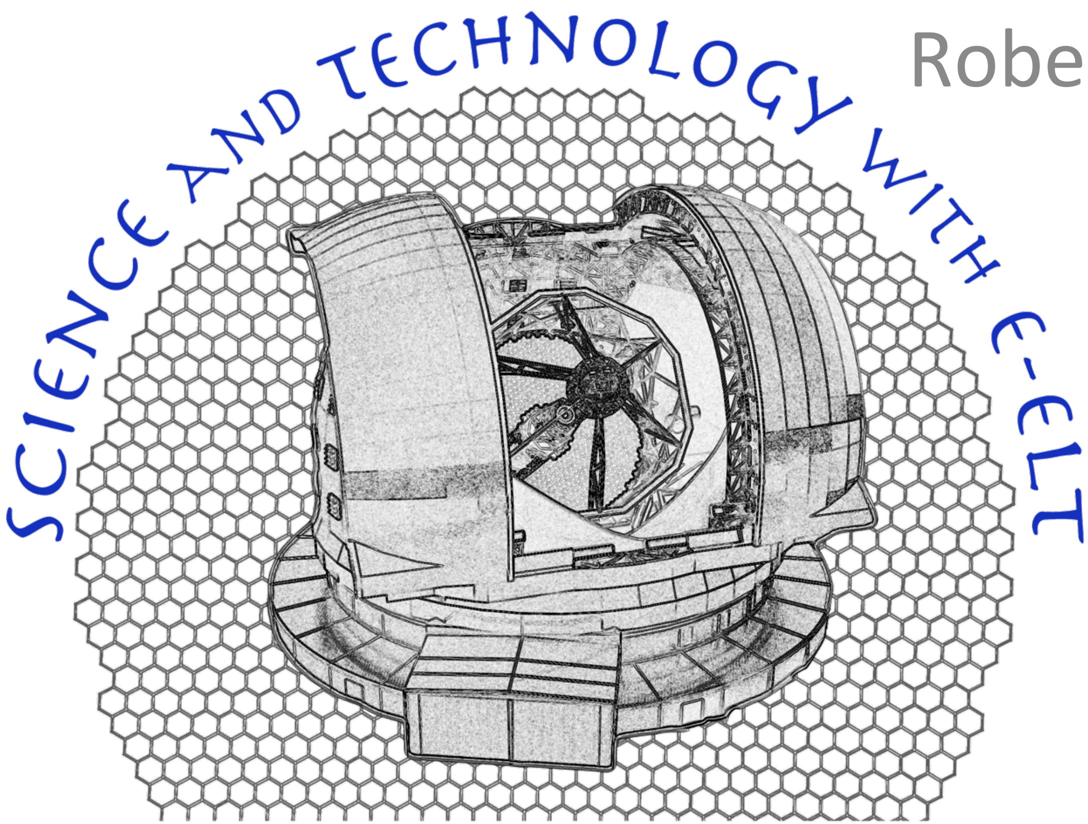
Adaptive Optics introduction with an historical perspective

Roberto Ragazzoni



INTERNATIONAL PHD SCHOOL "F. LUCCHIN"
XIV CYCLE - II COURSE
ERICE, SICILY
8-20 OCTOBER 2015

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Adaptive Optics introduction with an *historical* perspective

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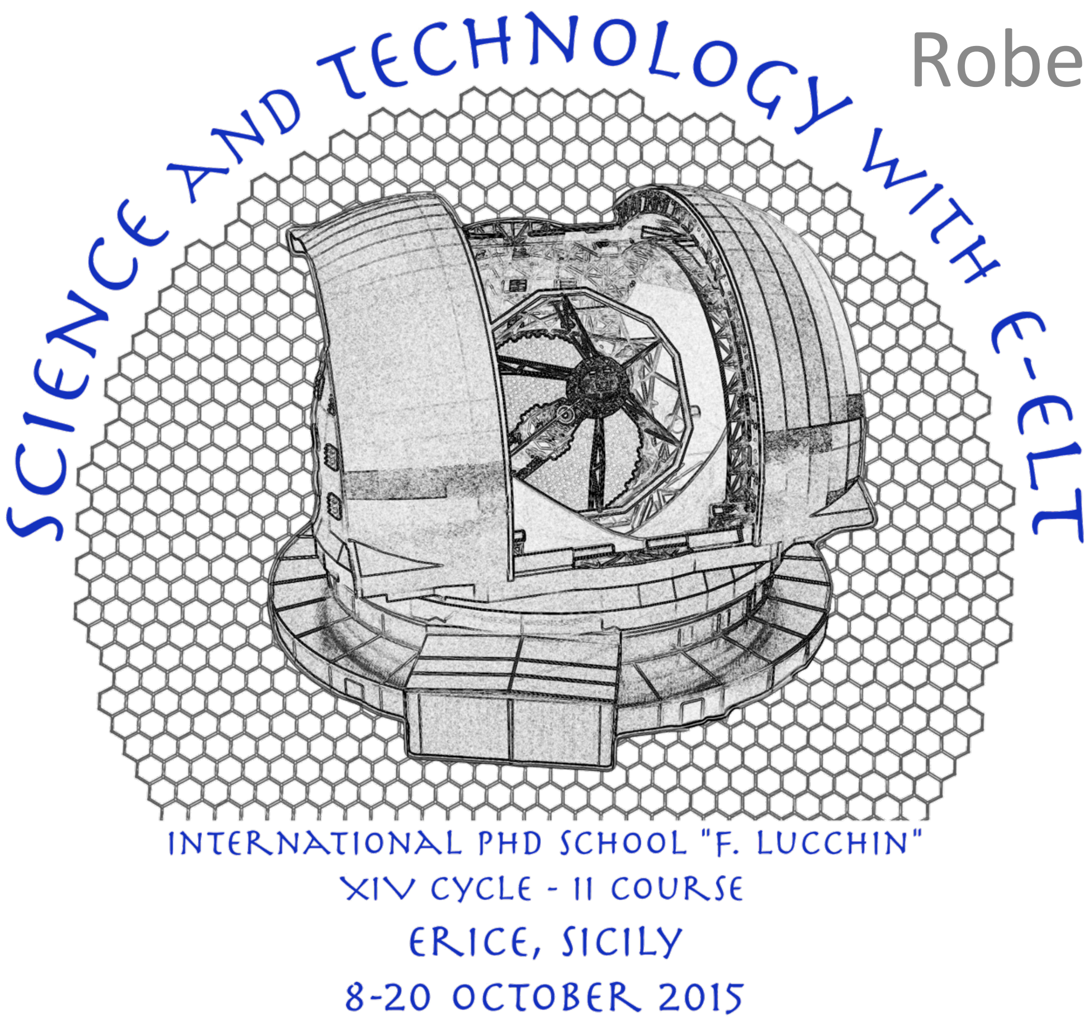

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TO PAY A PERMANENT TRIBUTE TO GALILEO GALILEI, FOUNDER OF MODERN SCIENCE AND TO ENRICO FERMI, "THE ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

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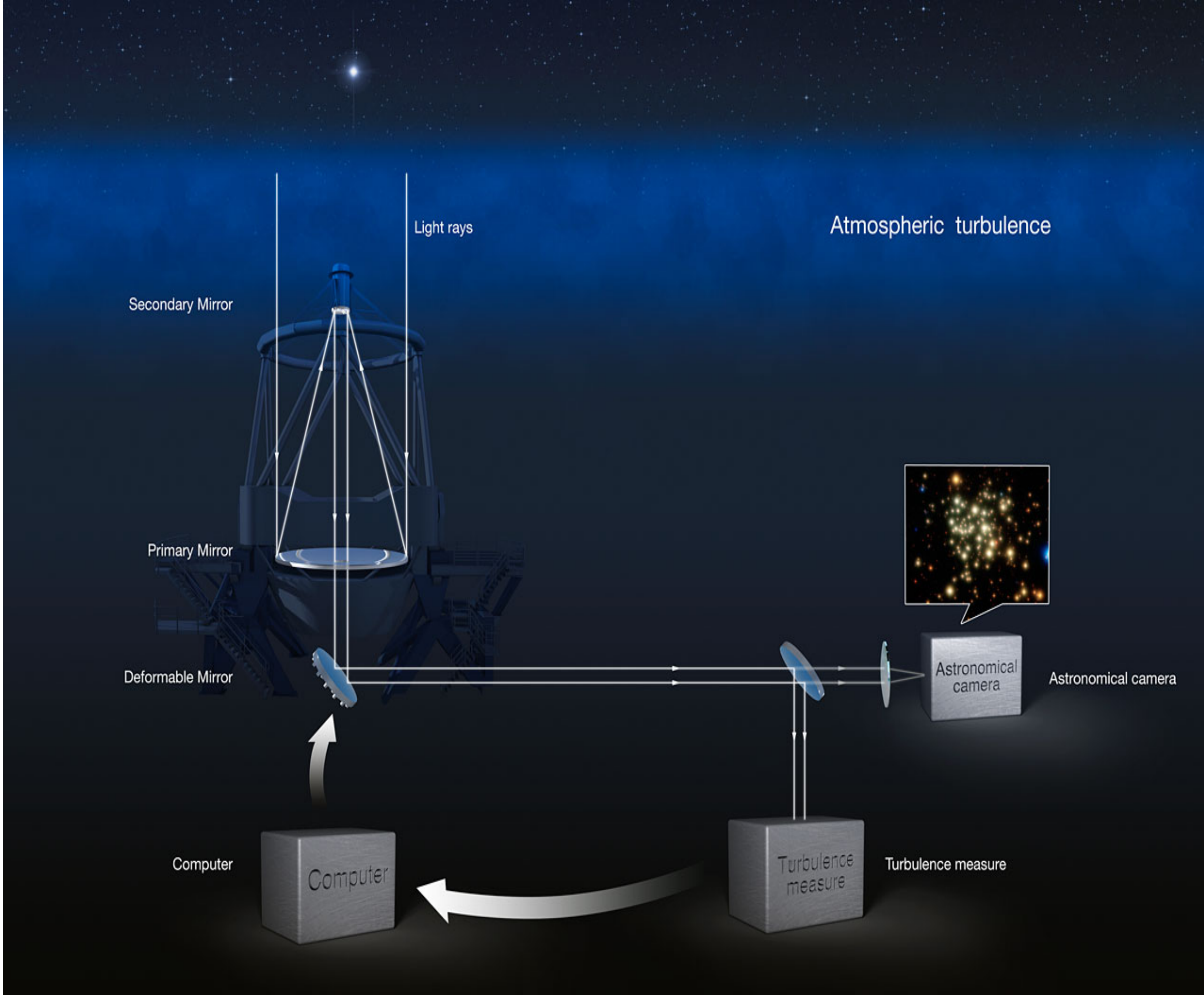

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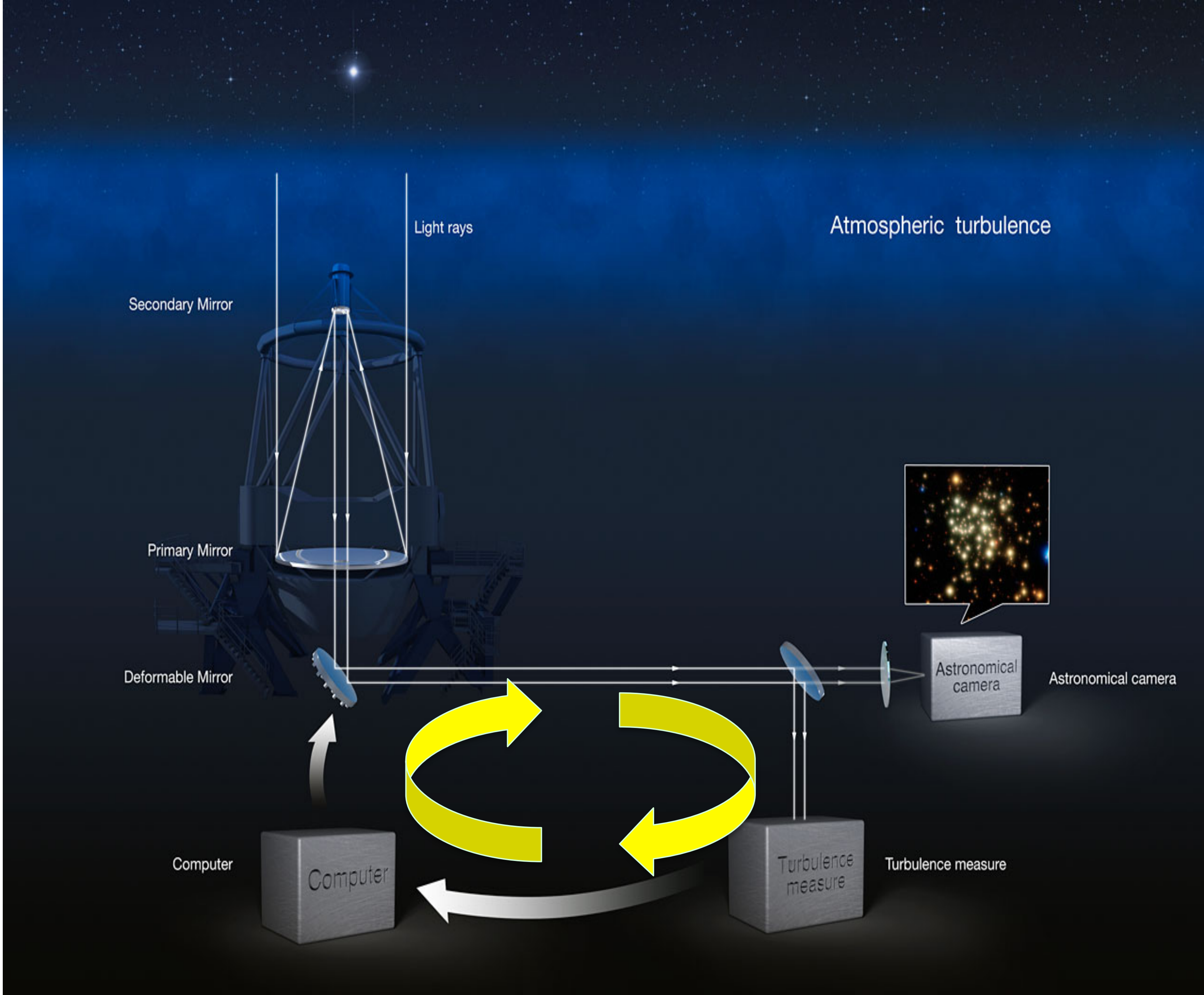
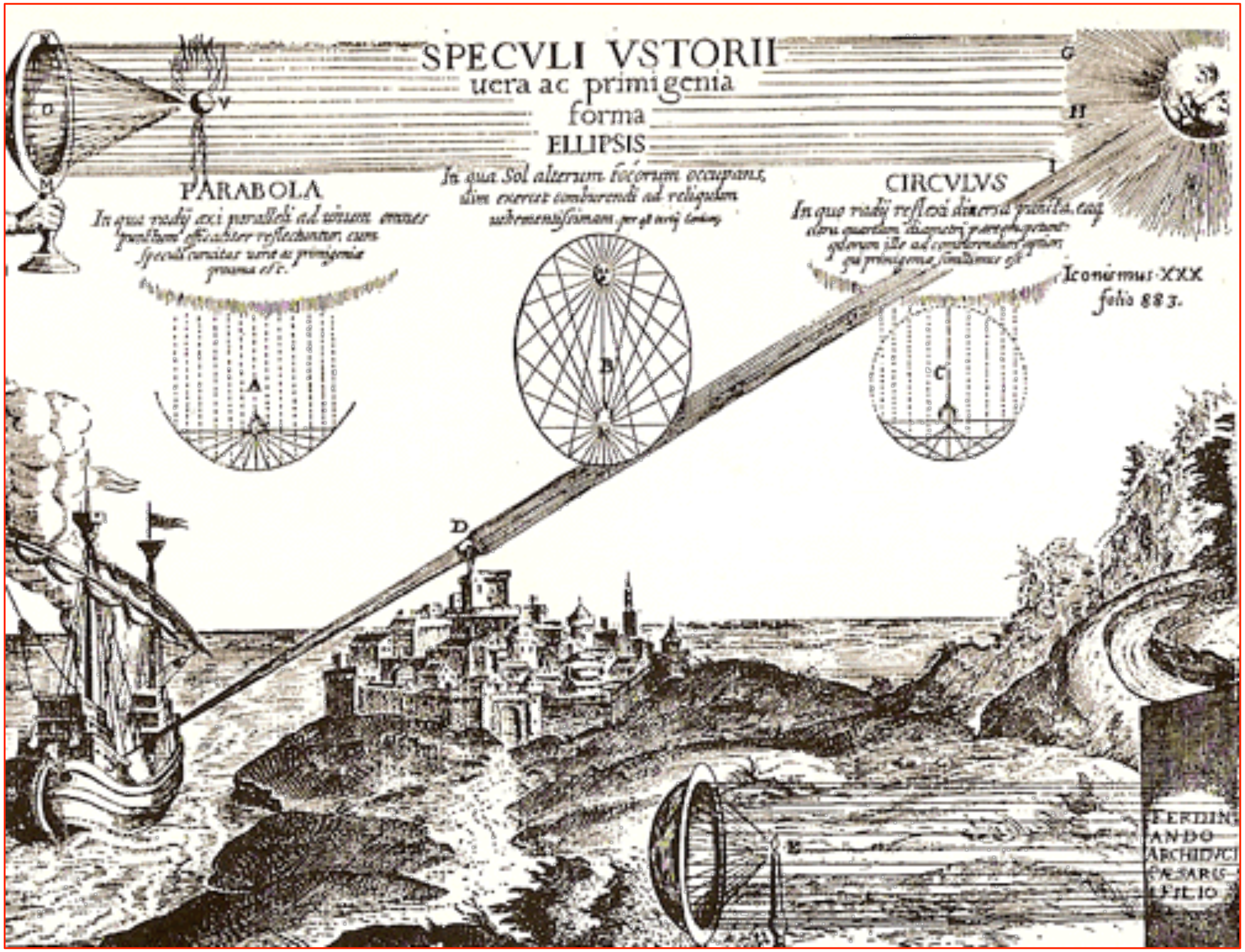


Syracuse – about 2215 years ago…



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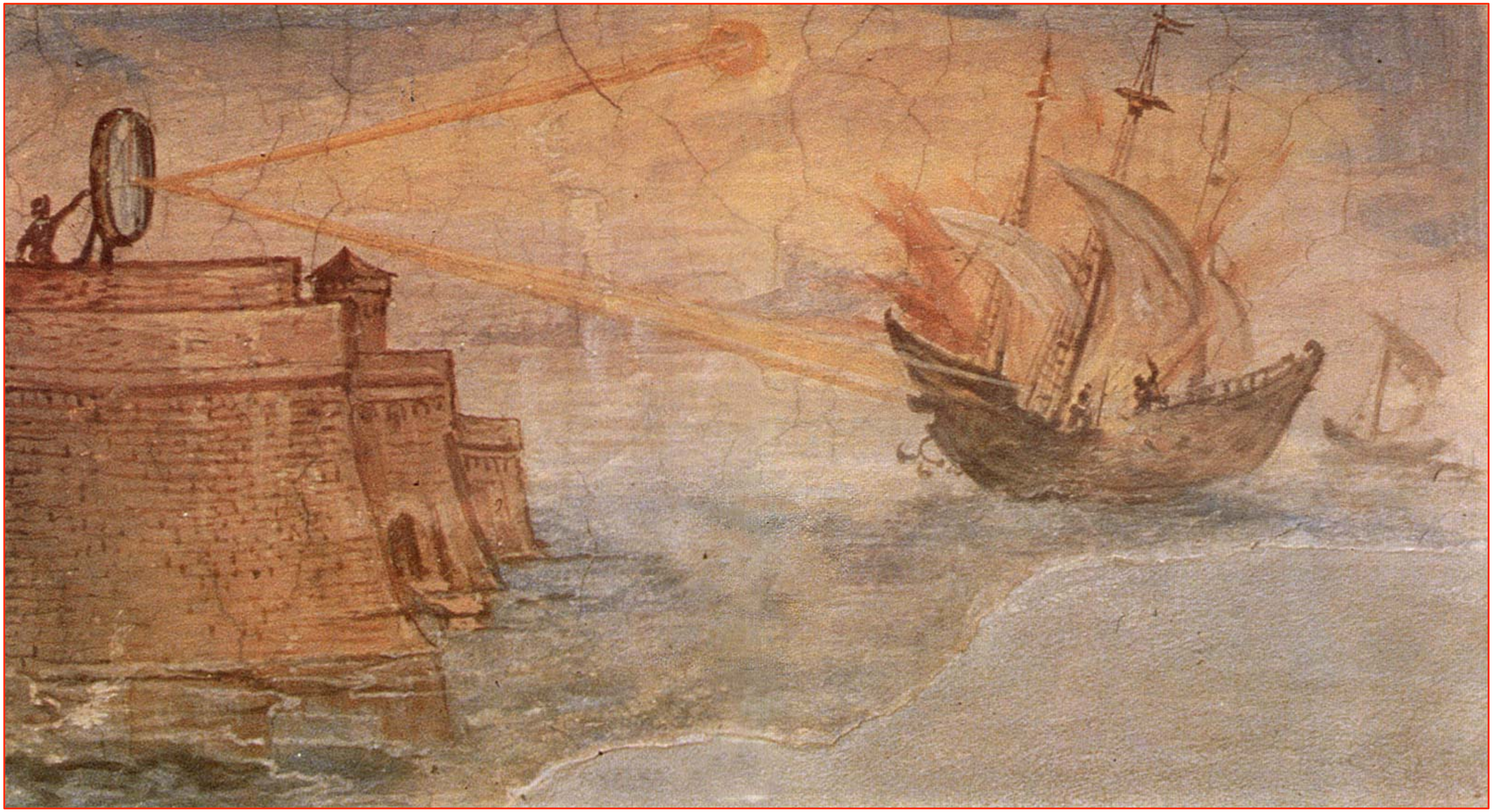

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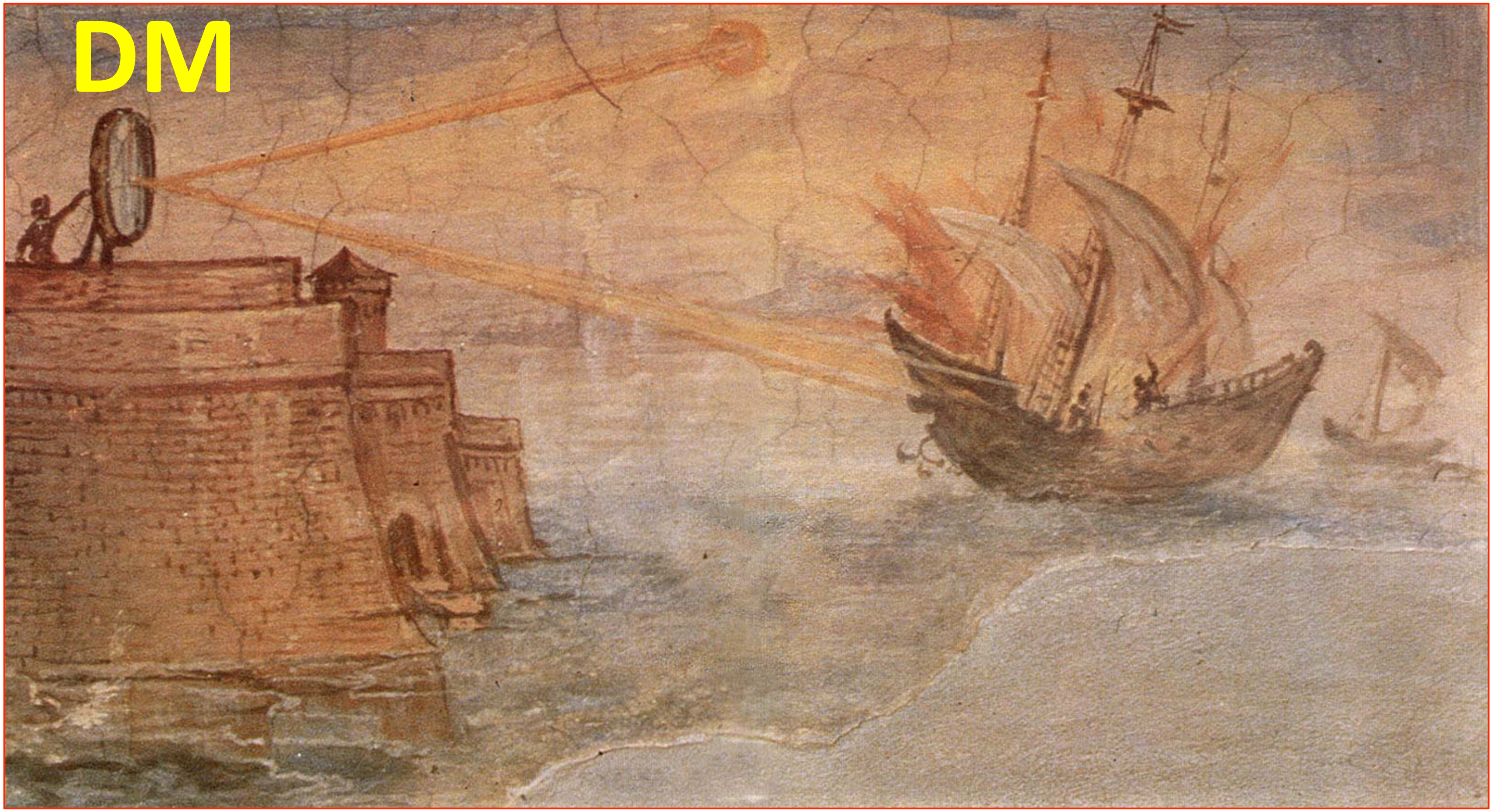

Syracuse – about 2215 years ago…

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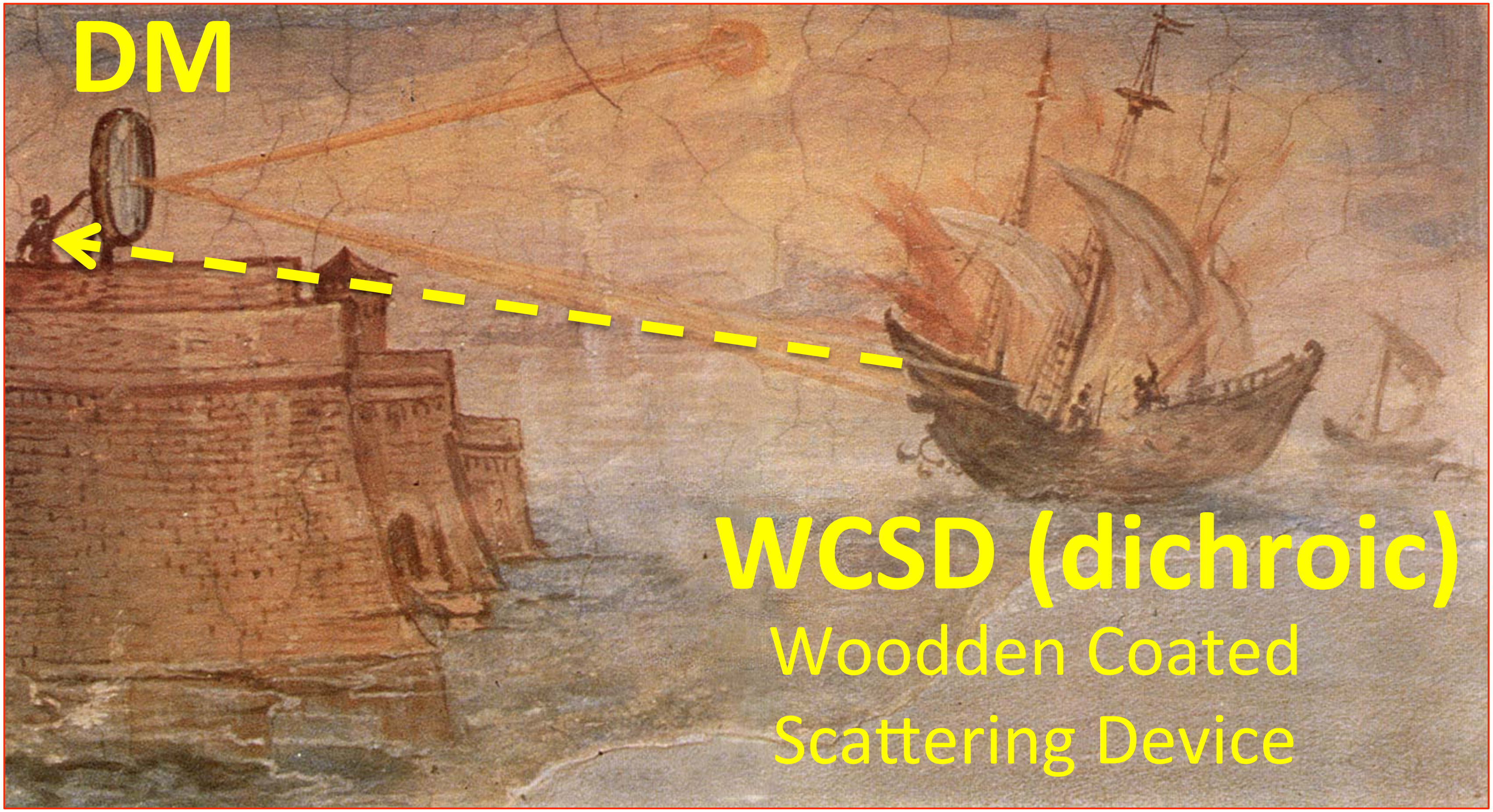
Syracuse – about 2215 years ago…



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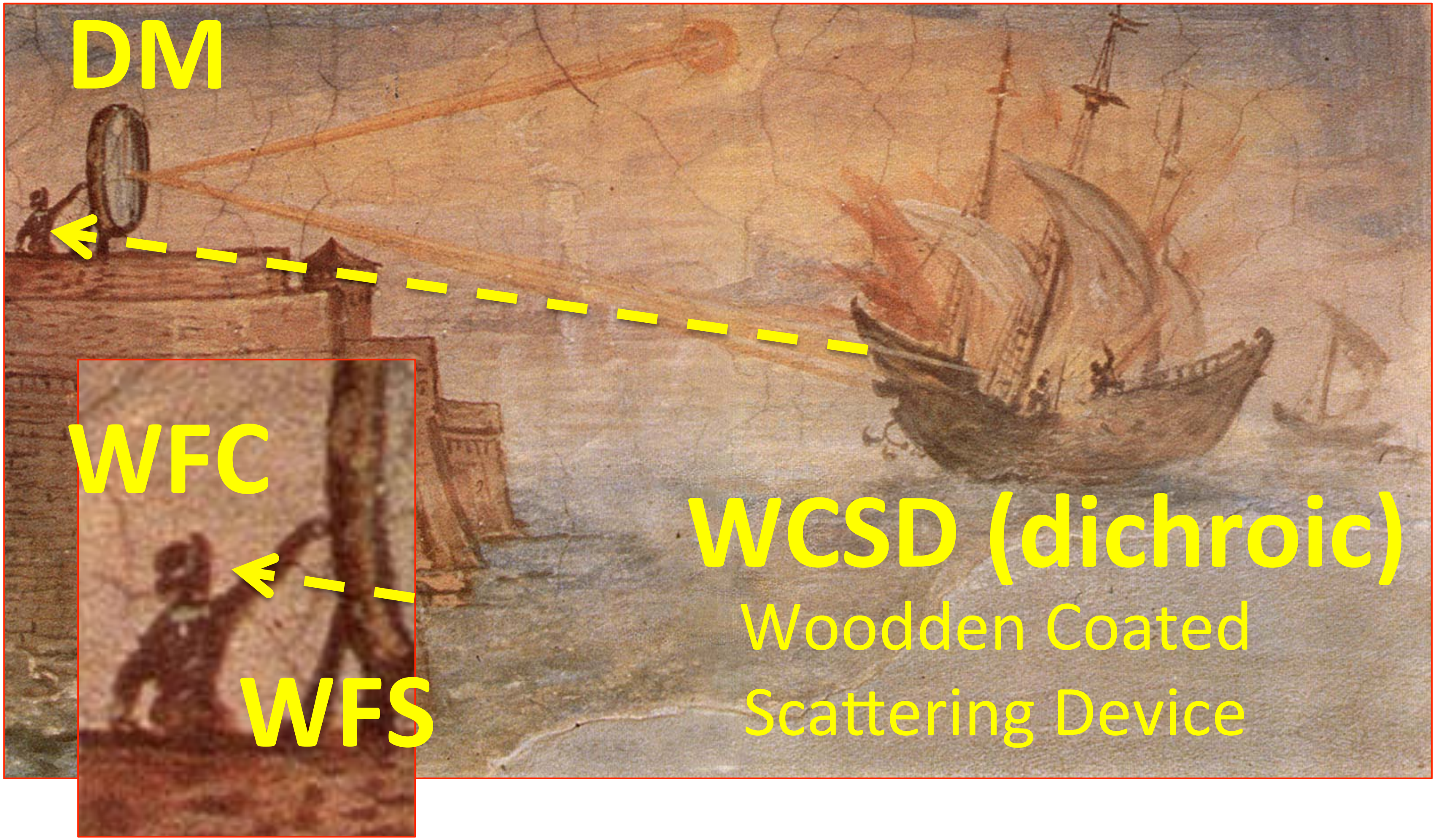
Syracuse – about 2215 years ago…



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California – about 62 years ago…

PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 65 | October 1953 | No. 386

THE POSSIBILITY OF COMPENSATING
ASTRONOMICAL SEEING

H. W. Babcock

Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

California – about 62 years ago…

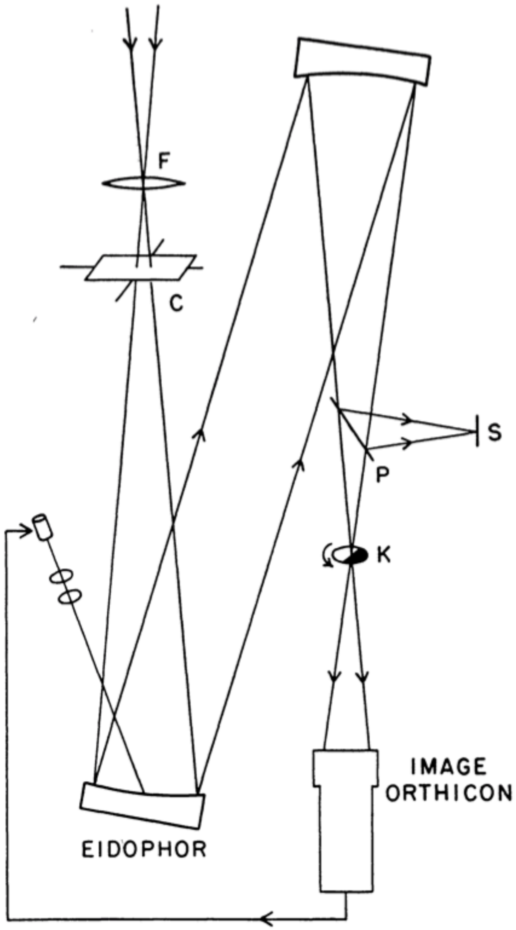

FIG. 1.—Schematic diagram of seeing compensator. A schlieren image of the telescope objective, formed on the image orthicon, is transferred electronically in the form of a modulated electric charge to the surface of the oil film covering the Eidophor mirror. This feed-back process results in the correction of ray deviations due either to atmospheric turbulence or to optical imperfections. *F* is a field lens and *C* is a fast guider for centering the control star on the knife-edge, *K*. The two mirrors are off-axis paraboloids.

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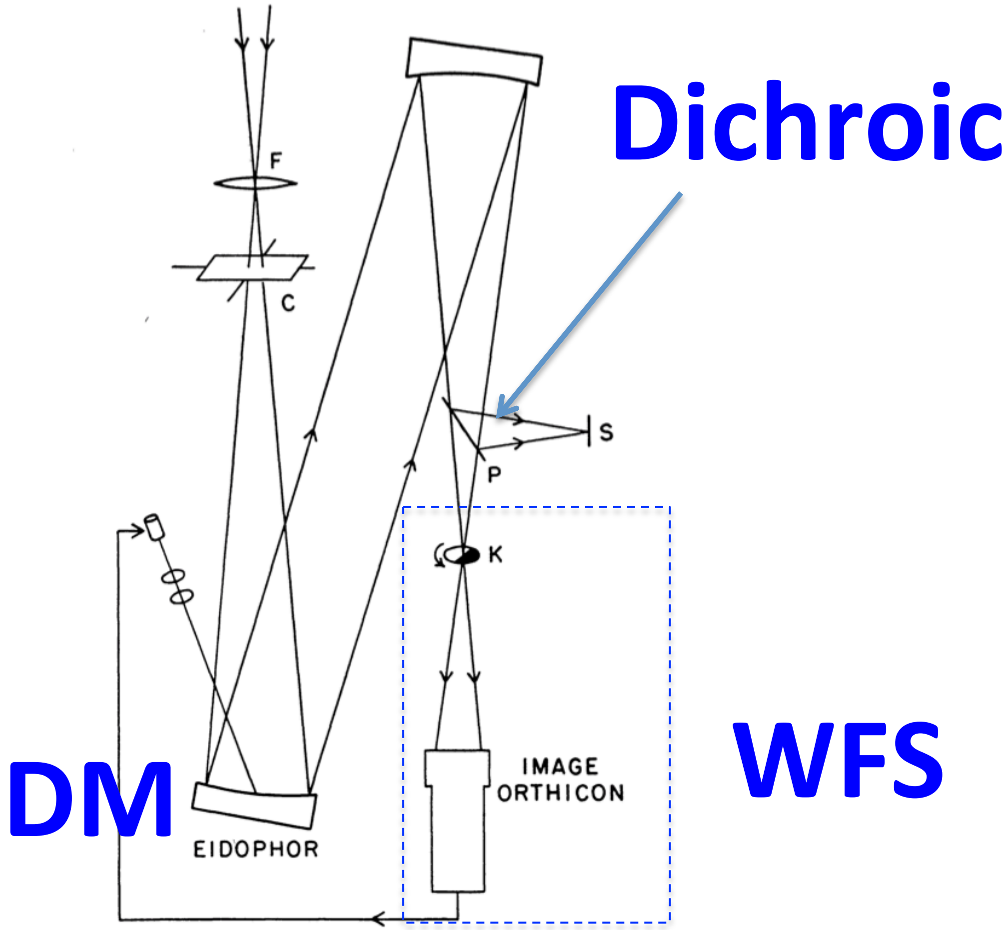
California – about 62 years ago…



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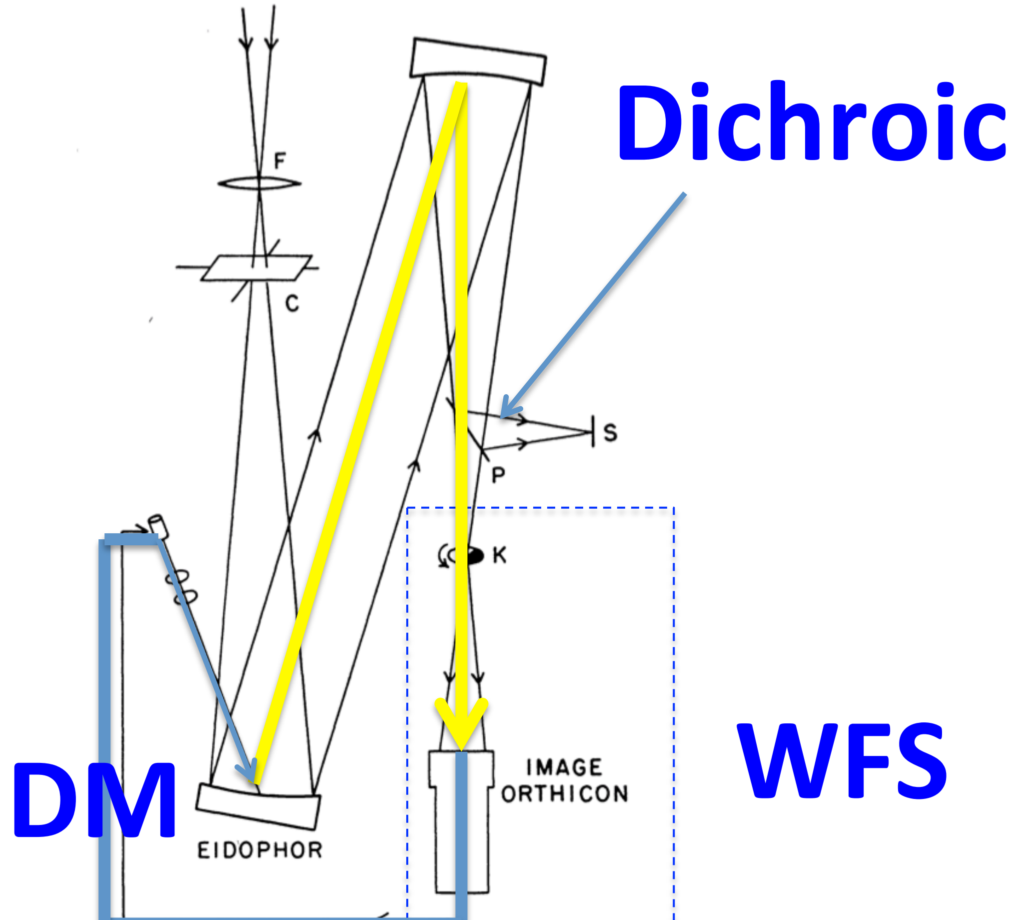

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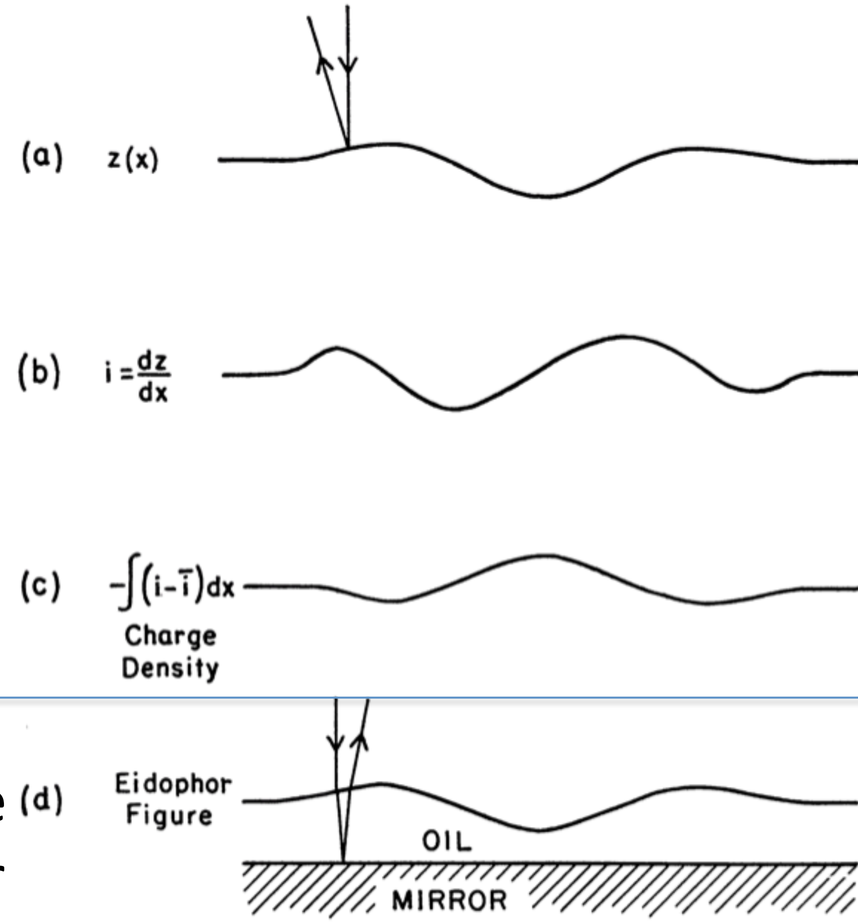
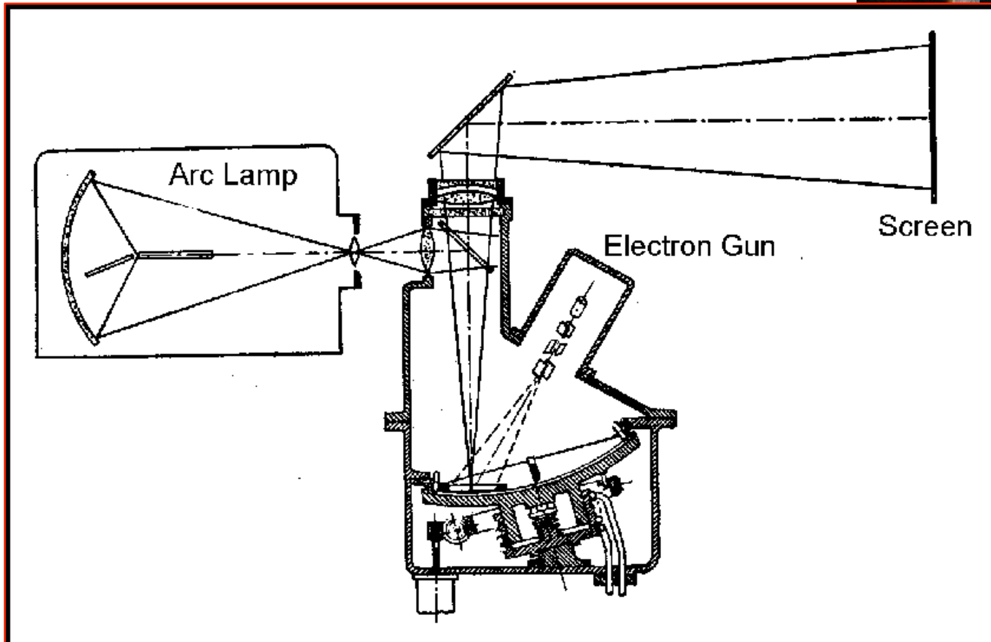


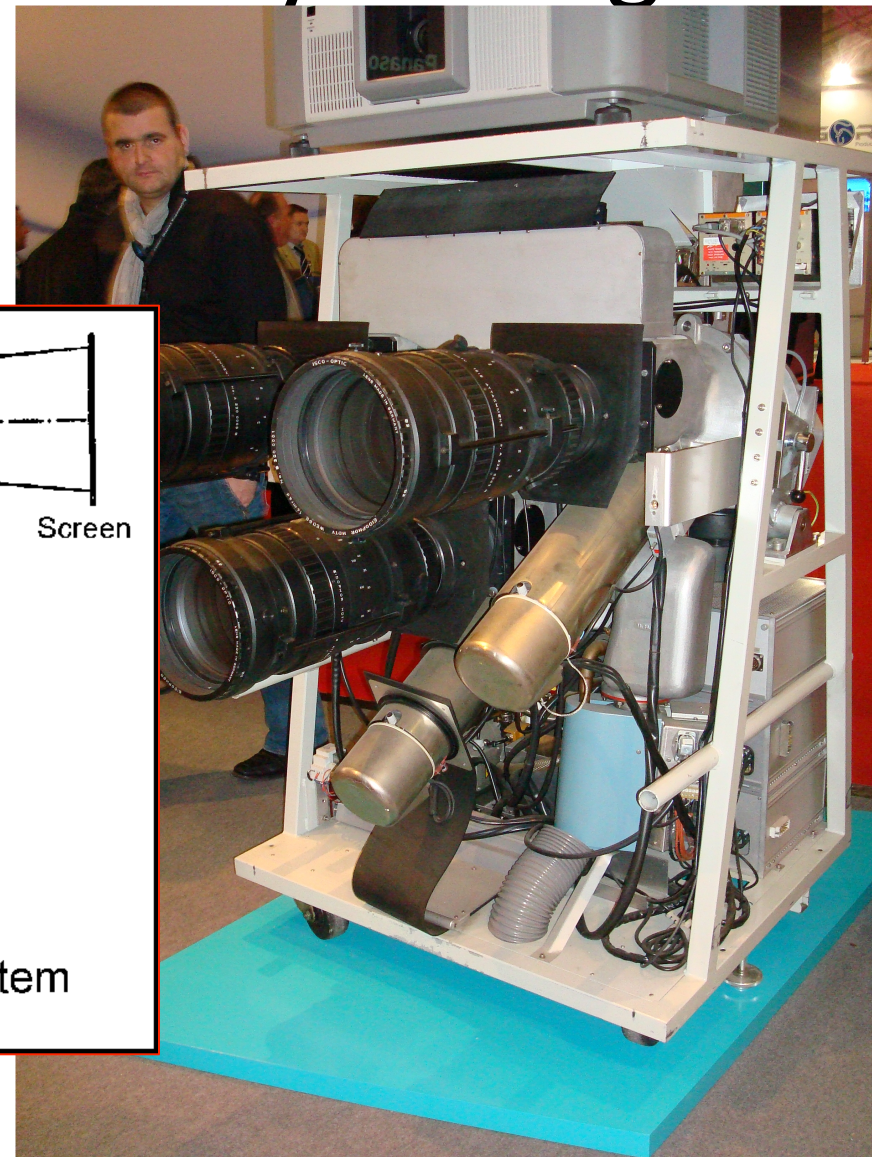
Resembling a variable Thickness Mangin mirror

FIG. 2.—(*a*) Cross section of corrugations in effective figure of telescope objective. (*b*) Corresponding intensity pattern observed in knife-edge image. (*c*) Integrated photoelectric current along trace of raster. (*d*) Resulting deformation of Eidophor figure, showing correction of deviated ray.

California – about 62 years ago…



Improved Eidophor System

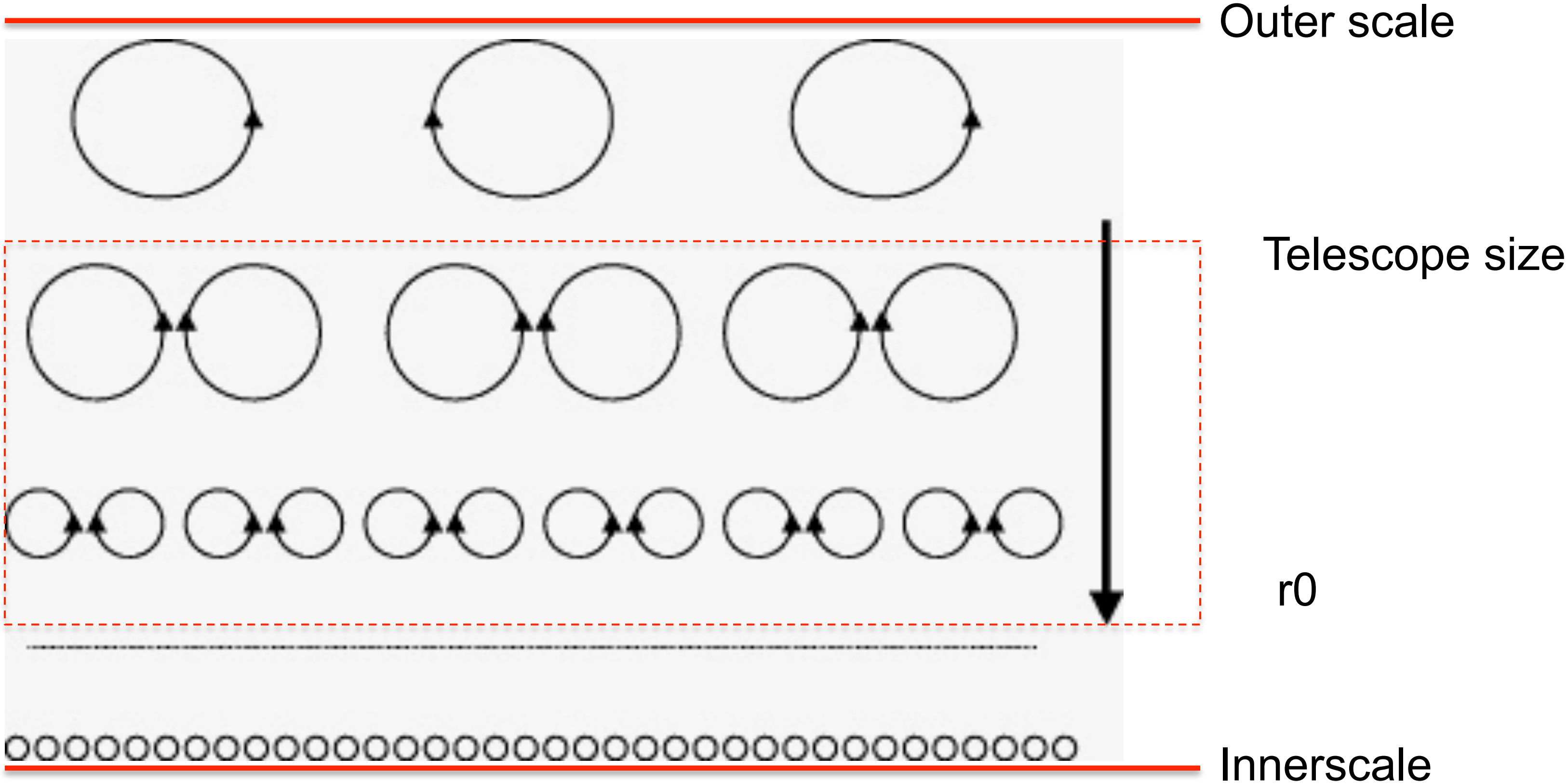


Kolmogorov

Andrey Kolmogorov

Born	Andrey Nikolaevich Kolmogorov 25 April 1903 Tambov, Russian Empire
Died	20 October 1987 (aged 84) Moscow, Soviet Union
Citizenship	Soviet Union
Nationality	Soviet Union
Fields	Mathematics

Kolmogorov



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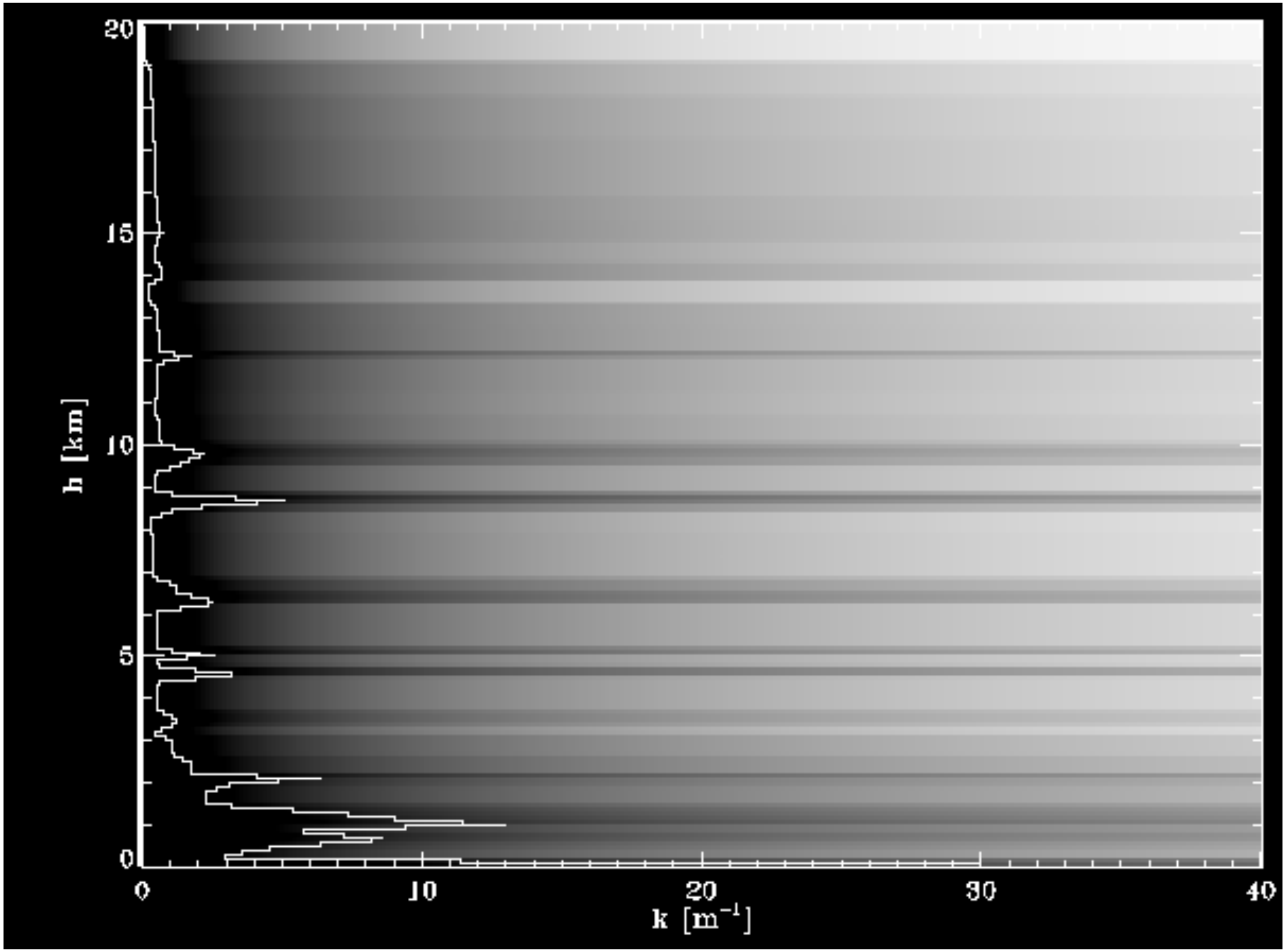
A 2D plot of turbulence



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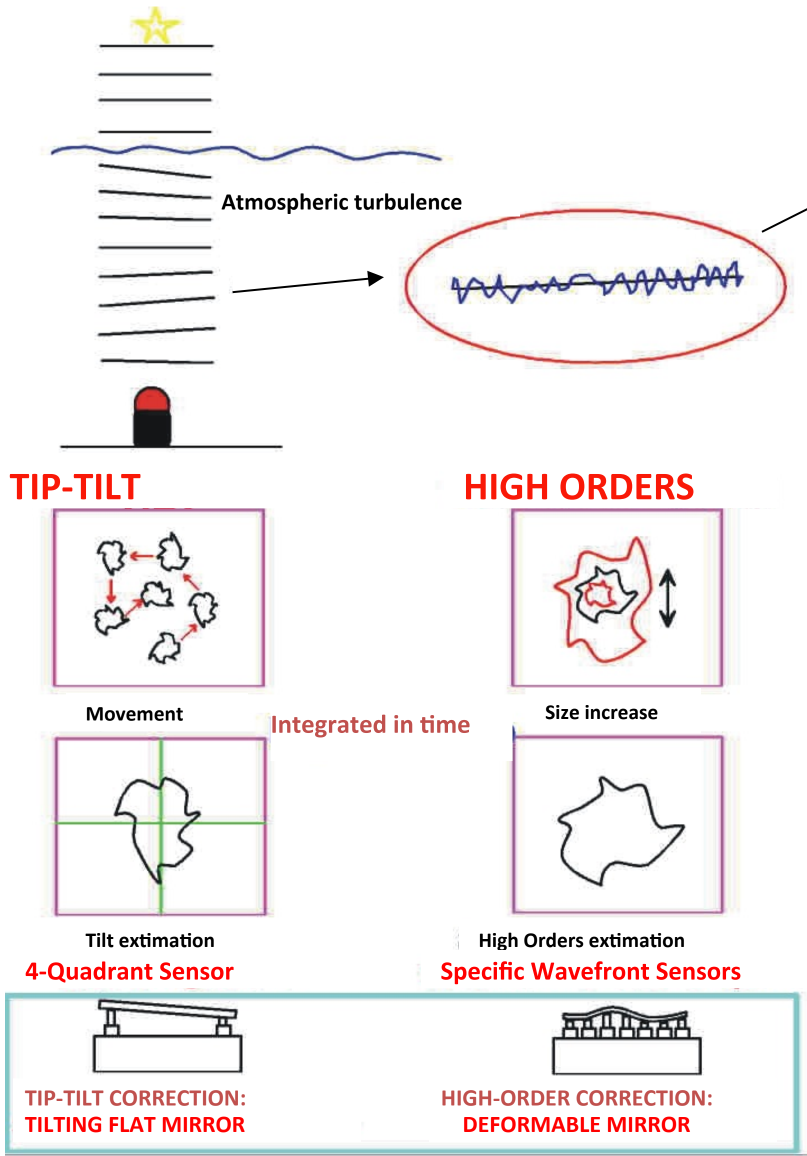

TIP-TILT: AVERAGE OF
ALL THE DEFORMATIONS!!

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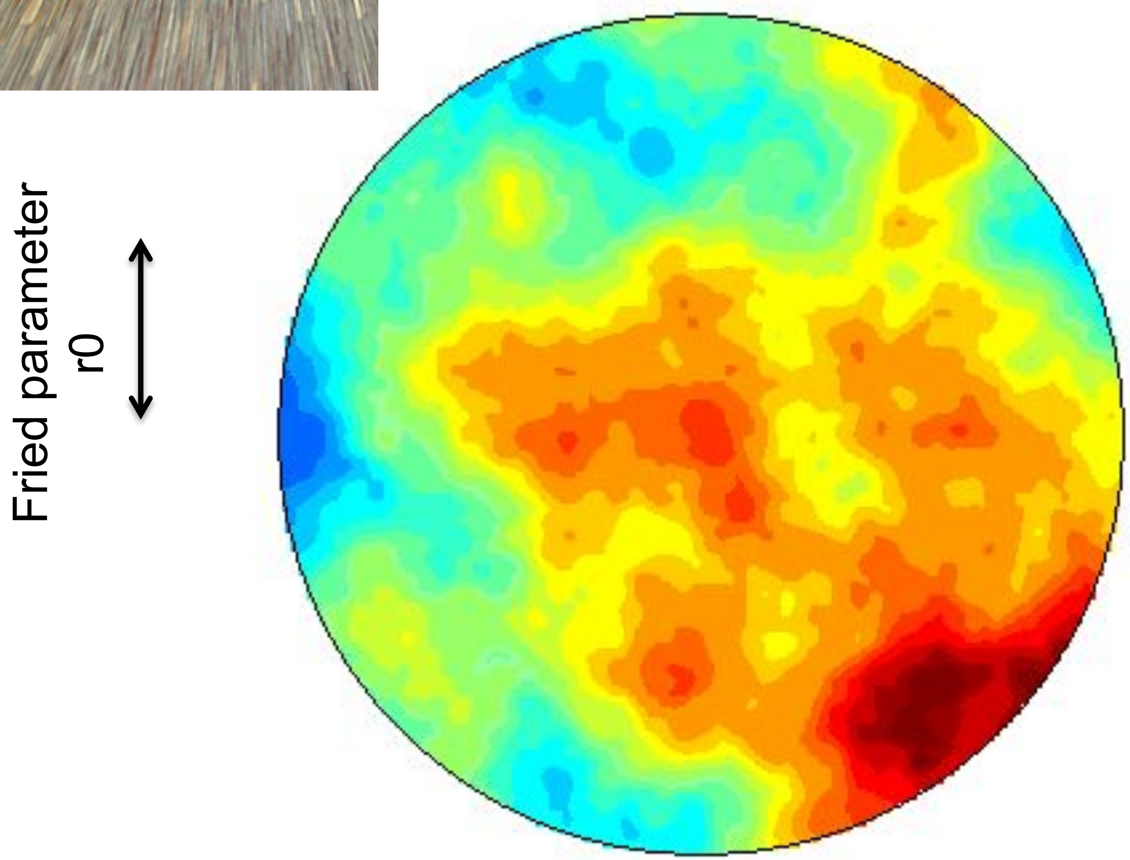
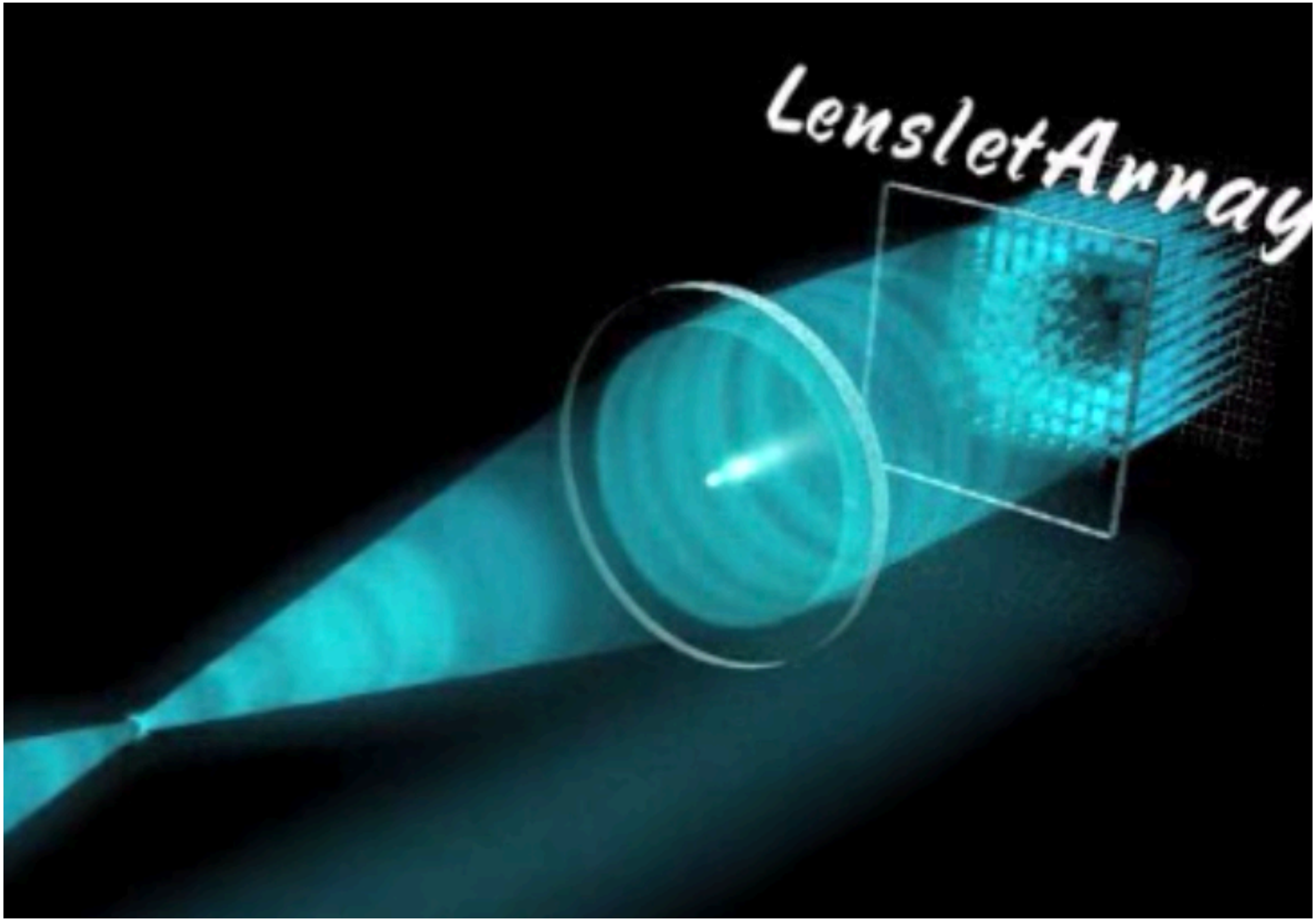
Our enemy… some figures



One rad of phase is our "unit"

Arizona – about 44 years ago…



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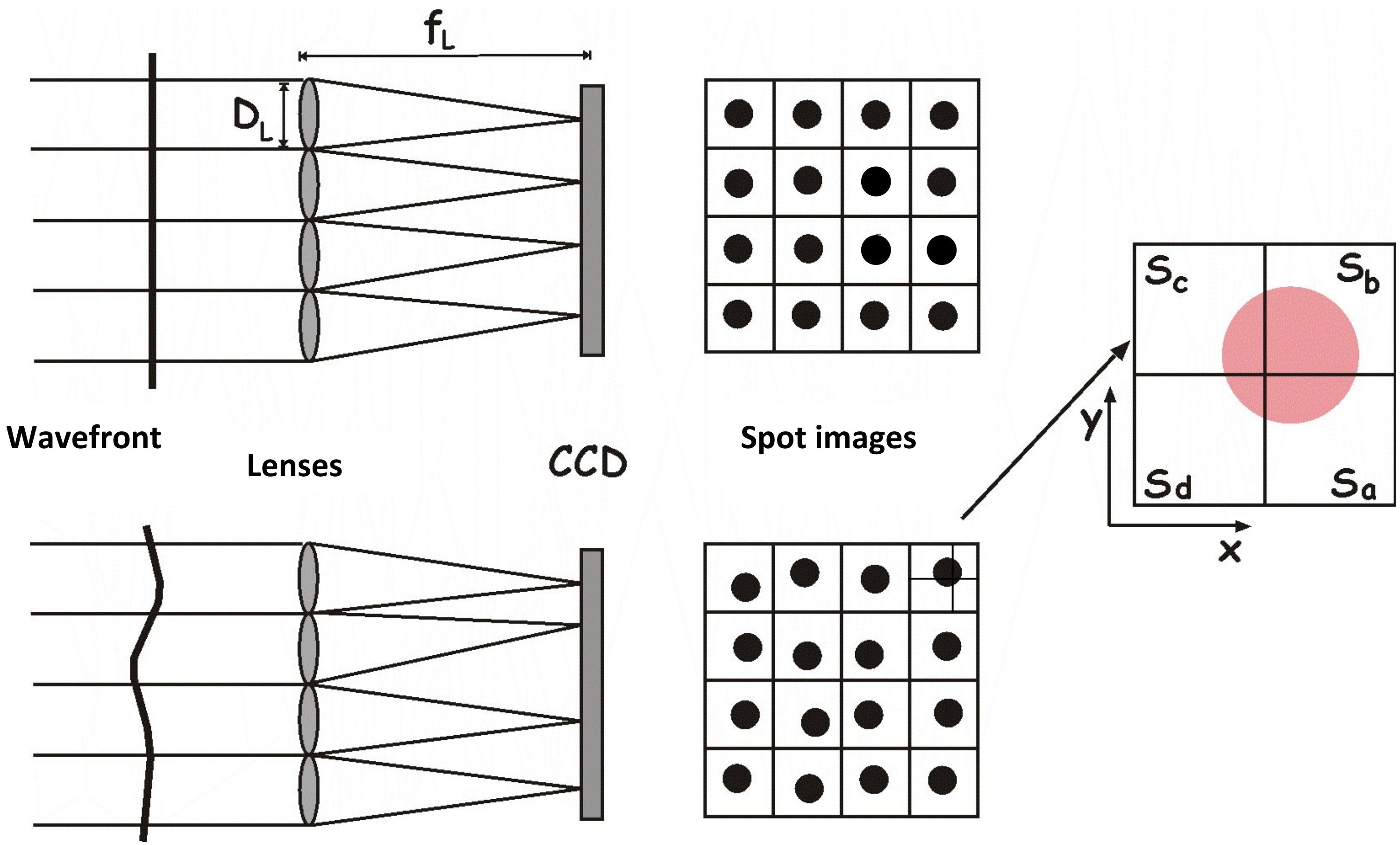
Arizona – about 44 years ago…



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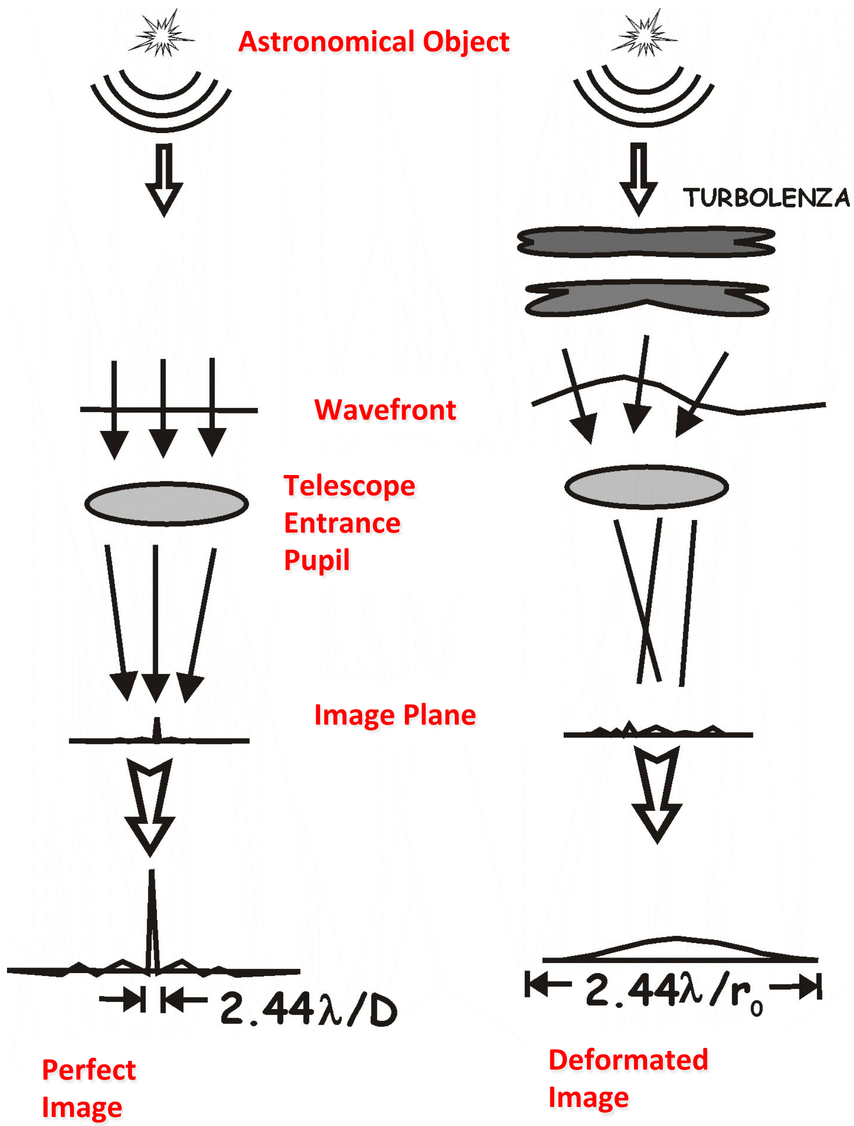

FRIED Parameter

$$r_0 \propto \lambda^{6/5}\left[\int_0^\infty dh\, C_n^2(h)\right]^{-3/5}$$

Temporal behaviour of the turbulence

$$\tau_o \propto \lambda^{6/5} r_0$$

$$\tau_0 \approx 1ms$$

Strehl Ratio: PSF_{obs}/PSF_{teo}

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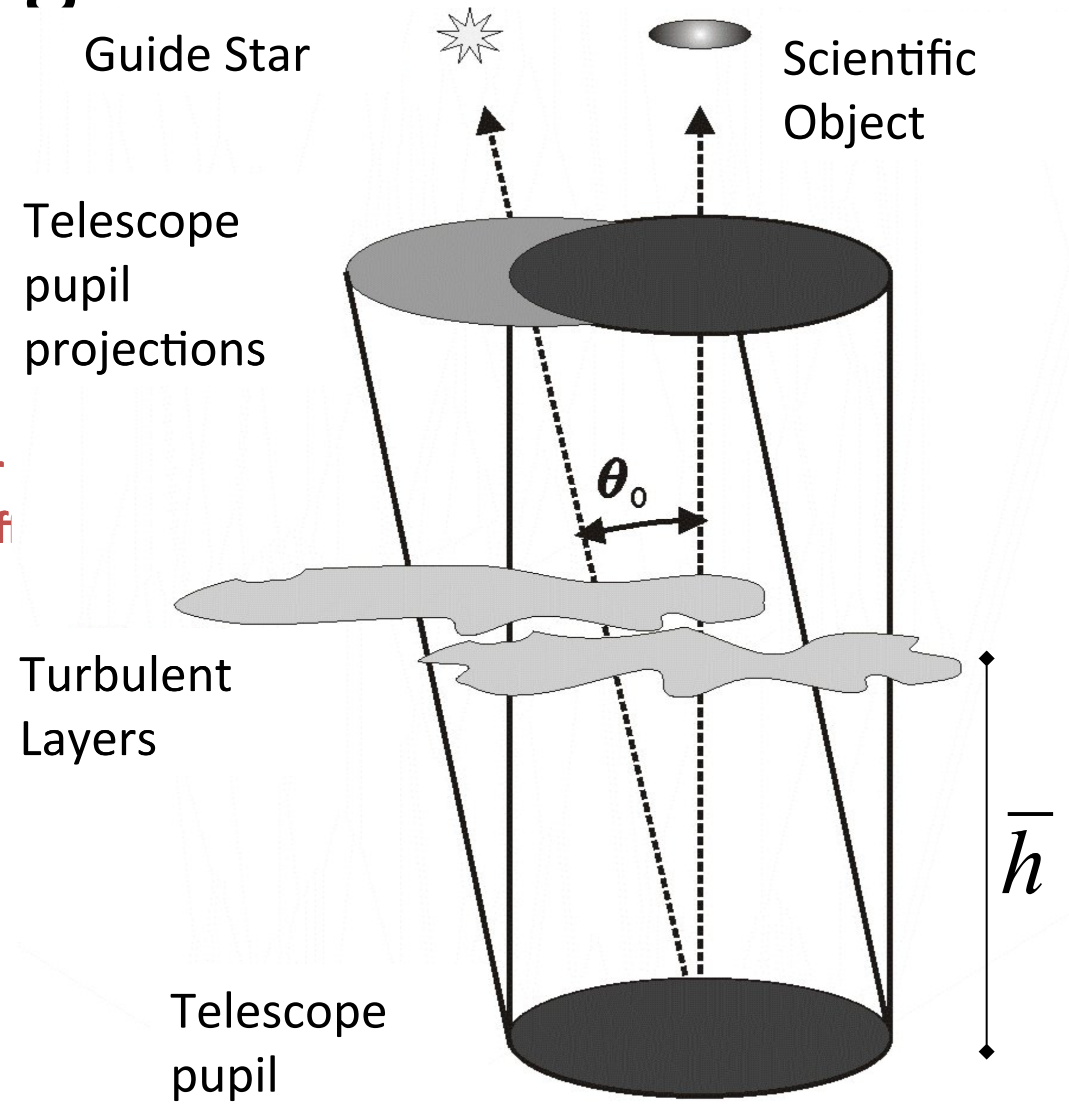
Isoplanatic angle

ISOPLANATIC ANGLE:
Angle from the reference star where the correction is still ef

$$\theta_0 \propto r_0 / \bar{h}$$



Turbulence parameters…

- Fried parameters (the size at which WF perturbation is statistically more than one radians)
- Greenwood frequency (the inverse of the time at which perturbation changes more than one radians)
- Isoplanatic angle (the angular distance between two sources whose wavefront is perturbed differently by more than a radians)

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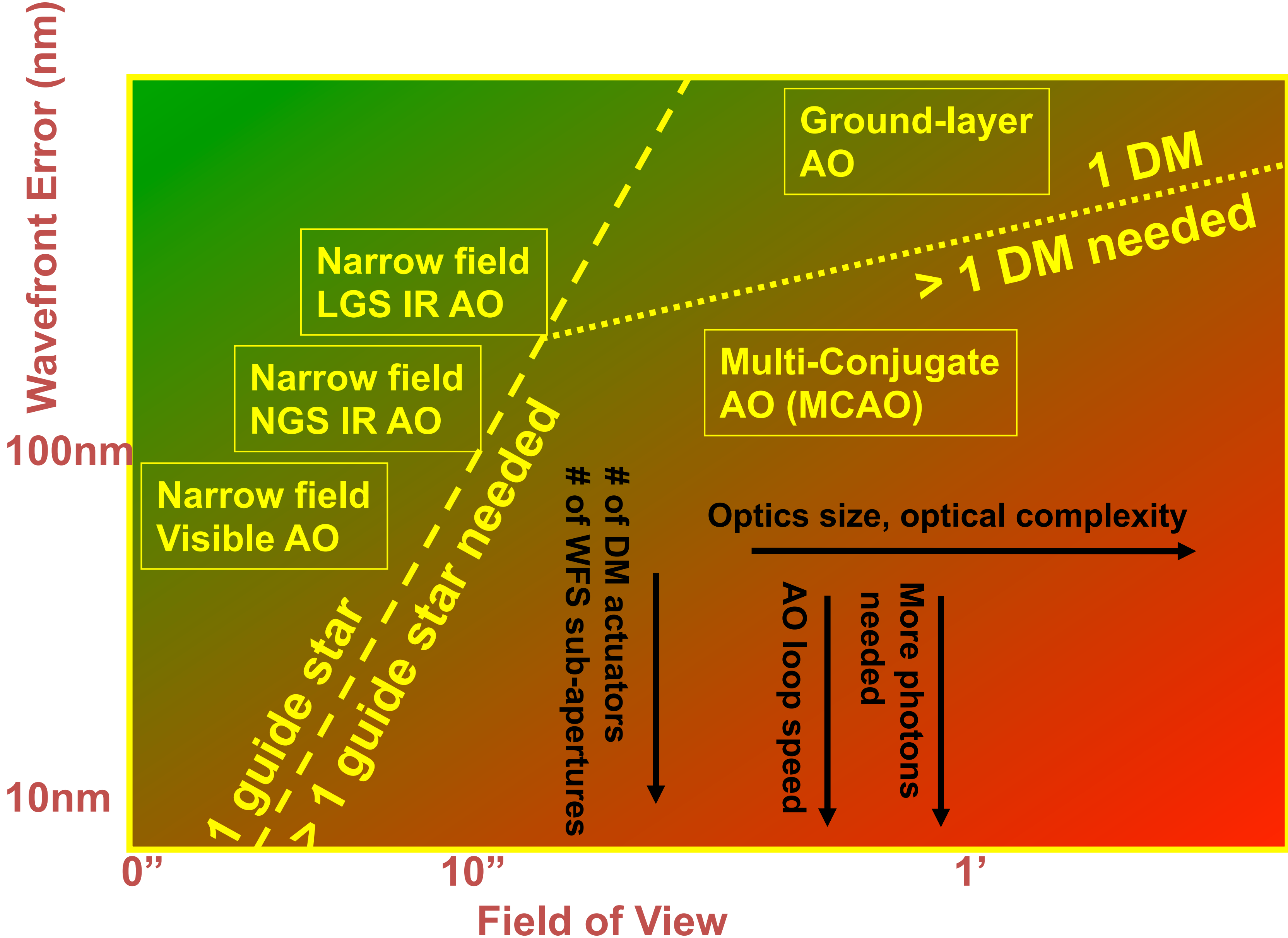

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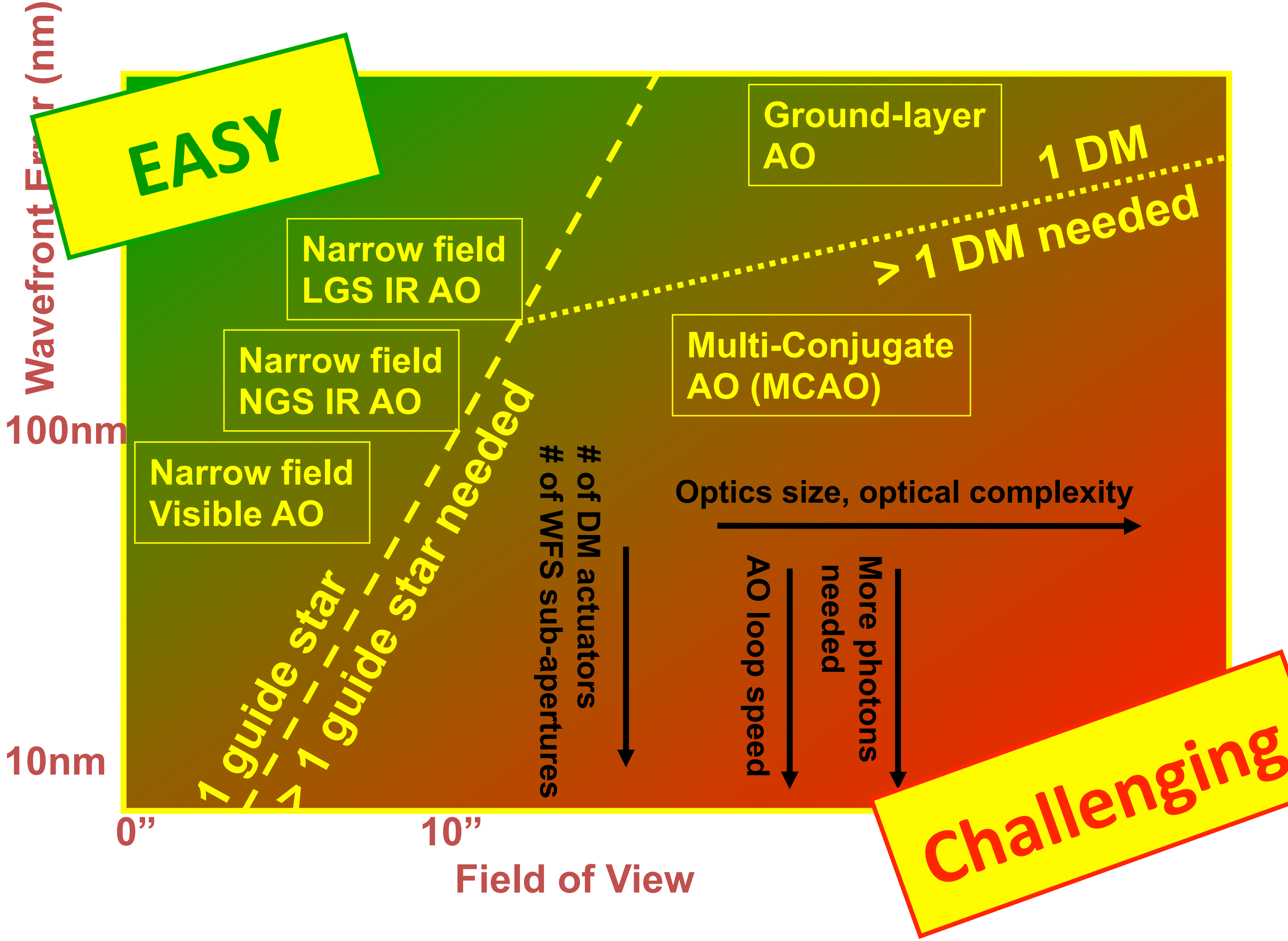

The strategic defense initiative
(propagation in the atmosphere declassified in 1991)

Kick off: March 23rd, 1983

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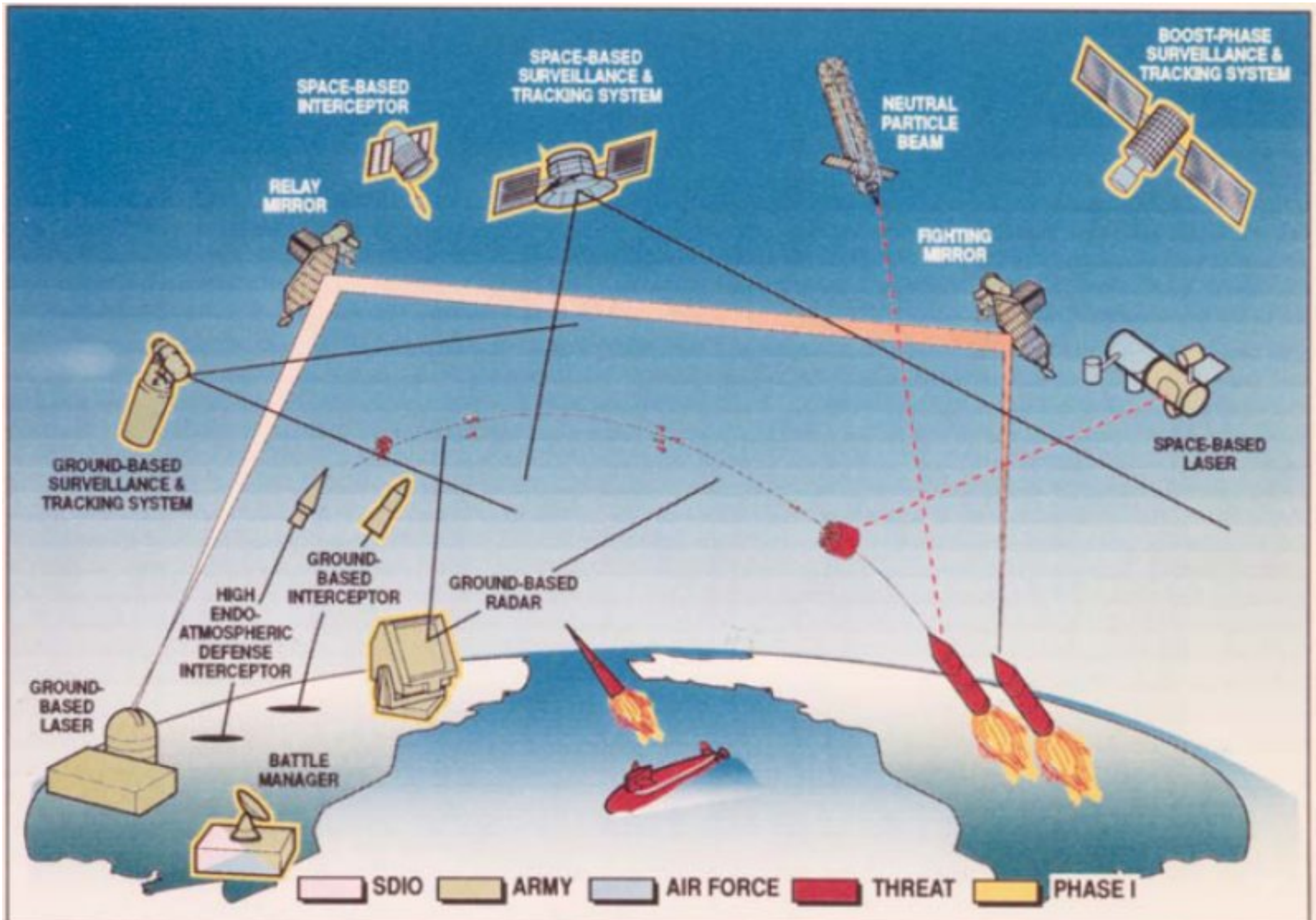
The strategic defense initiative
(propagation in the atmosphere declassified in 1991)



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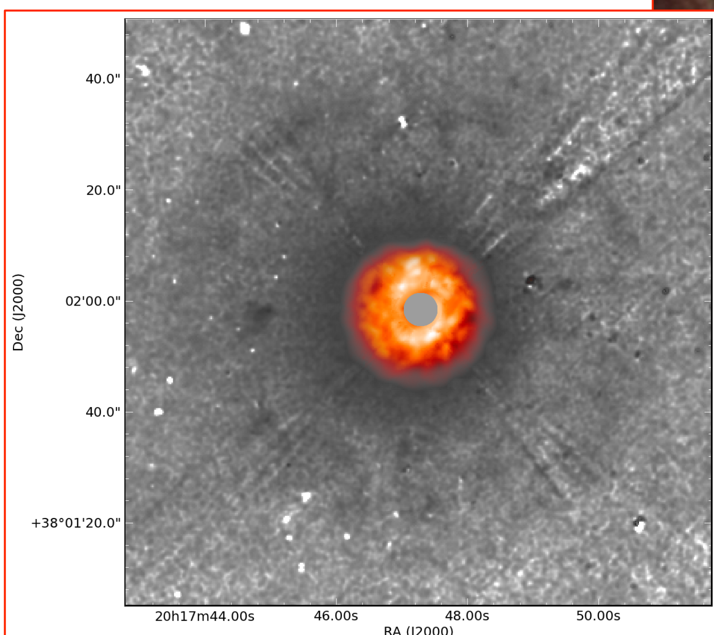
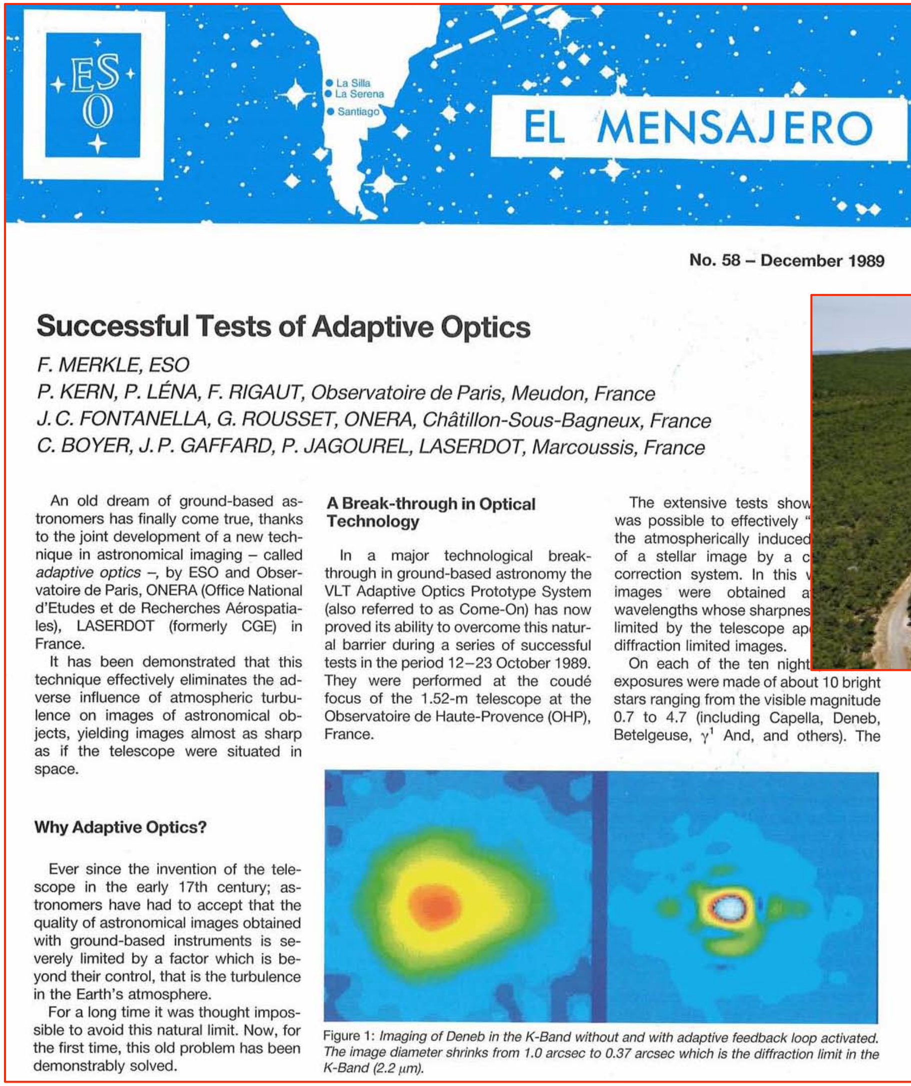


South of France – about 26 years ago


EL MENSAJERO

No. 58 – December 1989

Successful Tests of Adaptive Optics

F. MERKLE, ESO
P. KERN, P. LÉNA, F. RIGAUT, Observatoire de Paris, Meudon, France
J. C. FONTANELLA, G. ROUSSET, ONERA, Châtillon-Sous-Bagneux, France
C. BOYER, J. P. GAFFARD, P. JAGOUREL, LASERDOT, Marcoussis, France

An old dream of ground-based astronomers has finally come true, thanks to the joint development of a new technique in astronomical imaging – called *adaptive optics* –, by ESO and Observatoire de Paris, ONERA (Office National d'Etudes et de Recherches Aérospatiales), LASERDOT (formerly CGE) in France.

It has been demonstrated that this technique effectively eliminates the adverse influence of atmospheric turbulence on images of astronomical objects, yielding images almost as sharp as if the telescope were situated in space.

Why Adaptive Optics?

Ever since the invention of the telescope in the early 17th century; astronomers have had to accept that the quality of astronomical images obtained with ground-based instruments is severely limited by a factor which is beyond their control, that is the turbulence in the Earth's atmosphere.

For a long time it was thought impossible to avoid this natural limit. Now, for the first time, this old problem has been demonstrably solved.

A Break-through in Optical Technology

In a major technological breakthrough in ground-based astronomy the VLT Adaptive Optics Prototype System (also referred to as Come-On) has now proved its ability to overcome this natural barrier during a series of successful tests in the period 12–23 October 1989. They were performed at the coudé focus of the 1.52-m telescope at the Observatoire de Haute-Provence (OHP), France.

The extensive tests show was possible to effectively " the atmospherically induced of a stellar image by a c correction system. In this w images were obtained a wavelengths whose sharpnes limited by the telescope ap diffraction limited images.

On each of the ten night exposures were made of about 10 bright stars ranging from the visible magnitude 0.7 to 4.7 (including Capella, Deneb, Betelgeuse, γ^1 And, and others). The

Figure 1: *Imaging of Deneb in the K-Band without and with adaptive feedback loop activated. The image diameter shrinks from 1.0 arcsec to 0.37 arcsec which is the diffraction limit in the K-Band (2.2 μm).*

...and then at ESO – LaSilla 3.6m
With Come-On and Come-On+

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Deformable Mirrors

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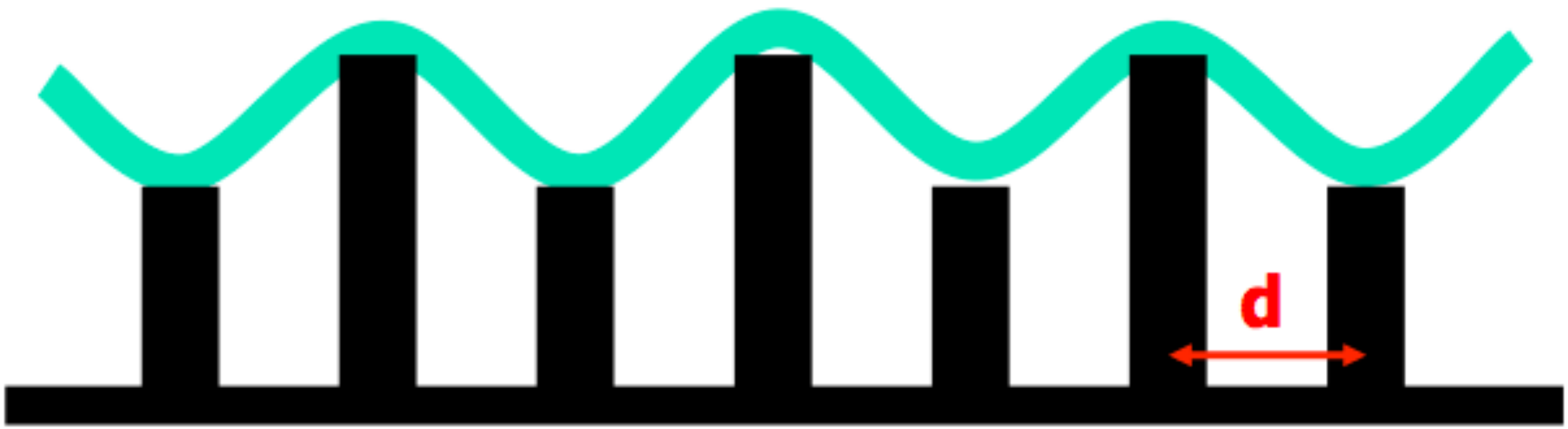
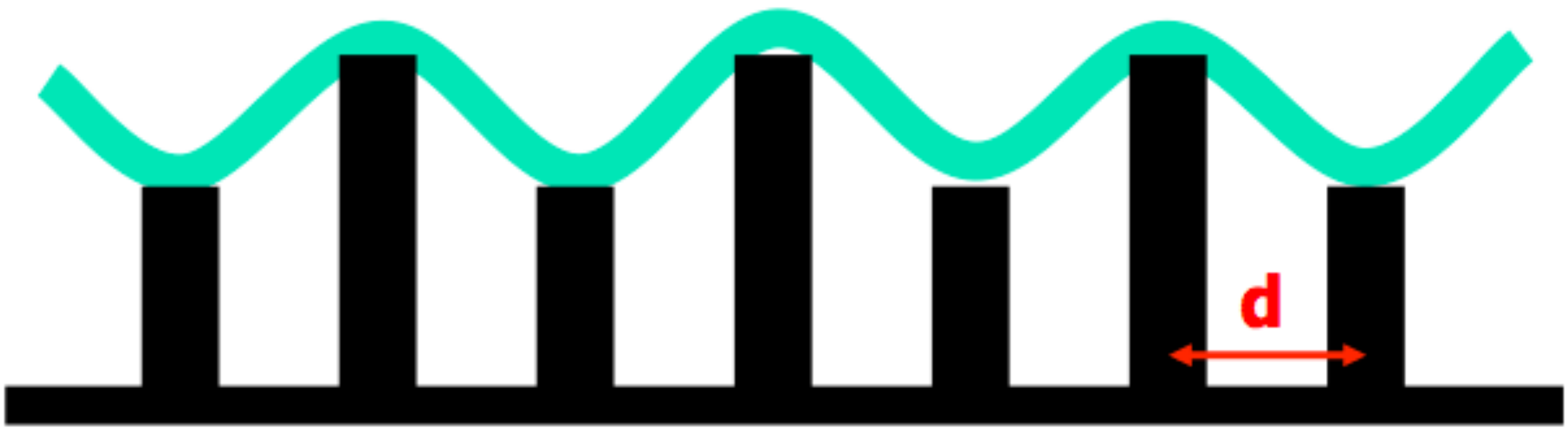
Deformable Mirrors



Densità attuatori

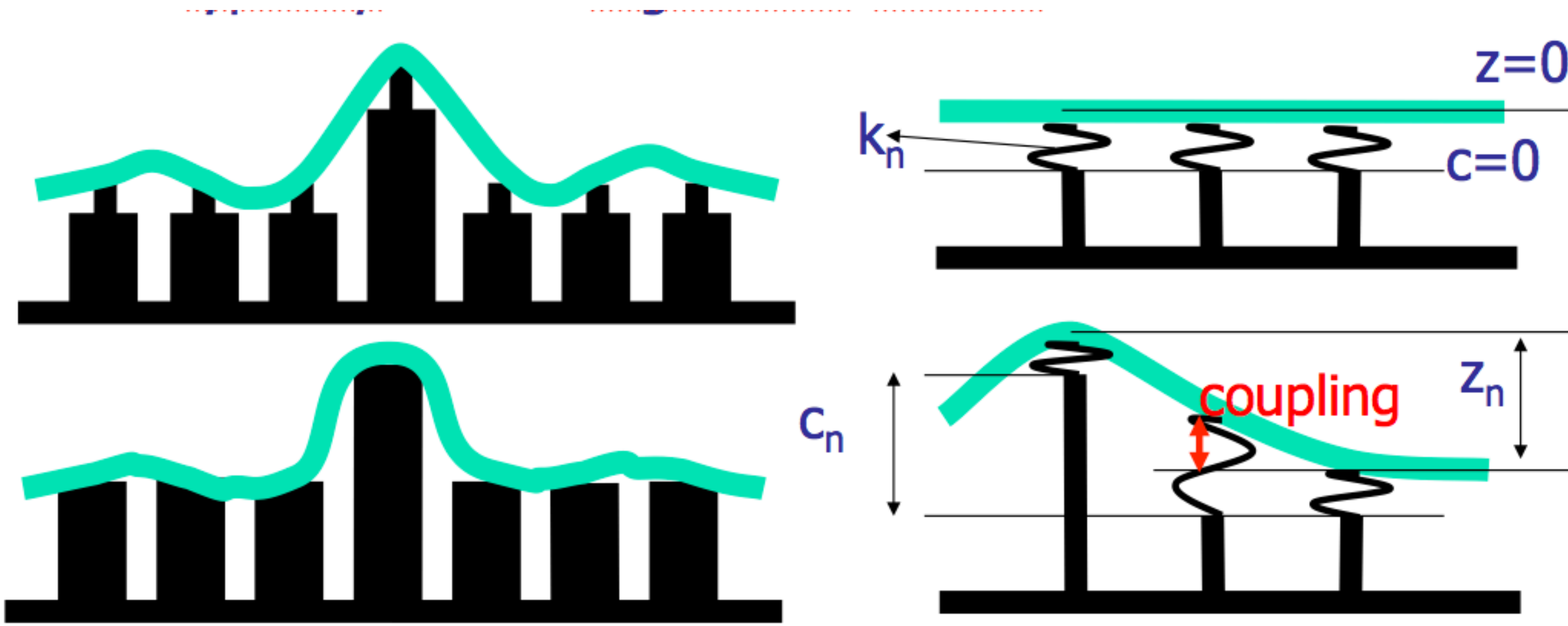
Deformable Mirrors



Densità attuatori

Frequenza temporale

Deformable Mirrors

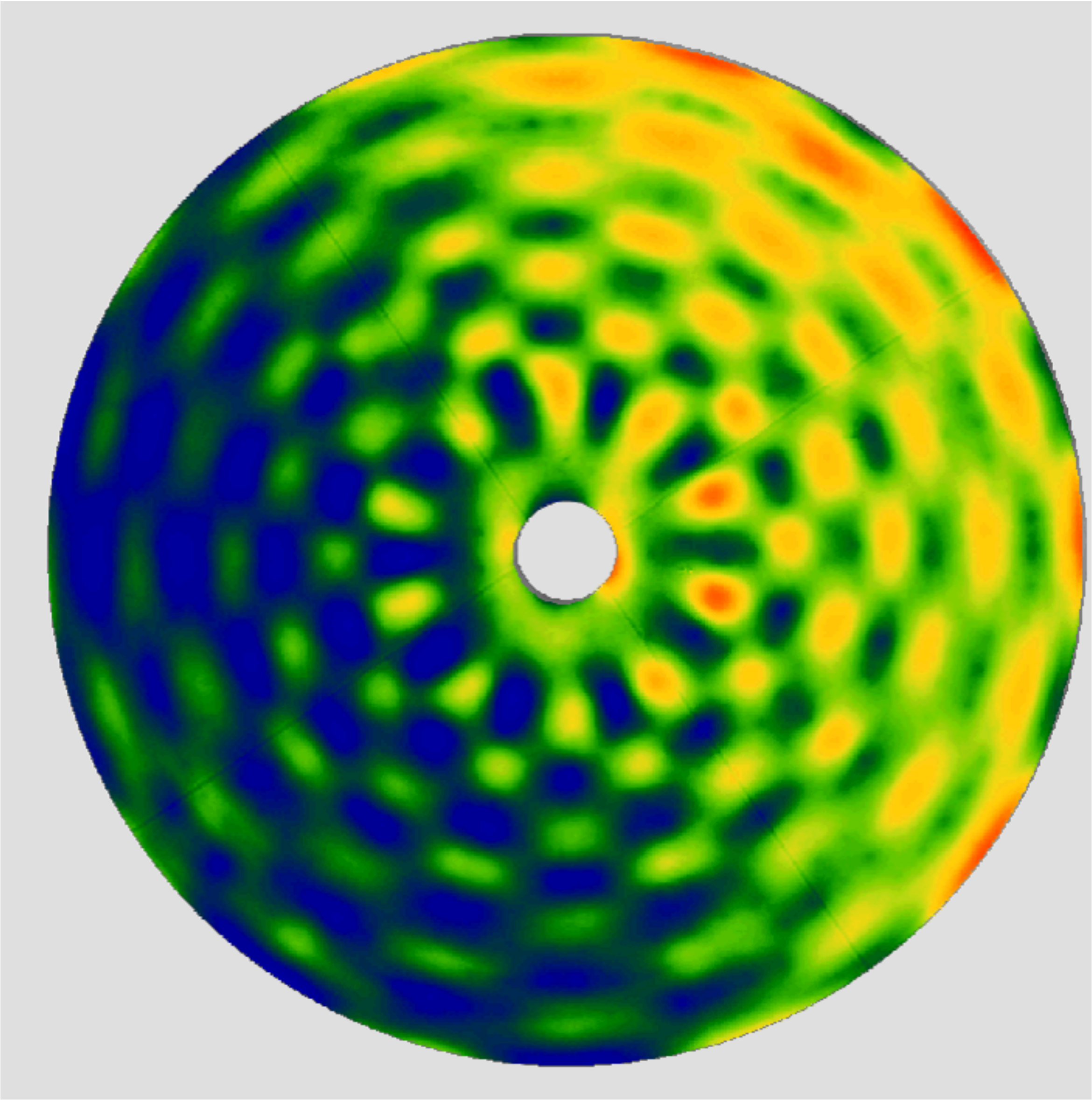


Densità attuatori

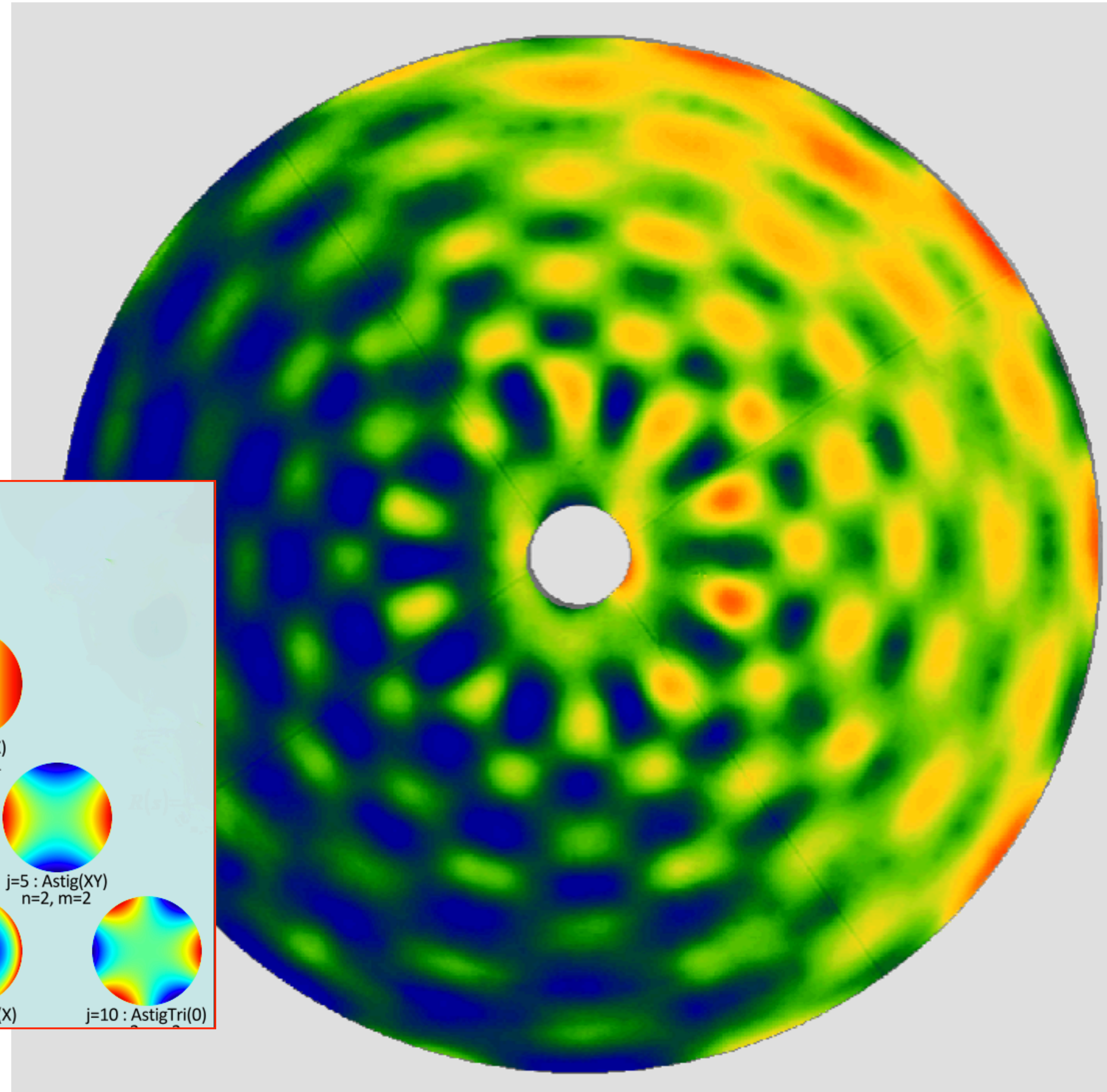
Frequenza temporale

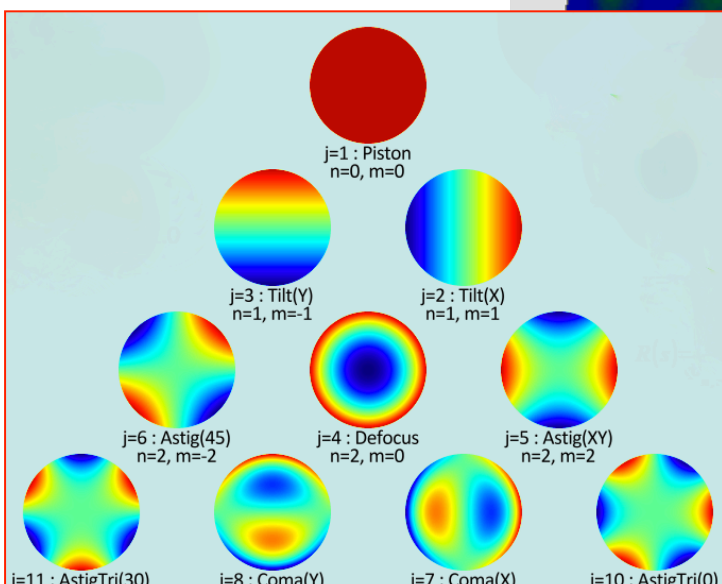
Accoppiamento

Deformable Mirrors



Deformable Mirrors





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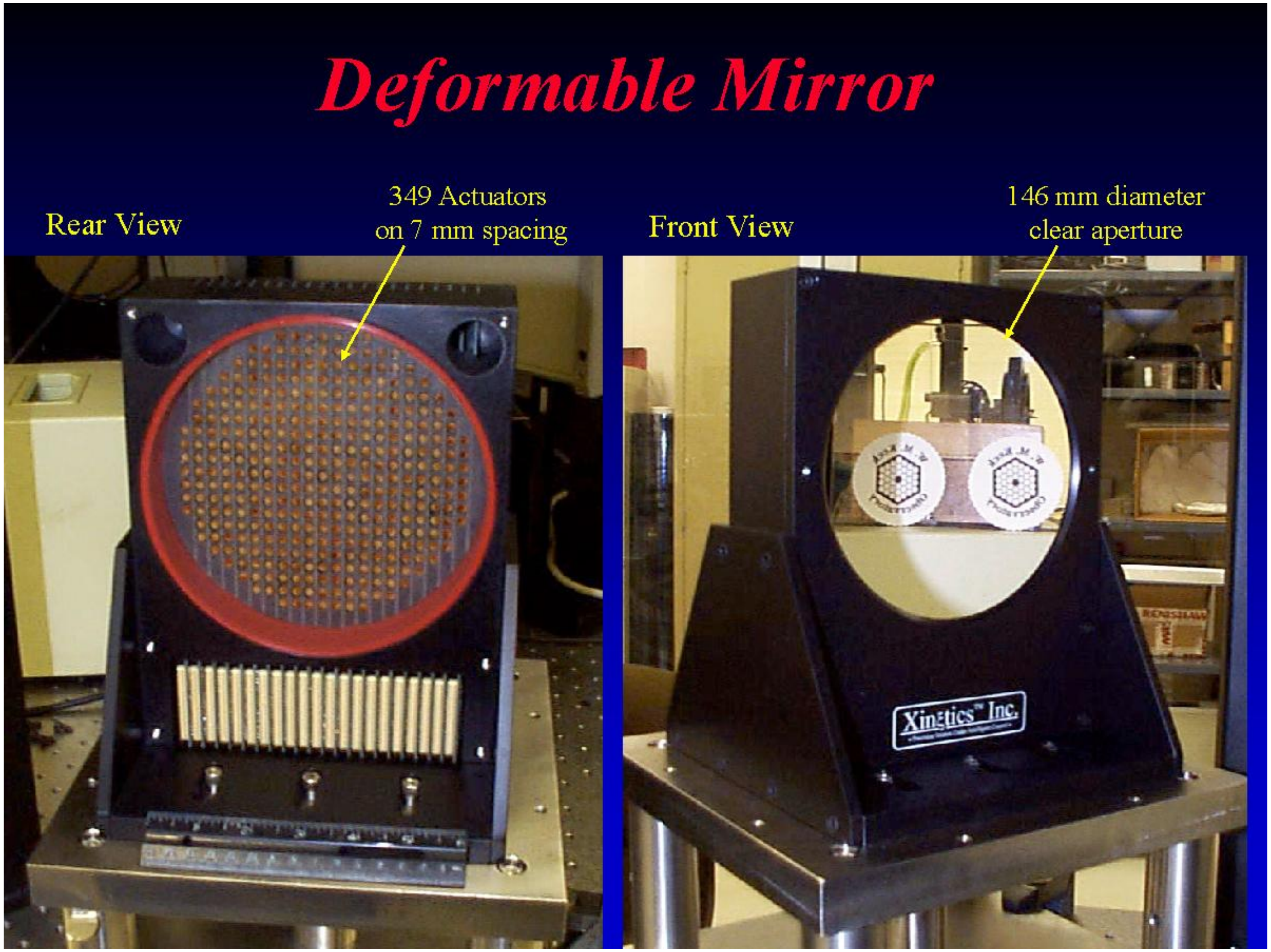

Deformable Mirrors

Florence – about 22 years ago

Active and adaptive optics: ESO Proceedings of the ICO-16 August 2-5, 1993, Garching

A STUDY OF AN ADAPTIVE SECONDARY MIRROR

P. Salinari, C. Del Vecchio, V. Biliotti
Arcetri Astrophysical Observatory
Florence, Italy

Abstract

We report the study of an adaptive secondary mirror providing high order correction of the wave front perturbed by propagation through the atmosphere (up to approximately 1000 degrees of freedom). The device, based on electromagnetic actuators and capacitive position sensors, can also provide chopping with simultaneous correction of the induced coma, and can be used statically for correcting low order aberrations (active optics). We discuss the characteristics of the most important components, such as actuators, sensors, and the ultra thin mirror, and report the expected performances in the three above mentioned modes of operation (adaptive, chopping, and active).

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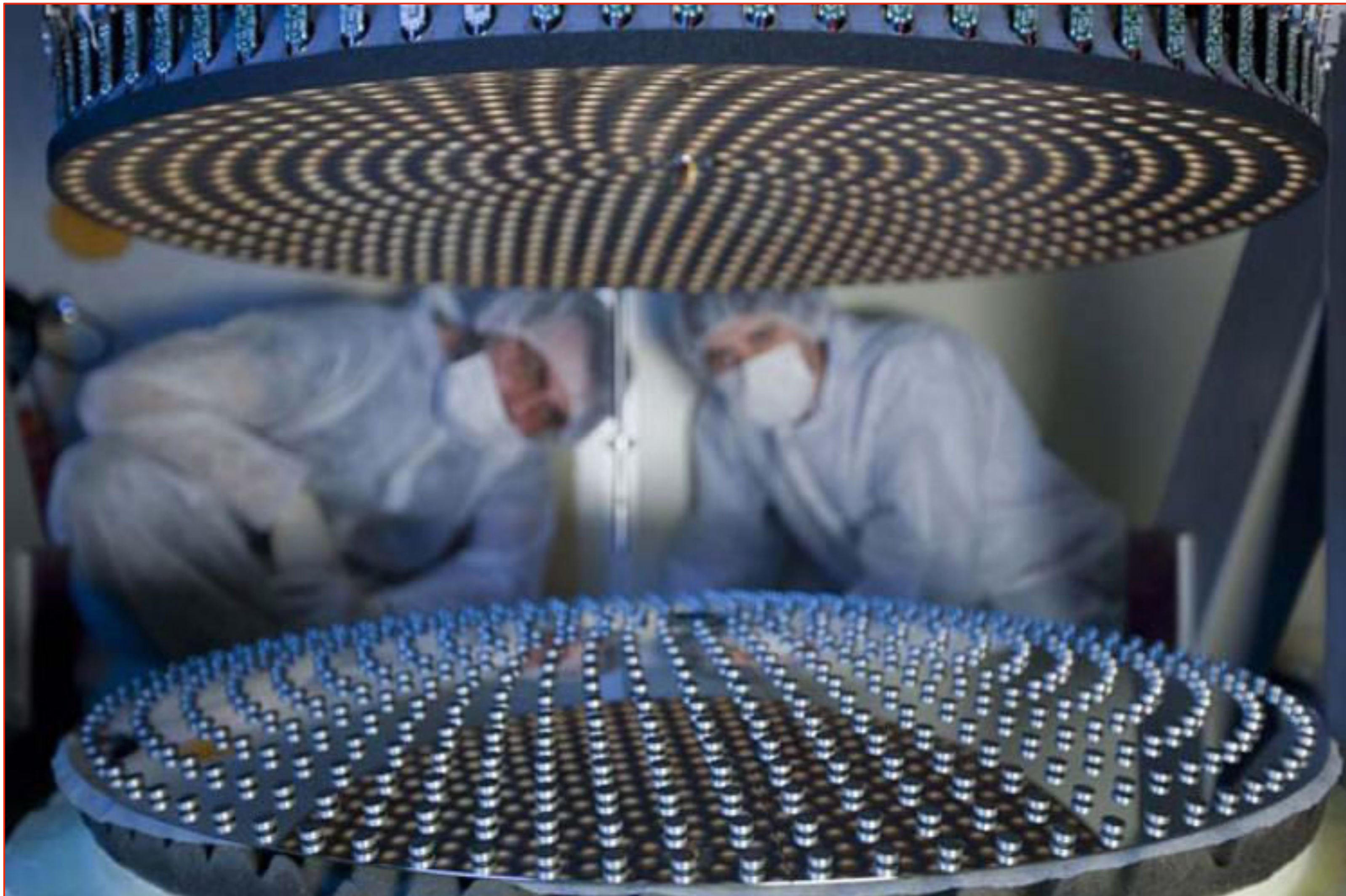
Secondary Adaptive Mirrors



Layers for an artificial reference

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.

Layers for an artificial reference

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}	(4.5×10^{-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													
1493, 1744													
2000–4000													
2160, etc.													
3371, etc.													
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})	3×10^{-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})	5.8×10^{-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}	<5×10^{-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})	9.5×10^{-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.

5893 $Na(^2P)$ 30 kR 92

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MONTHLY NOTICES
OF THE
ROYAL ASTRONOMICAL SOCIETY

Vol. 93 No. 9. Supplementary Number

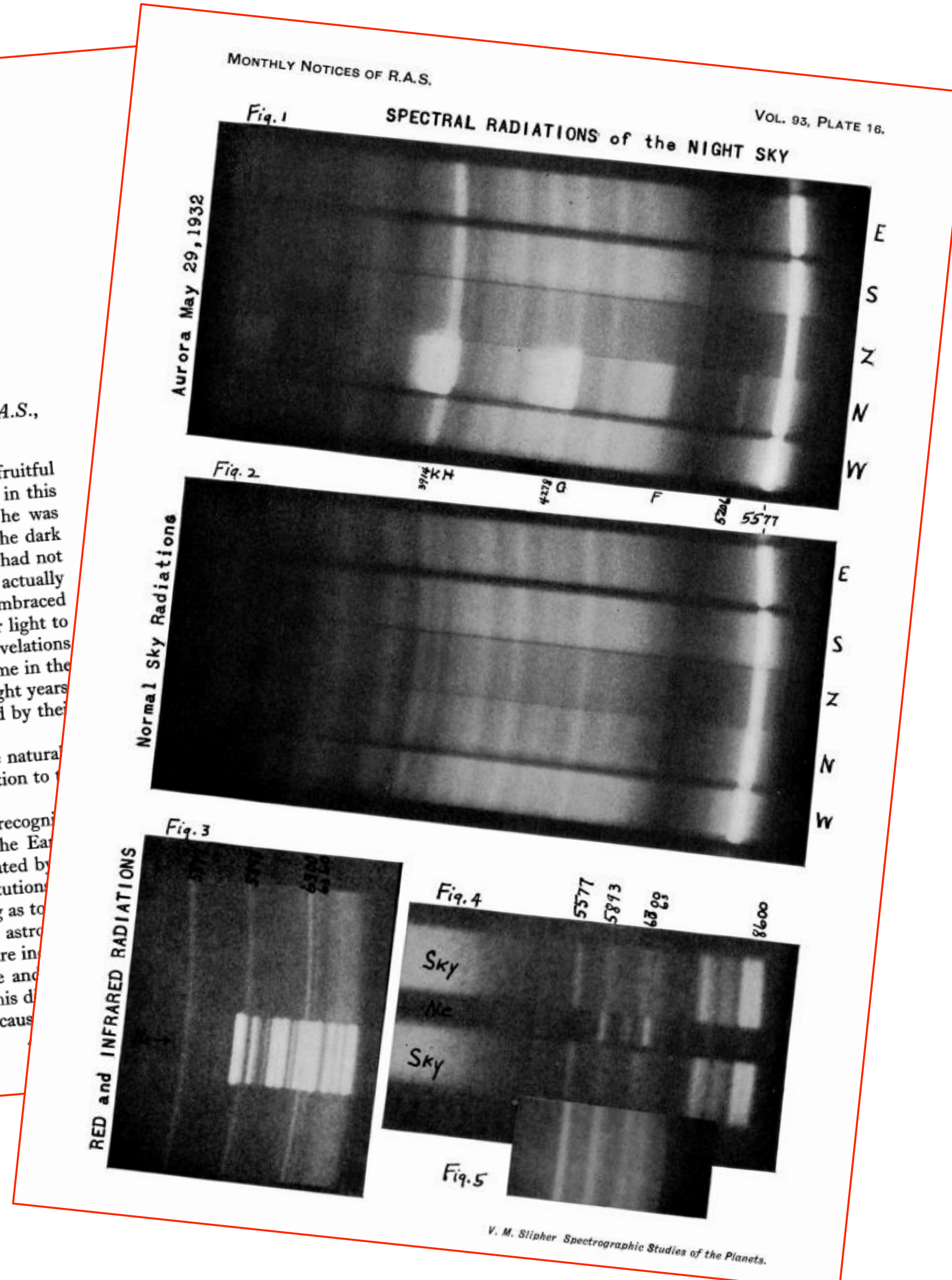
SPECTROGRAPHIC STUDIES OF THE PLANETS.

(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 the spectrally analysed light.

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

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



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!

Layers for an artificial reference

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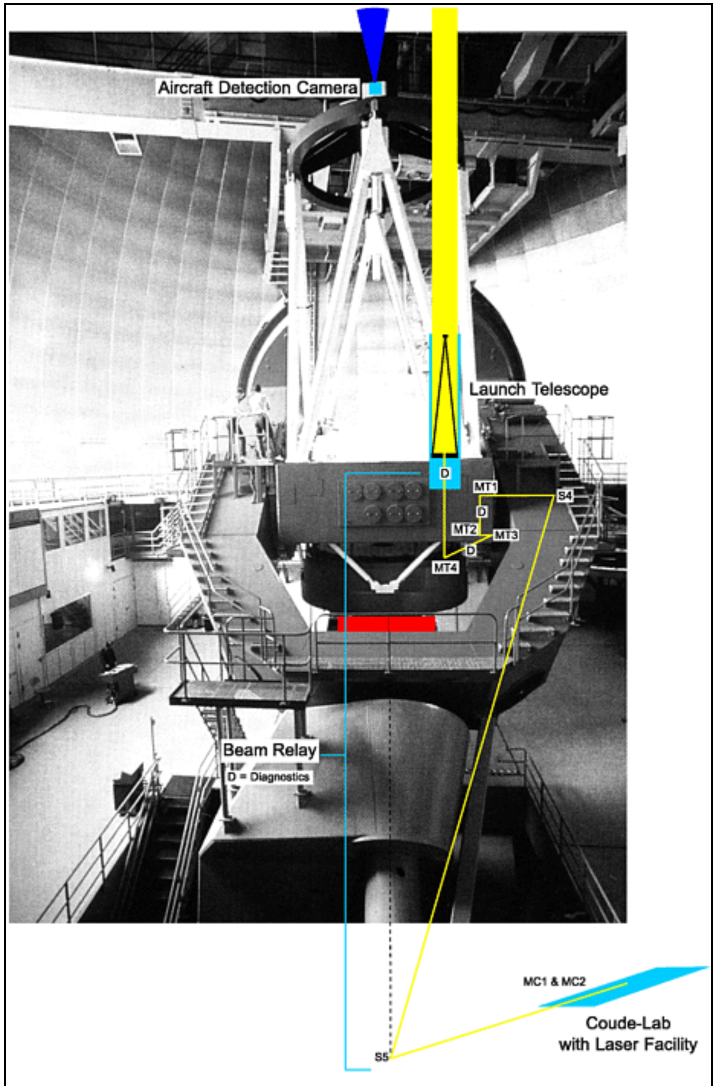
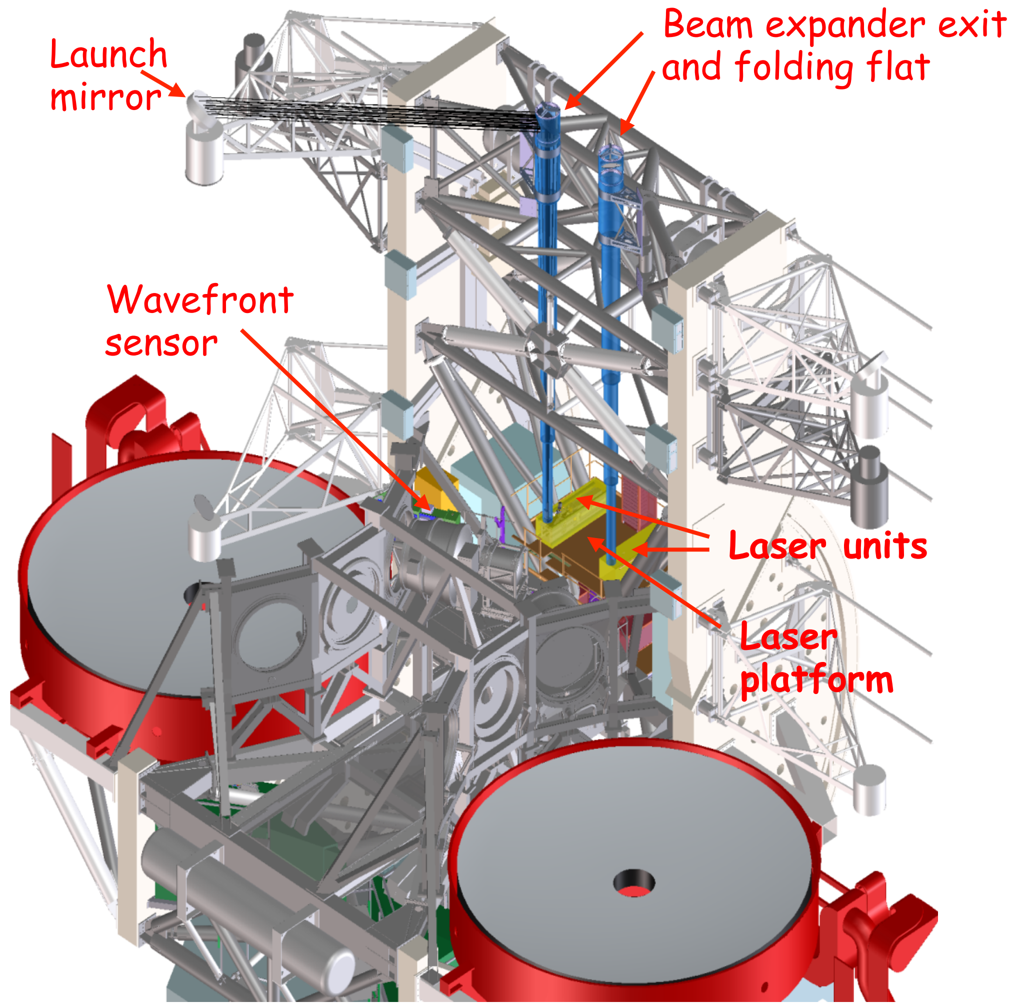
ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

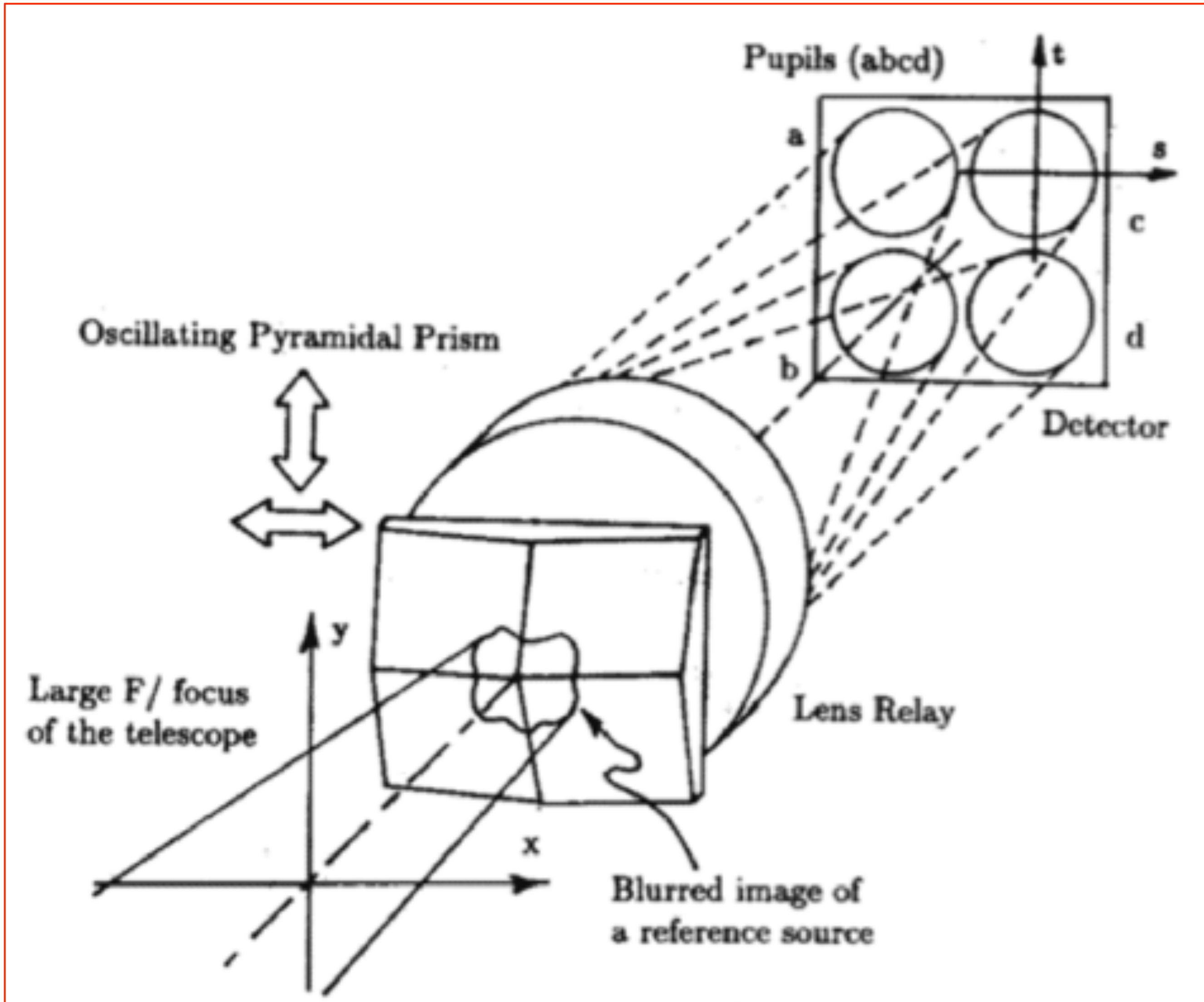
LGS launch systems



DSAZ 3.5 m Telescope and the ALFA LGS-System



Arizona (with some Italian flavor…) – about 20 years ago



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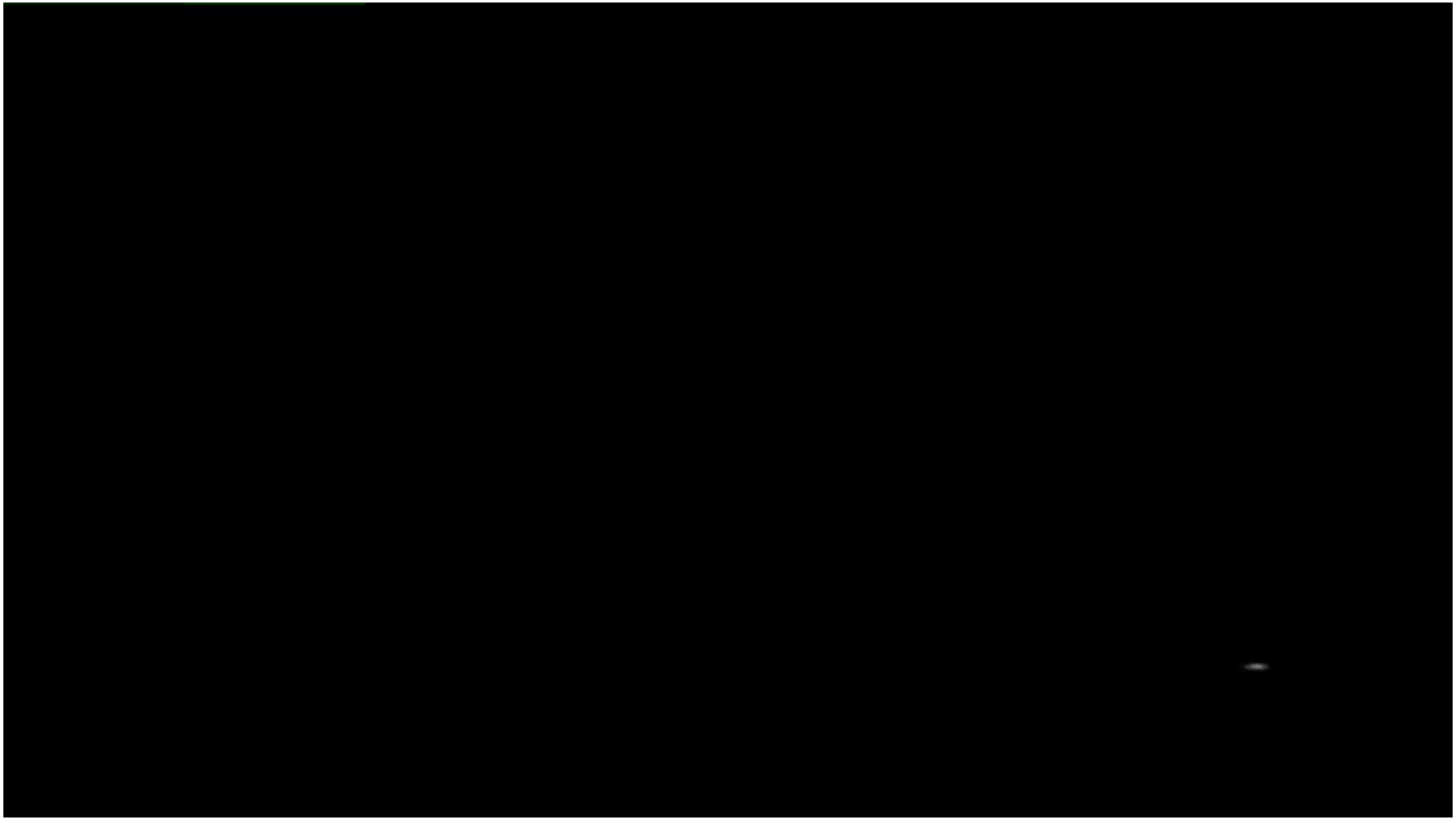
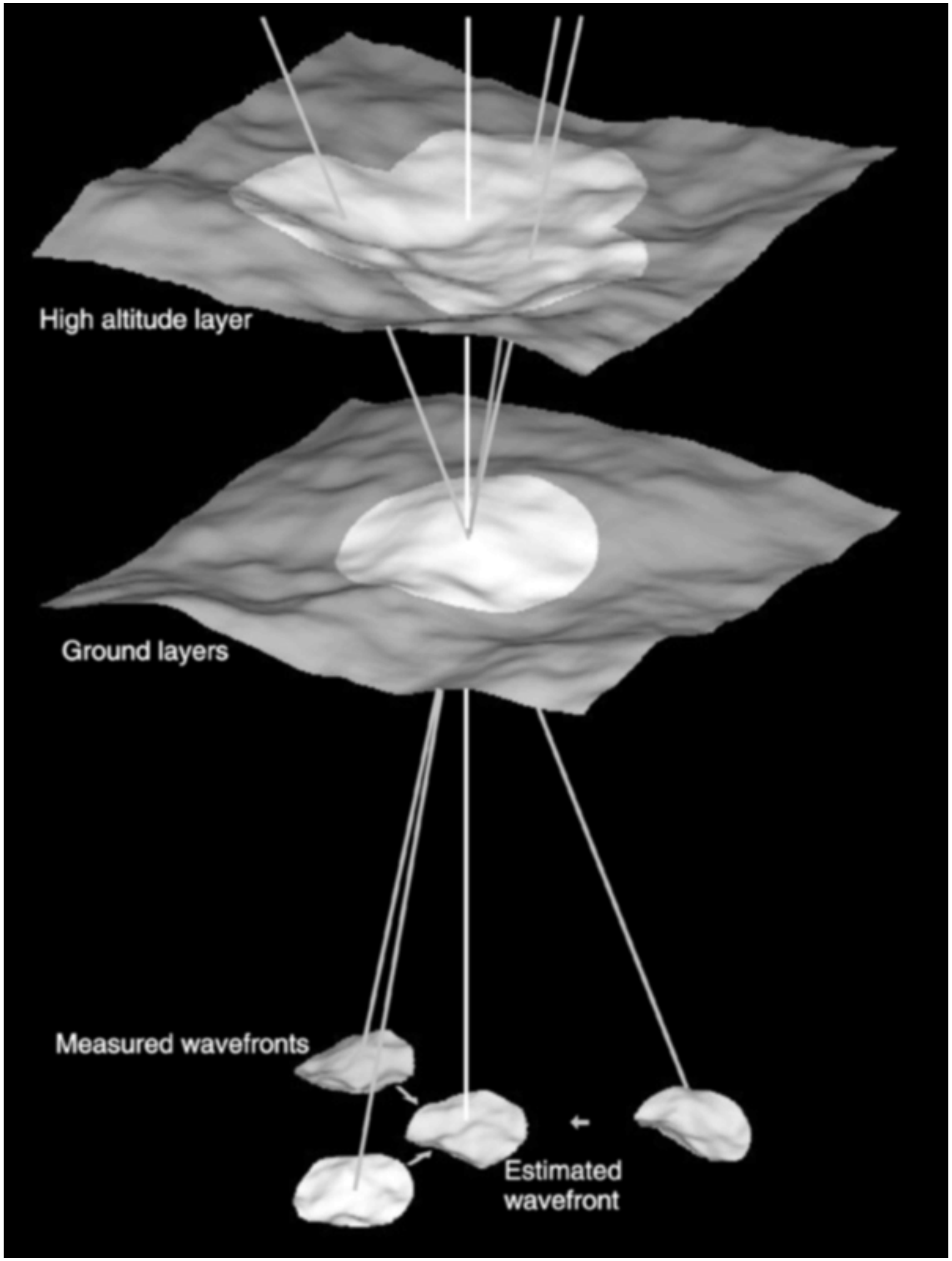


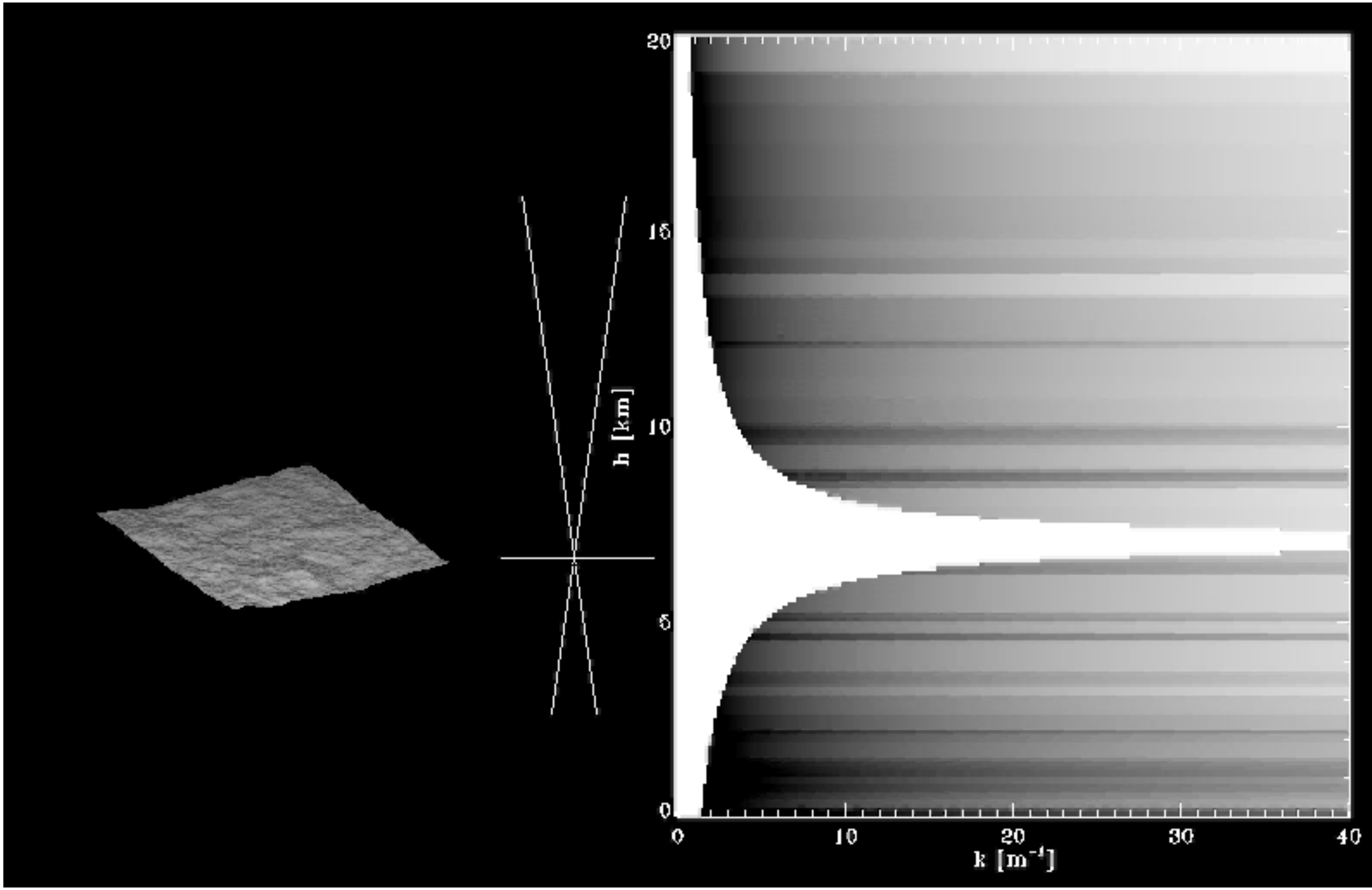
YouTube Canale: *PadovAdopt*

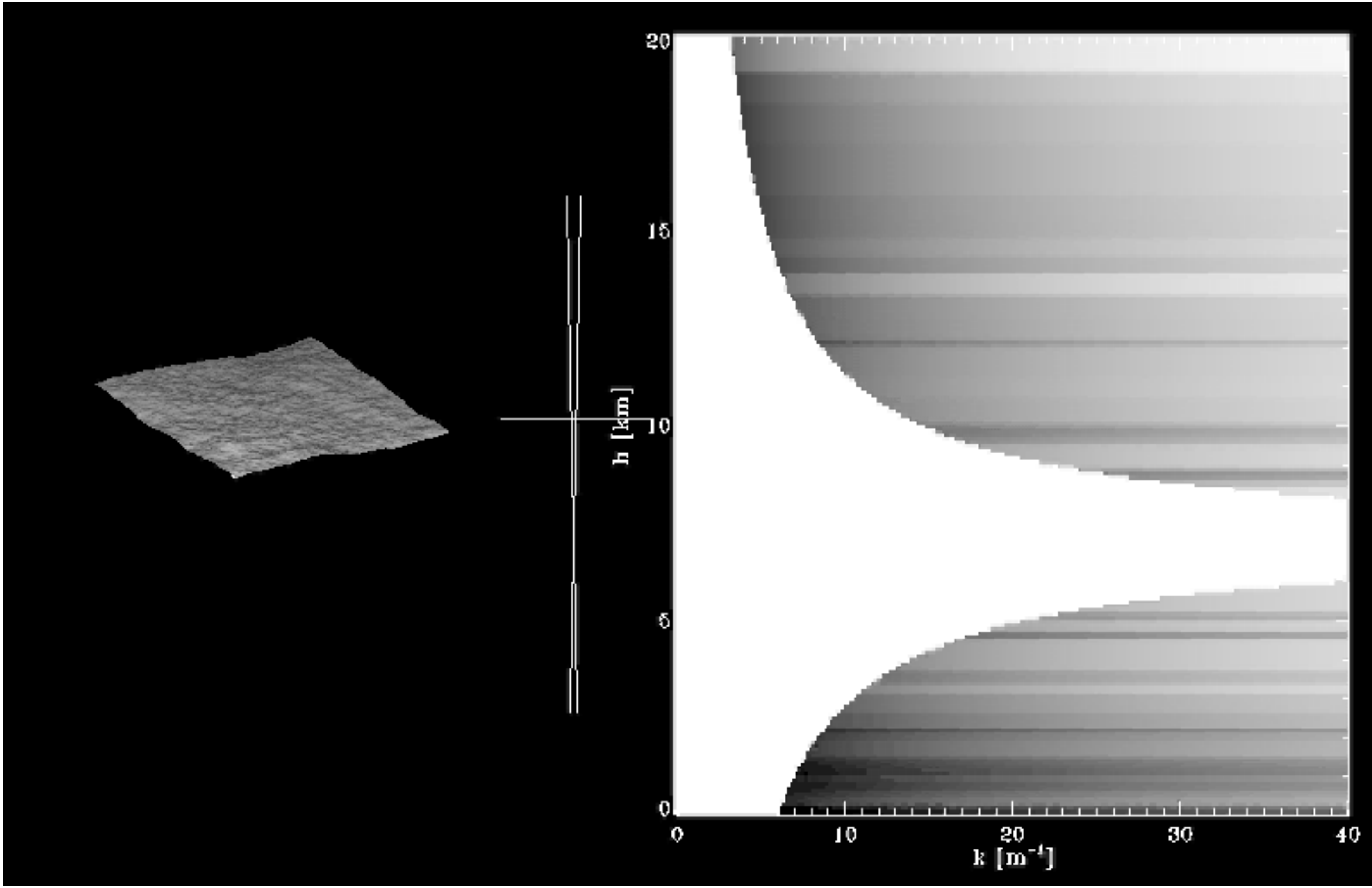
…present to future…

- High order AO with high efficiency mades XAO
- Wider Field of View achieved with multiple DMs
- Pushing into the visible and into larger Sky Coverage…
- Using LGSs or even higher efficient Wide Field AO (wait for a couple of days…)
- Making the telescope fully adaptive
- Making corrections achievable on a small scale (MOAO)

Wider Field of View




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

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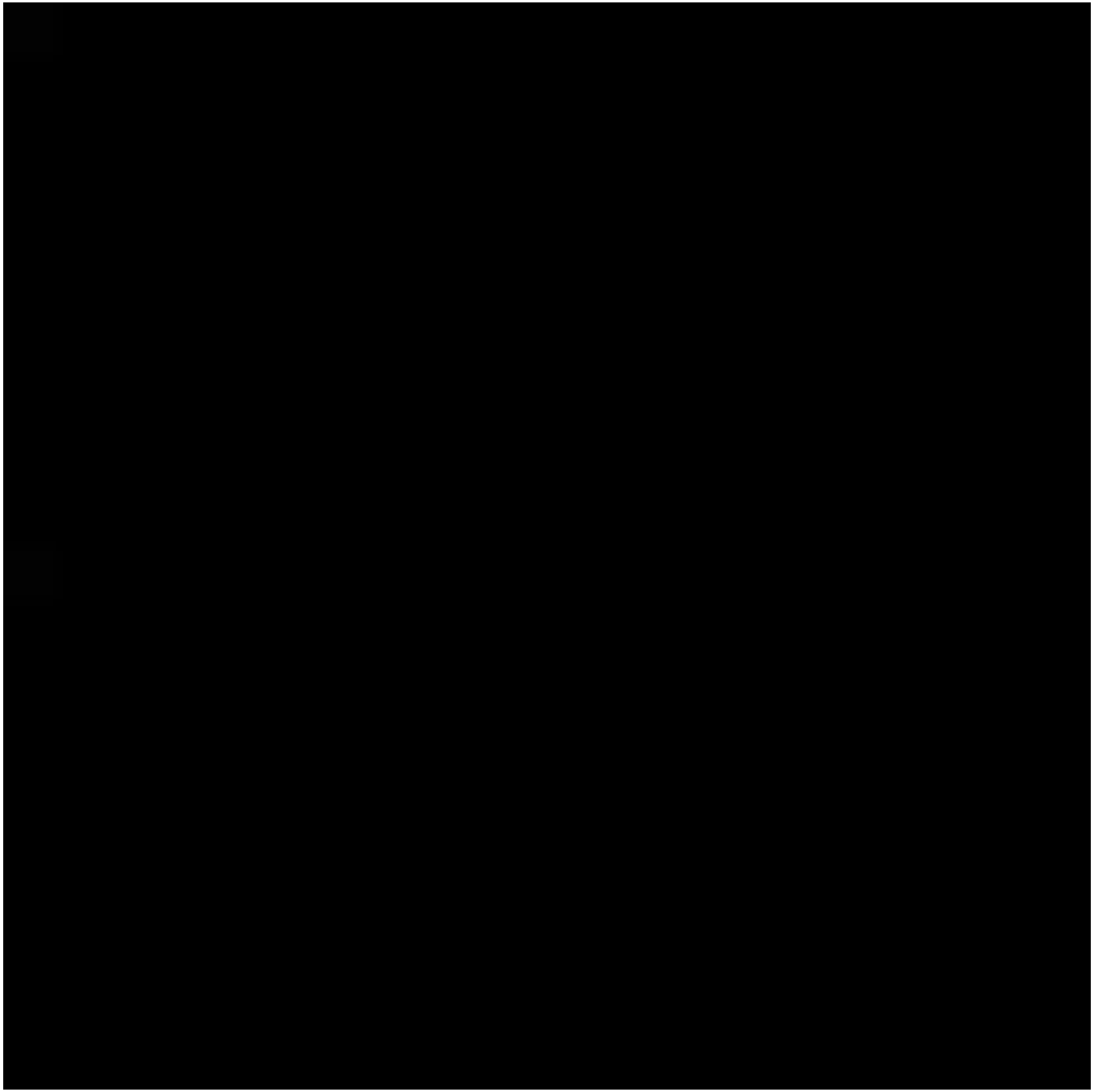
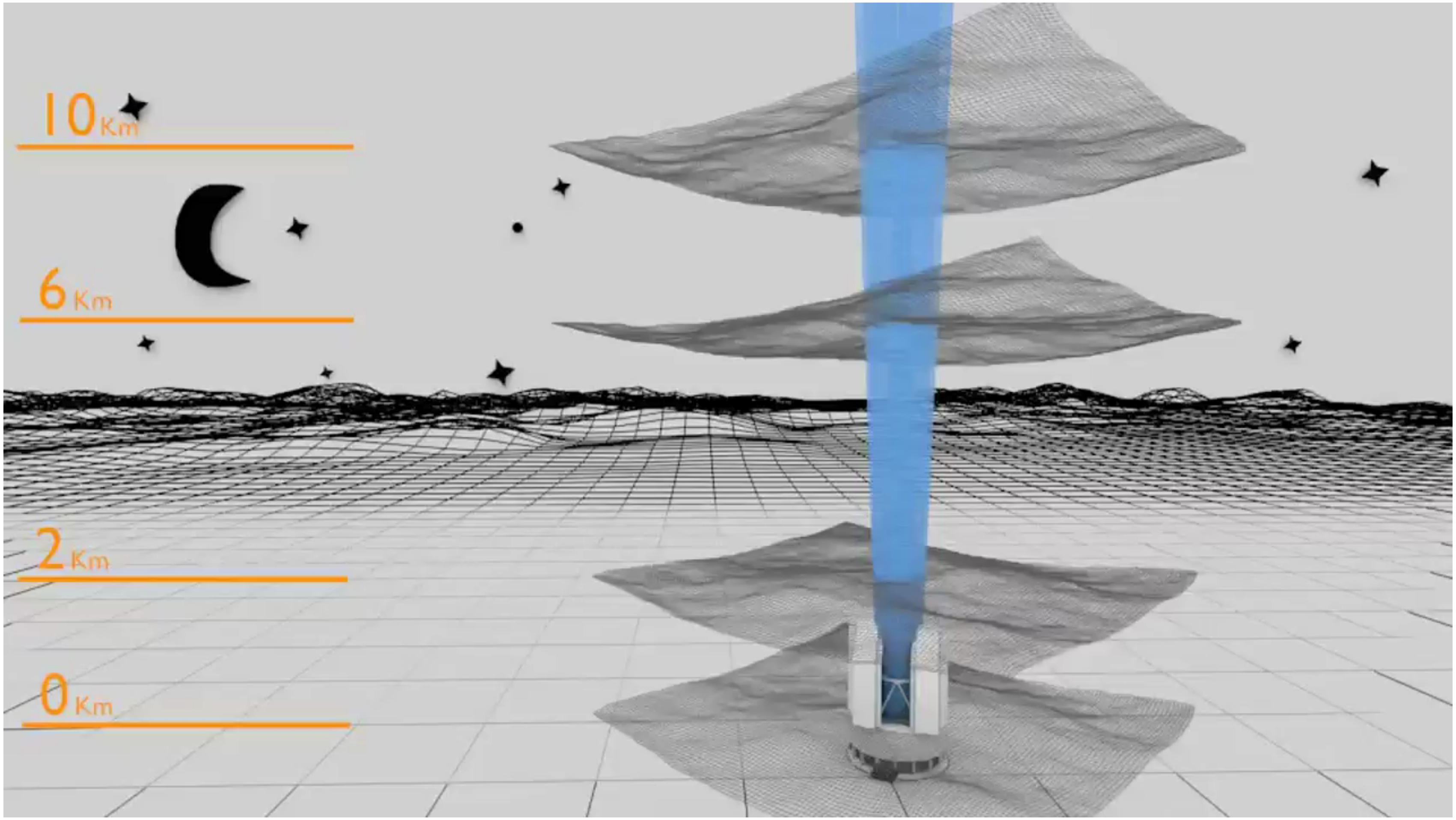


Wider Field of View



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Ettore Majorana Foundation and Centre for Scientific Culture

Thanks for your patience