Mapping the PSF across Adaptive Optics images

Laura Schreiber

Osservatorio Astronomico di Bologna

Email: laura.schreiber@oabo.inaf.it

Abstract

- Adaptive Optics (AO) 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 increases the energy concentration of the Point Spread Function (PSF) almost reaching the resolution imposed by the diffraction limit, but the PSF itself is characterized by complex shape, no longer easily representable with an analytical model, and by sometimes significant spatial variation across the image, depending on the AO flavour and configuration.
- The aim of this lesson is to describe the AO PSF characteristics and variation in order to provide (together with some AO tips) basic elements that could be useful for AO images data reduction.

What's PSF

- *'The Point Spread Function (**PSF**) describes the response of an imaging system to a point source'*

- Circular aperture of diameter D at a wavelenght λ (no aberrations) → **Airy diffraction disk**

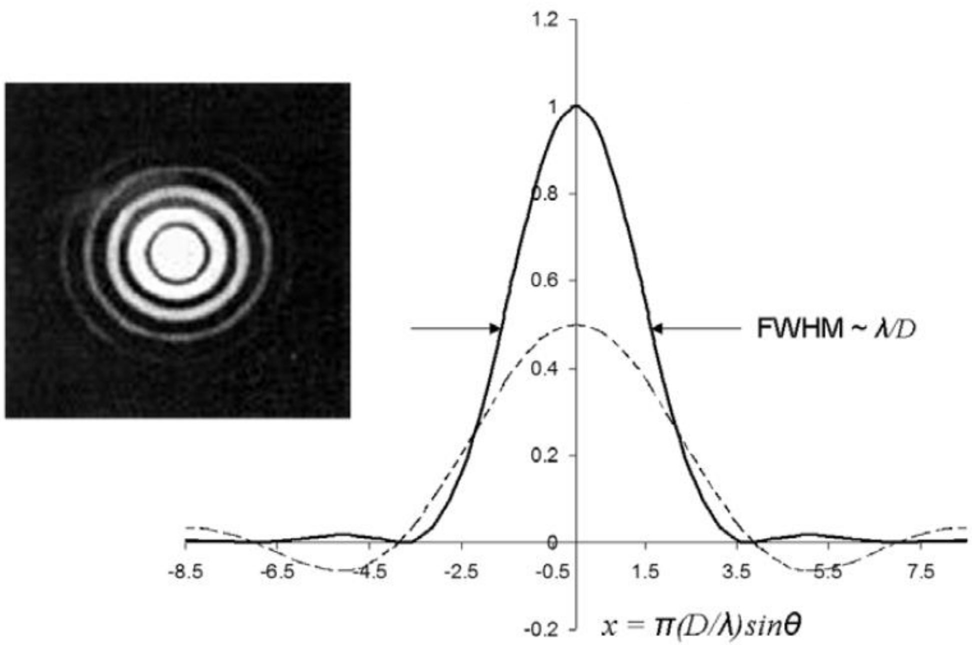


Figure 1.15. The point spread function (solid line) of the Airy diffraction pattern for a circular aperture of diameter D is illustrated both as an image and in cross-section.

$$I_\theta = I_0\{J_1(x)/x\}^2$$

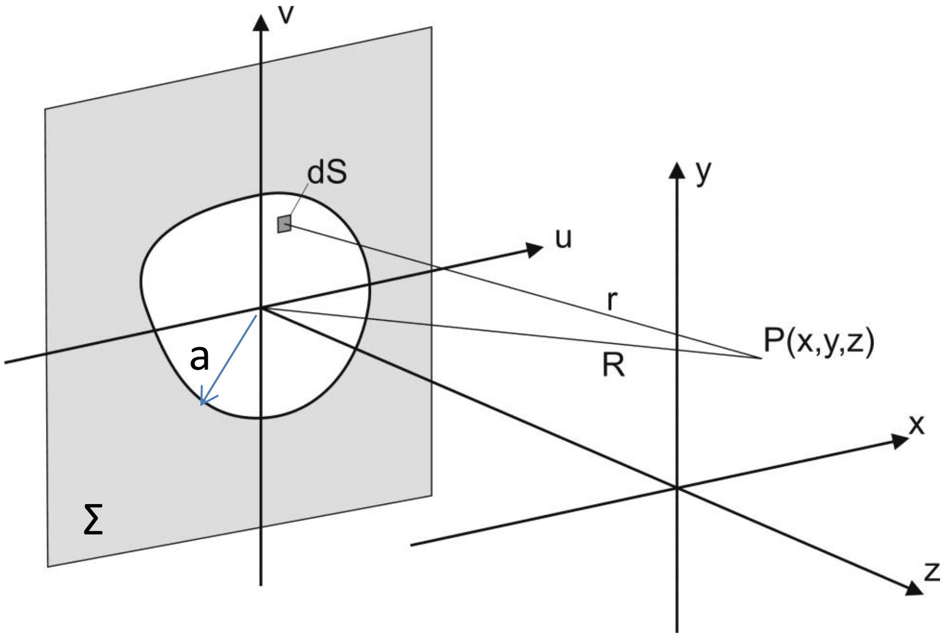
Where $J_1(x)$ represents the **Bessel function** of order 1

$$x = \pi(D/\lambda)sin\vartheta$$

ϑ is the angular radius from the aperture center

→ First goes to 0 when $\vartheta \sim 1.22\ \lambda/D$

Imaging of a point source through a general aperture



Consider a **plane wave** propagating in the z direction and illuminating an aperture.
The element *ds* = *dudv* becomes the sourse of a secondary spherical wave.
The complex field in *P* generated by *dS* is:

$$dE = \frac{\varepsilon_0}{r} e^{i(\omega t - kr)} dS$$

R >> a

$$R = \sqrt{x^2 + y^2 + z^2}$$

~ 0

Taylor

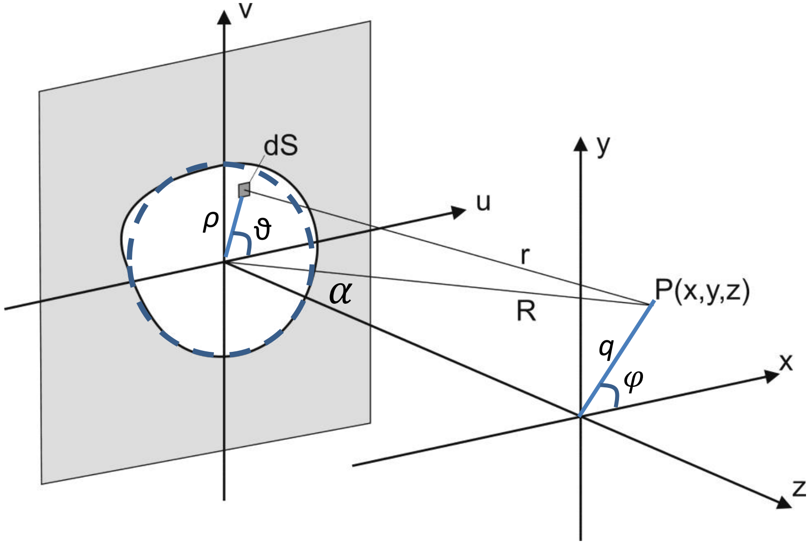
$$r = \sqrt{z^2 + (x-u) + (y-v)^2} = R\left[1 + \frac{u^2+v^2}{R^2} - \frac{2(ux+vy)}{R^2}\right]^{1/2} \sim R\left[1 - \frac{ux+vy}{R^2}\right]$$

$$E(x,y) \cong \frac{\varepsilon_0}{R} e^{i(\omega t - kR)} \iint_{aperture} e^{ik(ux+vy)/R} dudv$$

The PSF is the field intesity distribution in the image plane

Imaging of a point source through a circular aperture

- Spherical coordinates



$u = \rho \cos \vartheta \qquad v = \rho \sin \vartheta$

$x = q \cos \varphi \qquad y = q \sin \varphi$

$ds = \rho d\rho d\varphi$

$$E(x,y) \propto \int_0^a \rho \int_0^{2\pi} e^{i\left(\frac{k\rho q}{R}\right)\cos(\vartheta-\varphi)} d\rho d\vartheta =$$

$$= 2\pi a^2 \left(\frac{R}{k\rho q}\right) J_1\left(\frac{R}{k\rho q}\right)$$

$$I(\alpha) = I(0)\left[\frac{2J_1(ka\sin\alpha)}{ka\sin\alpha}\right]^2 \text{ where } \alpha = q/R$$

- …or we can define a function

$$A(u,v) \overset{def.}{=} \begin{cases} 1 & \text{if } (u,v) \in \text{aperture} \\ 0 & \text{otherwise} \end{cases}$$

$$E(x,y) \propto \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} A(u,v) e^{i\frac{k}{R}(ux+vy)} dudv$$

- $f_x = \frac{k}{R}x \qquad f_y = \frac{k}{R}y$

$$E(f_x, f_y) = \iint_{-\infty}^{+\infty} A(u,v) e^{i(f_x u + f_y v)} dudv$$

$$= FT[A(u,v)]$$

2D Fourier transform of the aperture function

- The field distribution in the image plane is the spatial frequency spectrum of the aperture function

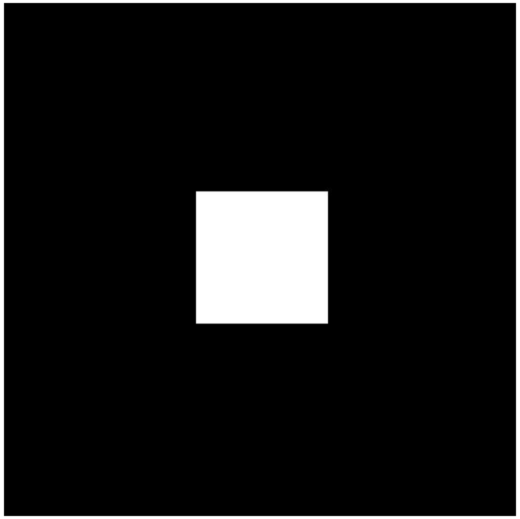
$$I(f_x, f_y) = |E(f_x, f_y)|^2 = |FT[A(u,v)]|^2$$

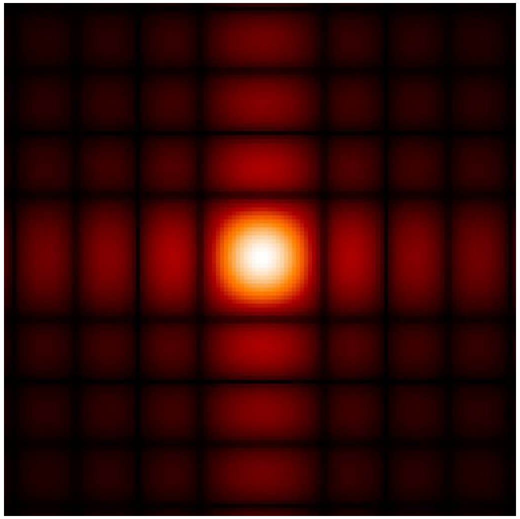
PSF computation using FFT

Aperture

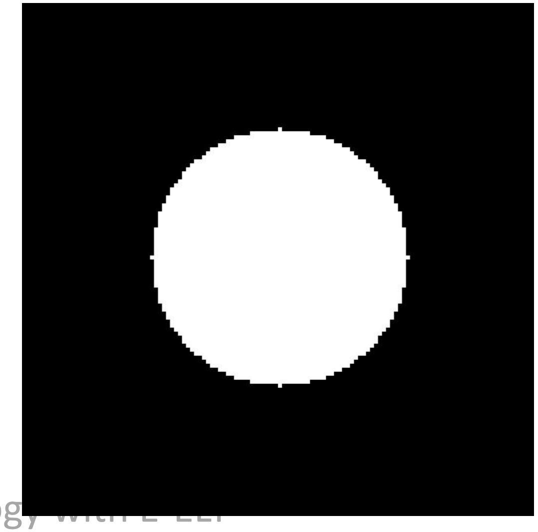
PSF

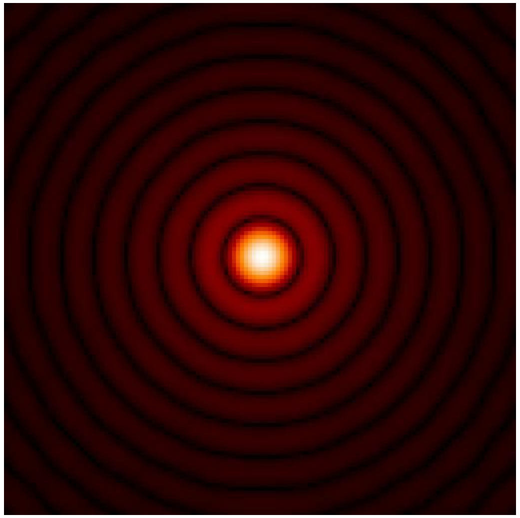
```
FUNCTION square_PSF, n, d

x = rebin(findgen(n) - n/2, n, n)
y = rebin(transpose(findgen(n)) - n/2, n, n)
a = abs(x) le d/2 and abs(y) le d/2
a = shift(a, -n/2, -n/2)
psf = abs(fft(a))^2
psf = shift(psf, n/2, n/2)
psf = psf / total(psf)
return, psf
end
```



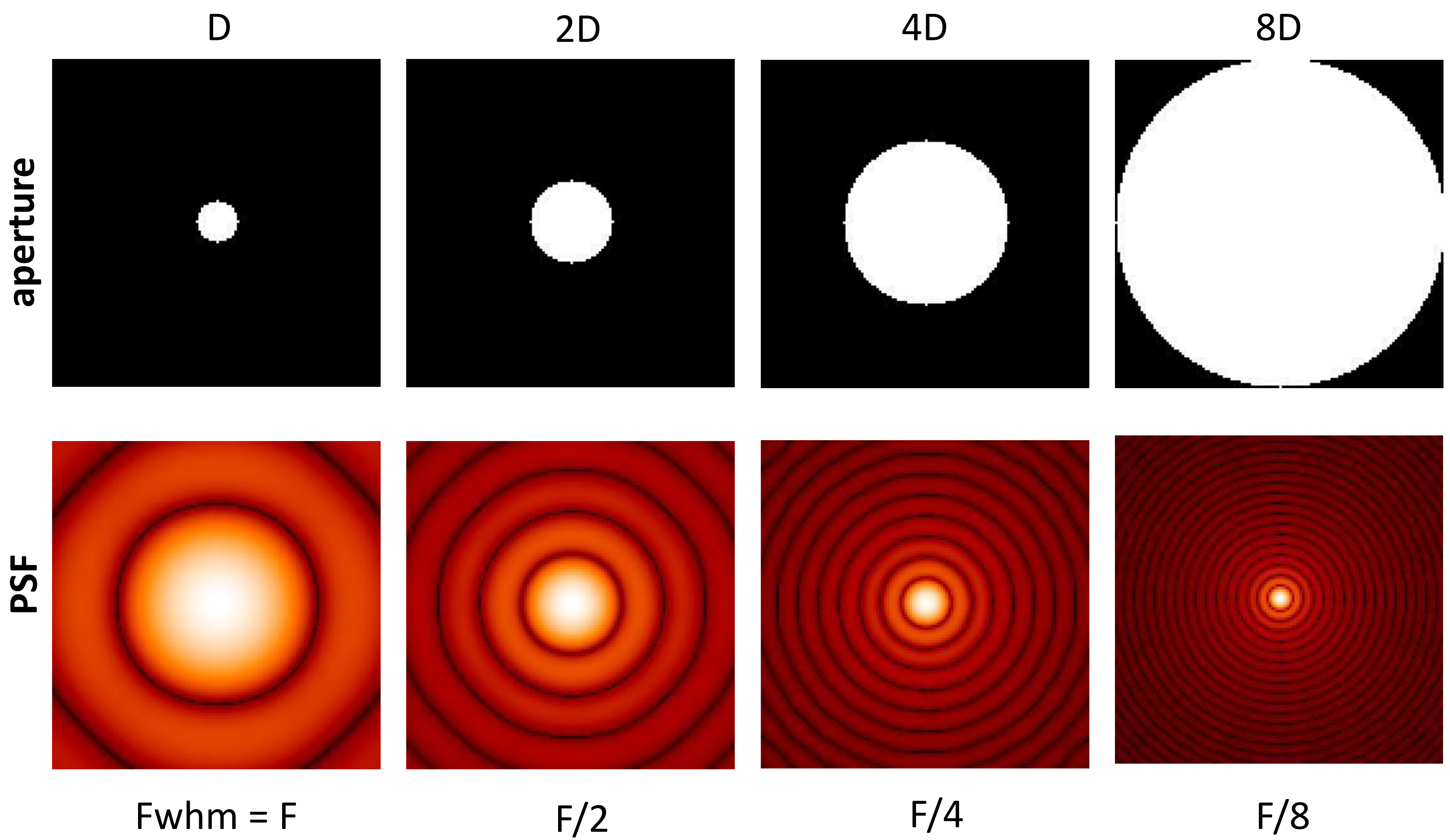


```
FUNCTION circ_PSF, n, d

x = rebin(findgen(n) - n/2, n, n)
y = rebin(transpose(findgen(n)) - n/2, n, n)
a = sqrt(x^2 + y^2) le d/2
a = shift(a, -n/2, -n/2)
psf = abs(fft(a))^2
psf = shift(psf, n/2, n/2)
psf = psf / total(psf)
return, psf
end
```

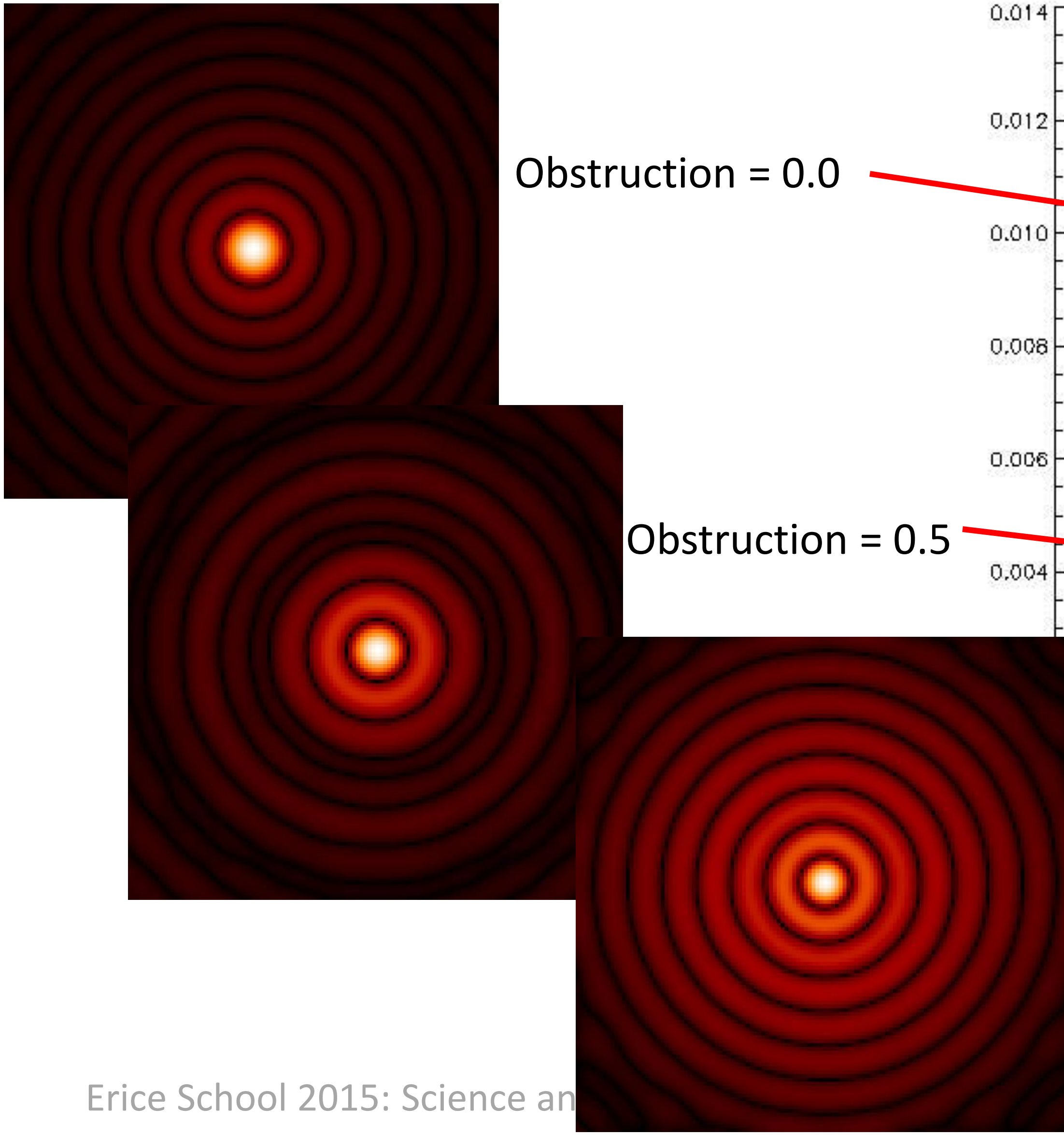


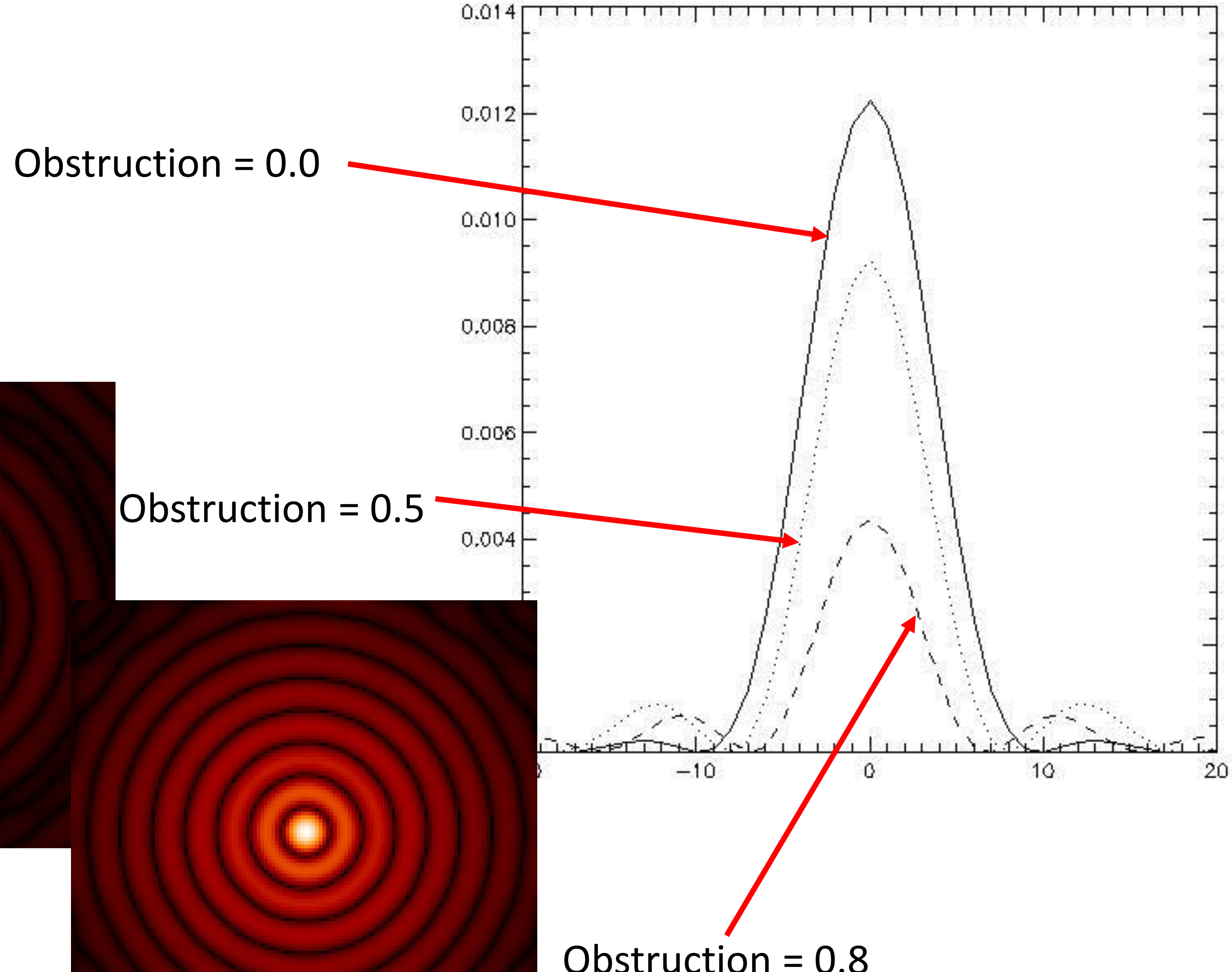


Circular apertures of different sizes

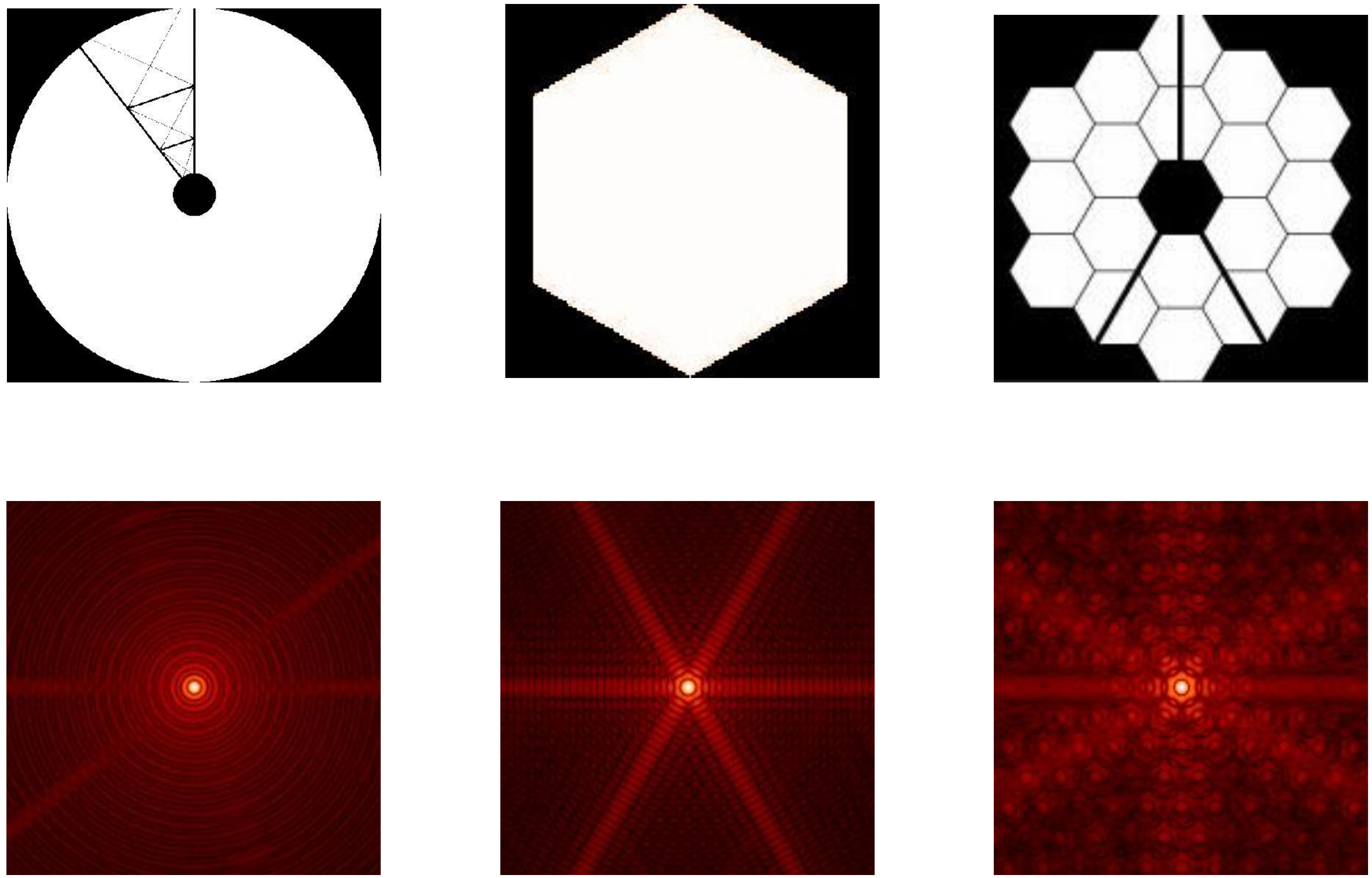


Circular aperture with central obstruction



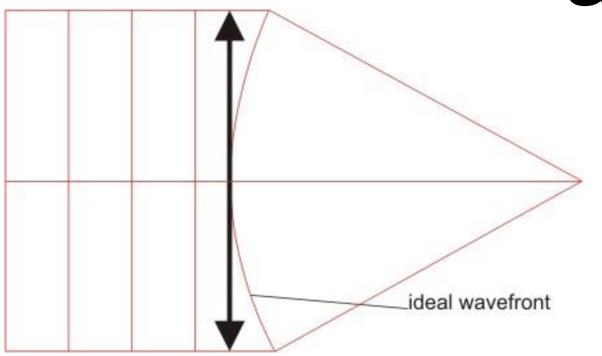


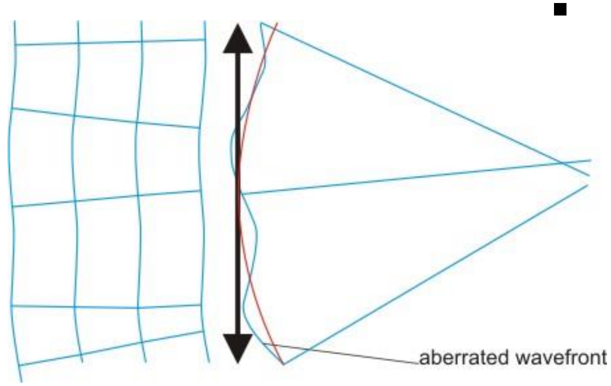
Different apertures



LBT JWST

Diffraction in presence of aberrations





- In the ideal case (red), the incident wavefront is flat; the converging optical element focuses on the focal plane the Fraunhofer diffraction pattern that would be observed at a very long distance
- In the aberrated case (blue), the wavefront is distorted and the diffraction pattern on the focal plane will be different.

NOTE that the aberrations can be introduced by the optical system itself

In presence of aberrations, the complex field of the incoming wave on the aperture can be expressed as:

$$E(u,v)=\varepsilon_0 e^{i\phi(u,v)}$$

The function $\phi(u,v)$ describes the wavefront distortions

The intensity distribution, in Fraunhofer approximation, becomes:

$$i(f_x,f_y)=\left|E(f_x,f_y)\right|^2=\left|FT\left[A(u,v)e^{i\phi(u,v)}\right]\right|^2$$

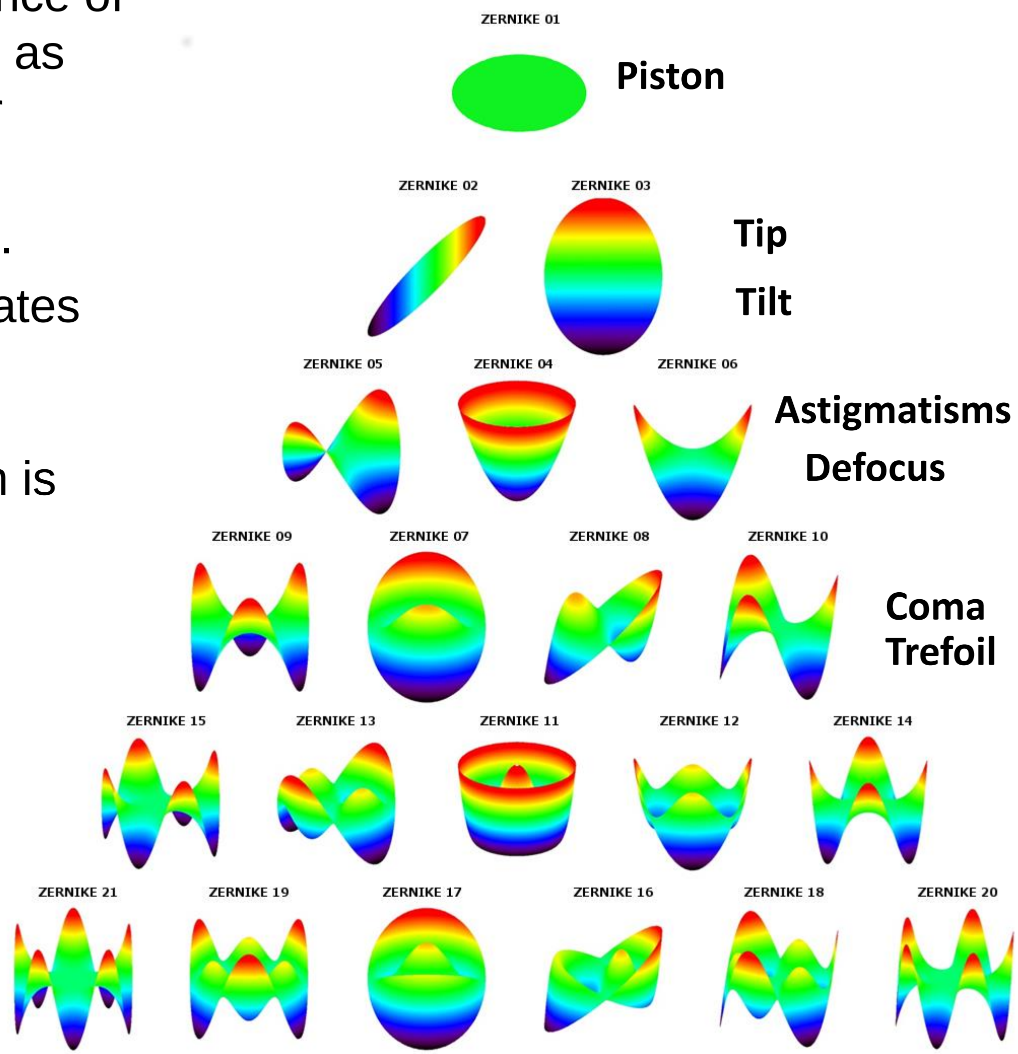
Modal Representation of aberrations

- Wavefront distortions at the entrance of the telescope can be represented as the linear combination of a proper defined basis of functions.
- Zernike polinomial are orthogonal.
- They are defined in polar coordinates on a unit circle as functions of azimuthal frequency m and radial degree n, where m ≤ n, and n – m is even.

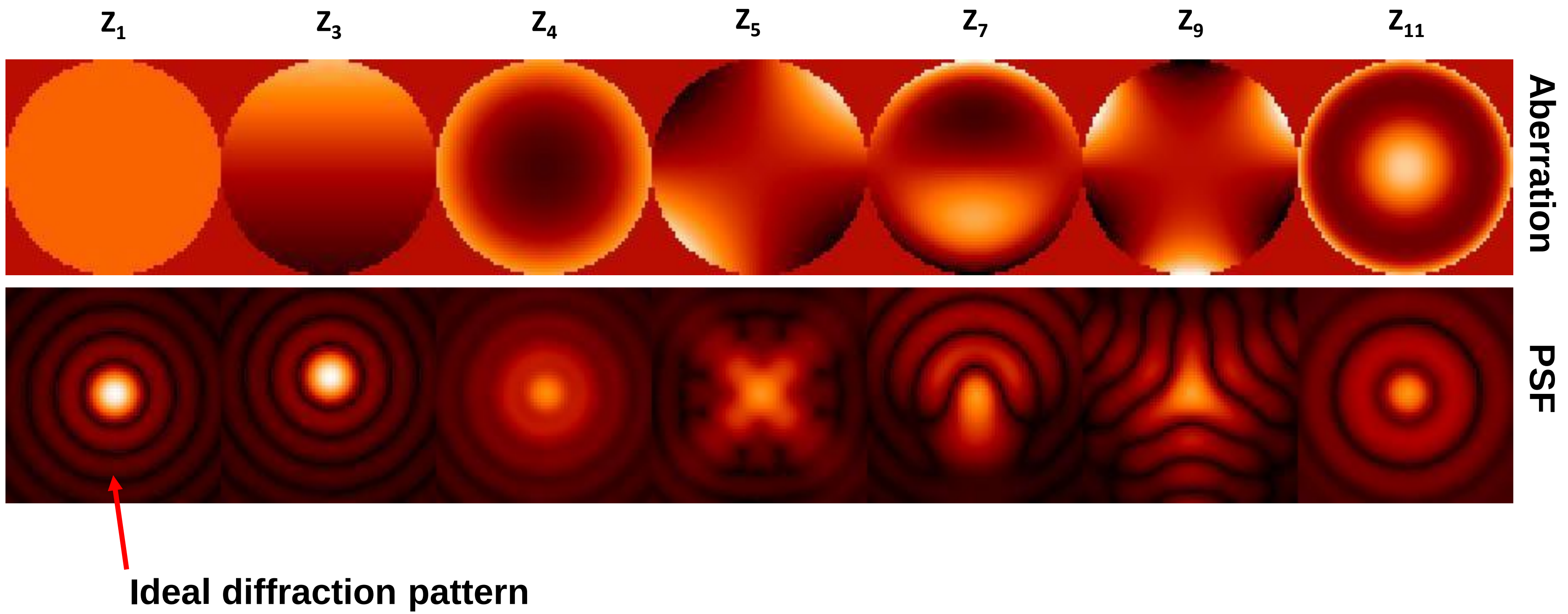
$$Z_{even,j} = \sqrt{n+1}R_n^m \rho \sqrt{2} \cos m\theta$$

$$Z_{odd,j} = \sqrt{n+1}R_n^m \rho \sqrt{2} \sin m\theta$$

$$Z_j = \sqrt{n+1}R_n^0(\rho)$$



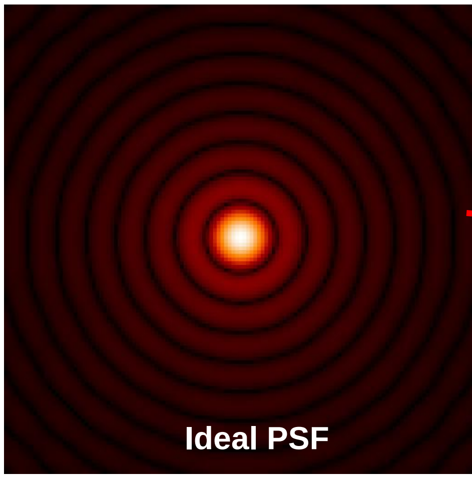
Circular Aperture PSF in presence of aberrations (static)



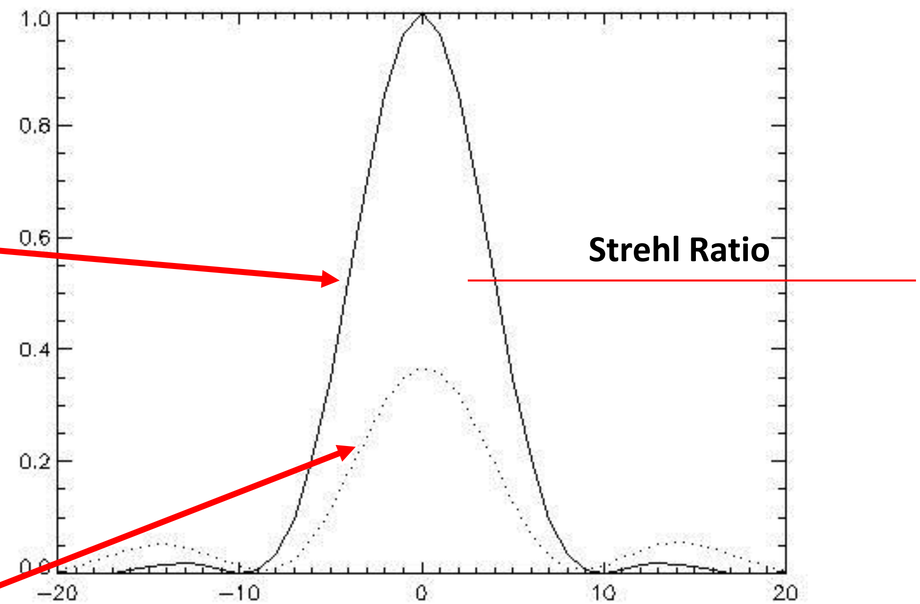
The first term (piston) does not have any effect on the image. The second term (tilt) produces a shift in the image. The higher orders terms introduce deformation in the PSF.

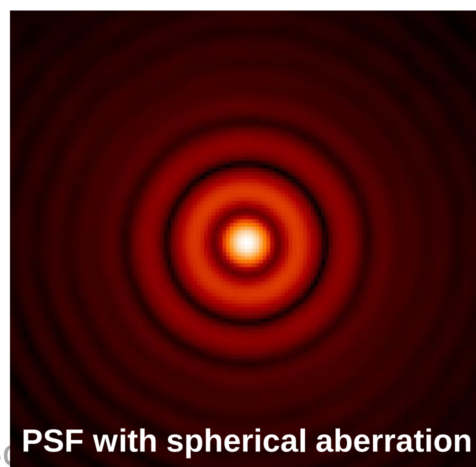
The Strehl Ratio

The Strehl Ratio **(SR)** is the ratio of the peak aberrated image intensity from a point source compared to the maximum attainable intensity using an ideal optical system limited only by diffraction over the system's aperture.


Ideal PSF

$$SR = \frac{I_0}{I_{0,\,DIFFR}}$$



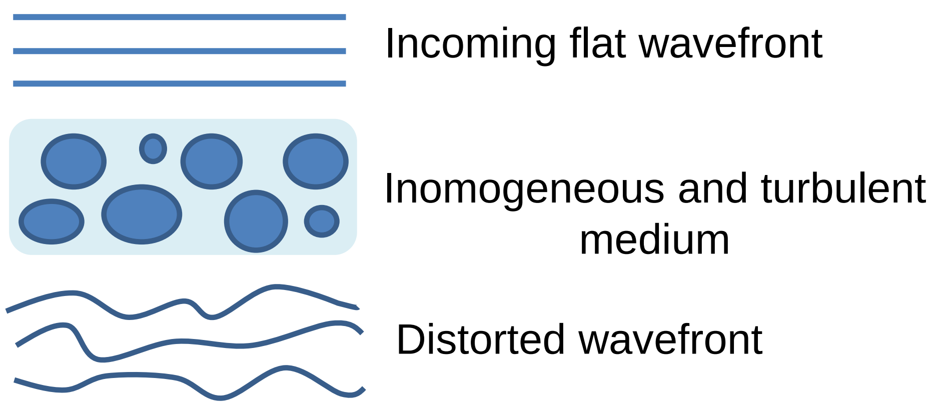

PSF with spherical aberration

$$\mathrm{SR} \approx \exp(-\sigma_\varphi^2)$$

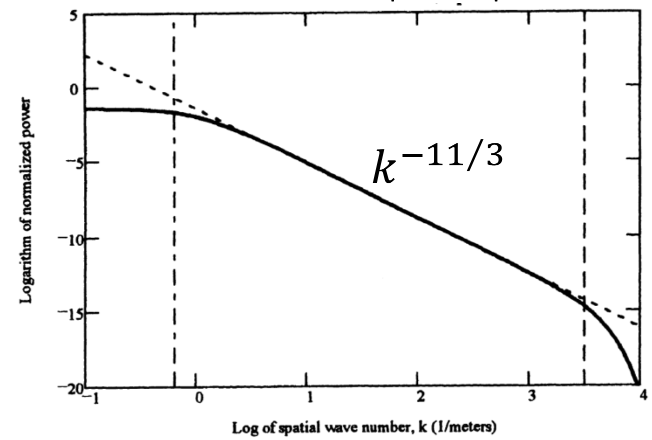
Marechal approximation: SR > 0.1
where σ_φ is the standard deviation of the phase (Wavefront error)

Circular Aperture PSF in presence of atmospheric turbulence

- Before entering the atmosphere, light from stars forms plane waves (flat wavefronts). Refraction index variations in space and time due to turbulent air cells along the wavefront path, produce local variations in the wavefront phase.



3D Refractive index power spectrum



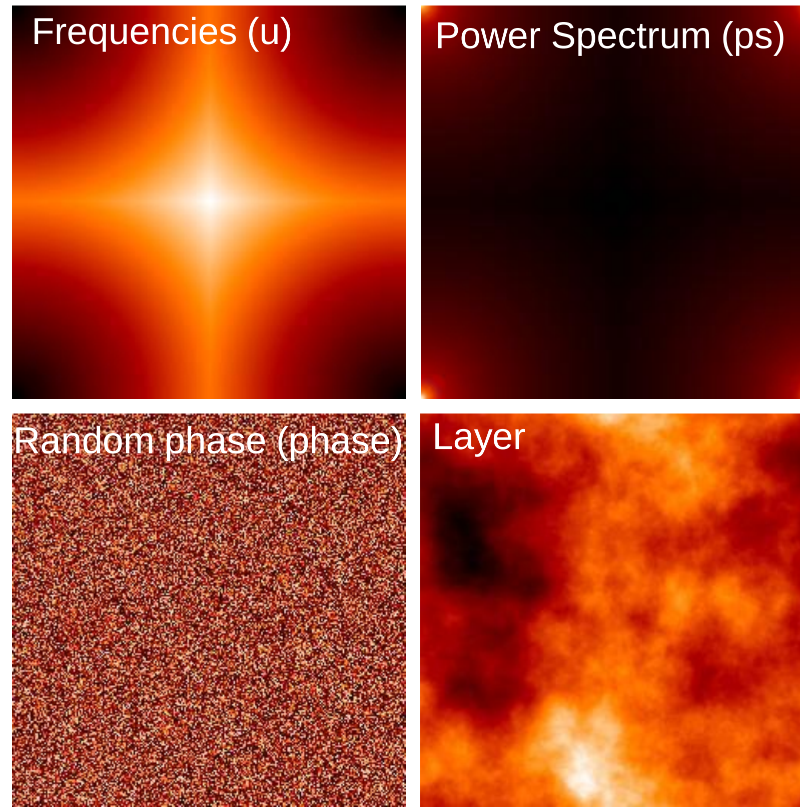
- From the Power Spectrum of the Refractive Index it is possible to build a ‘phase map’, that describe, point by point, the phase delay coused by the atmospheric refracion index variation.

- The Refractive index power spectrum follows a -11/3 power law (Kolmogorov)

How to build a phase map (screen)

- A turbolent layer can be simulated with the computer multiplyng the sqrt of power spectrum by a random phase.

```
pro makelayer, layer

nsize = 256
npupil = 64
d = 8.0
pixlayer = d / npupil
r0 = 0.5
Dr0 = d/r0
layer = dblarr(nsize,nsize)
f_sampling = double(pixlayer*double(nsize))
u = frequencies(nsize,pixlayer)

ps = double(abs(u)^(-11.d/3.d))
phase = (2.d0*randomu(Seed,nsize,nsize)-1.d0)*!Dpi
CPS = Sqrt(ps)*DComplex(Cos(Phase), Sin(Phase))
layer = fft(CPS,1,/Double)
layer = shift(layer,nsize/2,nsize/2)
layer = layer - (moment(layer, /DOUBLE))[0]
layer = layer * sqrt(1.0299d0*Dr0^(5.d0/3.d0))


return
end
```



The sqrt of the power spectrum is multiplied by sin and cos of the random phase and The fourier transform (from frequency to distance space) represents tha phase map

The Fried Parameter

- The Fried Parameter r_0 gives a measure of the strenght of the turbulence. It is defined as the following:

$$r_0 = [0.423 k^2 (sec\xi) \int dh\, C_N^2 (h)]^{-3/5}$$

Wave number

Zenith angle

Refractive index Structure function

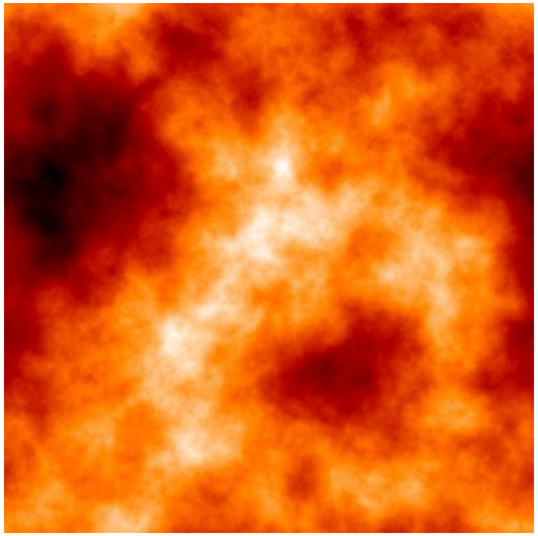
$$r_{0 \propto \lambda^{6/5}} (sec\xi)[\int dh\, C_N^2 (h)]^{-3/5}$$

- r_0 gets small when turbulence is strong (${C_N}^2$ large)
- r_0 gets bigger at longer wavelenghts (10-20 *cm* @ 550 *nm*, 50 *cm* @ 2200 *nm*)
- r_0 gets smaller as telescope looks toward the horizon
- r_0 defines an aperture size over which the mean-square wavefront error is 1 rad^2

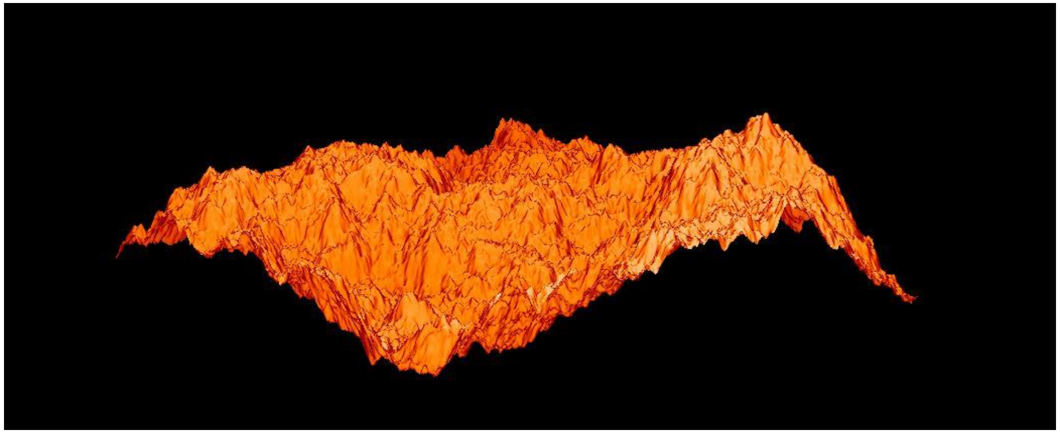
Circular Aperture PSF in presence of atmospheric turbulence

- We compute the istantaneus PSF remembering that:

$$i(f_x, f_y) = \left| E(f_x, f_y) \right|^2 = \left| FT\left[A(u,v) e^{i\phi(u,v)} \right] \right|^2$$



1 px ~ 30 cm



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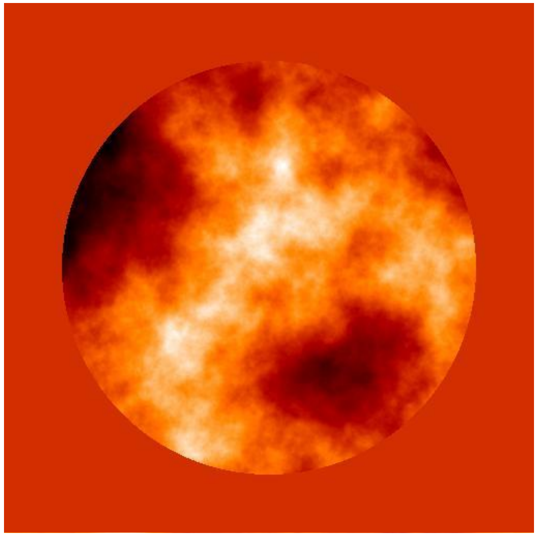
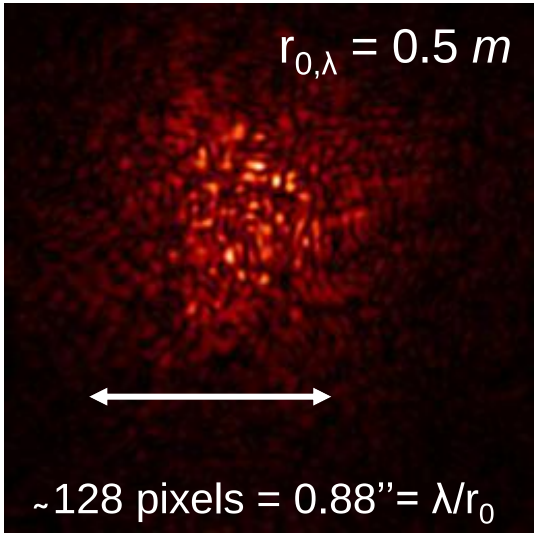


1 px ~ 30 cm



1 px ~ 7 mas

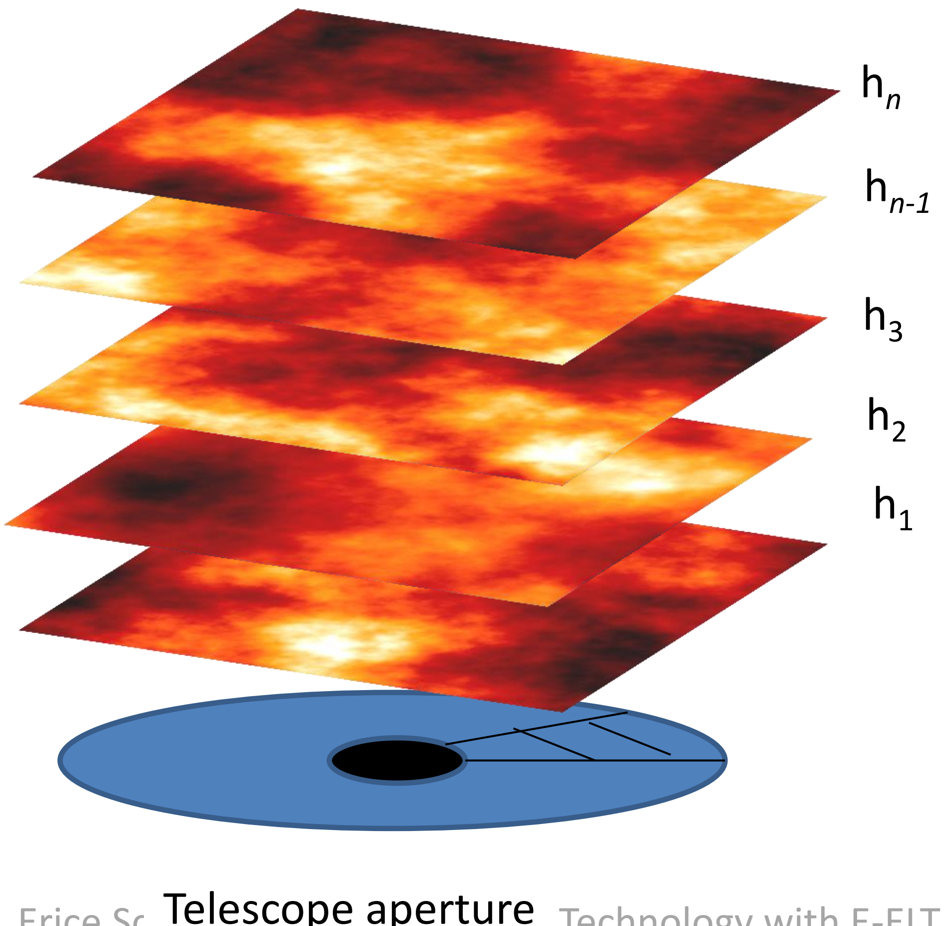
The short exposure image consists of a large number of speckles having size λ/D

Circular Aperture PSF in presence of atmospheric turbulence

- To produce long exposure PSFs, we need a dynamic atmospheric model.

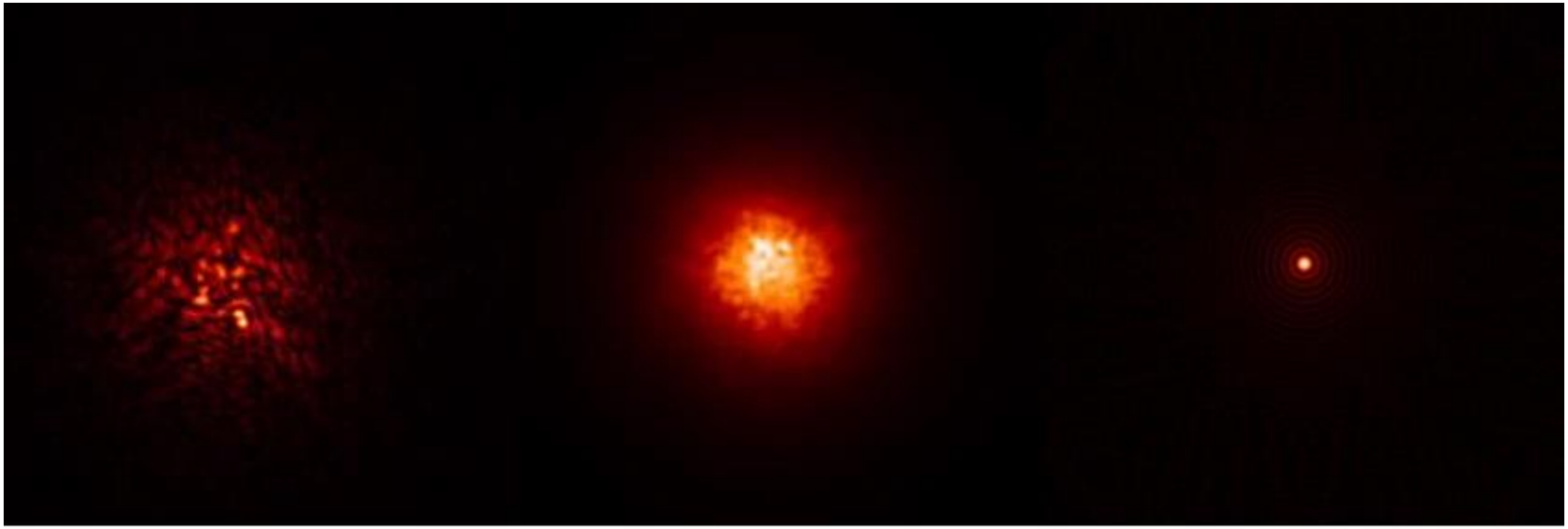
Each of the layer is characterized by Its altitude (h), it's altitude and its velocity.

The total phase delay at the telescope aperture is given by the $\sum_1^n layers$ in the star direction



Circular Aperture PSF in presence of atmospheric turbulence

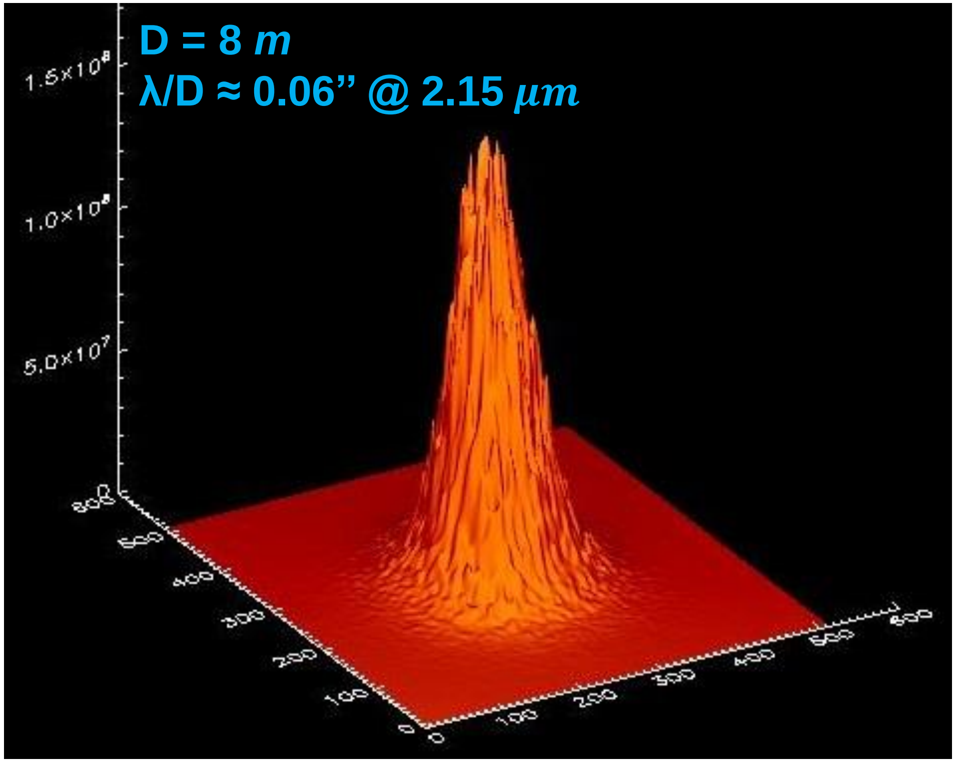
- The size of the turbulence degraded image is due to:
  - Diffraction limit of the aperture (λ/D)
  - Short Esposure image spread (λ/r_0)
  - Image motion due to overall tilt (determined by both D and r_0)

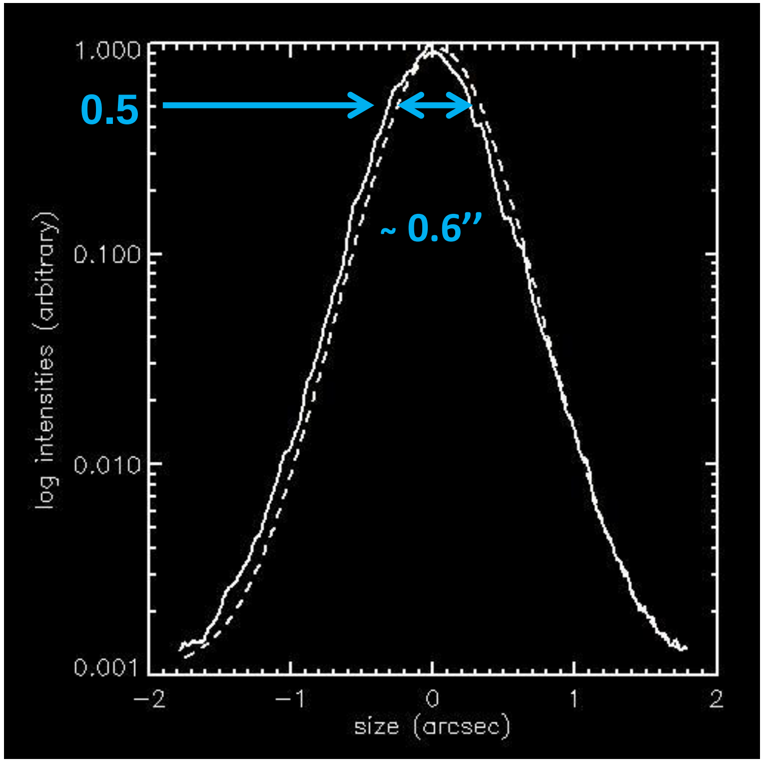


Short exposure PSF Long exposure PSF Diffraction limited PSF

Seeing limited PSF ($D/r_0 \sim 10$)

- The long exposure PSF (K band) looks like a 2D moffat function having FWHM = seeing



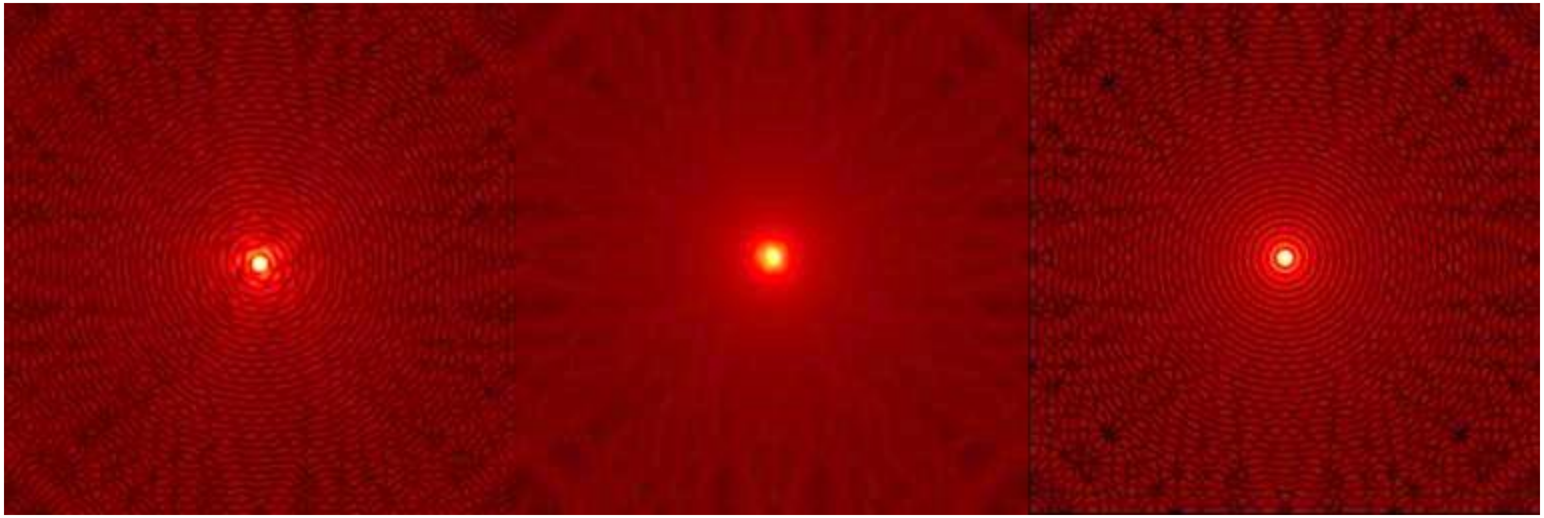


Moffat distribution: $I(r) = \frac{1}{1+(\frac{r}{r_m})^{2\beta}}$ [King 1971]

where r_m is the moffat radius and β describes the asymptotic power low of the wings

Seeing limited PSF (D = r_0)

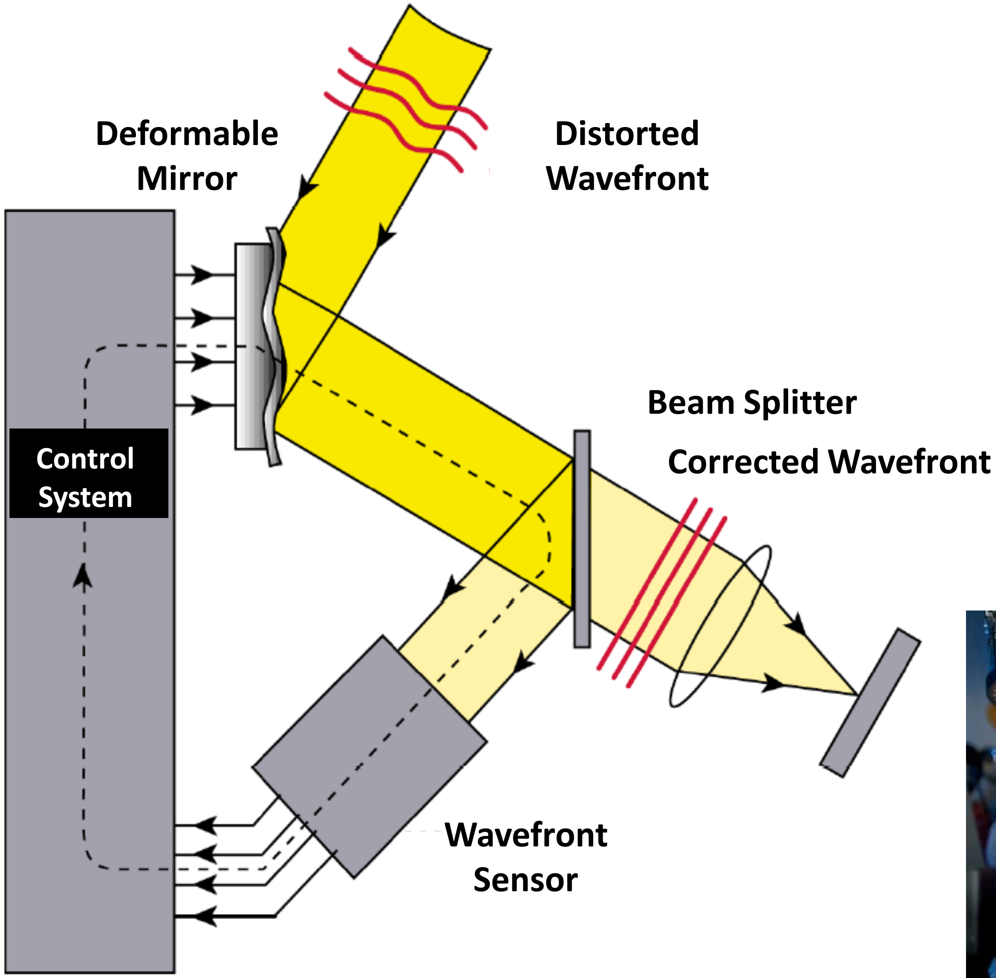
- For very small apertures, atmospheric turbulence has little effect on the image size, which is determined by D.
- Wavefront distortion is mainly overall tilt.

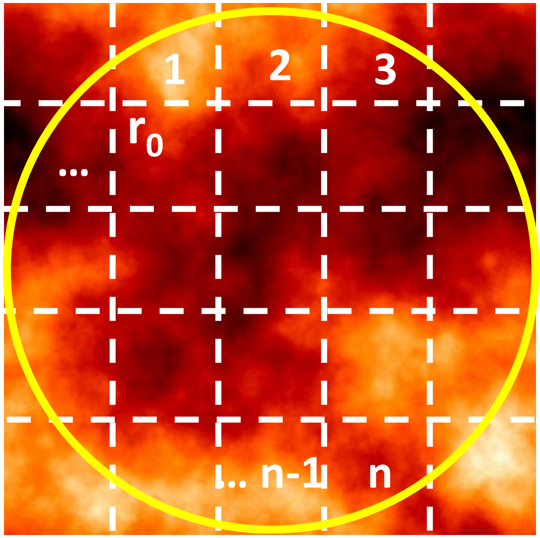


Short exposure PSF | Long exposure PSF | Diffraction limited PSF

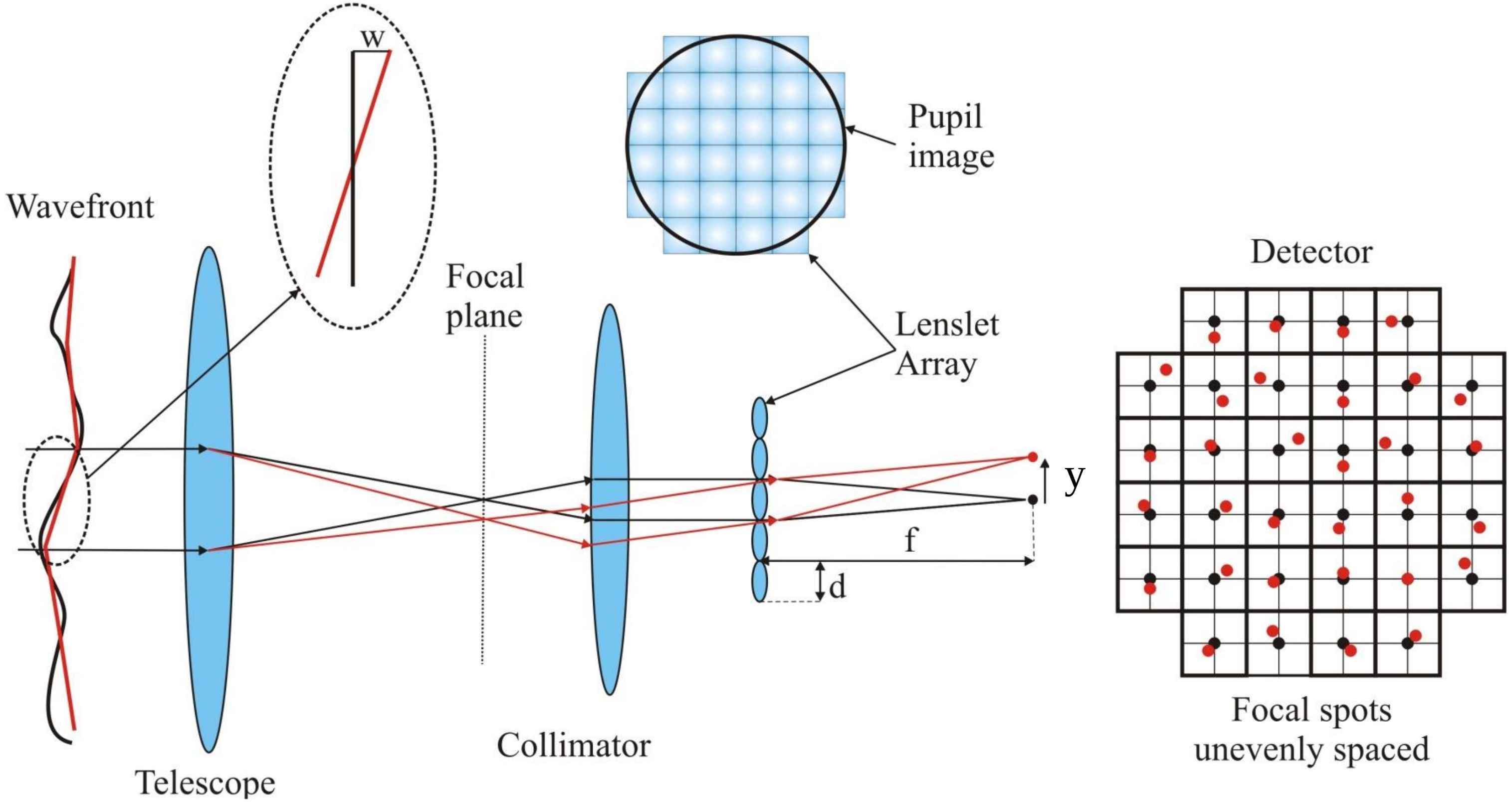
r_0 defines the diameter of a diffraction limited telescope

Adaptive optics concept





Wavefront Sensing

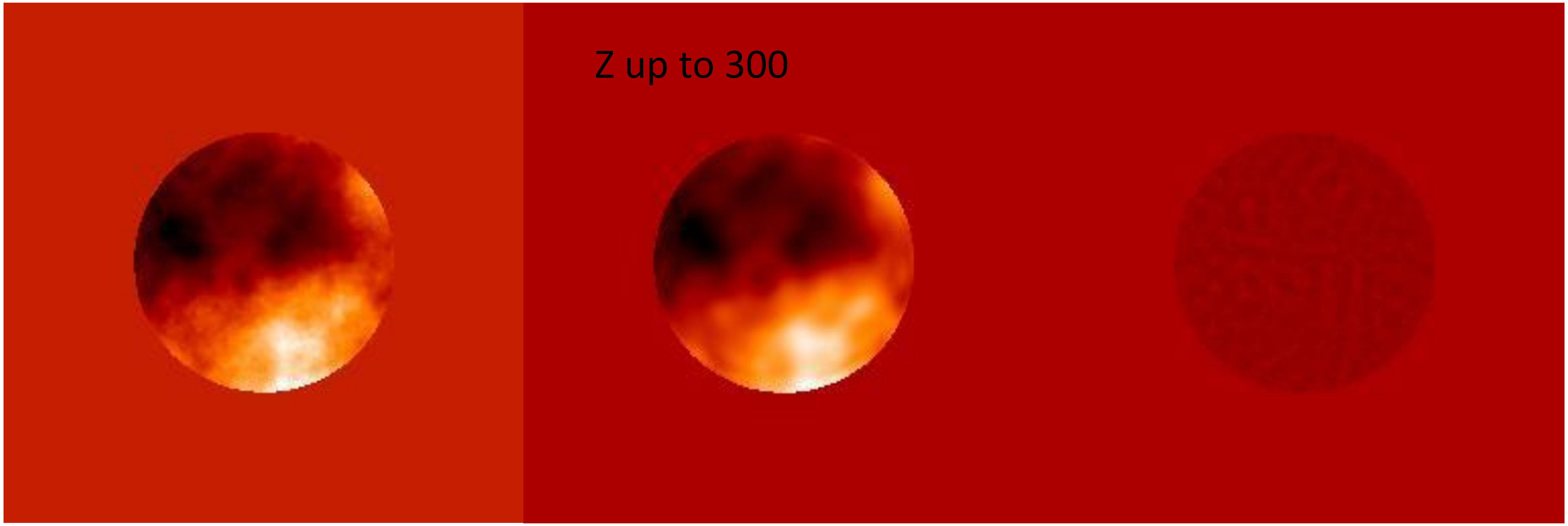


❑ Shack-Hartmann WFS (SH-WFS)

- array of lenses on a pupil image (num of sub-apertures $\propto (D/r_0)^2$, r_0 of the science observations)
- each lens re-images the source as seen by a small telescope having size r_0
- an incoming plane WF is focuses on the center of the sub-apertures
- an aberrated WF causes a spots displacement respect to the reference position prop to the local mean WF
- WF measurement performance depends on the centroiding accuracy (SNR of the spot)

Partial compensation

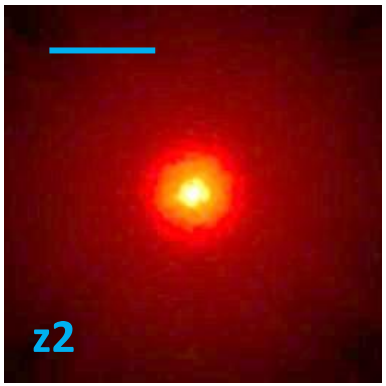
- Zernike modes to represent the aberrated wavefront $\phi = \sum_1^n a_j Z_j$
- Subtract the measured wavefront
- Compute the PSF
- Integration in time

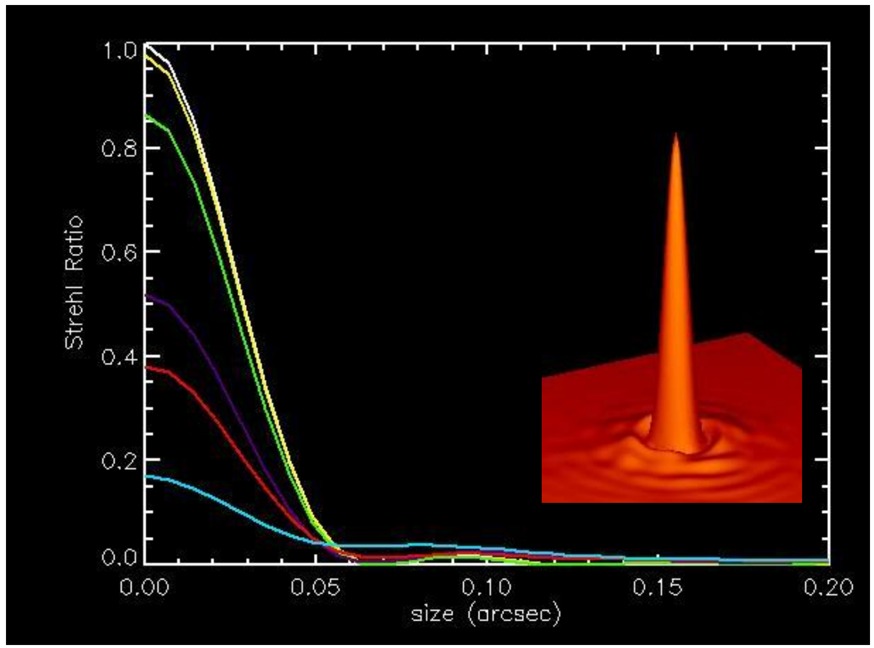


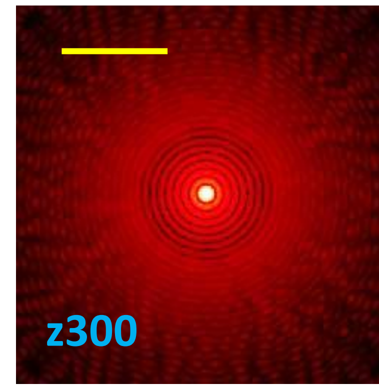
Incoming wavefront | Fit with zernike | Residual

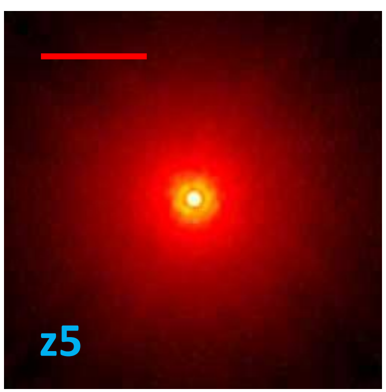
Partial compensation

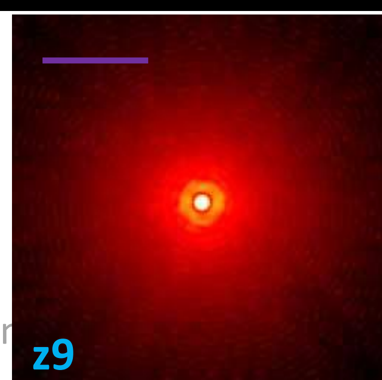
The fraction of light in the central core is related to the degree of correction and can be Roughly approximated with the Strehl Ratio

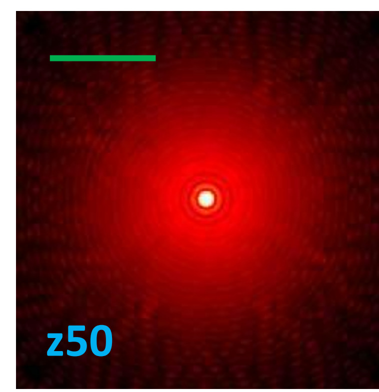




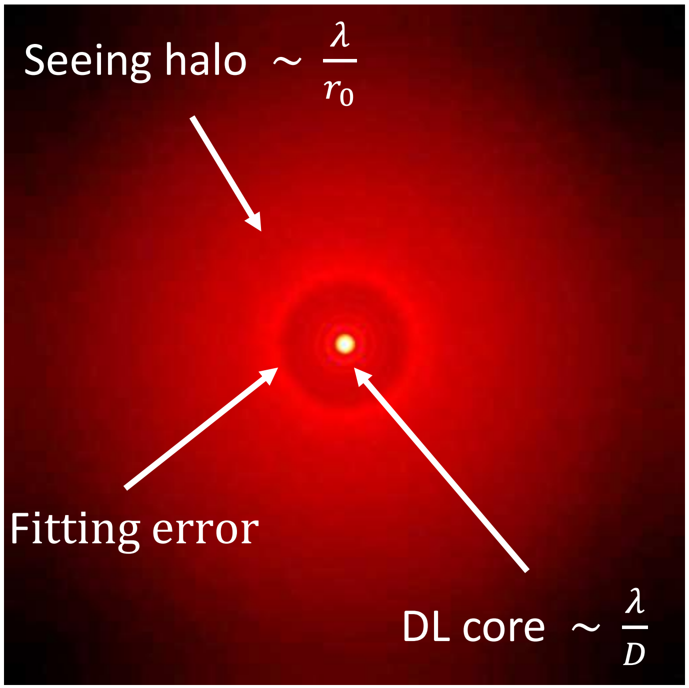


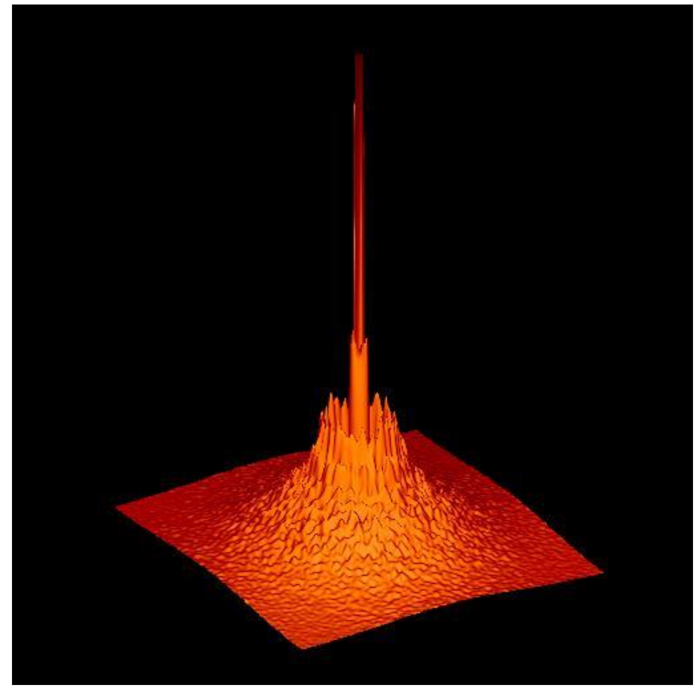


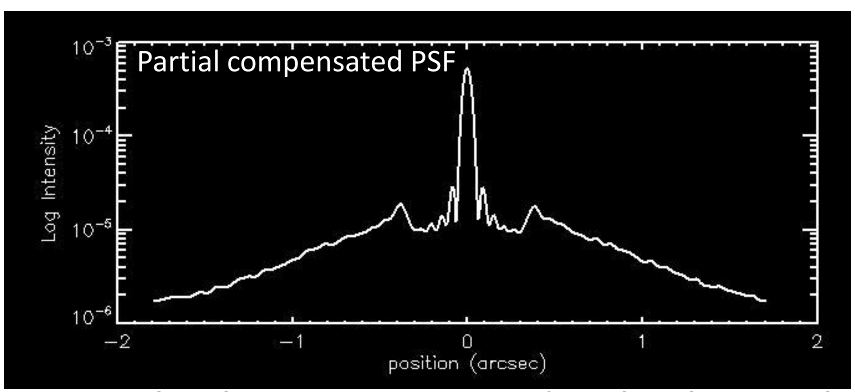


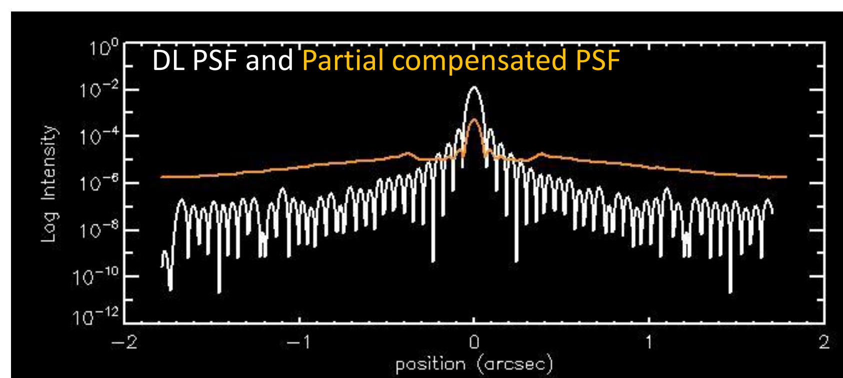


Partial compensated PSF



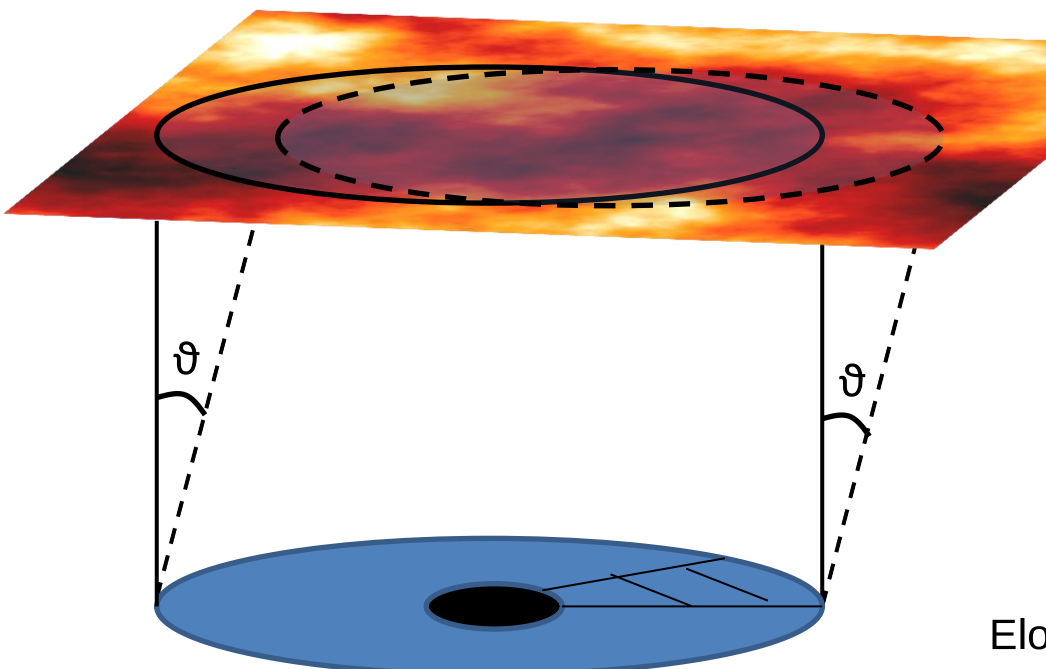


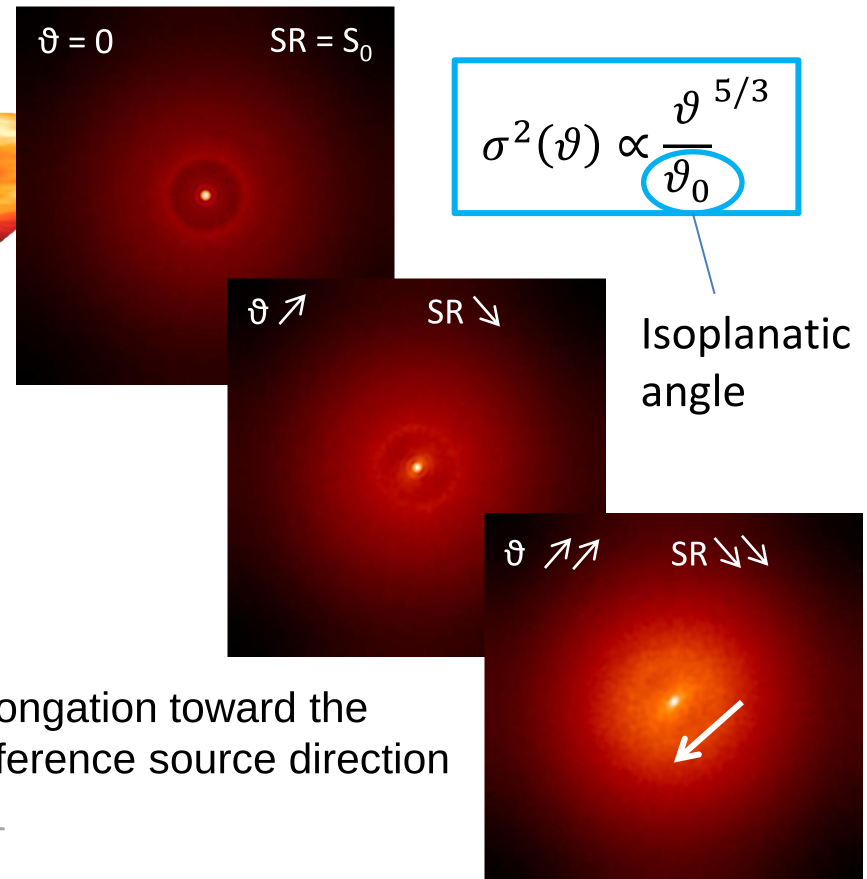




What happens across the FoV?

- The turbulence is measured only in the direction of the guide star, but the information is used to correct the wavefronts coming from all the directions within the FoV → This causes a degradation of the correction across the FoV. This error is called anisoplanatic error





$$\sigma^2(\vartheta) \propto \frac{\vartheta}{\vartheta_0}^{5/3}$$

Isoplanatic angle

Elongation toward the reference source direction

MEASUREMENT OF ISOPLANATISM

ISOPLANATISM ANISOTROPY:

An Intuitive Explanation

[McClure 1991]
[Sasiela & Shelton 1993]

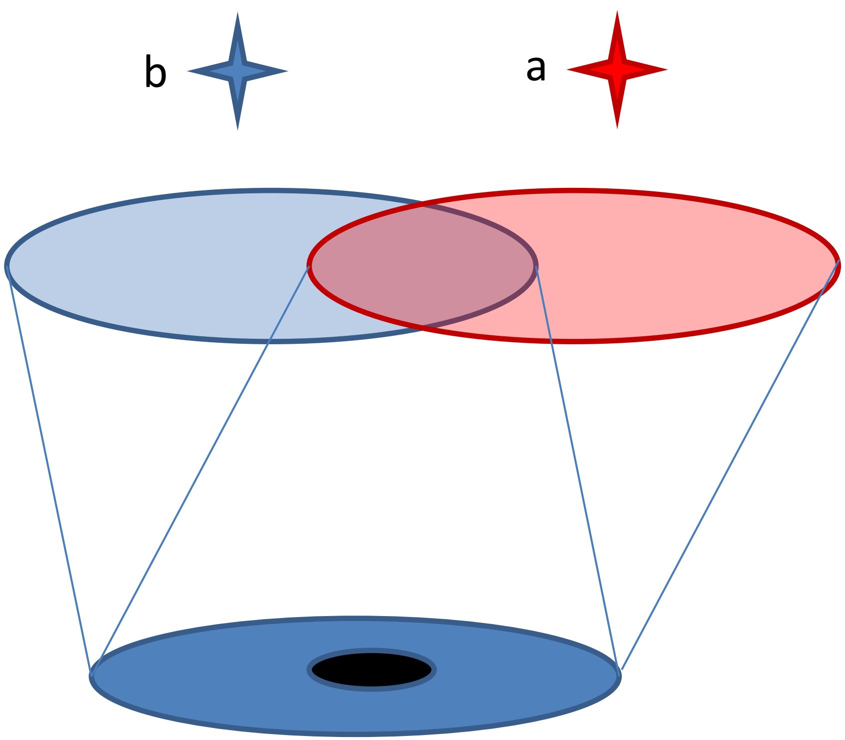
"Take an 'Oreo' cookie.

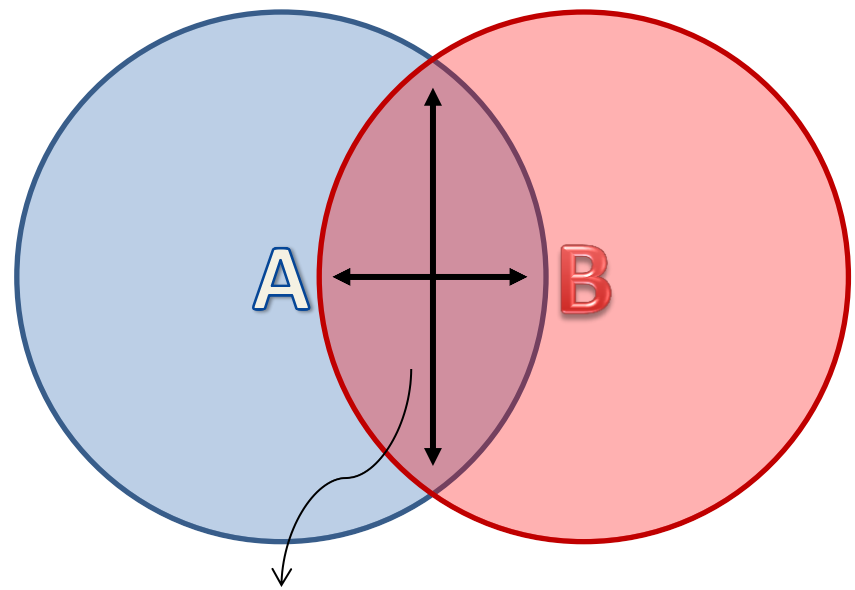
Take the wafers apart.

Stick them back together, but decentered a lot.

In which direction is it easiest to tip one wafer with respect to the other against the force of correlation exerted by the cream?"

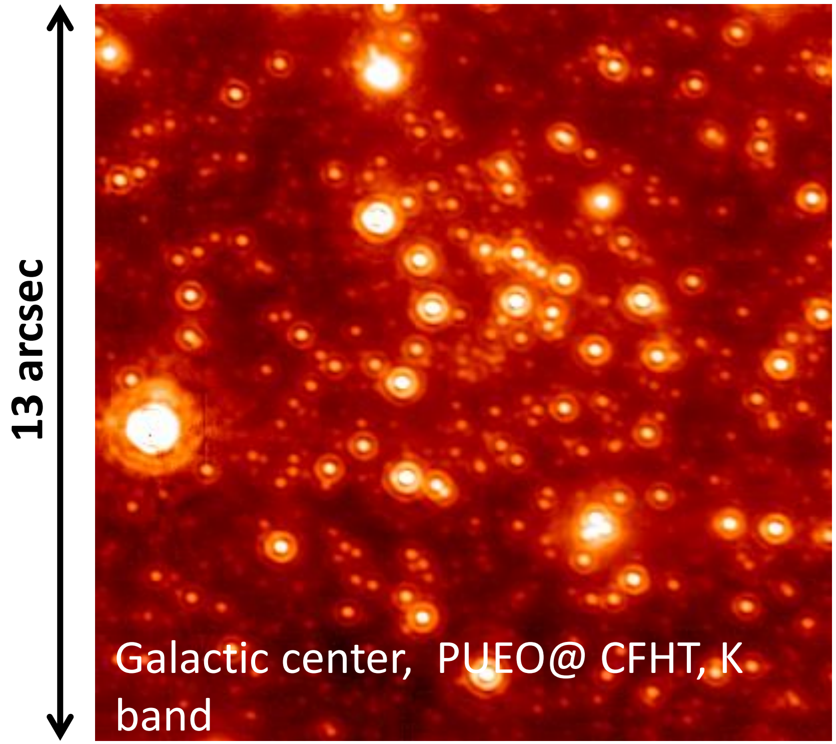
Anonymous



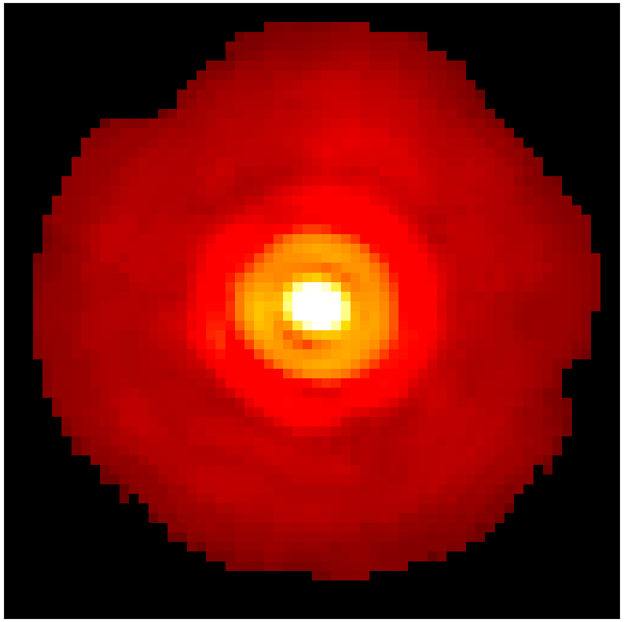


How do the data look like?

- **Single Conjugate AO** → Highly structured PSF, small FoV

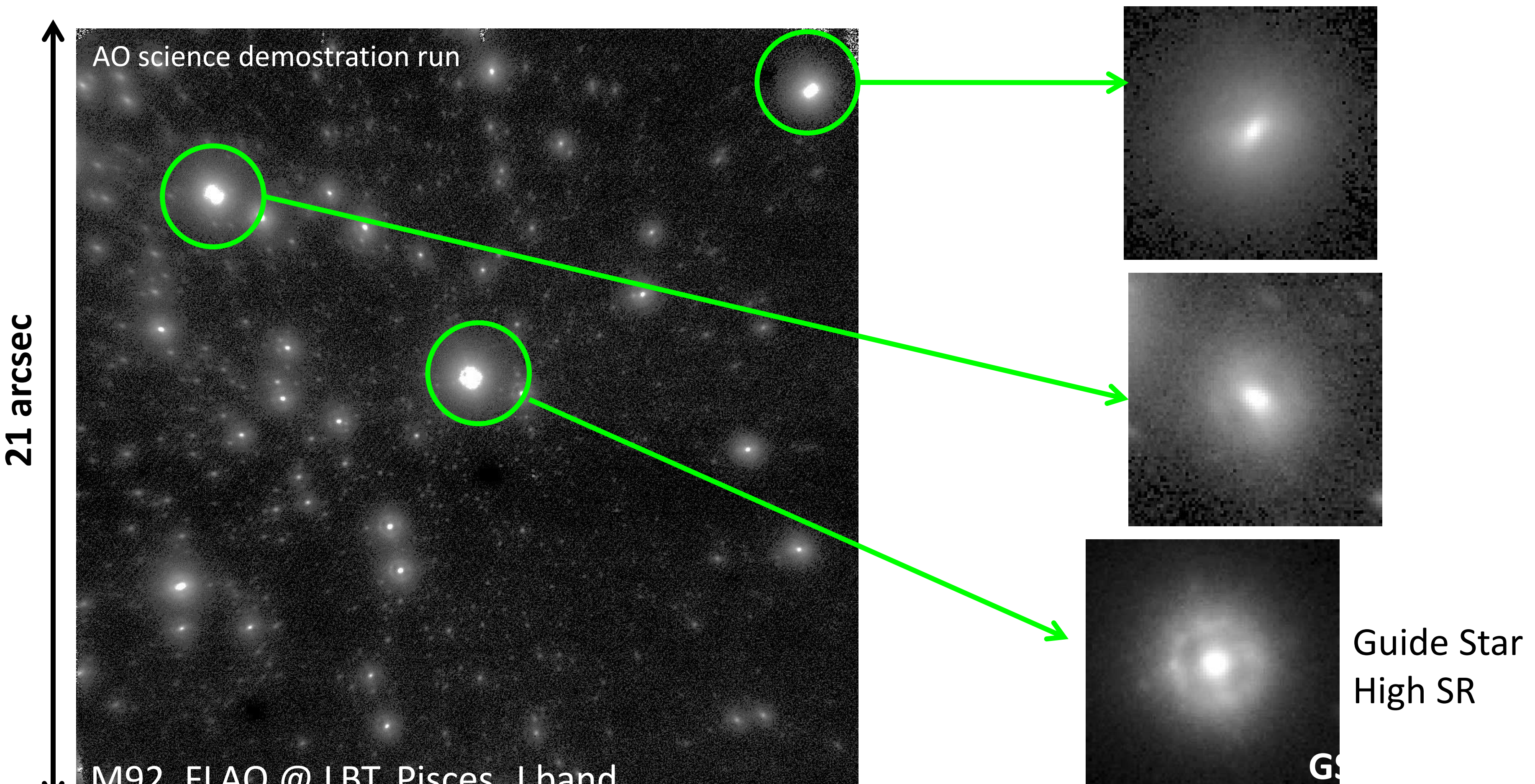


Courtesy of F. Rigaut



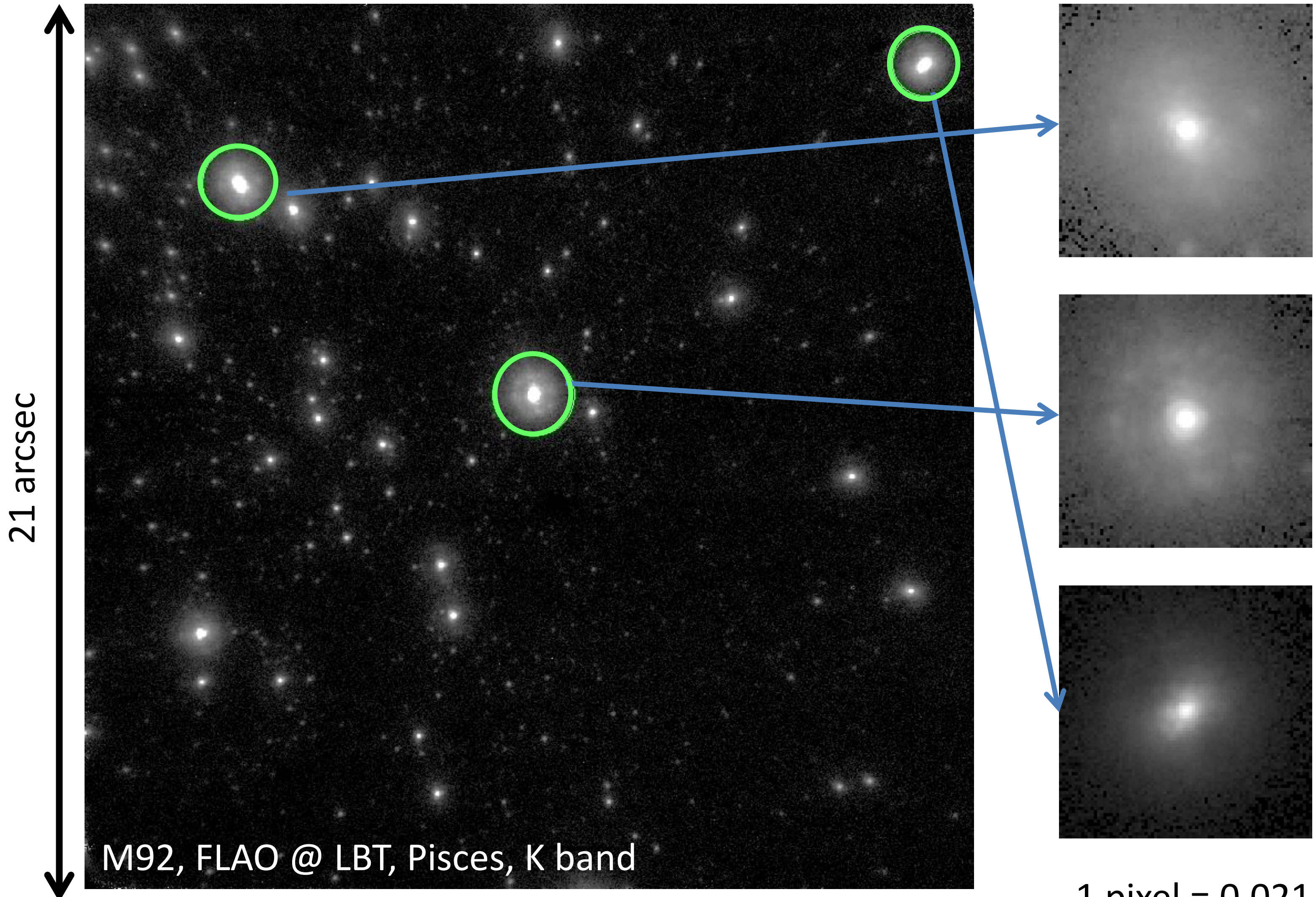
How do the data look like?

- **Single Conjugate AO** → Highly structured and variable PSF



1 pixel = 0.021 arcsec
Exposure Time = 6 s

How do the data look like?

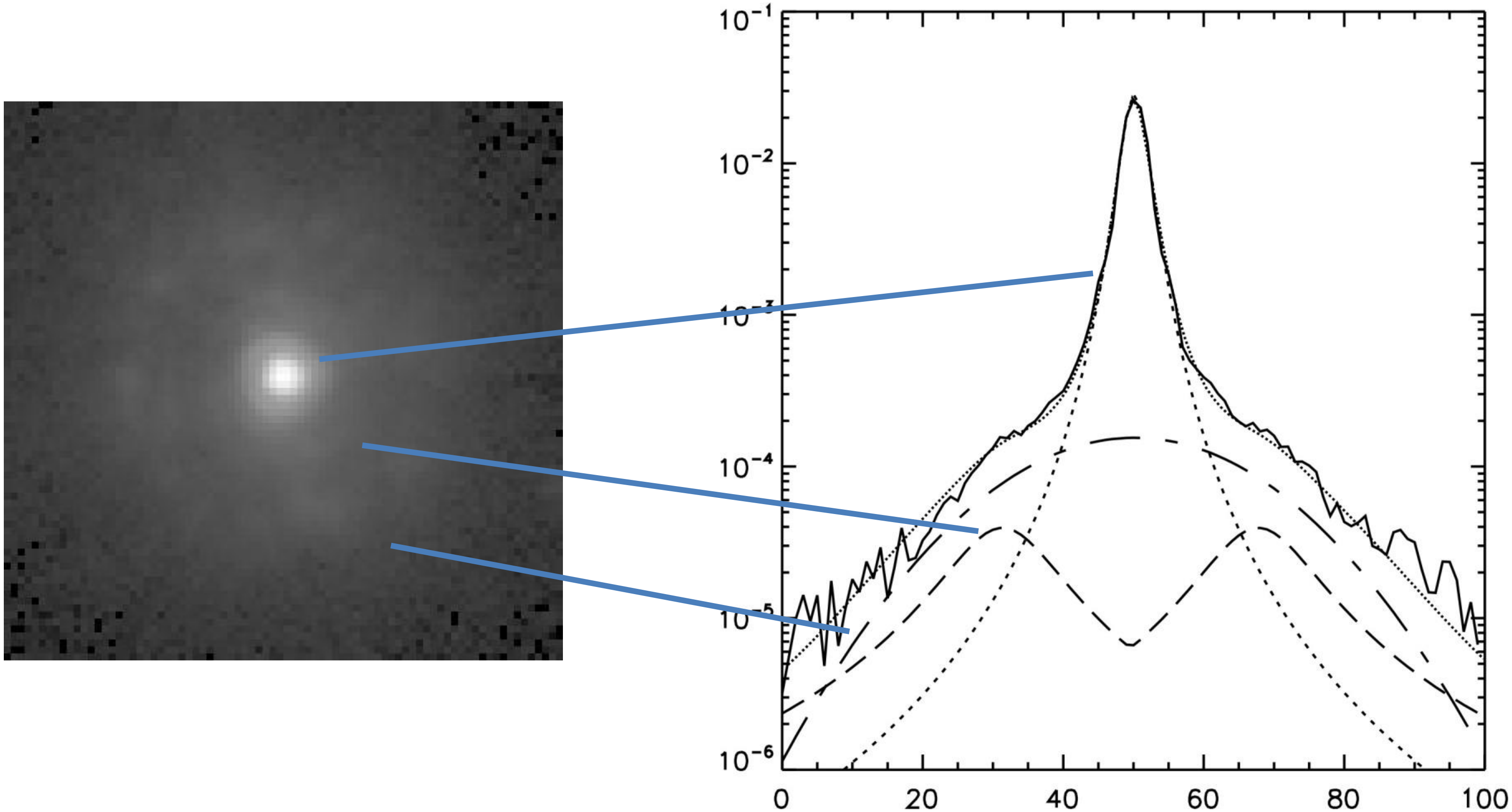


Guide Star
High SR

1 pixel = 0.021 arcsec
Exposure Time = 6 s

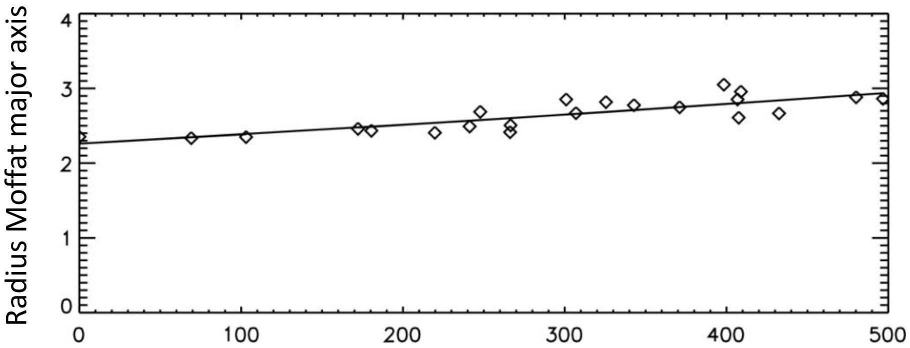
PISCES M92 PSF model

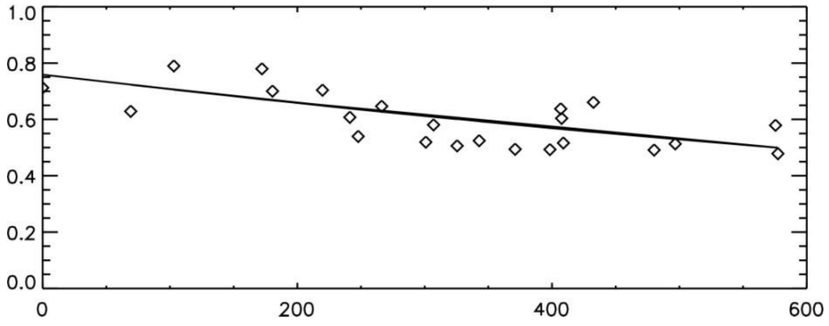
- The simplest analytical model that better represents the PSF is given by a narrow Moffat core, a broader Gaussian/Moffat halo and an external torus



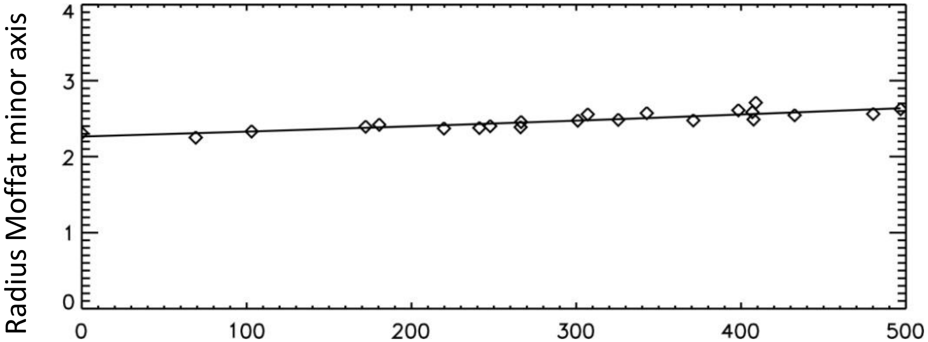
PSF model

- Variation of the PSF parameters across the FoV
  - Width of halo constant across the FoV
  - Width of core variable





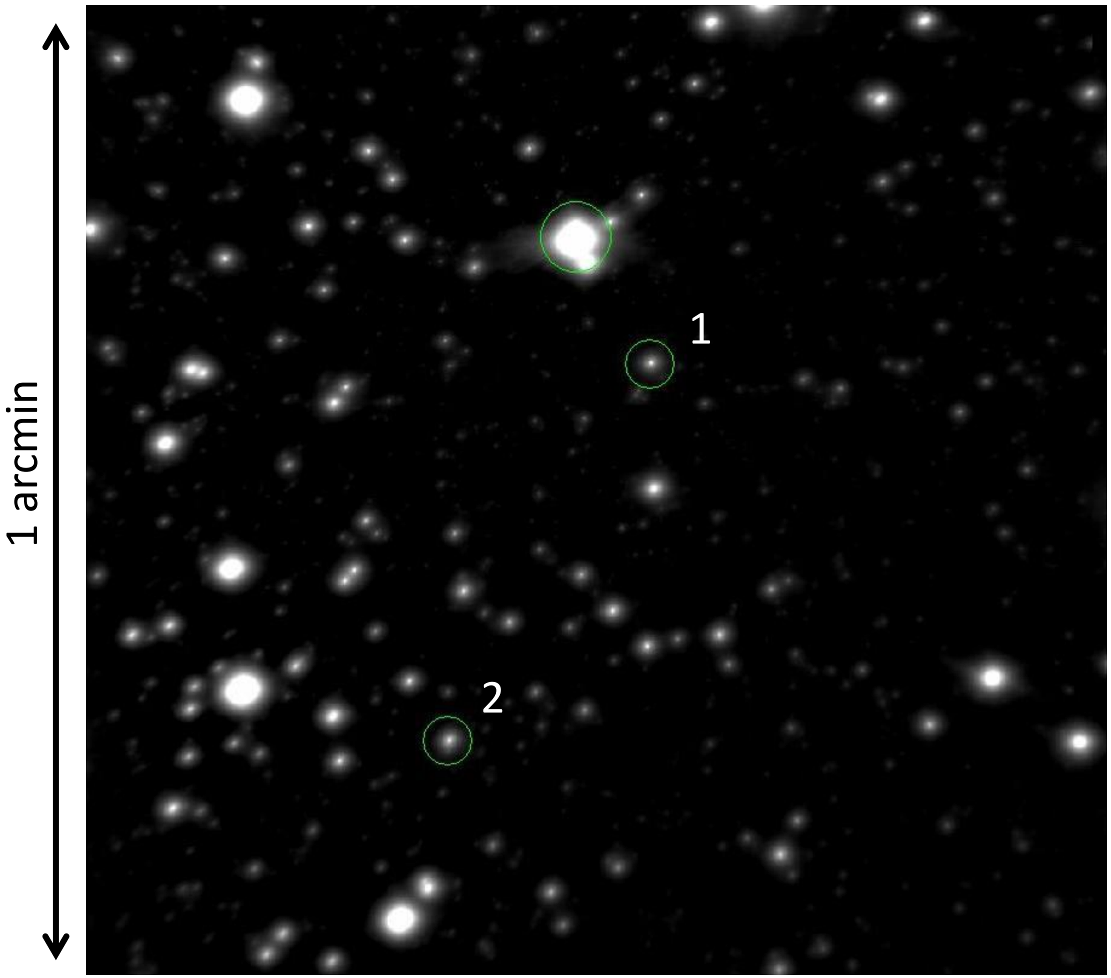
Flux in the core

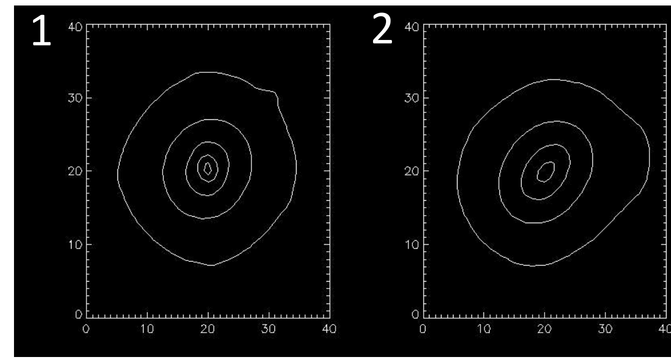


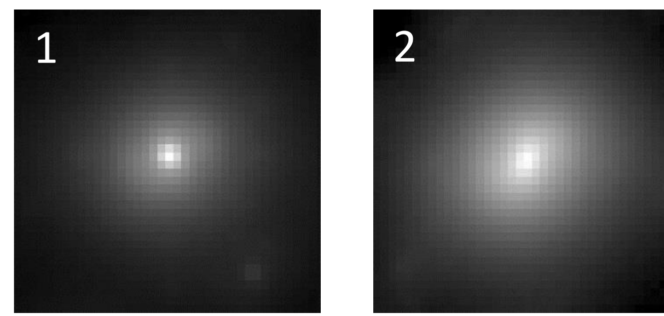
Distance form the GS (pixels)

Another example: NACO

- Image NACO@VLT of NGC 6440 GC *[Origlia 2008]*

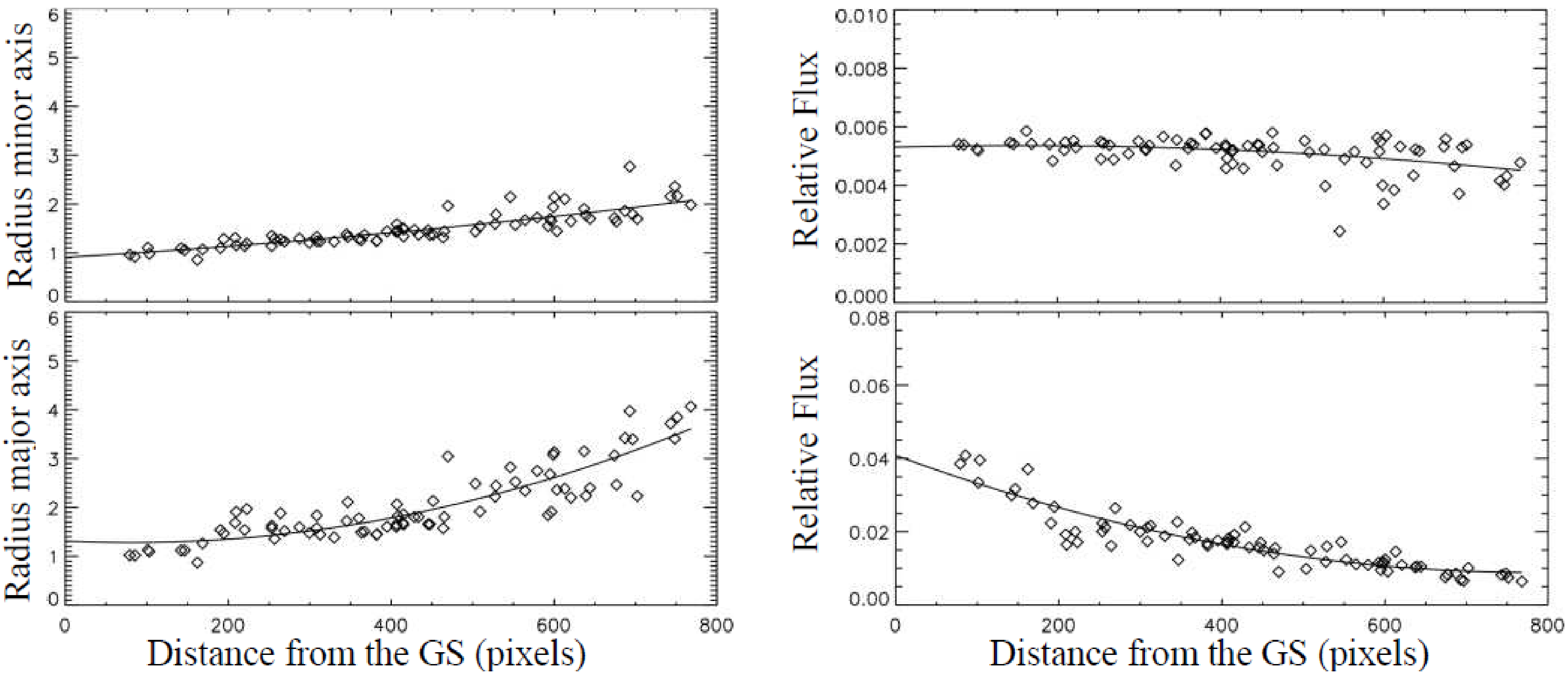






Another example: NACO

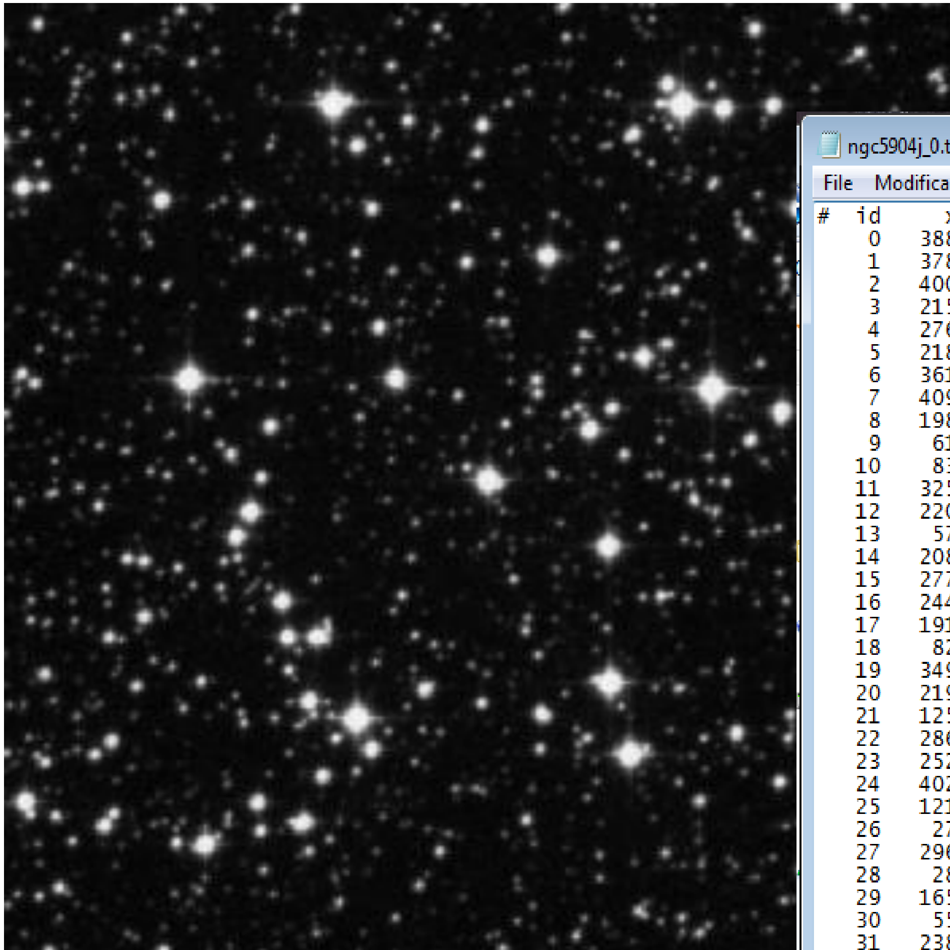
- Adopted PSF model:
  - PSF core: Elongated Moffat with axis varying over the FoV
  - Halo: round Moffat with radius = seeing constant over the FoV



Imaging techniques

- **Photometry:** *is the process of obtaining accurate numerical values for the brightness of objects (aperture phot./ PSF fitting).*
  - Time variability of individual sources
  - Flux ratios or luminosity functions of multiple systems [*Harayama et al. 2008*]
  - Color Magnitude Diagrams of resolved stars (GC age, stellar population, stellar evolution, SFH) […]
- **Astrometry:** *precise measurements of the relative positions of objects and their variations (parallax and proper motion)*
  - Dynamical masses of brown dwarfs [*Dupuy et al 2009*]
  - Our Galaxy's supermassive black hole [*Ghez et al 2005*]
  - Formation and evolution of young star clusters [Stolte et al 2008]
    …

Imaging techniques



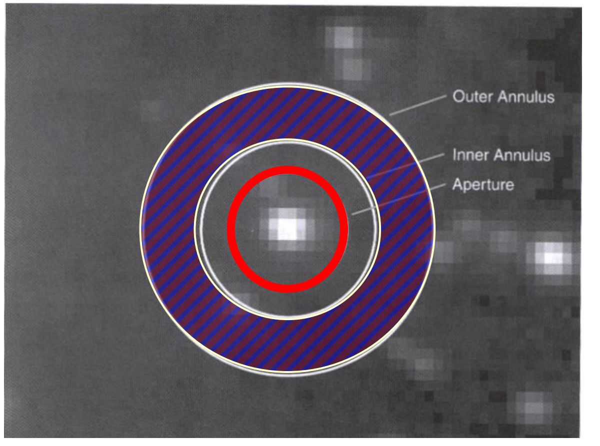
ngc5904j_0.txt - Blocco note

File Modifica Formato Visualizza ?

# id	x-pos	y-pos	counts	inst. magnitude	corr
0	3888.2576	2903.9890	7210705.5000	-17.1449	-1.000
1	3783.3491	1755.1215	5416843.0000	-16.8344	1.000
2	4006.8416	2275.8376	5256262.0000	-16.8017	1.000
3	2154.1626	4129.2842	5242022.0000	-16.7987	0.998
4	2761.9583	3107.9604	5102471.5000	-16.7695	0.922
5	2180.4338	2269.6968	5085190.0000	-16.7658	0.999
6	3611.6033	2525.5786	5031065.0000	-16.7542	0.996
7	4092.6113	147.9652	4424366.0000	-16.6146	0.941
8	1980.6786	72.0155	4282989.0000	-16.5794	0.996
9	610.6428	2789.5635	4273027.5000	-16.5768	1.000
10	833.9149	3484.8323	4171636.7500	-16.5508	-1.000
11	3252.2834	402.7260	4079414.0000	-16.5265	0.950
12	2201.8921	1732.3500	4066975.0000	-16.5232	1.000
13	573.6926	1803.9502	4049563.7500	-16.5185	1.000
14	2081.2419	3550.3442	3997382.0000	-16.5044	1.000
15	2779.1667	2692.4707	3885307.7500	-16.4736	0.977
16	2446.8521	3447.8284	3874751.7500	-16.4706	1.000
17	1911.8534	2954.7905	3872360.7500	-16.4699	1.000
18	826.6851	2600.0205	3861321.2500	-16.4668	0.985
19	3499.8584	2338.9248	3829810.0000	-16.4579	1.000
20	2190.3936	3657.5090	3820769.7500	-16.4554	1.000
21	1253.1691	1112.7214	3780391.2500	-16.4438	-1.000
22	2868.9526	1947.2902	3725255.7500	-16.4279	0.937
23	2529.8306	3139.6819	3690335.0000	-16.4177	0.995
24	4023.4260	1022.7120	3665485.5000	-16.4103	1.000
25	1212.0330	3857.9087	3606907.5000	-16.3928	1.000
26	279.9953	3701.1382	3602859.0000	-16.3916	0.921
27	2960.0457	2561.9578	3597791.0000	-16.3901	1.000
28	289.7184	3822.1609	3596791.7500	-16.3898	0.955
29	1653.6118	2400.1584	3593289.5000	-16.3887	0.944
30	553.0705	1300.6654	3579306.5000	-16.3845	-1.000
31	2389.9976	3083.1333	3579169.0000	-16.3845	0.965
32	3513.6548	2122.3220	3518720.7500	-16.3660	0.996
33	2282.4221	3120.0276	3501744.0000	-16.3607	-1.000
34	2012.5040	2167.2043	3490125.5000	-16.3571	0.983
35	682.2012	1823.5103	3436209.5000	-16.3402	0.917

Imaging techniques

- **Aperture Photometry**
  - Measurement of the image volume within an ‘appropriate’ aperture. The background is estimated in an annular outer region an subtracted.
  - The optimal aperture size depends on the PSF FWHM, on the S/N and on the crowding of the field
  - The star position can be computed as a simple center of gravity
  - Robust and precise for isolated stars
  - Risk of contamination between sources
  - *Sextractor [Bertin 1996], …*

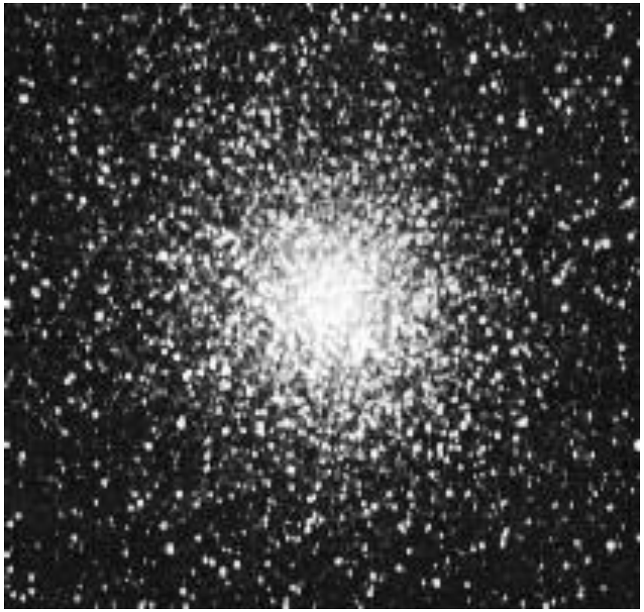


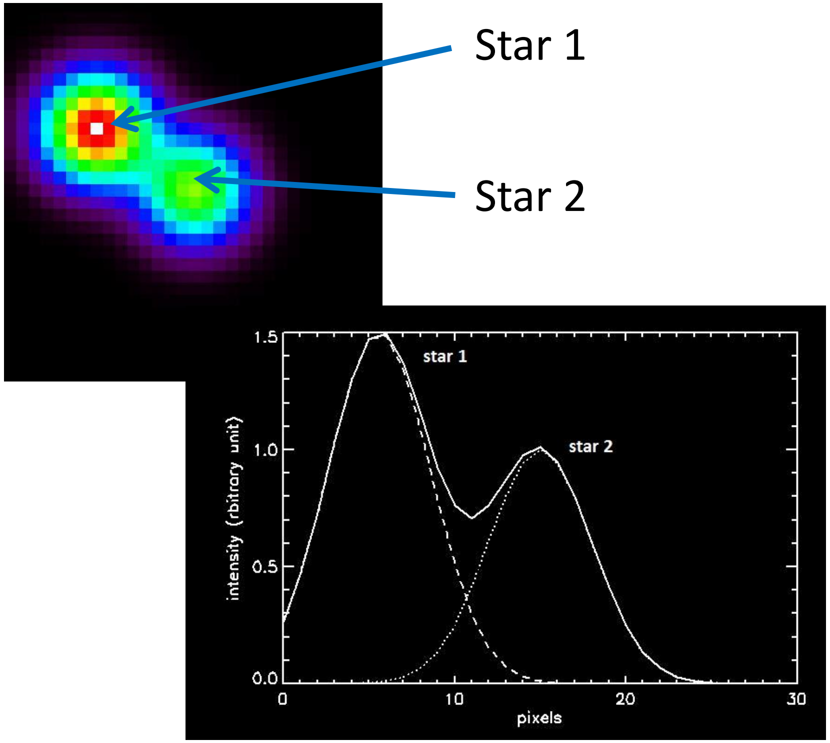
This method does not give us the possibility to take advantage from the resolution in crowded fields

It can be used in crowded fields after deconvolution for the PSF…

Imaging techniques

- **PSF fitting photometry**
  - Fit of the sources in the image with a PSF model
  - The result depends on the model accuracy and on the background estimation (in case of source contamination and/or PSF variability)
  - Suitable for dense stellar fields
  - Need for isolated and bright stars to model the PSF





PSF estimation

- **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)
  - Product of the Blind deconvolution

- **Implemented in image analysis softwares:**
  - **DAOPHOT** (analytical/hybrid/smoothly variable) *[Stetson 1987]*
  - **Romafot** (Purely analytic) *[Buonanno 1983]*
  - DoPHOT (Analytical) *[Schecter 1993]*
  - **PSFex** (analytical, linear combination of basis vectors) *[Bertin 2010]*
  - **STARFINDER** (numerical/analytical/hybrid, possible hacking) *[Diolaiti 2000]*
  - Dolphot (HSTPhot) *[Dolphine 2000]*, …

SCAO data reduction

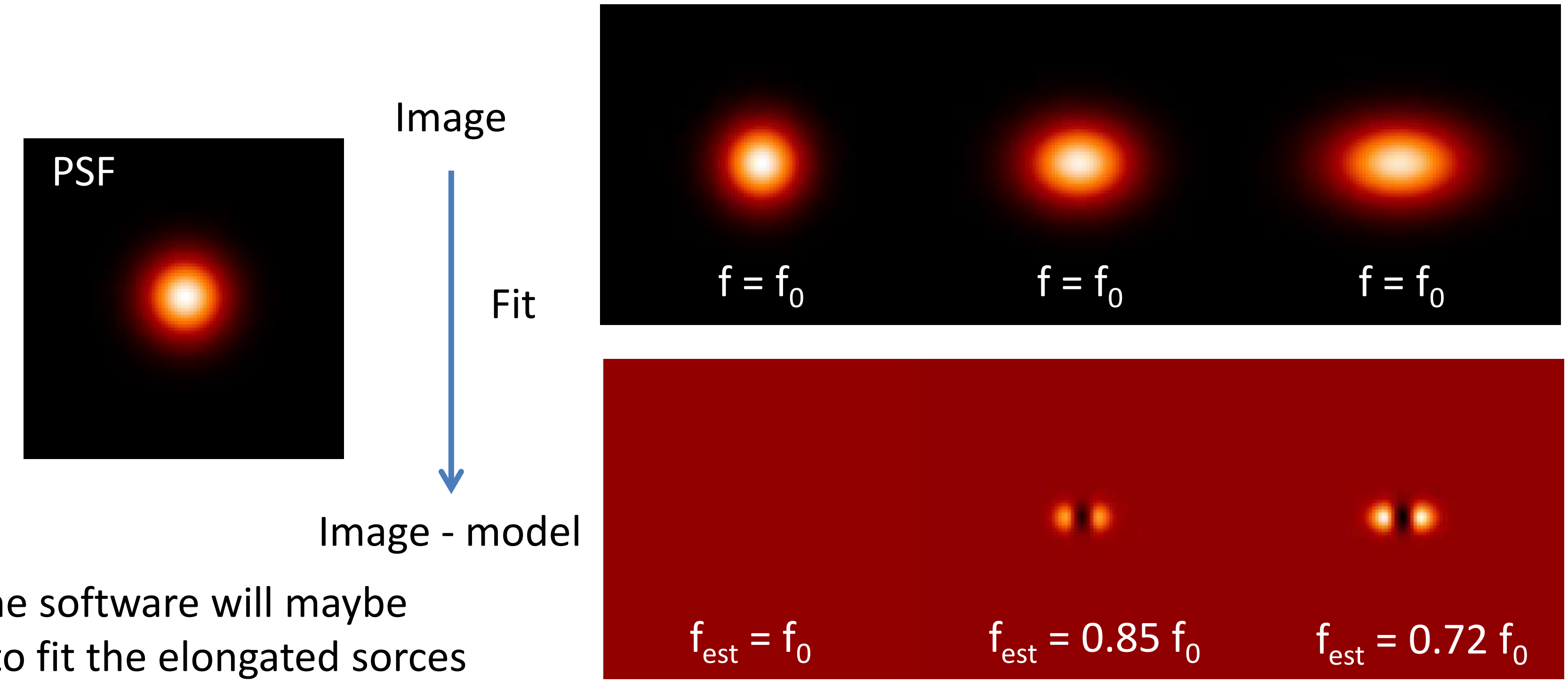
- **SCAO →** small corrected FoV, PSF spatial variation, high SR
  - Crowded-field AO **astrometry** appears to be limited by the inaccurate modeling of the Point Spread Function (PSF) *[Shoedel 2010]*
  - **astrometry** of faint sources is biased by residuals due to the incorrect subtraction of the PSF of brighter stars *[Fritz 2009]*
  - **photometric accuracy** is limited by the SNR and by the knowledge of the PSF *[Shoedel 2010]*
  - **detection** of elongated sources
  - **False detections**

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

  - Many 'exotic' solutions have been found to reduce data…

PSF fitting with constant PSF

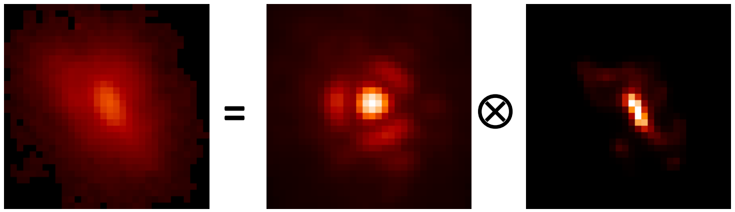
- When the PSF is invariant across the FoV, the photometric error is due mainly to SNR
- If the PSF elongation is field dependent, fitting the stars with a constant PSF causes the introduction of another (unknown) error source that is field dependent



… the software will maybe try to fit the elongated sorces with multiple stars

SCAO data reduction

- **SCAO →** small corrected FoV, PSF spatial variation, high SR
  - **Galactic center (NACO):** Image is first Wiener-filter-deconvolved using a suitable PSF (GS psf) . Local variations in PSF kernels and ringing is taken care with locally extracted PSF fitting. *[Schoedel 2010]*
  - **M15 GC (FLAO):** Modiefied Romafot software. PSFfitting with variable moffat (no parameters fixed). *[Monelli 2015]*
  - **NGC6440 GC (NACO):** PSFfitting with starfinder using an analitical model composed by 3 gaussian components. *[Origlia 2008]*
  - Usage of **calibration images** *[Steinbring et al. (2002)]*
  - Usage of **calibration HST fields**
  - **Galaxy Survey (NACO):** Estimate local PSF around guide star image and model the PSF in the field as the convolution of the GS PSF and a blurring kernel. *[Diolaiti 2000, Cresci 2006]*



off-axis PSF — guide star — blurring kernel (e.g. Gaussian)

Multi-reference Adaptive Optics

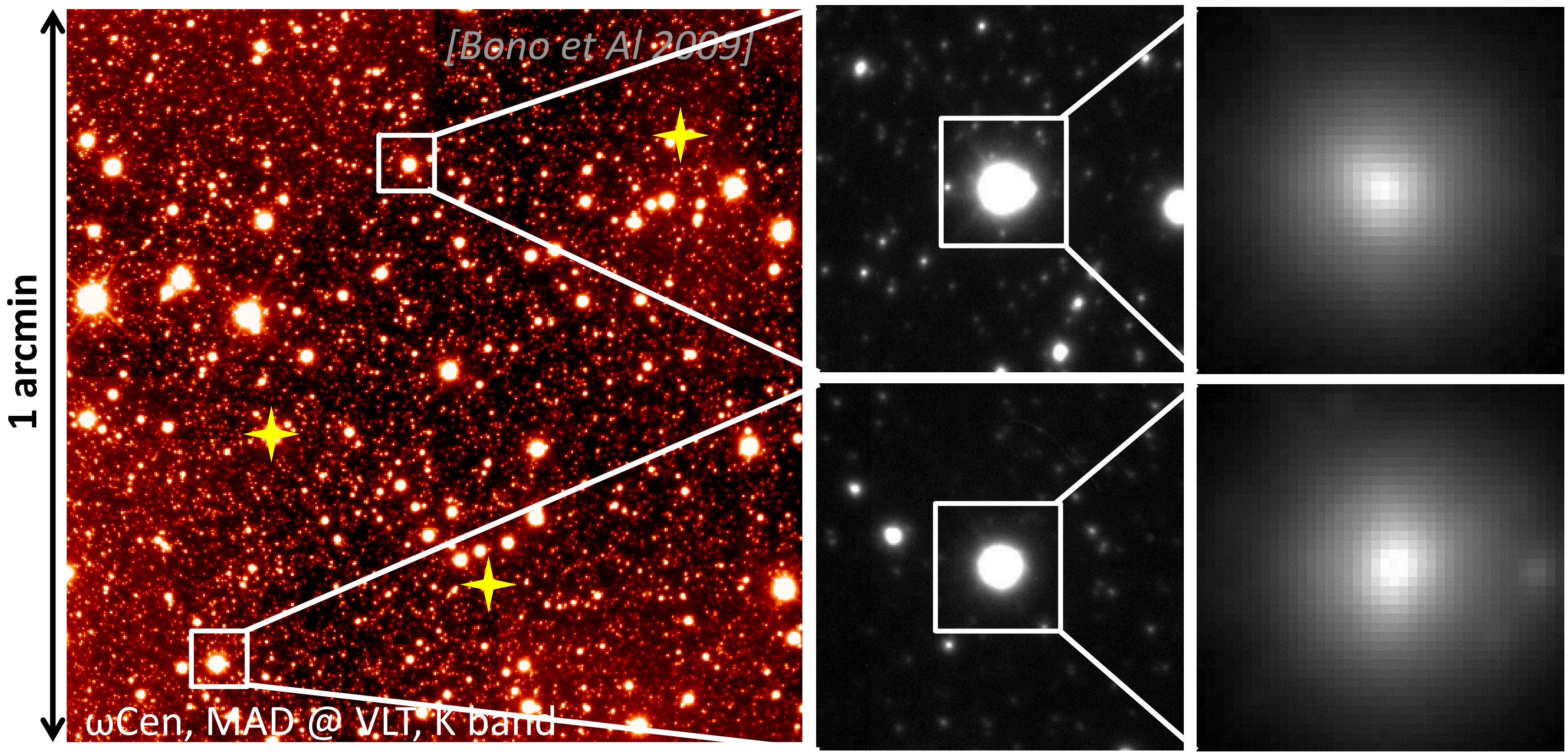
- Using **more reference stars** from different directions to analyze the wavefront, one can reduce the PSF variation across the FoV.

GLAO: Ground Layer Adaptive Optics
Using multiple reference sources it is possible to retrive the average contribution of the atmospheric tubulence within the guide stars directions → low SR, big FoV (some arcmin)

MCAO: Multi-Conjugate Adaptive Optics
Using multiple reference sources AND multiple deformable mirrors conjugated ad different altitudes, it is possible to measure the turbulent wavefronts at specific altitudes and to apply the correction directly where they are generated→ medium SR, medium FoV (~1 arcmin)

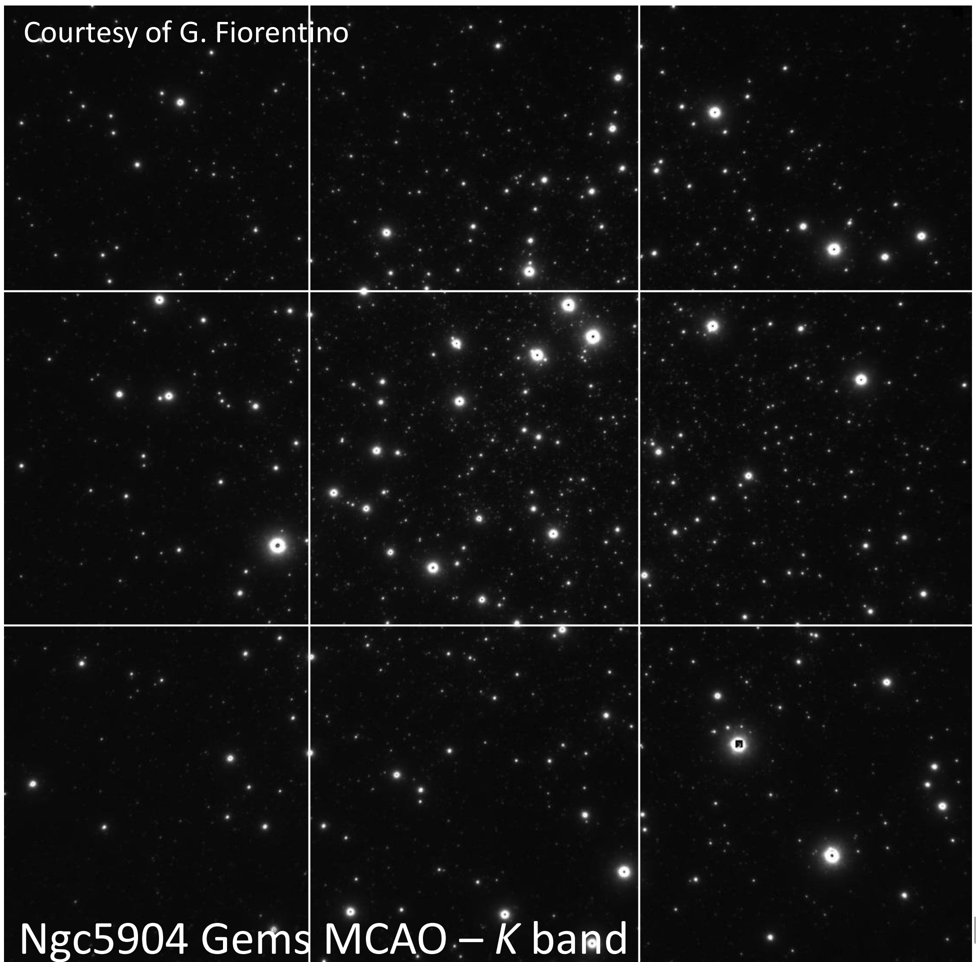
How do the AO data look like?

- **Multi Conjugate AO** → Improved PSF uniformity across a larger FoV



How do the AO data look like?

- **Multi Conjugate AO** → Improved PSF uniformity across a larger FoV



FoV = 2 arcmin

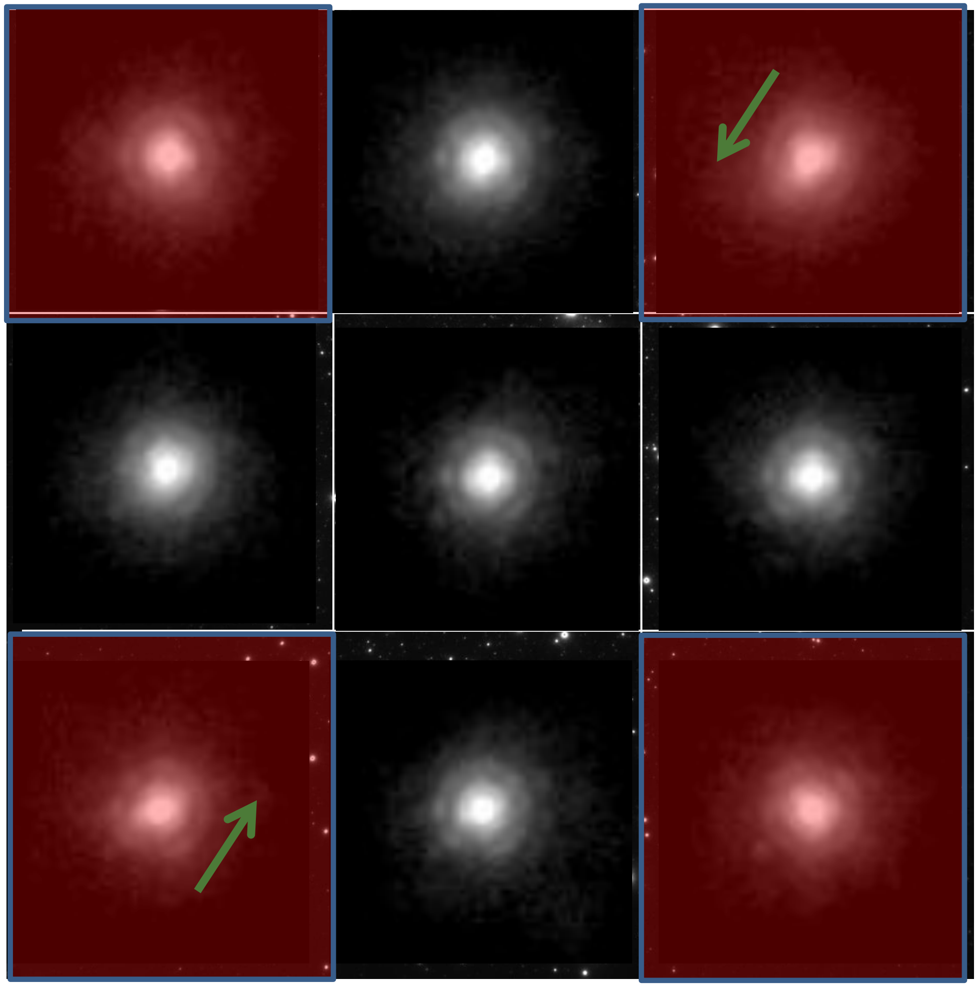
We extract numerically the psf from differen subregions of the field to analyze its variation

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

LT

How do the AO data look like?

- K – band image

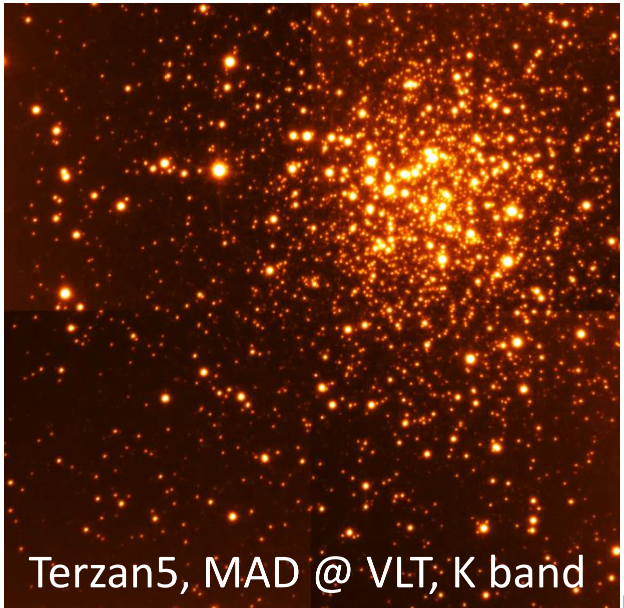


Local extracted PSFs

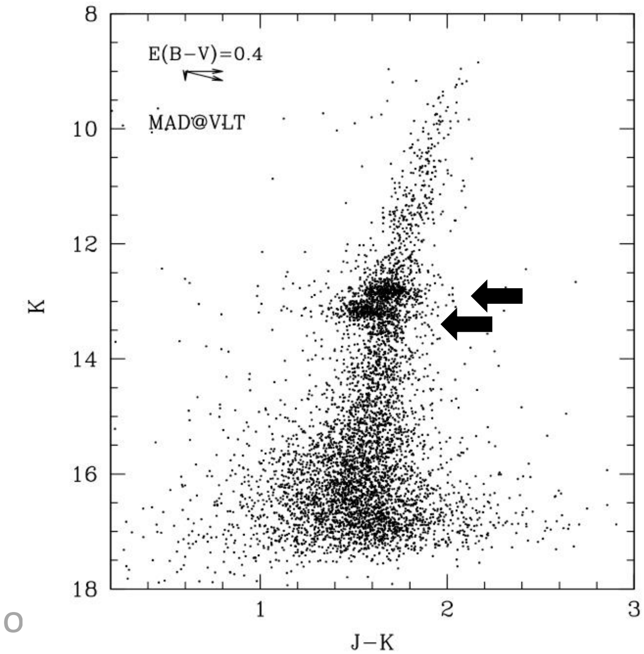
→ Small variation occurs: slightly elongated at the field corners

MCAO data reduction

- **MCAO →** To improve the PSF uniformity across the FoV
  - Suitable to study dense stellar field, galaxy morphology
  - MAD: **Many papers** have been pubblished *[Melnick SPIE 2012 for a review]*
  - GeMs: First papers are coming out
  - **Most diffused software for image analysis, not optimized for PSF variation across the FoV, has been used**



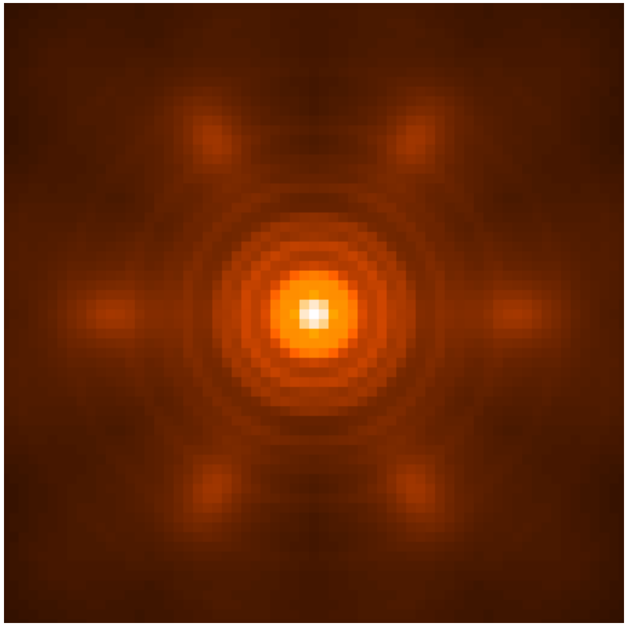
Terzan5, MAD @ VLT, K band

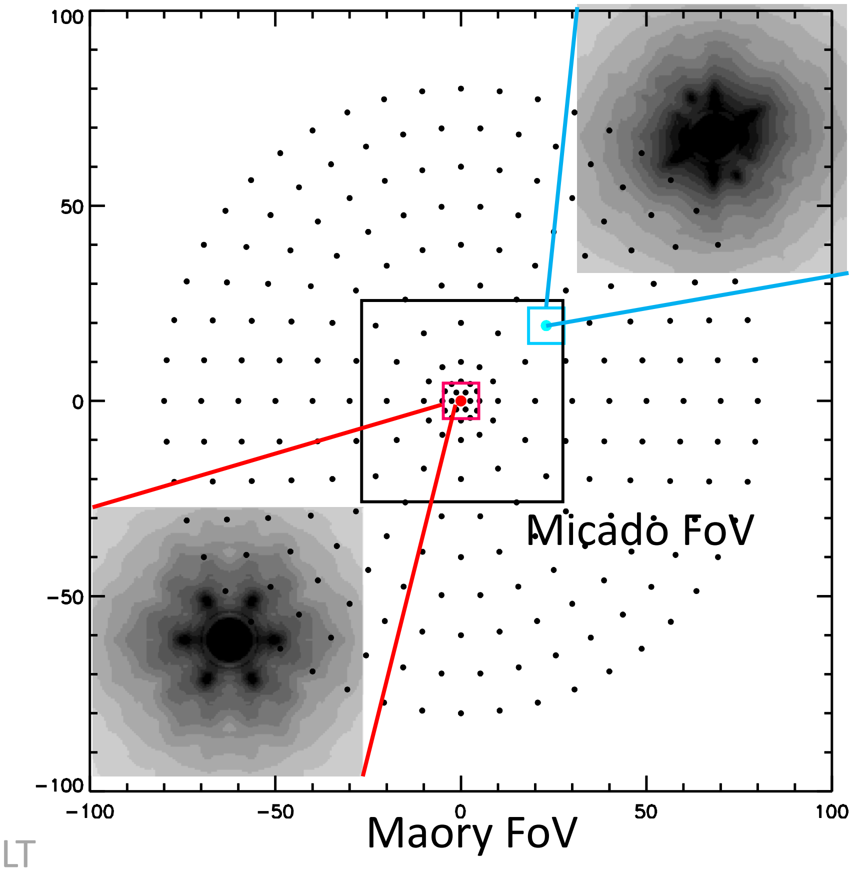


The presence of two red clumps implies the presens of two different stellar populations. *[Ferraro et Al, Nature, 2009]*

MAORY phase A PSF

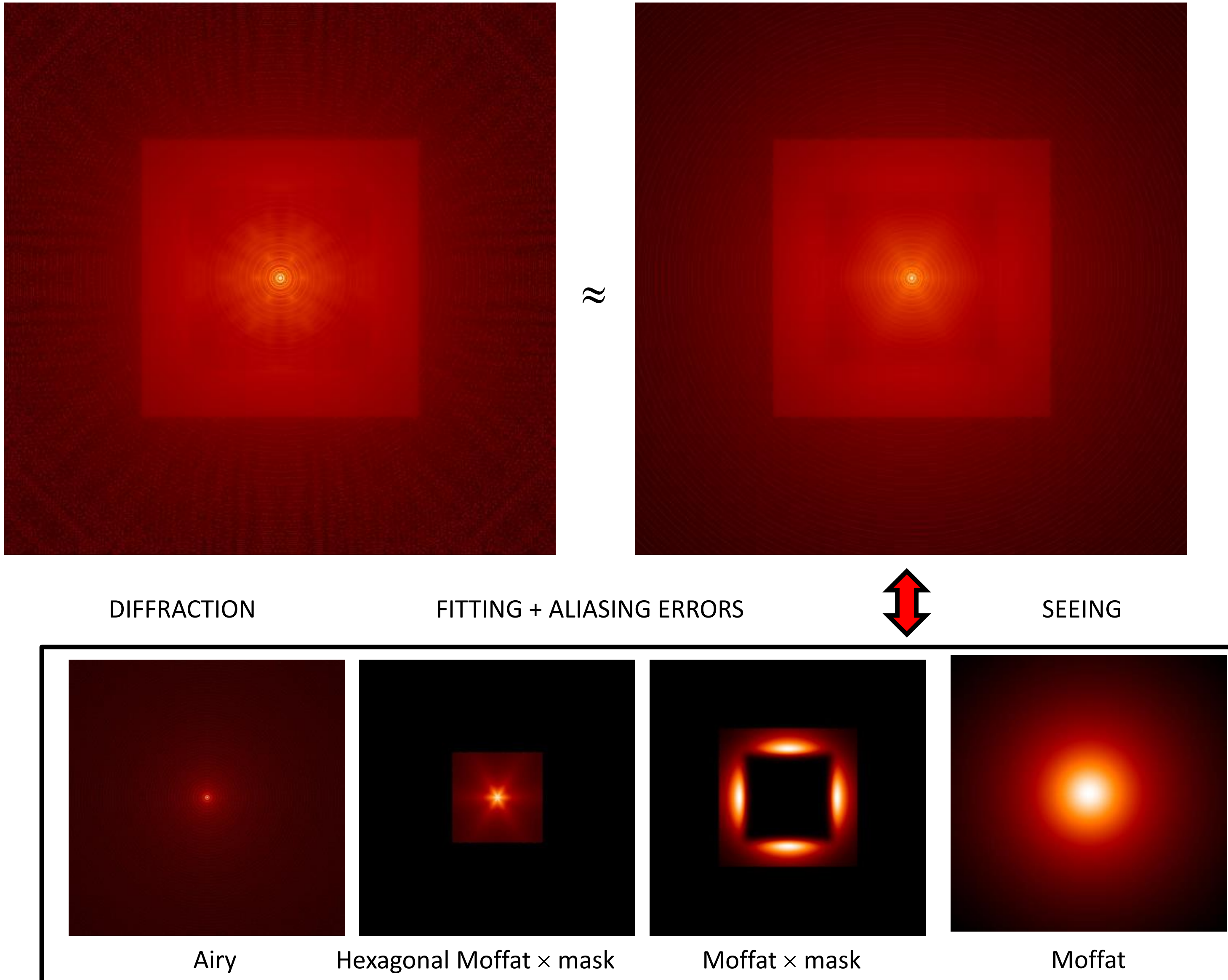
- Multi conjugate Adaptive Optics RelaY for the E-ELT
- Wavefront sensing based on 6 Sodium LGS and 3 NGS
- Uniform AO correction on a large FoV (2')





MAORY phase A PSF

K band PSF
SR ≈ 0.6
Image size = 2.7"



Conclusions

- If you want to gain in spatial resolution you need a big telescope
- If you want a big telescope, you have to stay on the ground
- If you want a big telescope on the ground and gain really in resolution, you need adaptive optics
- If you want to take full advantage of the scientific information encoded in AO images, you need to manage the data in the proper way
- If you want to manage data in the proper way, you need to know the PSF structure
- If you want to know the PSF structure, you need a flouring on Adaptive Optics techniques