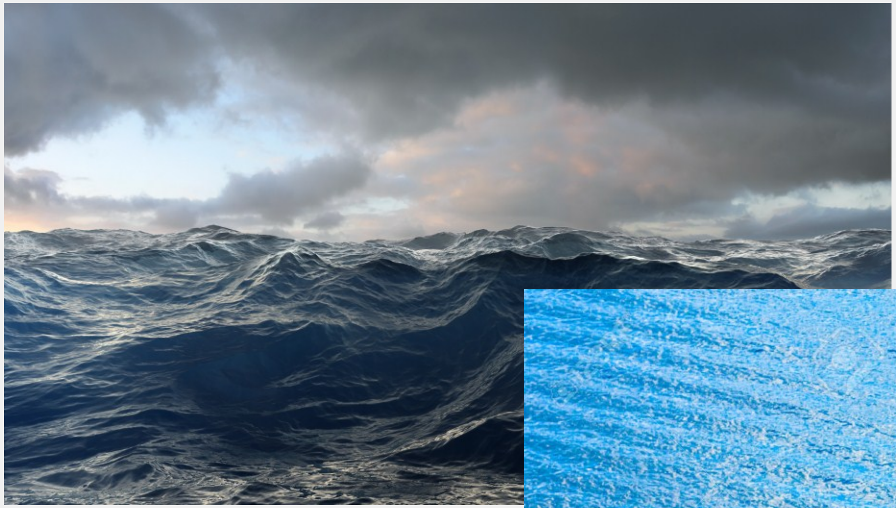
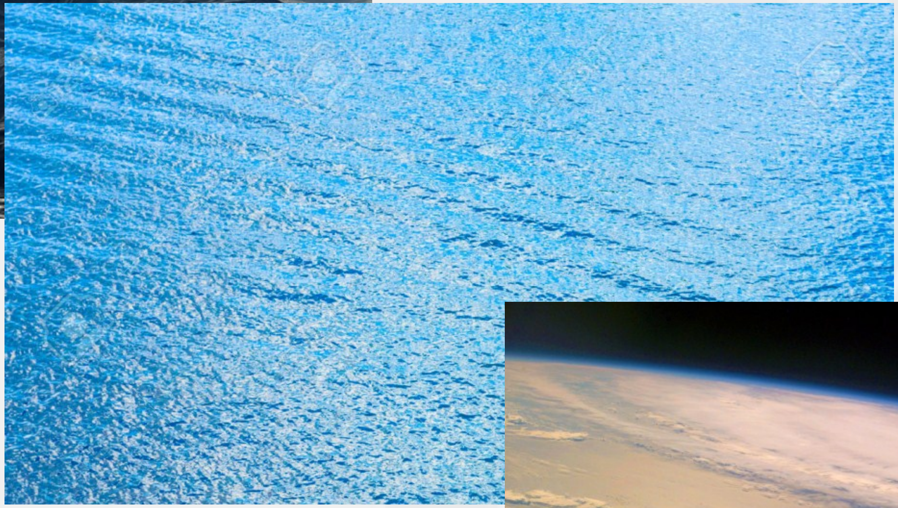
AO for the ELTs
Physical and Technological challenges

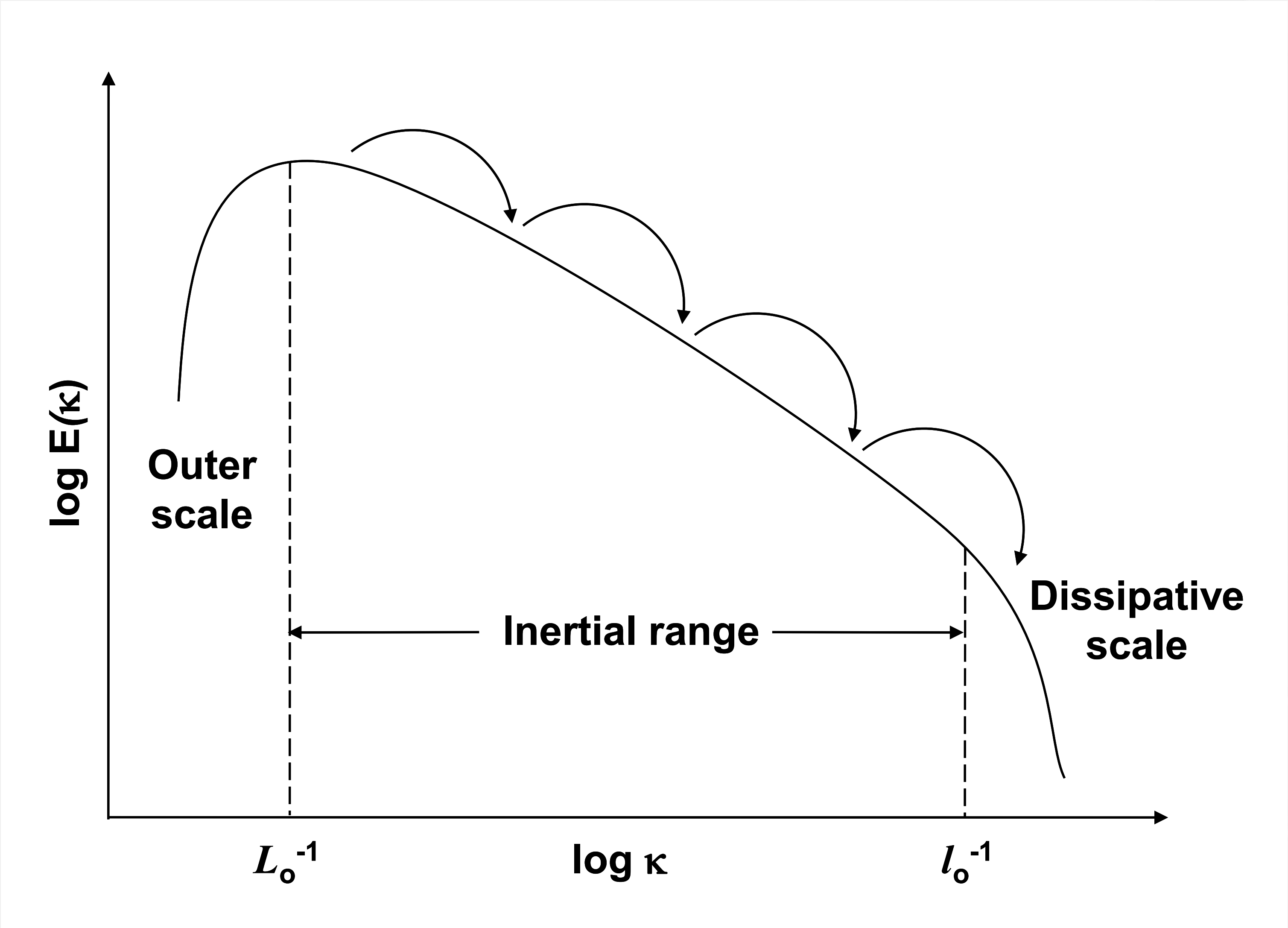
Enrico Marchetti

Outer scale: changing perspective





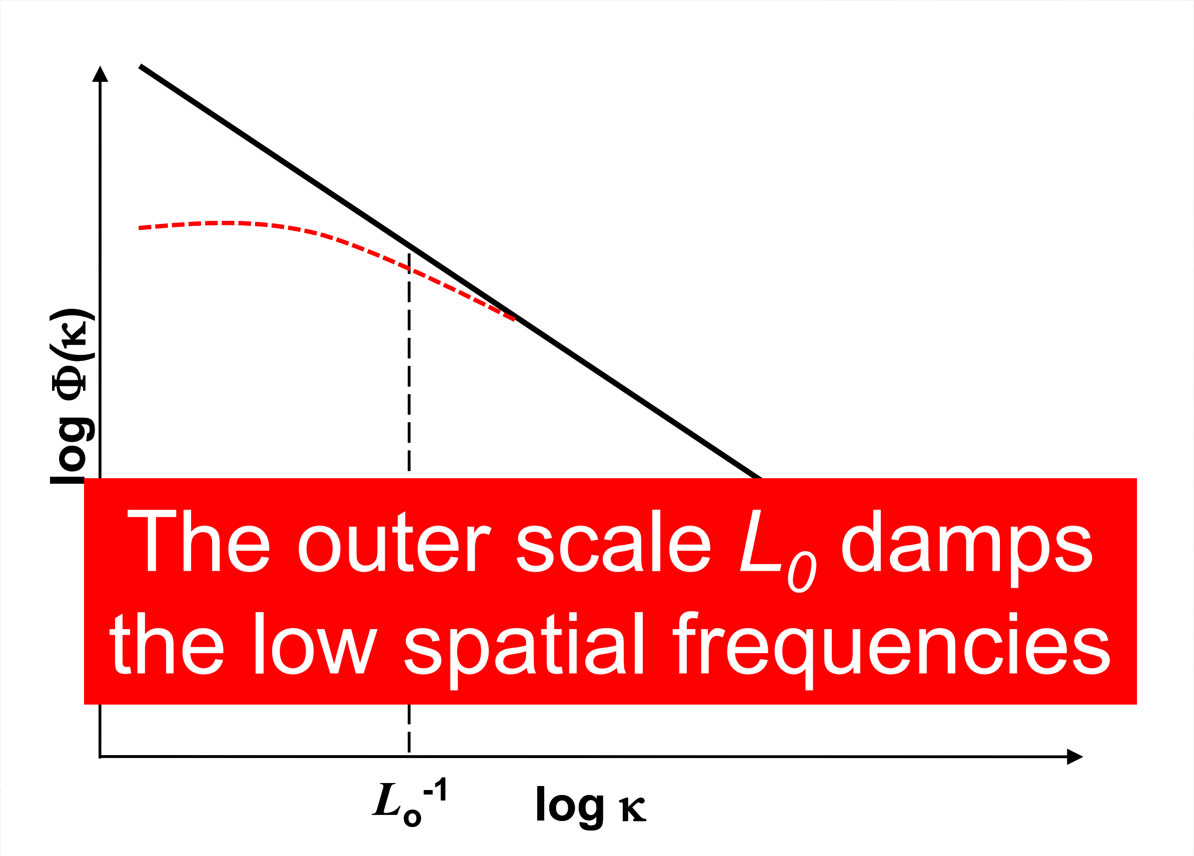
Atmospheric turbulence spectrum



From Kolmogorov to Von Karman

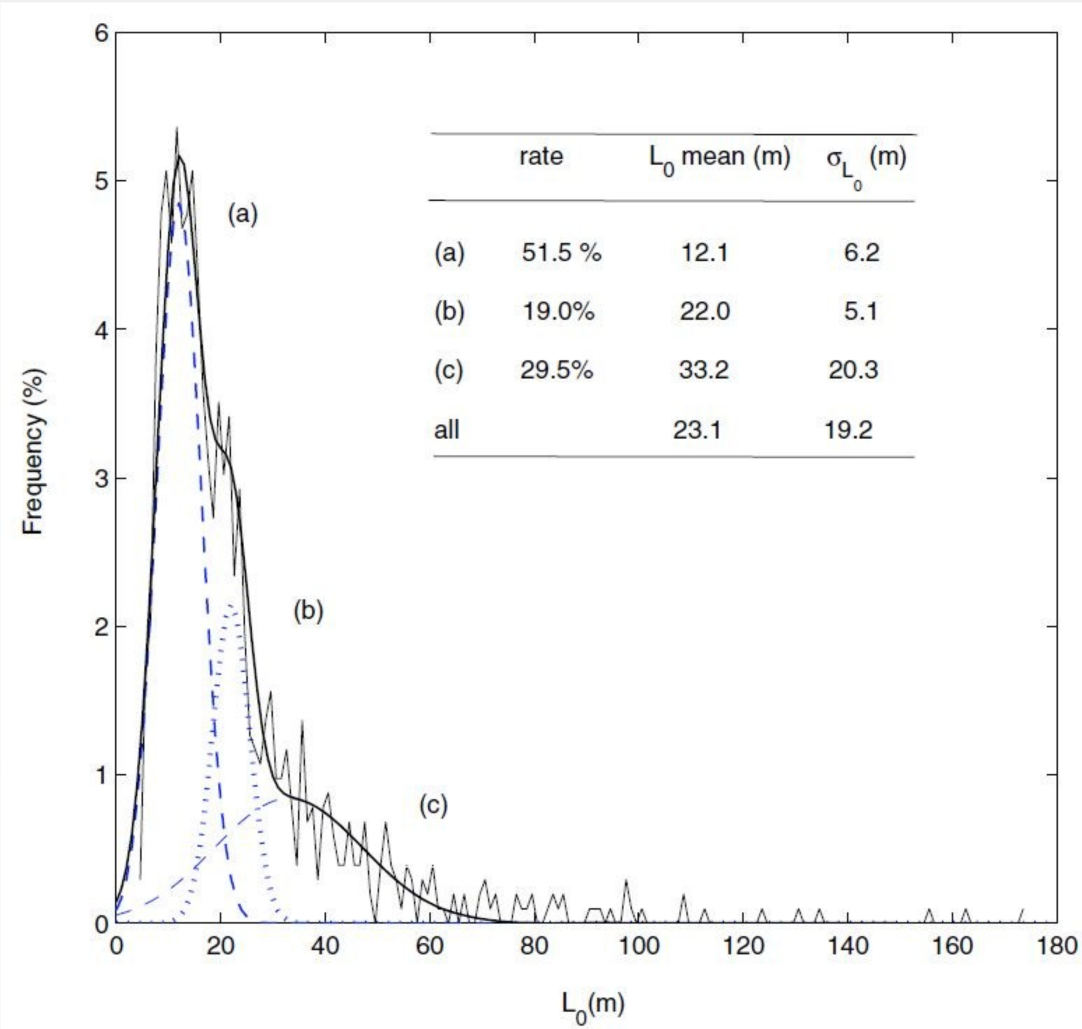
$$\Phi_{Kol}(\kappa) = 0.023\, r_0^{-5/3} \kappa^{-11/3} \qquad \sigma_{Kol}^2 = 1.03 \left(\frac{D}{r_0}\right)^{5/3}$$

$$\Phi_{VK}(\kappa) = 0.023\, r_0^{-5/3} \left[\kappa^2 + \left(\frac{2\pi}{L_0}\right)^2\right]^{-11/6} \qquad \sigma_{VK}^2 = \alpha \left(\frac{D}{r_0}\right)^{5/3}$$

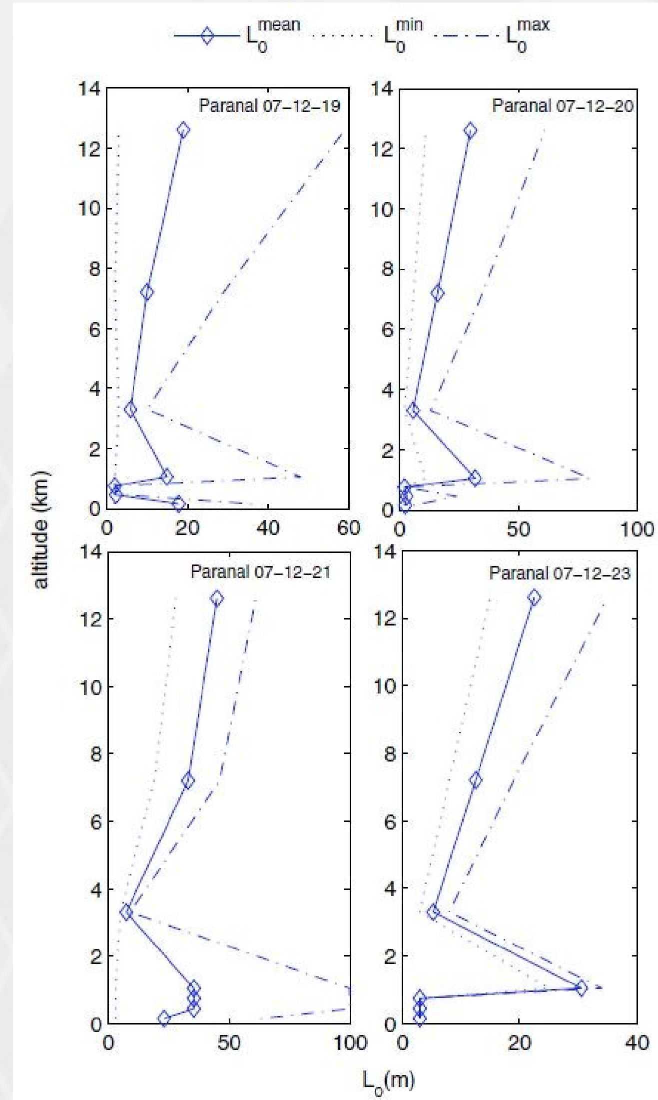


The outer scale L_0 damps the low spatial frequencies

How big is the Outer Scale?

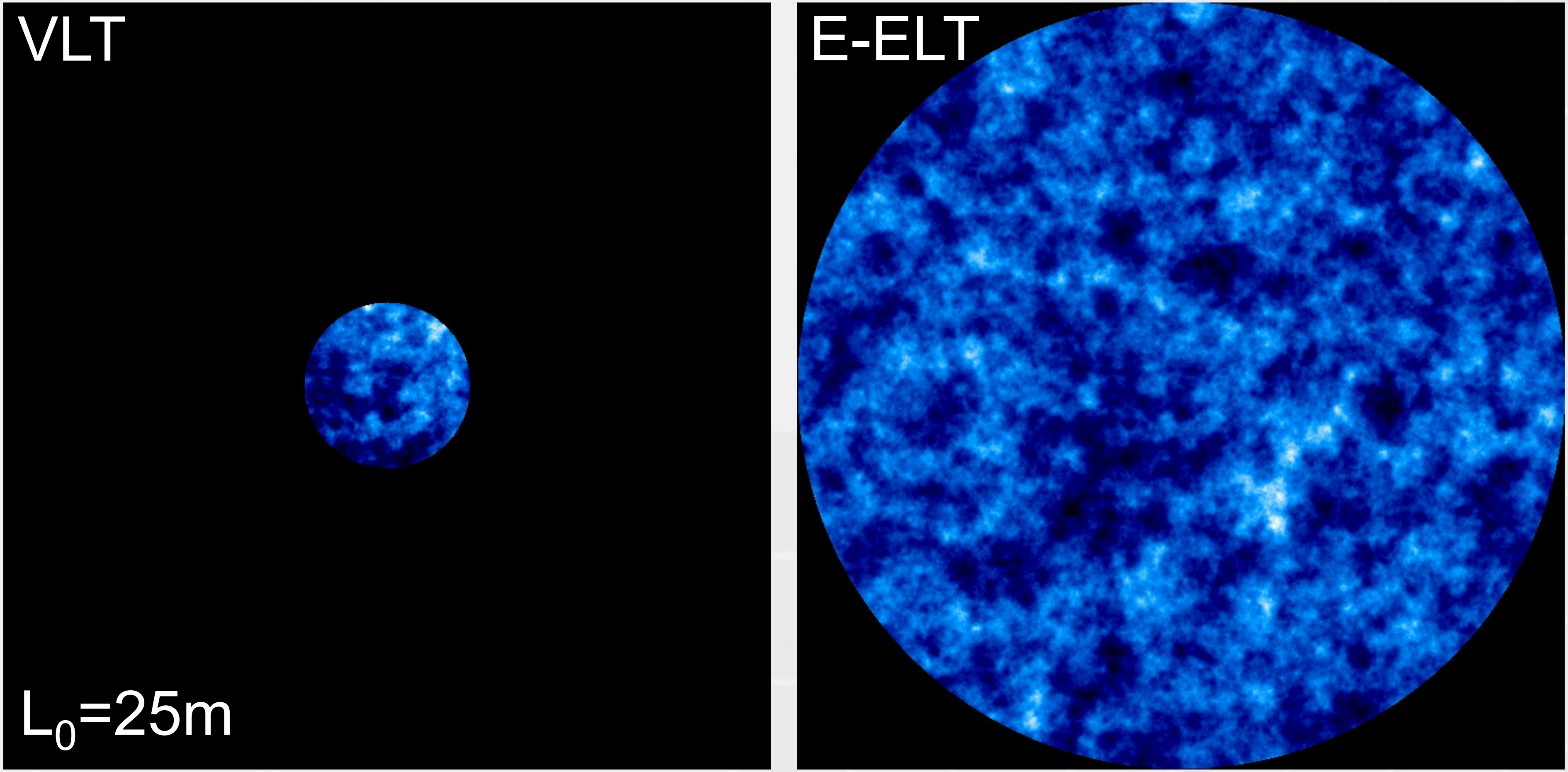


	rate	L_0 mean (m)	σ_{L_0} (m)
(a)	51.5 %	12.1	6.2
(b)	19.0%	22.0	5.1
(c)	29.5%	33.2	20.3
all		23.1	19.2



Dali Ali et al, A&A 524, 573 (2010)

Turbulence wavefront at larger scales



Outer scale and telescope diameter

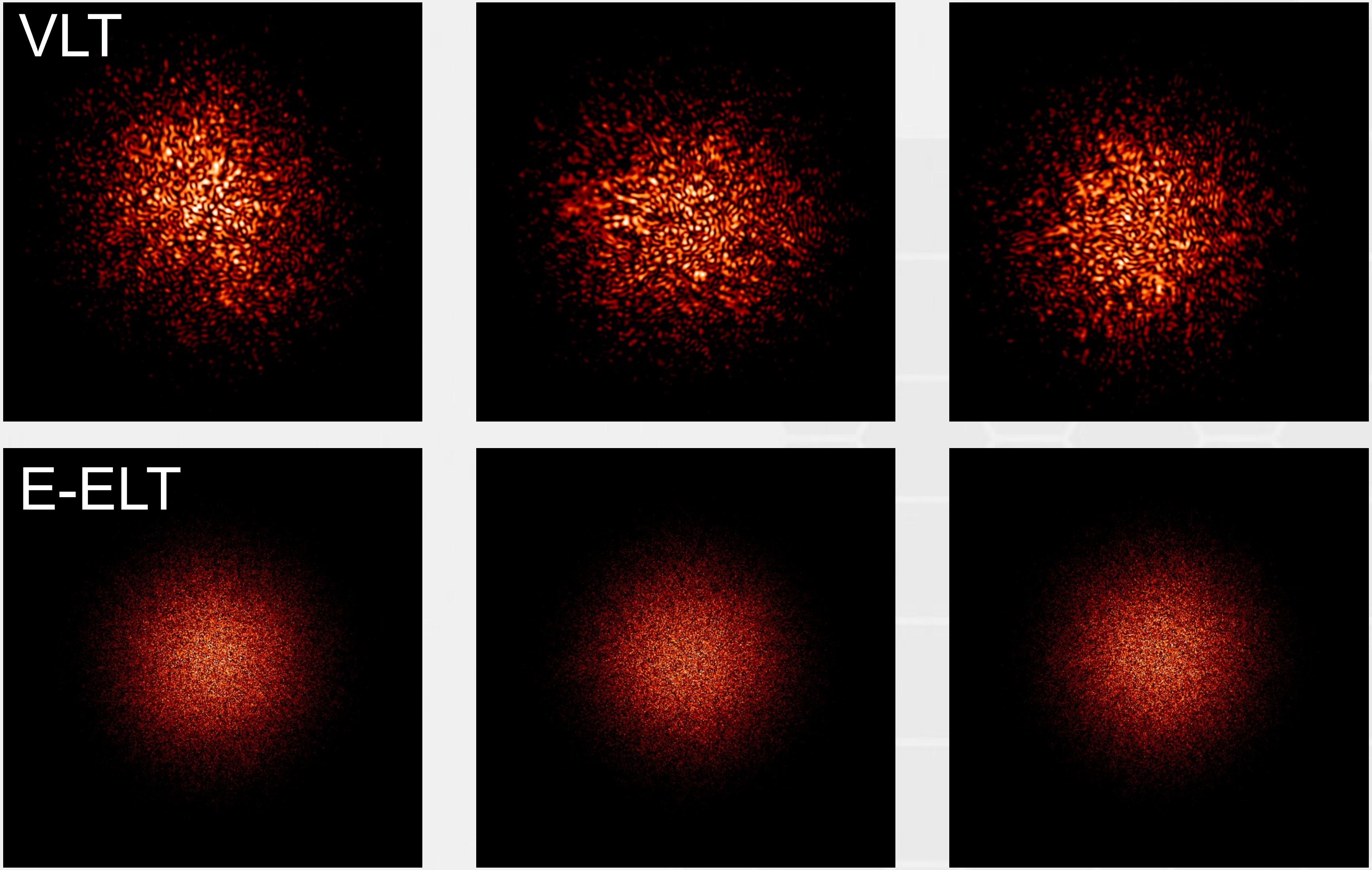
- What matters is D/L_0 *[Winker, JOSA A 8, 1568, (1991)]*

0.8" seeing – 2.2 μm (applies to the σ^2 and σ_{tilt} columns)

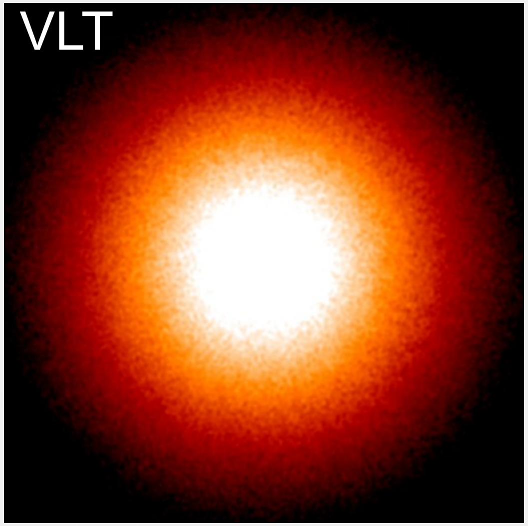
L_0 (m)	α_{VLT}	$\alpha_{E\text{-}ELT}$	σ^2_{VLT} [rad²]	$\sigma^2_{E\text{-}ELT}$ [rad²]	$\sigma_{tilt,VLT}$ ["]	$\sigma_{tilt,E\text{-}ELT}$ ["]
Inf	1.030	1.030	52	664	0.171	0.171
1000	0.776	0.608	39	392	0.145	0.097
100	0.485	0.206	24	132	0.108	0.046
50	0.357	0.101	18	65	0.089	0.026
25	0.249	0.039	13	25	0.064	0.011

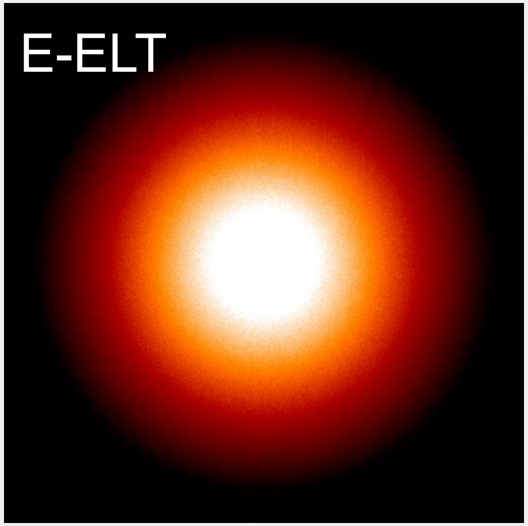
Short exposure PSFs @ 0.8 μm

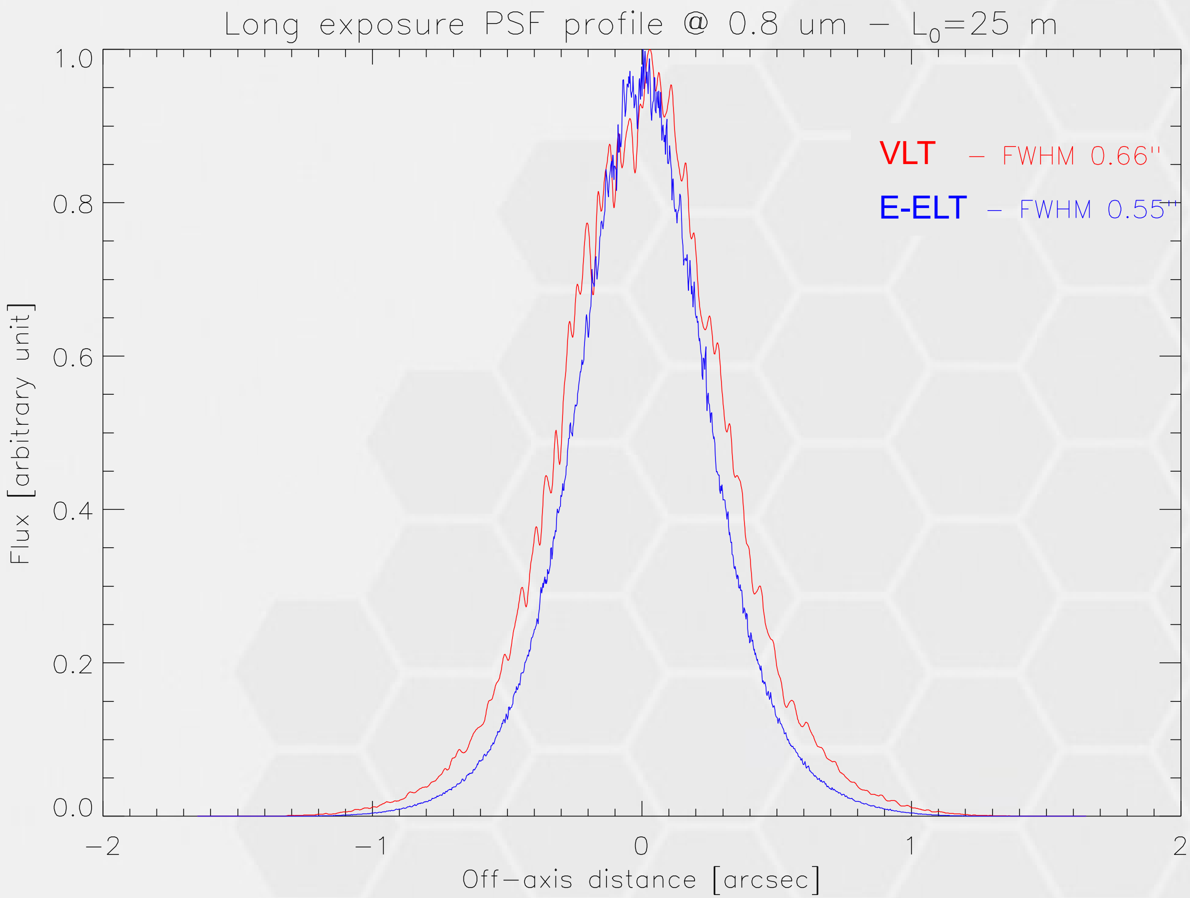
r_0=0.129 m – L_0=25 m – 2.23 mas/px – FoV 2.28” – ArcSinh LUT



Long exposure PSFs @ 0.8 μm

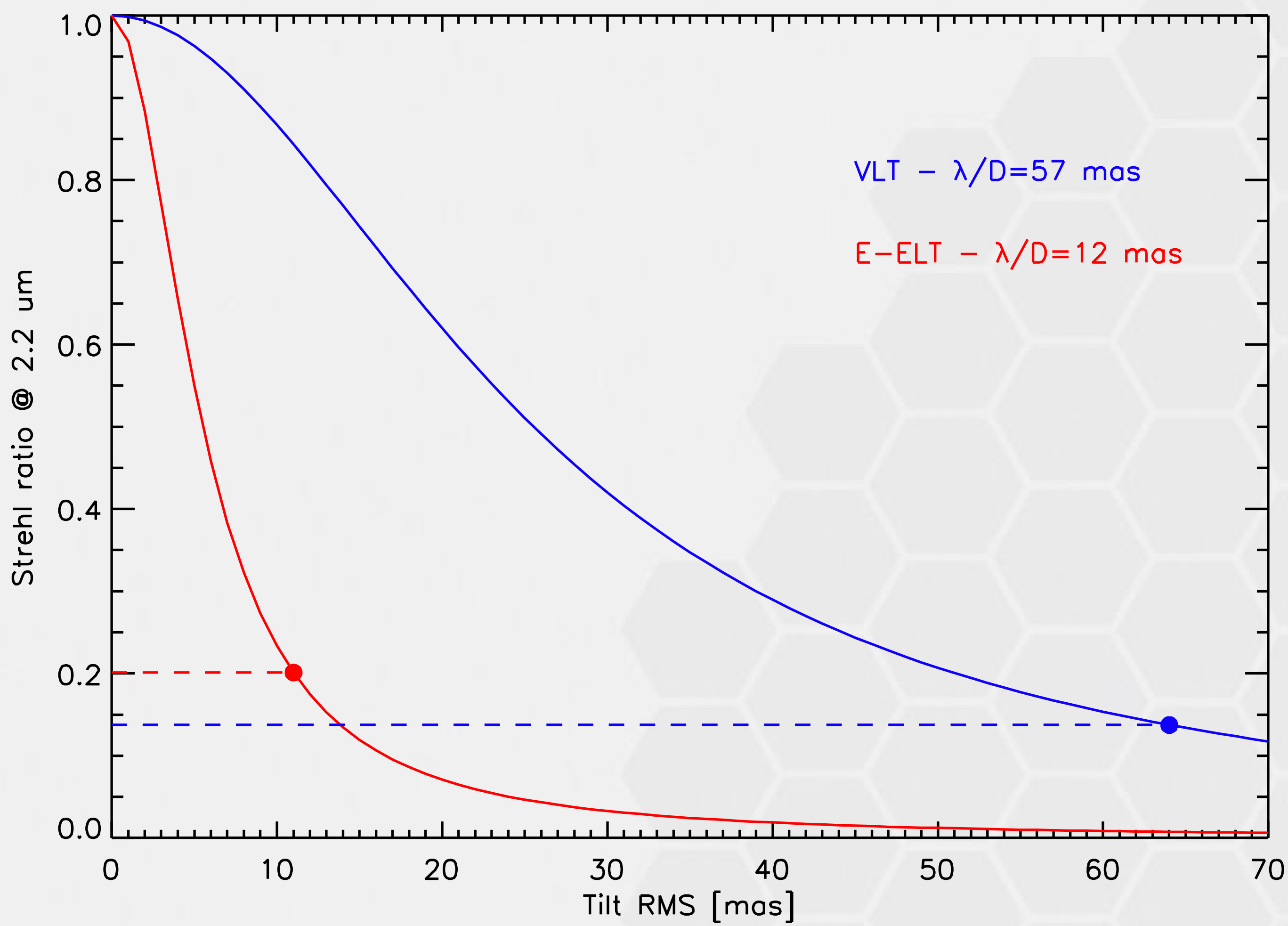






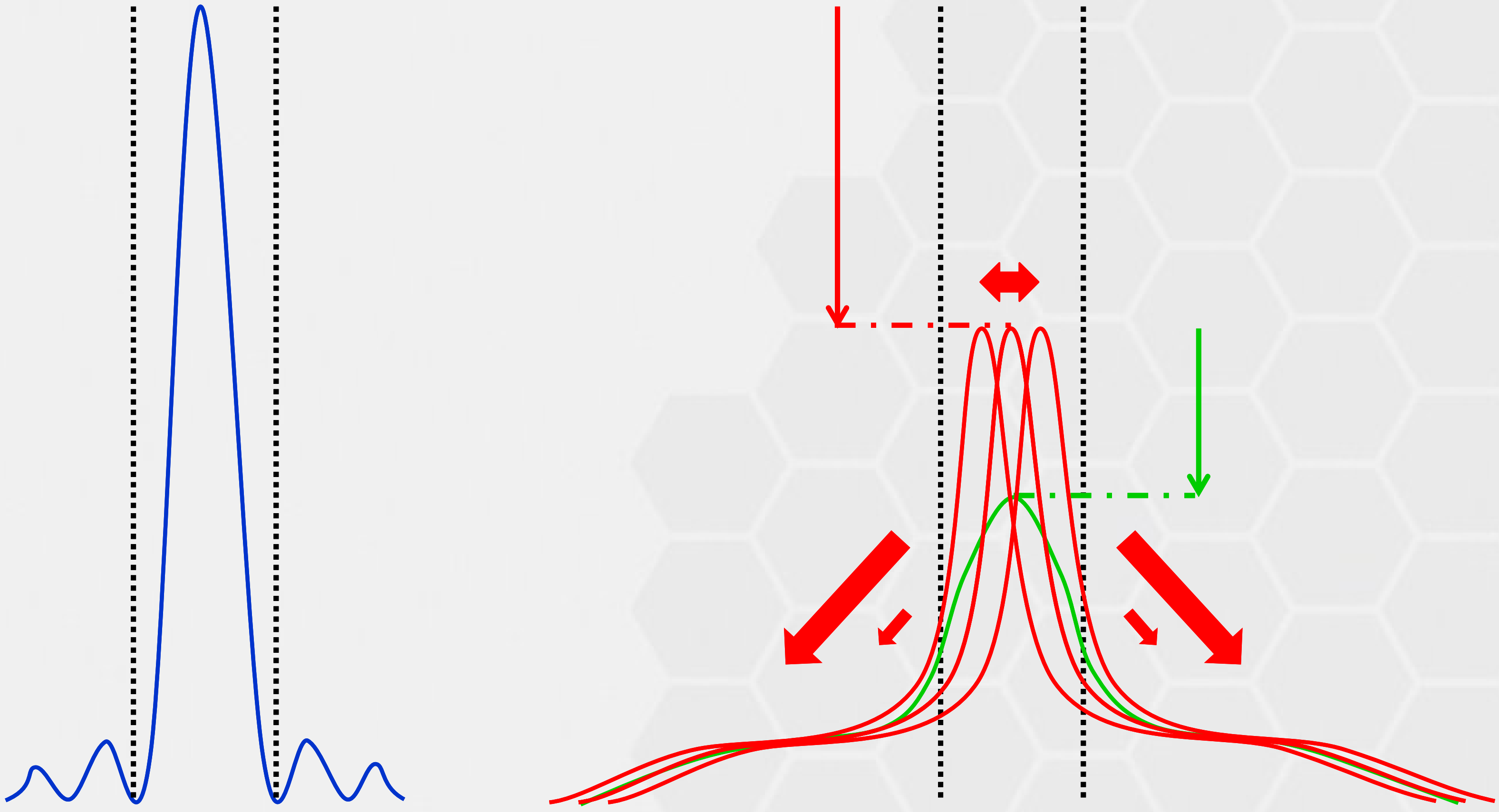
Kolmogorov spectrum ($D/L_0 \rightarrow 0$) – FWHM 0.71”

Tilt and Strehl ratio



Strehl vs. Ensquared Energy

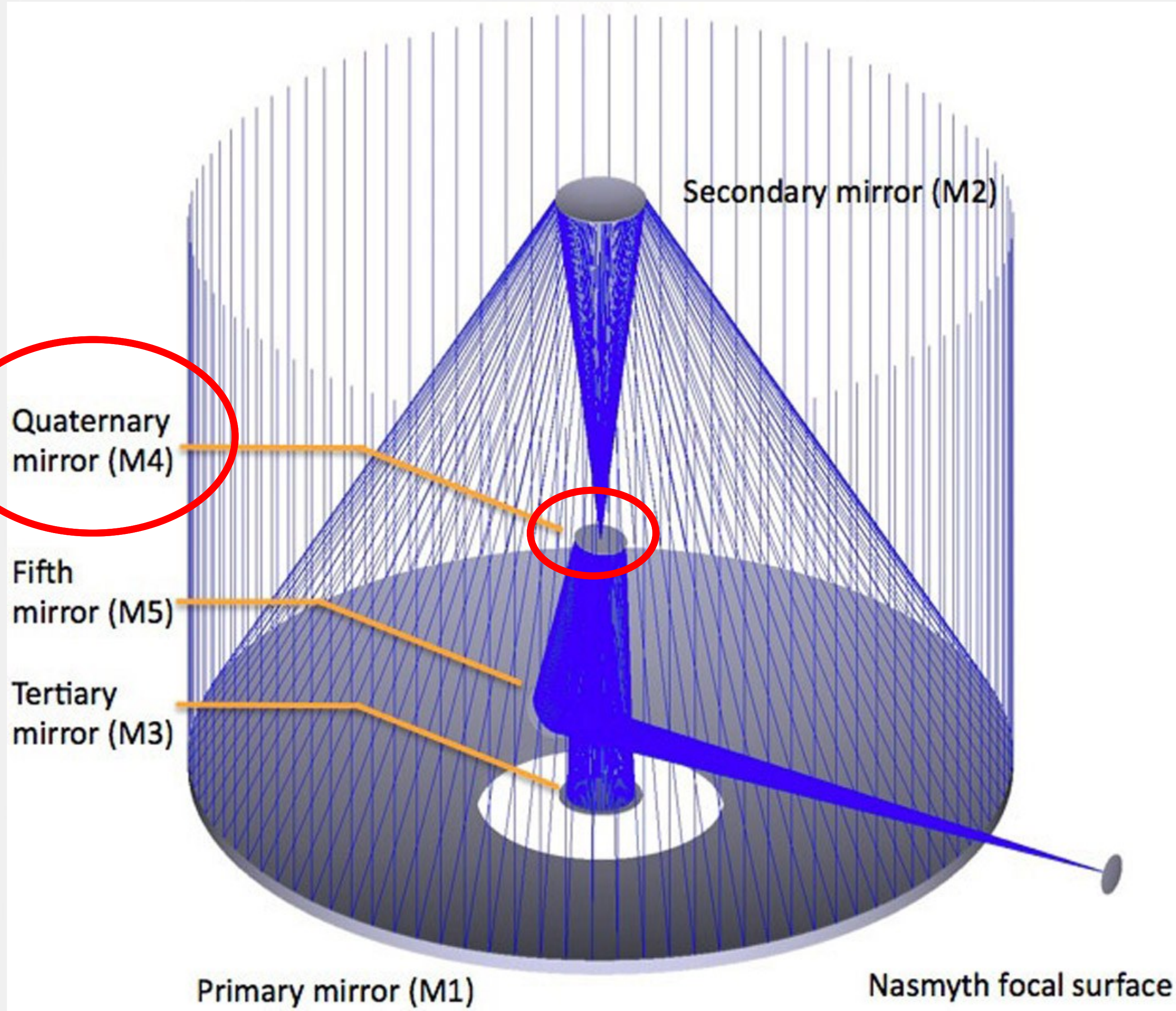
- EE less sensitive to image jitter than Strehl



Outer scale is gentler with ELTs

- More uniform short exposure PSF (mostly HO spatial frequencies): reduced noise in TT measurement
- Much less tilt: EE benefits vs. Strehl
- Relaxed stroke requirements for DMs

Deformable mirrors in the telescope

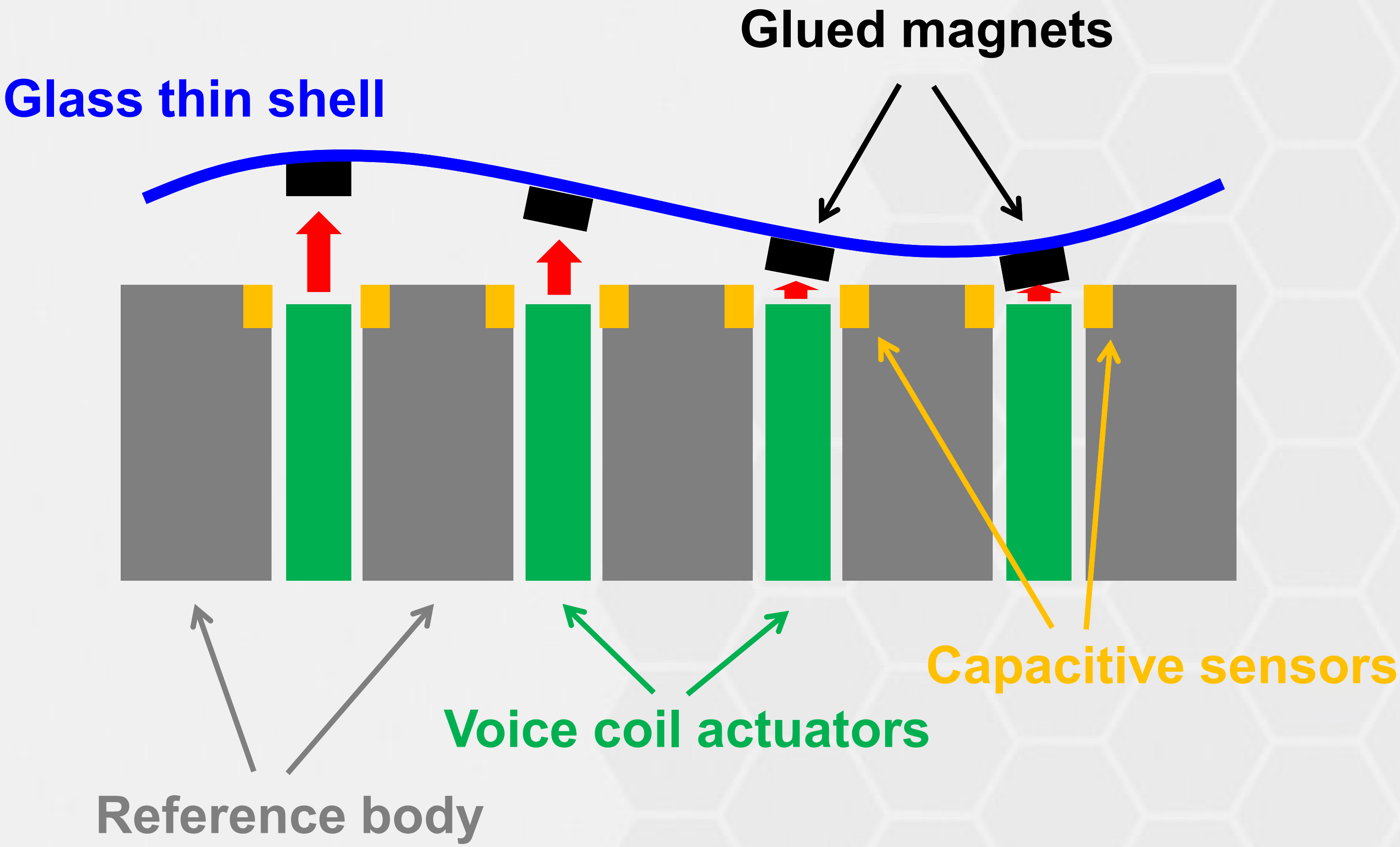


Why?

- To compensate for the atmospheric disturbances
- To compensate for telescope disturbances
- Avoid complexity of post-focal optical relay
- Maximized throughput
- Minimized thermal emission

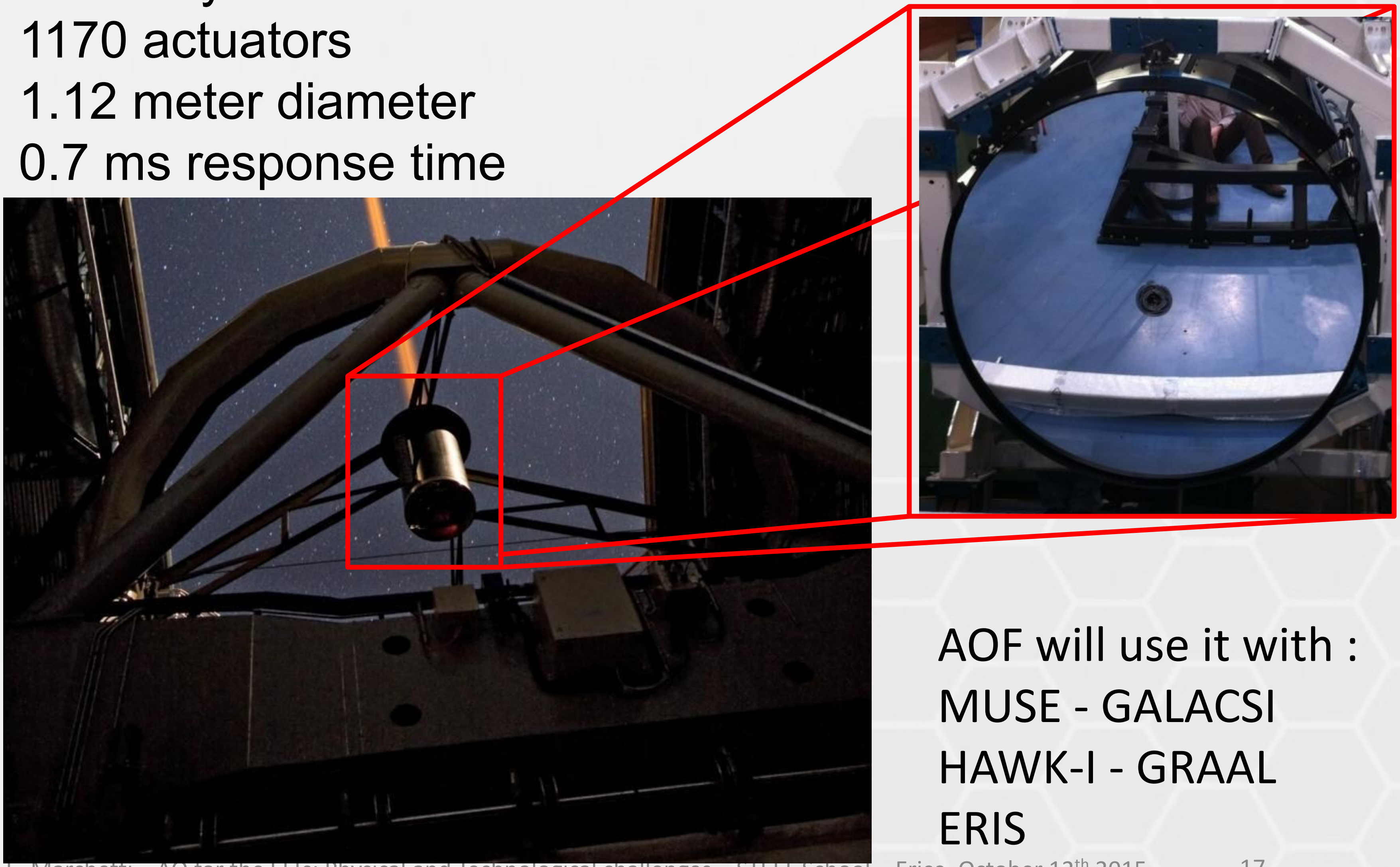
- Located at telescope pupil (or nearby)
- Installed and working at LBT and Magellan
- Soon installed at VLT (Adaptive Optics Facility)
- Baseline for E-ELT and GMT (not in TMT)

Large DMs: voice coil actuators



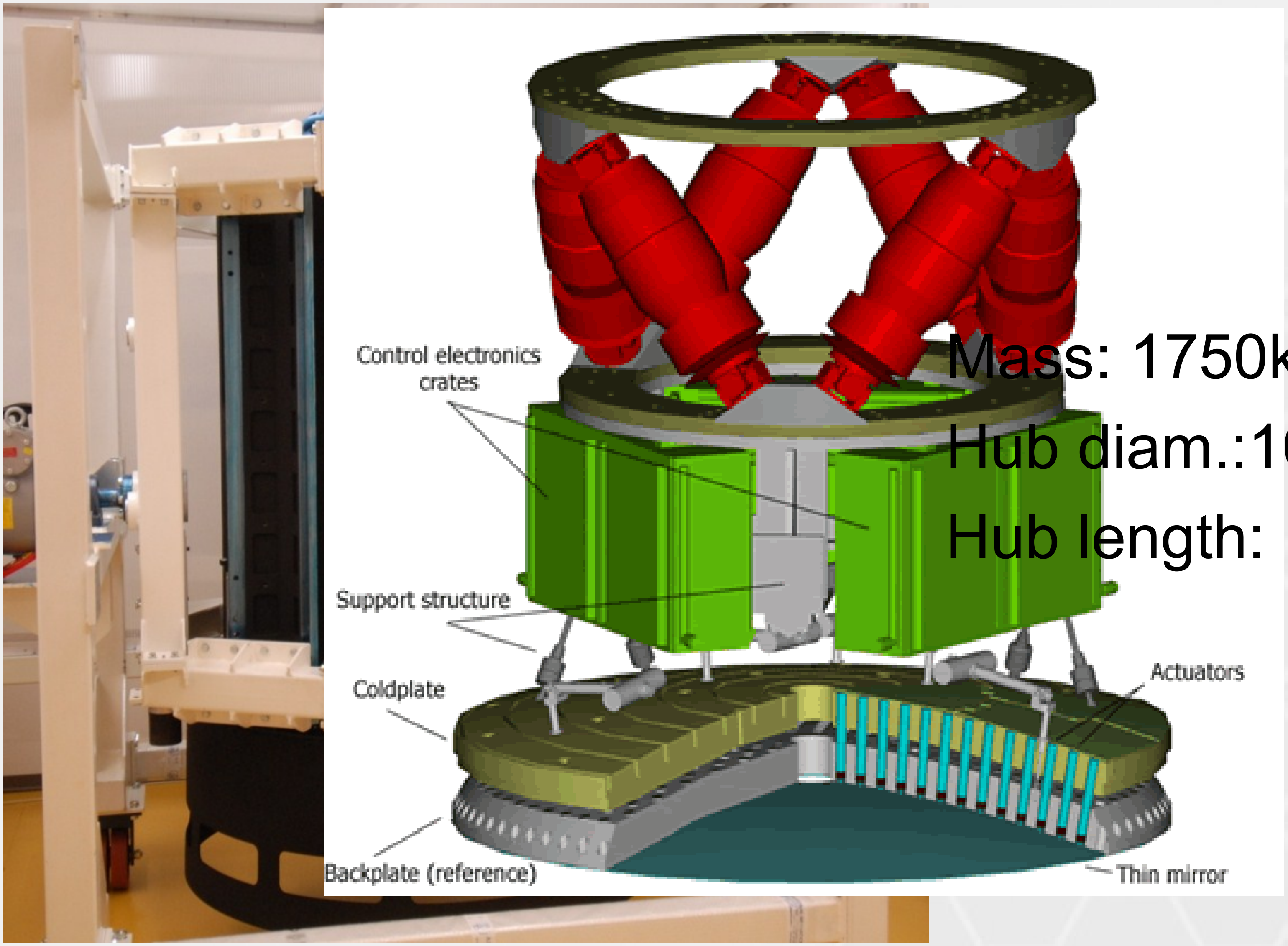
Deformable Secondary Mirror at VLT

DSM key characteristics:
1170 actuators
1.12 meter diameter
0.7 ms response time



AOF will use it with :
MUSE - GALACSI
HAWK-I - GRAAL
ERIS

AOF DSM assembly

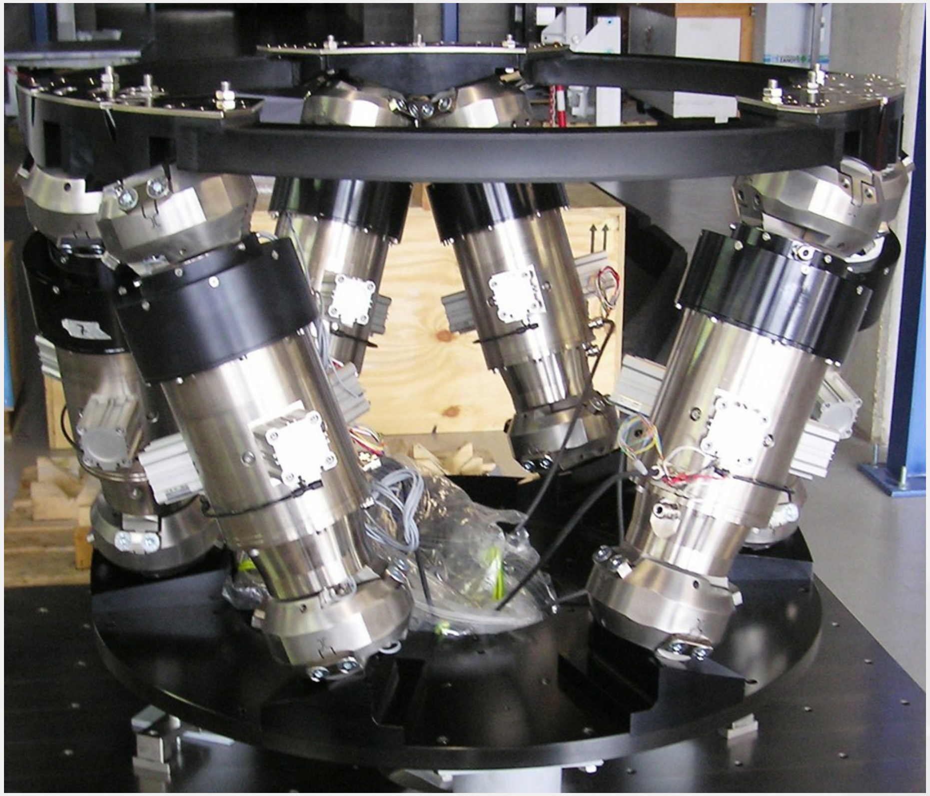


Mass: 1750kg

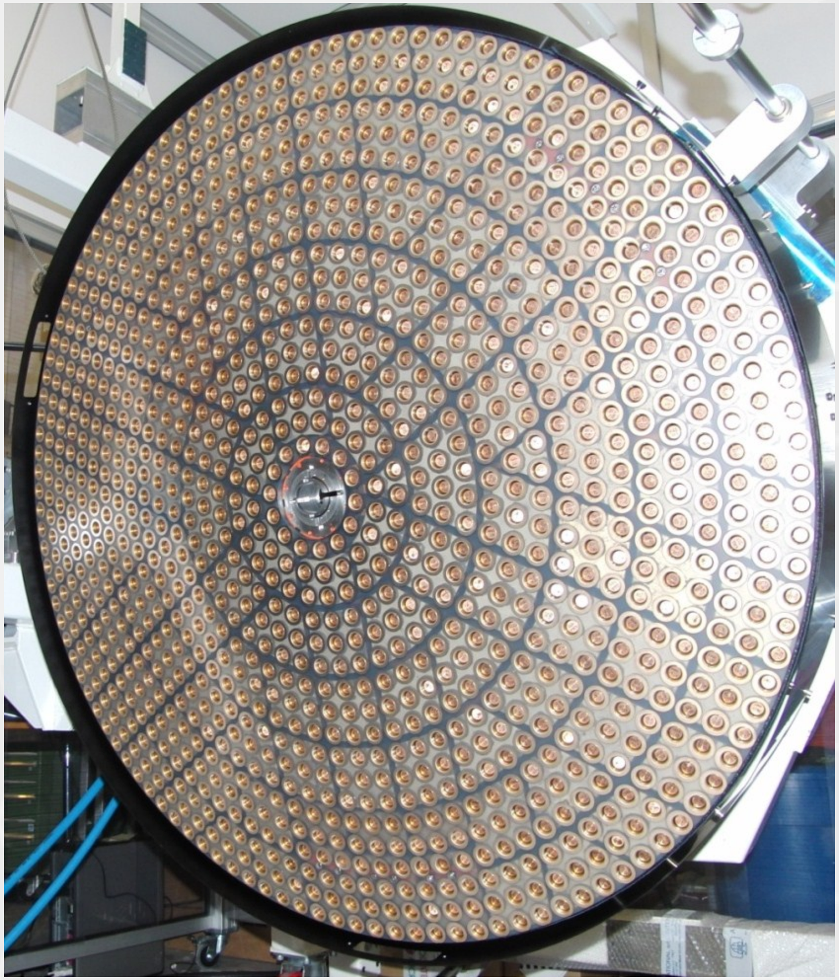
Hub diam.:1074 mm

Hub length: 1851 mm

Hexapod and reference body

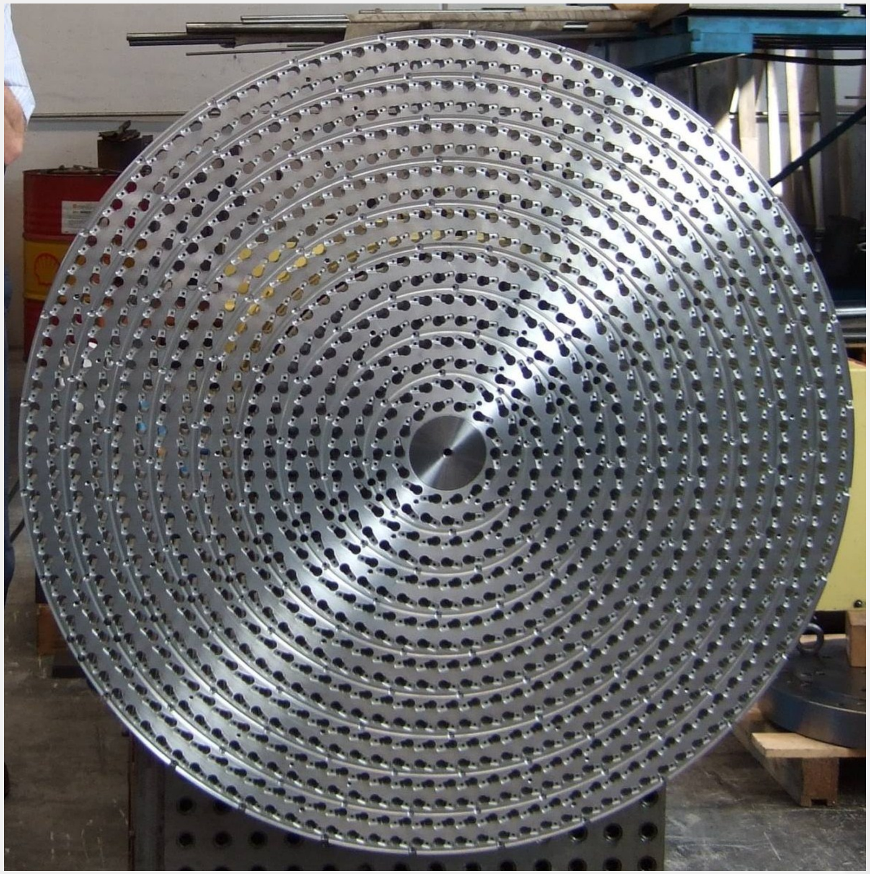


6 legs Hexapod for positiong:
- Focus selection (Nas/Cas) and ±8mm
- Centering ±6 arcmin

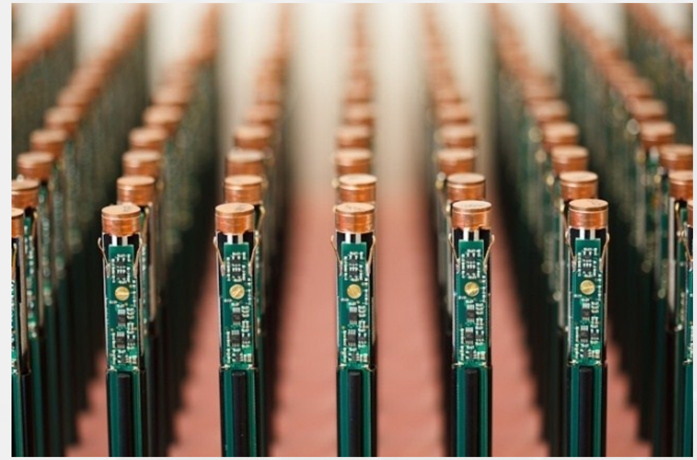


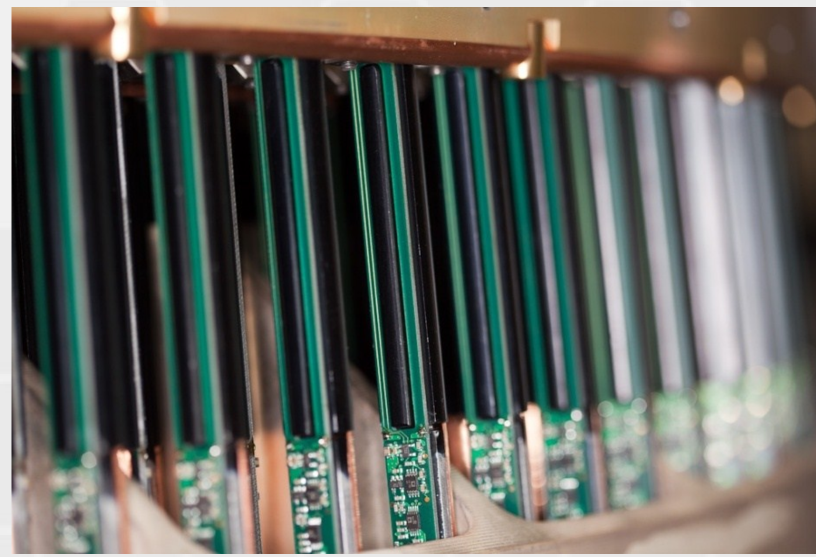
Reference body for the thin shell
- Light Weighted Zerodur 8 mm thick
- 1170 holes with 17mm diameter
- Capacitive sensor inside each hole

Cold plate and voice coil actuators



Cold plate in aluminum
- Mount the 1170 actuators
- Heat sink
- Holding the electronics



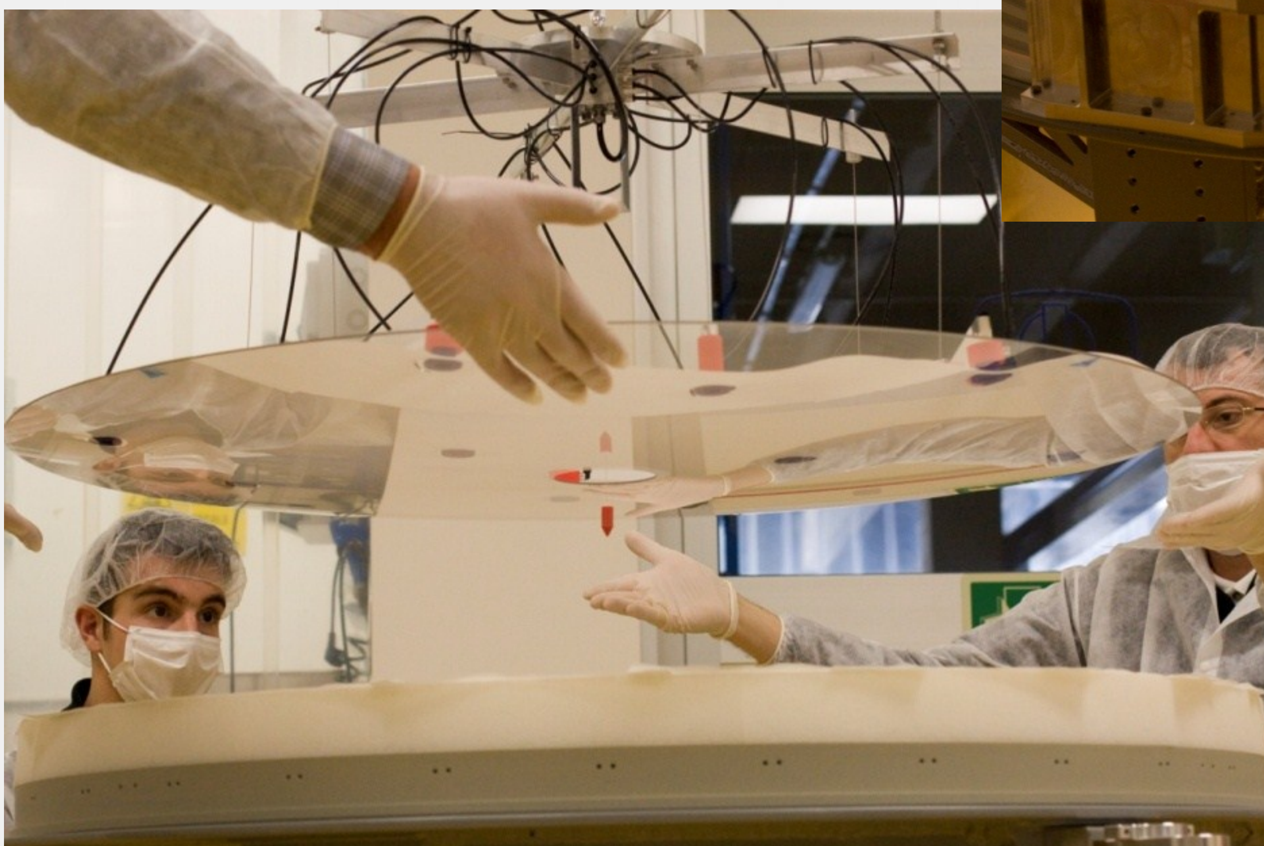


Voice coil actuators
- Bias magnet to hold the shell when it's off

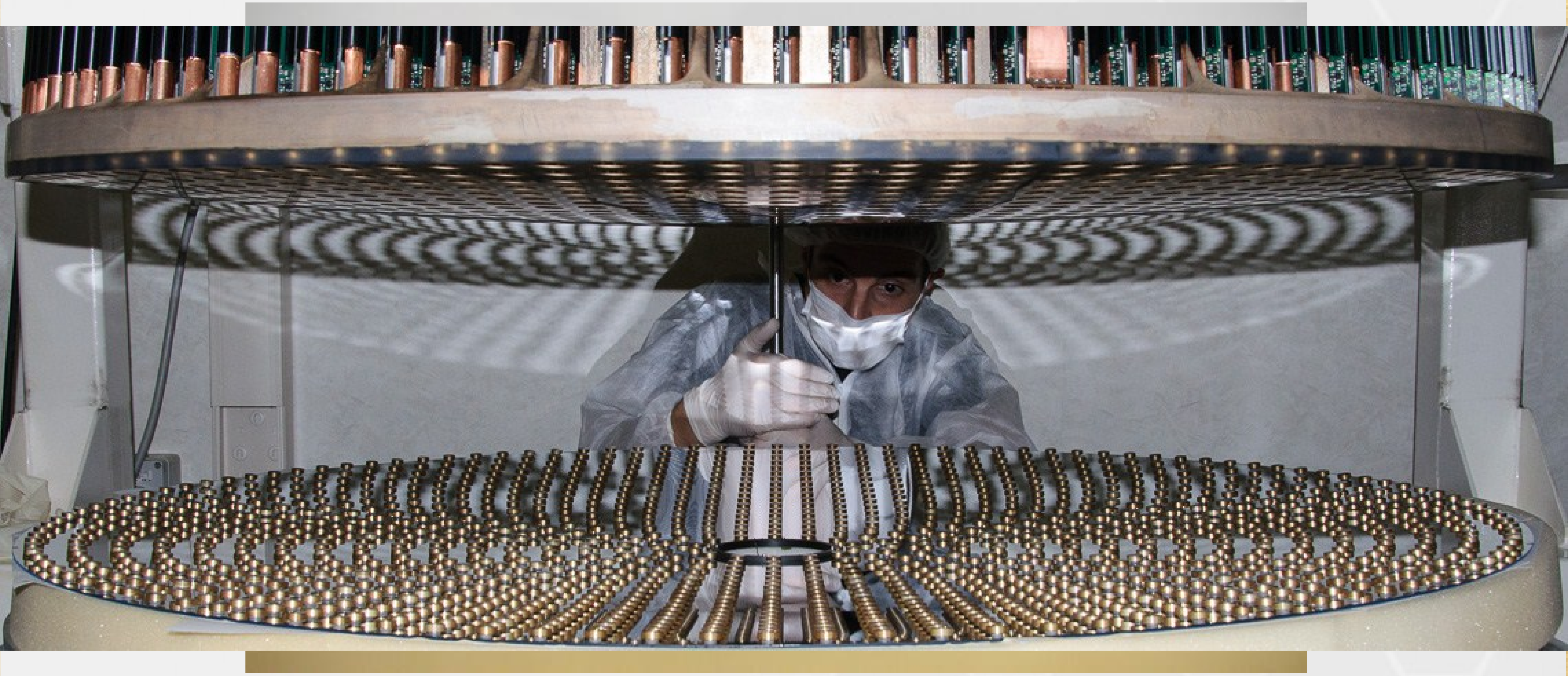
Thin shell

Thin shell mirror

- 1120 mm diameter
- 2 mm thickness



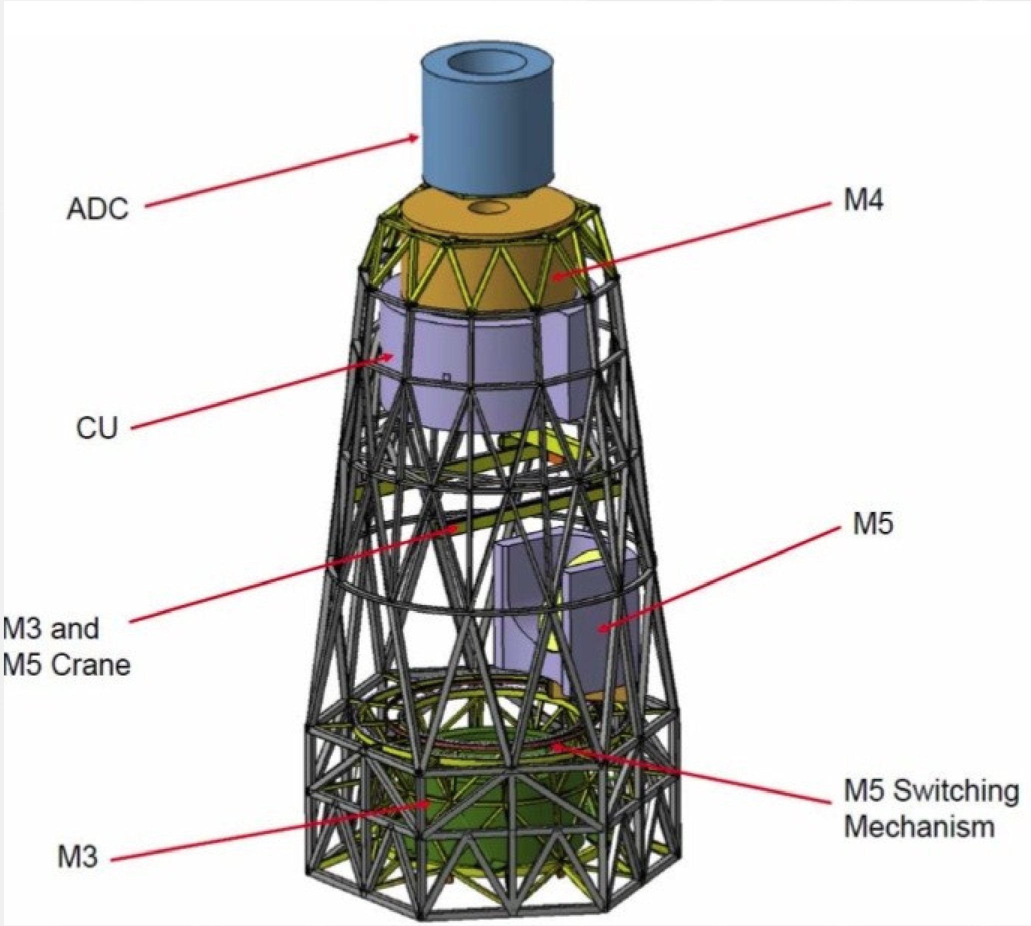
Magnets



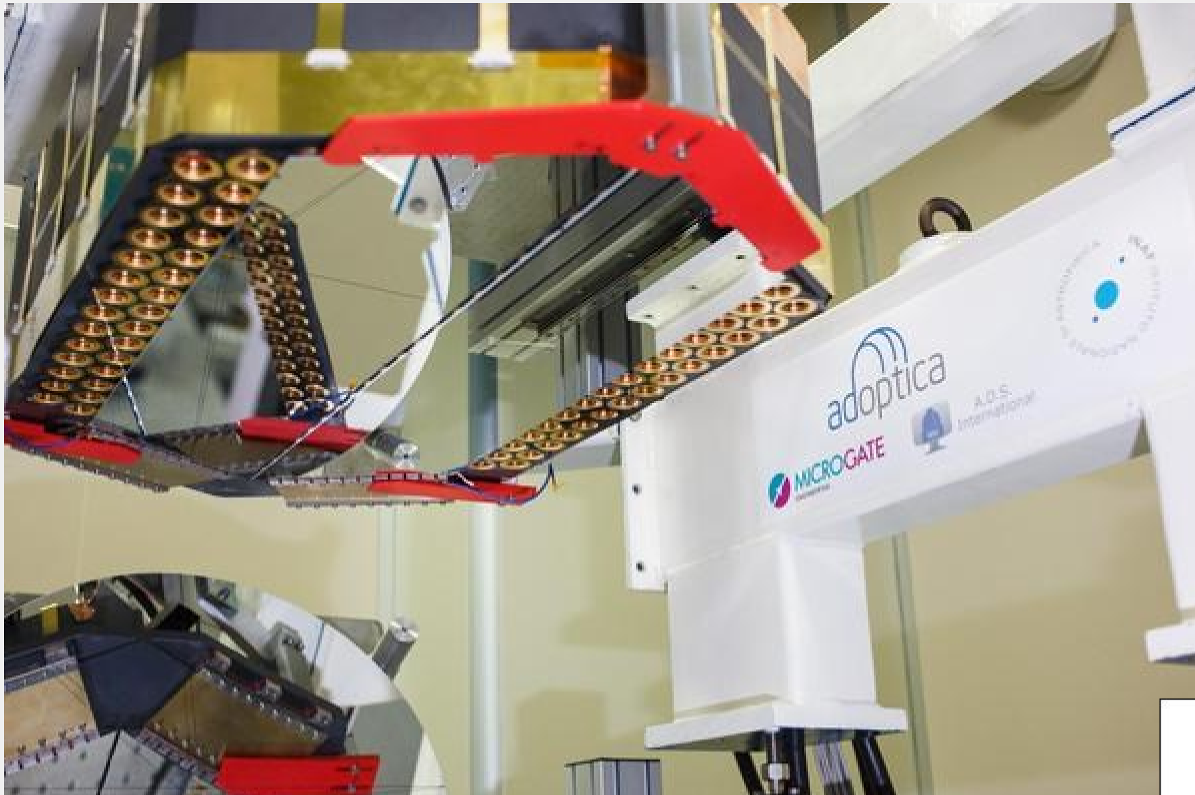
1170 permanent magnets manually glued on the back surface

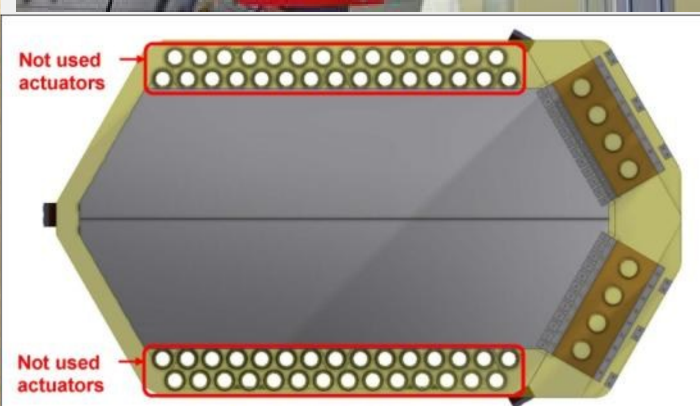
E-ELT M4 deformable mirror

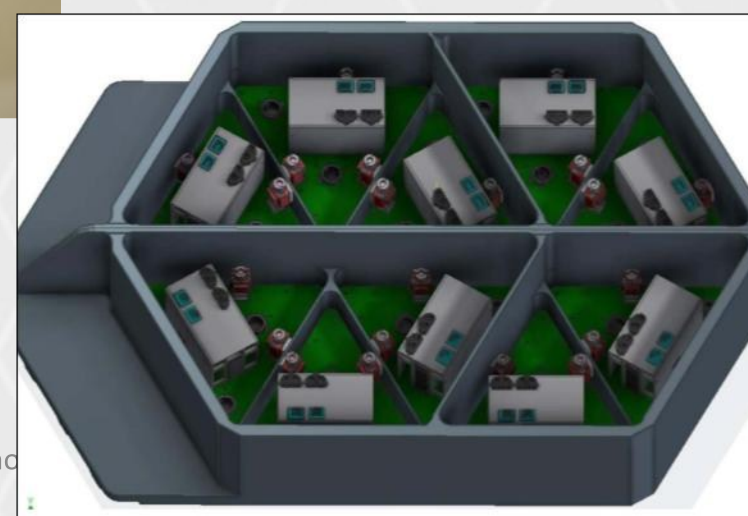
2480 mm diameter
5250 actuators
6 Segmented thin mirrors
2 mm shell thickness
Response time: 0.7 ms



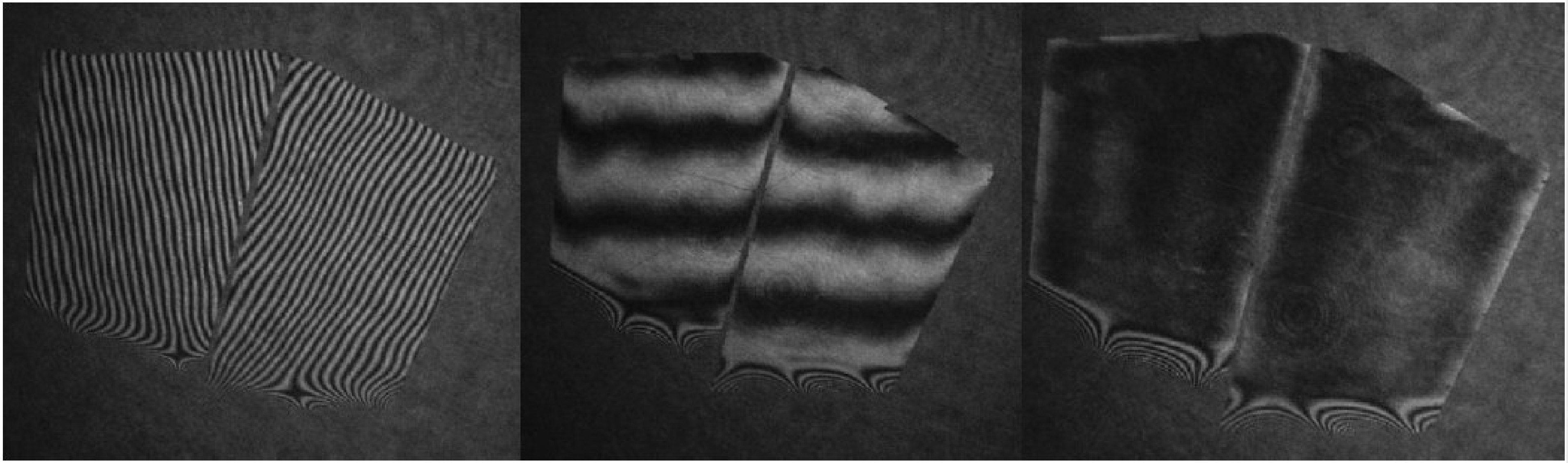
M4 prototype







M4 prototype tests



Two shells independently flattened

Shells cophased

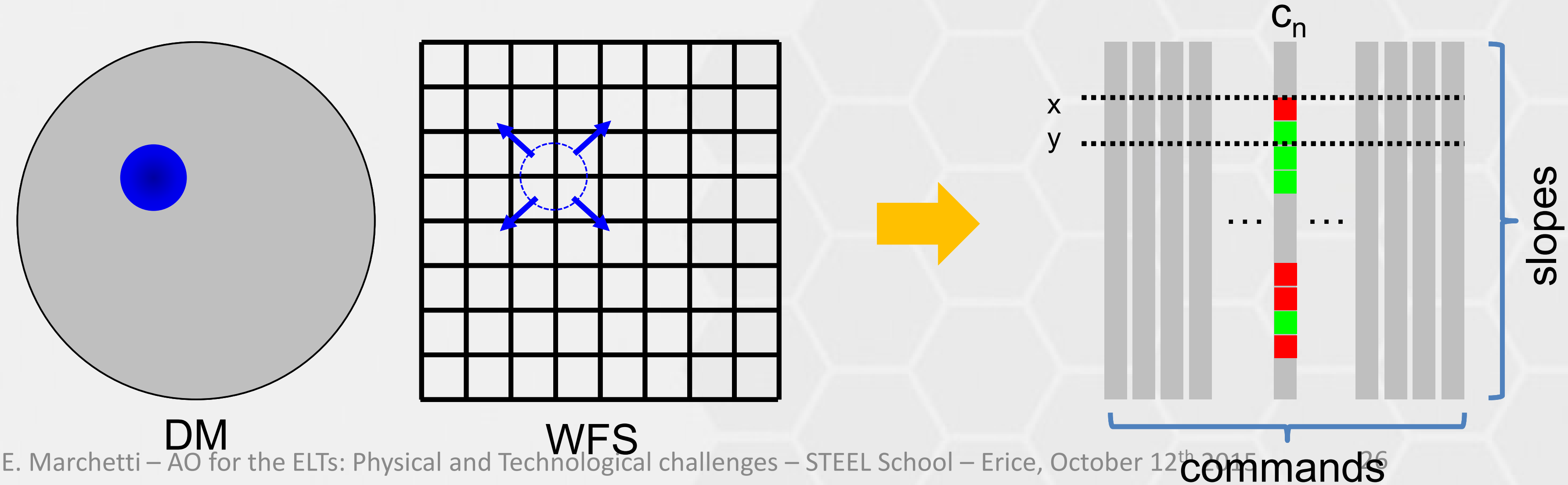
Global tilt removed

Interaction matrix calibration

- The calibration is a core component of an AO system

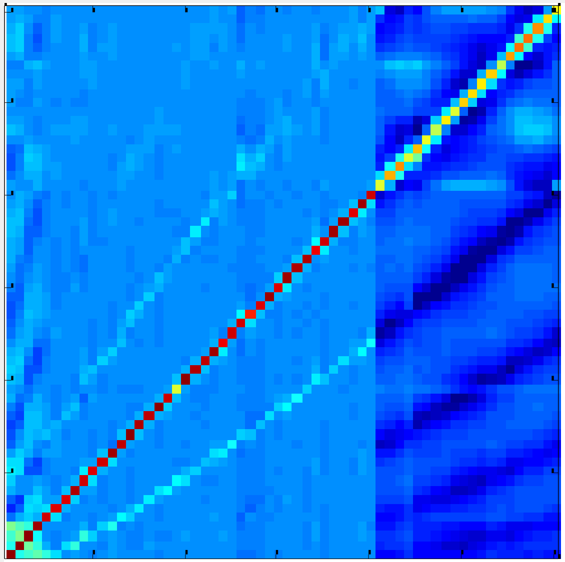
$$c = R \cdot s \quad R = IM^{-1}$$

- The interaction matrix ***IM*** links univocally the relation between the DM command ***c*** and WFS signals ***s***
- The IM is obtained by staking the WFS signals obtained by applying the commands to the DM



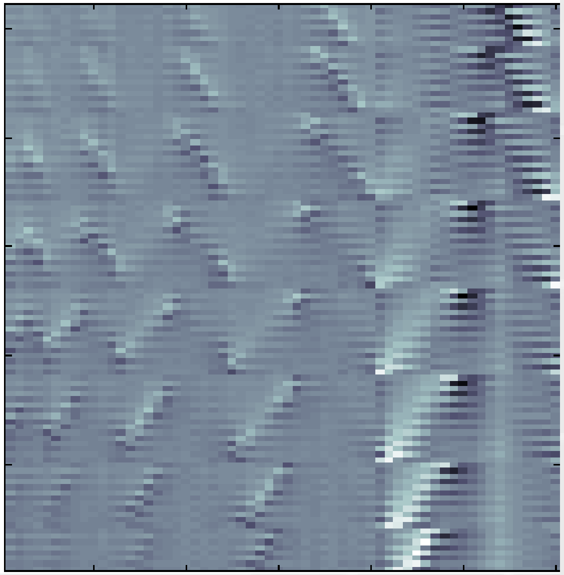
Example of IMs

MACAO



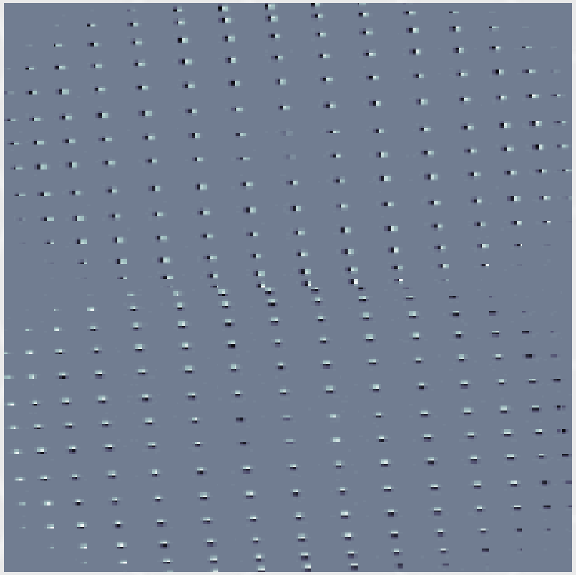
Curvature system
WFS matching DM geometry
Radial → Radial

MAD



MACAO DM and SH
Radial → Rectangular

NACO



Piezo-stack DM and SH
Rectangular → Rectangular

IM at ELTs

- Calibrate large number of degrees of freedom
- Keep the measurement noise low

Time consuming

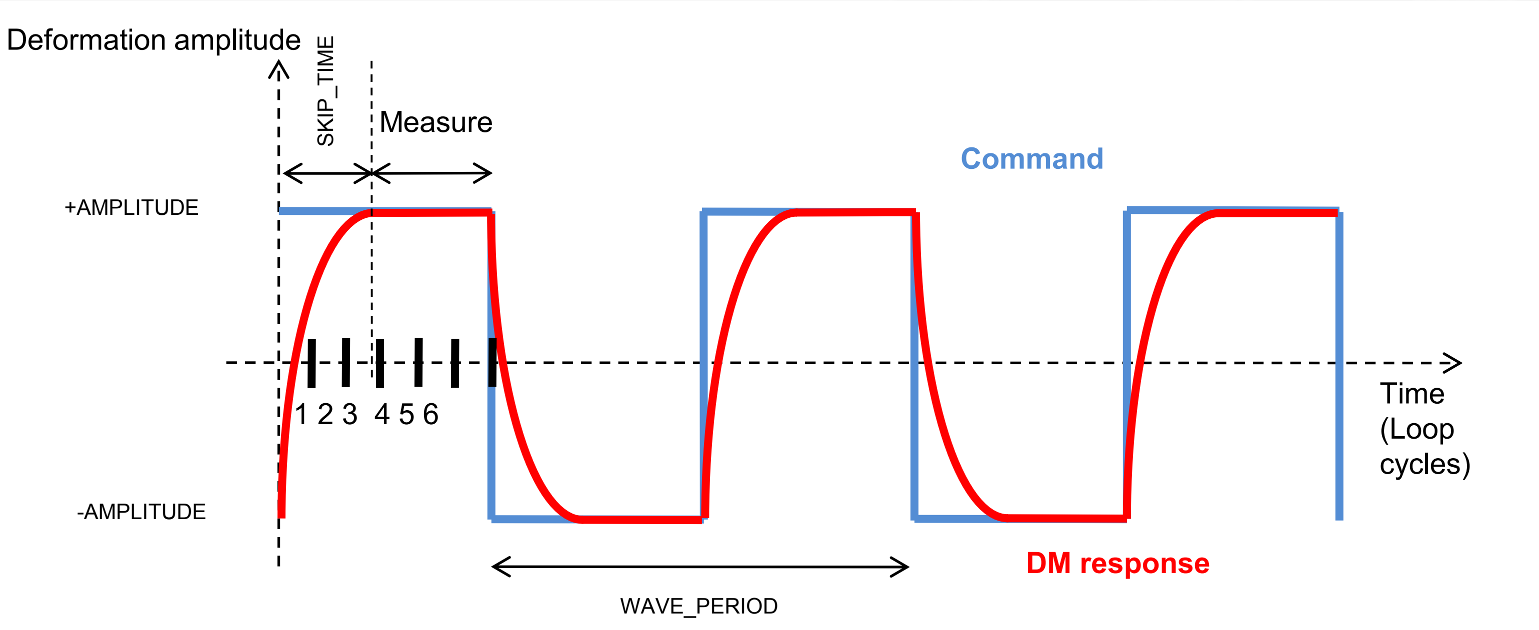
- Techniques for speeding up IM recording

Absence of calibration devices (fiber at focal plane upstream the DM)

- Pseudo-synthetic IM
- Calibration on sky (i.e. with turbulence)

Improving IM SNR

- The IM quality is limited by photon noise, detector noise, limited integration time and local turbulence
- The method of fast push-pull IM recording allows increasing the IM SNR



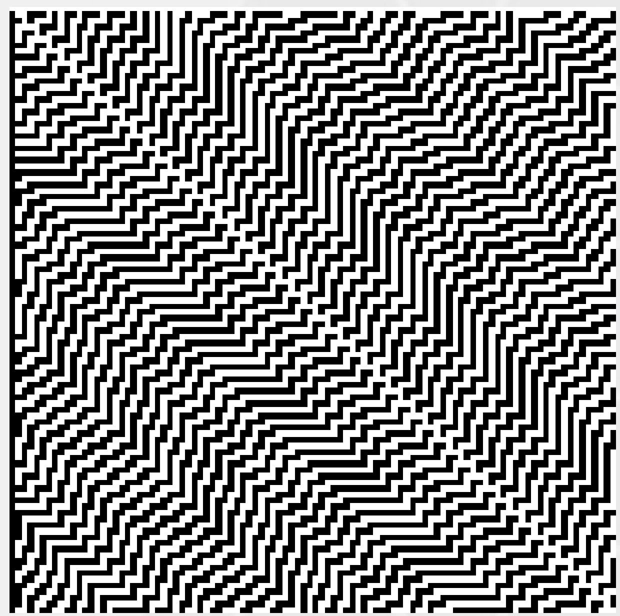
Repeated N times for each acuator

Fast IM recording

- Actuate simultaneously all *N* modes: N times faster or $\sqrt{N}$ times higher SNR for the same time
- Hadamard matrix (only 1s and -1s): $\boldsymbol{H \rightarrow HH^{-1} = HH^{T} = 1}$

$$\boldsymbol{IM = IM_{Hadamard}\, H^{T}}$$

MAD

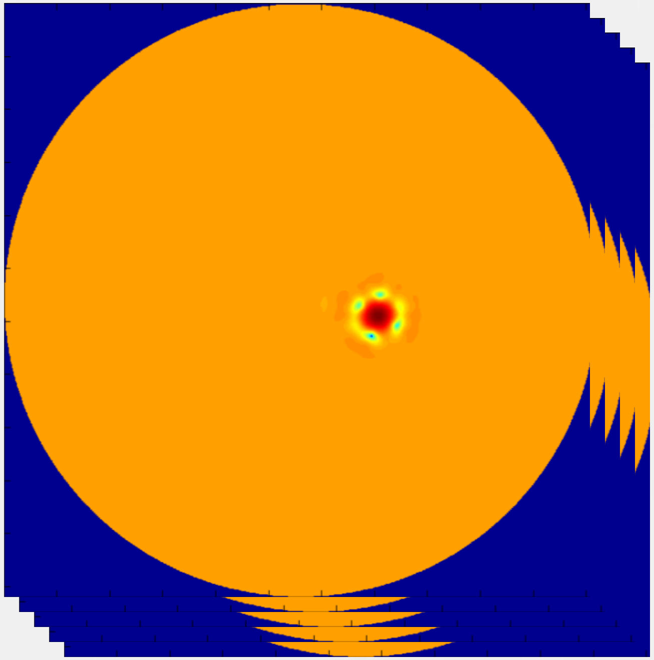


First 100x100 elements of the AOF Hadamard matrix

Pseudo-synthetic IM

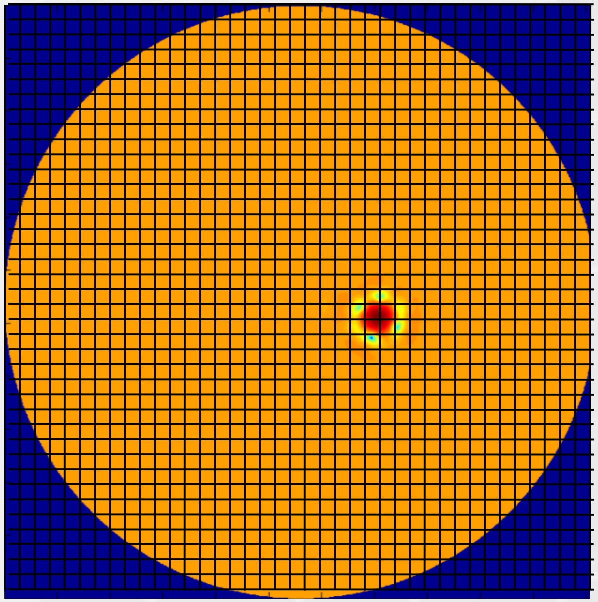
- Generate IM without direct measurement
- Synthetic: generated by a simulation model
- Pseudo: tune to quantities measured on the real system
  - DM influence functions
  - Pixel scale
  - Mis-registration
- Advantages: quick to compute, infinite SNR, reload new IM as soon system conditions are changed
- Drawbacks: model dependent, accuracy of the physical quantities

Pseudo-synthetic IM



1170 Influence Functions (FEA) or stiffness modes, or System modes

+



Shack-Hartmann model (geometric or diffractive, with or without noise) 40x40 sub-apertures (1240 valid)

+

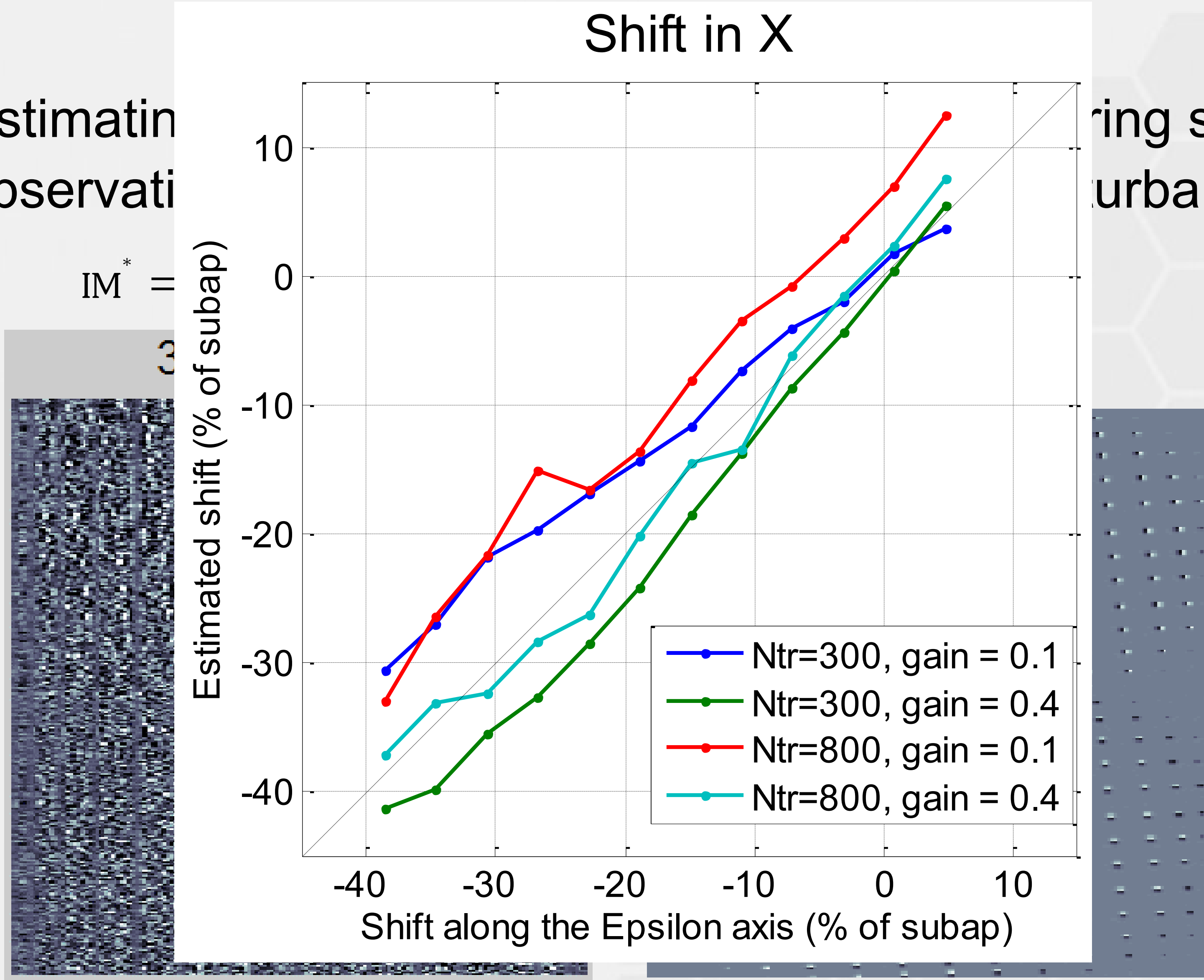
Mis-registrations: x & y shifts, rotation, x & y stretches of WFS w.r.t. DM

→ Interaction Matrix

IM from closed loop data

- Estimatin ... ring scientific observati ... urbance

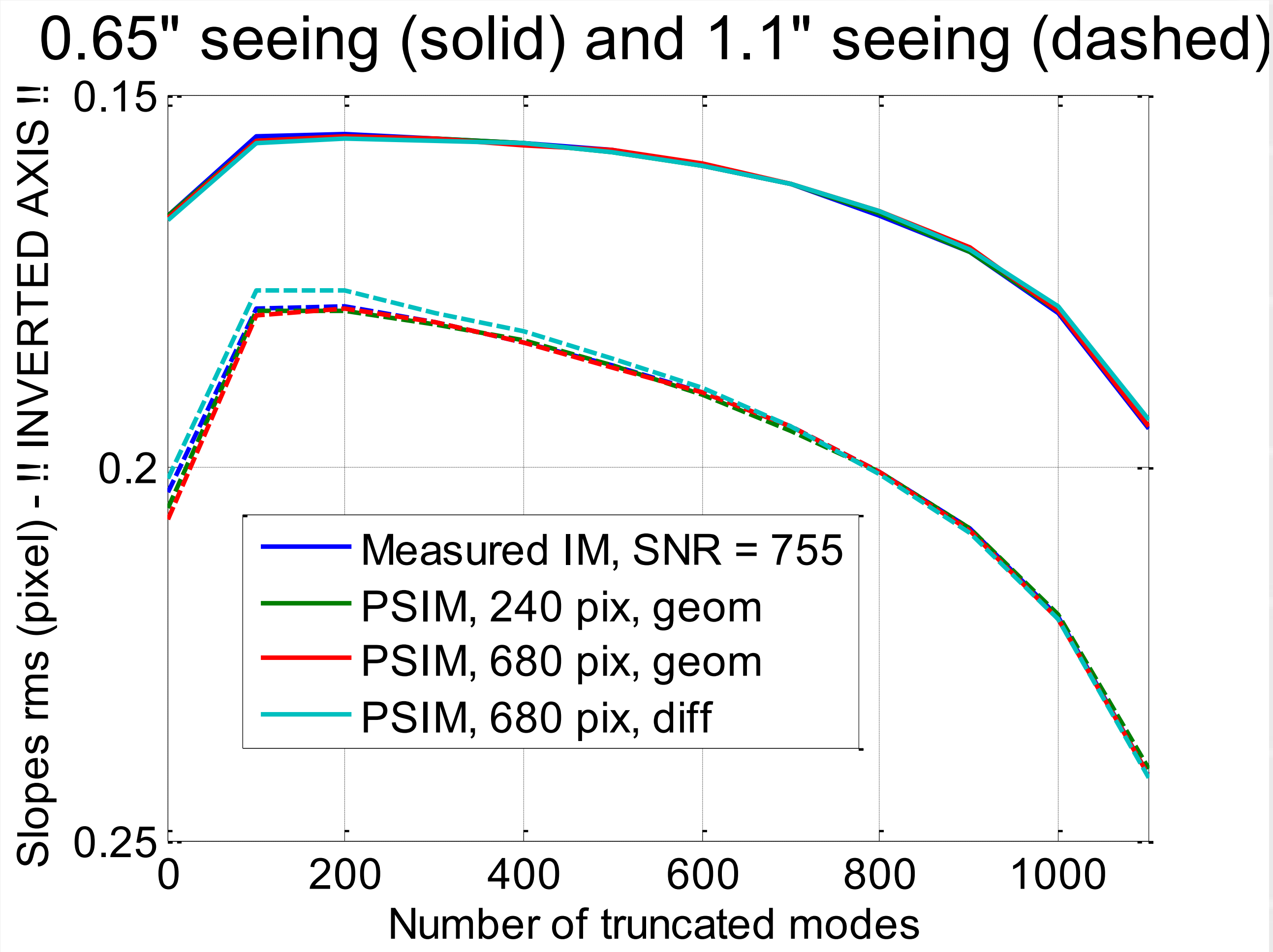
$IM^* =$



Measured on fiber

Validation

AOF



Calibration on sky

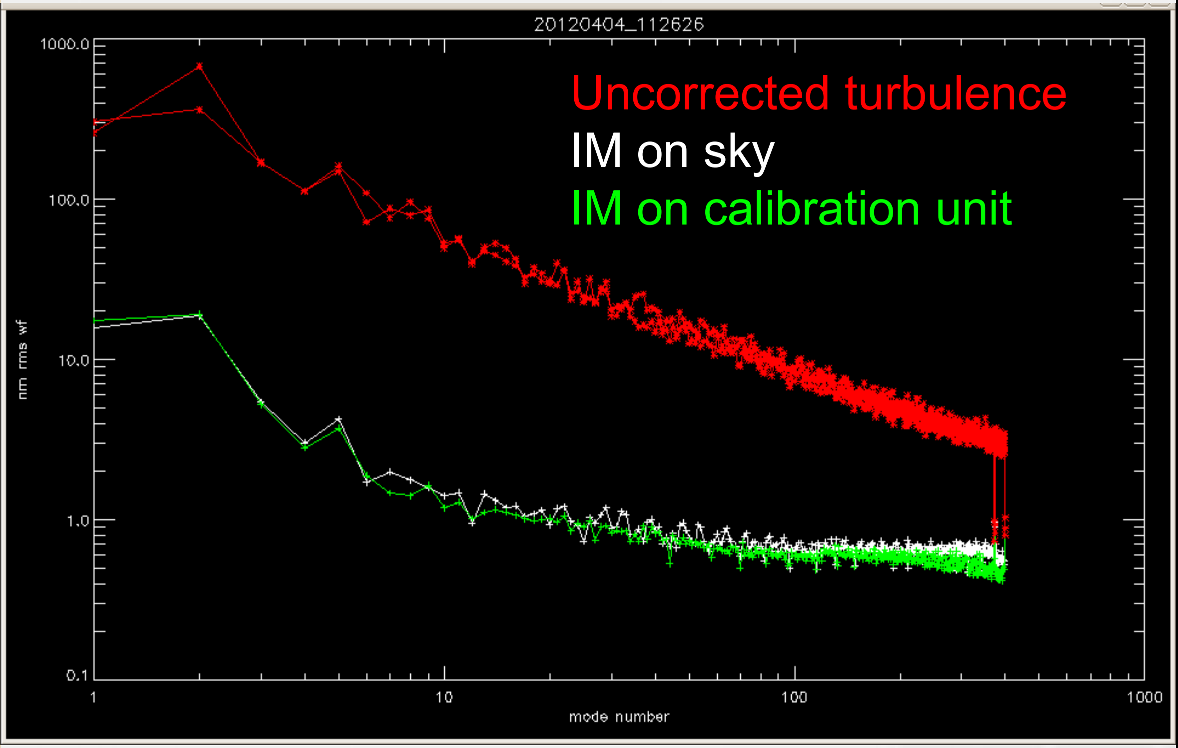
- Atmospheric turbulence injects noise on IM measurement
- “Freeze” the turbulence during IM measurement
- Even shorter integration with push-and-pull technique
- Closed loop IM

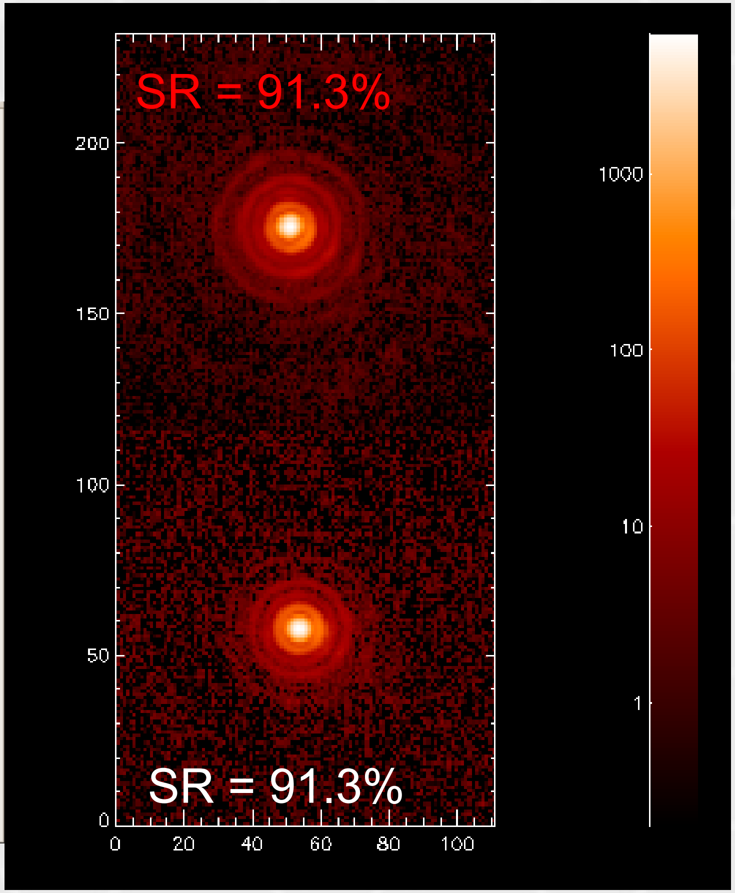
Closed loop IM

1. Close AO loop with preliminary IM (synthetic), not needed to be perfect
2. Send additional delta-command
3. The AO loop will compensate for the delta-command within one loop cycle
4. Synchronized WFS measurement and filter out the slope response at that cycle
5. Repeat until desired SNR is achieved
6. Build up IM

Closed loop IM

- On-sky validation with FLAO system (2012), 400 modes



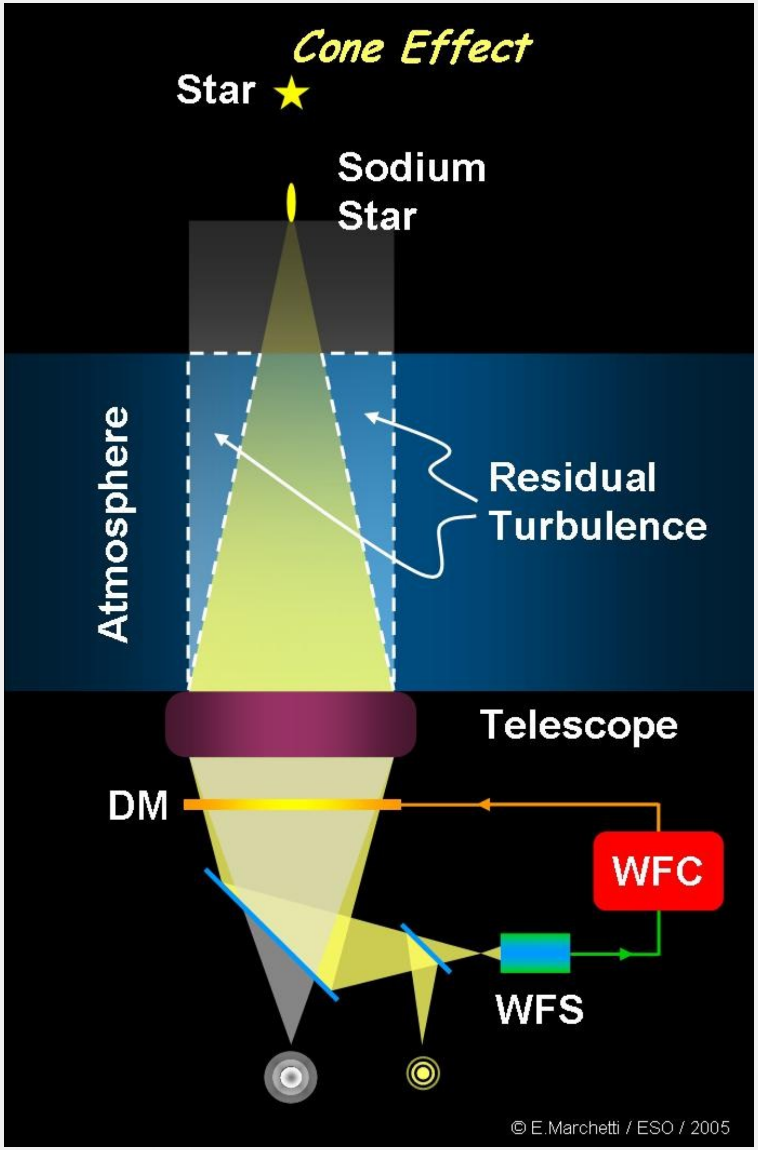


Laser guide stars

LGS the good and the bad

- Aiming at increasing sky coverage with AO
  - Placing anywhere in sky
  - Multi-LGS constellation for GL/MC/MO-AO configurations
  - Reliable and performing technology exists today
- LGSs hardly resemble NGSs
  - Not providing tip-tilt information → NGS WFS for tip-tilt
  - Cone effect
  - Strongly impaired focus information: Sodium vertical profile changes with time, even very fast → NGS WFS for focus
  - Extended sources (Sodium layer thickness)
  - Sodium abundance changes with time
  - Return flux depending on geomagnetic latitude

Cone effect



$$\sigma^2 = \left(\frac{D}{d_0}\right)^{5/3}$$

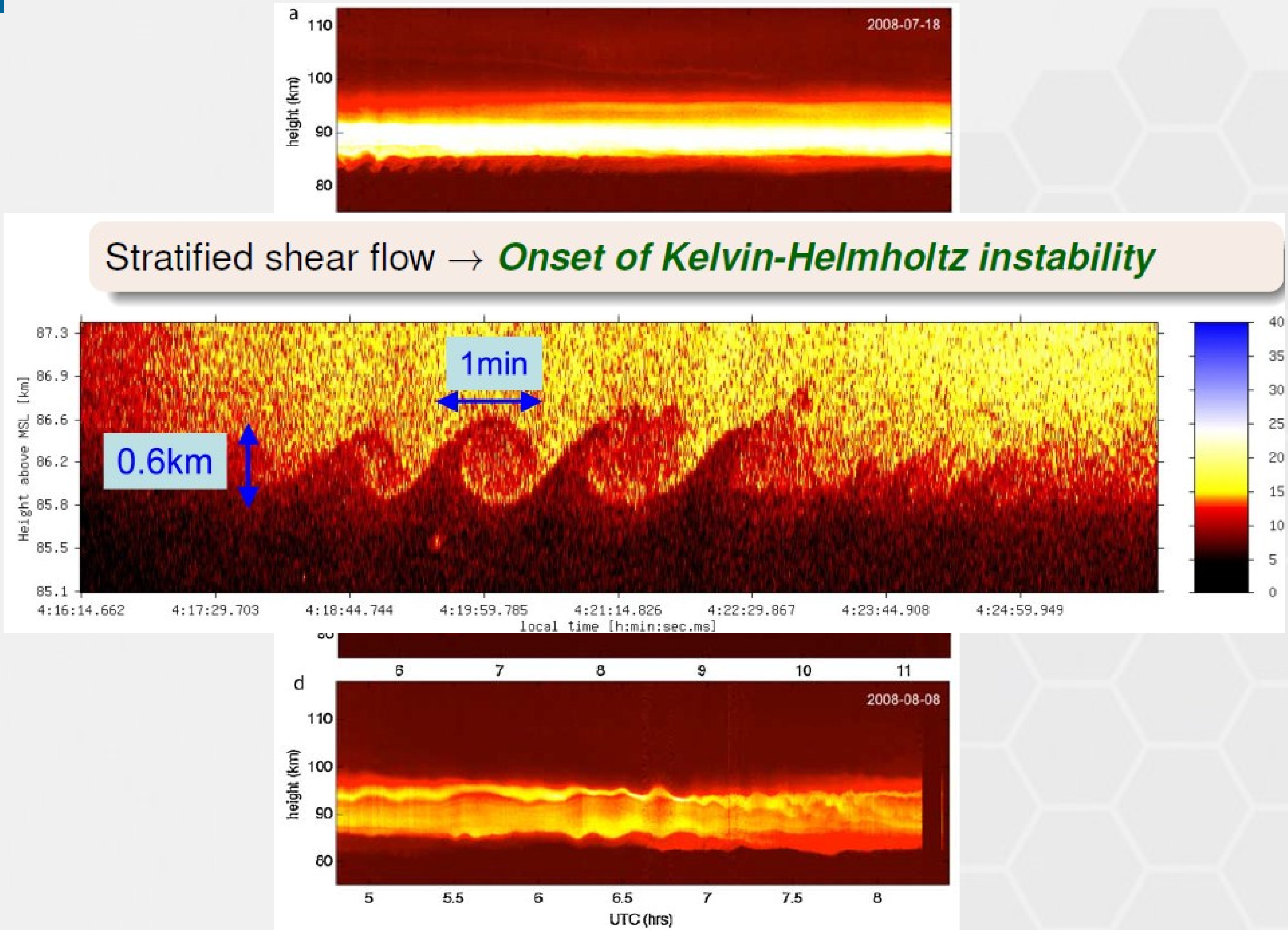
d_0 diameter of telescope for $\sigma^2 = 1$ rad^2

Median seeing:
d_0(0.5 μm) ~ 4 m
d_0(2.2 μm) ~ 24 m

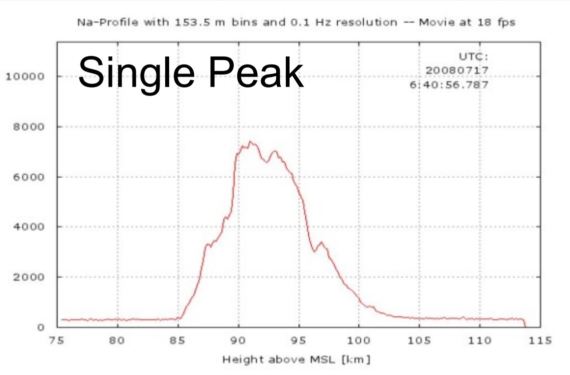
σ^2_{VLT} = 55 nm → SR(2.2 μm) = 0.85
$\sigma^2_{E\text{-}ELT}$ = 720 nm → SR(2.2 μm) = 0.13

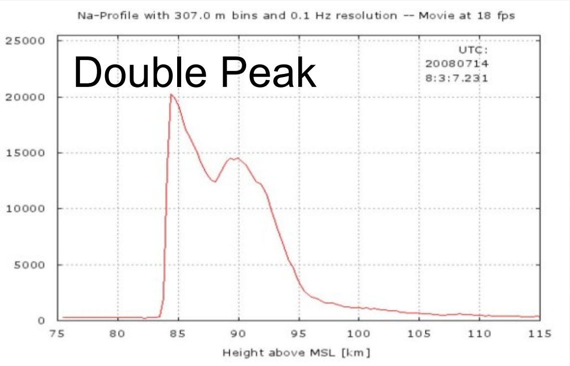
Single LGS AO not viable for ELTs → Laser Tomography Adaptive Optics

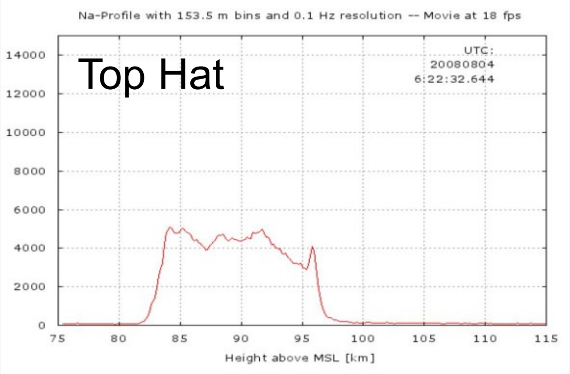
Sodium layer profile

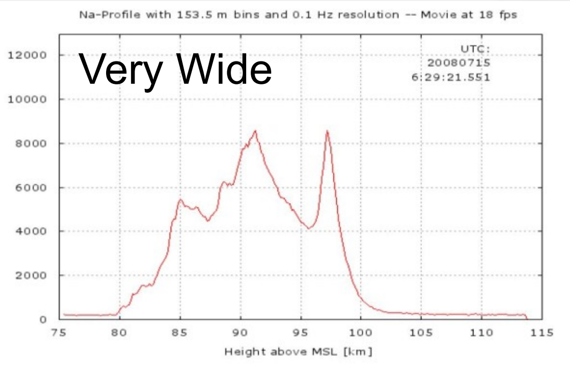


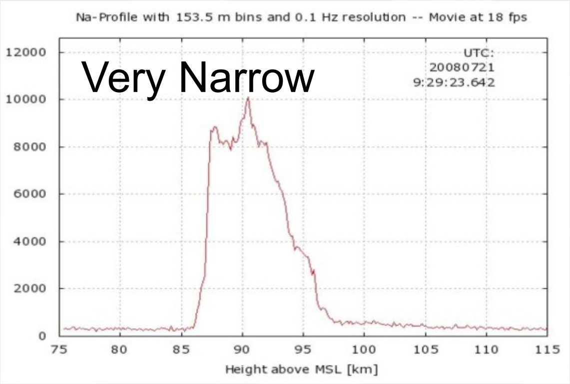
Sodium layer profile

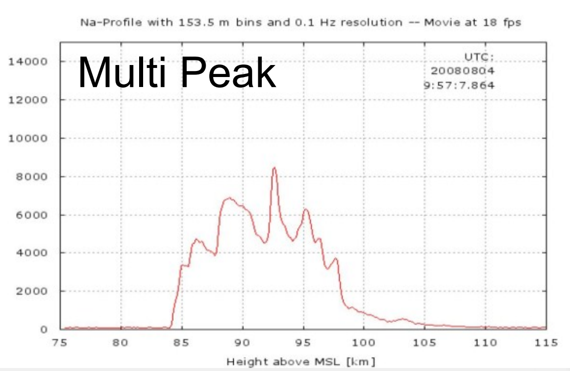


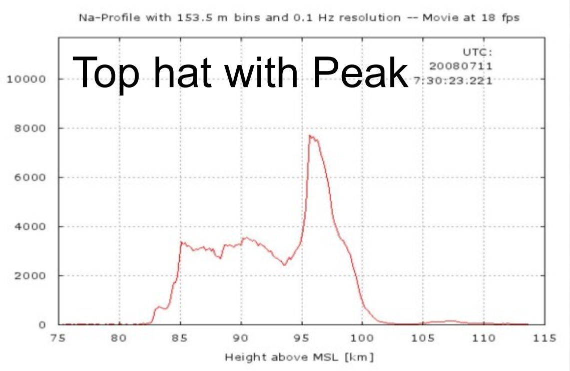




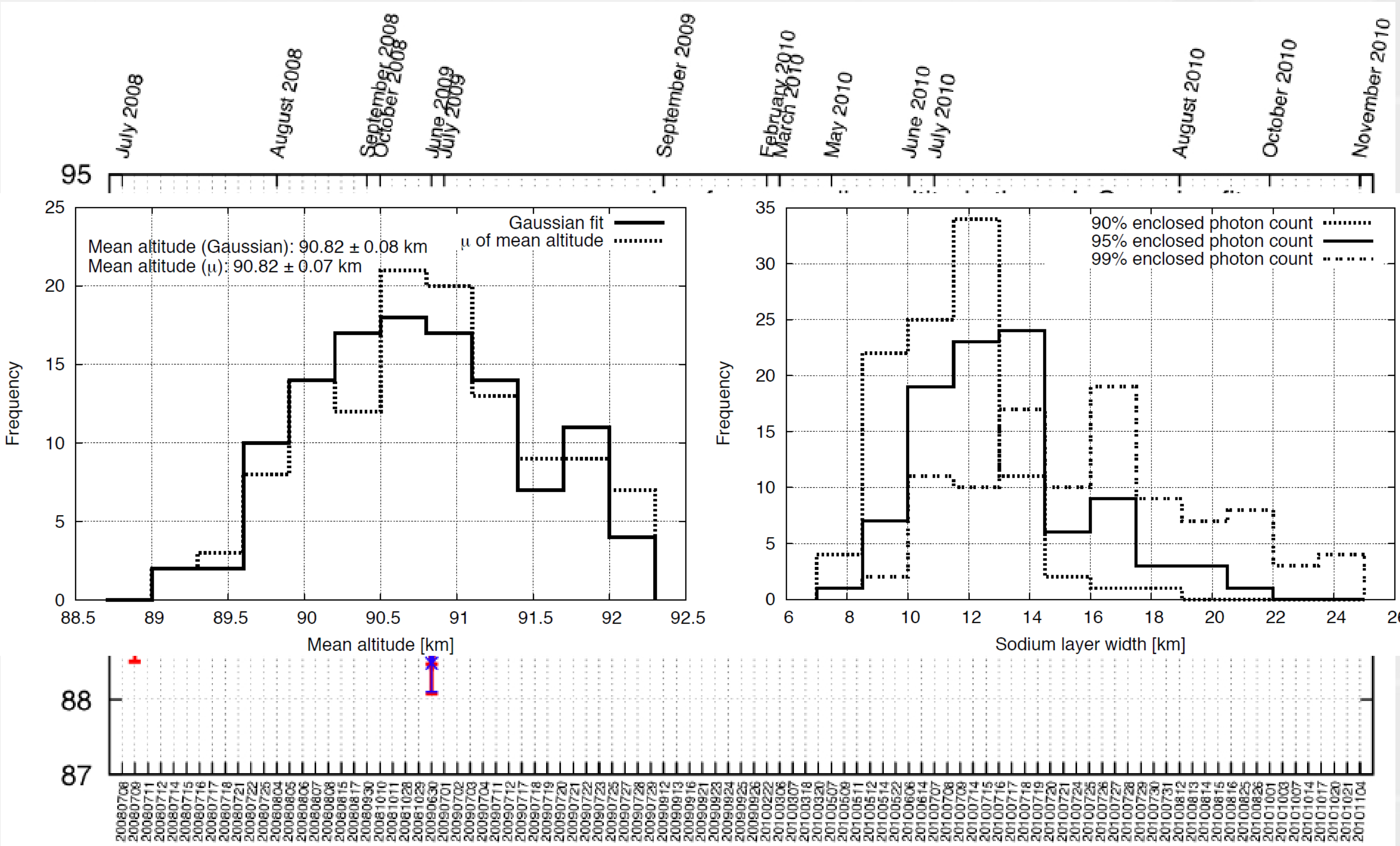




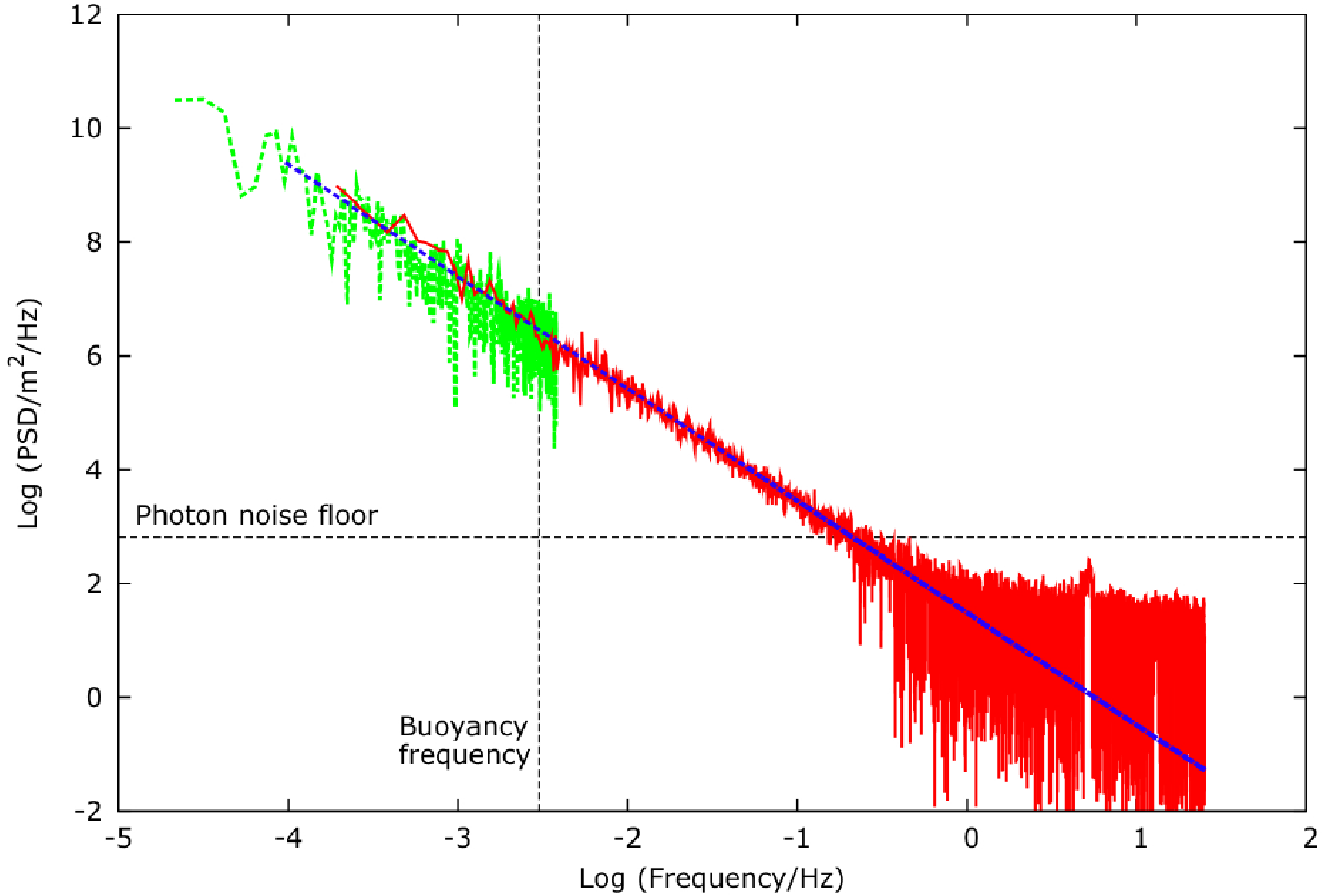




Mean altitude variation



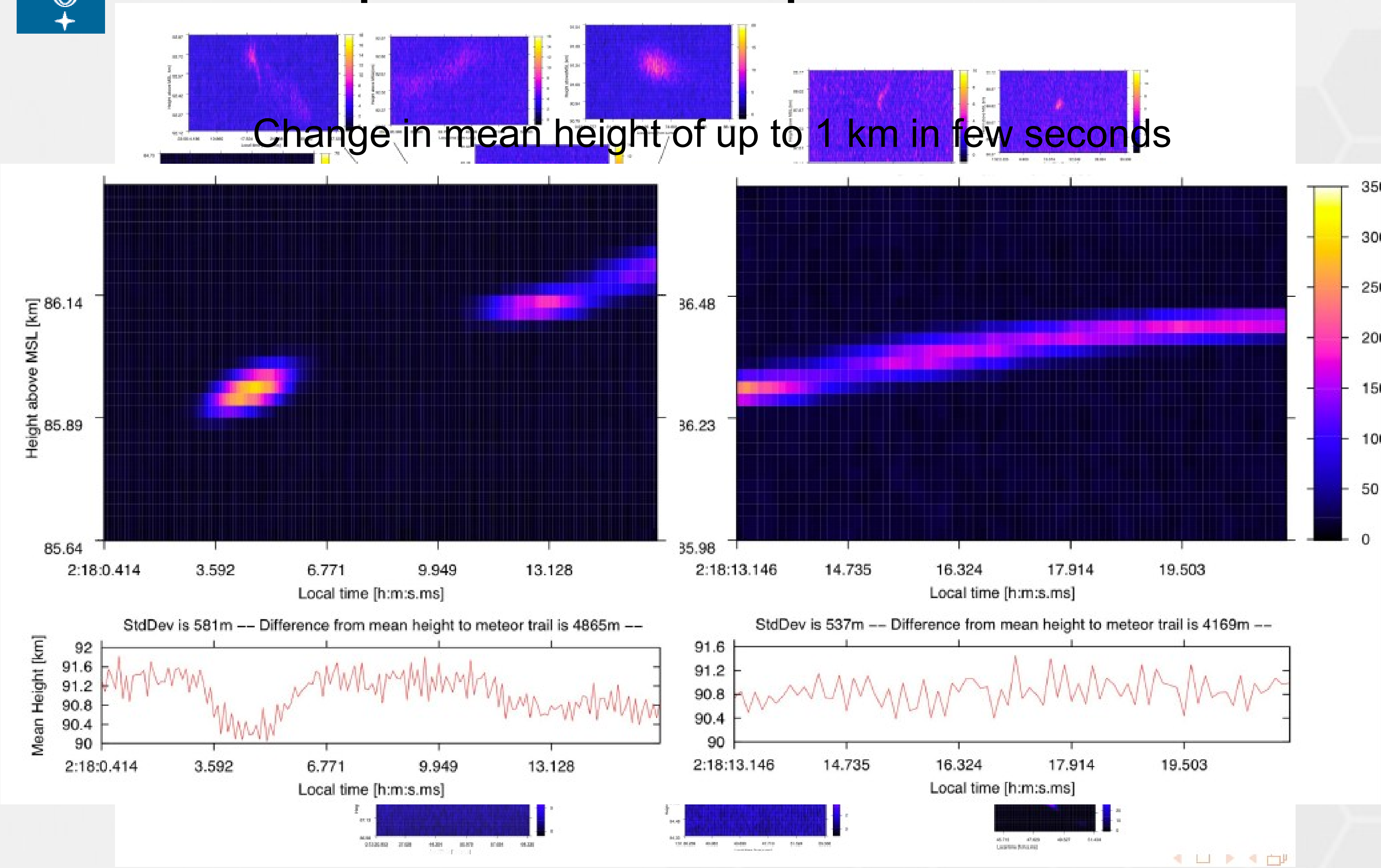
Mean altitude power spectrum



$$P_a(\nu) = \alpha\nu^{\beta}, \qquad \alpha = 34^{+6}_{-5}\frac{m^2}{Hz}, \beta = -1.87 \pm 0.02$$

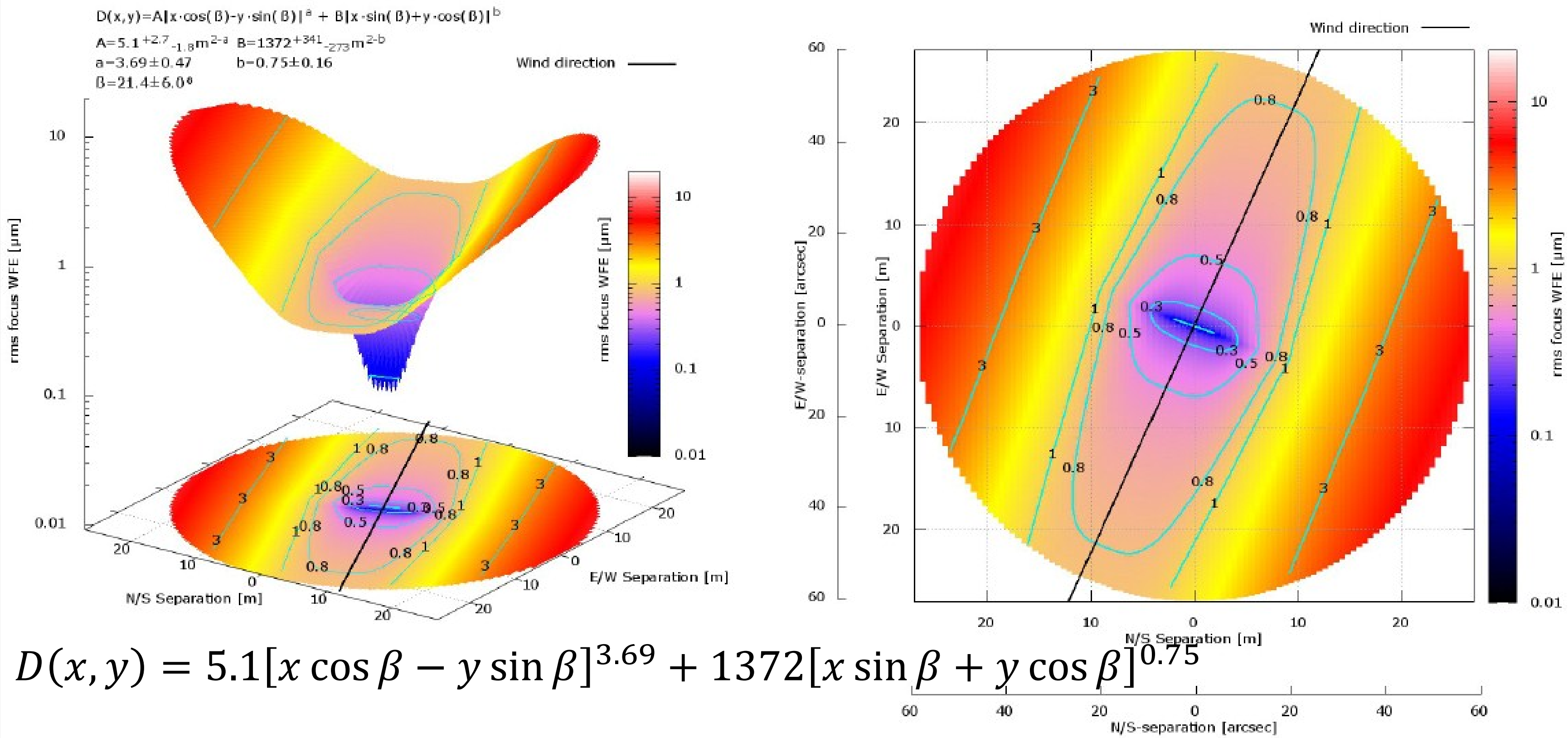
Expect the unexpected: meteors

Change in mean height of up to 1 km in few seconds



Horizontal focus error

- Multi LGS systems look at different positions in the Sodium layer: larger apertures require large LGS spatial separation



$$D(x, y) = 5.1[x \cos \beta - y \sin \beta]^{3.69} + 1372[x \sin \beta + y \cos \beta]^{0.75}$$

Compensating for Sodium altitude

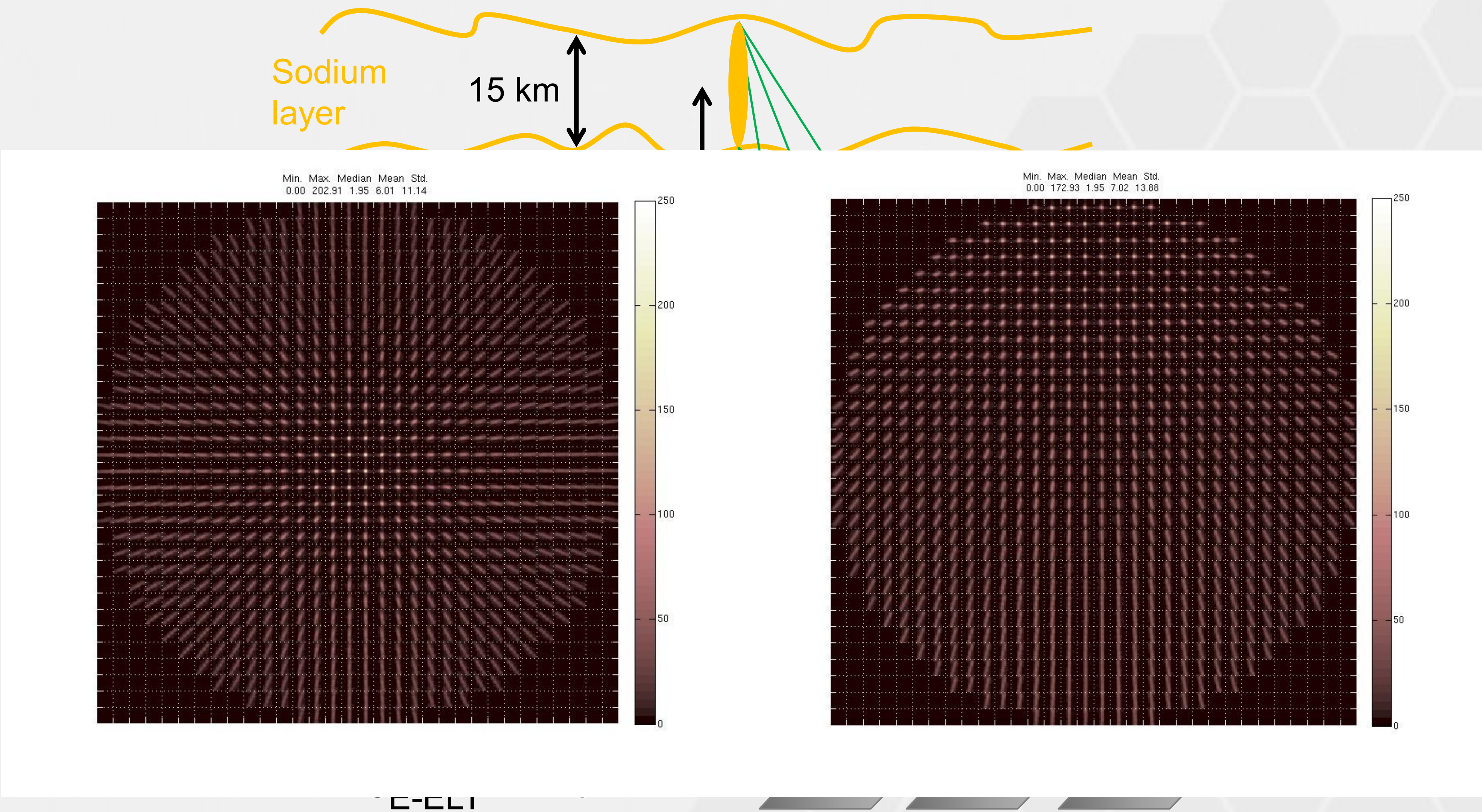
- Focus error strongly dependent from telescope diameter

$$\sigma_{WFE} = \frac{D^2 \sin z}{16\sqrt{3}(a-h)^2}\Delta a$$

- For 1m Sodium altitude variation:
  - VLT: σ_{WFE} = 0.3 nm
  - E-ELT: σ_{WFE} = 6.4 nm → **x 20!**

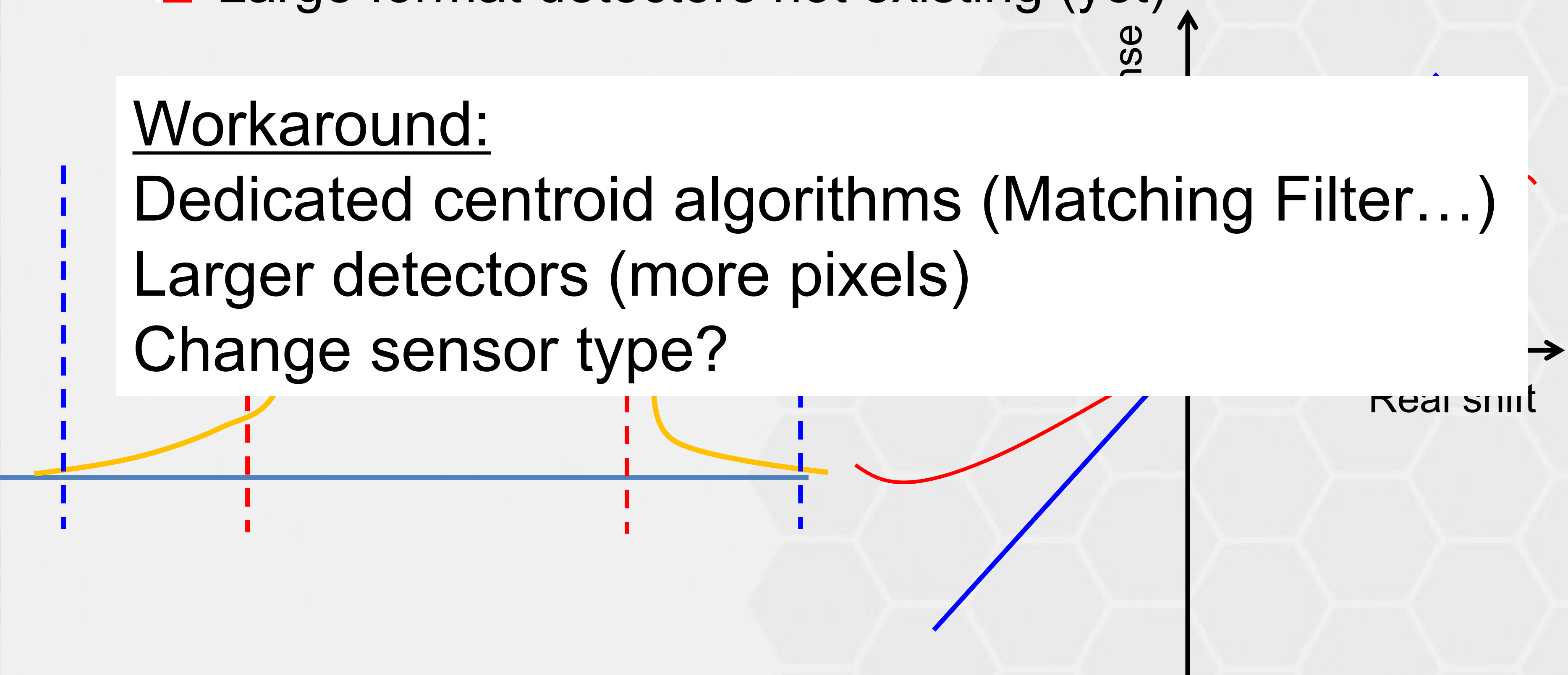
- In ELTs the focus must be sensed at higher frame rate (~1Hz)
- Several focus NGS WFS are likely needed

Spot elongation



Spot truncation and linearity

- Sampling requirements impose the number of pixels to be used to avoid LGS image truncation
- Linearity to centroid motion is affected by truncation
- Large format detectors not existing (yet)



Workaround:
Dedicated centroid algorithms (Matching Filter…)
Larger detectors (more pixels)
Change sensor type?

Thank you for listening!
(again)