Modélisation d'optique adaptative (OA) et imagerie post-OA en astronomie

Marcel Carbillet

Soutenance d'HDR

[Nice, 11 décembre 2013]

Devant le jury composé de :
Claude AIME
Marc FERRARI [Rapporteur]
Roberto RAGAZZONI [Rapporteur]
Farrokh VAKILI [Rapporteur]
Mario BERTERO
André FERRARI
Gérard ROUSSET

Adaptive Optics (AO) Modelling & Post-AO Imaging in Astronomy

Marcel Carbillet

'HDR' Defense

[Nice, December 11th, 2013]

Before the committee consisting of:

Claude AIME
Marc FERRARI [Reviewer]
Roberto RAGAZZONI [Reviewer]
Farrokh VAKILI [Reviewer]
Mario BERTERO
André FERRARI
Gérard ROUSSET

Outline

- **Introduction**
  [From PhD to HDR, Observations & Turbulence, `PSE CAOS`]
- **AO Numerical Modelling**
  [Atmosphere, Wavefront Sensing, M4/E-ELT, FLAO/LBT]
- **Post-AO Imaging**
  [LN/LBT, Super-Resolution, Strehl Constraint, SPHERE/VLT]
- **Summary & Prospects**
- **Demo.**
  [`Soft.Pack.CAOS`, `Soft.Pack.AIRY`]

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Introduction - From PhD to 'HDR'

- "Probability Imaging: Application to HAR in Astrophysics", Dépt d'Astrophysique, UNS (+Imperial College, London), 1993-1996.
- Post-doc. COTRAO, GAP, University of Geneva, 1997.
- Post-doc. TMR-UE "Laser Guide Stars for 8-m Class Telescopes", LBT group, INAF-OAA (Florence), 1997-2000.
- Post-doc./CDD INAF-OAA/Project LBT, 2000-2004.
- Since 2004 : MCF, LUAN>Fizeau>Lagrange (UNS/CNRS/OCA)
  + Local coordinator for SPHERE consortium [2005-2008]
  + *Associato* INAF at OAA since 2010.

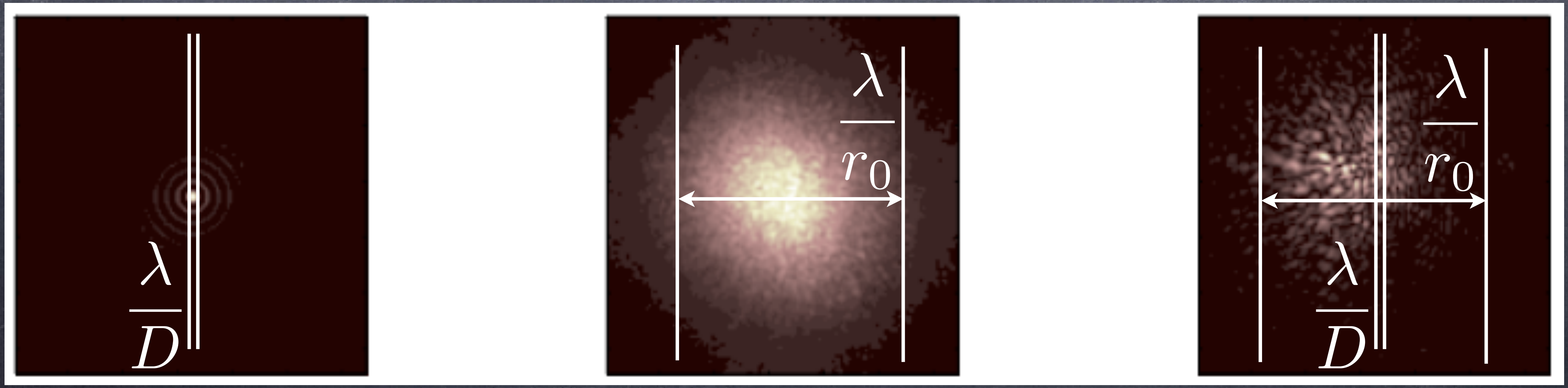
- 160+ references (30 journals, 8 invited comm., 86 conf. articles, 39 others)
- 4 co-directions of PhD theses (+5 co-supervisions)
- 7 directions/co-directions of Master-2 stages (+2 Licence-3)
- Co-organization of workshops/colloquia/summer schools

Introduction - Astronomical Obs. & Atmospheric Turbulence

- Image $I(\alpha)$ = Convolution of object observed $O(\alpha)$ with point-spread function (PSF) $S(\alpha)$ of the optical system atmosphere+telescope:

$$O(\vec{\alpha}) * S(\vec{\alpha}) = I(\vec{\alpha})$$

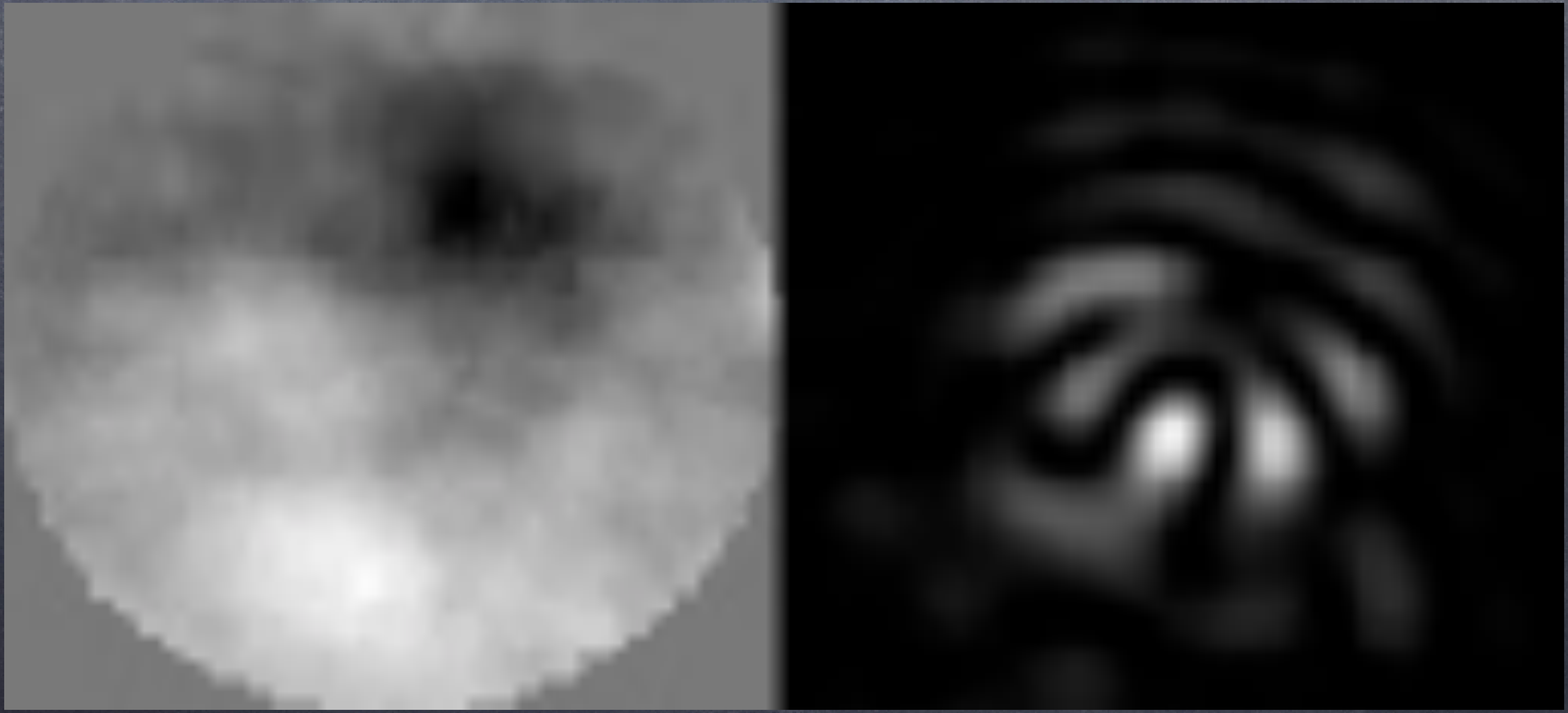
- The problem is that PSF is perturbated by the turbulent atmosphere: scintillation, image motion, spreading.



Introduction - Astronomical Obs. & Atmospheric Turbulence

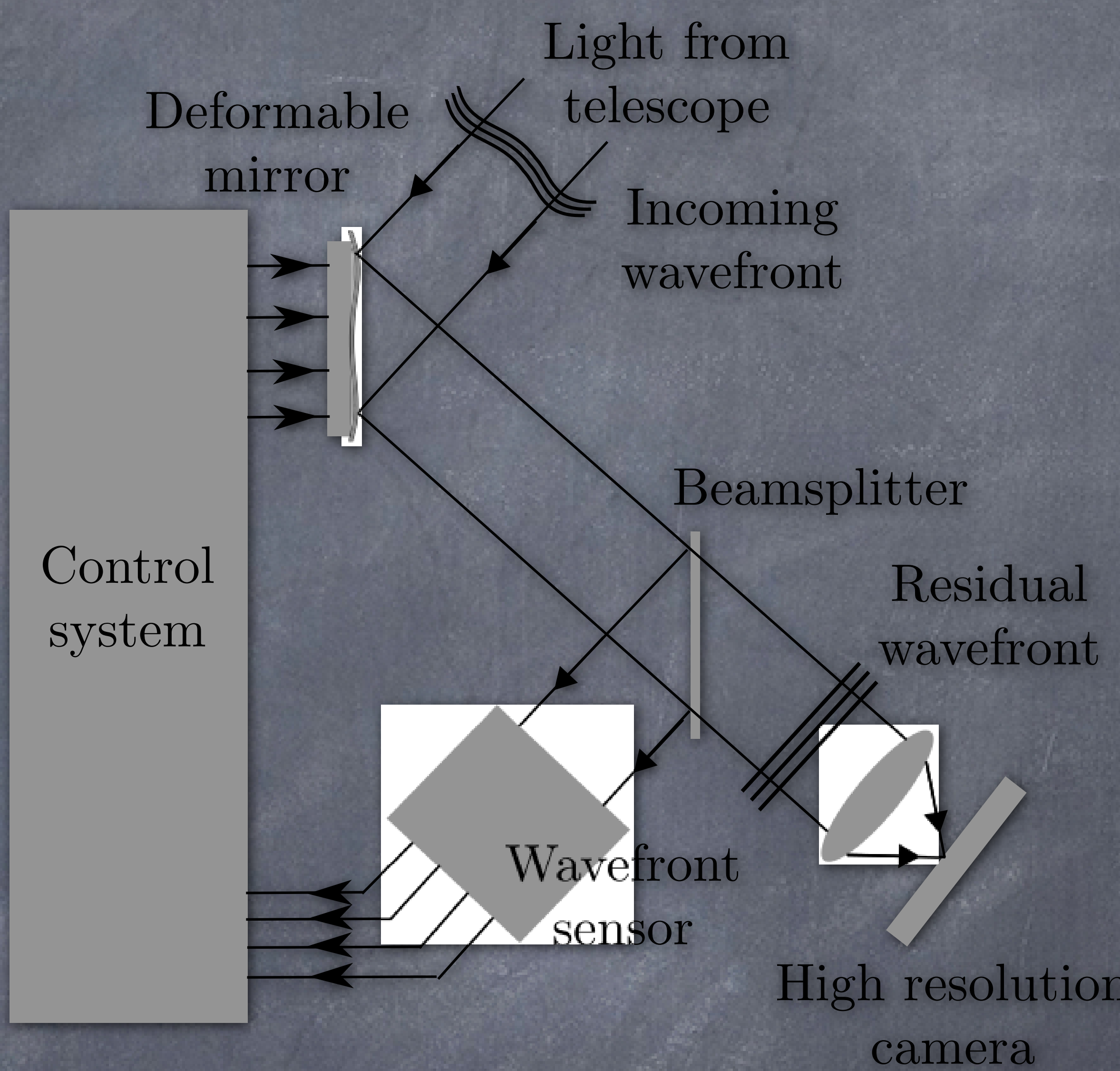
- PSF $S(\alpha)$ = Modulus squared of the Fourier transform of the incoming wave $A \exp \imath\phi$, with the phase following a Kolmogorov/von Kármán power spectral density (PSD) law:

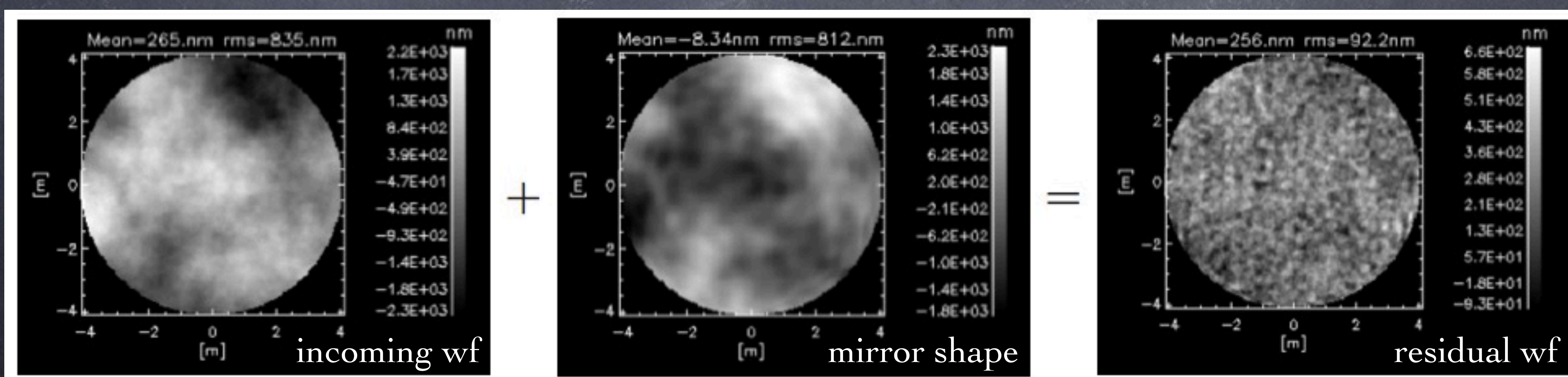
$$\Phi_\phi(\vec{\nu}) = 0.0228\, r_0^{-\frac{5}{3}} \left(\nu^2 + \frac{1}{\mathcal{L}_0^2}\right)^{-\frac{11}{6}}$$



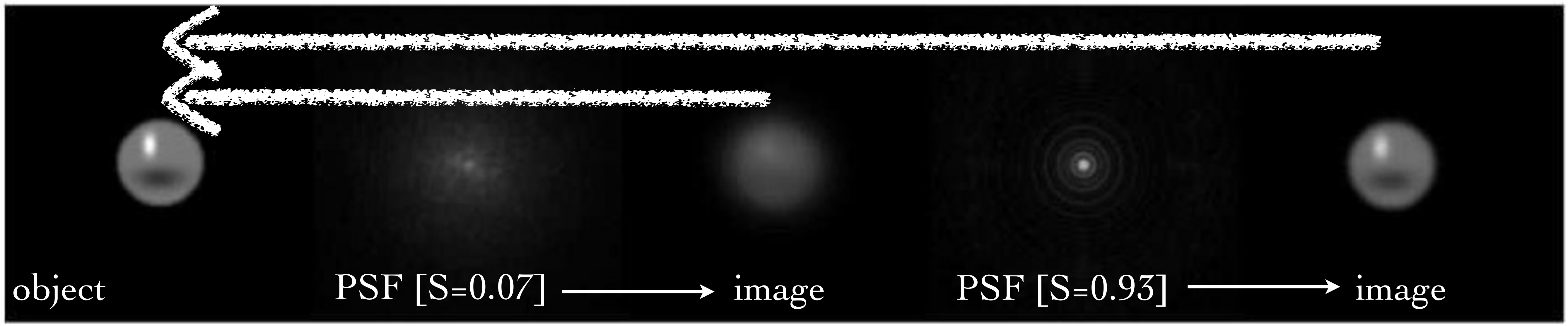
Introduction - Astronomical Obs. & Atmospheric Turbulence

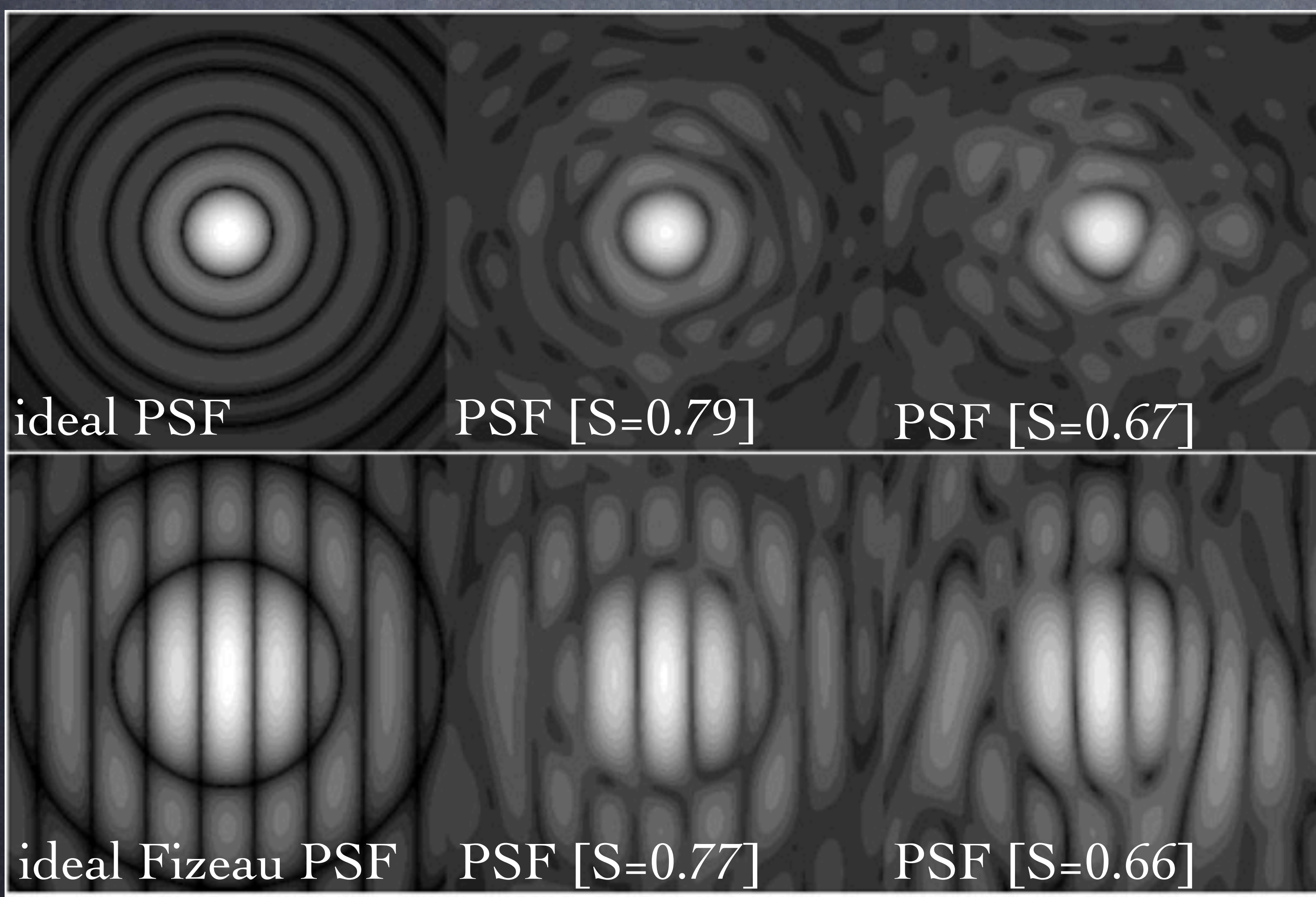
- An adaptive optics (AO) system aims to measure atmospheric perturbations on the phase (=2π/λ wavefront) through a wavefront sensor (WFS) and correct from them via a deformable mirror (DM), in (almost) real time...





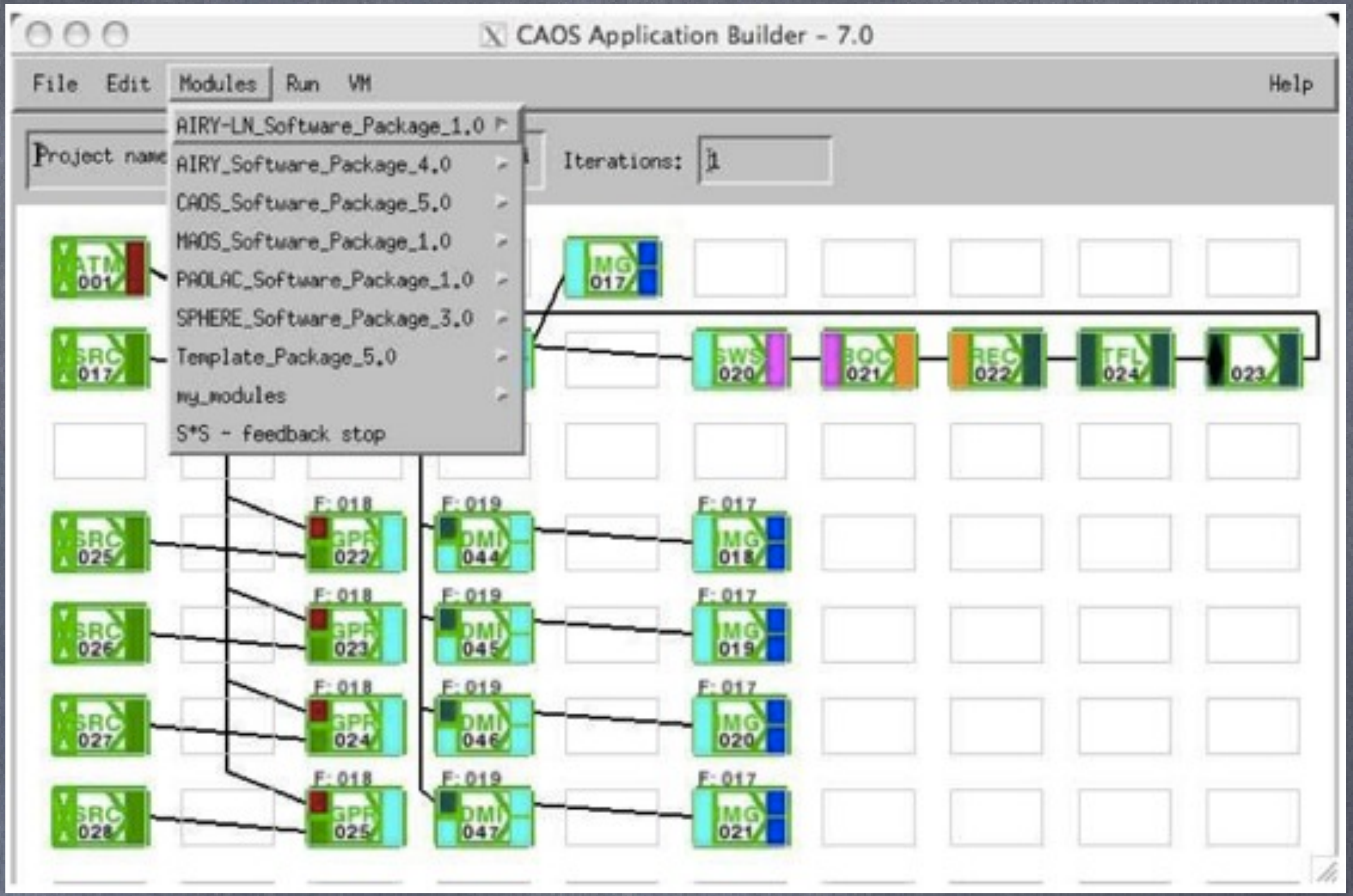
- But correction is not perfect...





- And we'd like even more: reconstruct the original object, deconvolving from the PSF...

Introduction - The CAOS Problem-Solving Environment (PSE)



- It is written in `IDL` language
- It is based on a modular structure
- It is composed of a global interface (the `CAOS App.Builder`), a library of utilities (the `CAOS Library`), and various scientific packages (the `Soft.Packages`)
- Each `Soft.Pack.` is a set of modules dedicated to a given scientific subject (AO modelling, imaging).
- http://lagrange.oca.eu/caos for free download (public parts)
- Mailing-lists: `Soft.Pack.CAOS` (122 users), `Soft.Pack.AIRY` (30), `Soft.Pack.SPHERE` (22), `Soft.Pack.PAOLAC` (3).
- Various contributors !

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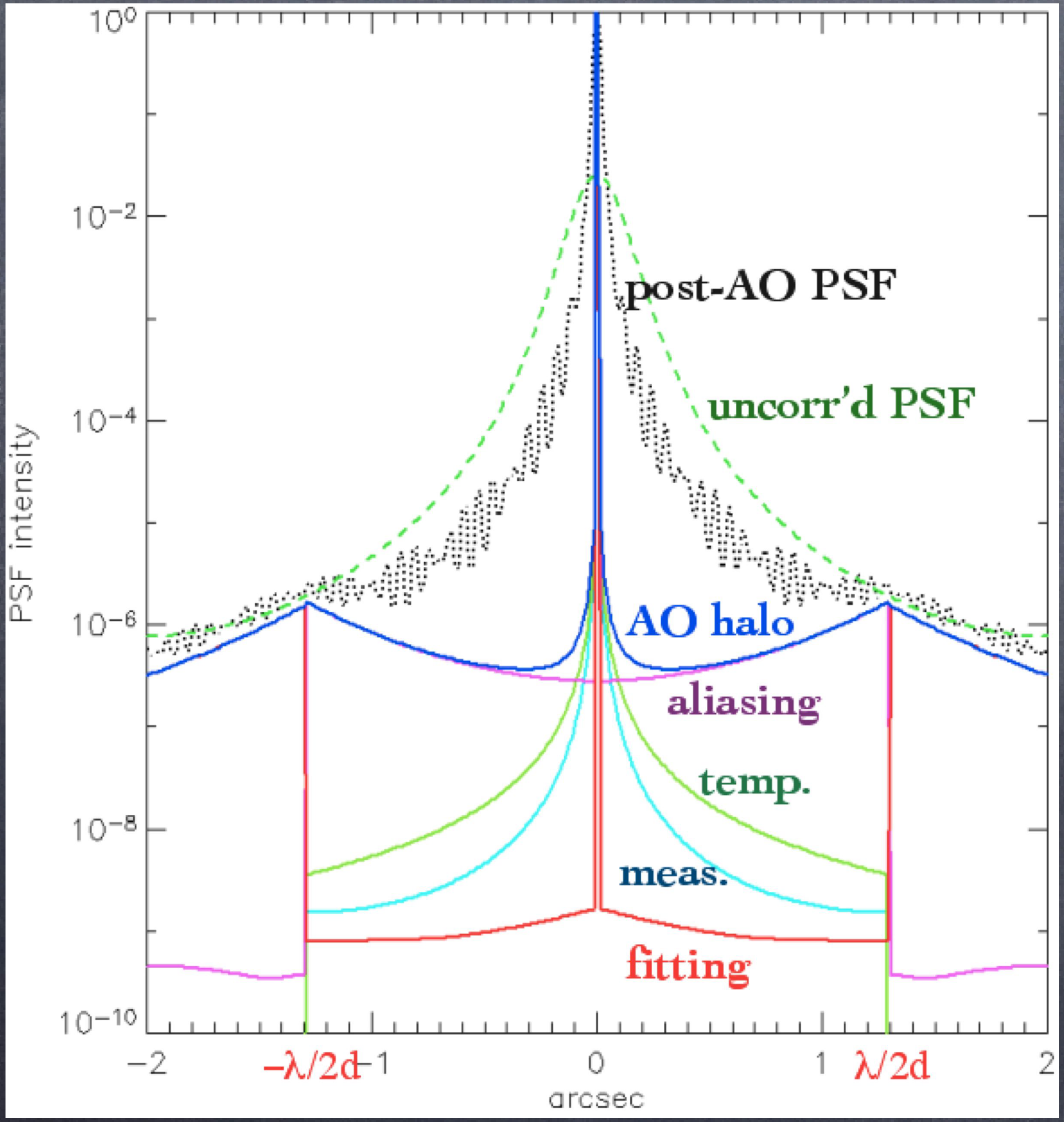
AO Modelling - Error Budget

atmosphere modelling — WFS modelling

$$\sigma^2_{\text{post-AO}} = \sigma^2_{\text{atm.}} + \sigma^2_{\text{fit.}} + \sigma^2_{\text{alias.}} + \sigma^2_{\text{meas.}} + \sigma^2_{\text{temp.}} + \ldots$$



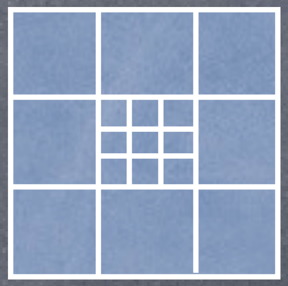
- In the following:
  - Efforts to properly evaluate these errors via modelling
  - Study solutions to keep these errors lower
  - Application to specific systems in the framework of large telescope instruments (M4/EELT, FLAO/LBT)

AO Modelling - Wavefront Forming

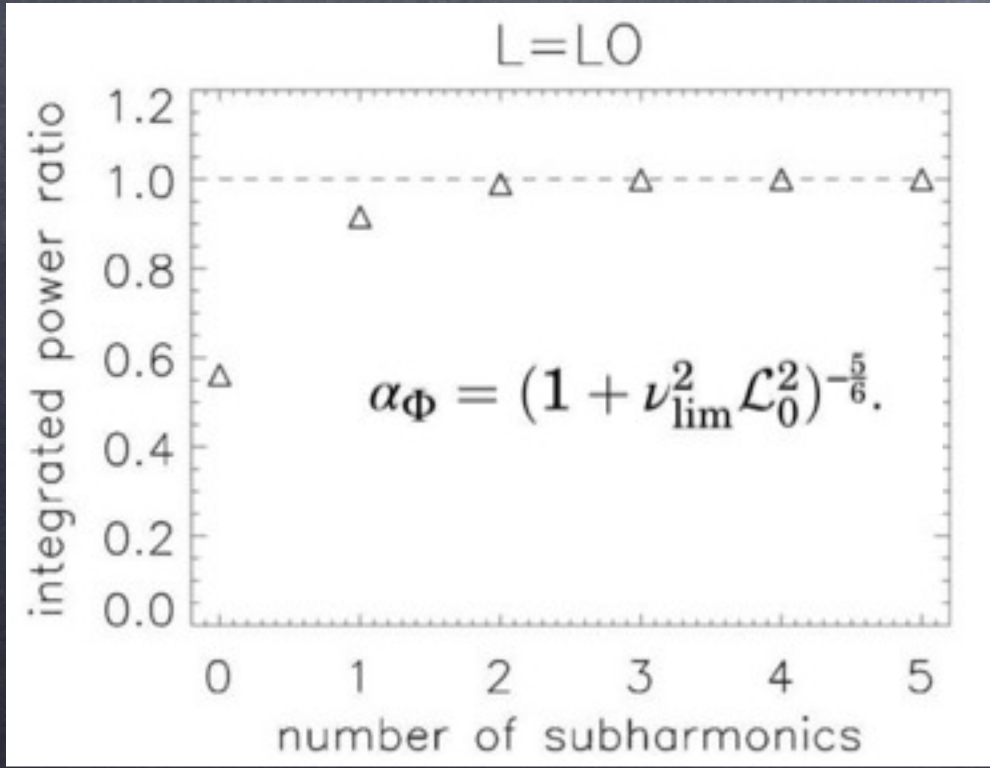
- Classical FFT method: lack of energy for the low spatial frequencies
=> sub-harmonics adding [Lane et al. 1995, Sedmak 2004].

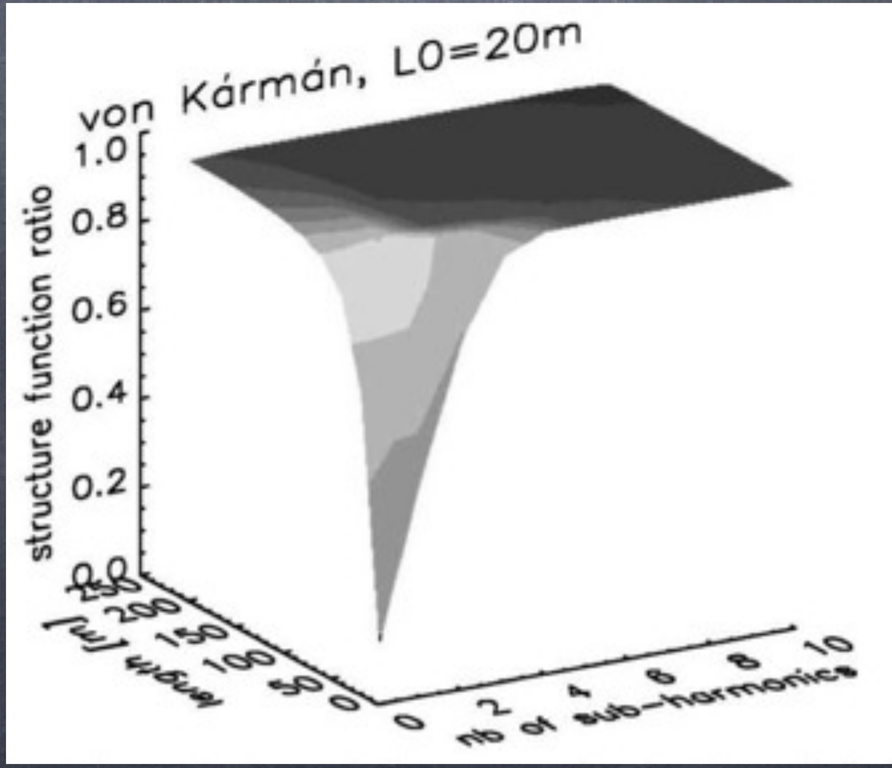
$$\phi_L(i,j) = \sqrt{2}\sqrt{0.0228}\left(\frac{L}{r_0}\right)^{\frac{5}{6}}\left\{FFT^{-1}\left[\left(k^2+l^2+\left(\frac{L}{\mathcal{L}_0}\right)^2\right)^{-\frac{11}{12}}\exp\{\imath\theta(k,l)\}\right]\right\}$$

$$\phi_{3^n L}(i,j) = \sqrt{2}\sqrt{0.0228}\left(\frac{L}{r_0}\right)^{\frac{5}{6}}\frac{1}{3^n}\left\{DFT^{-1}\left[\left(k_s^2+l_s^2+\left(\frac{L}{\mathcal{L}_0}\right)^2\right)^{-\frac{11}{12}}\exp\{\imath\theta(k_s,l_s)\}\right]\right\}$$

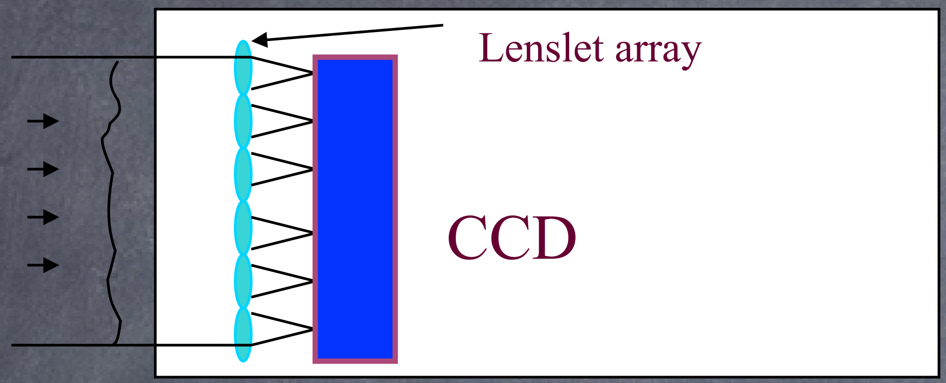


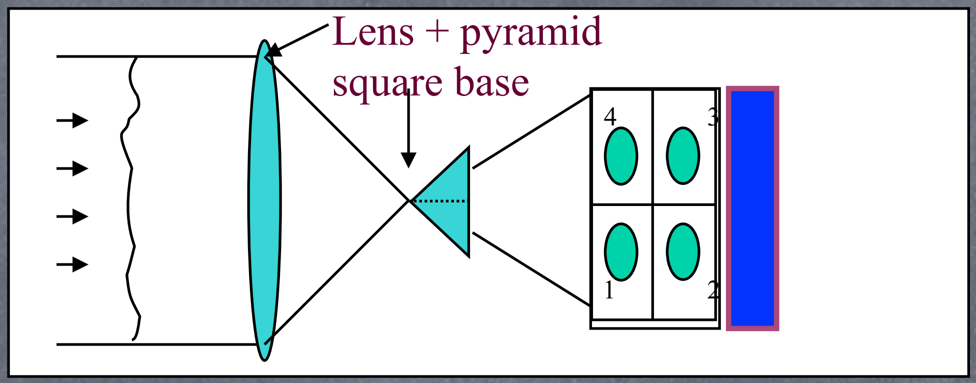
- How many sub-harmonics to be added ?
=> ratio between theoretical quantities and will-be-obtained ones (integrated power & structure function) [Carbillet & Riccardi *App. Optics* 2010a]

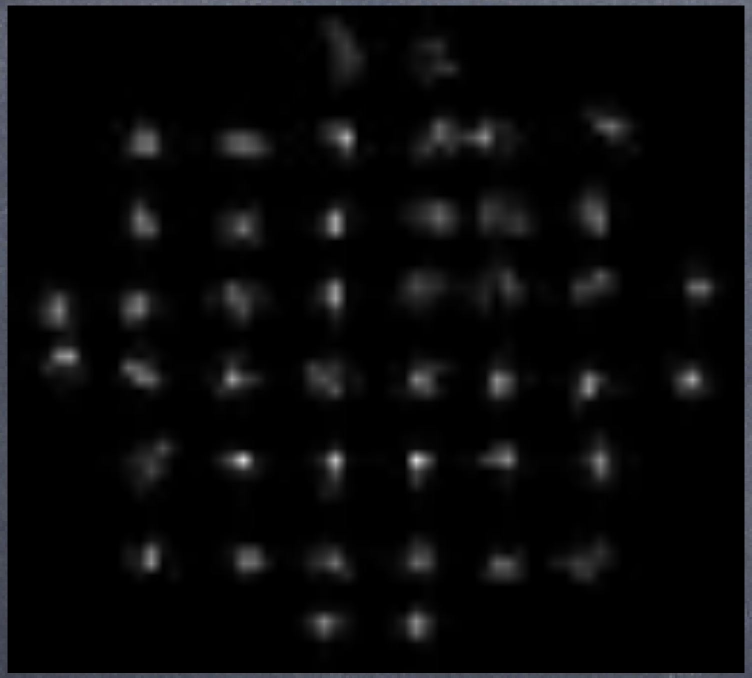




AO Modelling - Wavefront Sensing: SH vs. Pyramid



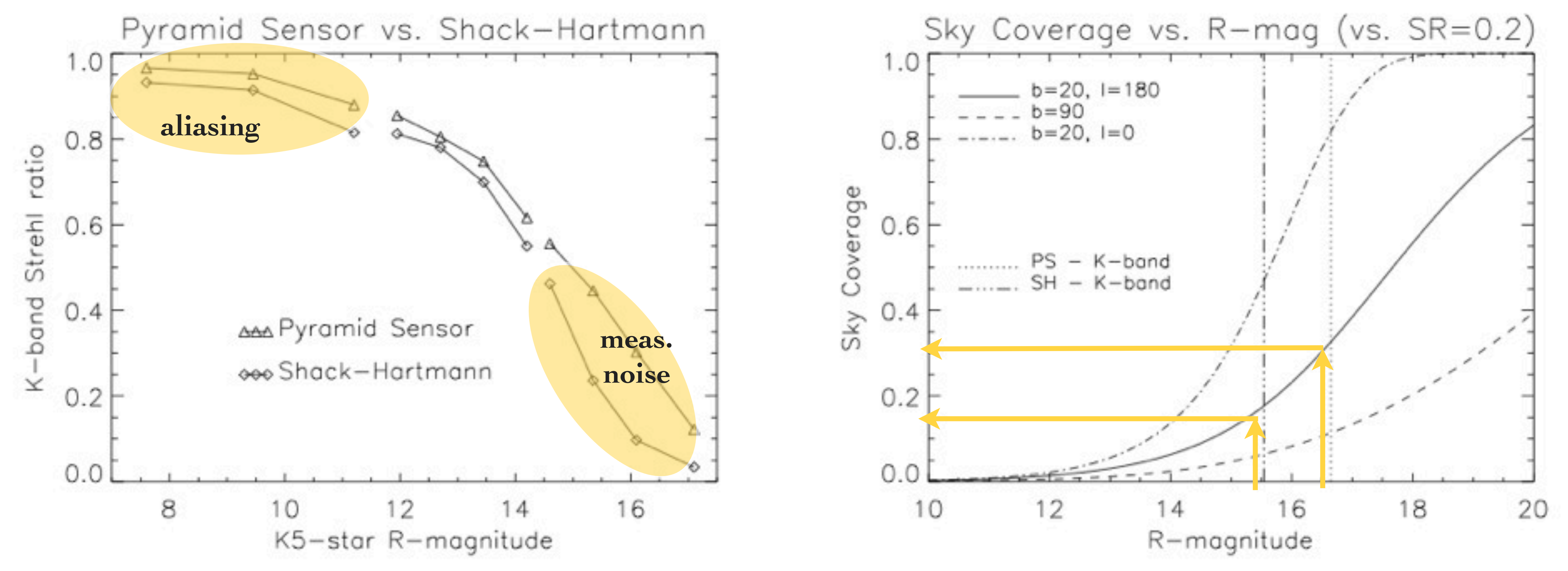




- SH: First on-sky AO results with COME-ON/VLT in 1989 [Rousset et al. 1990].
- Pyramid [Ragazzoni 1996], 2-*mag*. gain foreseen with respect to SH [Ragazzoni & Farinato 1999], confirmed by Monte-Carlo simulations [Esposito & Riccardi 2001].

AO Modelling - Wavefront Sensing: SH vs. Pyramid

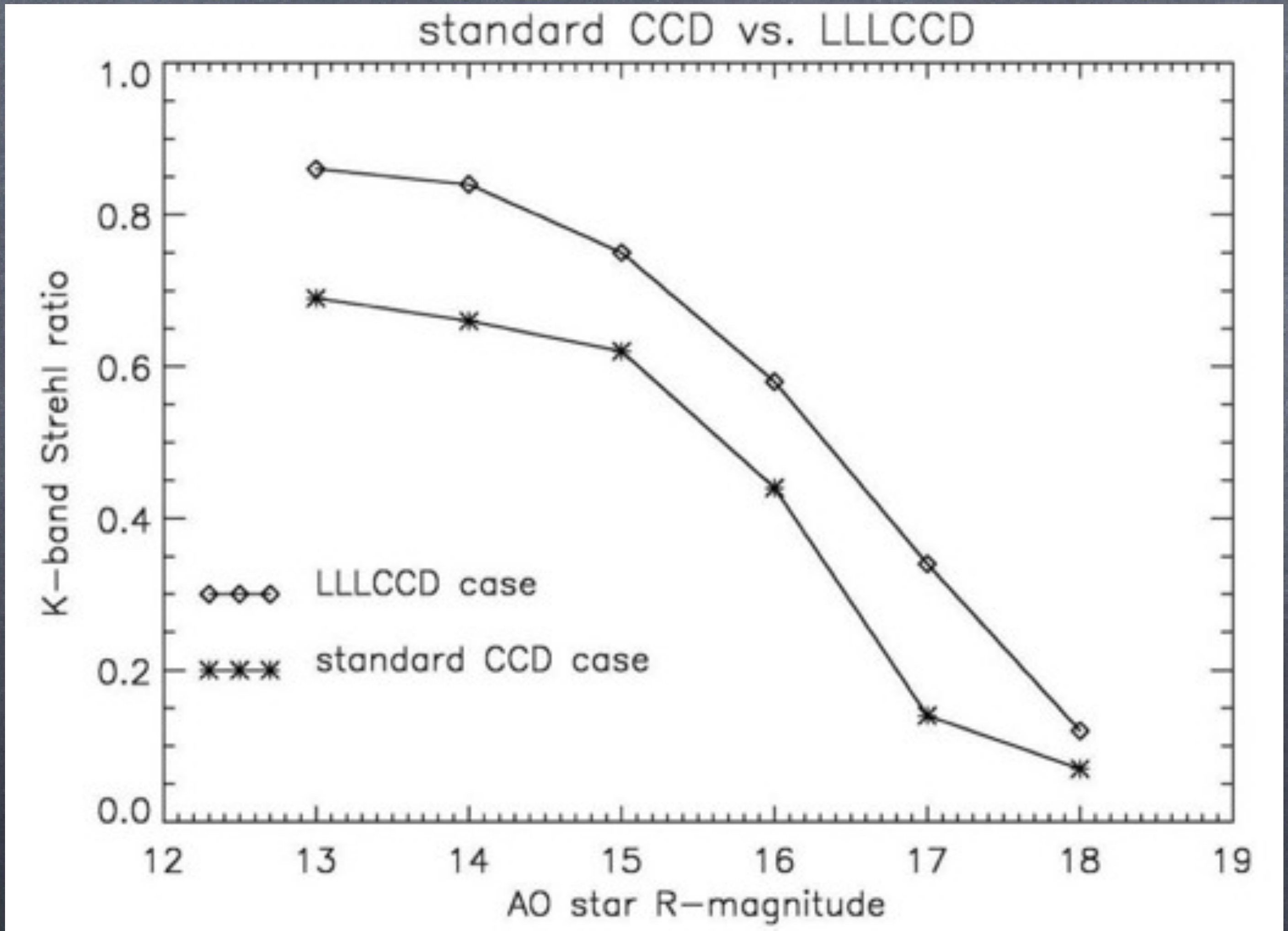
- Gain specified in the framework of FLAO/LBT end-to-end simulations: [Carbillet et al. SPIE *AO Conf. Proc.* 2003a]
  - 1-*mag*. gain in the faint end
  - a few % gain of Strehl ratio in the bright end



- .../...

AO Modelling - Wavefront Sensing: CCD vs. EMCCD

- What actual gain if using an Electron Multiplying CCD (EMCCD) instead of a standard CCD ?
- EMCCD: high internal gain => highly reduced read-out noise (RON)
  But: exotic dark current noise + “excess noise factor”
  In fact: amplification of the EMCCD => Gamma-distributed noise



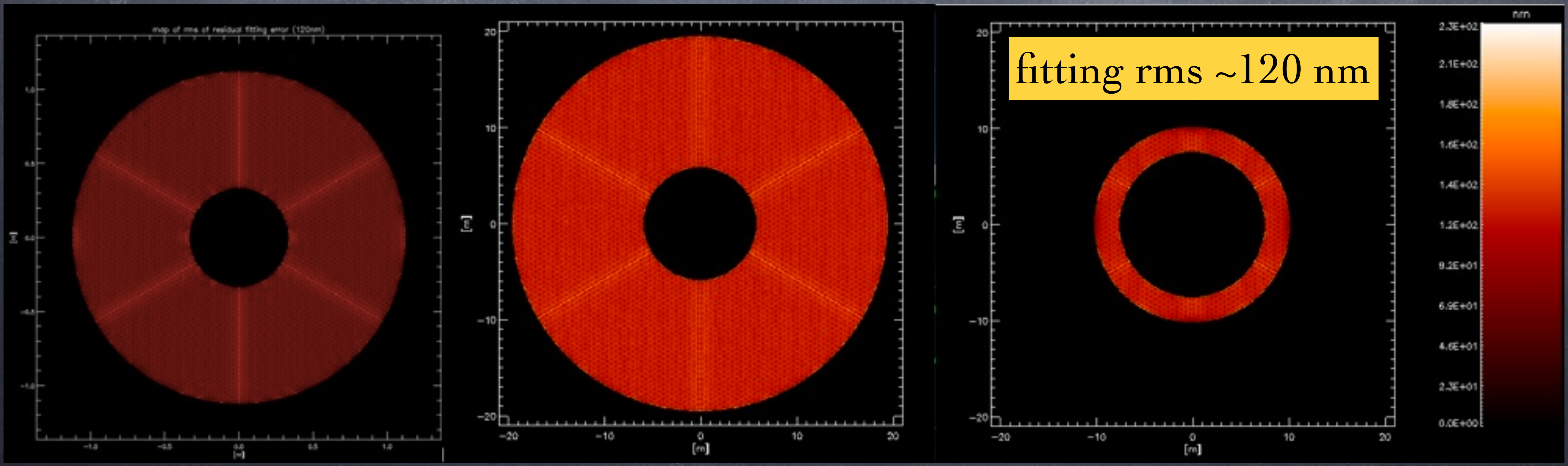
[Carbillet & Riccardi *App. Optics* 2010b]

AO Modelling - Wavefront Correction: M4/EELT

- *Secondary*-type adaptive mirror with ~5200 actuators (4300+ in pupil), 6 petals, ~2.5 m diameter.

- Goals:

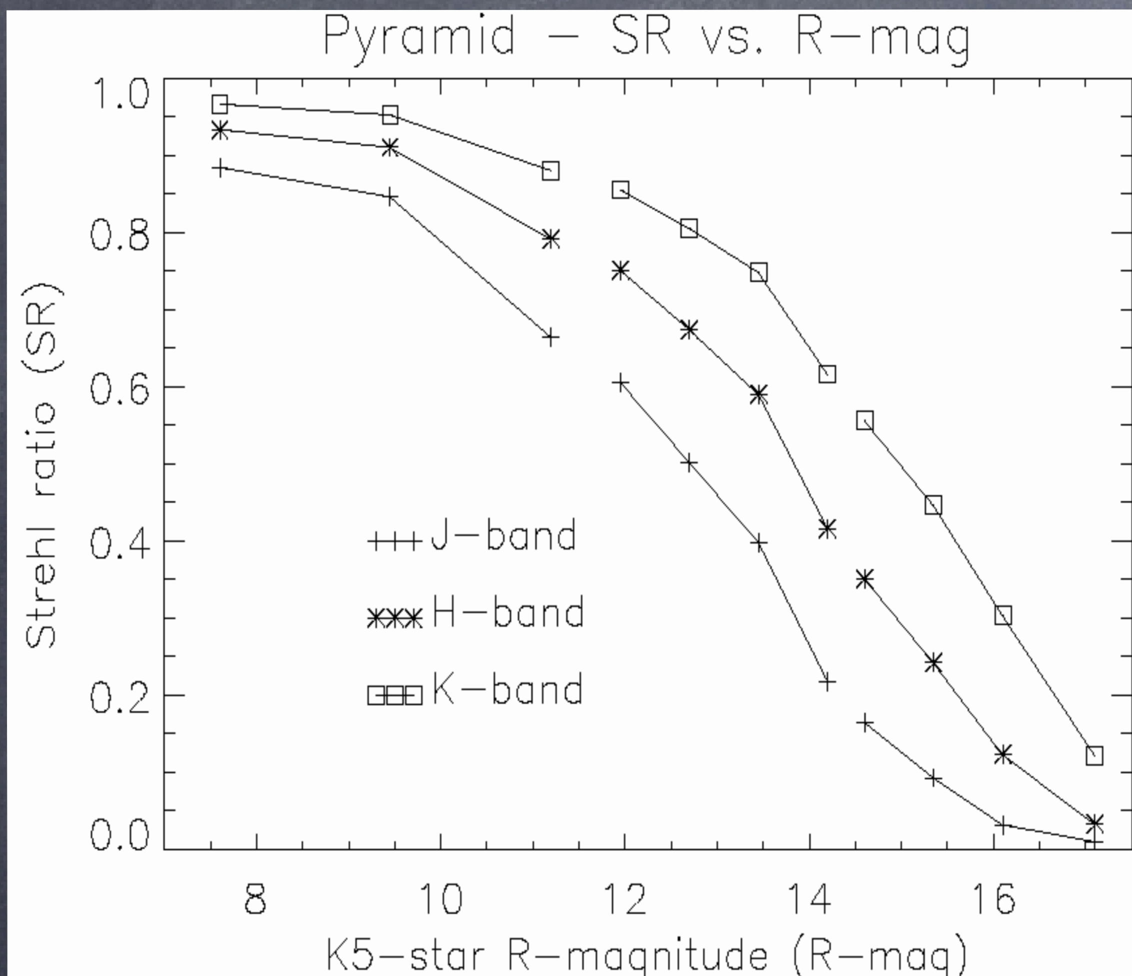
  + Exact evaluation of fitting error
  + Exact actuators management (*masters, forced slaves, unforced slaves*)
  + Assess simulation strategies (*petal-per-petal, whole pupil, reduced ring*)
  + But also: interaction with the WFS (Pyramid)...

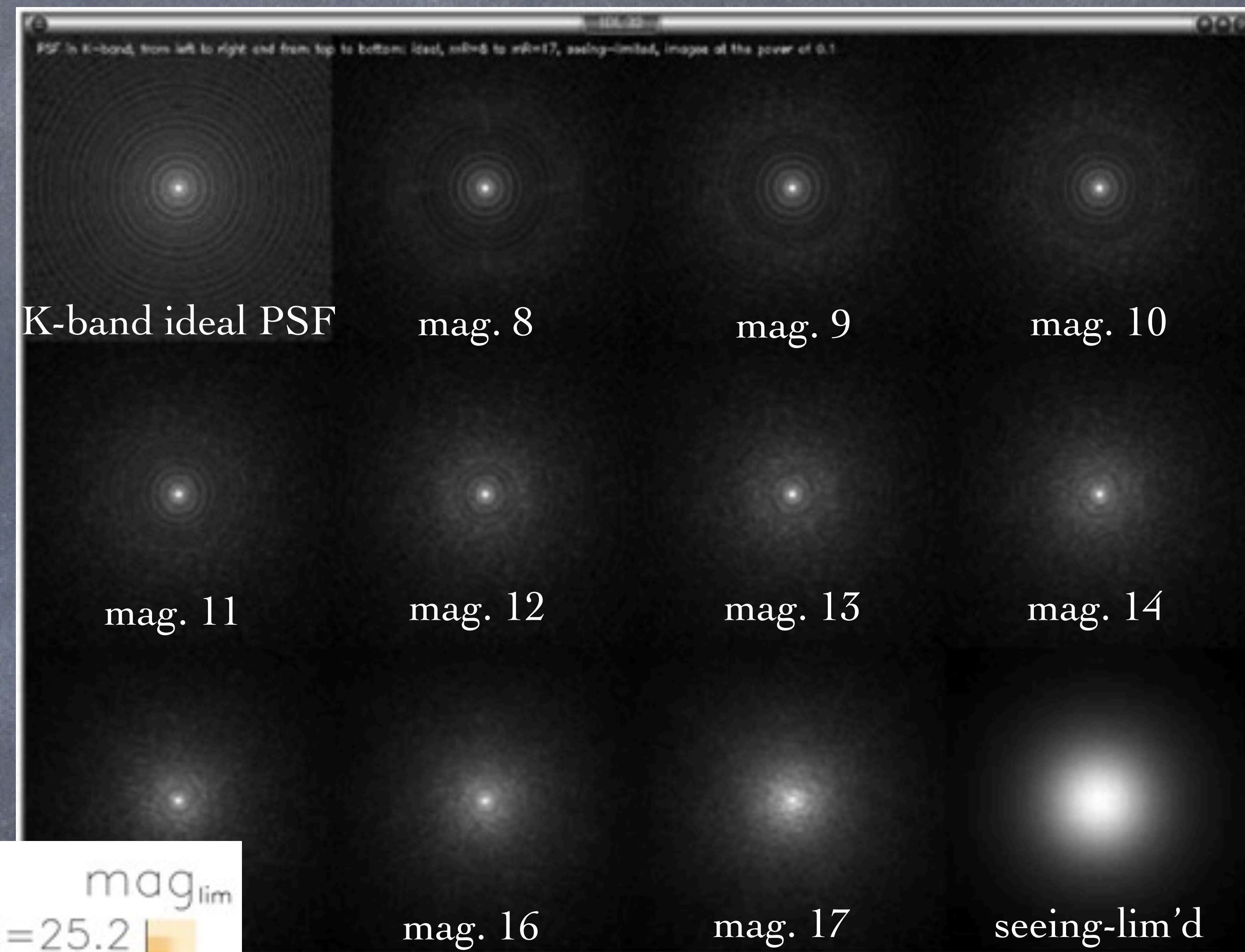


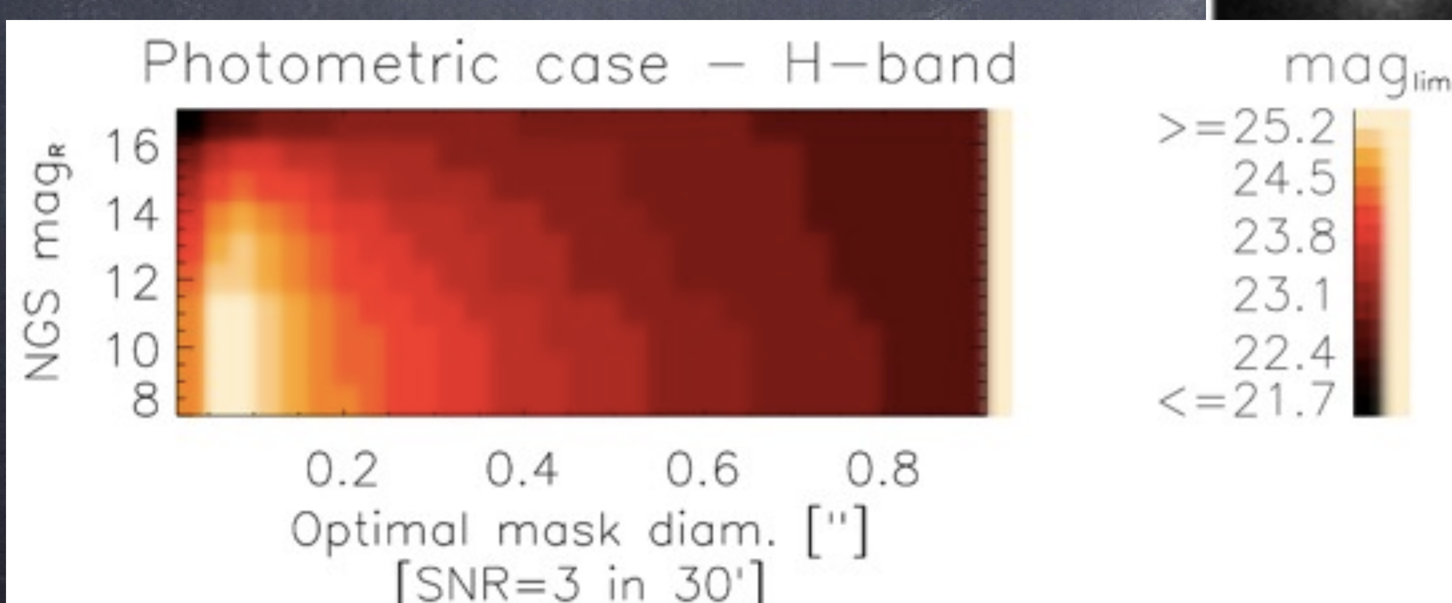
[Carbillet et al. SPIE *AO Conf. Proc.* 2012]

AO Modelling - Performance Studies: FLAO/LBT

- Simulated performances (and setting up) of FLAO/LBT, both in terms of Strehl ratio and in terms of coupling with scientific instrumentation.







AO Modelling - Performance Studies: FLAO/LBT

- In addition to performance, forecasting of optimization of the system wrt star *mag.* and AO system parameters [Carbillet et al. SPIE *AO Conf. Proc.* 2004]:

Table 3. Performance evaluation optimized parameters.

K5 star R-mag.	pyramid configuration	Δt [ms]	$\Rightarrow$ RON [e$^-$ rms]	number of modes	pyramid mod. [λ/D]
8	30×30	1.00	$\Rightarrow$ 8.4	671	±1
9	30×30	1.00	$\Rightarrow$ 8.4	500	±1
10	30×30	1.00	$\Rightarrow$ 8.4	450	±2
11	30×30	1.67	$\Rightarrow$ 8.4	400	±2
12	15×15	1.67	$\Rightarrow$ 5.8	150	±3
13	15×15	2.50	$\Rightarrow$ 4.5	130	±3
14	15×15	2.50	$\Rightarrow$ 4.5	105	±3
15	10×10	5.00	$\Rightarrow$ 3.5	60	±4
16	10×10	5.00	$\Rightarrow$ 3.5	55	±5
17	10×10	10.00	$\Rightarrow$ 3.5	45	±6

- Compared to what is done since 2010 on sky [Esposito et al. 2011-2012]:

Table 1. Typical system configurations used on sky as a function of the equivalent R-magnitude of the GS (M_R). The system parameters are: the binning mode, the temporal sampling frequency (f_s), the number of controlled modes (n_{mod}), and the pyramid modulation. Median RON values measured for each configuration are also listed.

M_R	Binning mode	*Pupil sampling (# subaps.)*	f_s (Hz)	n_{mod}	Pyr. mod. ($\pm\lambda/D$)	RON (σ_{e^-})
$M_R \leq 8.0$	1	30x30	990	500	2.0	10.5
$M_R \leq 10.0$	1	30x30	990	400	3.0	10.5
$10.0 < M_R < 13.5$	2	15x15	$990 \leq f_s \leq 300$	153	3.0	6.4
$13.5 \leq M_R < 14.5$	3	10x10	$500 \leq f_s \leq 200$	66	6.0	4.5
$14.5 \leq M_R < 16.5$	4	~7x7	$400 \leq f_s \leq 100$	36	6.0	4.6
$16.5 \leq M_R < 18.0$	4	~7x7	100	10	6.0	4.6

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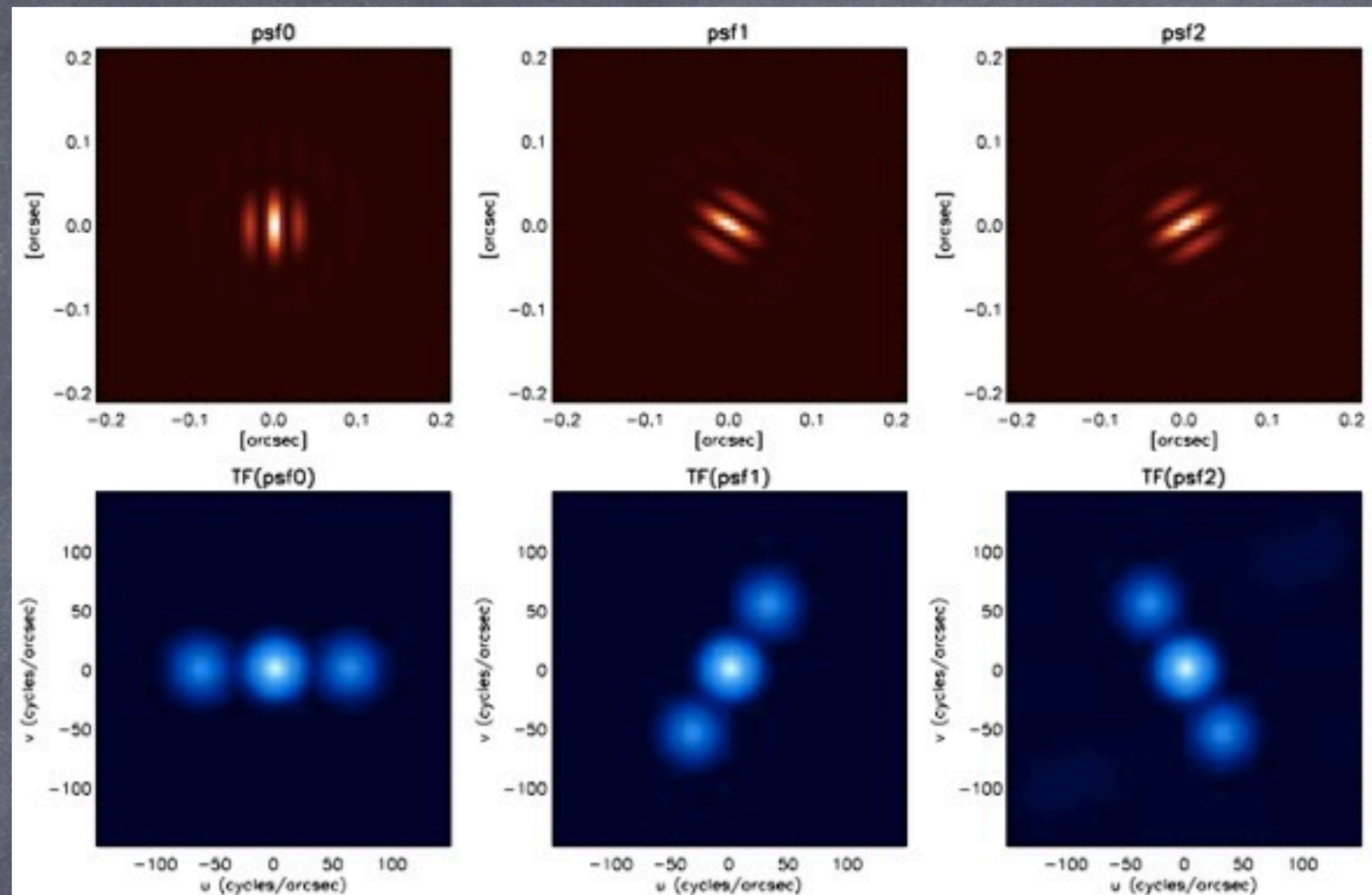
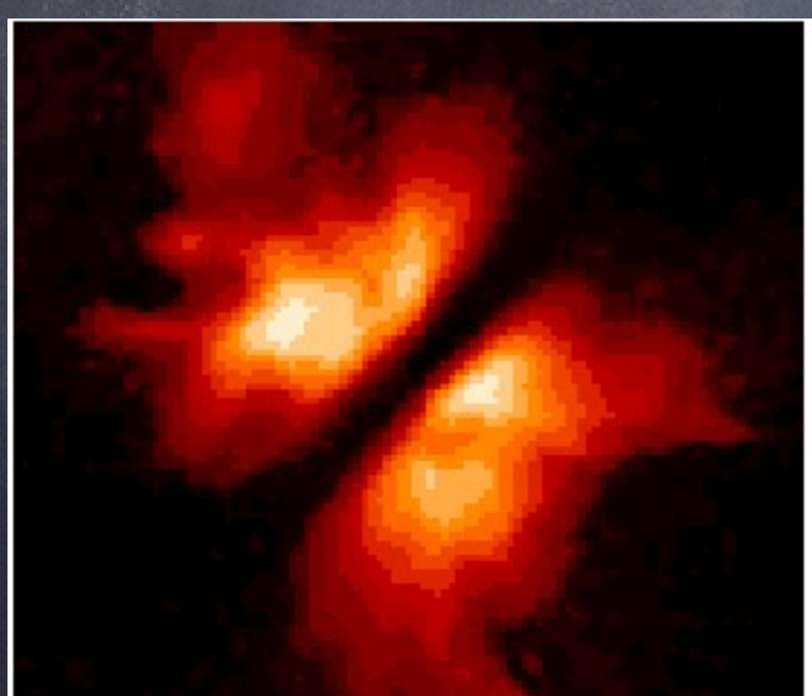
Post-AO Imaging - Context

- What we saw before: AO and instrument modelling for instrumental optimization.
- Can/must also be used then afterwards for (extended) performance evaluation, in terms of specific scientific return.
- For example, in the following: deconvolution methods (multiple dec. for Fizeau interferometric imaging, super-resolution, Strehl constraint for blind dec.), high-contrast imaging (coronagraphy), ...

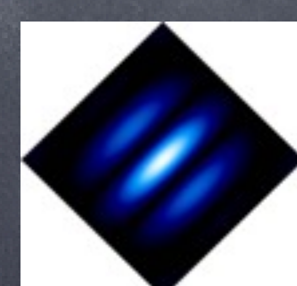
Post-AO Imaging - Fizeau interferometric imaging with LBT





astronomical object f

$*$



PSF K

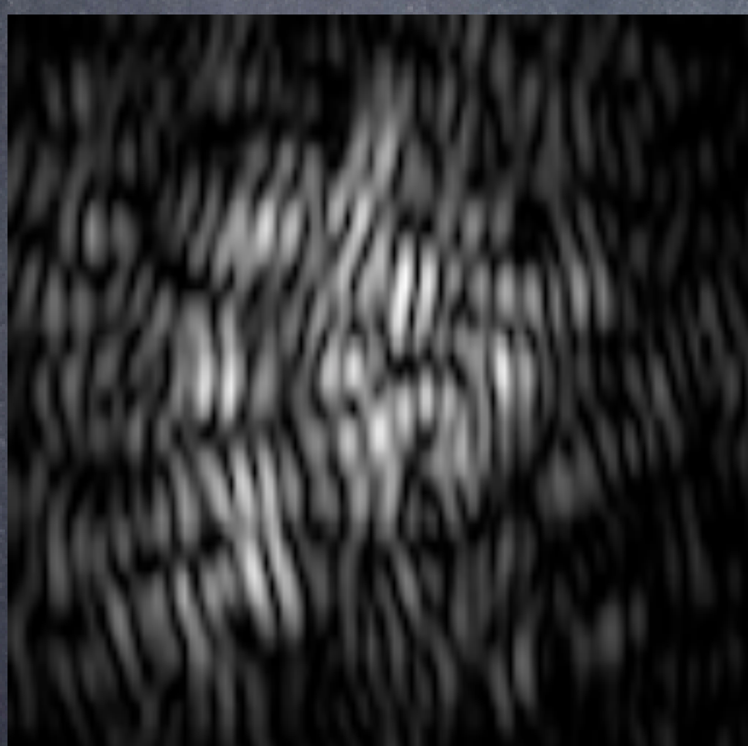
$=$

image g

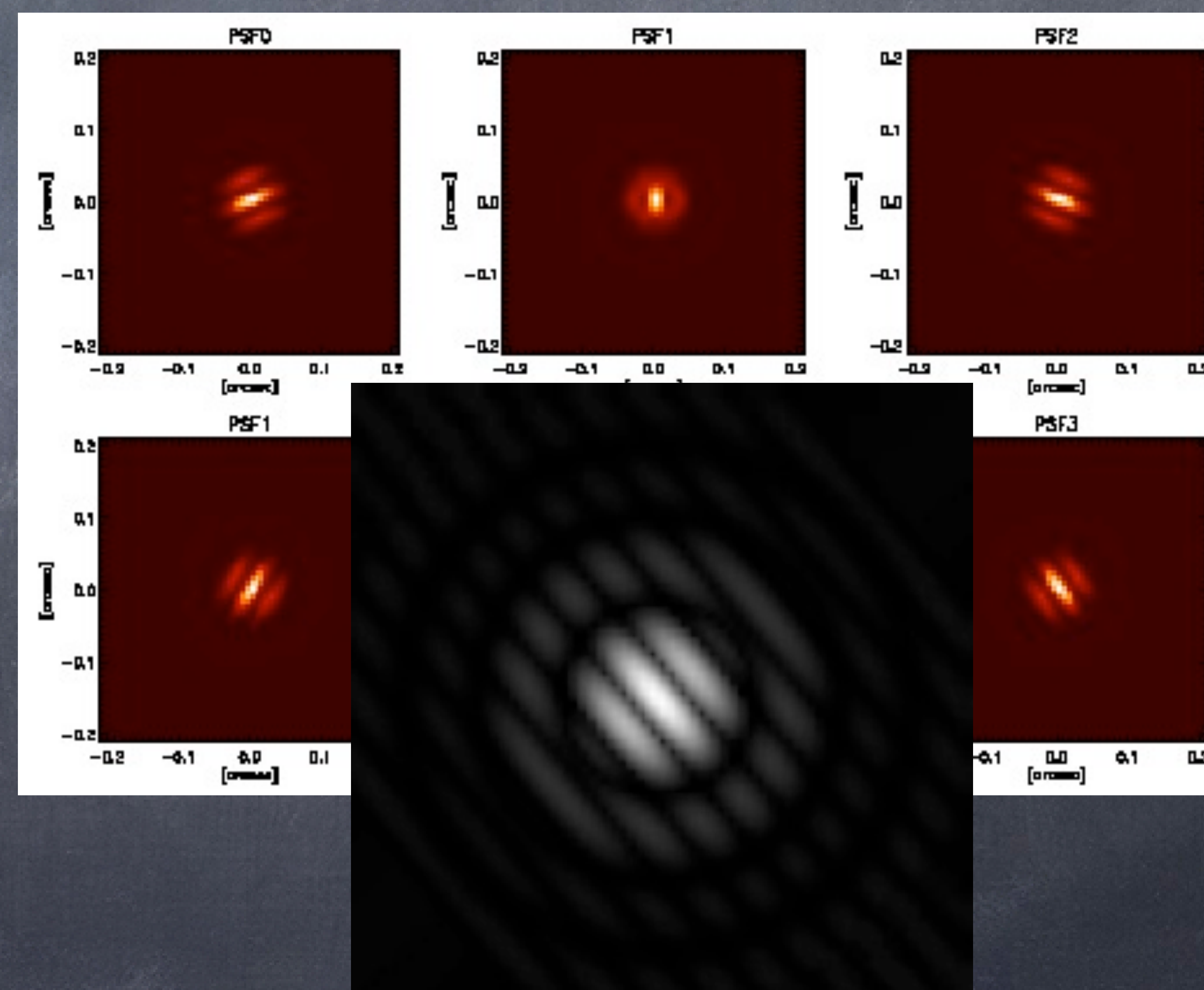
Post-AO Imaging - Fizeau interferometric imaging with LBT

- Multiple image deconvolution for object reconstruction: Ordered Subsets Expectation Maximisation (OSEM) [Bertero & Boccacci 2000]
- Implemented in `Soft.Pack.AIRY` [Correia, Carbillet et al. *A&A* 2002]

- Partial AO correction

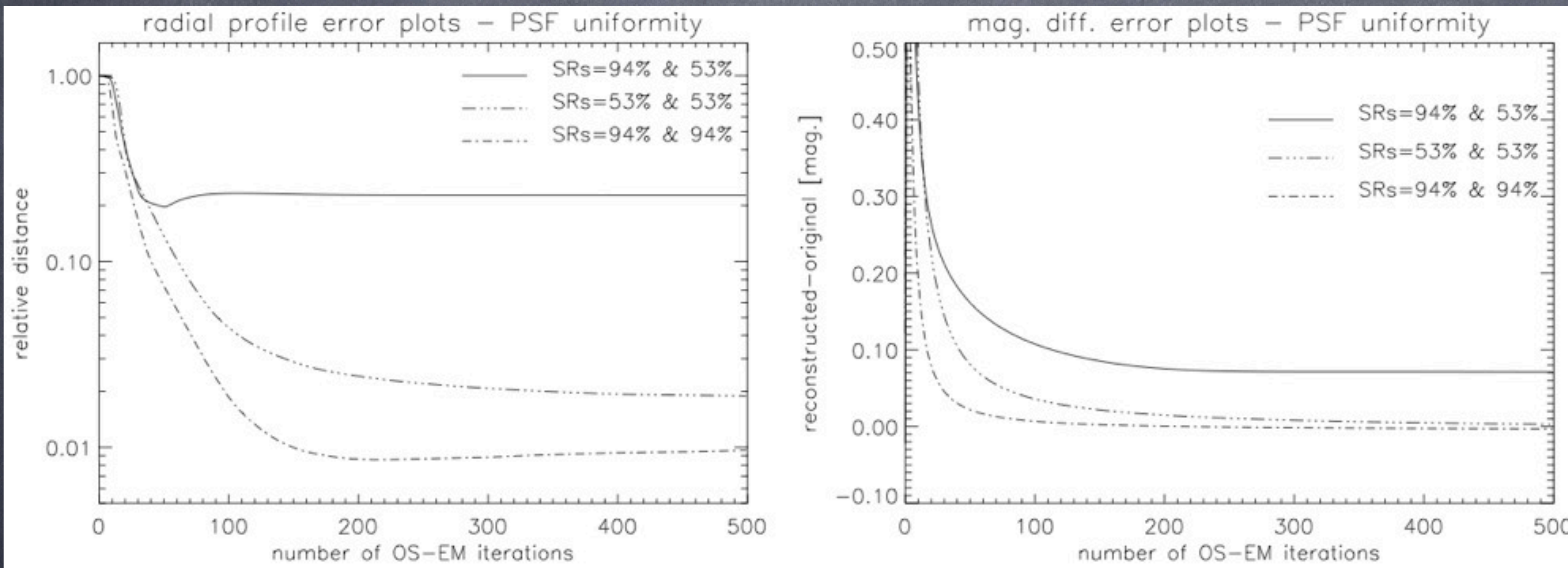


- Partial angular coverage



Post-AO Imaging - Fizeau interferometric imaging with LBT

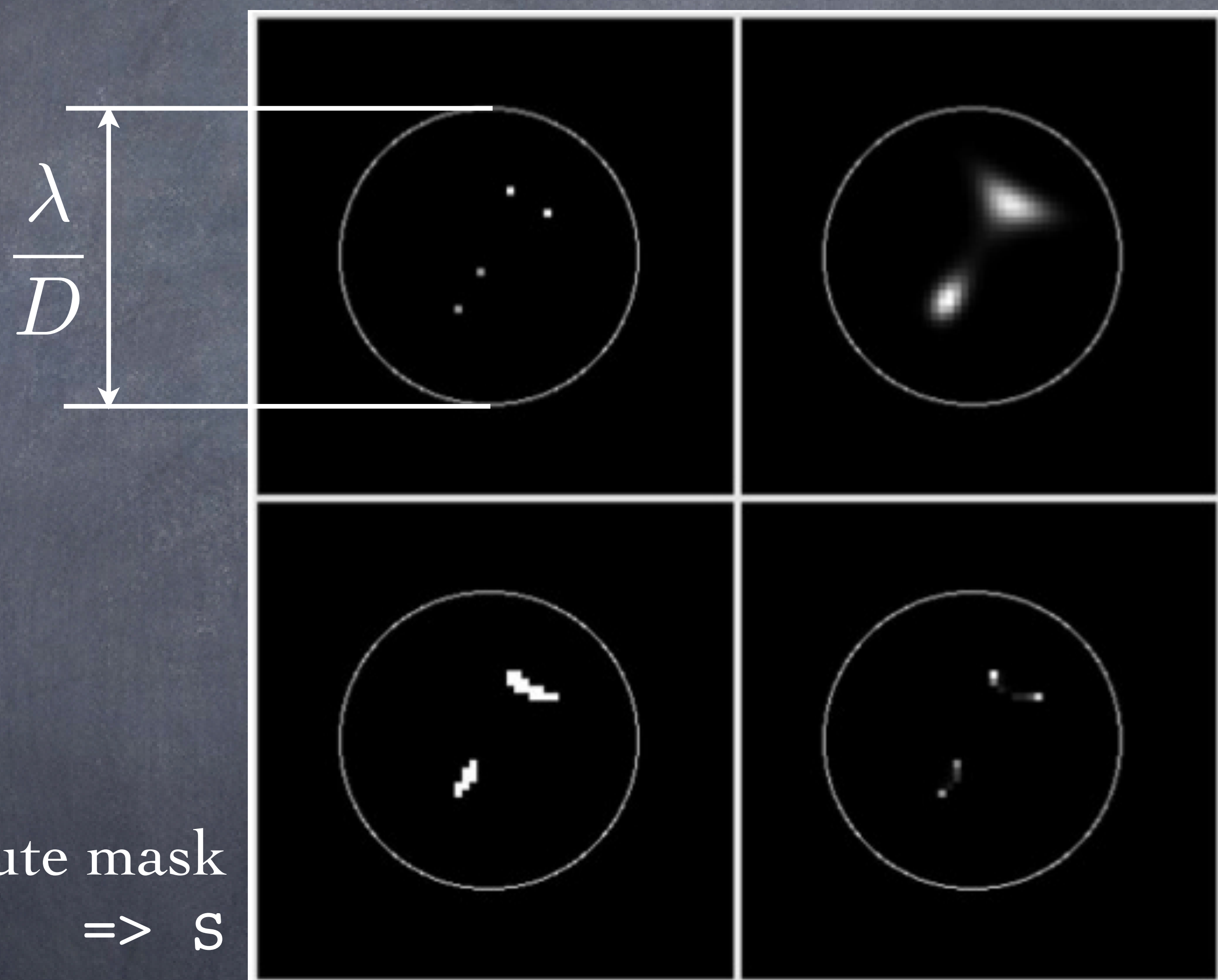
- Wide-field AO case (GLAO, MCAO):



=> Uniformity is a main issue, even at the cost of a lower average Strehl ratio [Carbillet et al. *A&A* 2002, Carbillet et al. SPIE *AO Conf. Proc.* 2003b]...

Post-AO Imaging - Deconvolution-Based Super-Resolution

- Method [Anconelli et al. *A&A* 2005]:



1st Lucy-Richardson deconvolution step
`[f₁⁽⁰⁾=const.]`

$[f_1^{(0)}=\text{const.}]$
$\Rightarrow f_1=f_1^{(\text{many iter.})}$

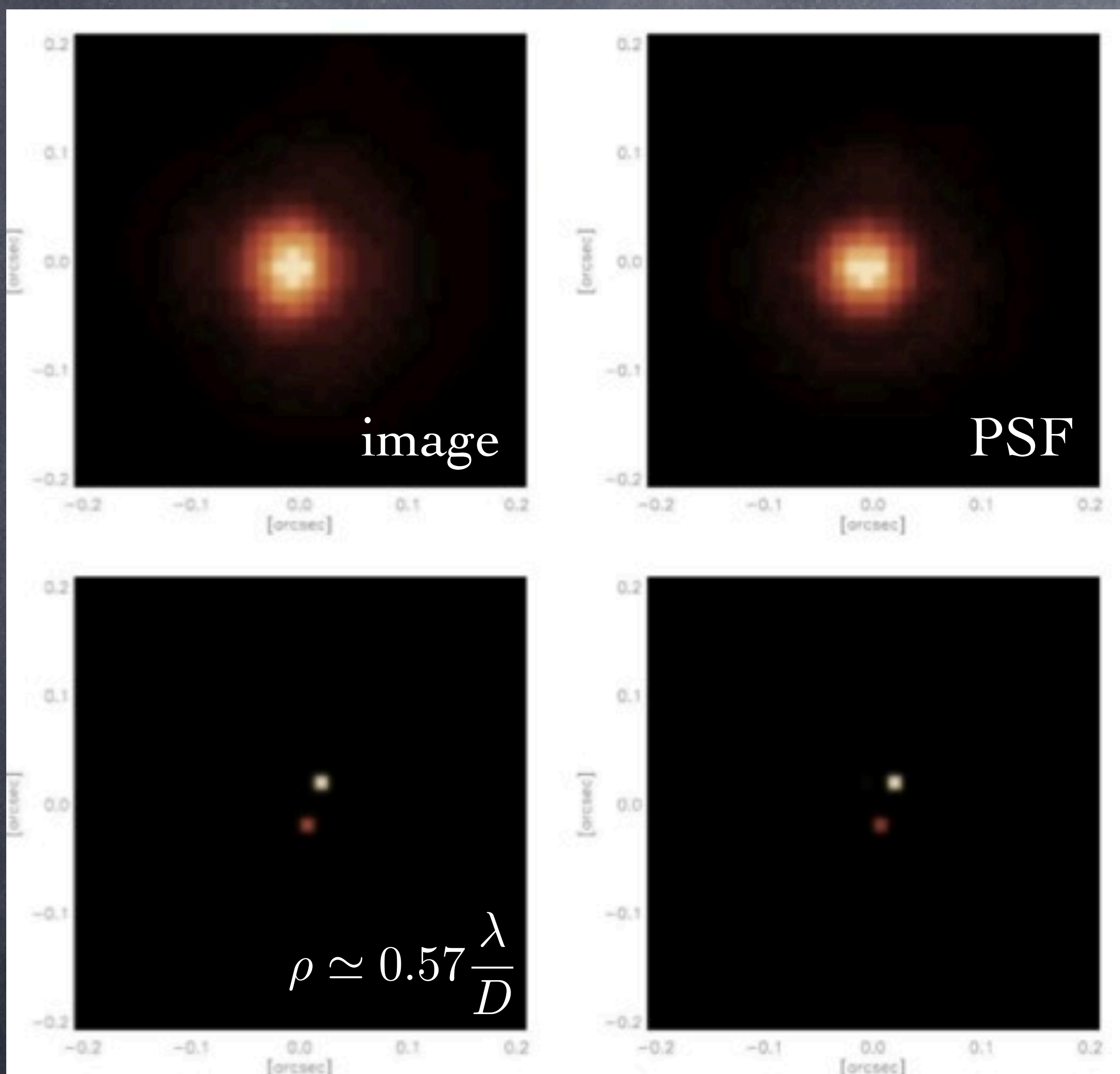
Compute mask
$\Rightarrow S$

2nd Lucy-Richardson deconvolution step
$[f_2^{(0)} = S]$
$\Rightarrow f_2=f_2^{(\text{many iter.})}$

Post-AO Imaging - Deconvolution-Based Super-Resolution

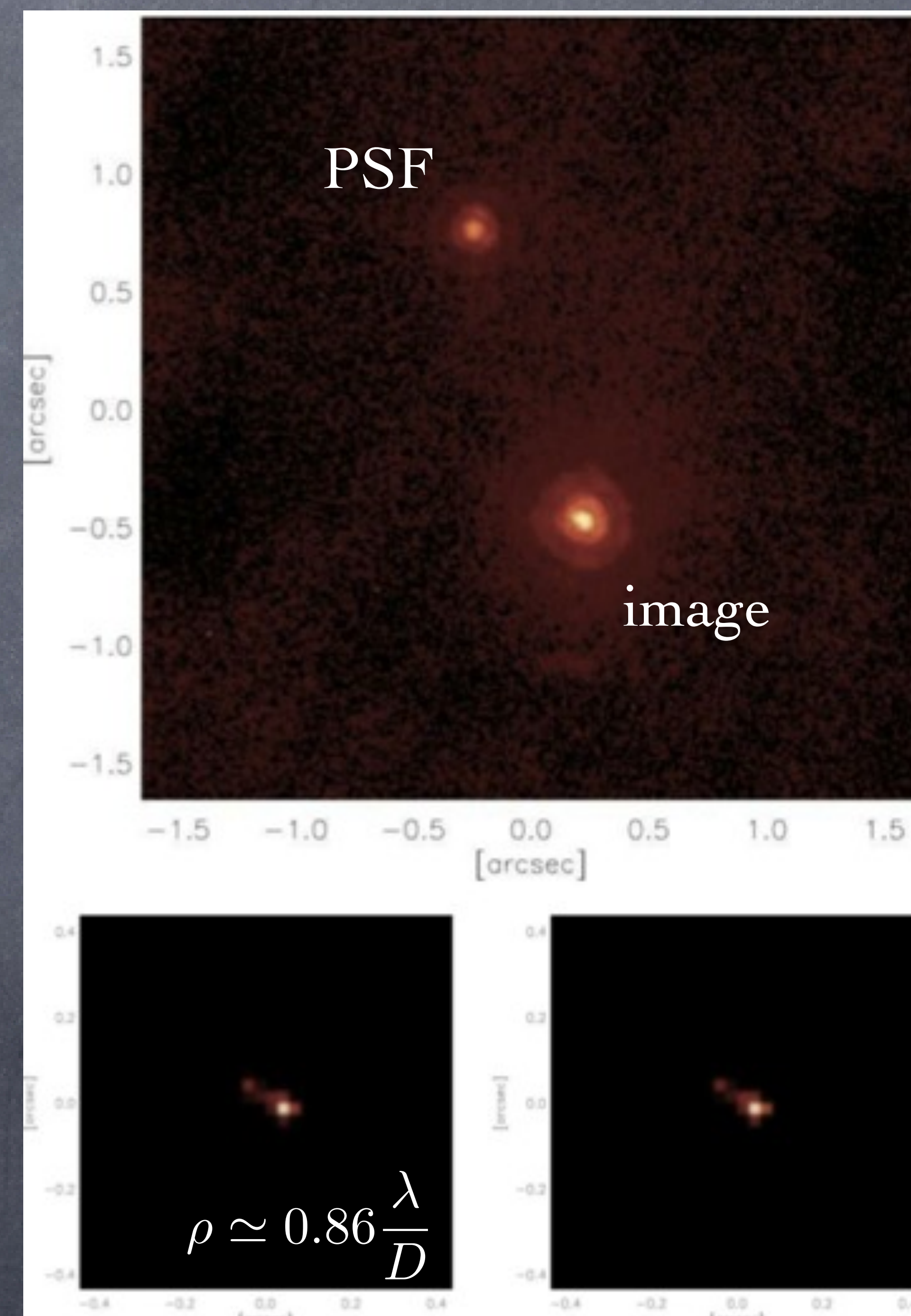
- First results on real post-AO data (NACO/VLT) [Carbillet et al. *AO4ELT#3* 2013]:

HD 87643



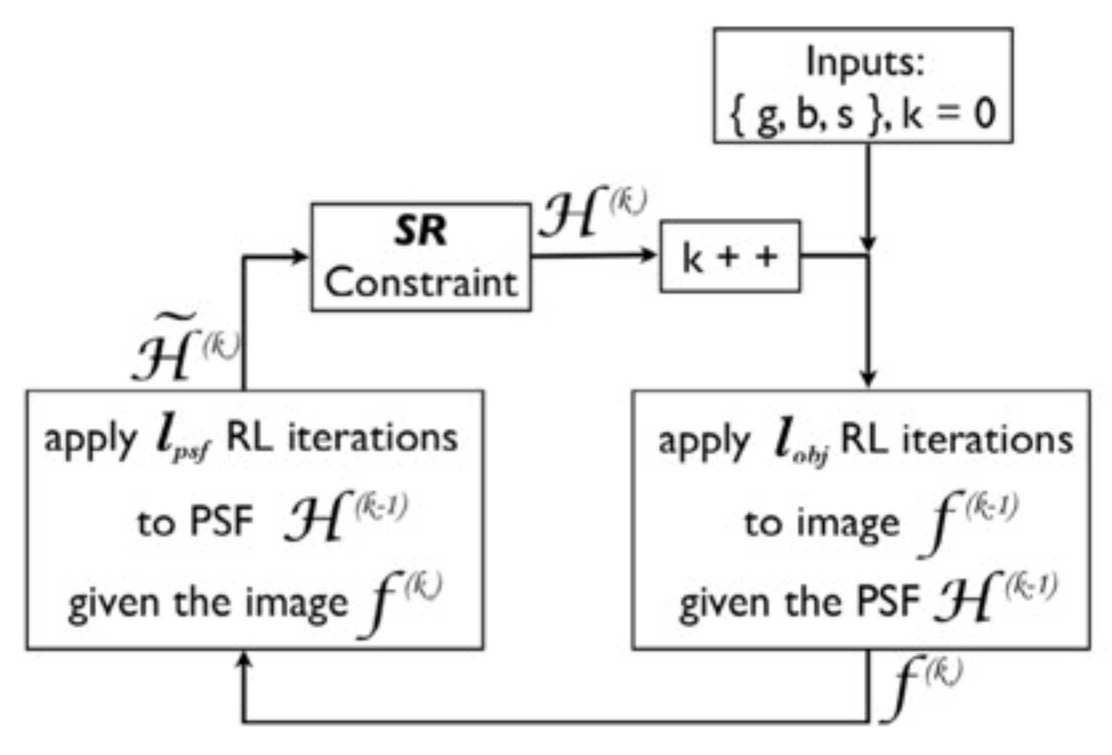
(HD 87643 confirmed by AMBER/VLTI obs.)

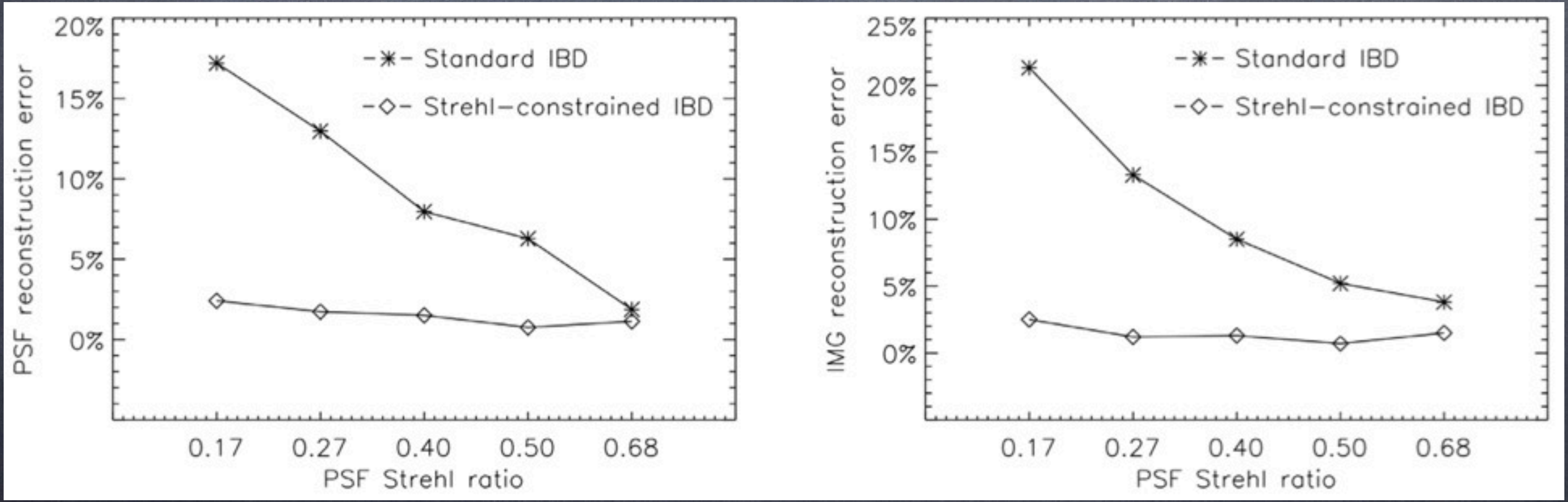
HD 216405



Post-AO Imaging - Strehl-Constrained Blind Deconvolution

- Application of a constraint on the Strehl ratio of the reconstructed PSF when performing iterative blind deconvolution (IBD) on post-AO data [Desiderà & Carbillet *A&A* 2009]



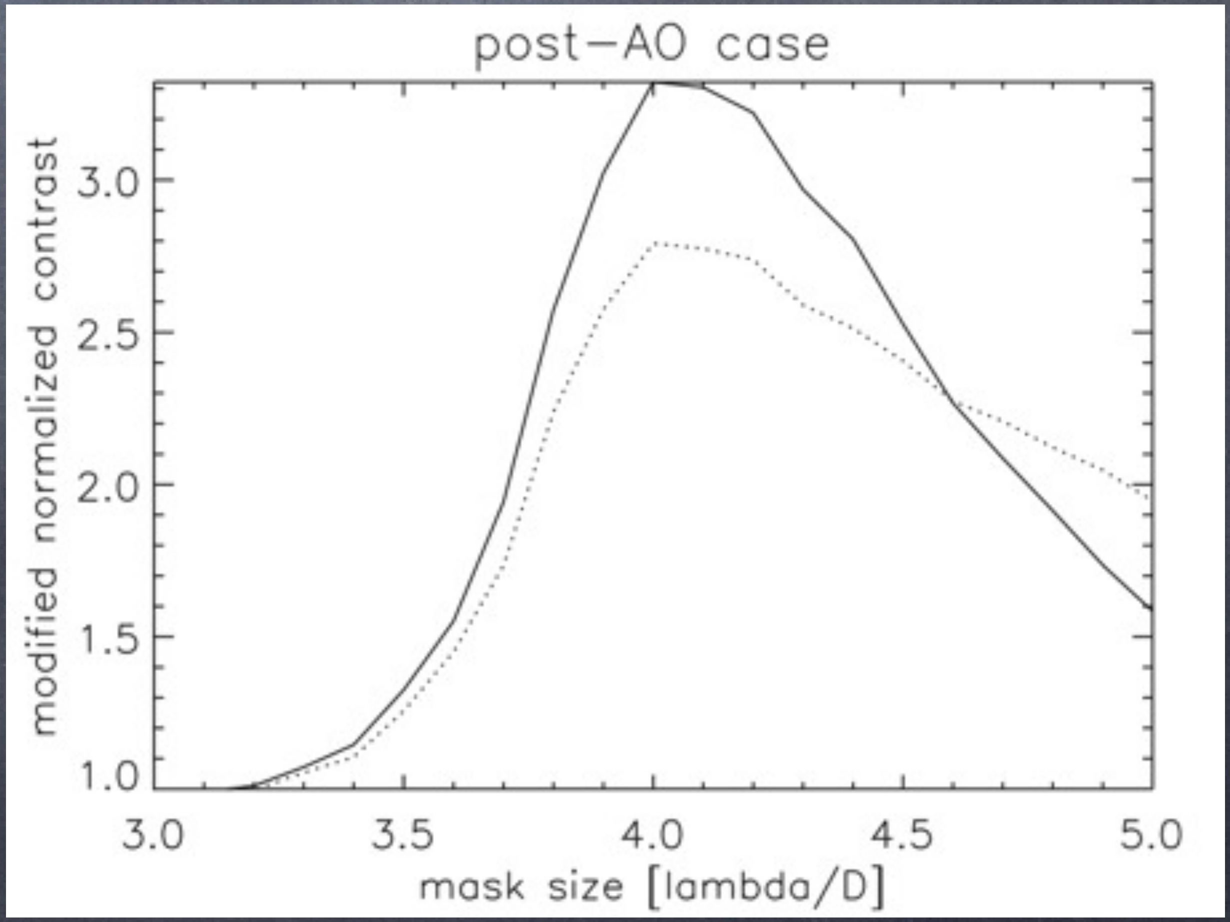


- Also regularizes the blind algorithm, making it more robust wrt choice of the reconstruction parameters !

Post-AO Imaging - High-Contrast Imaging with SPHERE

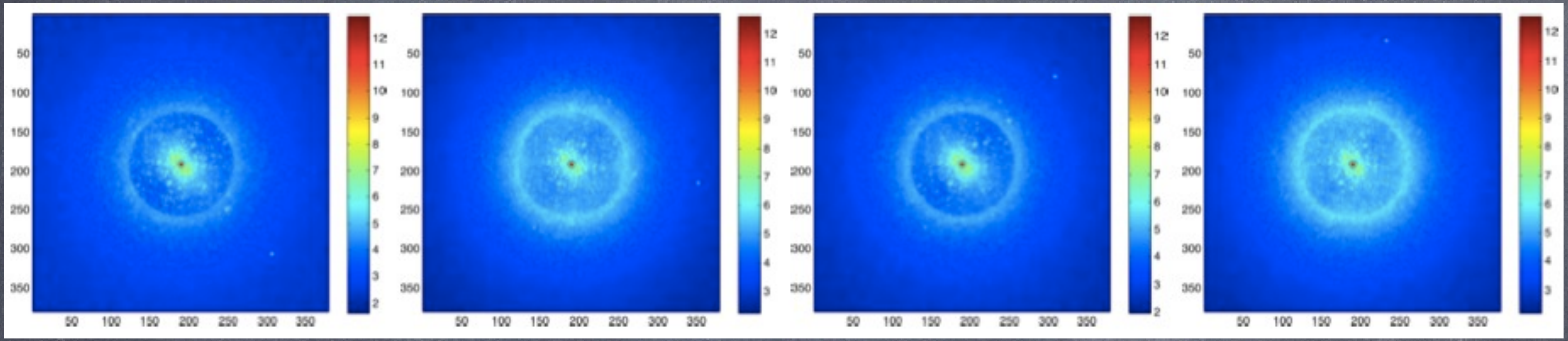
- `Soft.Pack.SPHERE` [Carbillet et al. SPIE *AO Conf. Proc.* 2008] within the `CAOS PSE` for:
  - “System” simulations (IRDIS, IFS, ZIMPOL, coronagraphs).
  - IRDIS test case data elaboration for testing of the algorithms for exoplanet detection.
  - Preparation of observations for the “Other Science” case.

- Apodized Lyot coronagraph detailed numerical studies: apodizer optimization through a *modified* contrast inside (---) and outside (...) AO-cleaned area
  + various defect studies (=> tolerance profile + spec. + reduction of Lyot stop to cancel out phase defects).
  [Carbillet et al. *Exp. Astronomy* 2010]

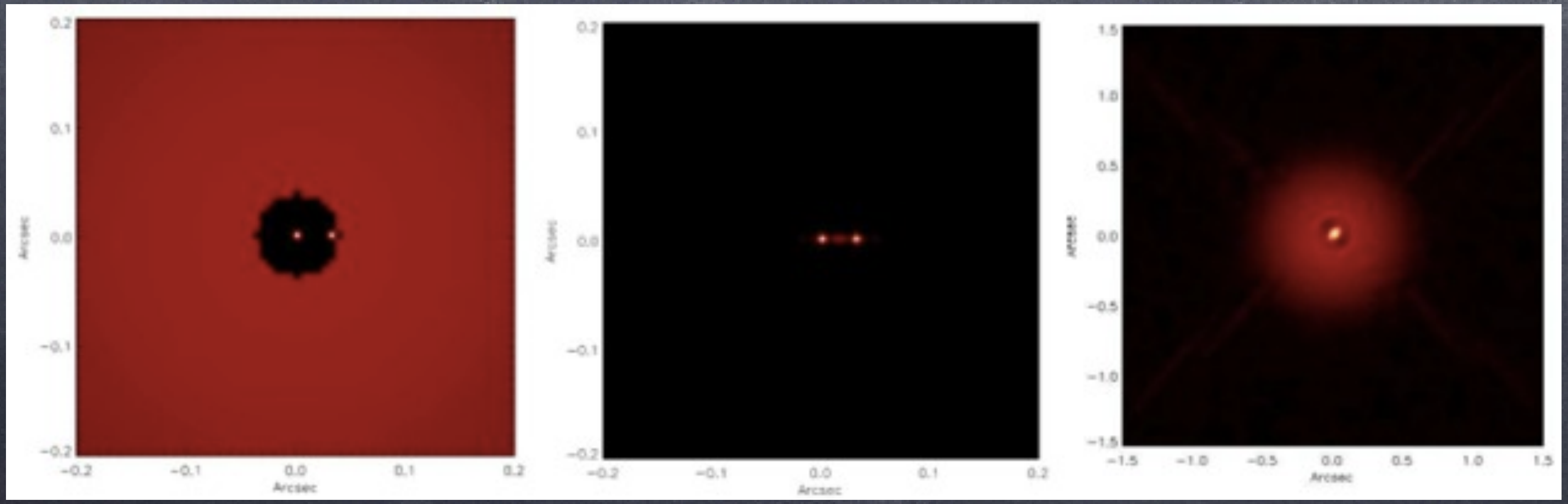


Post-AO Imaging - High-Contrast Imaging with SPHERE

- IRDIS test case data elaboration for testing exoplanet detection [Smith, Carbillet et al. *AO Conf. Proc.* 2008]: 4-hr observation, 100-s images, with seeing, wind speed, and quasi-static wavefront errors evolution, ADC residuals, etc.



- Preparation of observations for the "Other Science" cases



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  [`Soft.Pack.CAOS`, `Soft.Pack.AIRY`]

Outline

- **Introduction**
  [From PhD to HDR, Observations & Turbulence, `PSE CAOS`]
- **AO Numerical Modelling**
  [Atmosphere, Wavefront Sensing, M4/E-ELT, FLAO/LBT]
- **Post-AO Imaging**
  [LN/LBT, Super-Resolution, Strehl Constraint, SPHERE/VLT]
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Summary & Prospects - Summary

- AO Modelling
  - Numerical studies for FLAO/LBT + initial developments of the `Soft.Pack.CAOS` and the `CAOS PSE` [while at INAF-OAA]
    - Setting up and performance evaluation of FLAO/LBT
    - Atmospheric modelling enhancements
    - WFS studies (SH vs. Pyramid, EMCCD)
  - Numerical studies for M4/EELT [collaboration INAF-OAA]
  - AO system study for Dome C [local collaboration]
  - Intervalidation and search for trade-offs between end-to-end modelling and analytical modelling [collaboration L.Jolissaint]

Summary & Prospects - Summary

- Post-AO Imaging
  - Multiple image deconvolution for LN/LBT + initial developments of the `Soft.Pack.AIRY` [collaboration Università di Genova ++]
    - Partial AO and angular coverage limitation studies
    - Super-resolution, then applied to real NACO/VLT data
  - Strehl-constrained blind deconvolution [id.]
  - Studies for SPHERE [local+consortium collaboration]
    - Apodized Lyot coronagraph setting up
    - IRDIS test case data elaboration for detection tests
    - "Other Science" preparation of observations

Summary & Prospects - Prospects

- AO Modelling
  - Continue developments of `Soft.Pack.CAOS` et similia
  - Questioning of common assumptions in atmospheric turbulence modelling (Fresnel, Taylor, $L_0(h)$) [local collaboration]
  - Continue M4/EELT studies (interaction w/Pyramid)
  - Continue "end-to-end vs. analytical" work
  - Conclude AO-for-Dome-C study from last atmospheric measurements

Summary & Prospects - Prospects

- Post-AO Imaging
  - Continue developments of `Soft.Pack.AIRY` et similia
  - Continue to apply super-resolution to real post-AO data
  - Enhance (Prato et al. '13) Strehl-constrained blind deconvolution and apply to real post-AO data
  - Continue SPHERE/VLT preparation of observations
  - Set up techniques for low-Strehl regime post-AO data, at the boundary between "classical" deconvolution and speckle imaging techniques (ODISSEE/MeO, other ?) [ONERA collaboration]

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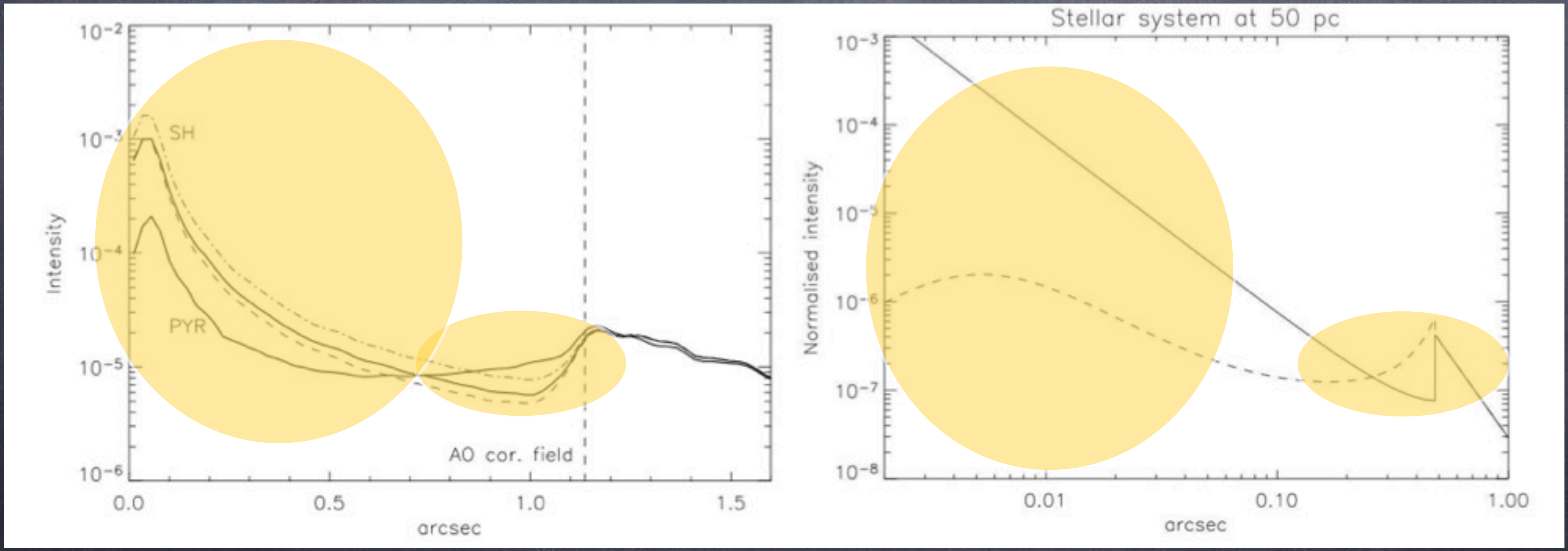
Demo...

Wavefront sensing: SH vs. Pyramid

- Poyneer & Macintosh 2004: spatially-filtered SH (aliasing)
  + Nicolle et al. 2004: optimized SH signals calculation
  => Fusco et al. 2005: SH ~ Pyramid (SPHERE/VLT studies)

- Vérinaud et al. *MNRAS* 2005: Pyramid best near the core of the PSF, SH best on the edge of the AO-cleaned area...

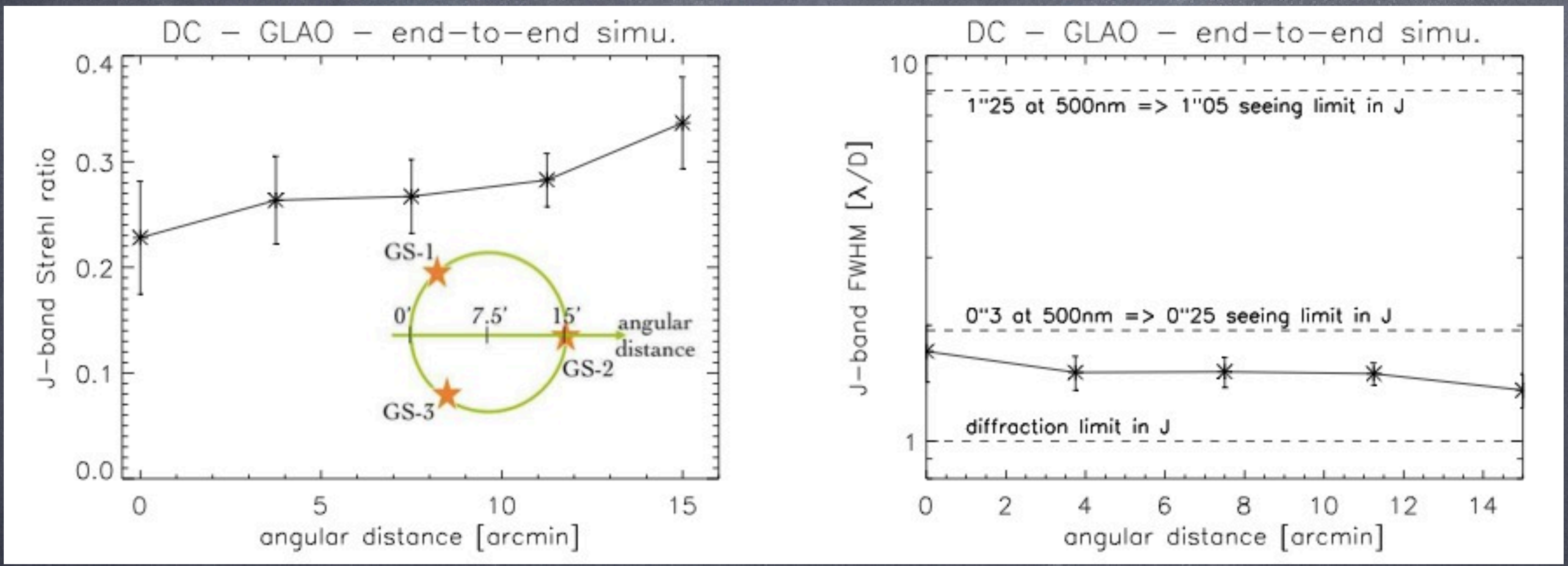


Wavefront sensing: SH vs. Pyramid

- First on-sky results of Pyramid-based FLAO/LBT: 2010.
- First on-sky results of SH-based SPHERE/VLT: 2014...

AO Modelling - Performance Studies: Which AO at Dome C ?

- Goal: exploitation of the ultimate data from site testing to define which AO system is best for Dome C (in particular for wide-field astronomy -- and possibly high-Strehl one).



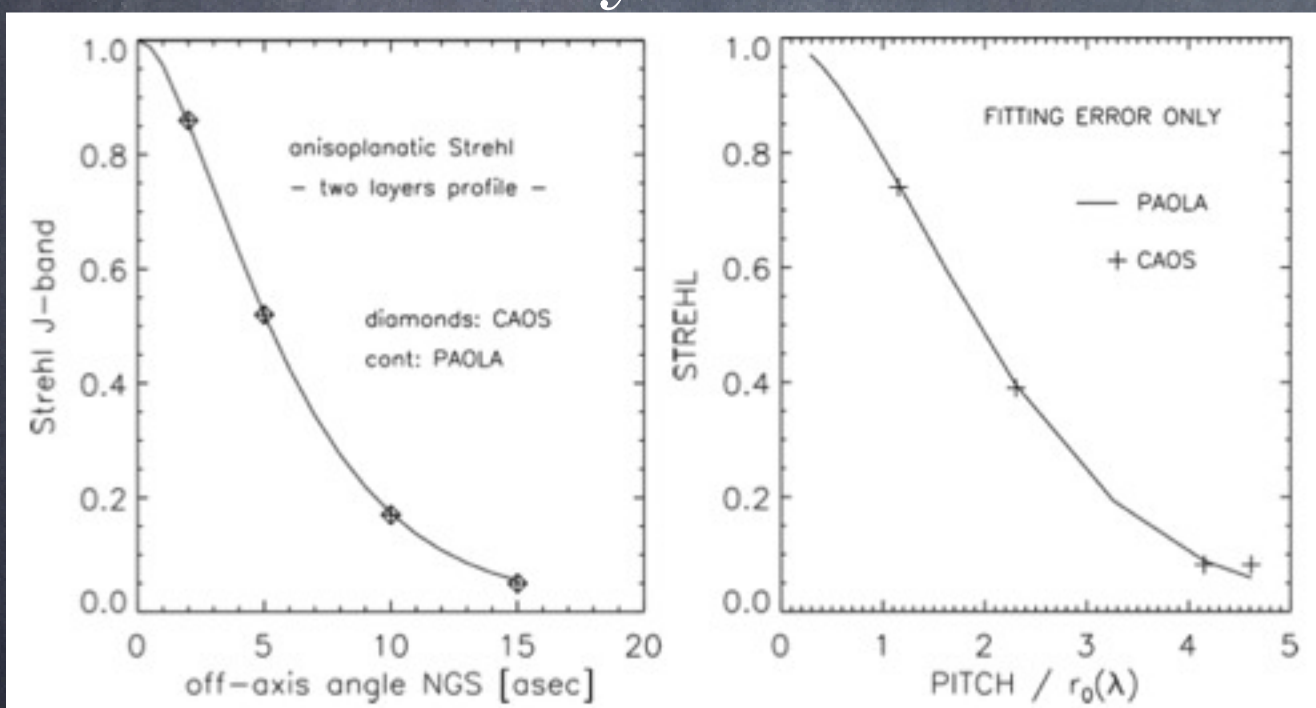
[Carbillet et al. *ARENA#3 Conf. Proc.* 2010]

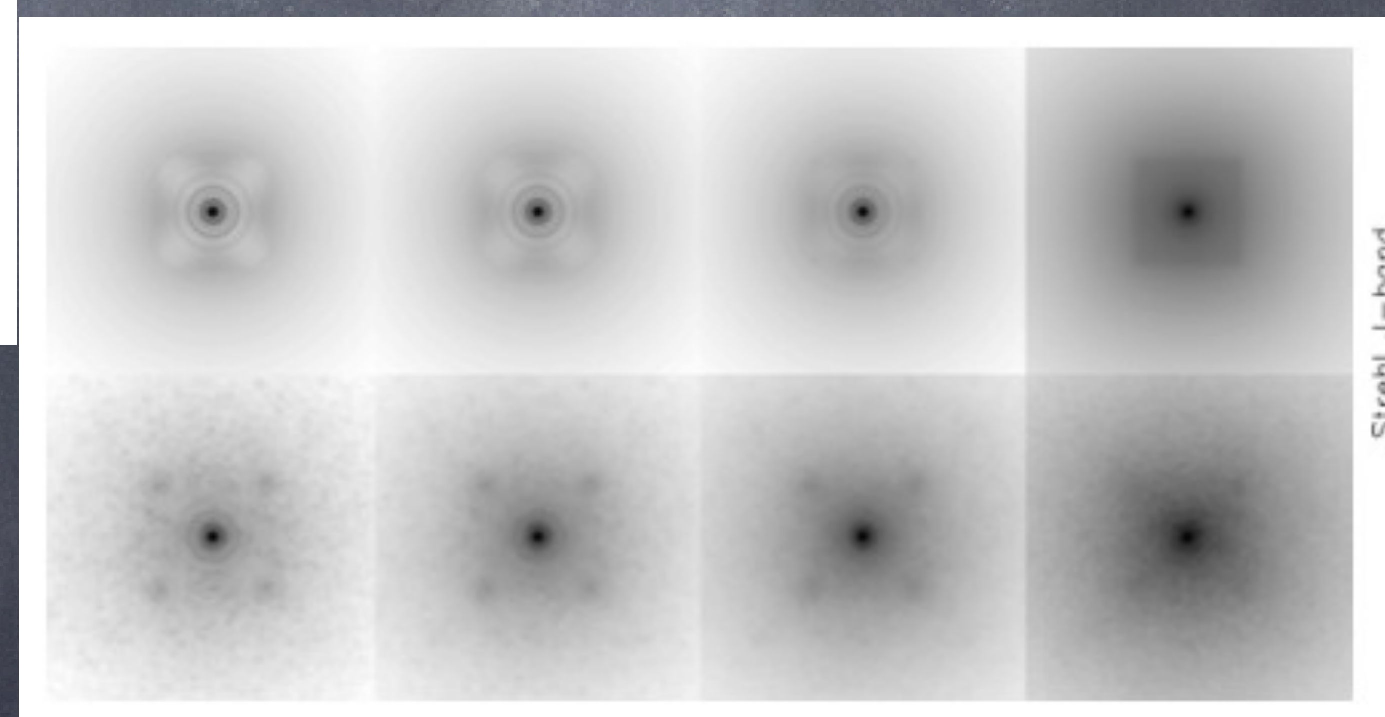
- But: seeing distribution is bi-modal [Aristidi et al. 2009], and (because!) ground layer is extremely thick (30-40m)...

AO Modelling - End-to-end Modelling vs. Analytical Modelling

- Comparison between end-to-end modeling “à la `CAOS`” (more precise but very time- and memory-expensive) and analytical modeling “à la `PAOLA`” (fast answer but lots of assumptions).

- Goals: inter-validation & search for useful trade-offs, in particular for wide-field AO, high-contrast imaging, extremely large apertures, long-baseline interferometry, etc.





[Carbillet & Jolissaint *AO4ELT#2 Conf. Proc.* 2012]

Post-AO Imaging - Fizeau interferometric imaging with LBT

- Multiple image deconvolution for object reconstruction: Ordered Subsets Expectation Maximisation (OSEM) [Bertero & Boccacci 2000]

Algorithm 1 RL method

Choose the starting point $\mathbf{f}^{(0)} \geq 0$

FOR $k = 0, 1, 2, \ldots$ COMPUTE:

$$\mathbf{f}^{(k+1)} = \mathbf{f}^{(k)} A^T \frac{\mathbf{g}}{A\mathbf{f}^{(k)} + \mathbf{b}}$$

END

1- initialize with $f^{(0)}$ positive

2- given $f^{(k)}$ set $h^{(0)}=f^{(k)}$ and, for $j=0,1..p$, compute

$$h^{(j)} = h^{(j-1)} K_j^{(-)} * g_j / (K_j * h^{(j-1)} + b_j)$$

3- set $f^{(k+1)} = h^{(p)}$

where:

k=index of the OS-EM iterative method,

p=nb of observations (at diff. angles),

$K_j^{(-)}=K_j$ reflected wrt the center of the array

$g = K*f + b$; $K*f = Af$