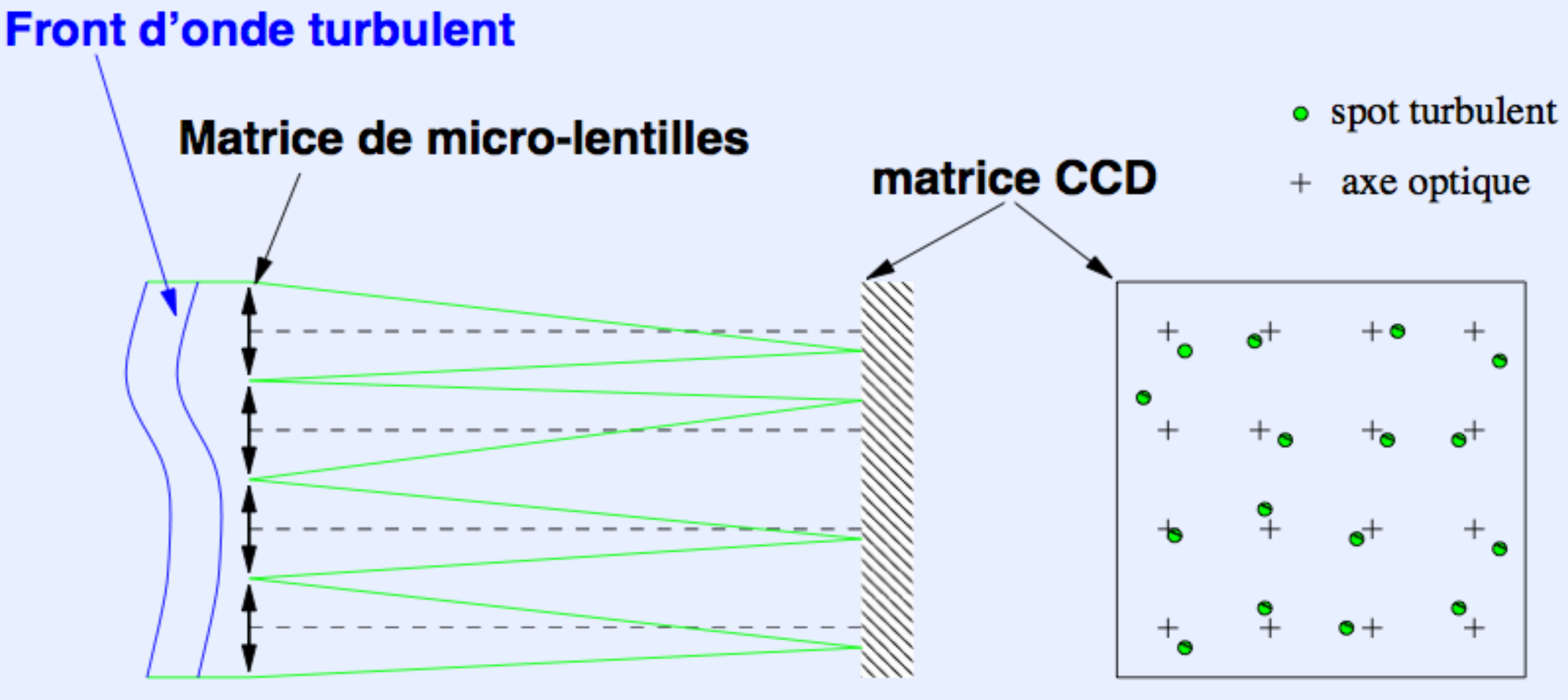
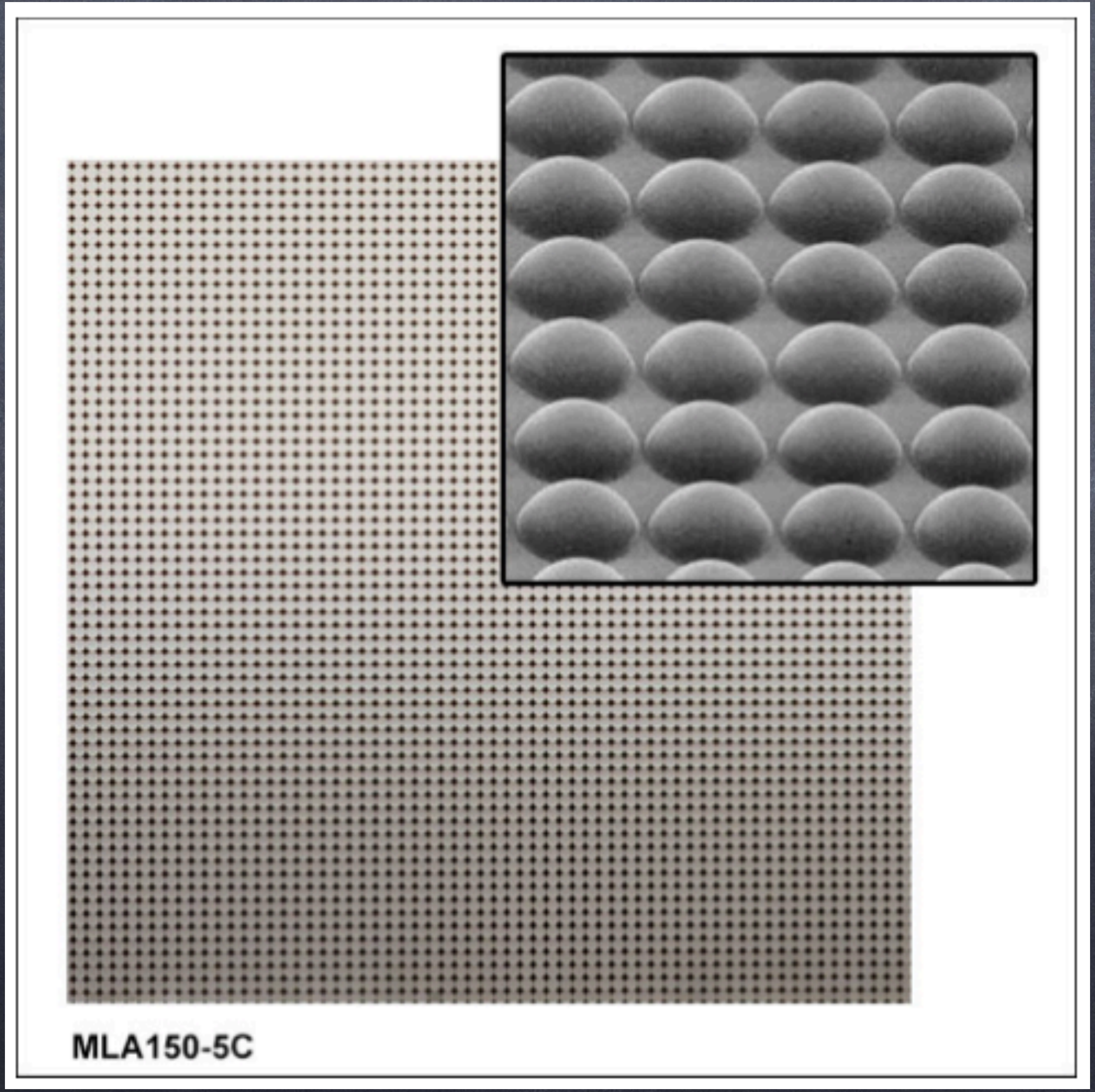
Wavefront sensors - 1

First example of wavefront sensor: Shack-Hartmann



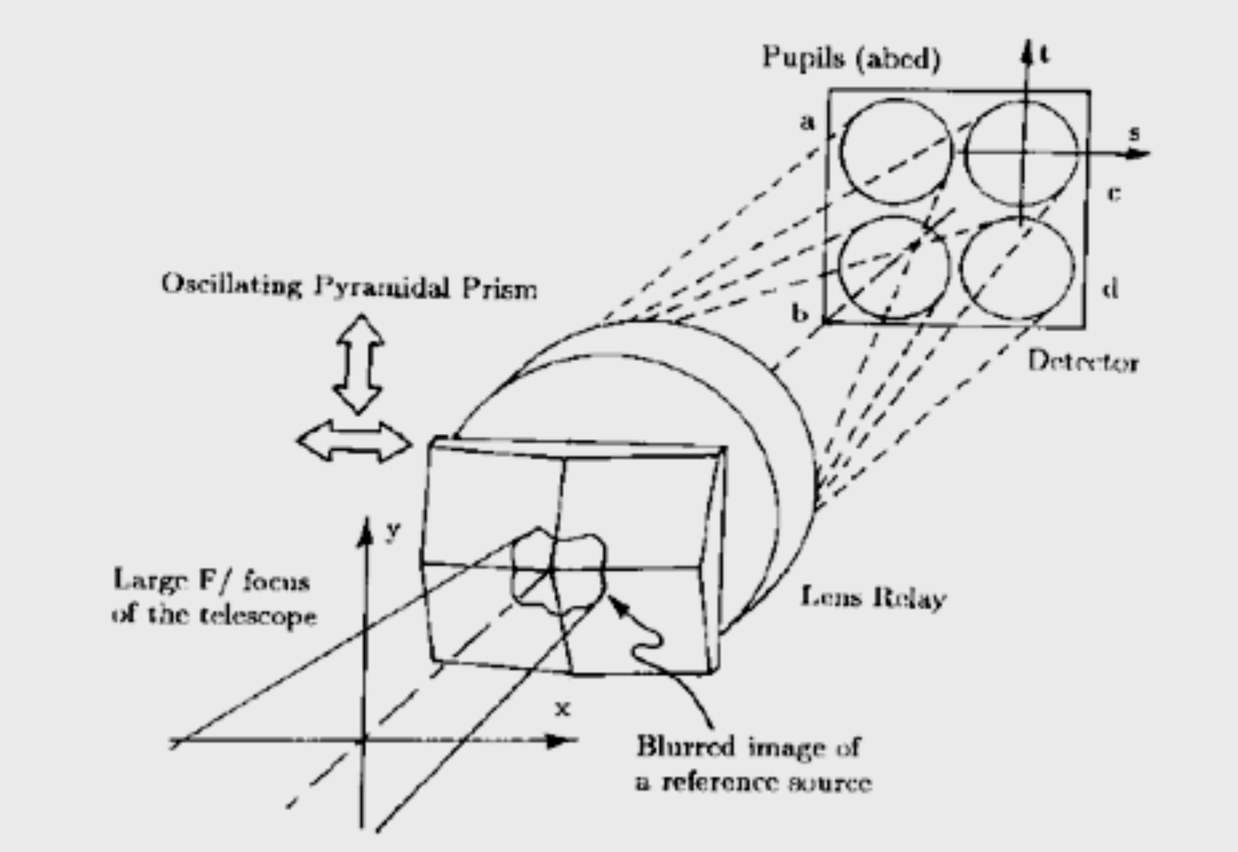
Wavefront sensors - 2

First example of wavefront sensor: Shack-Hartmann



Wavefront sensors - 3

Another example: the Pyramid WFS

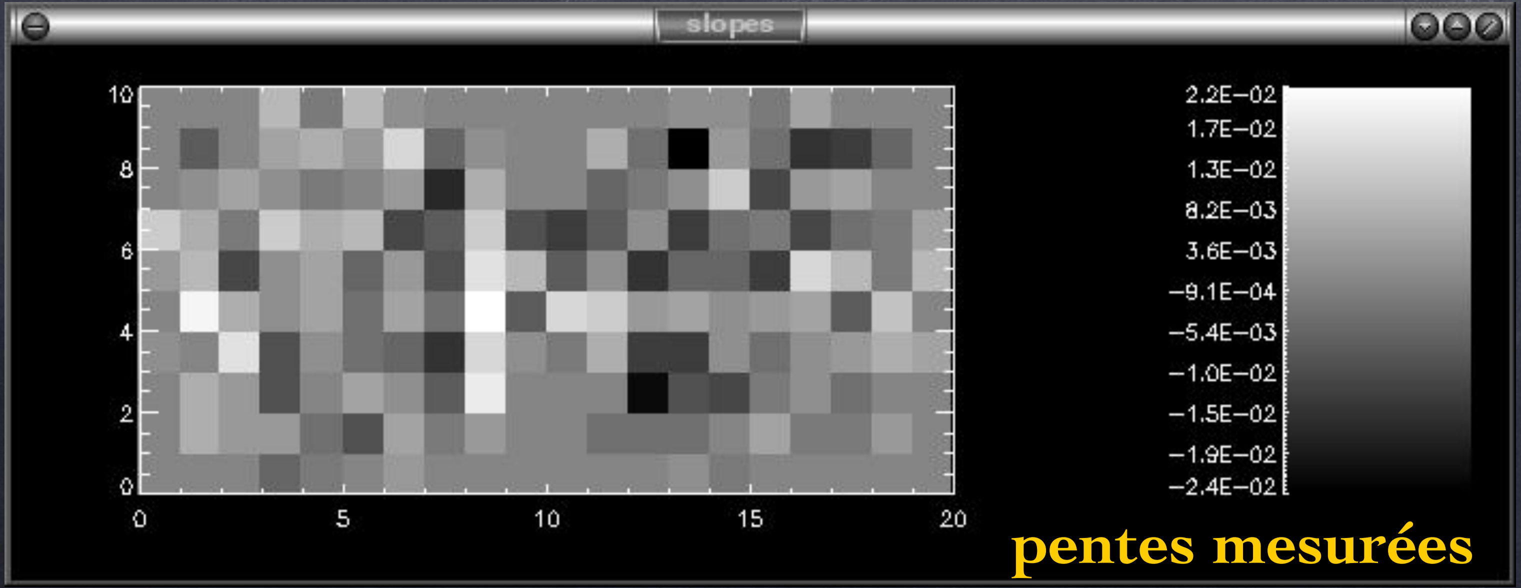


boucle ouverte

boucle fermée

$$S_x(x,y) = \frac{(I_1 + I_4) - (I_2 + I_3)}{\sum_i I_i}$$

$$S_y(x,y) = \frac{(I_1 + I_2) - (I_3 + I_4)}{\sum_i I_i}$$



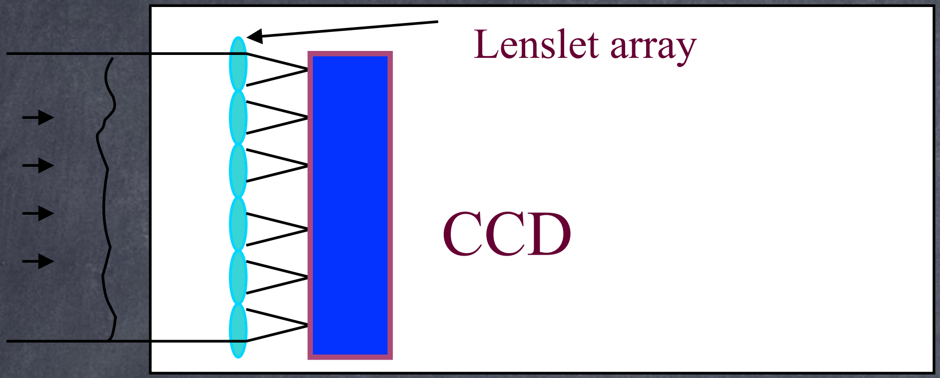
pentes mesurées

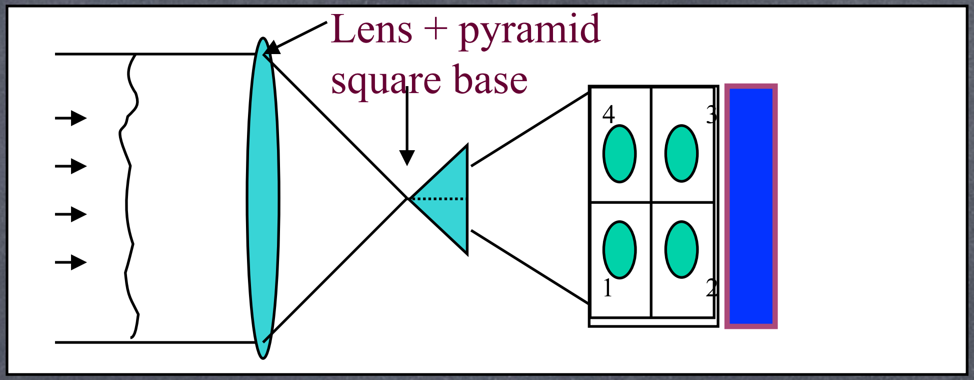
Wavefront sensors - 4

Another example: the Pyramid WFS

WH telescope's AO system

Wavefront sensors - 5





- 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].

Wavefront sensors - 6

Pyramid vs. Shack-Hartmann, 1st round

- Rousset et al., 1989-1990: 1st results of a SH WFS on sky on the VLT (COME-ON)
- Ragazzoni, 1996: proposal of a pyramid WFS
- Ragazzoni & Farinato, 1999: theoretical gain of 2 mag. (in limiting mag.)
- Esposito & Riccardi, 2001: gain confirmed by numerical simulations (but in open-loop and not the whole AO error budget)
- Carbillet et al., 2003: gain in limiting mag. confirmed (close loop & whole AO error), but also in the bright-end (lower aliasing!), from end-to-end simulations (for FLAO@LBT).

Wavefront sensors - 7

Pyramid vs. Shack-Hartmann, 2nd round

- Poyneer & Macintosh, 2004: spatial filtering of the SH WFS (lower aliasing error)
- Nicolle et al., 2004: optimized calculus of the SH signals (lower measurement error)
- Fusco et al., 2005: spatial filtering+optimized calculus => SH at the level of the Pyramid (and less uncertainties on stability and robustness...)
- Vérinaud et al., 2005 (in the framework of XAO and the ELT): Pyramid better close to optical axis, SH 'à la Fusco' better far from it.

Wavefront sensors - 8

Pyramid vs. Shack-Hartmann, 2nd round

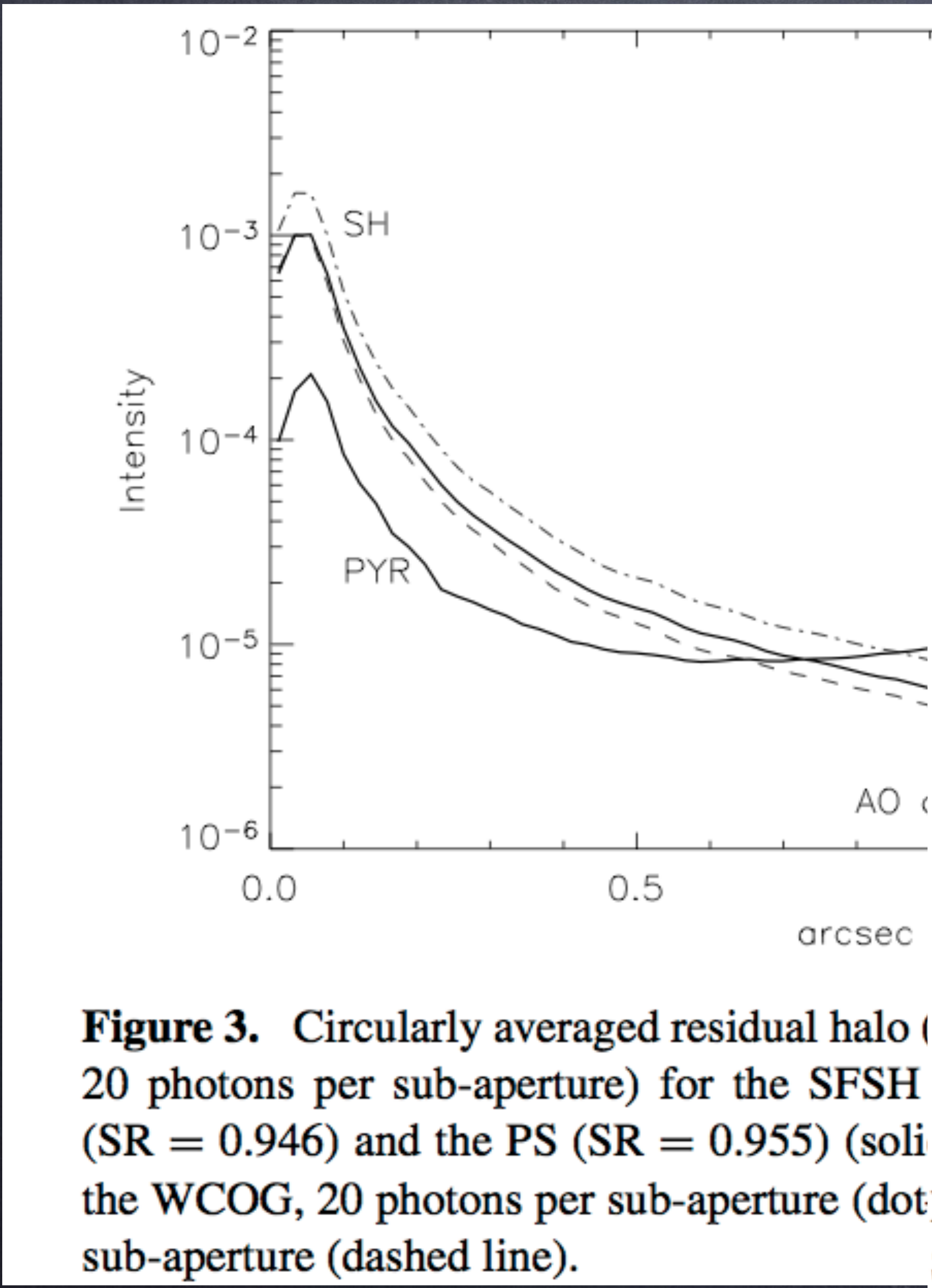


Figure 3. Circularly averaged residual halo (
20 photons per sub-aperture) for the SFSH
(SR = 0.946) and the PS (SR = 0.955) (soli
the WCOG, 20 photons per sub-aperture (dot
sub-aperture (dashed line).

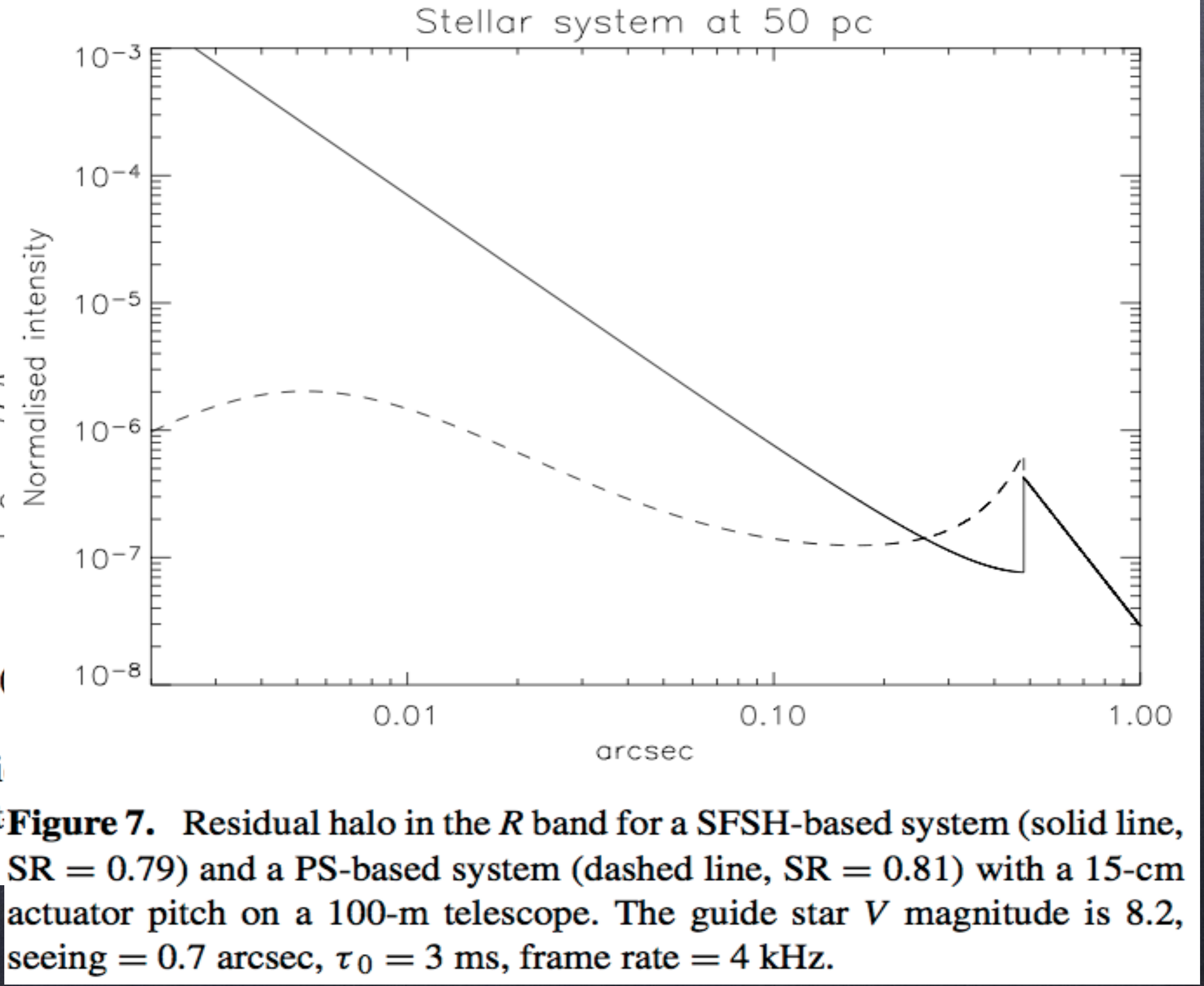


Figure 7. Residual halo in the *R* band for a SFSH-based system (solid line, SR = 0.79) and a PS-based system (dashed line, SR = 0.81) with a 15-cm actuator pitch on a 100-m telescope. The guide star *V* magnitude is 8.2, seeing = 0.7 arcsec, $\tau_0 = 3$ ms, frame rate = 4 kHz.

Wavefront sensors - 9

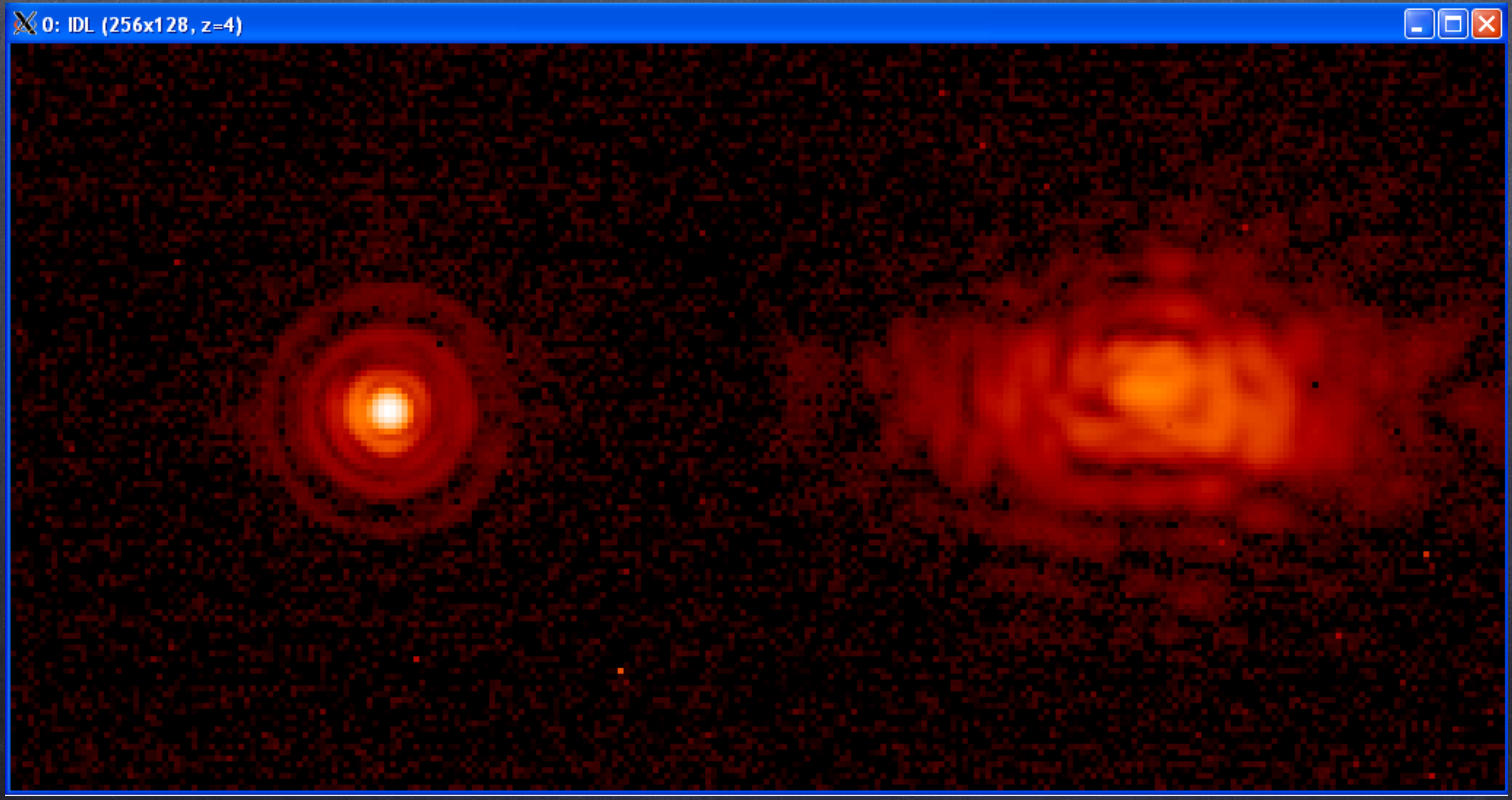
Pyramid vs. Shack-Hartmann, 3rd round

Press release (may/june 2010): LBT achieves breakthrough with adaptive optics ! (http://oldweb.lbto.org/AO/AOpressrelease.htm)

Wavefront sensors - 10

Pyramid vs. Shack-Hartmann, 4th round

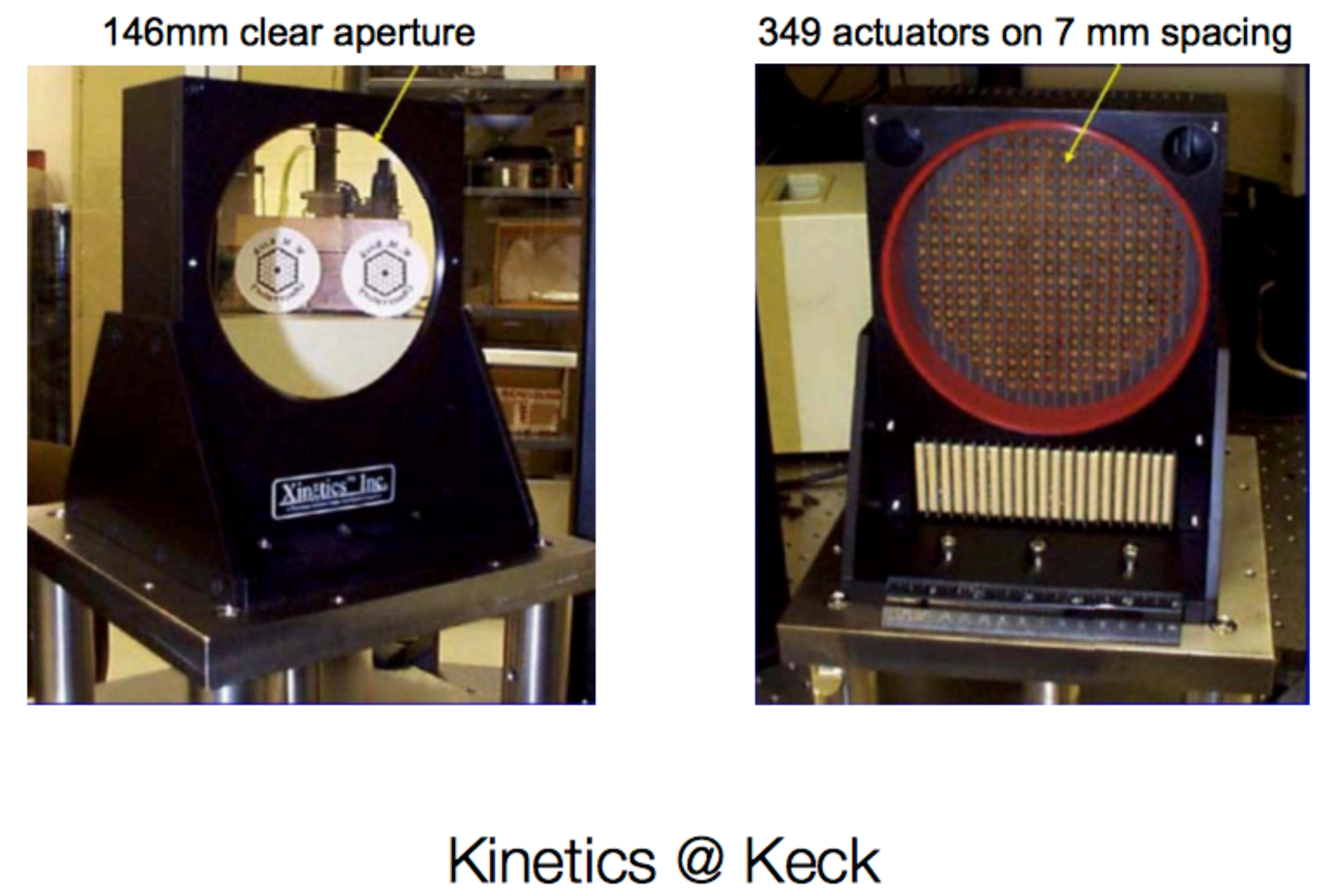
(2014)



Deformable correctors - 1

- Different technologies for correctors:
  - piezo-stacked arrays
  - piezo-electric bimorph mirrors
  - MEMS
  - voice-coil adaptive secondary mirrors (ASM)
  - multi-actuator adaptive <u>lens</u> (MAL) (!)
- Different coefficients for the fitting error, different strokes, different possible bandwidths, different possible number of modes, possible hysteresis, etc.

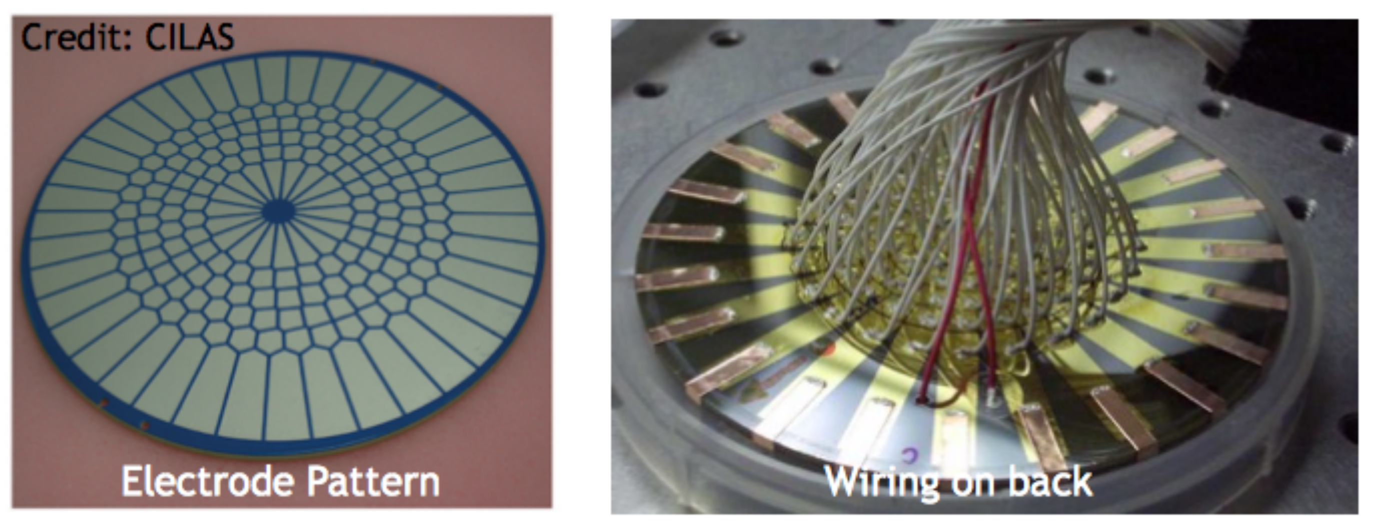
Deformable correctors - 2



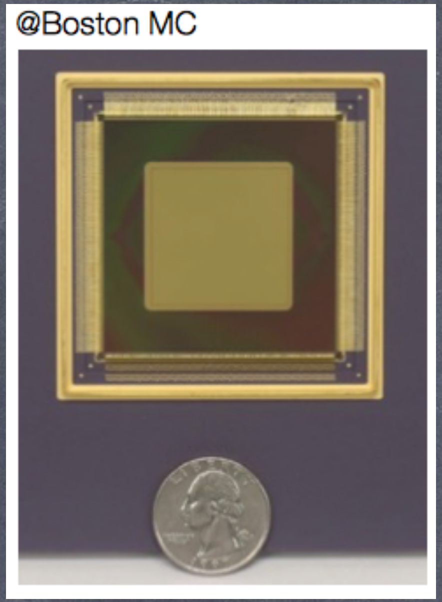
Kinetics @ Keck

Piezo-stacked array

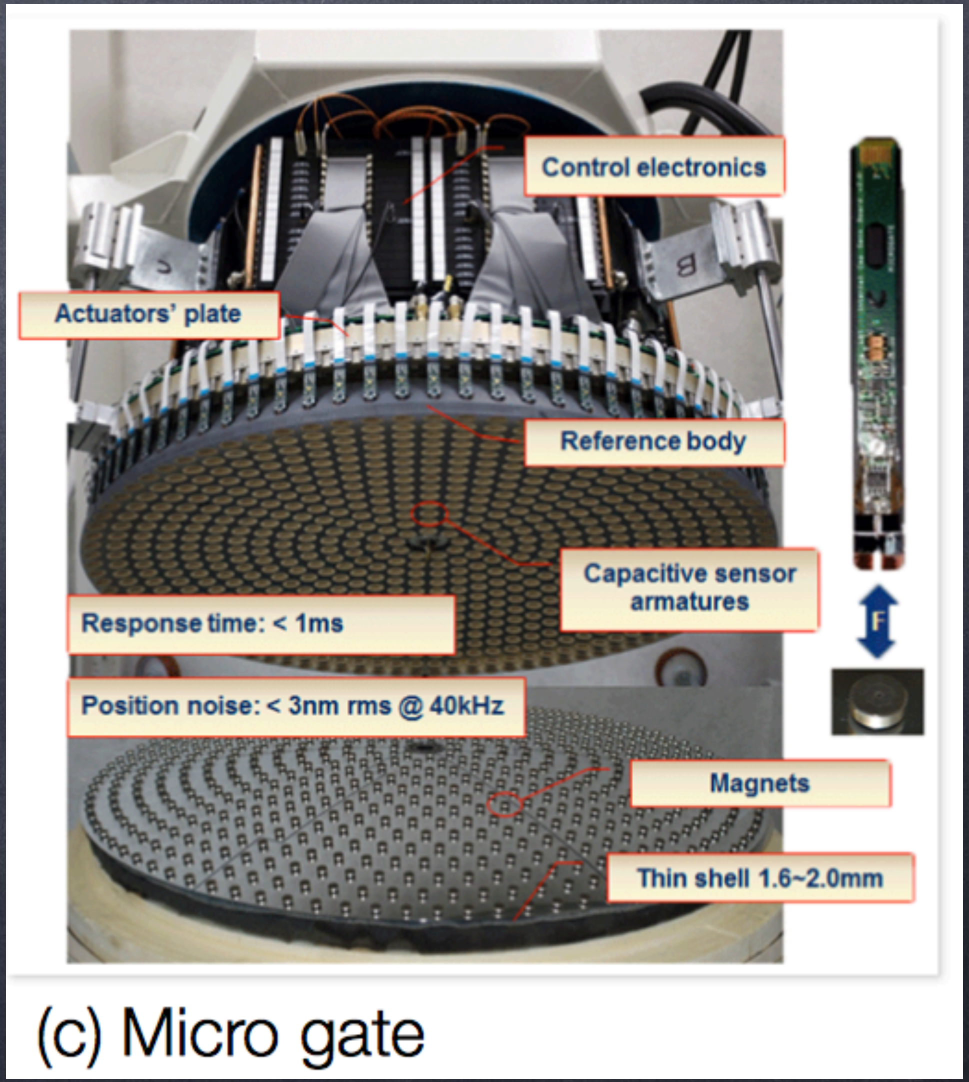
Bimorph


Credit: CILAS

MEMS


@Boston MC

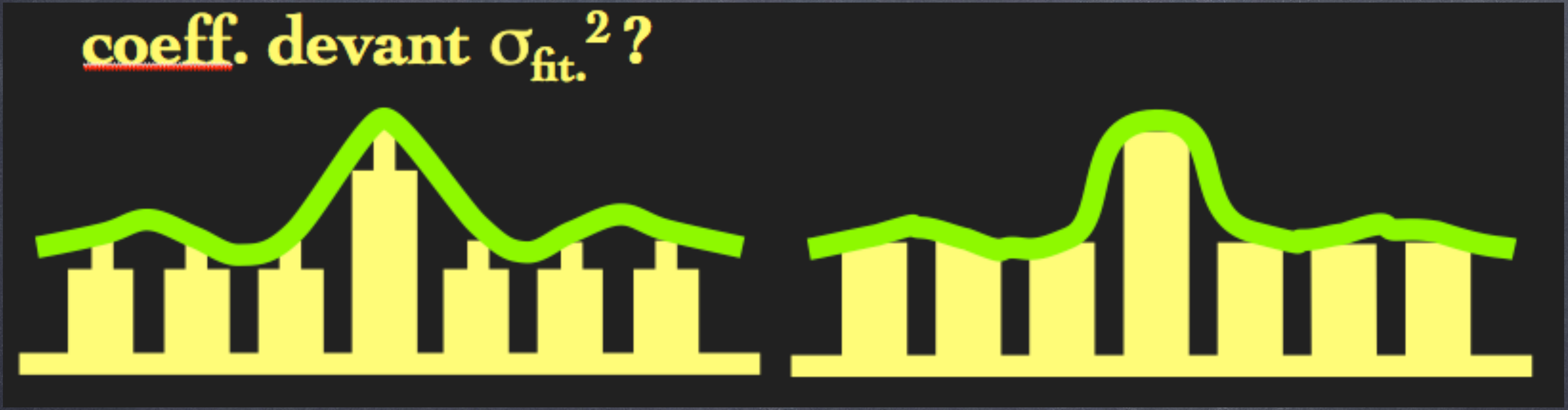
Voice-coil
('adaptive secondary')



(c) Micro gate

Deformable correctors - 3

- **Different coefficients for the fitting error:**



- **Is the stroke enough ?**
  If not: necessity to add a tip-tilt mirror…

Deformable correctors - 4

- **How many actuators for a given Strehl ratio ? (considering a coeff. 0.3 for the fitting error)**

$$\sigma^2_{\mathrm{fit.}} = 0.3 \left(\frac{d_{\mathrm{act.}}}{r_0}\right)^{\frac{5}{3}}$$

$$S_{\max} = \exp\left(-\sigma^2_{\mathrm{fit.}}\right)$$

- **if d = r_0 , then: S_{max}=exp(-0.3) ≈ 0.74**
  if d = $r_0/2$, then: S_{max}=exp($-0.3/2^{5/3}$) ≈ 0.91

Deformable correctors - 5

- **Influence functions $\longrightarrow$ mirror modes**

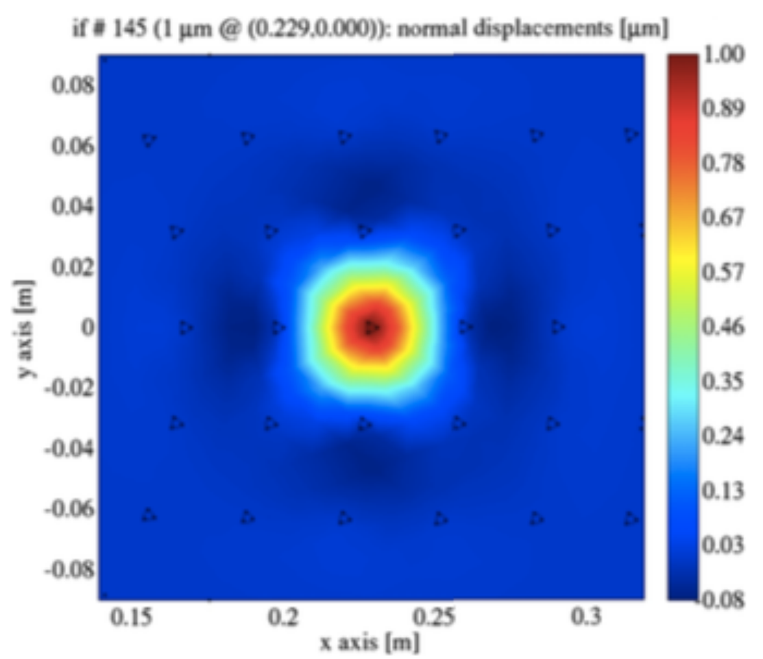
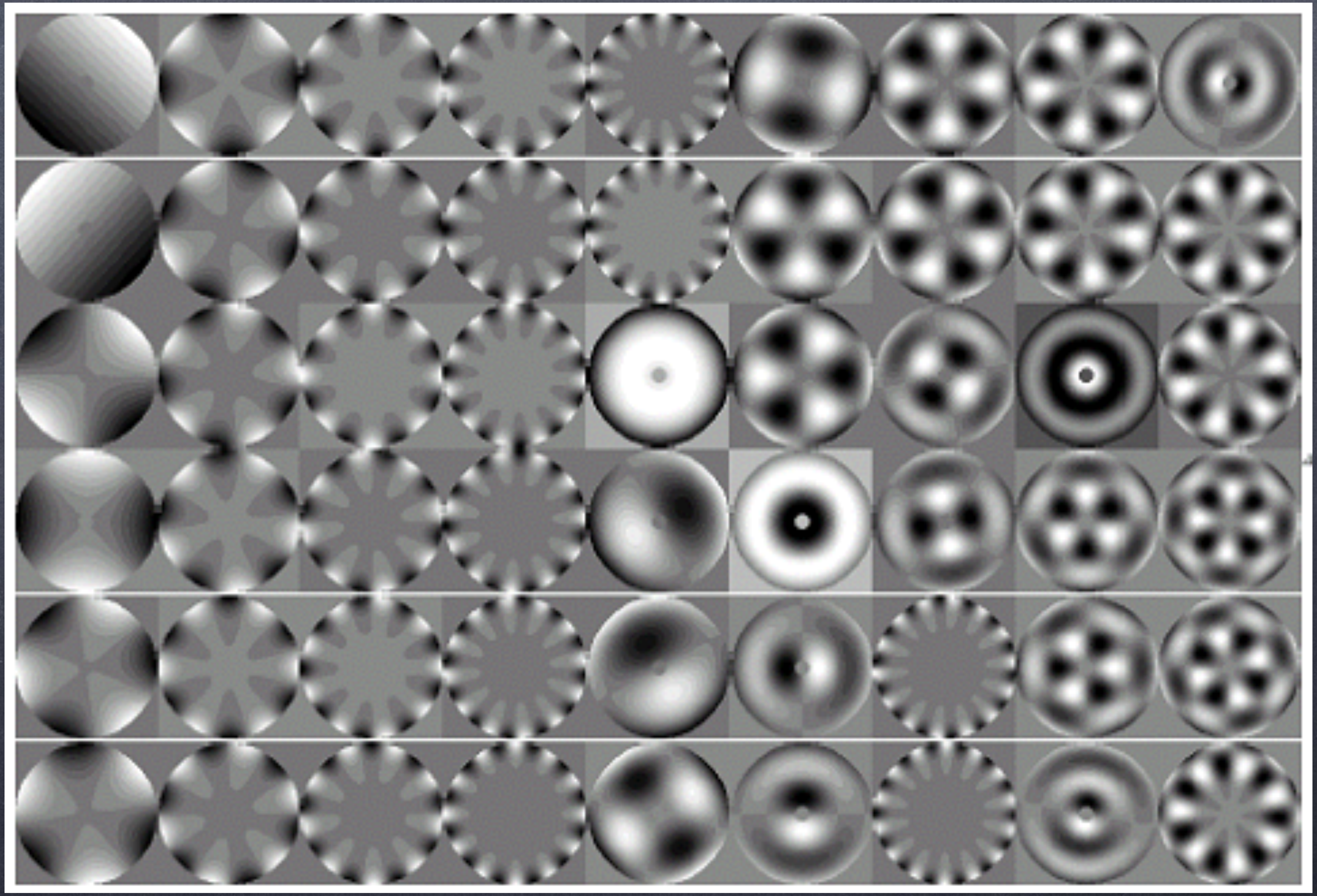
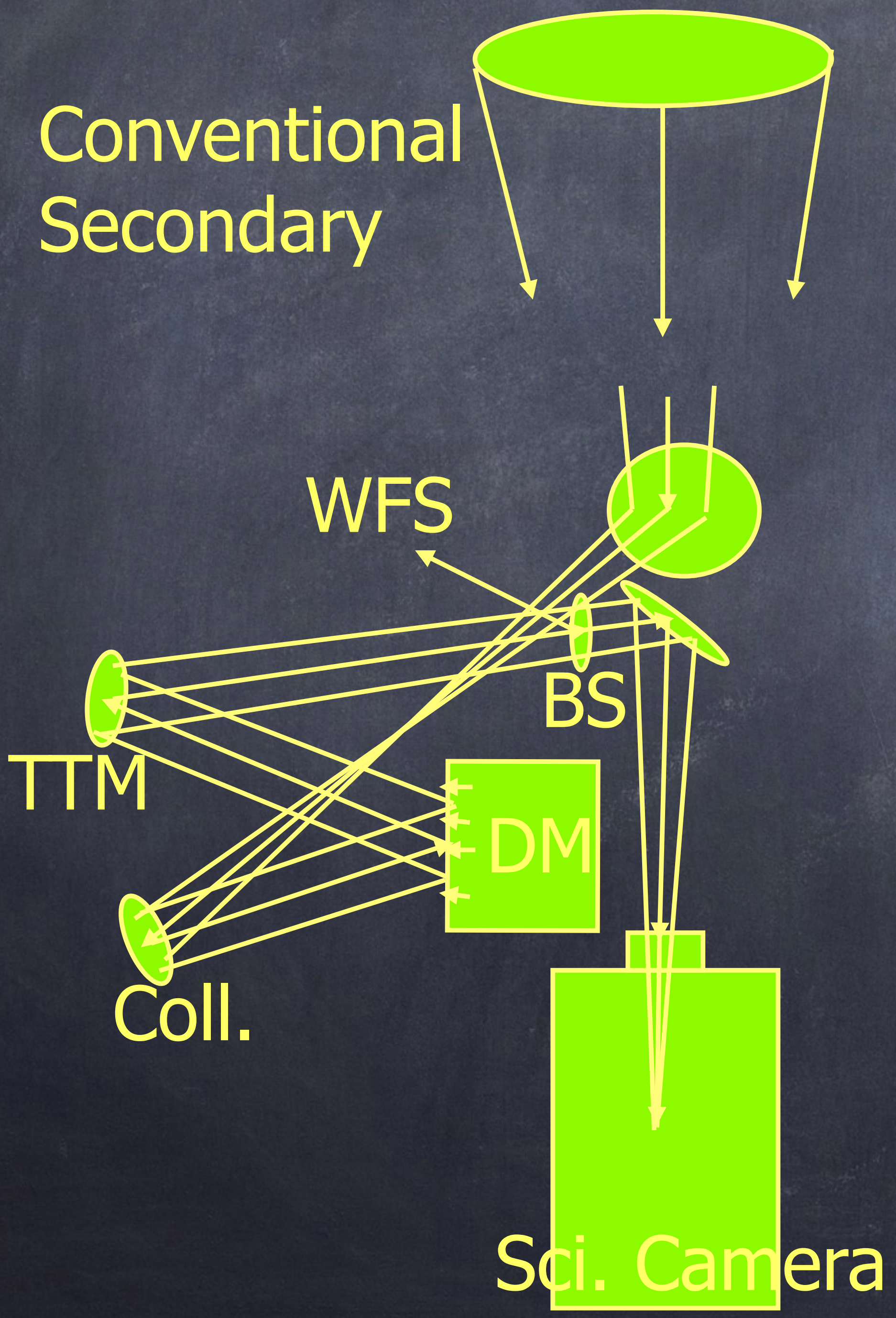


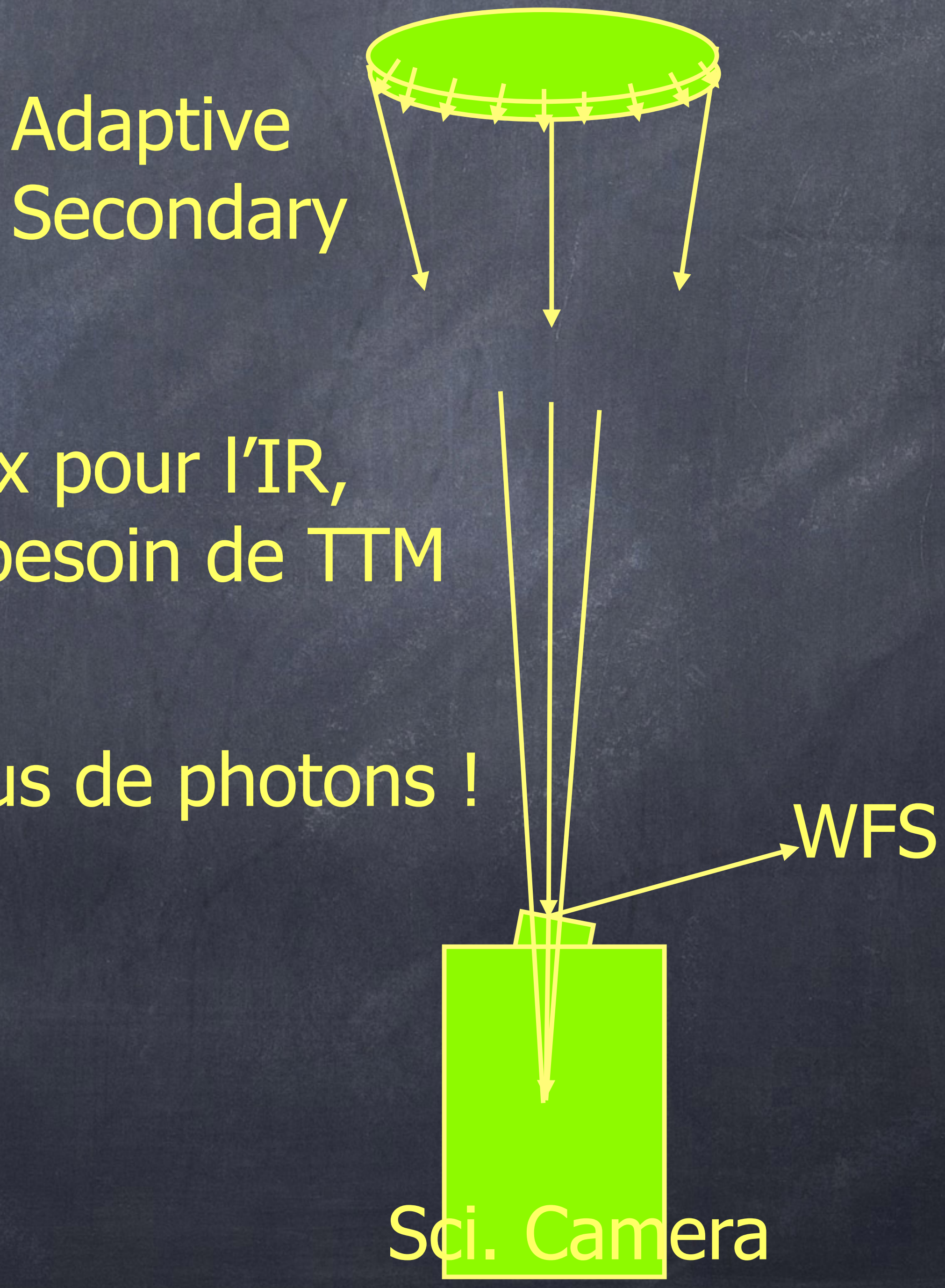
Figure 5: LBT DM: displacement normal to the surface when the actuator #145 is displaced by $w^* = 1$ µm.



Deformable correctors - 6

- **An interesting case: the Adaptive Secondary Mirror (ASM) technology developed for LBT [Brusa et al. 2003]**





Mieux pour l'IR,
Pas besoin de TTM

Plus de photons !

Reconstruction & control of the commands - 1

Pure integrator case:

$$c_{t+1} = c_t + g\,A\,m_t$$

where ***c*** is the commands vector (*n* actuators), ***m*** the measurement vector (*m* elements), ***g*** a scalar loop gain ($0 < g < 1$), ***A*** the (*nxm*) command matrix.

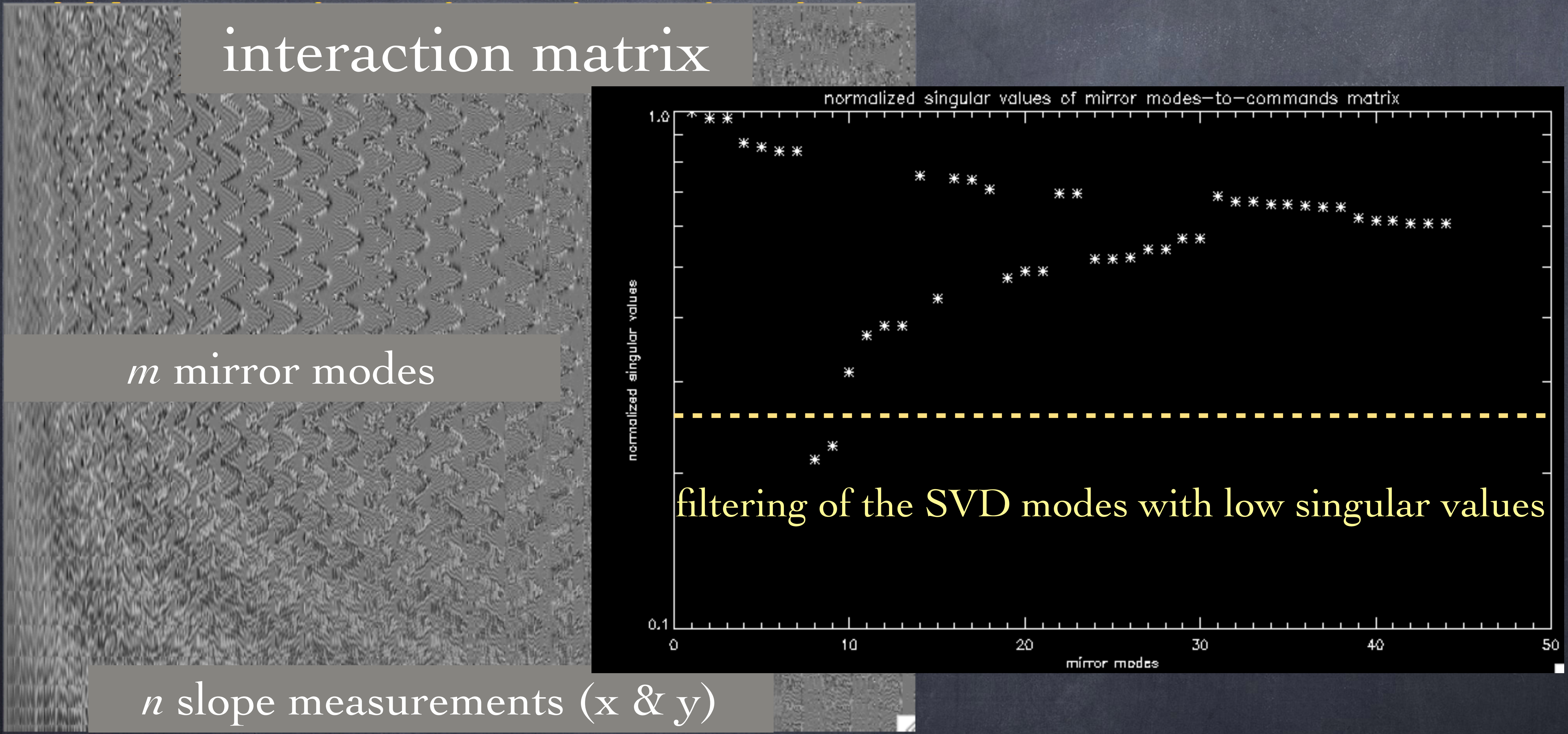
The commands matrix ***A*** is, in practice, the pseudo-inverse (SVD) of the measured (during calibration stage) interaction matrix ***D*** (*mxn*):

$$A = D^{+} = V\ \Sigma^{+}\ U^{*}$$

where Σ is an *mxn* rectangular diagonal matrix with non-negative numbers on the diagonal (Σ_{ii} are the singular values of ***D***), and ***U*** (*mxm*) and ***V*** (*nxn*) are orthonormal unitary matrices. (Note : $D^{+}=(D^{t}D)^{-1}D^{t}$)

Filtering of SVD modes: Σ_{ii} 'too small' => Σ^{+}_{ii} set to ***0*** (truncated SVD).

Reconstruction & control of the commands - 2



interaction matrix

m mirror modes

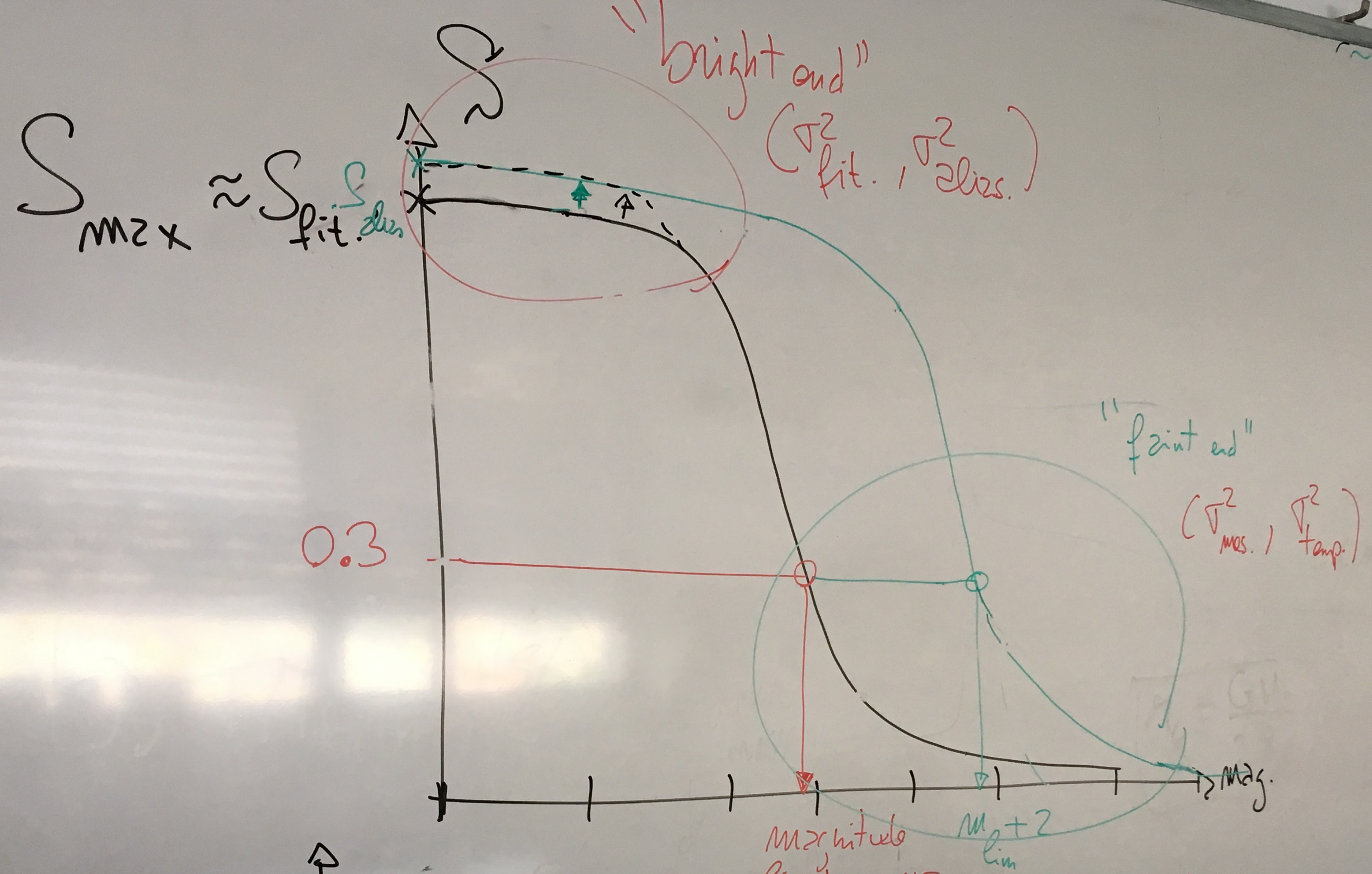
n slope measurements (x & y)

filtering of the SVD modes with low singular values

Reconstruction & control of the commands - 3

<table>
<tr><th>Reconstruction</th><th>Contrôle</th></tr>
<tr><td>Inverse généralisée (SVD tronquée)
→ matrice d’interaction</td><td>Intégrateur (ou autre filtrage temp.)
→ déf. du filtre, déf. des gains/mode</td></tr>
<tr><td>MAP (Fusco 2001)
→ + coeff. bruit, var./covar. spat.</td><td>Idem</td></tr>
<tr><td colspan="2">OMGI (Gendron & Léna 1994)
→ matrice d’int., coeff. bruit/mode, DS de la phase/mode (débruitée)</td></tr>
<tr><td colspan="2">OMGI alternatif (Dessenes 1998)
→ matrice d’int., DS de la phase/mode (bruitée)… + ajustement de la DS !</td></tr>
<tr><td colspan="2">Kalman (éq. MAP en boucle fermée - Le Roux et al. 2004)
→ matrice d’interaction, coeff. bruit, var./covar. spatio-temp.</td></tr>
</table>

$S_{max} \approx S_{fit.} \; S_{alias}$



magnitude limite pour S=0.3 dans la bande qui m'intéresse