STARFINDER

2.0

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Context

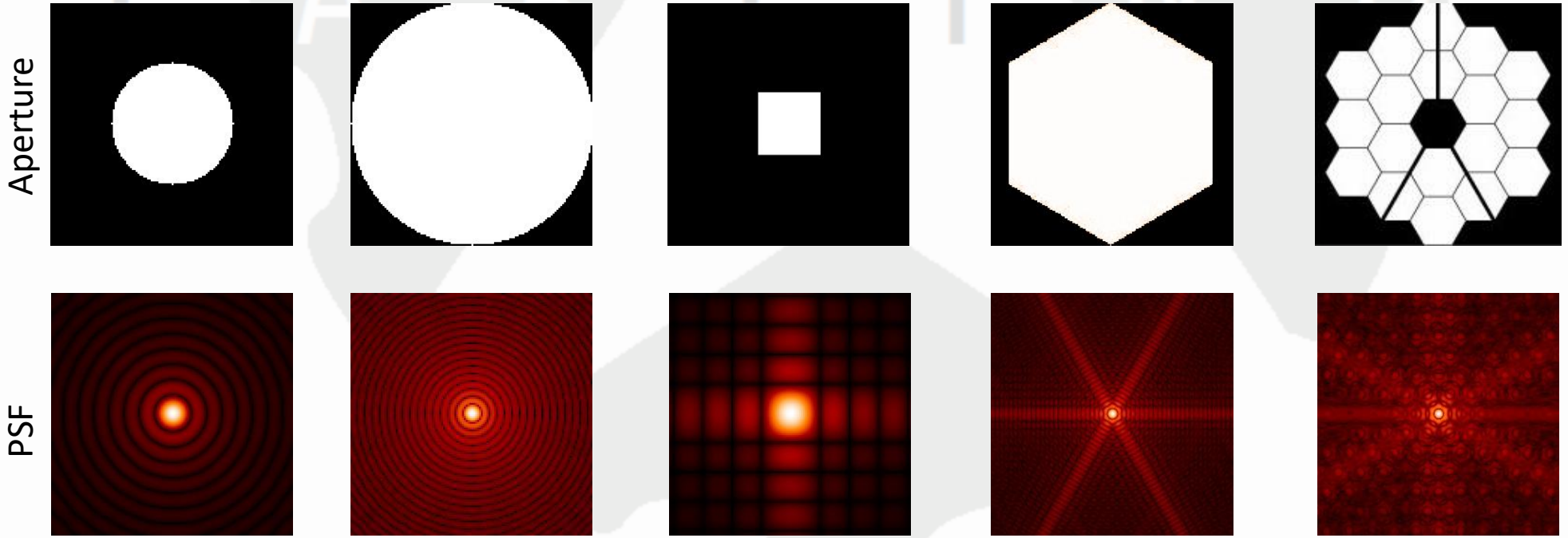
- Adaptive Optics has become a key technology for all the main existing telescopes (VLT, Keck, Gemini, Subaru, LBT..) and is considered a kind of enabling technology for future giant telescopes (E-ELT, TMT, GMT)

- AO systems increase the energy concentration of the Point Spread Function (PSF), but the PSF itself is also characterized by complex shape and spatial variation

- the exceptional **advancement in AO** technology and observational capability **has not been followed by a comparable advancement in the development of data analysis methods**

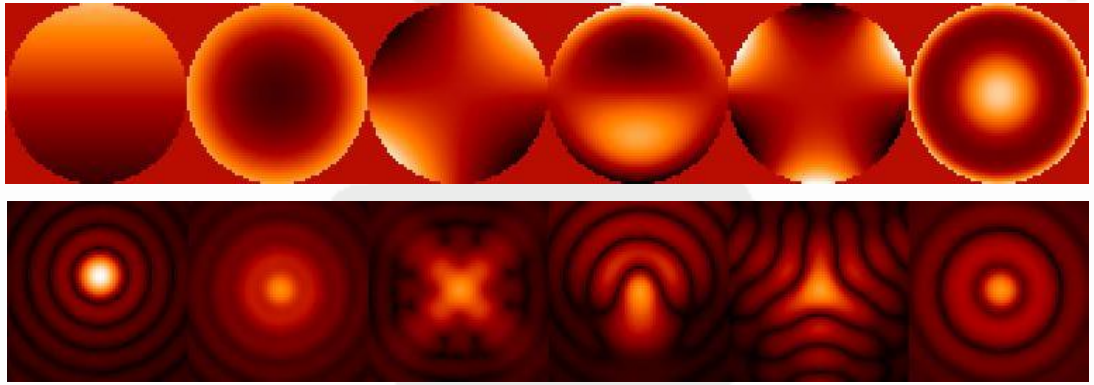
The PSF

- The PSF is the intensity distribution (the square modulus) of the field in the image plane
- The PSF describes the response of an imaging system to a point source
- The PSF is limited in spatial frequencies by the system aperture



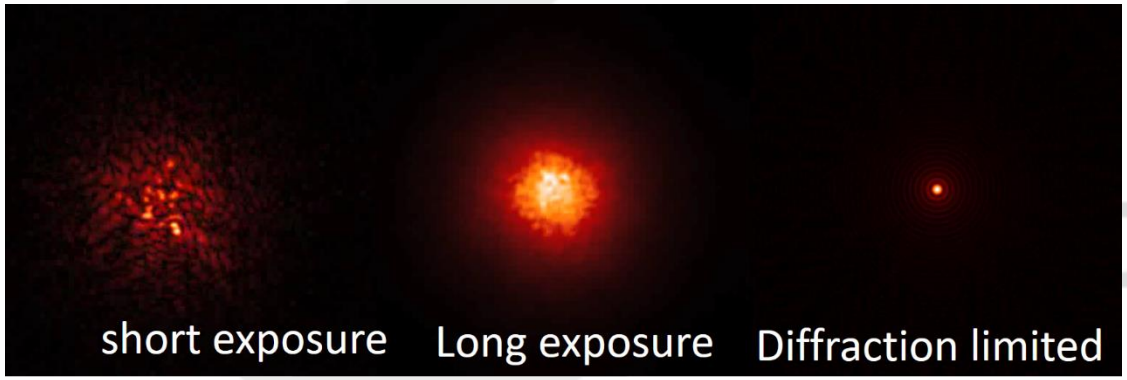
The aberrated PSF

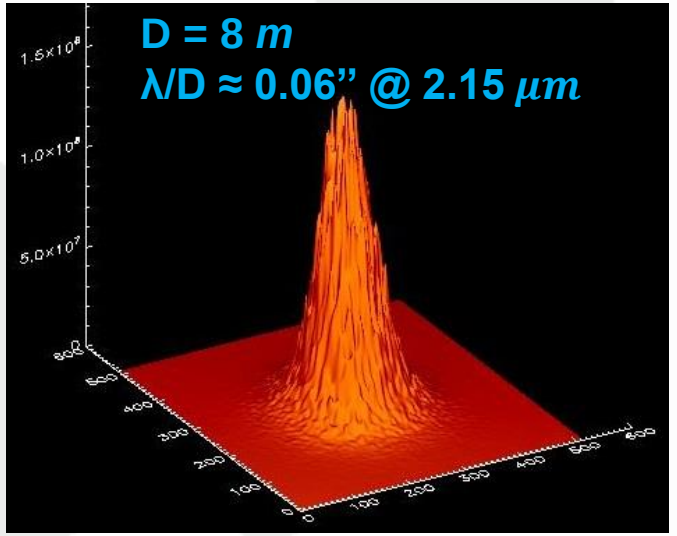
System aberrations

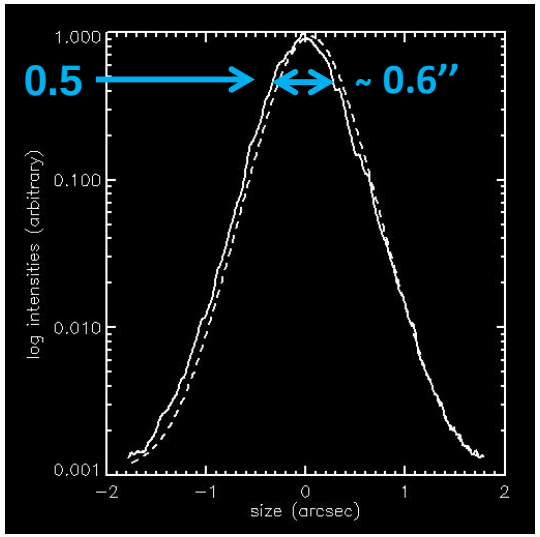


- The tilt produces a shift in the image. The higher orders terms introduce deformation in the PSF.

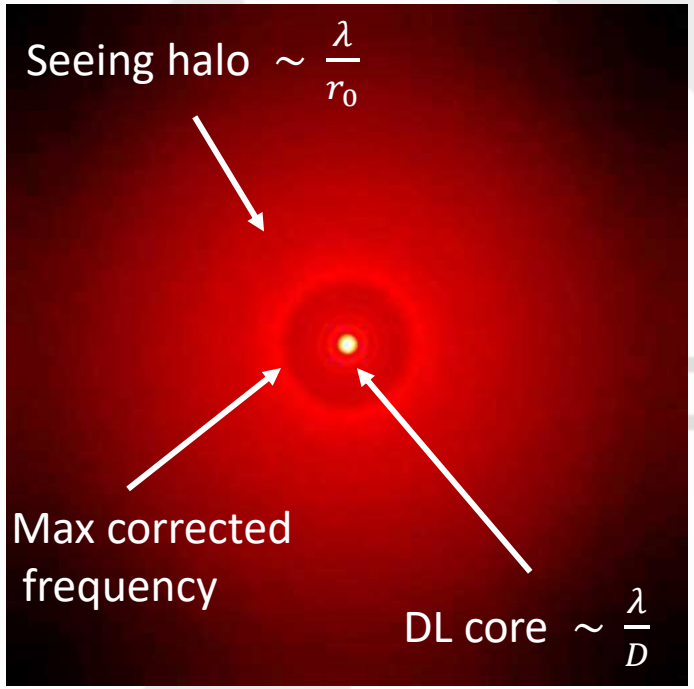
Atmospheric turbulence

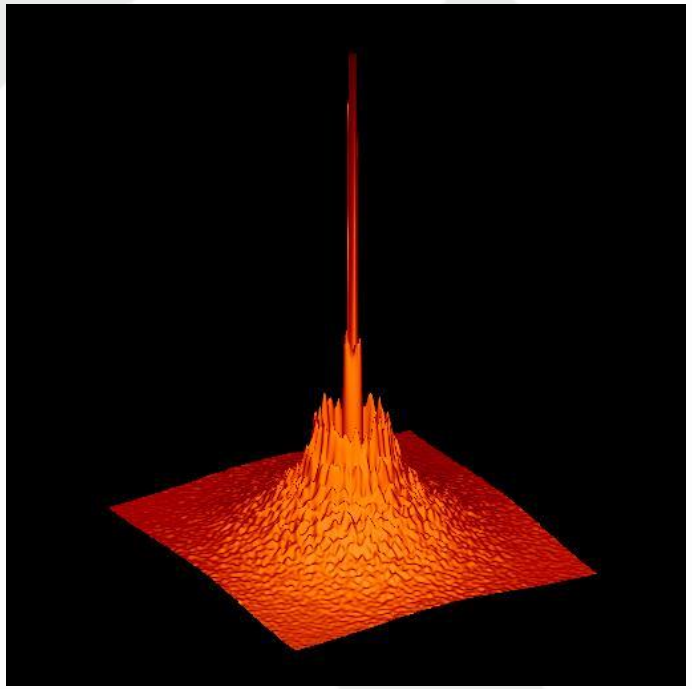


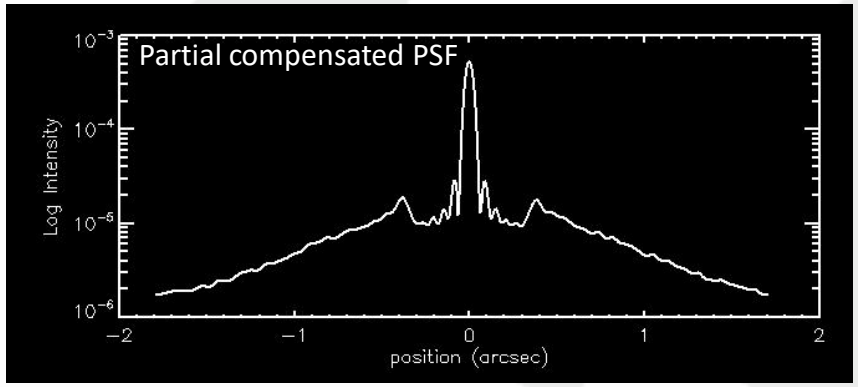


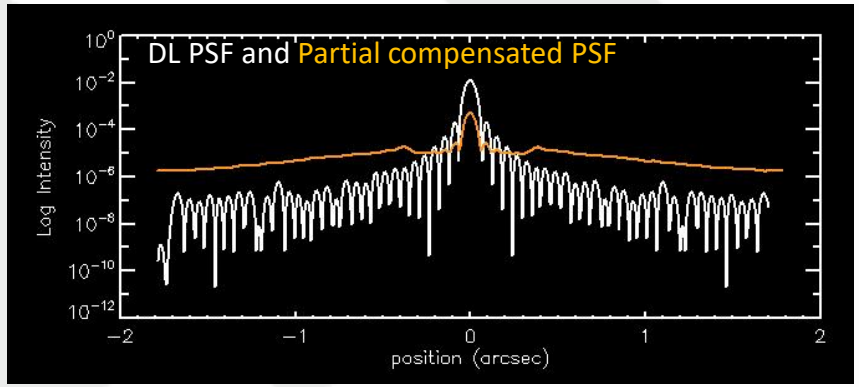


The PSF in AO


Seeing halo $\sim \frac{\lambda}{r_0}$
Max corrected frequency
DL core $\sim \frac{\lambda}{D}$

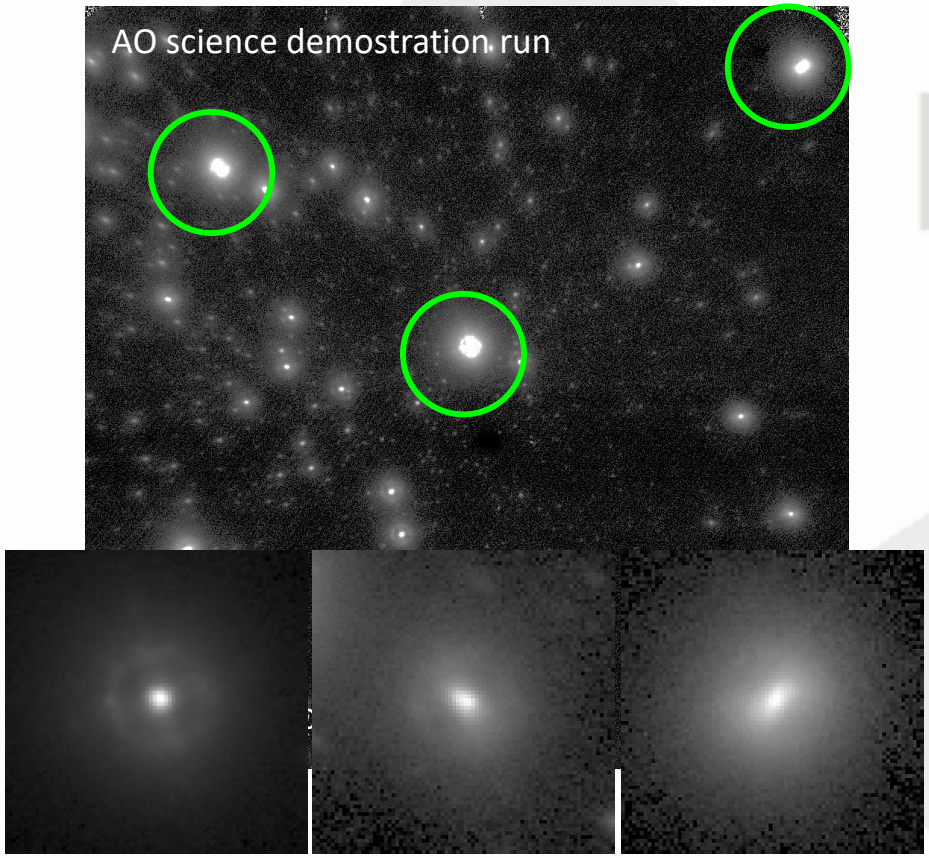



Partial compensated PSF
Log Intensity
position (arcsec)

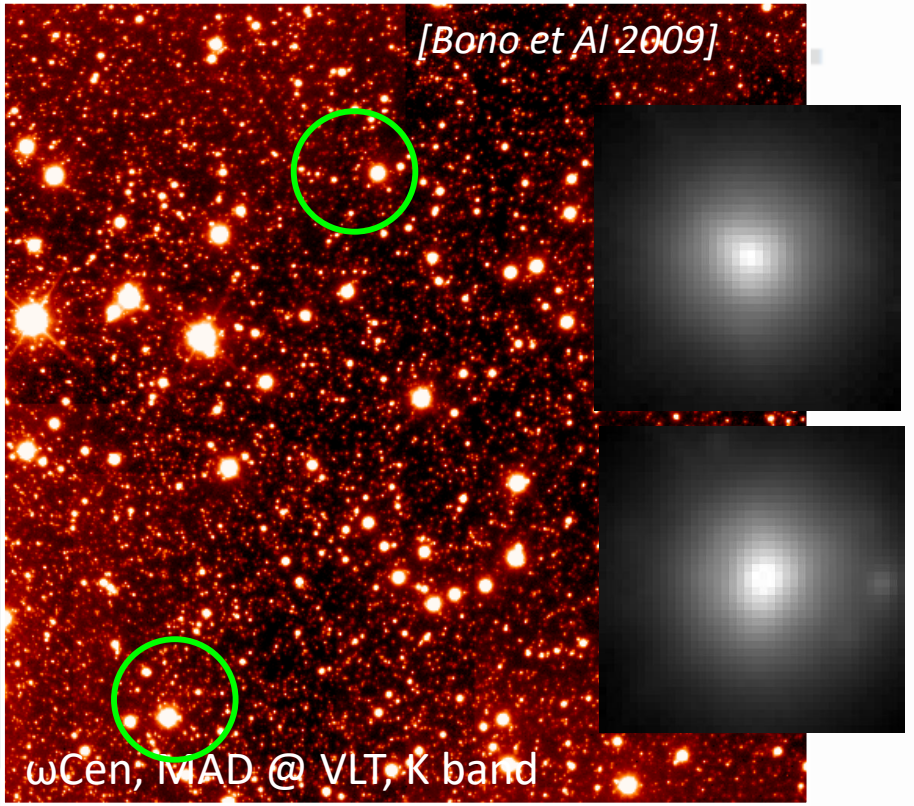

DL PSF and Partial compensated PSF
Log Intensity
position (arcsec)

The PSF in AO

- More variable across the FoV (e.g. SCAO)



- Less variable across the FoV (e. g. MCAO)



The importance of PSF estimation

- Crowded-field AO **astrometry** appears to be limited by the inaccurate modeling of the Point Spread Function (PSF) *[Shoedel 2010]*
- **astrometry** of faint sources is biased by residuals due to the incorrect subtraction of the PSF of brighter stars *[Fritz 2009]*
- **photometric accuracy** is limited by the SNR and by the knowledge of the PSF *[Shoedel 2010]*
- Fake **detections**

Astrometric and photometric measurements with AO systems are mainly limited by errors in the PSF modeling and fitting.

PSF estimation from data

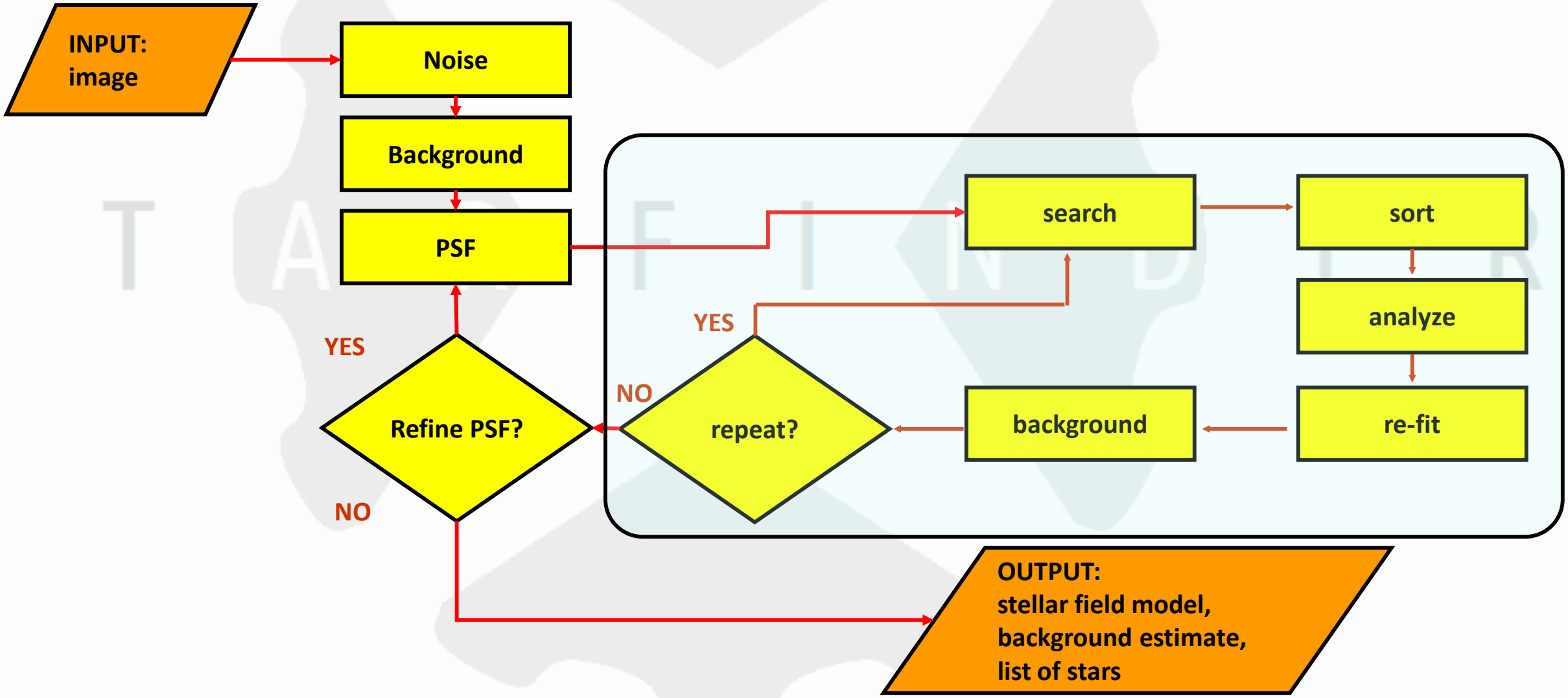
- Analytical PSF (constant or variable)
- Numerical PSF (constant over the entire frame or in subdomains)
- Hybrid PSF (analytical model + numerical residual map)

- **Implemented in image analysis softwares:**
  - **DAOPHOT** (analytical/hybrid/smoothly variable) *[Stetson 1987]*
  - **Romafot** (Purely analytic) *[Buonanno 1983]*
  - DoPHOT (Analytical) *[Schecter 1993]*
  - **PSFex** (analytical) *[Bertin 2010]*
  - **STARFINDER** (numerical/analytical/hybrid, possible hacking) *[Diolaiti 2000]*
  - **SUPERSTAR** (numerical) *[Marasco]*

STARFINDER

- Designed and developed (1997-2000) for images with **structured PSF and variable across field of view** (2012 Tecno INAF – Fellowship INAF**)**
- Code for identification and analysis of point-like sources
- **Numerical** / analytical / hybrid PSF extracted from the image.
- Written in IDL
- Graphical User Interface (does not include yet all the functionalities)
- Available on the Web (https://www.oas.inaf.it/en/research/m5-en/starfinder-en/)

STARFINDER: the main flowchart



STARFINDER: PSF extraction

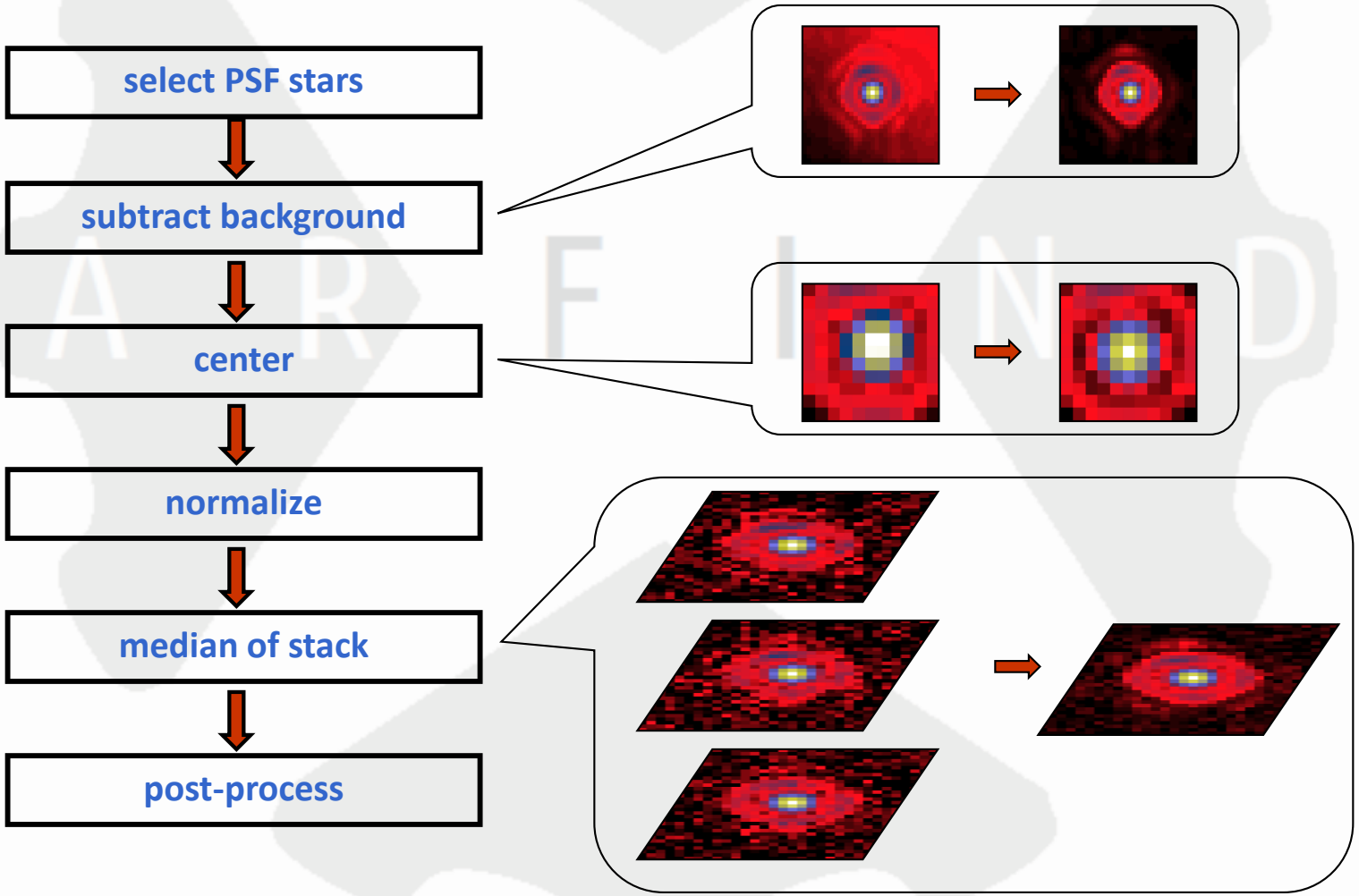
- **Constant PSF:**
  - Extract a PSF by stacking and combining the PSF of the brightest stars of the field, after having subtracted the secondary components in the sub-images of the PSF stars
  - After every fitting iteration the background and the PSF is refined

In this talk we consider the variable PSF option

- **Variable PSF:**
  - Divide image in sub-domains and use set of local PSFs
    - The stars lying close to the sub-domain edge are fit with the proper PSF
  - If the PSF can be modeled by **multi-component parametric model** (Gaussian, Moffat, Lorentzian), it is possible to make the model vary across the field of view → e.g. Origlia et al. 2008, ApJ 687, L79 (on NACO images)
  - Also a **map of numerical residuals** can be added to the analytical model

STARFINDER: PSF extraction

- Numerical PSF



STARFINDER: PSF extraction

- Analytical / Hybrid PSF

PSF stars selection (bright, distributed in the FoV)

PSF model components selection

Parameters variation model

Residual map = stars – model

Stack, combine and normalize residuals

$$PSF(r) = \sum_n F_n * Comp_n(r) + (1 - \sum_n F_n) * residual$$

STARFINDER

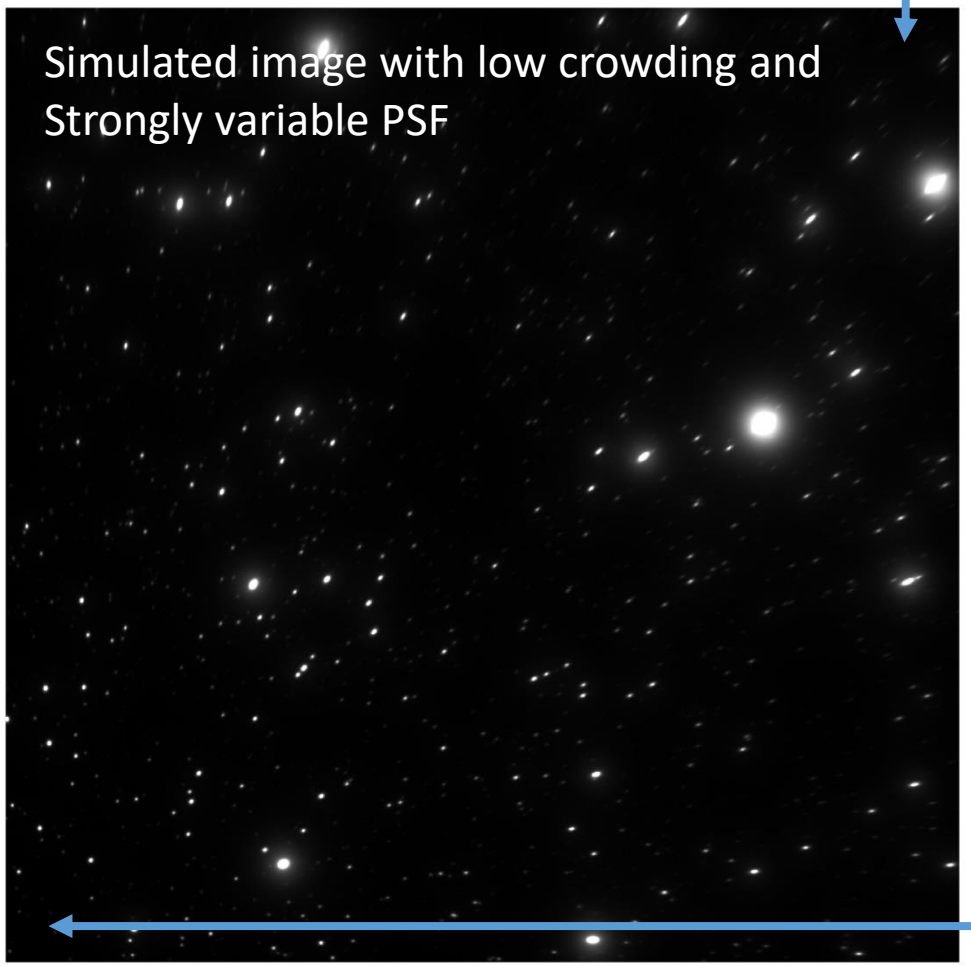
Photometry and stars positions

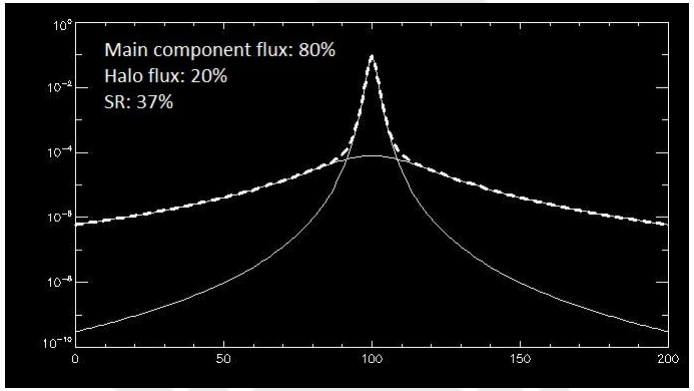
PSF refining

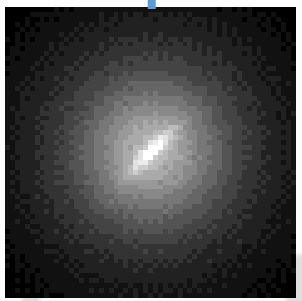
STARFINDER: variable PSF

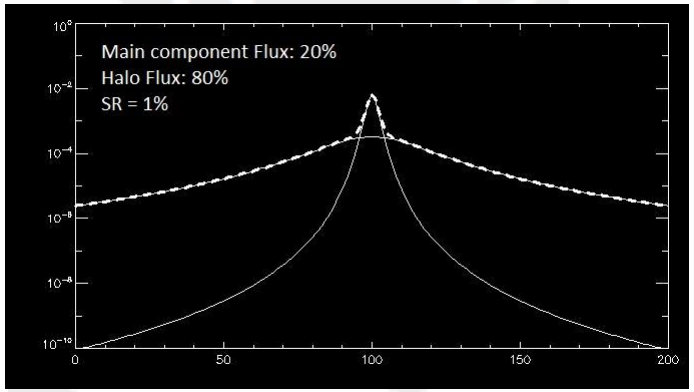
- In this presentation we want to show how starfinder can deal with images with variable PSFs.
- We have simulated a star field, not particularly dense, with a PSF that varies a lot over a FoV of few tens of arcseconds. This variation is not realistic but this kind of image can be used to show some interesting effect
- High SNR → all the stars of the population of the cluster are detectable
- The PSF is the combination of two Moffat functions, one representing the variable core with an elongation that is field dependent, and the other representing a field-independent broad seeing halo

STARFINDER: variable PSF







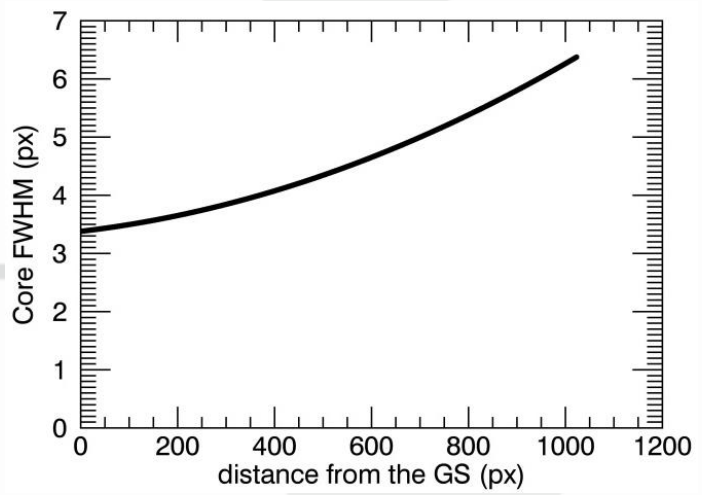


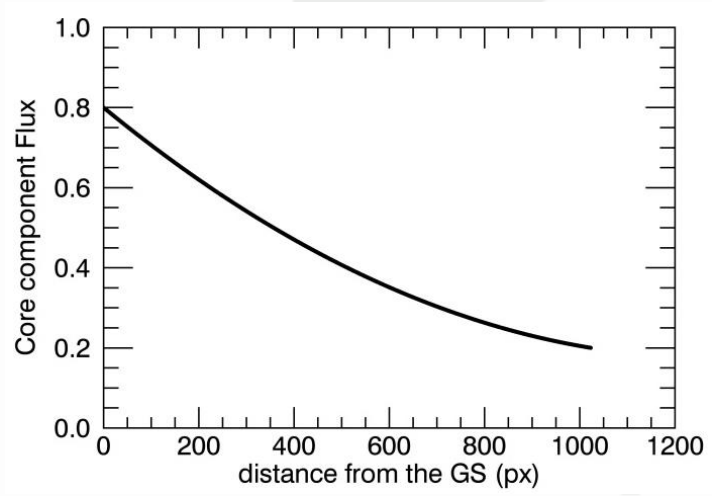
SR ≈ 0.01 ÷ 0.37
Magnitude range ≈ 10 mag
High SNR

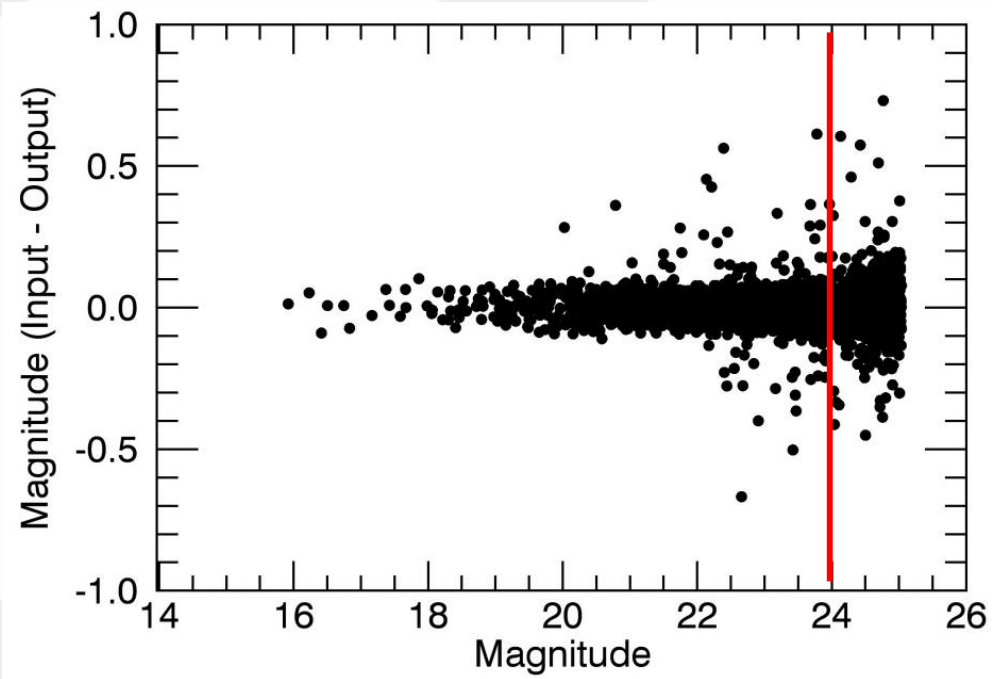
STARFINDER: variable PSF

- PSF fitting photometry using the input PSF model

PSF core component main parameters



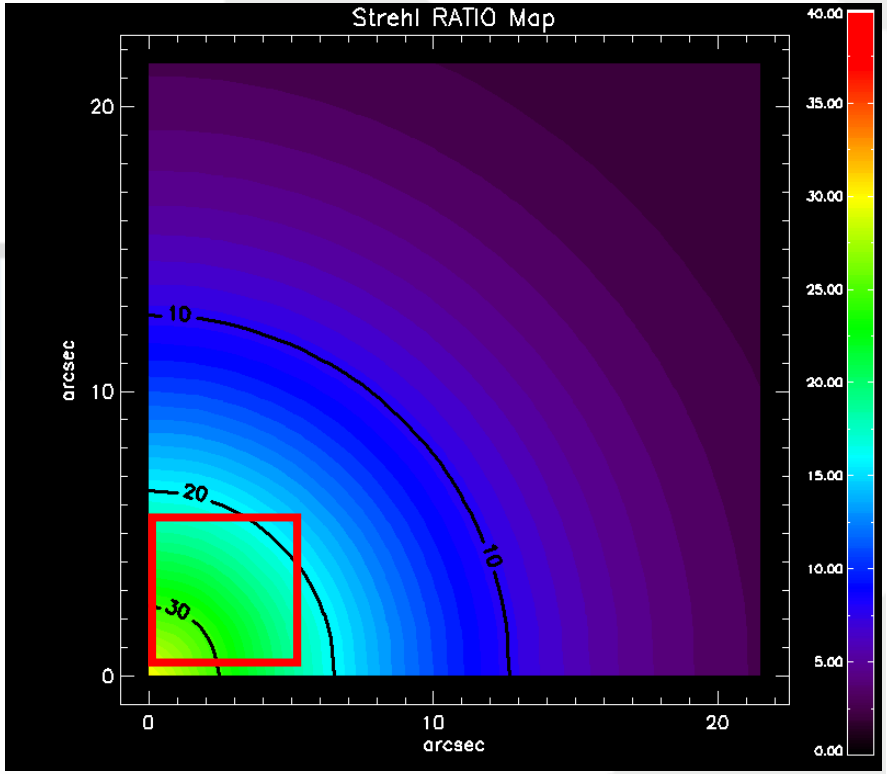




Photometric error in the fainter magnitude bin ≈ 0.11 <- reference case
Mainly due to SNR and crowding

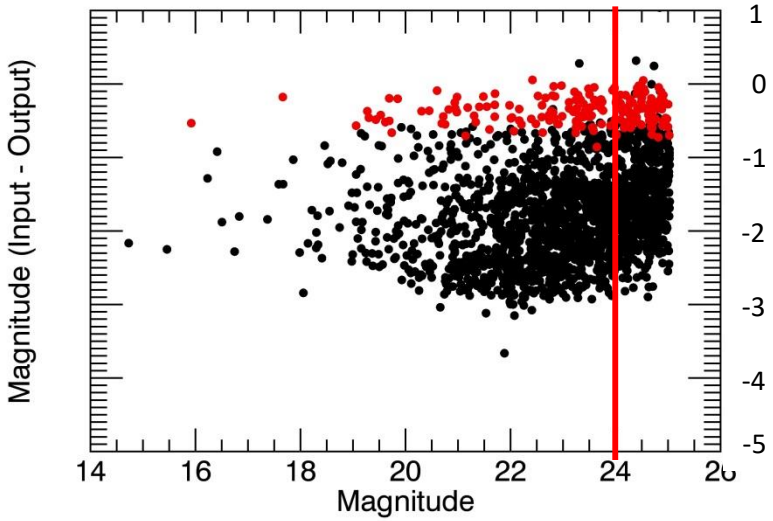
SF variable PSF: numerical

- PSF fitting photometry using the guide star: <u>simulated data</u>



$\Delta mag \cong 0.18$

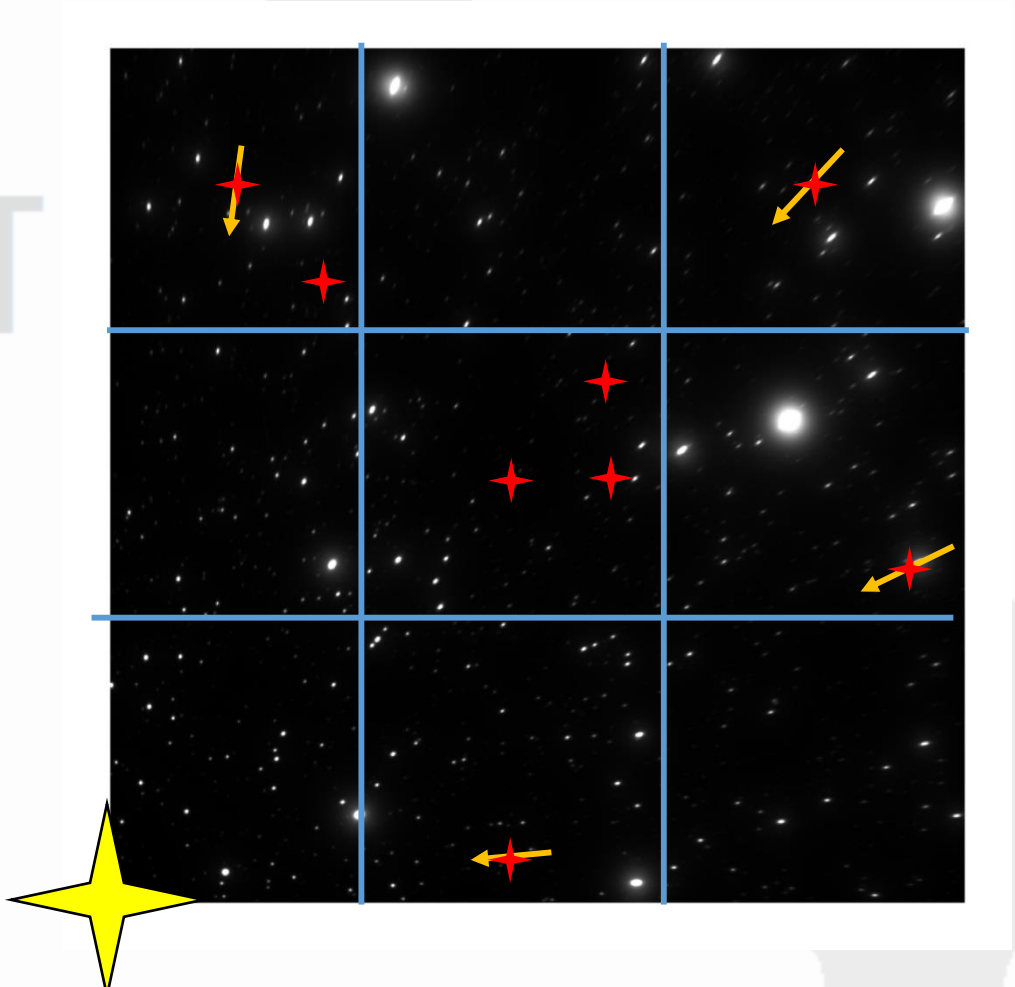
When the PSF varies across the FoV, the **photometric error** depends mainly on the goodness of the **PSF model adoped**

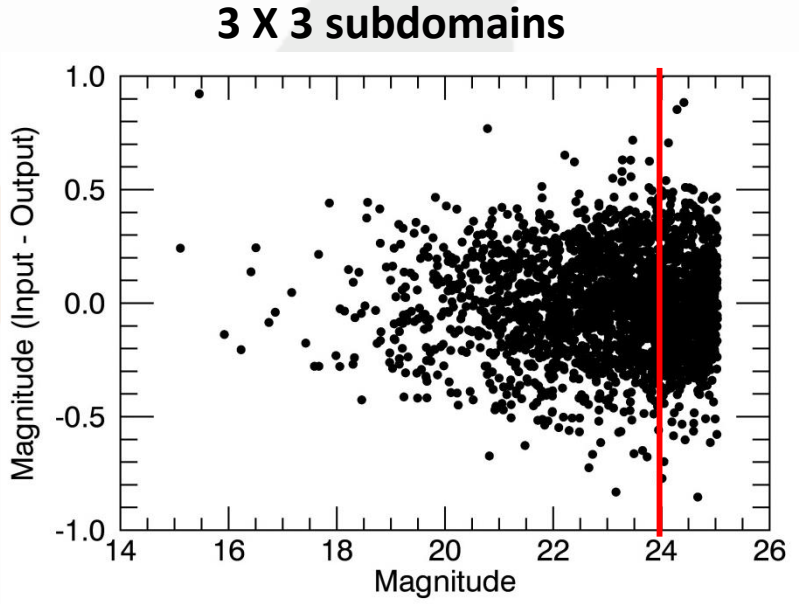


Photometric error in the fainter magnitude bin ≈ 0.7

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>simulated data</u>



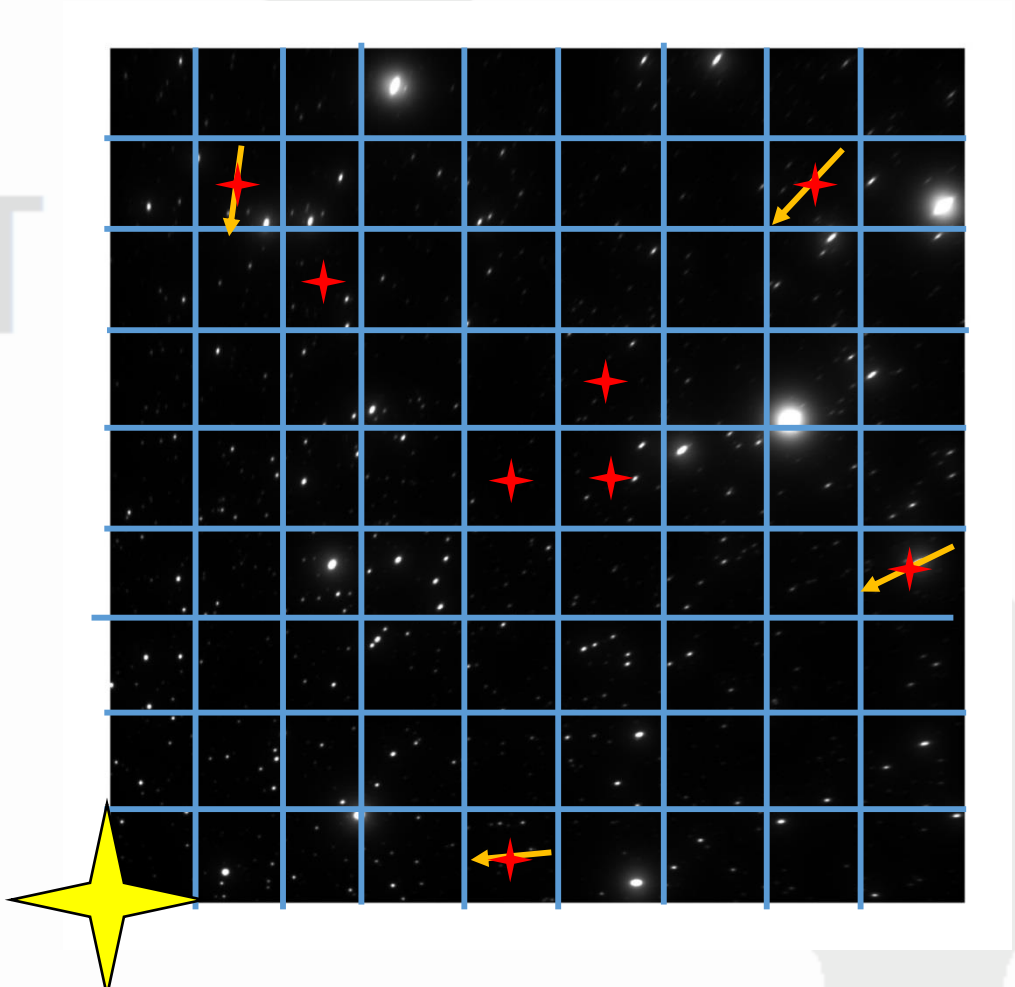


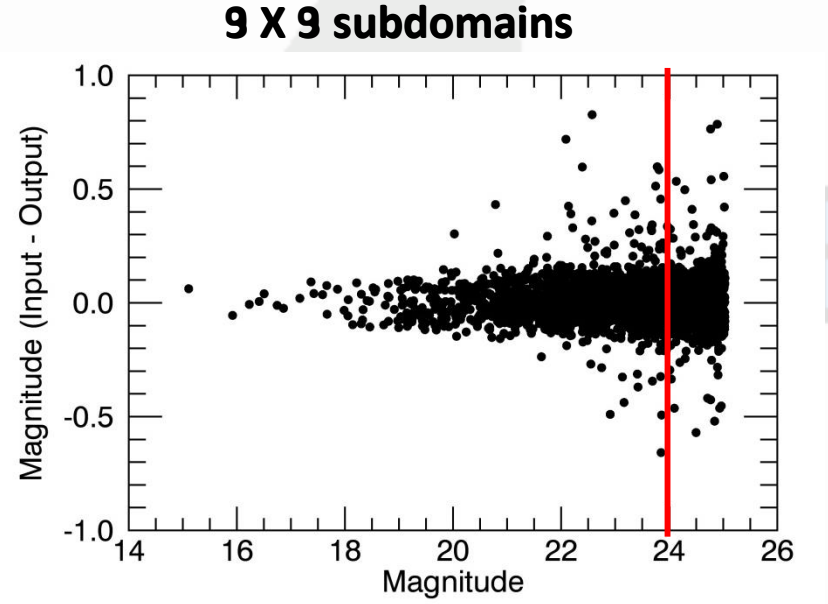
Photometric error in the fainter magnitude bin ≈ 0.26

To be compared with the error when perfect PSF is used ≈ 0.11

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>simulated data</u>



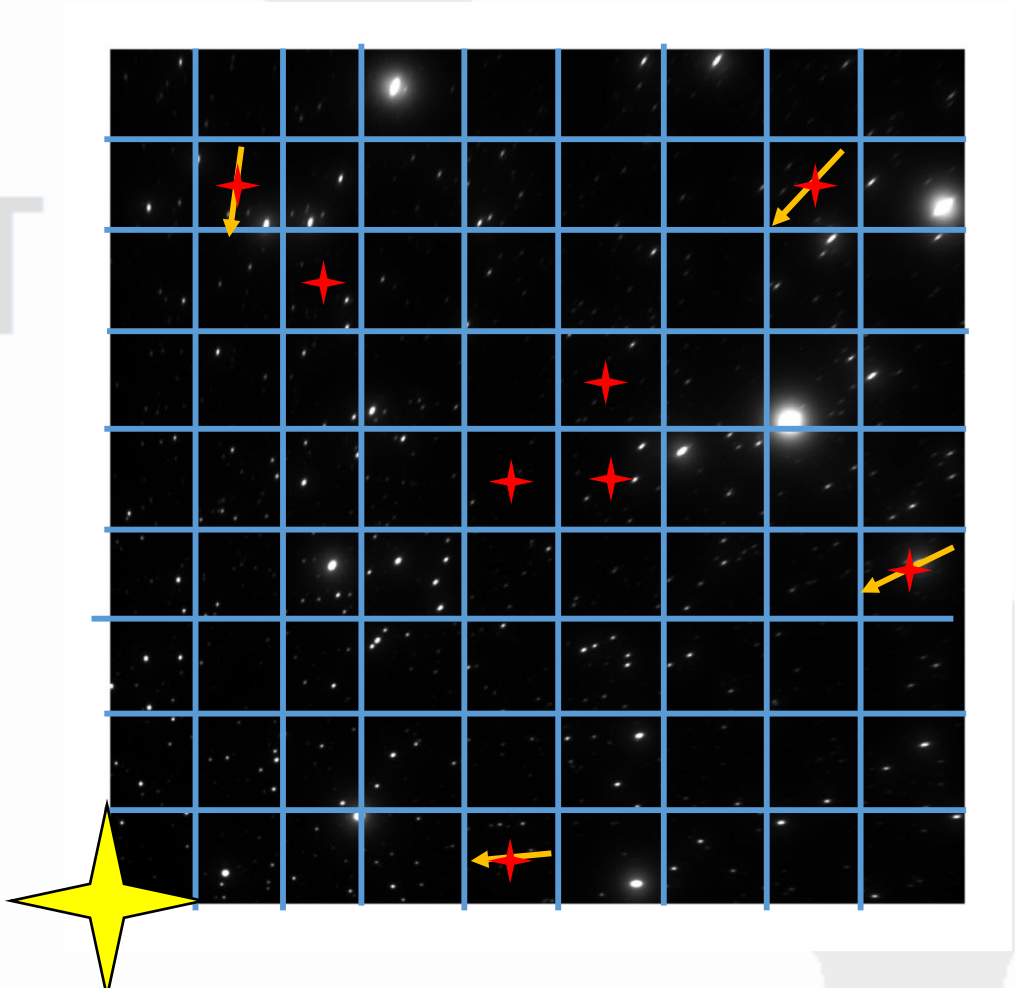


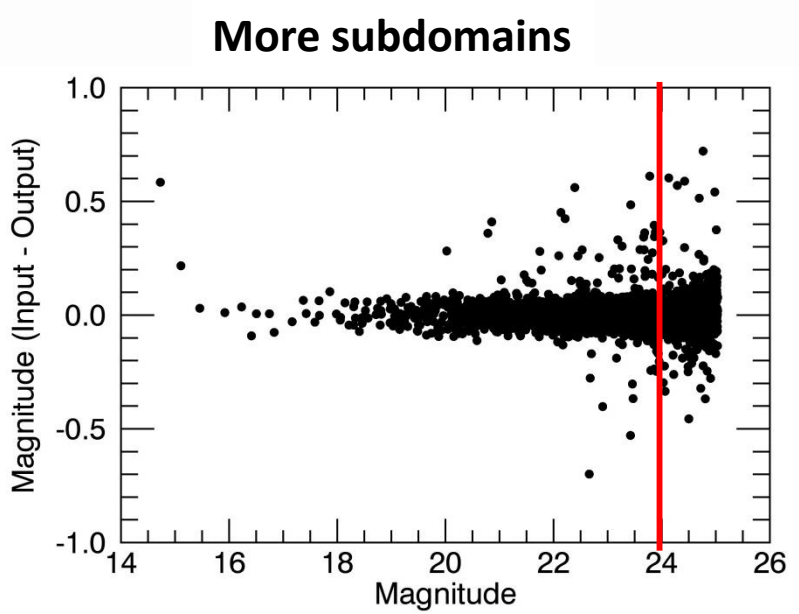
Photometric error in the fainter magnitude bin ≈ 0.14

To be compared with the error when perfect PSF is used ≈ 0.11

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>simulated data</u>





Photometric error in the fainter magnitude bin ≈ 0.11

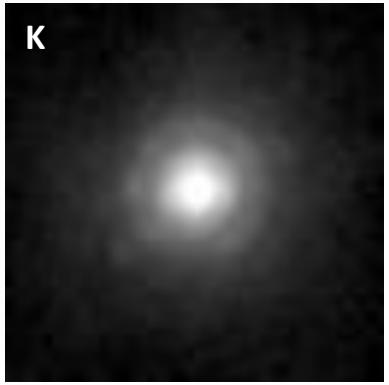
To be compared with the error when perfect PSF is used ≈ 0.11

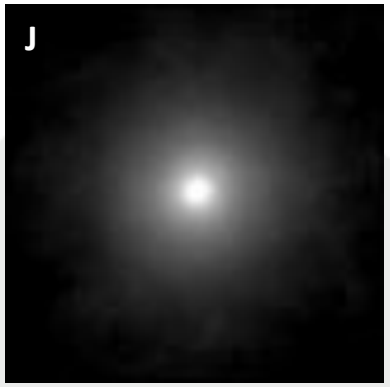
SF variable PSF: numerical

- PSF fitting photometry using the local PSF: application to NGC5904
  - First we consider the PSF constant across the entire FoV

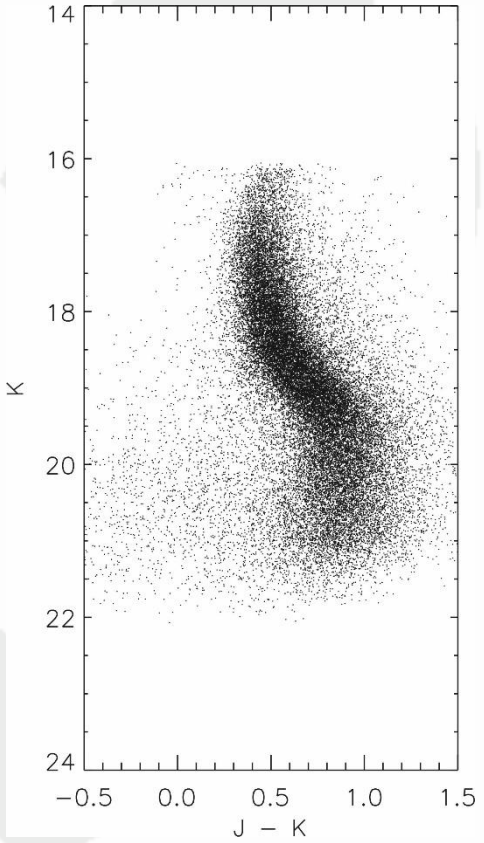
The image

The PSFs





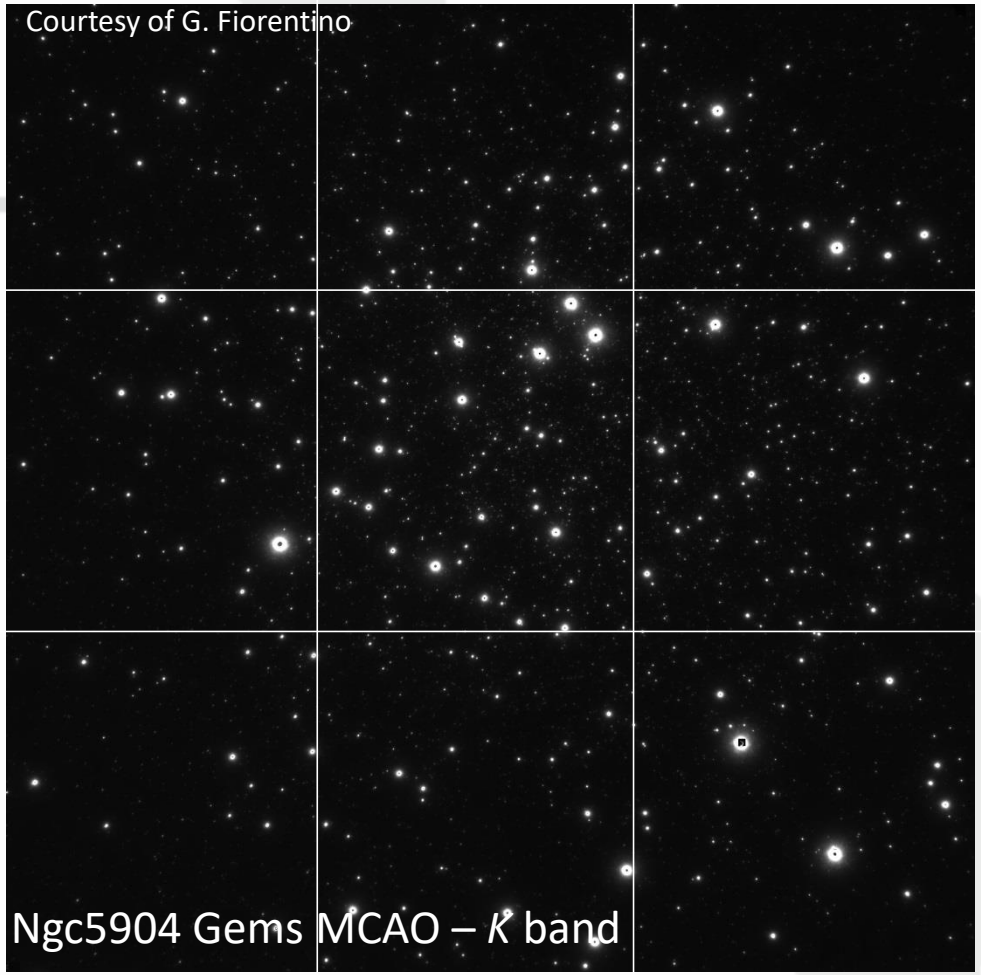
The CMD



Even in case of MCAO, where the PSF is pretty constant across the FoV, small variations in the bluer bands could cause an Enlargement of the CMD

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>application to NGC5904</u>
  - Now we divide the FoV in sub-domains and we consider local PSFs

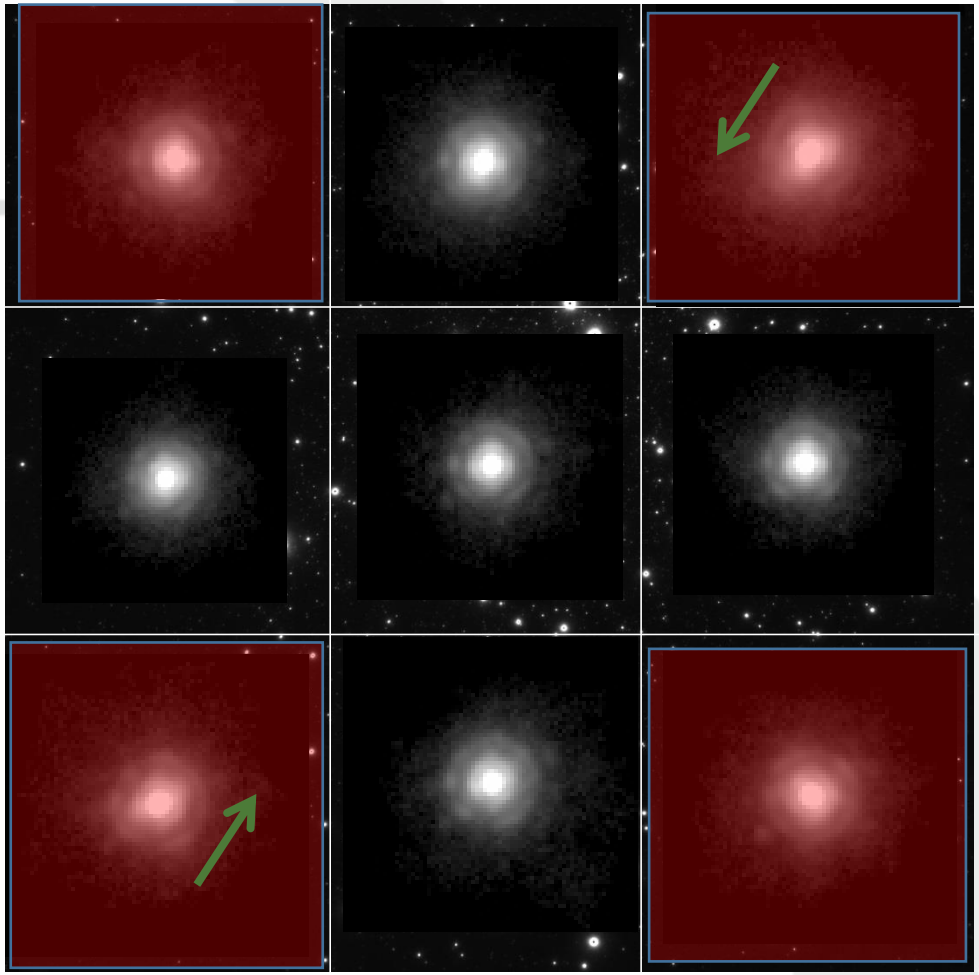


Same image, 3X3 sub-domains of 1400^2 pixels each (~ 30 ‘’ FoV).

→ **The accuracy of the local PSF depends on the local crowding and on the presence of bright local stars**

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: application to NGC5904
  - Now we devide the FoV in sub-domains and we consider local PSFs



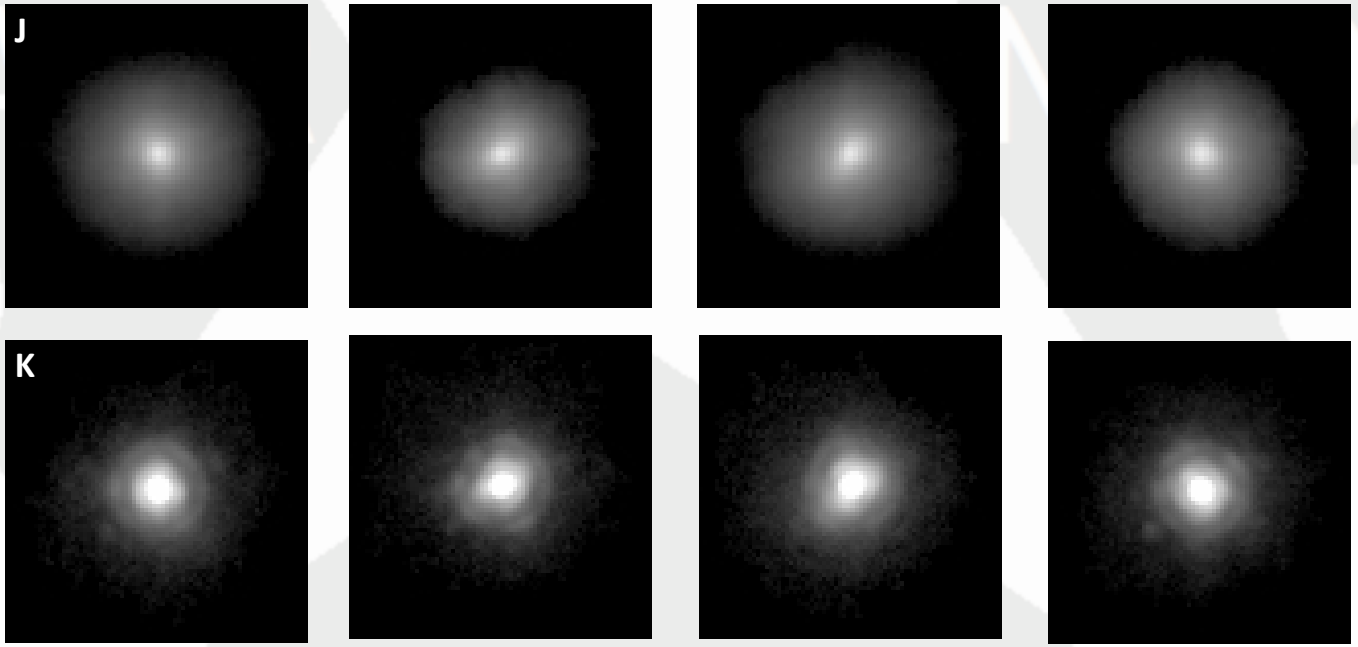
K band image:

Local extracted PSFs

→ Small variation occurs: slightly elongated at the field corners

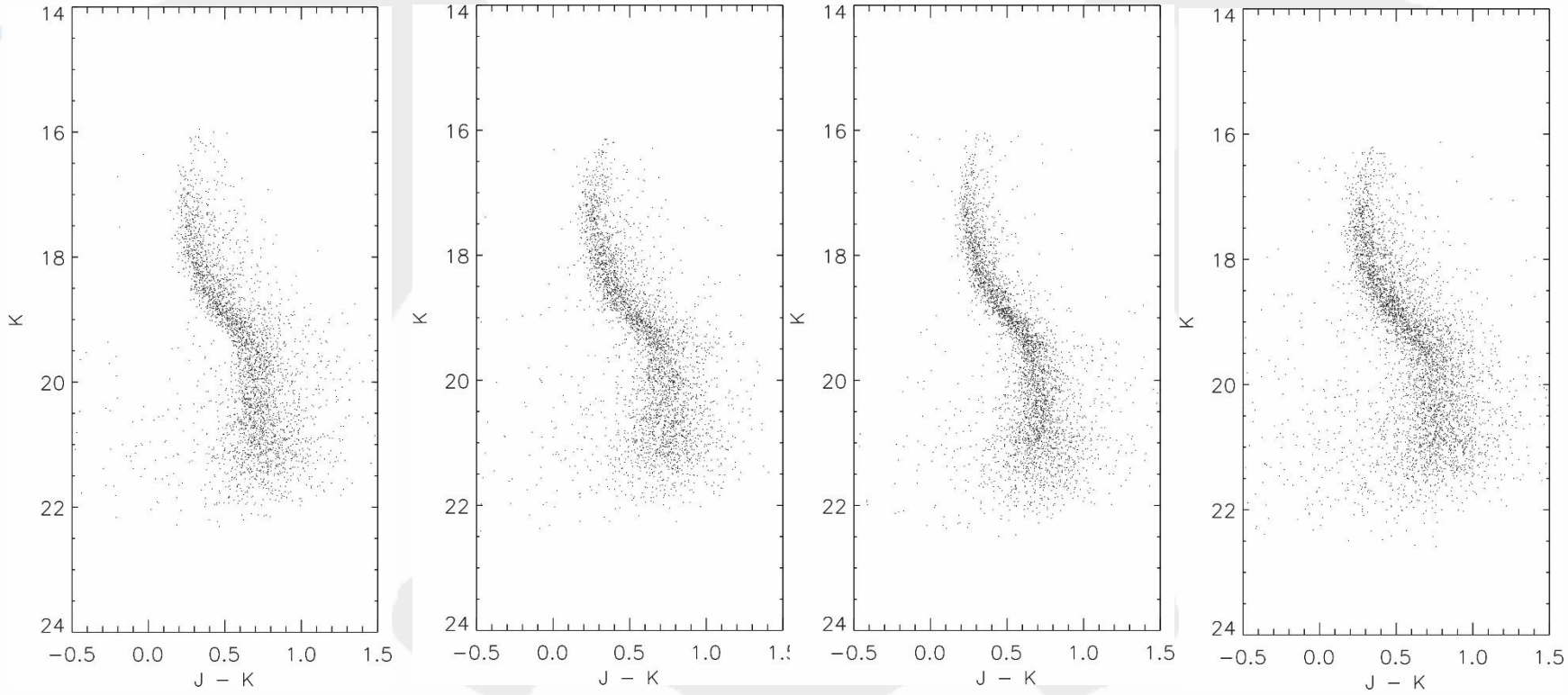
SF variable PSF: numerical

- We build the CMDs corresponding to the 4 corners of the image, where the local PSF looks slighly elongated toward the image center



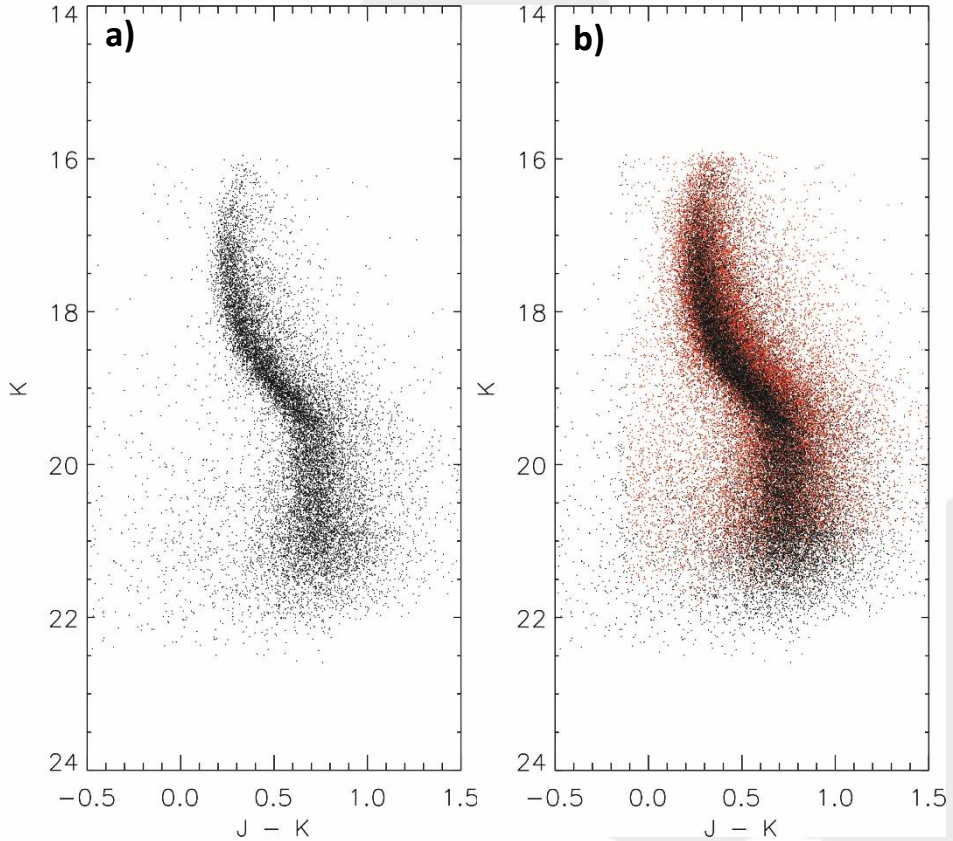
SF variable PSF: numerical

- We build the CMDs corresponding to the 4 corners of the image, where the local PSF looks slighly elongated toward the image center



SF variable PSF: numerical

- We build the CMDs corresponding to the 4 corners of the image, where the local PSF looks slighly elongated toward the image center



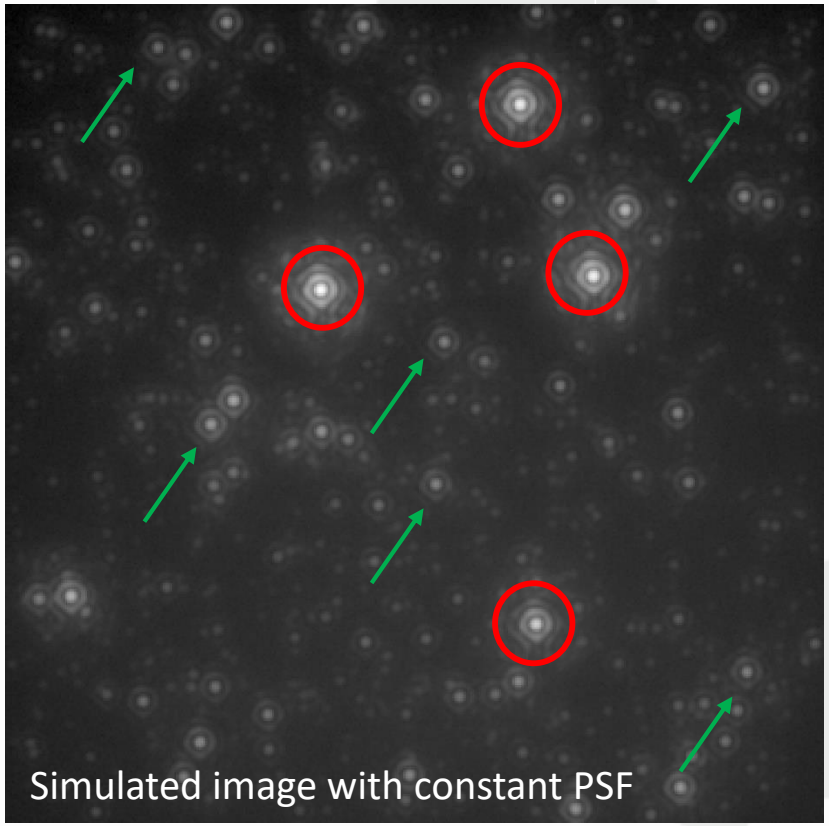
a) Superimposed CMDs corresponding to the image edge stars

b) In red: comparison with single PSF CMD

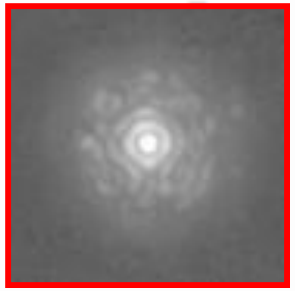
→ Photometric errors among sub-domains require local zero point calibration (explanation in the following…)

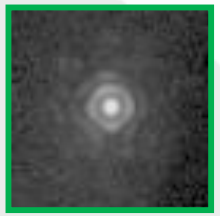
SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>inter-calibration problems</u>
  - The estimated flux depends on the quality of the local extracted PSF. This effect depends mainly on the variable crowding across the FoV



Simulated image with constant PSF



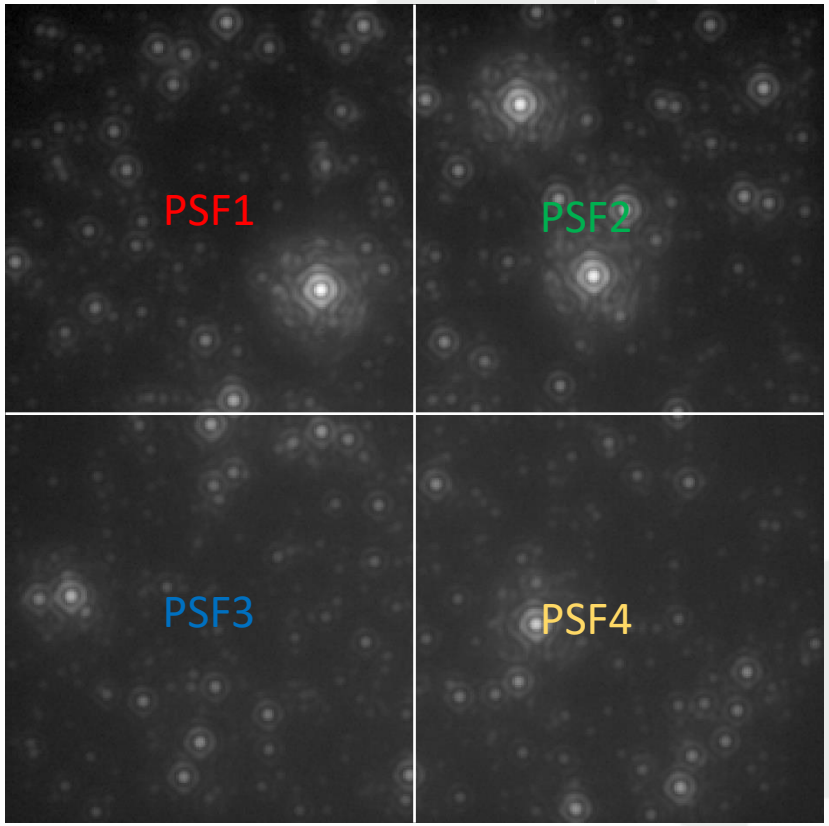


The result of the photometry on the same image with constant PSF but using different sets of stars to compute the PSF produces a difference of Δ mag $\approx$ 0.5 mag

This effect is not important when considering a single PSF for the entire image

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: inter-calibration problems
  - The estimated flux depends on the quality of the local extracted PSF. This effect depends mainly on the variable crowding across the FoV

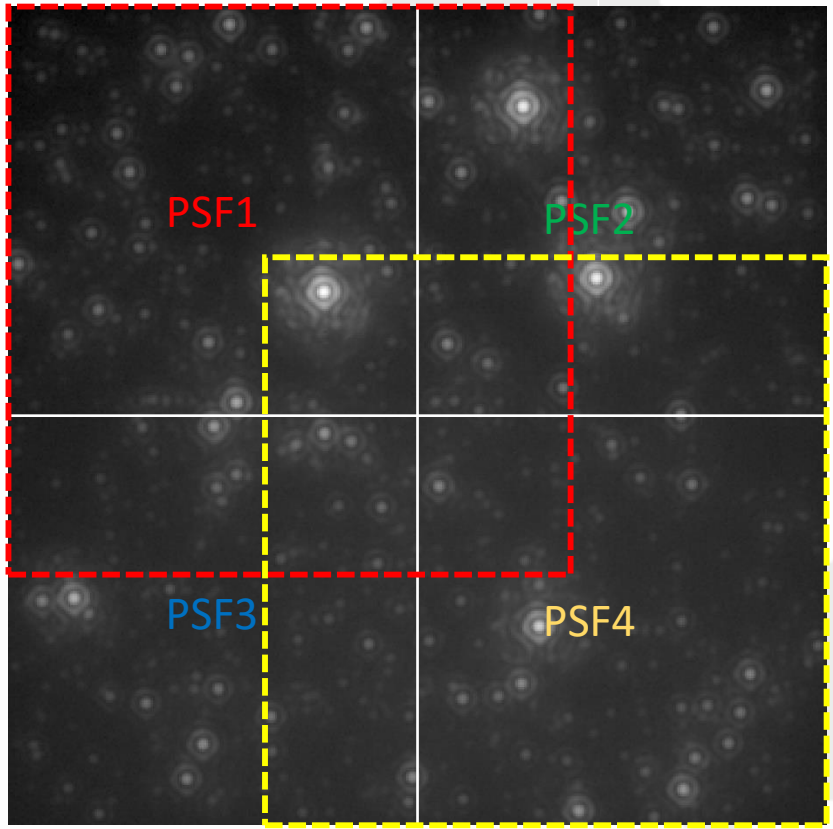


Estimating local PSF means to use different sets of stars to compute the PSF.

The photometry has a different zero point in each sub-domain and requires a different calibration

SF variable PSF: numerical

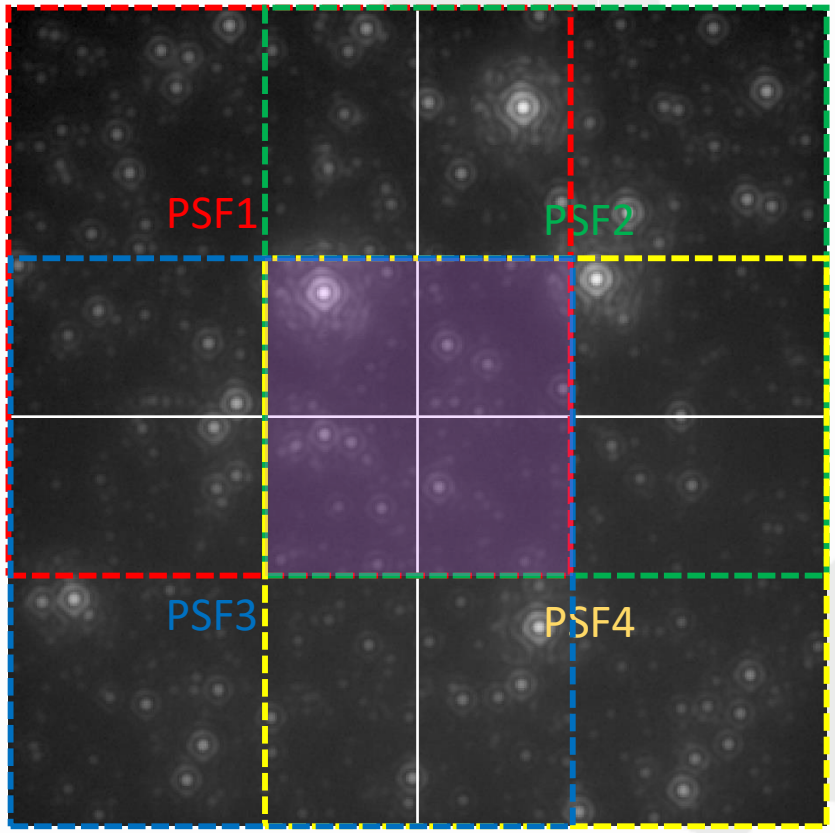
- PSF fitting photometry using the local PSF: inter-calibration problems
  - The estimated flux depends on the quality of the local extracted PSF. This effect depends mainly on the variable crowding across the FoV



STARFINDER works on bigger sub-domains in order to make the photometry of the same star with different PSFs

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: <u>inter-calibration problems</u>
  - The estimated flux depends on the quality of the local extracted PSF. This effect depends mainly on the variable crowding across the FoV

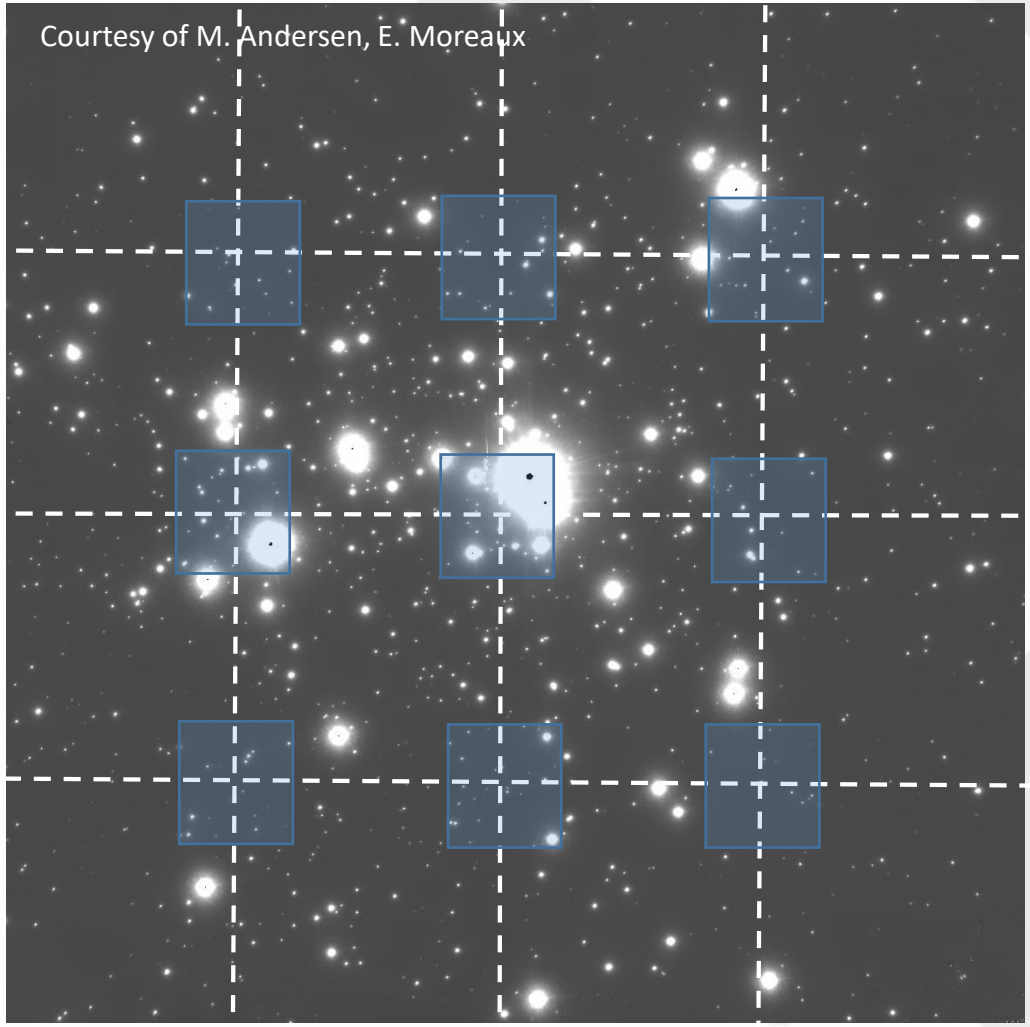


The stars common to all the 4 catalogues are used for the inter-calibration (strumental)

The overlap region size depends on the PSF variation, on the number of common bright Stars, ecc…

SF variable PSF: numerical

- PSF fitting photometry using the local PSF: application to Tr14

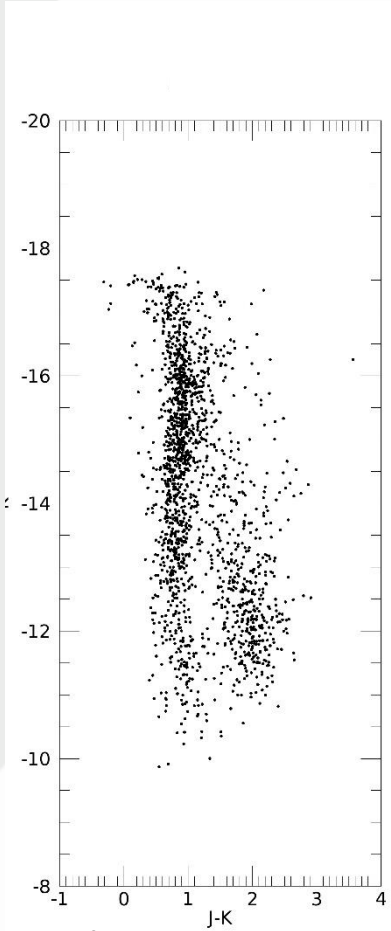


J and K bands

4 X 4 sub-domains with local numerical PSF

The stars in the blue squares are used for inter-calibration

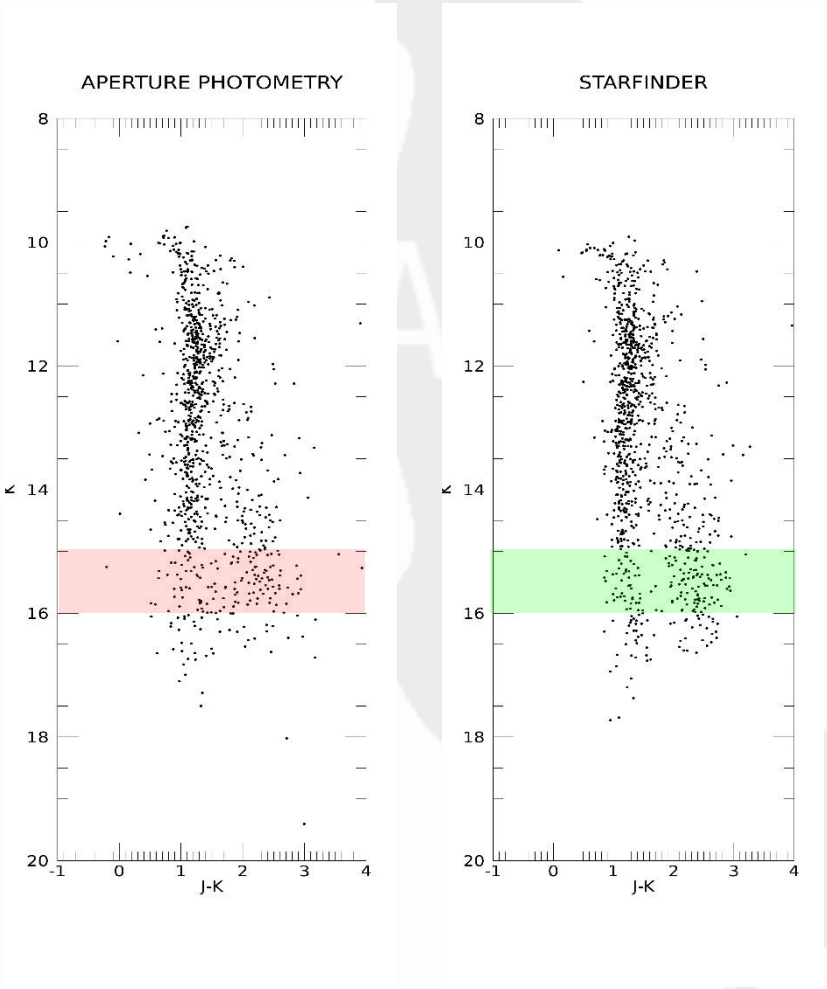
Preliminary CMD shows a well defined separation between main sequence stars and pre-main sequence stars



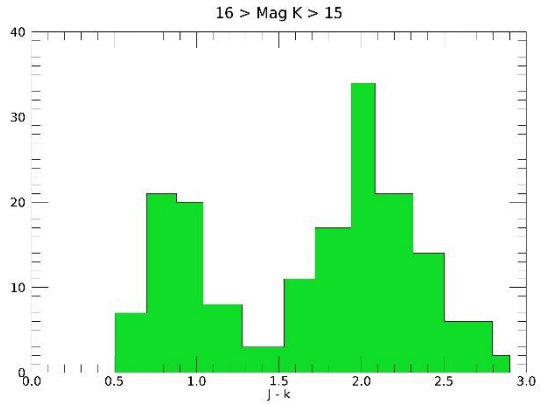
The magnitudes are strumental and the CMD is contaminated by field stars

SF variable PSF: numerical

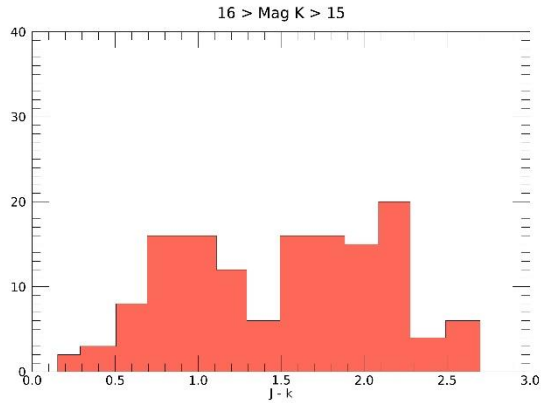
- PSF fitting photometry using the local PSF: <u>application to Tr14</u>



STARFINDER



APERTURE PHOTOMETRY



A preliminary comparison with aperture photometry performed by Daophot shows a less defined separation and a larger main sequence.

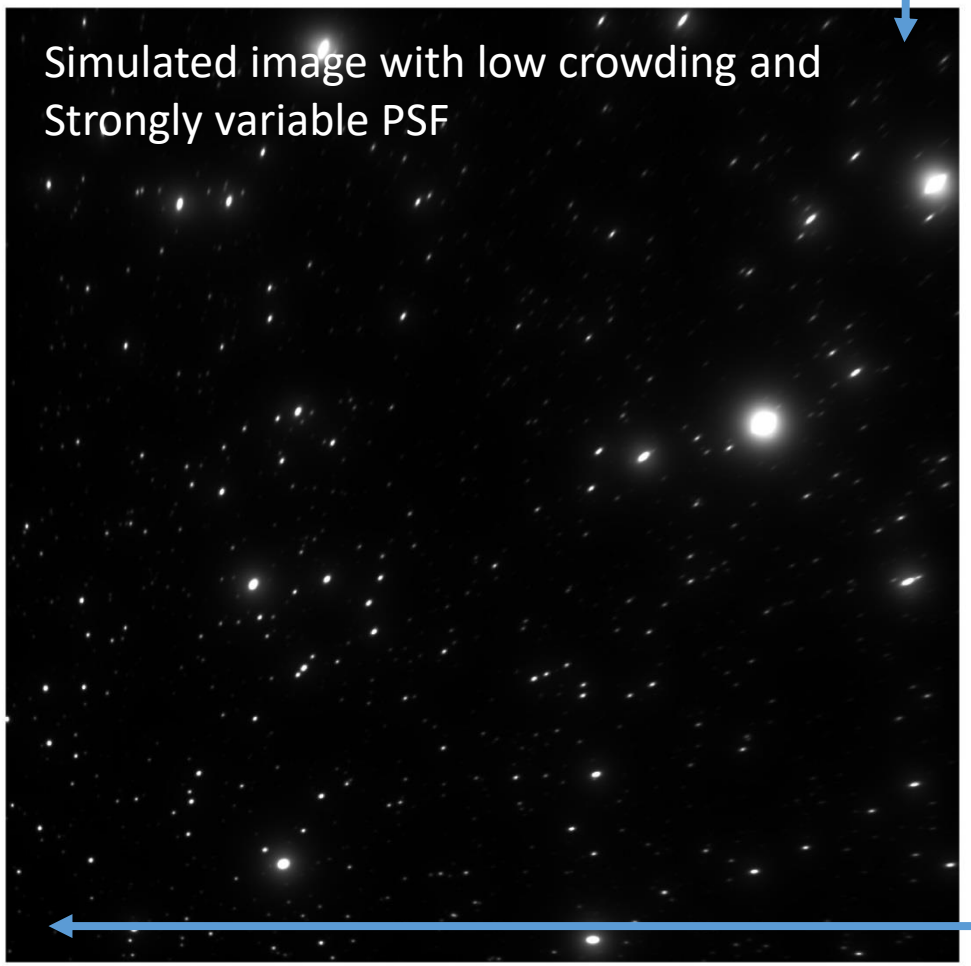
This test has been done only to validate the PSF inter-calibration technique

The possible preliminary conclusions are:

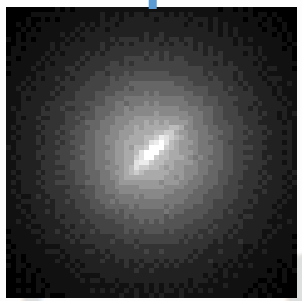
- STARFINDER works better than aperture photometry even in not crowded fields in presence of AO PSF
- Aperture photometry is probably not the best choice to deal with AO PSF

More interesting comparison with HST will be performed

STARFINDER: variable PSF

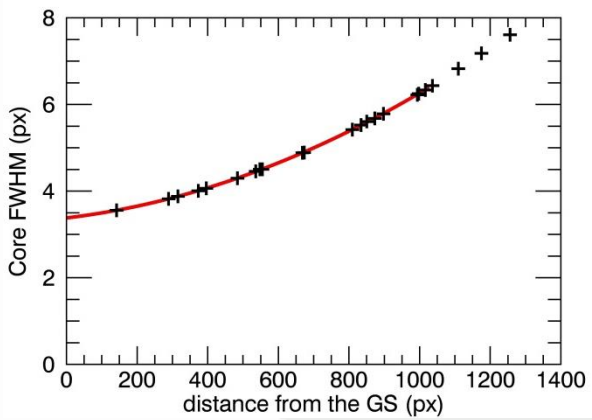


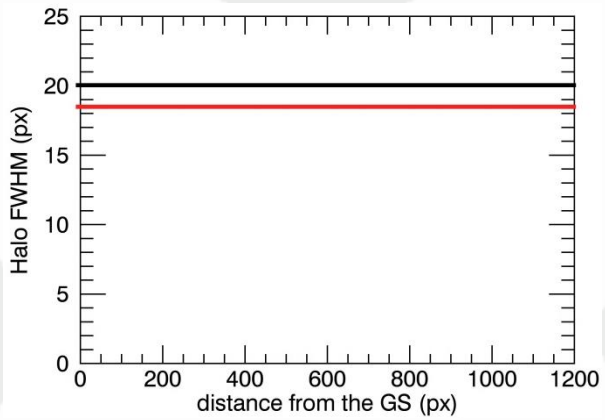
Using the same simulated image as before (pg 15), we perform photometry with STARFINDER considering an analytical model for the PSF and its variation.

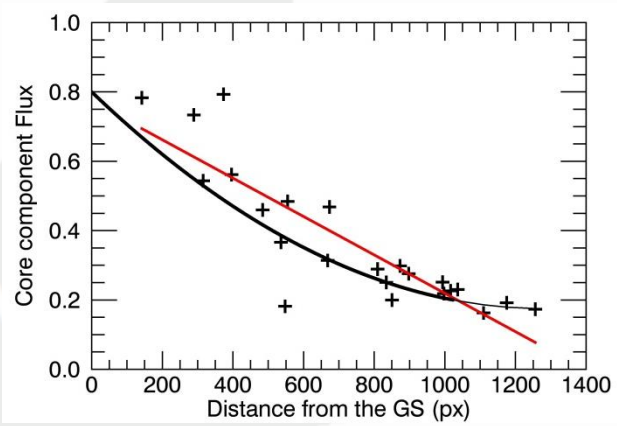


SF variable PSF: analytical

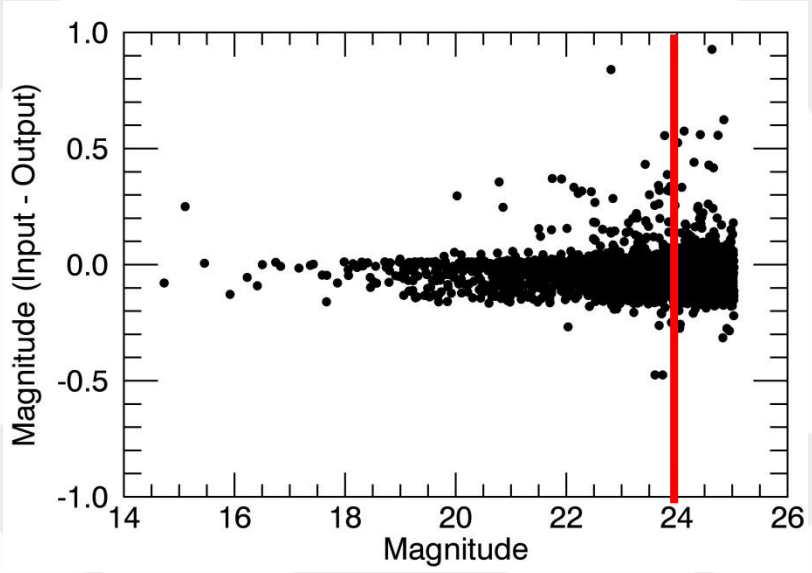
- PSF fitting photometry using the estimated PSF model: <u>results</u>







We modelled the PSF as the combination of two Moffat Functions. The black curves represent the input PSF parameters while the red ones represent the estimated parameters across the FoV

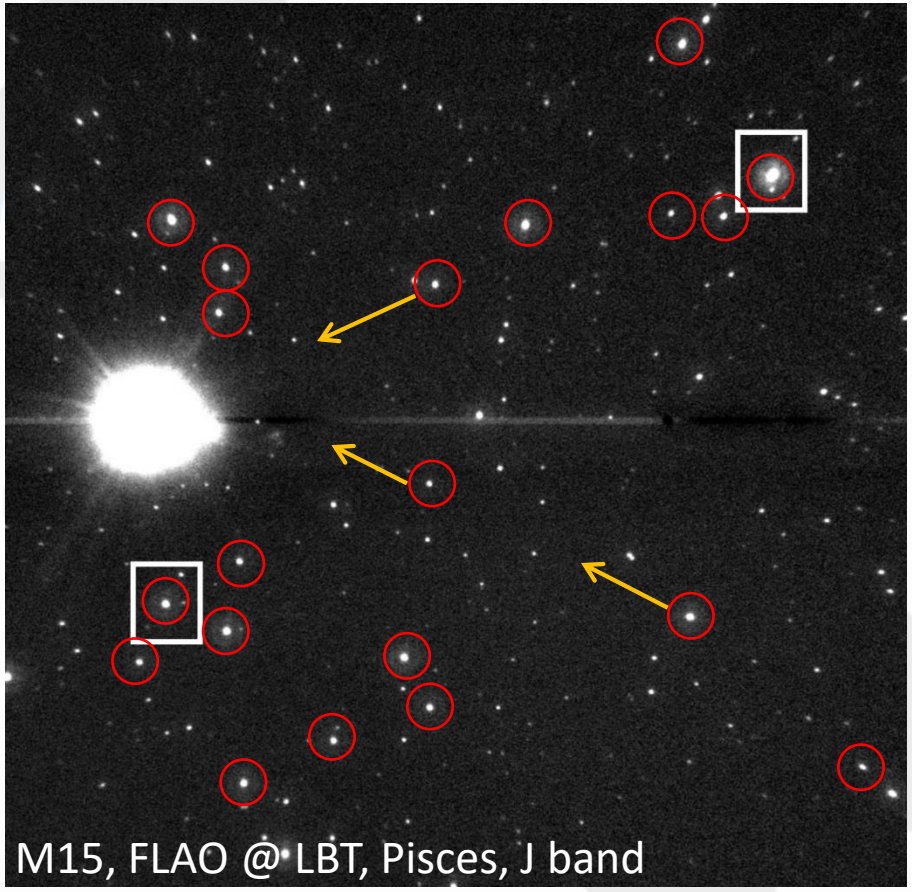


Photometric error in the fainter magnitude bin ≈ 0.13

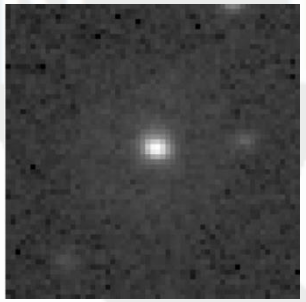
To be compared with the error when perfect PSF is used ≈ 0.11

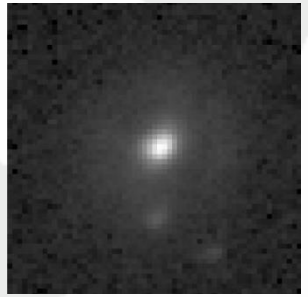
SF variable PSF: analytical / hybrid

- PSF fitting photometry using the estimated PSF model: application to real data



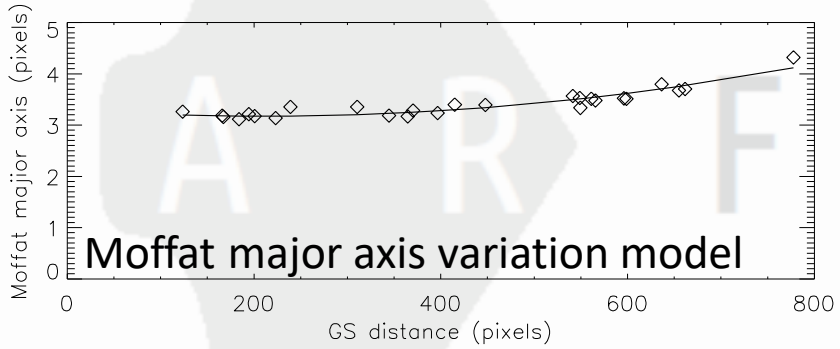
1 - PSF stars selection: possibly bright and isolated

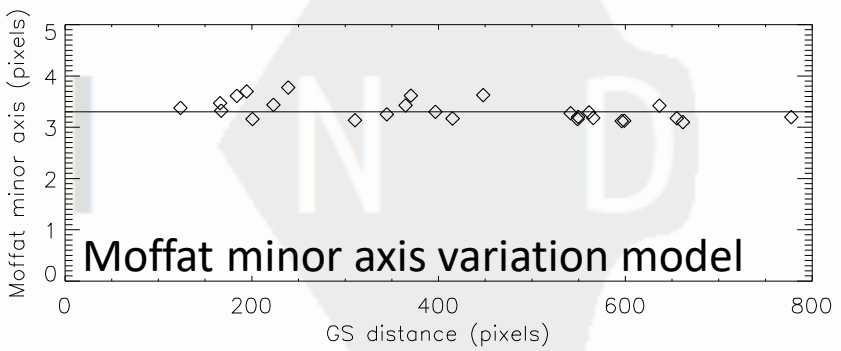


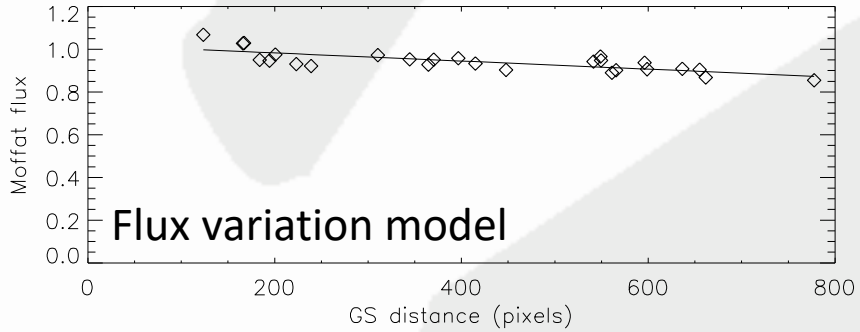


SF variable PSF: analytical / hybrid

- 2 – Definition of the analytical model: 2D single Moffat
- 3 – Estimation of the Moffat parameters variation across the FoV



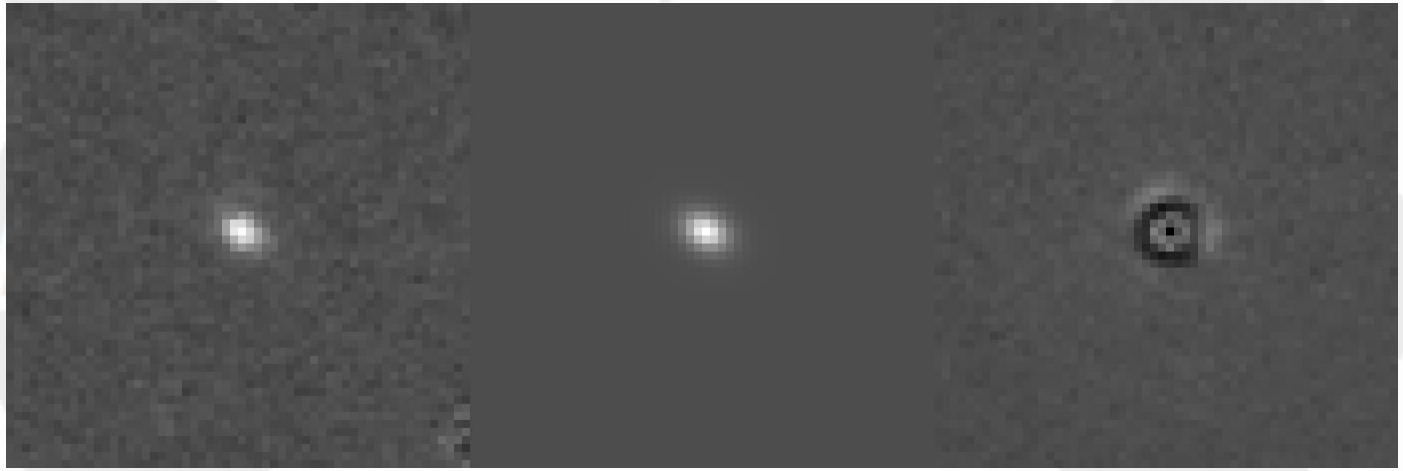




This represents the variation of the flux ratio between the analytical component and the numerical residual. The total is 1

SF variable PSF: analytical / hybrid

- Final PSF: PSF analytical model + numerical residual

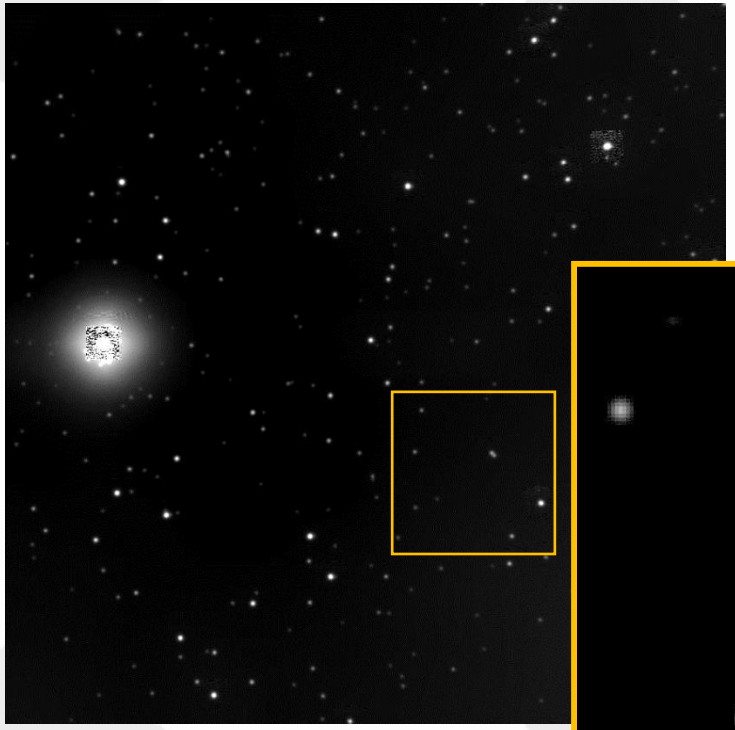


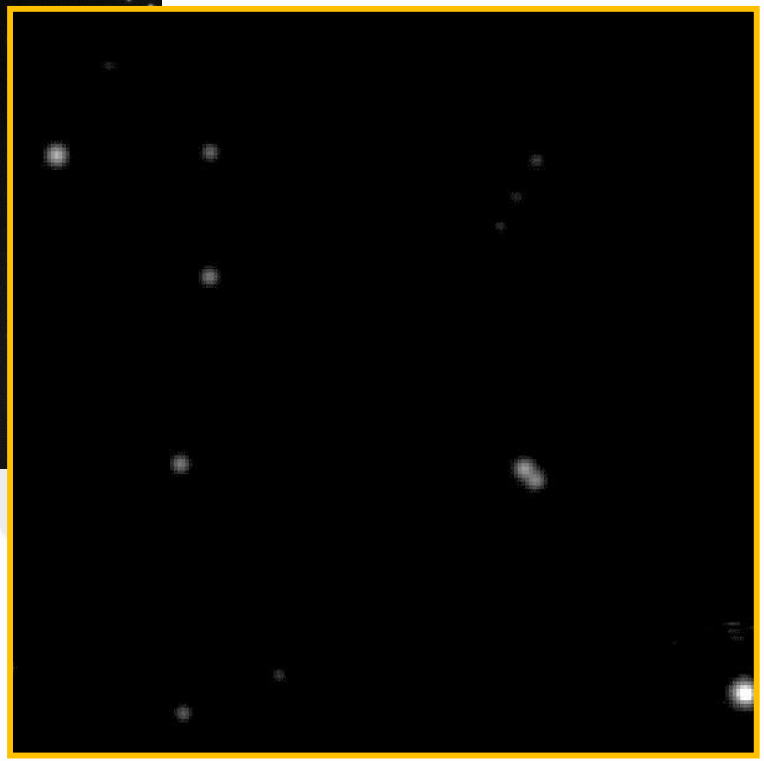
- The residual is computed by stacking and properly shifting and averaging the numerical residuals obtained by subtracting from the PSF stars the analytical component
- These residuals can be considered constant or locally variable across the FoV

SF variable PSF: analytical / hybrid

Image

Synthetic Image model built by STARFINDER





In spite of the large variation of the PSF, the stars are well recognised

Summary and conclusion

- STARFINDER has been developed to work with (also) higly structured PSF;
- It can work with variable PSF;
- The PSF can be numerical, analytical and hybrid;
- The PSF can be also provided as an input (very interesting for sinergies with PSF reconstruction techniques);
- Most of the presented work have been already implemented in the released version, but still not included in the GUI;

Future work

- Documentation will be updated
- User Interface implementation for variariable PSF modelling
- Adding functionalities and re-styling of the GUI
- Non radial PSF analytical parameters variation model across the FoV
- Code optimisation for ELTs use
- Large scale reduction of public AO data to create a PUBLIC dataset of AO photometry starting from stellar clusters.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High-Angular Resolution Observations from the ground: the hitchhiker's guide to the PSF
Observatoire Haute Provence (OHP)
5th to 9th October 2020