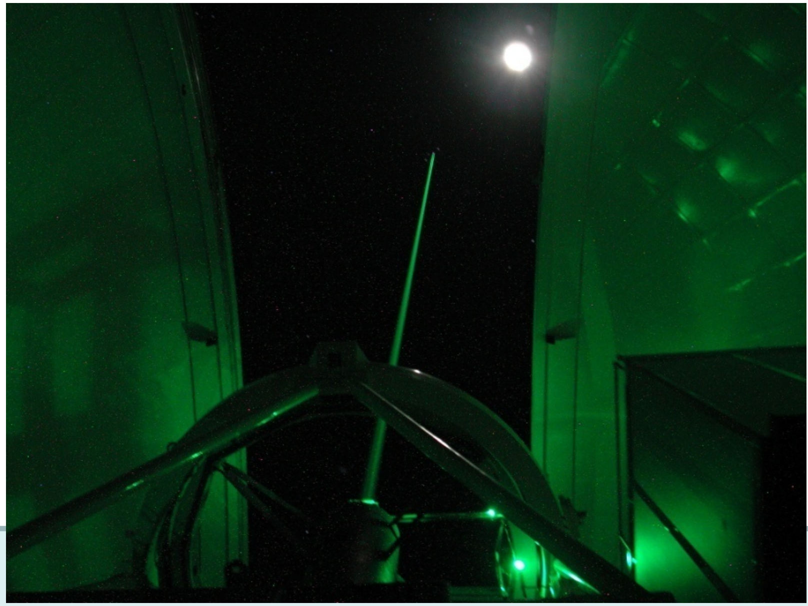
Adaptive Optics & Laser Guide Stars



by Roberto Ragazzoni

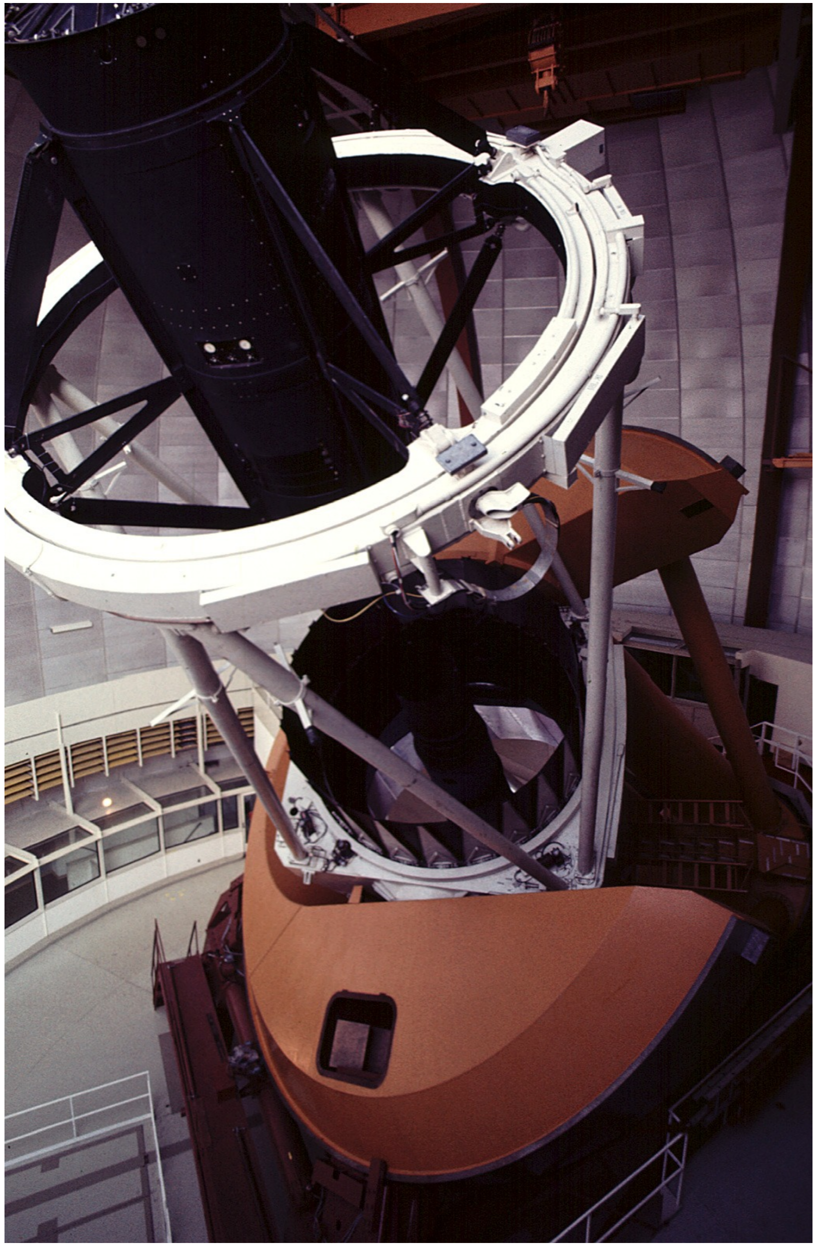
INAF – Astronomical Observatory of Padova (Italy)

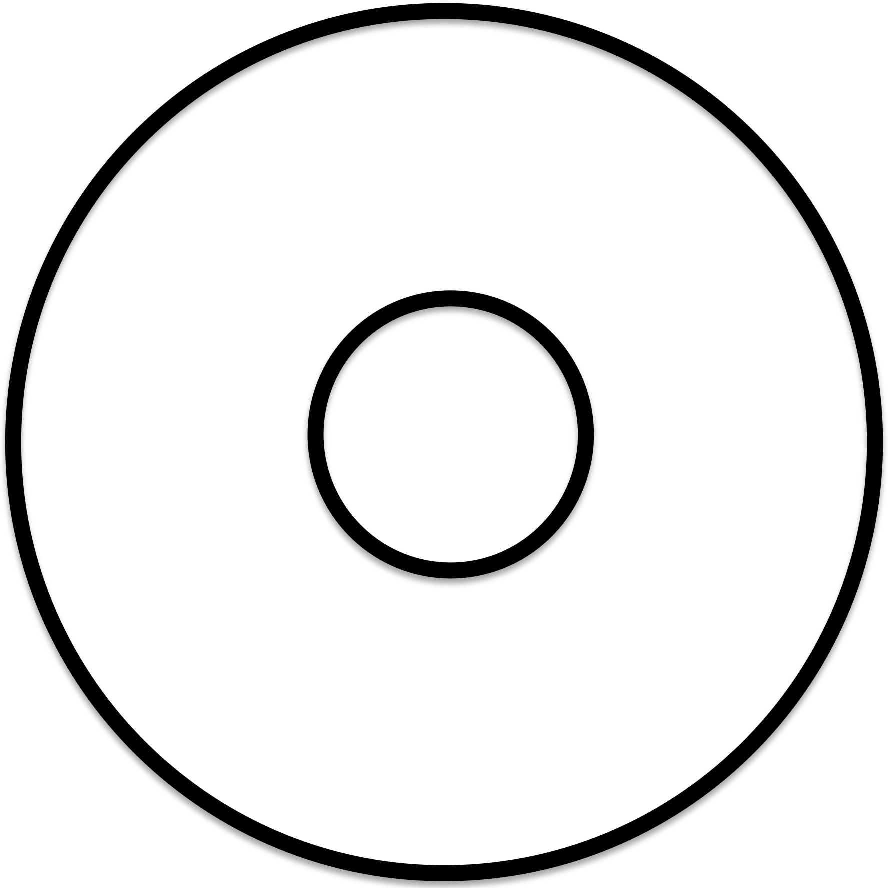
roberto.ragazzoni@oapd.inaf.it

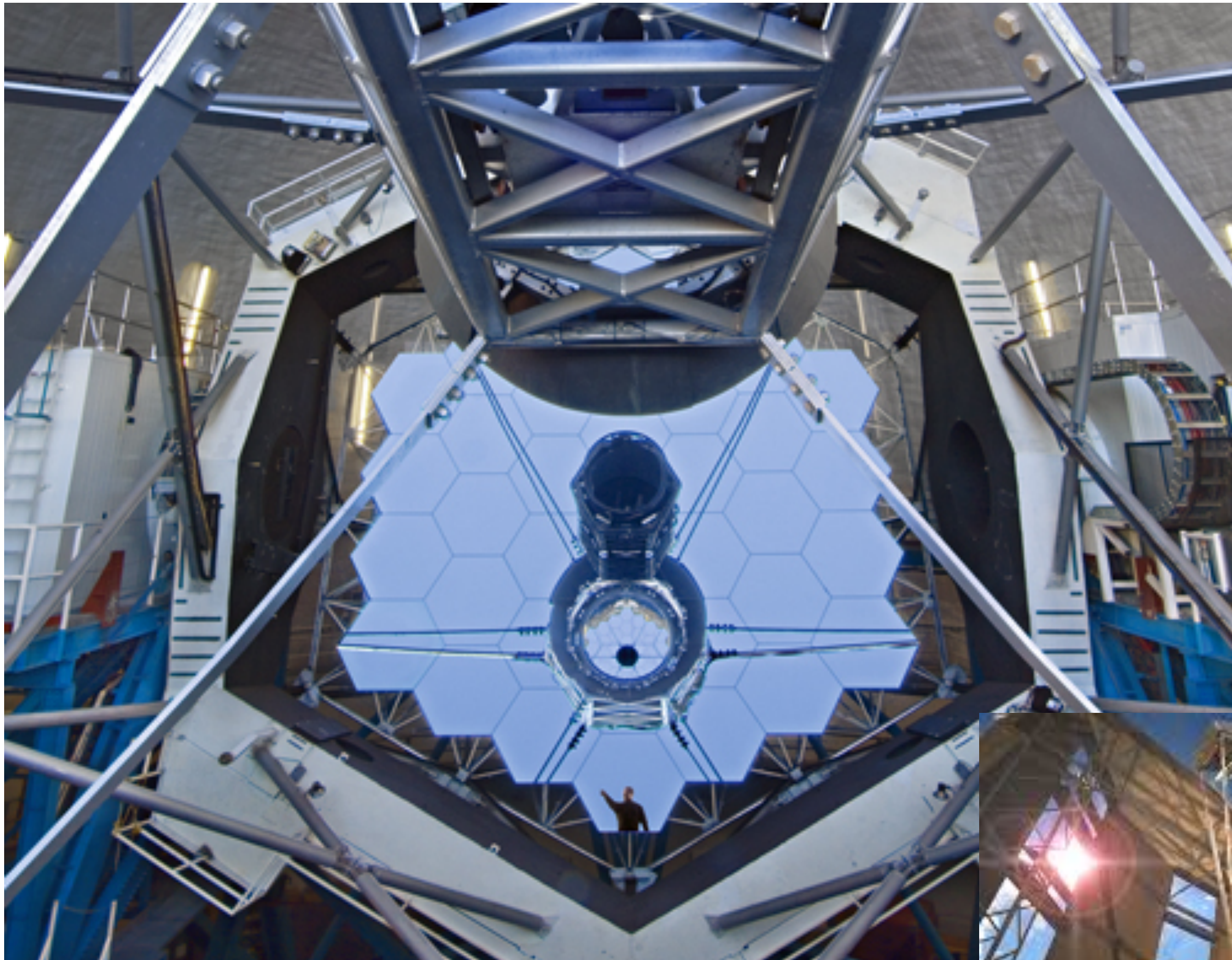
ICTP The Abdus Salam International Centre for Theoretical Physics 50th Anniversary 1964-2014

INAF - Osservatorio Astronomico di Padova

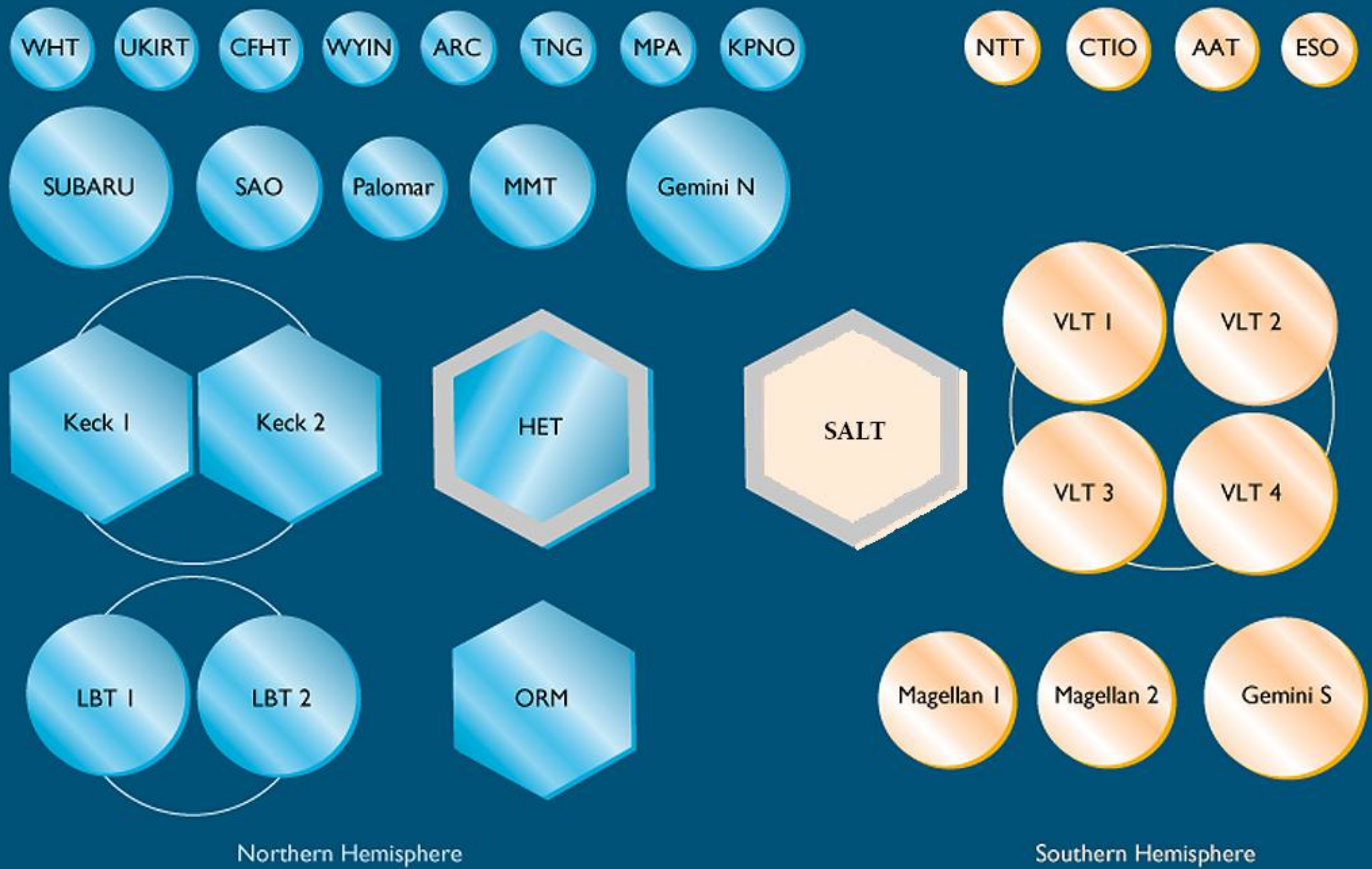
A pupil



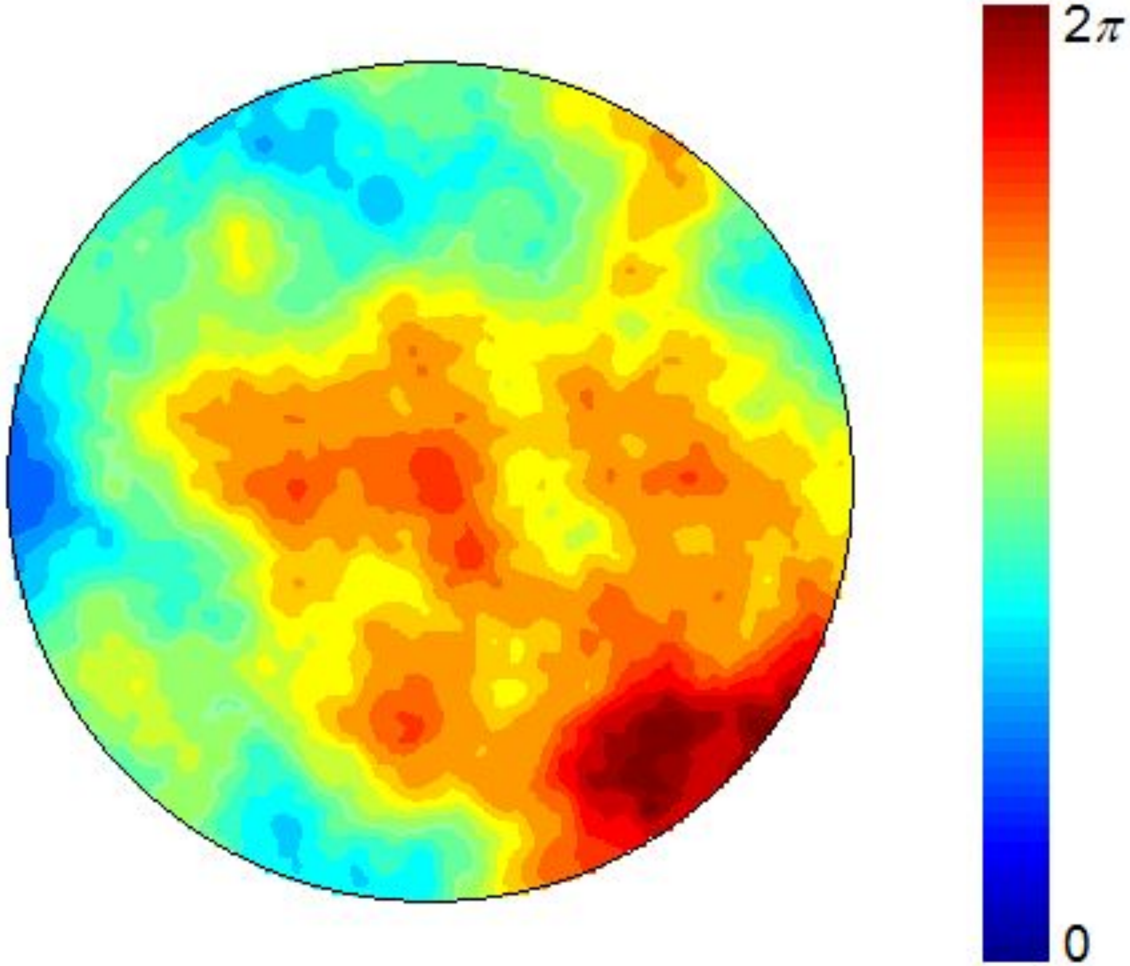





COLLECTING AREA OF THE LARGE TELESCOPES



One rad of phase is our “unit”



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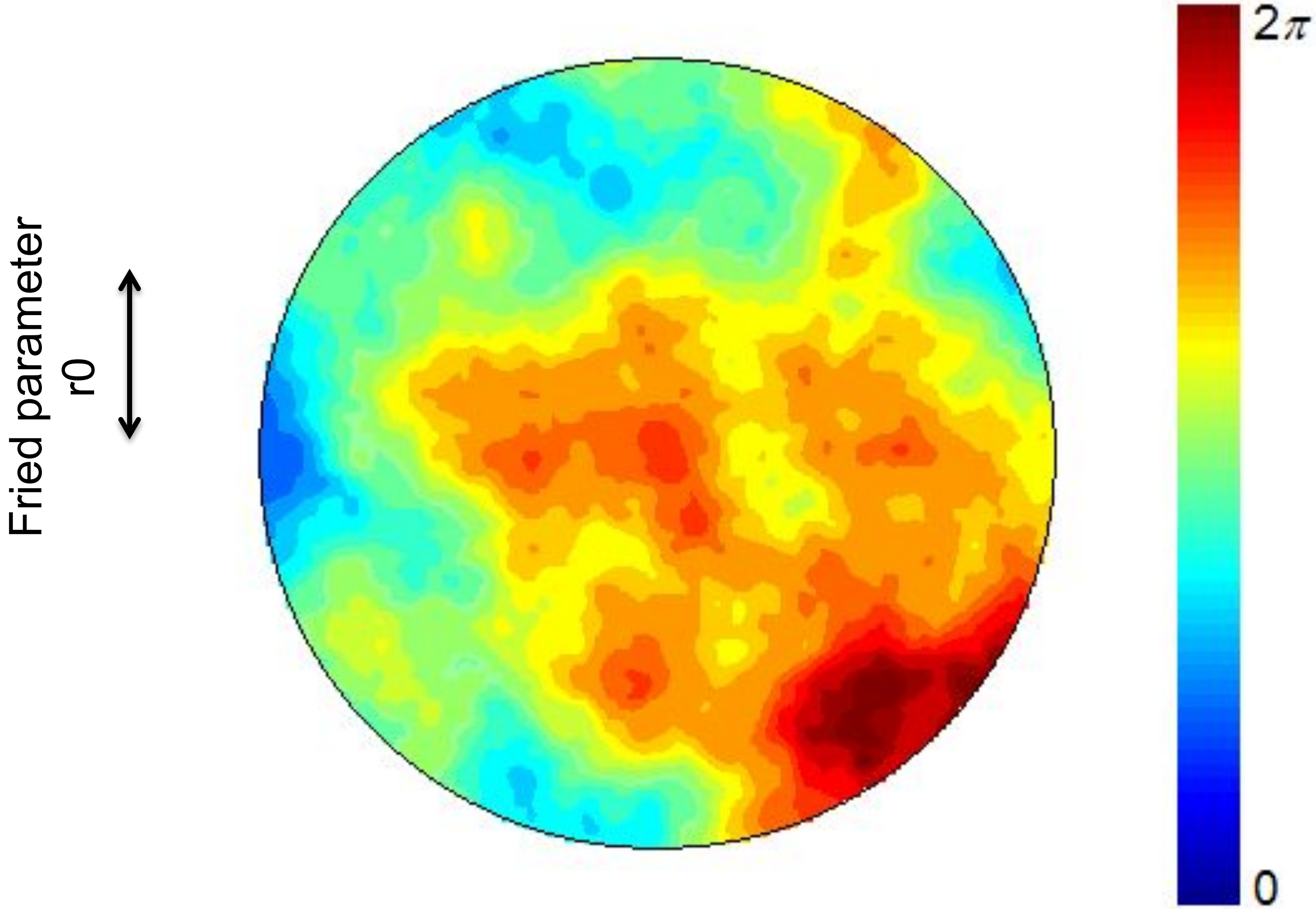
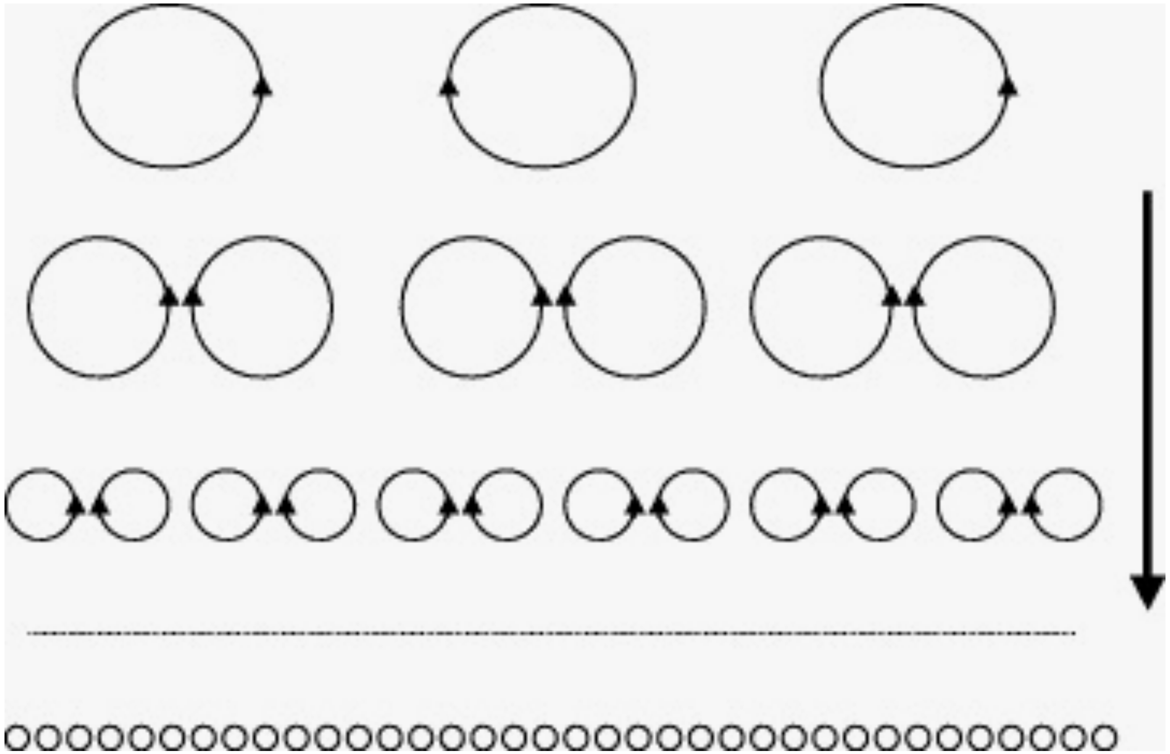
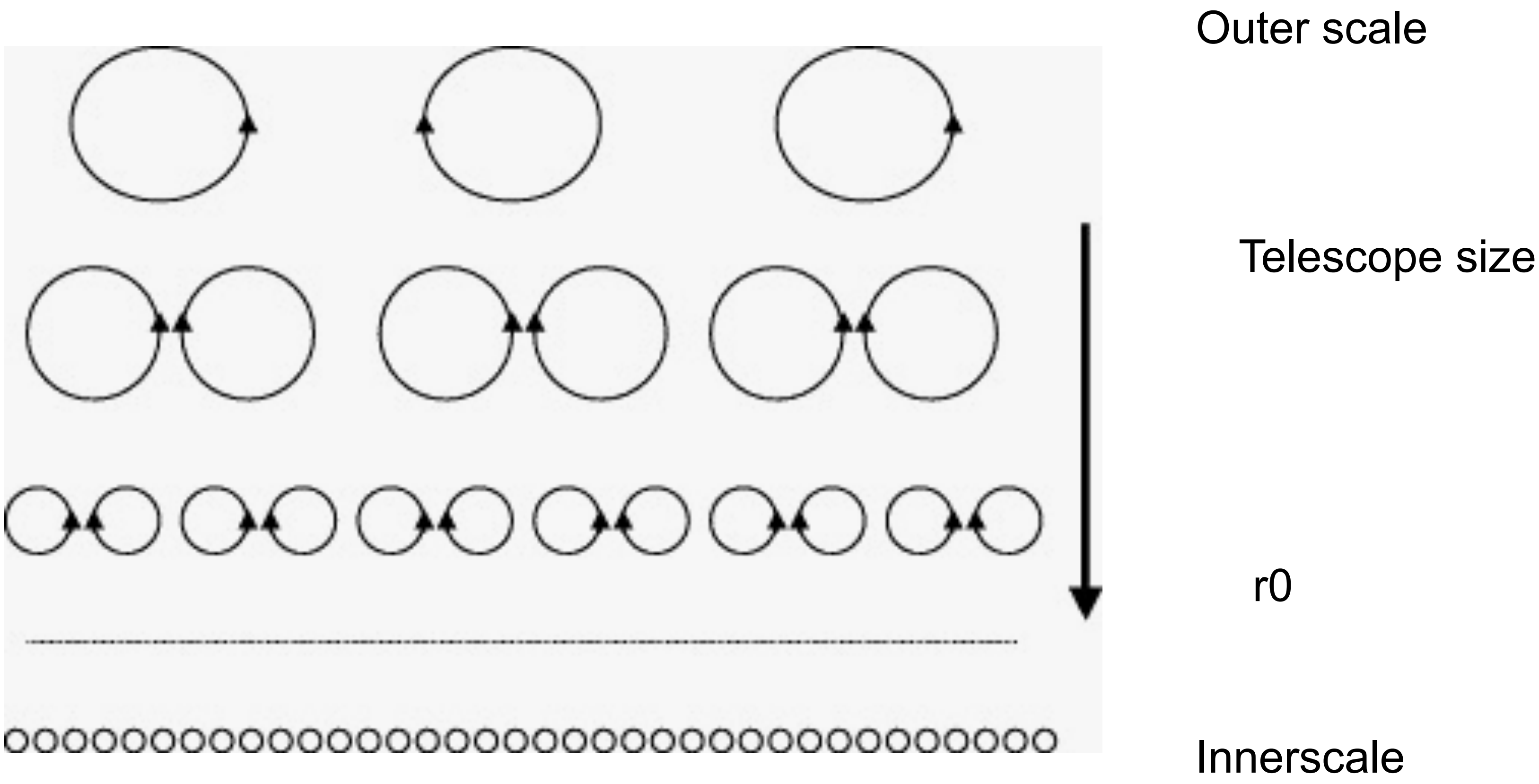
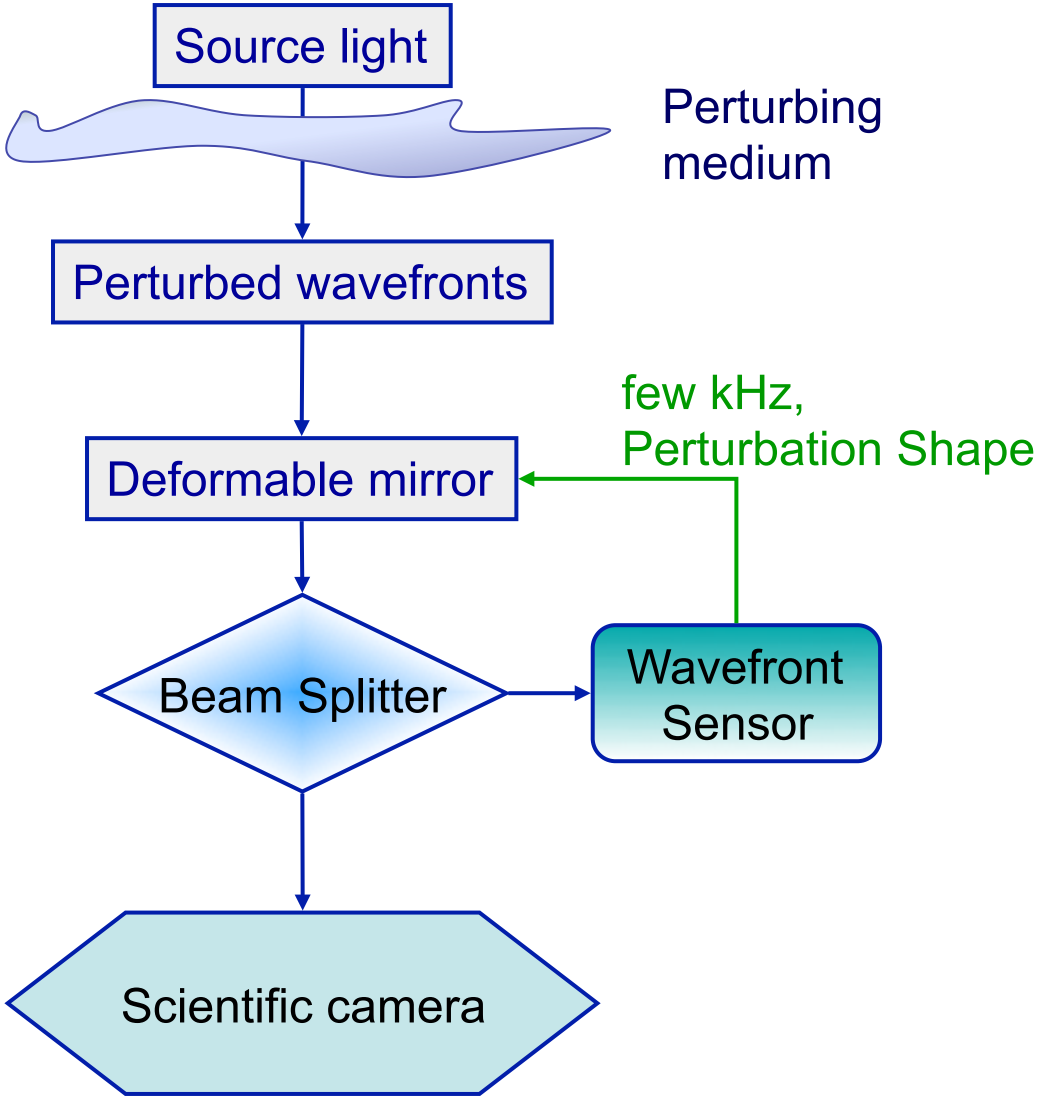



Outer scale
Innerscale


Outer scale
Telescope size
r0
Innerscale

Adaptive Optics

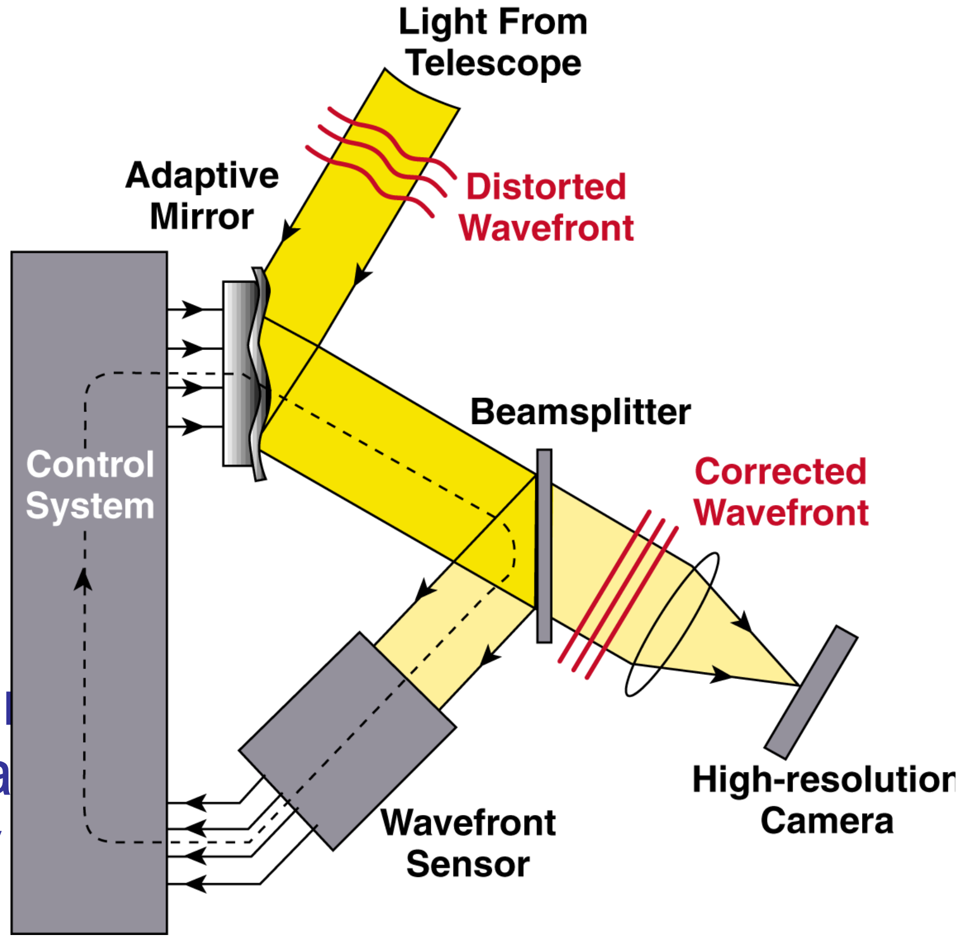


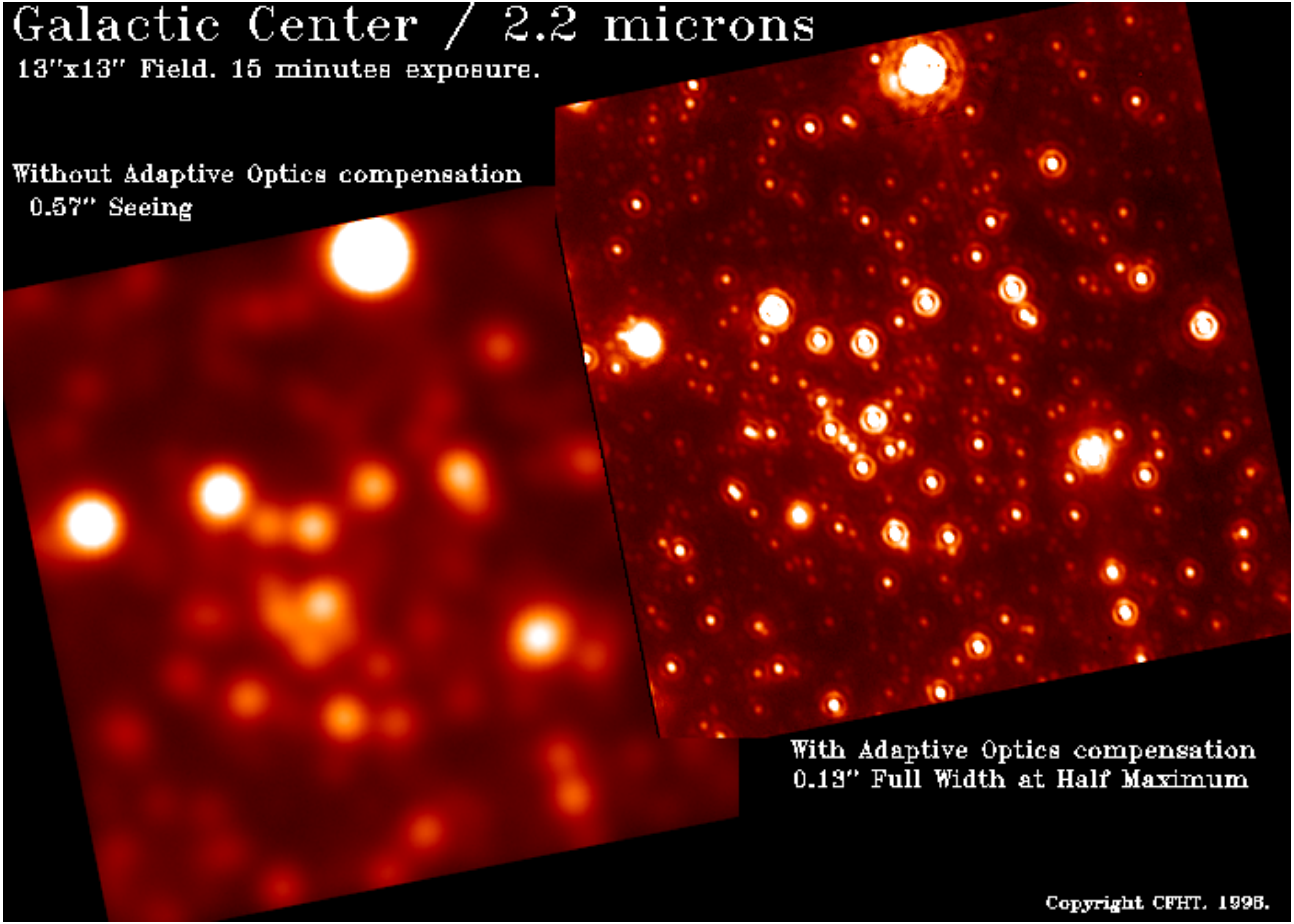
- Point-like bright sources are used as references
- Spatial and temporal sampling depending upon atmospheric parameters (wind speed, C_n^2 profile,…)

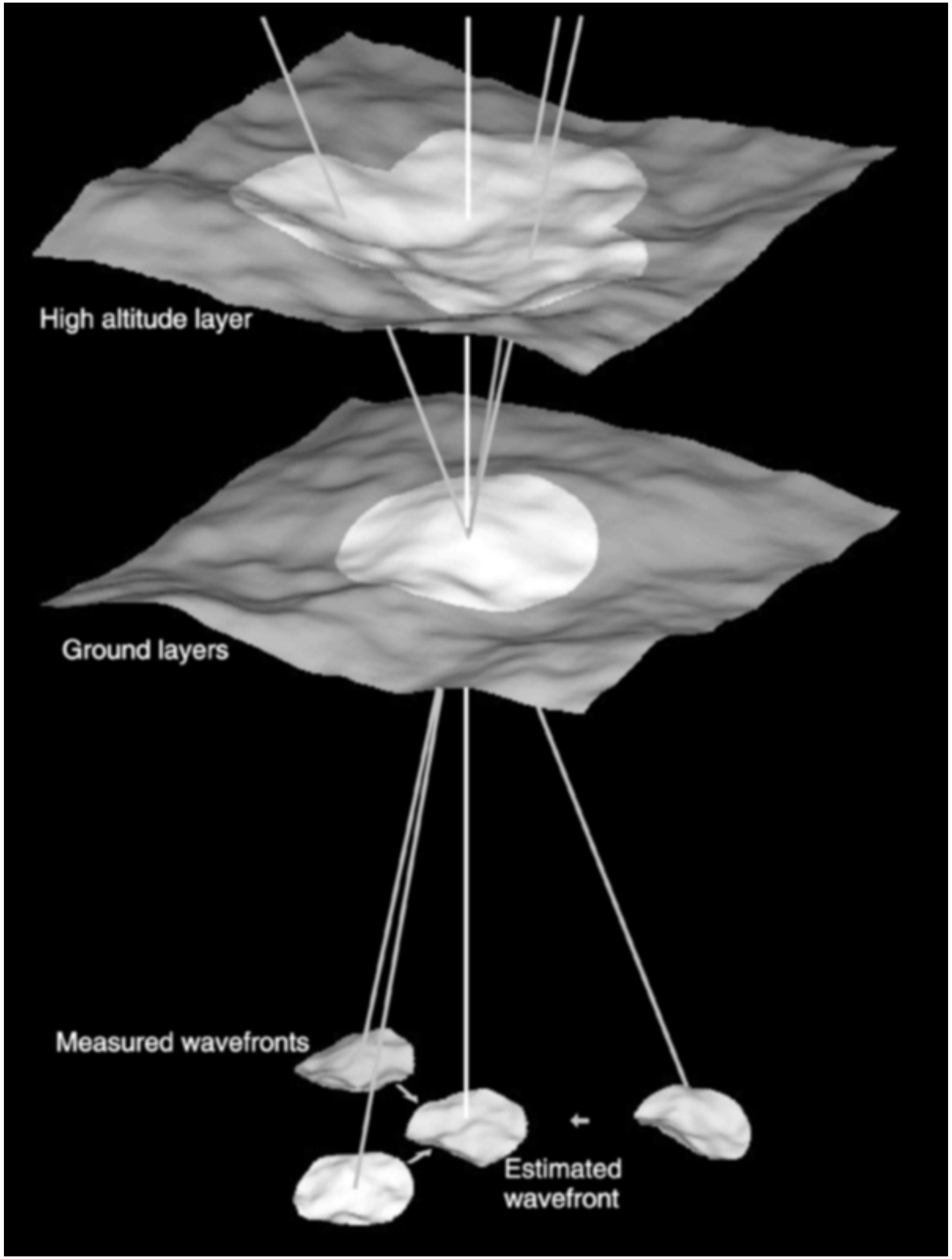
- The wavefront sensor retrieves the wavefront aberration
- The deformable mirror corrects the aberration

Adaptive Optics

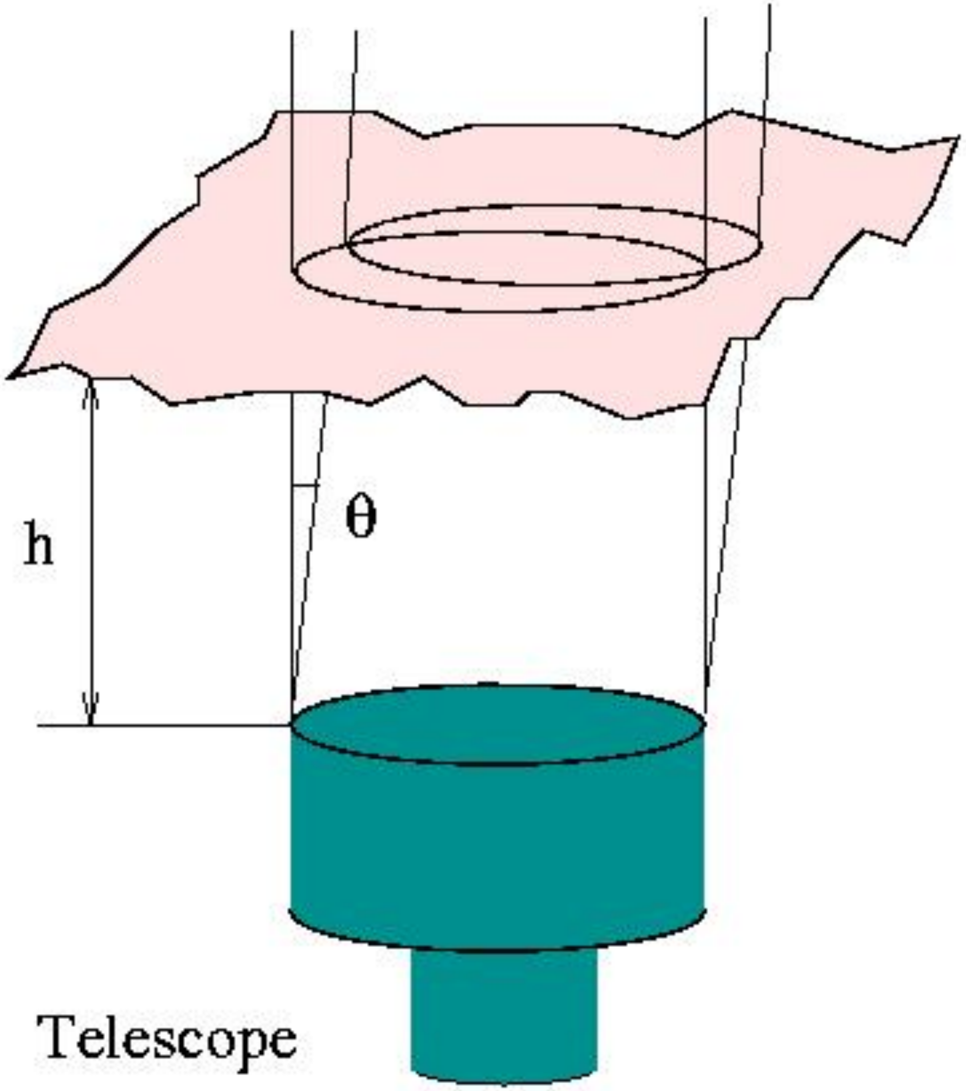
- The atmospheric distorted WF can be corrected using a Deformable Mirror (DM).
- The wavefront sensor (WFS) measures the WF of a reference star-object
- The measurement is used to drive the DM to introduce an opposite WF-deformation.
- A new WF measurement is then performed to apply a differential correction in a closed loop way



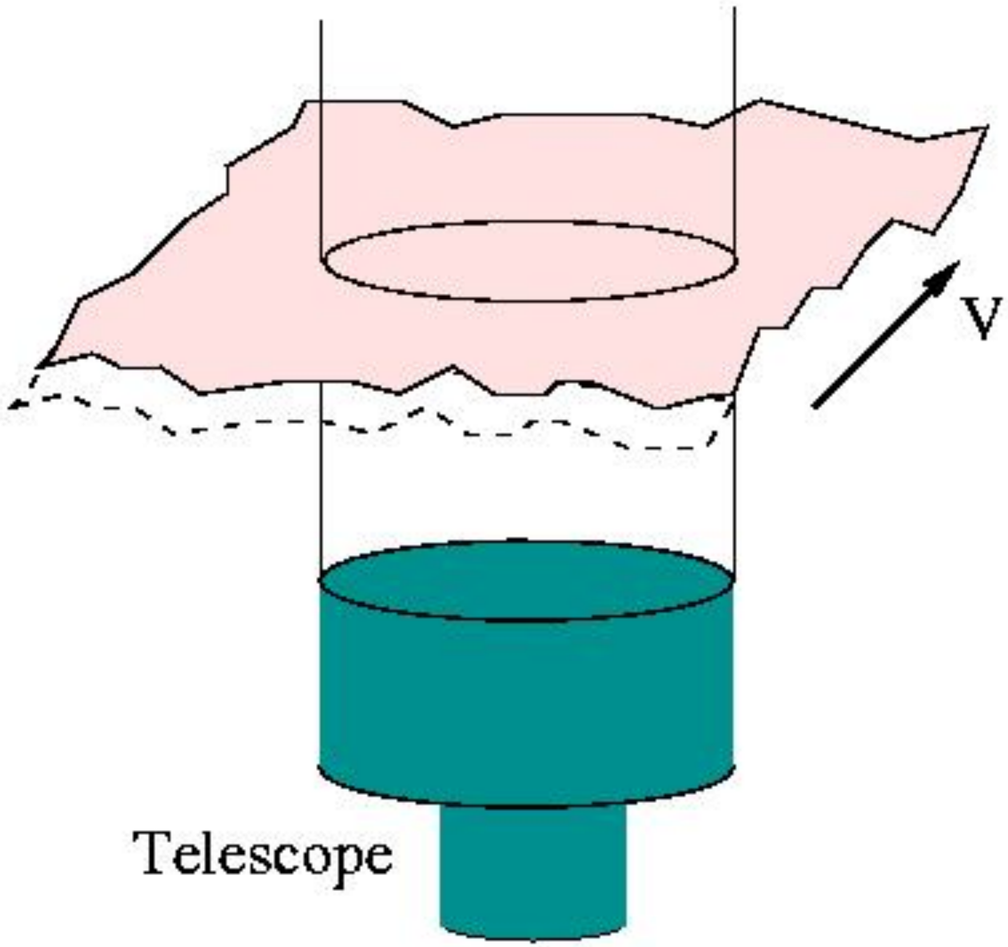

Galactic Center / 2.2 microns
13"x13" Field. 15 minutes exposure.
Without Adaptive Optics compensation
0.57" Seeing
With Adaptive Optics compensation
0.13" Full Width at Half Maximum
Copyright CFHT. 1996.


High altitude layer
Ground layers
Measured wavefronts
Estimated wavefront

Isoplanatic Angle

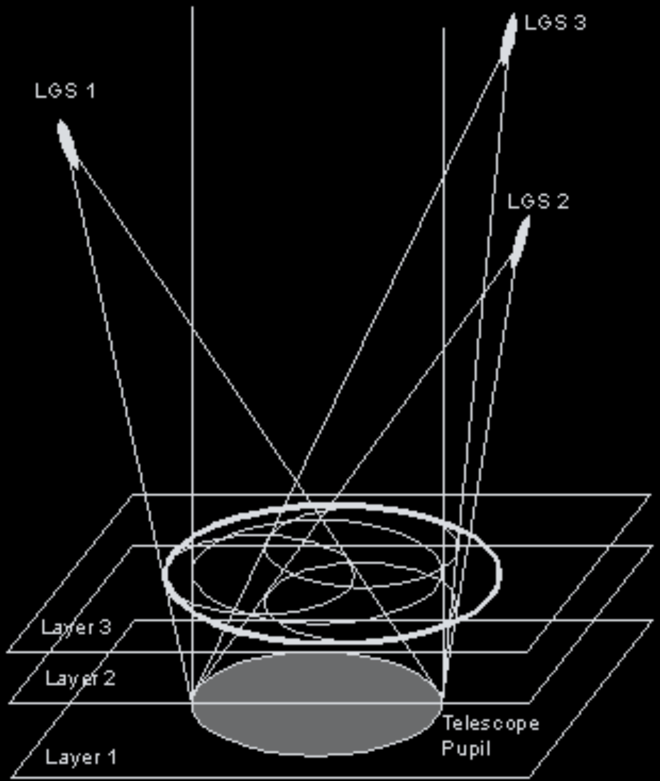


Greenwood frequency



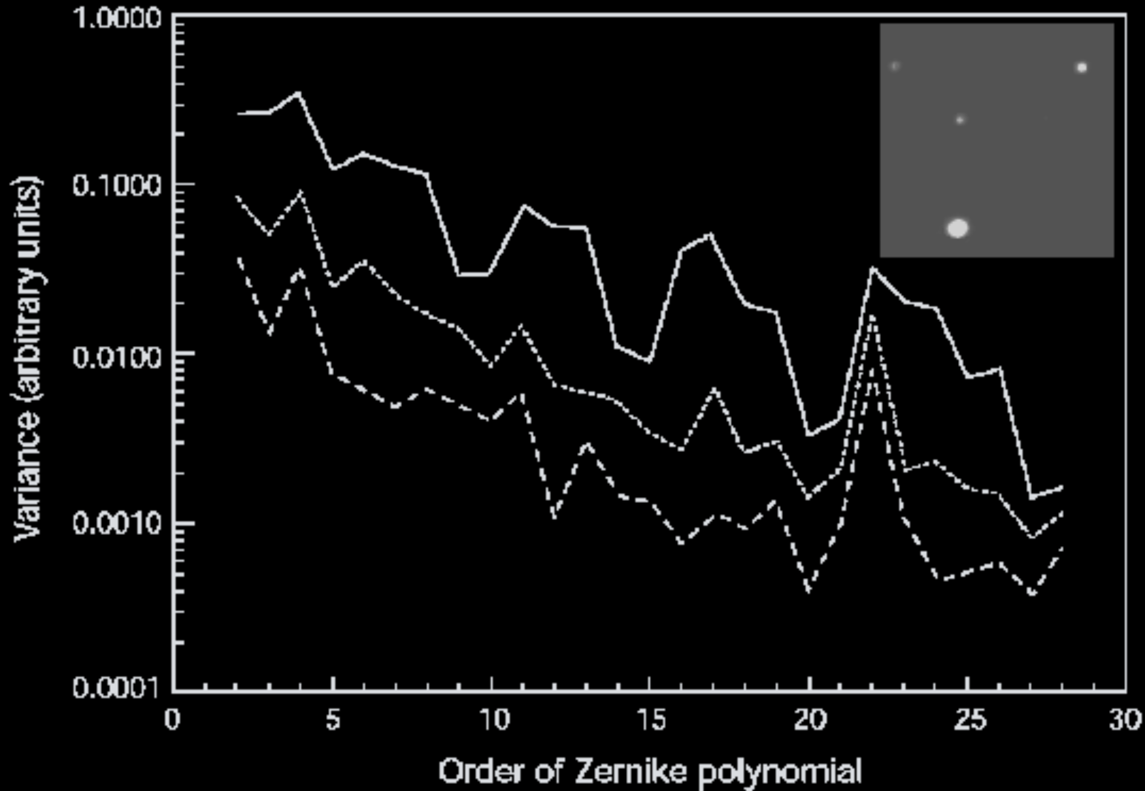
Modal tomography: from mathematics to open loop experiment

Modal formulation allow to easier determination of WF from off-axis measurements

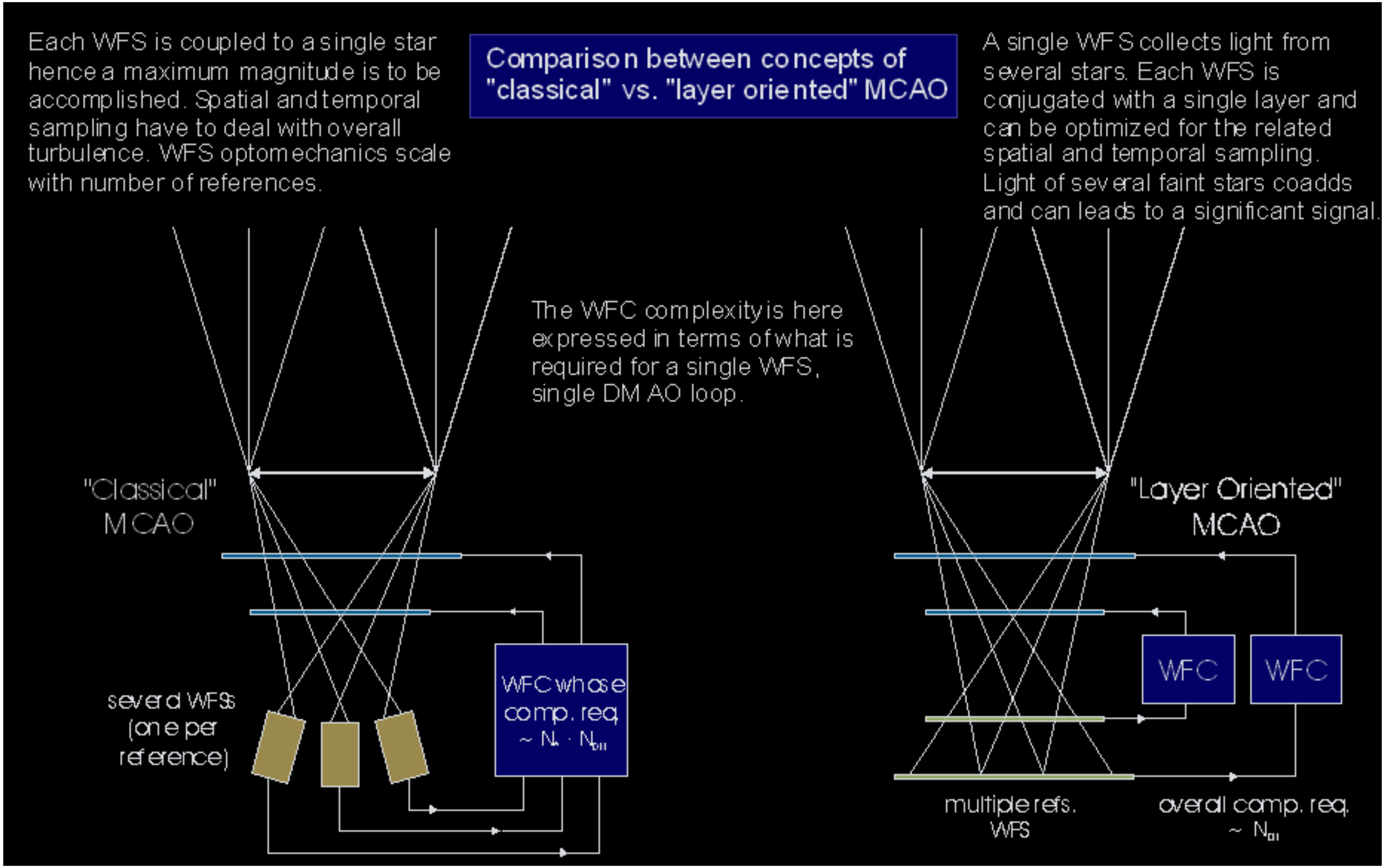


A&A 342, L53 (1999)

Open-loop experiment with the 3.5m TNG on a Y-shaped four stars asterism succesful.
Solid line: Central star variance
Dotted line: average of neighborouds stars
Dashed line: Modal tomographyc result

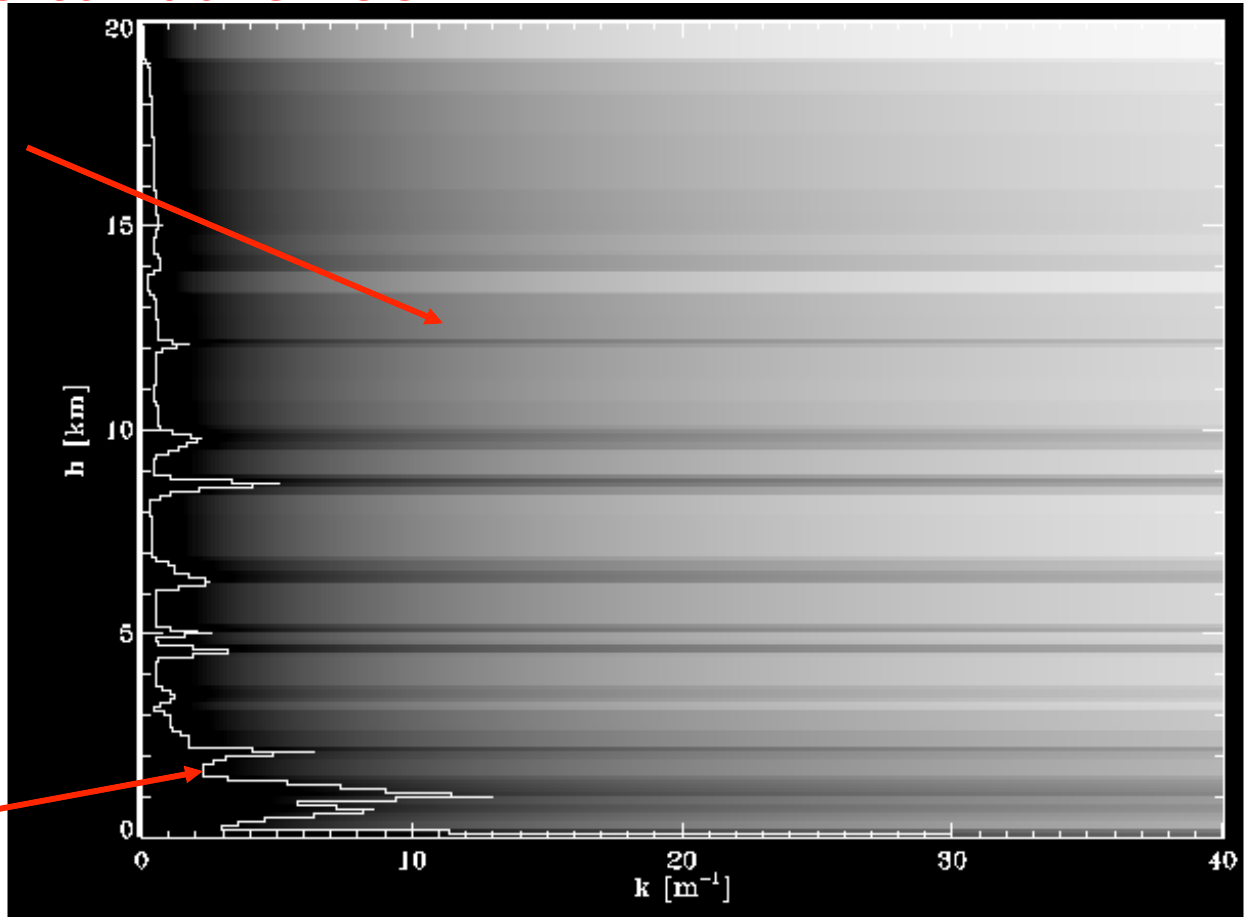


Nature 403, 54 (2000)

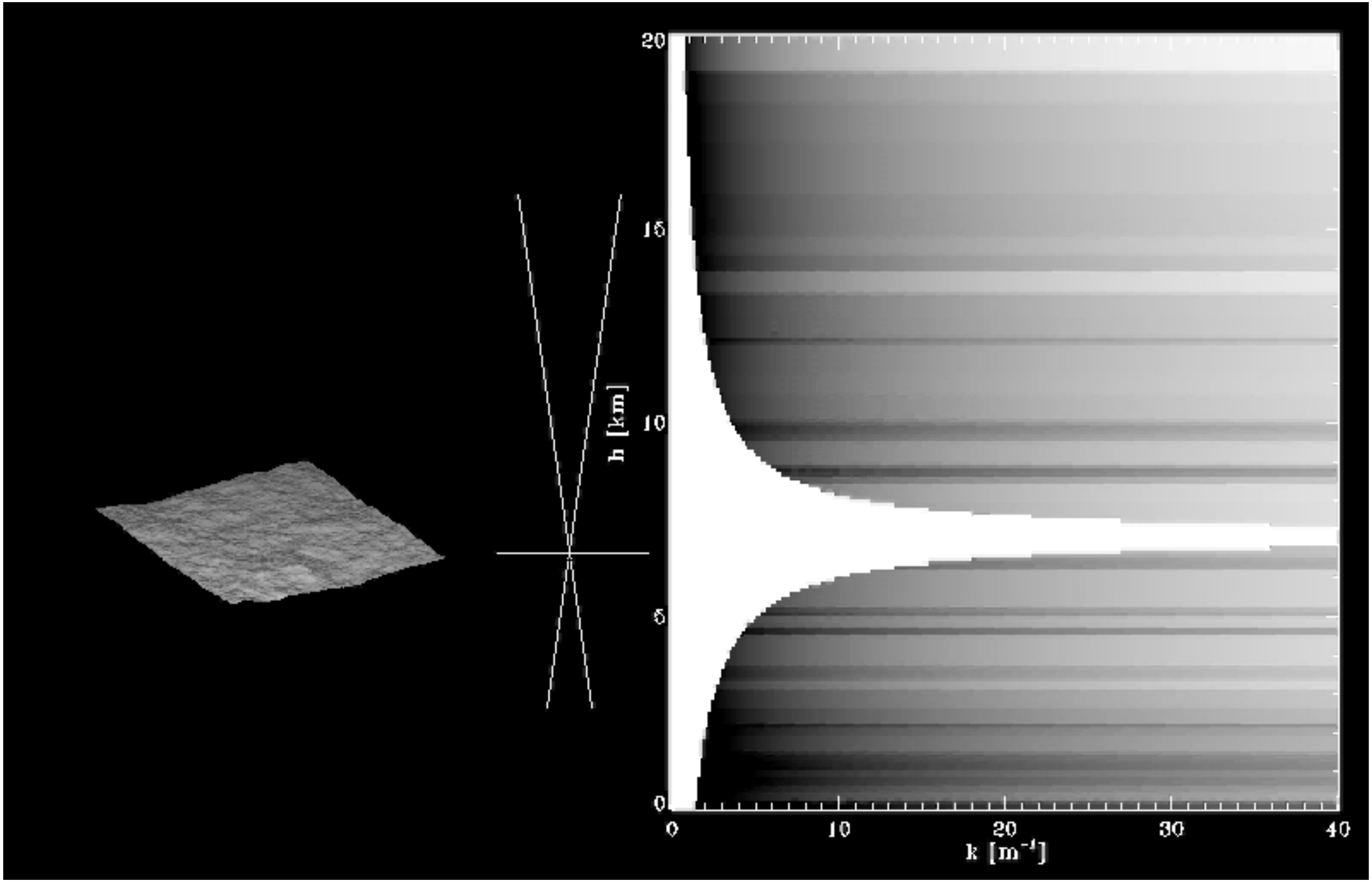

Comparison between concepts of "classical" vs. "layer oriented" MCAO
Each WFS is coupled to a single star hence a maximum magnitude is to be accomplished. Spatial and temporal sampling have to deal with overall turbulence. WFS optomechanics scale with number of references.
A single WFS collects light from several stars. Each WFS is conjugated with a single layer and can be optimized for the related spatial and temporal sampling. Light of several faint stars coadds and can leads to a significant signal.
The WFC complexity is here expressed in terms of what is required for a single WFS, single DM AO loop.
"Classical" MCAO
several WFSs (one per reference)
WFC whose comp. req. $\sim N_* \cdot N_{DM}$
"Layer Oriented" MCAO
WFC
WFC
multiple refs. WFS
overall comp. req. $\sim N_{DM}$

A bi-dimensional rappresentation Of the atmospheric turbulence

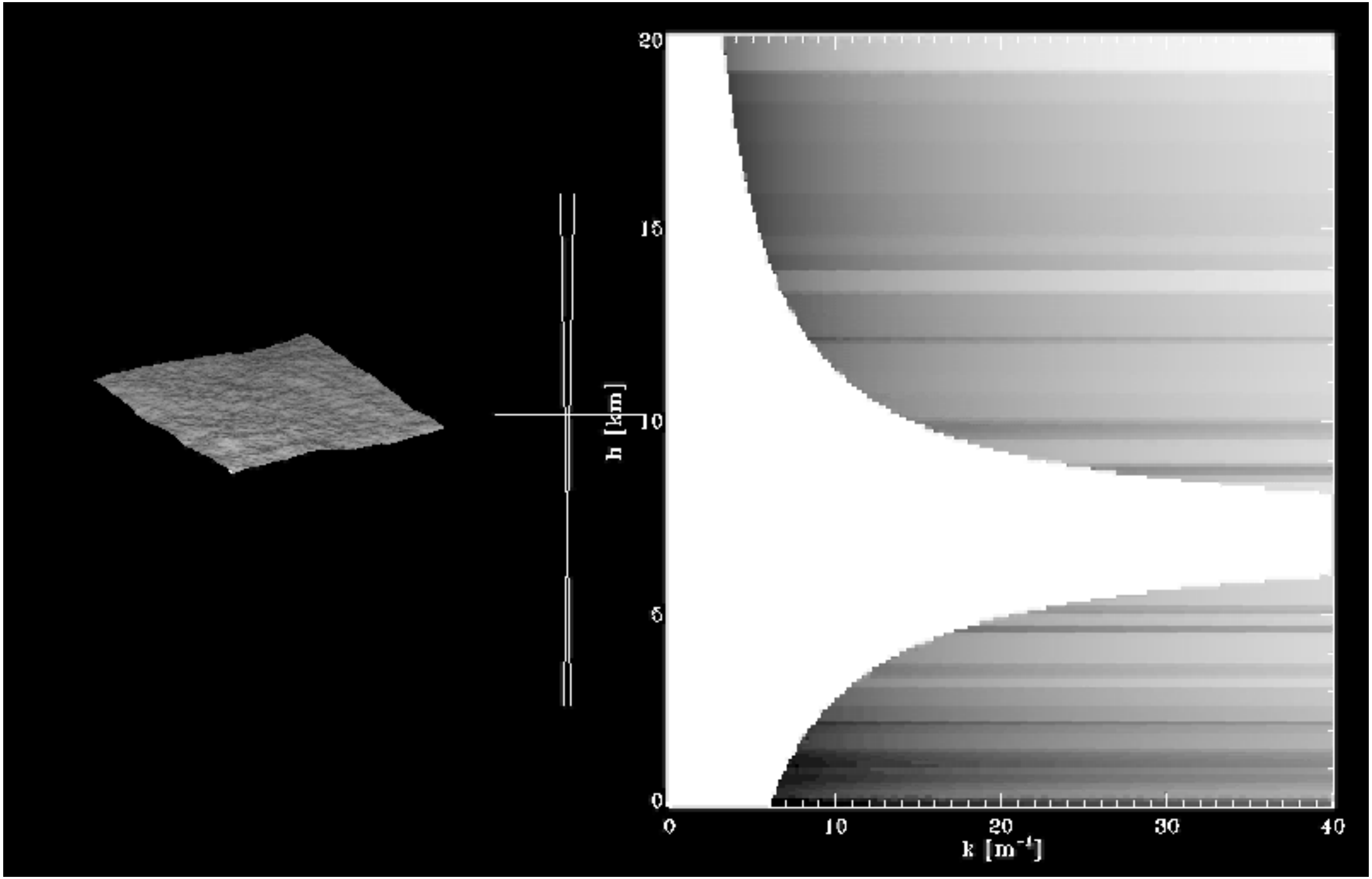
Power spectrum is kolmogorov profiled



Profile as from
Hubin et al.
SPIE 4007, 1100
(mean Paranal)

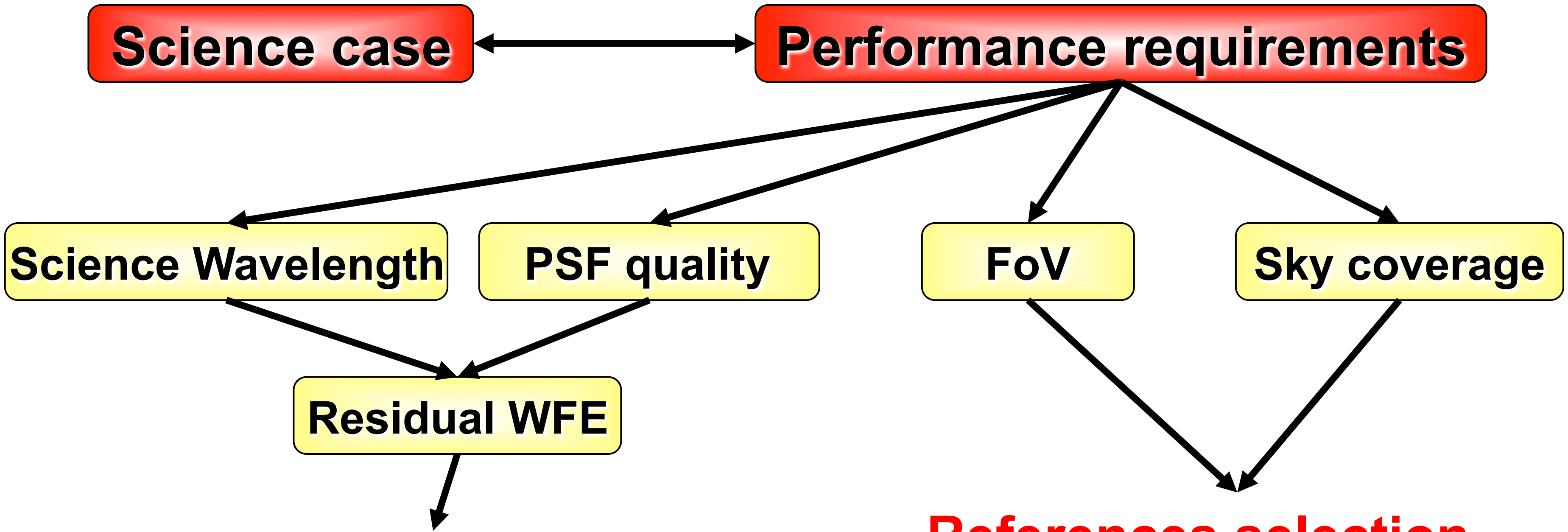


20
15
10
5
0
h [km]
0
10
20
30
40
k [m⁻¹]



20
15
10
5
0
h [km]
0
10
20
30
40
k [m⁻¹]

AO technique selection



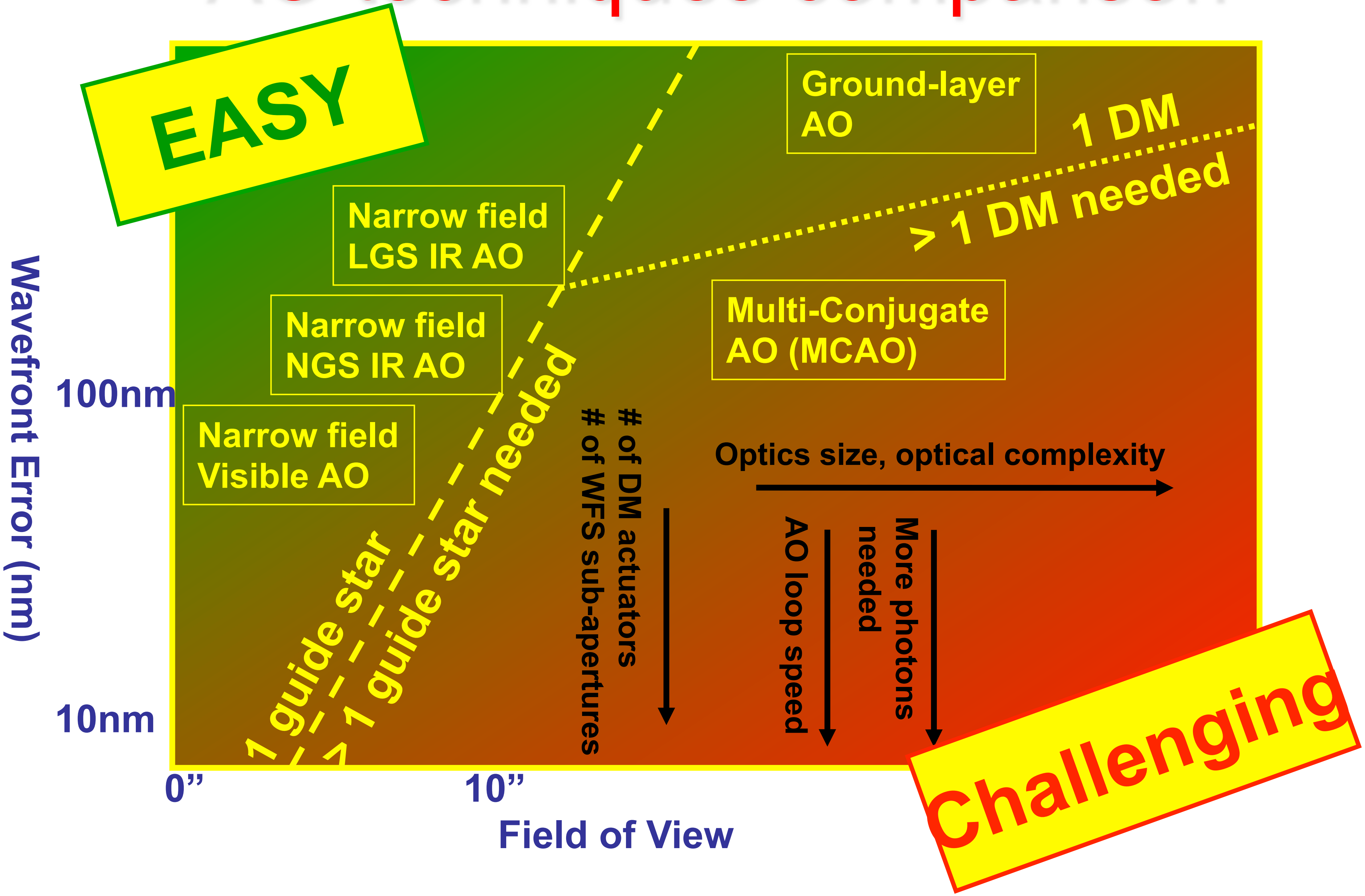
WFS selection

- Shack-Hartmann
- Curvature
- Pyramid
- Other…

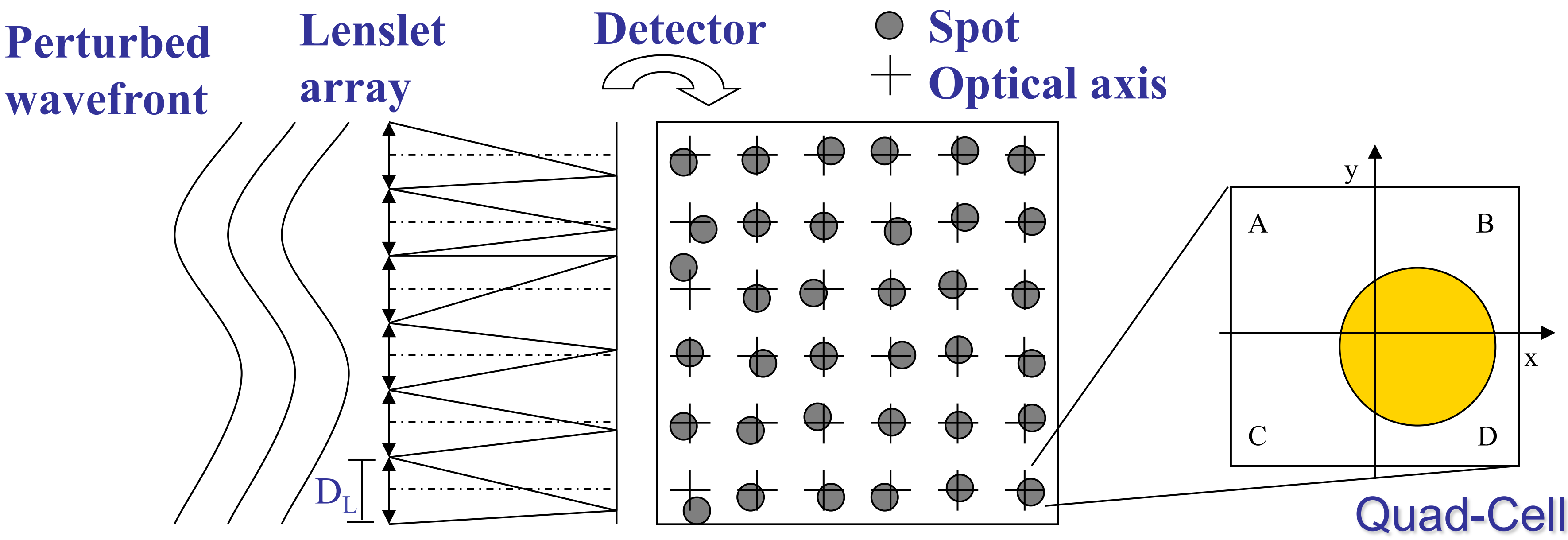
References selection

- NGS
- LGS
- How many GS?
- WFS wavelength

AO techniques comparison



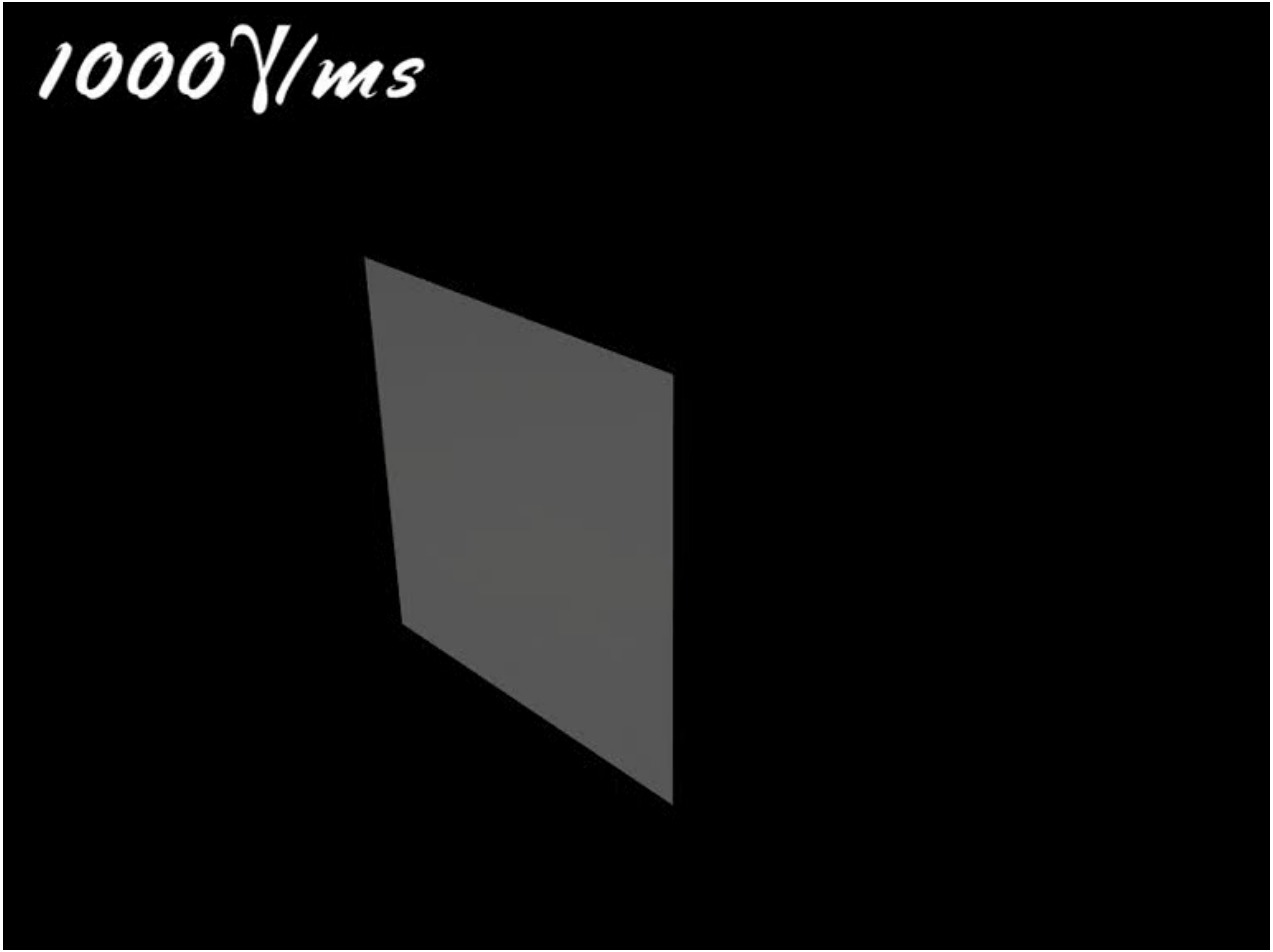
Shack-Hartmann WFS



Basically, S-H reconstructs the Tip-Tilt of smaller parts of the wavefront!

- N increasing better sampling
- N increasing less photons for each sub-aperture
- NxN > # actuators No sense! Oversampling..
- N depends on r_0 site, λ...

Very important: minimum spot dimension in closed loop is equal to λ/


1000γ/ms

Shack-Hartmann features

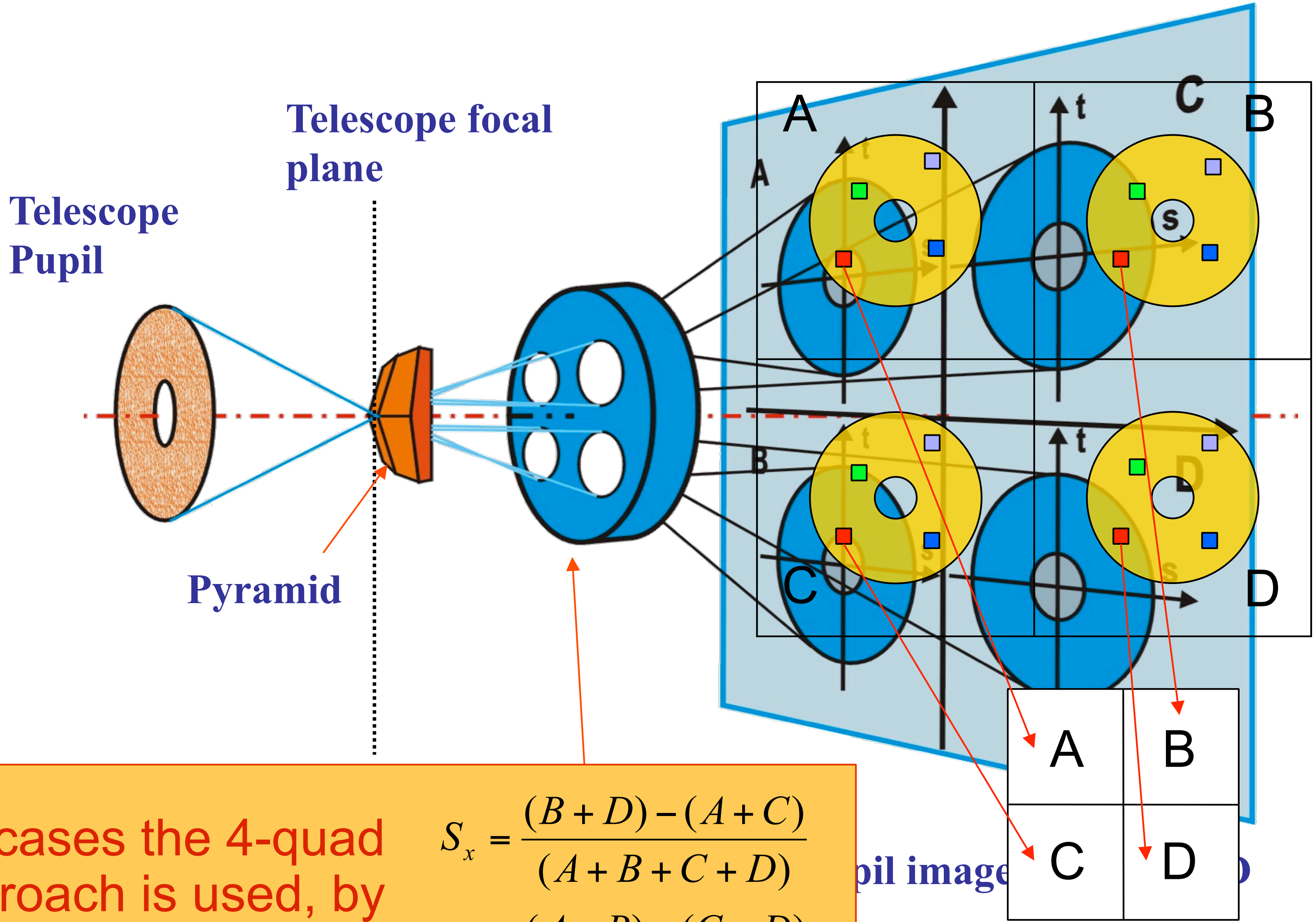
PROs:

- High Order correction possible
- Possibility to change the spatial sampling changing lenslet array or by using zoom optical relays

- Fixed sensitivity due to the fixed spot sizes
- Difficult implementation due to alignment between lenslet array and CCD

CONs:

Pyramid WFS: high orders

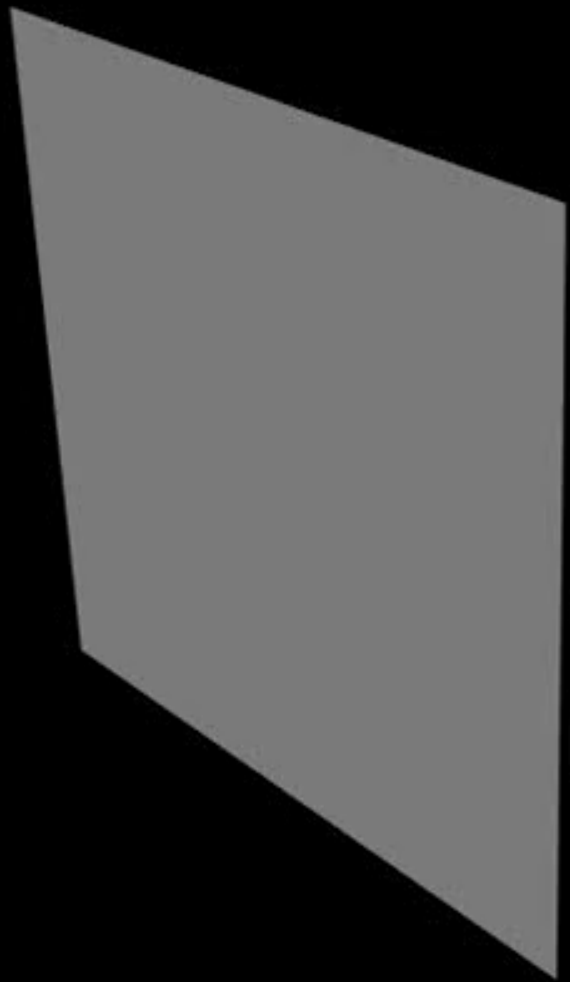


In both cases the 4-quad approach is used, by calculating the SIGNAL:

$$S_x = \frac{(B+D)-(A+C)}{(A+B+C+D)}$$

$$S_y = \frac{(A+B)-(C+D)}{(A+B+C+D)}$$

$1000\gamma/ms$



Pyramid WFS features

PROs:

- Variable Gain
- Higher Sensitivity (uses whole telescope aperture)
- "Higher" Dinamic Range
- Easily rebinnable (no extra RON)
- Easy alignment with the CCD

$(D/r_0)^2$ in closed loop

From λ/D to Pyramid size

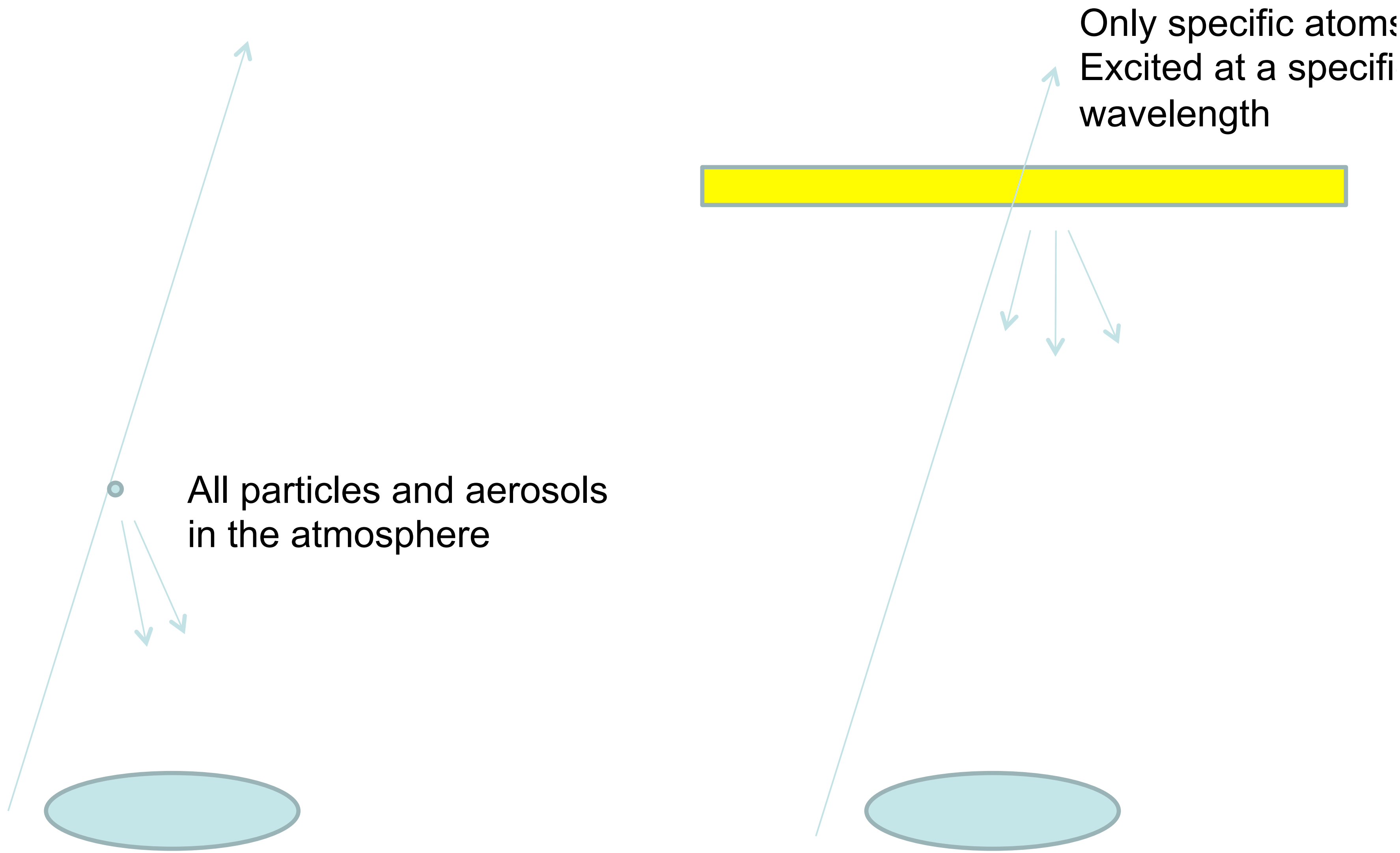
- Modulation??? (Dynamic range)

CONs:

What are Laser Guide Stars?

- They are artificially generated sources of light..
- Light is pumped into the atmosphere from the ground…
- …in some way they produces some lights that fly back to the ground…
- …and this is perceived as a sort of artificial star that can be used as reference for Adaptive Optics.

Rayleigh vs. resonant scattering



Atmospheric-turbulence compensation by resonant optical backscattering from the sodium layer in the upper atmosphere

Table 1. Known Airglow Emissions for the Earth[a]

λ (Å)	Emitter State	Day Intensity	Height (km)	Process	Twilight Intensity	Height (km)	Night Intensity	Height (km)	Process	$g(s^{-1})$	d (source)	h_q (km)	Remarks
304	He^+	Present		R			(4.8)			1.1×10^{-4}			Nightglow radiation could be either or both
584	He	Present		R			(12)			1.7×10^{-5}			
834	O^+	Present		R									
1025	HLy-β	Present	200 to 10^4	R			10 R	200	R	2.6×10^{-6}			
1200	$N(^4P)$	400 R	180	R?									
1216	HLy-α	6 kR	100 to 10^5	R			2 kR	100 to 10^5	R	2.1×10^{-3}	$(4.5 \times 10^{-8}\,[H_2])$		
1302, 1304, 1306	$O(^3S)$	7.5 kR	190	eFR						1.0×10^{-4}			
1356	$O(^5S)$	350 R	140	e									
1300–1500	$N_2(a\,^1\Pi_g)$	Present		e									Lyman–Birge–Hopfield
1493, 1744	N	Present		e									
2000–4000	$N_2(A\,^3\Sigma_u^+)$	Present		e									Vegard–Kaplan
2160, etc.	$NO(A\,^2\Sigma^+)$	1 kR	70–150	R						4.0×10^{-6}			γ bands; g for 1–0 band
3371, etc.	$N_2(C\,^3\Pi_u)$	900 R	≥130	e									2nd Positive
2600–3800	$O_2(A\,^3\Sigma_u^+)$						600 R	90	C				Herzberg
3466	$N(^2P)$	Present		e									
3889	$He(^3P)$			R	1 R	>400?				0.1			Scatterer is $He(^3S)$
3914, etc.	$N_2^+(B\,^2\Sigma_u^+)$	2.0 kR	150	RF	200–500 R	300	<1 R			0.050	$10^{-8}\,[N_2]$	46	1st Negative
3933.68	$Ca^+(^2P)$				<100 R	80–200				0.3, 0.15			
4368	$O(4\,^3P)$				1 R								
5200	$N(^2D)$	90 R	~200	I	10 R		1 R	~250	I	(6×10^{-11})		~200	Also quenched by electrons
5000–6500	NO_2?						1 R/Å	~90	C				Continuum
5577	$O(^1S)$	3.0 kR	90, 175	Ce	400 R	200?	250 R	90, 300	C, I	(1×10^{-11})	$3 \times 10^{-8}\,[O_2]$	94	2972 Å (5%)
5893	$Na(^2P)$	30 kR	92	R	1–4 kR	92	20–150 R	~92	C	0.80		40	
6300, 64	$O(^1D)$	2–20 kR	250	FIe	1 kR	300	10–500 R	300	I	(4.5×10^{-10})	$5.8 \times 10^{-6}\,[O_2]$	340	
6563	$H(3\,^2P)$						3 R	200	F	2.6×10^{-6}			
6708	$Li(^2P)$				10–1000 R	~90				16			May be of artificial origin
7619, etc.	$O_2(^1\Sigma)$	300 kR	40–120	RFT			6 kR	~80	C	6.3×10^{-9}	$<5 \times 10^{-3}\,[O_3]$	90	Atmospheric
7699	$K(^2P)$				40 R	~90				1.67			
7774, 8446	O	1.6, 1.1 kR	~150	e									
10510, etc.	$N_2(B\,^3\Pi_g)$	900 R	150	e								37	1st Positive
10830	$He(^3P)$				3 kR	500				16.8		~400	Scatterer is $He(^3S)$; h_q for its destruction
11036, etc.	$N_2^+(A\,^2\Pi_u)$	4 kR	150	RF						0.042	2.8×10^{-8}		Meinel; g, d for 1-0 band (9200 Å)
12700, etc.	$O_2(^1\Delta)$	20 MR	50	F	5 MR	80	80 kR	90?	C?	(9.4×10^{-11})	$9.5 \times 10^{-3}\,[O_3]$	75	IR atm; 0-1 band 1.58 μm; Noxon bands 1.9 μm
2800, etc.	$OH(\nu < 9)$	4.5 MR		C			4.5 MR	90	C				Meinel; 4.5 μm to 3816 Å

[a] From Ref. 20. Production processes are R, resonance scattering; F, fluorescence; C, chemical association; I, ionic reactions; e, photoelectrons; T, excitation transitions. Production rate factors are g and d; h_q is the quenching height.

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MONTHLY NOTICES

OF THE

ROYAL ASTRONOMICAL SOCIETY

Vol. 93 No. 9. SUPPLEMENTARY NUMBER

SPECTROGRAPHIC STUDIES OF THE PLANETS.

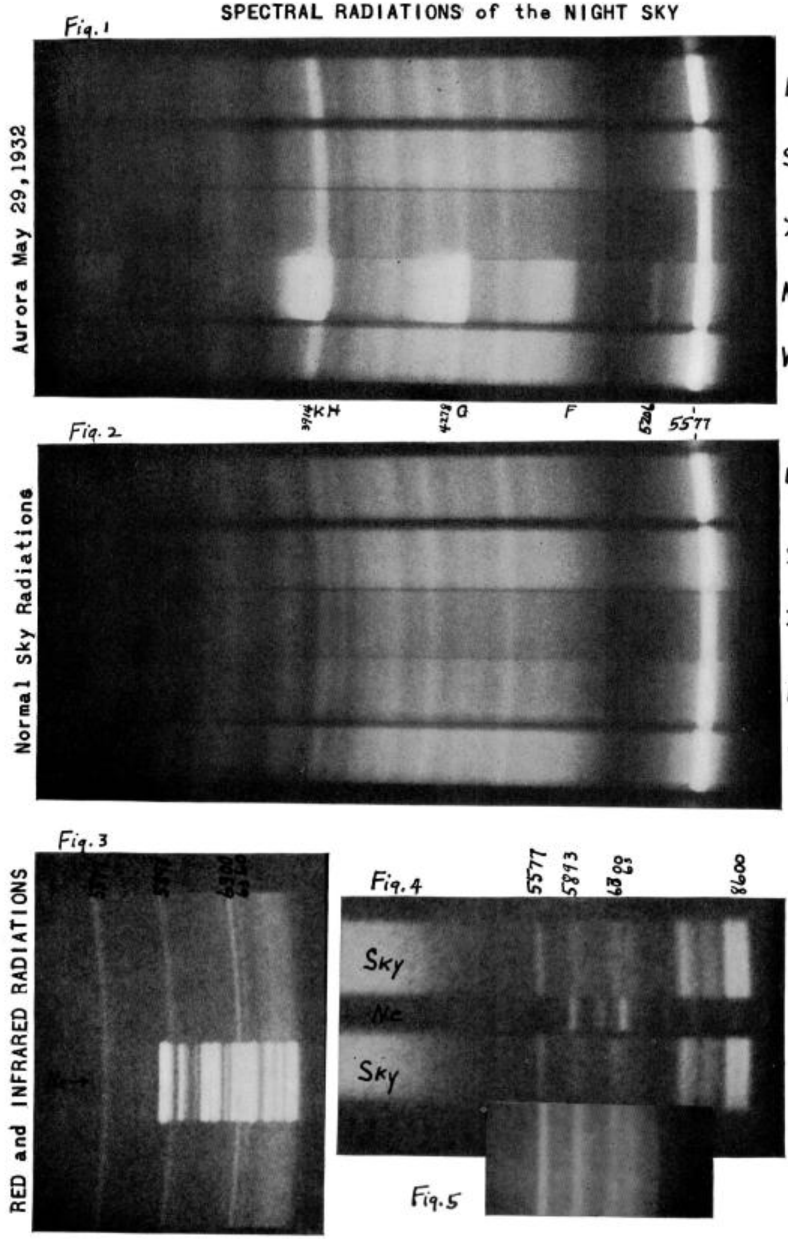
(*George Darwin Lecture, delivered by Dr. V. M. Slipher, Assoc.R.A.S., on* 1933 *May* 12.)

Spectrum analysis may fairly be said to have entered upon its fruitful application to astronomy with the work of the great English pioneer in this field, Sir Wm. Huggins. In the early sixties of the last century he was inspired to take up this new study by Kirchhoff's interpretation of the dark lines of the solar spectrum, just then published. Up to that time it had not been thought possible that man could ever know the substances actually composing the distant heavenly bodies. But he, with rare vision, embraced this marvellous new means for their study and began analysing their light to read their secrets. And after seventy years of truly wonderful revelations this work is still going on with as fruitful results to-day as at any time in the past. The distance to the heavenly bodies, be it even millions of light years, is no obstacle to the definiteness of the message that may be carried by their spectrally analysed light.

Others also soon took up this new study of the stars, and quite naturally they must have eagerly sought to apply this new means of observation to the brighter planets.

It is just one hundred years ago that Sir David Brewster recognized absorption lines in the spectrum of sunlight that were due to the Earth's atmosphere. And what the air of the Earth did might be duplicated by the atmospheres of the other planets in accordance with their constitutions and conditions, and hence by their spectra they should show something as to their atmospheres. Sir Wm. Huggins and others in this branch of astronomy studied the spectra of the planets visually. And to Huggins we are indebted for the greater contribution of the first photographs of the blue and violet of the spectra of the planets. His efforts and those of others in this direction were confined to the more refrangible end of the spectrum, because plates

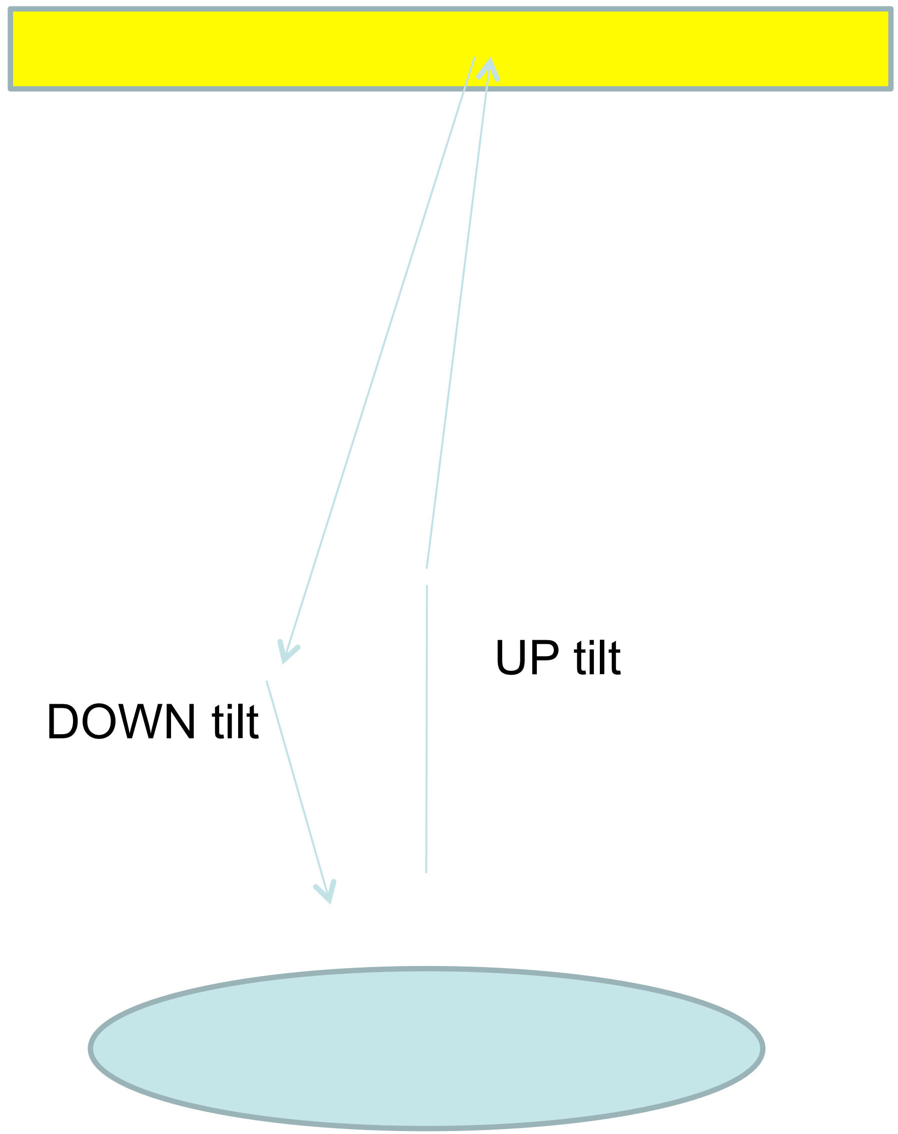
SPECTRAL RADIATIONS of the NIGHT SKY

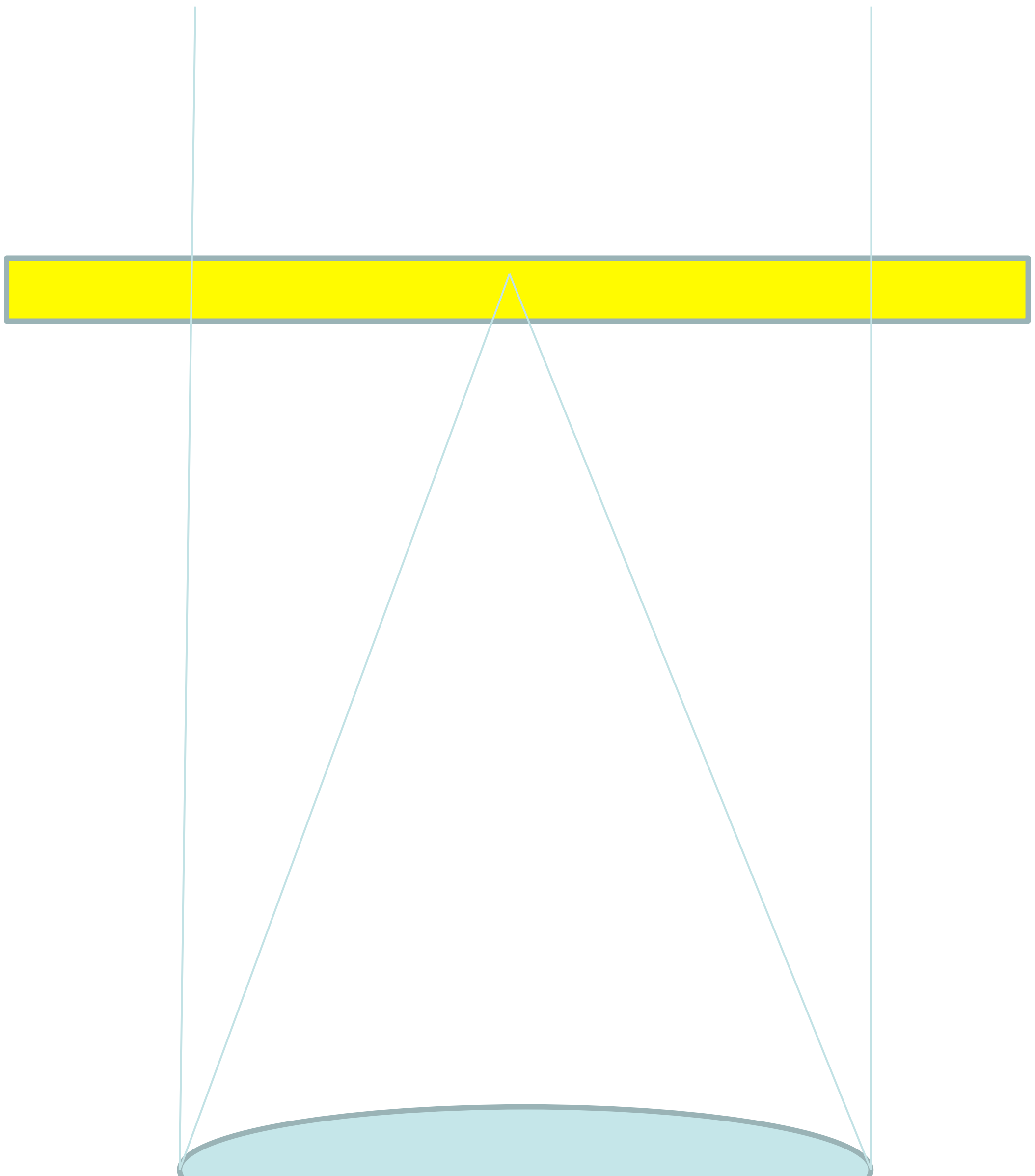


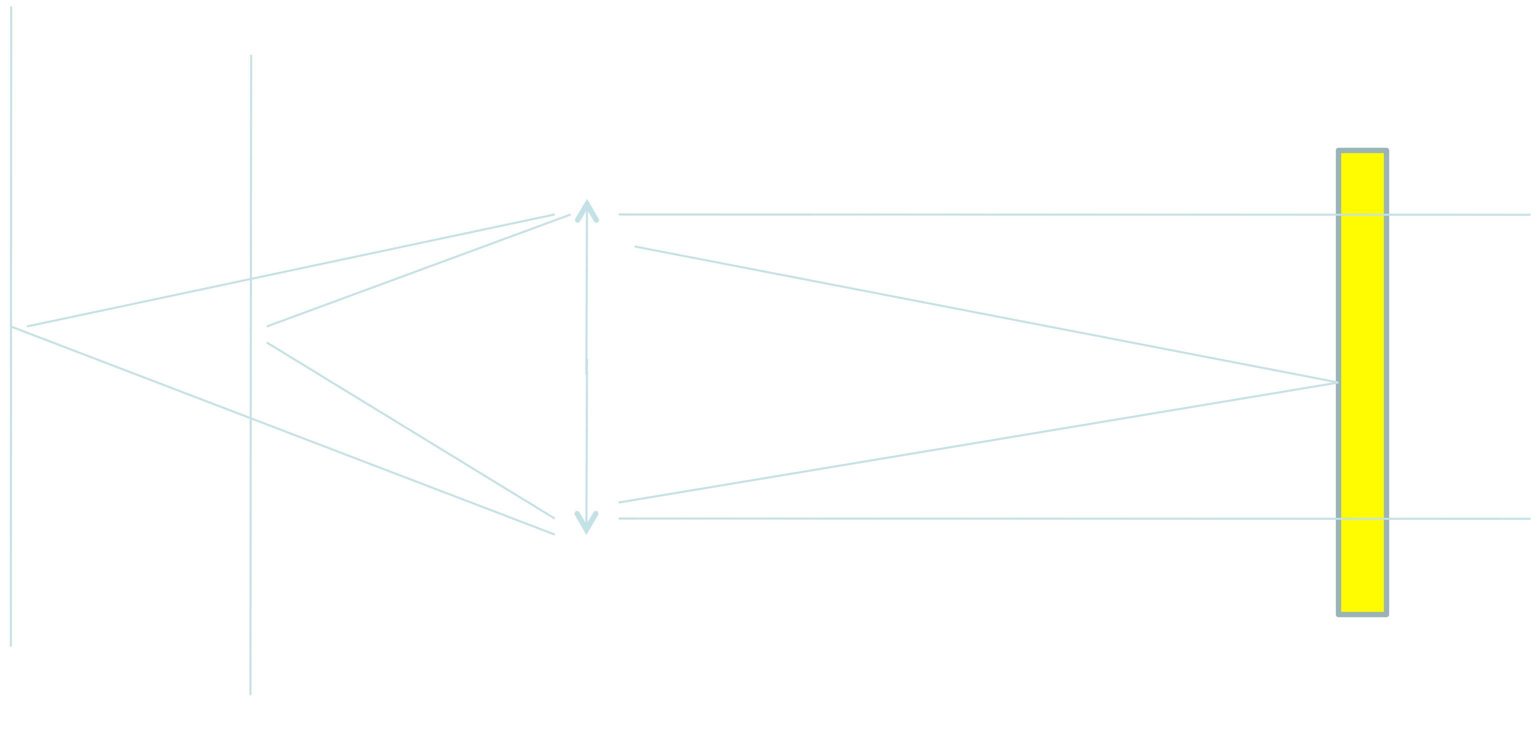
V. M. Slipher Spectrographic Studies of the Planets.

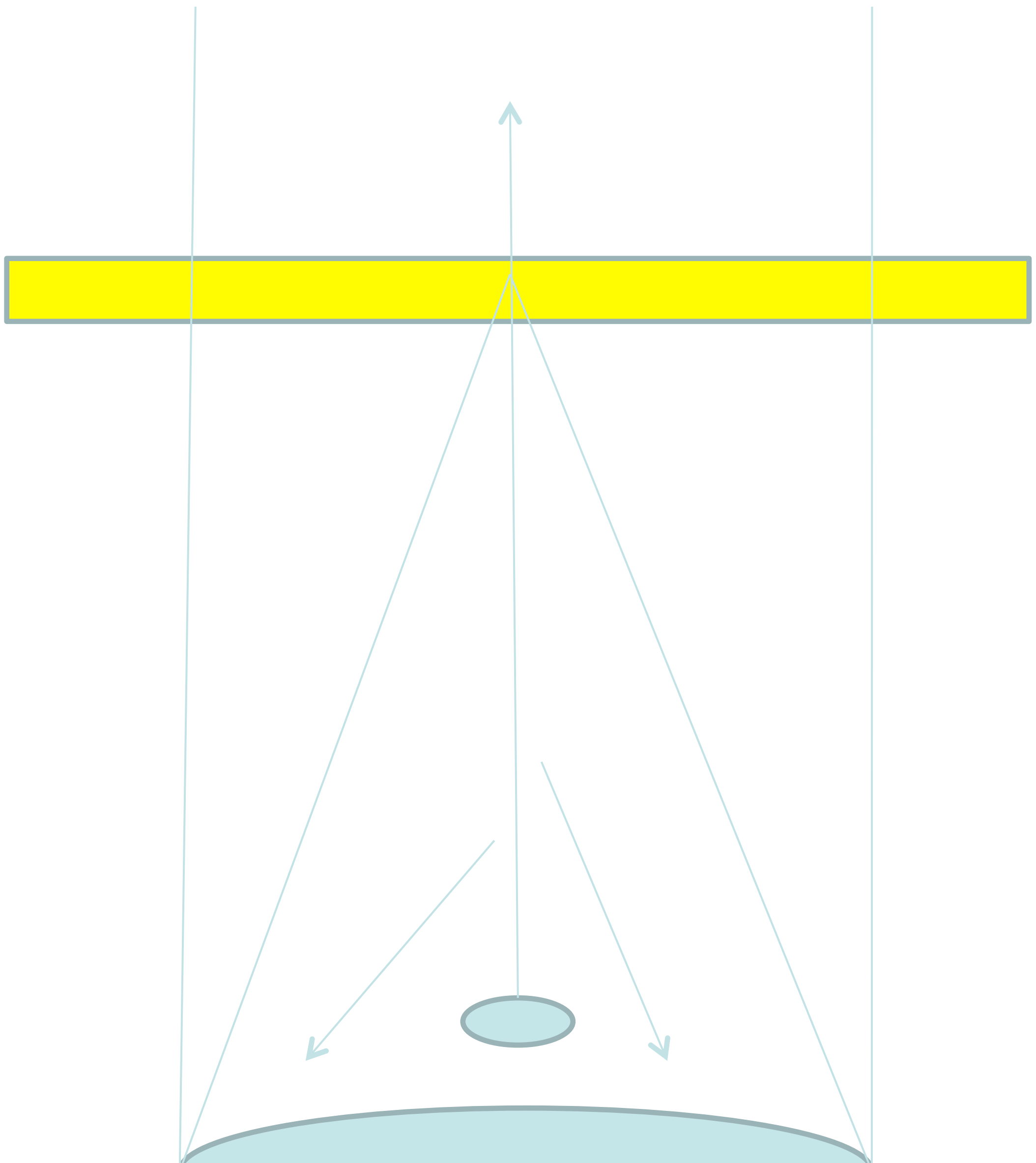
Problems of LGSs

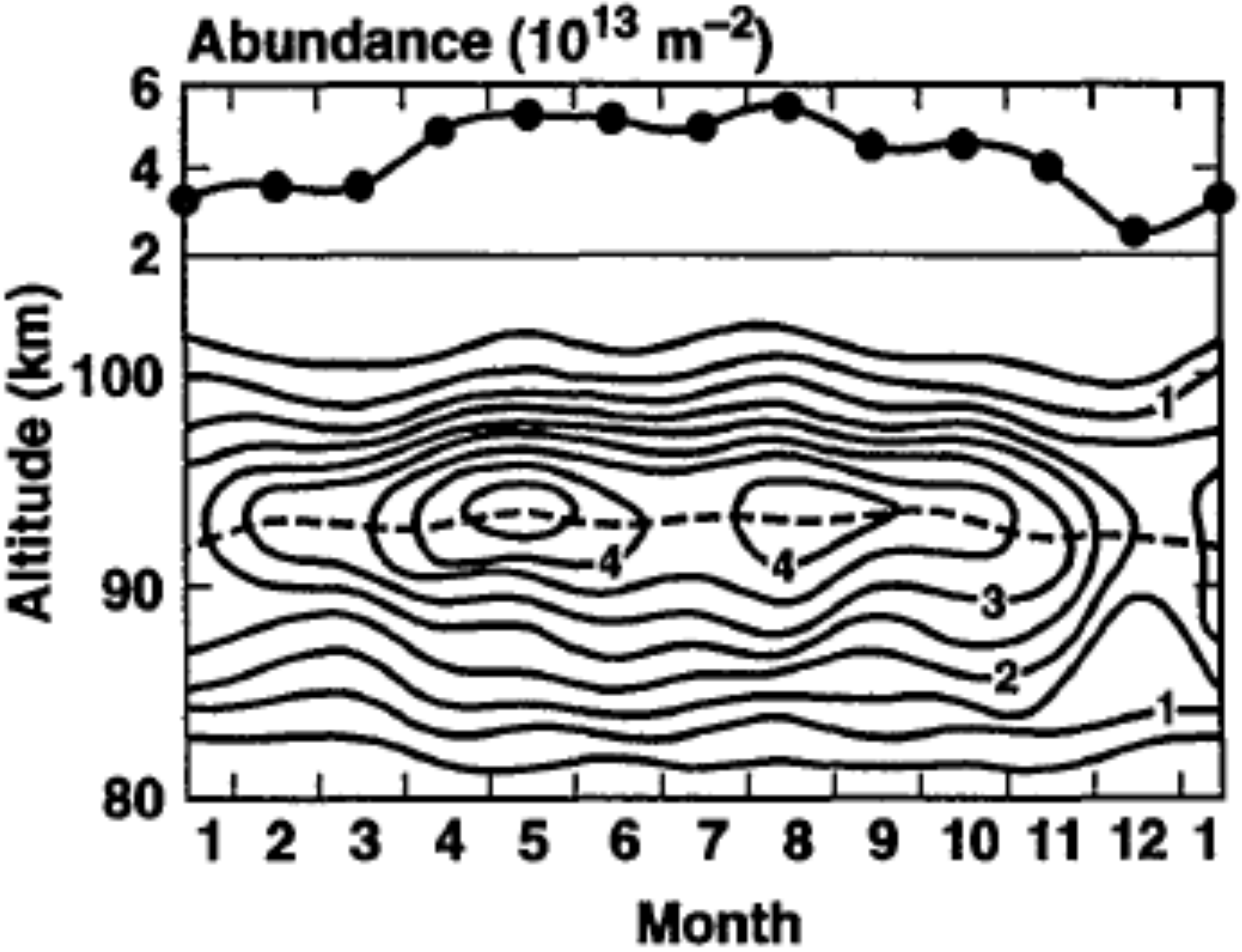
- Tip-tilt indetermination problem
- Conical anisoplanatism
- Focus at a finite distance
- Rayleigh fratricide effects
- Actual distance depends upon altitude and layer local variations
- Cyrrus can make large scattered light
- Aircraft and satellite hazards
- You need a working laser!


UP tilt
DOWN tilt

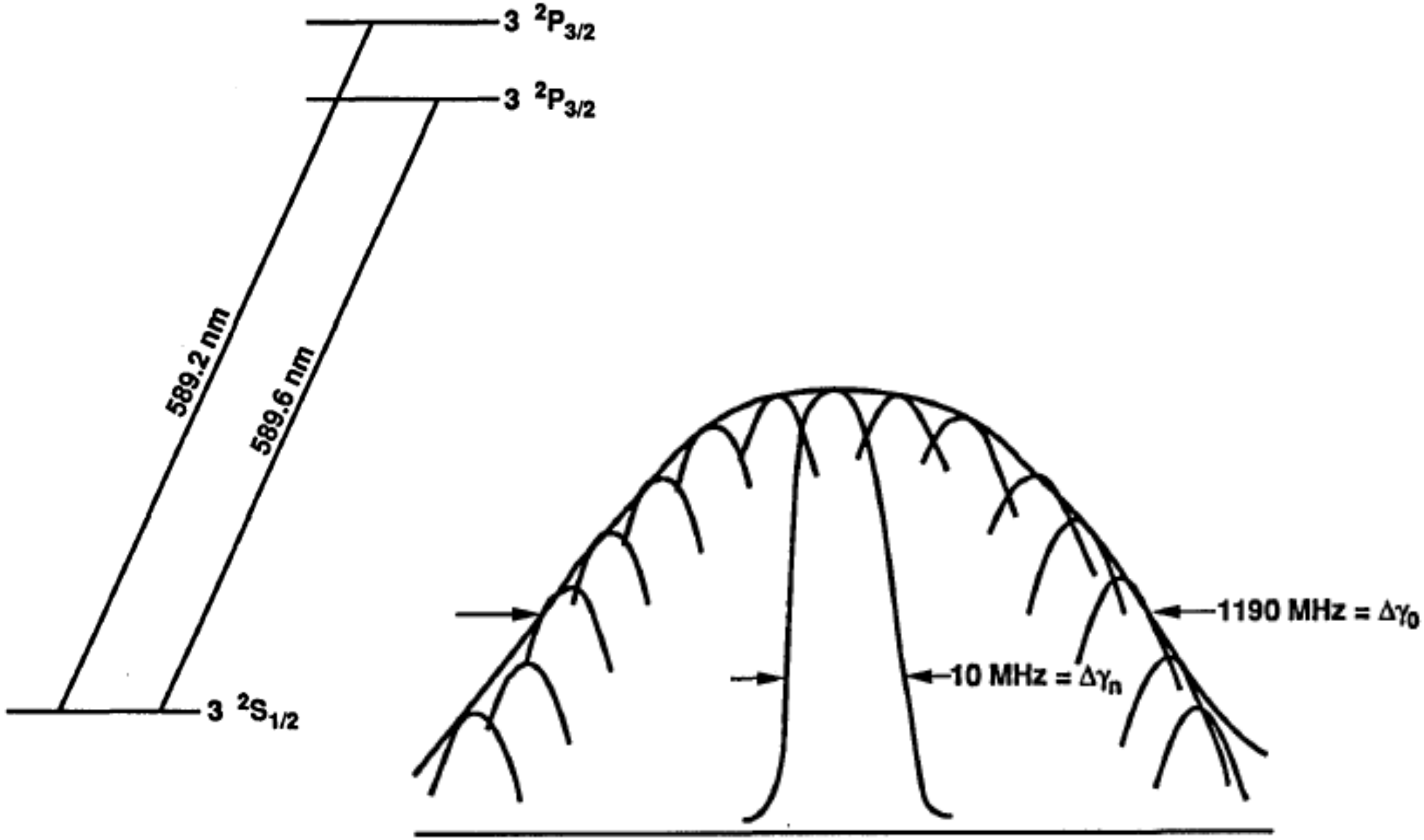








Abundance (10^{13} m^{-2})
6
4
2
Altitude (km)
100
90
80
1
2
3
4
1 2 3 4 5 6 7 8 9 10 11 12 1
Month

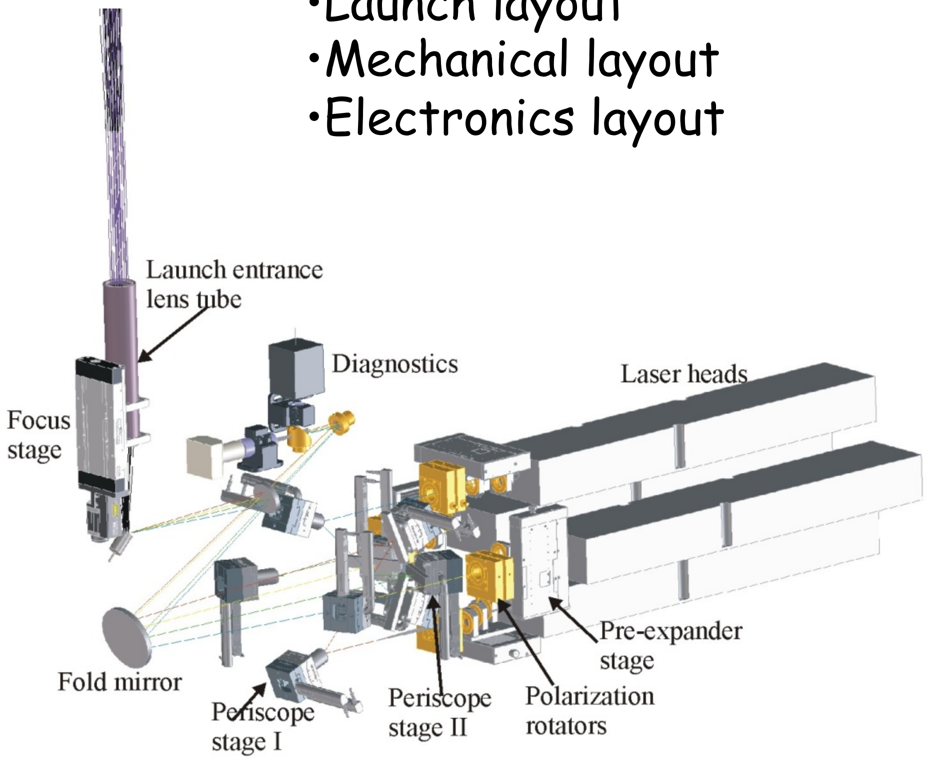

3 ²P3/2
3 ²P3/2
589.2 nm
589.6 nm
3 ²S1/2
1190 MHz = Δγ0
10 MHz = Δγn

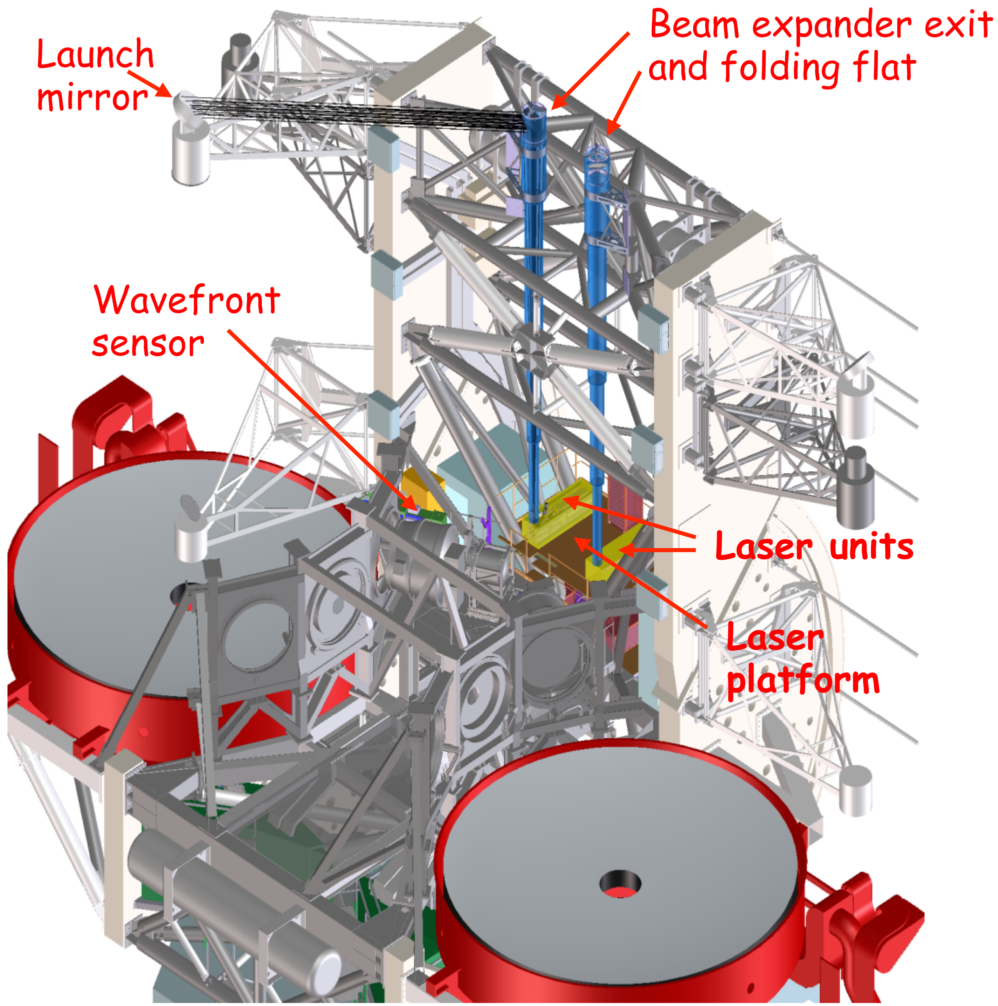
Pulsed vs. CW lasers…

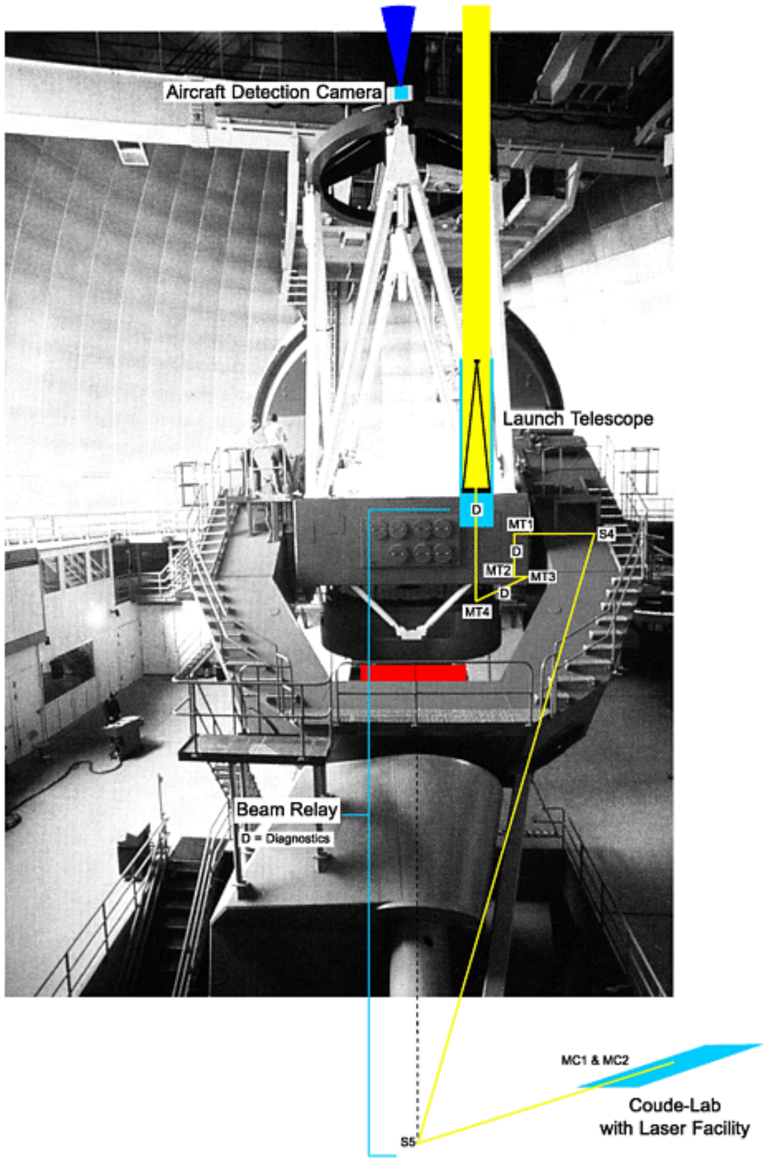
- Rayleigh positively needs pulsed lasers and a gating system synchronized with the laser
- Sodium lasers has to comply with saturations of Sodium layer so CW are superior, in general..
- Be warned that Lasers can have micro and macro pulses…

Laser & Launch system

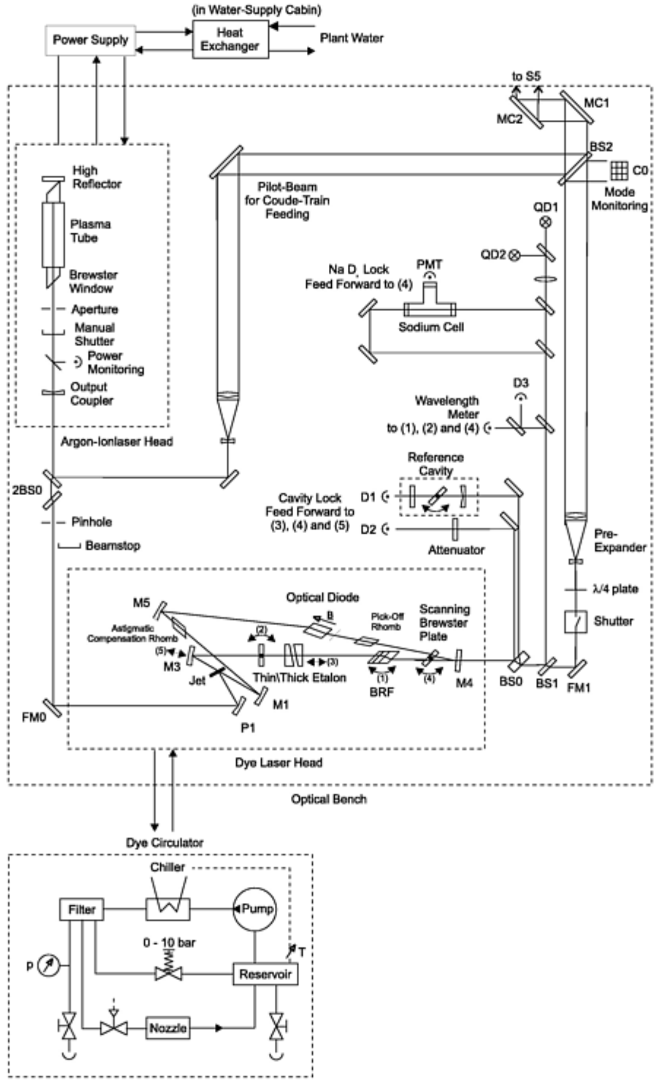
- System layout
- Laser source availability
- Launch layout
- Mechanical layout
- Electronics layout



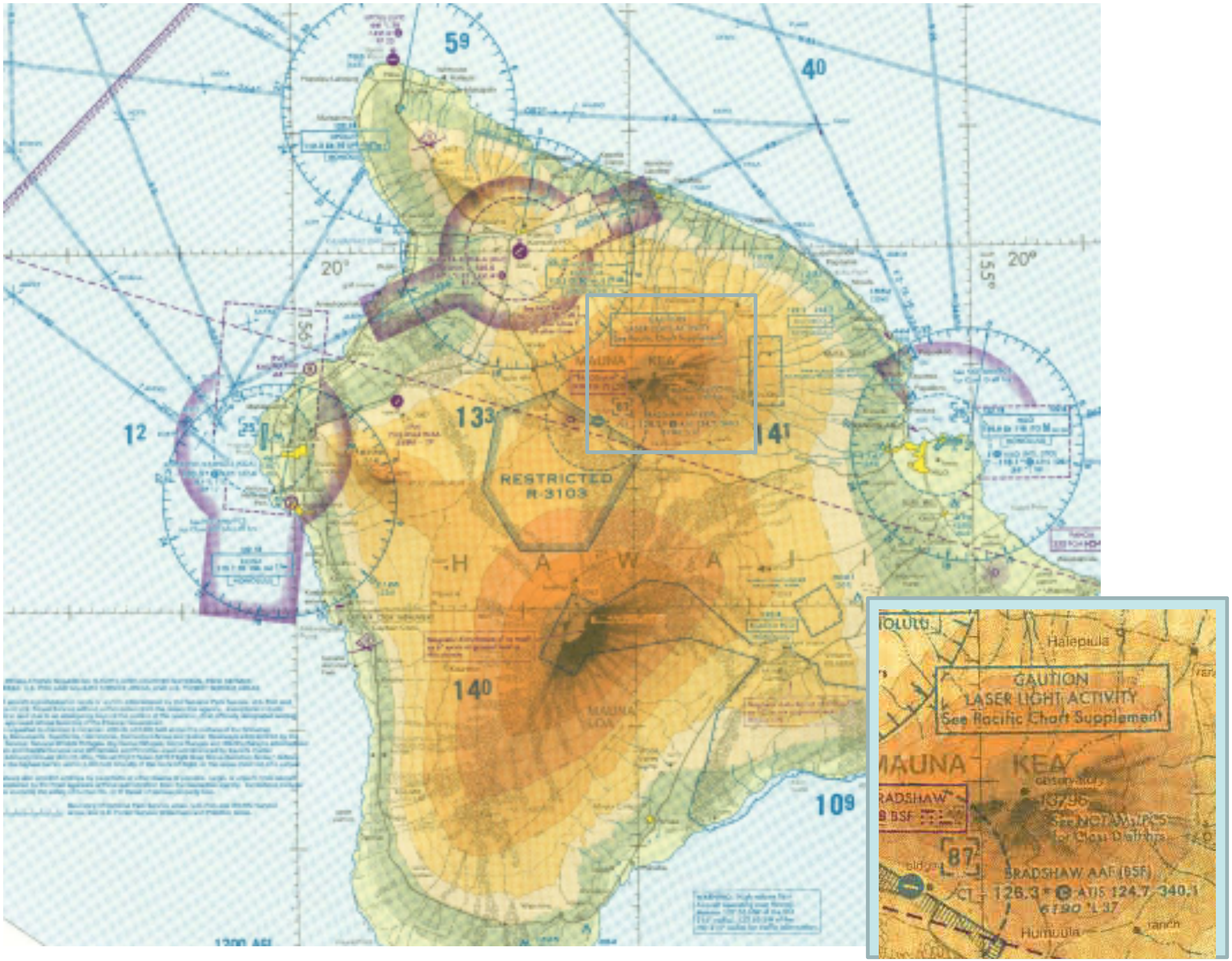




DSAZ 3.5 m Telescope and the ALFA LGS-System



Optic and Supply Schematic of the ALFA Laser Facility

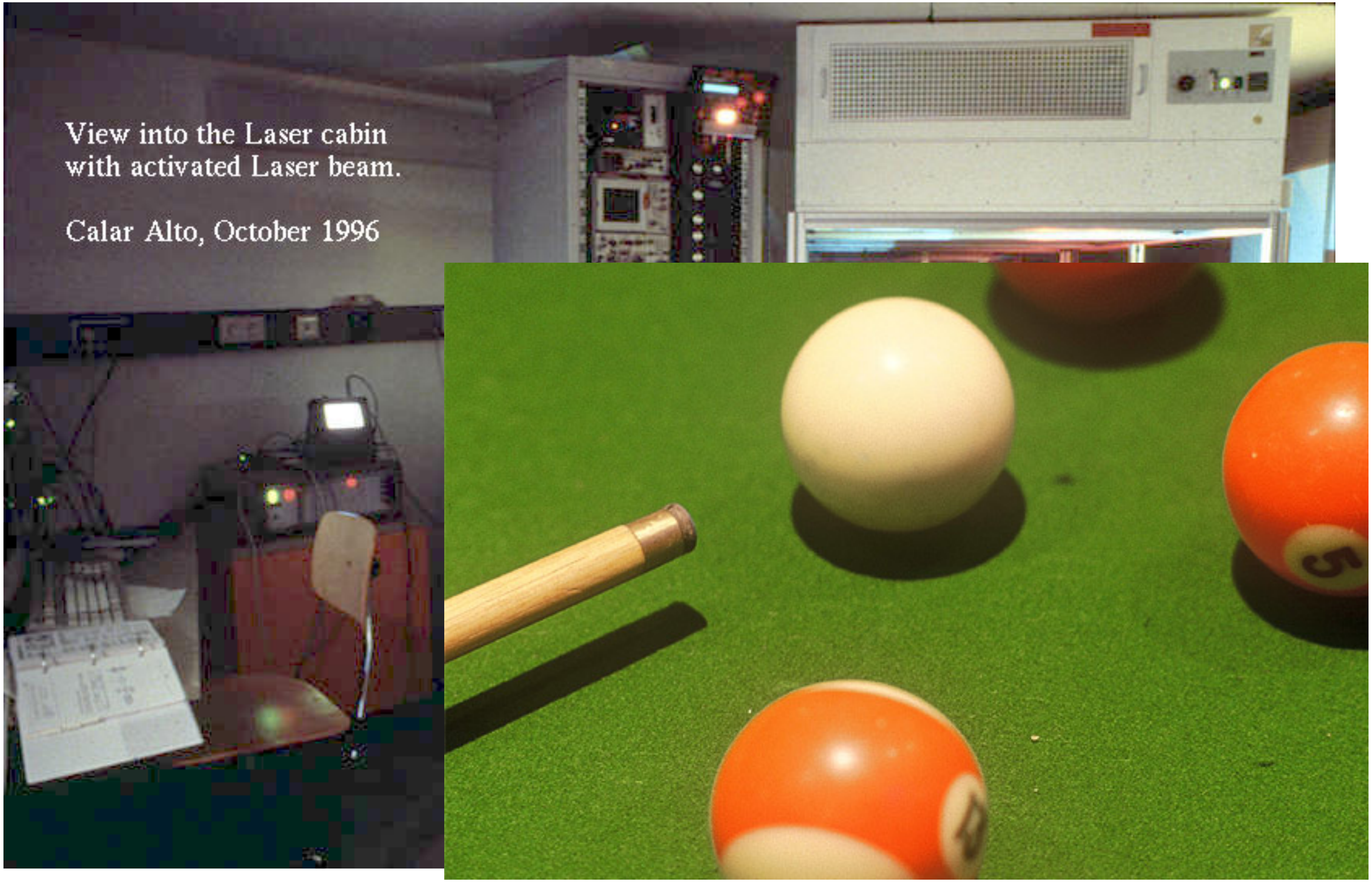


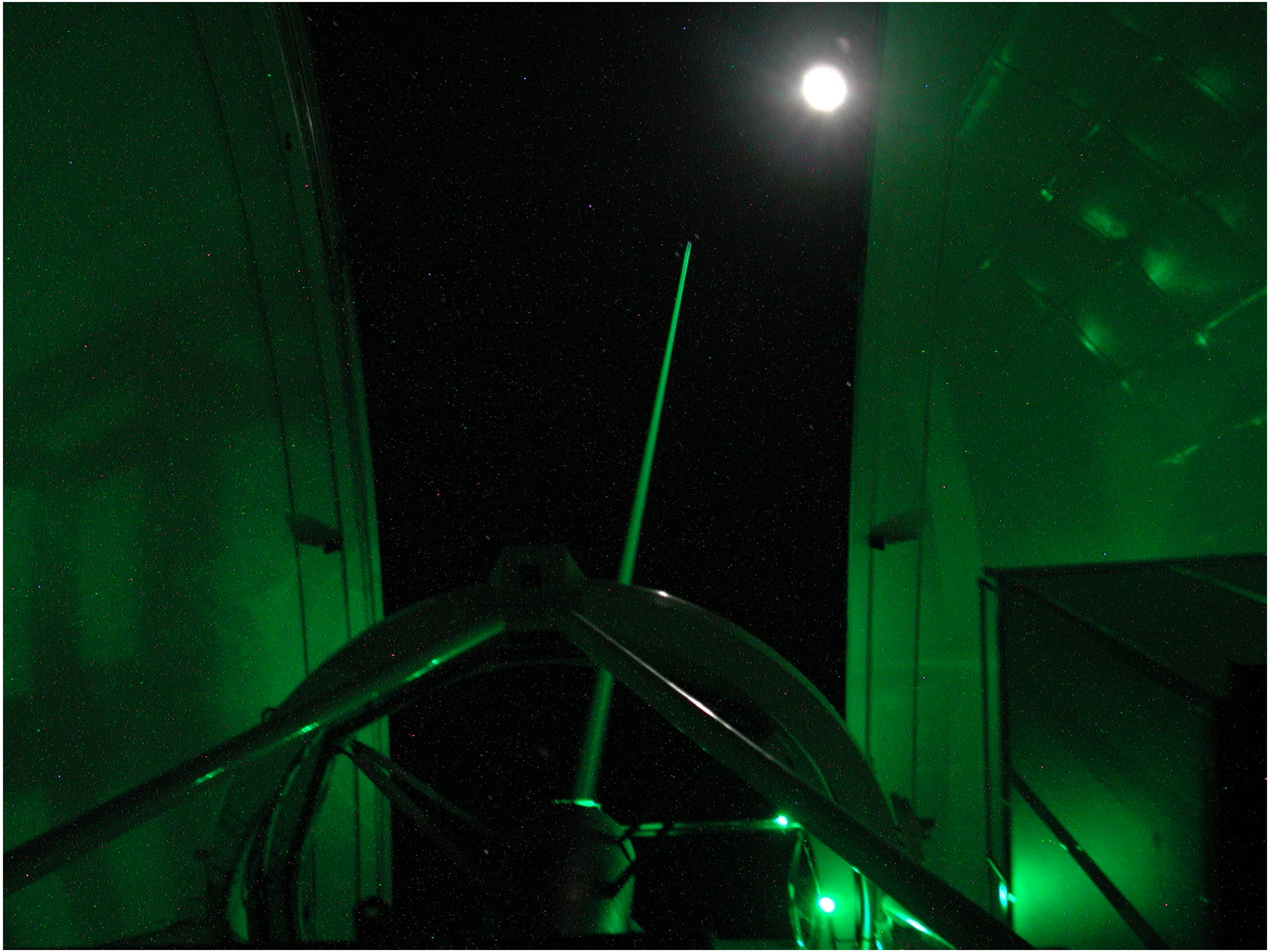
59
40
20°
155°
20°
12
133
141
RESTRICTED
R-3103
H A W A I I
140
109
CAUTION
LASER LIGHT ACTIVITY
See Pacific Chart Supplement
MAUNA KEA
13796
BRADSHAW AAF (BSF)
126.3
ATIS 124.7 340.1
Humuula
ranch

A dye laser…


View into the Laser cabin
with activated Laser beam.
Calar Alto, October 1996

A dye laser…


View into the Laser cabin
with activated Laser beam.
Calar Alto, October 1996



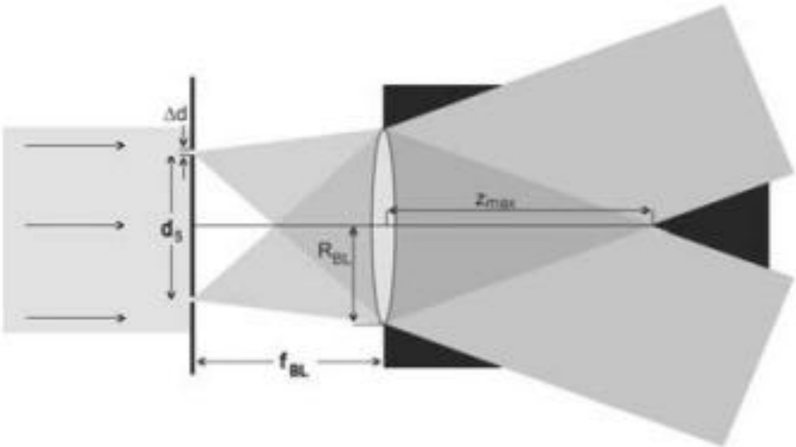


Figure 1. Arrangement to create a non-diffractive beam. Collimated light is sent through a circular slit mask in the focal plane of a lens with an F-ratio of $f_{\mathrm{BL}}/2R_{\mathrm{BL}}$. The light will form, after the lens, a beam along the optical axis which does not diffract until the shadow zone at $z_{\max}$ is reached (Durnin et al. 1987).

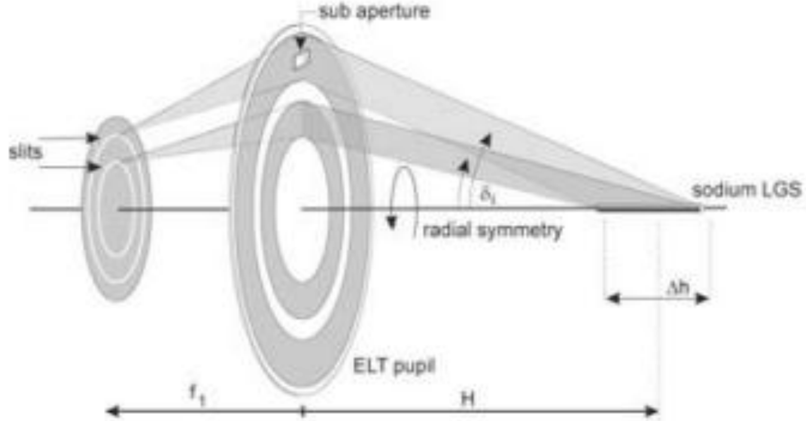


Figure 2. A mask with circular slits in the focal plane of the telescope selects particular angular directions of light rays originating from an LGS. This can be done simultaneously with several directions, leading to a novel gating technique, called 'angular gating'.

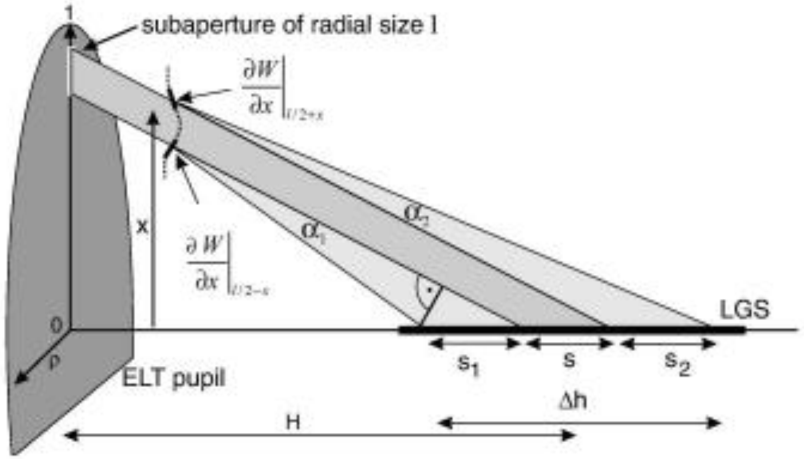
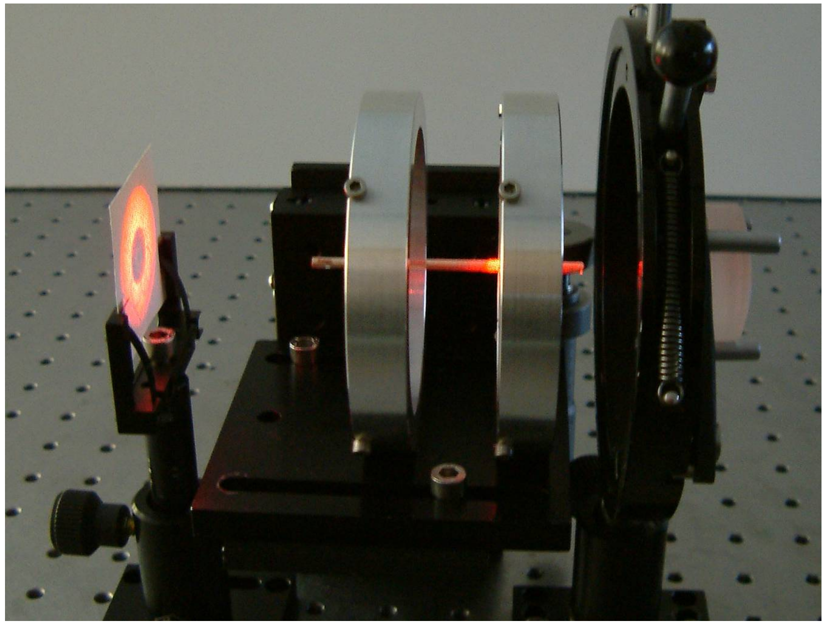
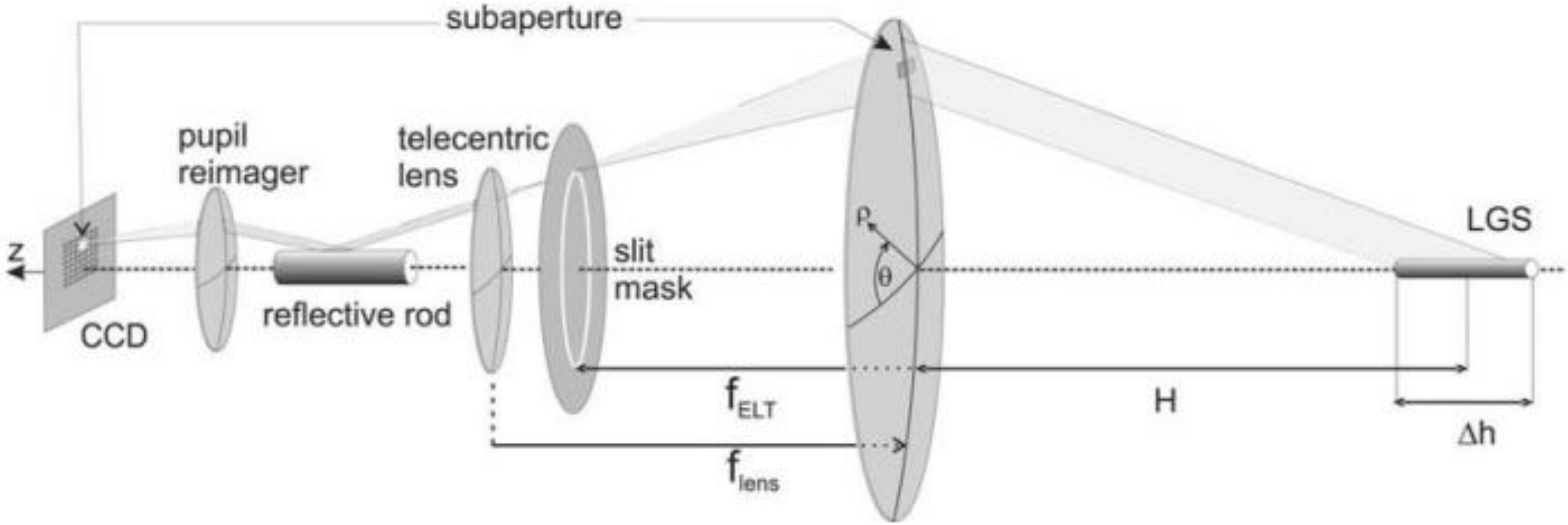
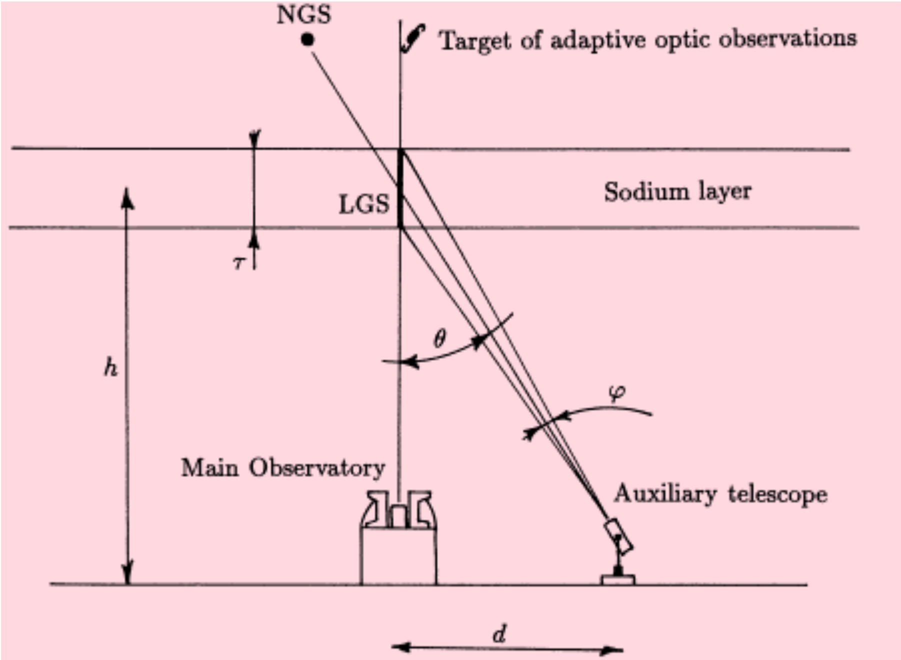


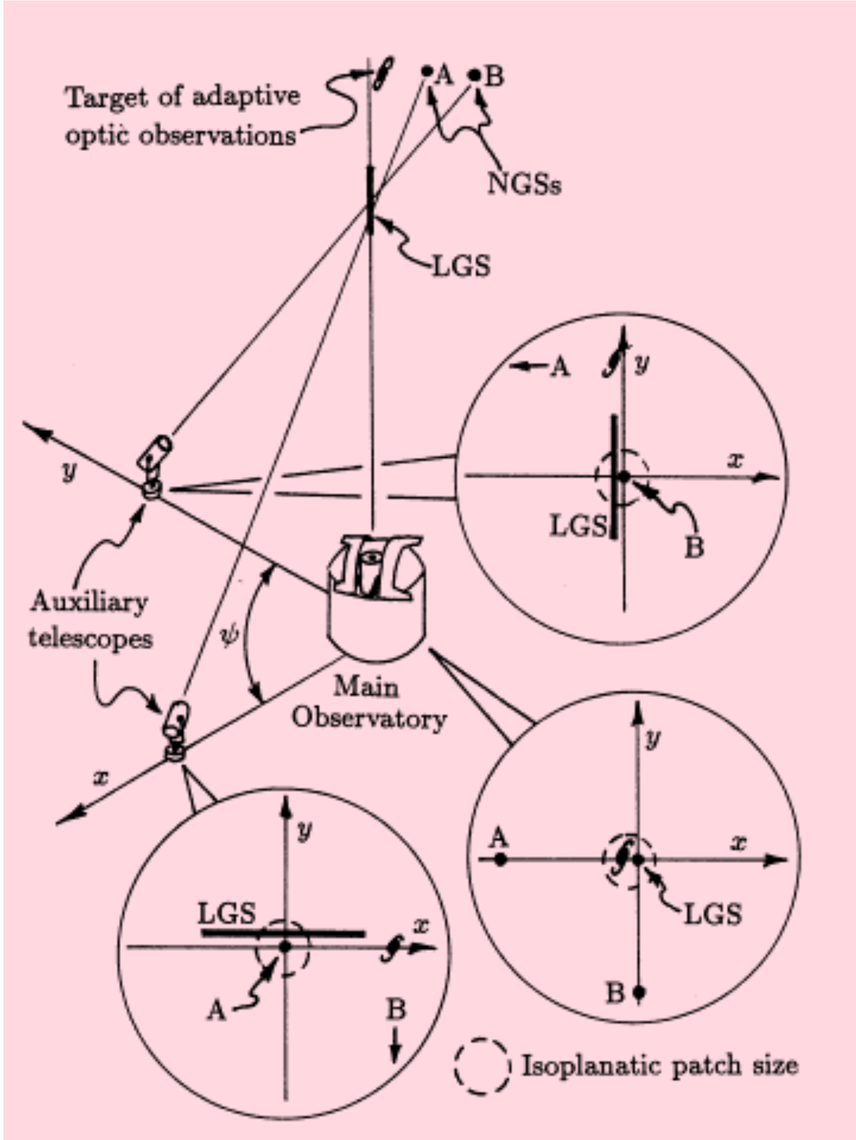
Figure 3. A radial wavefront error at the edge of the subaperture leads to a change of the 'effective' length of the laser beacon illuminating the subaperture.

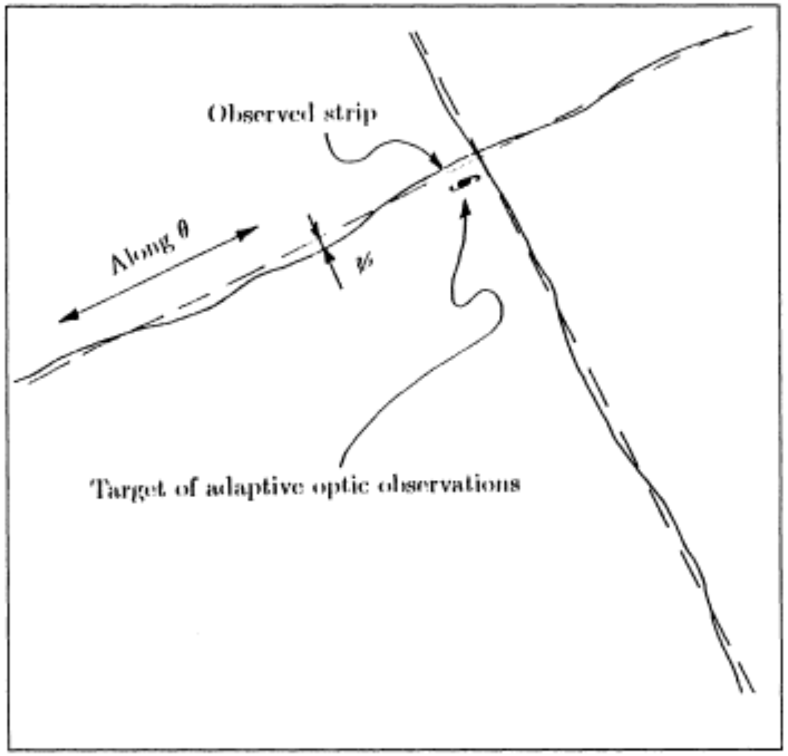


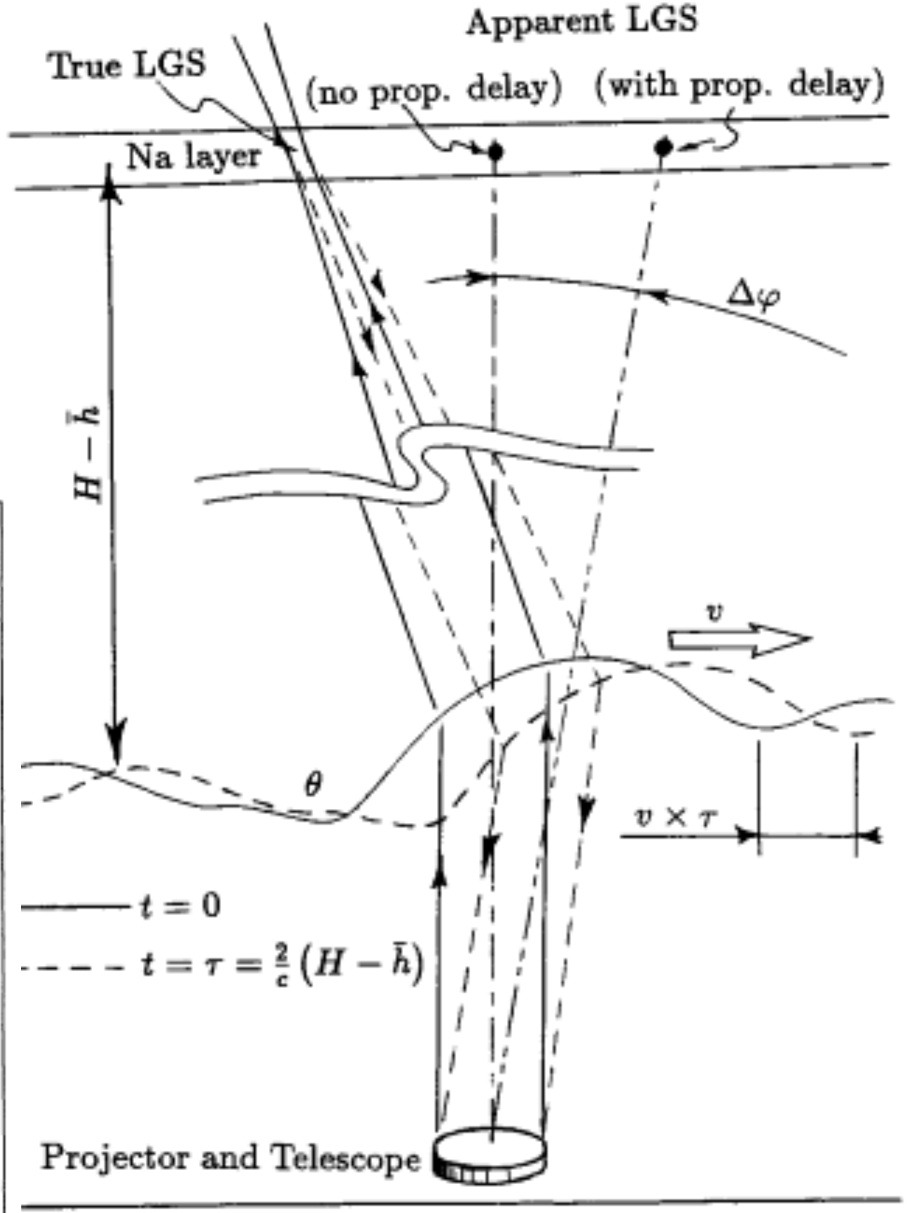
A z-invariant WFS…




NGS
Target of adaptive optic observations
LGS
Sodium layer
τ
h
θ
φ
Main Observatory
Auxiliary telescope
d


Target of adaptive optic observations
A
B
NGSs
LGS
y
x
Auxiliary telescopes
ψ
Main Observatory
Isoplanatic patch size


Observed strip
Along θ
Target of adaptive optic observations


Apparent LGS
True LGS
(no prop. delay)
(with prop. delay)
Na layer
$H - \bar{h}$
$\Delta\varphi$
v
θ
$v \times \tau$
$t = 0$
$t = \tau = \frac{2}{c}\,(H - \bar{h})$
Projector and Telescope

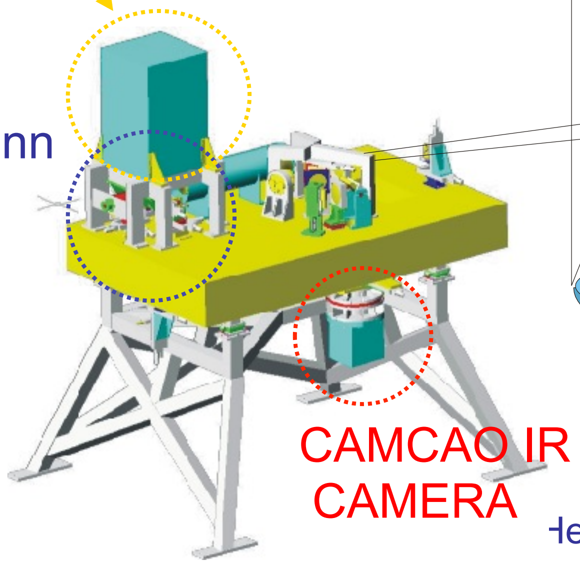
Polychromatic LGS

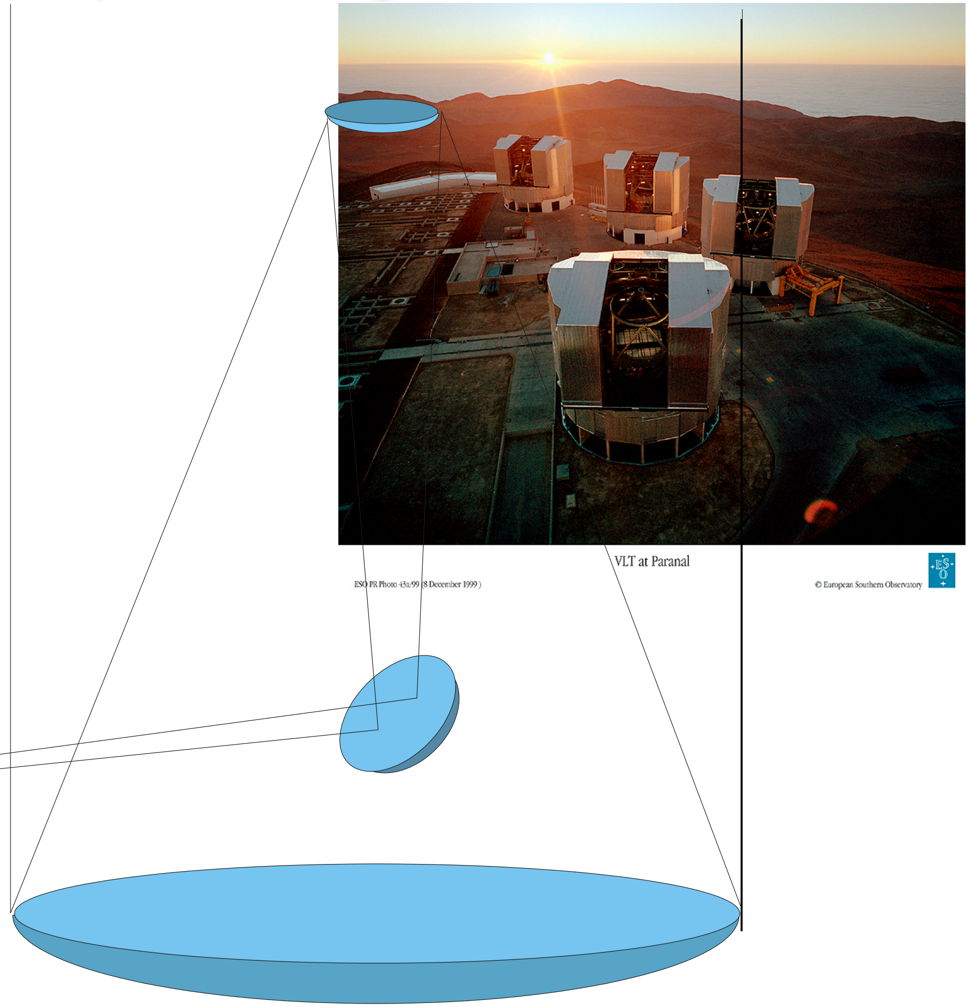
- A combination of wavelengths close one to each other is sent up…
- ..the resonant scattering pumps up some electrons level such that in the decay two very different wavelengths are sent back…
- So the way-UP is wavelength independent while the way-DOWN is not…
- …a little signal with absolute tilt information.

Laser Guide Stars…

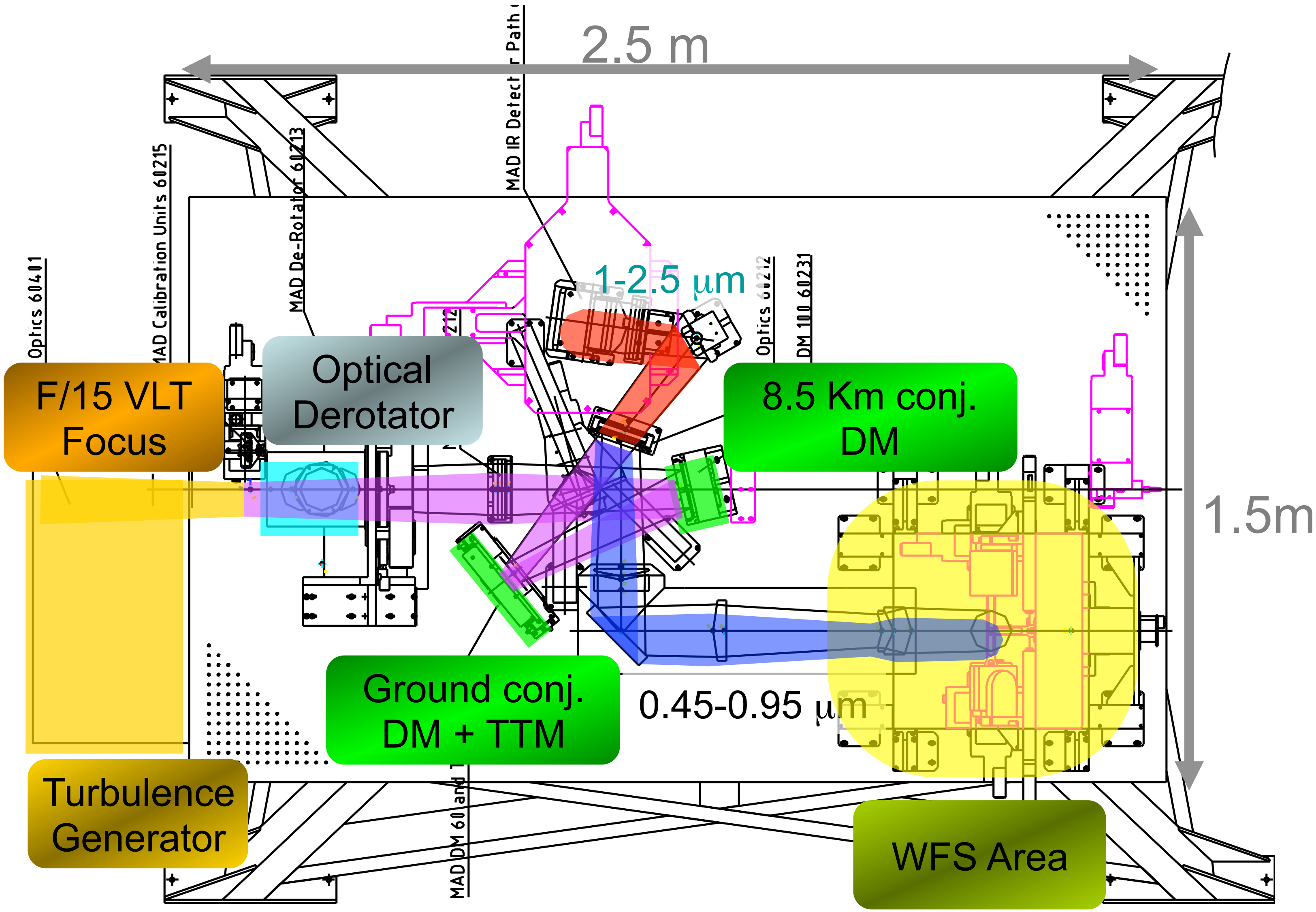
- Are now in operation at Keck, Gemini and VLT…
- Science is mostly with spectroscopy…
- Some telescopes are more effective than others…
- Foreseen in various telescopes
- Tilt and low orders is made through NGSs
- Still sky coverage is not 100% and some significant FoV is required…
- …MCAO with NGSs…????

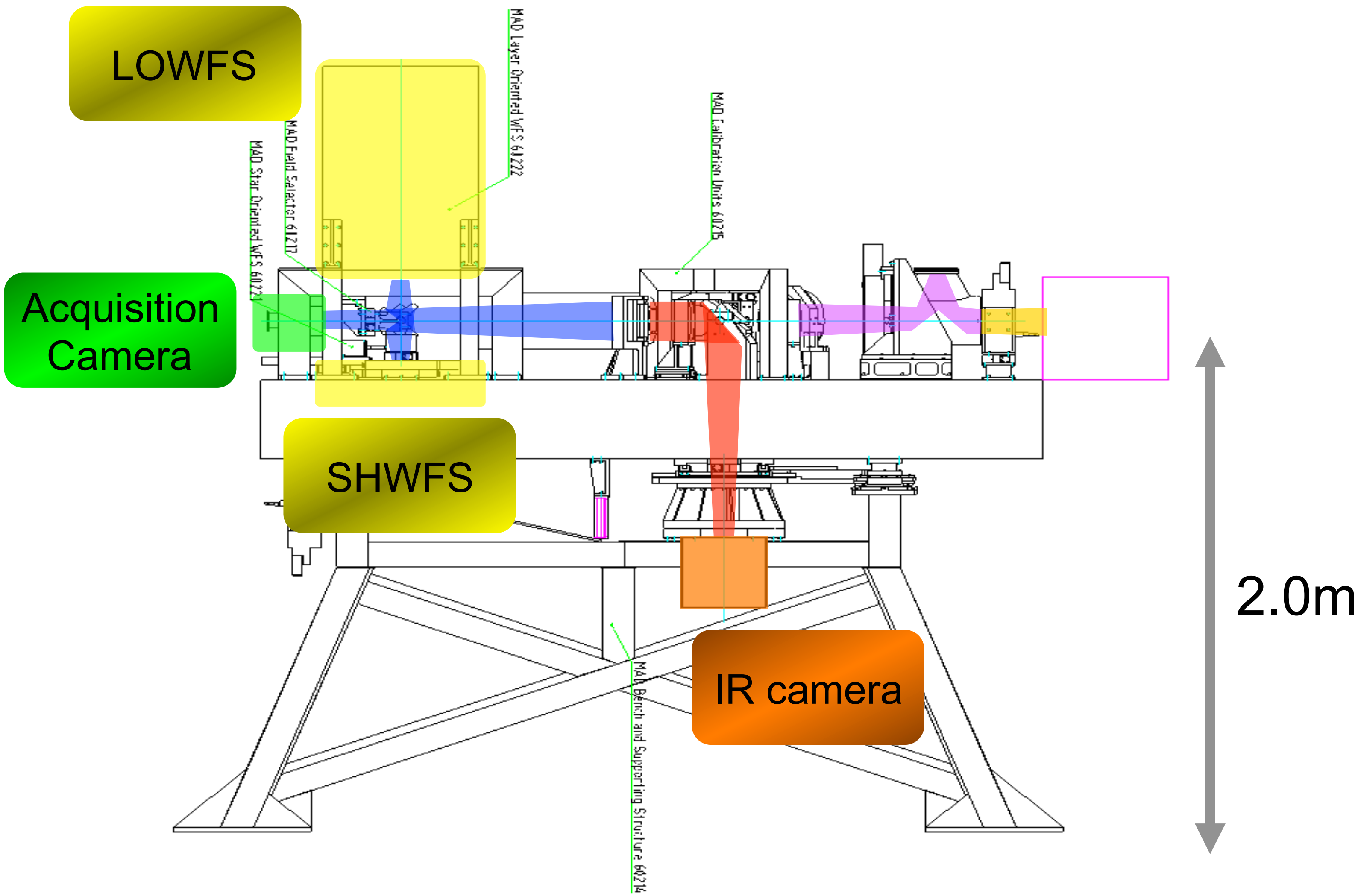
Layer-Oriented WFS per MAD@VLT





Dimostratore strategico per OWL!


2.5 m
1.5m
1-2.5 μm
0.45-0.95 μm
F/15 VLT Focus
Optical Derotator
8.5 Km conj. DM
Ground conj. DM + TTM
Turbulence Generator
WFS Area
Optics 60401
MAD Calibration Units 60215
MAD De-Rotator 60213
MAD IR Detect r Path
DM 100 60231

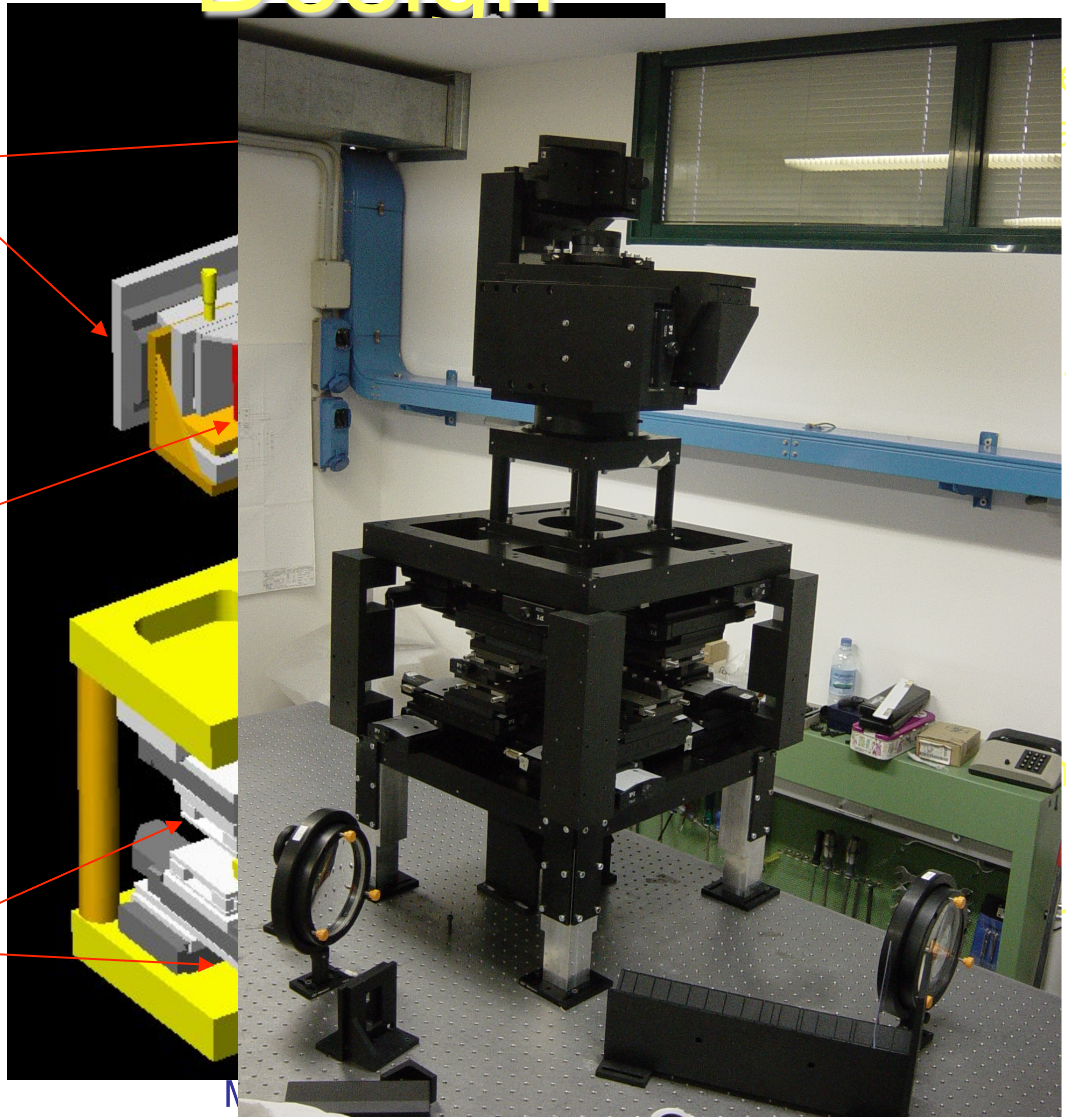

LOWFS
Acquisition Camera
SHWFS
IR camera
2.0m

MAD LOWFS: Mechanical Design

Focusing
mechanisms

CCD conjugated to
8.5 km

XY stages for
Stars positioning



ed to
ayer

tter

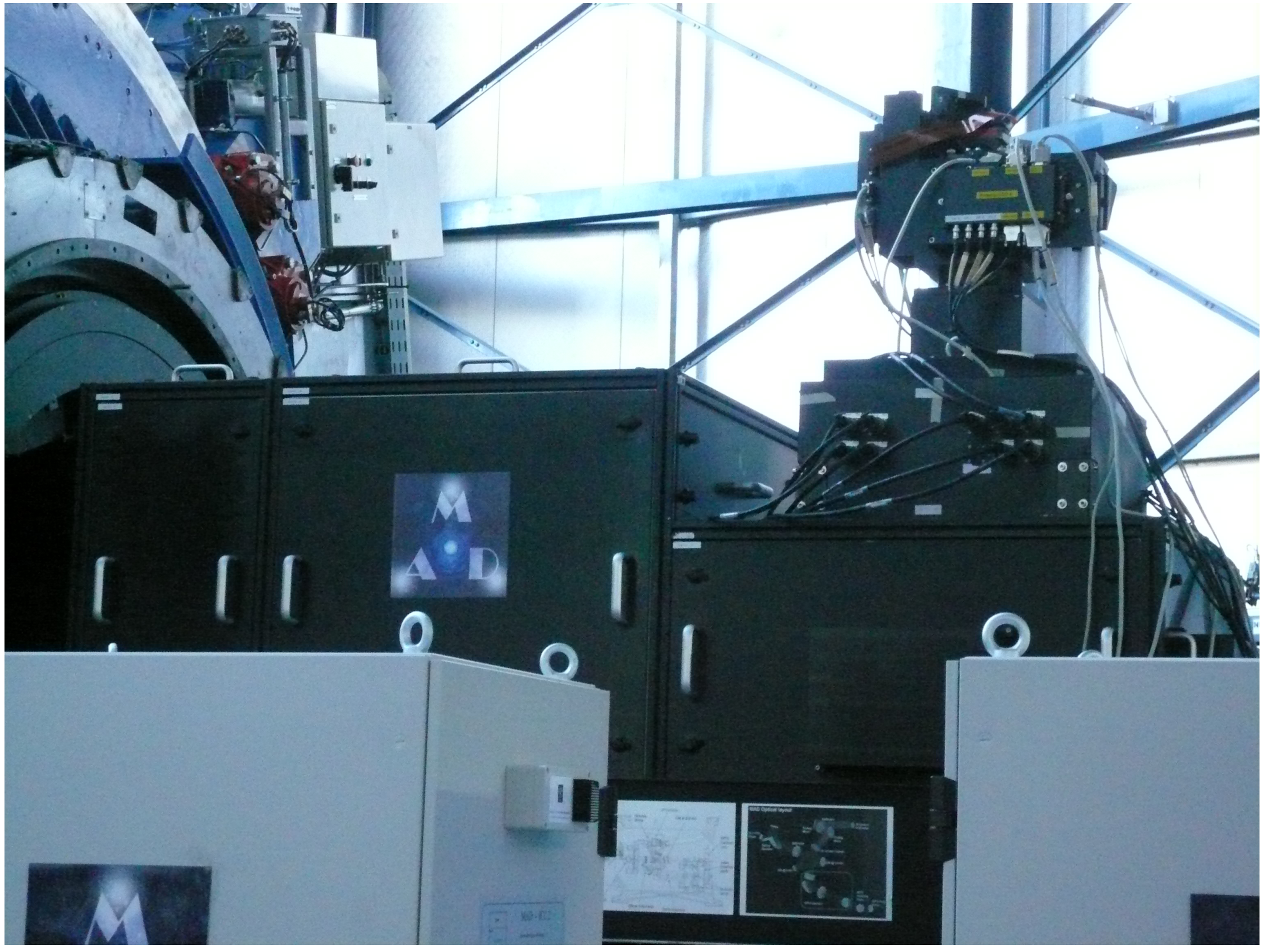
g optics

nlargers

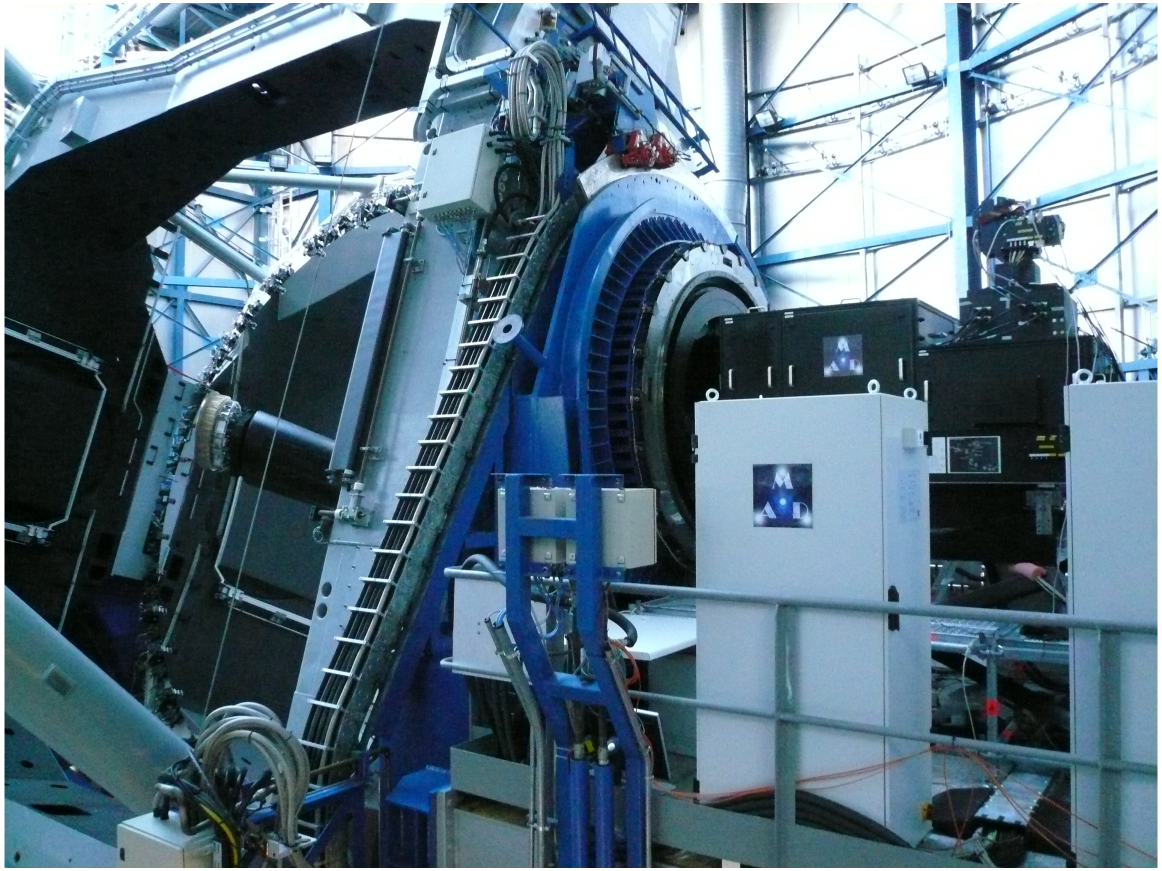
F/20 focal plane

The LOWFS on board on MAD

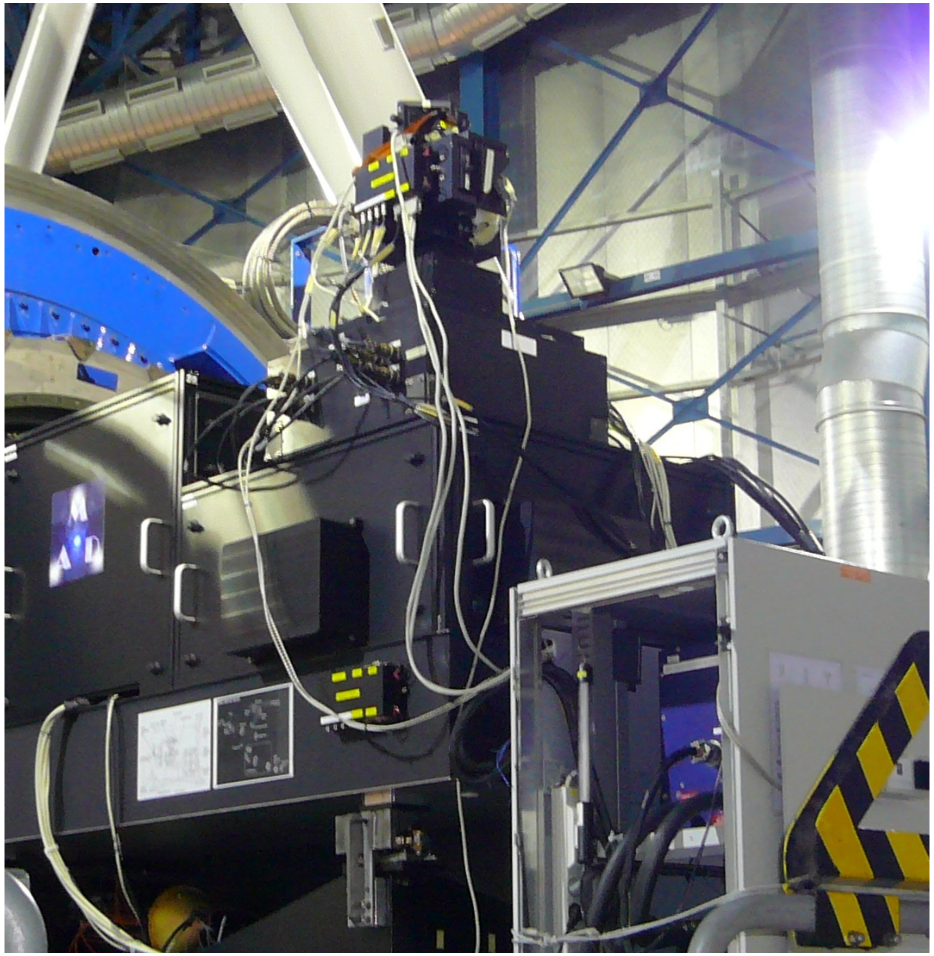
The LOWFS on board on MAD



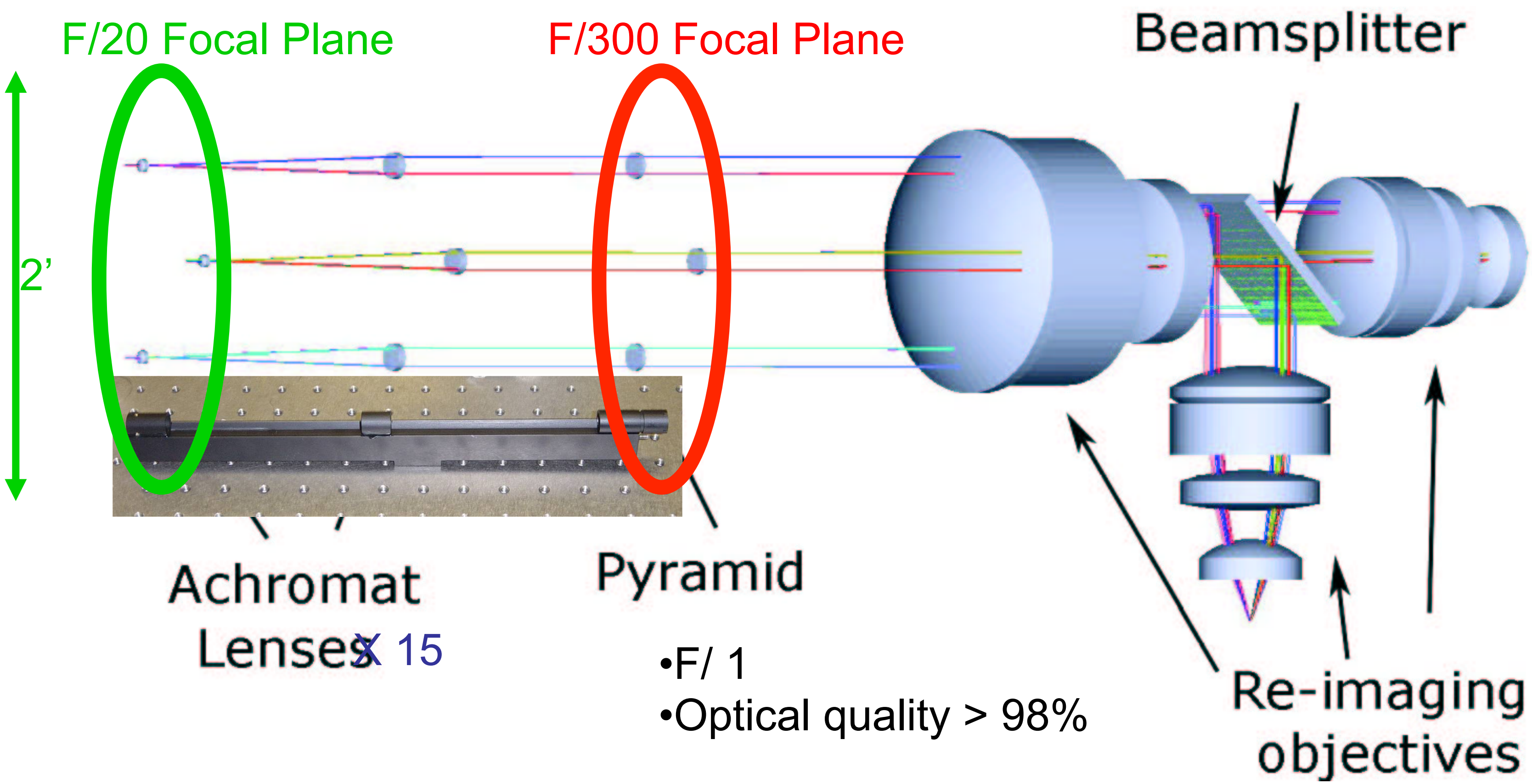
On board



On board



LOWFS: Optical design concept



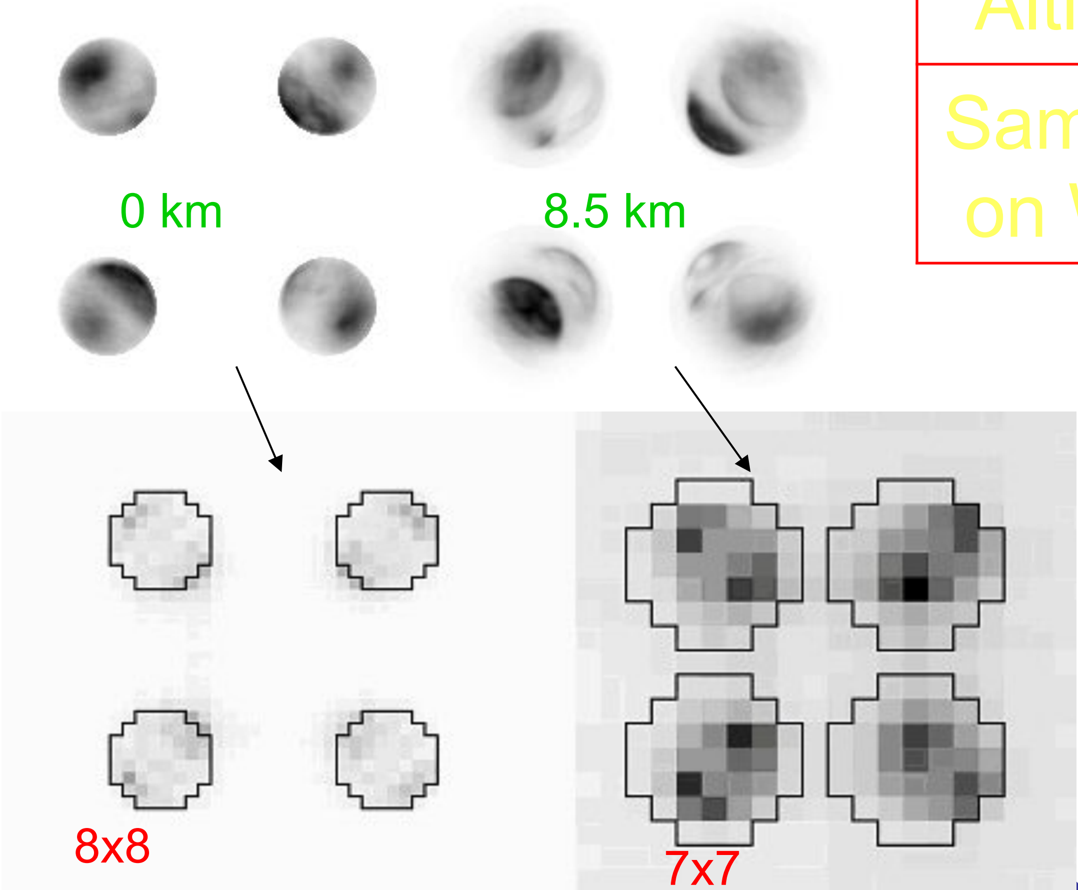
- F/ 1
- Optical quality > 98%

- 8 reference Stars-pyramids
- 2 conjugated planes-objectives-CCDs

Footprint Size on CCD

- F/300 beams
- Pyramid angle $\alpha = 1.23° \pm 0.01°$

Loop	Ground	High
Altitude	0	8.5
Sampling on WFS	8x8	7x7



Wavefront sensing supposed in R…

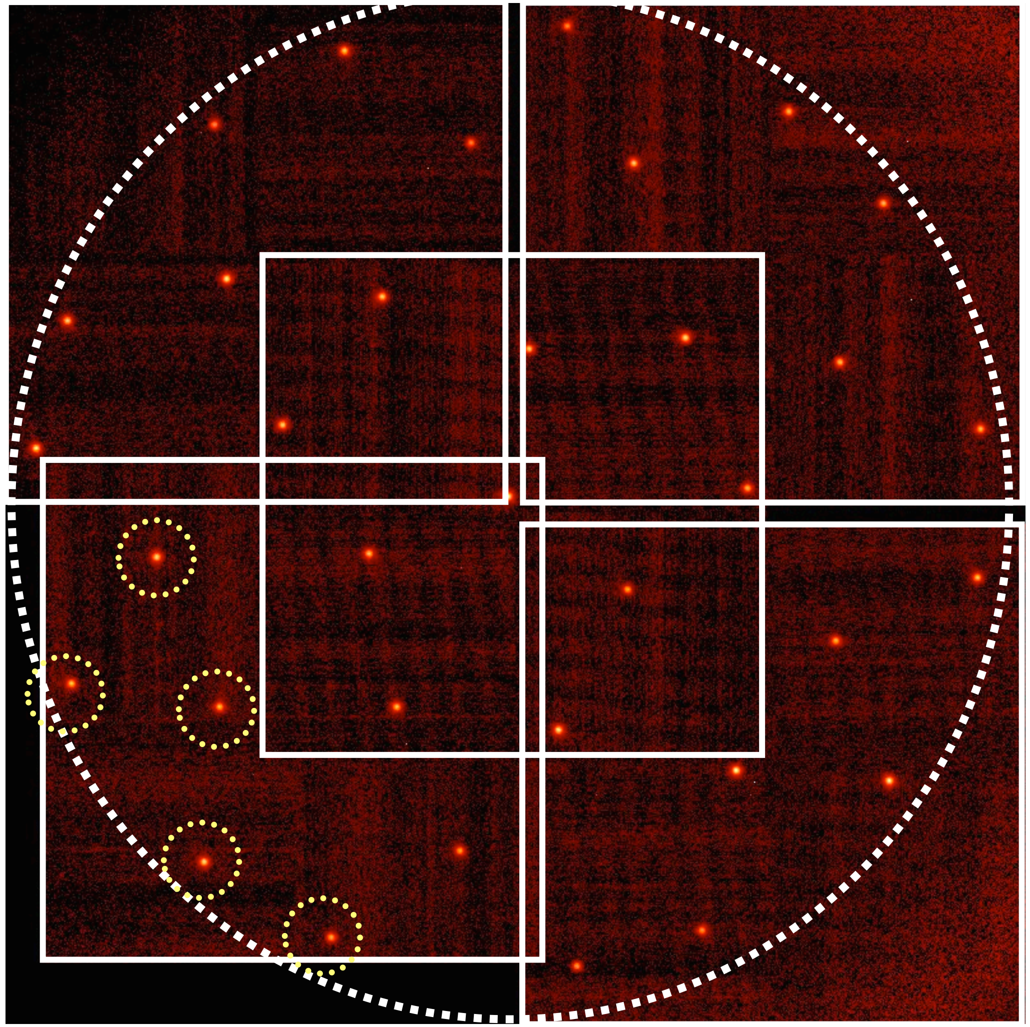
Correction for the IR

1 subaperture $\sim r_{0,K}$

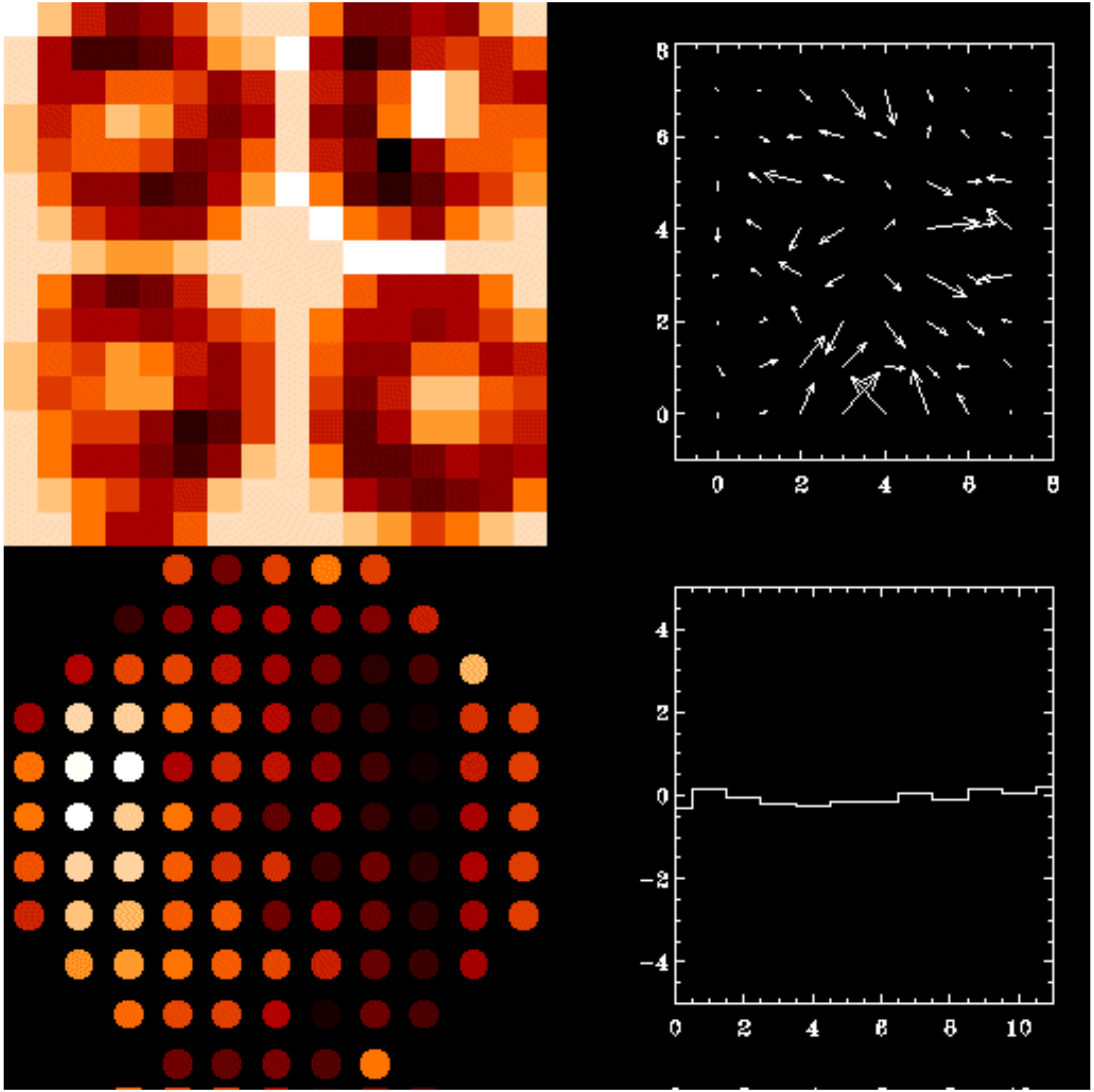
CAMCAO images

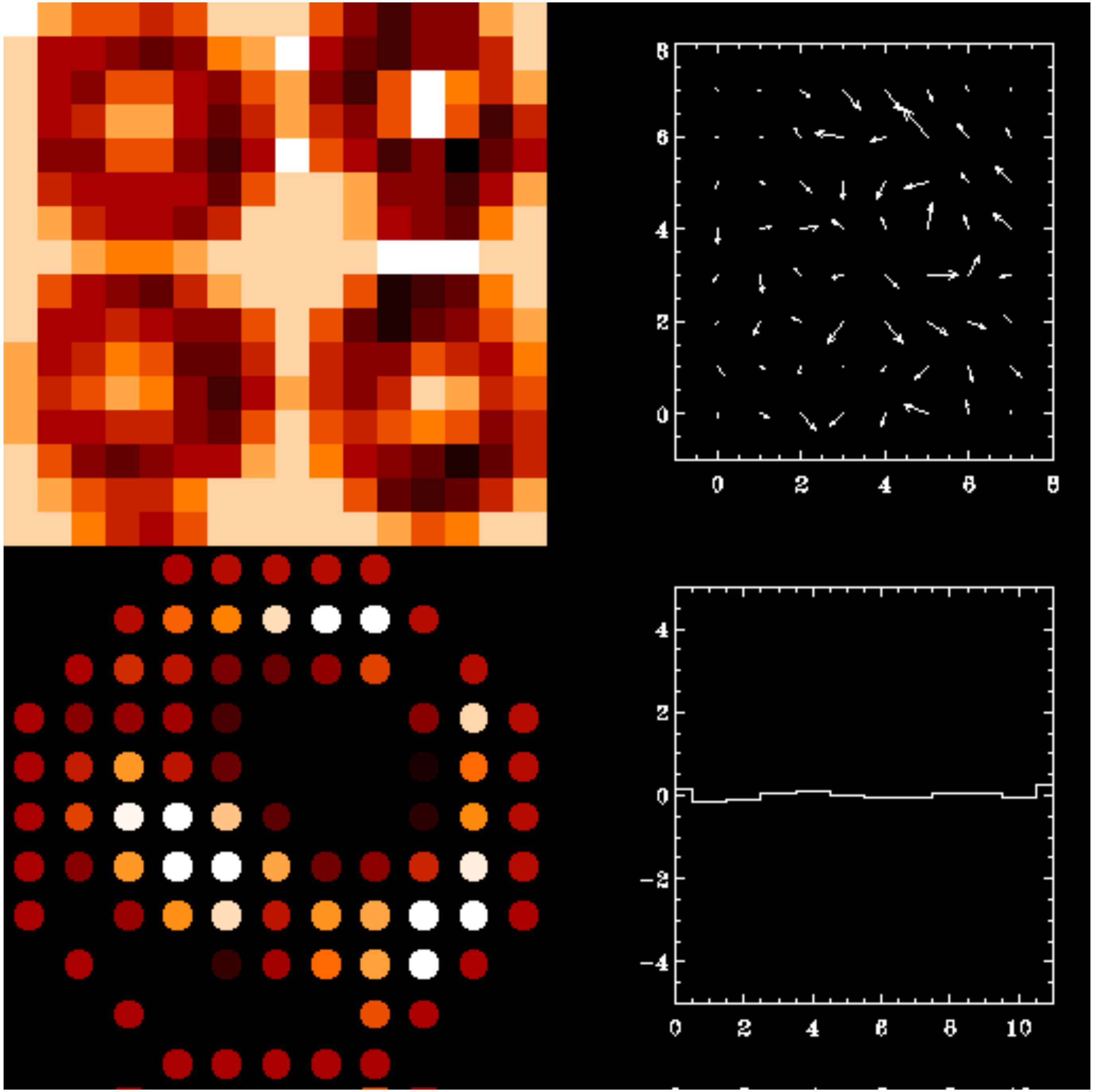
•Hawaii 2 Detector
•2048 x 2048 pixels, 28 mas/ pixel, ~58 arcsec FoV
•Full 2’ FoV scanning
•J, H, Kn broadband, Brg and Brg continuum narrowband filters

▪Mosaic of five 2048x2048 images



Test stars


8
6
4
2
0
0 2 4 6 8
4
2
0
−2
−4
0 2 4 6 8 10



8
6
4
2
0
0
2
4
6
8
4
2
0
-2
-4
0
2
4
6
8
10