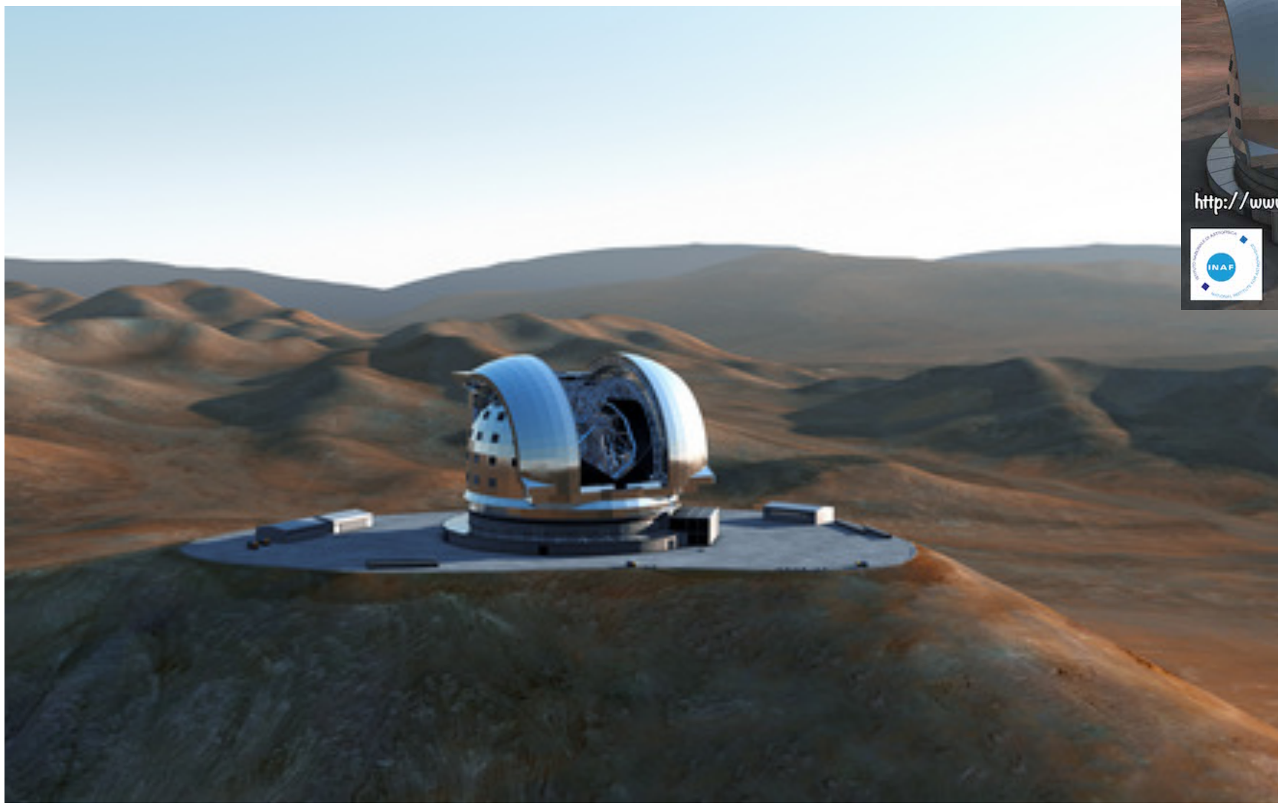
The E-ELT and SCAO systems

Arcetri Observatory AO group



presented by S. Esposito

Science & technology with E-ELT, Erice, 8-20 October 2015

Talk summary

An introduction of Single Conjugate AO (SCAO) system in general

SCAO characteristics & comparison for 8m and 40m telescopes

E-ELT Simulated performance for imaging and high contrast

E-ELT instruments

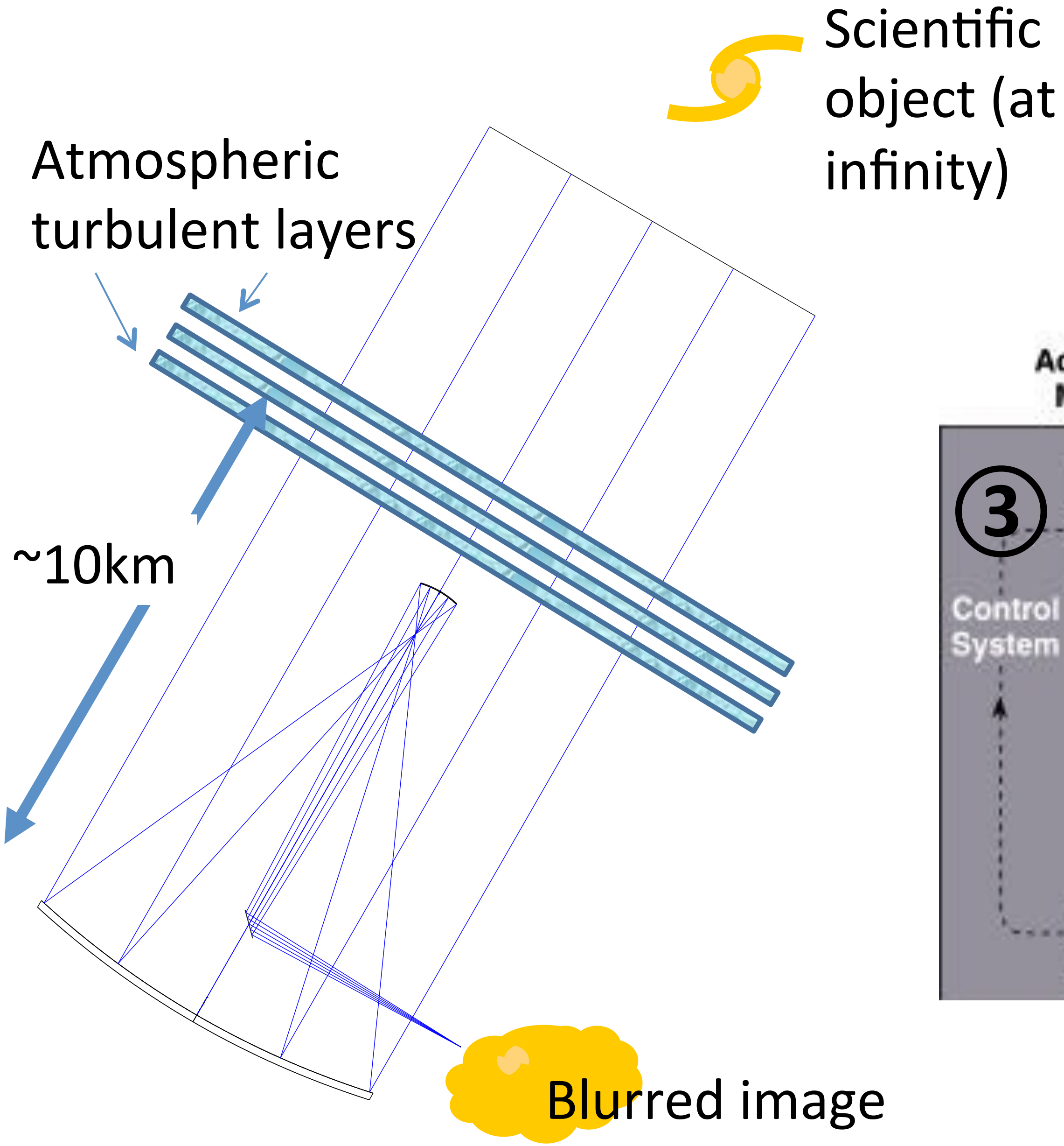
Instruments - First Light	AO	Mode	λ (µm)	Resolution	FoV / Sampling	Add. Mode
E-CAM – **2023**	SCAO, MCAO	- IMG - MRS	0.8 – 2.4	BB, NB 3000	53.0” / 3 mas	Astrometry 40mas Coronography
E-IFU – **2023**	SCAO, LTAO	- IFU	0.5 – 2.4	4000 10 000 20 000	0.5×1.0” / 4mas 5.0×10.0” / 40mas	Coronography
E-MIDIR – **2024/2028**	SCAO, LTAO	- IMG - MRS - IFU	3 – 13 3 - 13 3 - 5	BB, NB 5000 100 000	18” / 12 mas 0.4”×1.5” / 4 mas	Coronography Polarimetry
E-HIRES - **2024/2028**	SCAO	- HRS	0.37 – 0.71 0.84 – 2.50	200 000 120 000	0.82” 0.027”×0.5”	Polarimetry
E-MOS - **2024/2028**	MOAO	Slits IFUs IFUs	0.37 – 1.4 0.37 – 1.4 0.8 – 2.45	300- 2500 5000 – 30 000 4000 – 10 000	6.8” / 0.1” 420’ / 0.3” 2” / 40mas	Multiplex ~ 400 Multiplex ~100 Multiplex ~10 Imaging?
E-PCS - **2027/2030**	XAO	EPOL IFS	0.6 – 0.9 0.95 – 1.65	125 – 20 000	2.0” / 2.3 mas 0.8“ / 1.5 mas	Coronography Polarimetry

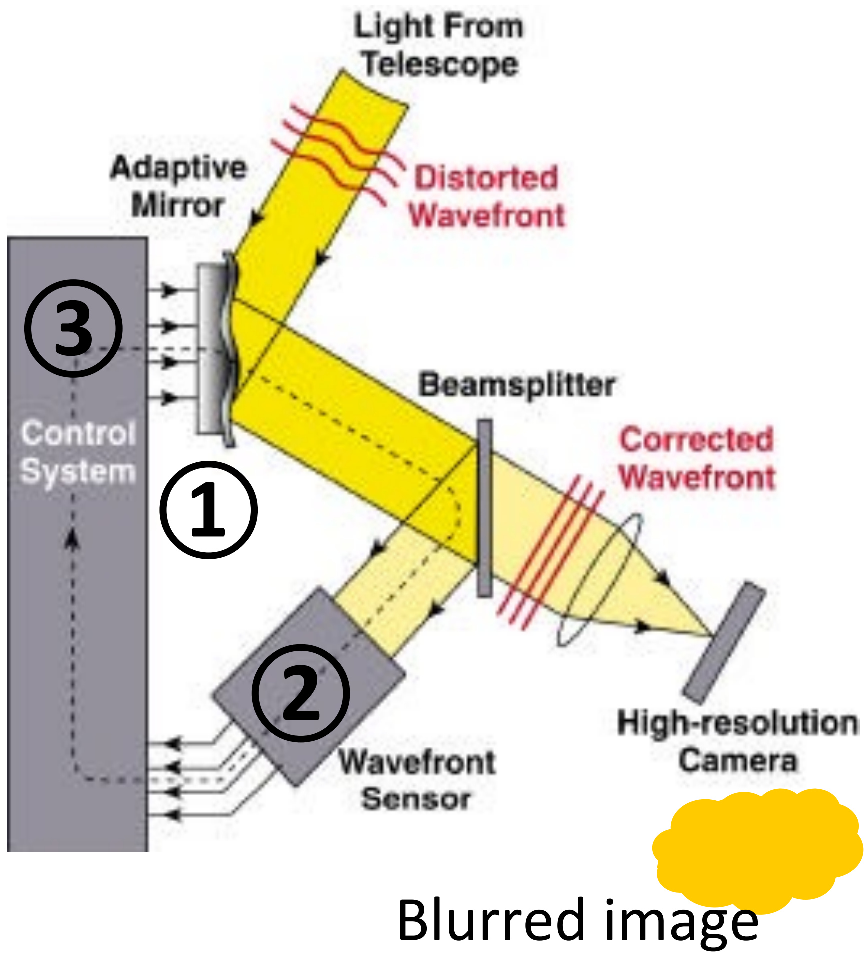
SCAOs systems are used by all instruments (excl. E-MOS)

From G. Chauvin, AO4ELT3, 2013

An Astronomical AO system

Main components:
1) Adaptive mirror
2) Wavefront sensor
3) Control system





A quick discussion of r0.....

...the light rays propagates trough the atmosphere and cumulate phase delay due to air refraction index fluctuations...

Phi_ray_a = phi0 + phi1a+phi2a+phi3a

Phi_ray_b = phi0 + ph1b+phi2b+phi3b

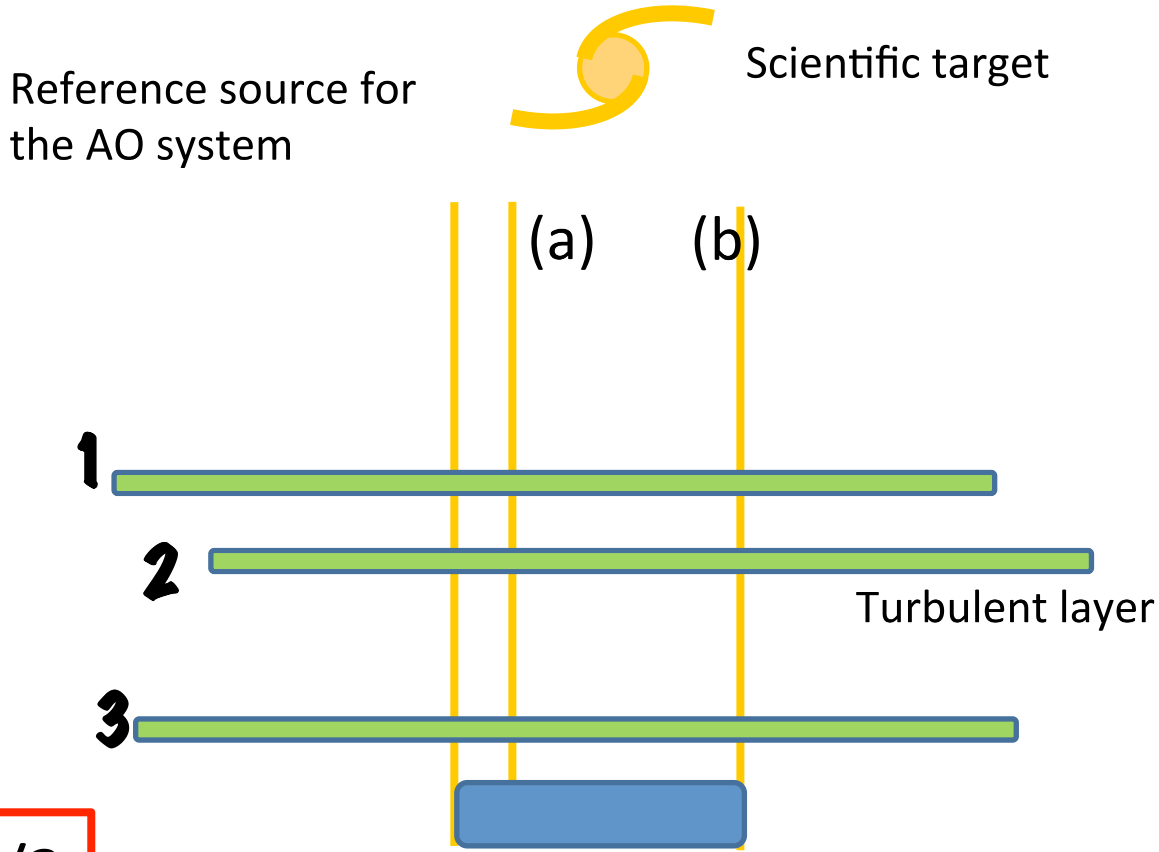
r0 proportional to lambda (6/5)

12cm at 500nm

50cm at 2200nm

wf_variance ~ (D/r0)^5/3

SR = exp(-wf_var)

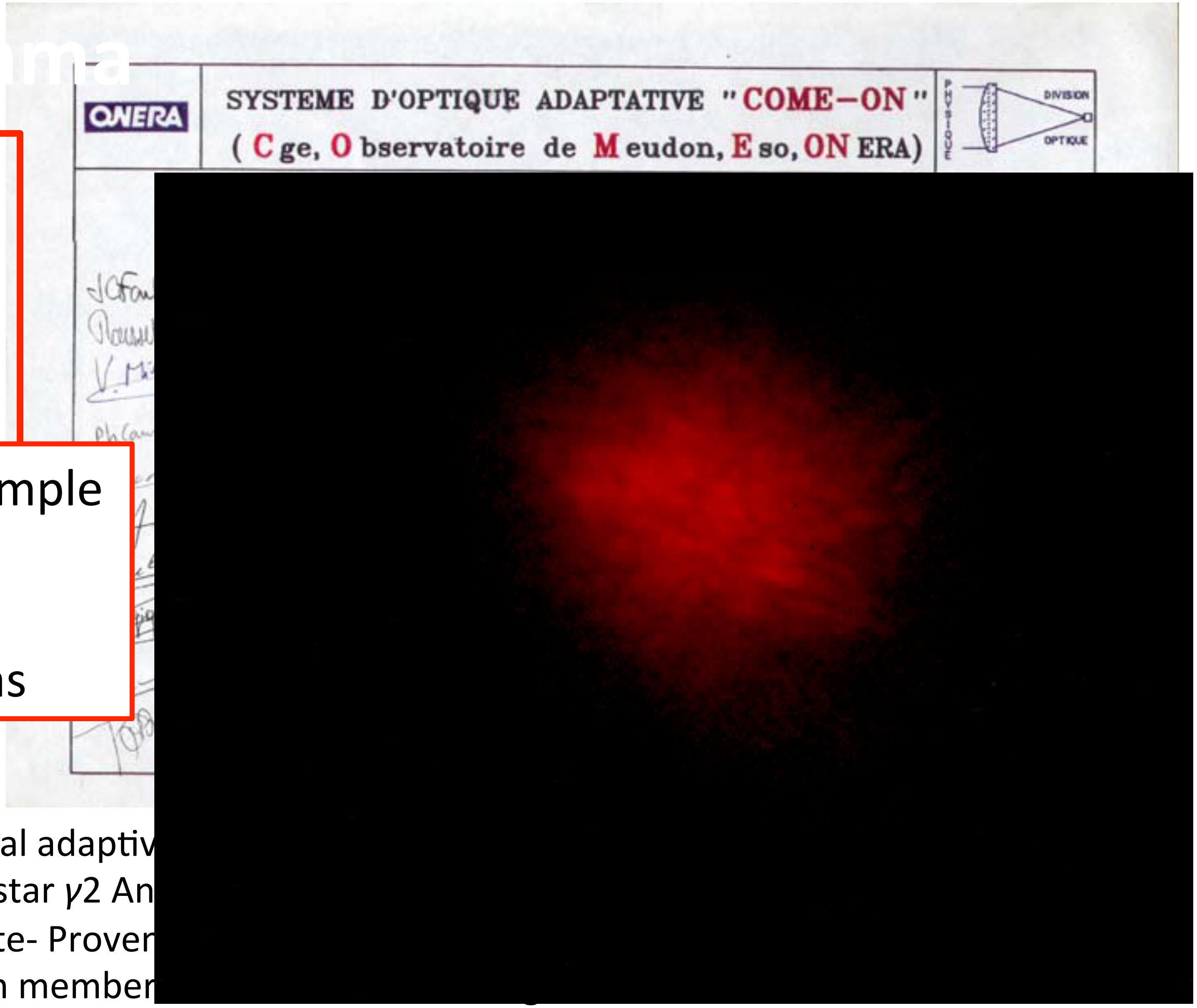


......one acts per r0 able to get 1rad^2

Examples:

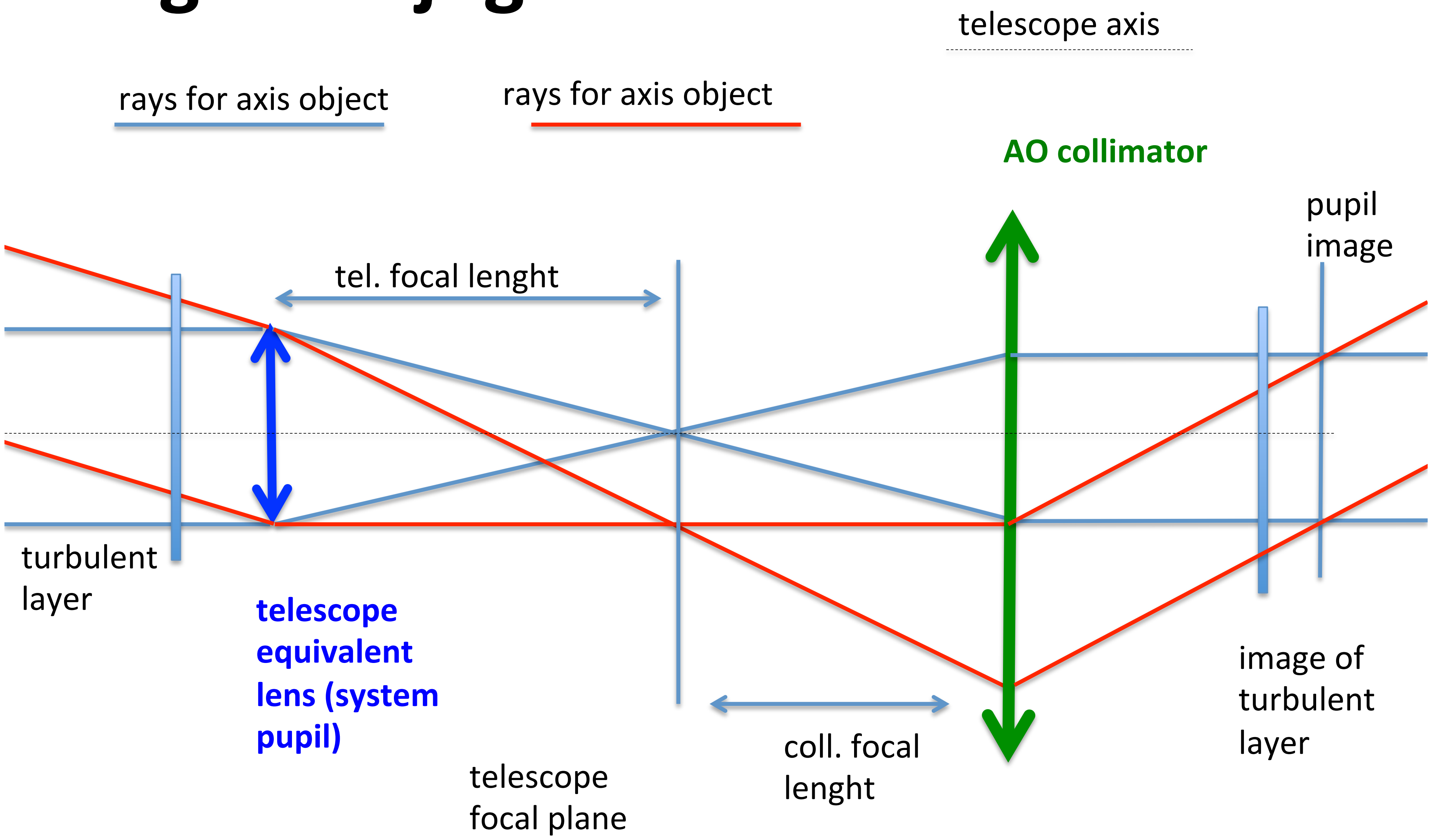
A double star with separation smaller than the seeing value (0.8 arcsec). An example from Come-OnAO system

An updated example from LBT:
SR>60% H band
FWHM DL 40mas



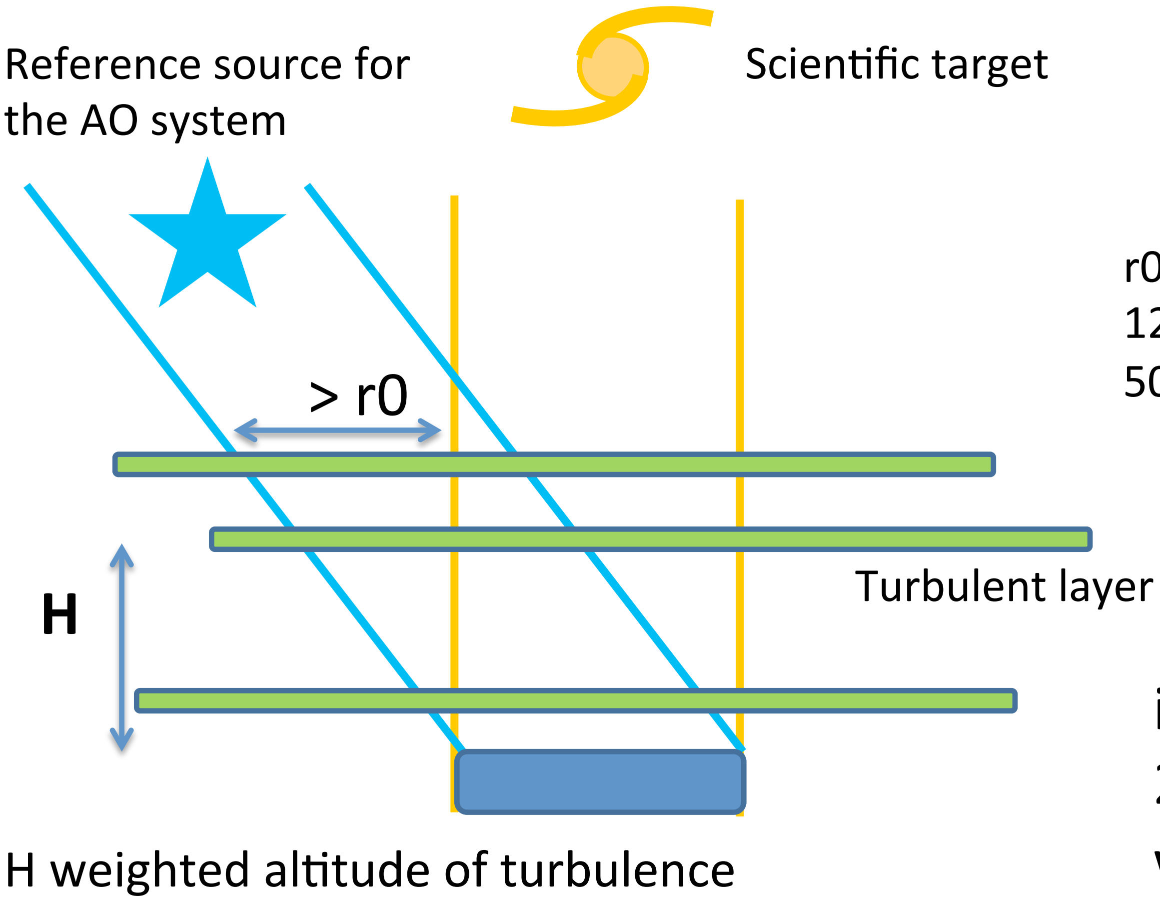
"The first astronomical adaptiv
image of the double star γ2 An
Observatoire de Haute- Proven
Signatures from team member
Rousset and a few others celebrate the event." (Picture & text from P. Lena, 2009)

Single conjugate ?



SCAO system constrain: sky coverage

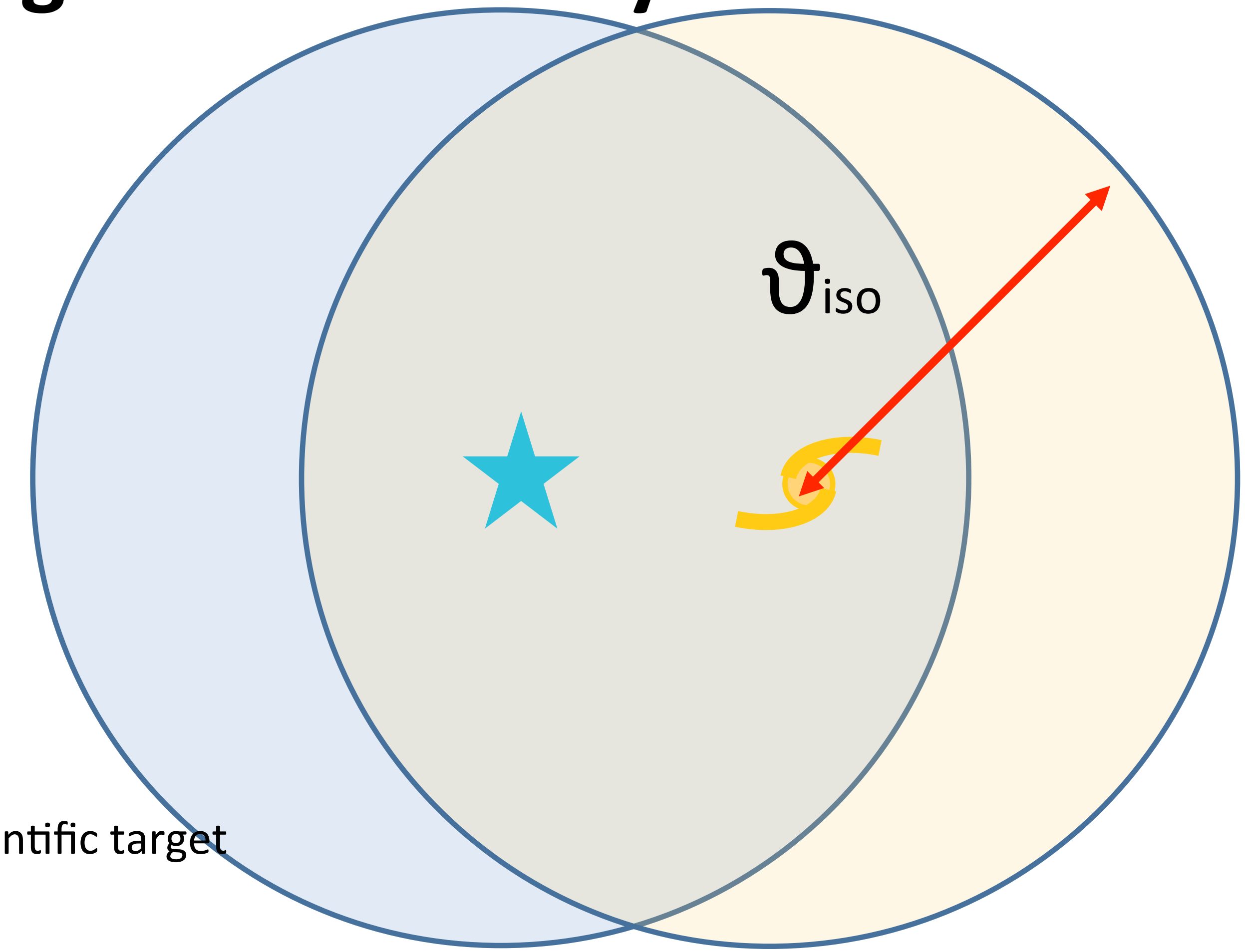
The Single Conjugate Adaptive Optics system (SCAO) uses a single reference source and a single deformable mirror to correct for turbulence. The source can be a Natural Guide Star or a Laser Guide Star.

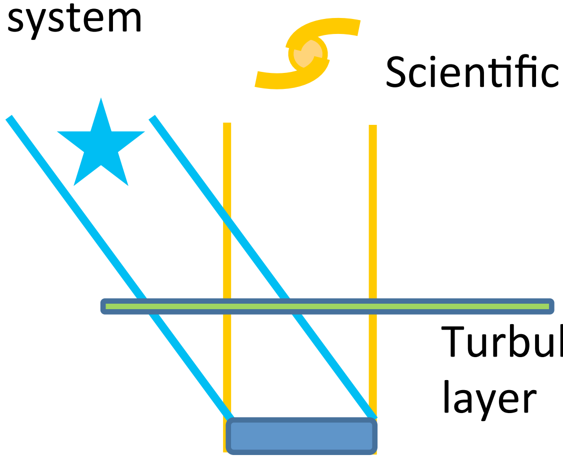


r0 proportional to lambda (6/5)
12cm at 500nm
50cm at 2200nm

isoplanatic_angle ~ r0/H
20arcsec in K band
wf_var (teta/teta0)^5/3

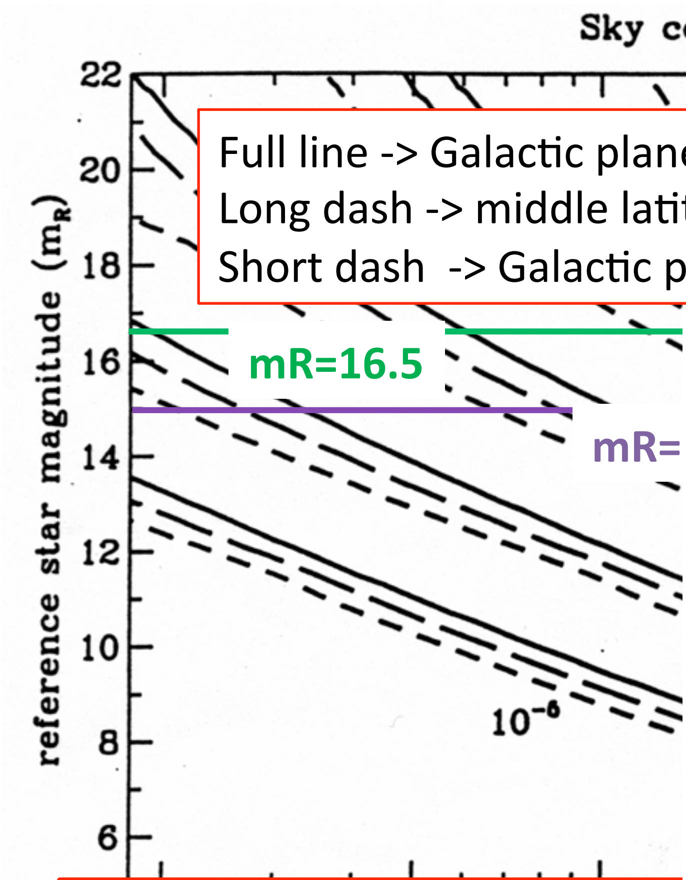
Sky coverage for a SCAO system II

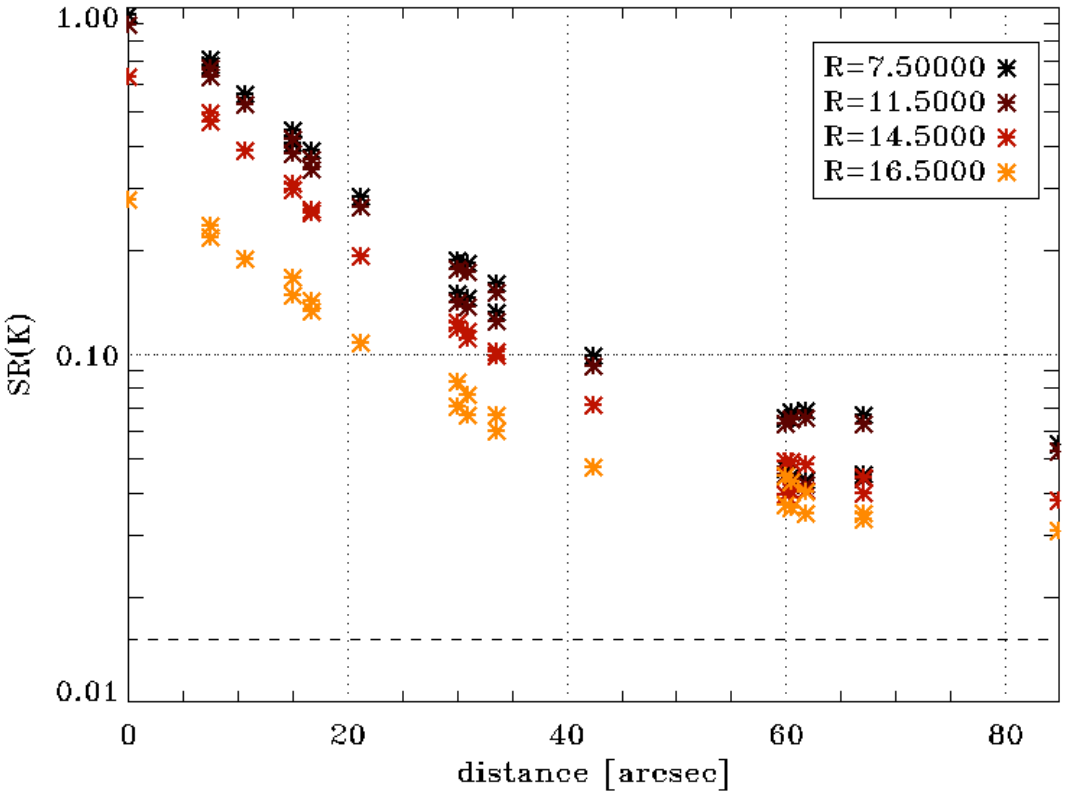




A typical ϑ_{iso} value for astronomical observations is 20-30 arcsec for K band

Sky coverage

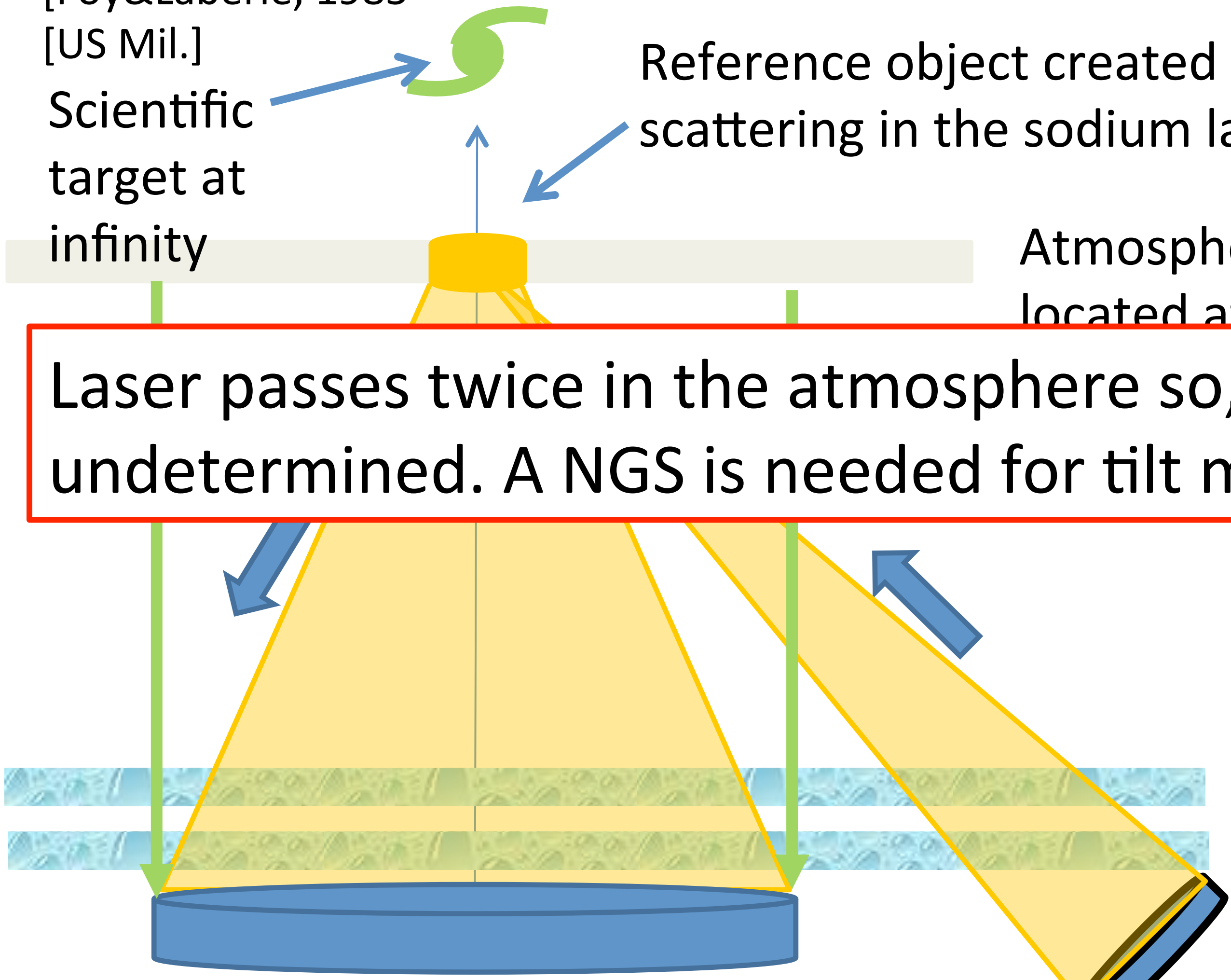




~ 30% at mid gala

~ 10% at galactic

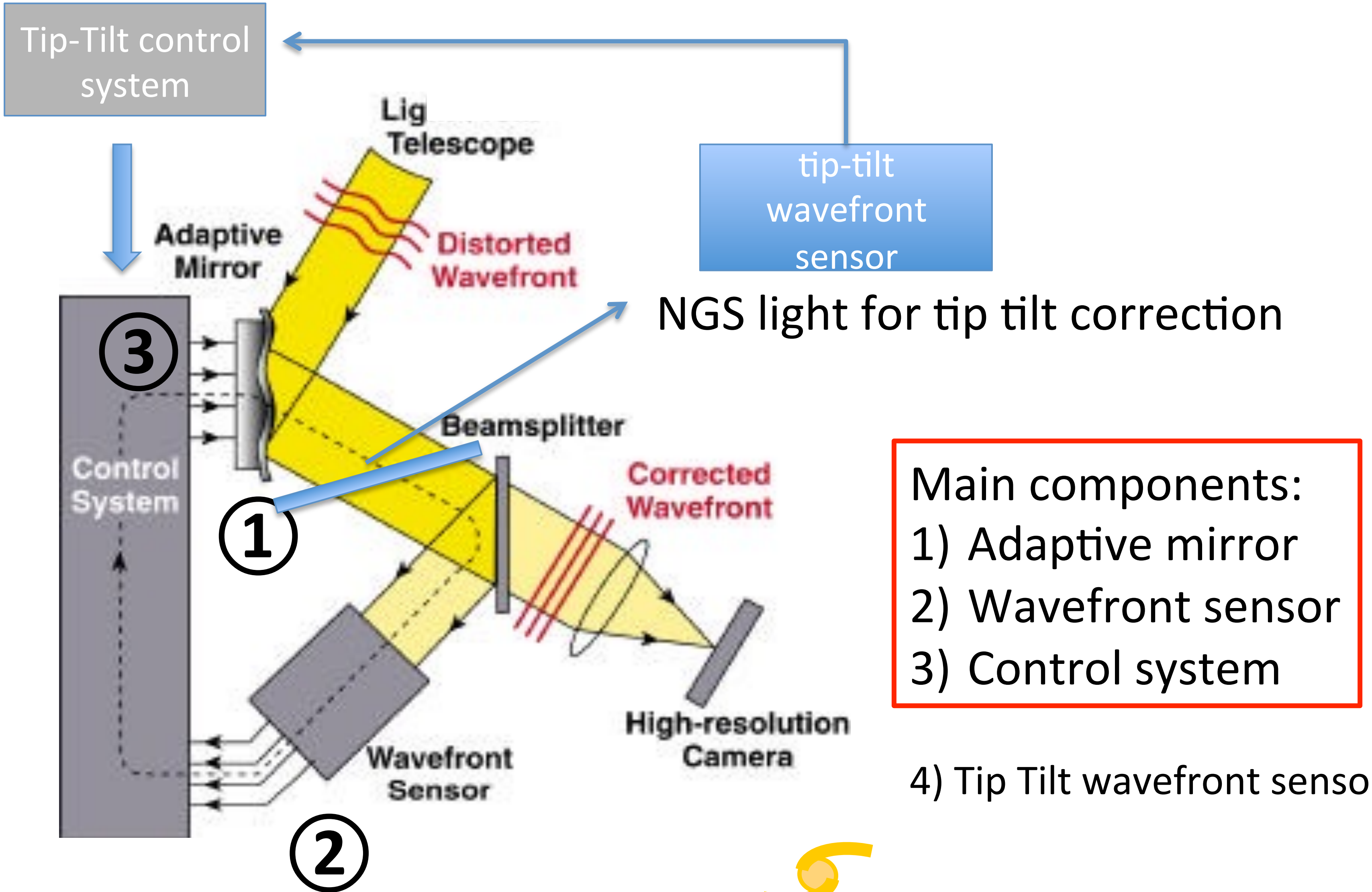
Laser Guide stars (the sodium case)



Laser passes twice in the atmosphere so, tip tilt is undetermined. A NGS is needed for tilt measurements.

Laser beam samples a cone, some part of the atmosphere were starlight is passing is unsampled.

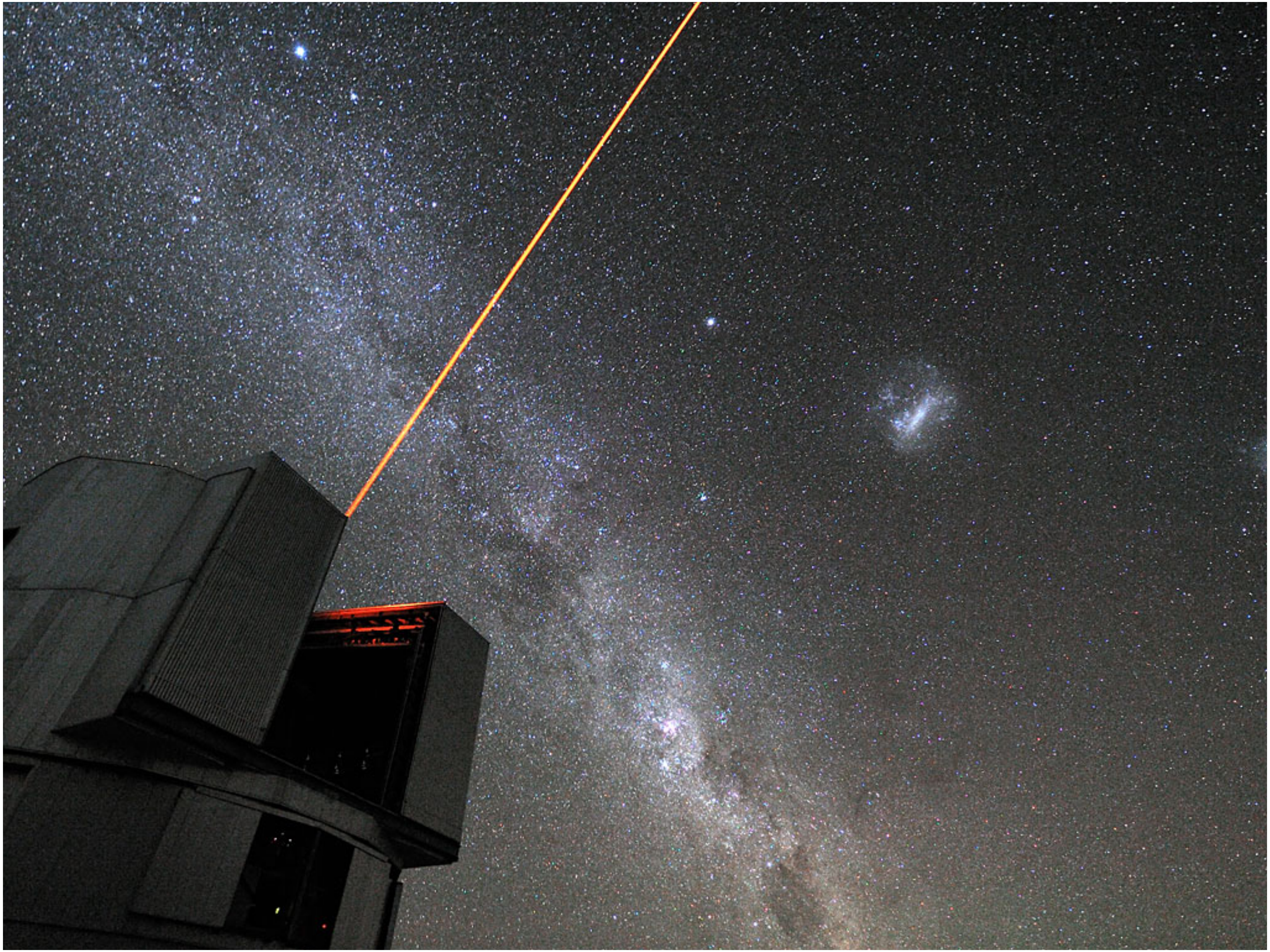
An LGS SCAO system sketch



Main components:

1) Adaptive mirror
2) Wavefront sensor
3) Control system

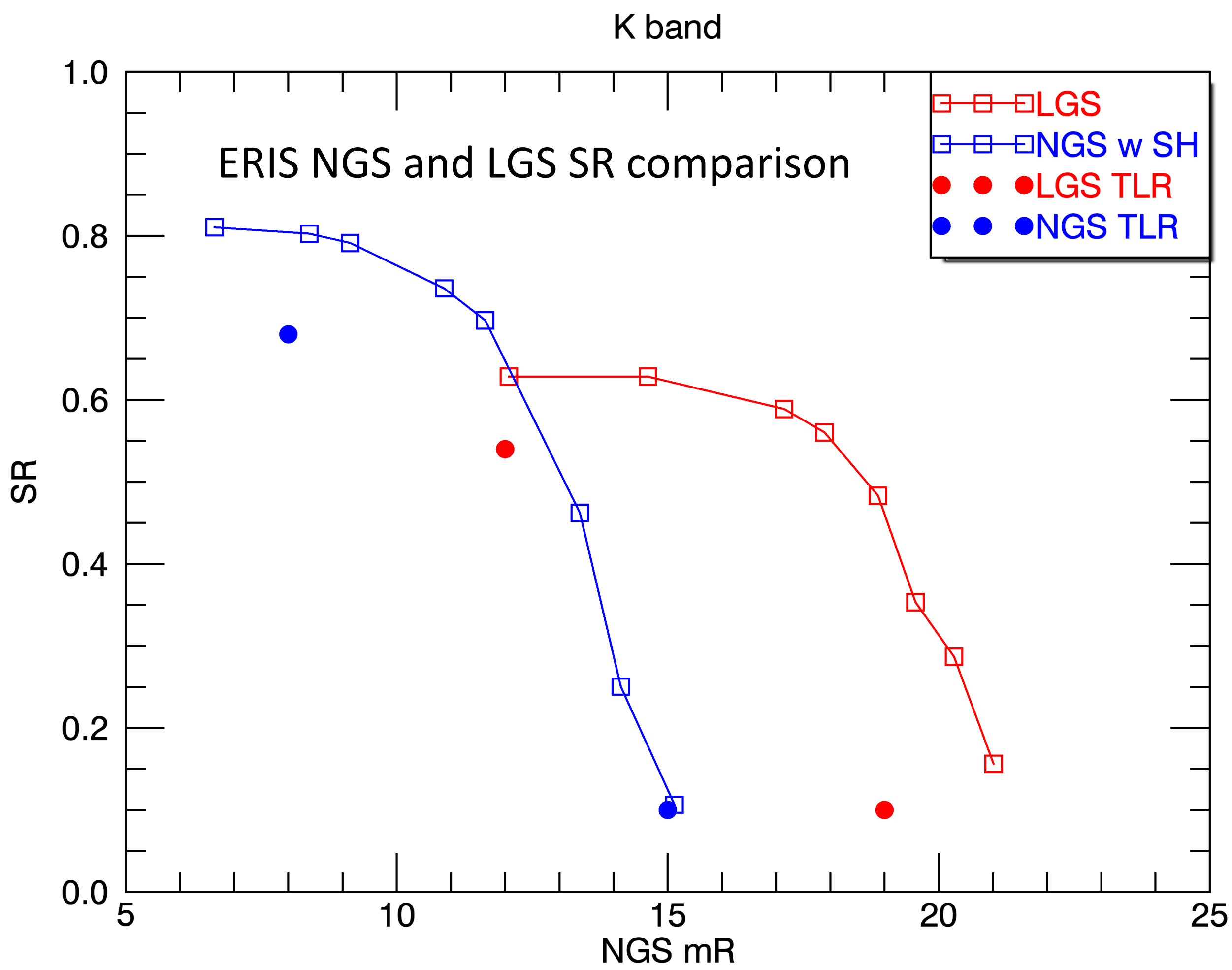
4) Tip Tilt wavefront sensor



The ERIS SCAO AO performances

NGS brightness for NGS and LGS system is on axis in both cases.

starting from mag 12 the LGS SCAO provides better performance on axis and off axis.

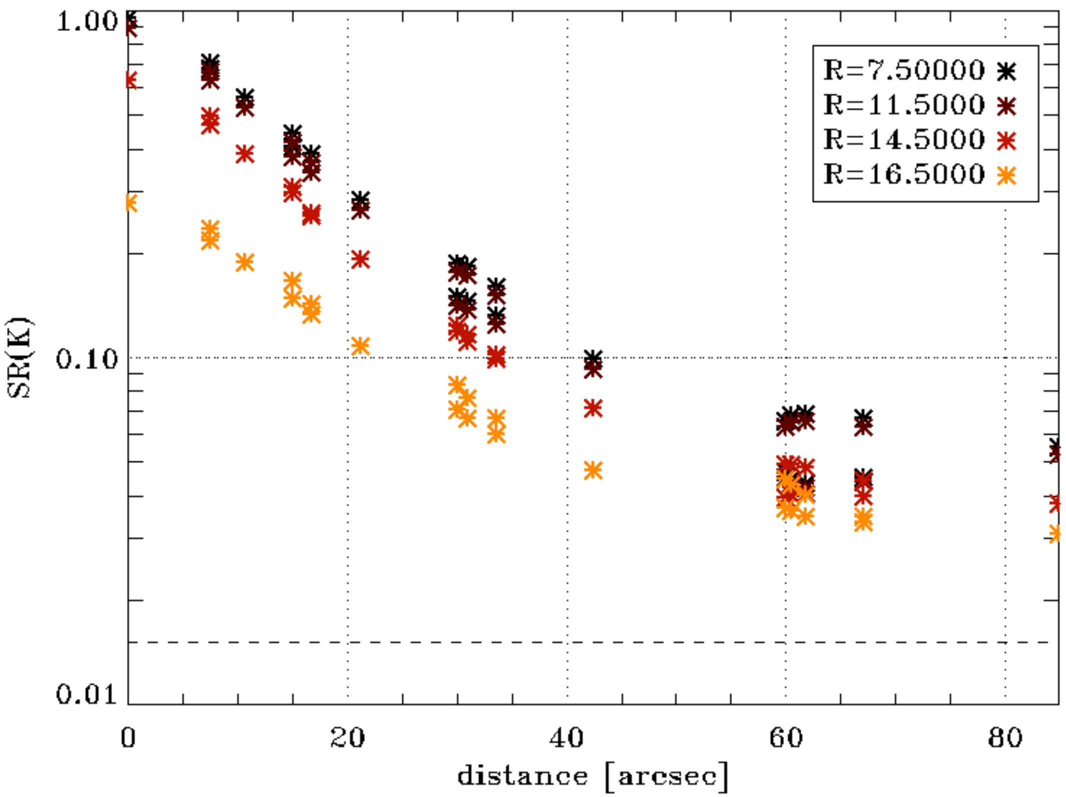


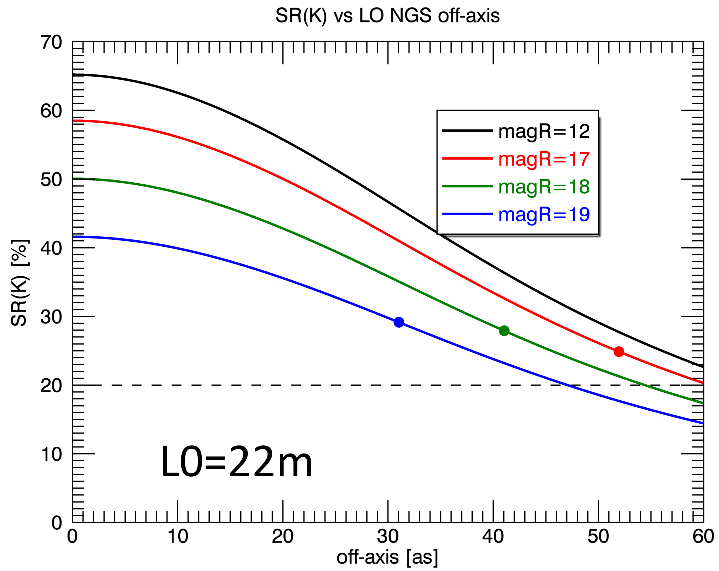
Simulation results for ERIS NGS and LGS SCAO, E. Marchetti, M. Le Louarn, ESO

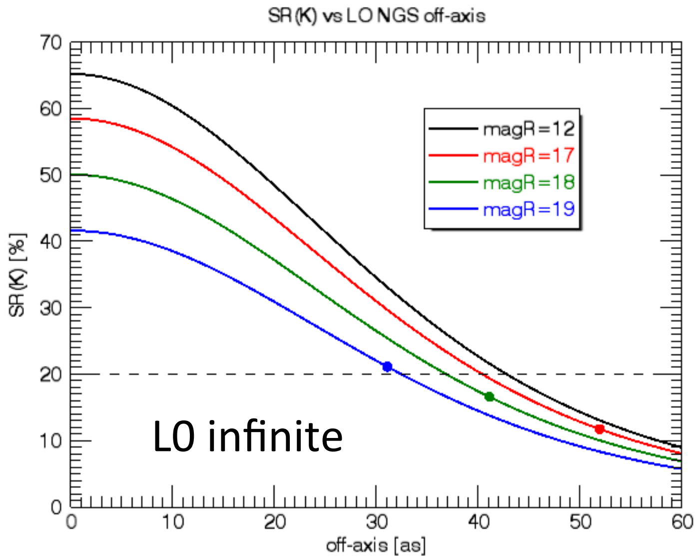
Isoplanatic angle and isokinetic angle

Comparison between NGS SCAO and LGS SCAO, performance vs reference magnitude star.

LBT SOUL AO performance vs FoV



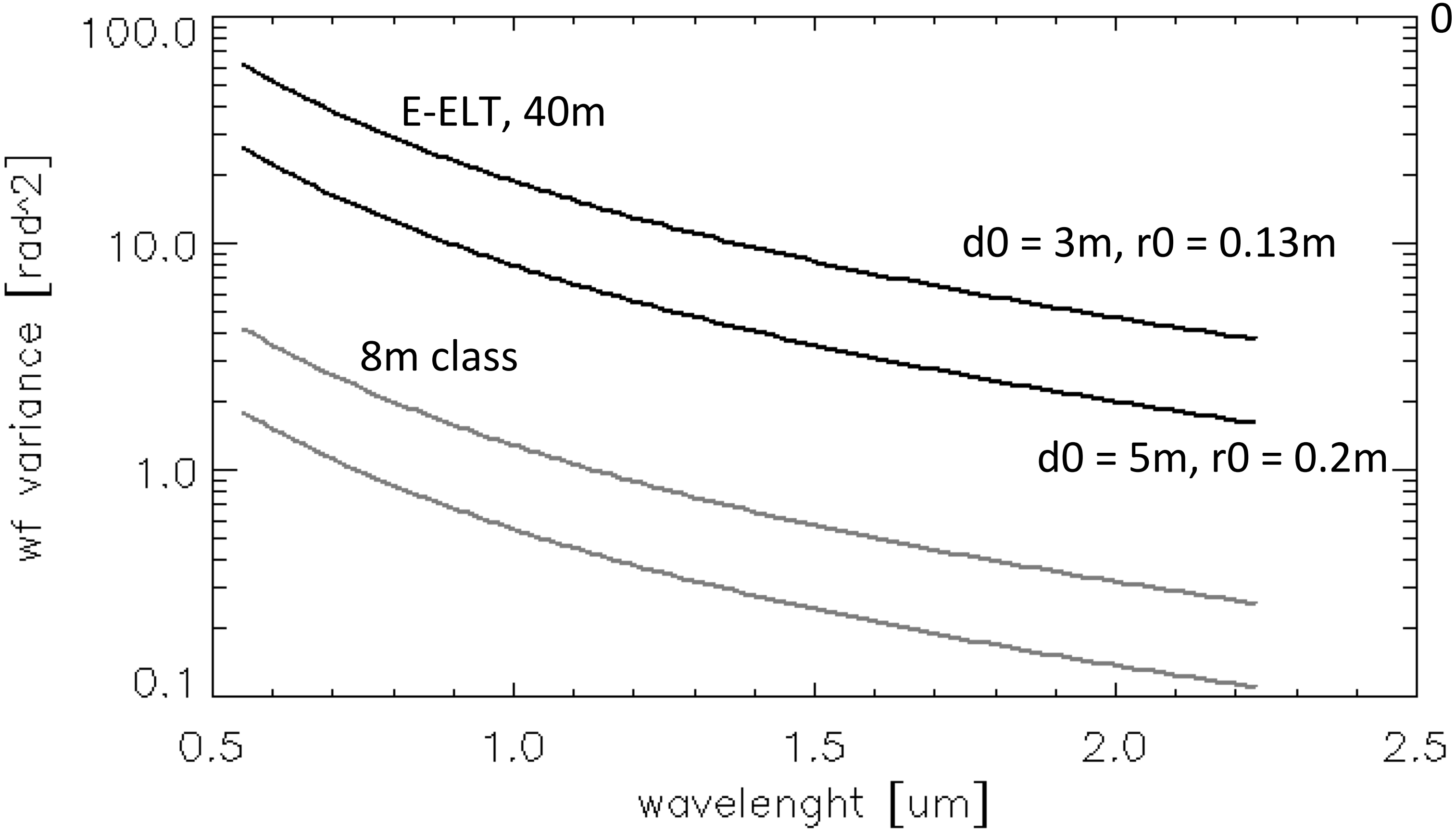




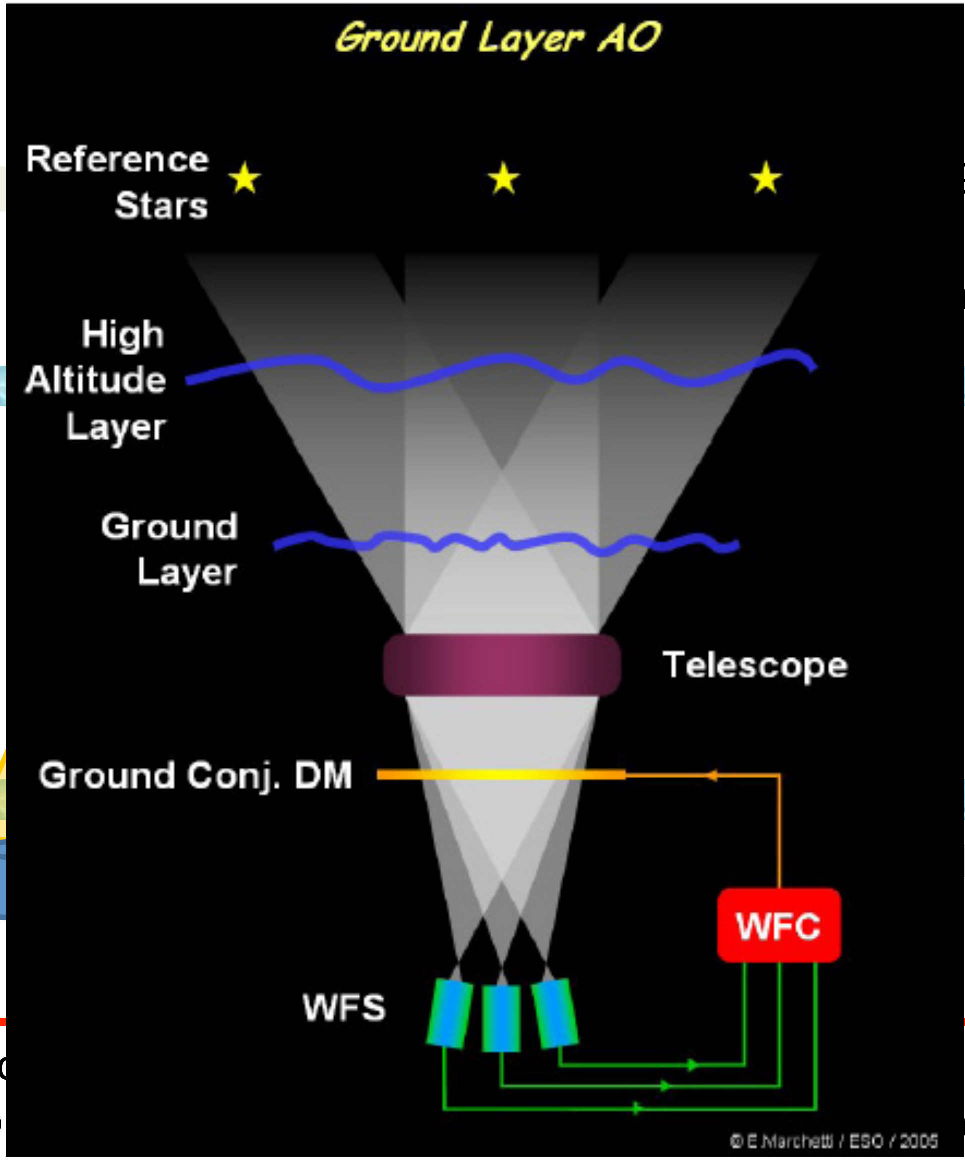
Conical anisoplanatism and tel. diameter

The conical error variance scales with D^(5/3) so it is approx. 25 times larger for the E-ELT than for an 8m telescope. So a single LGS not really useful for an E-ELT SCAO.

r0 dato a 0.5 um
0.15 and 0.2



Conical effect and Ground Layer AO (GLAO)



0km)

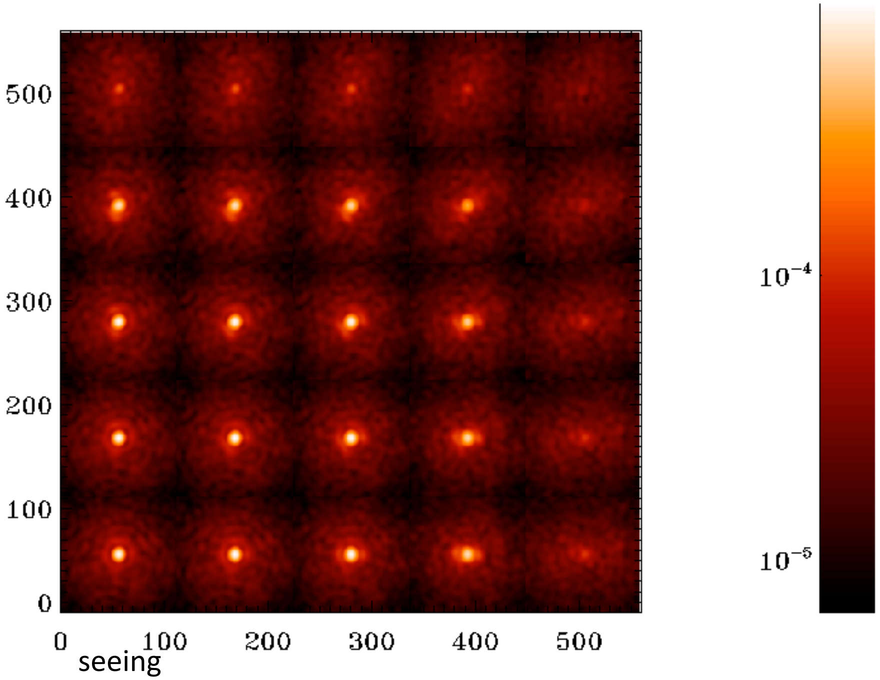
igh altitude turbulent layer (15km)

The phase perturbation detected is mostly located close to the telescope, the so called ground layer.

turbulent layer

The effe be seen a sort of
GLAO co d do not decorrelate
with off-axis angle. Correction is somewhat uniform across the FoV.

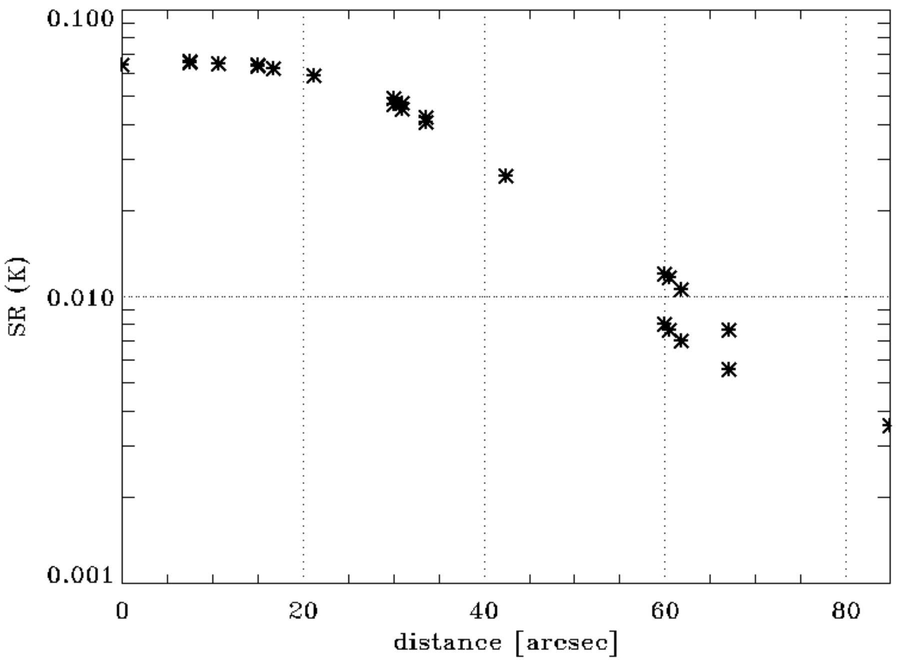
EELT SCAO 1 LGS (K band)



Seeing on-axis SR(K) = 0.08%

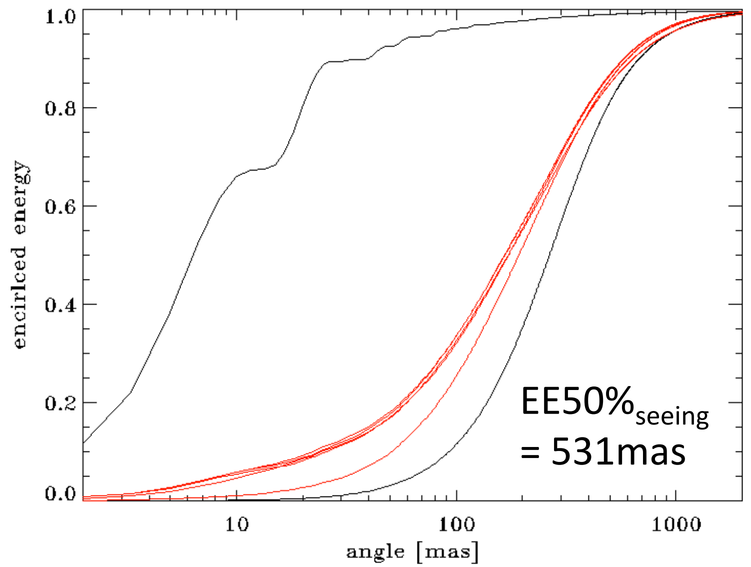
Seeing = 0.87”
LGS on-axis (D.L. source)
NGS on-axis
1127 modes corrected

- Position grid:
  - X distance = 0, 7.5, 15, 30, and 60”
  - Y distance = 0, 7.5, 15, 30, and 60”
- PSF in K band (2200nm)
- ESO Paranal atmospheric profile

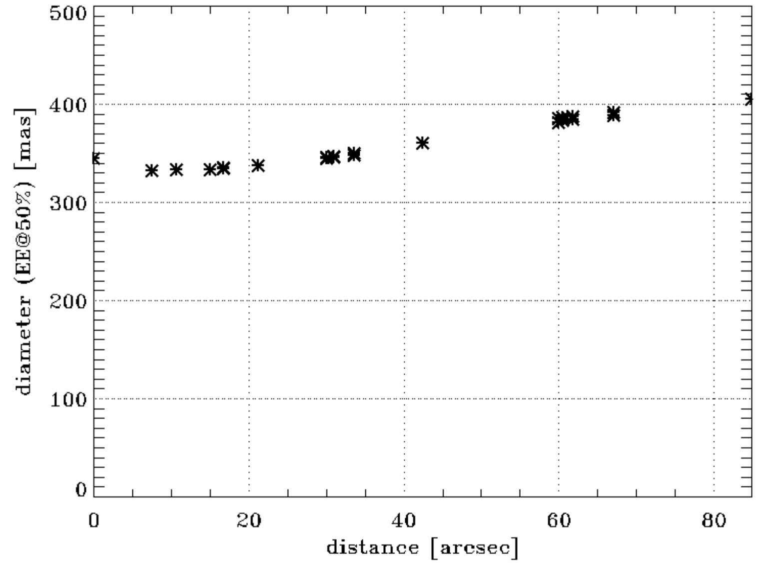


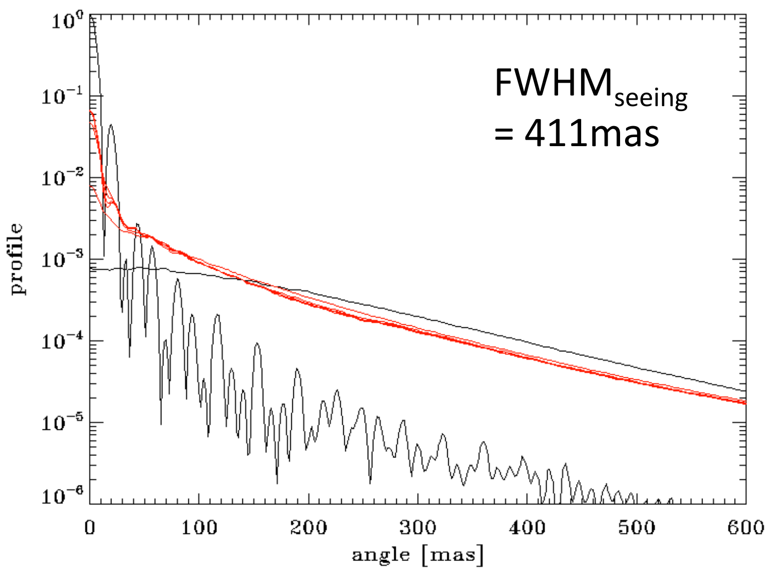
EELT SCAO LGS (R=∞, K band)

EE and profiles shown are the ones on the first raw of the grid

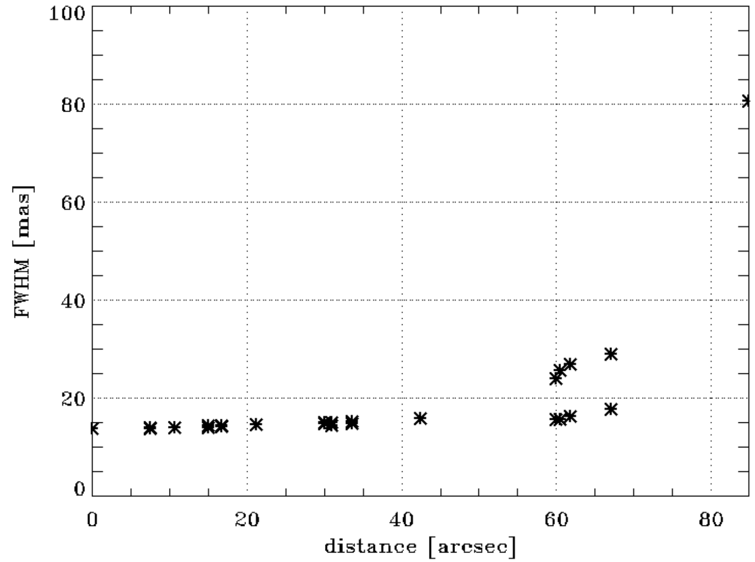


EE@50%

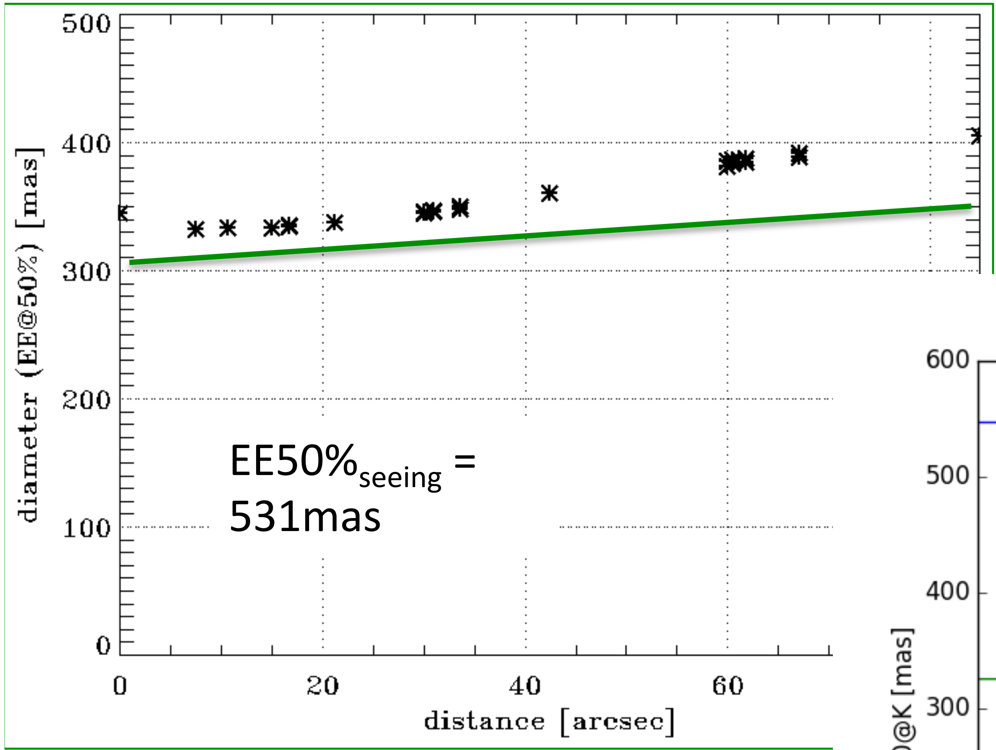




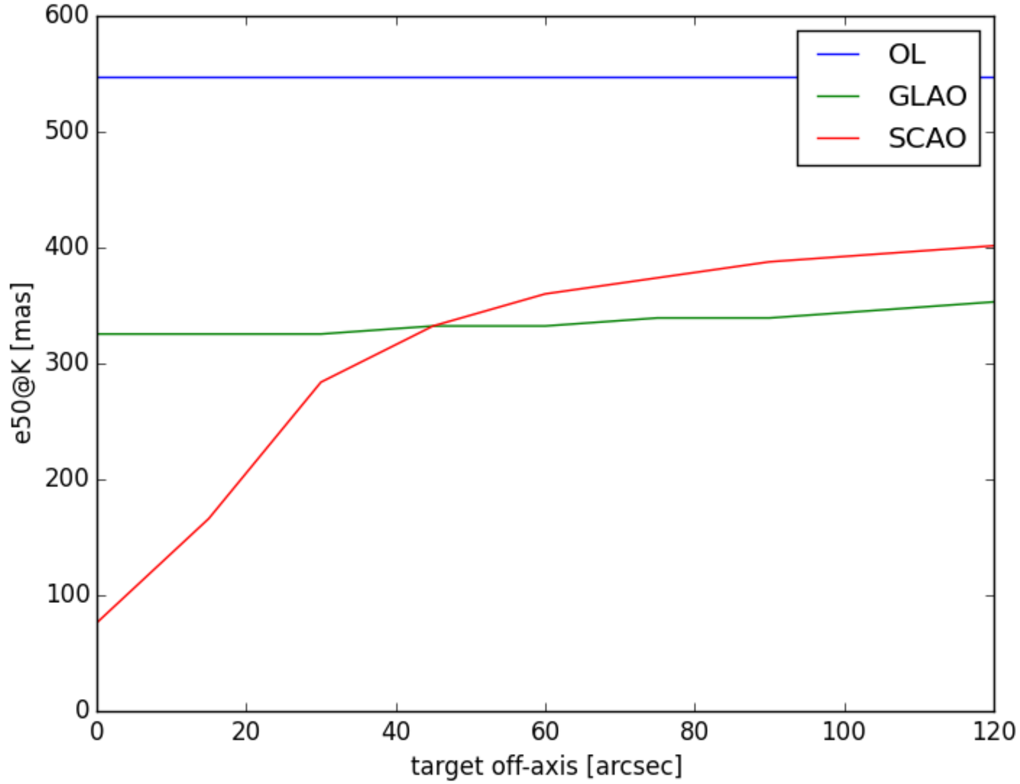
FWHM



E-ELT SCAO with 1LGS & 8m GLAO

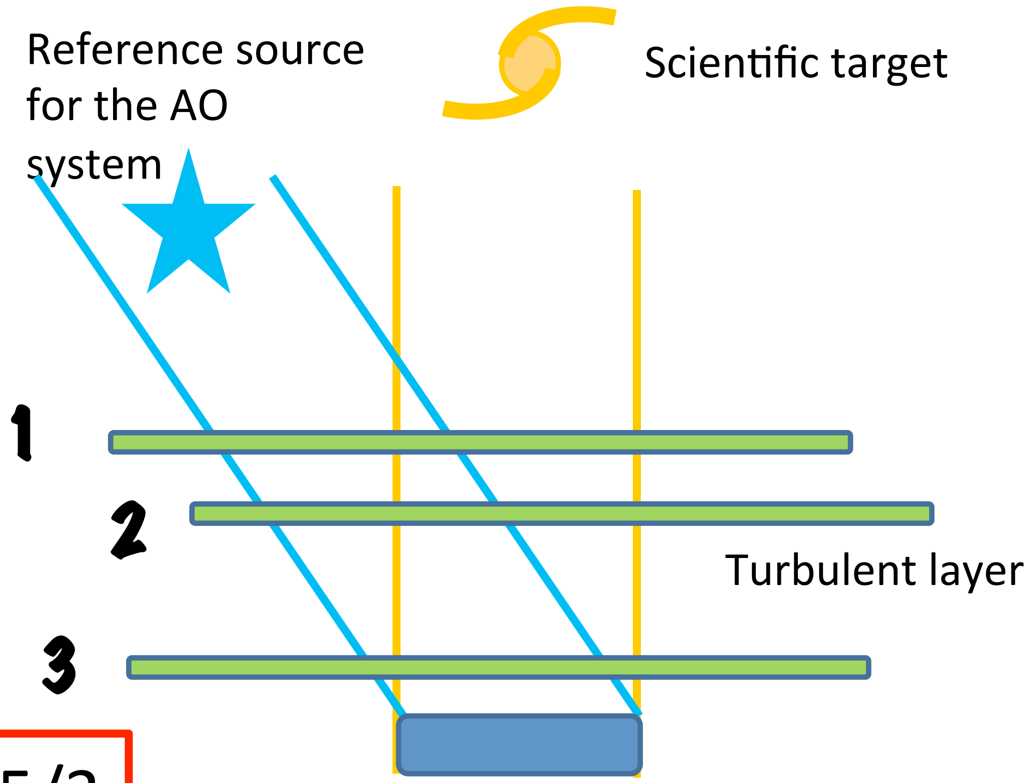


Simulated performance of an 8m GLAO LGS system



Back on r0.....

the light rays propagates trough the atmosphere and cumulate phase delay due to air refraction index fluctuations.



Phi_ray_a = phi0 + phi1a+phi2a+phi3a

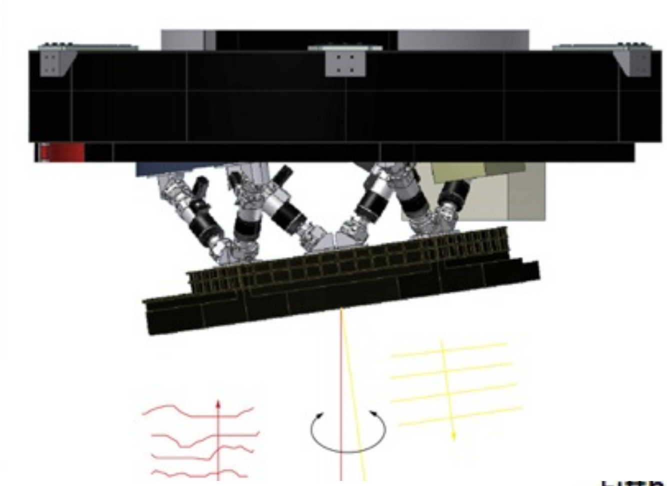
Phi_ray_b = phi0 + ph1b+phi2b+phi3b

wf_variance ~ (D/r0)^5/3

......one acts per r0 able to get 1rad^2, on the E-ELT requires about 80 over the diameter or ~ 5000-6000 acts total

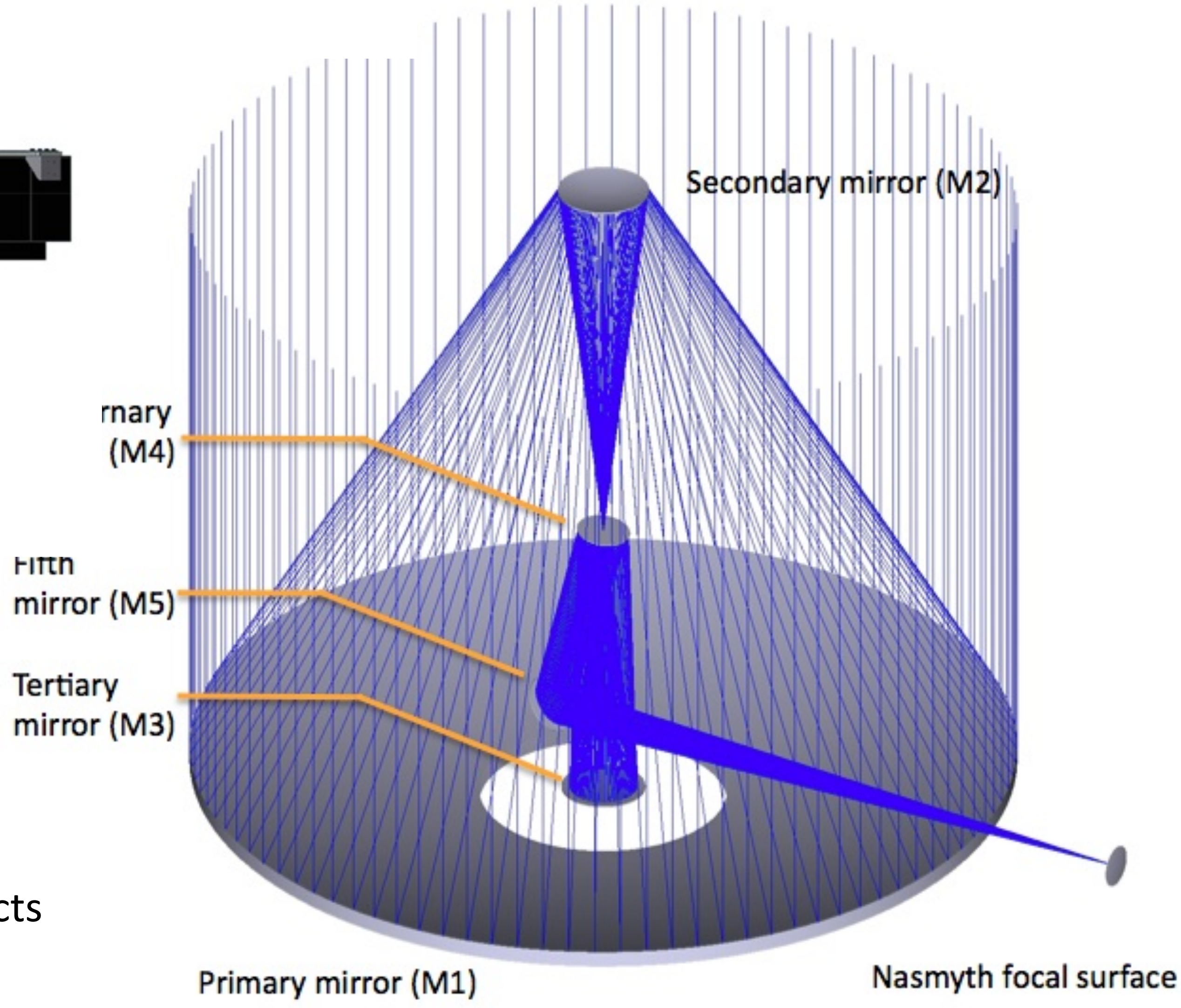
The E-ELT optical train

ideally correction done on the primary but unpractical. Correction done using a deformable M4.



Selecting voice coil actuators technology from LBT and VLT with a pitch of ~ 30mm.

M4, 2.4 diam. with ~ 5300 acts equivalent to 0.5m on M1



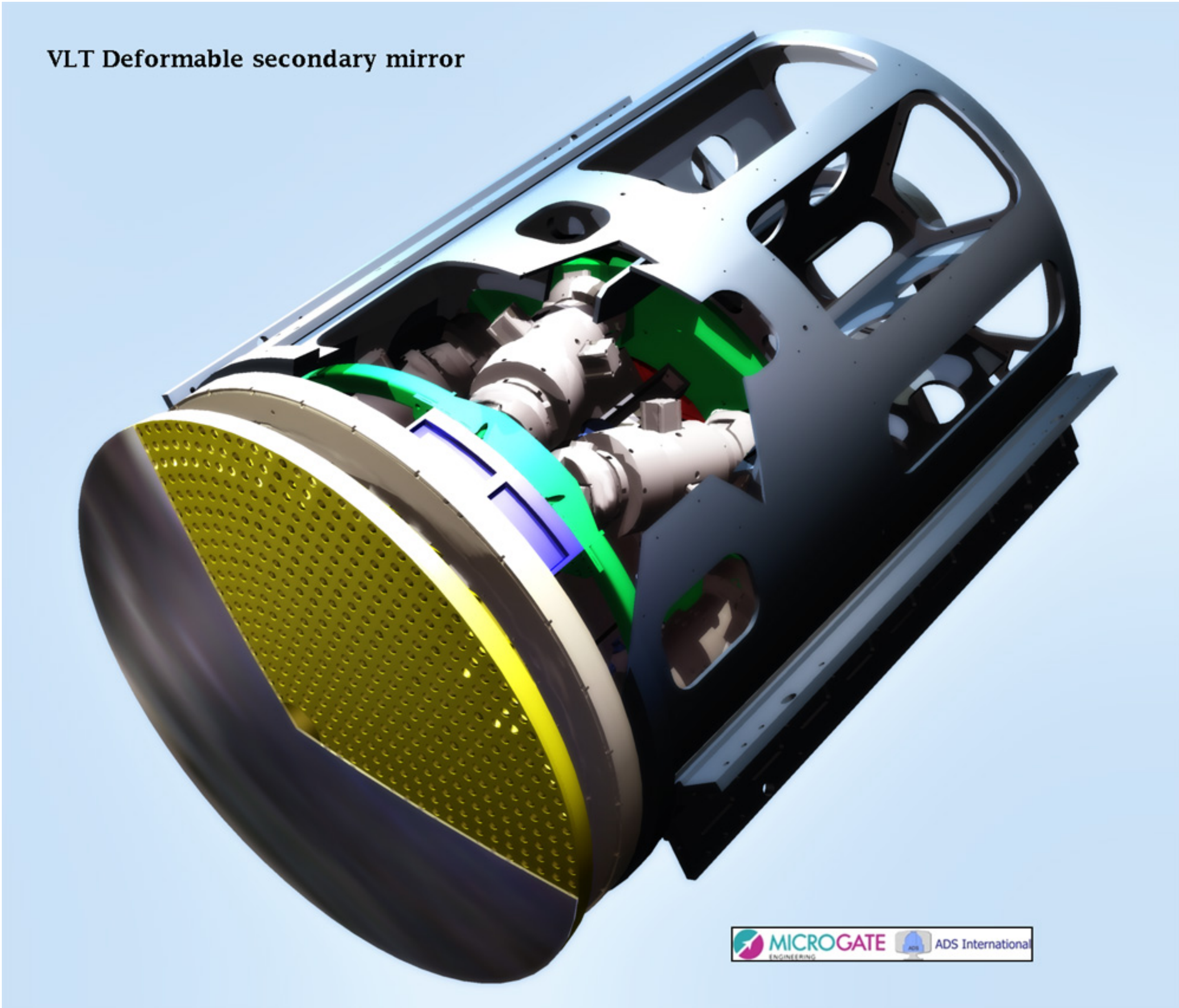
The LBT672 unit

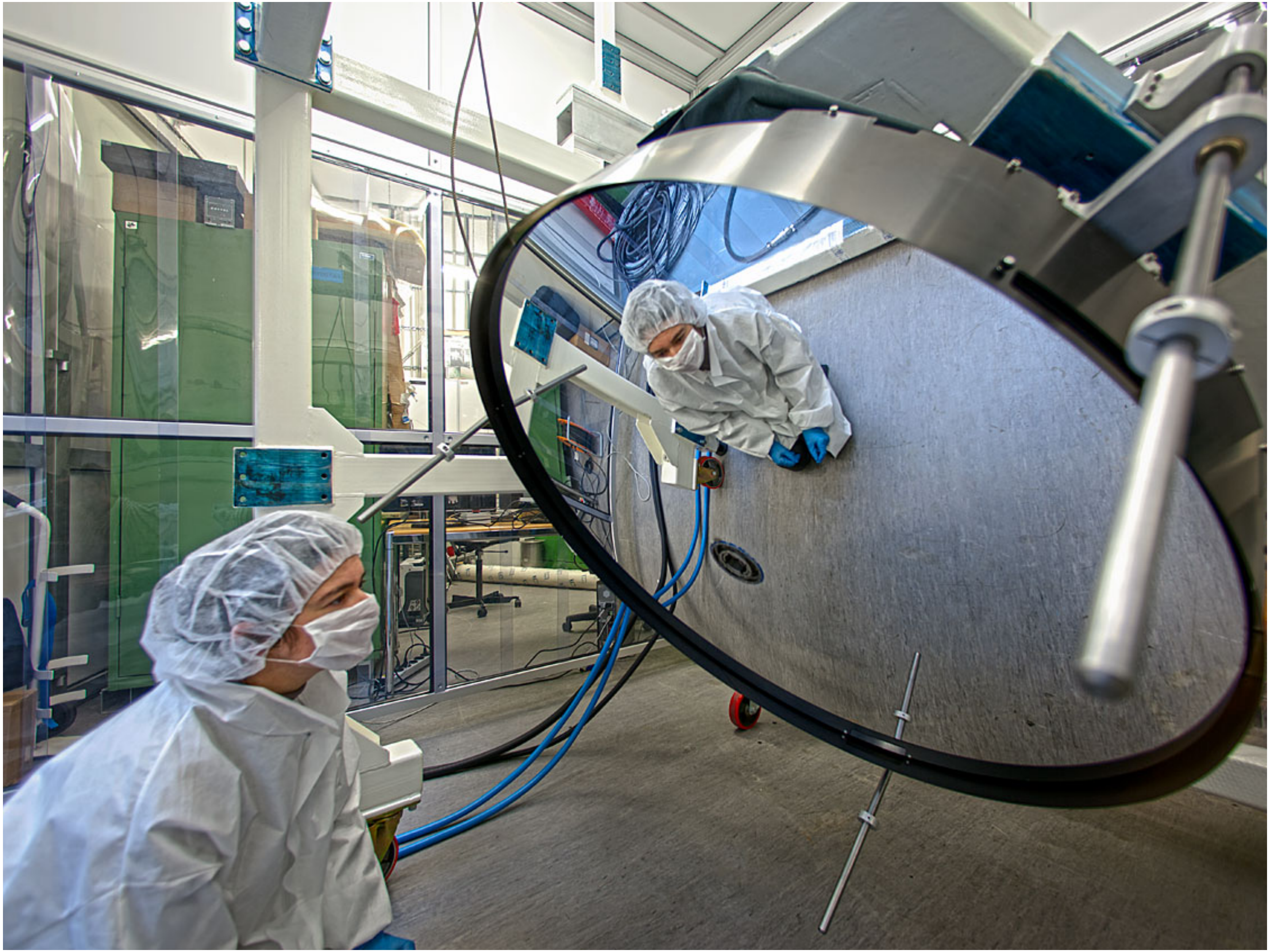
Adsec concept, [P. Salinari, 1994]
MMT unit, [Brusa, 1999]
LBT unit, [Riccardi, 2003]

Main specs.:

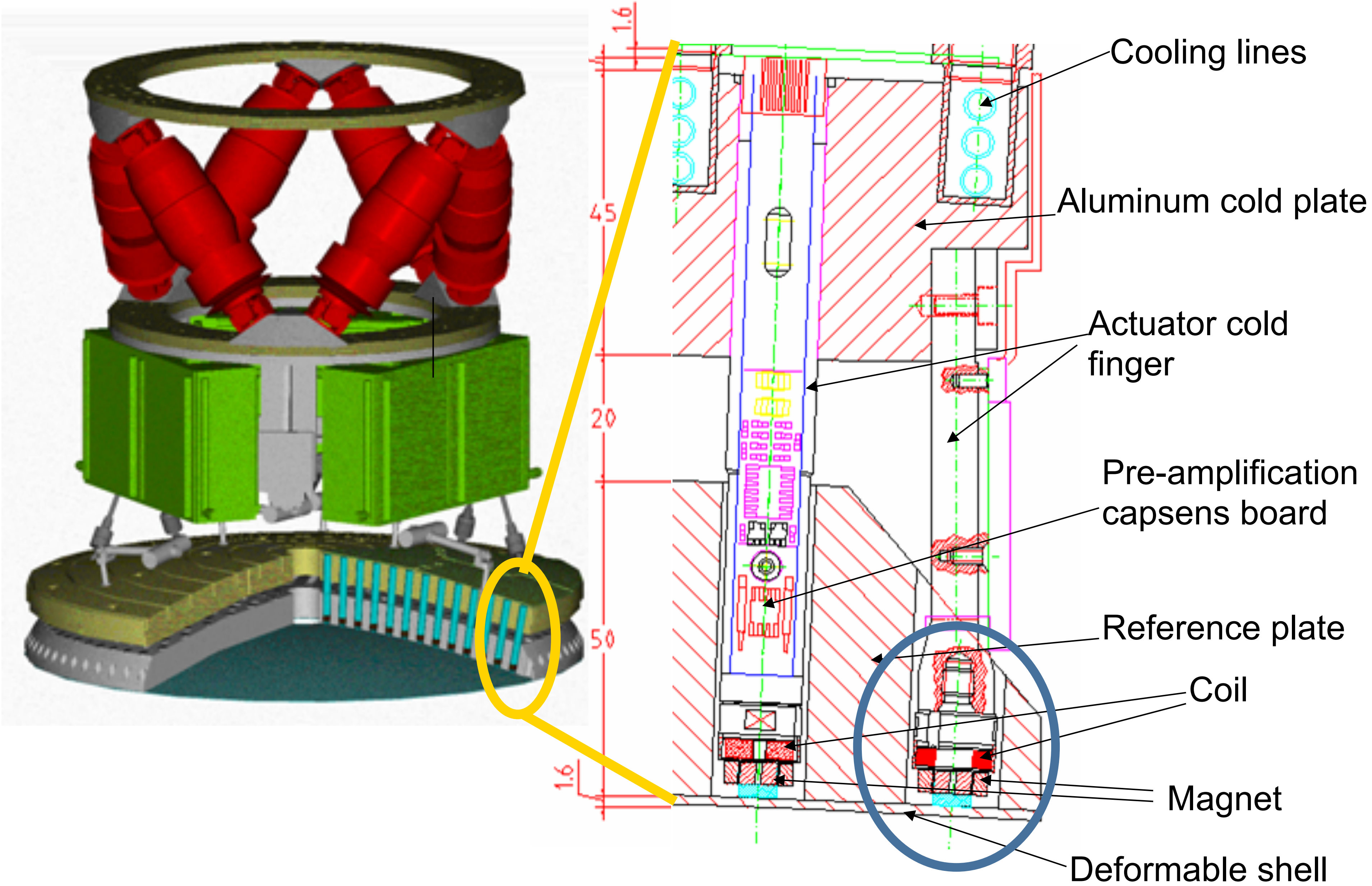
- 672 actuators
- 911mm diam.
- 1.6mm shell tickness
- 30mm act pitch
- 100μm stroke
- 360kg (wo hub)
- 1.8kW power
- 10 l/min cooling@-3C

The VLT DSM 1170 acts.

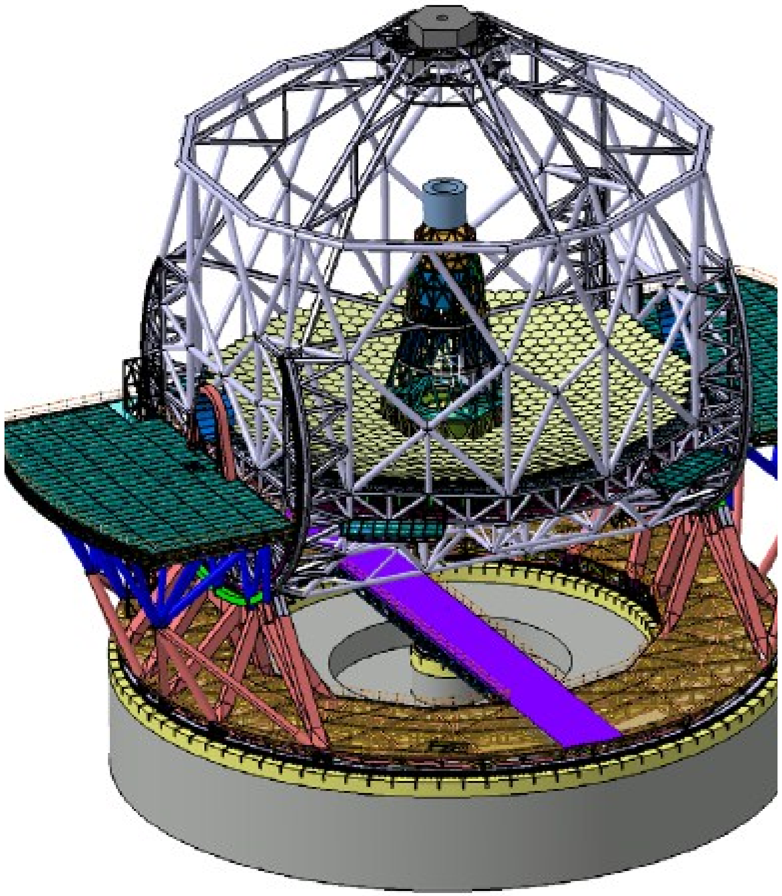


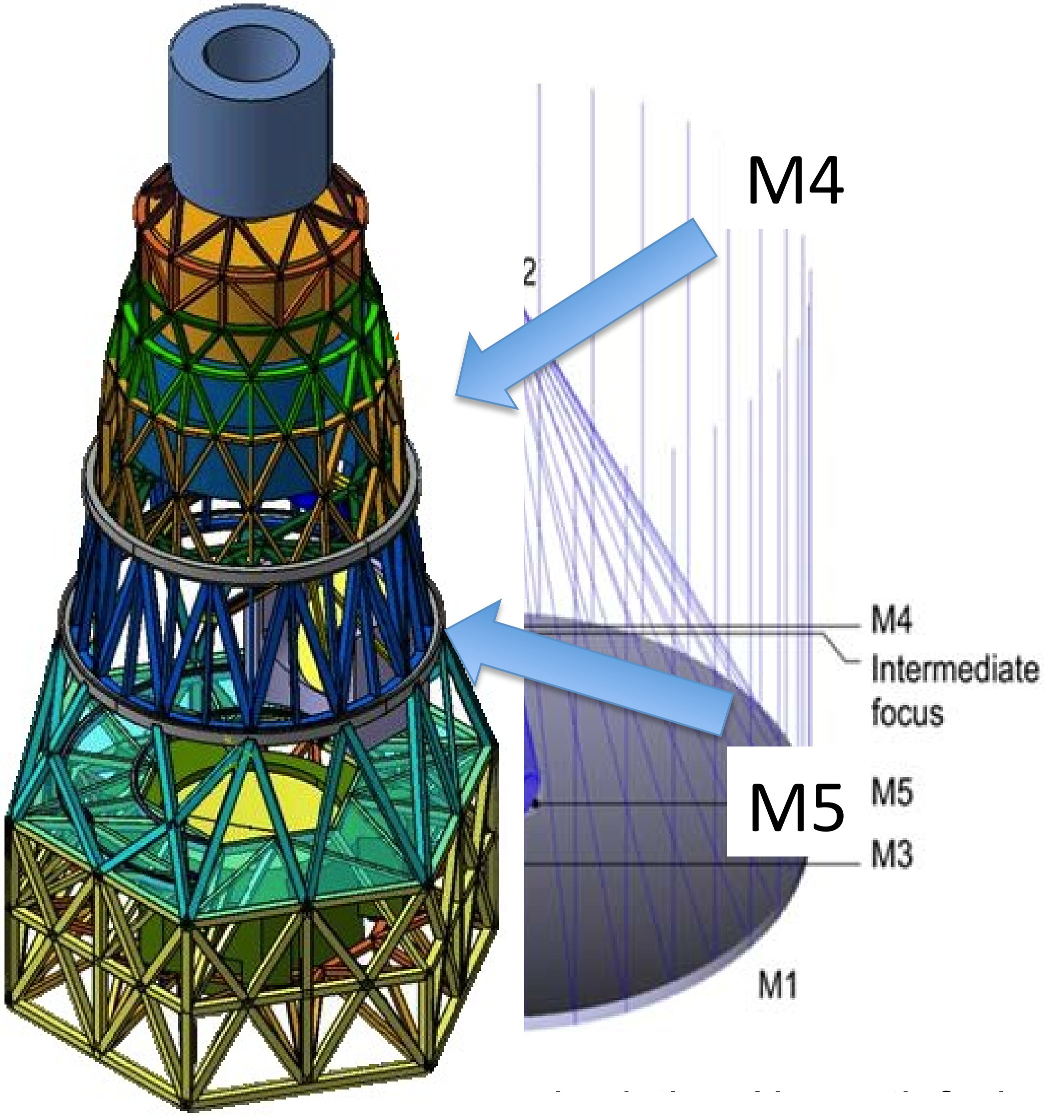


The mirror control

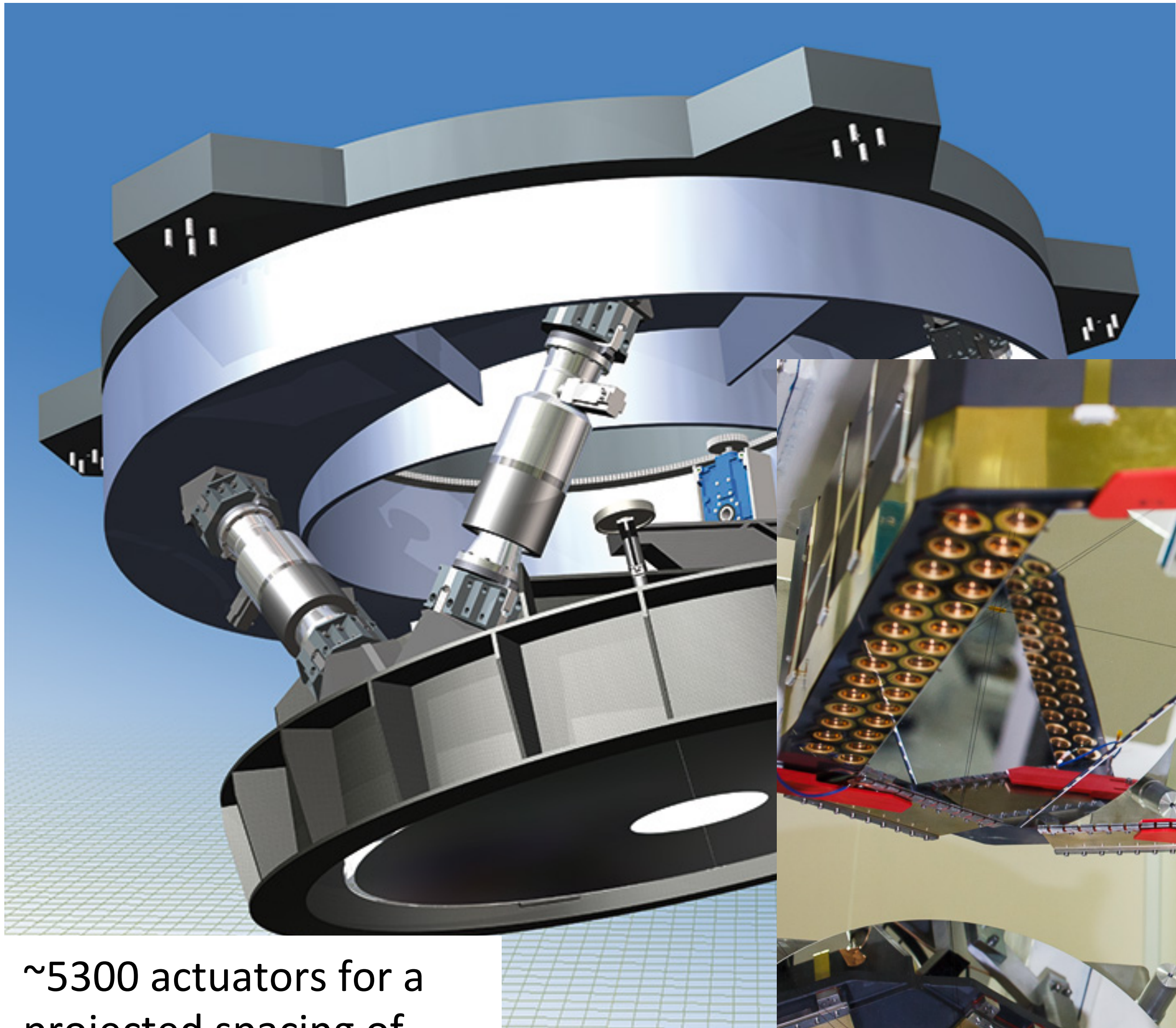


The E-ELT structure

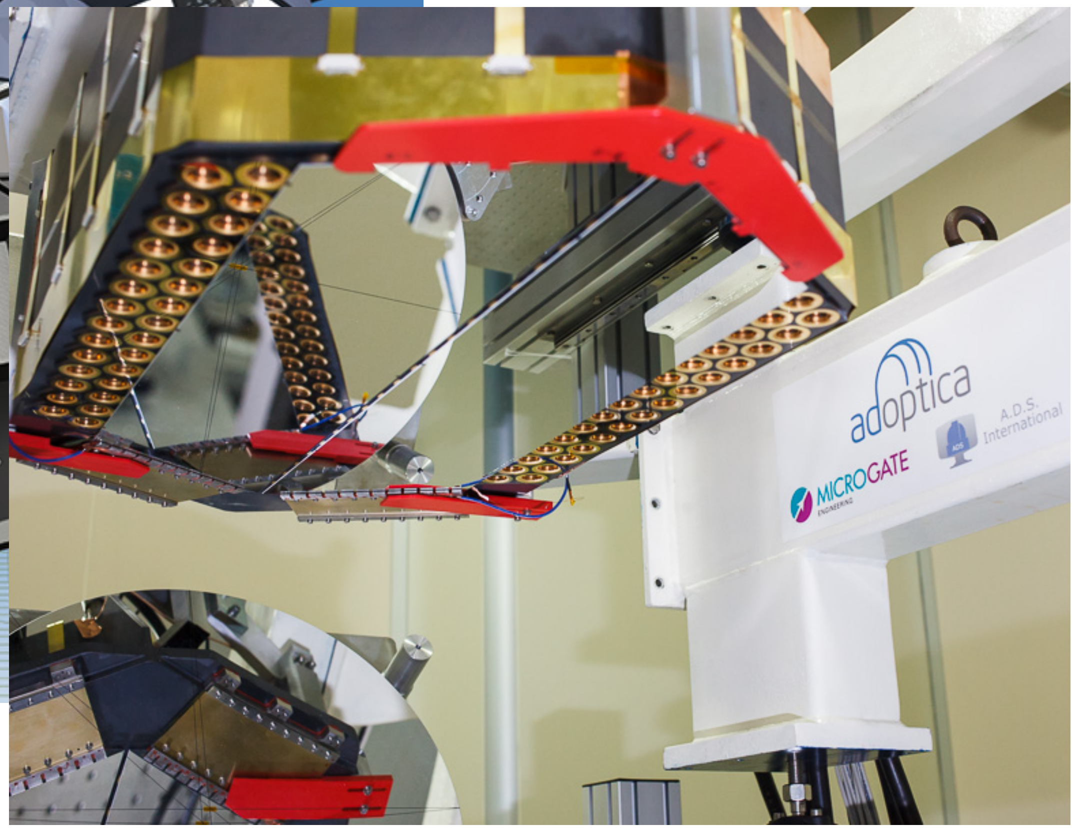




The E-ELT deformable M4



robust to actuator failures, very important when you have 5300 actuators!!!



~5300 actuators for a projected spacing of 0.48m over M1.

Simulated SCAO performances

E-ELT & SCAO performance

From MICADO documentations:

On-Axis Strehl Ratio: the SCAO module shall enable the delivery of on-axis diffraction- limited images to MICADO with a Strehl ratio >70% in the K-band for zenith angles <30°.
[INFO-XXX-NNN] The SCAO performance requirements shall be met under the following conditions: a circular E-ELT pupil of diameter 38.5 m with a circular central obscuration of diameter 11.5 m, a perfect telescope (no windshake, no M1 cophasing error, etc), on-axis seeing <= 0.8” at 500nm

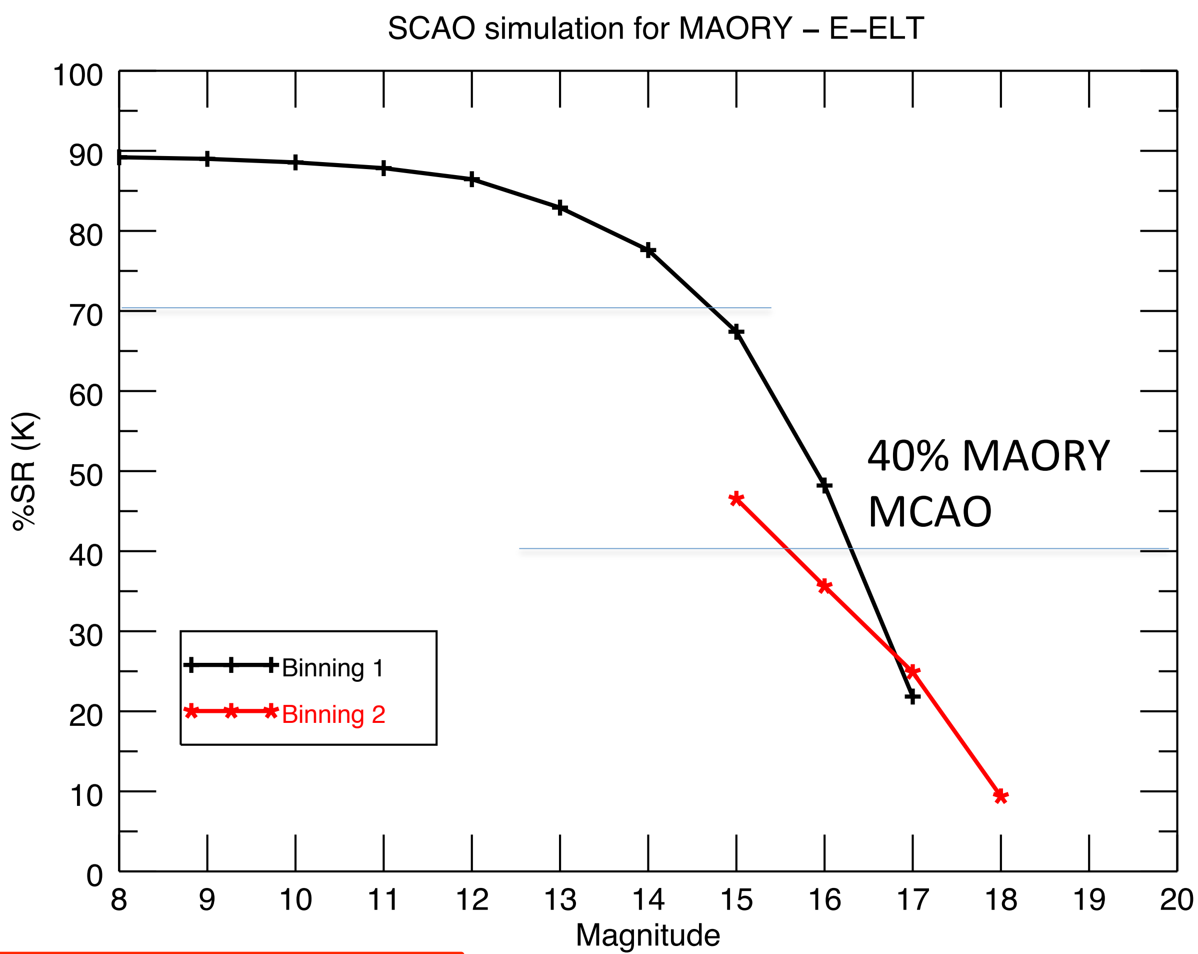
Contrast: MICADO shall reach the following contrasts (5σ) when using the coronagraphic imaging mode and after appropriate post-processing using any non-commercial code (there is no restriction to using the pipeline):
110-4 (goal: 510-5) at a separation of 100 mas (goal: 20 mas)
110-5 (goal: 510-6) at a separation of 500 mas (goal: 100 mas)

NGS HO SR (K band) vs reference star magnitude (R mag)

Line of sight SR for NGS HO PWFS 80x80 subaps., (SCAO/MCAO)

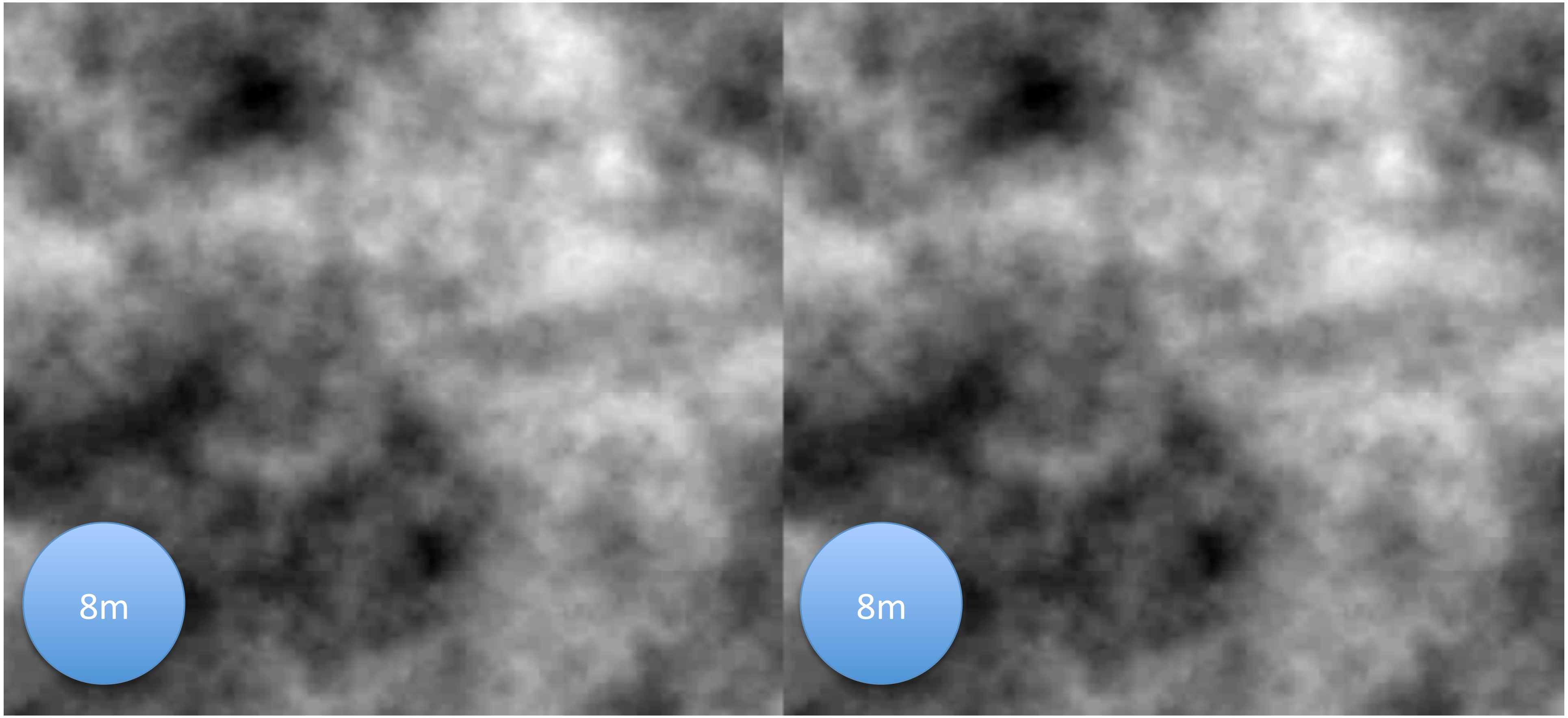
seeing median value of 0.67 arcsec equivalent vwind 9.7m/s

PWFS VIS (CCD220)
FoV 1.9”
# of pixel 80
# of corrected modes 1127 - 3654
bw 300
wl 700
sky 34
ron 0.37 e-
fps 600 - 1000



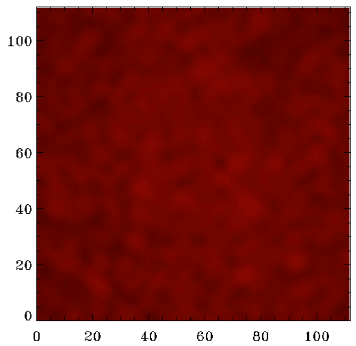
90% and SR for 8mag star, 45% for 16mag star.

The E-ELT size…



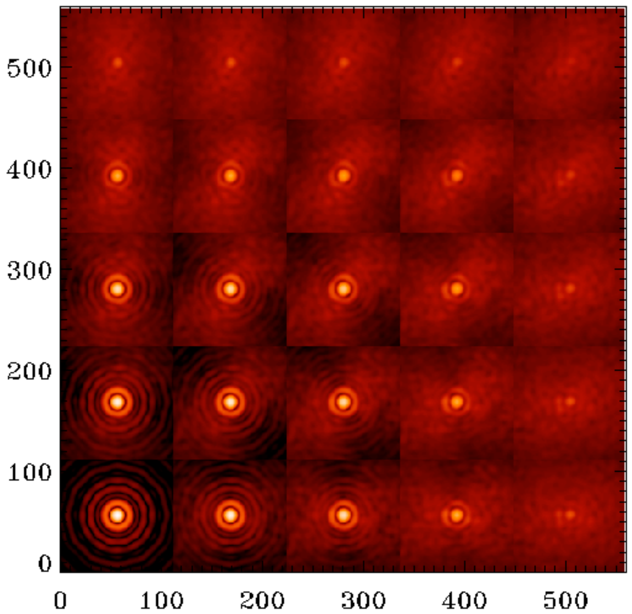
EELT PSF vs Fov (K band)

Seeing on-axis
SR (K)= 0.14%

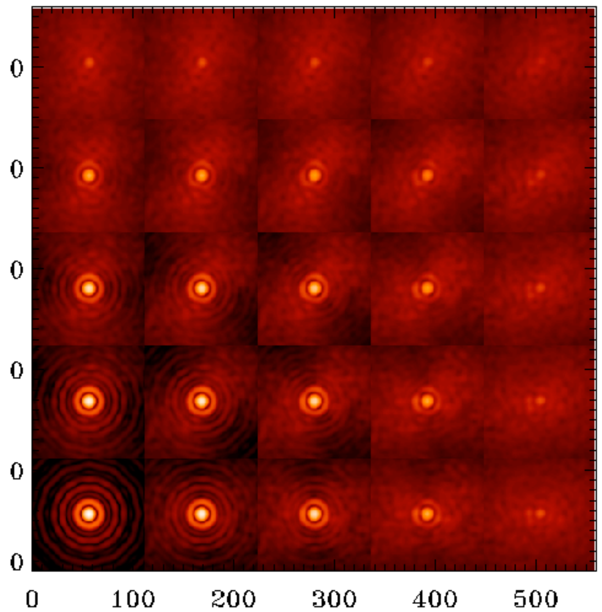


- Position grid:
  - X distance = 0, 7.5, 15, 30, and 60”
  - Y distance = 0, 7.5, 15, 30, and 60”
- PSF in K band (2200nm)
- ESO Paranal atmospheric profile

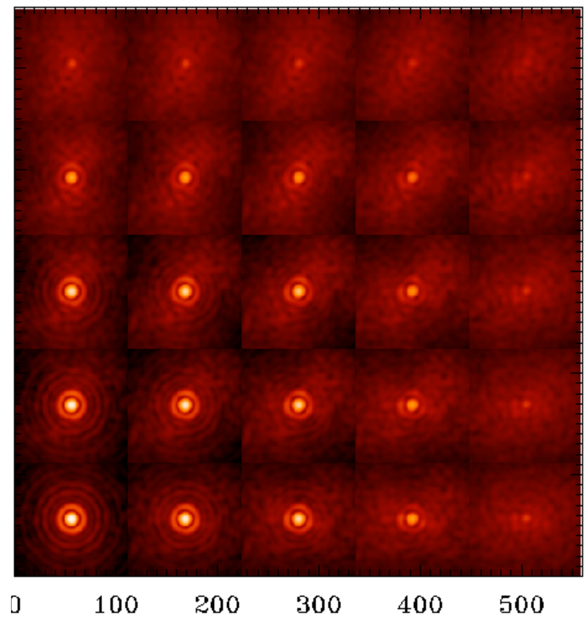
8mag



12mag



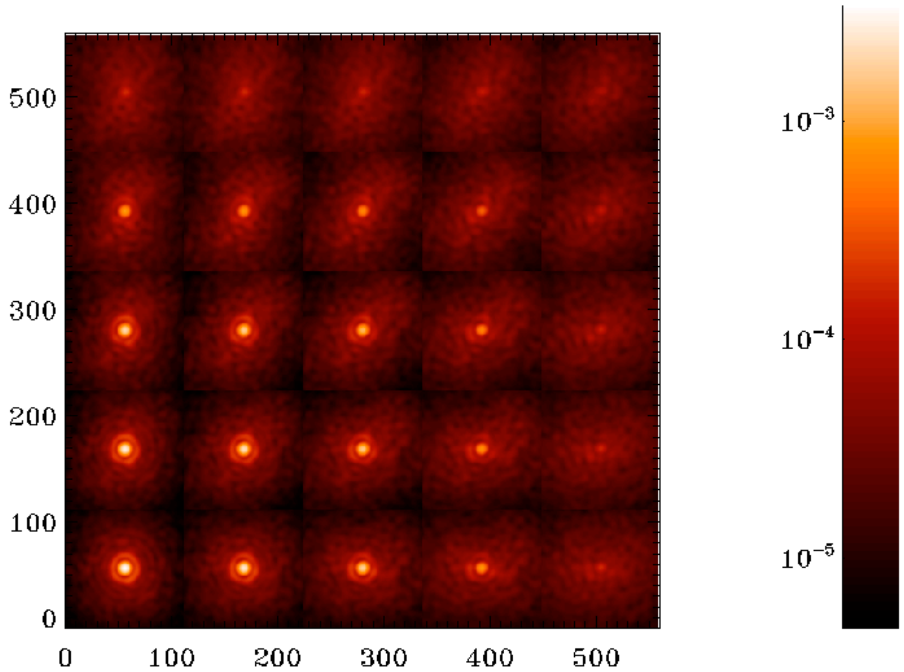
15mag



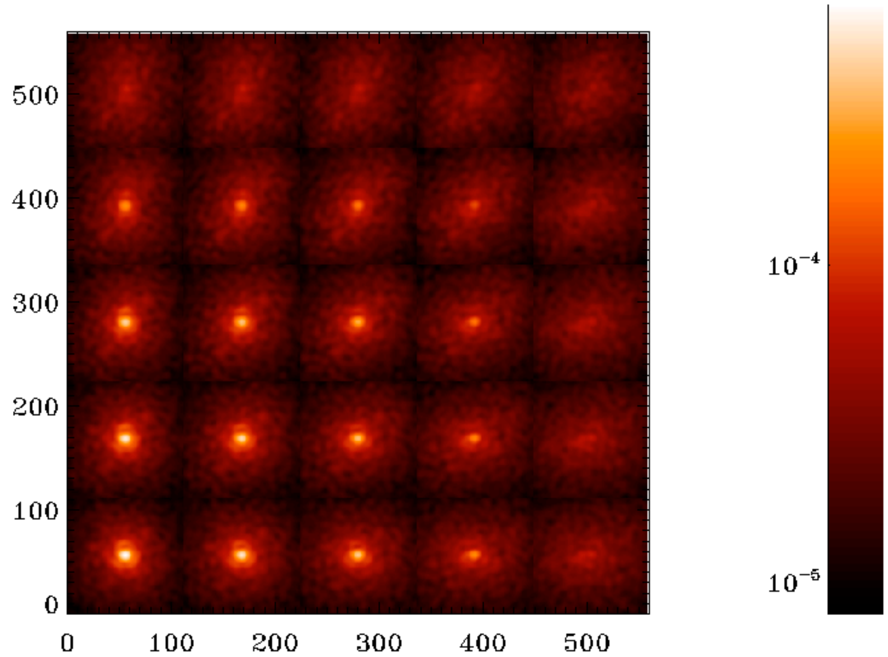
EELT PSF vs FoV

- Position grid:
  - X distance = 0, 7.5, 15, 30, and 60”
  - Y distance = 0, 7.5, 15, 30, and 60”
- PSF in K band (2200nm)
- ESO Paranal atmospheric profile

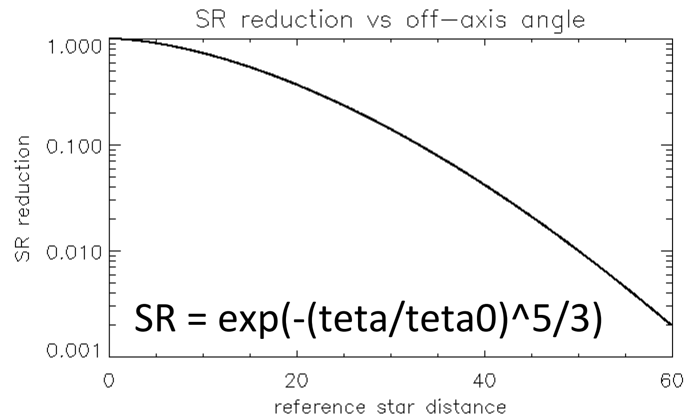
16.5 mag

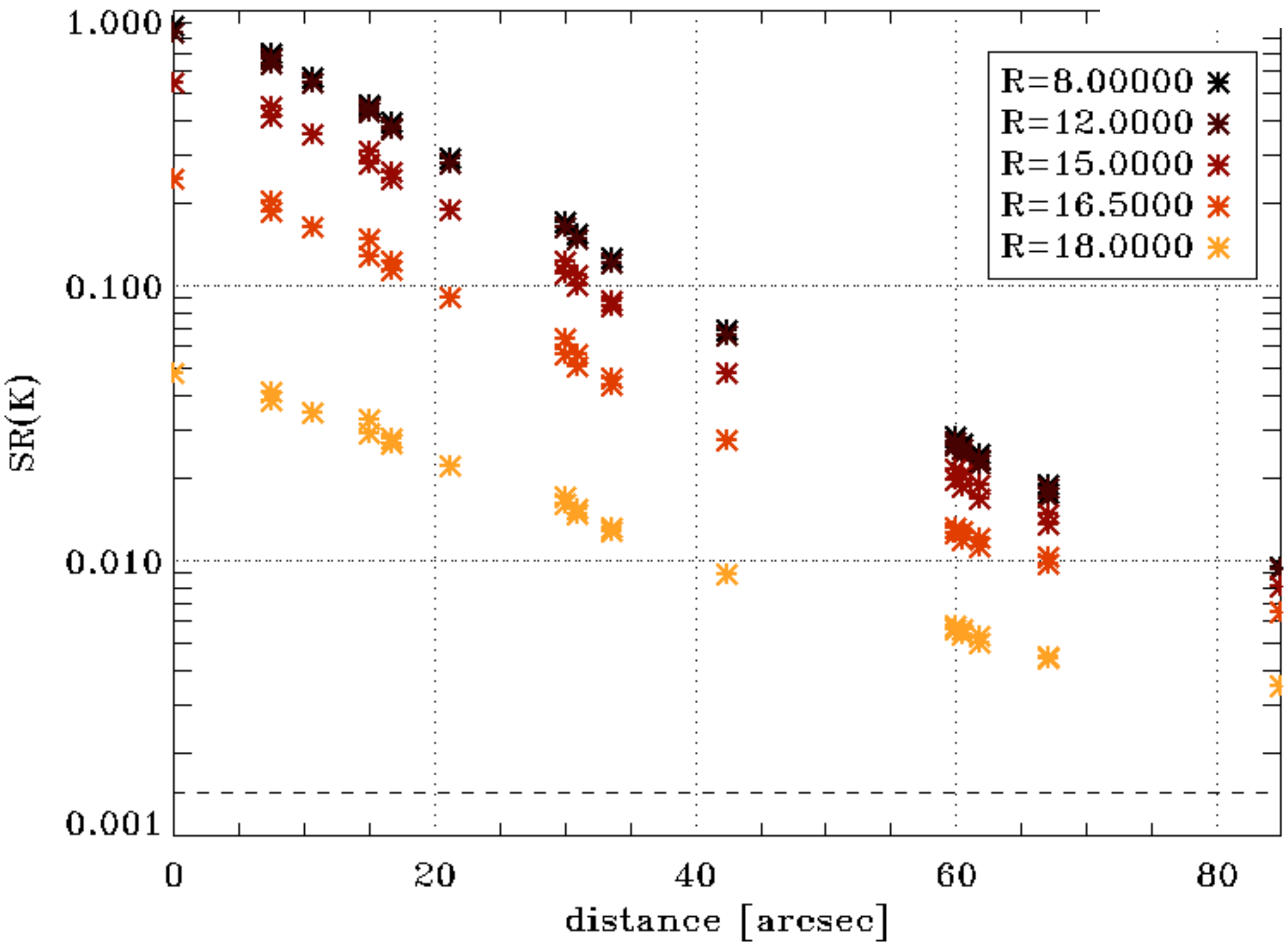


18 mag



SR vs mag and FoV position

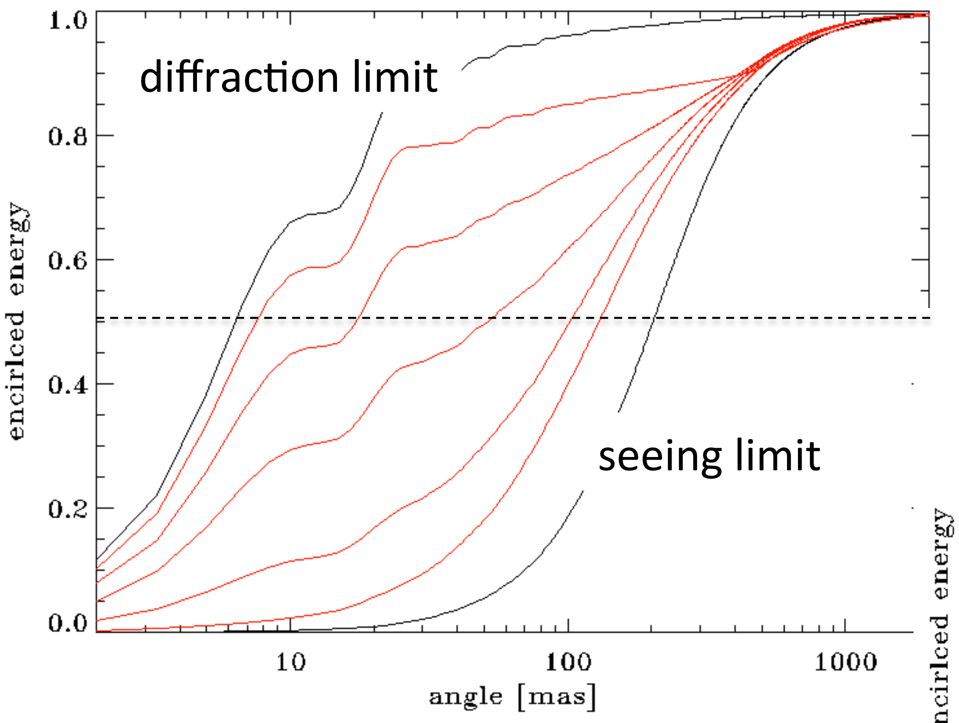




the strong degradation of performance found with the formula (teta/teta0)^5/3 is not seen in simulations. The Kolmogorov model do not represent reality completely.

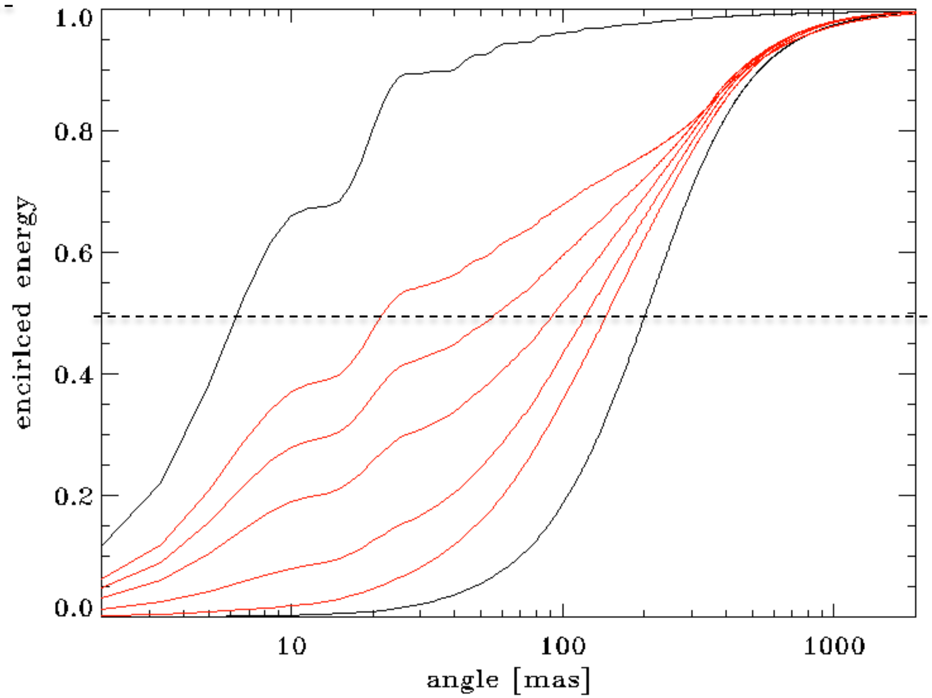
EE profiles

8mag



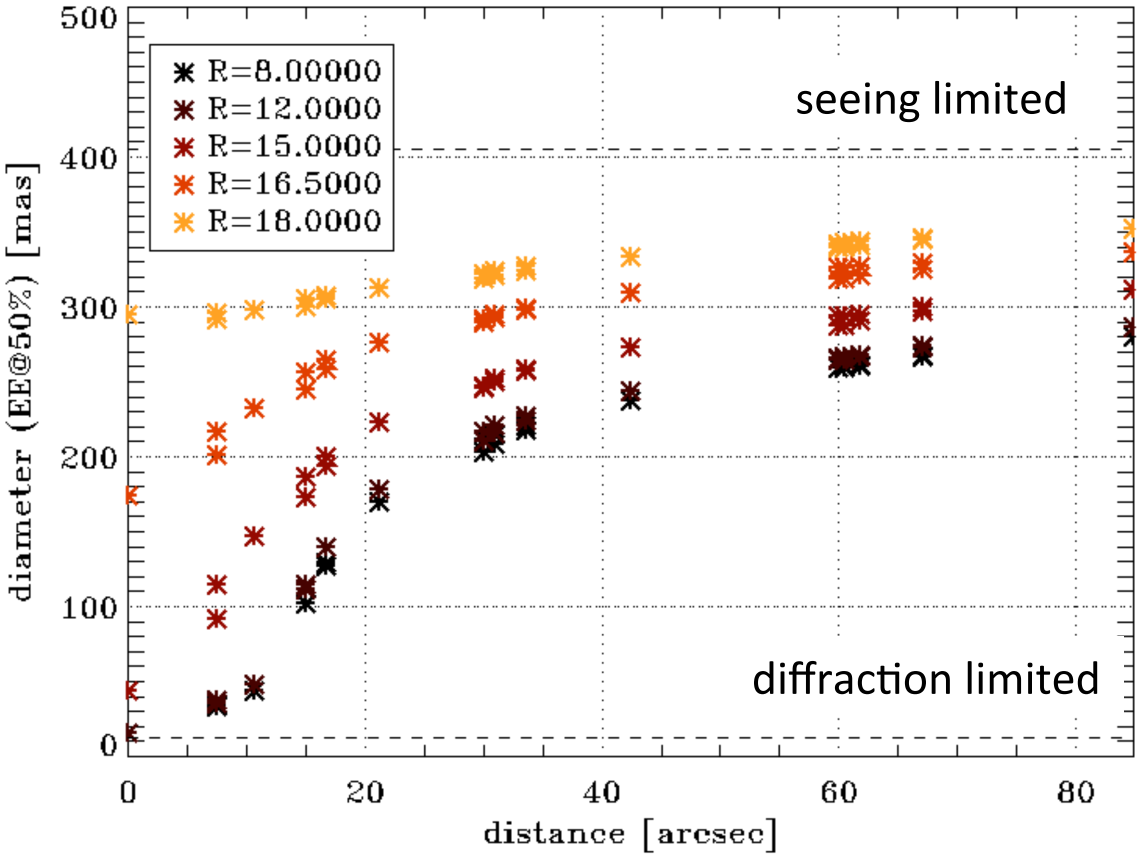
EE profiles for off axis angles of 7, 15, 30, 45, 60, 85 arcsec

15mag

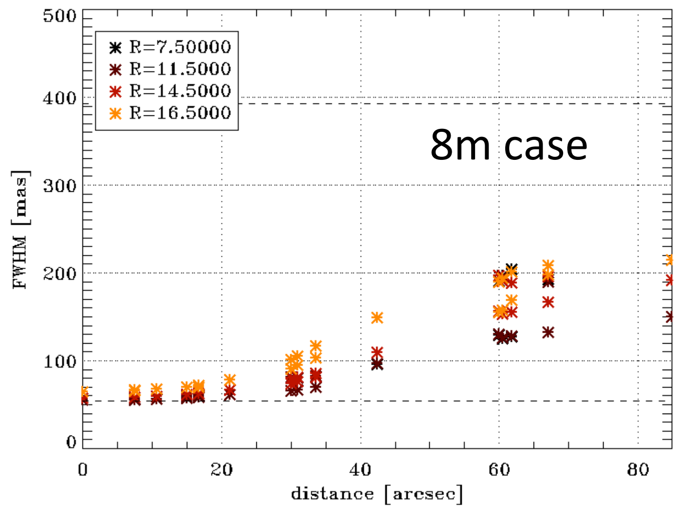


EE given in radius in this plots

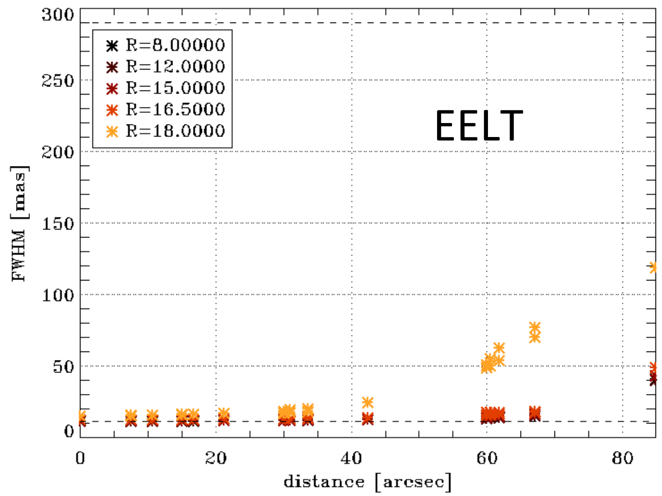
EE and FWHM



R=8.00000
R=12.0000
R=15.0000
R=16.5000
R=18.0000
seeing limited
diffraction limited
diameter (EE@50%) [mas]
distance [arcsec]



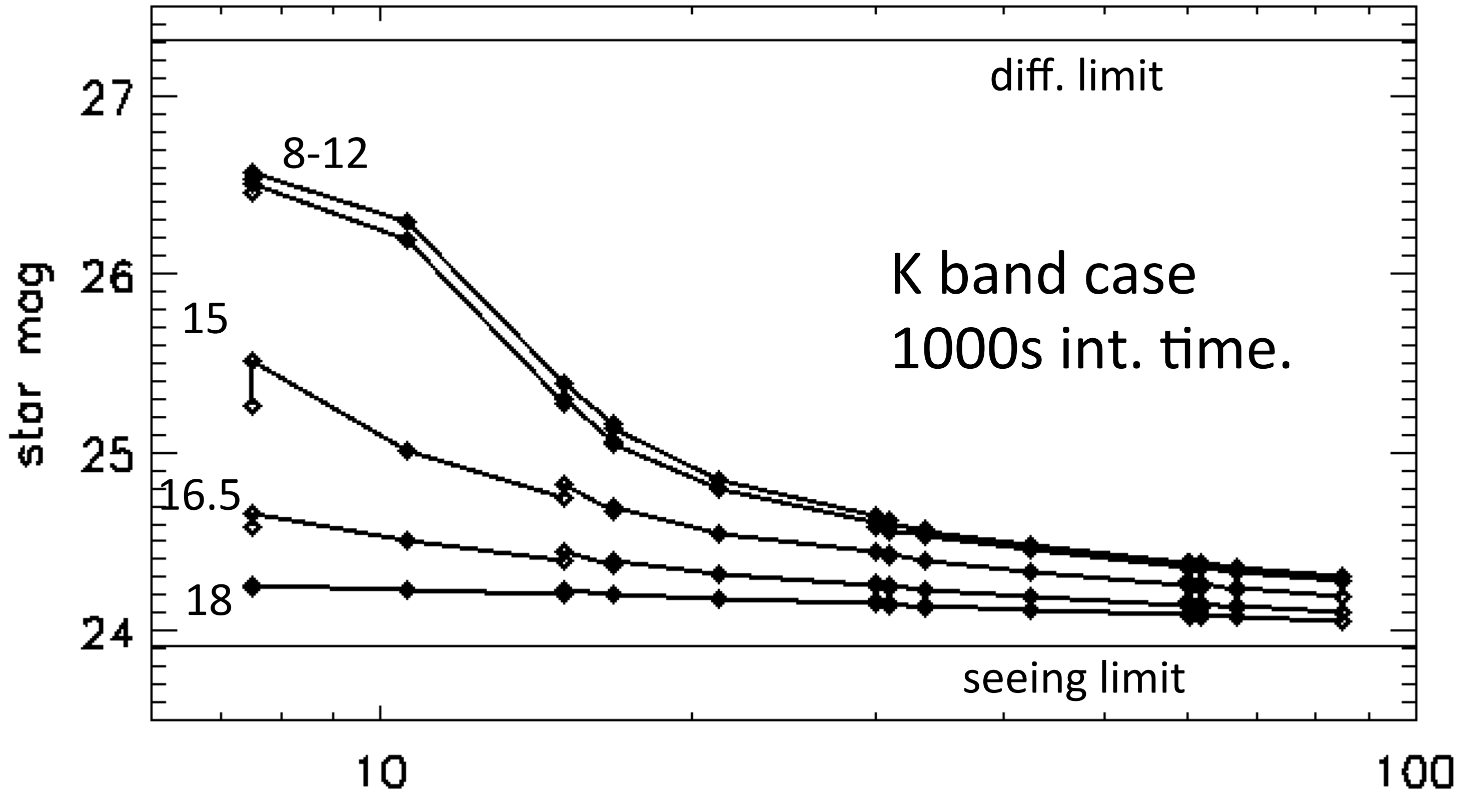
R=7.50000
R=11.5000
R=14.5000
R=16.5000
8m case
FWHM [mas]
distance [arcsec]



R=8.00000
R=12.0000
R=15.0000
R=16.5000
R=18.0000
EELT
FWHM [mas]
distance [arcsec]

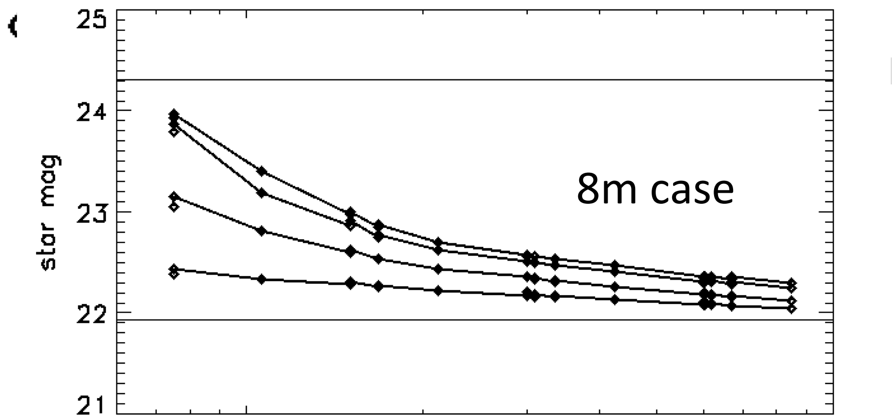
Sensitivity to point sources

5sigma detectable mag vs. ref star mag and off-axis distance



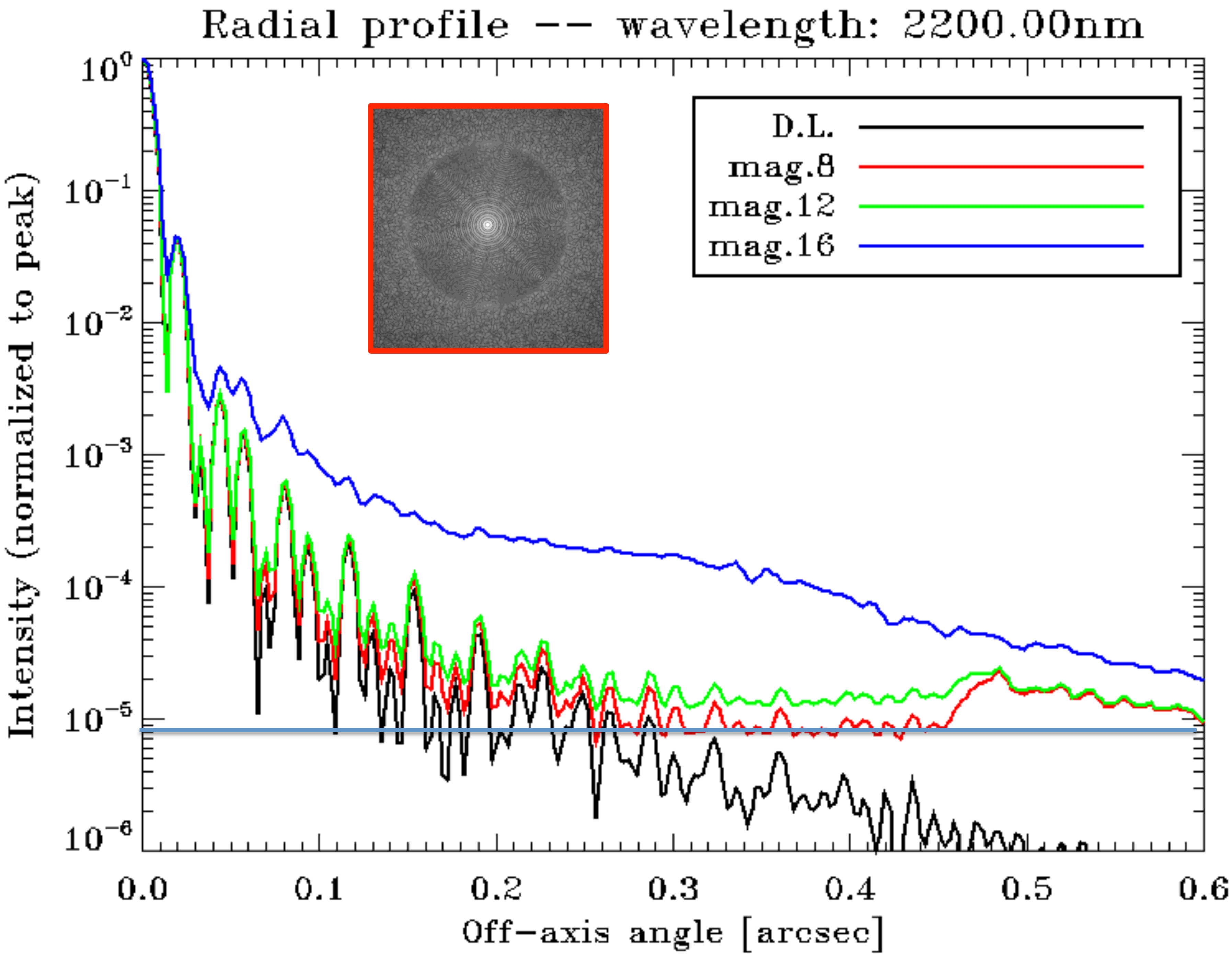
SNR ~ star_flu
sqrt(bckg_flux*e50^2)

$$SNR \sim \frac{D\_tel^2}{D\_tel / (D\_tel*G\_ao)}$$



PSF contrast and planets detection

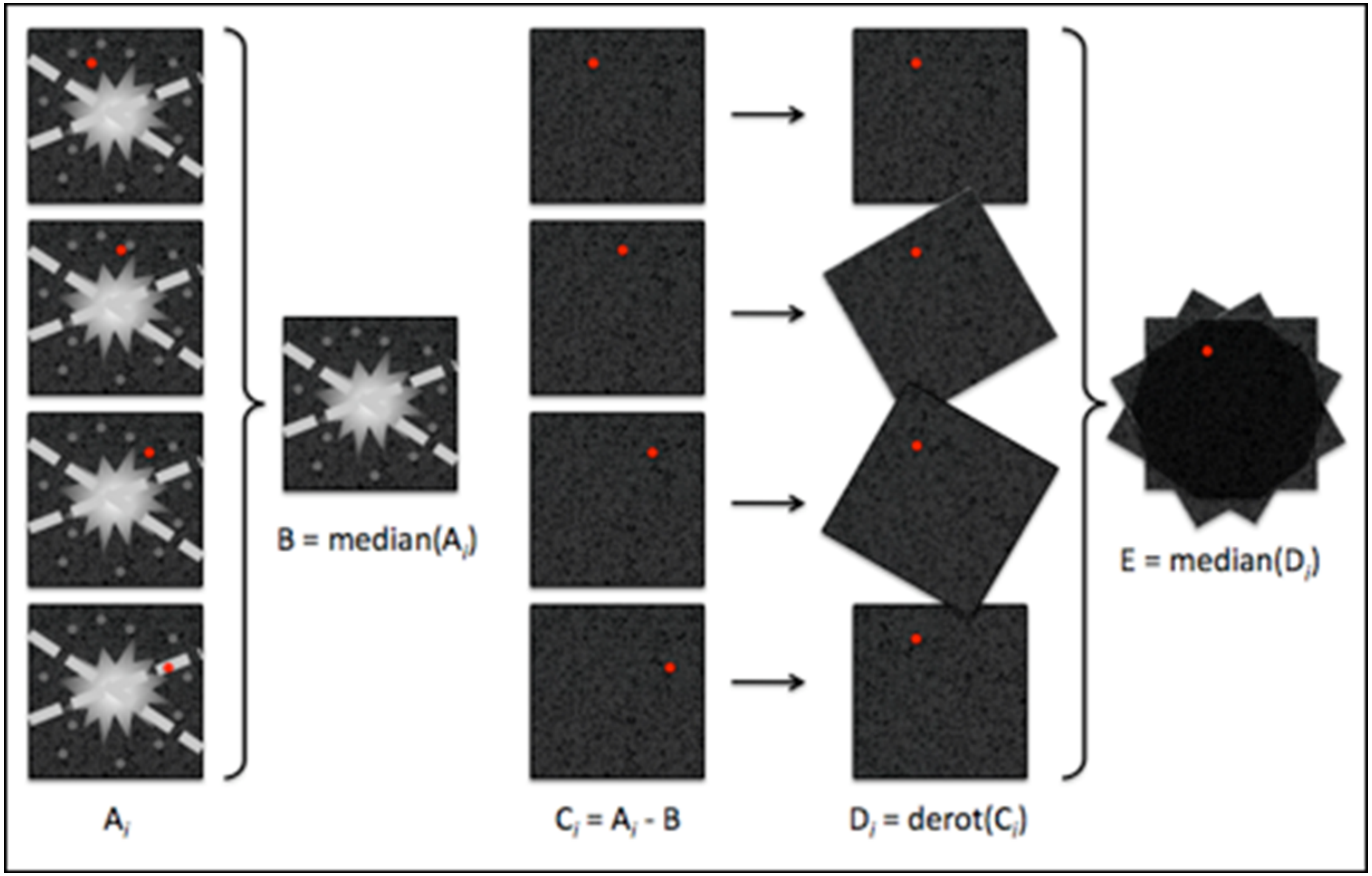
R-XXX-NNN] **Contrast:** MICADO shall reach the following contrasts (5σ) when using the coronagraphic imaging mode and after appropriate post-processing using any non-commercial code (there is no restriction to using the pipeline):
110-4 (goal: 5*10-5) at a separation of 100 mas (goal: 20 mas)
110-5 (goal: 5*10-6) at a separation of 500 mas (goal: 100 mas)



Radial profile -- wavelength: 2200.00nm
Intensity (normalized to peak)
Off-axis angle [arcsec]
D.L.
mag.8
mag.12
mag.16
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0
0.1
0.2
0.3
0.4
0.5
0.6

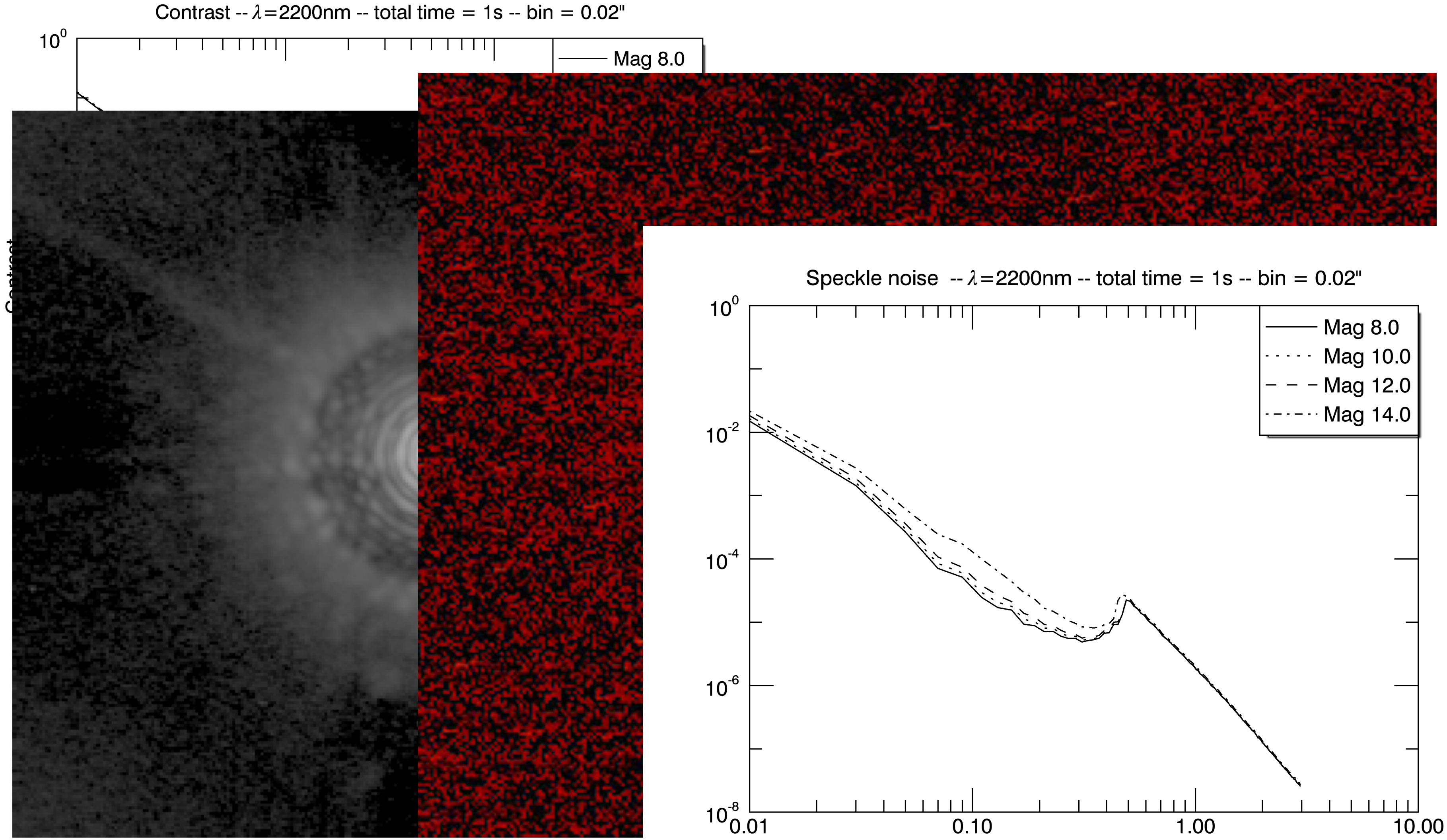
Angular Differential Imaging

FoV is left rotating during integration

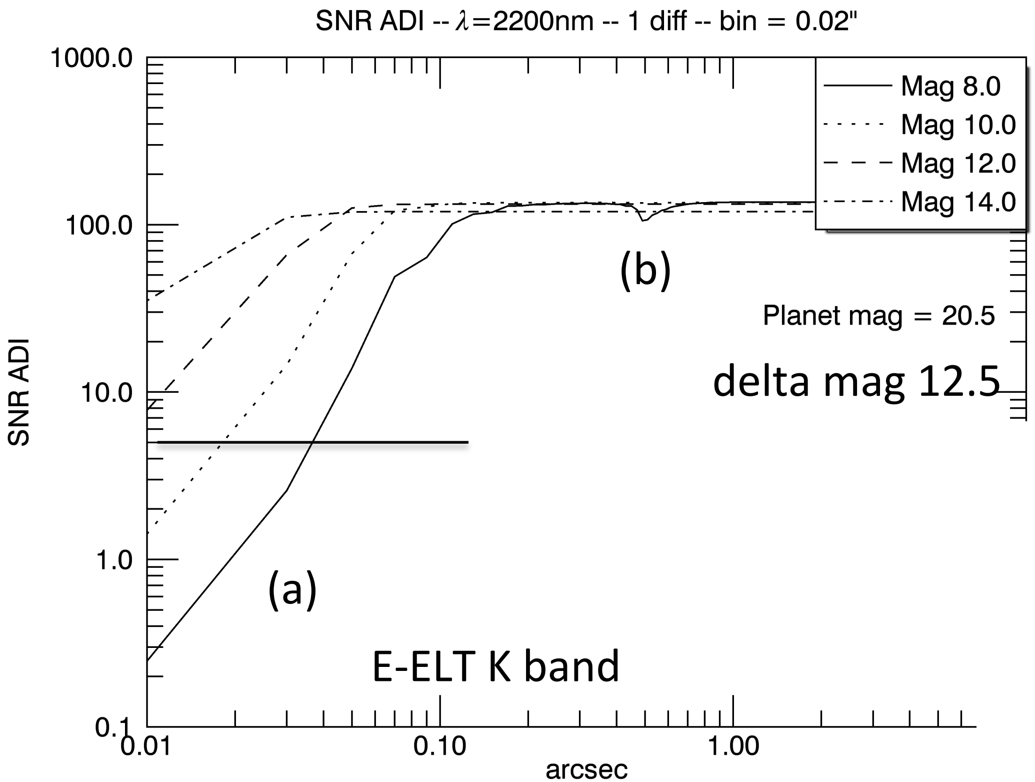


PSF intensity fluctuation from AO residuals is unavoidable

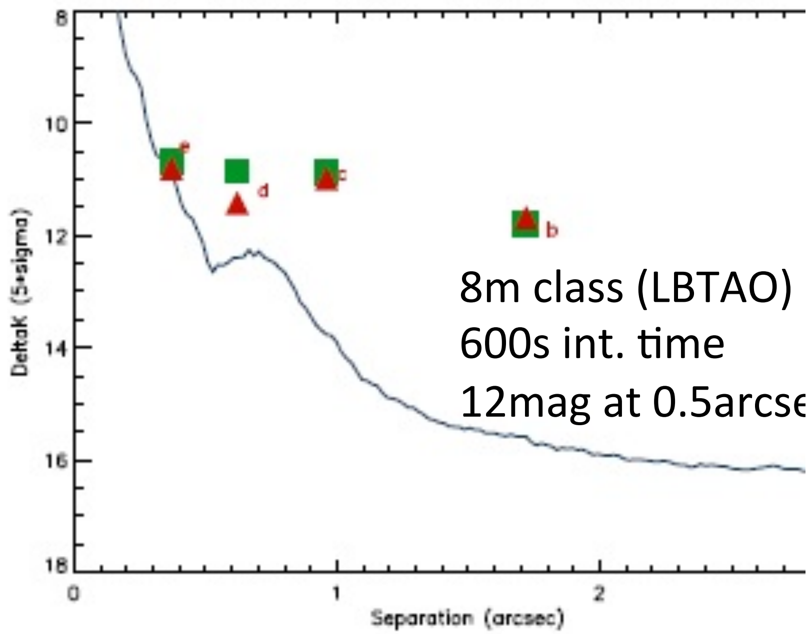
Planet detection noise terms



The achieved planet d_mag



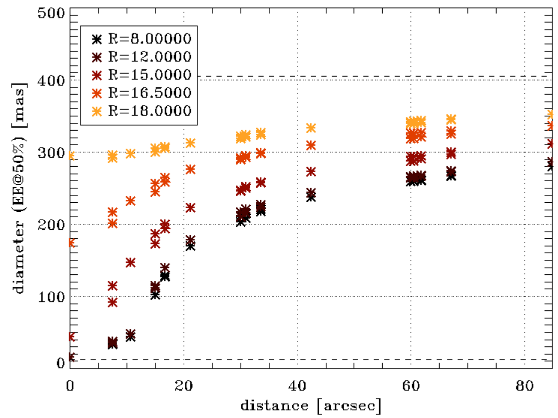
scaling results for 500mas:
int time to 600s => sqrt(t)
SNR 100 to 5
deltaMag ~ +6.5
detectable planet delta_mag 19
~ 10^-7 contrast



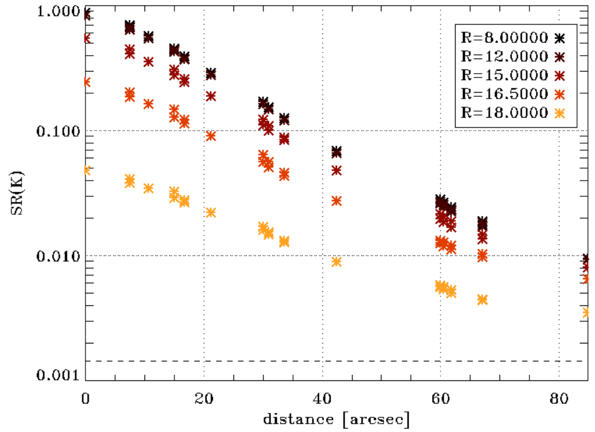
goal for MICADO contrast:
(a) 5*10^-5 @ 20mas (11 delta_ mag)
(b) 5*10^-6 @ 500mas (13.5 delta_mag)

Conclusions

The SCAO operating mode for the E-ELT is frequently used. The main limitations of such an operating mode are (a) limited sky coverage and (b) field dependent PSF.



Point (a) can be reassessed depending on the selected astronomical target(s). SCAO systems works with ref star mag 16.5-17.0 achieving EE50 in 200-250mas, FWHM is mostly DL.

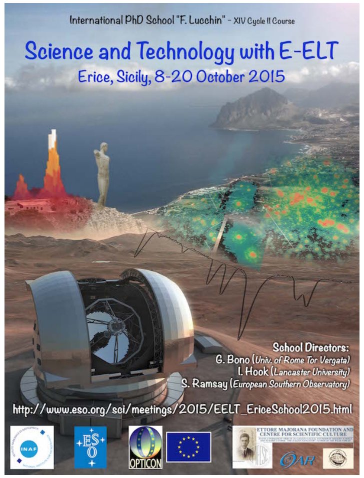


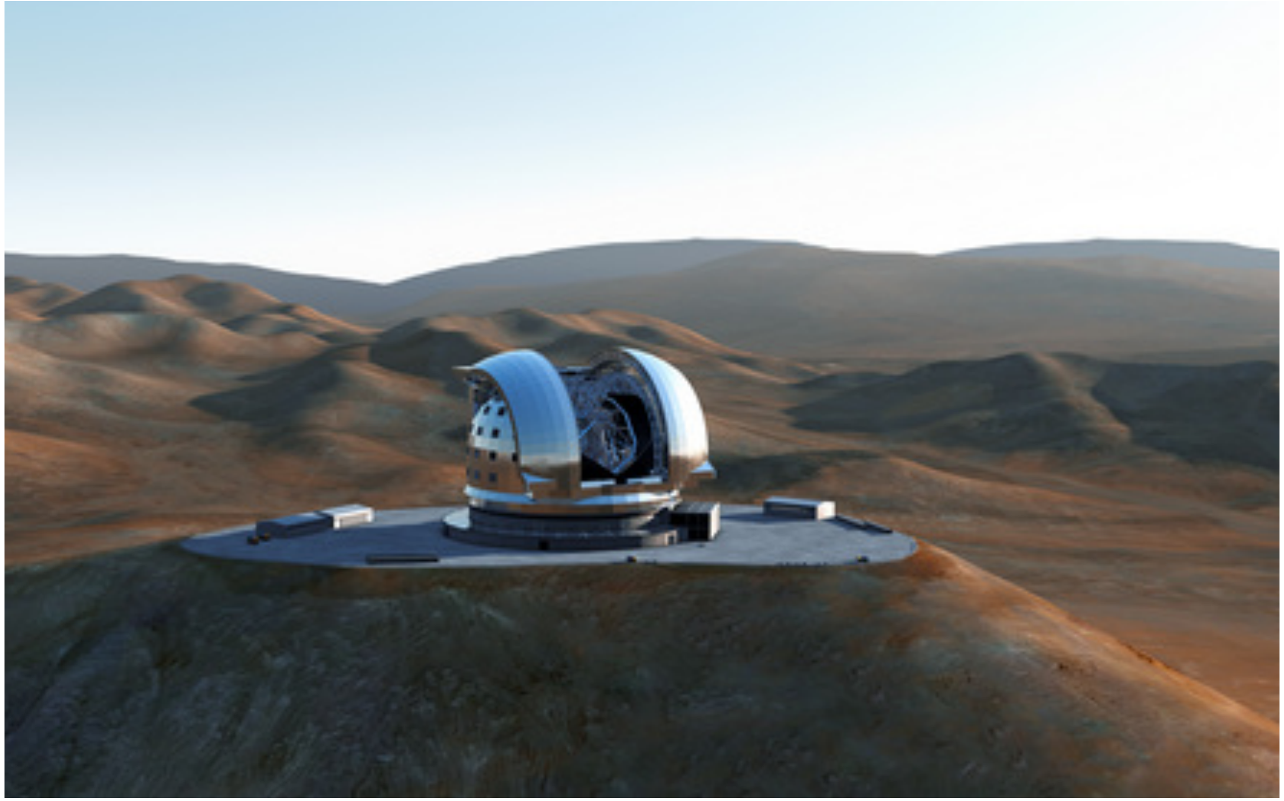
Point (b) has to be evaluated considering the width of the required FoV and effect of angular anisoplanatism over the PSF. SR variation of factors 2-4 found in simulations over 15arcsec rad.

Simulated performance shows:

(a) star detection up to mag 1-1.5 mag wrt seeing with reasonable 15-14 mag ref star (20" FoV)
(b) planet detection fulfill specs for r=500mas, specs for r=20mas in reach but to be assessed

Thanks for your attention !!

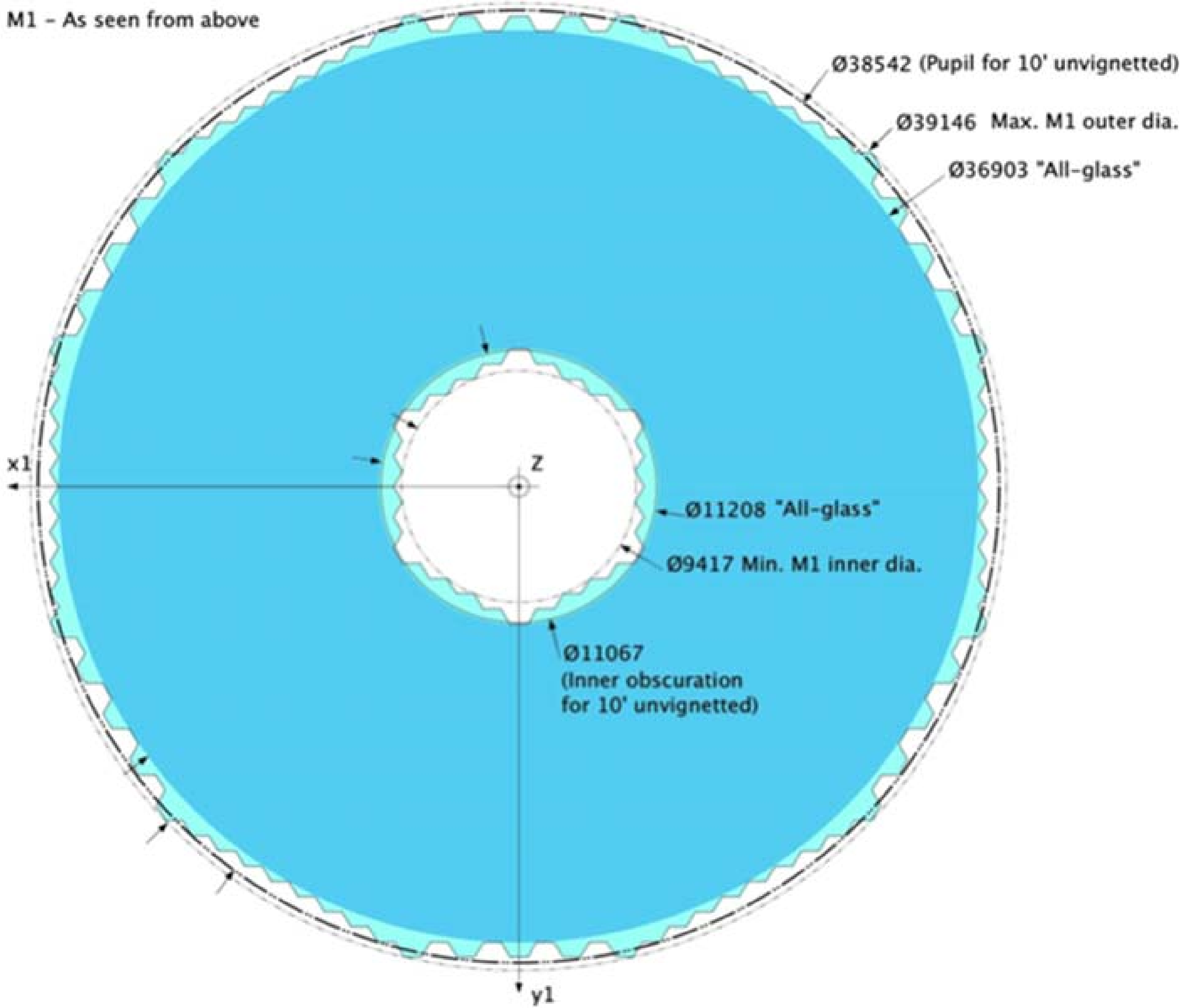


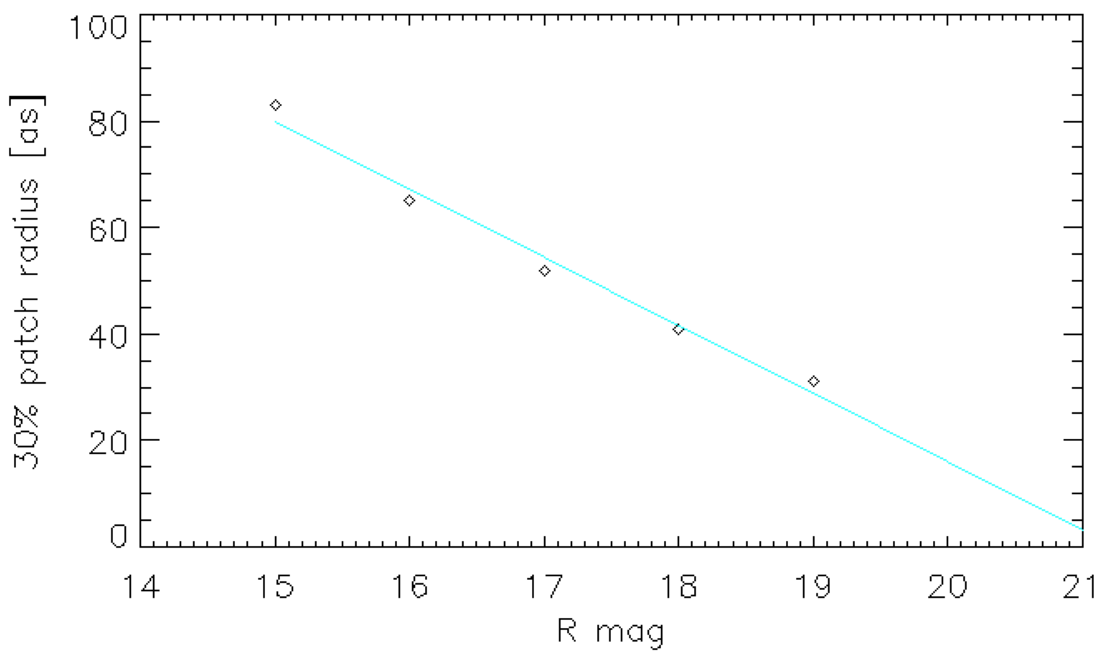


MICADO, SCAO & MCAO
HARMONI, SCAO & LTAO
METIS, SCAO & LTAO
MOS, MOAO
HIRES, SCAO
EPICS, SCAO (XAO)

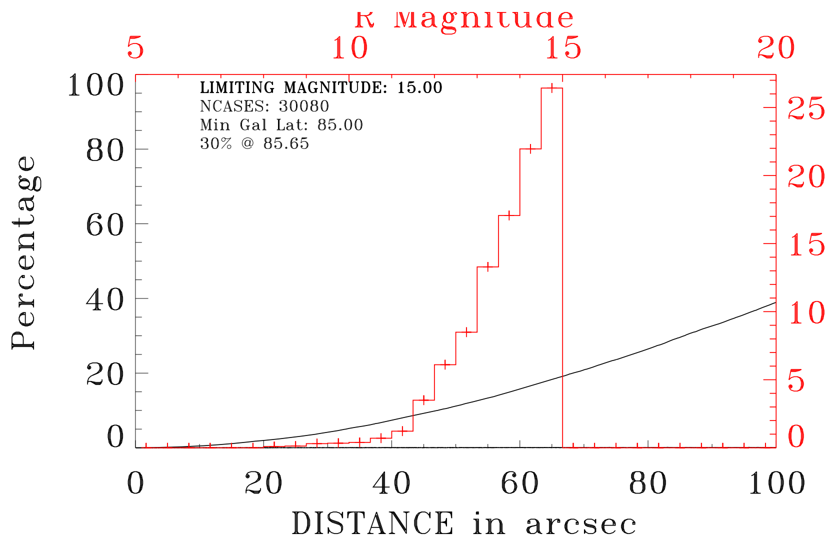
NGS SCAO & LGS SCAO this one not really suited for 40m telescope

Primary mirror and pupil

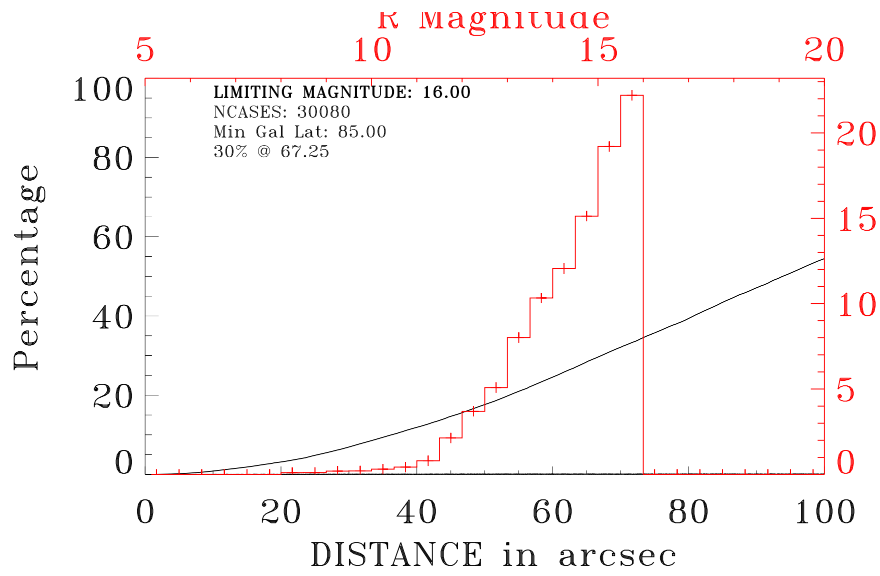




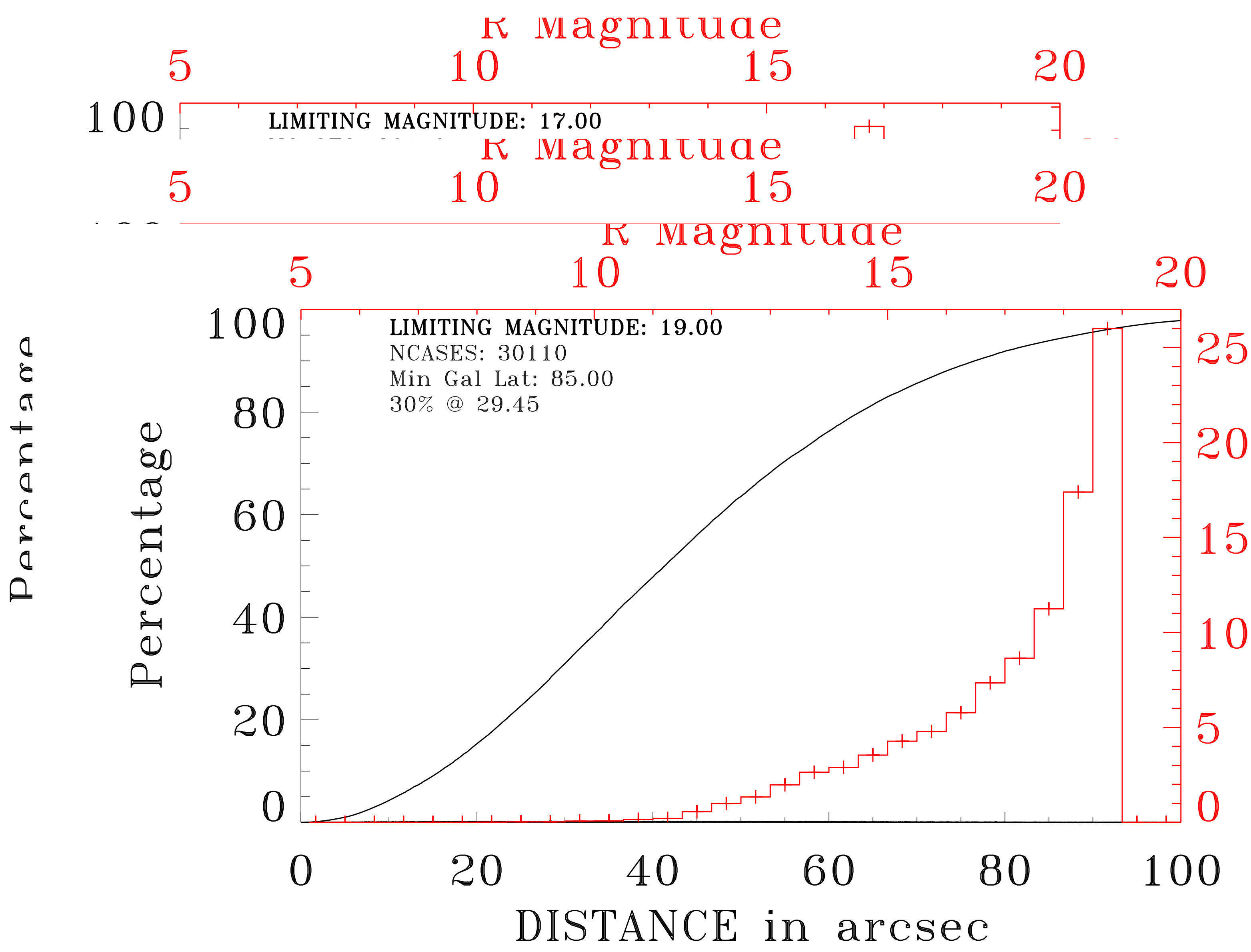
100
80
60
40
20
0
30% patch radius [as]
14
15
16
17
18
19
20
21
R mag



R Magnitude
LIMITING MAGNITUDE: 15.00
NCASES: 30080
Min Gal Lat: 85.00
30% @ 85.65
Percentage
DISTANCE in arcsec



R Magnitude
LIMITING MAGNITUDE: 16.00
NCASES: 30080
Min Gal Lat: 85.00
30% @ 67.25
Percentage
DISTANCE in arcsec



R Magnitude
LIMITING MAGNITUDE: 17.00
LIMITING MAGNITUDE: 19.00
NCASES: 30110
Min Gal Lat: 85.00
30% @ 29.45
Percentage
DISTANCE in arcsec

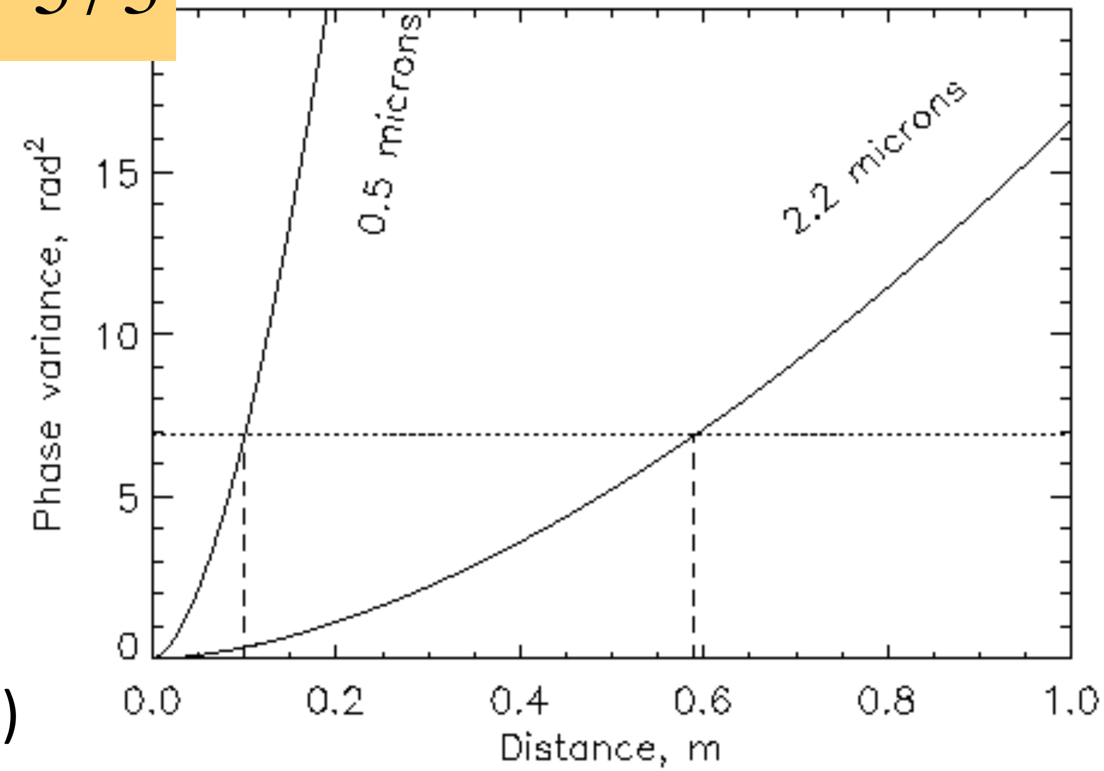
A quick discussion of r0……

The phase structure function

$$D_\phi(\vec{r}) \equiv \left\langle \left| \phi(\vec{x}) - \phi(\vec{x}+\vec{r}) \right|^2 \right\rangle = \int_{-\infty}^{\infty} dx \ \left| \phi(\vec{x}) - \phi(\vec{x}+\vec{r}) \right|^2$$

$$D_\phi(\vec{r}) \equiv 6.88(D/r0)^\wedge 5/3$$

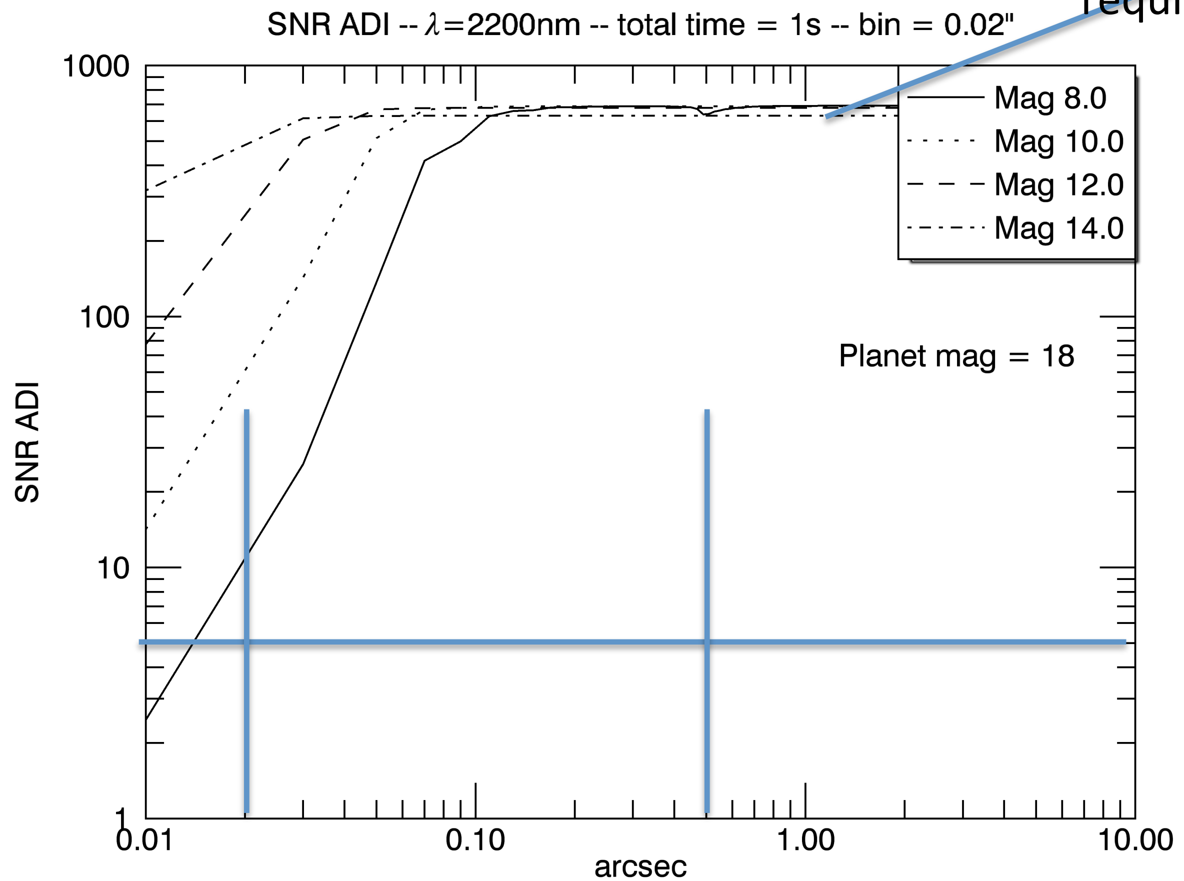
acts. spacing
~ r0 at
correction
wavelength



r0 ~ 0.5m at k band
D/r0 ~ 80 at the E-ELT(40m)

SNR for ADI technique

SNR = 77 when scaled to requirement (b)



SNR scales with:

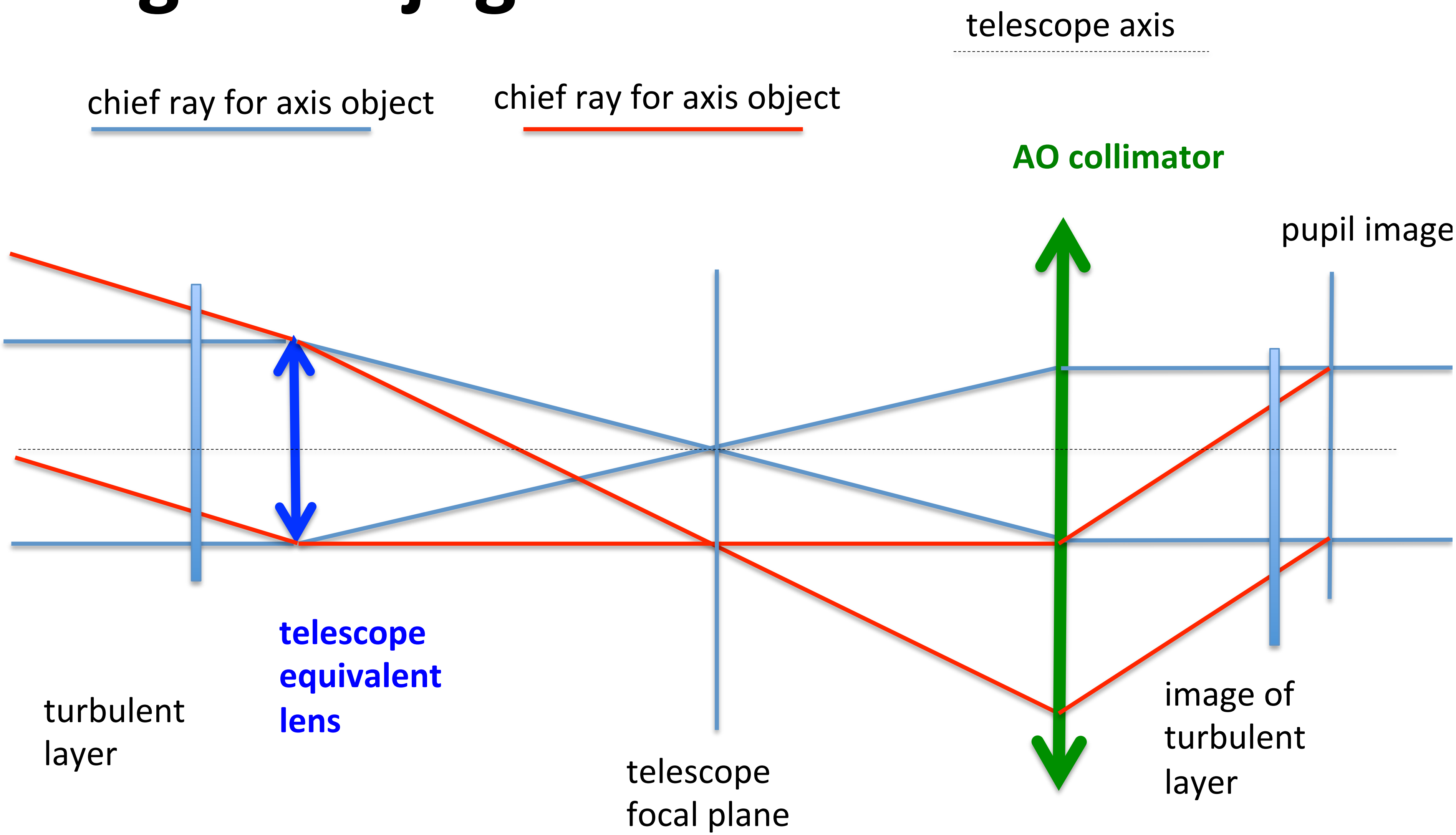
star_flux / sqrt(bckg_flux * teta^2)

8m tel.
teta^2 ~ 25 larger
star_flux 25 smaller

compare with LBT res

goal for MICADO contrast
(a) 5*10^-5 @ 20mas
(b) 5*10^-6 @ 500mas

Single conjugate ?



$$SNR = \frac{N_{planet}}{\sqrt{\sigma^{2}_{DIFF} + 2N_{planet} + 2N_{star} + 2N_{BG}}}\sqrt{n_{DIFF}}$$