# Imaging and treatment of the PSF in AO instruments

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(1- PHASE: OdP and ONERA, 2- ESO)

# AO: a young but mature technique

- The first AO system for astronomers: ADONIS
  - Open to community in 1993: less than 15 years ago !
  - Already at ESO (La Silla 3.6m) !

- AO on a great number of (large) telescopes

# AO: an evolving technique

- Numerous new AO concepts, driving technological breakthrough
  - MCAO
  - LTAO
  - XAO
  - MOAO
  - Adaptive secondary
  - AO for the eye
- No new telescope without AO➔ELT

# AO & calibration

- PSF !
  - Estimation of the image quality/AO correction
    - Strehl ratio
    - FWHM
  - Input for post-processing software
    - Astrometry-photometry
    - Deconvolution

# AO PSF shape

QuickTimeª et un
dcompresseur Cinepak
sont requis pour visionner cette image.

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dcompresseur Cinepak
sont requis pour visionner cette image.

# AO PSF shape

AO-corrected short exposure

AO-corrected long exposure

$$PSF(\vec{r}) = I_{coh}(\vec{r}) + I_{halo}(\vec{r})$$

# AO PSF

- Variable
  - In time
  - In the field

- Constraining factors
  - Reference source brightness
  - Reference source shape
  - Atmospheric conditions (seeing, coherence time, wind speed)
  - Airmass
  - Distance science object - reference source
  - AO system calibrations
  - AO system direct environment

# PSF characteristics

- Strehl ratio
  - $$SR = \frac{PSF(0)}{Airy(0)}$$
  - Good estimator of the AO correction quality
  - Sometimes approximated to the coherent energy

$$Ec = exp(-\sigma^2_{res}) = \frac{I_{coh}(0)}{Airy(0)}$$

    - Cf. NACO fits file header
    - Approximation ok if Ec≈1 i.e. if SR>30%
    - SR>Ec

# PSF characteristics

- Full Width at Half Maximum FWHM
  - Estimation of the spatial resolution
  - Related to the tip/tilt residual errors

- 50% energy radius r50
  - Within which radius is concentrated 50% of the energy
  - Relevant for spectroscopy

# What is my Strehl ?

- A precise computation from a scientific image is difficult ! Even for a single isolated star !
- Result highly dependant on an accurate background subtraction
  - Positive residual background: SR underestimated
  - Correction of background spatial variation
  - Windowing the image but part of the halo can be lost (SR overestimated)

# What is my Strehl ?

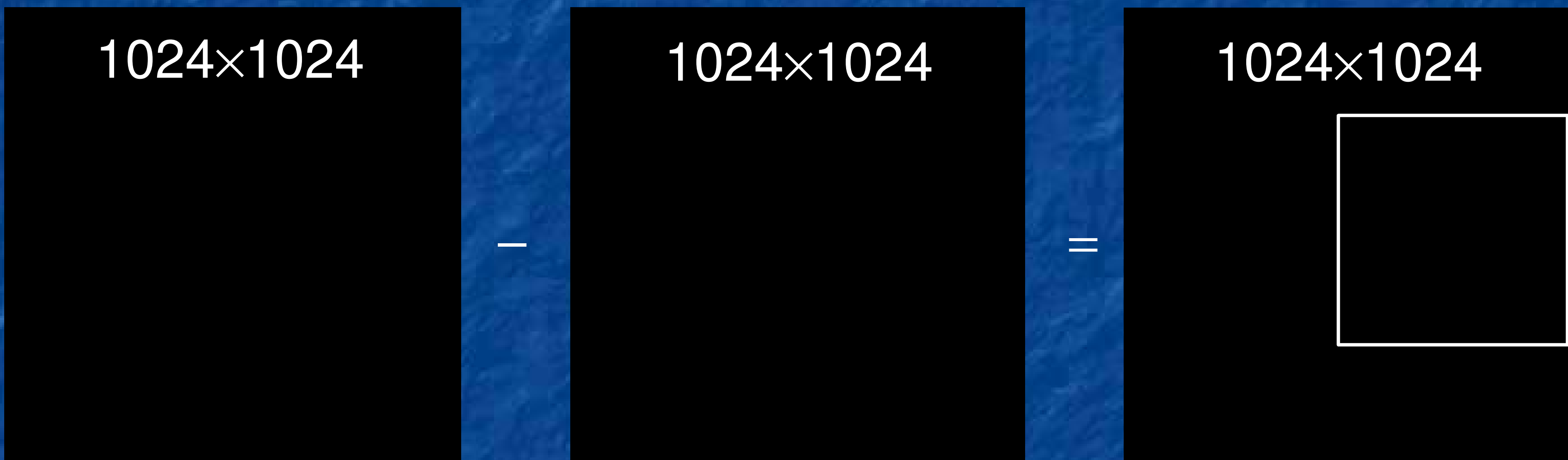
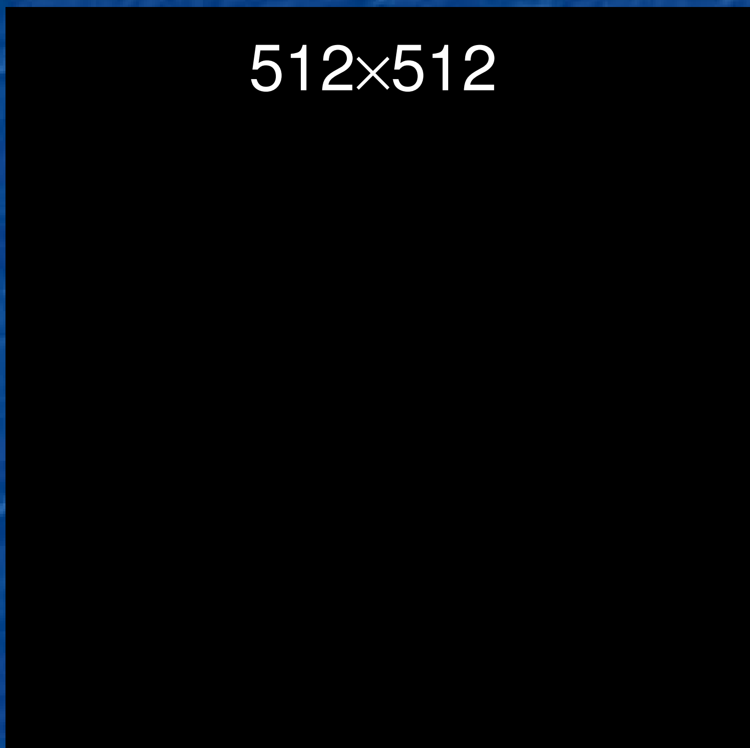



image − sky = $\frac{\text{image-sky}}{\text{flat}}$

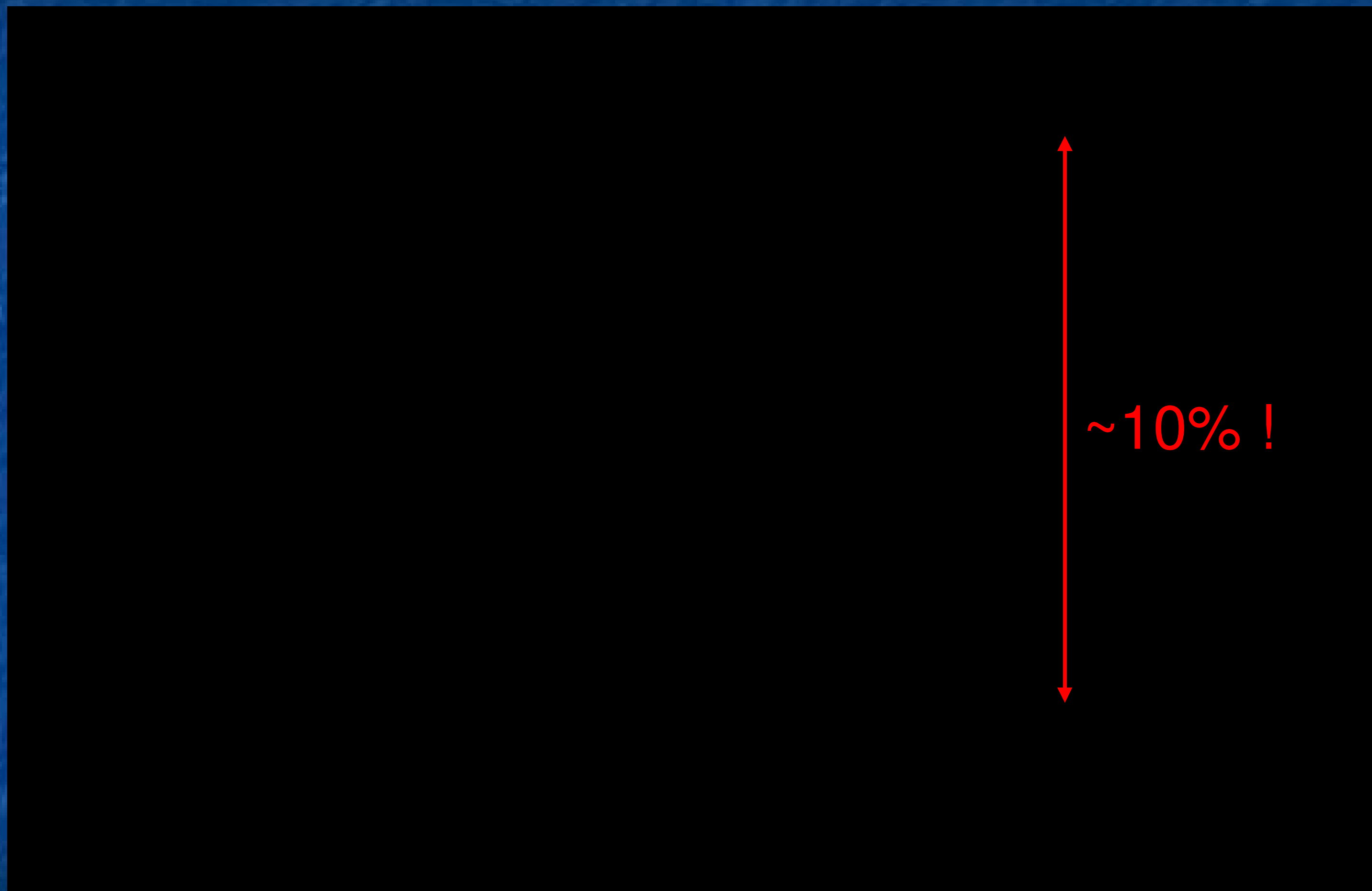
# What is my Strehl ?




- Non-zero background

⇨ Subtraction of the median as a first-order background estimation

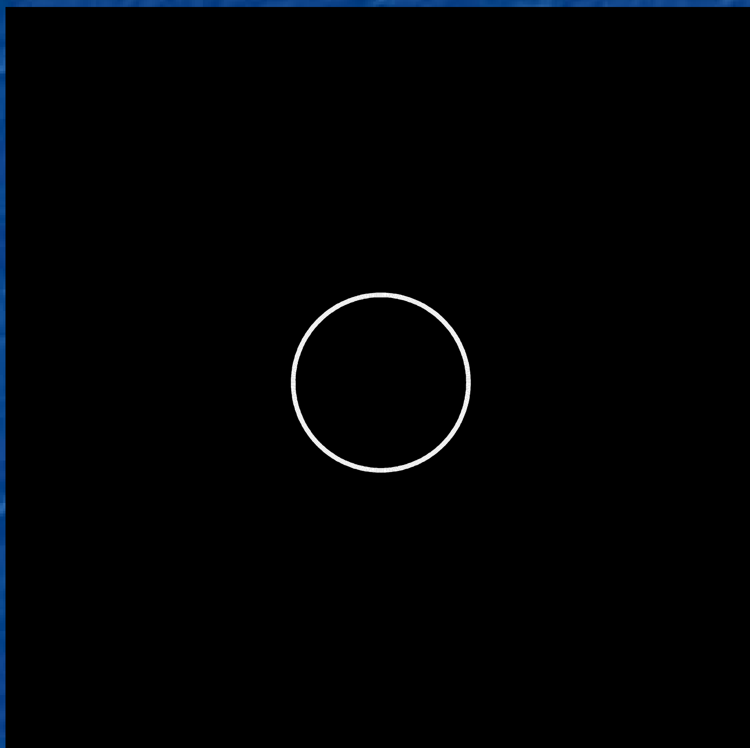
# What is my Strehl ?

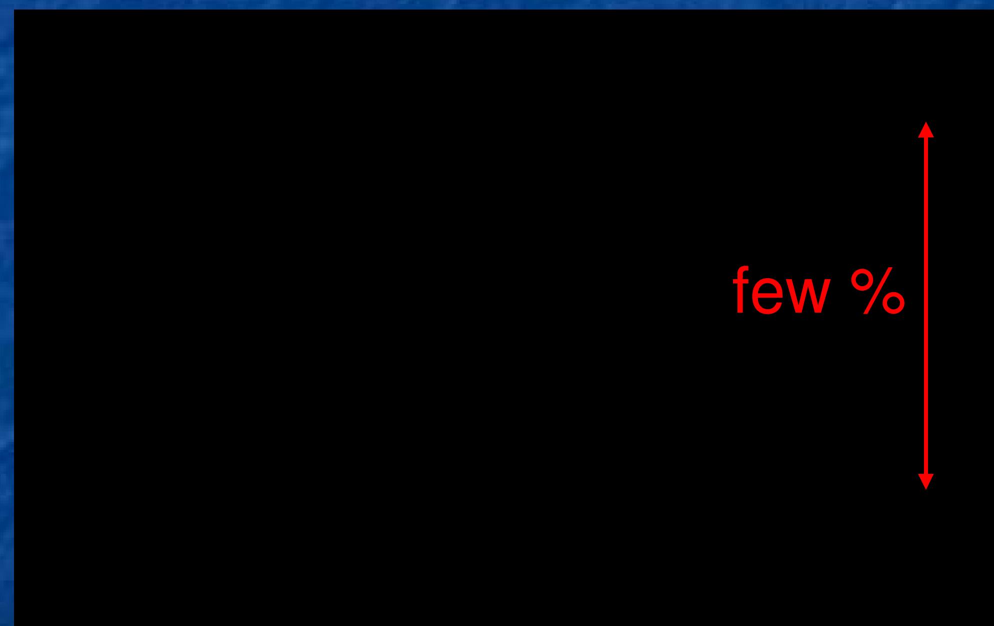


# What is my Strehl ?

# What is my Strehl ?

- New background estimation: mean of pixels outside r=60

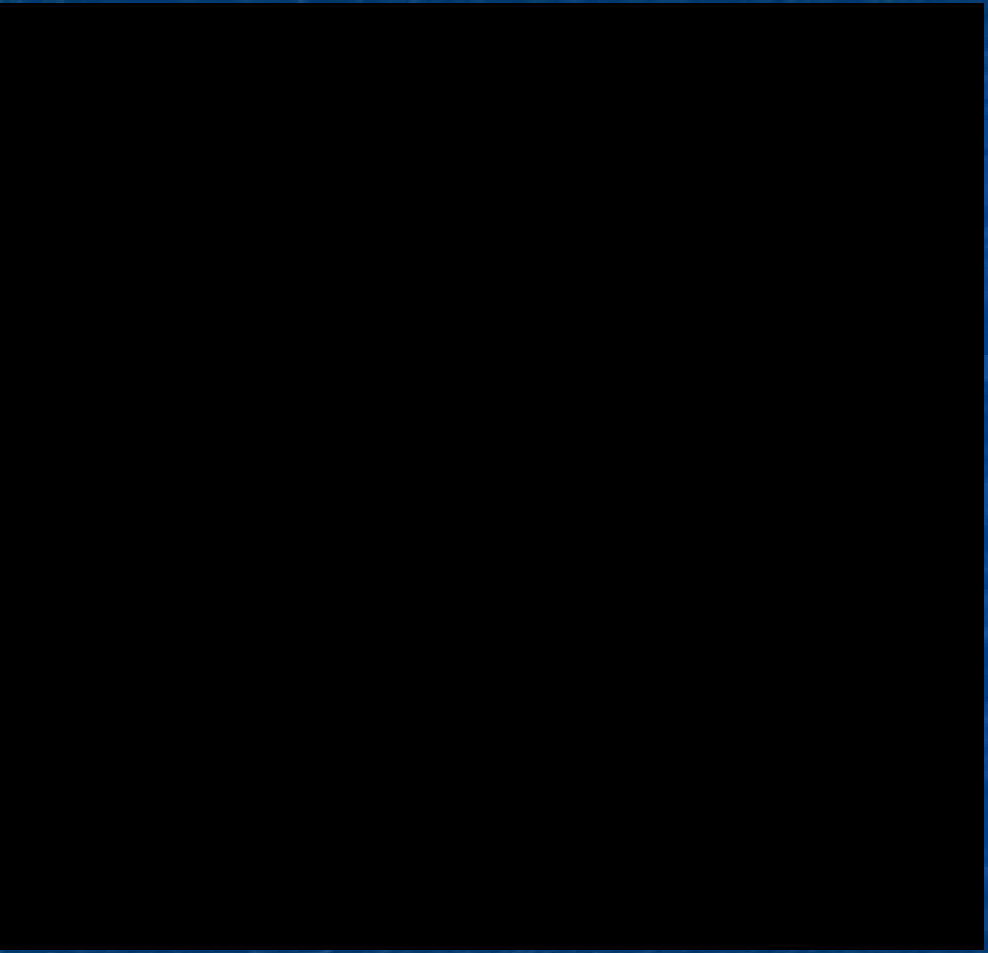




# Temporal PSF variability

- 10 min lag
  - Average seeing change of 13% for instantaneous exposures
  - Average seeing change of 10% for finite exposure

# Temporal PSF variability



- With a simple seeing-Strehl model

$$SR = \exp(-\sigma_\phi^2)$$

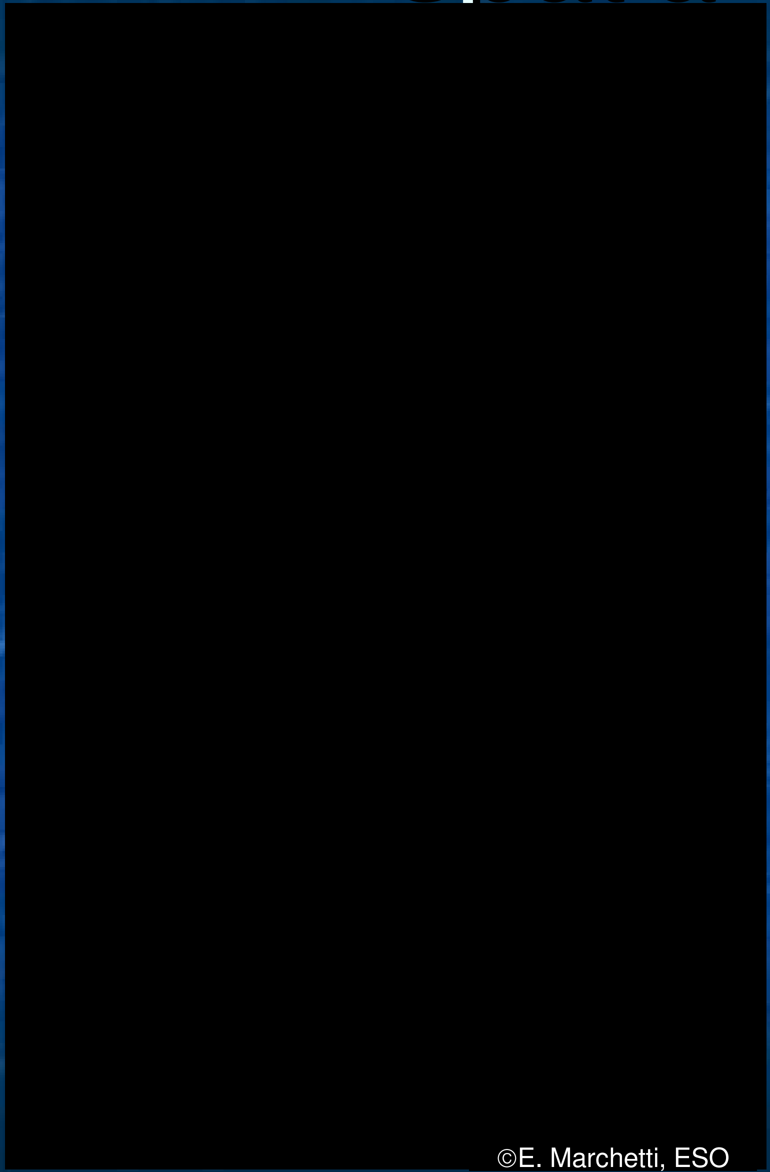
$$\sigma_\phi^2 \propto r_0^{5/3}$$

- 10 min lag⇨ 20% of SR error for SR=30%

# Temporal PSF variability

- Alternance of science/calibration exposures decreases FSC ($\sqrt{N_{exp}}$)
- But for 10 min lag: goal of 2% error ⇨ 100×O/C !

# Spatial PSF variability



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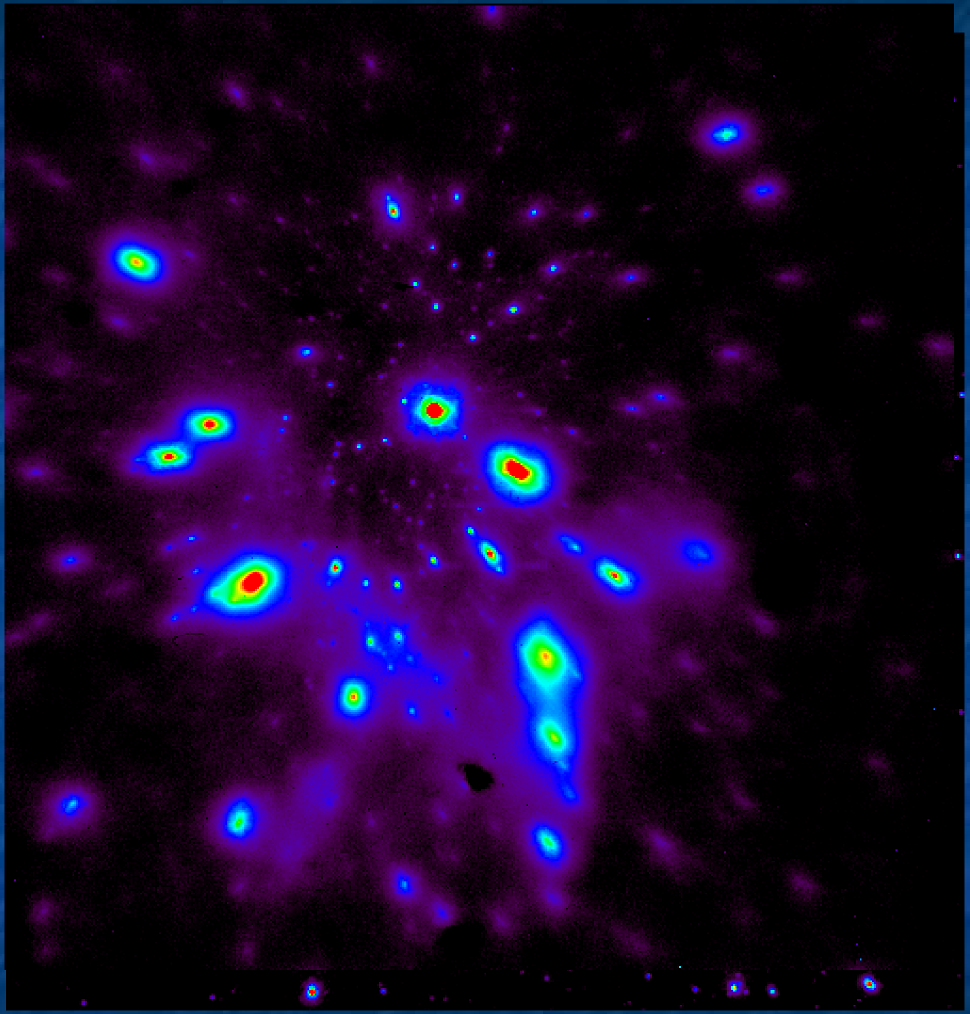


# Measurement of the PSF

- Sequential calibration
  - science/calibration acquisition alternatively

    need for the same correction !!
    - Same S/R (and ~time) on both PSF and science target $\Rightarrow$ lot of time ! (may not be the photometric calibrator!)
    - Difficult to achieve/control: same WFS noise level (source magnitude, colour, shape, airmass, atmospheric conditions…)

- Stars in the field

  anisoplanatism

# Measurement of the PSF

- ⇨ Need for specifications on the photometric/astrometric accuracy

OR

- PSF reconstruction

# PSF reconstruction

- Make use of the WFS real-time data
- Initiated by J.P. Véran at CFHT
- Few critical assumptions
  - High bandpass of the WFS
  - "Not too noisy" real-time data

$$\left\langle OTF(\vec{\rho}/\lambda)\right\rangle = \left\langle OTF_{\phi_{\epsilon_{\|}}}(\vec{\rho}/\lambda)\right\rangle \times \left\langle OTF_{\phi_{\epsilon_{\perp}}}(\vec{\rho}/\lambda)\right\rangle \times OTF_{\mathrm{tel}}(\vec{\rho}/\lambda)$$

$$\langle \epsilon_{\|}\epsilon_{\|}{}^{t}\rangle = \langle \hat{\epsilon}_{\|}\hat{\epsilon}_{\|}^{t}\rangle - \langle nn^{t}\rangle + \langle rr^{t}\rangle$$

# PSF reconstruction: PUEO/CFHT

- J.P. Véran et al. (1997)
- Curvature WFS, 19 act. DM, 36 controlled modes
- Few critical assumptions ⇨ in practice $m_V$<13.5
- Few computations dedicated to curvature WFS
  - Real-time data noise (depends on the type of measurements and the kind of detector)
  - Aliasing (non linear measurements of the high order modes)
- Reconstructed PSF routinely delivered to observers

# PSF reconstruction: PUEO/CFHT

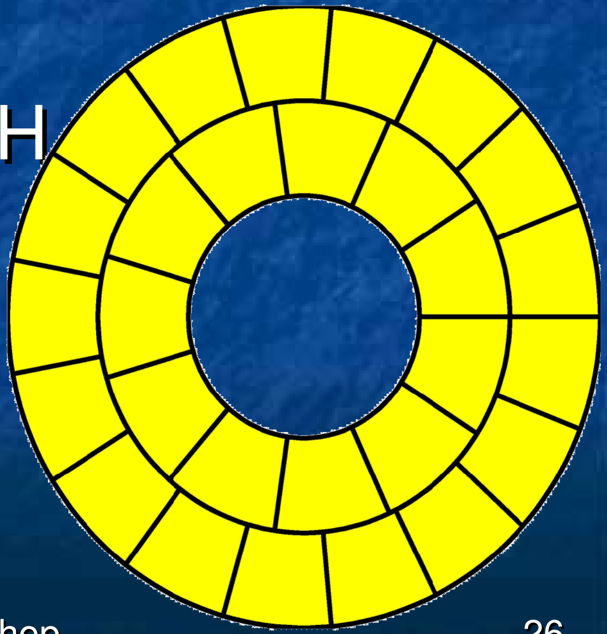
[redacted]

# PSF reconstruction: PUEO/CFHT

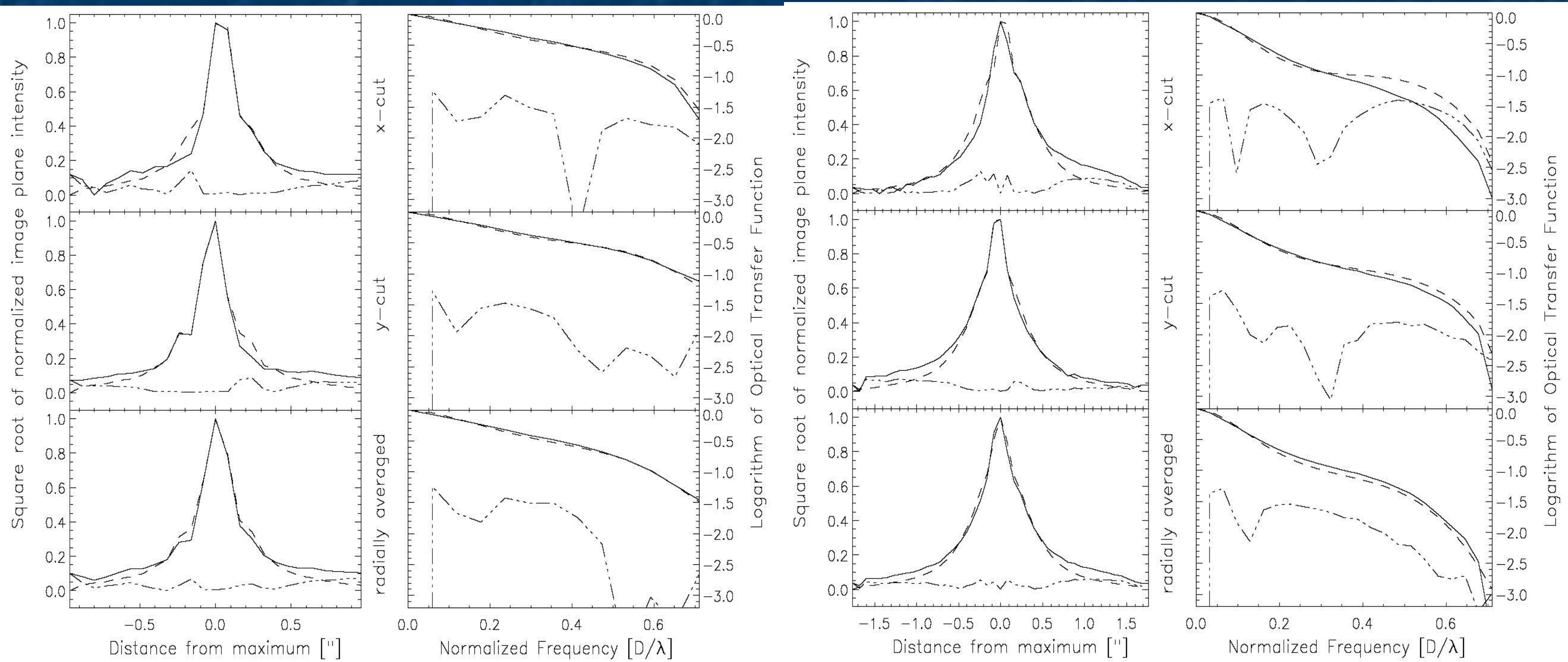
[redacted]

# PSF reconstruction: ALFA

- Calar Alto 3.5m/ALFA
- R. Weiss (2003)
- 7 or 28 subpupils SH, 97 act. DM, up to 32 controlled modes
- Véran et al. algorithm, adapted to SH
- Few tests
- Extended to off-axis PSF !



# PSF reconstruction: ALFA




| Guide star | $m_V$=7.14 | | $m_V$=13 | |
|---|---|---|---|---|
| | Real | Estimated | Real | Estimated |
| Strehl (%) | 45.7 ± 2.0 | 47.6 | 13.2 ± 1.9 | 13.3 |
| FWHM (") | 0.14 ± 0.01 | 0.13 | 0.24 ± 0.02 | 0.22 |

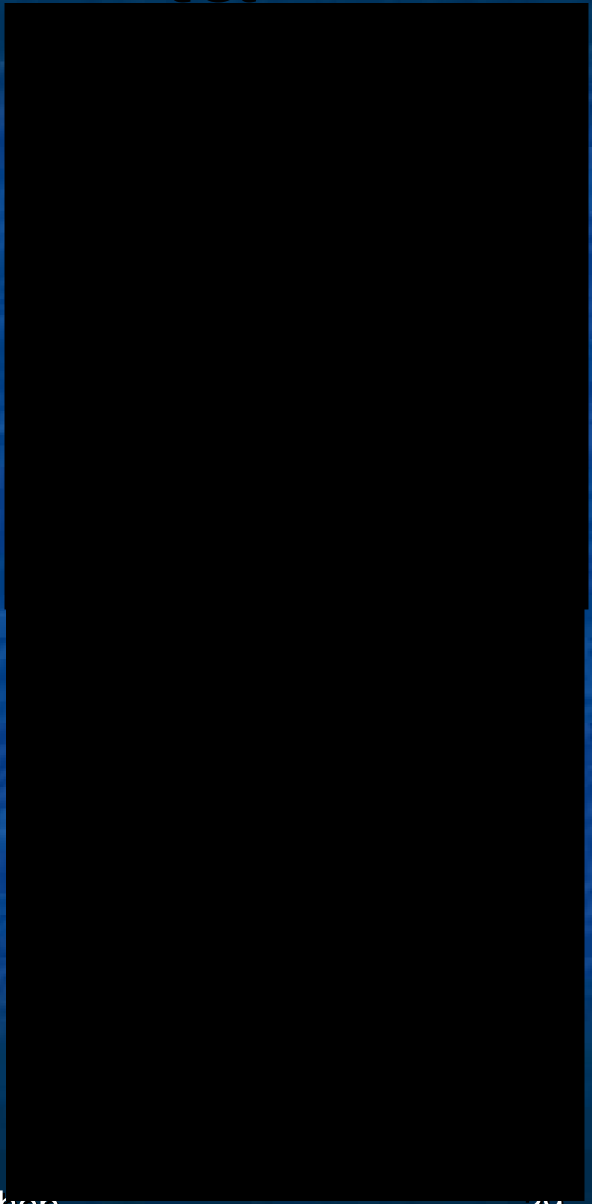
# PSF reconstruction: Lick Obs.

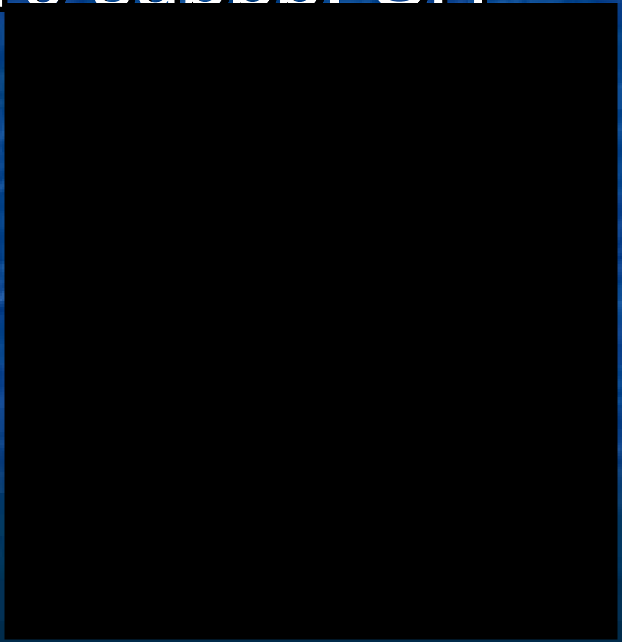
- Lick Observatory 3m Shane telescope
- M. Fitzgerald (2004)
- 40 subpp. SH
- 61 act. DM

[redacted]

# PSF reconstruction: Altaïr

- Gemini North/Altair
- L. Jolissaint (2004)
- 4-quadrant ~110 subap. SH
- 177 act. DM,
  128 controlled
  modes





# PSF reconstruction: NAOS

- PSF reconstruction considered from the design
  - 2 covariance matrices attached to the image fits file
  - Estimation of few atmospheric parameters written in the image fits file header: $r_0$, $L_0$, $\tau_0$
  - Estimation of the global noise written in the image fits file header
- But no dedicated algorithm then

# PSF reconstruction: NAOS

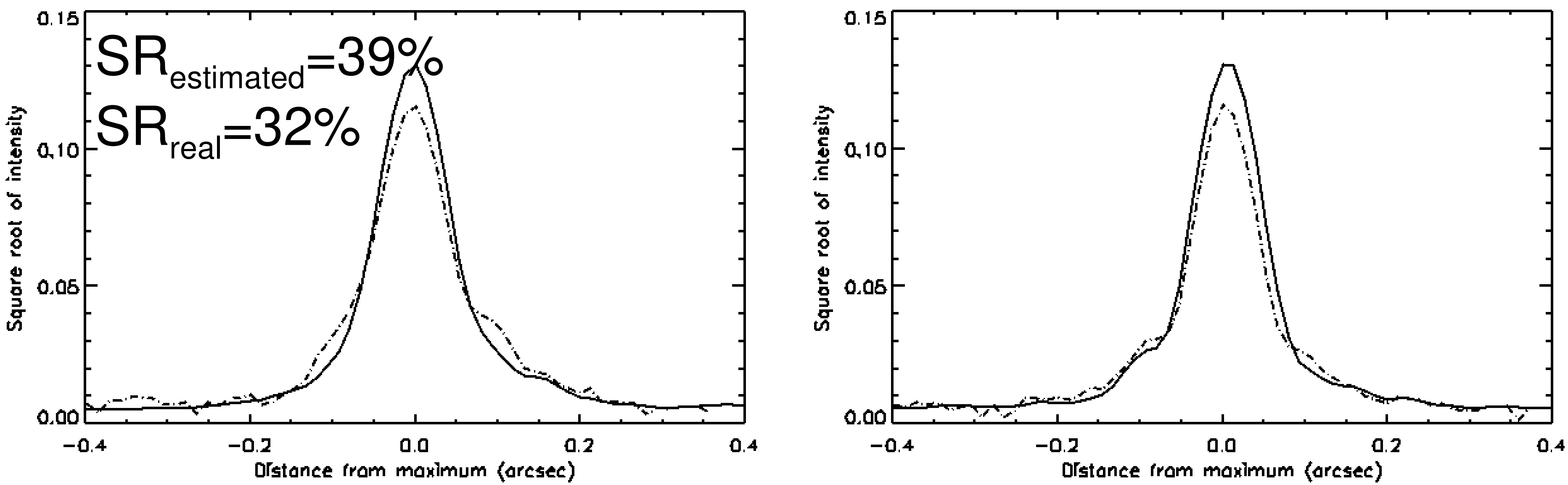
- First idea: adapt the ALFA software
- But too large differences between the systems:
  - Modes (KL/NAOS modes)
  - Available wavefront-related measurements

⇨ Development of a piece of software dedicated to NAOS

# PSF reconstruction: NAOS

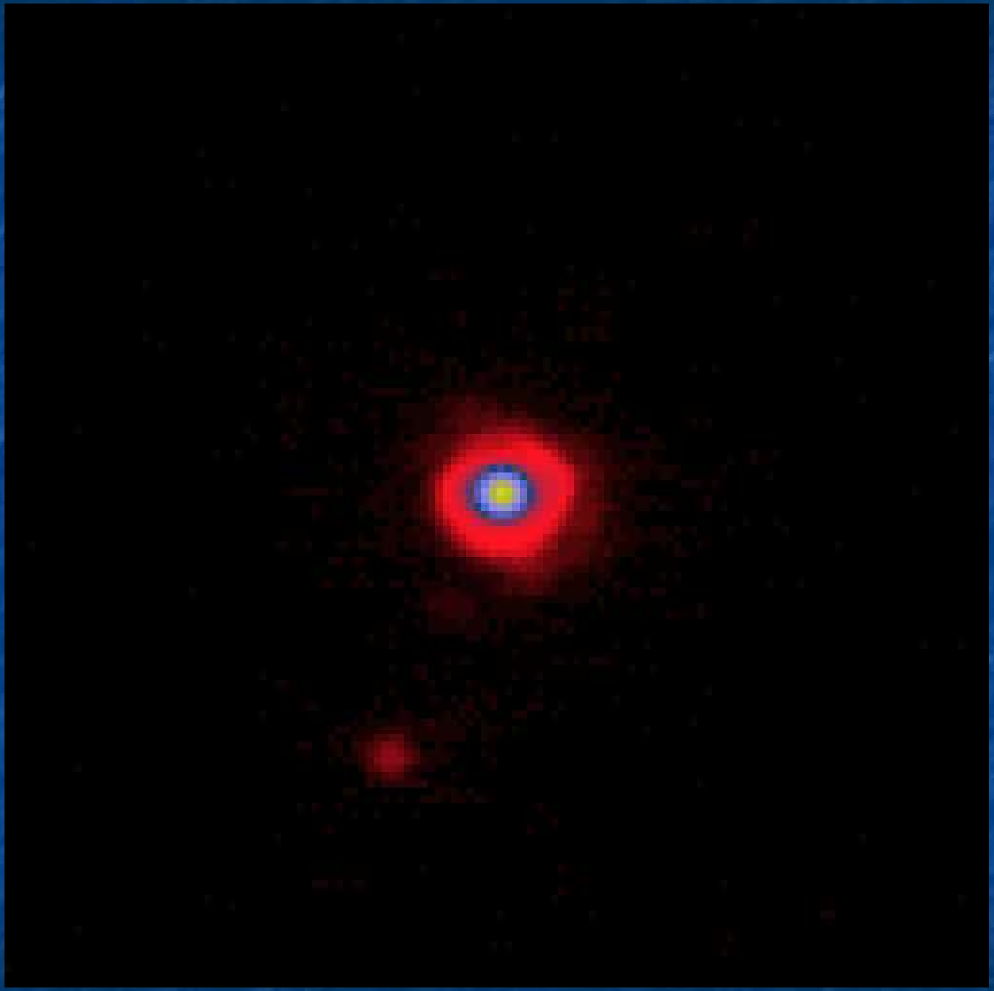
- Modified Véran et al. algorithm
  - $U_{ij}$
    - $N \times (N-1)/2$ functions
    - computed once for all and stored before reconstruction
    - Read during reconstruction
  - $V_{ii}$
    - N functions
    - computed on the fly during reconstruction
- No aliasing yet

# PSF reconstruction: NAOS




- No aliasing ⇨ SR overestimated
- Fibre image for static aberrations instead of true star image
- Companion

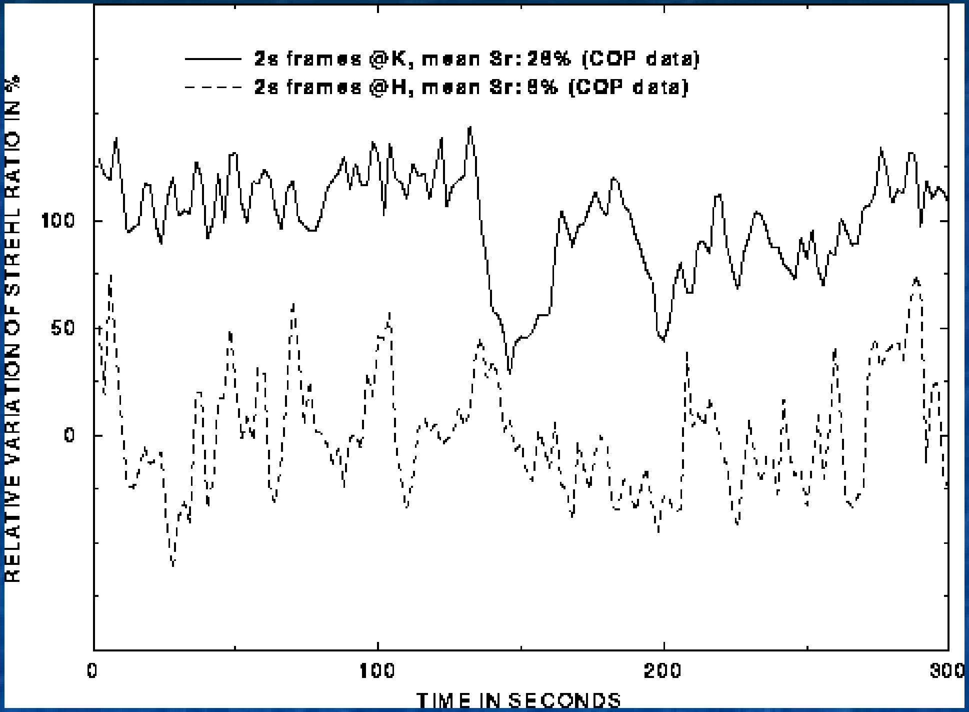
# PSF reconstruction: NAOS



# Conclusion

- Beware the Strehl !
- PSF reconstruction for NACO is ongoing
- Need for post-processing software accounting for variable PSF in the field
- Need for photometric accuracy specifications for PSF reconstruction

# Temporal PSF variability




| Strehl ratio | 0.25 | 0.10 | 0.015 |
|---|---|---|---|
| r50 (λ/D) | 2.5 | 4.5 | 7.8 |
| FWHM (λ/D) | 1.25 | 1.8 | 5.0 |
| $\sigma_{SR}$/SR | 15% | 26% | 22% |
| $\sigma_{r50}$/r50 | 15% | 9% | 6% |
| $\sigma_{FWHM}$/FWHM | 6% | 16% | 24% |

- Image quality study from Tessier (1997): Come-on+ data (!), 2 second images

# Temporal PSF variability

- For good correction: FWHM stable ("always diffraction limited") but not r50
- For poor correction: r50 stable but not FWHM
- SR always variable on short time scale

| Strehl ratio | 0.25 | 0.10 | 0.015 |
|---|---|---|---|
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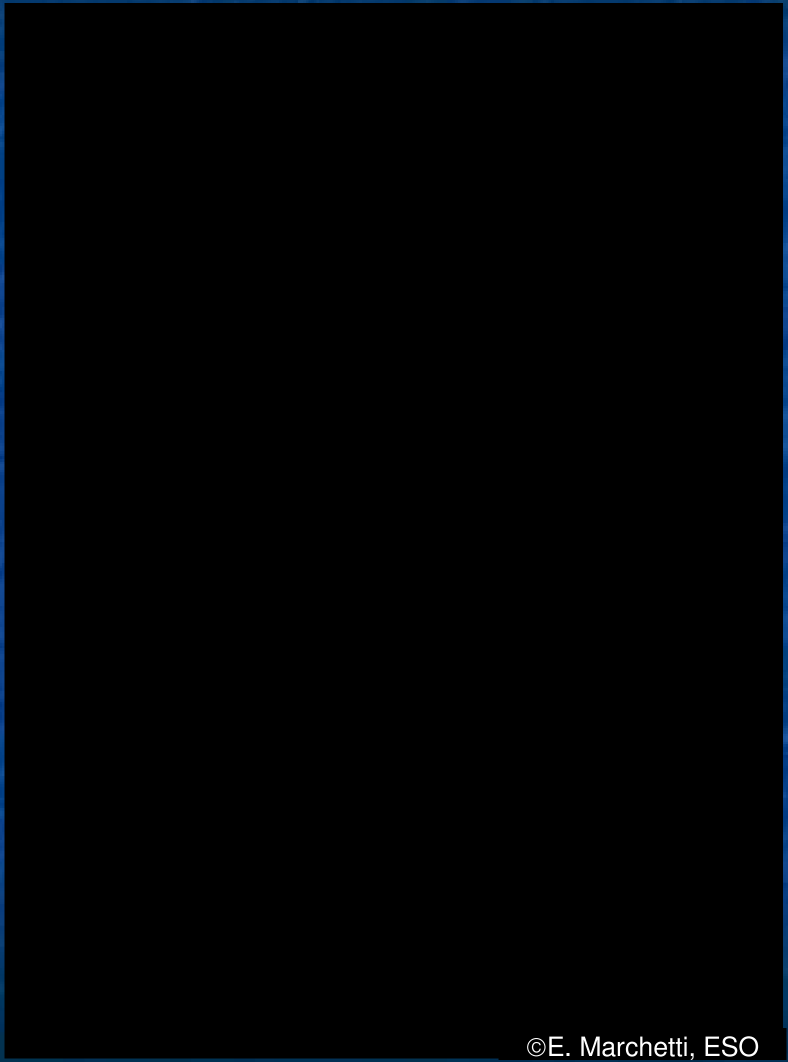
# Multi Object Adaptive Optics



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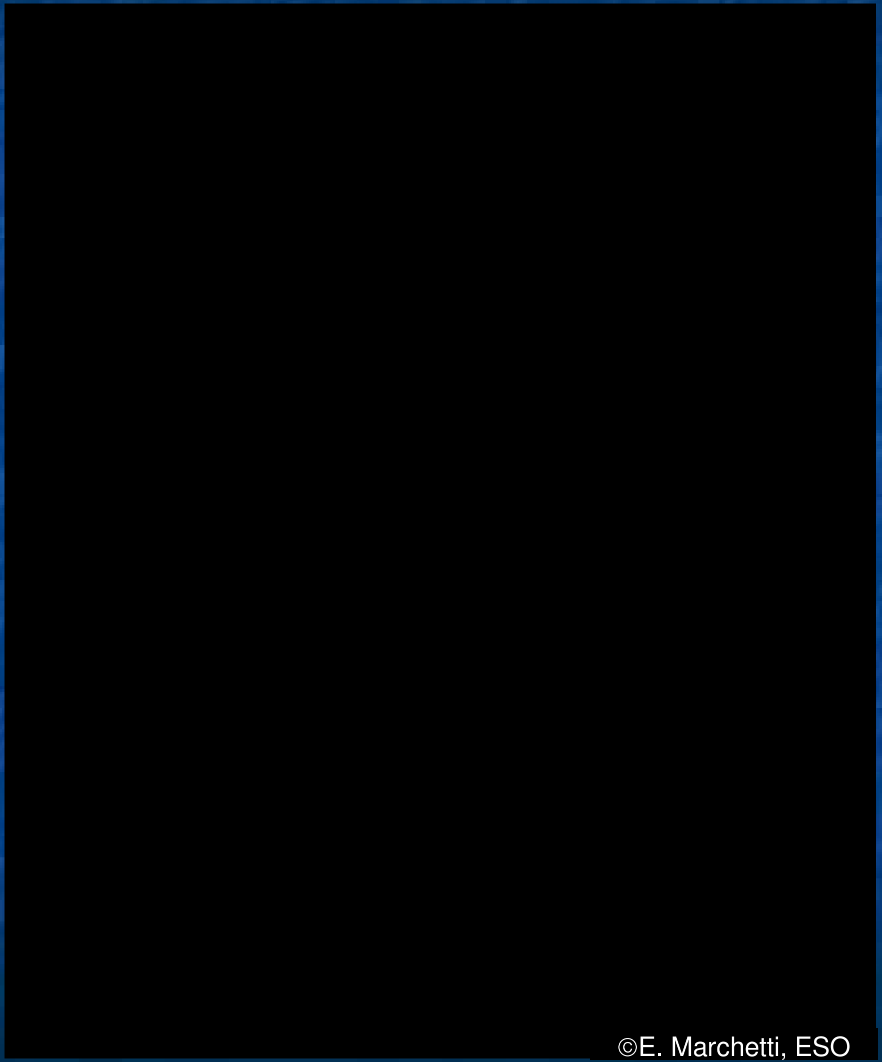

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