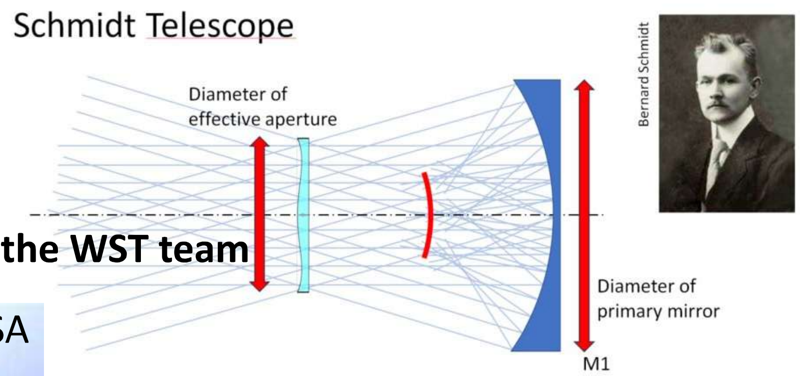
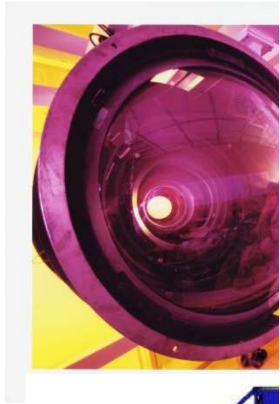
New Enabling (disrupting) technolo
(concerning Wide Field Telescope

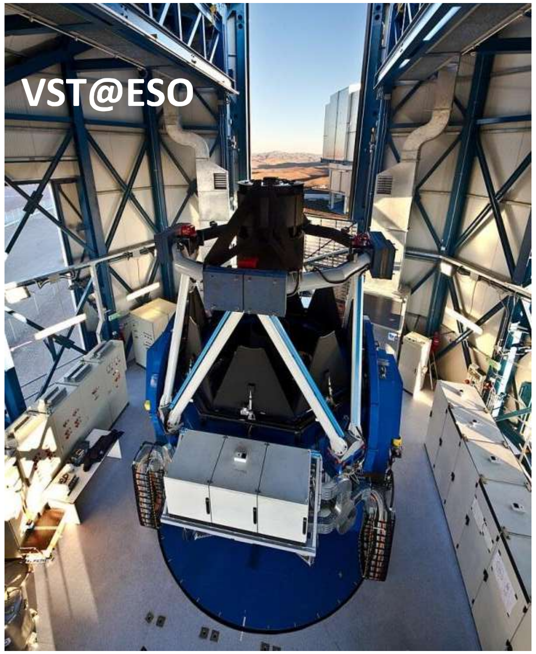
Jacopo Farinato

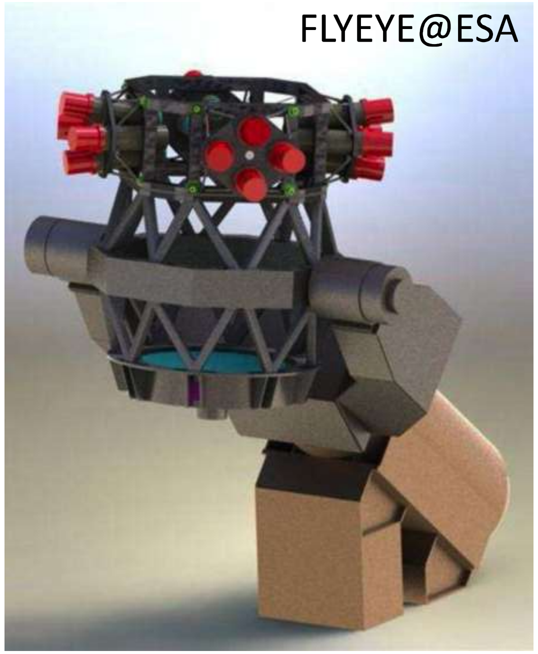
INAF – OAPd – March 12 2025

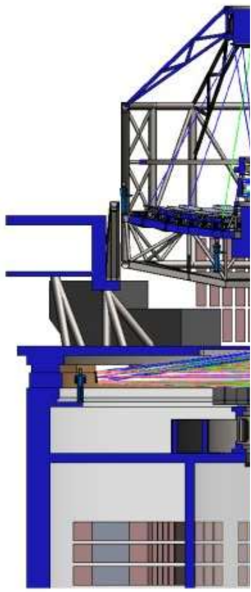
Special thanks to: Roberto Ragazzoni, Valentina Viotto and the WST team







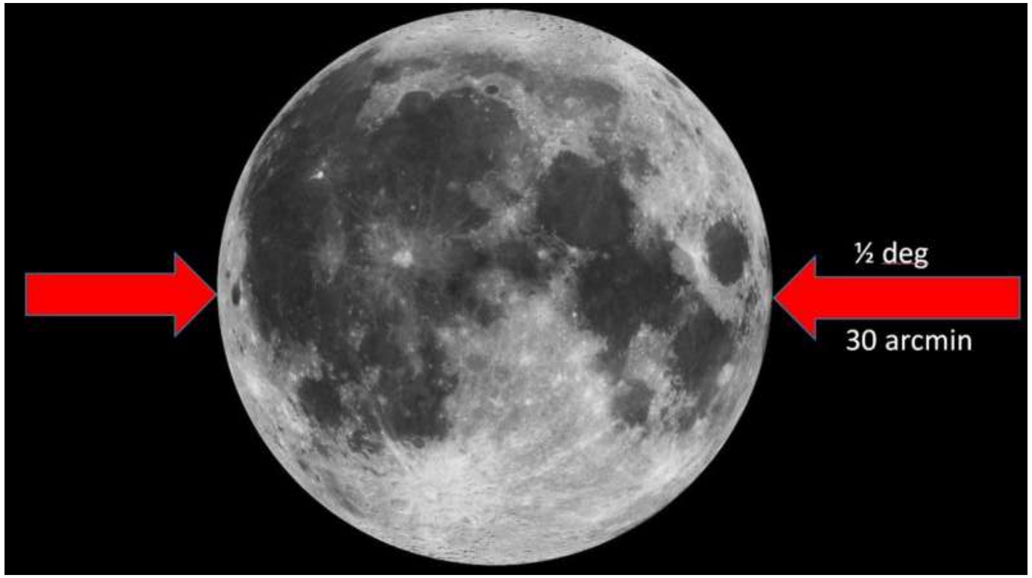


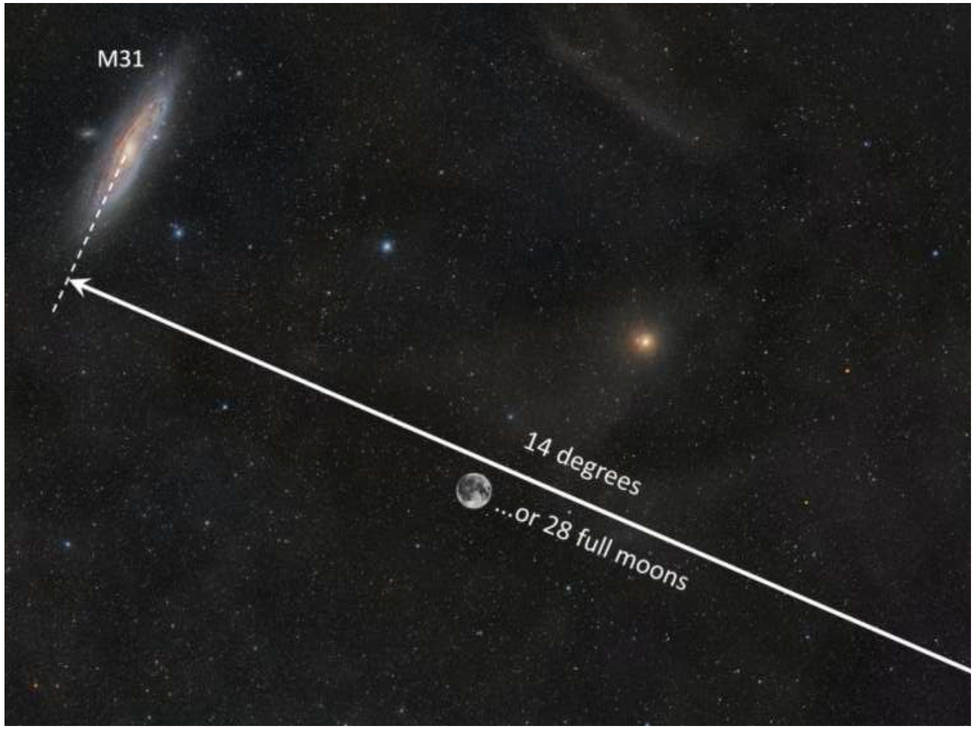


What is a wide field telescope?

The idea of what can be considered a wide field telescope changed quite
the last 60 years, and of course the science to be done on the field plays a
fundamental role.

New opto-mechanical design and the technologies available along the yea
played also a fundamental role, and new achievements in the optical eler
quality and dimensions and on the detectors quality, size and pixel dimen
gave the green light for the implementation of new (disruptive??!!) ideas

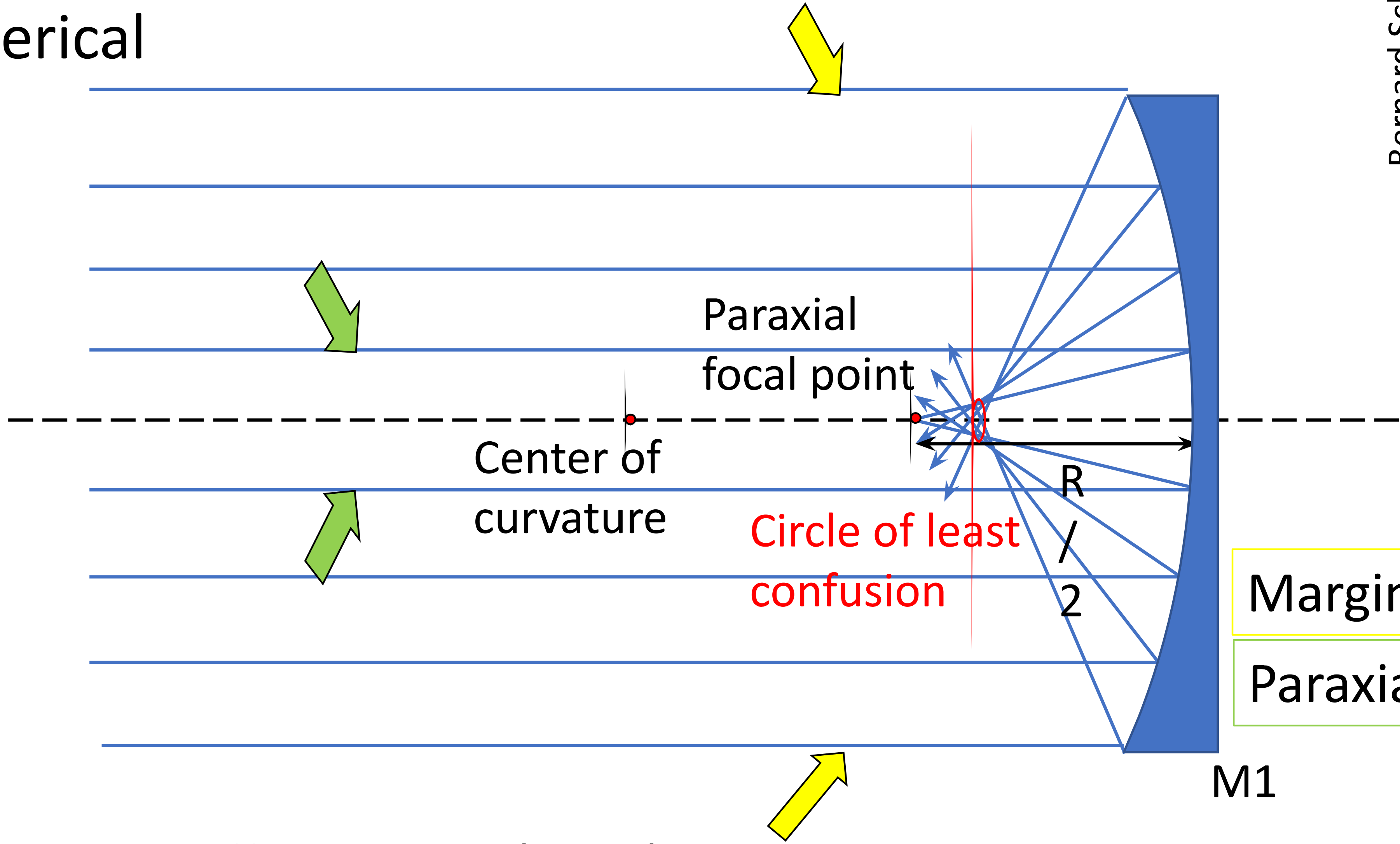


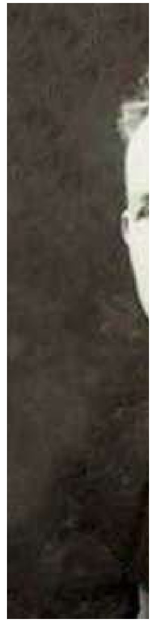


But… a little bit of

Nearly 100 years ago… the Schmidt telescope

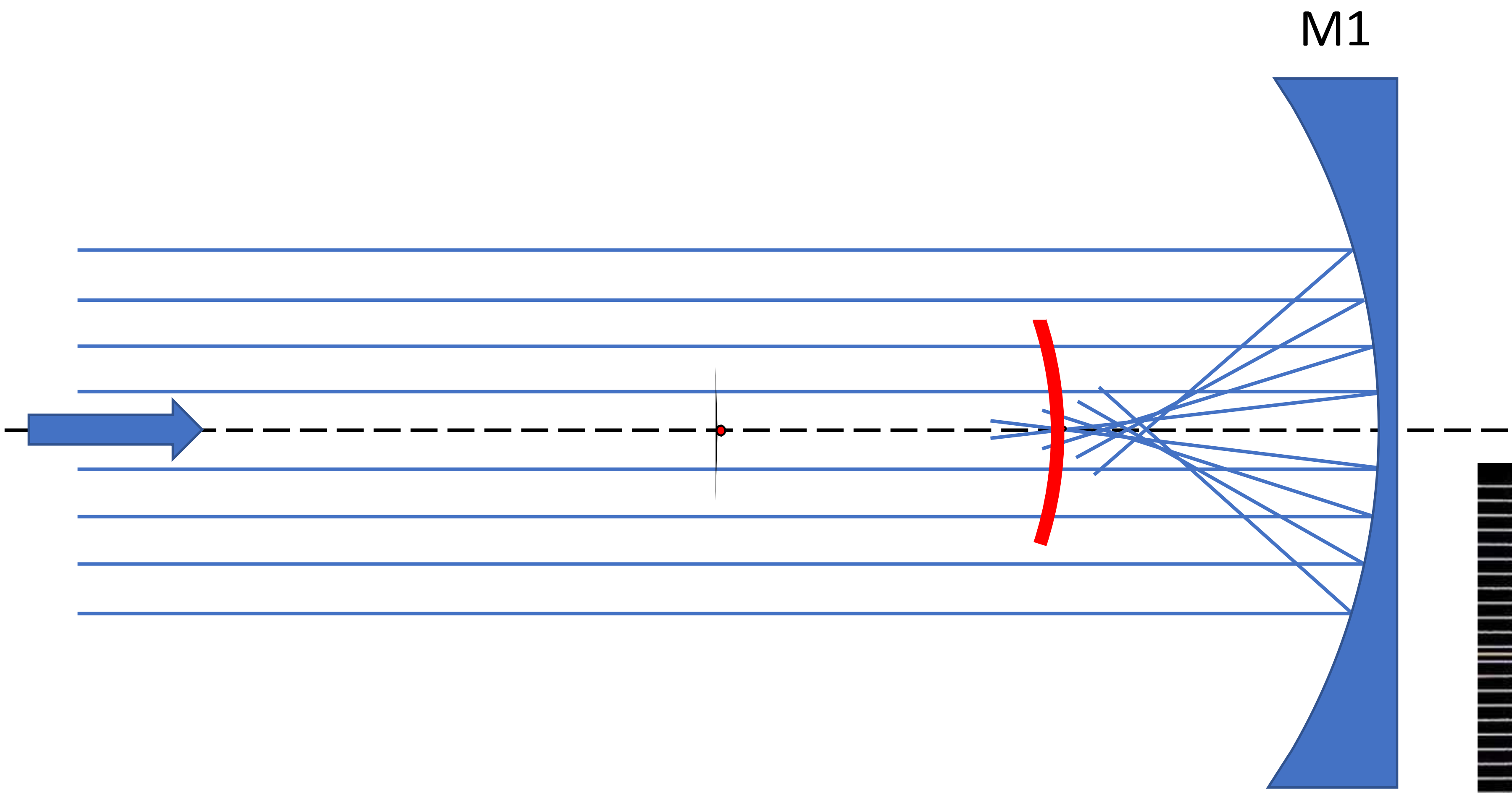
A Spherical
M1…



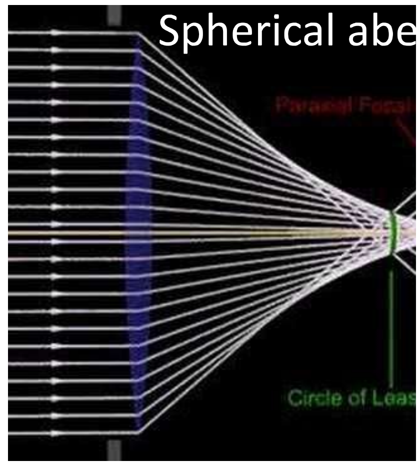

Bernard Schmidt

The sphere is affected by a (large) spherical aberration, but it is uniform
the FoV…

A Spherical M1…

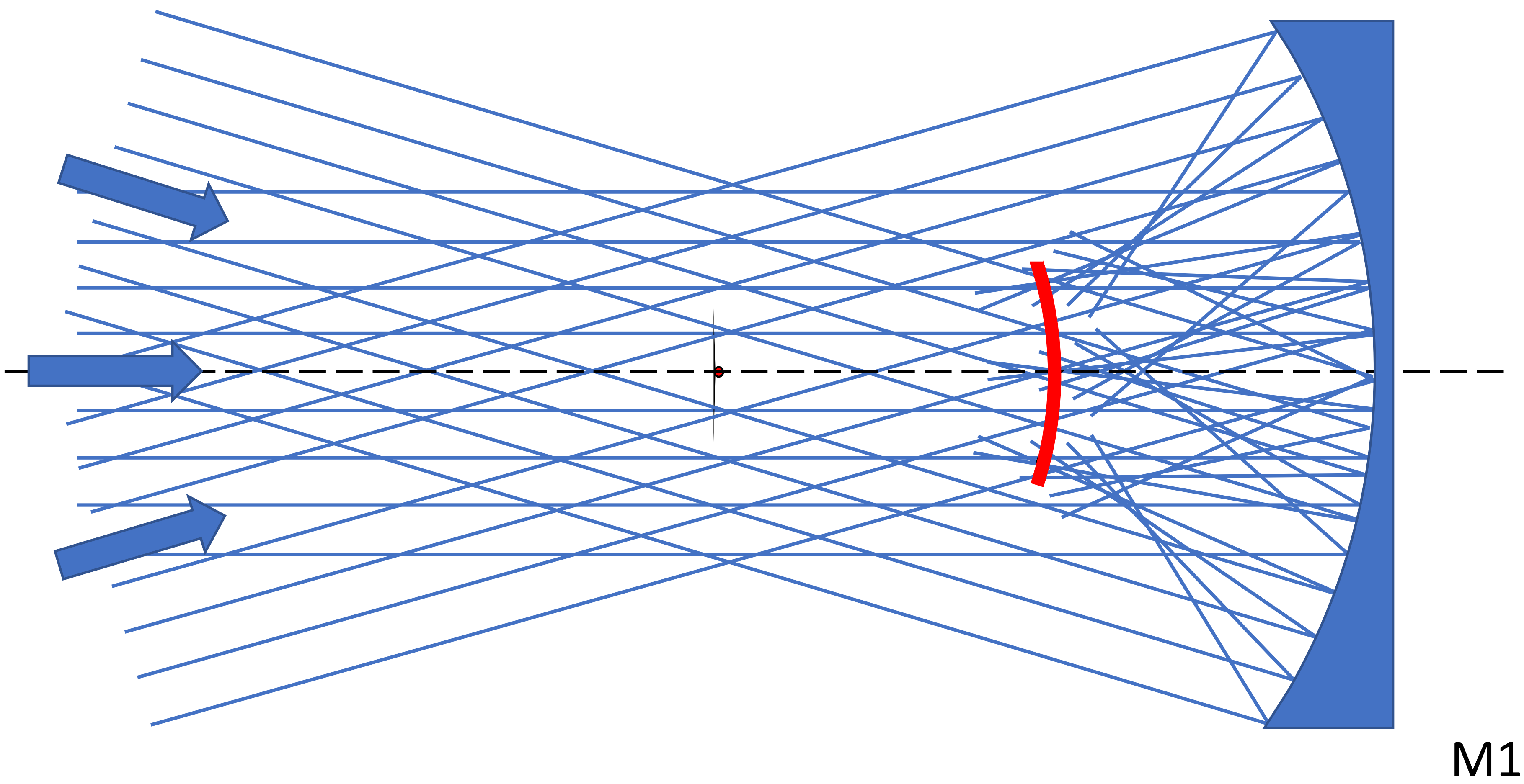


Bernard Schmidt



Curved focal plane (but photographic plates where “easy” to be kept curved)

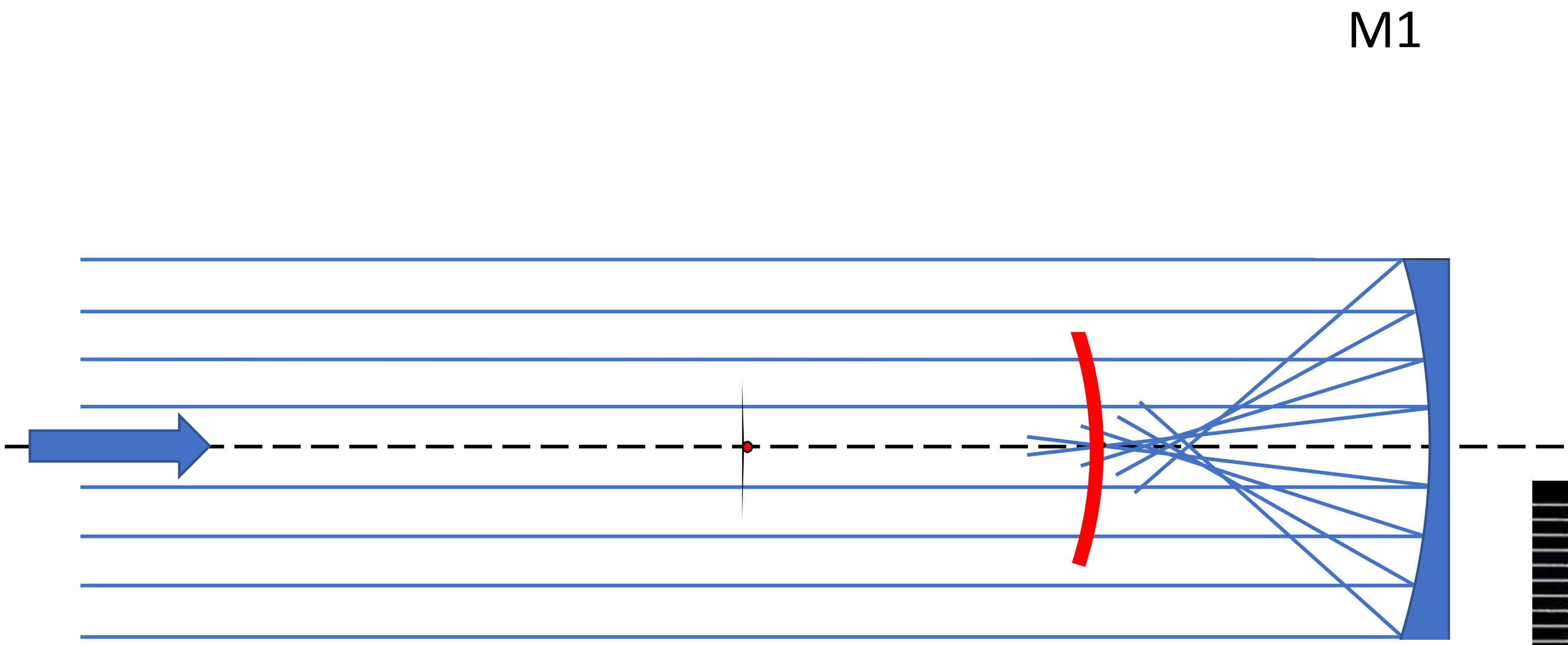
A Spherical M1…



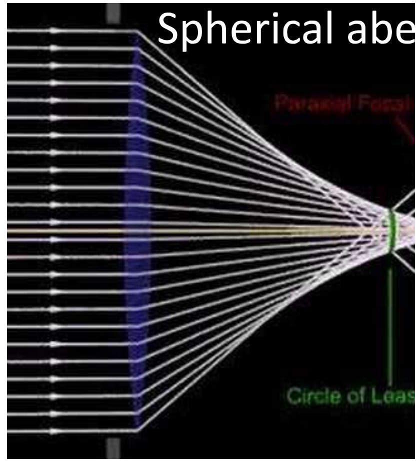

Bernard Schmidt

The sphere is affected by a (large) spherical aberration, but it is uniform
the FoV (identical for on-axis and off-axis references)

A Spherical M1…



Bernard Schmidt



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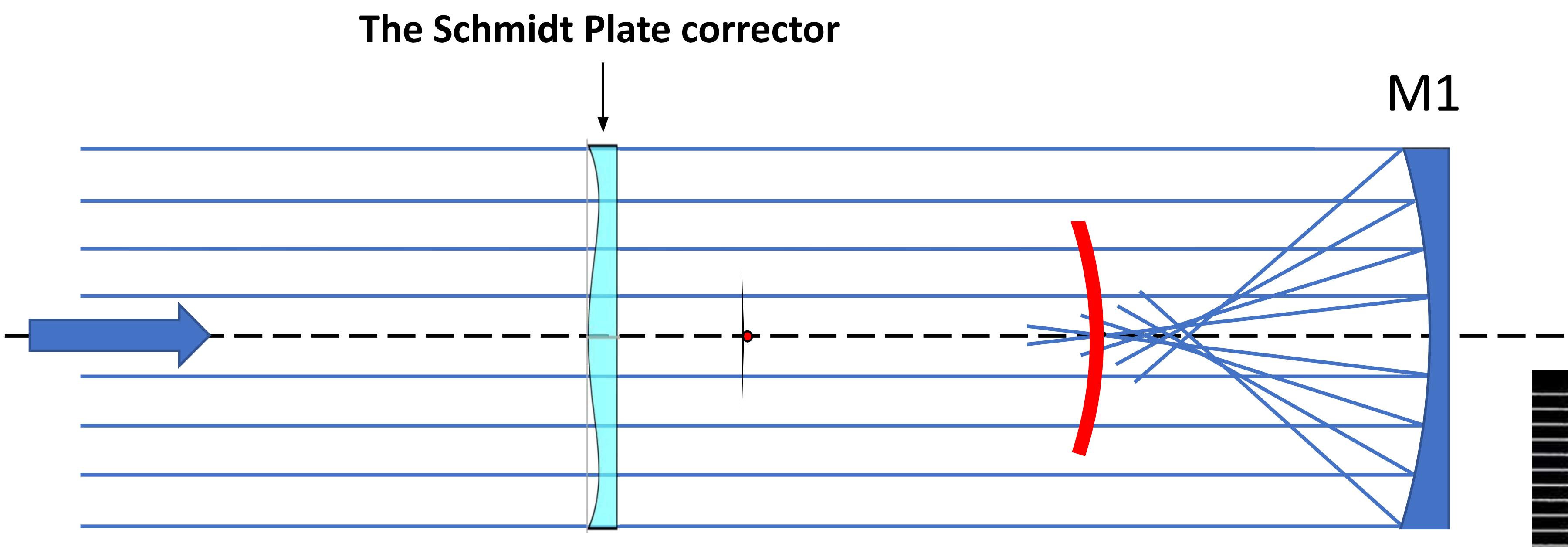
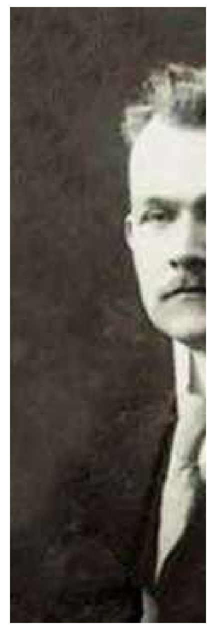
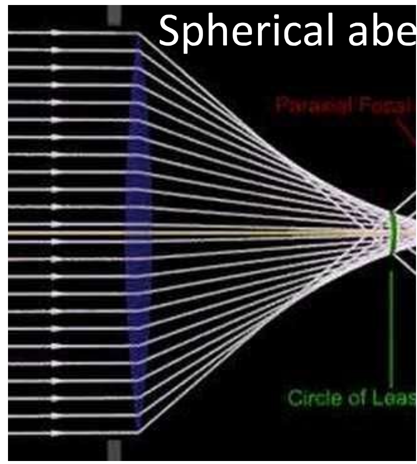


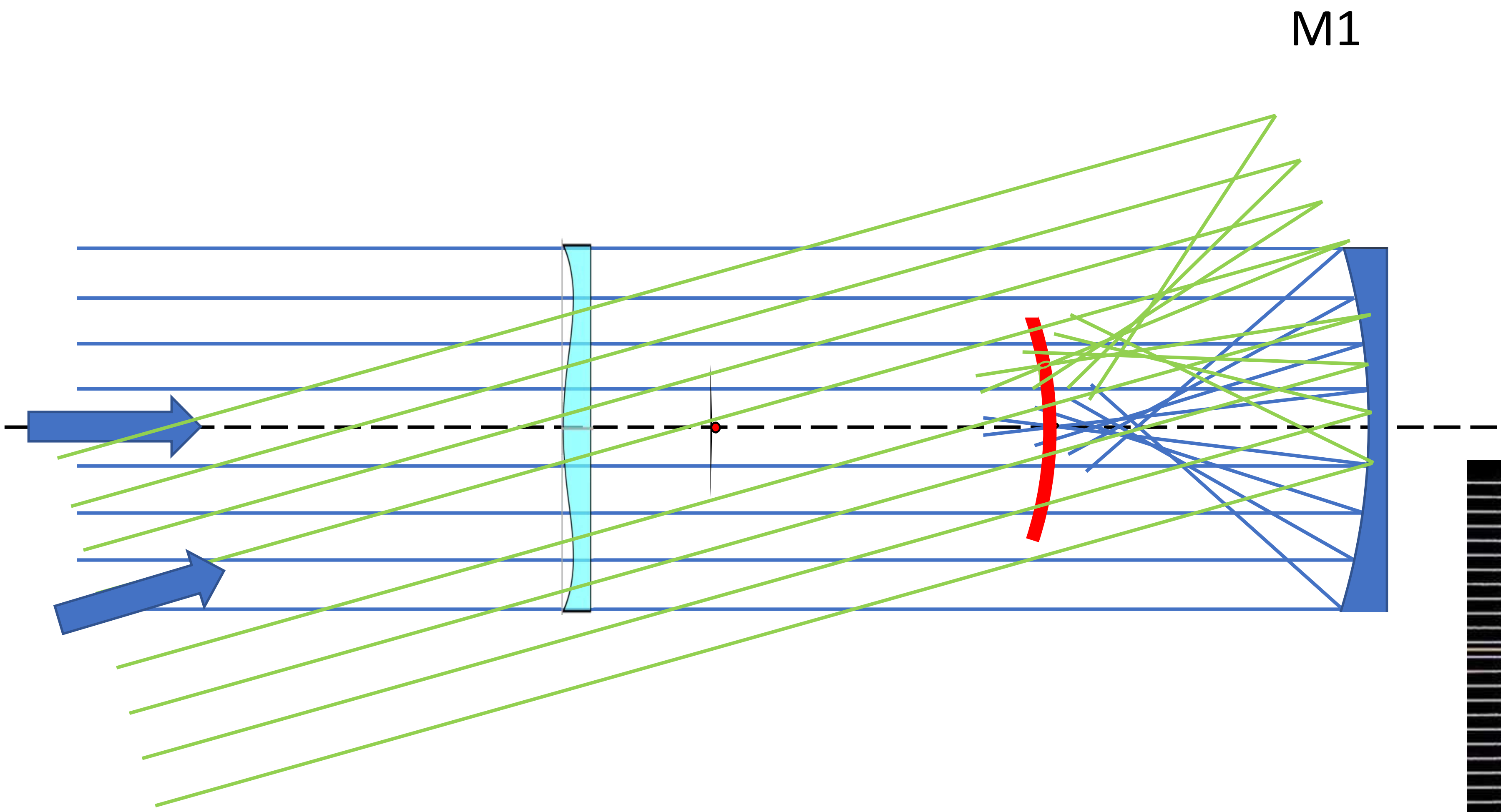


Bernard Schmidt

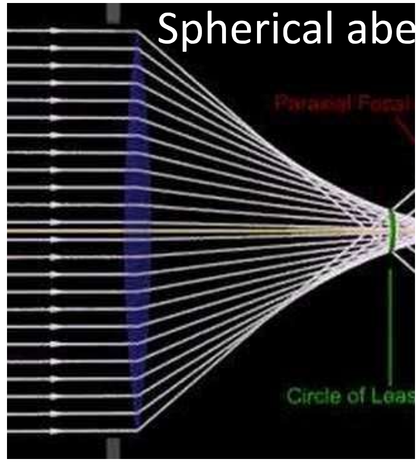


Note that, being the pupil defined by the primary mirror M1, only the on-axis object will be unvignetted!

A Spherical M1…



Bernard Schmidt



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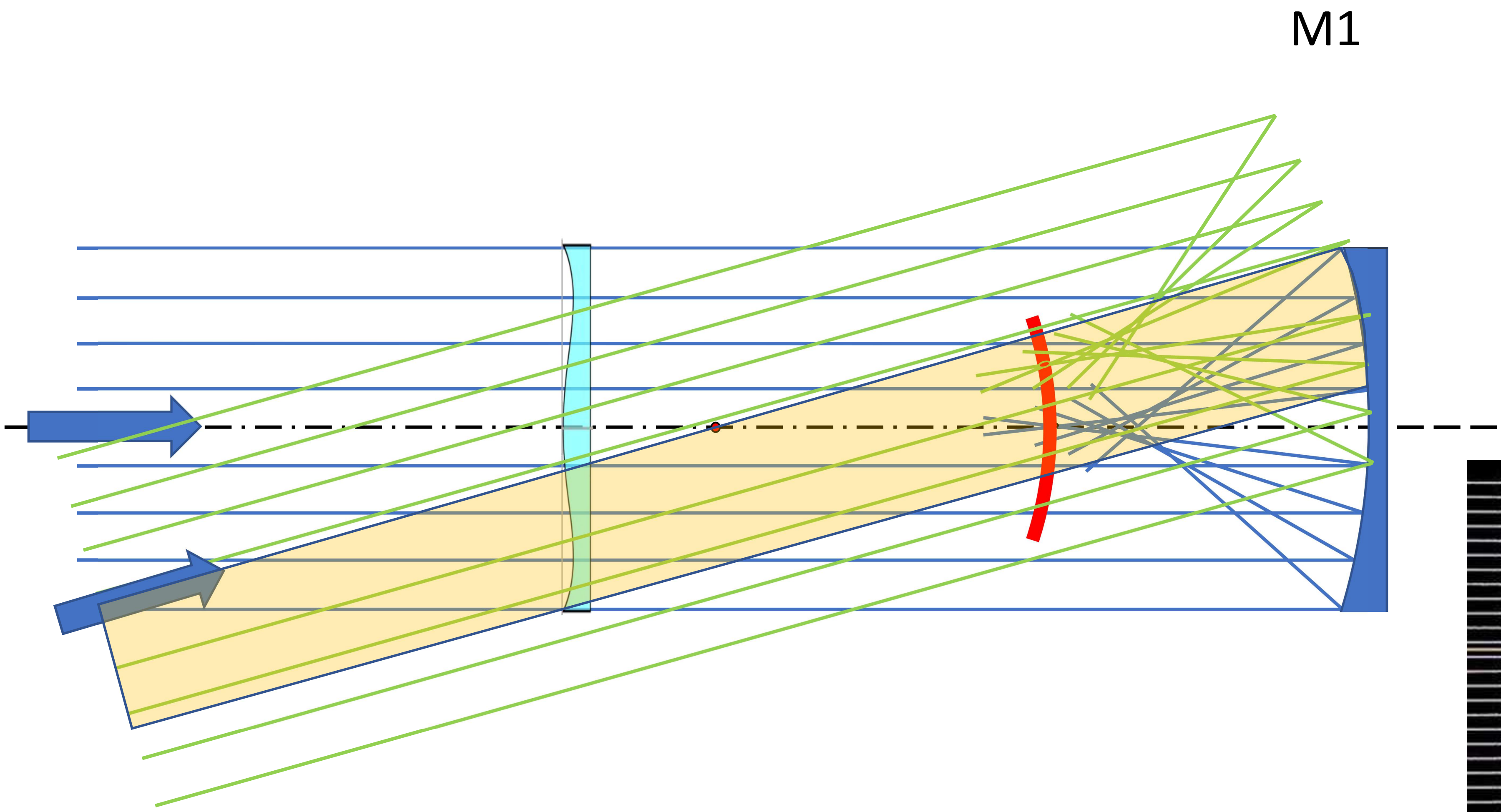
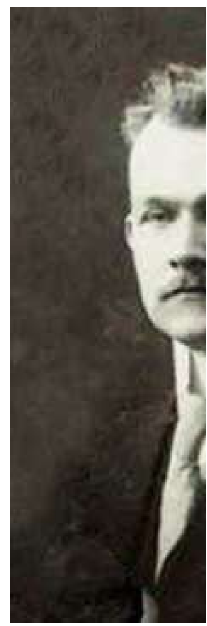
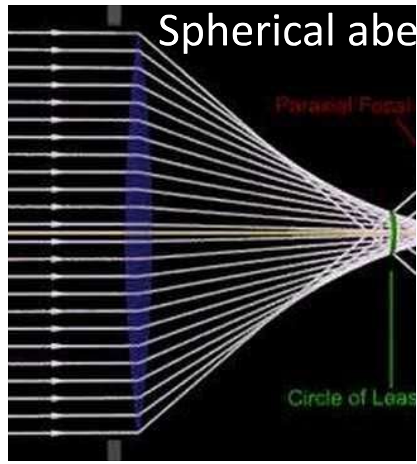
A Spherical M1…



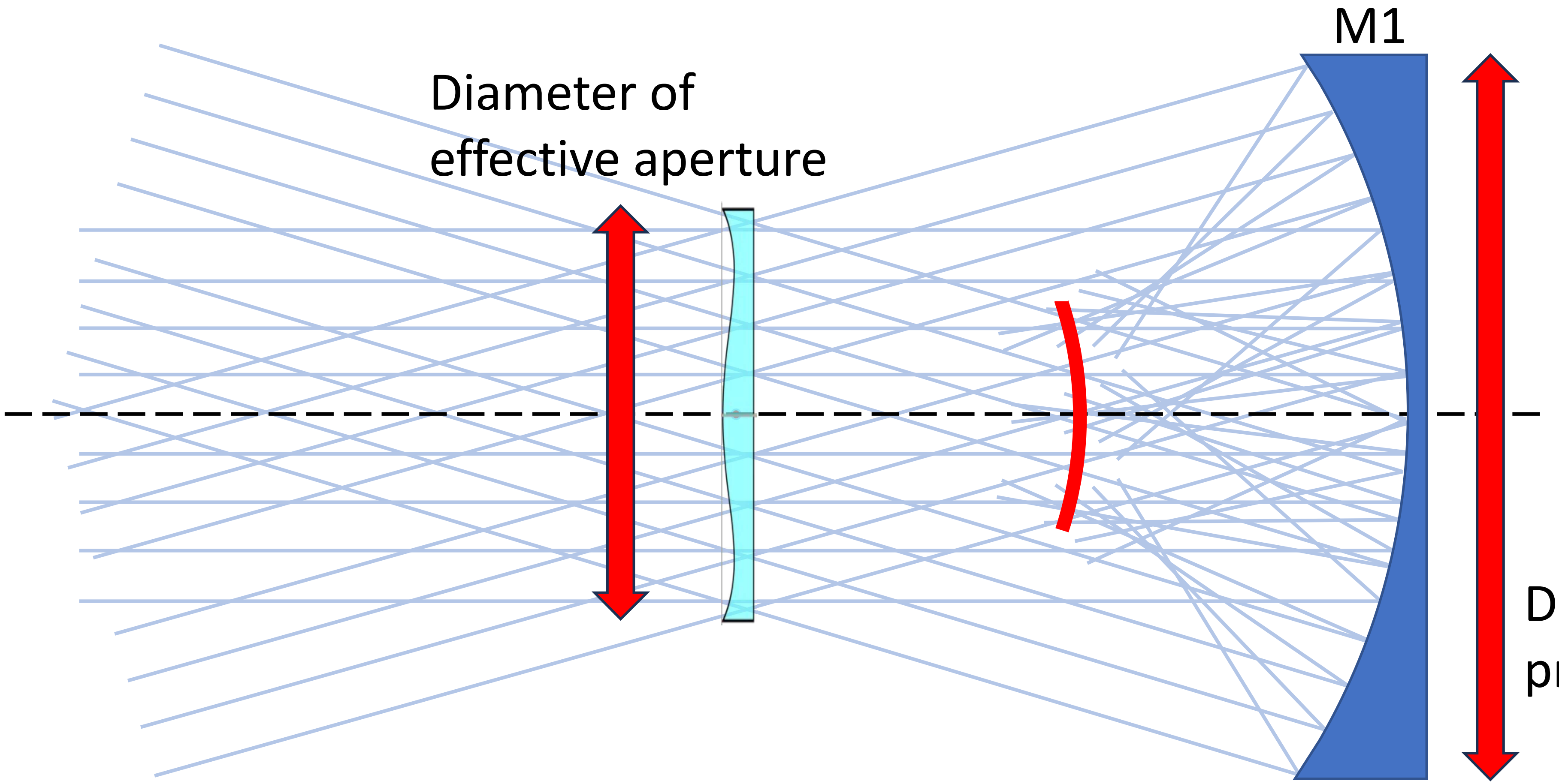


Bernard Schmidt



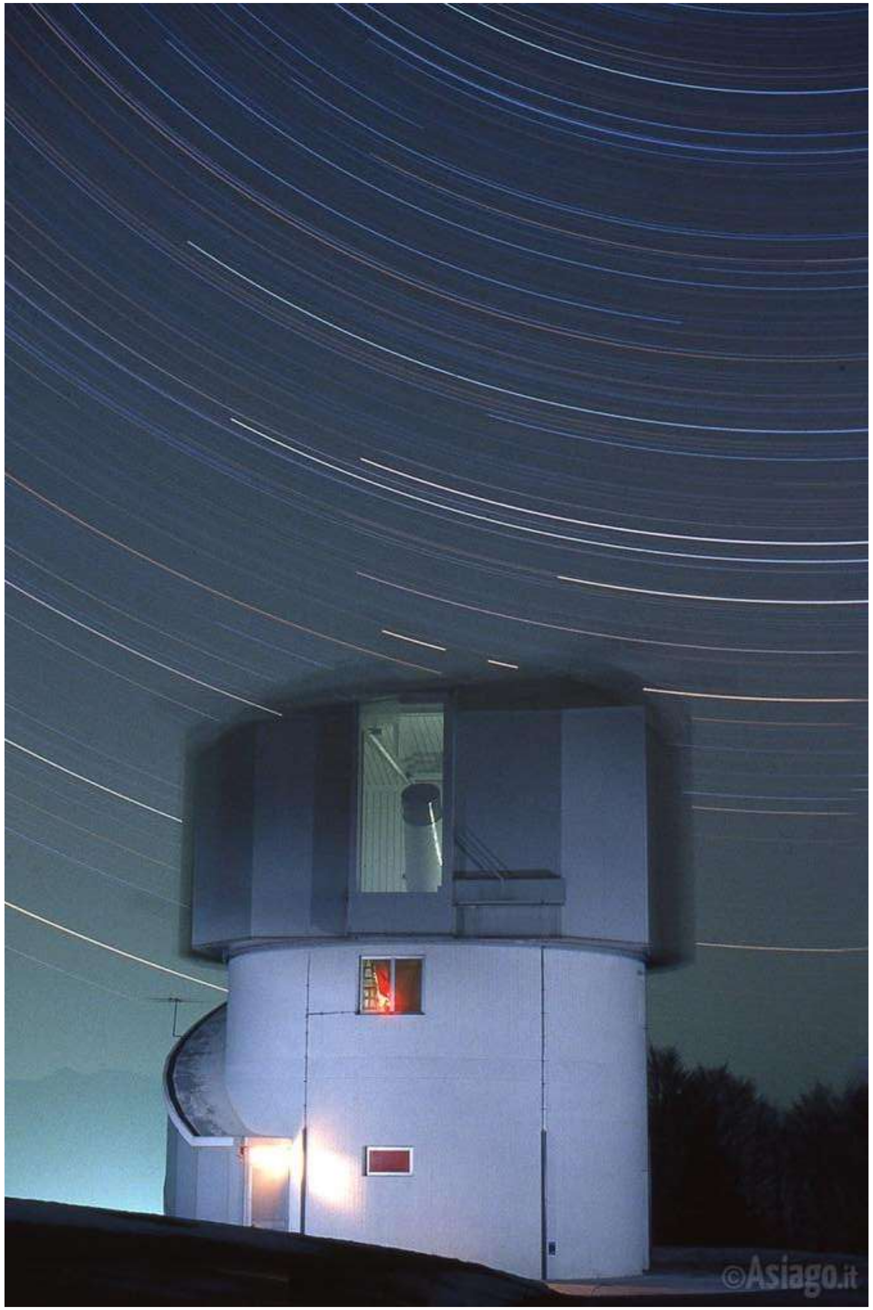
Note that, being the pupil defined by the primary mirror M1, only the on-axis object will be unvignetted!

Schmidt Telescope



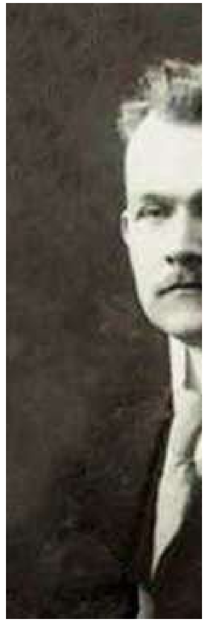
To avoid Vignetting: Schmidt Plate undersized wrt primary mirror ϕ of a f
which depends on the desired unvignetted FoV

Palomar 122/182 (48”/72”)



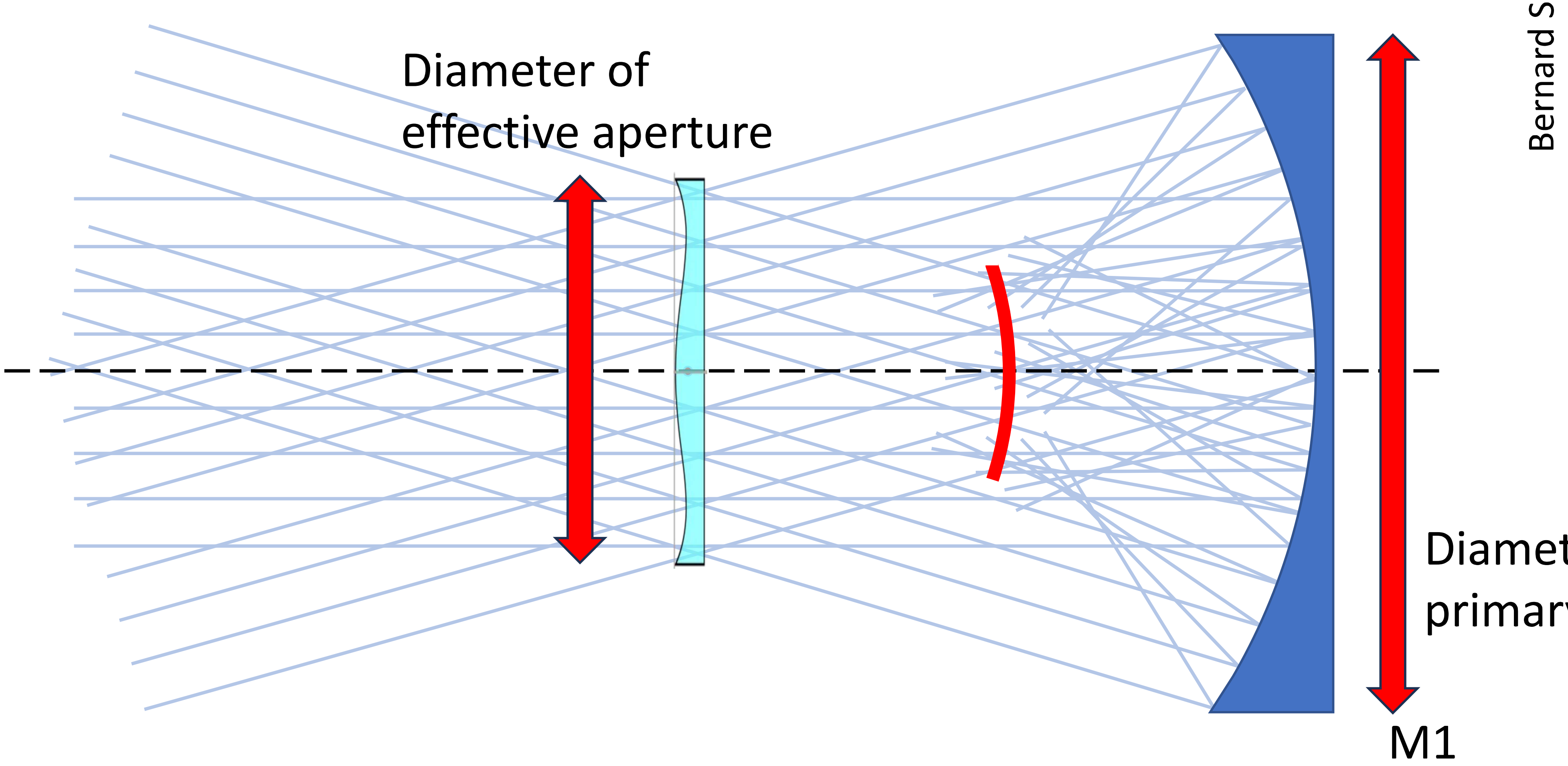
Asiago 67/92

Bernard Schmidt



Both desi
have ~6^0x

Schmidt Telescope

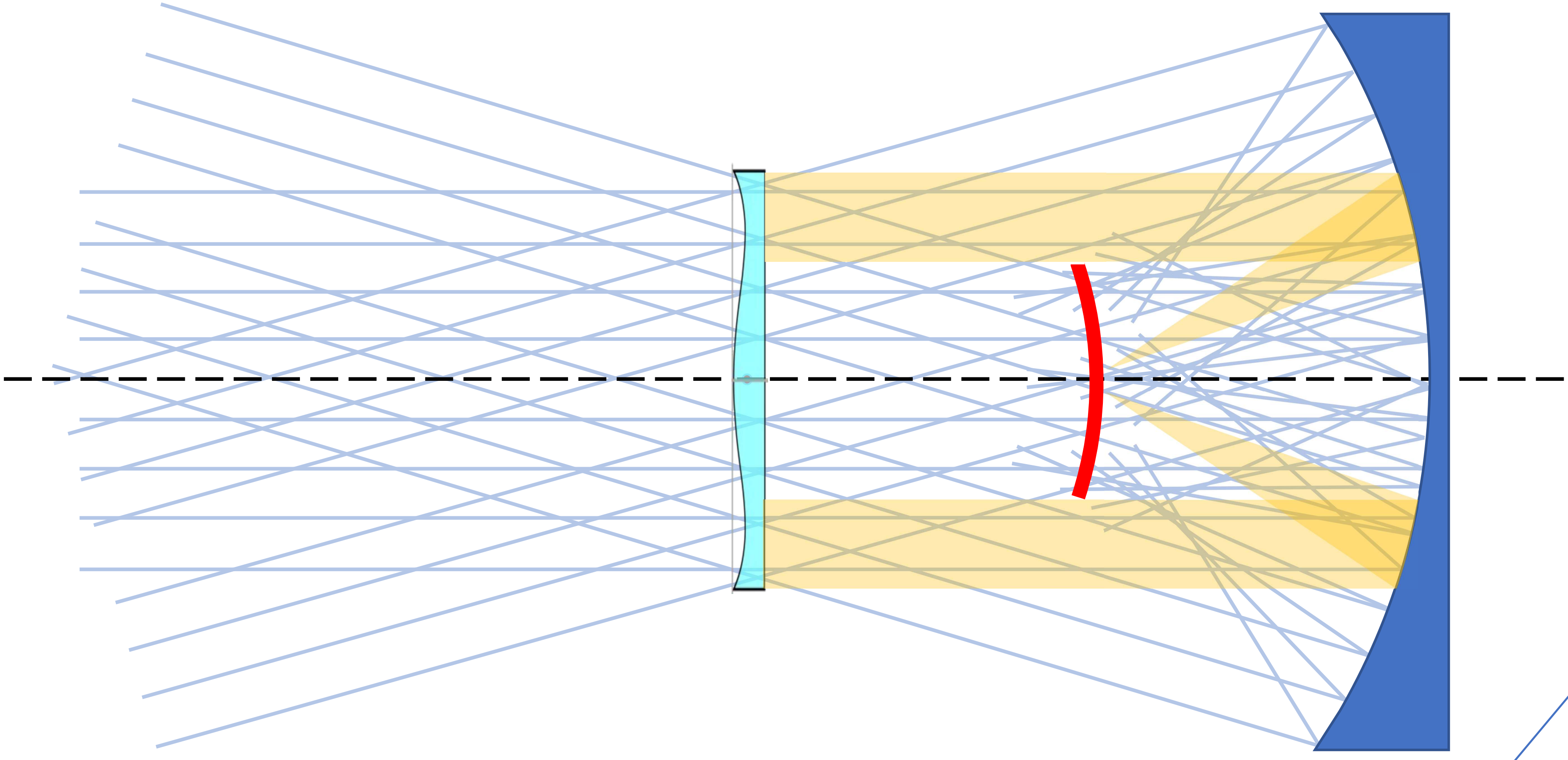


Enabling technology: Schmidt Plate dimension

Wide field enabling technologies

	Technology	FoV
Schmidt Telescope	Schmidt plate diameter	5°x 5°!!!

Schmidt Telescope




Bernard Schmidt

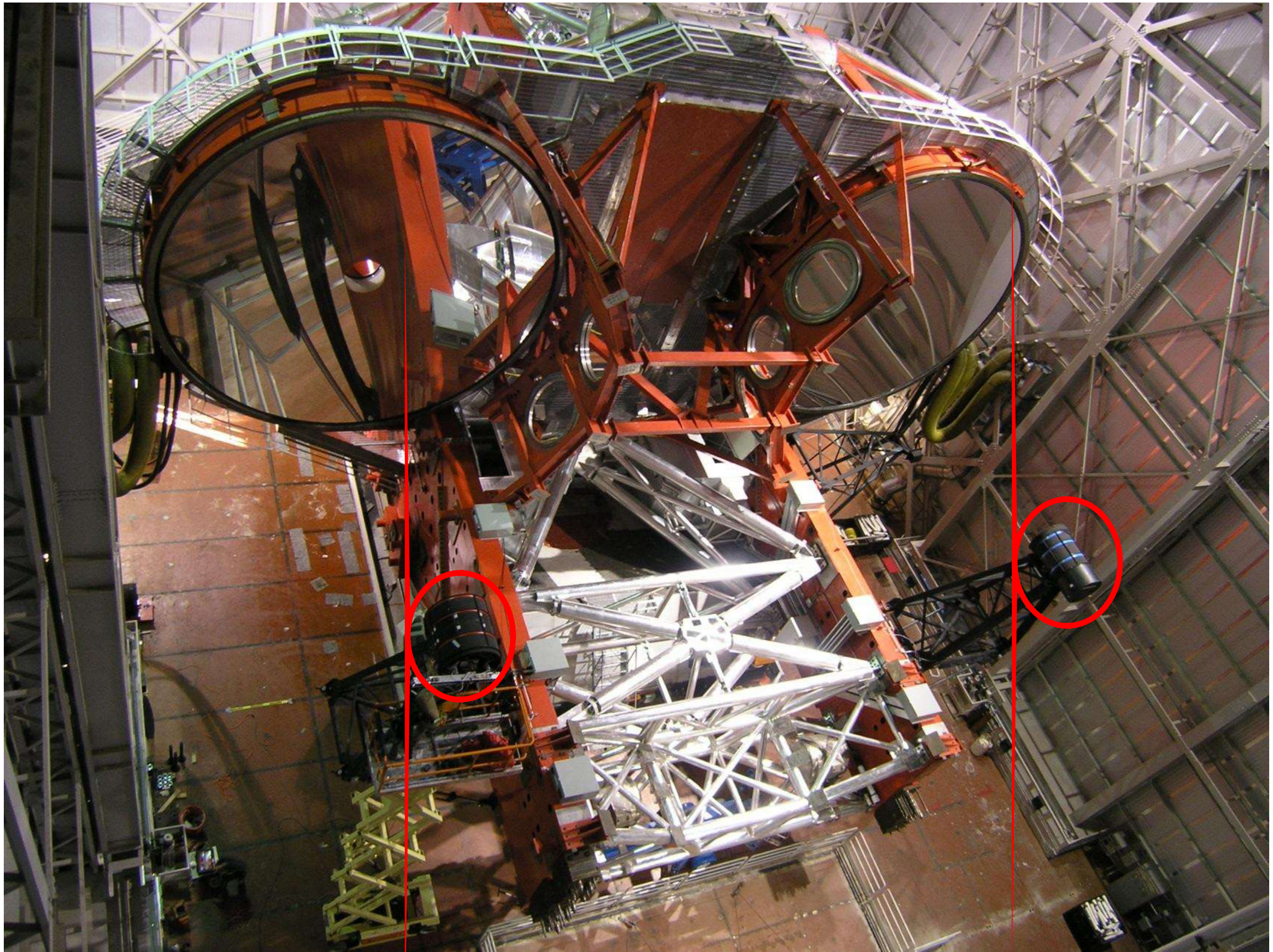
Increasing the FoV of a Schmidt telescope has two effects on the design & performances

The obst
in

The corre
the sp
aberratio
and less

Prime Focus Corrector (for LBT): LBC Large Binocular Camera

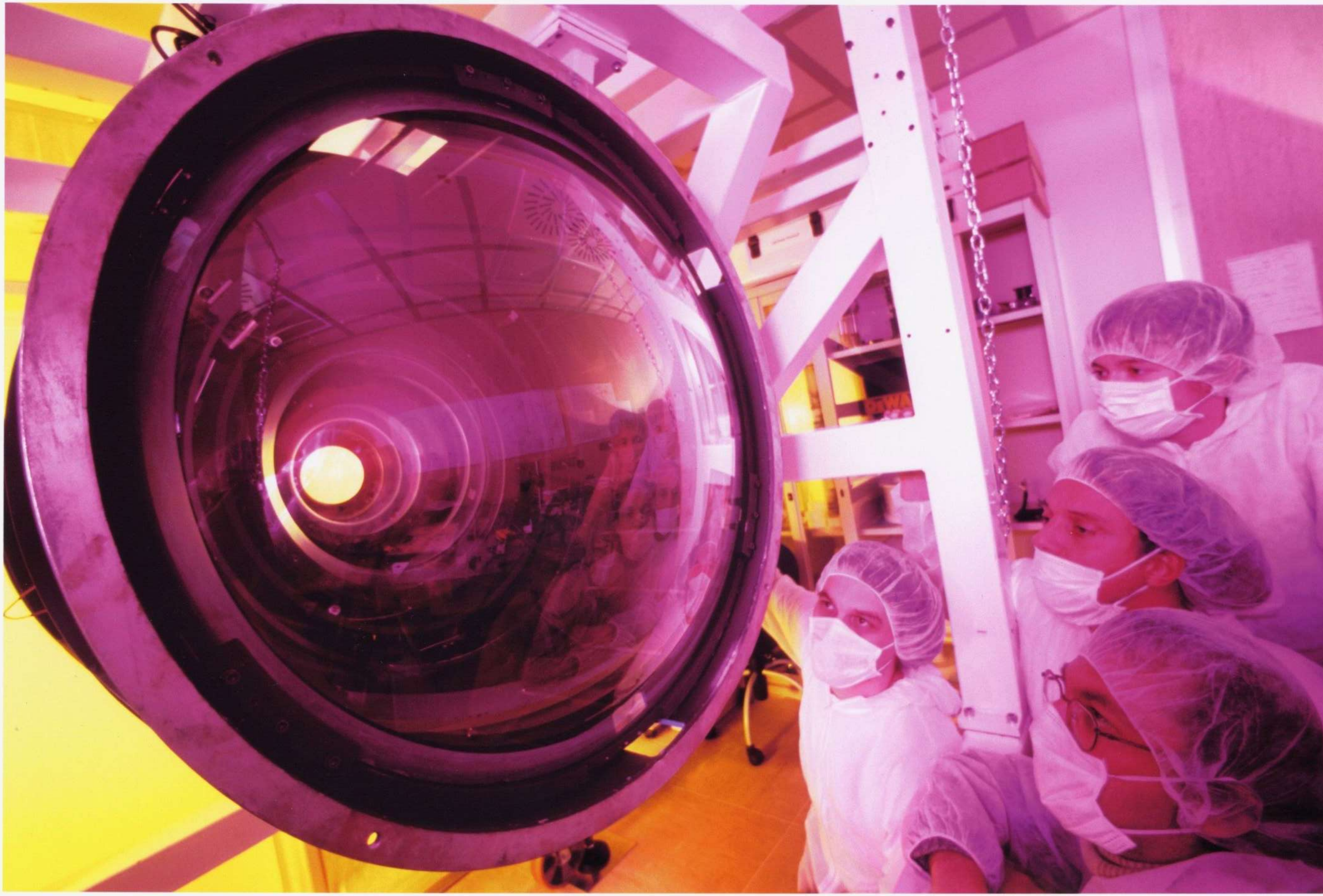
2001 "**Double Prime Focus Imag**
Giallongo, E.; Fontana, A.



LBT is a Gregorian Telescop
M1:

- Paraboloid (8.4m diamet
- F1.14

Strong (variable) off axis aberrat
lenses corrector
1st lens 82cm 180Kg about
Why Prime Focus? In principle v
in a reasonable area (very fast F
Focal Plane: four EEV42-90 CCD
4608 pixels, 13.5 x 13.5 μm per
focal plane scale is 16.9 arcsec/
pixel scale for both LBC Blue and
0.2255 arcsec/pixel. Each CCD c
approximately 7.8 arcmin x 17.6
gaps between the chips of ~18 a
(70 pixels). The science field of v
25' (81mm x 88mm).



Renato Cerisola
Fotografo

The LBC adventure

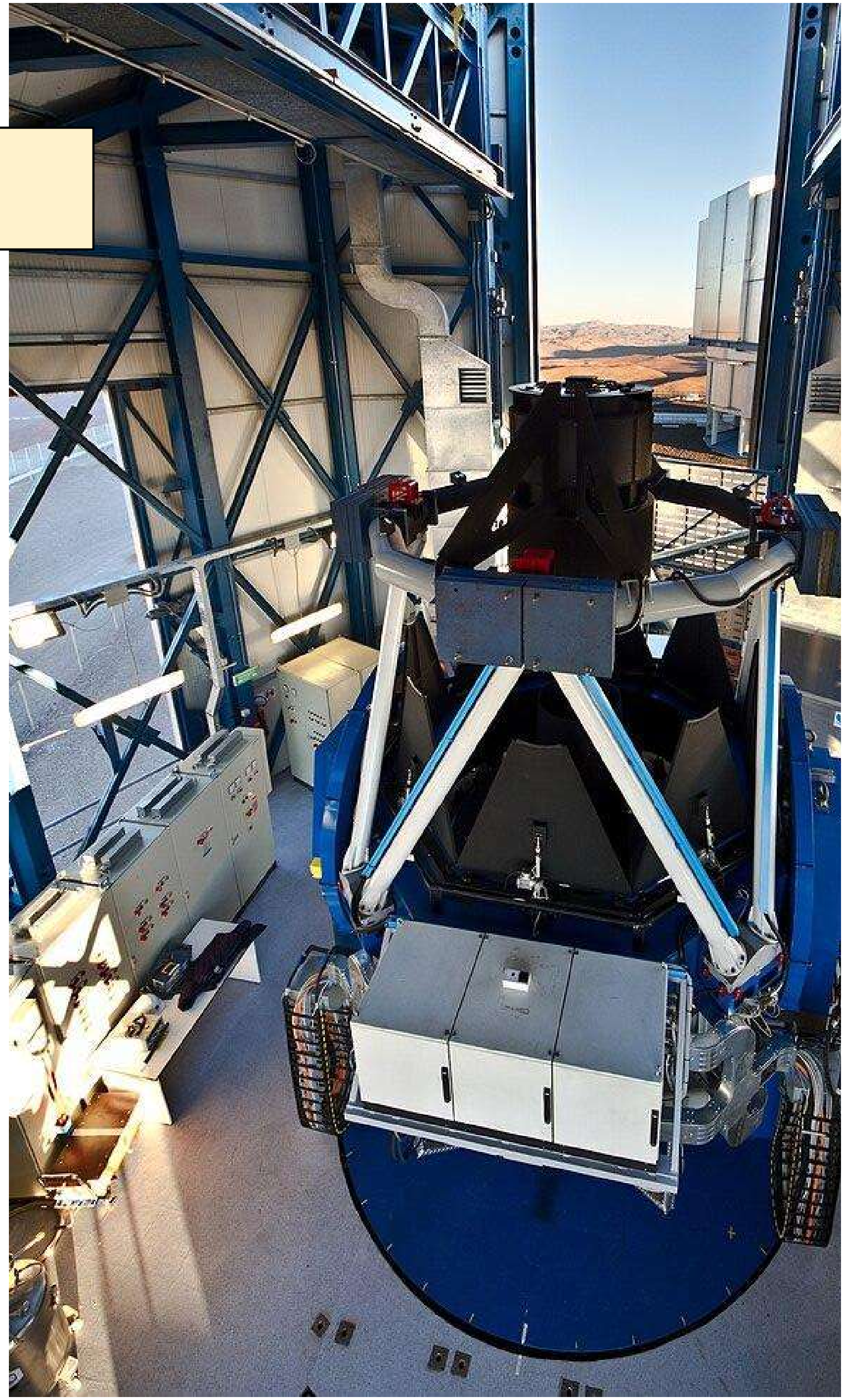
Wide field enabling technologies

	Technology	FoV
Schmidt Telescope	Schmidt plate diameter	6°x6°!!!
Prime focus corrector	Corrector 1st lens diameter	23’x25’

VLT Survey Telescope (VST)

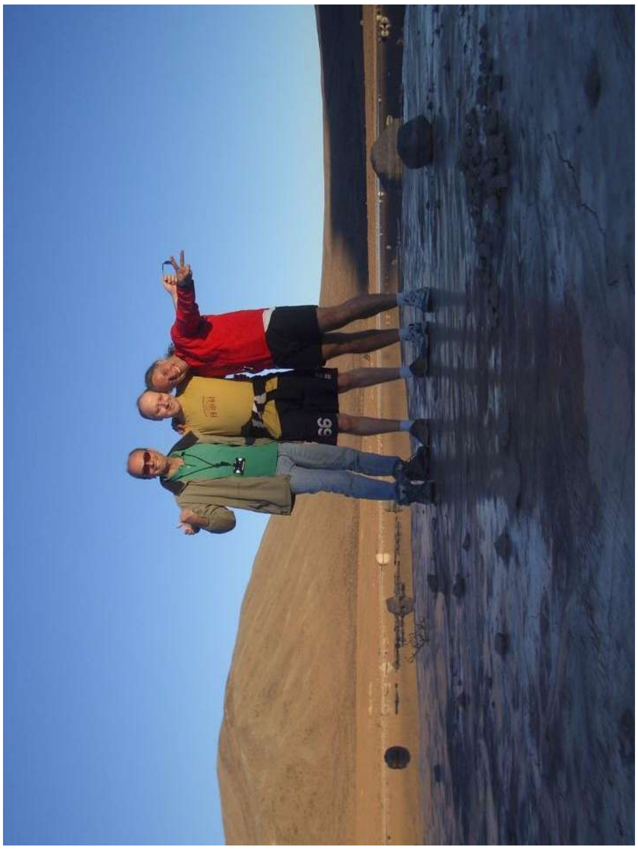
2000 "**VST project: technical overview**", Mancini,D.; Sedmak,G.; Brescia,M.; Cortecchia,F.; Fierro,D.; Fiume Garelli,V.; Marra,G.; Perrotta,F.; Rovedi,F.; Schipani,P.

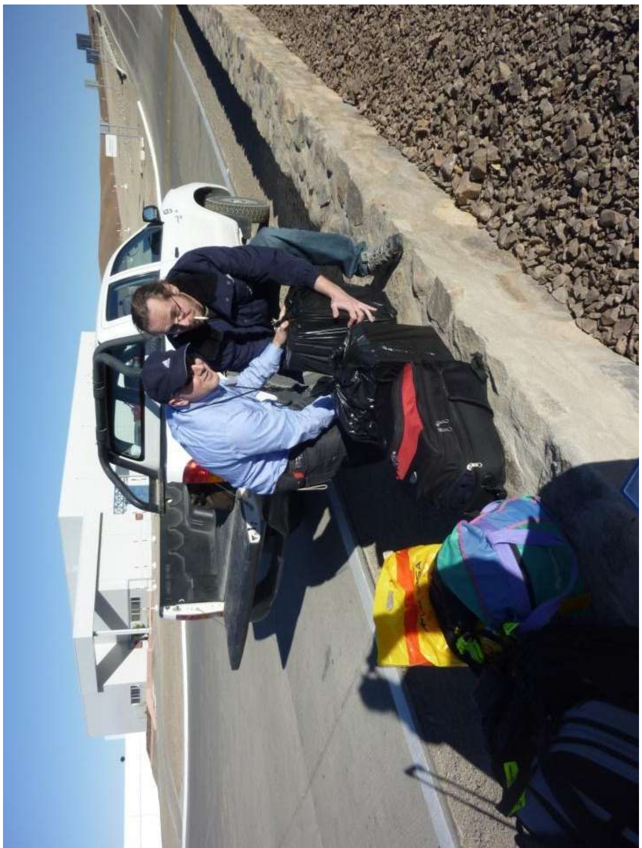
- 2.6m optical survey telescope
- F/5.5 modified Ritchey-Chrétien layout
- 3-lenses wide-field corrector
- corrected field of view of 1°x 1°

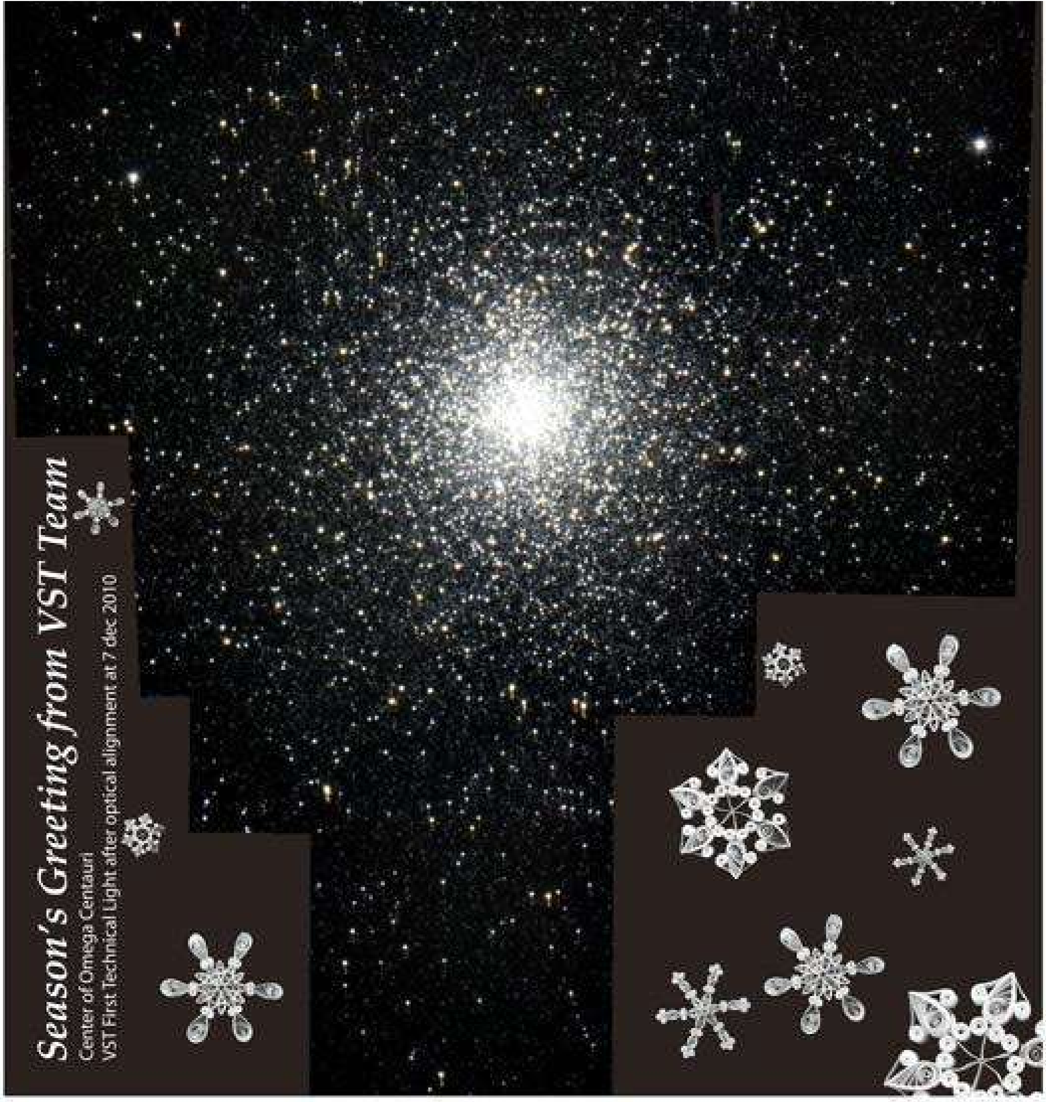


OmegaCAM

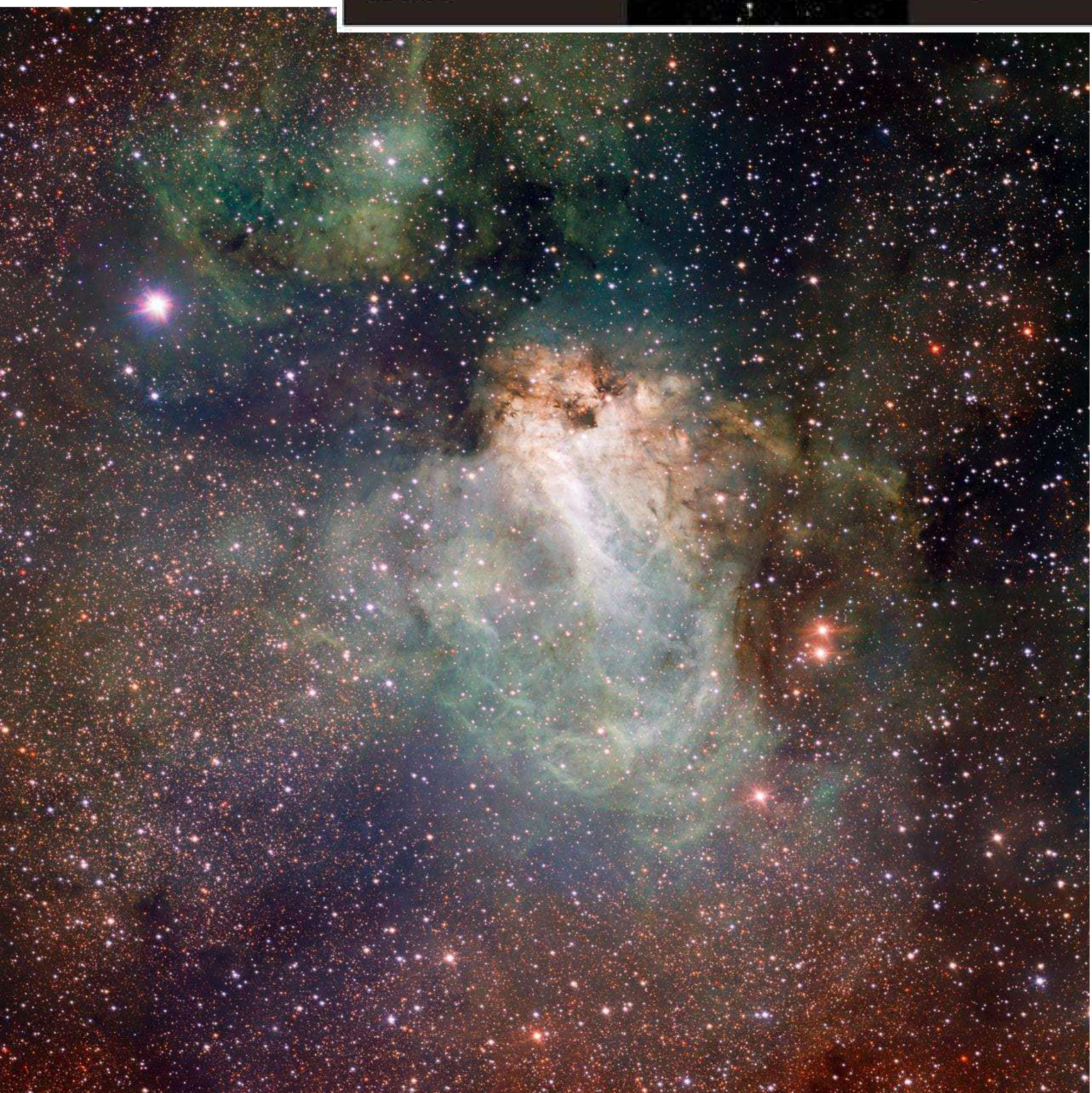
- 1°x 1° FoV
- 32-CCD 44-82 from e2v, 16k x 16k detector mosaic @0.21 "/px.
- Thinned, blue-sensitive, 3-edge buttable CCD44-82 devices from e2v of high cosmetic quality.
- Geometric filling factor: 91.4%.
- Auxiliary CCDs for autoguiding, curvature wavefront sensing and active optics system control.
- Compared to LBC, 8 times the FoV area







Season's Greeting from VST Team
Center of Omega Centauri
VST First Technical Light after optical alignment at 7 dec 2010



Wide field enabling technologies

	Technology	FoV
Schmidt Telescope	Schmidt plate diameter	5°x5°!!!
Prime focus corrector	Powerful aberration corrector	23’x25’
VST	"Physically large detector"	1°x1°

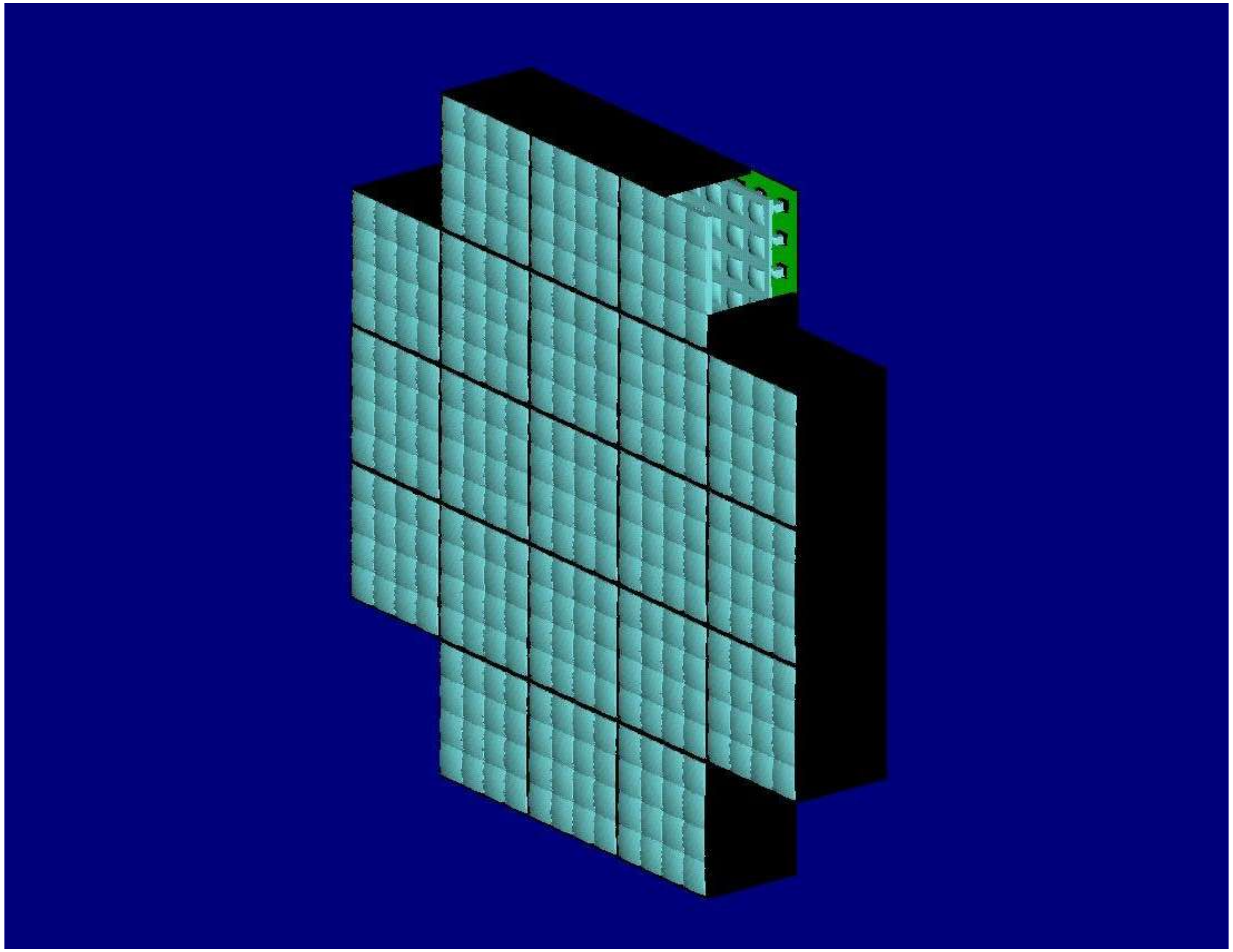
Sphere vs Paraboloid…

	Paraboloid	**Sphere**
Stigmatic for a point at infinity (star)	Yes (on axis)	No
Main aberration (impact on FoV…)	Coma (field-dependent)	Spherical (uniform in fi
Easy to manufacture	Easier than Hyperboloid, harder than Sphere	Easier than other conic mirrors
Radius of curvature (segmented mirrors…)	Continuously varying point-by-point	Uniform
Symmetry axis	Yes, one	Infinite

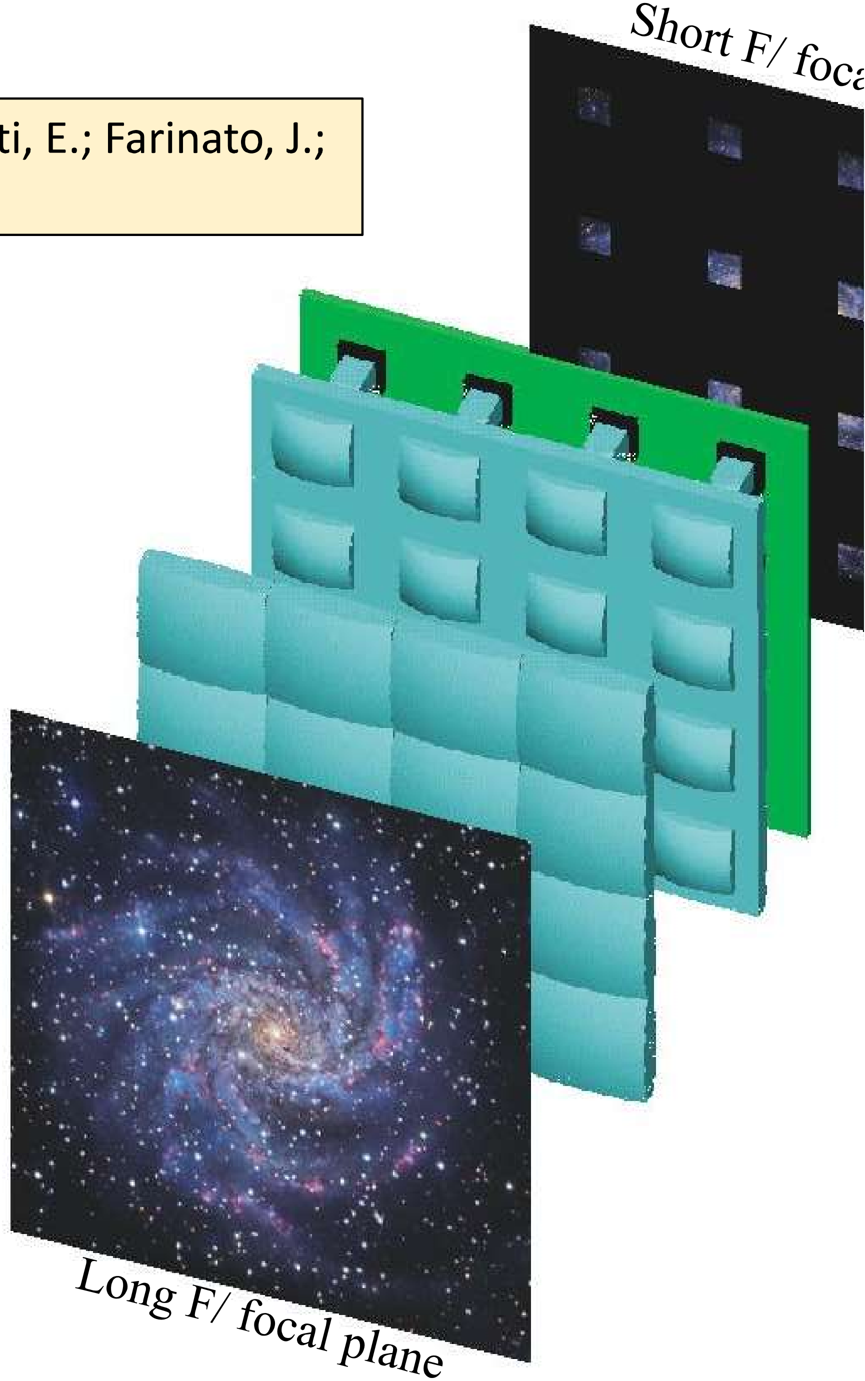
It would be great to have a «Spheraboloid», in which the Spherical aberration is cor

A Smart Fast Camera....???

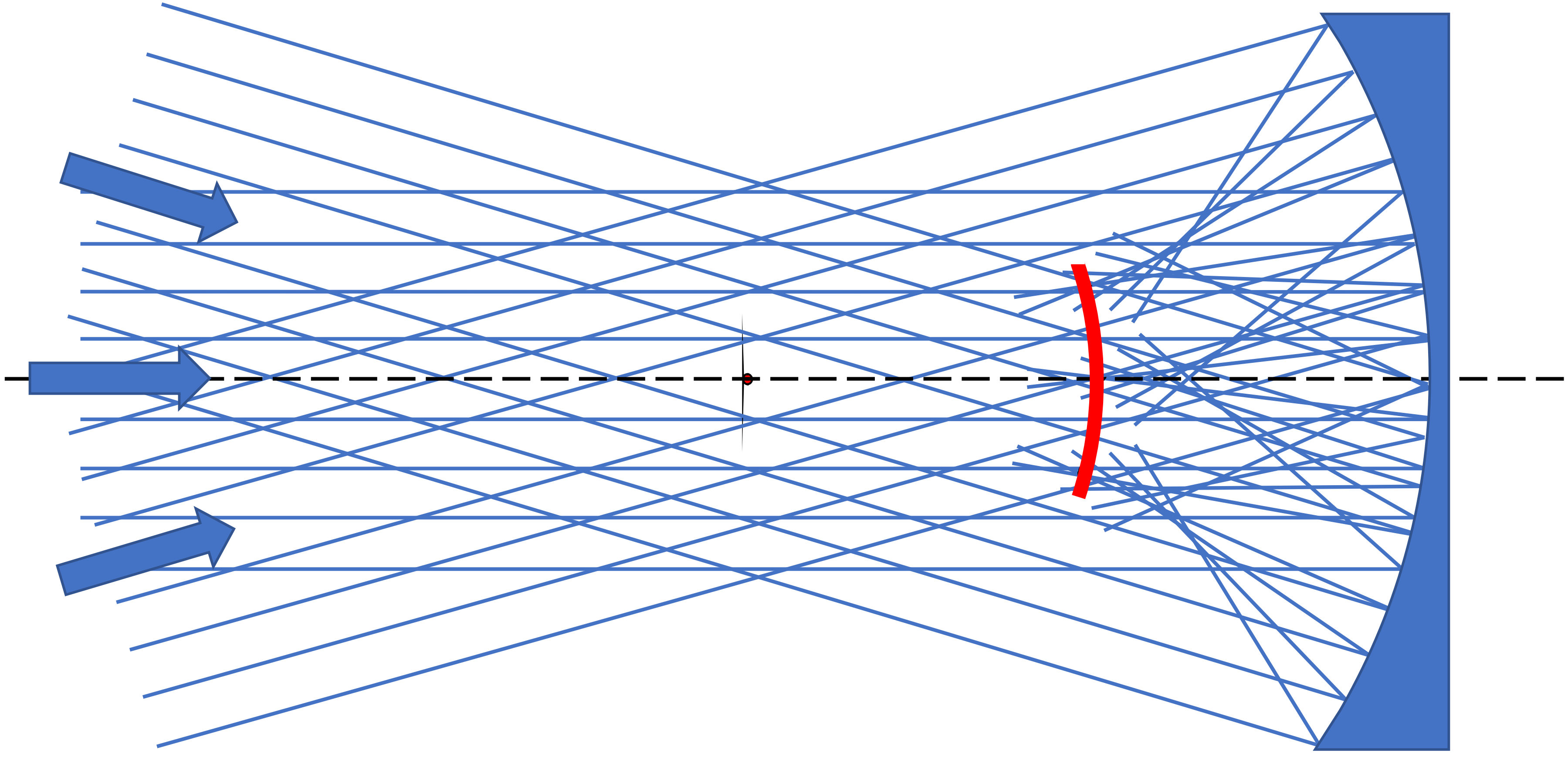
2004 "**A Smart Fast Camera**", Ragazzoni, R.; Arcidiacono, C.; Diolaiti, E.; Farinato, J.; Moore, A. M.; Soci, R.



A project for an array of correctors, each slightly different from each other, to cover a 1.5x1.5deg FoV, never really emerged from the conceptual phase...



Schmidt Telescope Design implications…



Bernard Schmidt

The sphere is affected by a (large) spherical aberration, but it is uniform
the FoV…


Arecibo

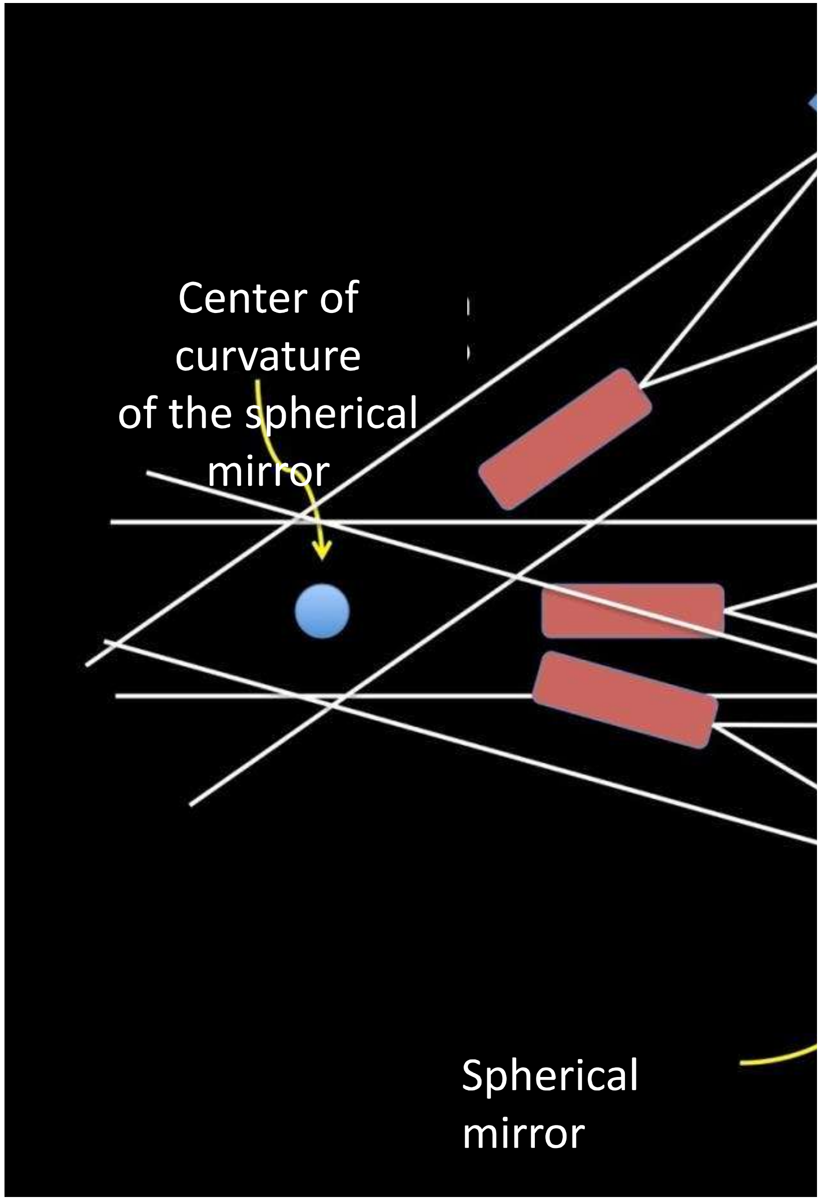
Fly-Eye@ESA

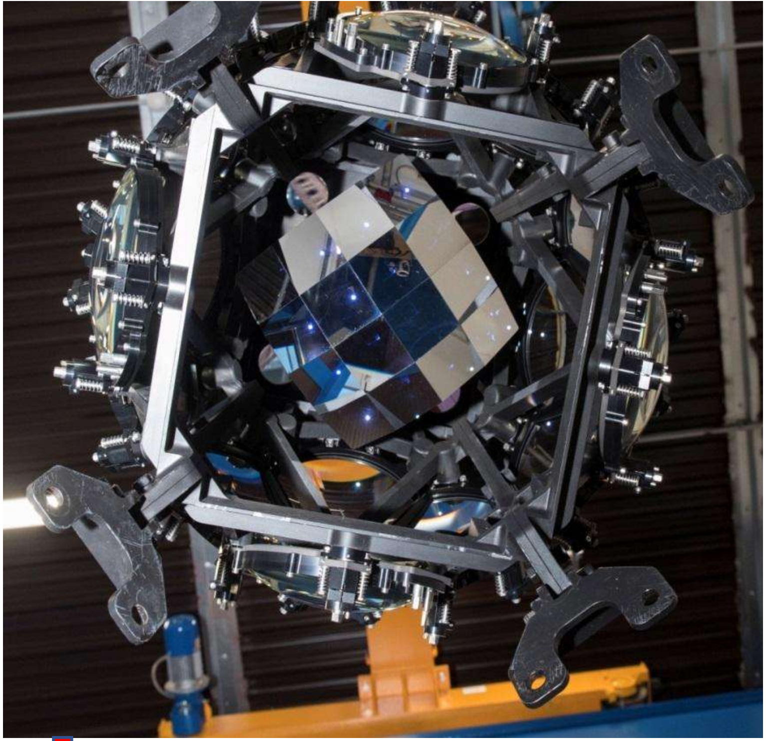
2023 "**FLYEYE family tree, from smart fast cameras to MezzoCielo**", Ragazzoni, R.; Di Rosa, S.; Arcidiacono, C.; Dima, M.; Magrin, D; Corso, A.J.; Farinato, J.; Pelizzo, M.; Santi, G. L.; Simioni, M.; Zaggia, S.

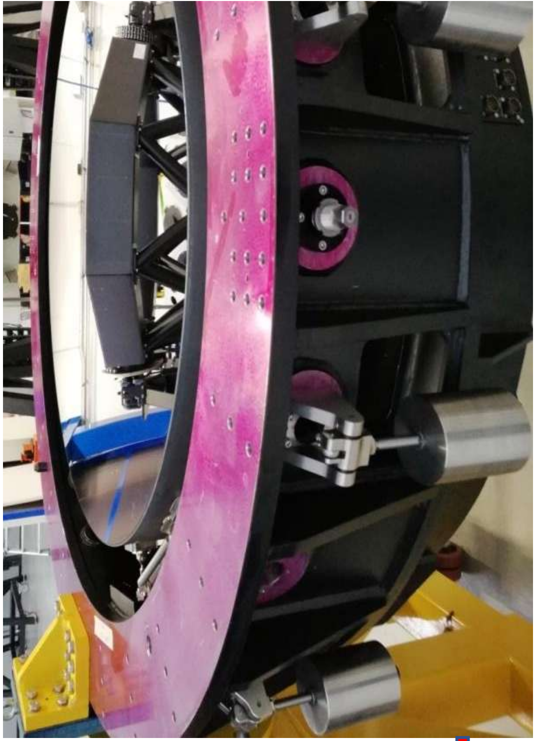
Lesson learned from Schmidt layout:

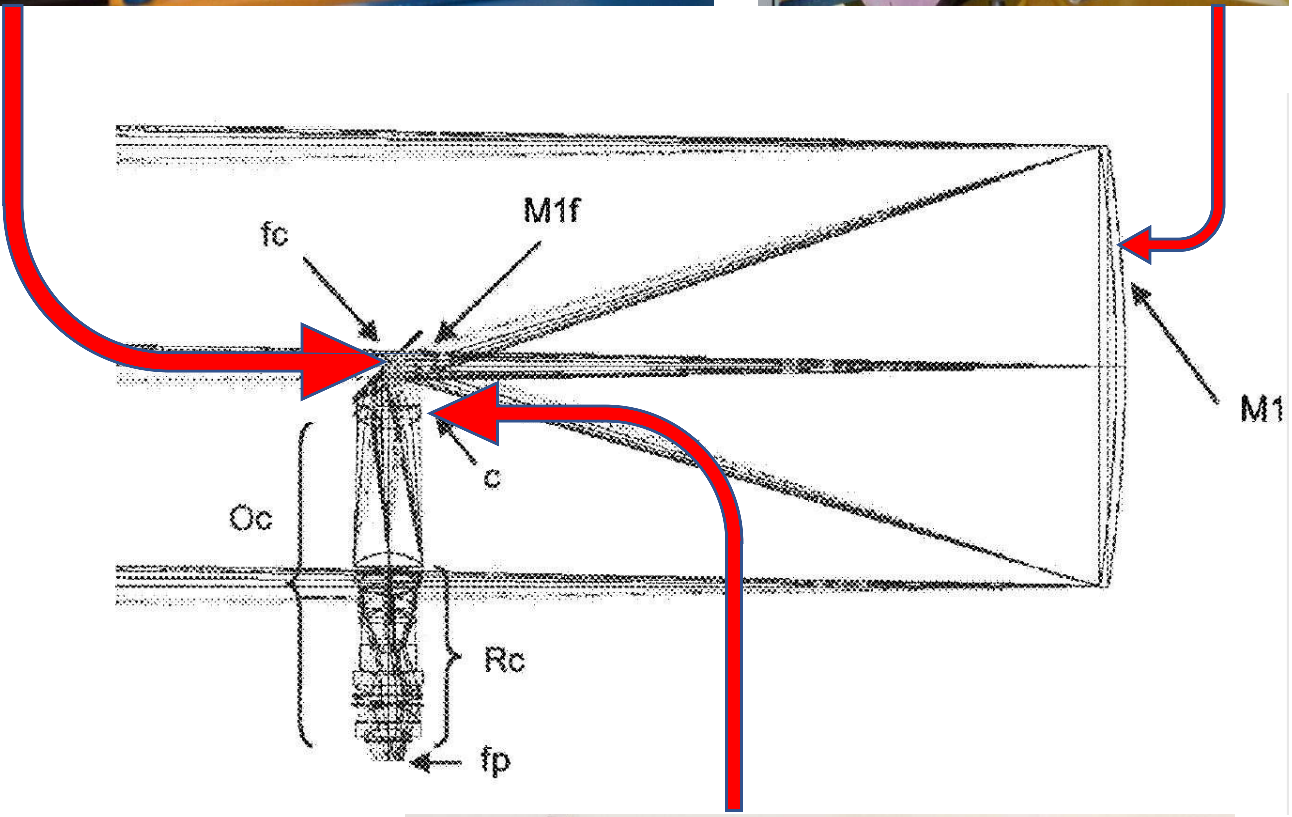
- Suitability of spherical mirror for wide field applications (infinite symmetry axes)
- Very similar aberrations over the FoV
- FoV vs obstruction&quality trade-off

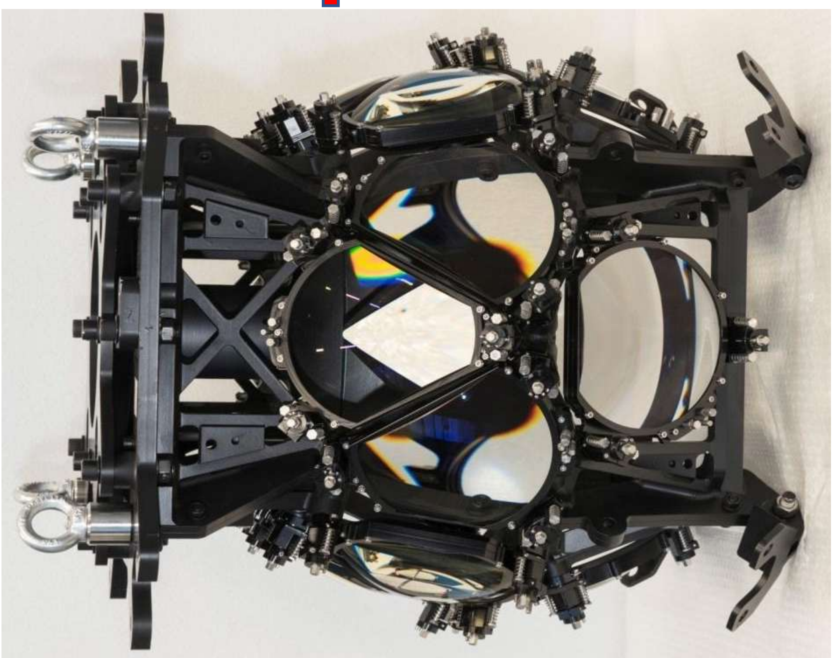
Introducing modularity!








fc
M1f
M1
c
Oc
Rc
fp



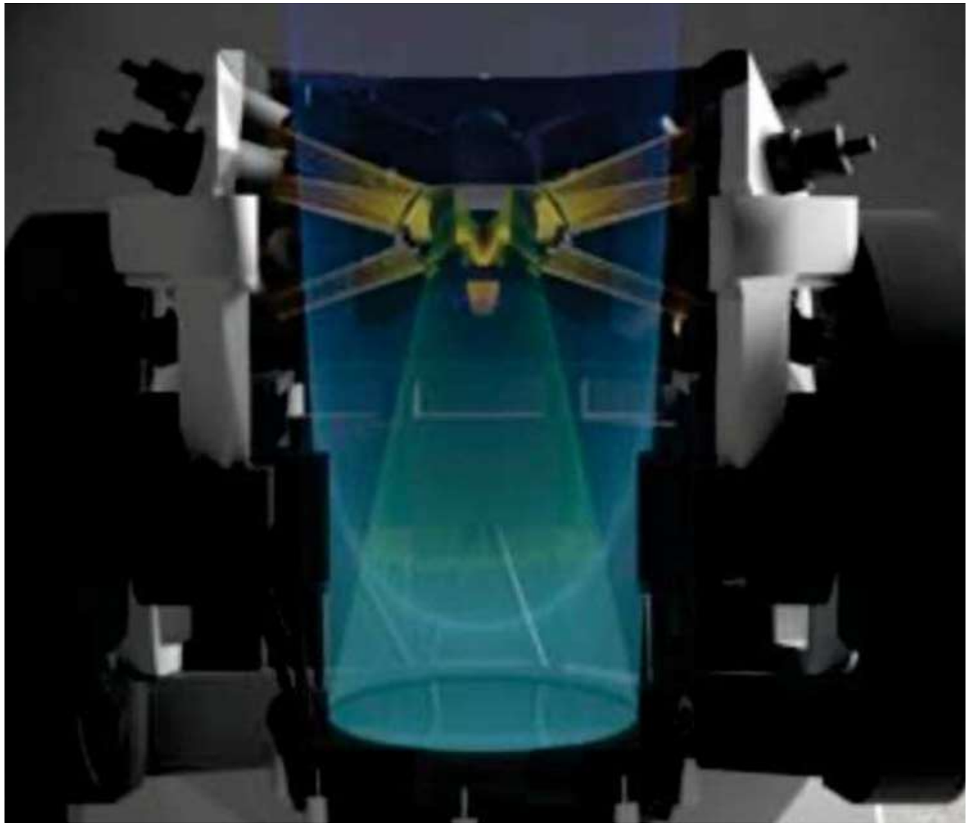
Fly-Eye Key concept:

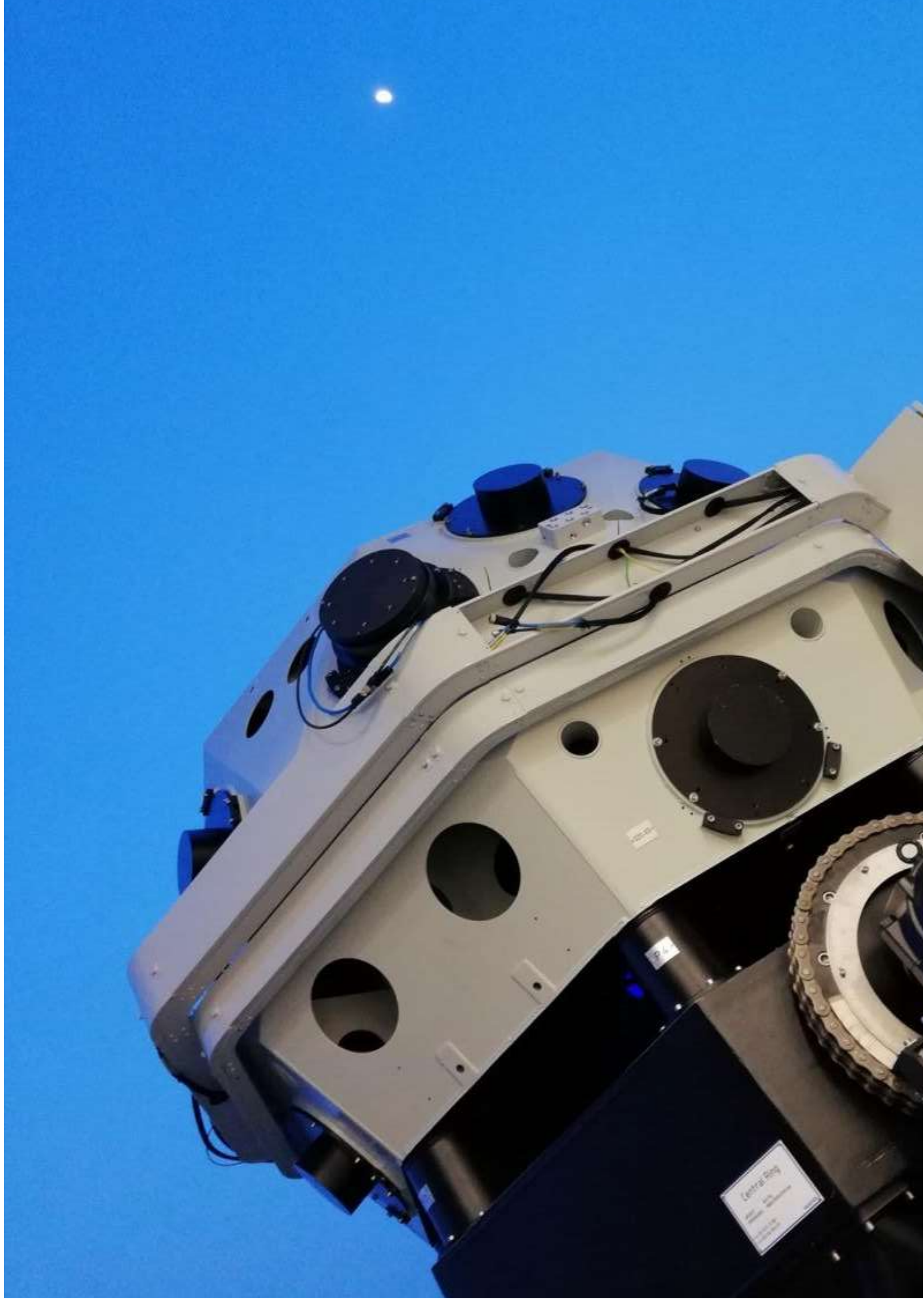
Full 1m mirror is used to collect light for each direction in the sky, only the camera part is modular

In the current design 16 correctors

~ 45^0 FoV (~6.8^0x$6.8\ ^0$)!

OHB ITALIA

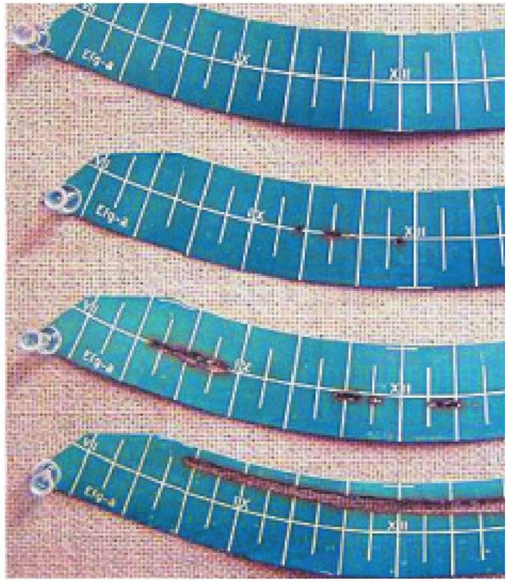




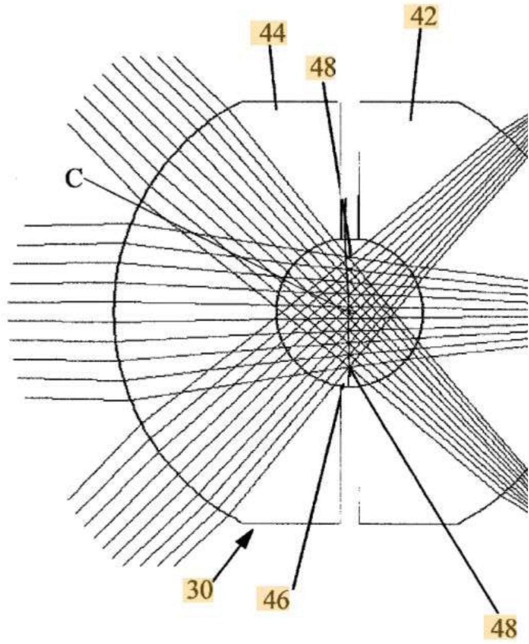
Wide field enabling technologies

	Technology	FoV
Schmidt Telescope	Schmidt plate diameter	5°x5°!!!
Prime focus corrector	Powerful aberration corrector	23’x25’
VST	Physically large camera	1°x1°
Fly-Eye	Modularity	More than 6°x6°

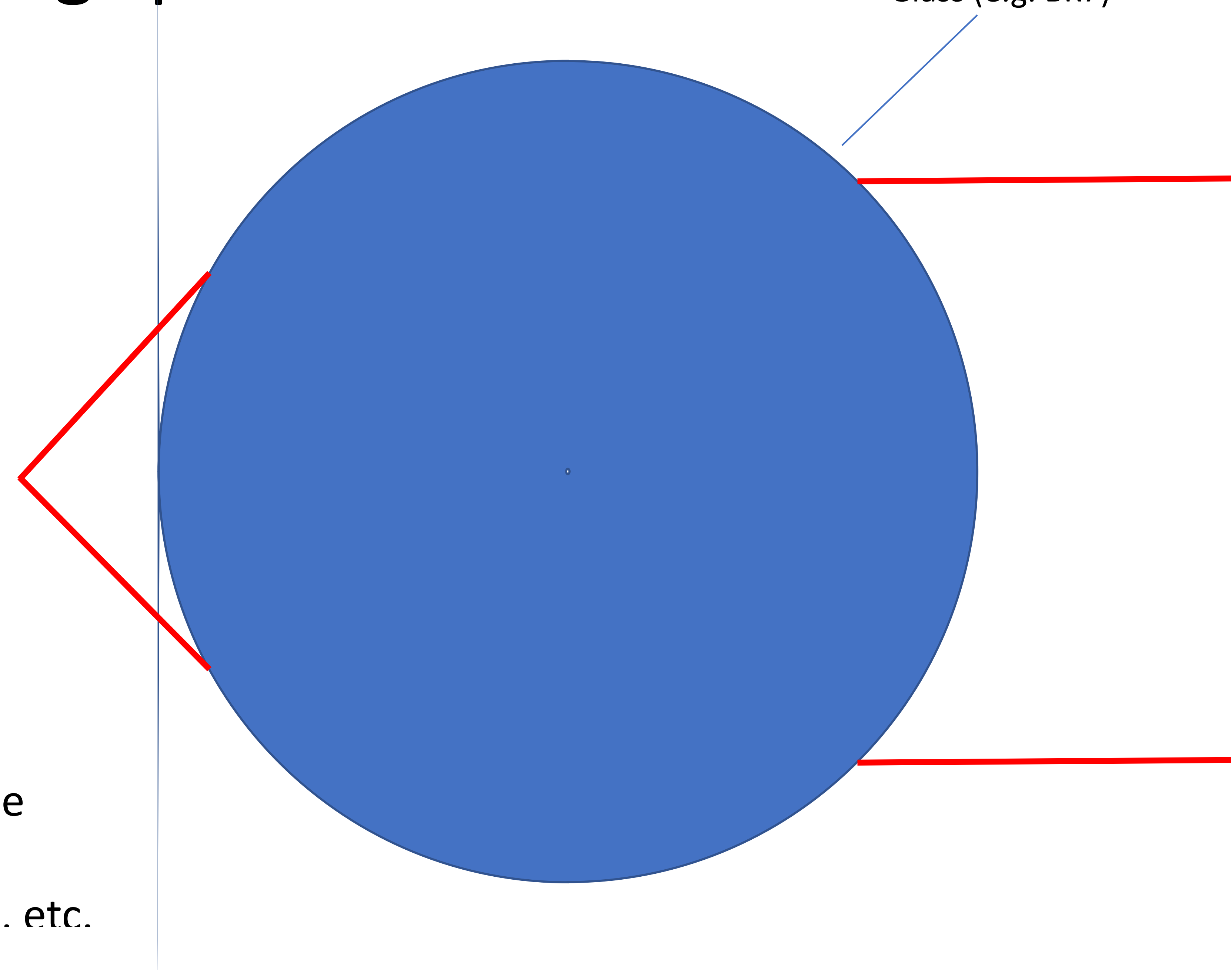
A sunshine recorder (eliofanografo)



A monocentric optic

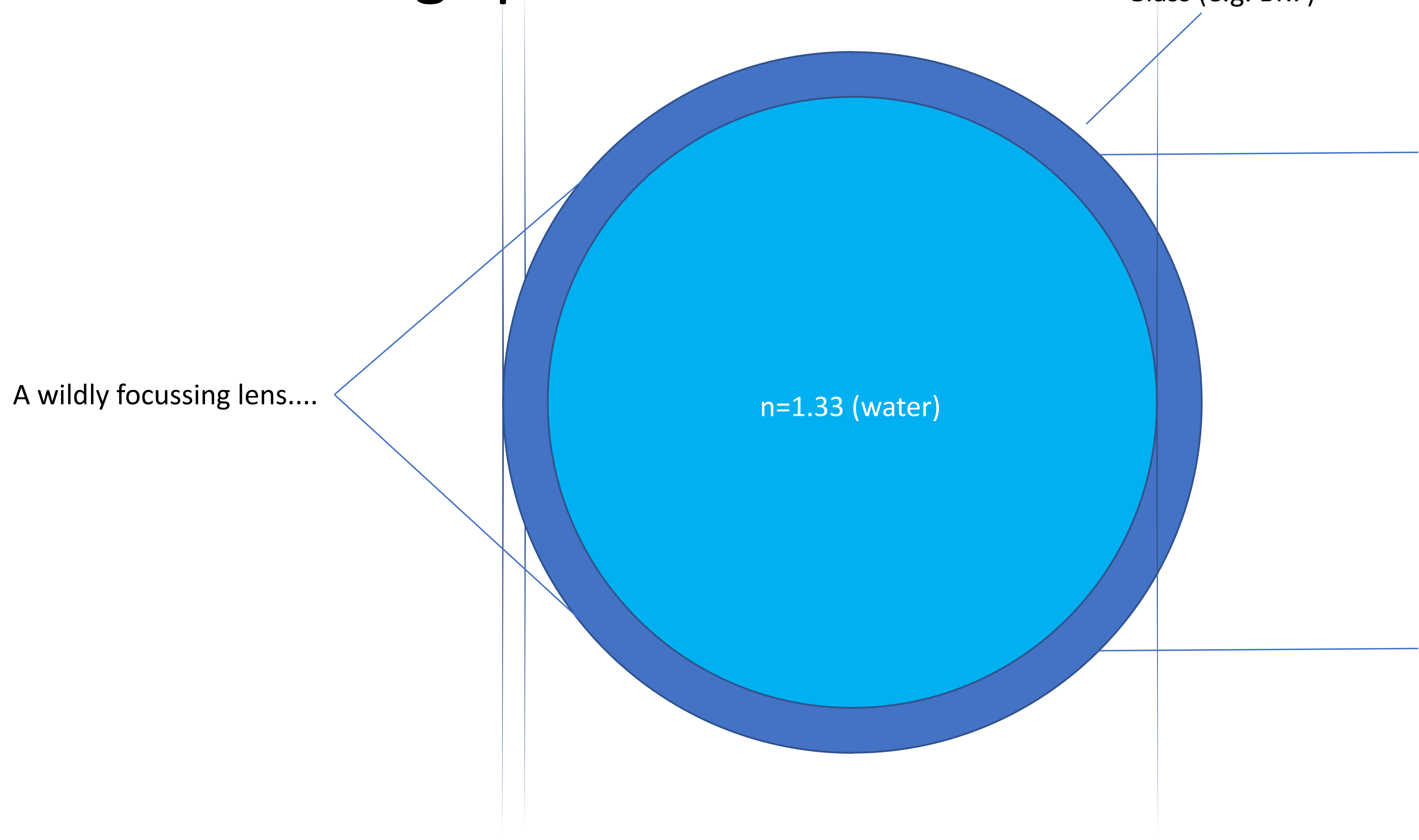


A focussing sphere...



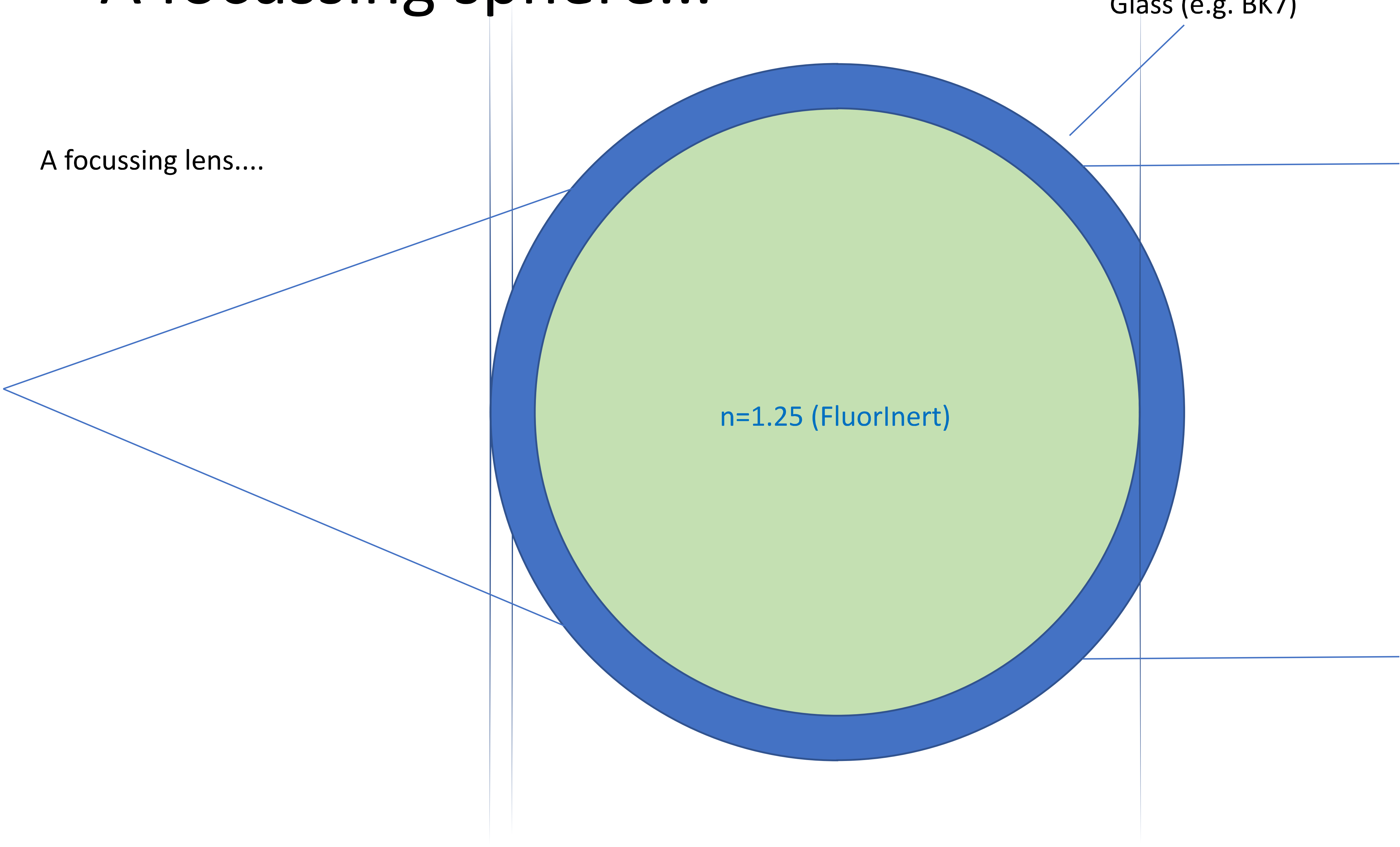
...not to mention the weight,
stress, fusion issues, etc.

A focussing sphere...



A focussing sphere...

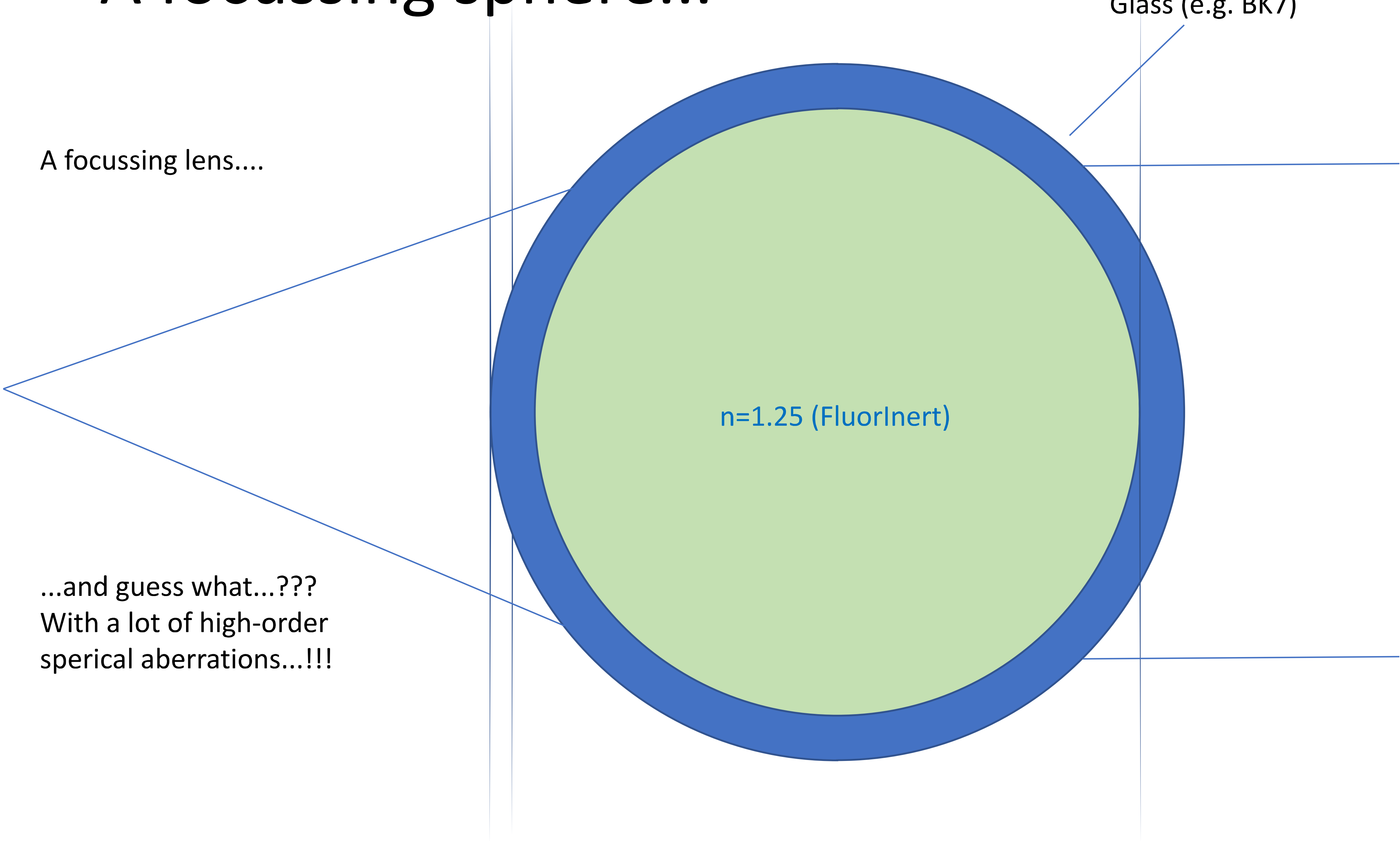
A focussing lens....



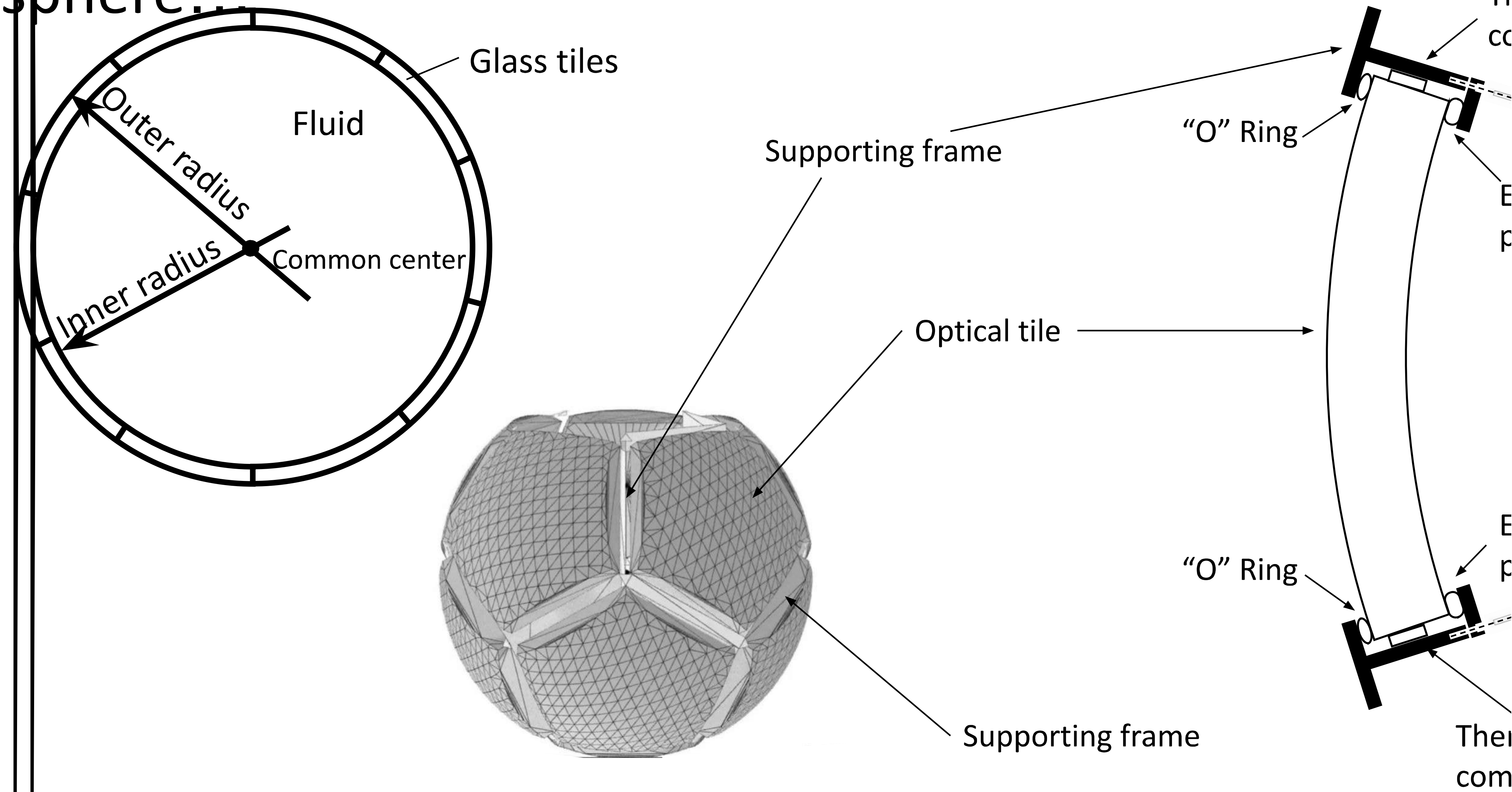
A focussing sphere...

A focussing lens....

...and guess what...???
With a lot of high-order sperical aberrations...!!!

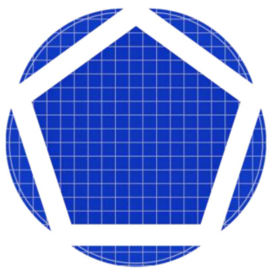


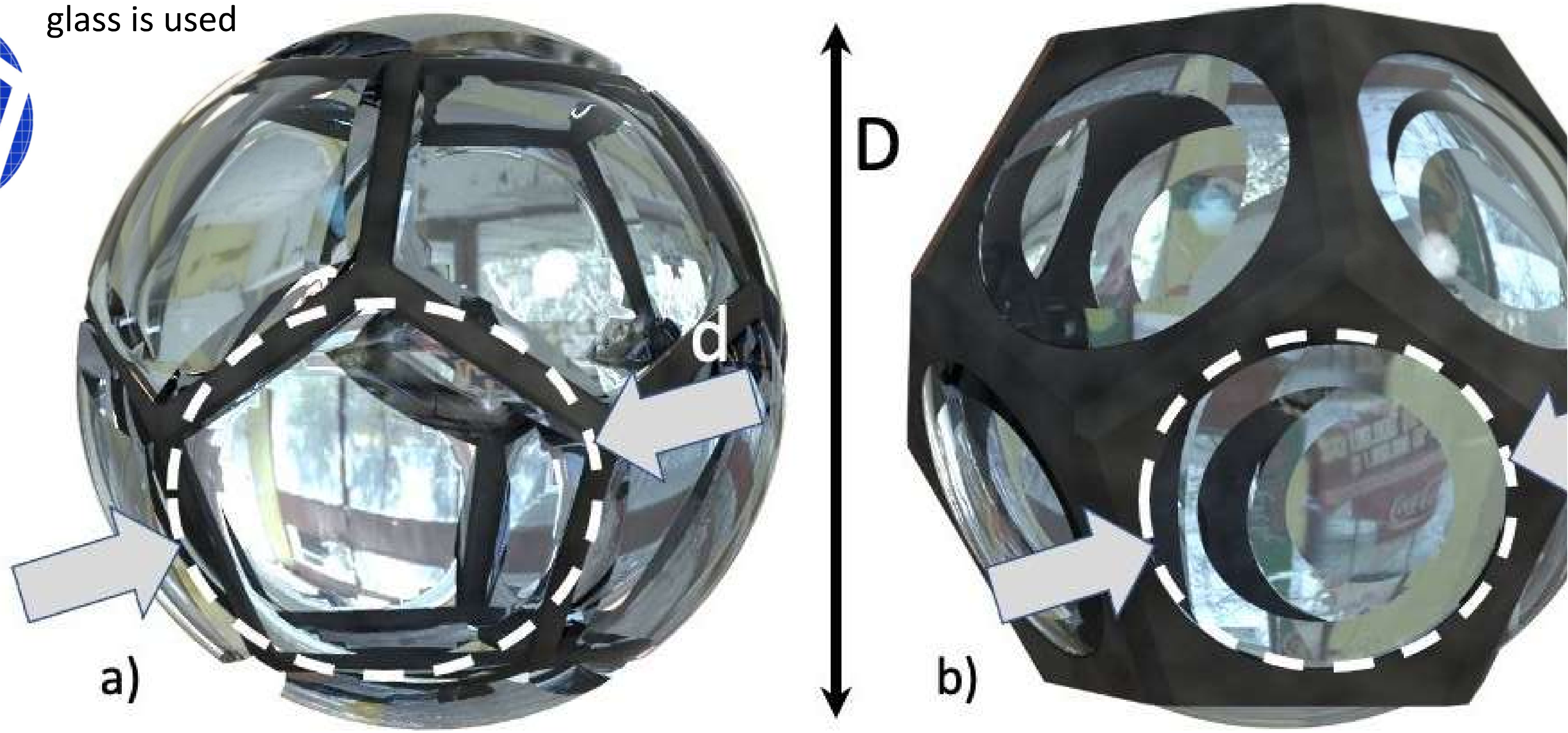
The sphere...


Glass tiles
Fluid
Outer radius
Inner radius
Common center
Supporting frame
Optical tile
Supporting frame
"O" Ring
"O" Ring

Filling factor up to 100%

Approx 76% of the glass is used





$$D = \frac{(1+\sqrt{5})\sqrt{30-6\sqrt{5}}}{8} d \cong 1.95d$$

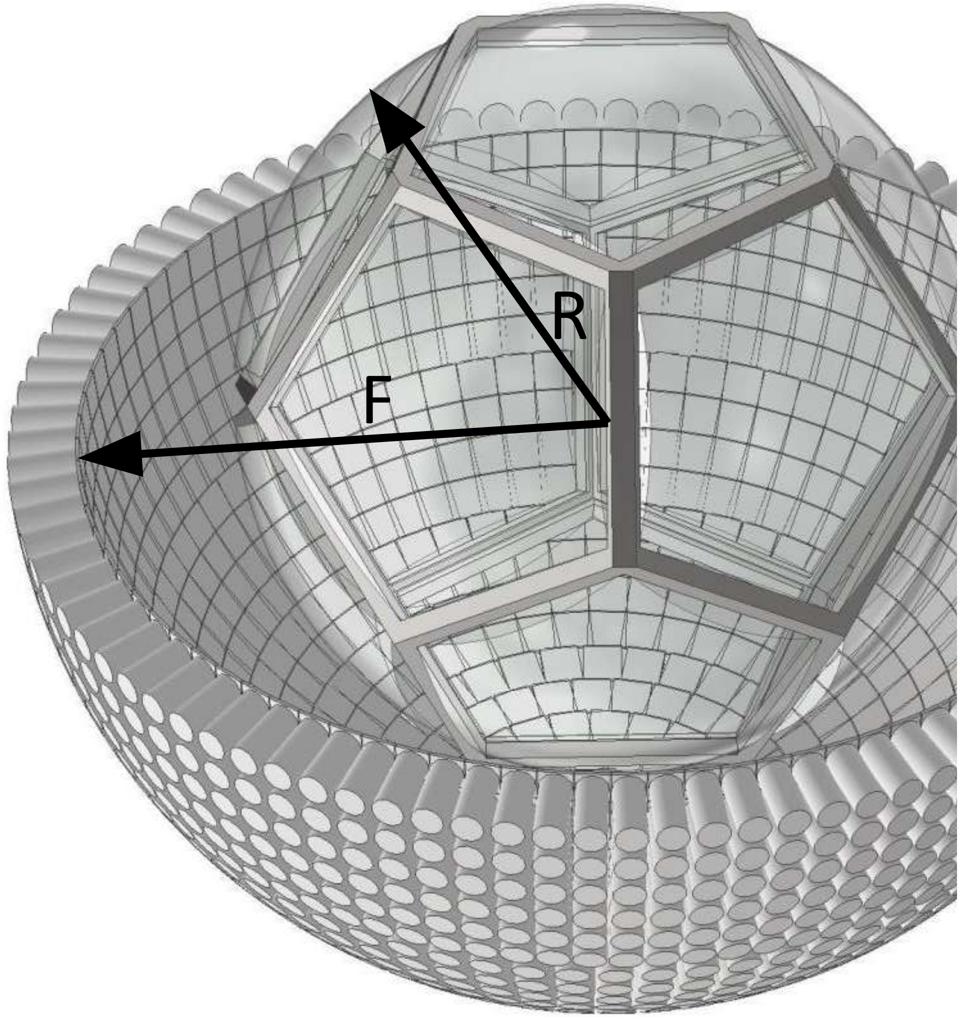
Filling factor ~ 5

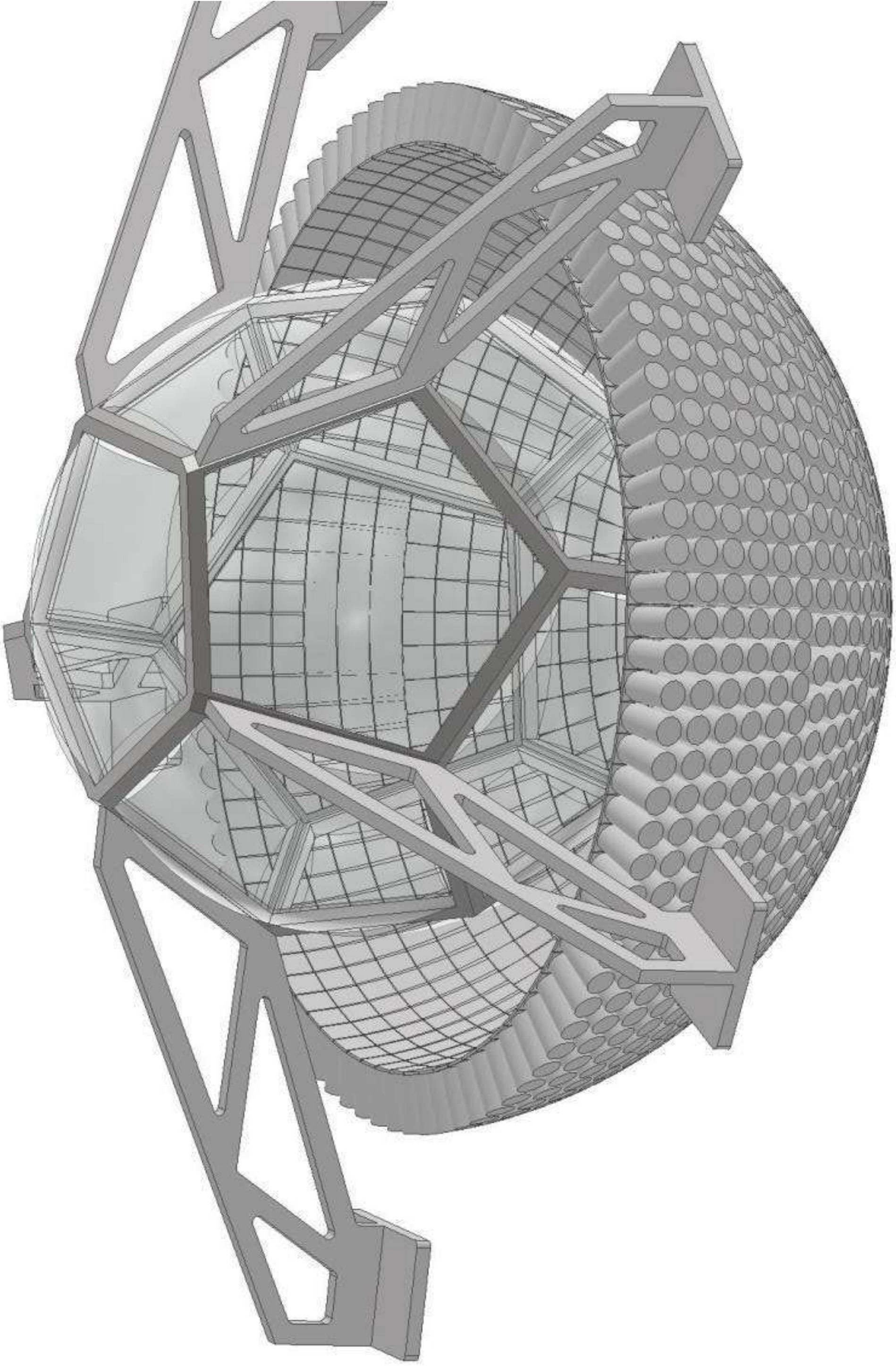
All the glass is u

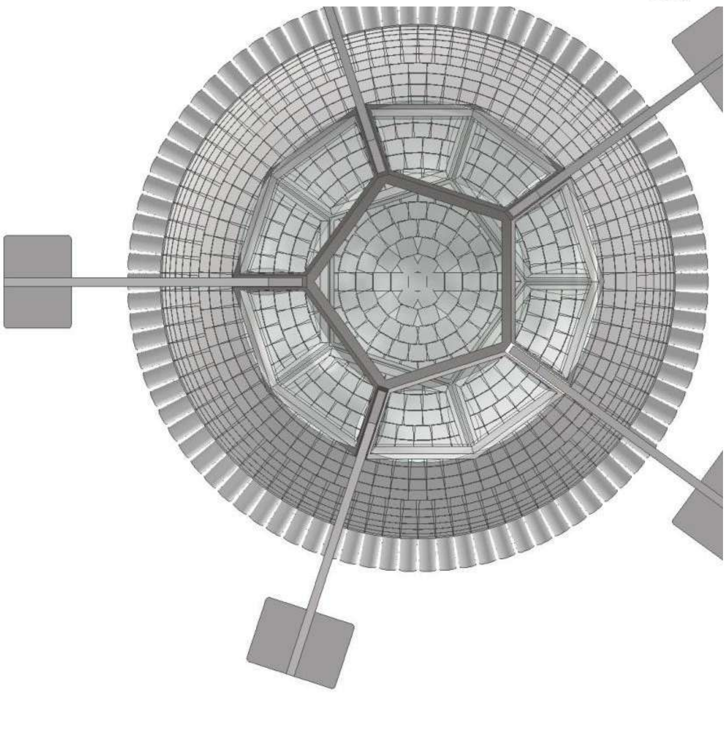
$$D = \frac{\sqrt{30-6\sqrt{5}}}{2} d \cong 2.42d$$

Mezzocielo

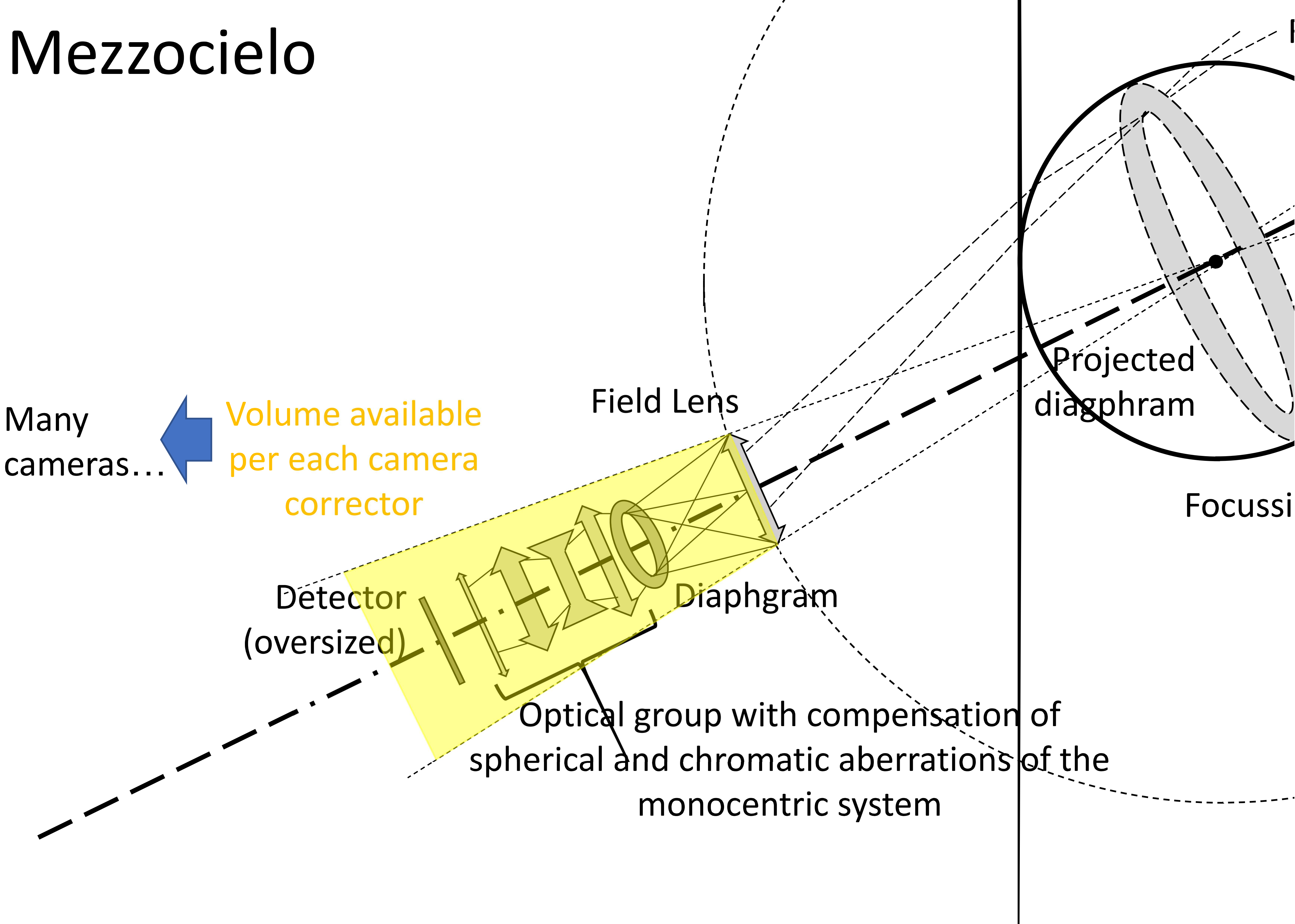
- A sphere of 1-3m class (a sphere with 1m class elements - LBC-like - can form a 1.5..2..2.5..3m aperture sphere, depending upon the choosen geometry
- FoV: all sky above 30° elevation
- About 4000 cameras with a 8kx8k detectors sampling @1"
- Trade-off: a heavier fragmentation of the FoV increases the required number of cameras, but they are much simpler...







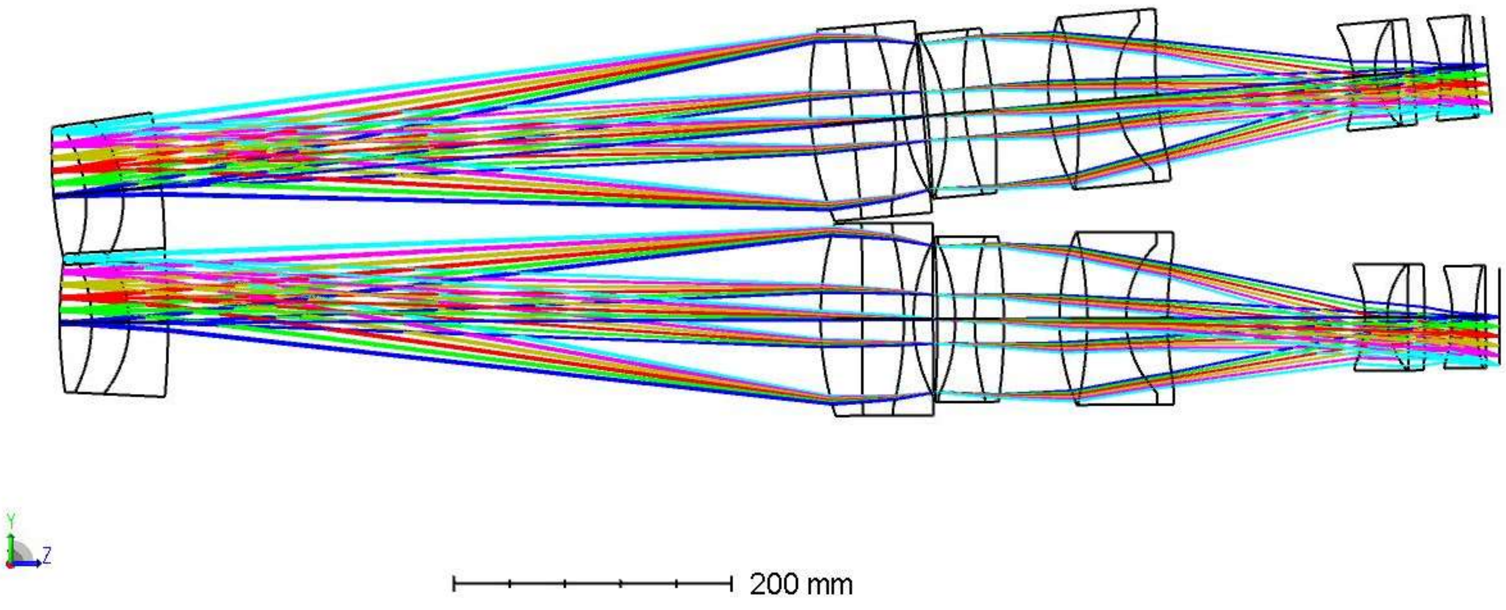
Mezzocielo

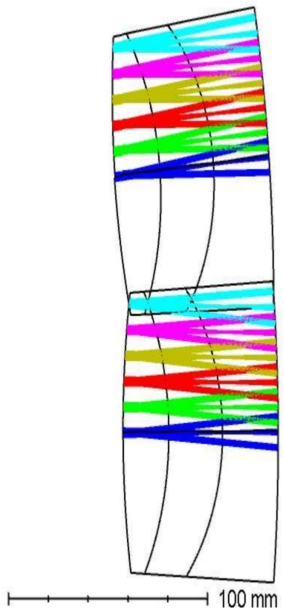

Many
cameras…
Volume available
per each camera
corrector
Field Lens
Projected
diagphram
Focussi
Detector
(oversized)
Diaphgram
Optical group with compensation of
spherical and chromatic aberrations of the
monocentric system

Camera Optical Design (900 identical cameras)

each camera 3.4x3.4 degrees

- 1st triplet:
  - First & last surface diameter 100 mm, 102 mm
  - focal length forced to be < 380 mm
- Air Separation limited to 500 mm





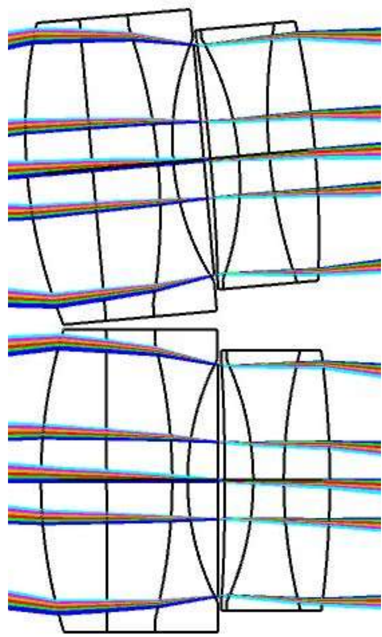
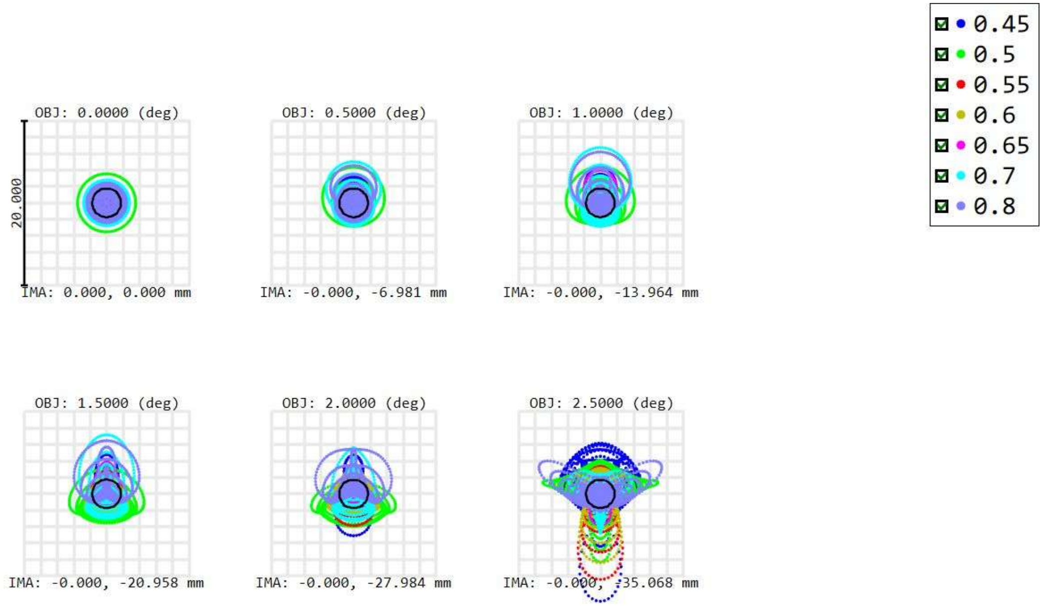


Image Quality



Surface: IMA

Spot Diagram

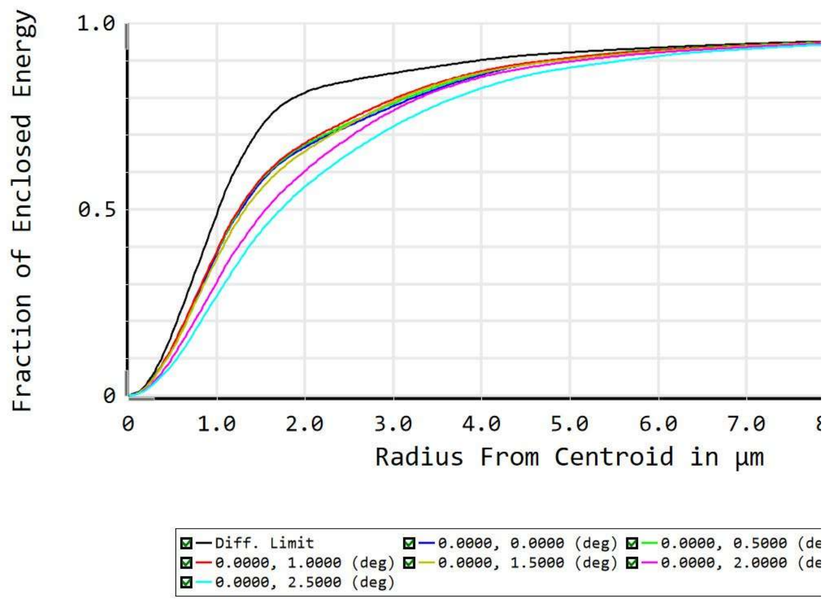
2/4/2025
Units are µm. Airy Radius: 1.749µm. Legend items refer to Wavelengths

Field :	1	2	3	4	5	6
RMS radius :	1.578	1.605	1.669	1.790	2.000	2.493
GEO radius :	3.531	4.991	6.723	7.182	5.626	13.075

Scale bar : 20.000 Reference : Centroid

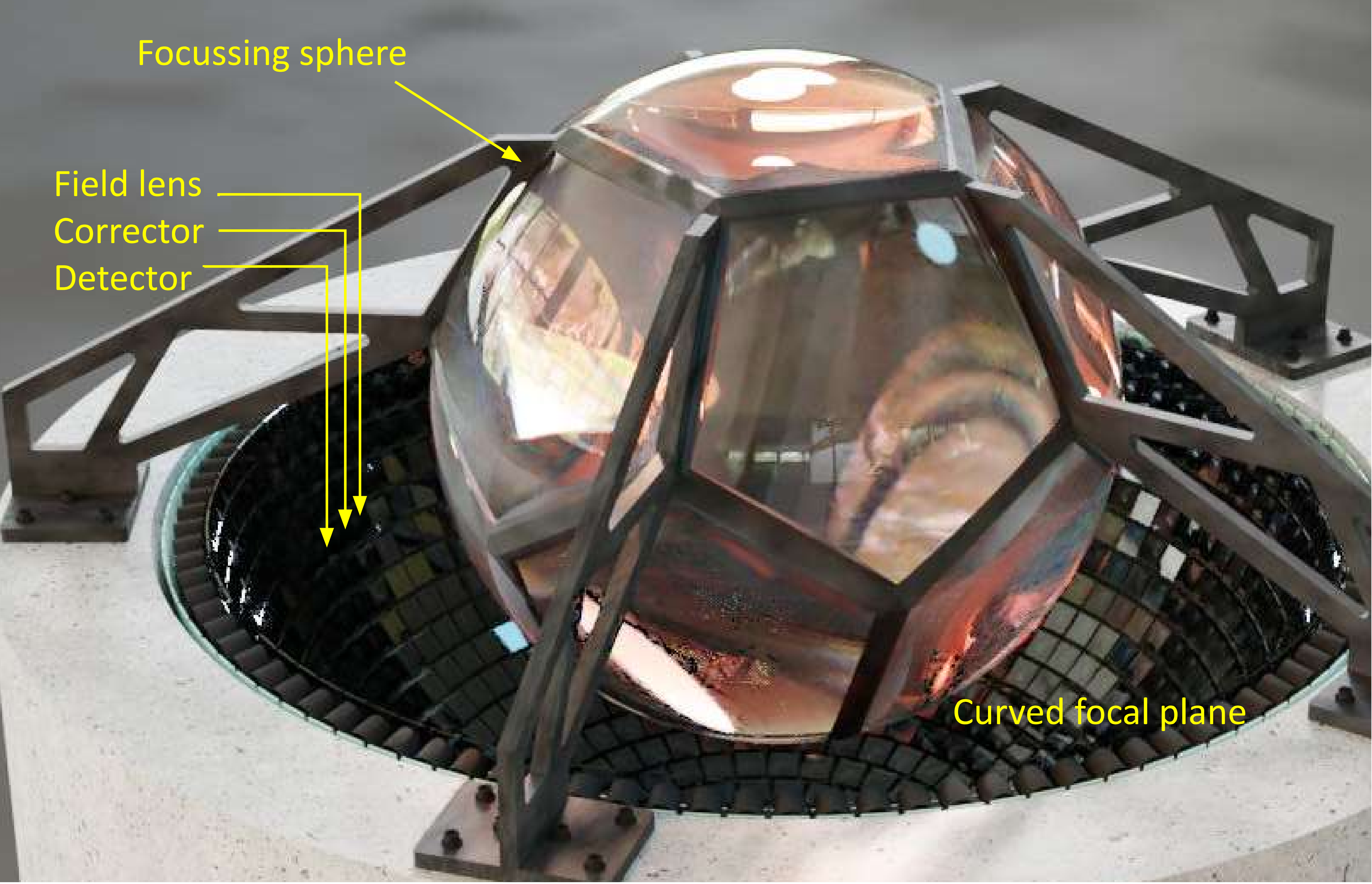
Zemax
Zemax OpticStudio 23.1

Mezzocielo_5T3A_CN_Catalogue.zmx
Configuration 1 of 2

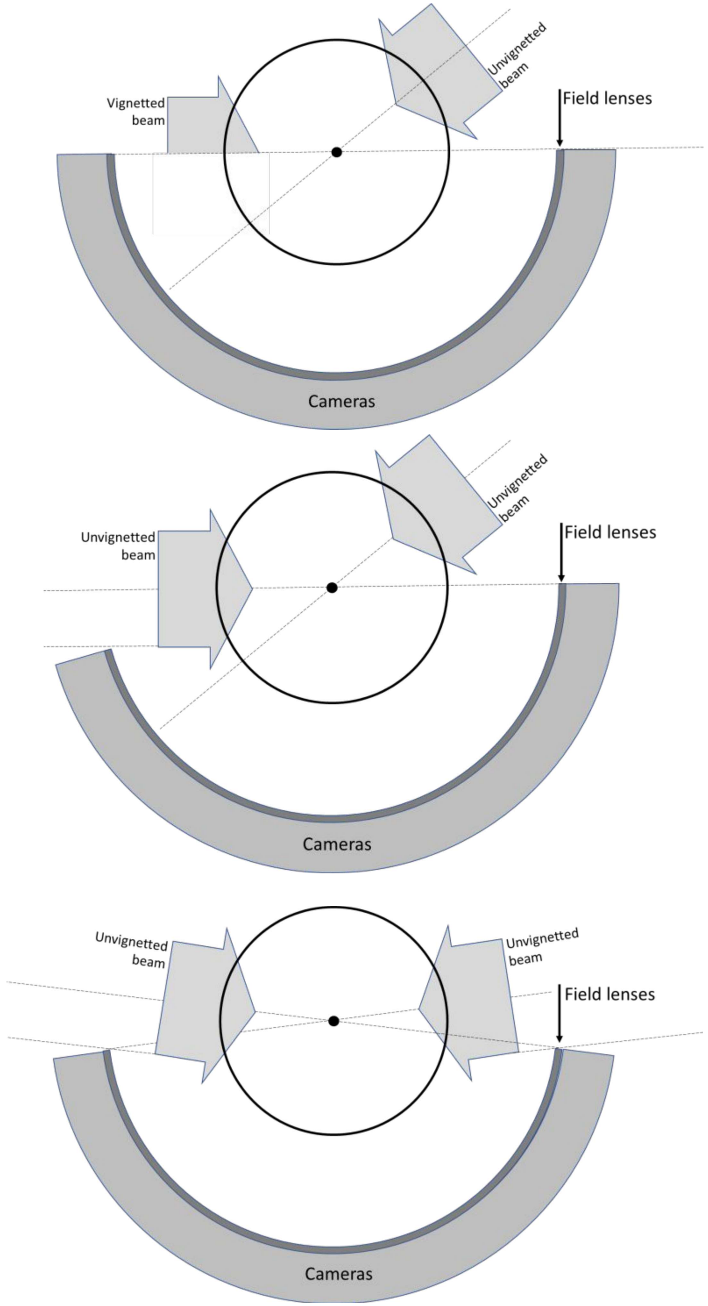


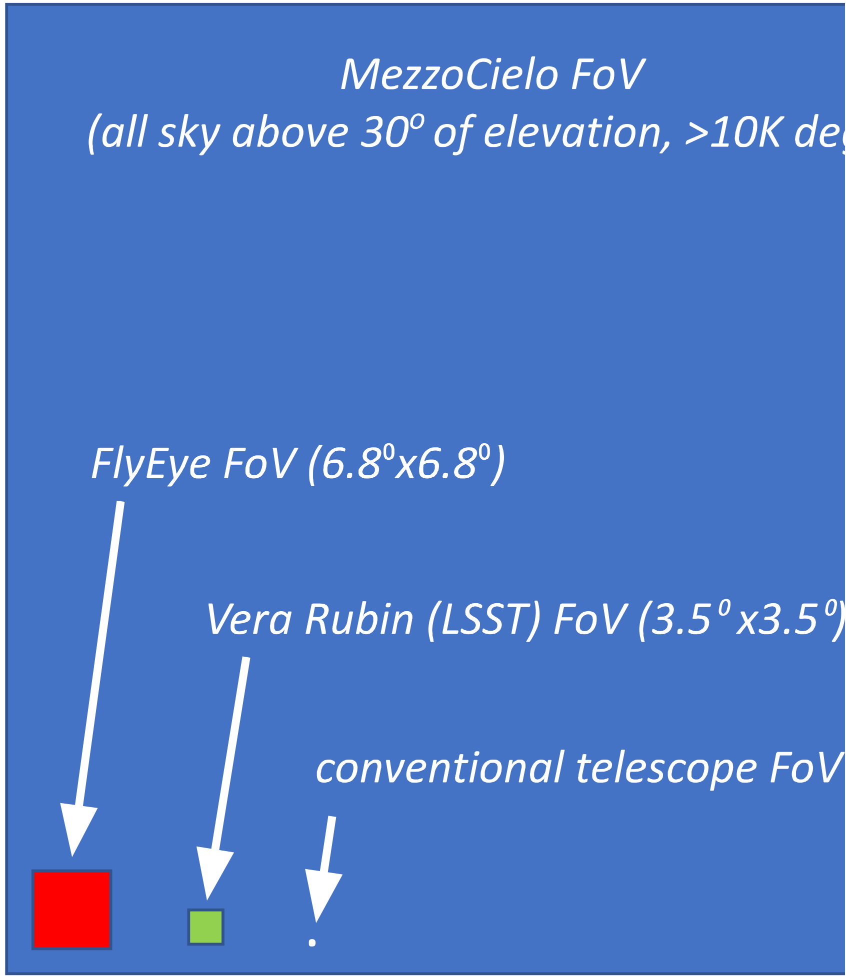
FFT Diffraction Encircled Energy

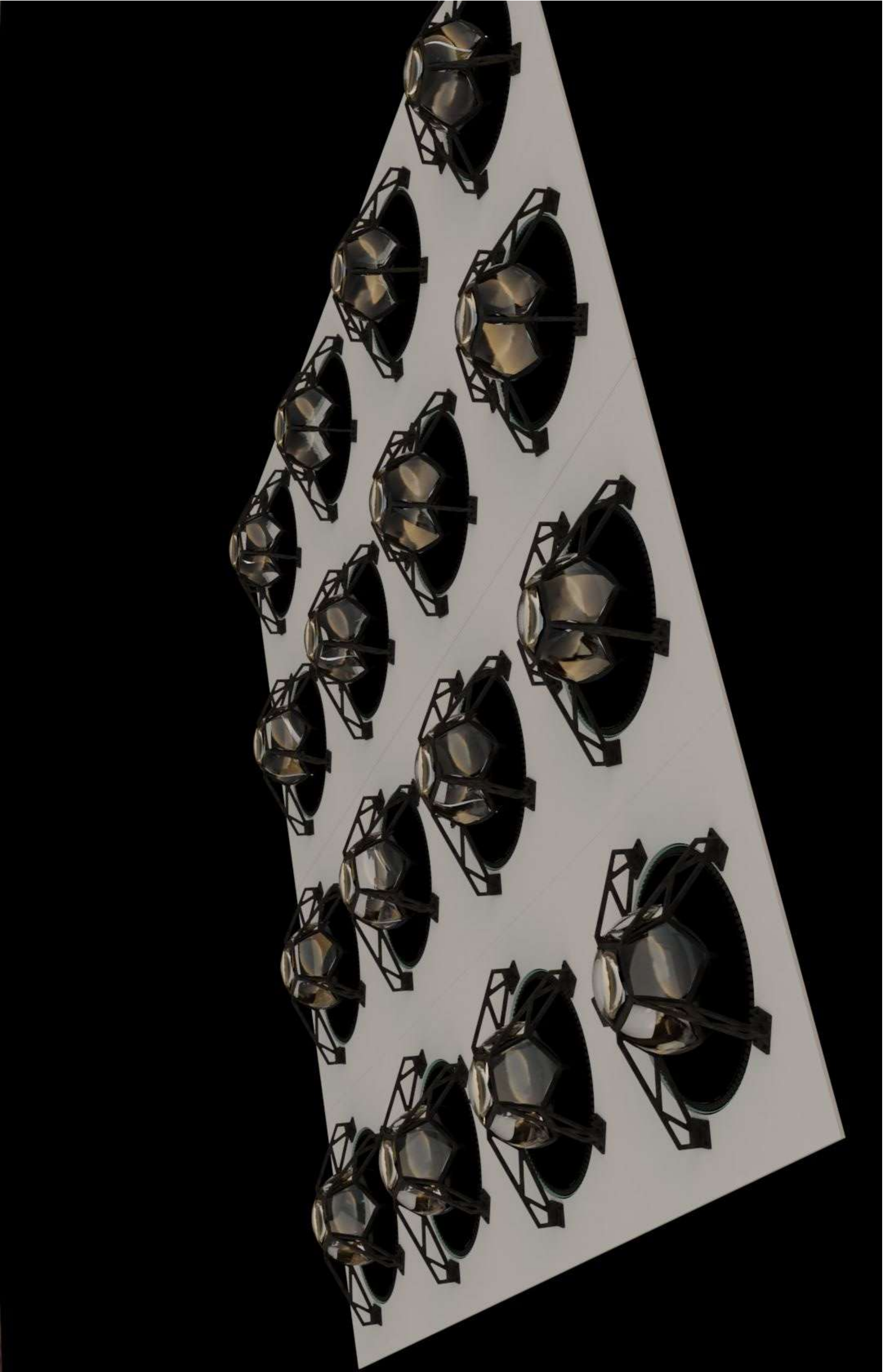
80% EE < 3.712 um


Focussing sphere
Field lens
Corrector
Detector
Curved focal plane

Mezzo Cielo FoV







Wide field enabling technologies

	Technology	FoV
Schmidt Telescope	Schmidt plate diameter	5°x5°!!!
Prime focus corrector	Powerful aberration corrector	23’x25’
VST	Physically large camera	1°x1°
Smart Fast Camera	Modularity	More than 6°x6°
Mezzocielo	The "sphere / Data volume"	>10000 squared degree

A ***glob***al telescope

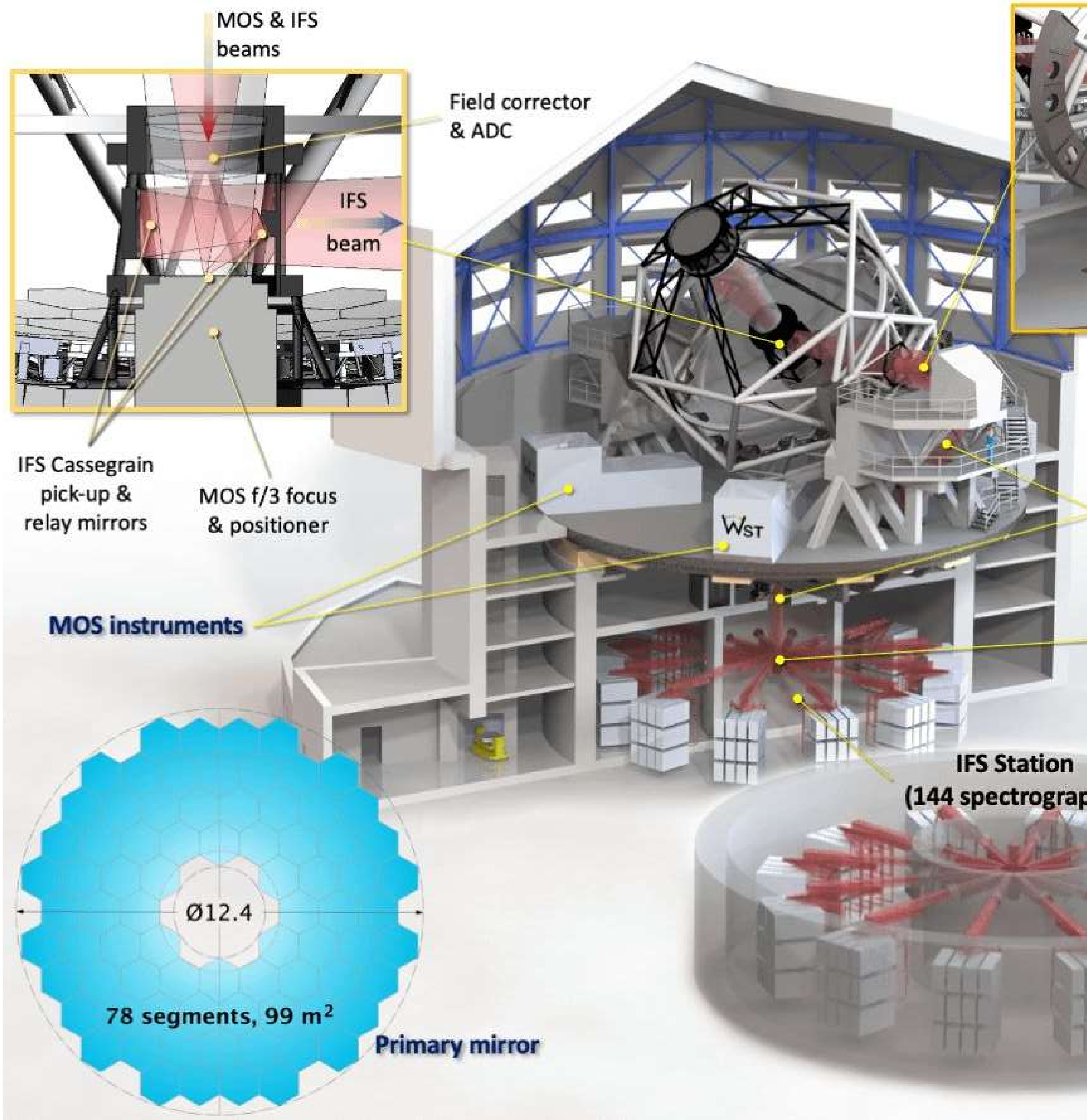
- Correctors can ”travel” on a curved surface or corotate with Earth’s rotation;
- Mass production of the cameras with correctors;
- CMOS became very attractive because of three orders of magnitud smaller cost;
- Field derotation can be compensated by few degs rotation of the curved focal plane along the Earth’s axis;
- A challenge can becomes the larga data flow to hanlde...!!!

MezzoCielo challenges…

- Deciding which level of segmentation (it is nevertheless mass producti
  - A lot of smaller cameras made the camera's optics simple
  - A "smaller" number of large cameras made them more complex
  - We are currently thinking to about 900 cameras => 3.4^0x 3.4^0 FoV on each cam
- CMOS detector makes the project affordable in term of costs (not CCD moreover, in 10 years from now CCDs may not exist anymore
- Detailing the overall efficiency (obstructions vs. FoV)
- Minimum power consumption by running 900 or so CMOS camera anc download to (local) computers
- 900 x 8k x 8k (58G) data is the "one frame" data volume. One night (12 60sec cadence is a further x 720 making 41TB per day (SKA is producin 2000TB per night, LSST 20TB per night)

WST: the Wide field Spectroscopic Telescope

- alt-azimuthal, compact 12.4-m telescope
- 2-mirror telescope design (M1 F/1), M1 has 78 segments
- 0.35-1.6 μm wavelength range
- seeing limited 0.25" arcsec sampling
- provides two concentric fields, that can be used simultaneously
    - a 3.1 deg^2 field (MOS) at a corrected f/3 Cassegrain focus located above the primary mirror
    - a 13' diameter field (IFS) in a Nasmyth configuration. In such field, any 3' x 3' sub-field can be selected and propagated through a Coudé optical relay, down to the gravity-stable f/35 IFS Coudé station



Credit of WST consortium

Low-Resolution MOS

MOS LR Multiplex	20,000
MOS LR Resolution	3,000-4,000
MOS LR Spec Range	370-970 nm (simultaneous)

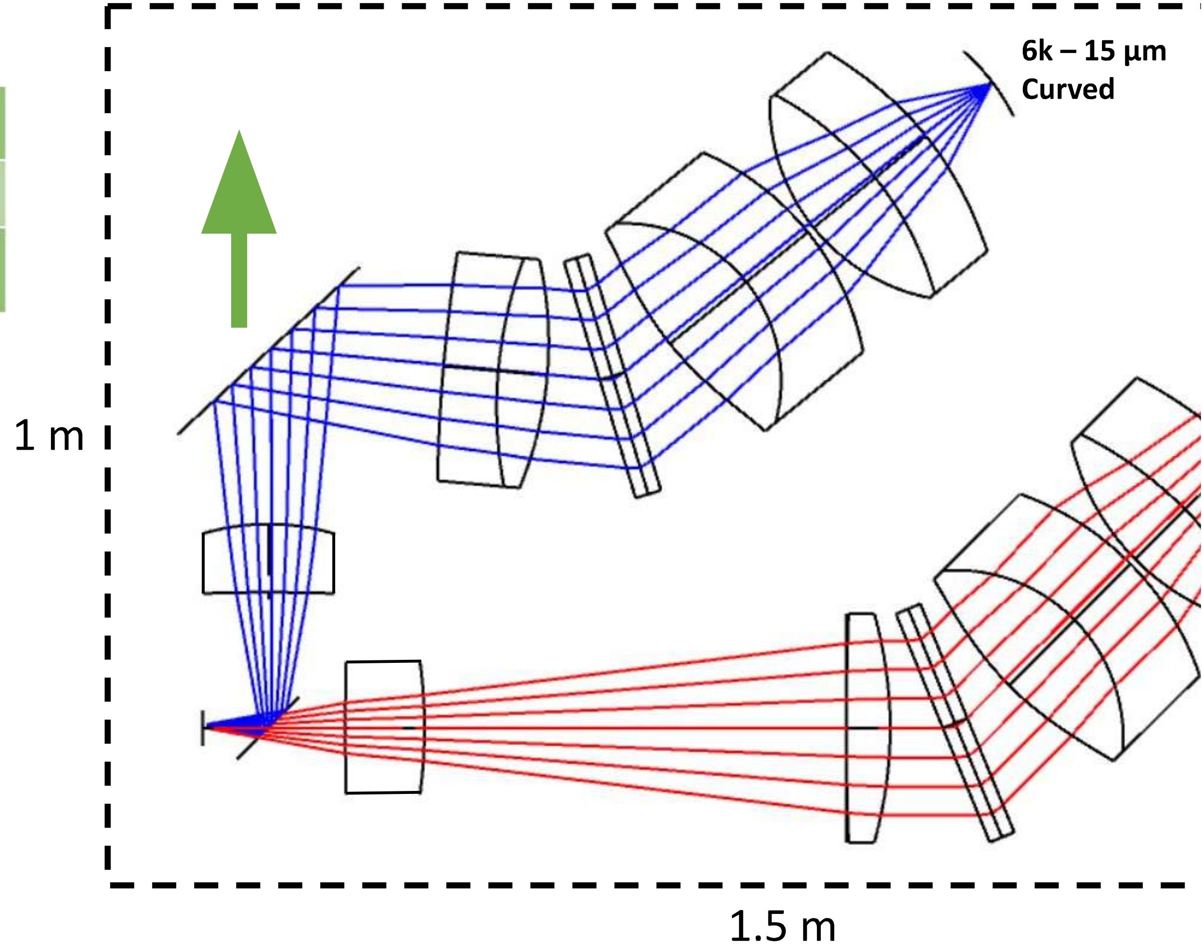
Optical design is like IFS.

Uses curved detectors.

Existing design has two wavelength channels, with space for a third channel.

20 – 40 spectrographs needed.

The spectrograhs are not required to be strictly identical (science targets will fall in different modules, each properly characterized)



Credit of WST consortium

Integral Field Spectrograph

144 IFUs, all identical

IFS FoV	3x3 $arcmin^2$
IFS Resolution	3,500
IFS Spec Range	370-970 nm (simultaneous)
IFS Mosaic	9x9 $arcmin^2$

MUSE like image slicer

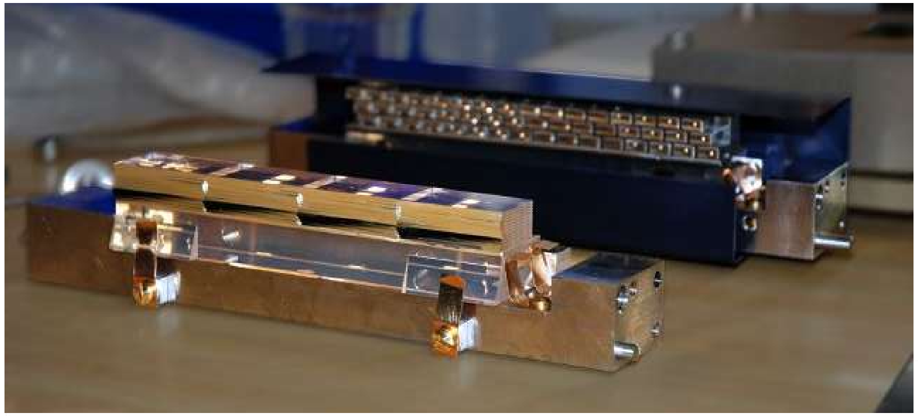
Spectrograph design based on an earlier concept by Pasquini et al.

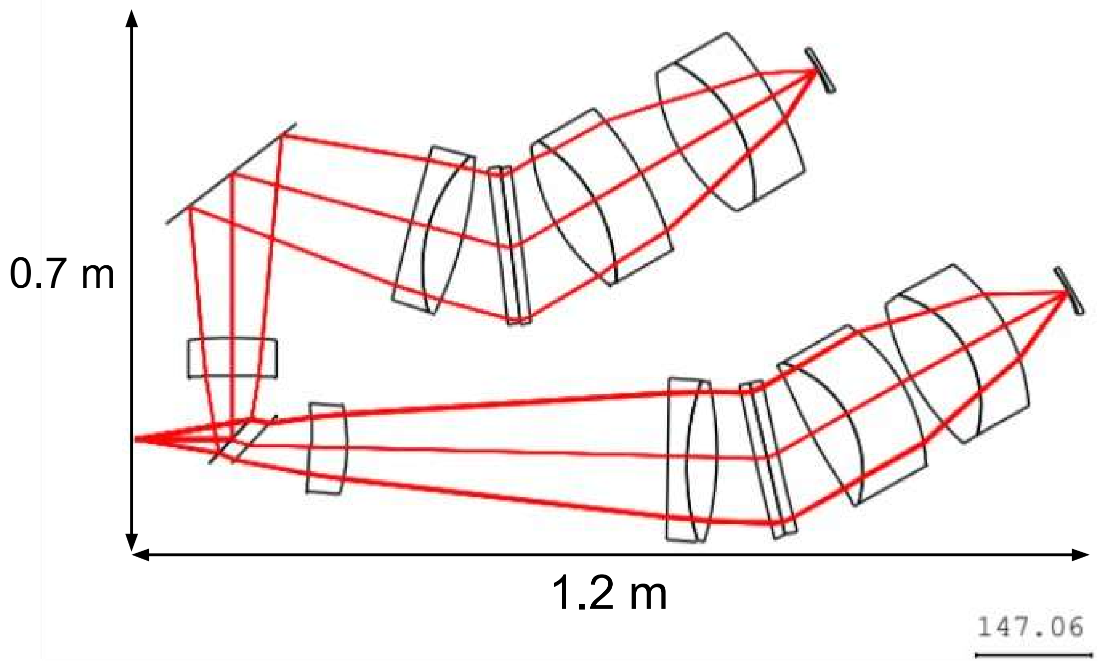
Slit length 240 mm.

Transmissive disperser.

Curved detector, 4k x 4k

In this case, the IFUs modules are required to be extremely similar in terms of throughput, since the object spectra will be reconstructed using all of them simultaneously





Reference: Luca Pasquini, B. Delabre, R. S. Ellis, J.-A. Marrero, L. Cavaller Marques, T. de Zeeuw, "A concept for a new spectroscopic facility," Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 107004E (6 July 2018); doi: 10.1117/12.2313076

Credit of WST consortium

GLAO for WST?

- the IFS field of 3’x3’ would be perfectably suitable for GLAO
- GLAO would give an improvement on the PSF dimension of a factor from 2 to improvement in term of exposure)
- NGS would be the simplest and cheaper choice, with probably good sky cover
- LGS beacon would be probably recommended to increase the Sky coverage
- Being GLAO, also Raylegh LGS might be considered (cheaper)
- the telescope design should of course consider such an option ASAP (3-4 LGS 1 NGS WFS have to pe positioned possibly at the edge of the FoV, and a corrector/deformable mirror, conjugated (close) to the pupil, shall be introduc least) in the IFS optical path. GLAO is not straightforward and is not "for free! cost-wise nor complexity-wise)
- NCPA characterization strategy would be critical for such a telescope
- Secondary mirror dimension and shape would probably allow to consider a se Adaptive Secondary Mirror (simplifying the design, but most probably more e than having a local DM in the IFS common optical path, positioned on a re-ima pupil)

GLAO for WST? The IFS channel

a 13’ diameter field (IFS) in a Nasmyth configuration. In such field, any 3’ x
sub-field can be selected and propagated through a Coudé optical relay, d
the gravity-stable f/35 IFS Coudé station

This should leave room for positioning the NGS/LGS outside the IFS selected field.

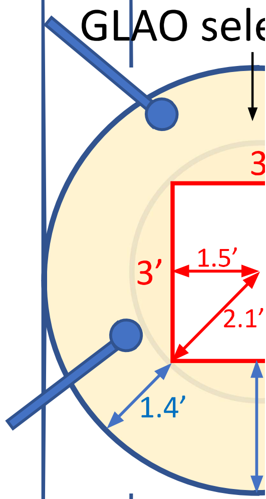
In the case of LGS, spot elongation should be evaluated (very variable depending on the type of laser, where the laser launcher are positioned, …)

In the case of NGS, simulations concerning the probability to find suitable AO references in the area outside the IFS selected field (similar cases simulated for MCAO systems, and thus I would guess numbers close to 80% looking at the galactic plane, 20% looking at the galactic pole, just for GLAO they will be better).

GLAO for WST? The IFS channel

Probably, having 3-4 probes to exploit 3-4 possible references for the GLA
would be a reasonable compromise between GLAO performance, cost an
complexity.

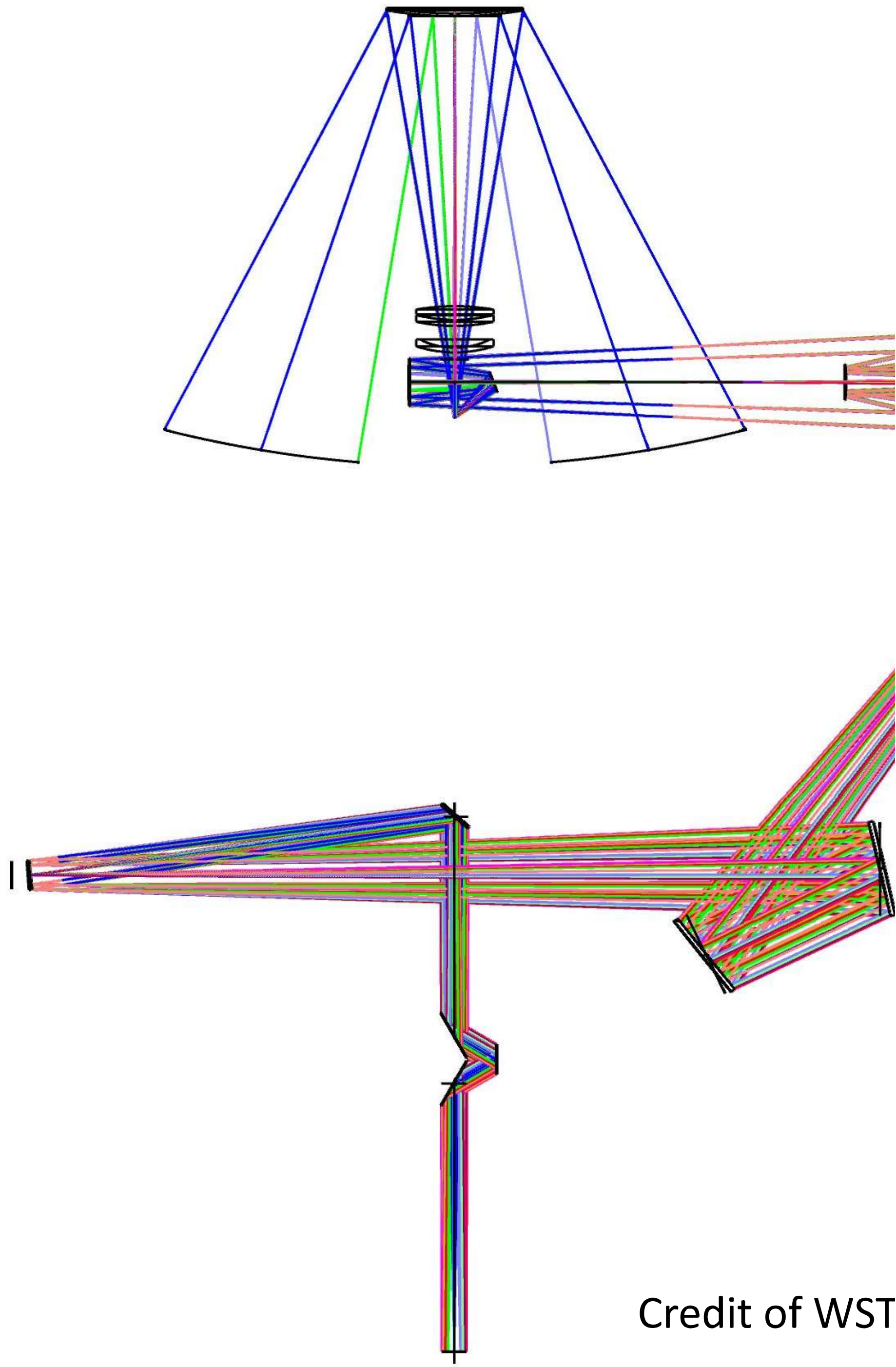
Opical co-add (Layer-Oriented GLAO) might be evaluated if a pupil plane wavefront sensor will be used (such as the Pyramid) although for a GLAO system (with moderate correction) the Pyramid gain will be very small and with the current detectors (RON nearly 0) the optical co-add of the pupils will also give a very moderate gain, in spite of a more complex opto-mechanics.



The probes shall be positioned in an intermediate focal plane as much as close to the location where the light to be sent to the IFUs is selected.

Telescope Designs: Two-Mirrors

- Optical ray-trace diagram of a two-mirror telescope with relay to integral field spectrograph focal station.
- IFS beam is picked off via a fold mirror in the centre of the MOS focal plane.
- Less vignetting than four-mirror design.
- Near-Infrared compatible.



GLAO for WST? The IFS channel – dimensioning WFS

r0 in the Ground Layer at Paranal/Armazones should be around 0.25m (in
diameter (TBC), and thus 50 subapertures on the diameter should make t

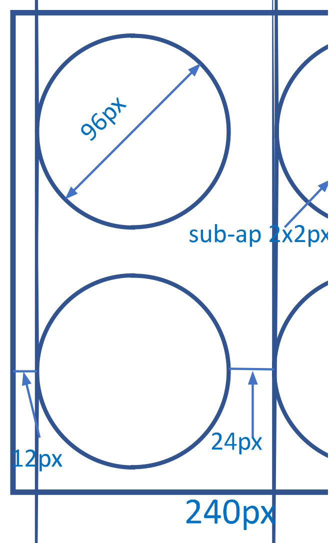
Thus, a DM with about 2500 actuators over the diameter should be «eno

And, in term of suitable cameras/detectors for the WFS, the OCAM 2K (us
SOUL@LBT) has the following characteristcs:

OCAM 2K: (E2V CCD220) of 240x240 pixels of 24µm (RON of 0.37e- at 2.0
framerate)

In 240 pixels diameter, you can have 96 pixels on the pupil diameter with sup-apertures of 2x2 pixels

In case of NGS, very important to have the possibility to bin the detector, to have less correction but to possibly use fainter objects to increase the Sky-Coverage



GLAO for WST? "… (at least) in the IFS optical path.

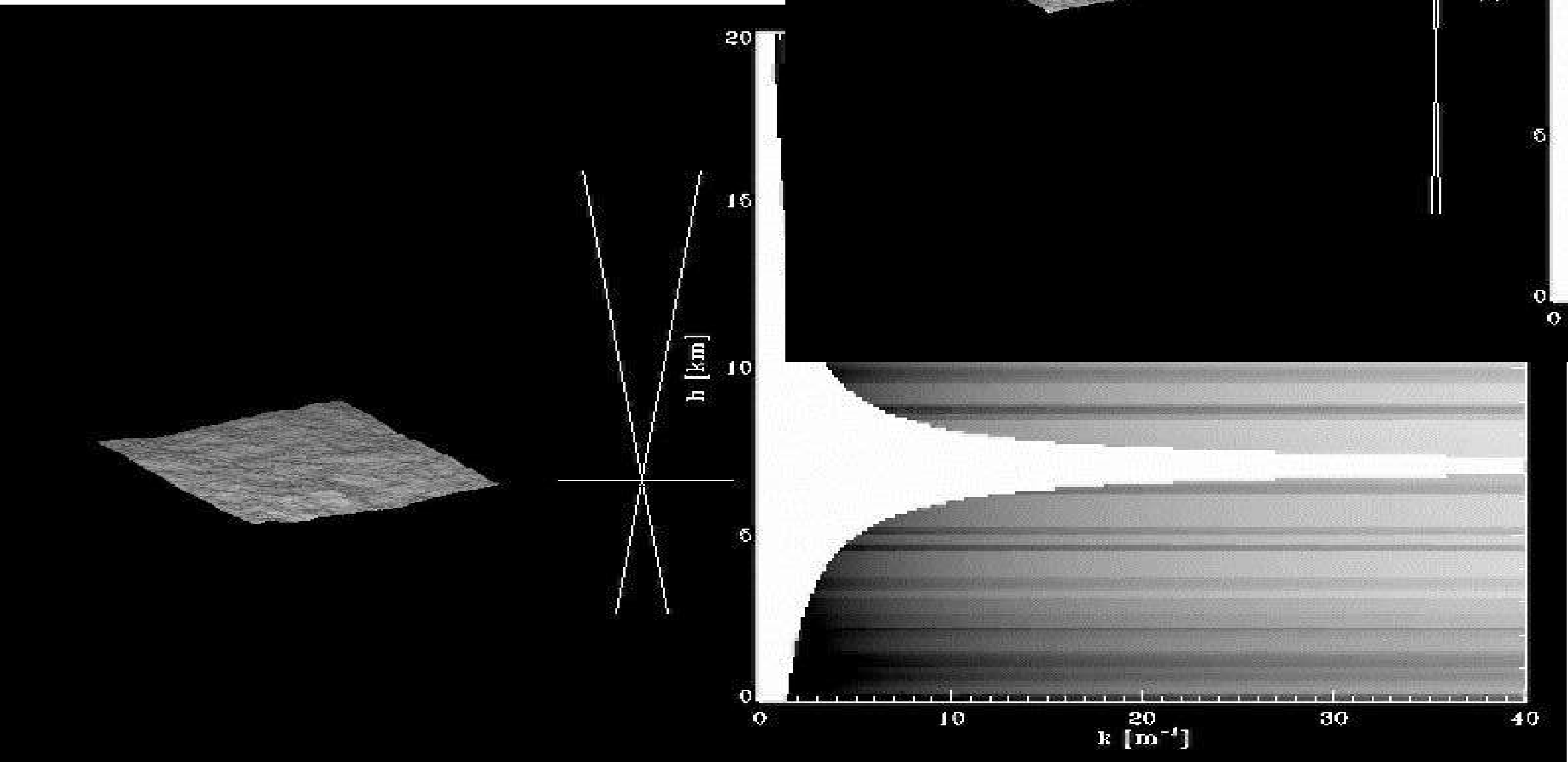
I said "… (at least) since (having the possibility to change the position of t
if any - on sky) one could even think to exploit GLAO on the full 3 deg^2 fie
view.

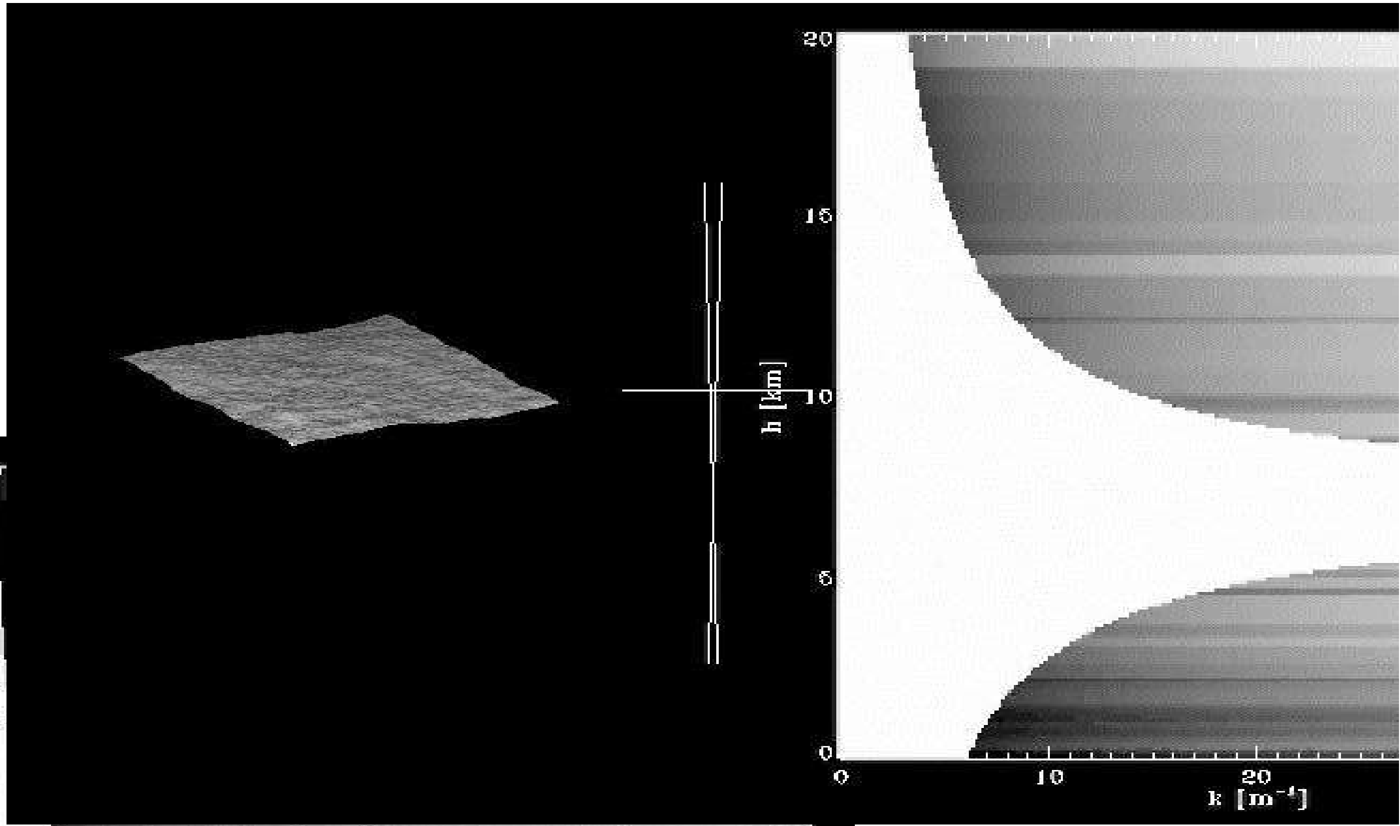
Selecting the LGS on such a wide FoV will simply decrease the WFSs depth
focus, meaning that the Ground Turbulent Layer reconstruction should be
as possible tuned to the effective height of such a layer, and the DM shou
be accurately positioned at the right Ground Turbulent Layer height. Simu
with precise turbulent profile might help a lot to understand which type c
might be reached (probably very modest).

Clearly, this would mean to duplicate the LGS/NGS WFSs also in the Casse
MOS channel (otherwise huge differential NCPA between the MOS and th
channel will probably kill the performance).

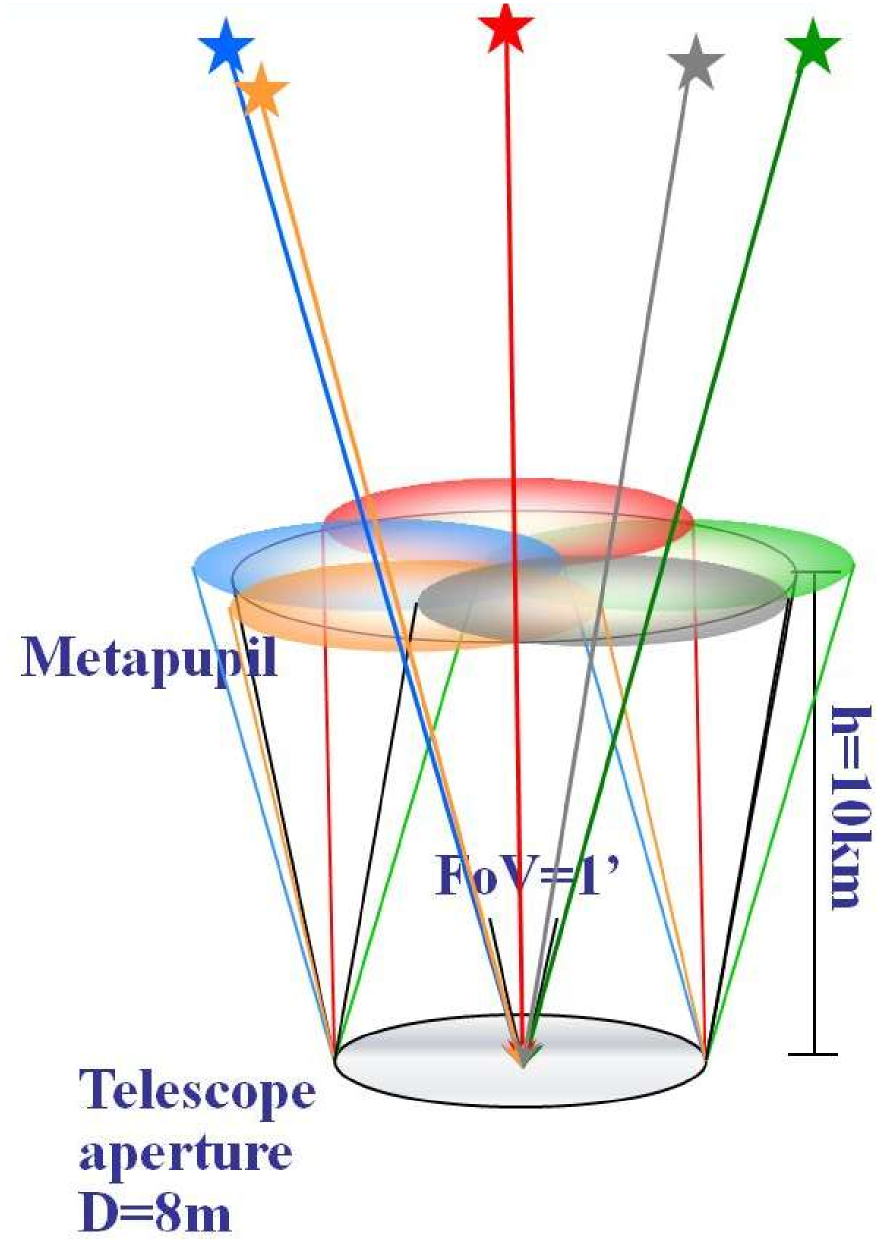
The additional cost and complexity of such an option, together with the (probably) very moderate gain would probably push not to consider such possibility.

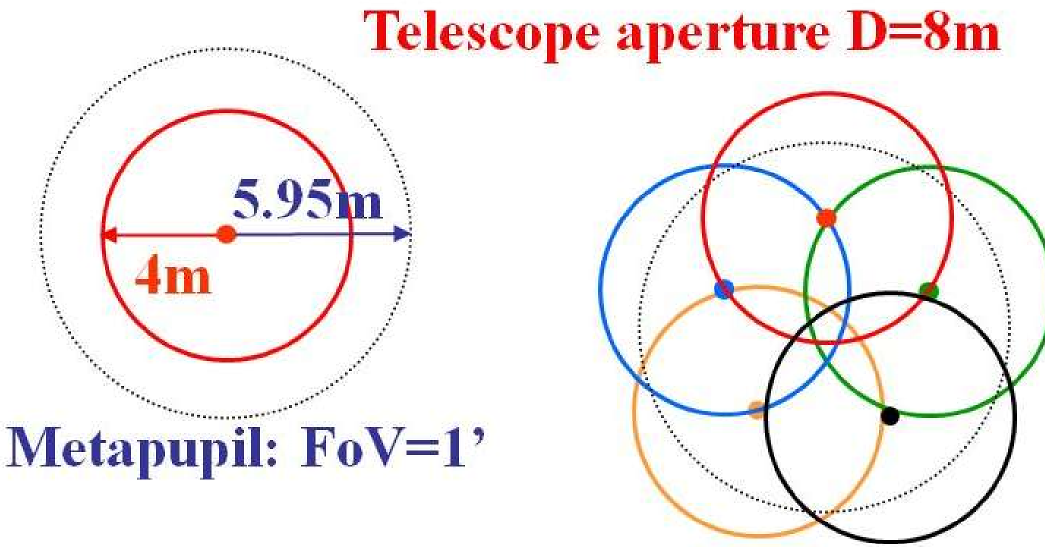
FoV vs Depth of focus





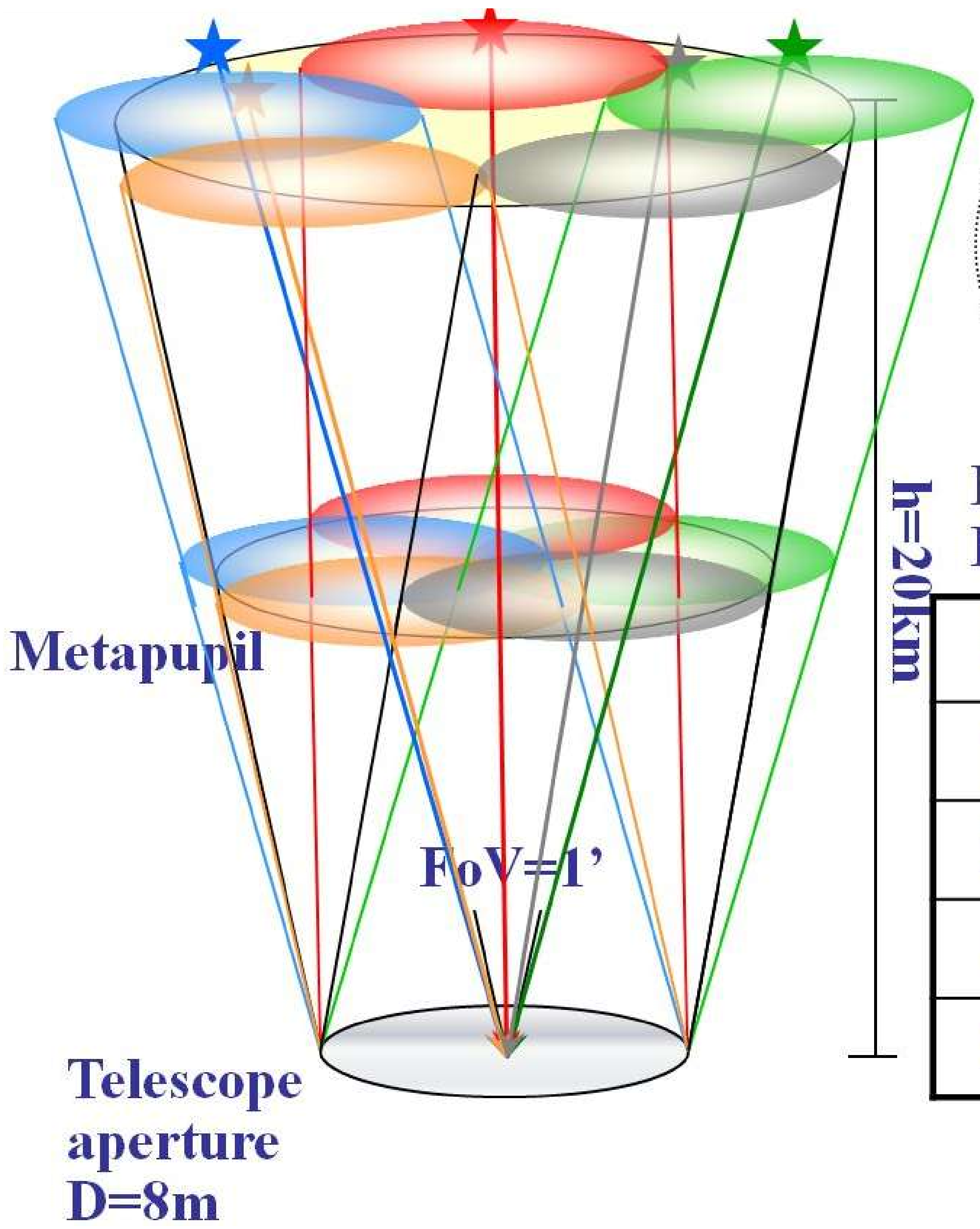
NGS-MCAO FoV choice: pupils superimposition

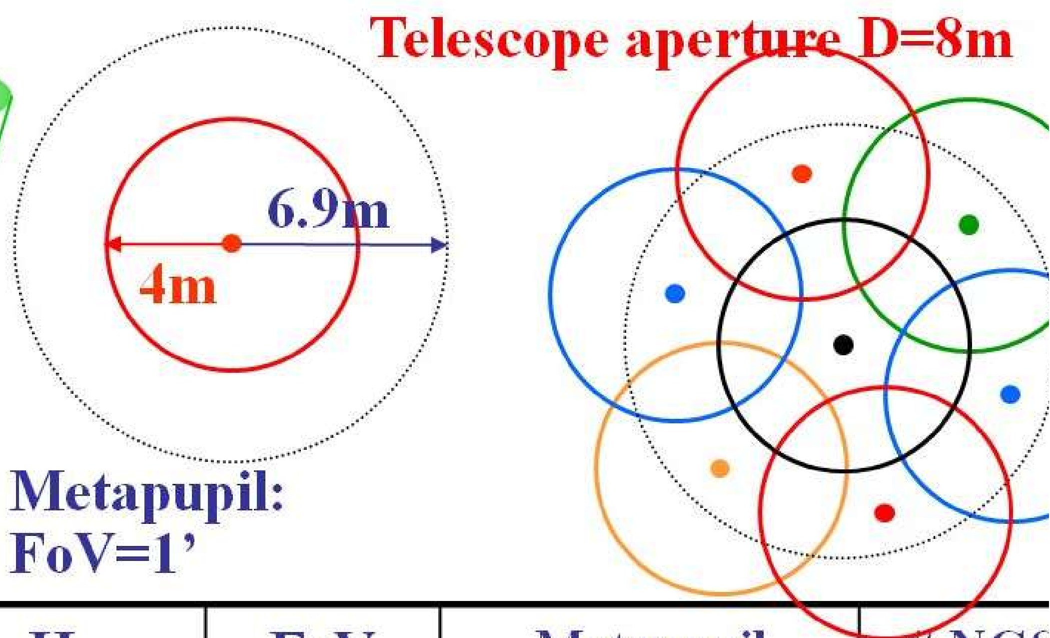




H_{max}	FoV	Metapupil	# NGS
10km	30"	8+1.45=9.45m	3
20km	30"	8+2.9=11.9m	5
10km	1'	8+2.9=11.9m	5

NGS-MCAO FoV choice: pupils superimposition





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10km	30"	8+1.45=9.45m	3
20km	30"	8+2.9=11.9m	5
10km	1'	8+2.9=11.9m	5
20km	1'	8+5.8=13.8m	7

Concerning LGS… Satellite LGS possible *game chang*

In the time frame of WST, the current research field concerning satellites artificial stars in space, which might be targetted from Ground Telescopes give the possibility to simplify much more the GLAO WFS channel and to a use LGS beacons launched from the telescope area.

Such technique consists in an innovative way to provide the AO artificial references, using a modest laser signal (< 1 W) from an orbiting small sate pointed at the observatory.

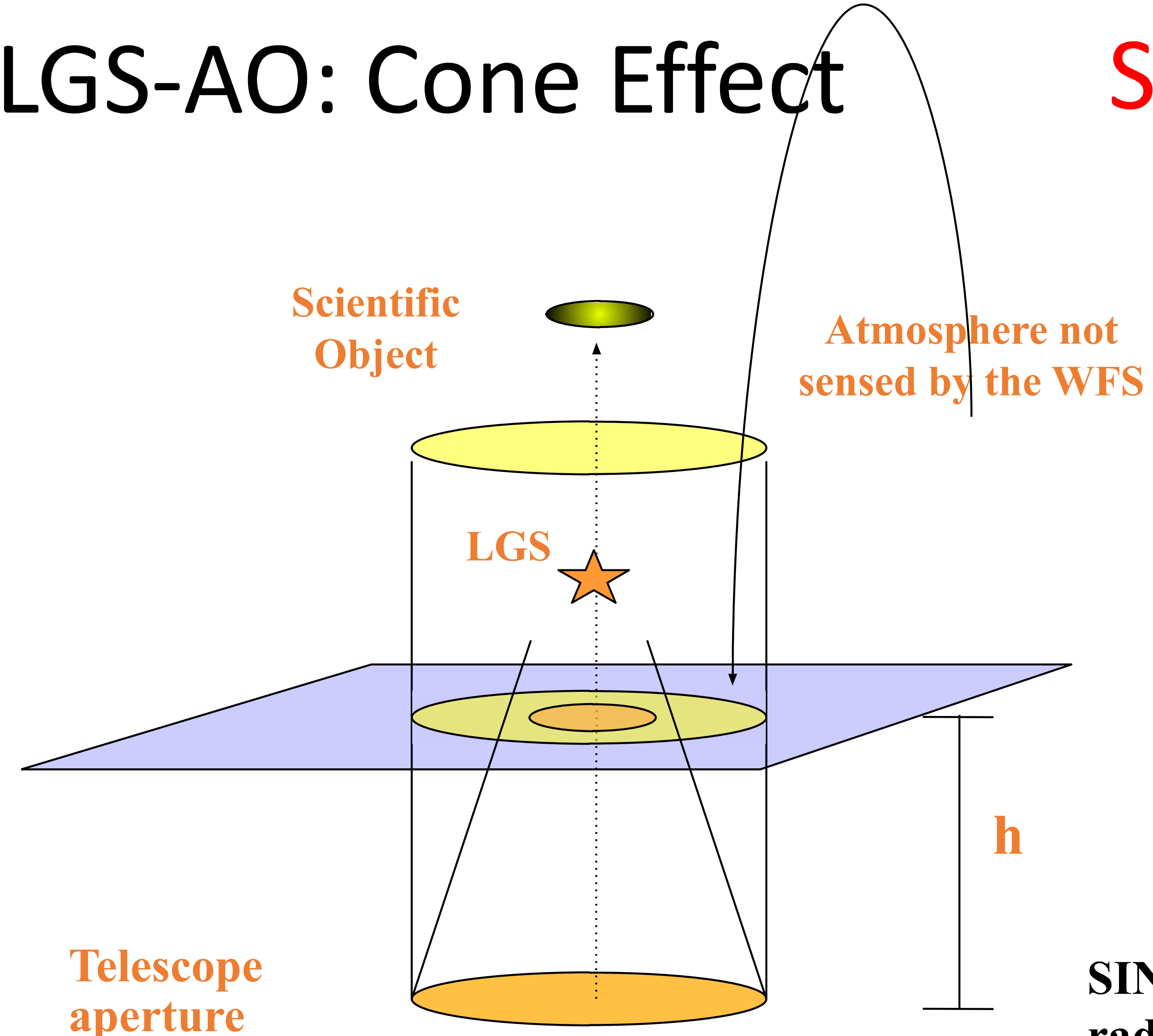
There is a NASA program, ORCAS (ORbiting Configurable Artificial Star) wh on-going, and test have already been performed with the Keck and the LB (artificial references have been properly imaged from both facilities).

This type of artificial stars would inherently solve most of the problems of current ground based LGS, such as the LGS elongation, the cone effect, "blindness" to the Tip-Tilt, wavelength dependent AO correction and safe

This is a research field that must be pushed, to reach a TRL as high as pos

LGS-AO: Cone Effect

SOLVED with satellite



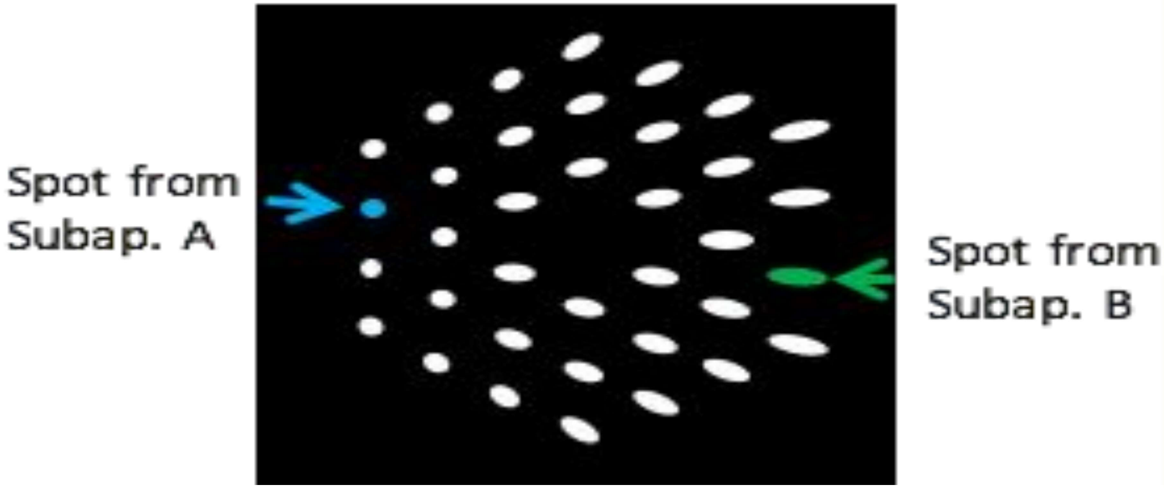
Cone effect huge with Rayleigh LGS, but not negligible also with the Sodium LGS!

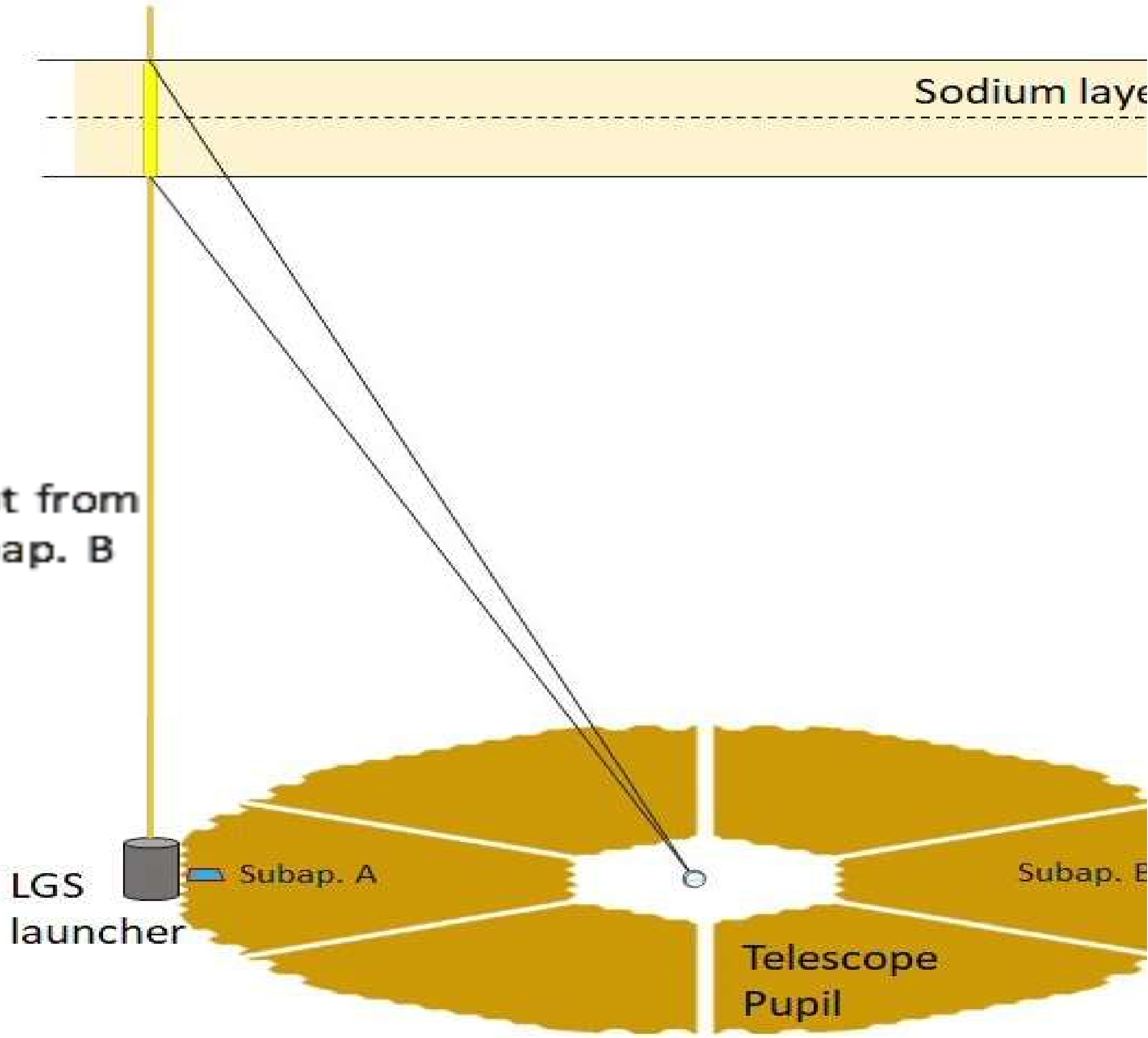
Band	J	H
σ_{cone}	0.91	0.70
Strehl loss	0.44	0.61

SINFONI@VLT: wavefront error in phase radians and Strehl reduction factor due to the cone effect with sodium LGS at 0.65” seeing

LGS-AO: Spot elongation SOLVED with satellite

In focal plane WFSs (e.g. S-H):





Food for thought

- GLAO would be a way to increase the IFS channel performance (not «disruptive» but «incremental» technology??? To be discussed!)
- CMOS technology fundamental both because CCD technology might be obsolete in 1 from now and cost-wise
- Curved detector is probably the real *game changer* to minimize the opto-mechanical complexity, the volume constraints and (above all for the IFS channel) the requireme channels similarity/equality; research in this field shall be pushed to reach a TRL as h possible in a reasonable time frame for the project
- It is necessary to develop, in close connection with the industry, an *economy of scale* concerning:
  - A *mass production oriented* design (final materials choice, loose alignment tolerances, …)
  - The mass production of critical optical and electronics components
  - The optimization and automation of the assembly line for crucial sub-systems (fibers assembly MOS and IFS monochromators)
- WST shall be a leverage to push/enable technologies that are possibly improving the design wrt the already existing and proven baseline (curved detectors); of course sha needs with other facilities/telescopes/instruments would increase the critical mass t industry (curved detectors will be a great simplification also for the Fly-Eye and Mezz objectives! Many more instruments may have the same need!