calibration
    * Calibrating Earth’s atmospheric absorption
* Determining transit timing through model fitting

Basic CCD calibrations

- Review the content of Lecture 12 and Howell Chapter 4.
- Empirical estimation of gain and read noise
- Create master calibration frames
- Bias subtraction, Overscan subtraction*, flat correction
- Identification and corrections for bad pixels, hot pixels, and cosmic rays
- Keep track of uncertainties at every step.

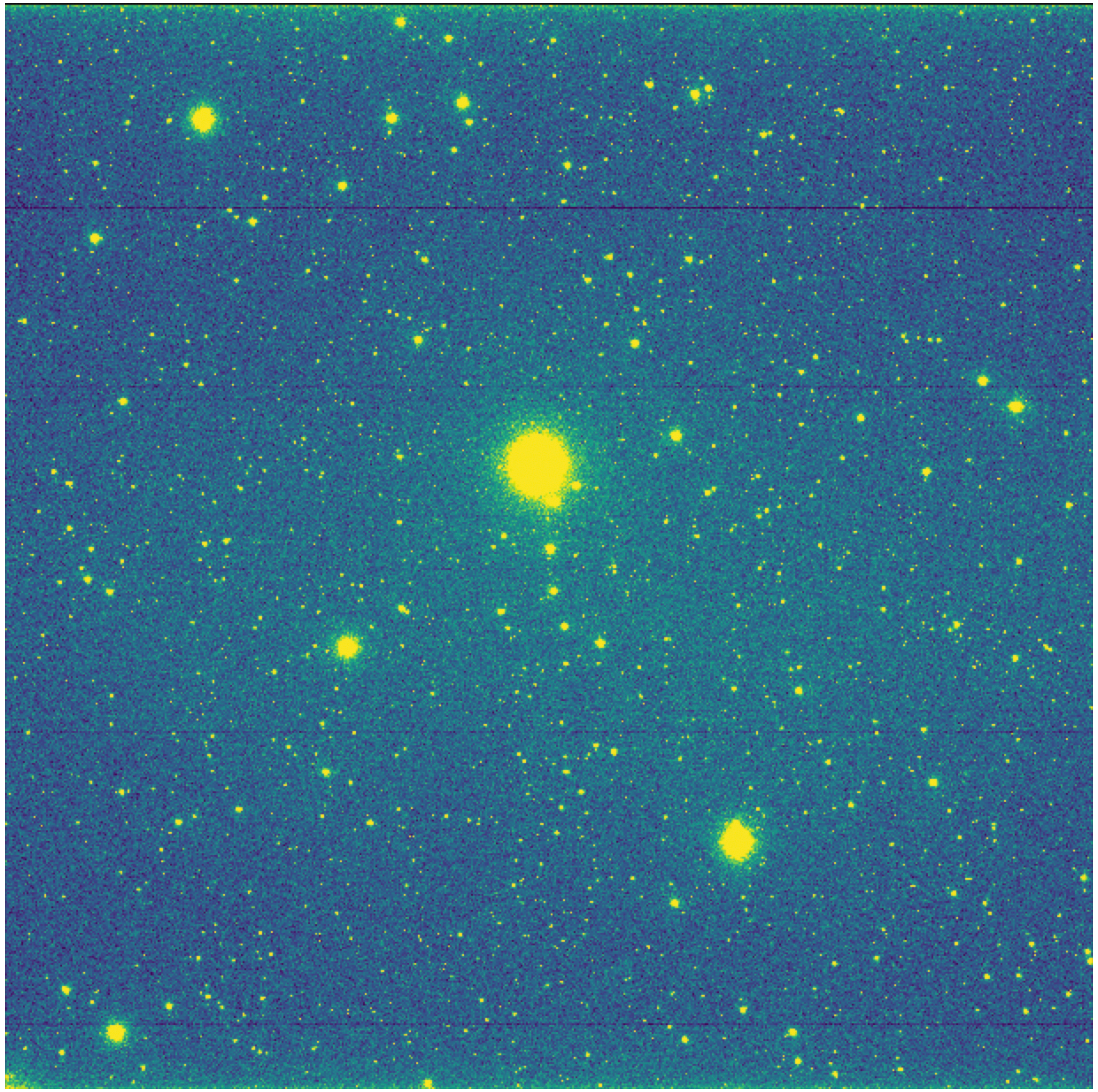
Treatment of spurious pixels

- Spurious pixels can be caused by detector defacts and cosmic rays
- Detector defacts can be identified in bias and flat frames.
- In time series data, cosmic rays can be identified using sigma clipping method.
- Sigma clipping: a statistical technique that iteratively removes data points deviating from the mean by more than a specified number of standard deviations (σ), thereby reducing the influence of outliers.
- Other cosmic ray detection methods: LACosmic.

Procedures of sigma clipping

- Step 1: align images to remove telescope pointing drift/jitter
- Step 2: for each pixel, calculate the moving median along the time dimension and identify outliers. A conservative (>7σ) is preferred to avoid false positives. This step can be done using astropy's implementation of sigma clipping
- Step 3: Examine the identified outliers, adjust the sigma threshold if necessary.
- Step 4: mask or replace the identified outliers using interpolations
- Step 5: report the outlier identification statistics

Photometry: necessary steps



Locate the target: centroiding

Flux measurement: Aperture vs. PSF fitting

Estimate the background

Calibrate the flux

Centroid estimates

Image moments defined by computer version

$$M_{pq} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} x^p y^q f(x, y)\, dx\, dy$$

M_{01} and M_{10} give the centroid measurements.

Other often used methods: 1-D and 2-D profile fitting.

Radio/IFU data reduction definition:

$$M_0 = \sum_i^N I_i \, \Delta v_{\mathrm{chan},i}$$

$$M_1 = \frac{\sum_i^N I_i v_i}{\sum_i^N I_i}$$

$$M_2 = \sqrt{\frac{\sum_i^N I_i (v_i - M_1)^2}{\sum_i^N I_i}},$$

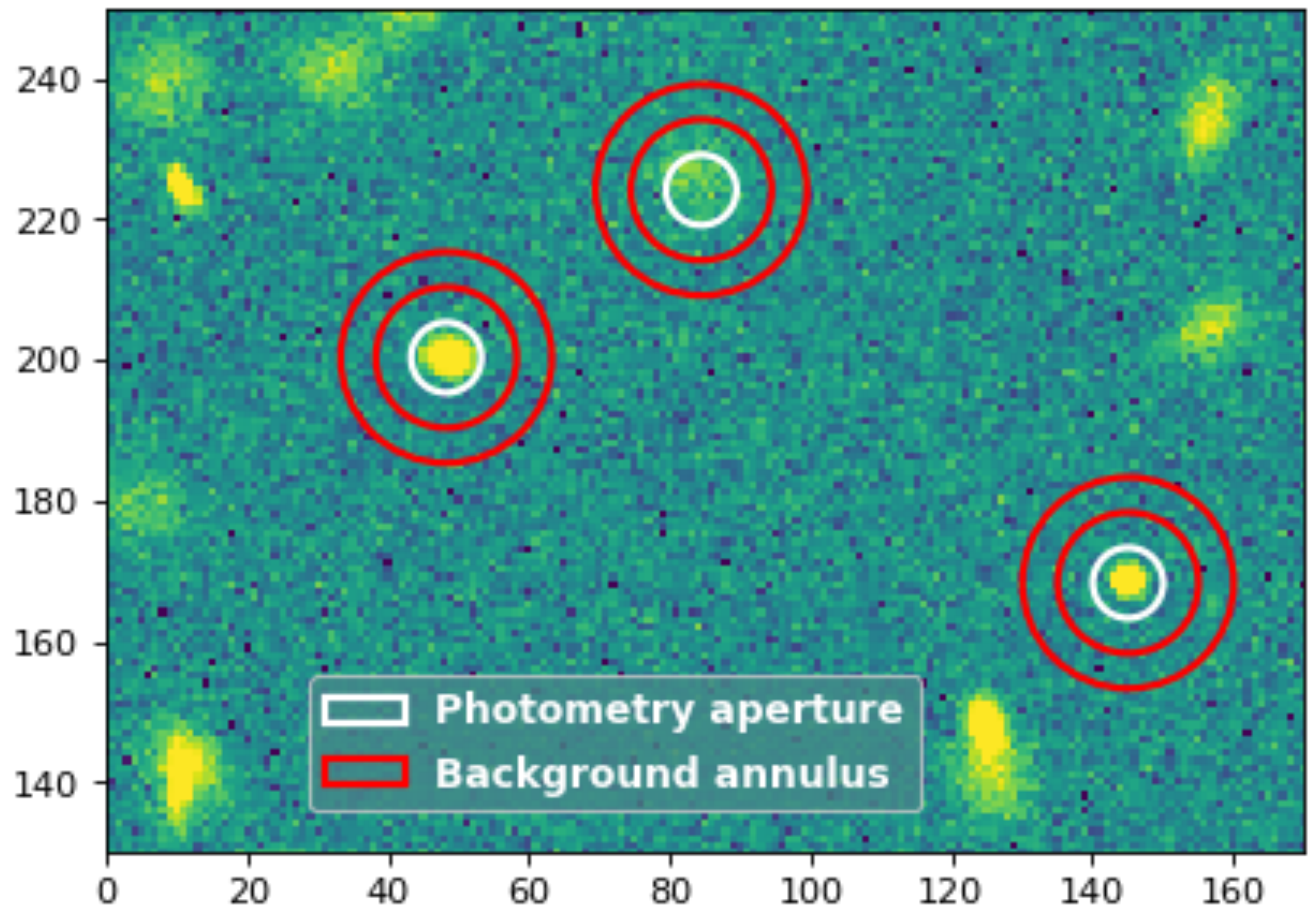
Align the images

- Telescope pointing drifts cause the image series to misalign
- The amount of drift can be determined by the centroid differences, preferrably by a grid of high S/N stars across the detectors
- Cross-correlation against a reference image is also an effective method
- After determining the amount of pointing change, shift the image (you may use scipy.ndimage's shift function) to align the images.

Aperture photometry

Definition: Aperture photometry measures source brightness by summing observed counts within a defined aperture centered on the source, without assuming a specific PSF shape.

Aperture shape: The aperture may be circular (common for point sources), square, or any other useful shape.



Procedure:

- Estimate the PSF center.
- Place a circular aperture of radius r
- Sum pixel counts within the aperture area
- Subtract background sky contribution from the summed counts to obtain the source intensity I.

PSF Fitting Photometry

- Fit a normalized profile to the observed sources to determine the flux.
- Often used profile: 2D Gaussian, Lorentzian, or Moffat.
- Empirically constructed PSF models (ePSF) often perform better than analytical models
- ePSF models can be derived by combining high-quality background stars.

Aperture Photometry vs. PSF Fitting Photometry

- Aperture photometry is computationally and conceptually simpler.
- Aperture photometry can be severely impacted by spurious pixels or contaminating sources in a crowded field.
- PSF fitting photometry suffers from inaccurate PSF models
- PSF fitting photometry is necessary when the astrophysical scene is complex: e.g. exoplanet direct imaging.
- Aperture photometry is the prefered method for the time series analysis.

Determining the optimal aperture size

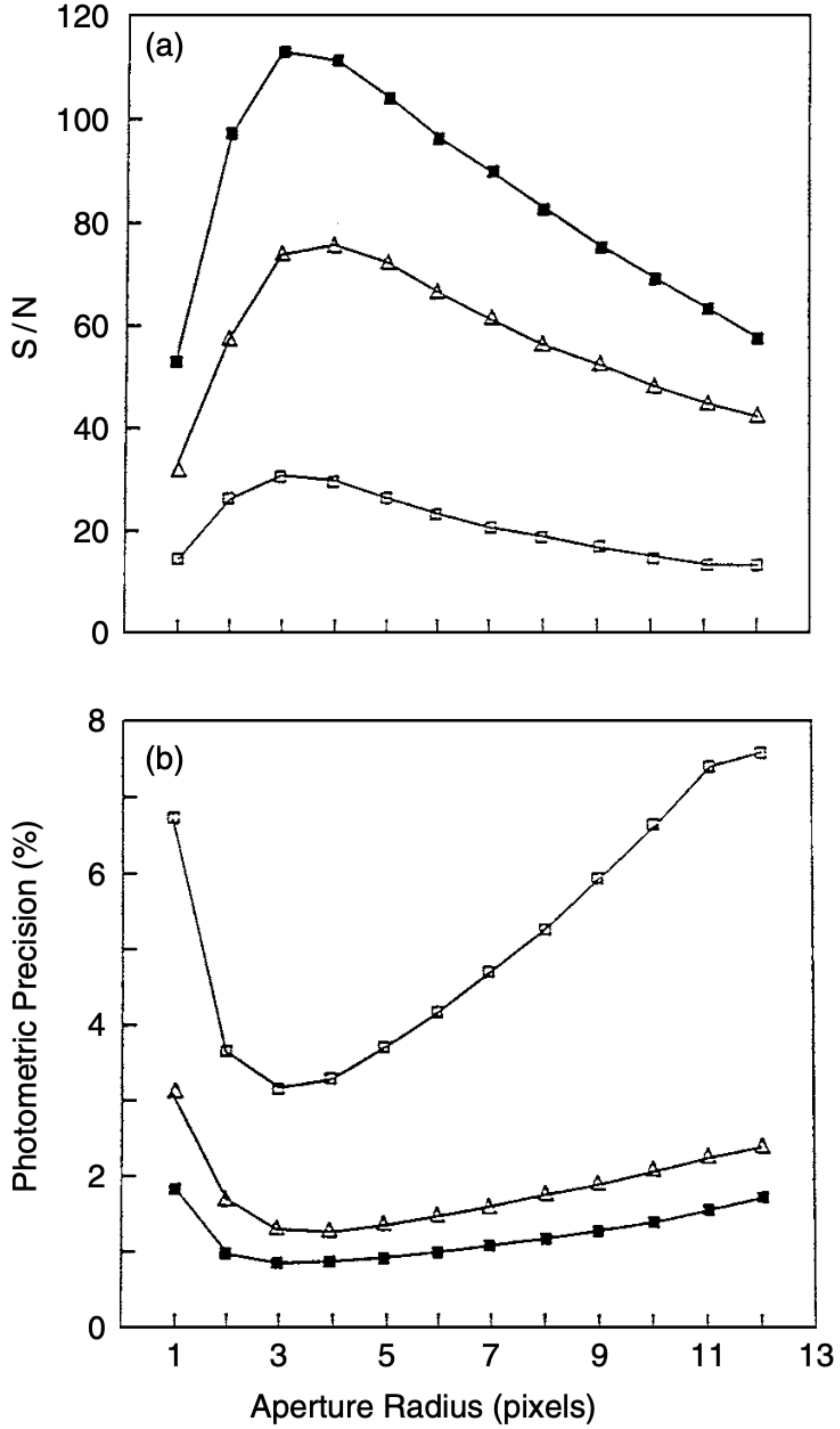
- Goal: Find the aperture radius that maximizes the signal-to-noise ratio (S/N).

- Increasing aperture radius collects more signal, improving S/N.

- However, a larger radius also increases the number of pixels and therefore the noise contribution.

- Too small a radius loses part of the source flux, while too large a radius adds excess background noise.

- An optimum radius exists that balances signal gain and noise increase,



Treatment of partial pixels

1. Do not use partial pixels at all. Any source intensity that falls into the source aperture but within a partially inscribed pixel is simply not used in the calculation of S.

2. Re-sampling the images and divide one pixels into subpixels.

3. Calculate the fraction of pixels within the aperture region

aperture_photometry

```
photutils.aperture.aperture_photometry(data, apertures, error=None, mask=None, method='exact', subpixels=5, wcs=None)
```
[source]

method : *{'exact', 'center', 'subpixel'}, optional*

The method used to determine the overlap of the aperture on the pixel grid. Not all options are available for all aperture types. Note that the more precise methods are generally slower. The following methods are available:

- `'exact'` **(default):**

  The exact fractional overlap of the aperture and each pixel is calculated. The aperture weights will contain values between 0 and 1.

- `'center'`**:**

  A pixel is considered to be entirely in or out of the aperture depending on whether its center is in or out of the aperture. The aperture weights will contain values only of 0 (out) and 1 (in).

- `'subpixel'`**:**

  A pixel is divided into subpixels (see the `subpixels` keyword), each of which are considered to be entirely in or out of the aperture depending on whether its center is in or out of the aperture. If `subpixels=1`, this method is equivalent to `'center'`. The aperture weights will contain values between 0 and 1.

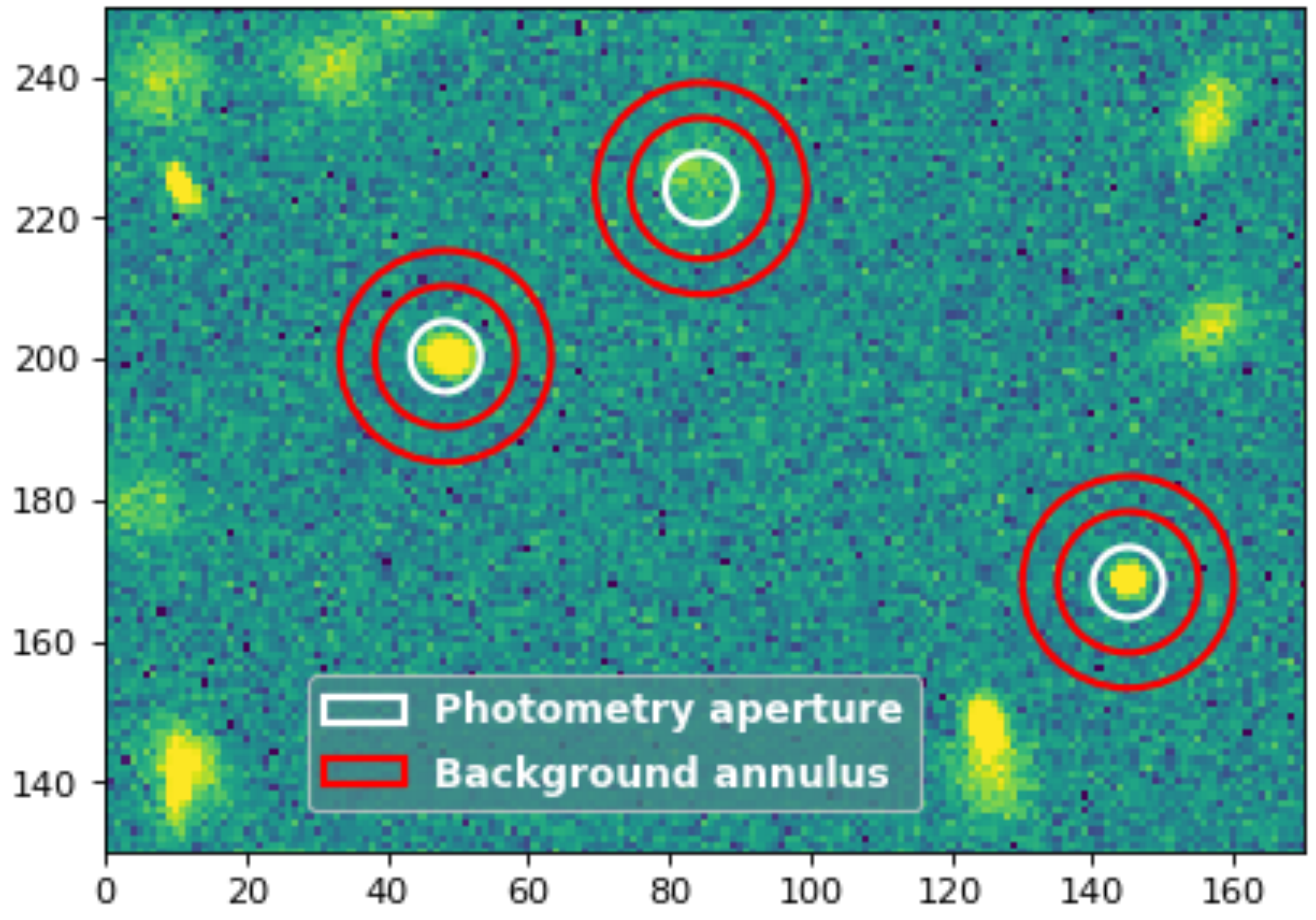
Estimating the background

In aperture photometry, sky background is estimated locally (near the target star).

Median values among pixels within the annulus provide a good estimate.

For a crowded field, the annulus size needs to be carefully chosen to avoid stars comtaminating sky background.

Masking the bright sources before background estimates is a good practice.



Precision time series photometry

- Goal: precisely calibrate the relative photometric change.
- Systematic noise sources: sky airmass variation, sky brightness change, clouds, telescope pointing drifts, flat field uncertainty, etc.
- Systematic noise can be calibrated using non-variable comparison stars that have similar brightness as the target star.

Calibration procedures

- Step 1: use Bouguer's law to derive the extinction coefficient and calibrate the airmass variation.
- Step 2: median combine airmass corrected comparison star light curves to derive a correction term
- Step 3: divide the airmass corrected target light curve by the correction term
- Steps 2 and 3 are better done iteratively.

Advanced methods for calibrating the light curves

- Principal Component Analysis (PCA): a statistical method that transforms correlated variables into a set of uncorrelated components ordered by the amount of variance they explain in the data.

- Gaussian process: a probabilistic model that defines a distribution over functions, where any finite set of points follows a joint Gaussian distribution characterized by a mean function and a covariance (kernel) function