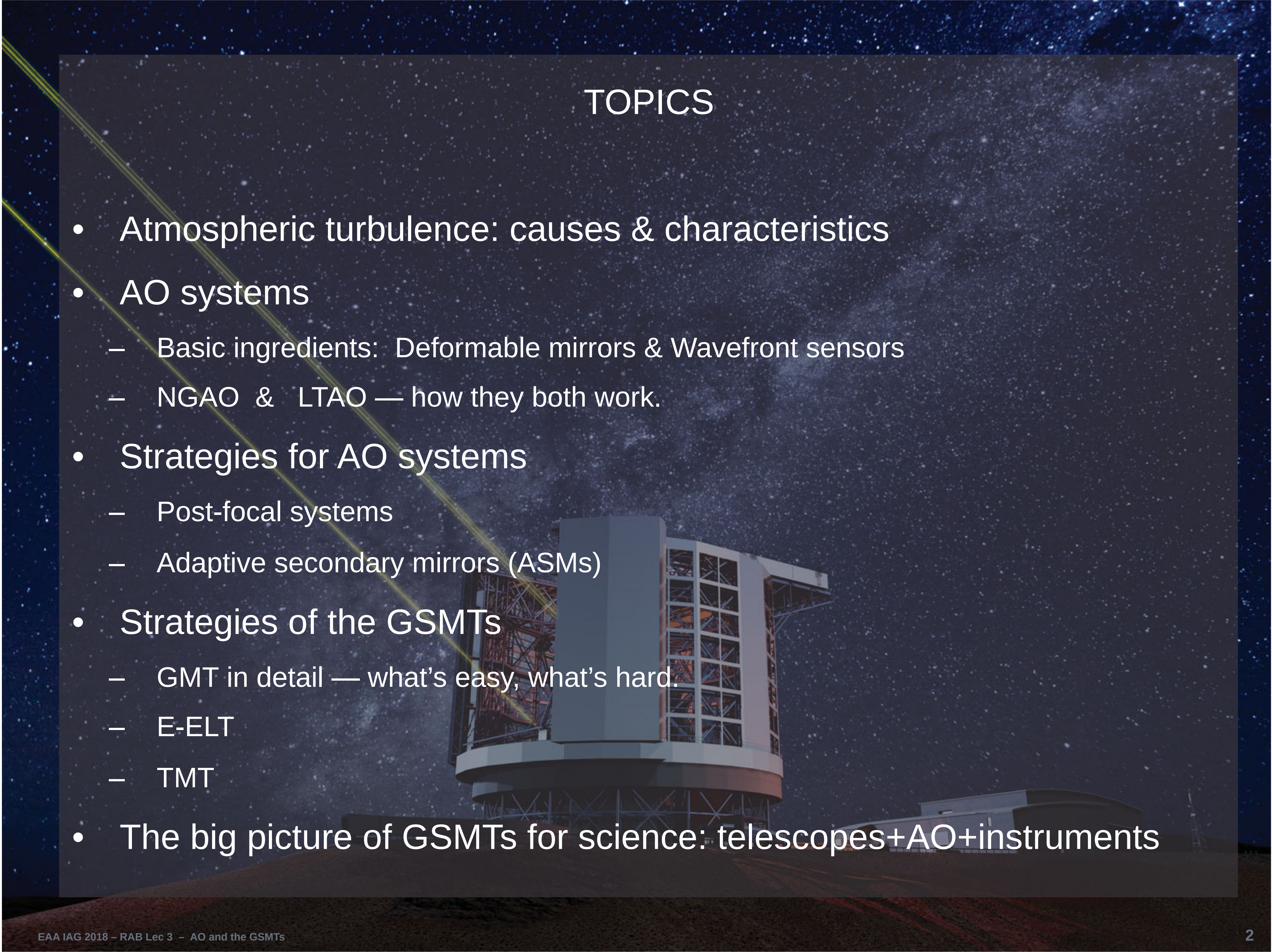
Adaptive Optics Strategies of the GSMTs.



TOPICS

- Atmospheric turbulence: causes & characteristics
- AO systems
  - Basic ingredients: Deformable mirrors & Wavefront sensors
  - NGAO &   LTAO — how they both work.
- Strategies for AO systems
  - Post-focal systems
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  - E-ELT
  - TMT
- The big picture of GSMTs for science: telescopes+AO+instruments

Who did you steal those nice slides from?

So, so many people:

Marcos van Dam,

Claire Max…

and everyone they stole slides from.

For GMT work:

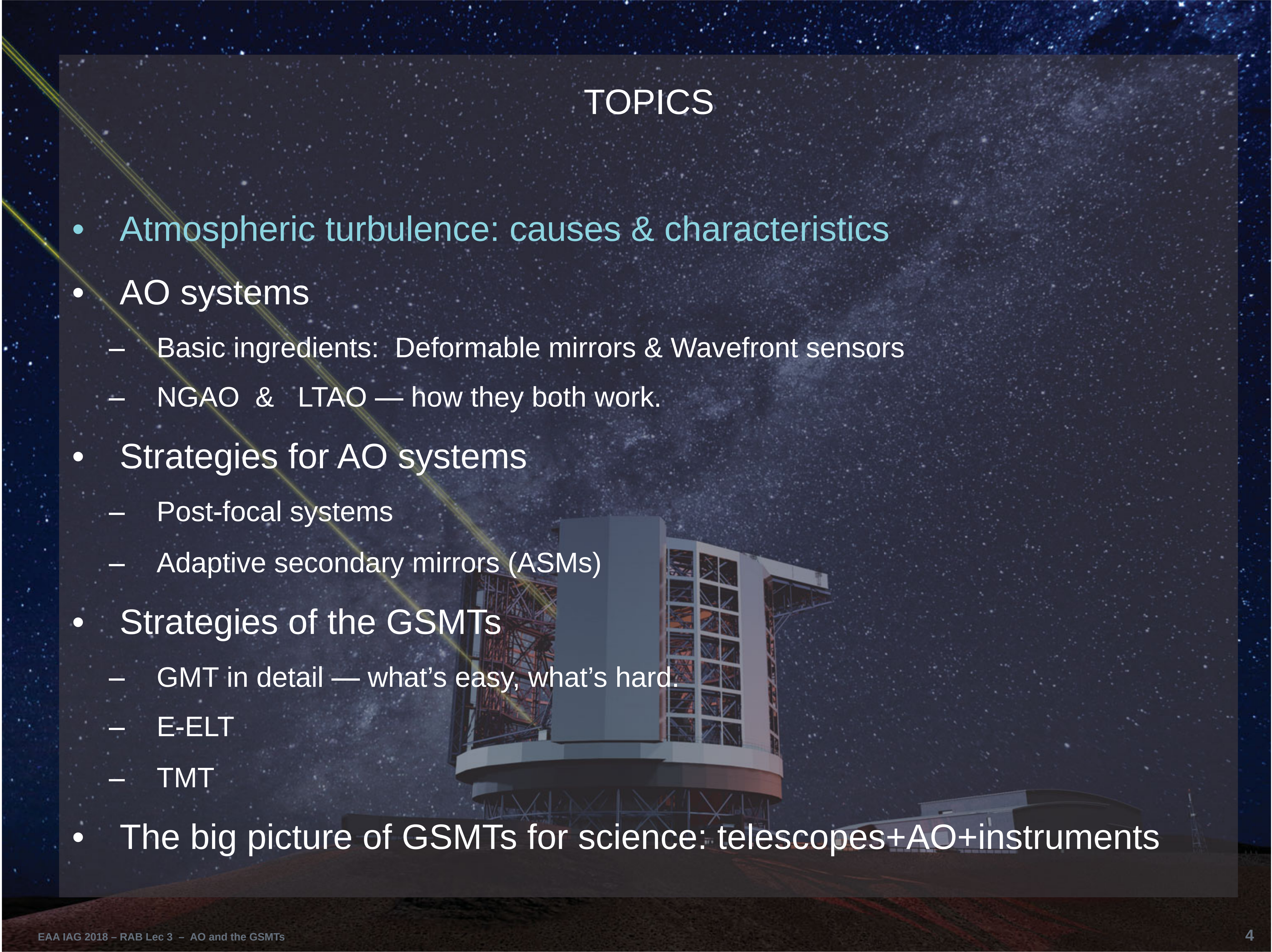
the GMT team!

Antonin Bouchez (work on GMT)

Brian McLeod (work on GMT)

and the folks working with them.

TOPICS



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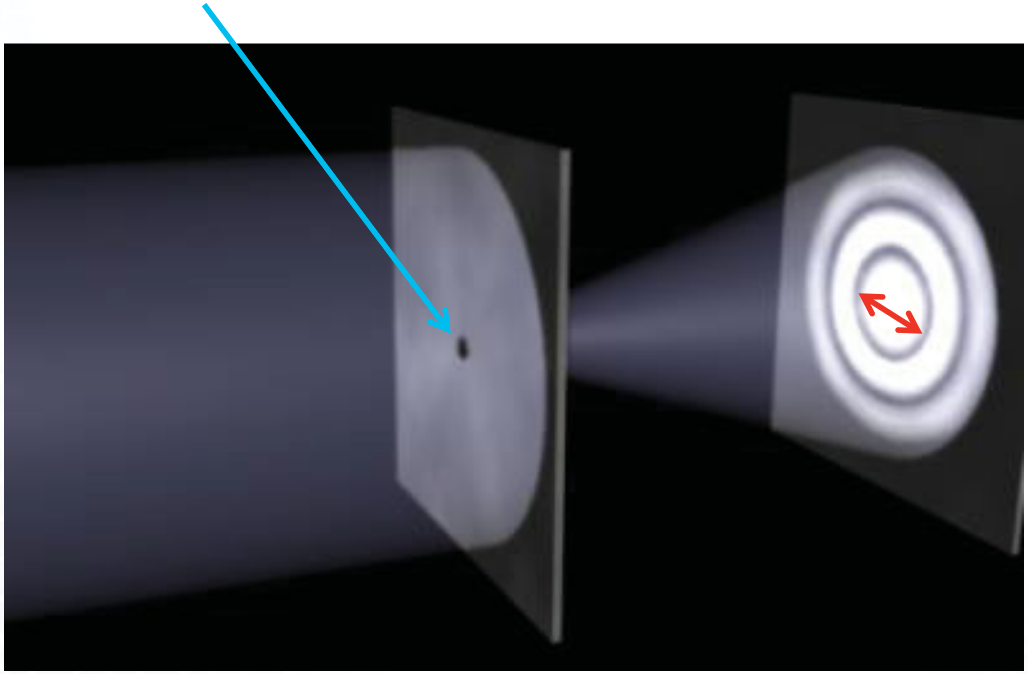
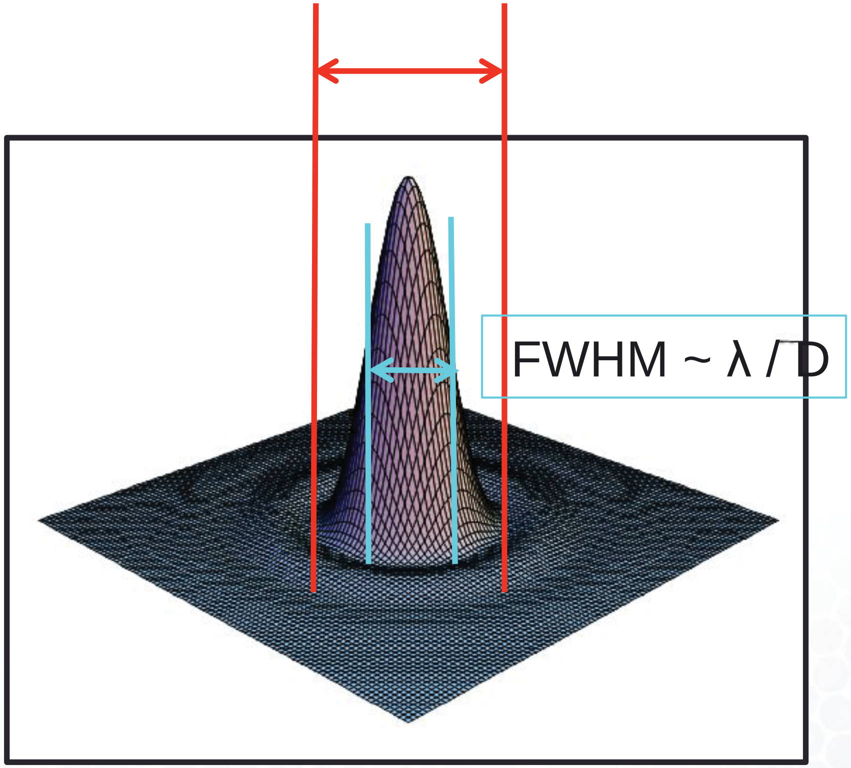
The goal:
diffraction limit images from telescopes

Minimum size of an image formed by light passes through an aperture:

Diameter of the first interference ring = 2.44 λ / D

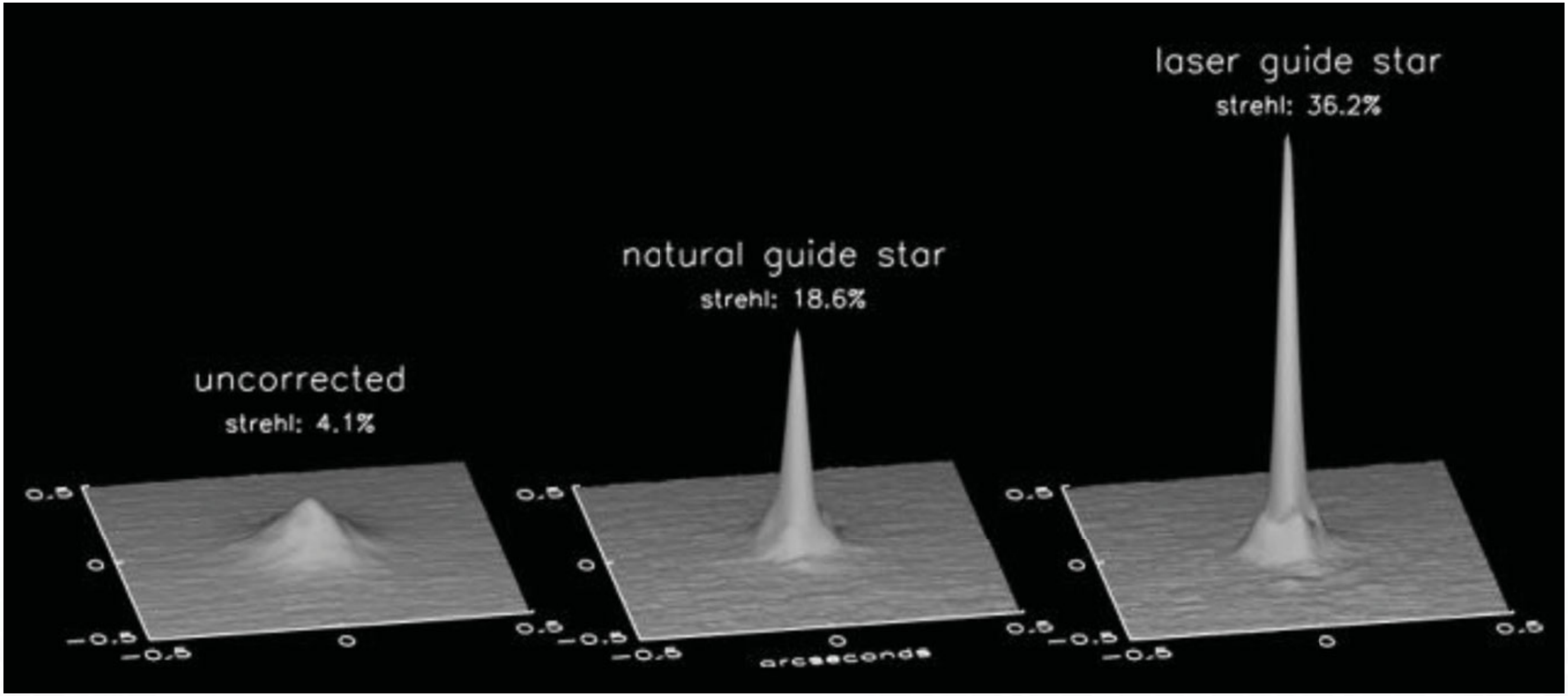
D is the diameter of the aperture.





Key definition: Strehl ratio

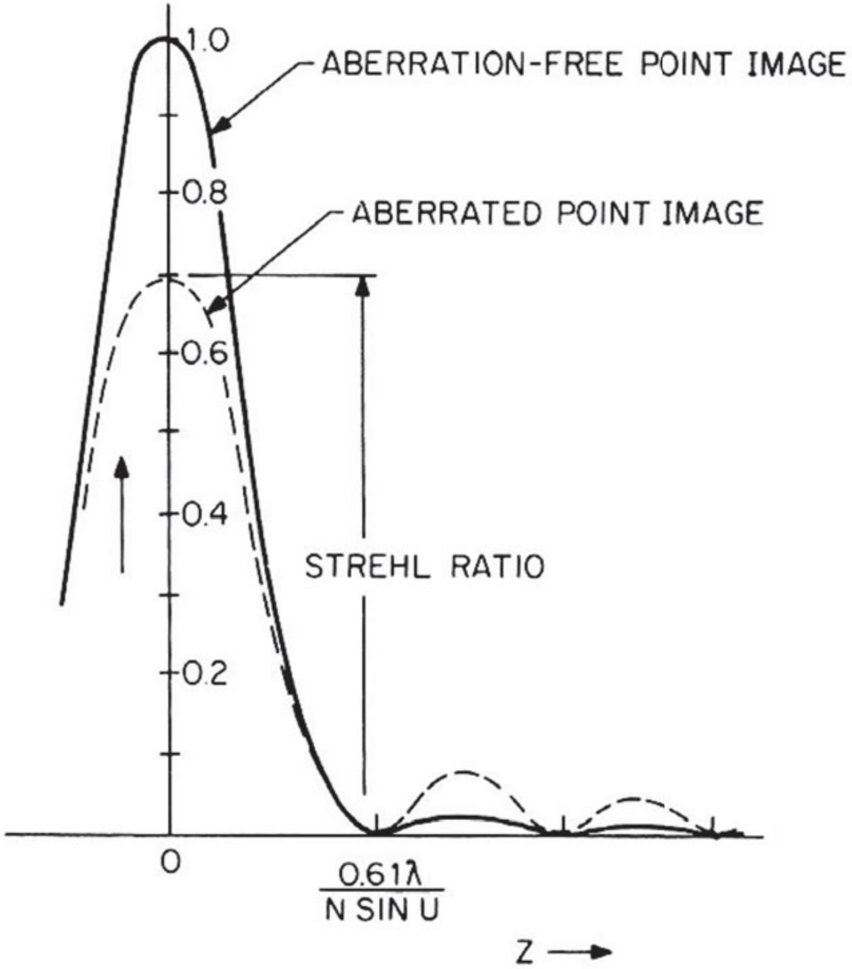
The Strehl ratio is the ratio of peak focal intensities in the aberrated and ideal point spread functions



Credit: Keck Obs.

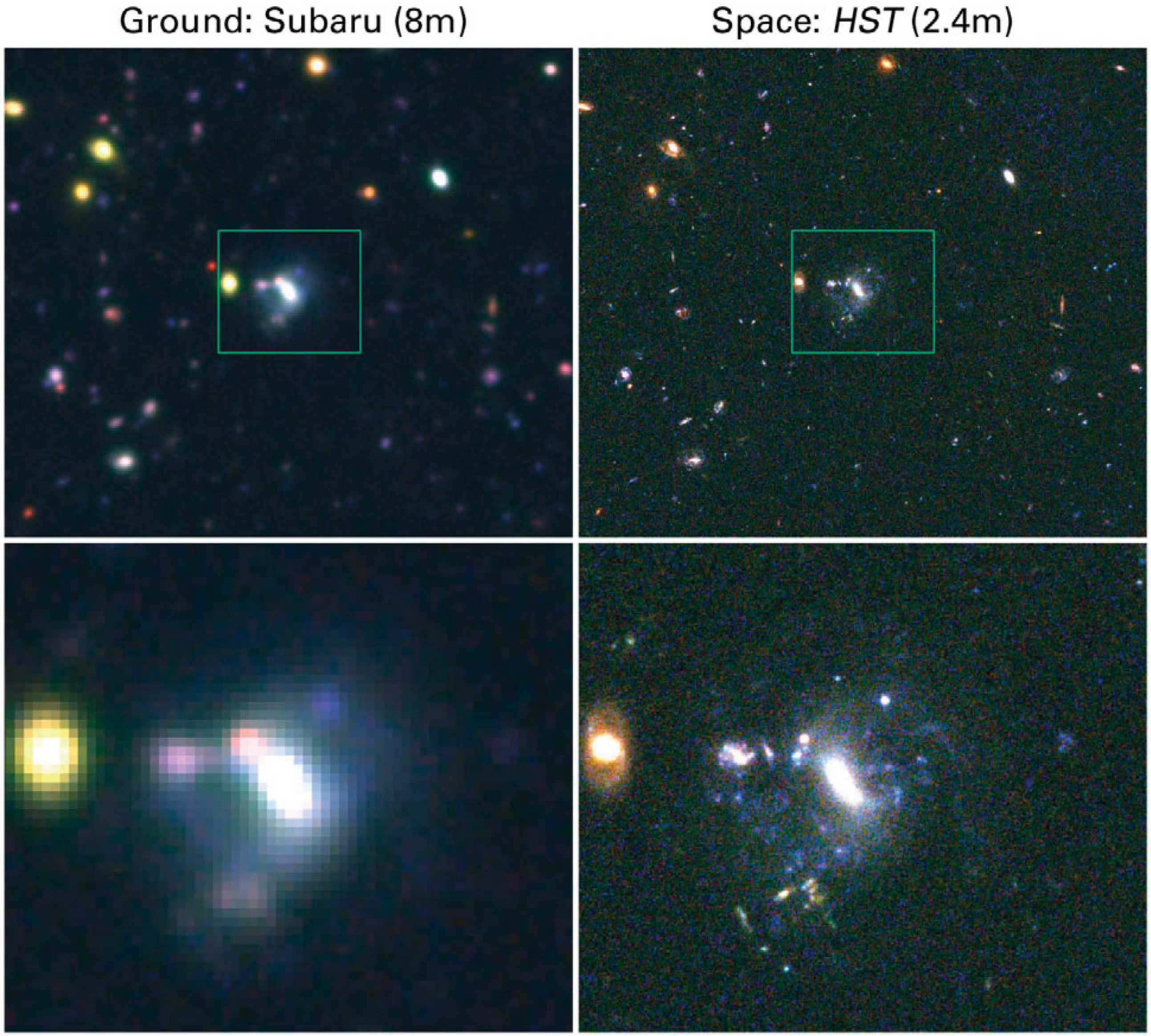
Key definition: Strehl ratio

The Strehl ratio is the ratio of peak focal intensities in the aberrated and ideal point spread functions



Credit: Keck Obs.

Long exposures through the atmosphere


Ground: Subaru (8m)

Space: *HST* (2.4m)

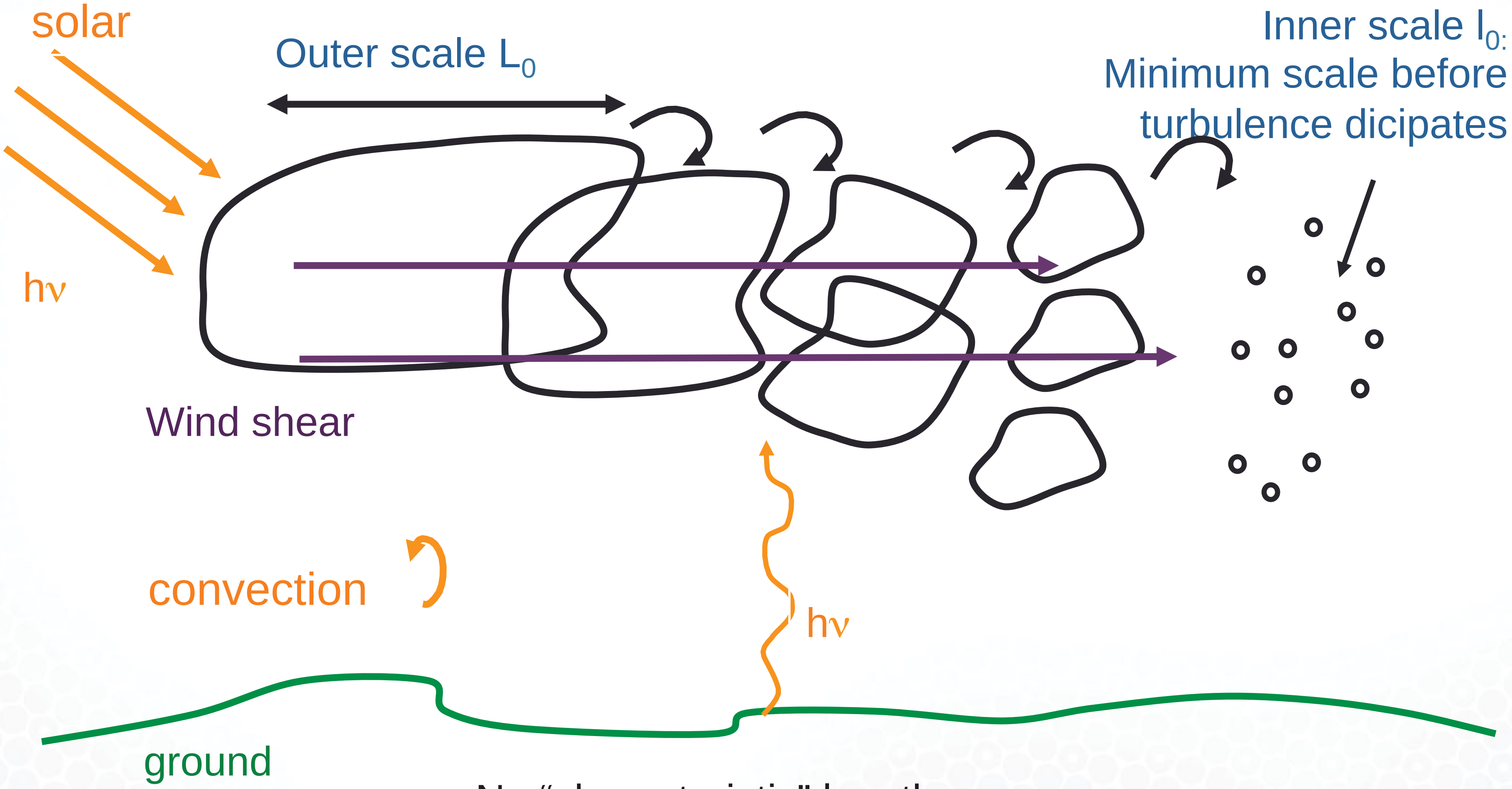
The problem: atmospheric turbulence

The rippling appearance over a hot road is the same effect:

$N_{air}(\lambda)$ is a function of pressure and temperature.

The problem: atmospheric turbulence

Cells of air at different T,P (“Kolmogorov” turbulence spectrum.)



solar

$h\nu$

Outer scale L_0

Inner scale $l_{0:}$
Minimum scale before turbulence dicipates

Wind shear

convection

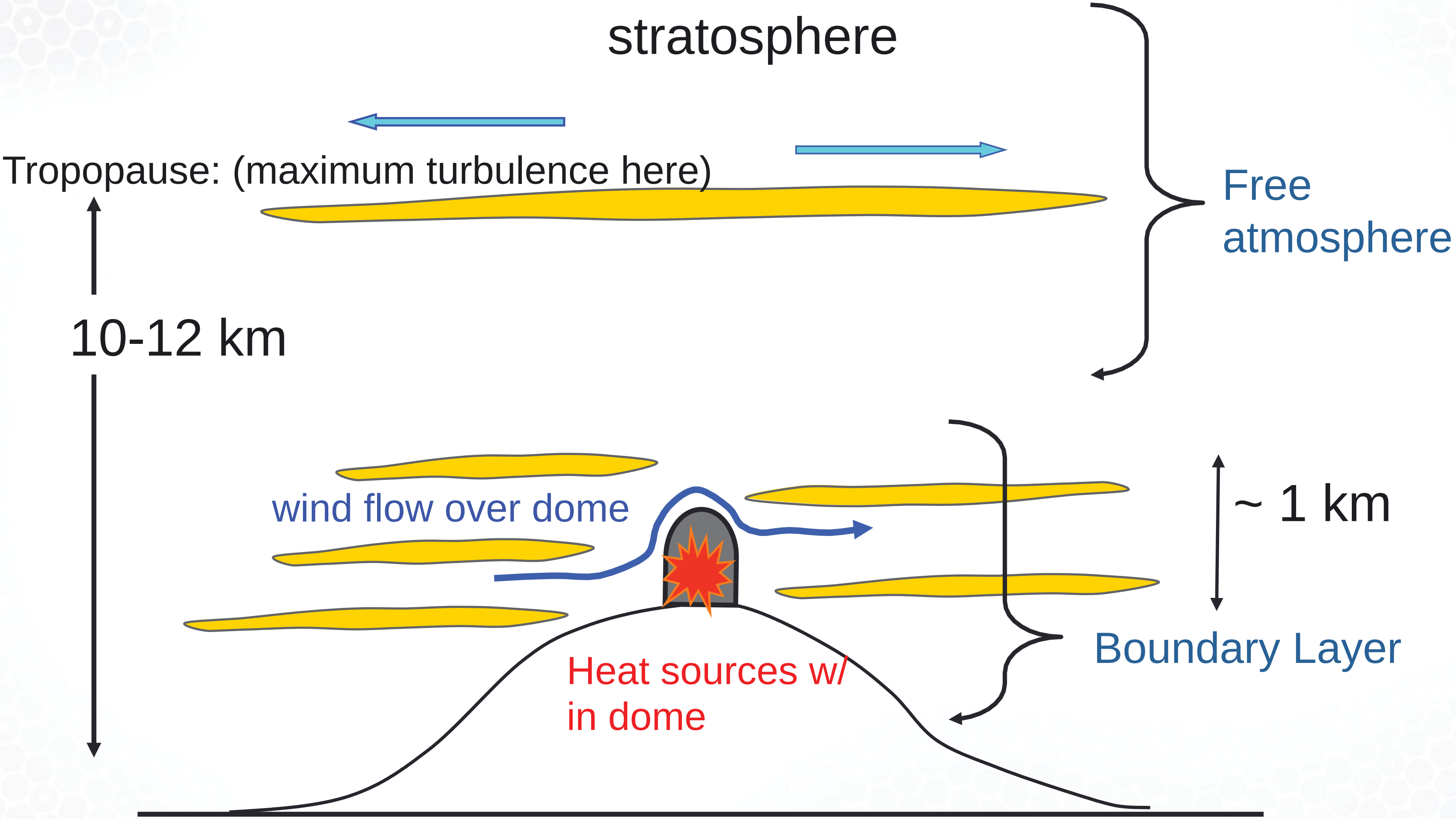
$h\nu$

ground

No “characteristic” length.

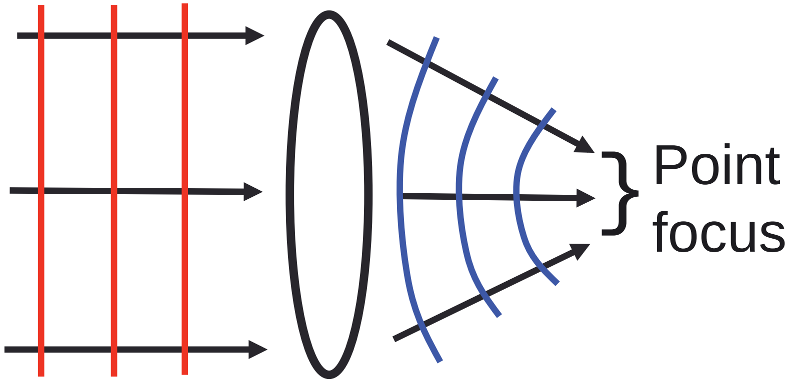
Atmospheric turbulence: Kolmogorov spectrum

Turbulence arises in several places:

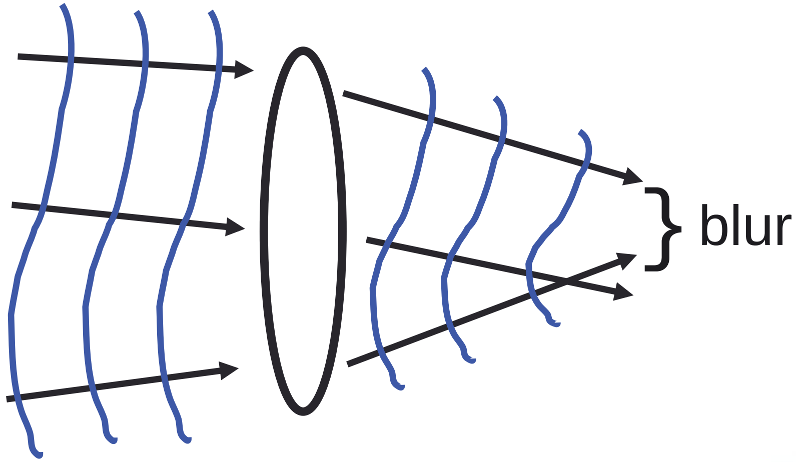


Light rays and the wavefront

- Light rays are refracted many times (by small amounts)
- Smooth wavefronts → damaged



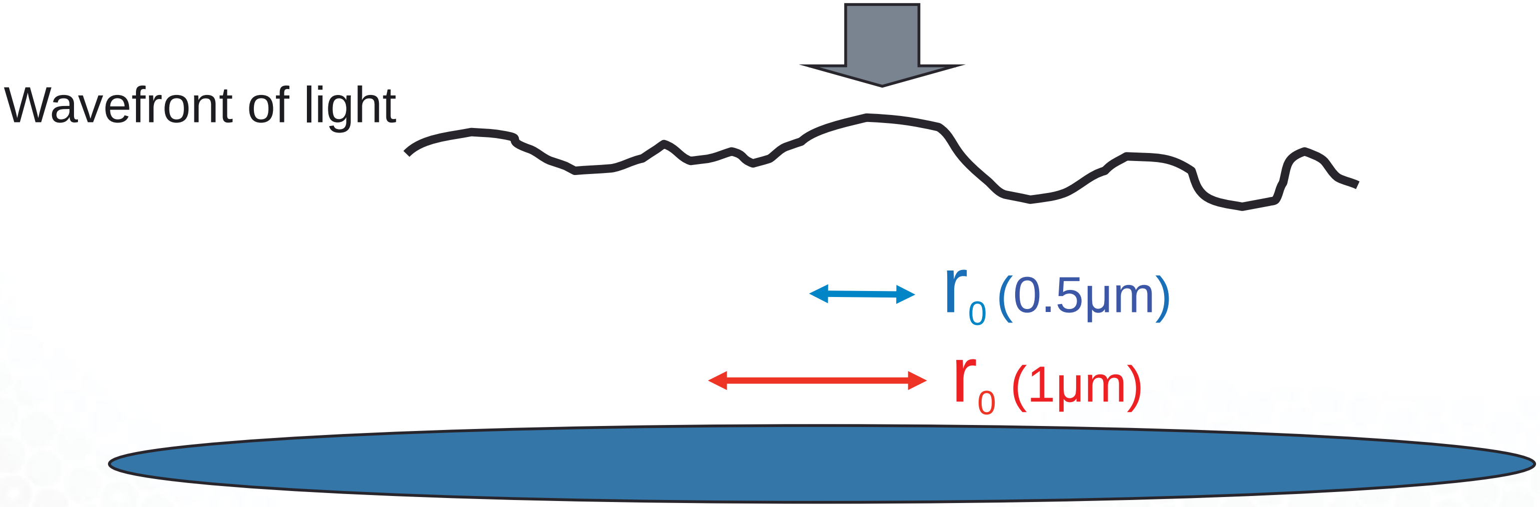
Parallel light rays



Light rays affected by turbulence

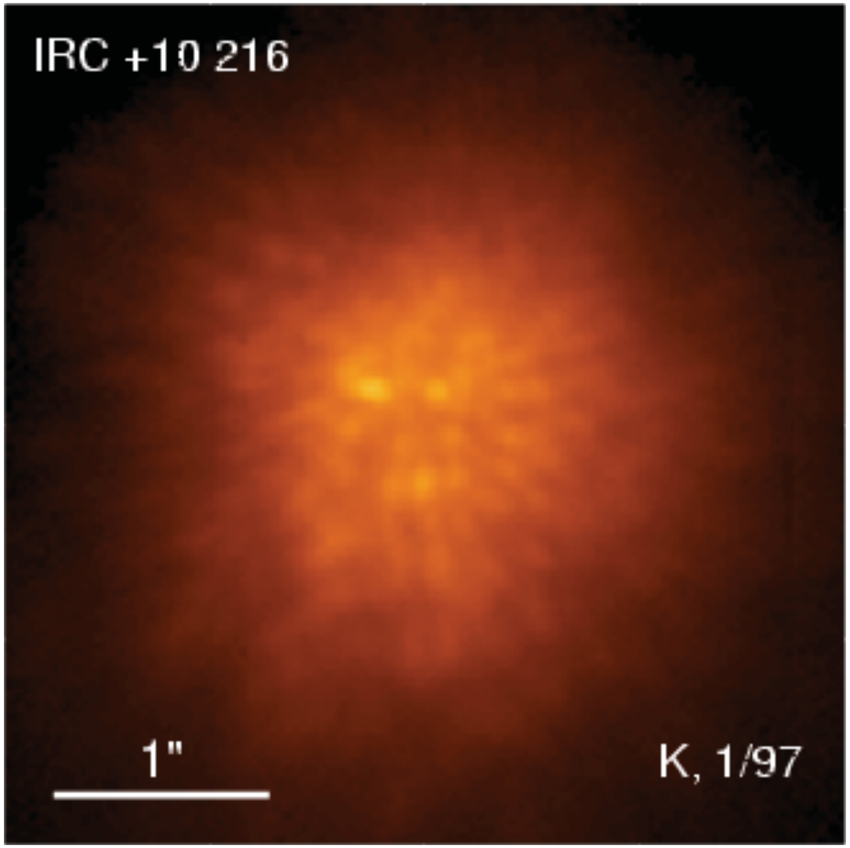
Characterize turbulence strength by quantity r_0

- Fried parameter: r_0 = Coherence Length
  - size of the patch on the primary mirror over which the wavefront is correlated
  - $r_0(0.5\mu m) \sim 15\text{-}30$ cm at a good site (high altitude, west edge of a continent)
  - $r_0 \sim \lambda^{6/5}$ (so "seeing" is worse at short wavelengths!)



Primary mirror of telescope

Coherence patches: t= 0.001 sec explosure

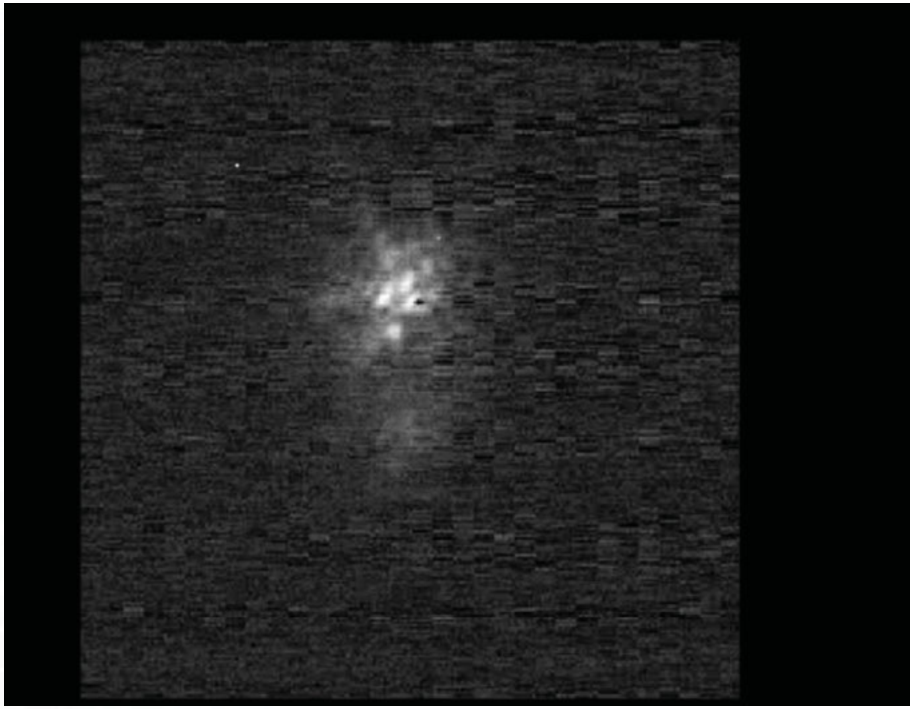


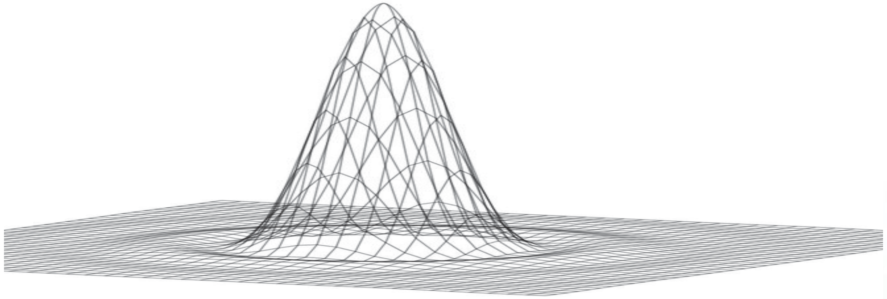
Coherence patches: t > 0.1 sec explosure

In the “seeing” limit: θ_{seeing}

→ Sensitivity ~ D^2

What a star looks like averaged over long timescales.



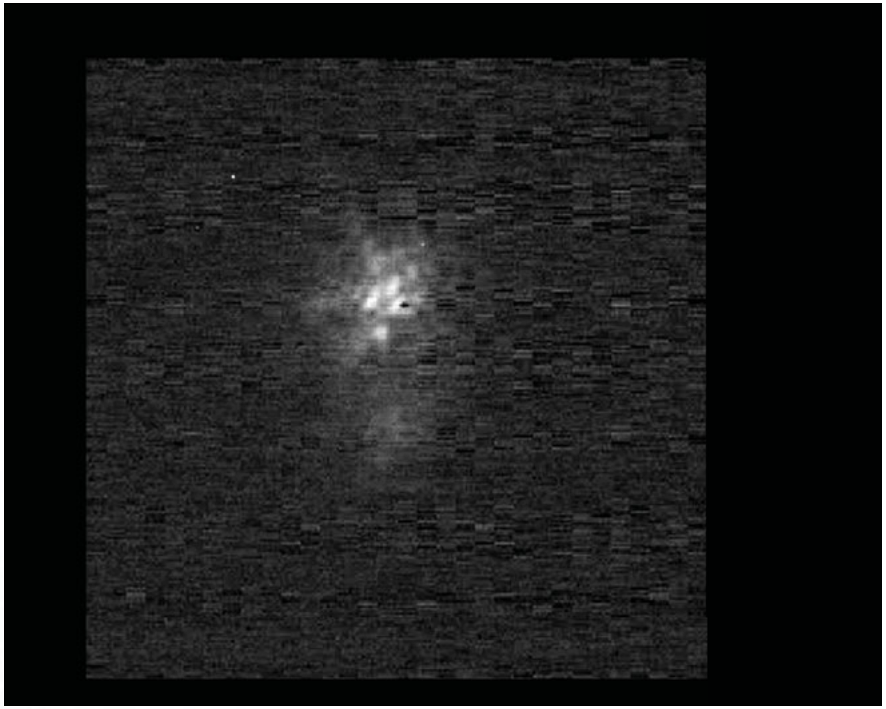


(Credit: VLT)

Coherence patches averaged: t > 0.1 sec exp.

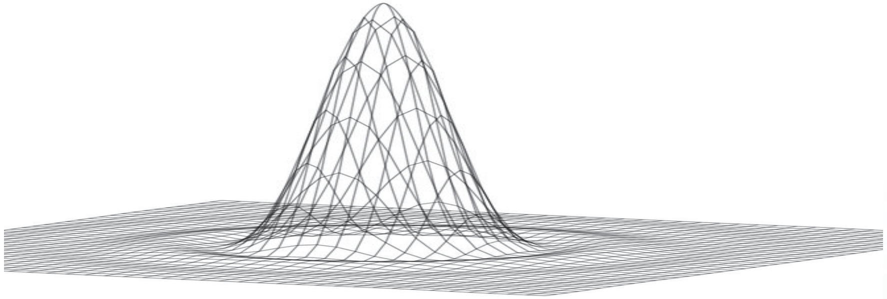
In the "seeing" limit: $\theta = \theta_{seeing}$

→ Sensitivity ~ D^2



(Credit: VLT)

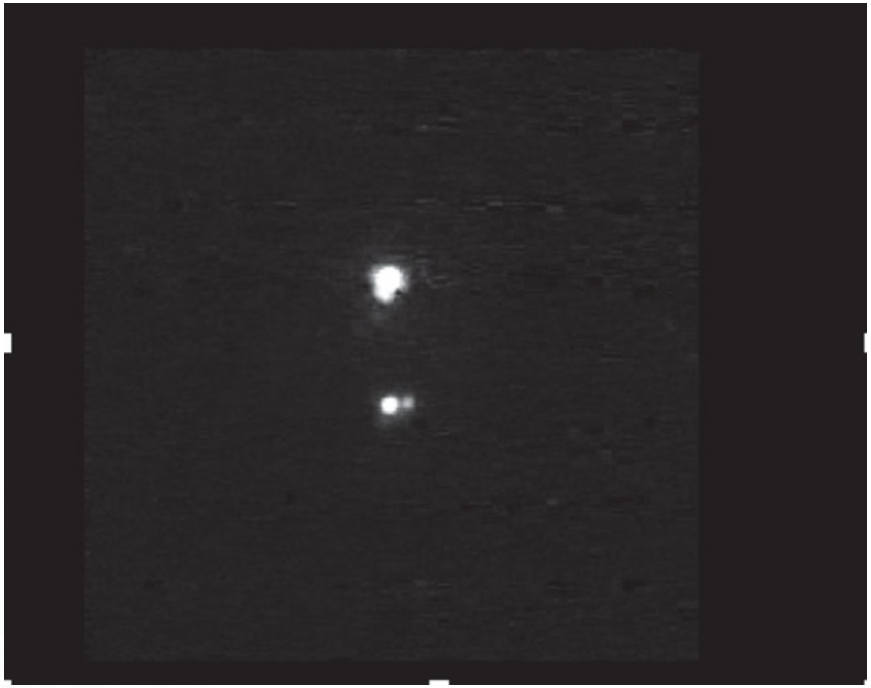
What a star really looks like averaged over long timescales.



Coherence patches .. corrected by AO.

In the diffraction limit: $\theta \sim (1.22\ \lambda/D)$

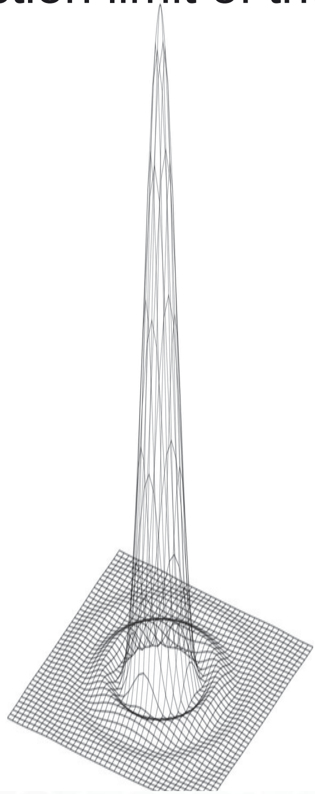
→ Sensitivity ~ D^4

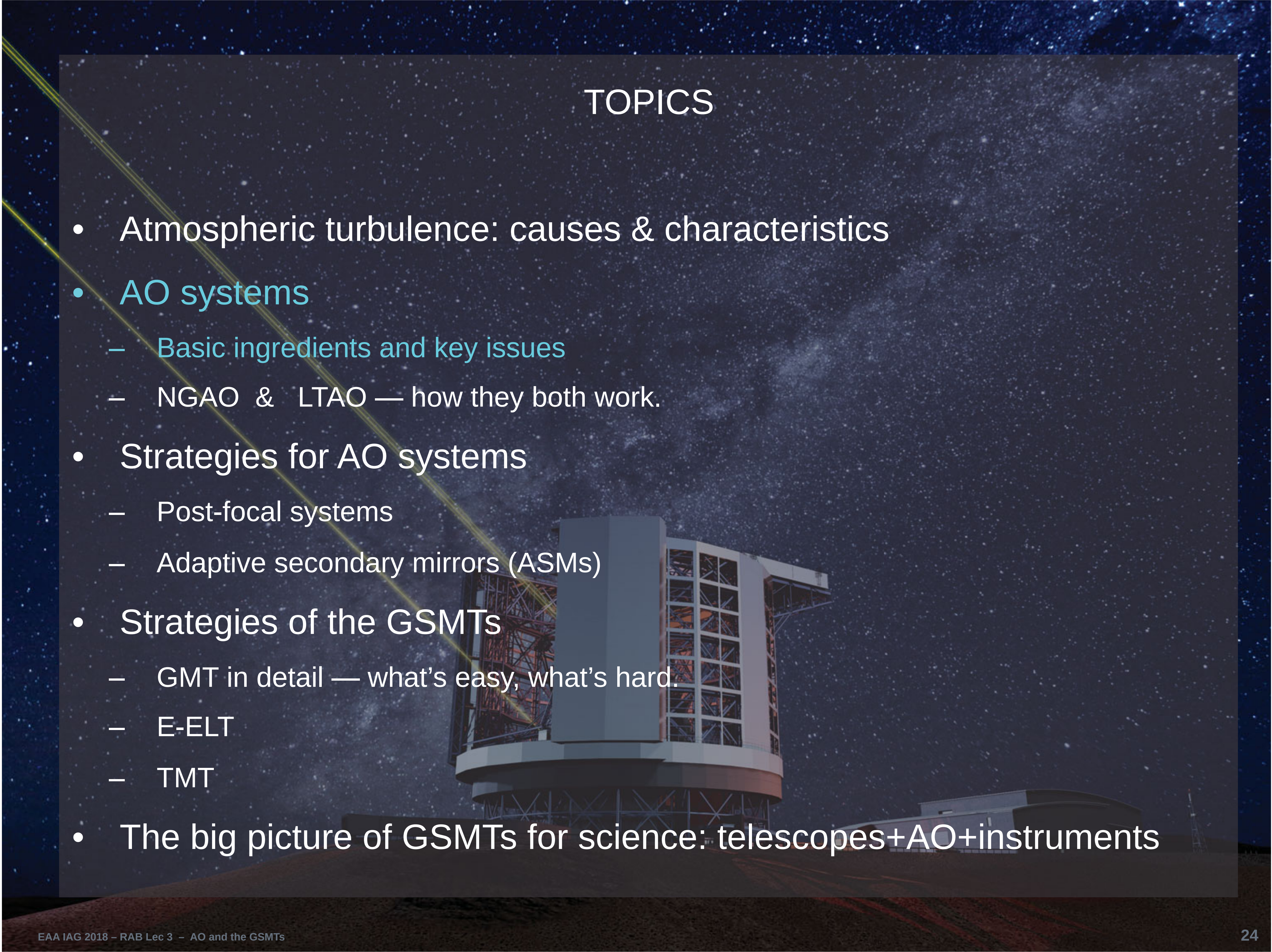


(Credit: VLT)

What a star really looks like
on an 8m with AO correction:

The diffraction limit of the telescope.





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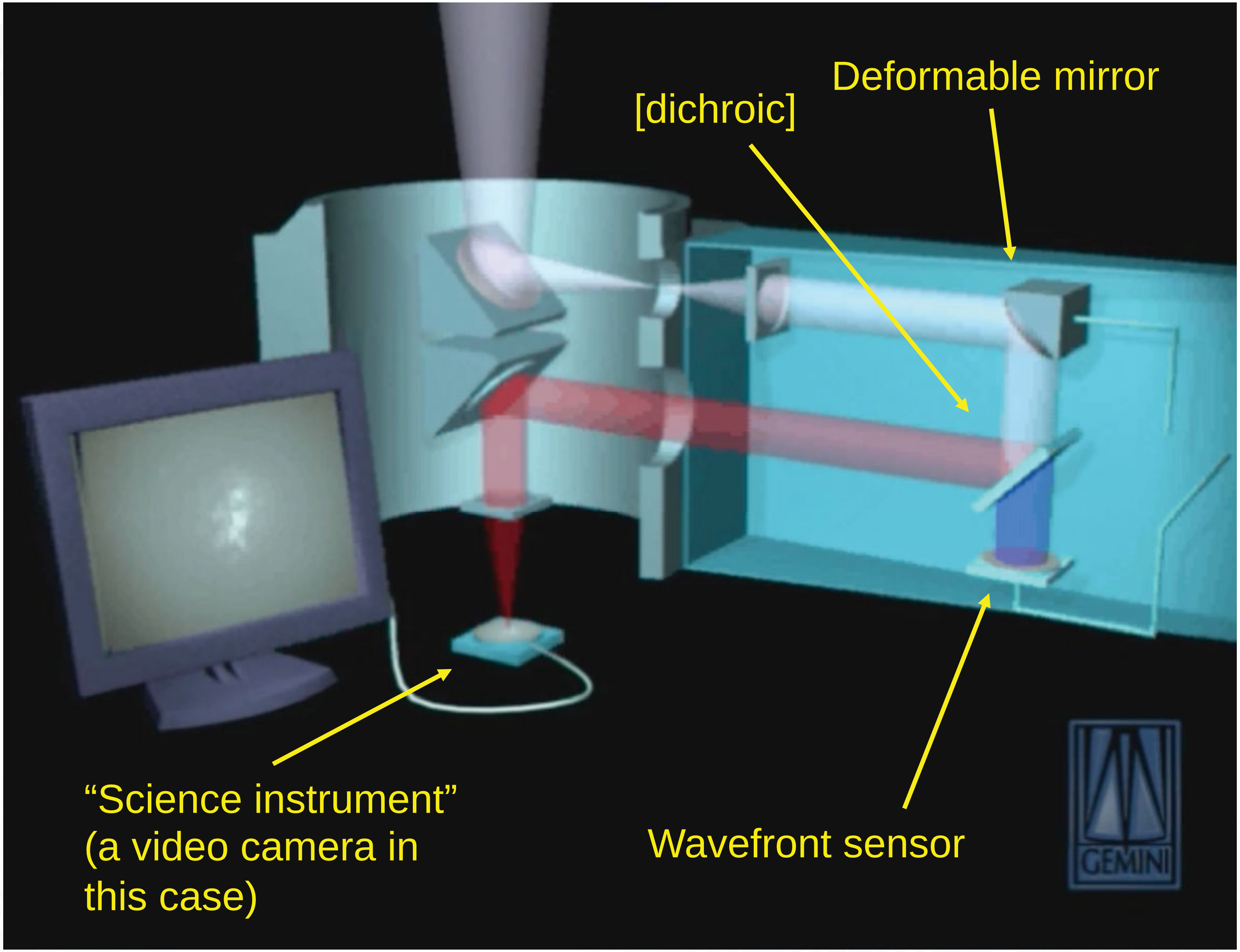
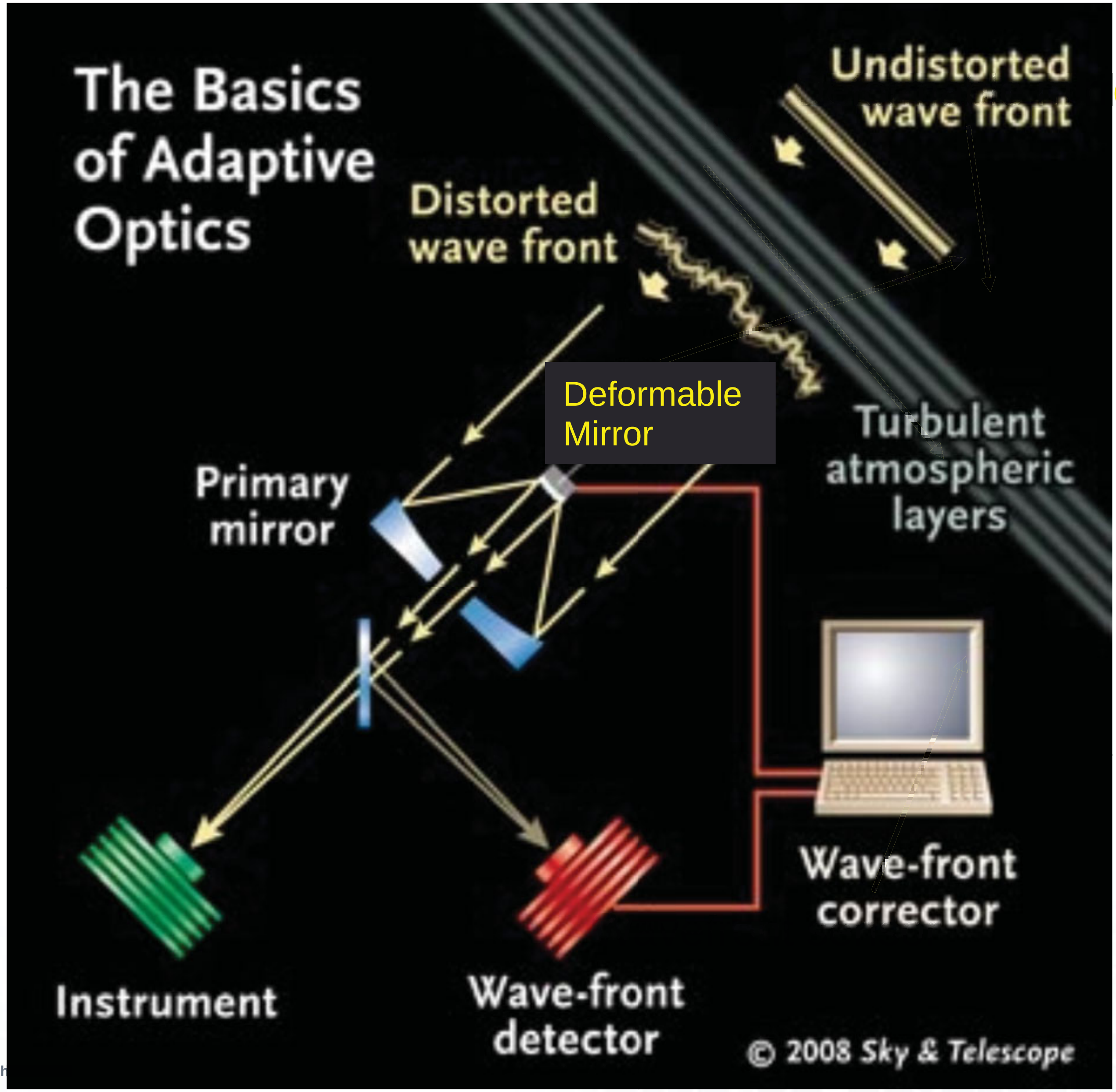
Correcting the atmosphere over 1 segment:

Correcting the atmosphere over 1 segment



Correcting the atmosphere over 1 segment



Deformable
Mirror

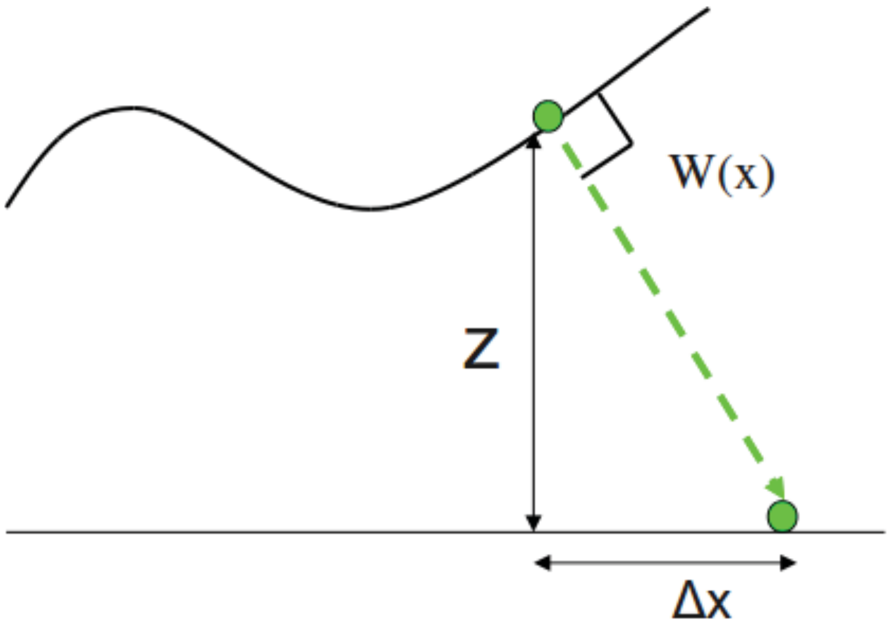
or

Step 1: “wavefront sensing”

Universal method:

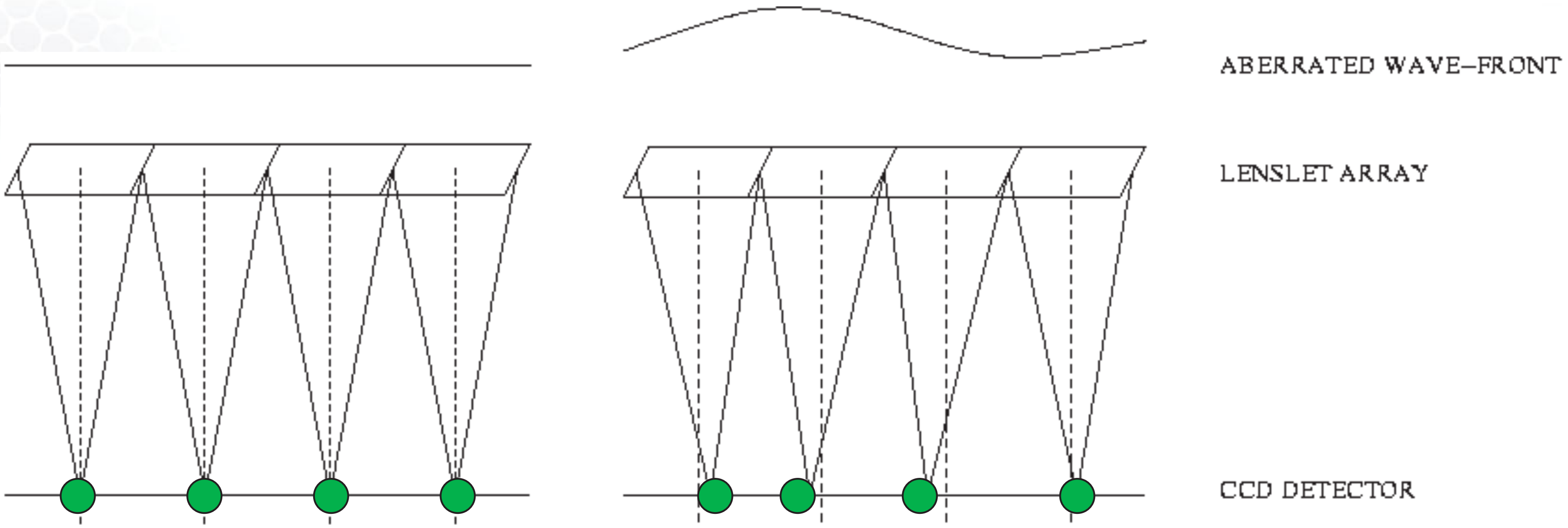
wavefront slope (pupil plane) → image displacement (image plane)

$\Delta x = z W_x$



Light propagates in the direction normal to the wavefront

Step 1: “wavefront sensing” … Shack-Hartmann lenslet array

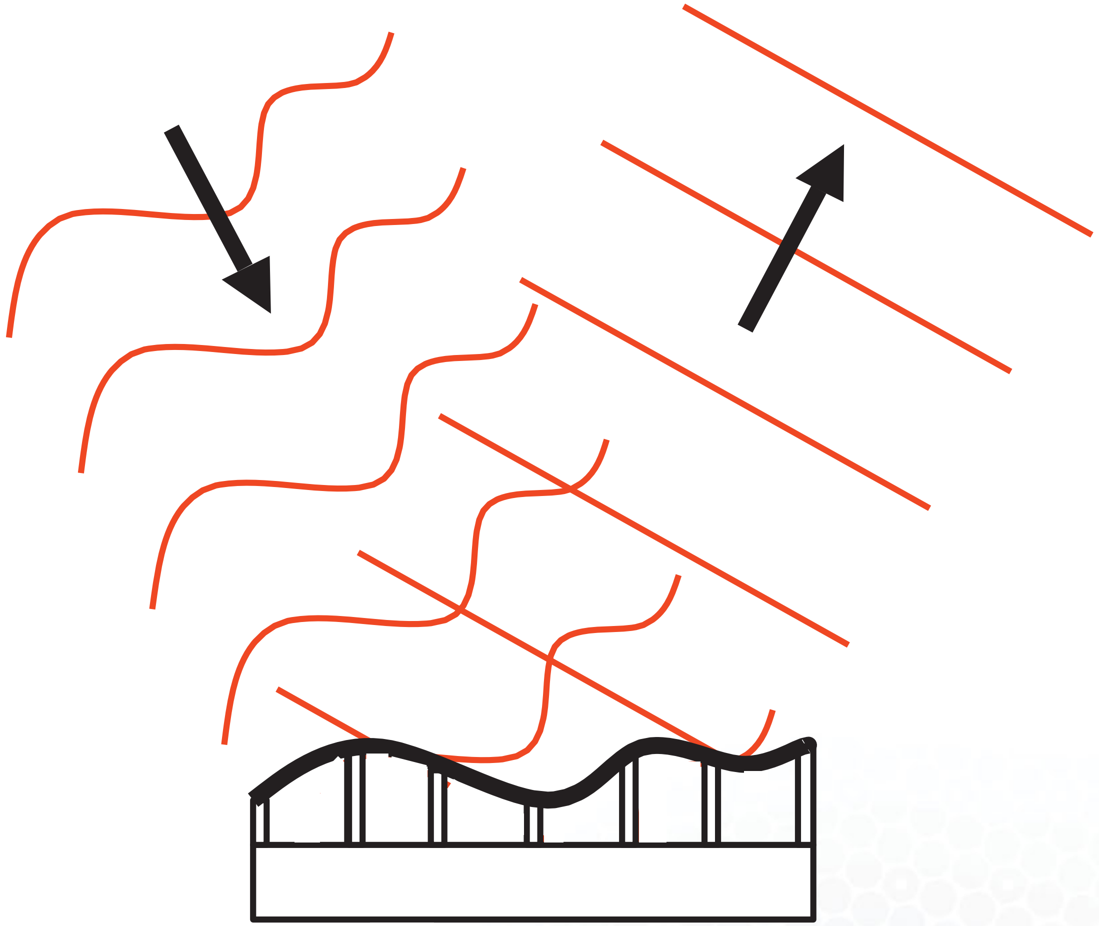


At the pupil: sub-divide the aperture using a lenslet array.

Images form DISPLACED due to the wavefront tilt at that location in pupil.

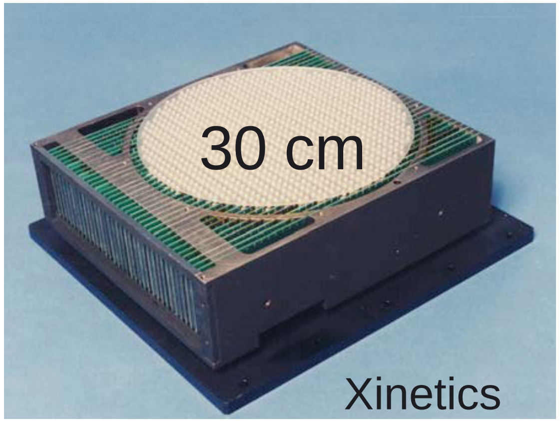
All wavefront sensors measure wavefront derivatives

Step 2: put the opposite shape on a deformable mirror

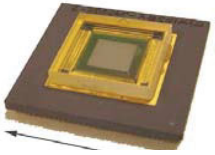


Deformable mirrors: lots of options

Glass facesheet
1000 actuators



MEMS
1000 actuators

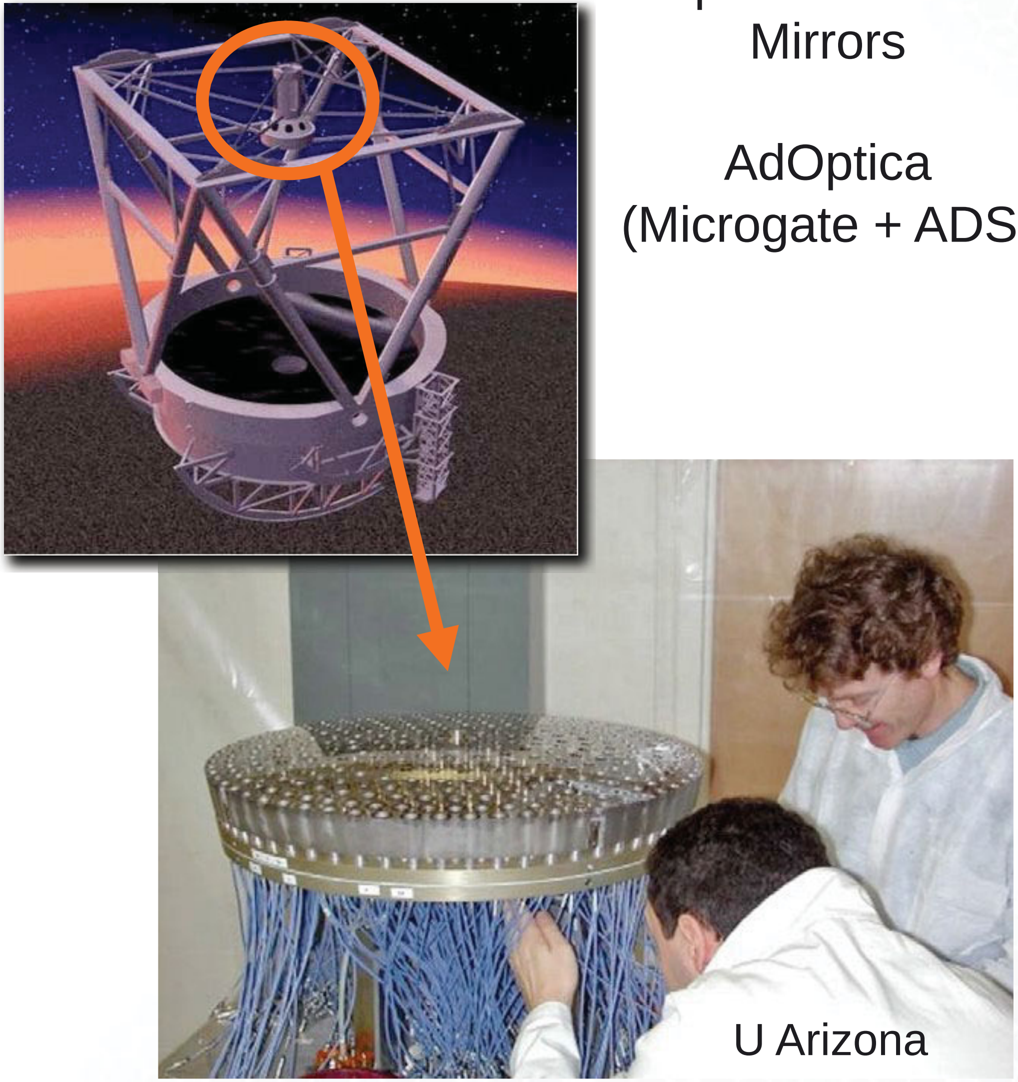


1 cm

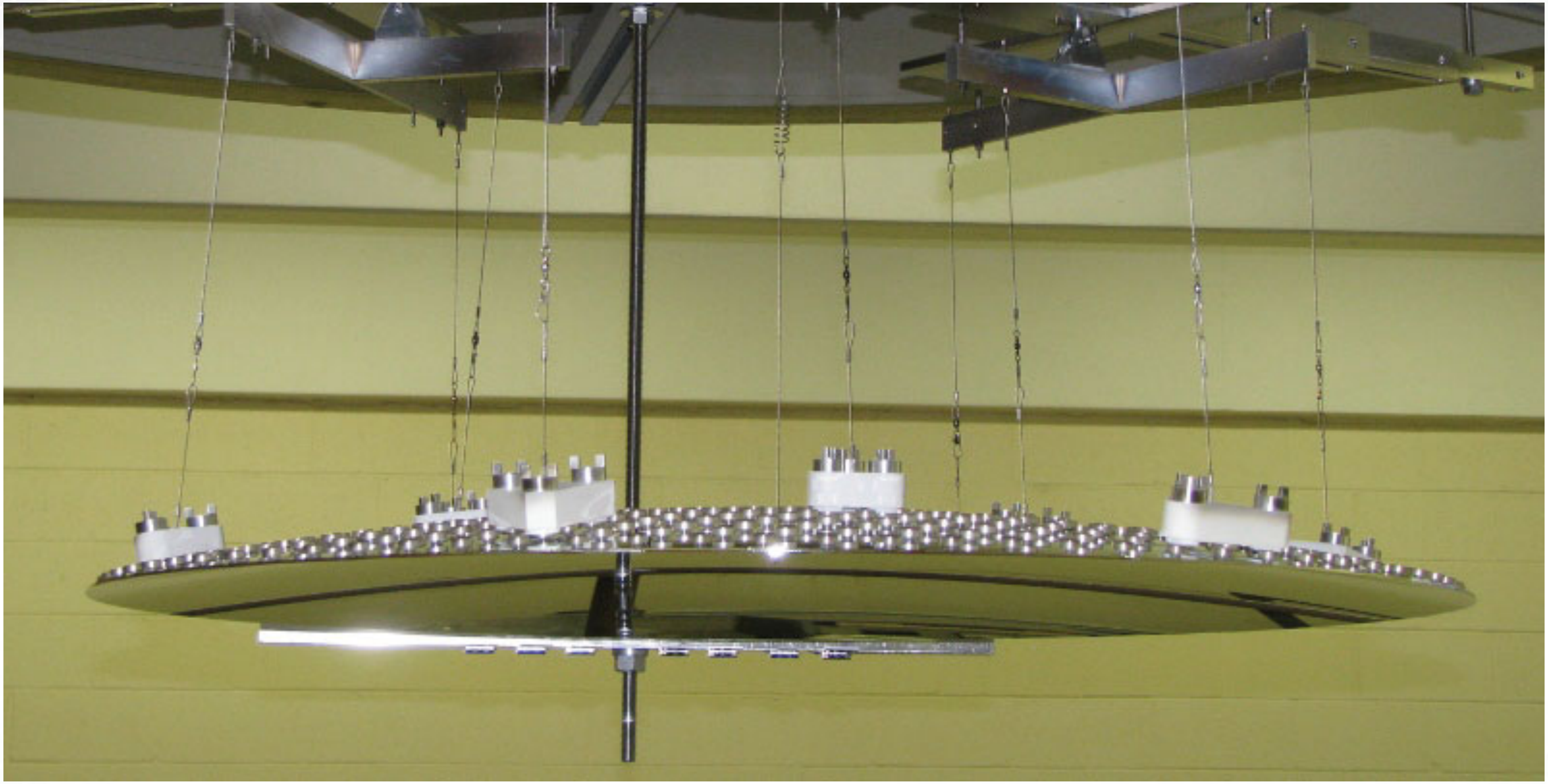
Boston
Micro-
Machines

Adaptive Secondary
Mirrors

AdOptica
(Microgate + ADS)

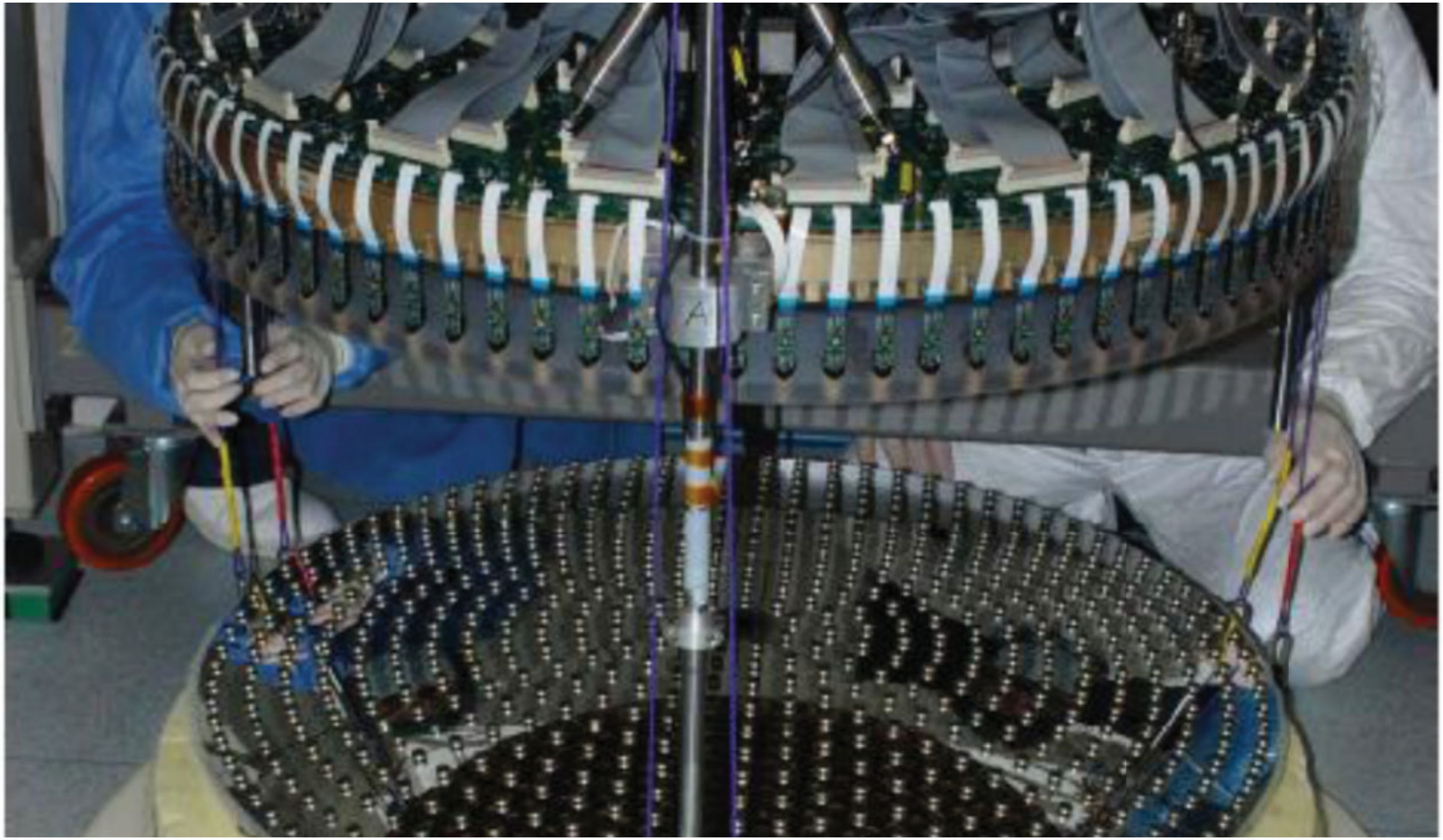


Deformable mirrors: secondary mirror option

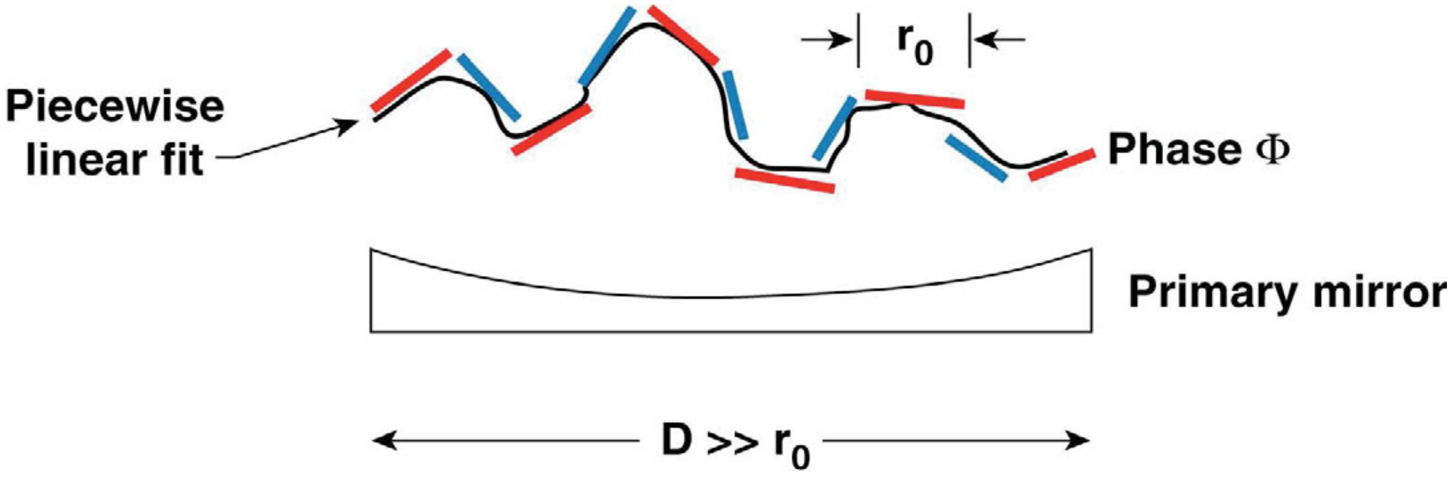


2 mm thick Zerodur face sheet (hanging in the Magellan coating tank)

Deformable mirrors: secondary mirror option



Key issues: actuator density matters!



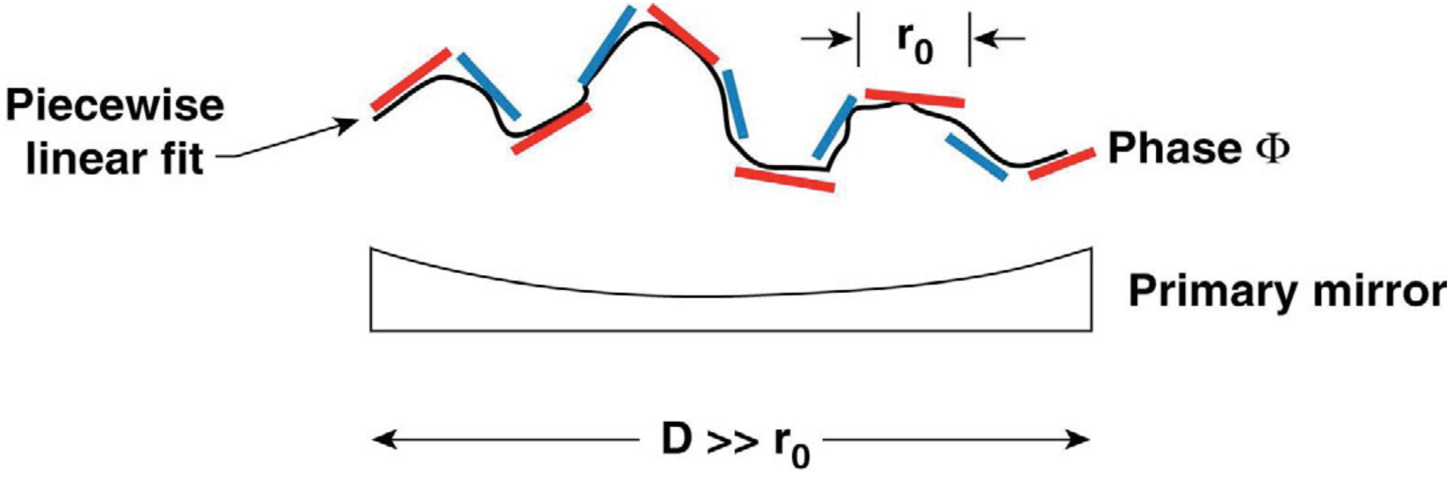
Deformable mirror makes a piece-wise fit to the

shape of the incoming wavefront.

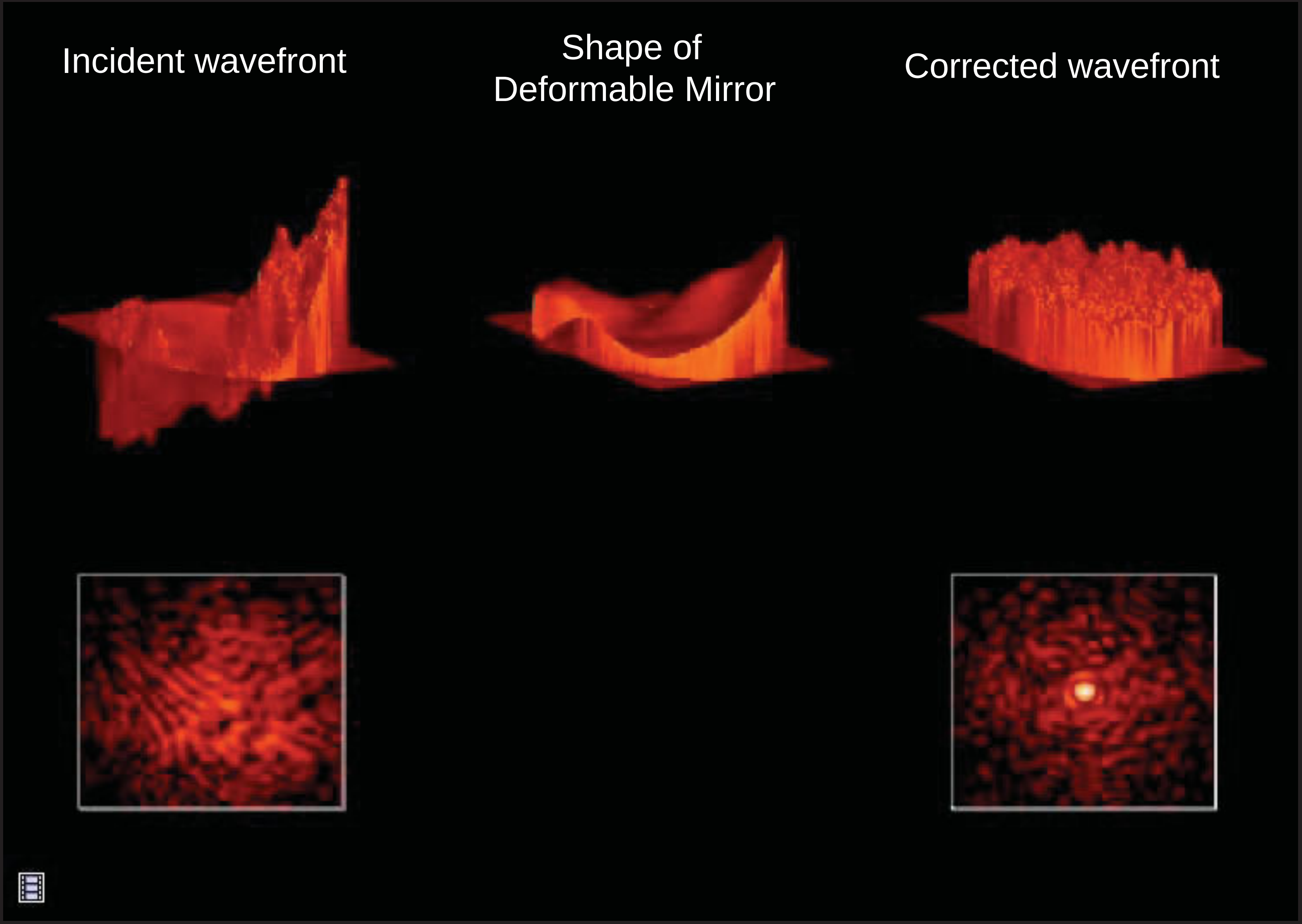
More pieces (better fits) are better!

Key issues: actuator density needed

- Actuators needed for different telescopes



Observing wavelength (μm) ⇒	10	2.2	0.8	0.5
Telescope diam. (m) ⇓				
4	1.1	7.6	22.8	40
10	2.7	18.9	56.9	100
30	8.2	56.8	170.7	300

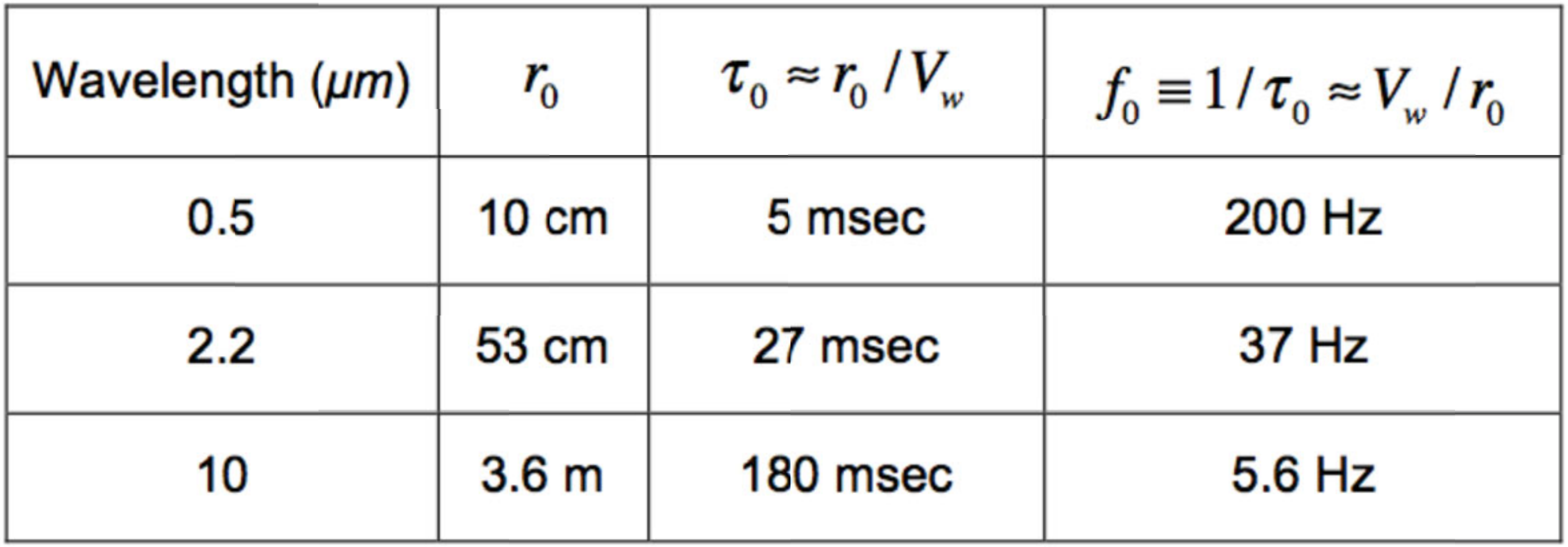


Credit: James Lloyd, Cornell Univ.

Key issues: rate of correction needed

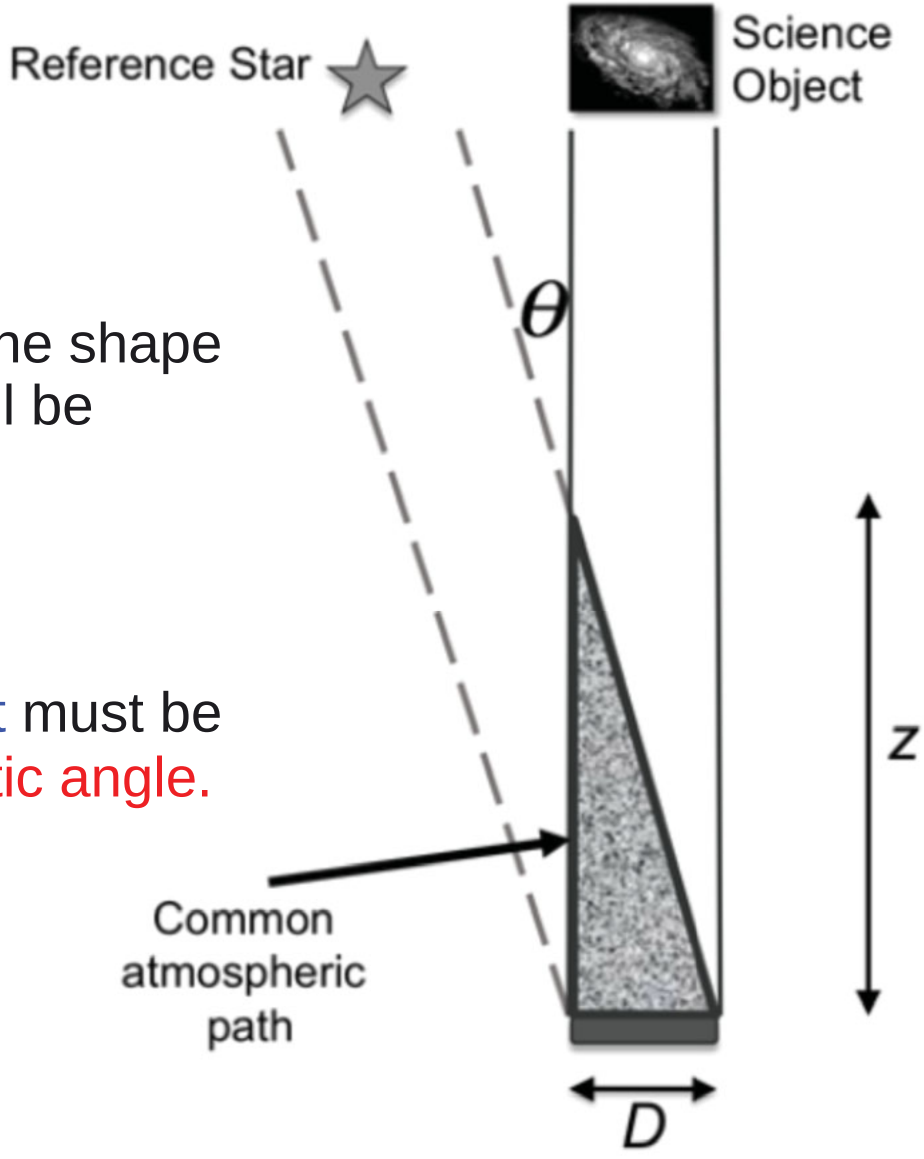
- Imagine a “frozen flow” of air … how fast are the cells going by?
  - size of the correlation length (cell in air): r_0
  - The wind speed where the turbulence is dominant: V

    (the average windspeed above telescope, weighted by turbulence strength)

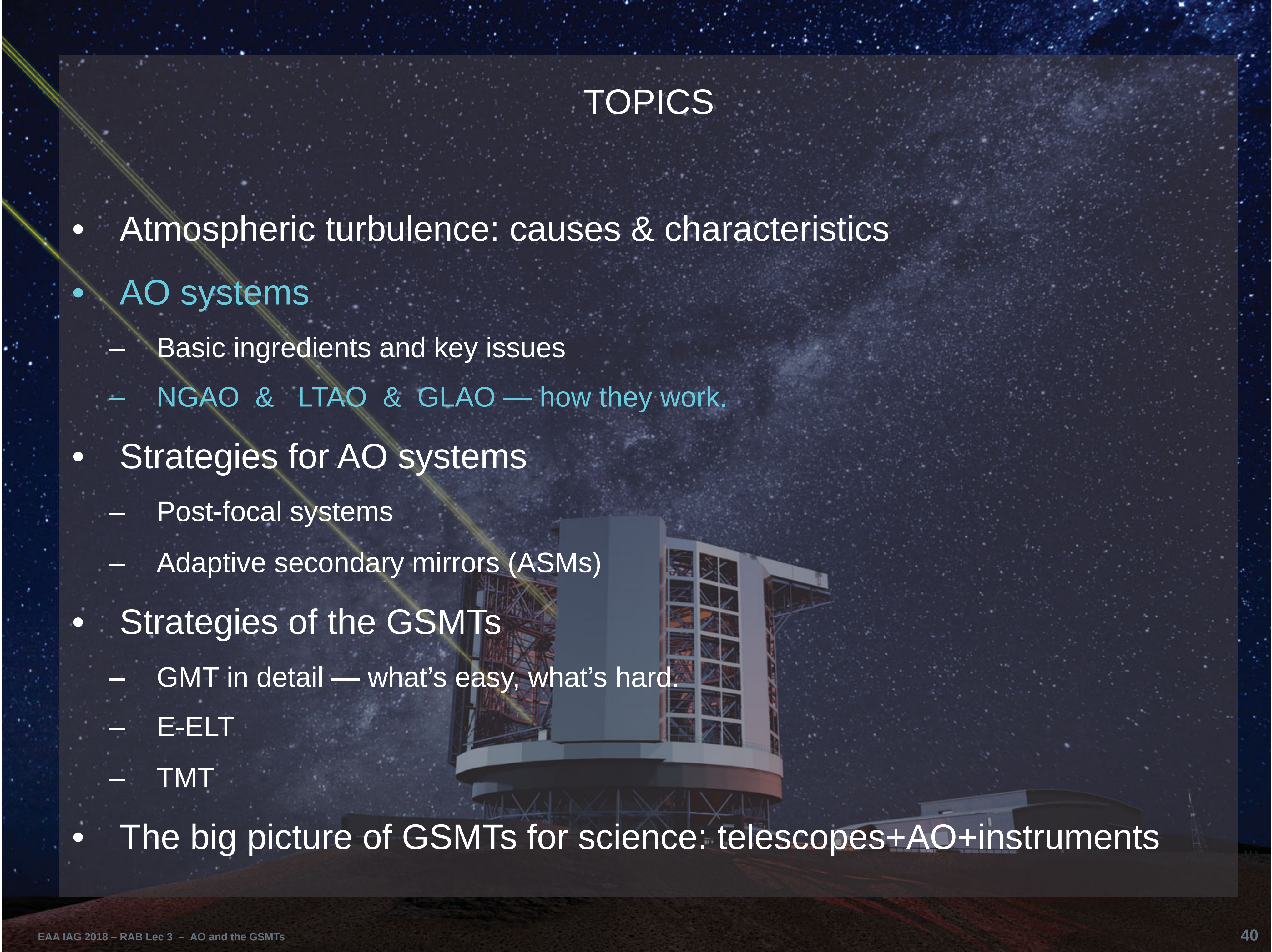


Wavelength (μm)	r_0	$\tau_0 \approx r_0 / V_w$	$f_0 \equiv 1/\tau_0 \approx V_w / r_0$
0.5	10 cm	5 msec	200 Hz
2.2	53 cm	27 msec	37 Hz
10	3.6 m	180 msec	5.6 Hz

Key issues: isoplanatic angle



- the angle on the sky over which the shape of the wavefront (from 2 stars) will be approximately the same
- The guide star and science target must be closer together than the isoplanatic angle.



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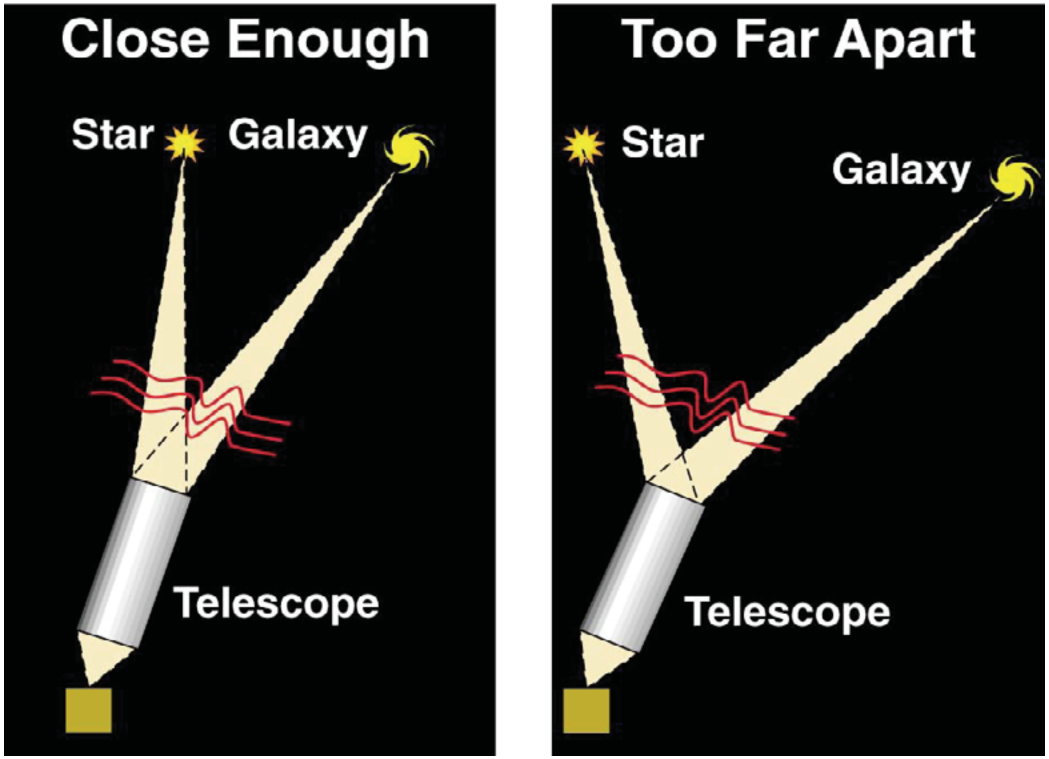
Limitations of NGAO: guide stars need to be bright & close

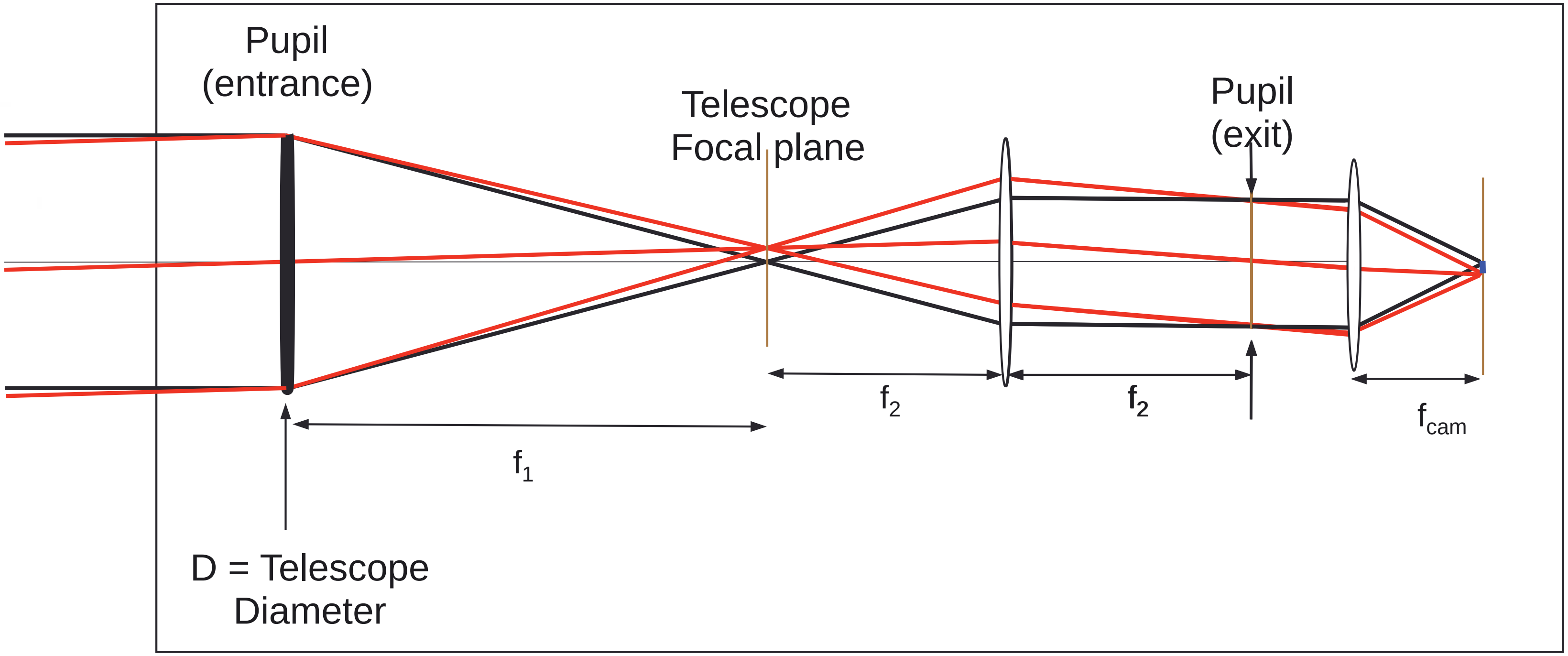
“Same turbulence”



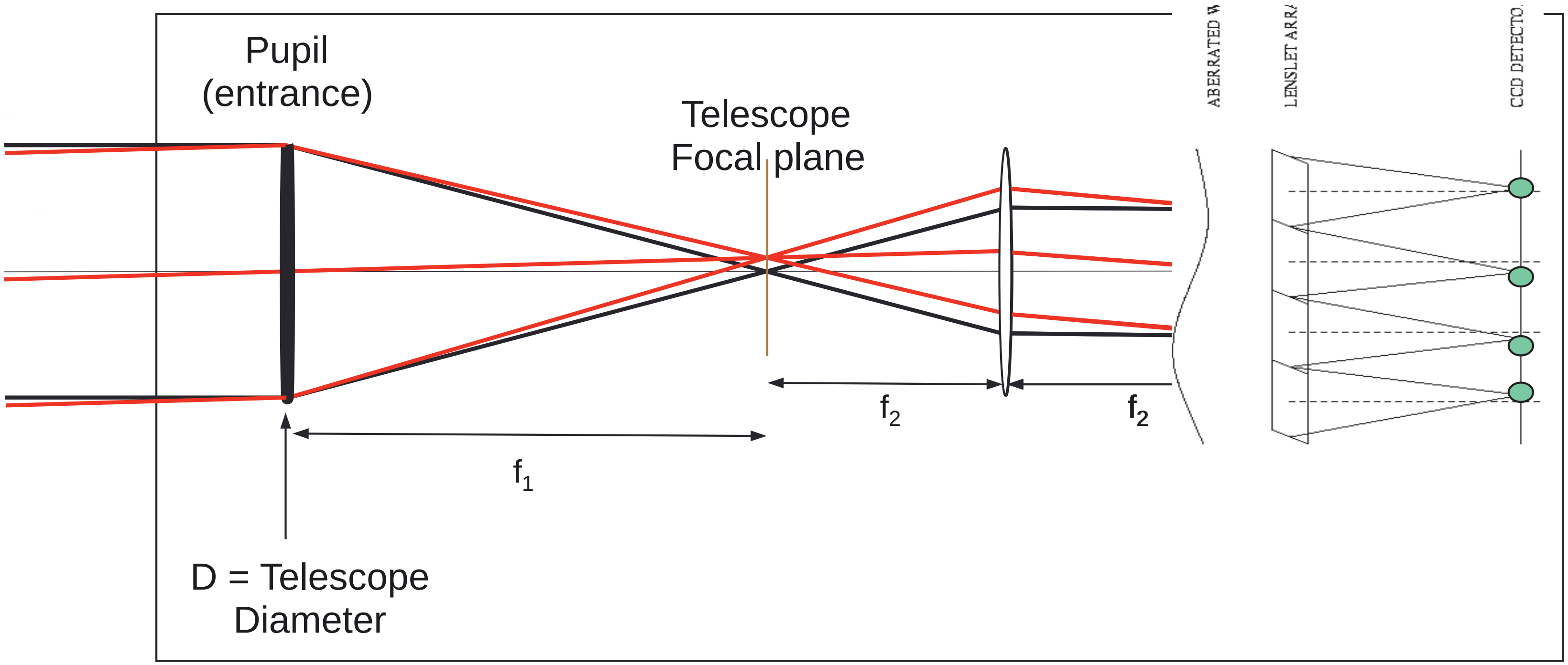
“Different turbulence”

Less than 10% of objects in the sky have a bright enough star nearby!

Limitations of NGAO: guide stars need to be bright & close



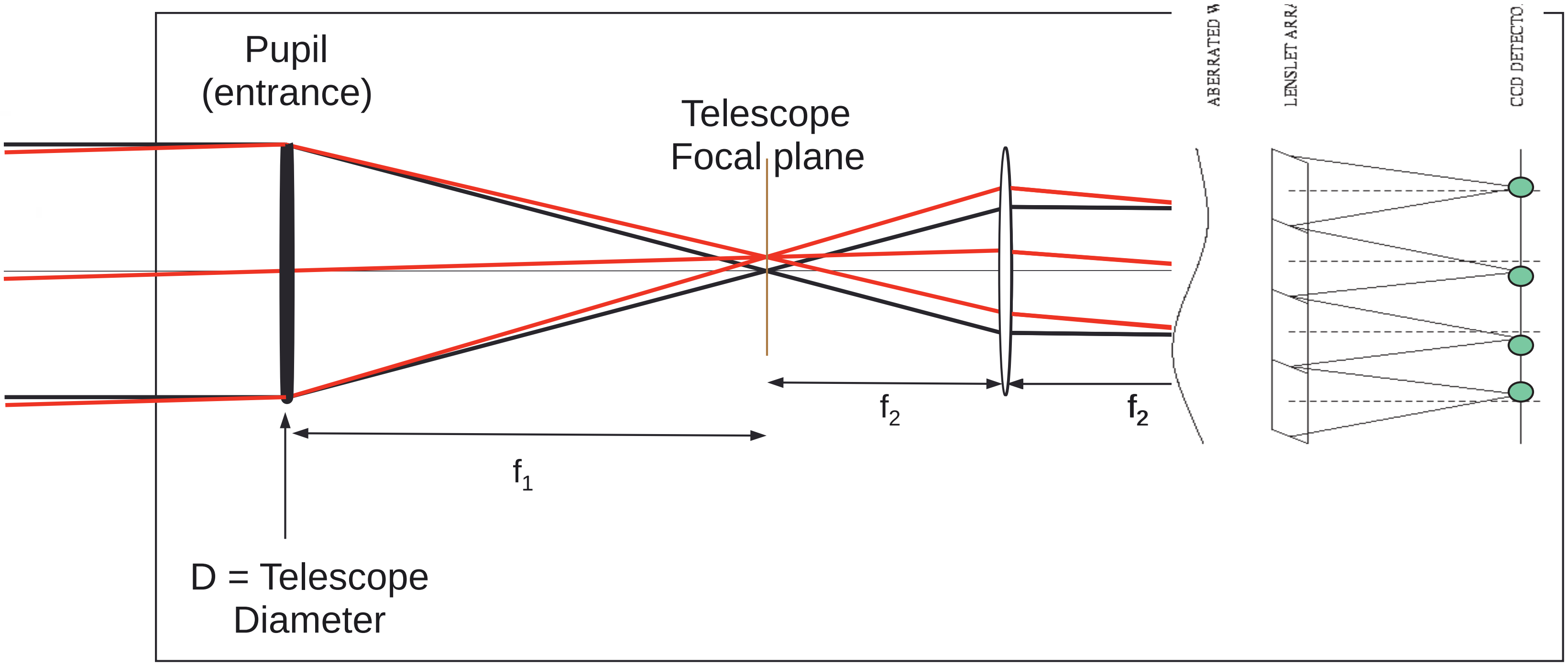
Limitations of NGAO: guide stars need to be bright & close



You need enough photons in ~r_0 (20cm) aperture on the primary to make a good measurement of the wavefront shape 1000 times per second!

Limitations of NGAO: guide stars need to be bright & close

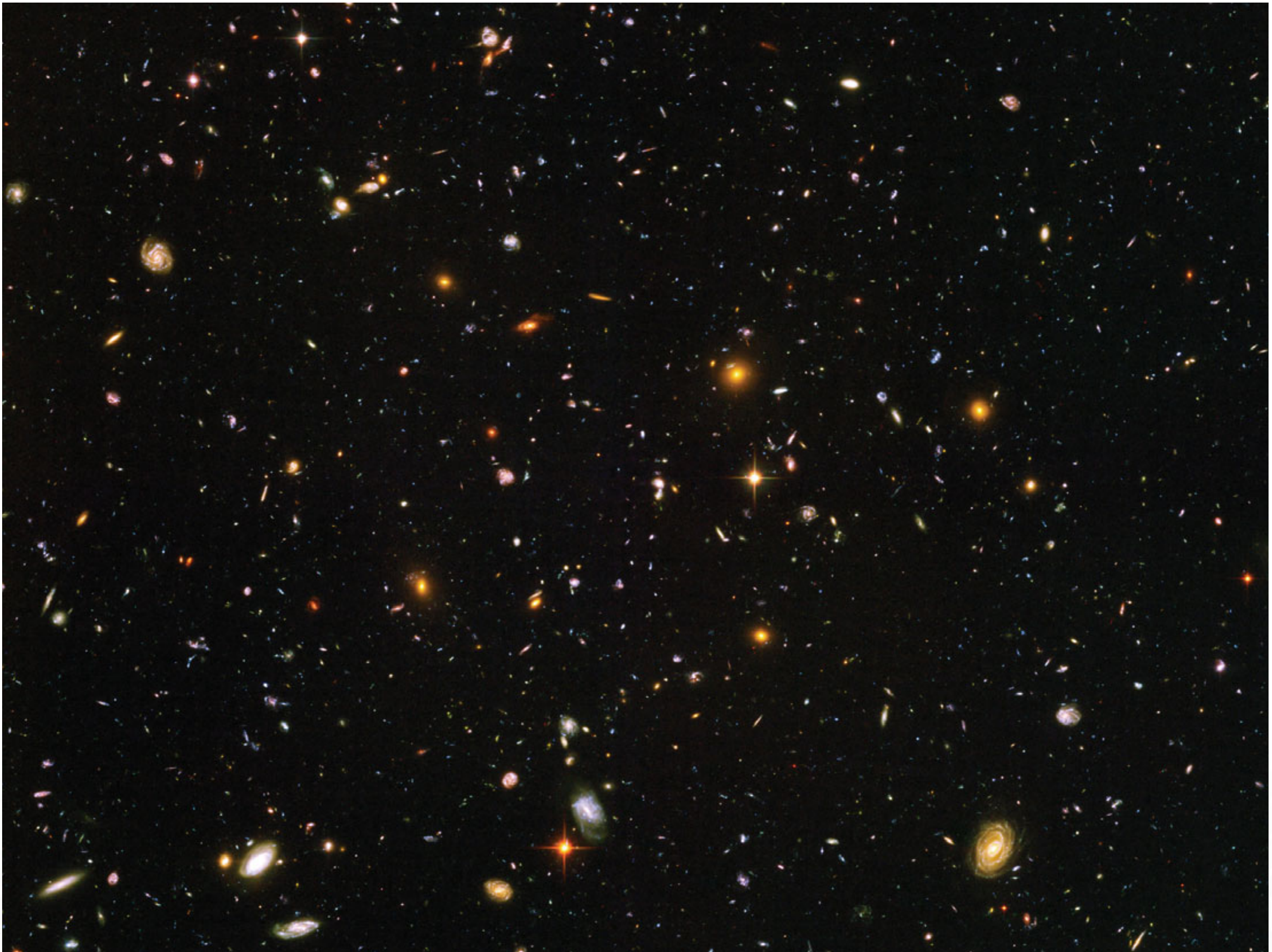
Bigger telescopes need THE SAME brightness guide stars!



You need enough photons in ~r_0 (20cm) aperture on the primary to make a good measurement of the wavefront shape 1000 times per second!

Limitations of NGAO: guide stars need to be bright & close

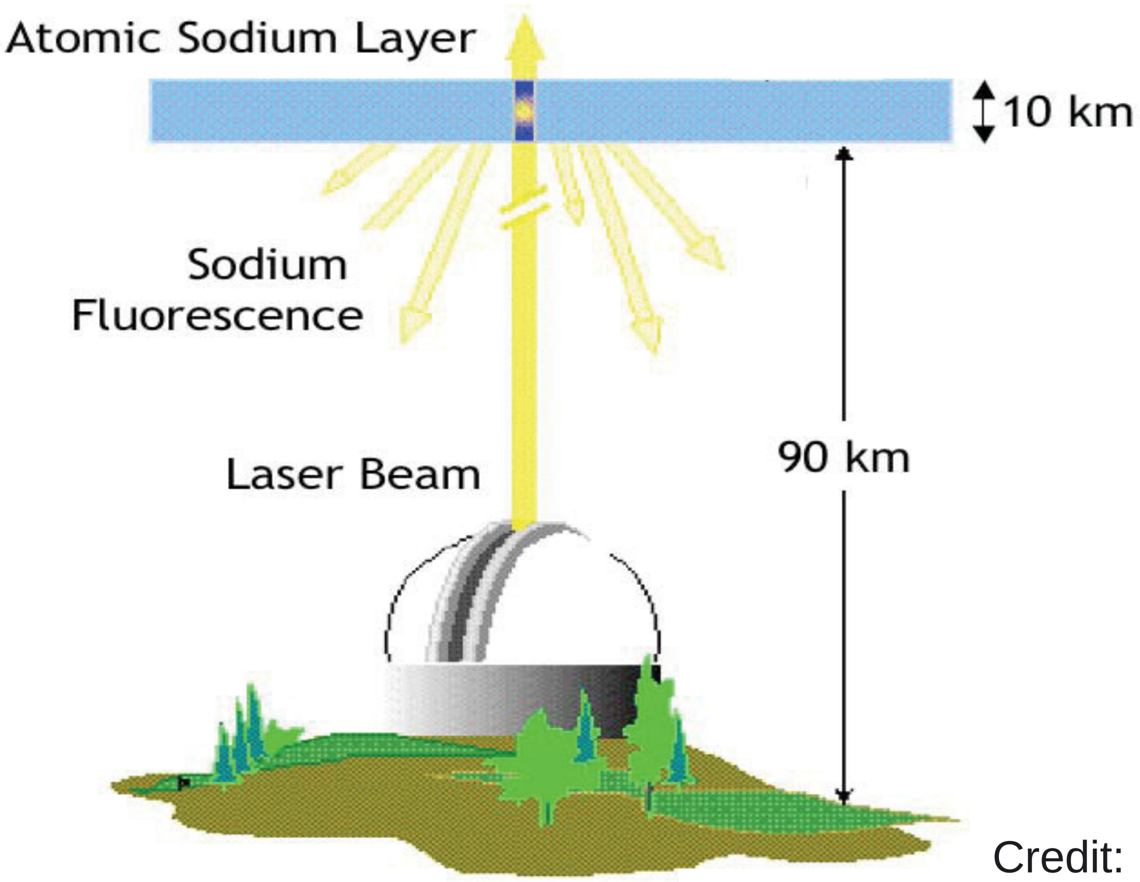
Only ~5% of the sky is close to a bright enough star for NGAO



Solution: Laser guide stars

GMT

Excite sodium atoms by shining 589 nm light onto sodium layer (Na D_2 line)



Credit: Peter Milone

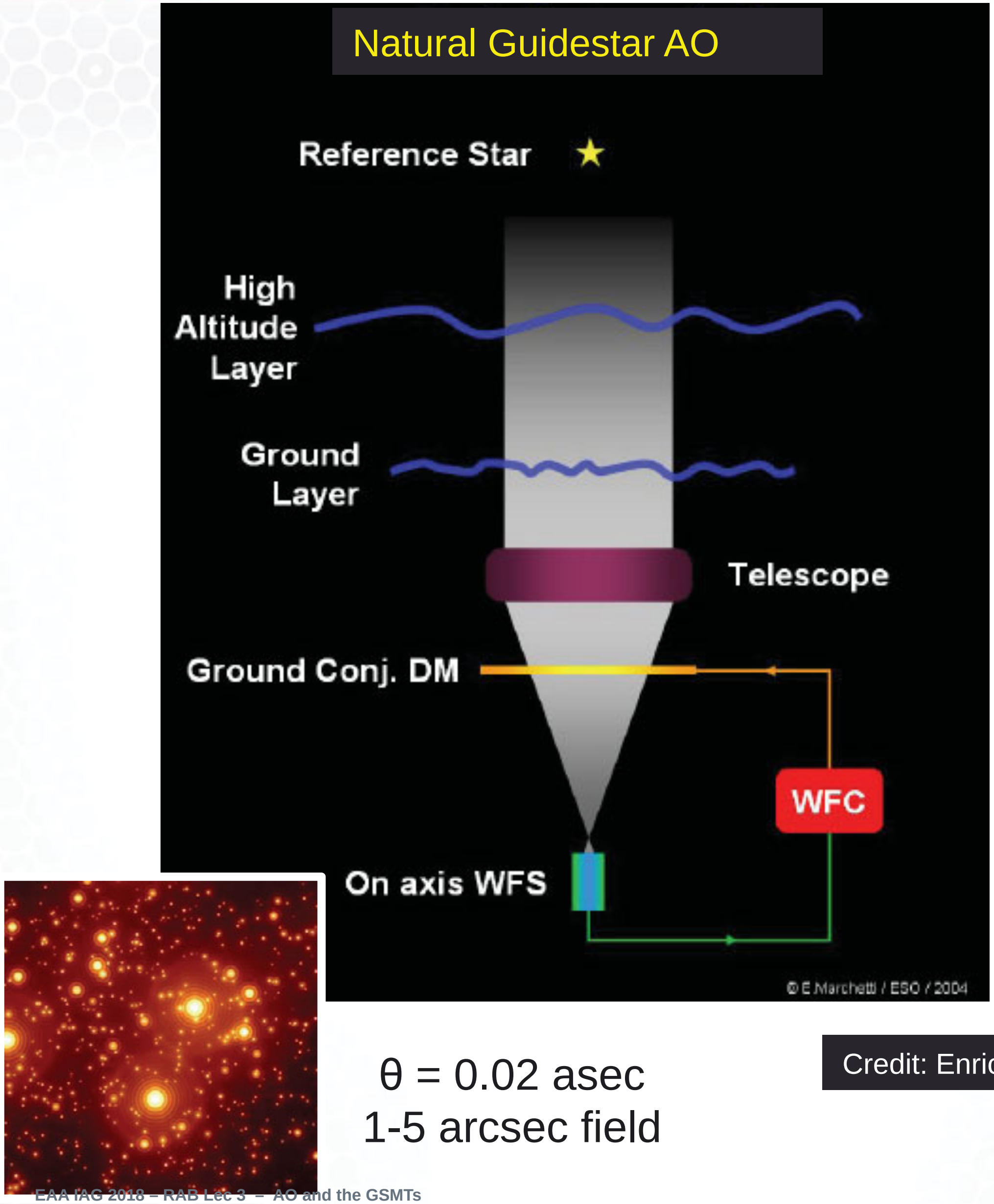
Lasers making guide stars on 8-10m telescopes

Left: Keck 2

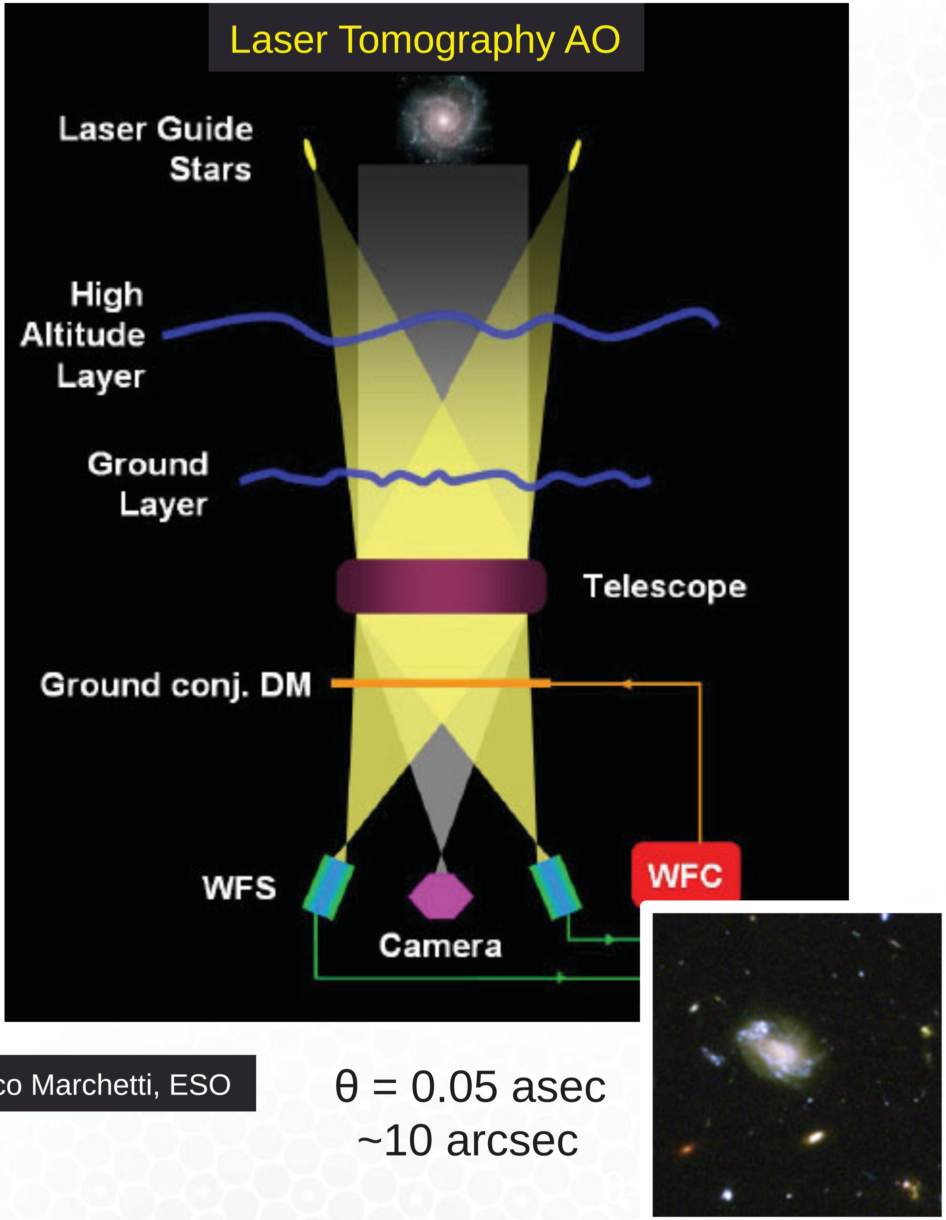
Middle: Gemini N

Right: VLT

Diffraction limited AO modes:



θ = 0.02 asec
1-5 arcsec field



Credit: Enrico Marchetti, ESO

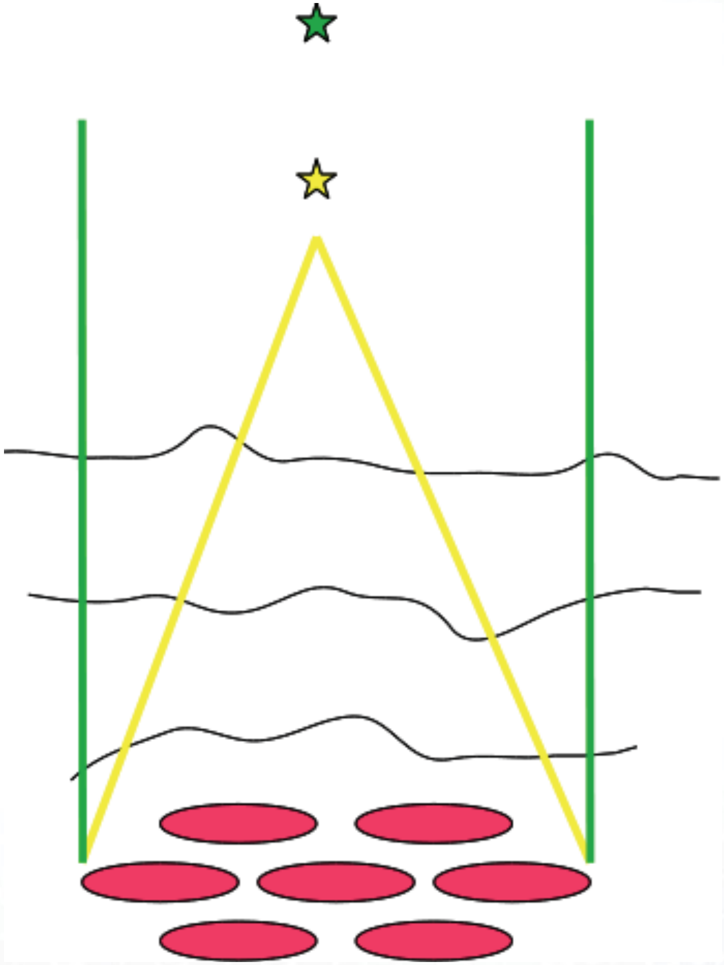
θ = 0.05 asec
~10 arcsec

Limitations of Laser Guide Stars: Cone Effect

[Sodium layer is at 90 km] vs. [astronomical objects at infinity]

→ Different turbulence is sampled

→ Problem worse for big telescope



“Cone effect” or “focal anisoplanatism”

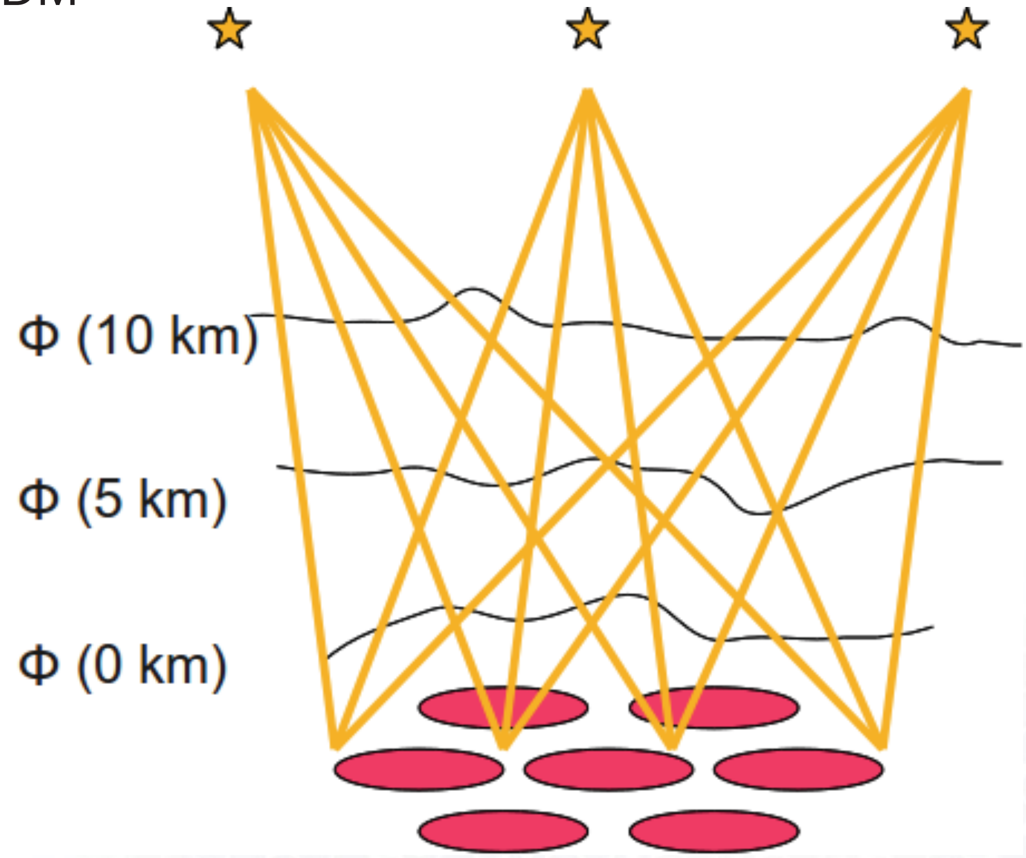
Limitations of Laser Guide Stars: Cone Effect

- Solution:
  - Use multiple laser guide stars to estimate the turbulence at many layers
  - Isolate the different contributions
  - Apply the full correction with 1 DM

$$\phi(DM)=\phi(0km)+\phi(5km)+\phi(10km)$$

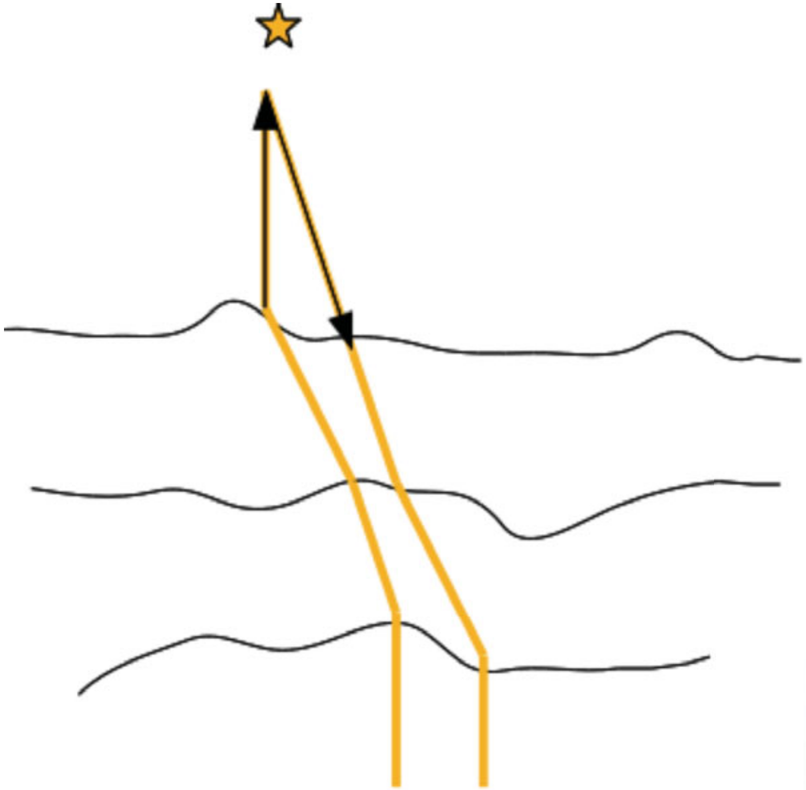
Hence “LTAO”:

L aser
T omography
A daptive
O ptics

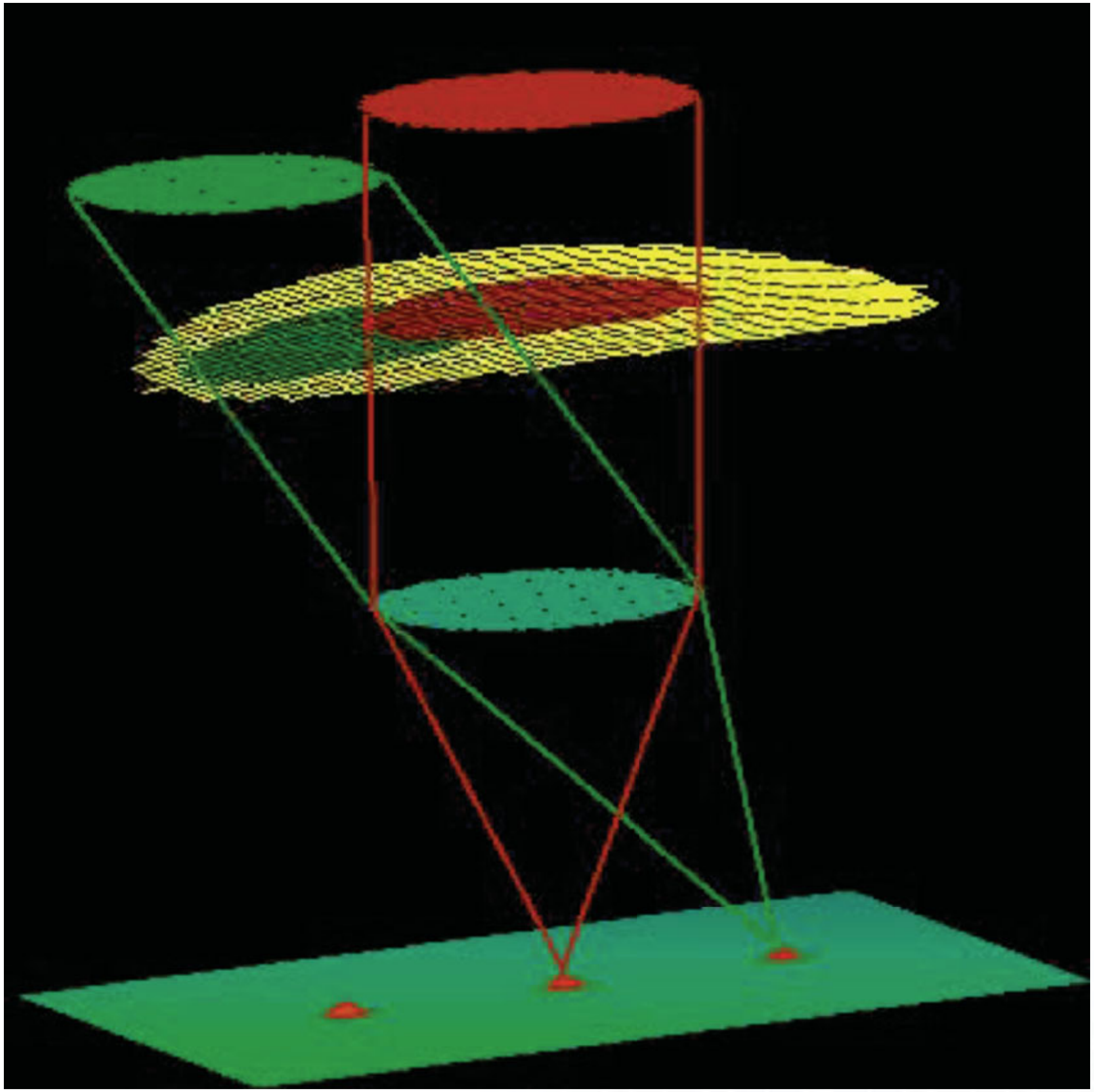


Limitations of Laser Guide Stars: tip tilt

- LGS is displaced on way up as well as on way down (snell's law)
- Can't determine overall tip-tilt of wavefront
- Tip-tilt causes causes image motion or jitter



Limitations of Laser Guidestars: tip tilt



Limitations of Laser Guidestars: tip tilt

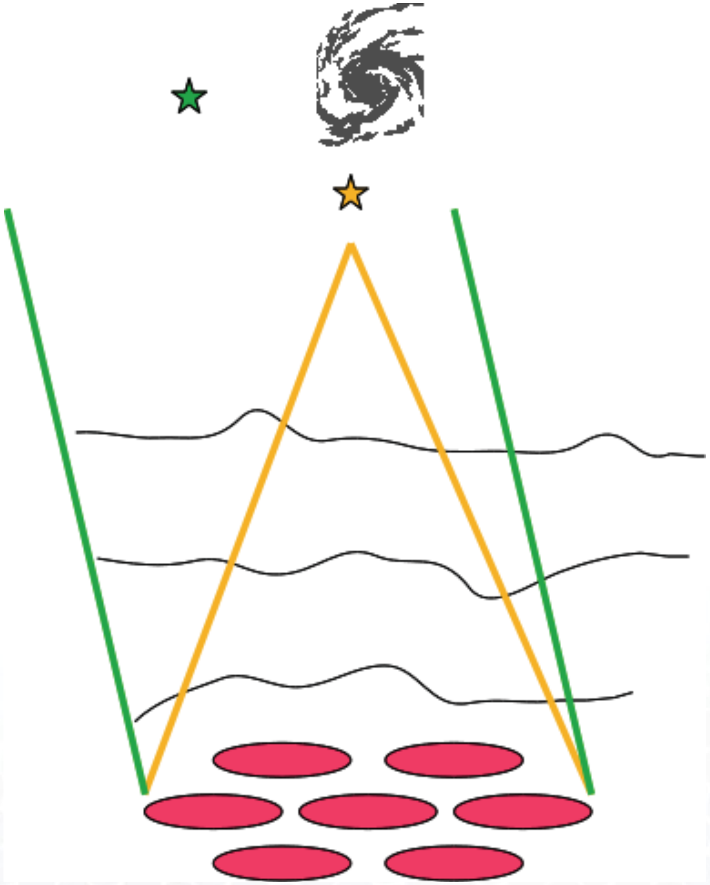
- Solution: use one (or more) natural guide stars to sense tip-tilt
  - Can use much fainter stars
  - Can use stars further from science object

Guide star needed (for NGAO):

$m_R < 15$, $\theta < 20''$

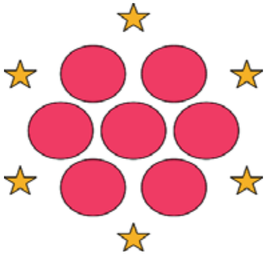
“Tip Tilt” Guide star needed (with LTAO):

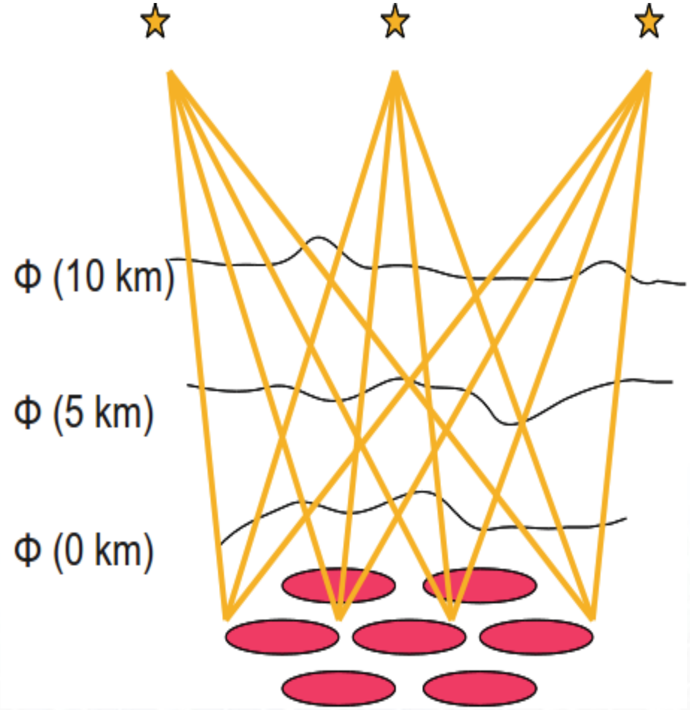
$m_R < 18$, $\theta < 60''$



LTAO: laser placement

- Place lasers to avoid contaminating your own field of view!

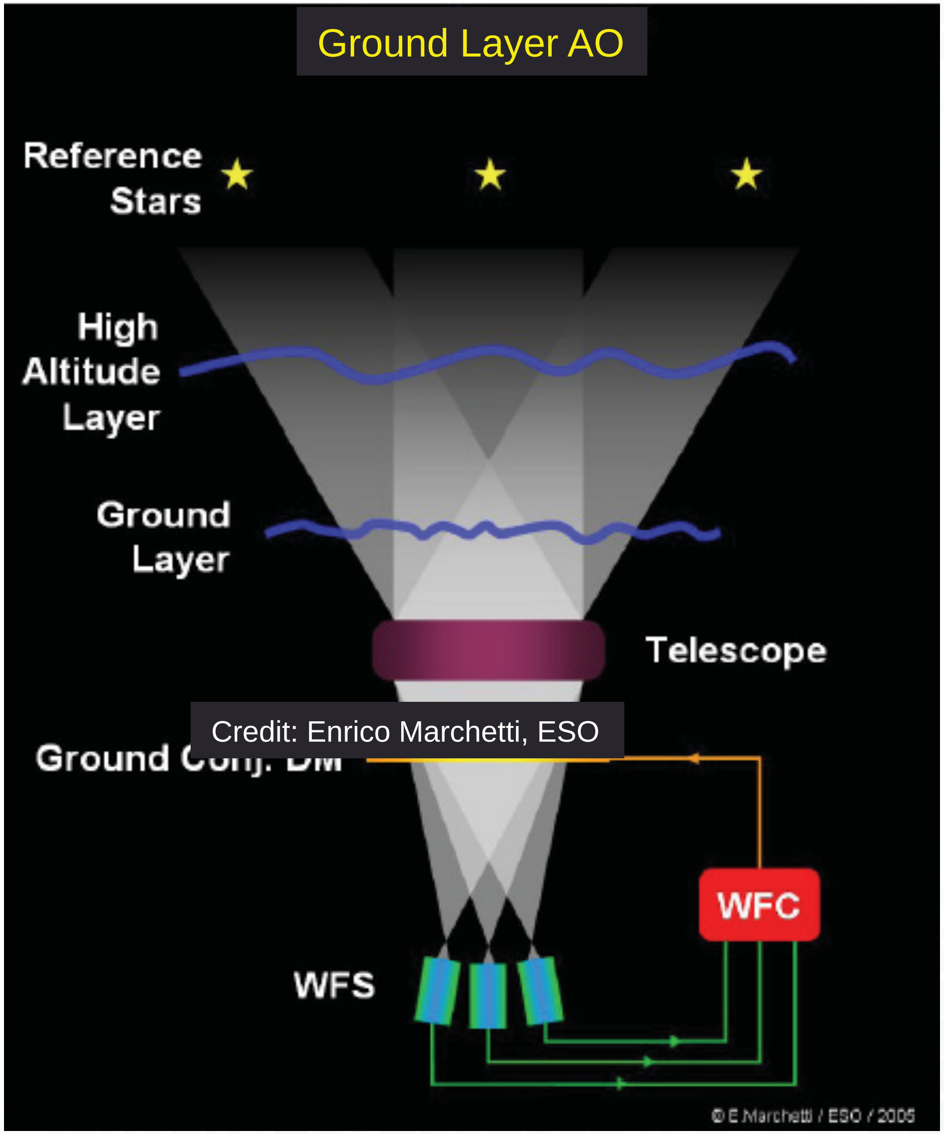




GLAO: Partial atmospheric correction

- A large fraction of turbulence is near the ground
  - Denser air
  - Heating (ground)
  - Convection and mixing

- Ground layer contribution is constant over a wide field of view.

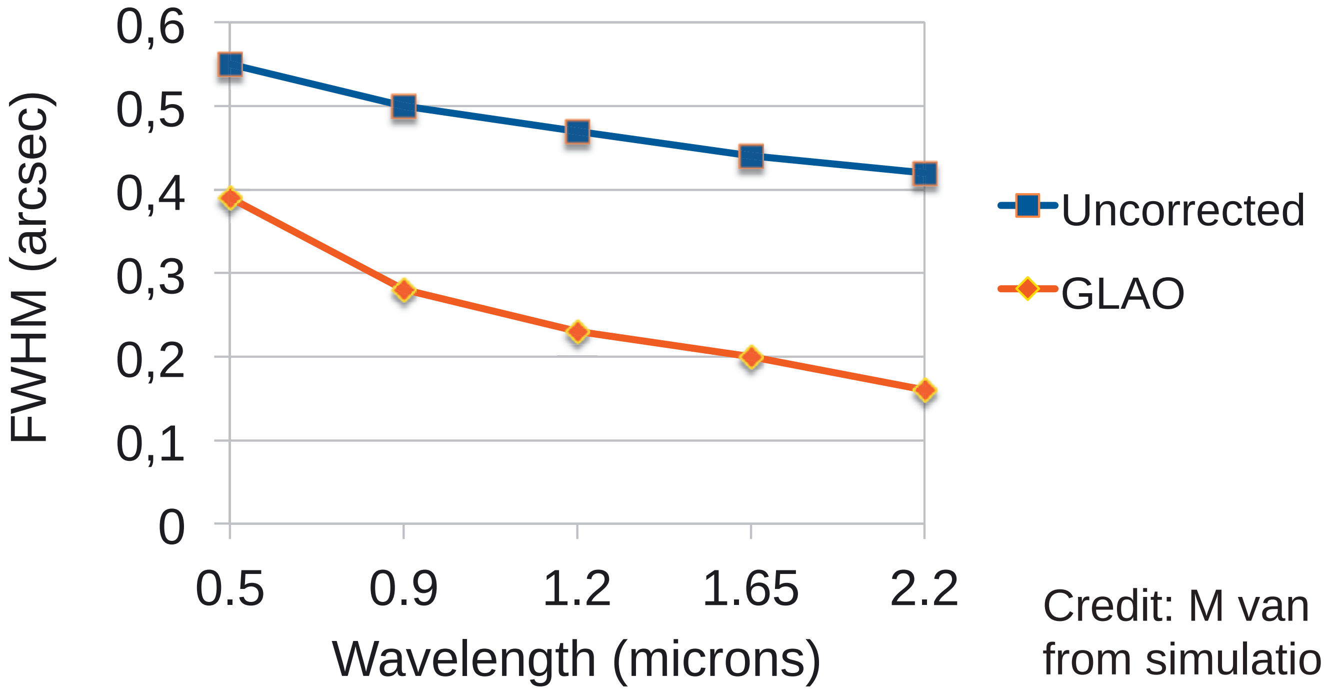


Credit: Enrico Marchetti, ESO

Ground Layer Adaptive Optics

GMT

Simulations predict we will get a 30-50% improvement over a wide field of view from GLAO (up to ~10 arcmin)



Credit: M van Dam, Adapted from simulations by Flicker

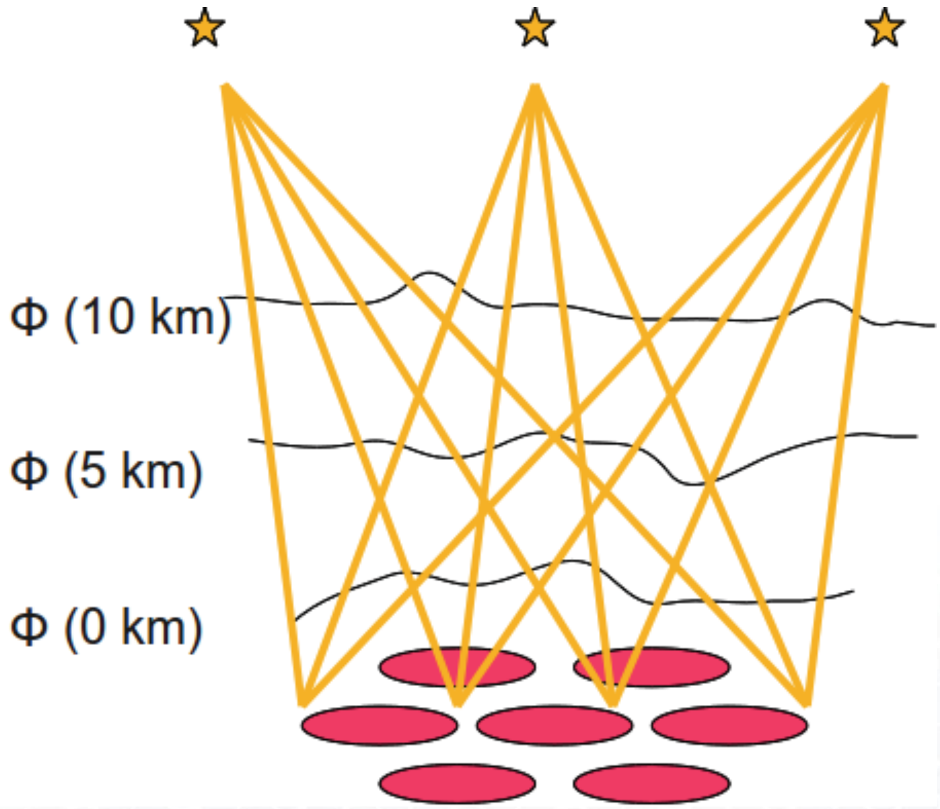
Ground layer AO works well at visible wavelengths, too!

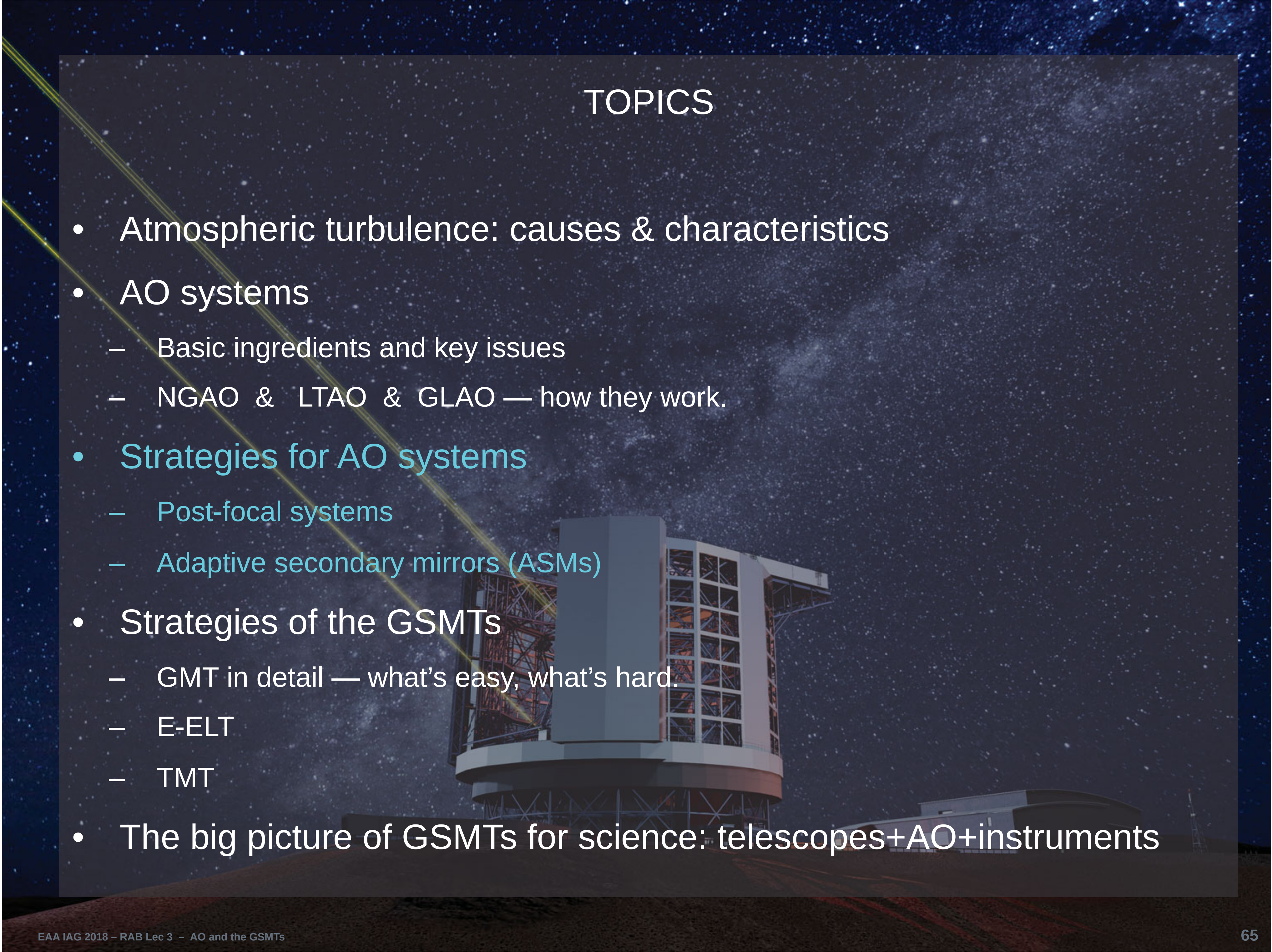
Ground Layer Adaptive Optics

- Use multiple laser guide stars to estimate the wavefront over many layers
- Place the ground layer contribution on the DM.

$$\phi(DM)=\phi(0\,km)$$

$$\phi(DM)=1/N\,(\phi(\theta_1)+\phi(\theta_2)+\ldots+\phi(\theta_N))$$





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  - Basic ingredients and key issues
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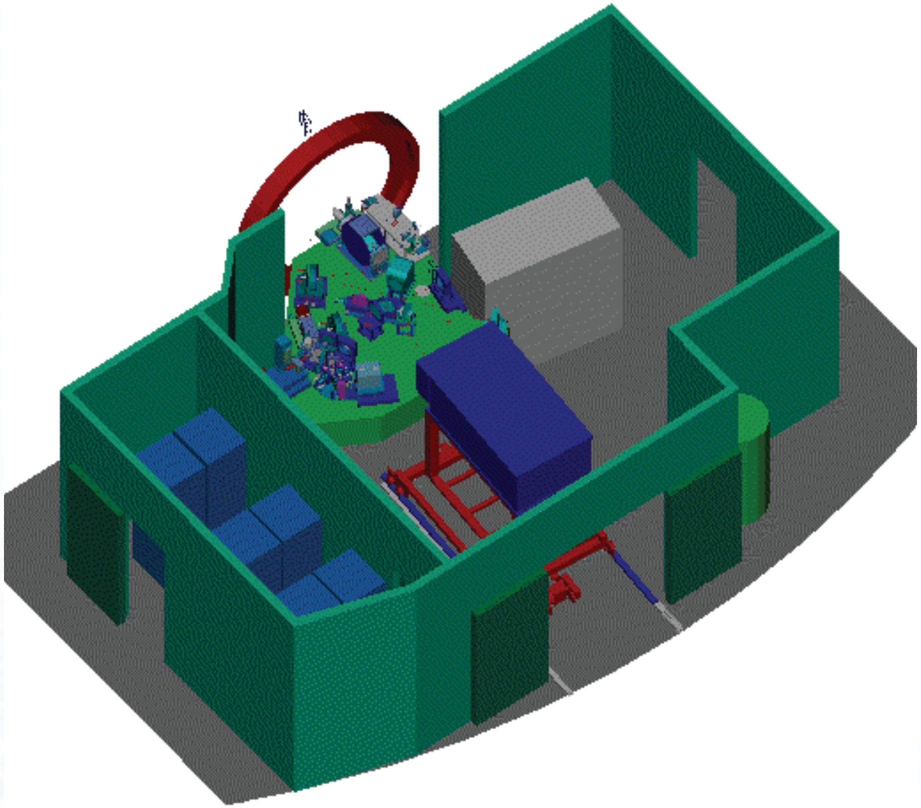
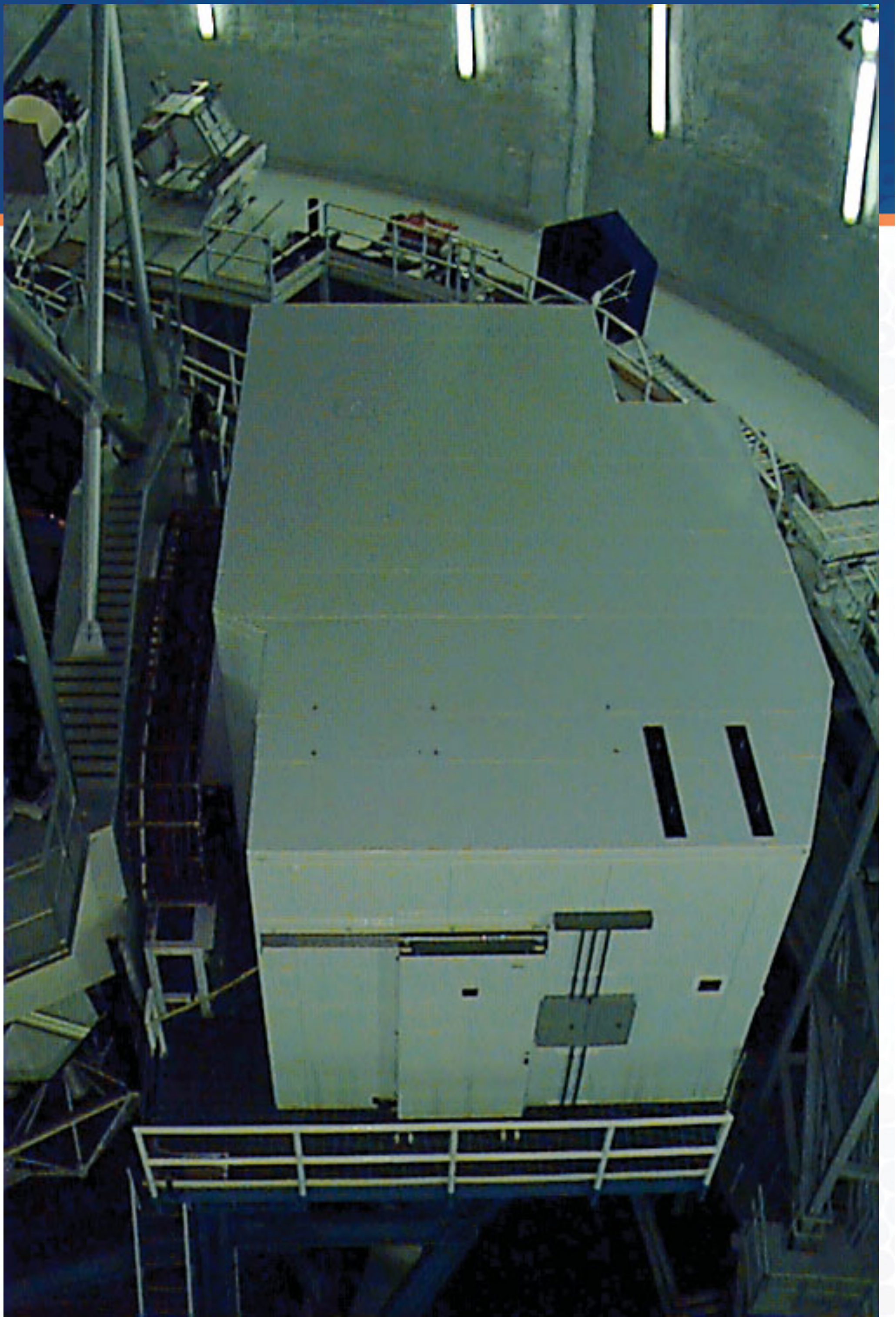
  - Post-focal systems
  - Adaptive secondary mirrors (ASMs)
- Strategies of the GSMTs
  - GMT in detail — what’s easy, what’s hard.
  - E-ELT
  - TMT
- The big picture of GSMTs for science: telescopes+AO+instruments

Strategies: post-focal

An early AO system on Keck II





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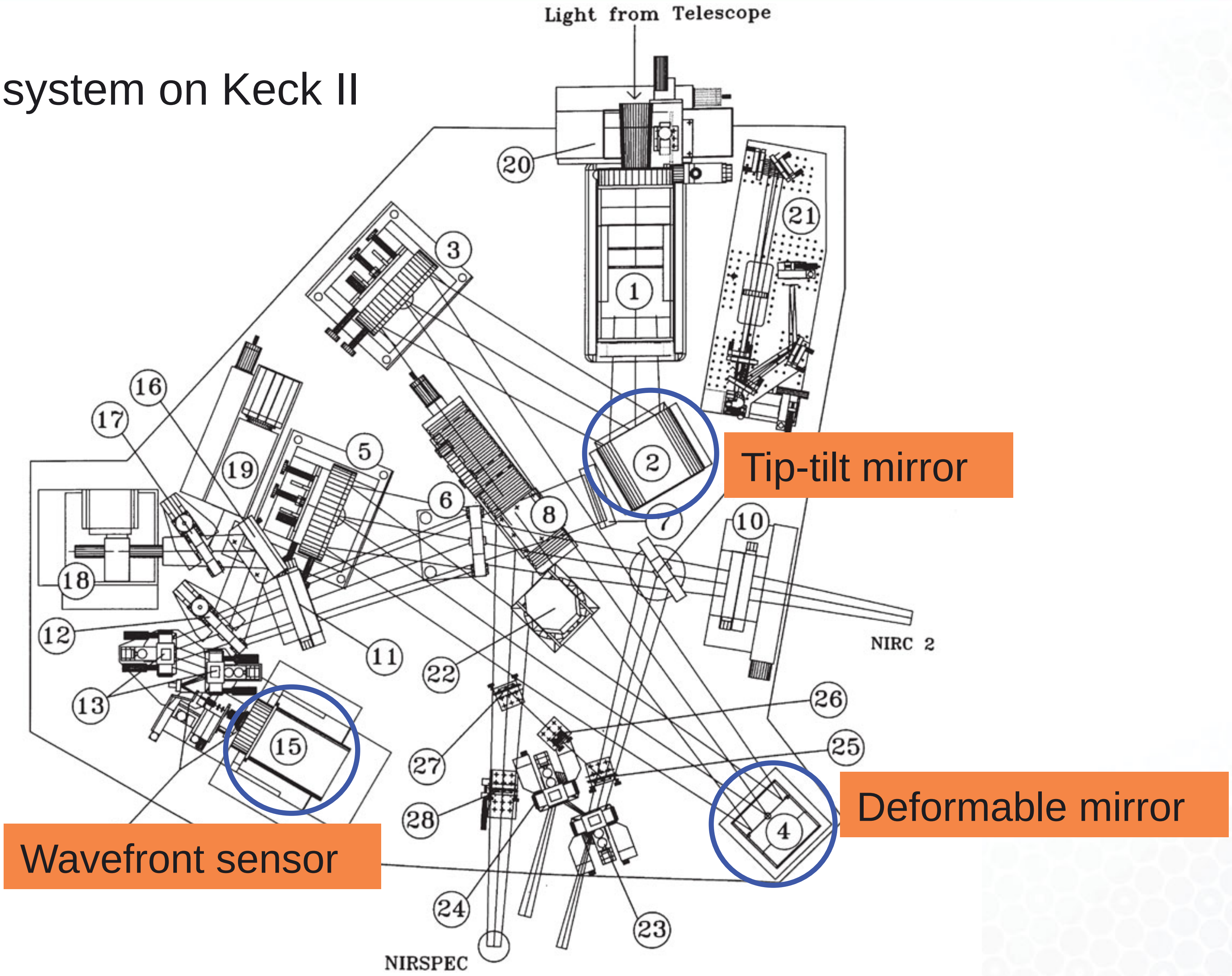


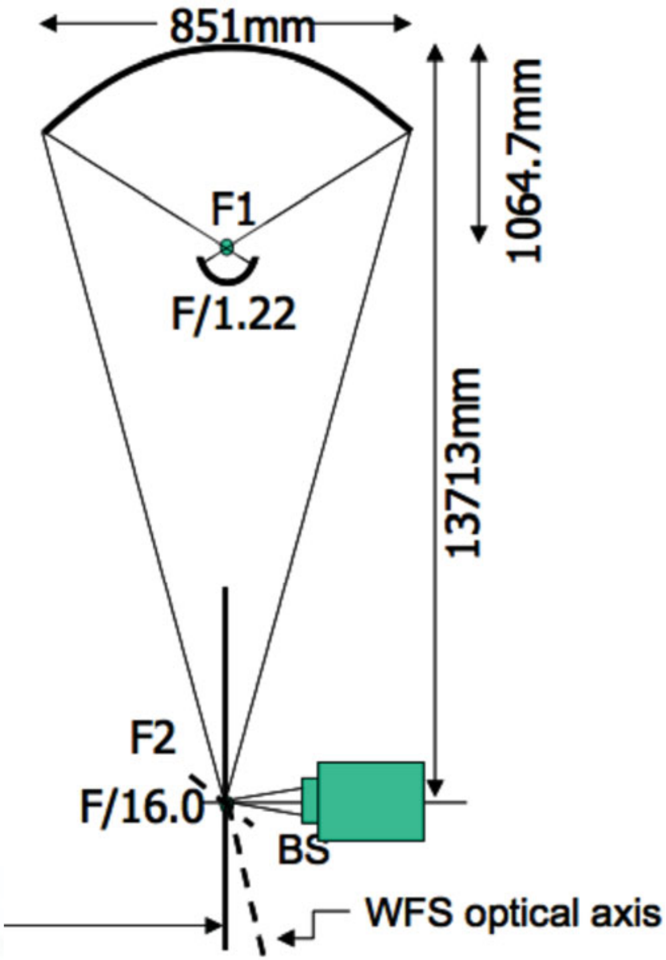
Tip-tilt mirror

Deformable mirror

Wavefront sensor

Strategies: deformable secondaries

World’s first deformable secondary: MMT (R. Angel & L. Close)



Magellan F/11 Adaptive M2

Figure 1. The world’s first adaptive secondary: a 65cm 336 actuator ASM at the MMT.

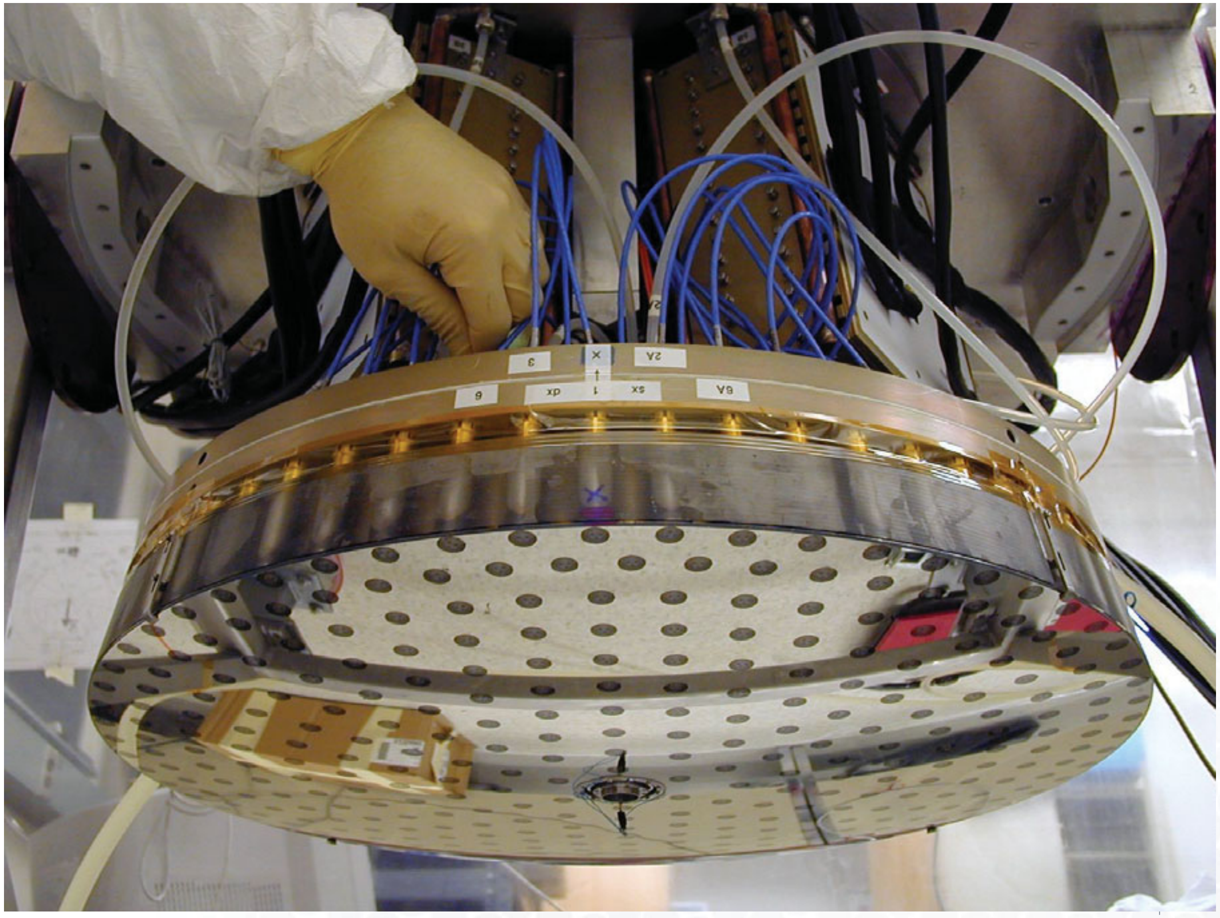
Adaptive Secondary Mirrors

- 2mm thick Zerodur face sheet (mirrored)
- Stable "reference body" surface

- Voice coil actuators push on permanent magnets face sheet and controlled in closed loop.

- Capacitive sensors measure location of face sheet relative to the reference body (~3 nm precision at 37 kHz)

VLT Adaptive Secondary Mirror



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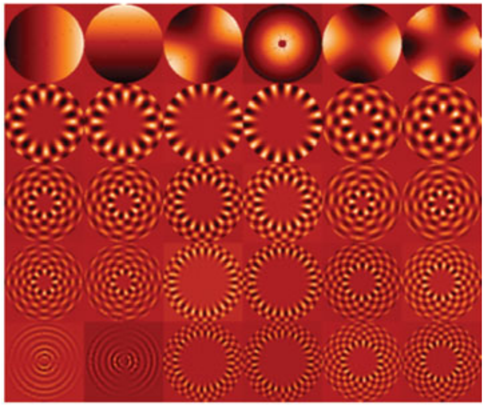
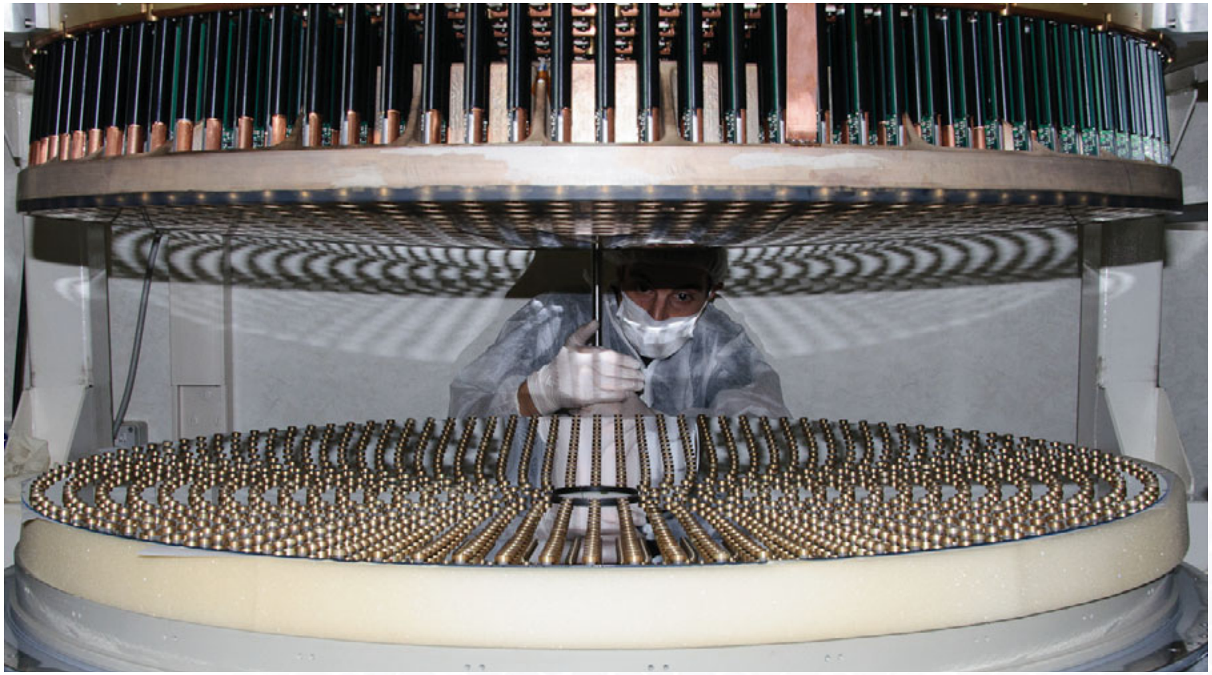
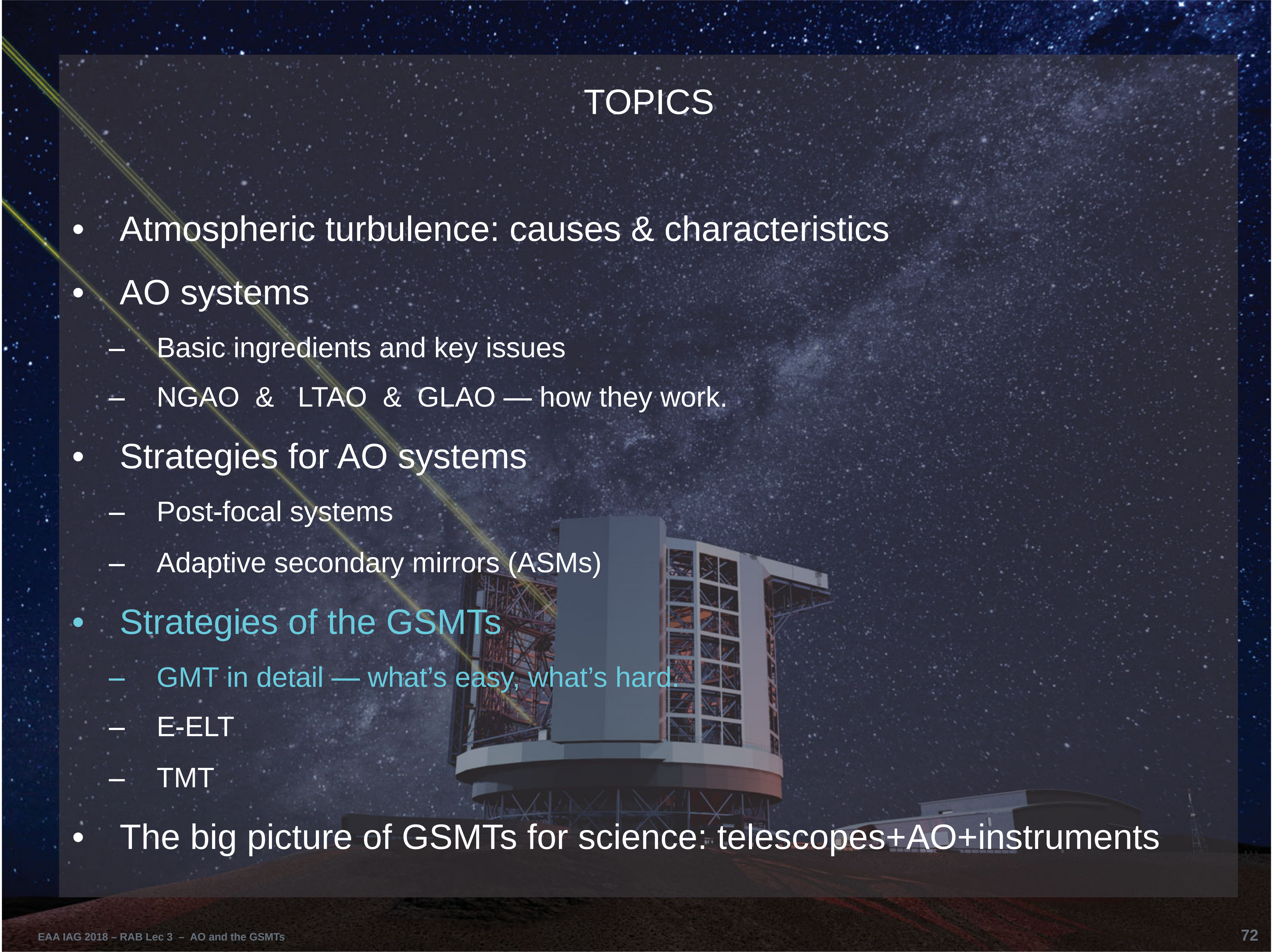


LBT mode shapes

VLT Adaptive Secondary Mirror





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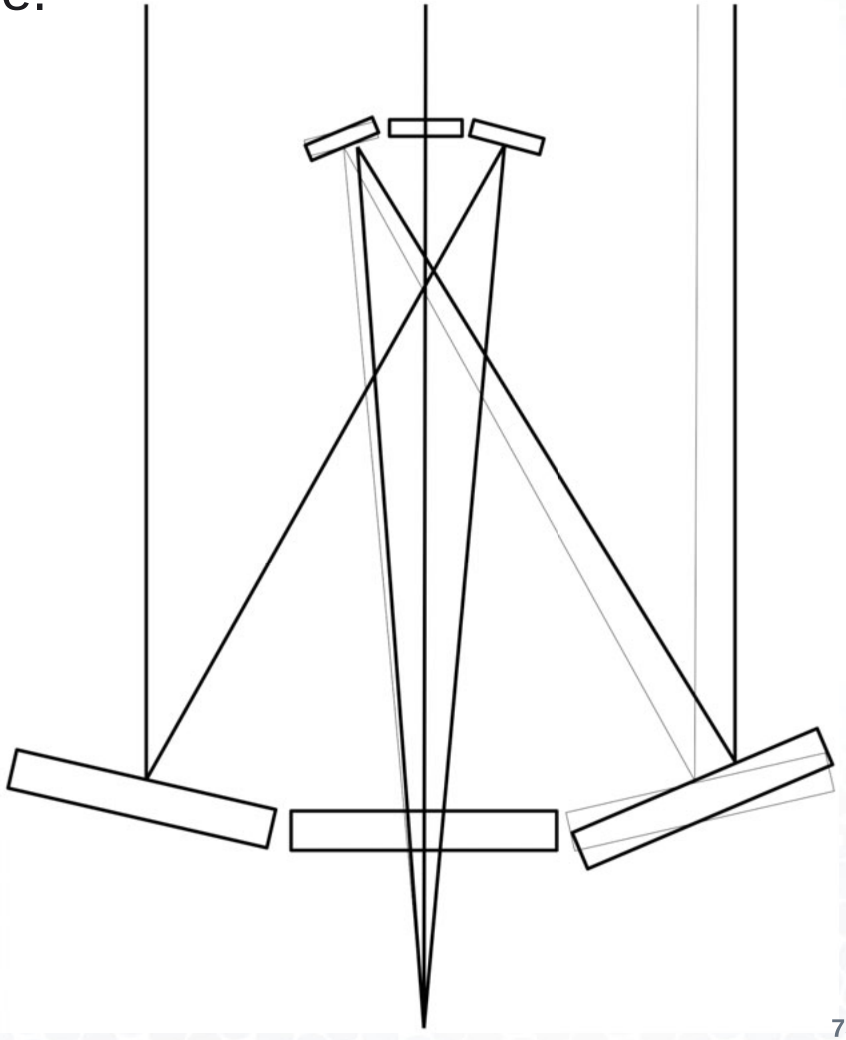
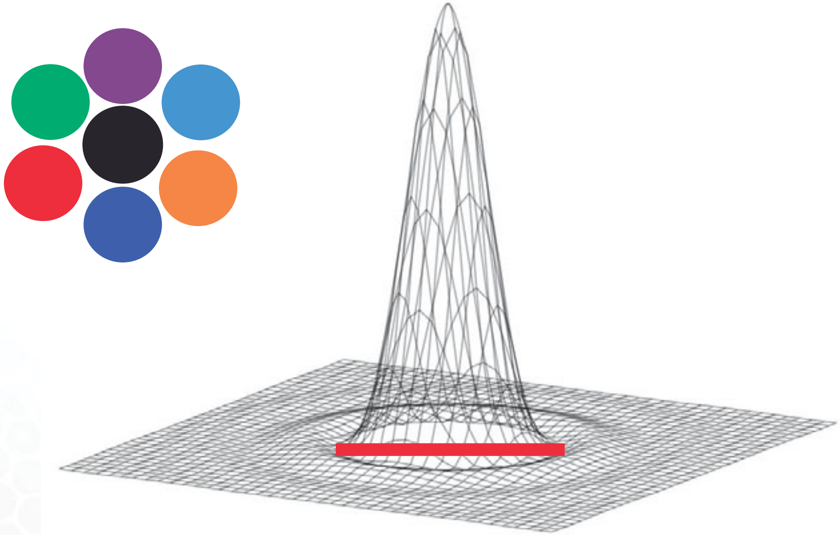
AO on GMT: 7 segments UNPHASED

If you can correct the atmosphere,

you get the diffraction limit of the telescope.



minimum size = 2.44 lambda / (D)

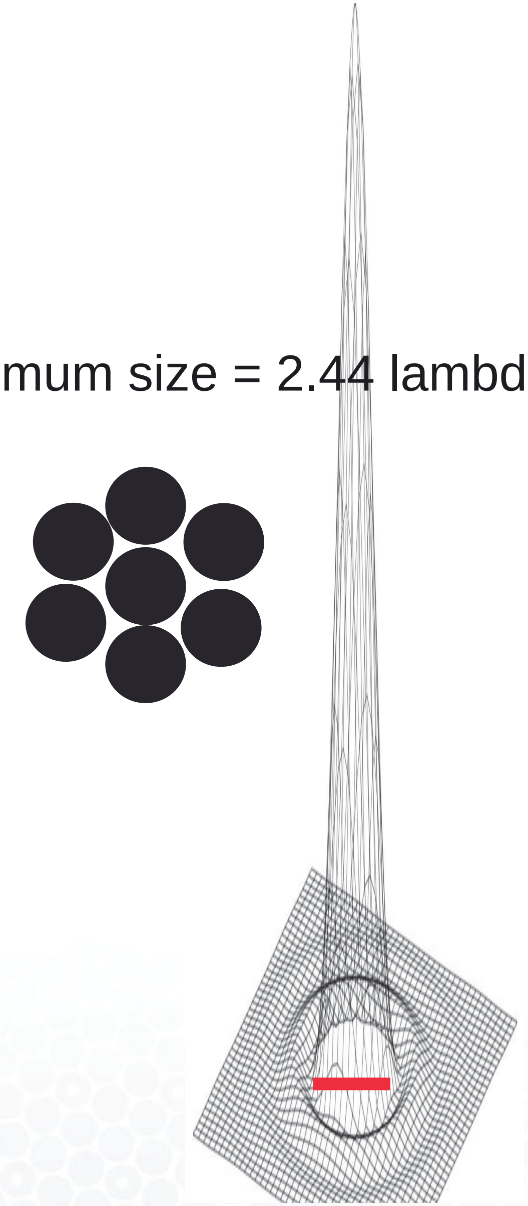


AO on GMT: 7 segments PHASED

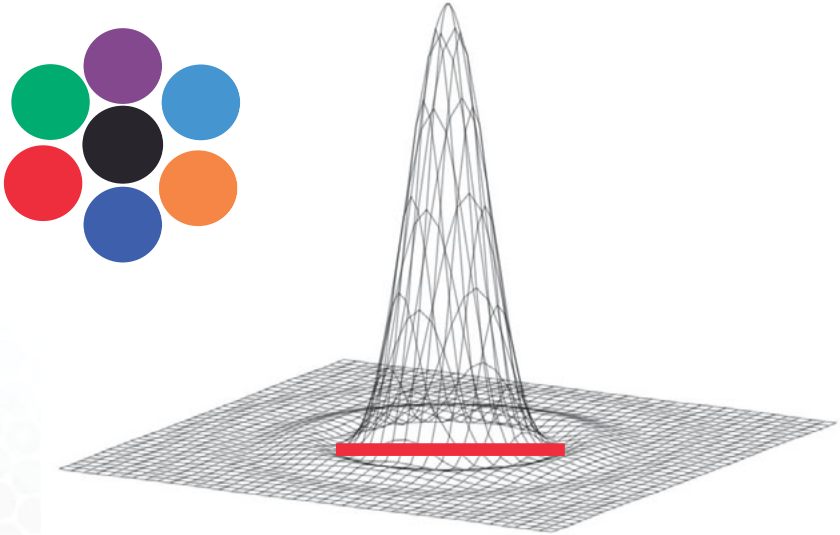
If you can correct the atmosphere,

you get the diffraction limit of the telescope.

minimum size = 2.44 lambda / (3D)



minimum size = 2.44 lambda / (D)



GMT levels of image correction:

- Natural seeing — no correction of the atmosphere
- GLAO (ground layer corrected only) — 30-50% better than natural seeing
- NGAO or LTAO atmosphere corrected over each segment, no phasing —

  This gives the 8.4 m diffraction limit

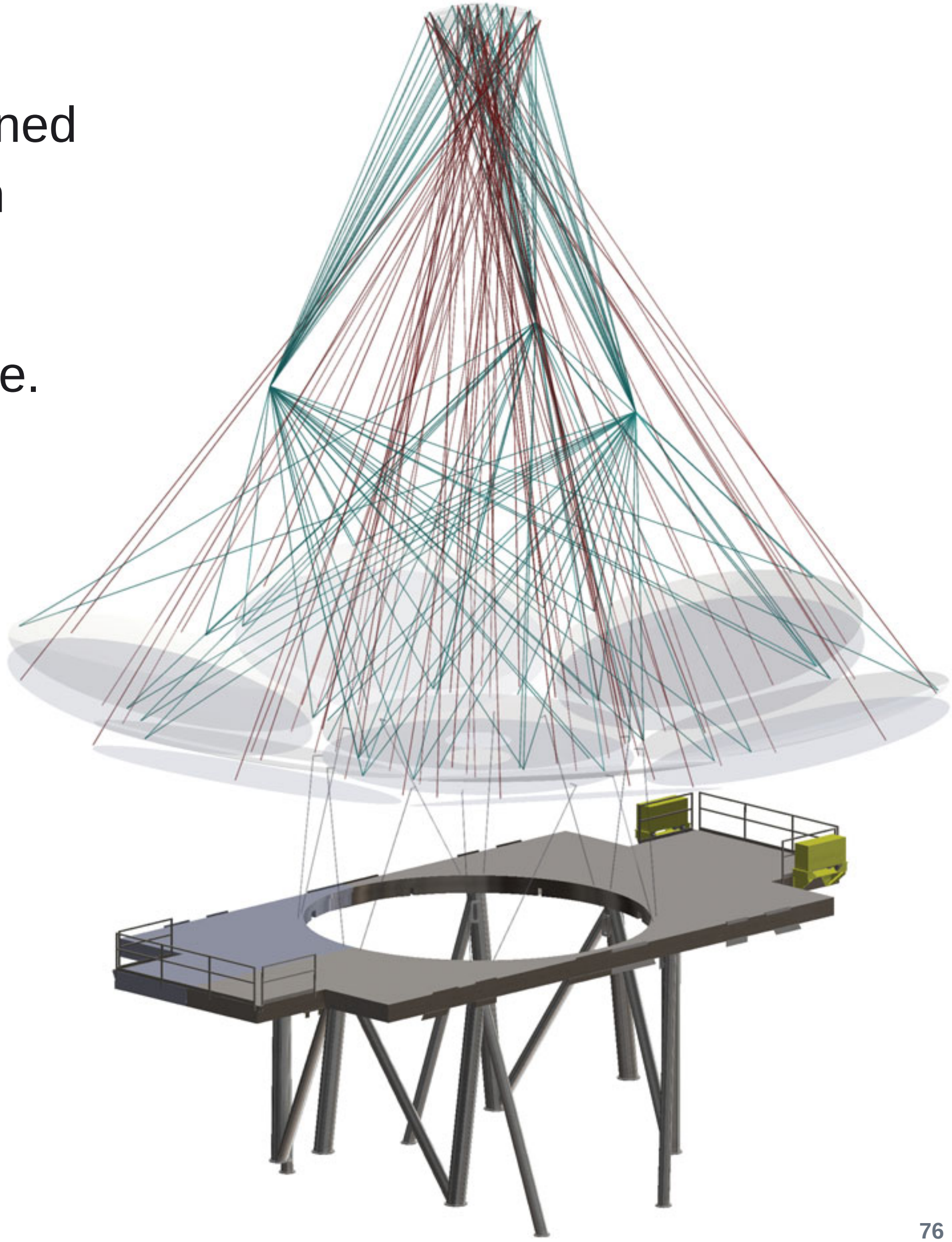
  This is not the goal.
- NGAO or LTAO atmosphere corrected over each segment, phasing —

  This gives the full ~25m diffraction limit.

NGAO on GMT: get rough alignment

- Step 1: Get the telescope roughly aligned using a “metrology truss”” laser system (“Absolute Multiline” by Etalon Inc)
- Rate: once after acquisition of a source.
- Accuracy: ±10 µm (±10,000 nm)

Tested and demonstrated on LBT!

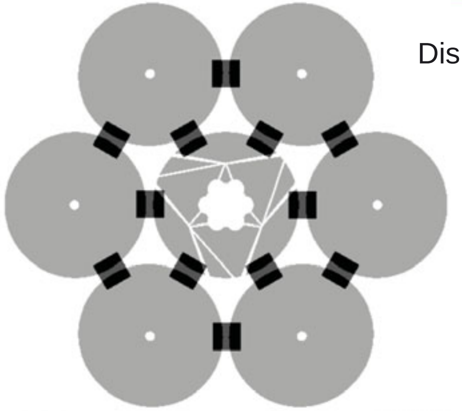


NGAO on GMT: phase telescope fast

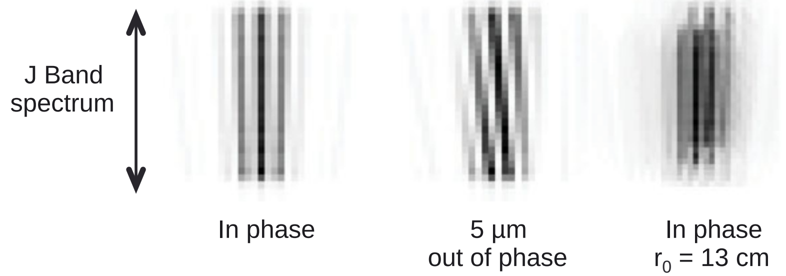
- Step 2: align in piston using “phasing cameras”
- Rate: 30 second frame rate
- Accuracy: <50 nm RMS

dispersed fringe sensors:

- using a double slit sampling a 1.5 m-equivalent square apertures of adjacent segments
- Prism disperses fringes in vertical direction
- Tilt gives piston phase of adjacent segments



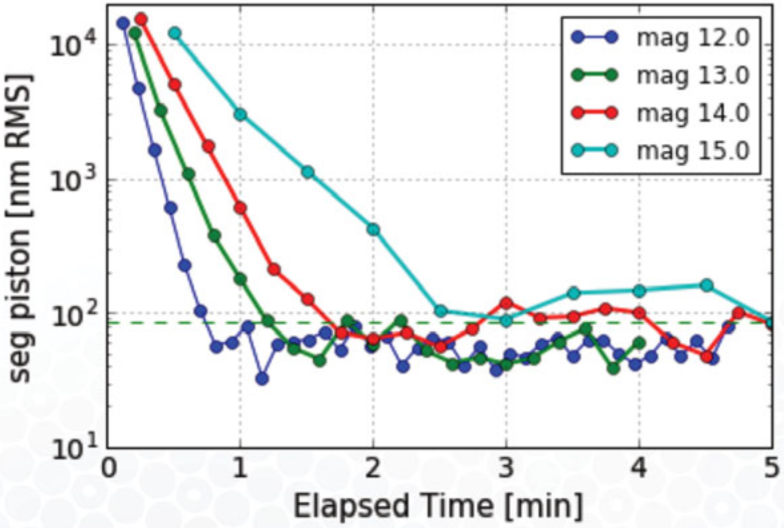
Dispersed Fringe Sensor



In phase

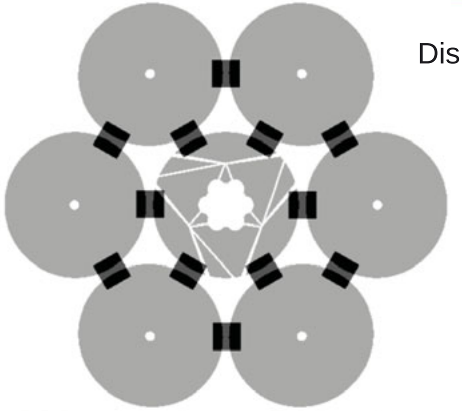
5 µm out of phase

In phase r_0 = 13 cm



NGAO on GMT: phase telescope fast

- Step 2: align in piston using “phasing cameras”
- Rate: 30 second frame rate [faint stars ok!]
- Accuracy: <50 nm RMS



Dispersed Fringe Sensor

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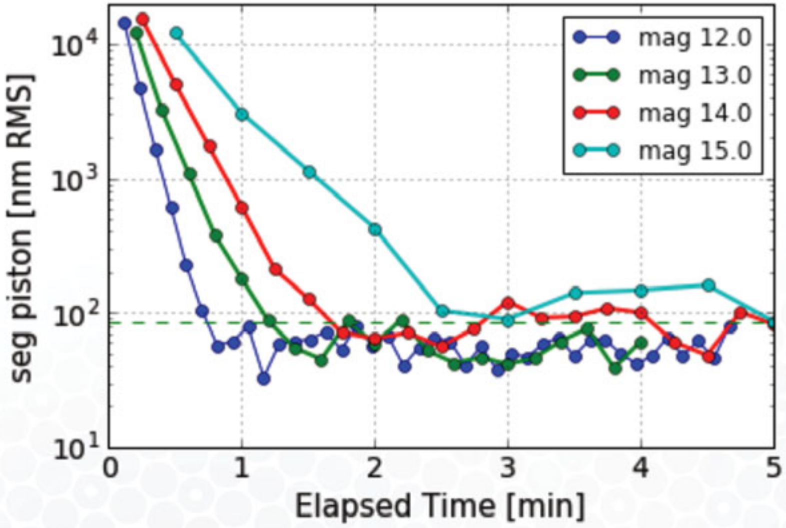
- Prism dis s fringes in vertical direction
- Ti s piston phase of adjacent ments

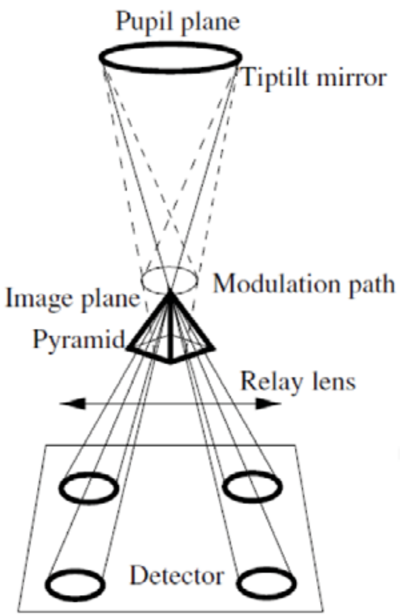
Tested and demonstrated on Magellan



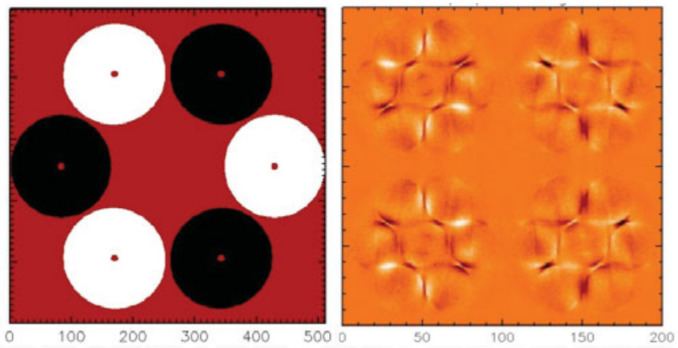
NGAO on GMT: hold phase, correct atmosphere

- Step 3: Pyramid wavefront sensors measure atmospheric turbulence AND segment piston during exposures.
- Accuracy:
  - 30 nm RMS mirror alignment
  - Total wavefront correction with ASMs: ±200 nm
- Rate: 1000’s Hz

Pyramid WFS Schematic



Credit: C. Verinaud, ESO



Input wavefront (± 65 nm)

detector signal (1λ/D mod.)

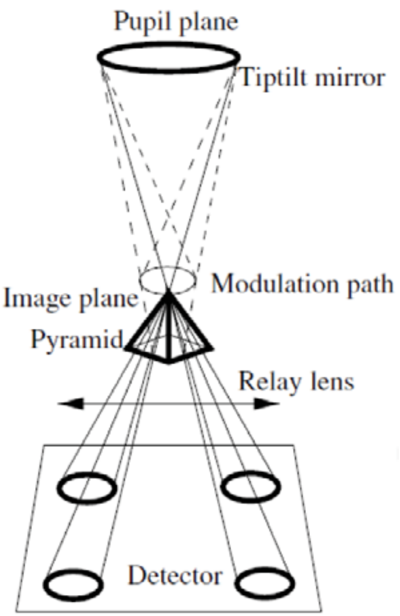
NGAO on GMT: hold phase, correct atmosphere

- Step 3: Pyramid wavefront sensors measure atmospheric turbulence AND segment piston during exposures.
- Accuracy:
  - 30 nm RMS mirror alignment
  - Total wavefront correcti… nm
- Rate: 1000's H…

Existing systems ASM systems use these.

Next steps: develop test to refine the design.

Pyramid WFS Schematic



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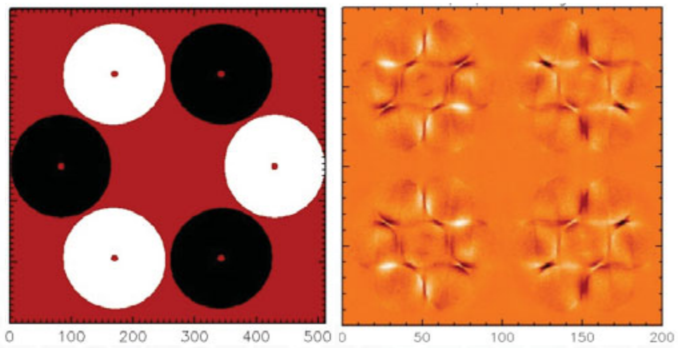
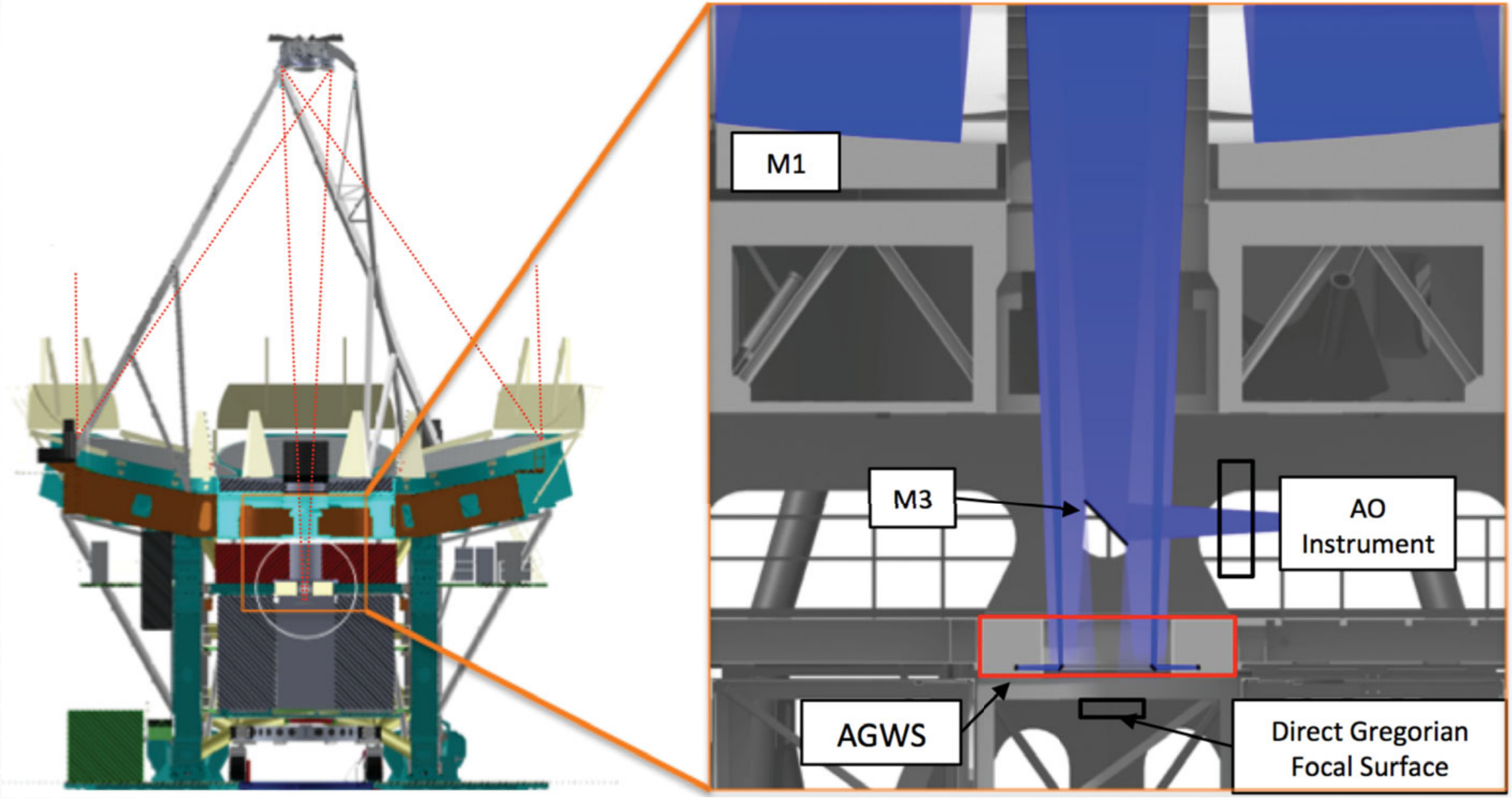


Input wavefront (± 65 nm)

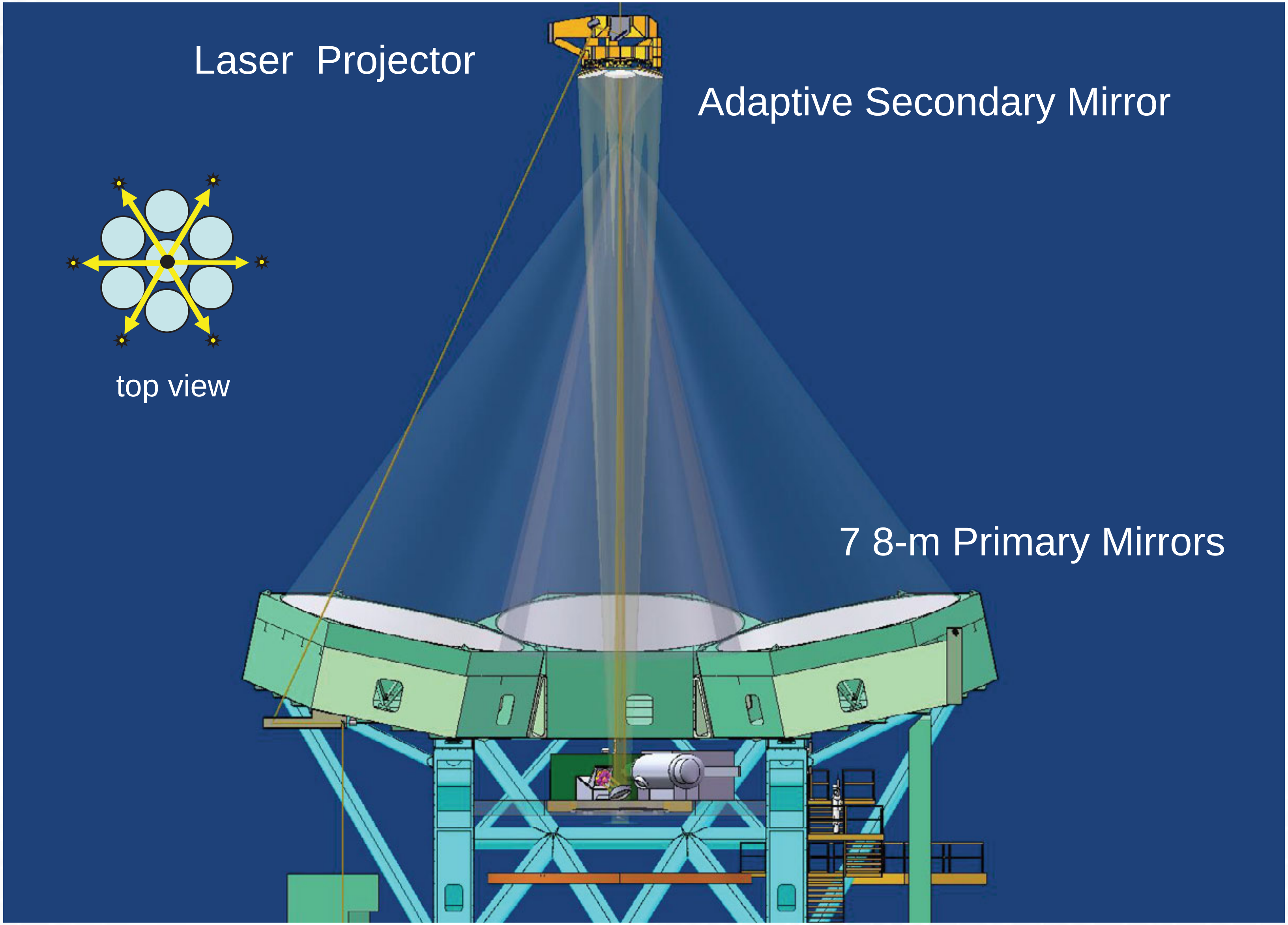
detector signal (1λ/D mod.)

AGWS: Located at Heart of GMT

Acquisition, Guiding, and Wavefront Sensing System



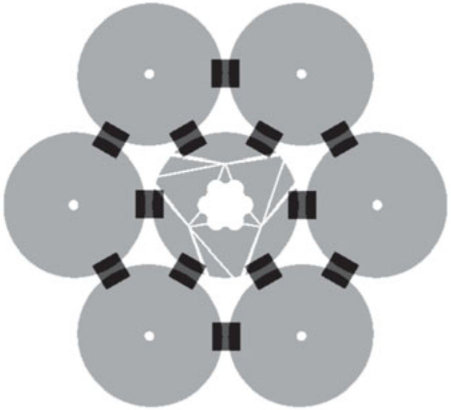
LTAO on GMT:

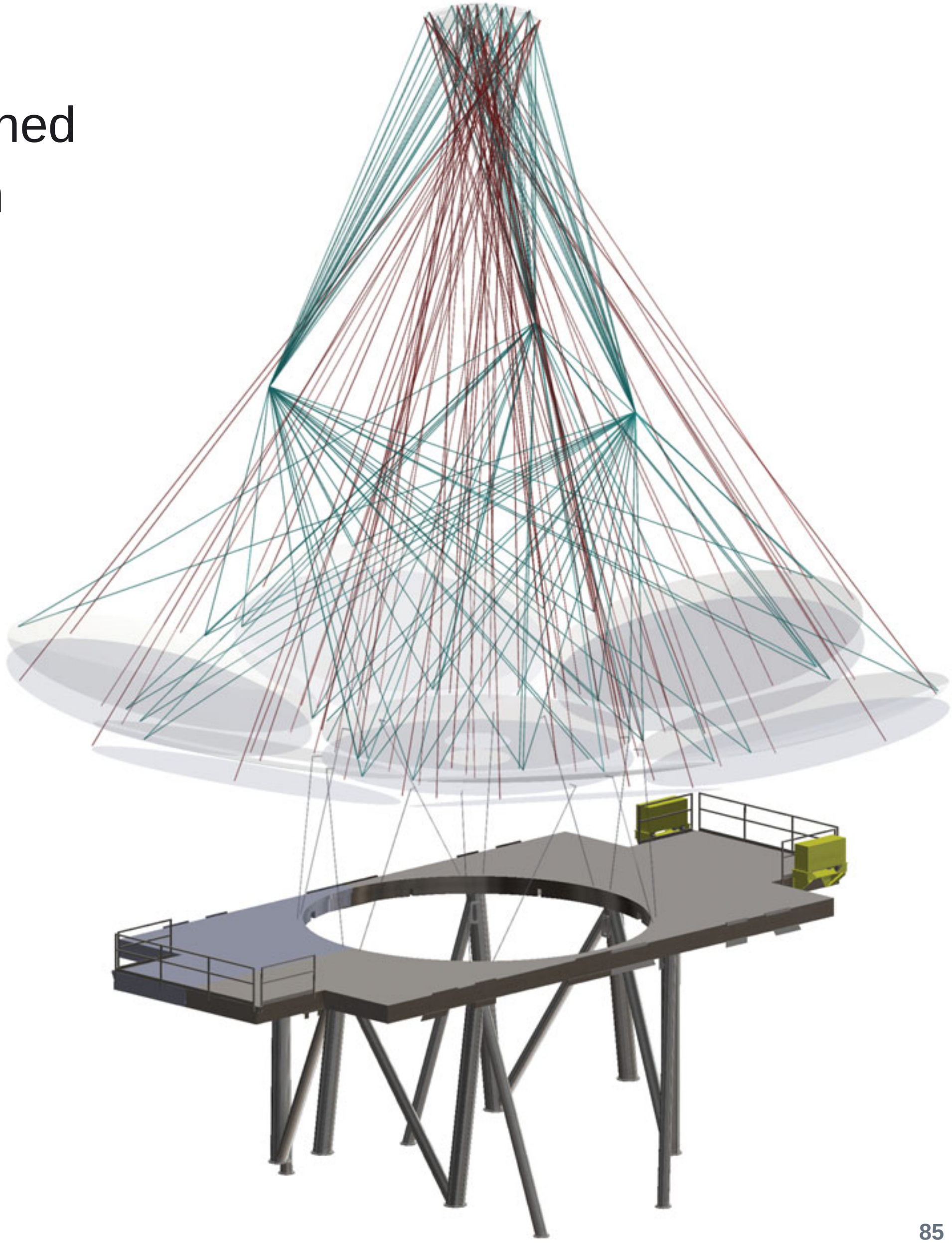

Laser Projector
Adaptive Secondary Mirror
top view
7 8-m Primary Mirrors

LTAO on GMT: phase the telescope

- Step 1: Get the telescope roughly aligned using a “metrology truss”” laser system (“multiline system”)

- Step 2: align in piston using “phasing cameras” [uses faint stars!]

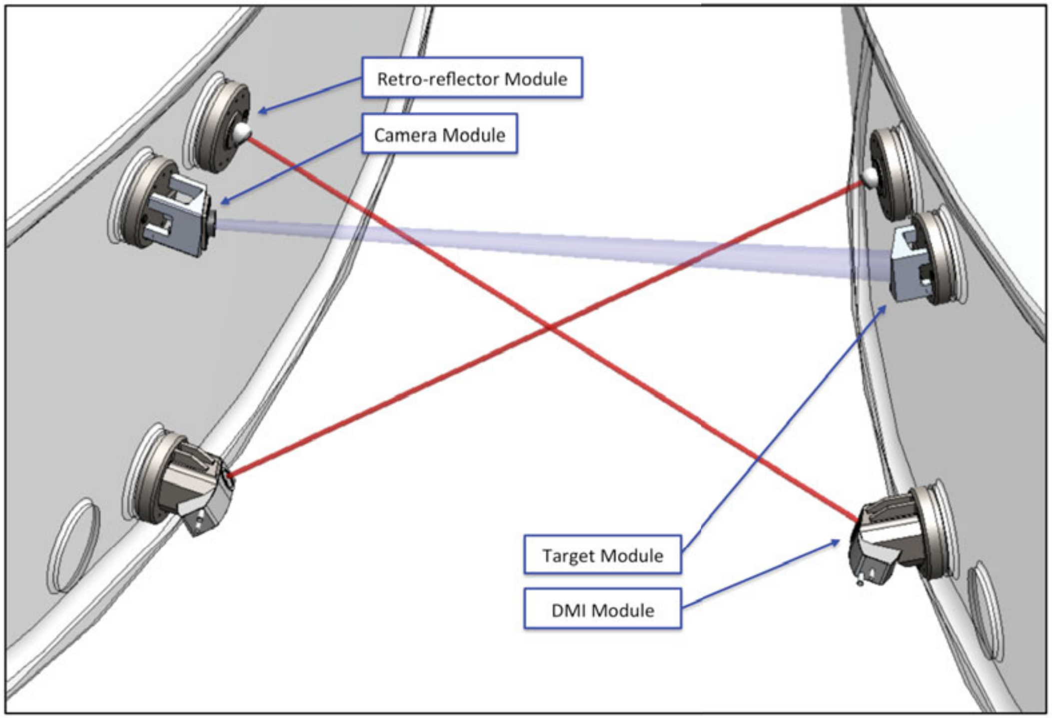




LTAO on GMT:
holding phase, correcting the atmosphere

- M1 and M2 edge sensor MAINTAIN position.
- Use Laser guide stars to measure and correct atmospheric wavefront **over each segment.**
- Rate: 1000’s Hz

M1 Edge Sensor Unit



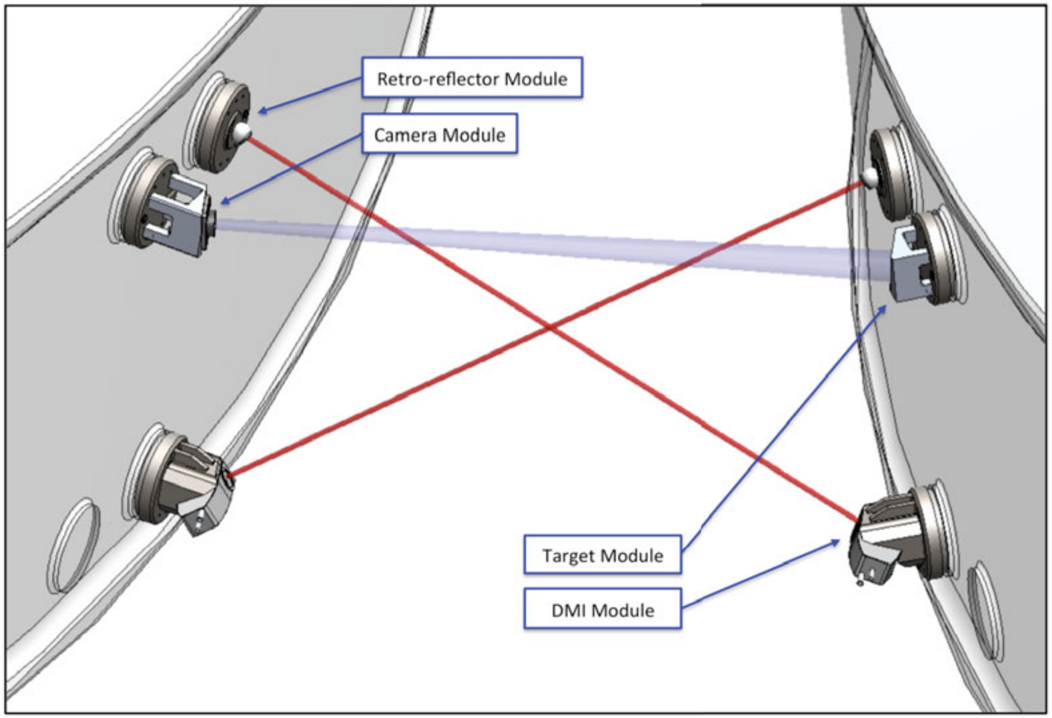
LTAO on GMT:
holding phase, correcting the atmosphere

- M1 and M2 edge sensor MAINTAIN position.
- Use Laser guide stars to measure and correct atmospheric wavefront **over each segment.**
- Rate: 1000’s Hz

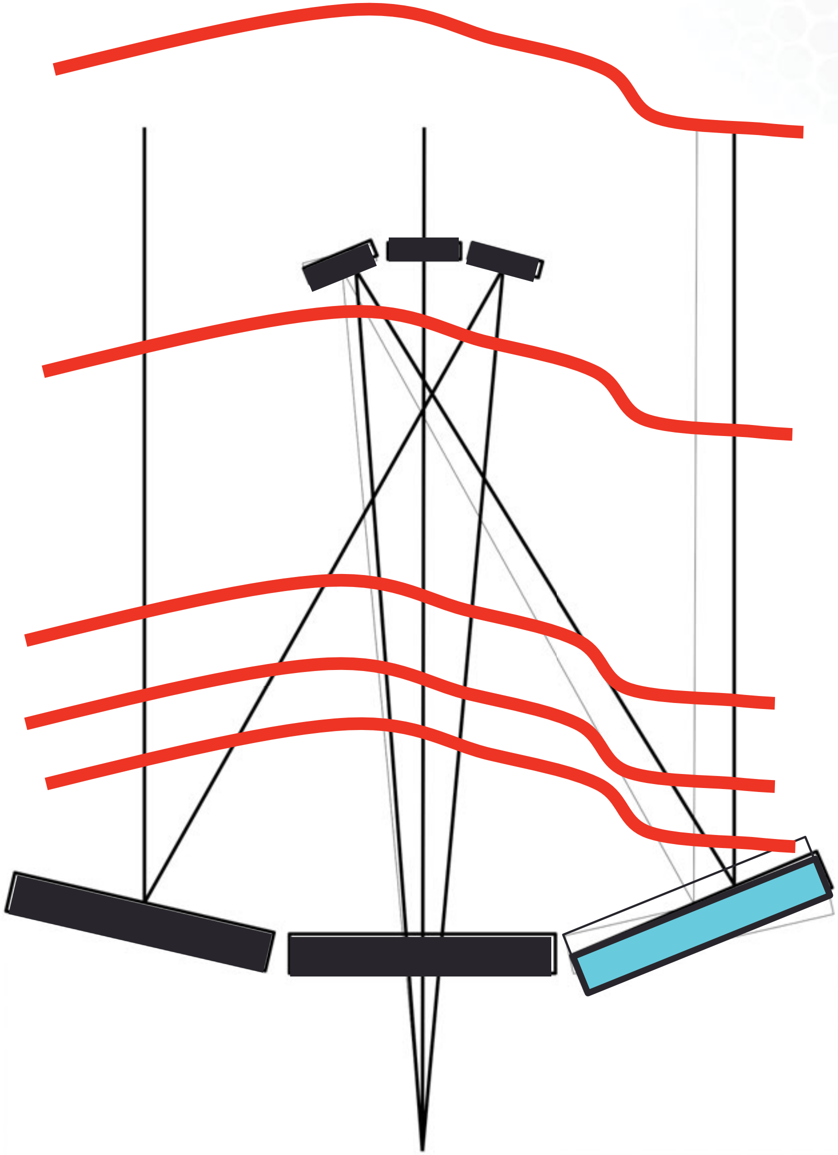
Optical metrology like this
is done all over the planet.

Next steps:
design,
Simulate,
Test,
and refine.

M1 Edge Sensor Unit

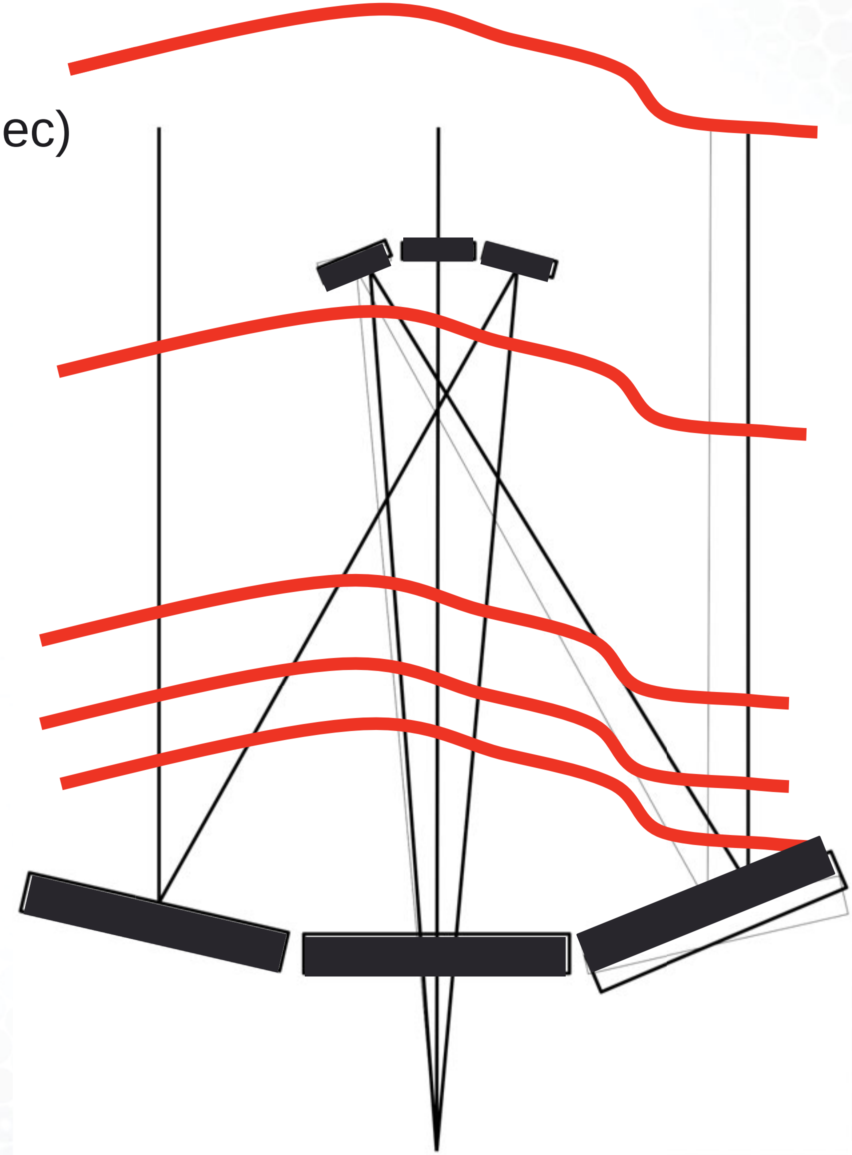


Summary:
Correcting telescope phase AND atmosphere



Summary:
Correcting *telescope phase* AND atmosphere

- Telescope phase error:
  - Average over atmospheric changes (30sec)
  - Measure phase with Pyramid WFS



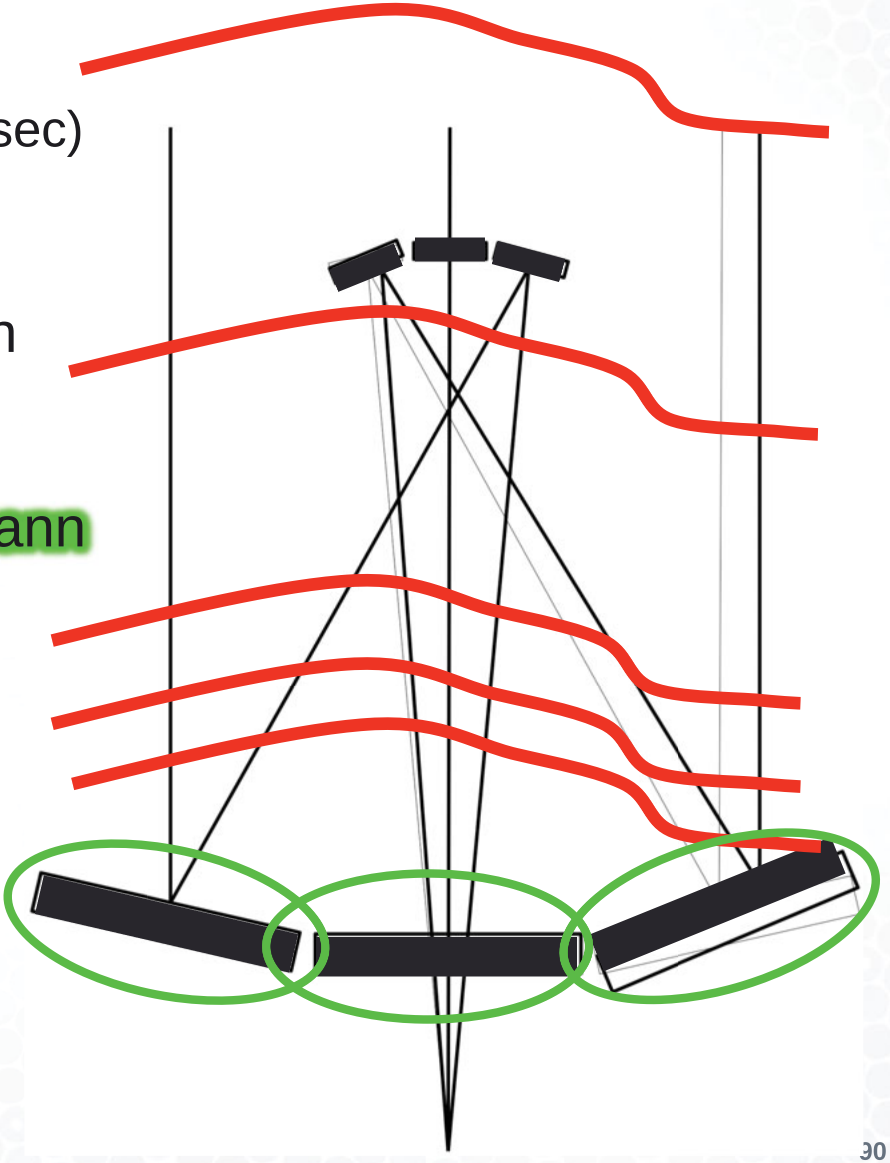
Summary: Correcting *telescope phase* AND atmosphere

- Telescope phase error:
  - Average over atmospheric changes (30sec)
  - Measure phase with Pyramid WFS

- Measure atmospheric shape over each segment with Pyramid (NGAO)

  or

  over segments only with Shack-Hartmann wavefront sensor (LTAO)



Summary:
Correcting *telescope phase* AND atmosphere

- Telescope phase error:
  - Average over atmospheric changes (30sec)
  - Measure phase with Pyramid WFS
- Measure atmospheric shape over each segment AND gaps with Pyramid (NGAO)
  or
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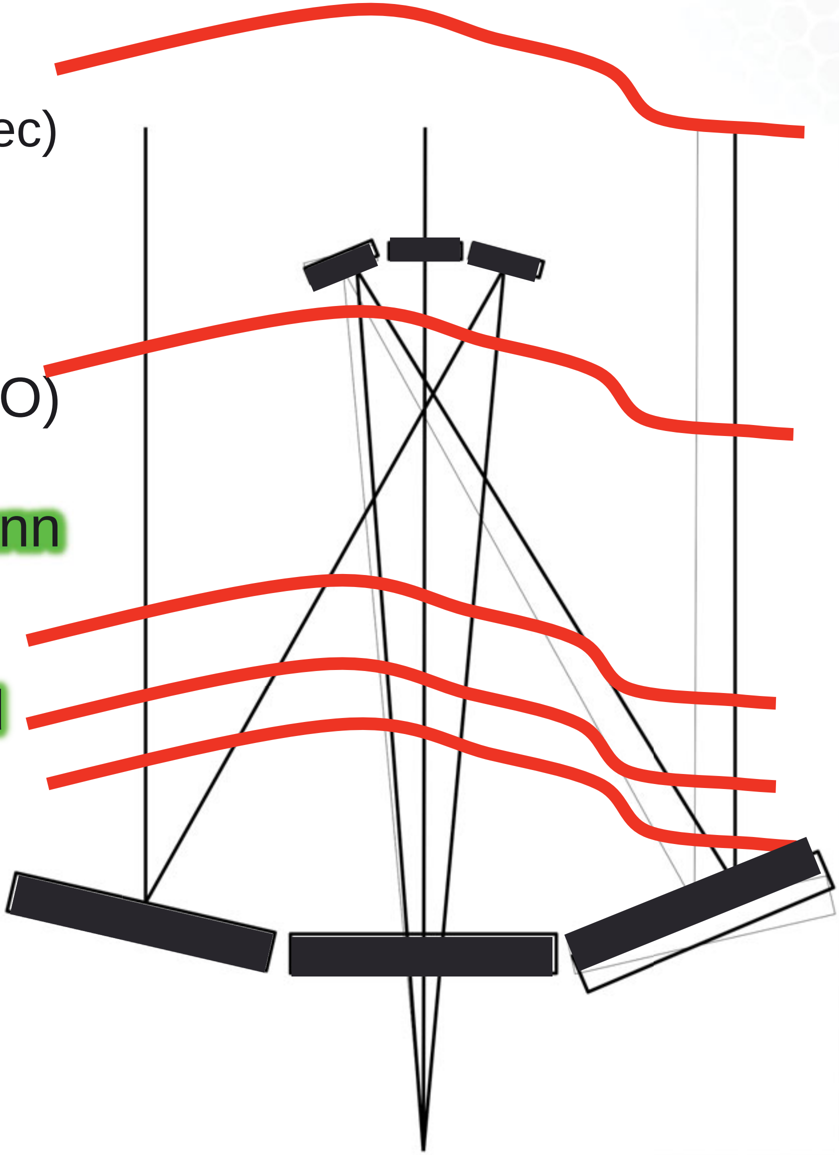
- Hold phase during observation Pyramid (NGAO) or Edge sensors (LTAO)



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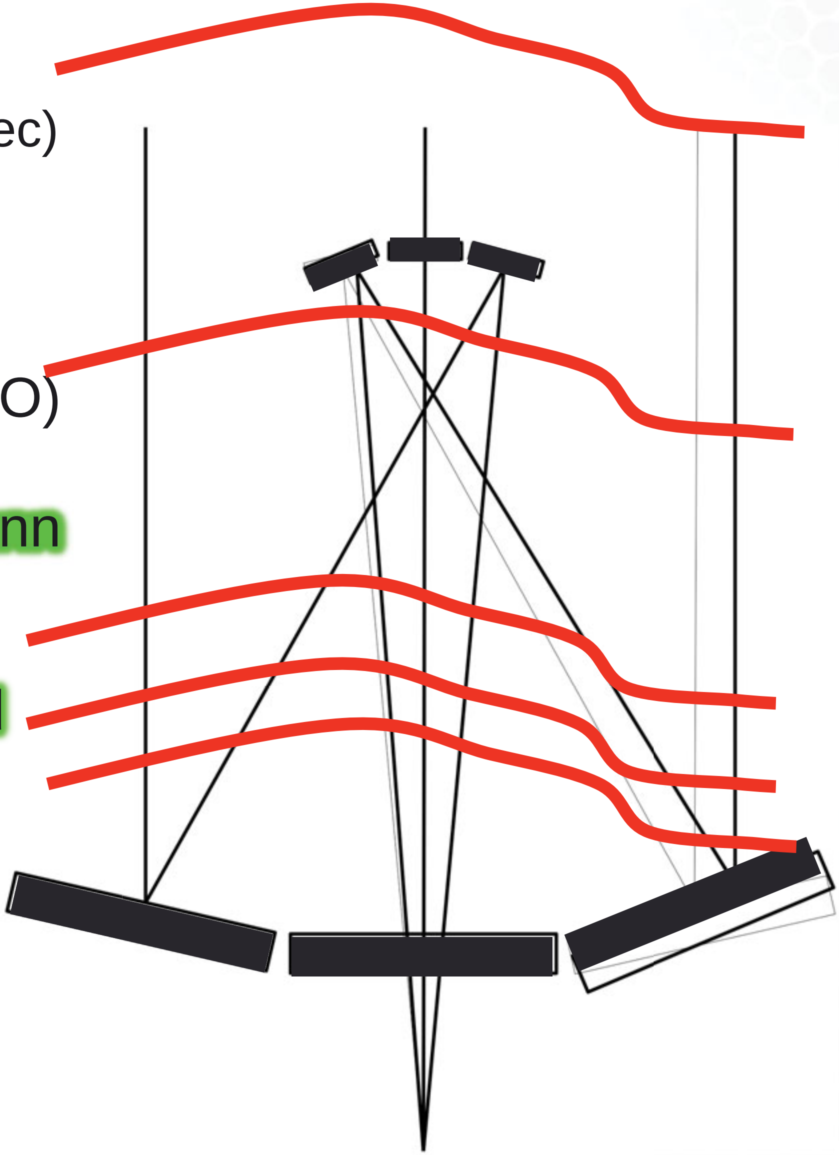
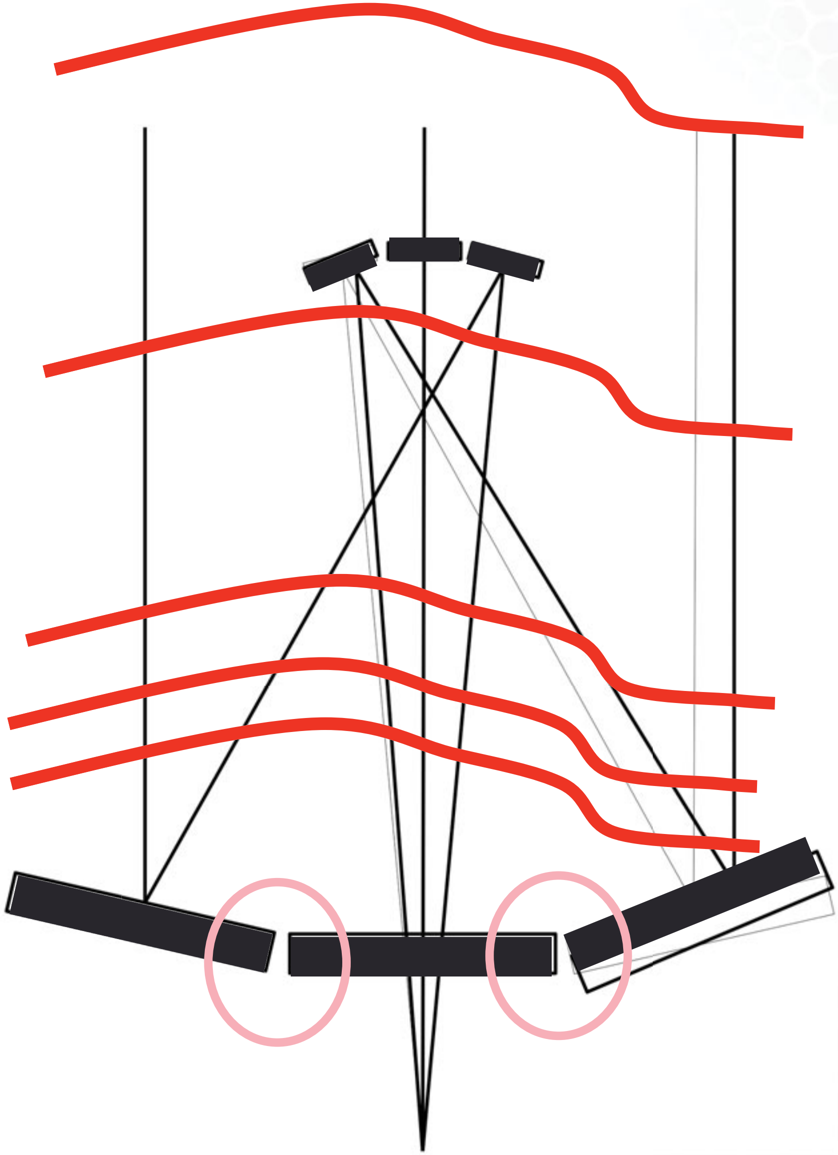


Summary: Correcting *telescope phase* AND atmosphere

- Measure atmospheric wavefront shape over the gaps (**LTAO**)
  - Problem: lasers can't be used with the pyramid WFS, so there isn't a good measurement across the gap.
  - Solution: interpolate
  - Uncertainty: ~125 nm **bad** weather
  - Good enough?
    - In good weather: YES
    - In bad weather: boarderline.
  - Impact: **diffraction limit 0.07"** vs 0.02:



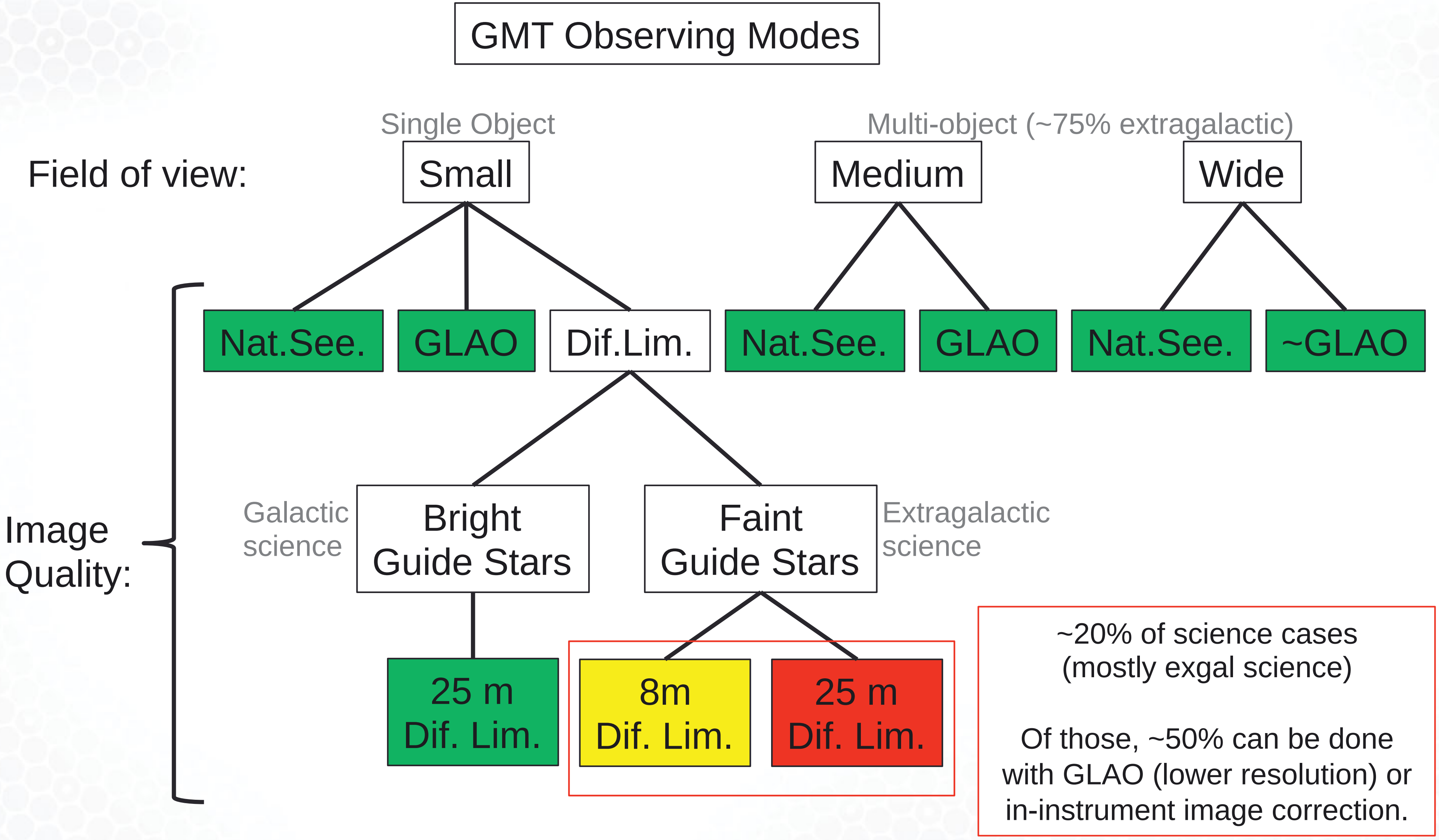
E-ELT has exactly the same problem

Summary:
GMT AO strategies: demonstrated vs being developed

- **Atmosphere limits image quality:** no phasing needed
  - Natural Seeing — active optics only: ASMs or FSMs
  - GLAO — adaptive optics (ASMs), ground layer corrected over each segment

- **Diffraction limits image quality:** phasing needed
  - NGAO — adaptive optics (ASMs),
    phasing (pyramid WFS),
    full atmosphere corrected over segments
    AND gaps (pyramid WFS),
  - LTAO— adaptive optics (ASMs), lasers,
    holding phase (edge sensors),
    full atmosphere corrected over segments (Shack-Hartman WFS)
    AND gaps (interpolate!)

GMT observing modes: Science Cases



GMT Observing Modes

Field of view:

Single Object

Small

Multi-object (~75% extragalactic)

Medium

Wide

Image Quality:

Nat.See.

GLAO

Dif.Lim.

Nat.See.

GLAO

Nat.See.

~GLAO

Galactic science

Bright Guide Stars

Faint Guide Stars

Extragalactic science

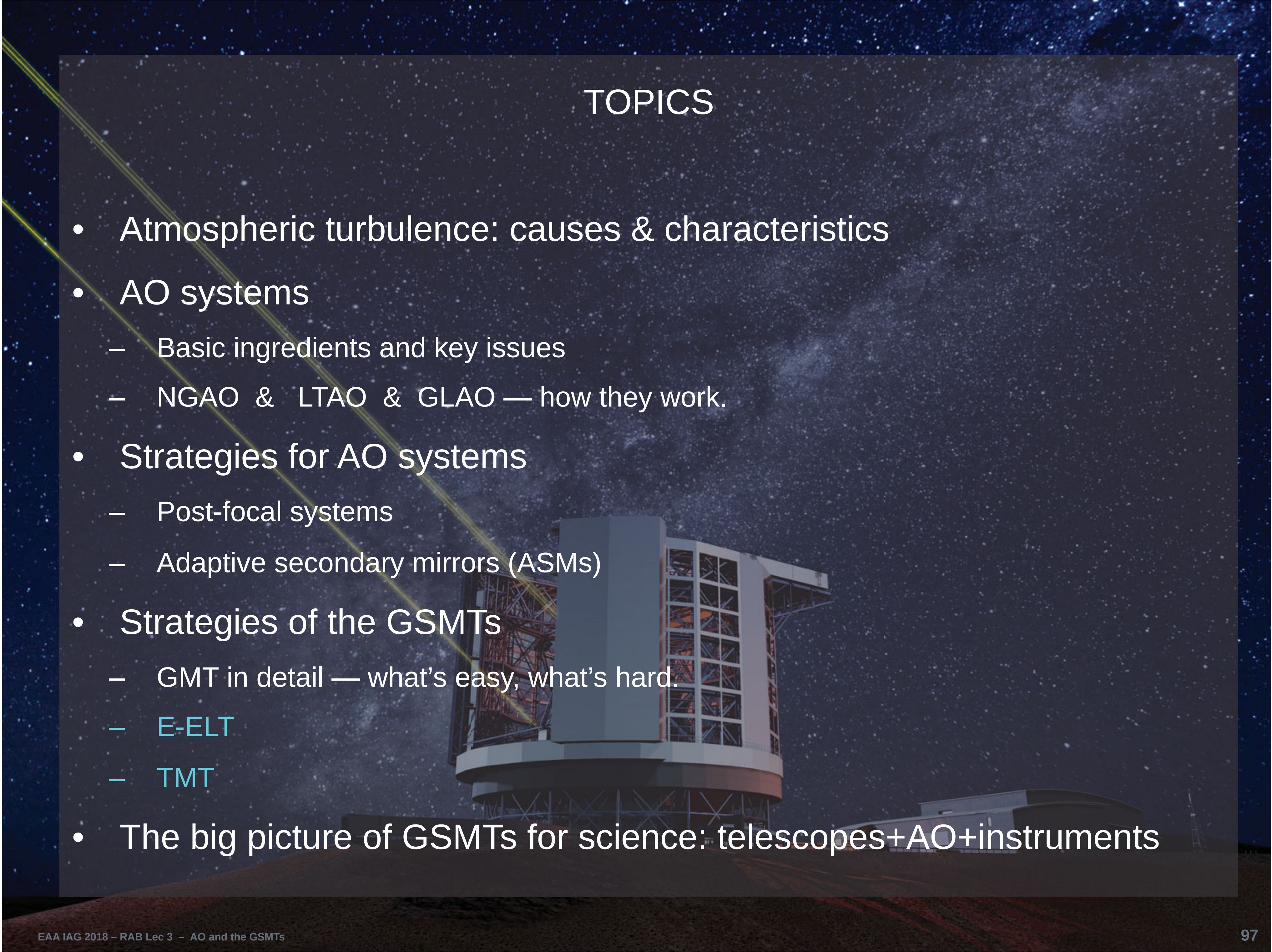
25 m Dif. Lim.

8m Dif. Lim.

25 m Dif. Lim.

~20% of science cases (mostly exgal science)

Of those, ~50% can be done with GLAO (lower resolution) or in-instrument image correction.



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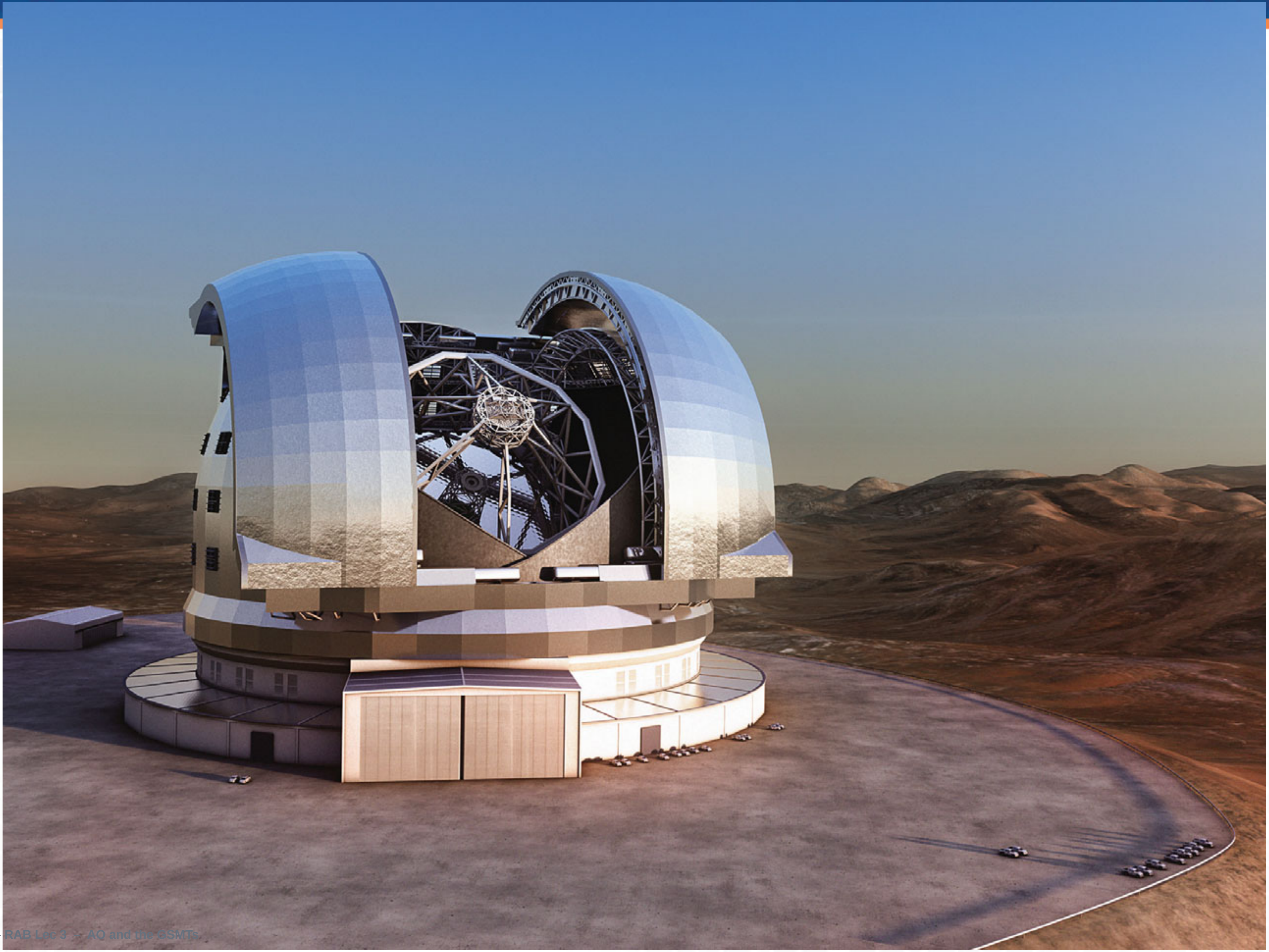
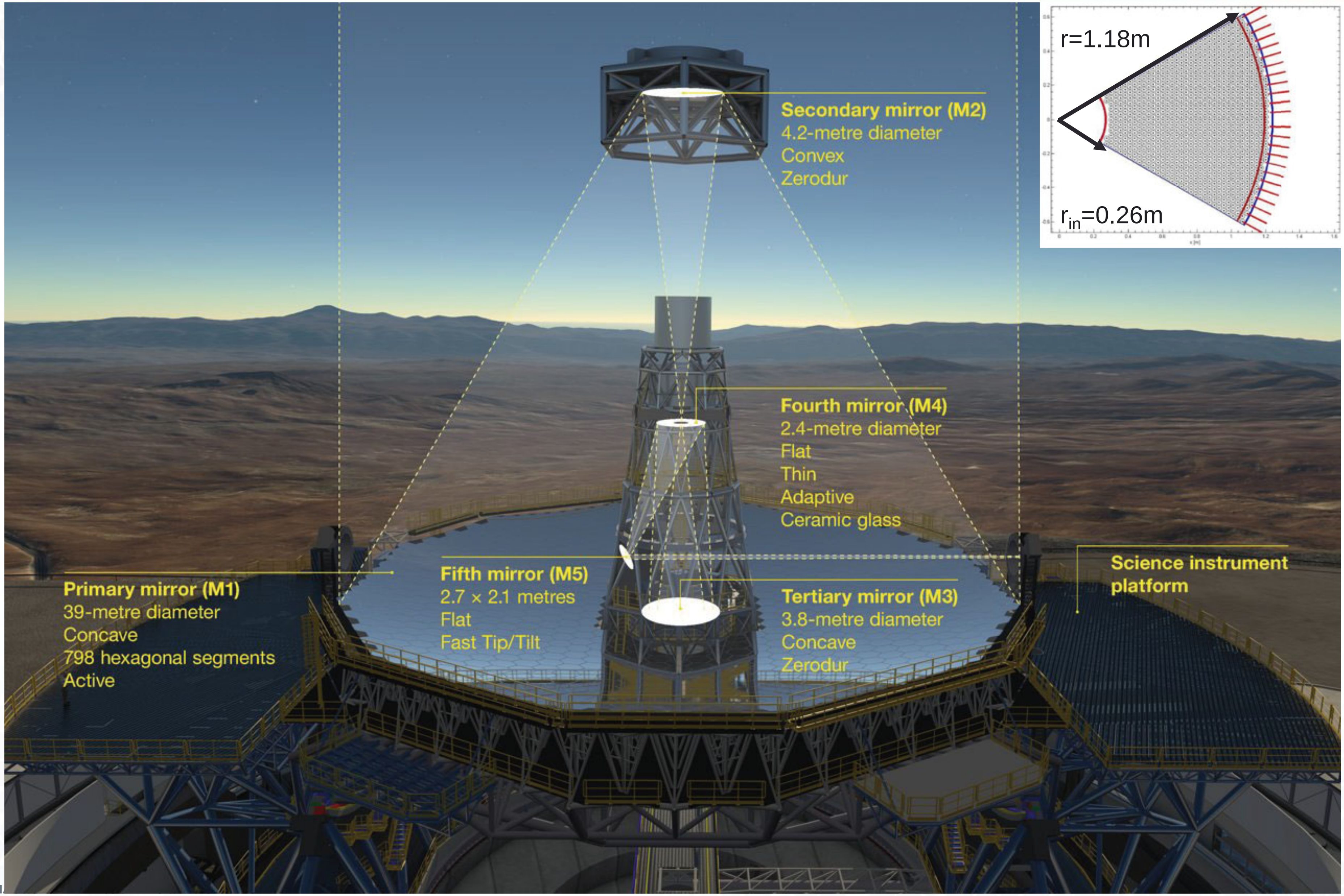
E-ELT:



E-ELT: deformable flat at M4, tip-tilt at M5



Secondary mirror (M2)
4.2-metre diameter
Convex
Zerodur

Fourth mirror (M4)
2.4-metre diameter
Flat
Thin
Adaptive
Ceramic glass

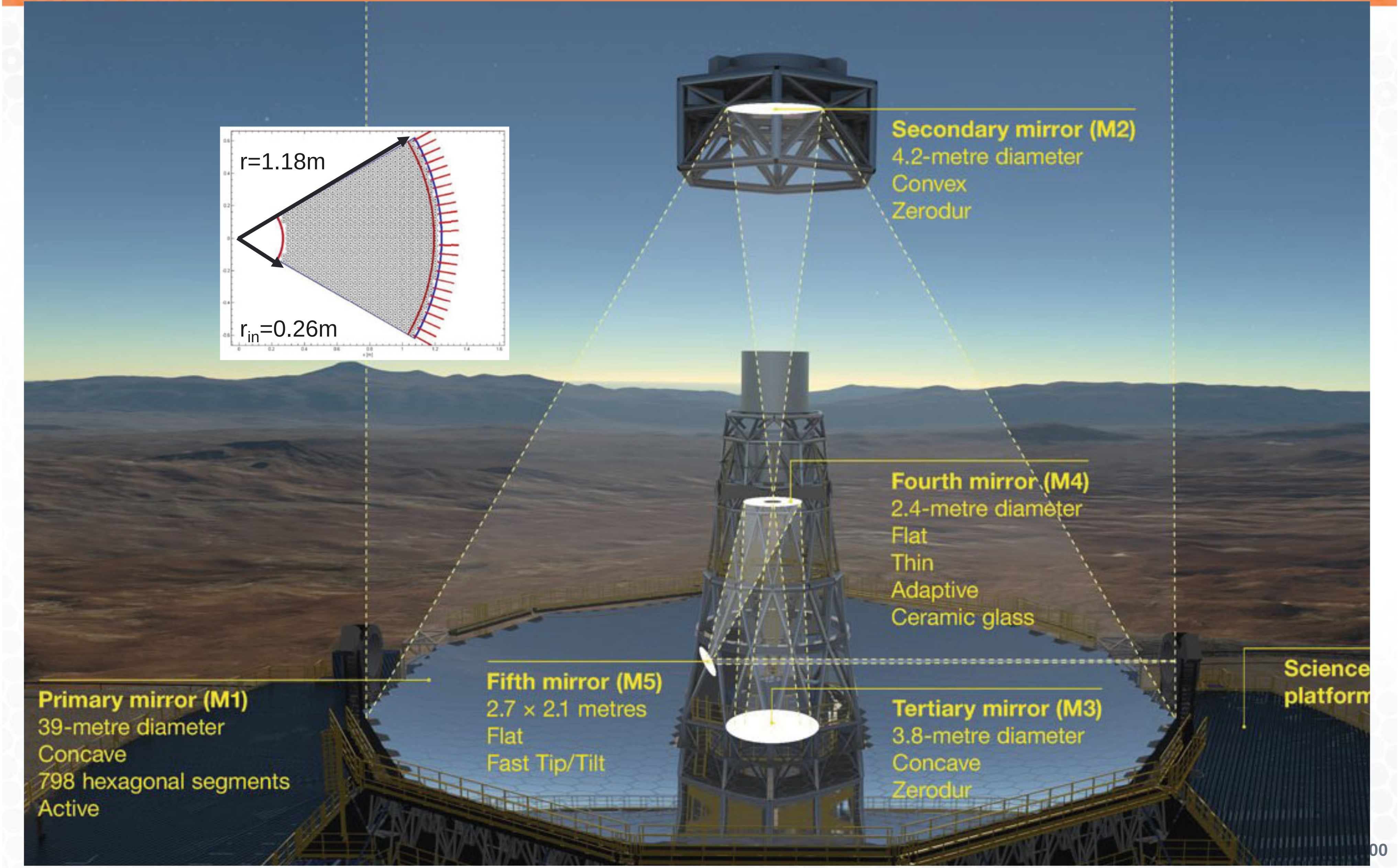
Science instrument platform

Primary mirror (M1)
39-metre diameter
Concave
798 hexagonal segments
Active

Fifth mirror (M5)
2.7 × 2.1 metres
Flat
Fast Tip/Tilt

Tertiary mirror (M3)
3.8-metre diameter
Concave
Zerodur

E-ELT: deformable flat at M4, tip-tilt at M5



Secondary mirror (M2)
4.2-metre diameter
Convex
Zerodur

Fourth mirror (M4)
2.4-metre diameter
Flat
Thin
Adaptive
Ceramic glass

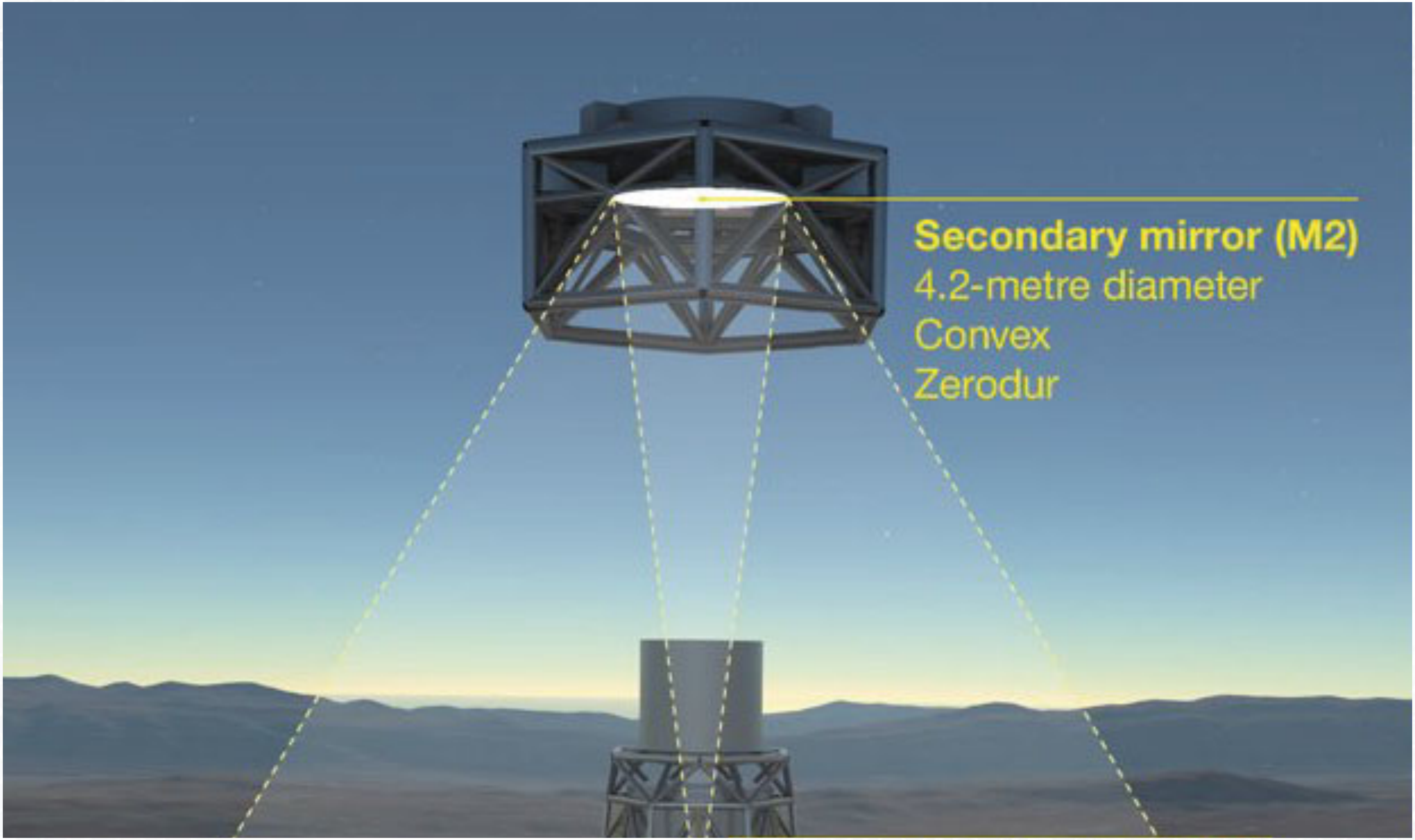
Fifth mirror (M5)
2.7 × 2.1 metres
Flat
Fast Tip/Tilt

Tertiary mirror (M3)
3.8-metre diameter
Concave
Zerodur

Primary mirror (M1)
39-metre diameter
Concave
798 hexagonal segments
Active

Science platform

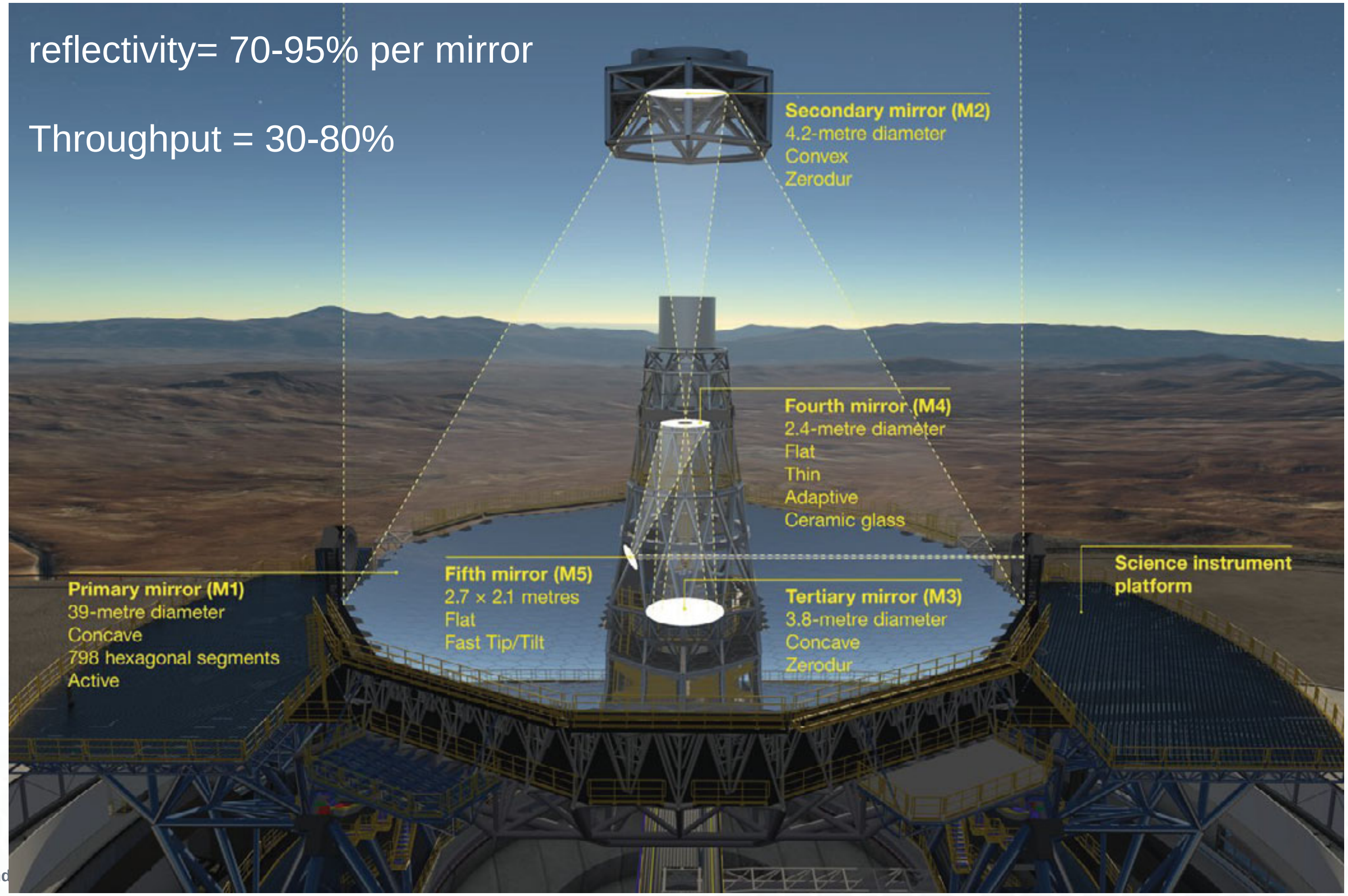
E-ELT:



New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Collecting power: primary mirror area (~D^2)

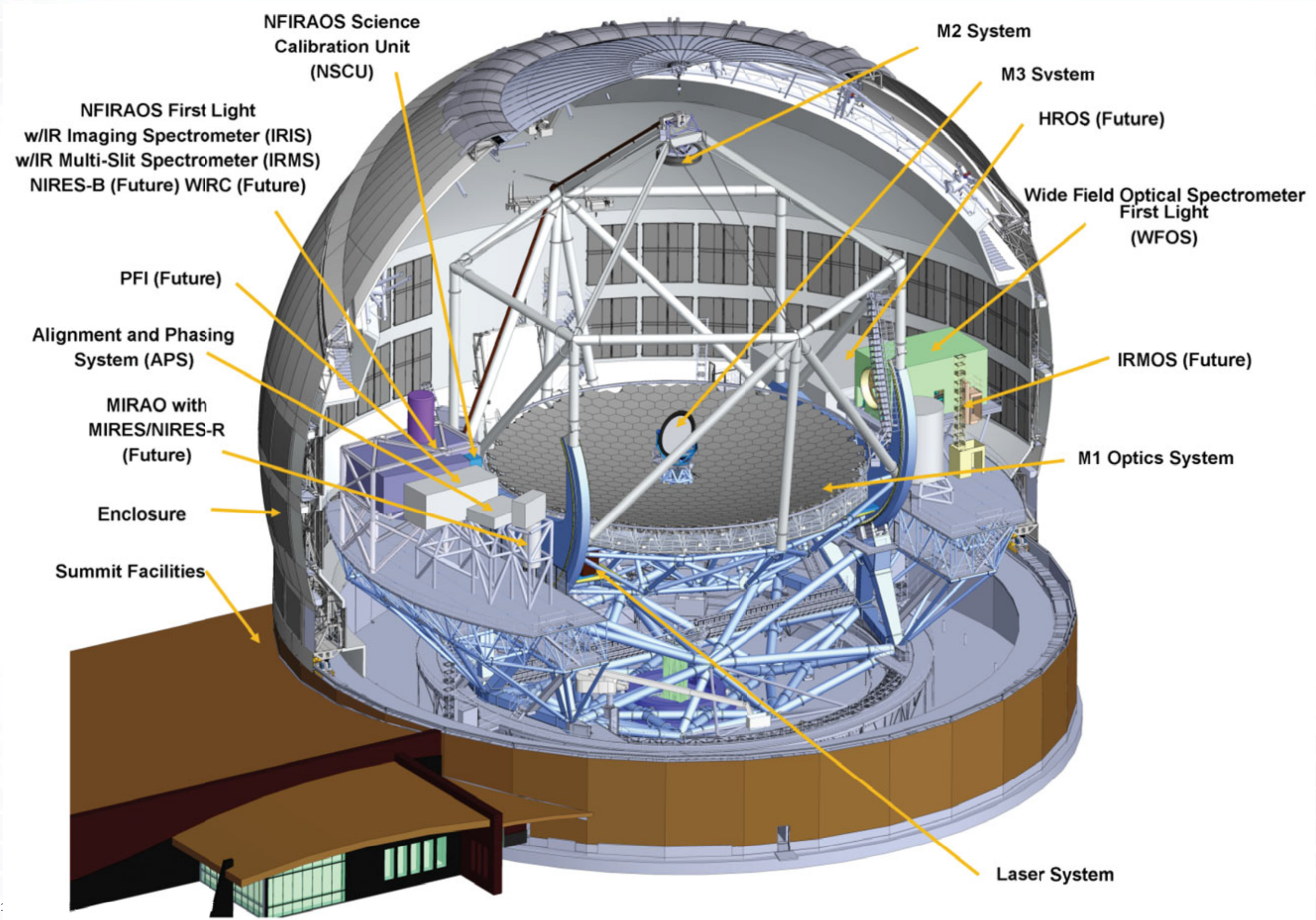
  …but throughput goes *down* with the number of mirrors



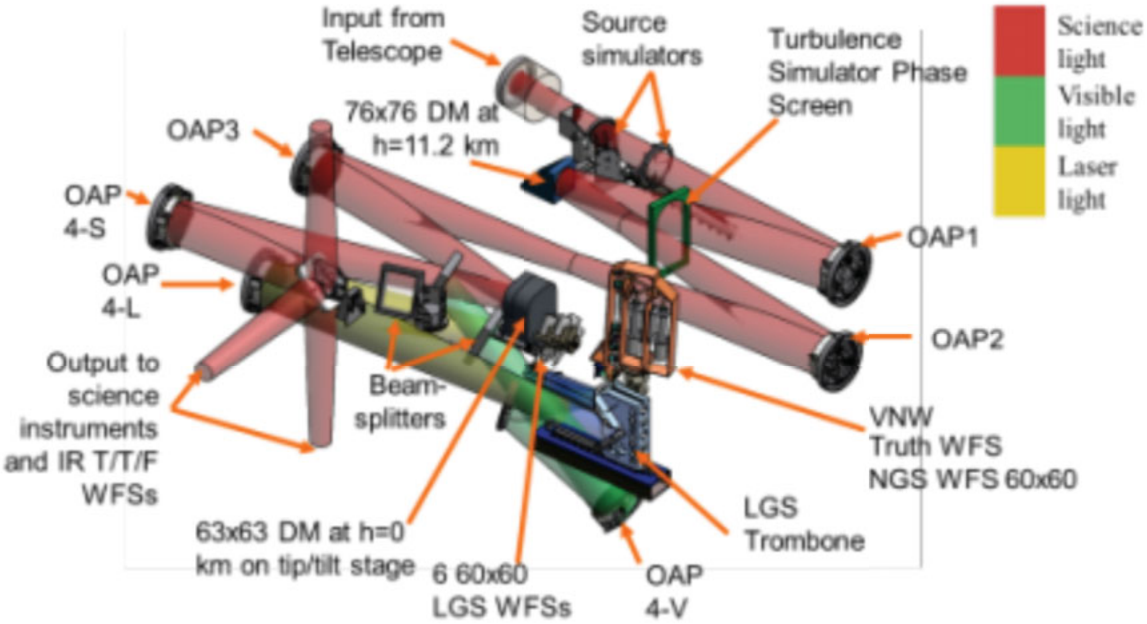
reflectivity= 70-95% per mirror

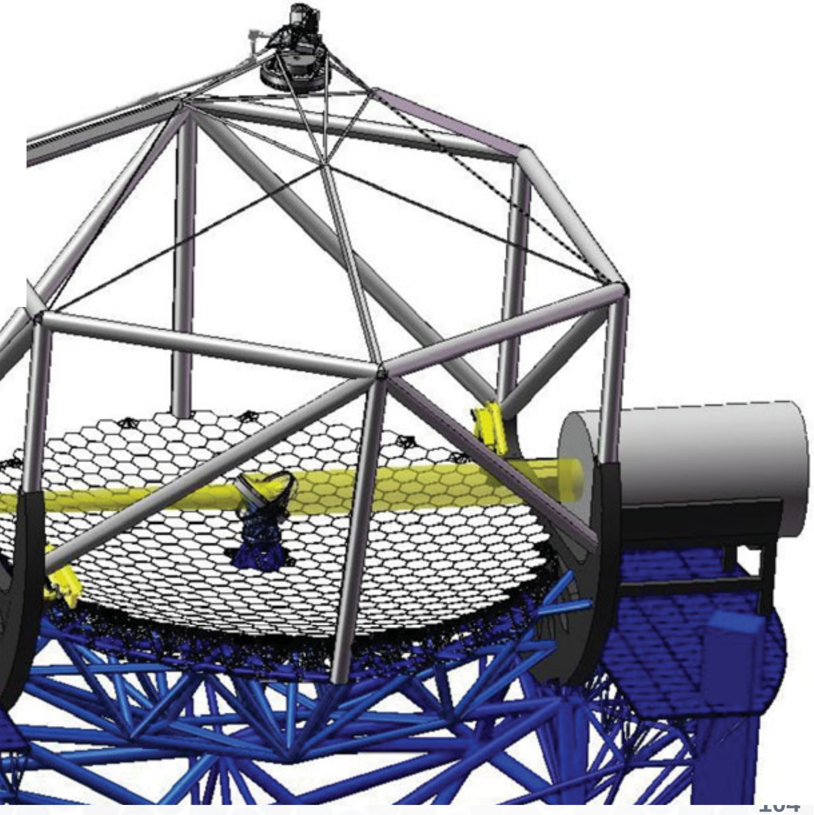
Throughput = 30-80%

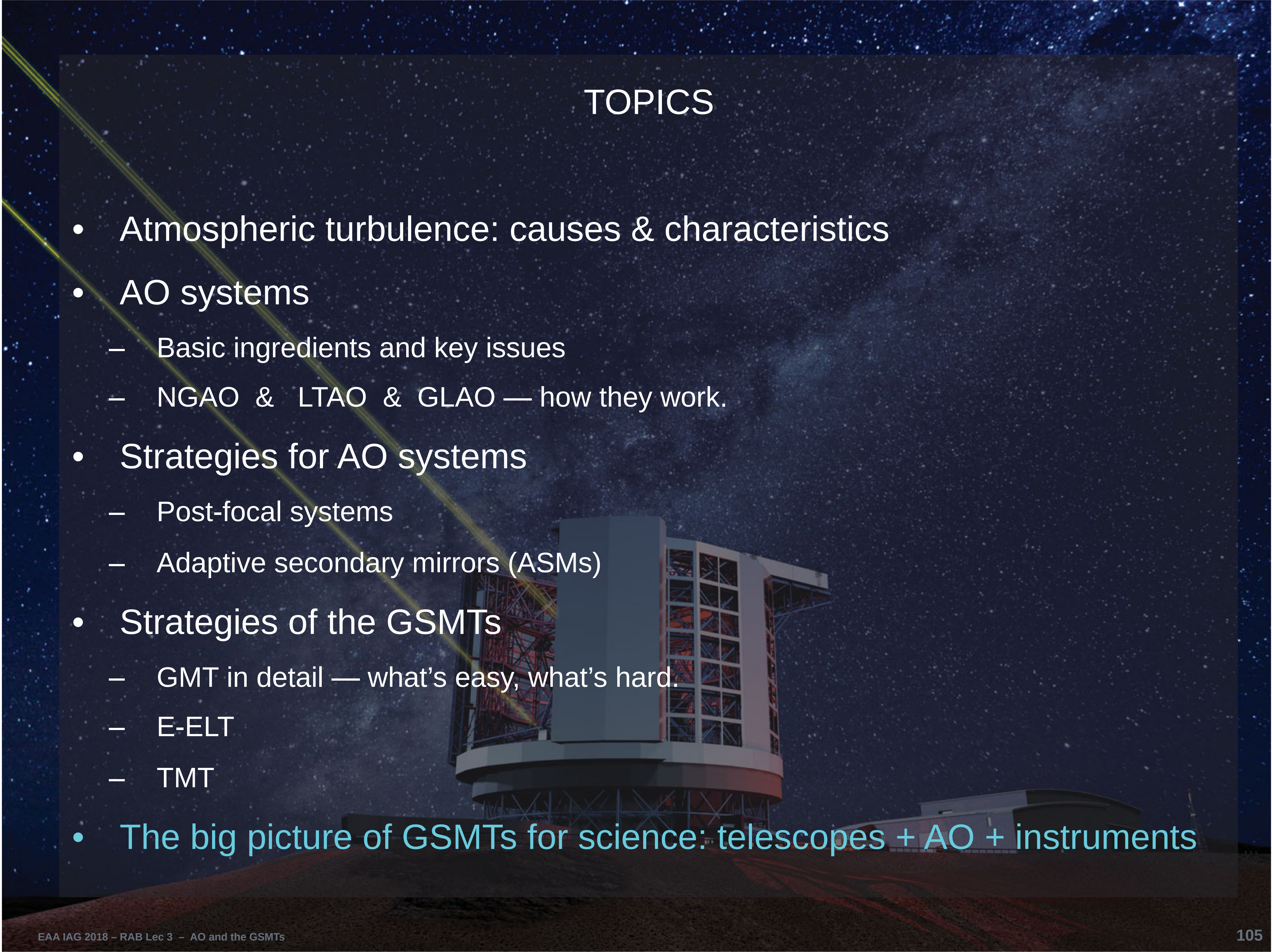
TMT:


NFIRAOS Science Calibration Unit (NSCU)
M2 System
M3 Svstem
HROS (Future)
NFIRAOS First Light w/IR Imaging Spectrometer (IRIS) w/IR Multi-Slit Spectrometer (IRMS) NIRES-B (Future) WIRC (Future)
Wide Field Optical Spectrometer First Light (WFOS)
PFI (Future)
Alignment and Phasing System (APS)
IRMOS (Future)
MIRAO with MIRES/NIRES-R (Future)
M1 Optics System
Enclosure
Summit Facilities
Laser System

TMT: like Keck — post-focal AO system







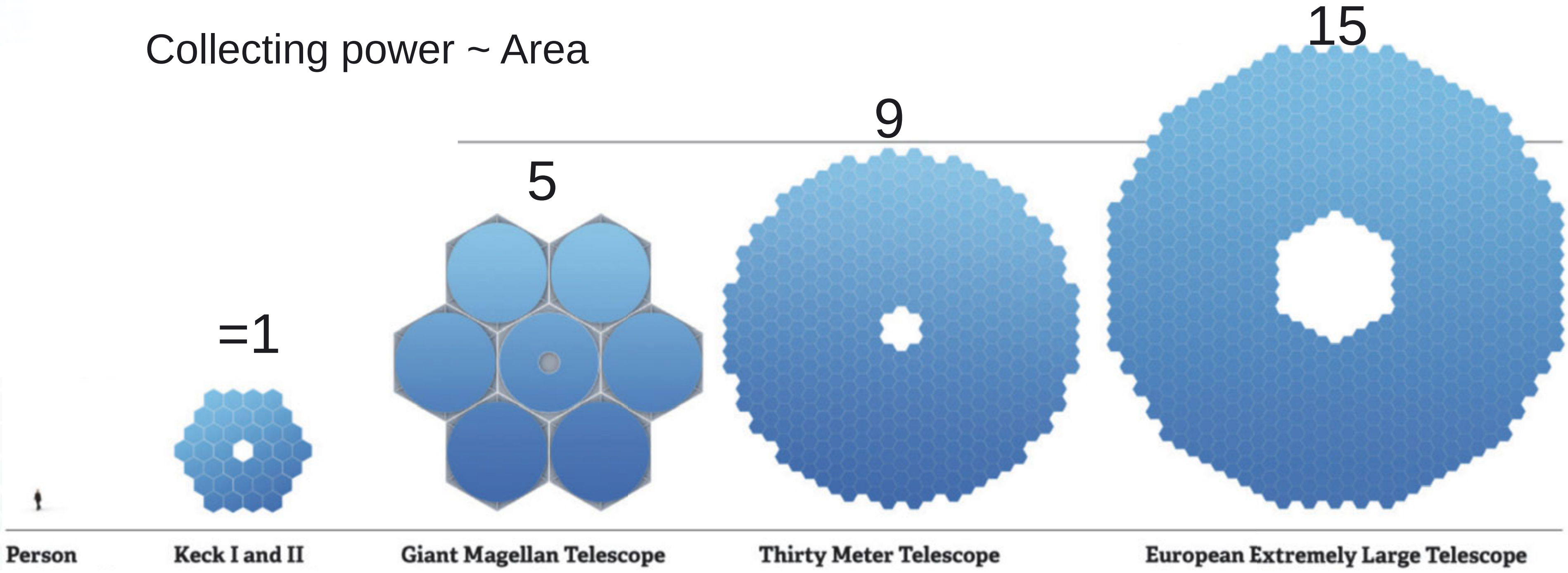
TOPICS

- Atmospheric turbulence: causes & characteristics
- AO systems
  - Basic ingredients and key issues
  - NGAO & LTAO & GLAO — how they work.
- Strategies for AO systems
  - Post-focal systems
  - Adaptive secondary mirrors (ASMs)
- Strategies of the GSMTs
  - GMT in detail — what's easy, what's hard.
  - E-ELT
  - TMT
- The big picture of GSMTs for science: telescopes + AO + instruments

New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Mirror collecting power: increases with primary mirror area (~D^2)

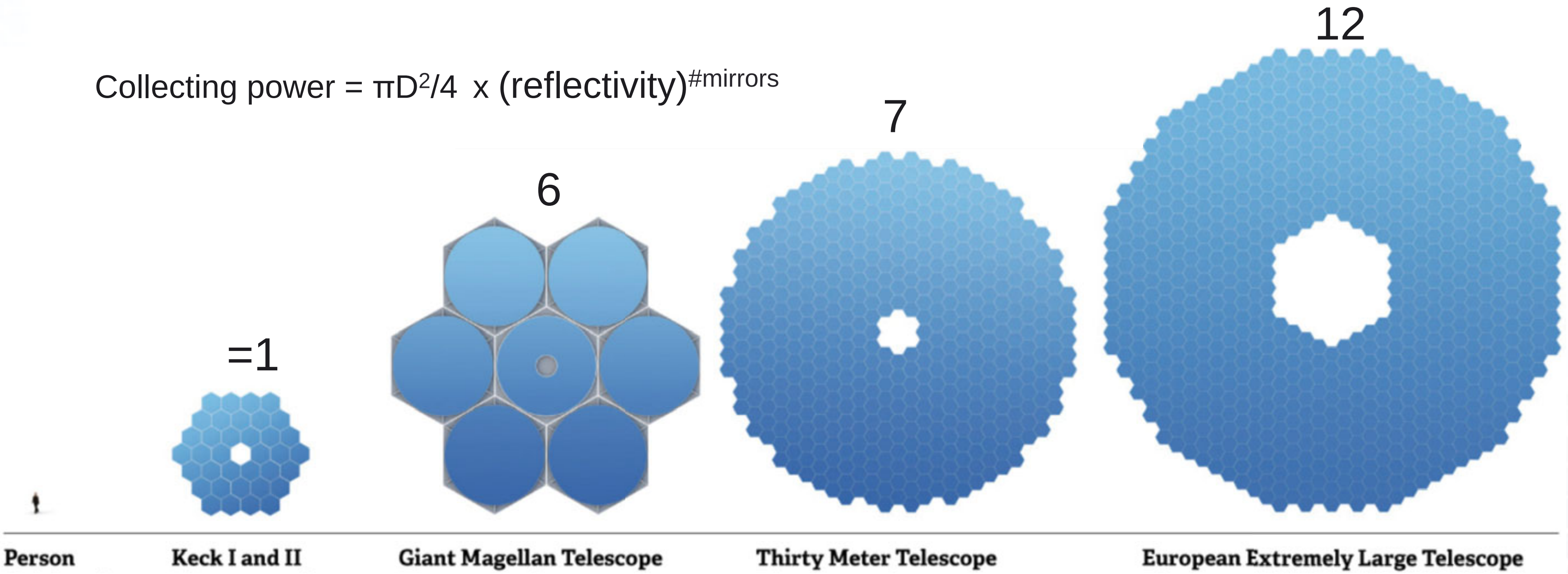
Collecting power ~ Area



New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Total collecting power: increases with D^2, goes down with # mirrors

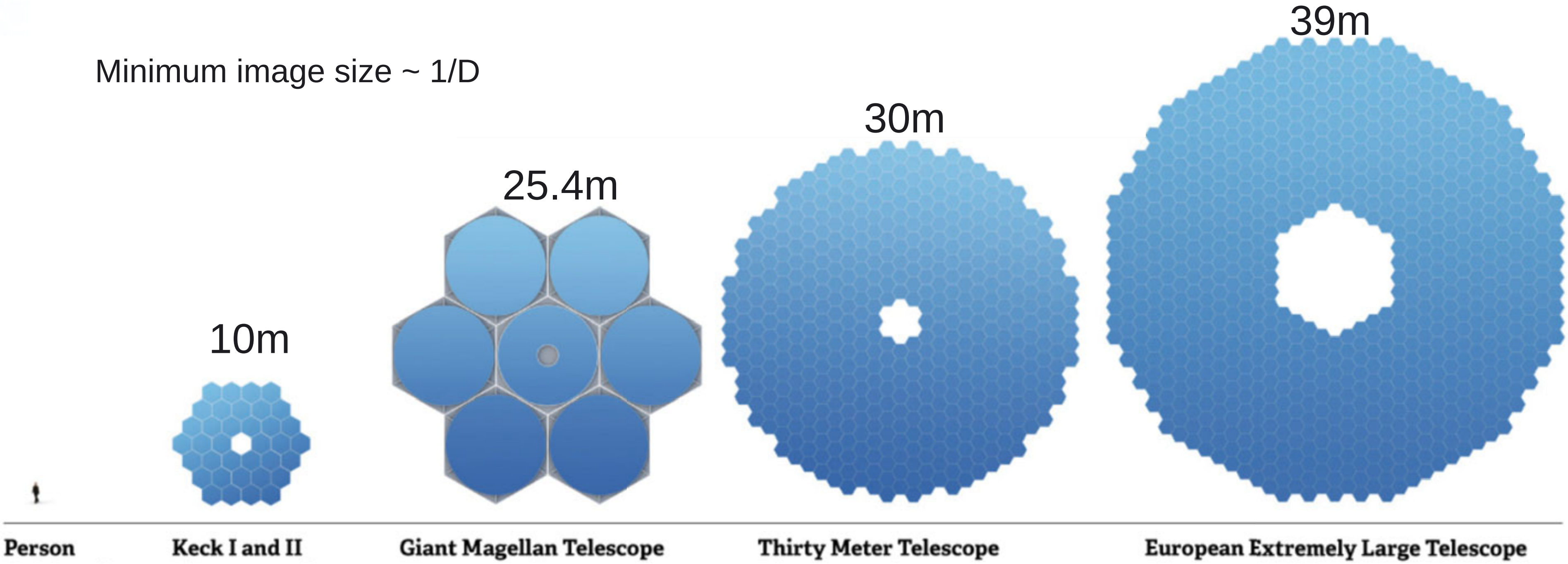
Collecting power = $\pi D^2/4 \times (\text{reflectivity})^{\#\text{mirrors}}$



New science with new capabilities:

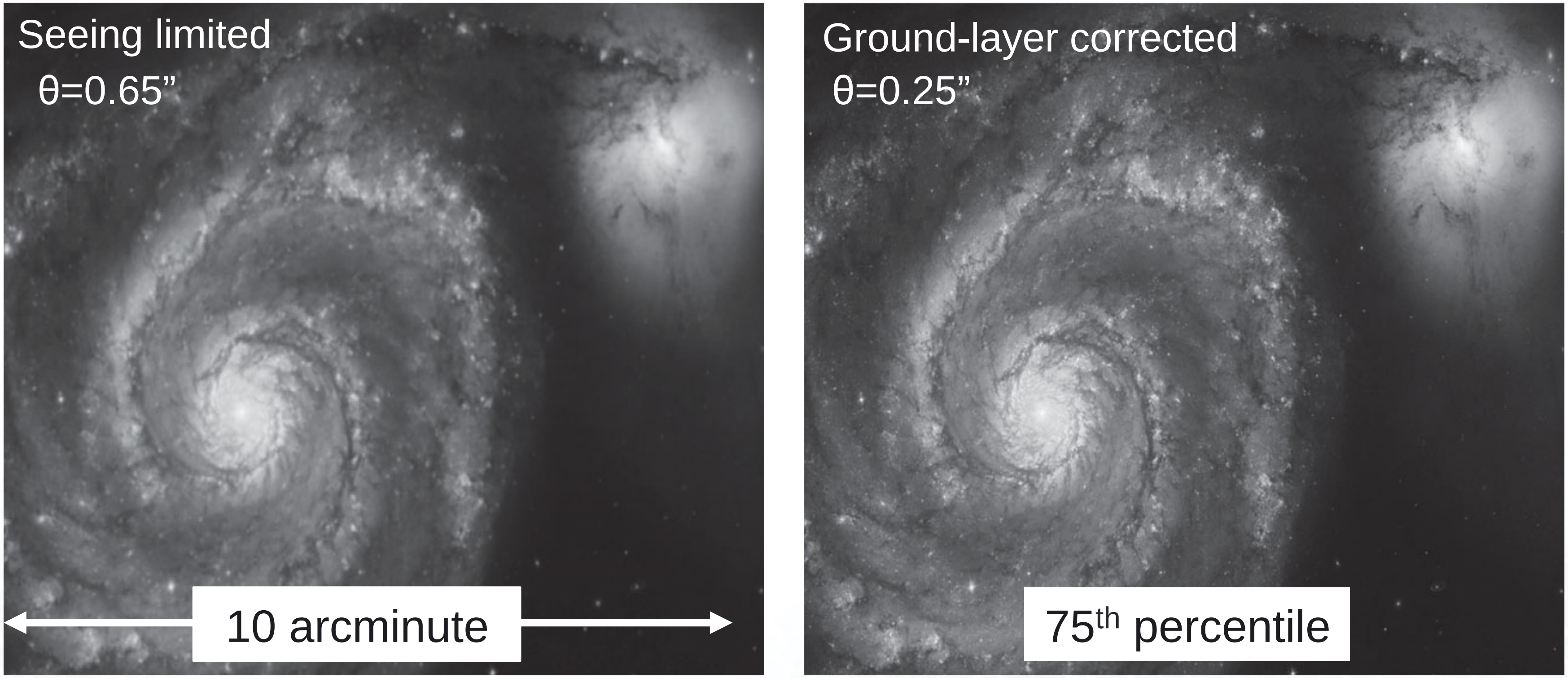
- Increased sensitivity: LIGHT!
  - Total collecting power: increases with D^2, goes down with # mirrors
- Increased angular resolution: sharper images
  - Diffraction limit: improves with D

Minimum image size ~ 1/D



New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Total collecting power: increases with D^2, goes down with # mirrors
- Increased angular resolution: sharper images
  - Diffraction limit: improves with D
  - *Full time AO and Ground layer AO*: enabled by telescope configuration and ASMs



New science with new capabilities:

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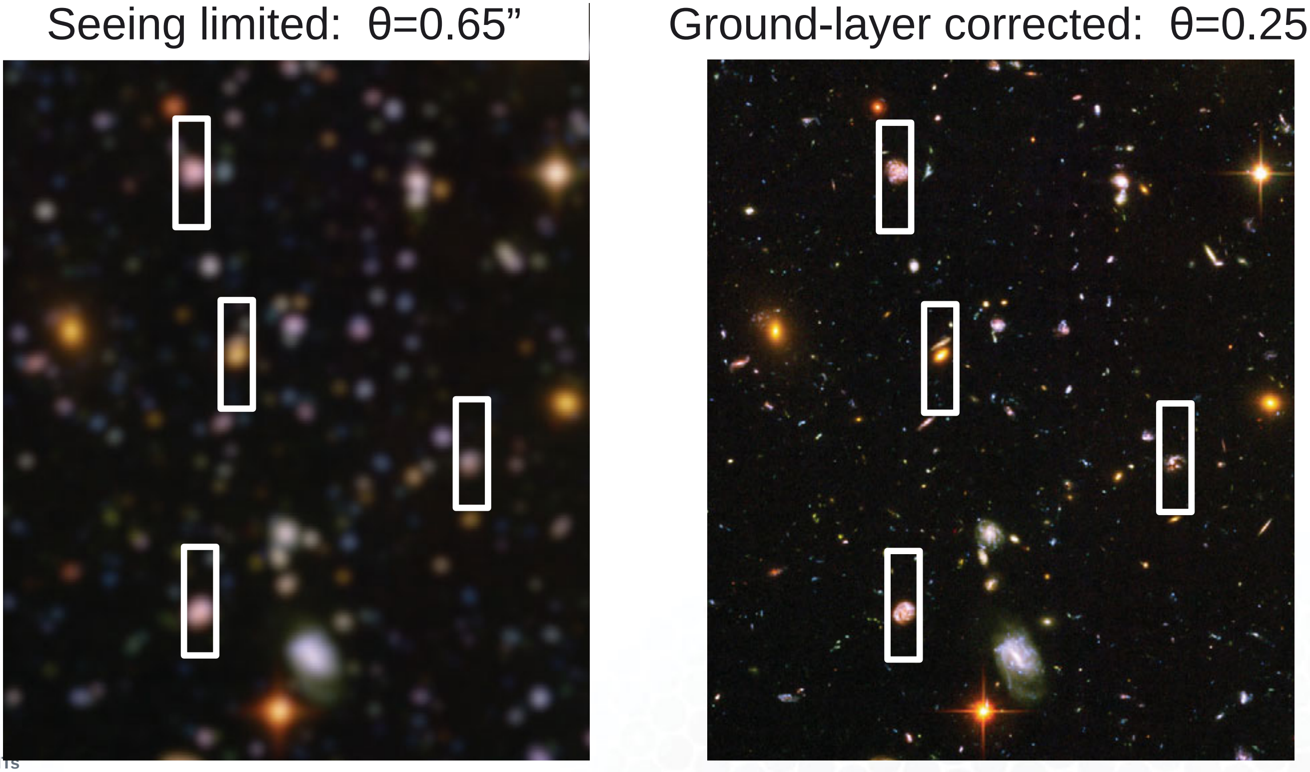


Seeing limited: θ=0.65”

Ground-layer corrected: θ=0.25”

Full time AO: NGAO, LTAO, & GLAO

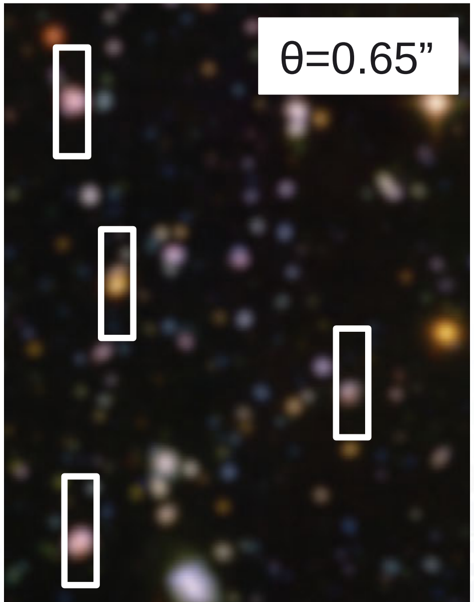
Telescope + planned instrument field of view:

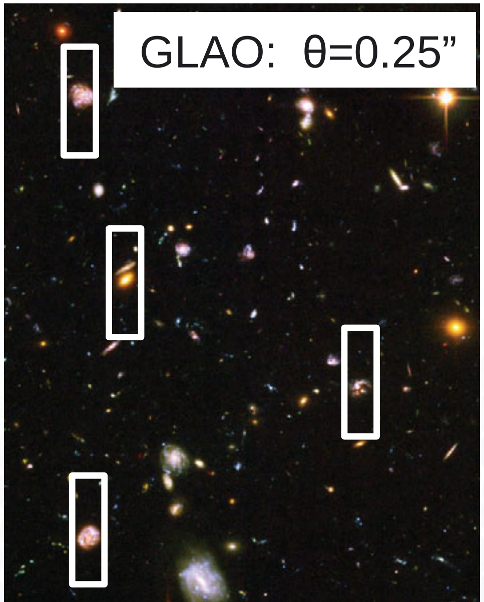
	Keck	**GMT (2 mirrors)**	**GMT with GLAO**	**TMT (3 mirrors)**	**ELT (5 mirrors)**
Aε	1	6	6	9	14
Ω	81	50	50	24	11
θ^2 **	(0.65”)^2	(0.65”)^2	**(0.25”)^2**	(0.65”)^2	**(0.25”)^2**
AεΩ/θ^2 (relative)	1	4	25	3	10

Metric for **wide field** science: **AεΩ/θ^2**

A = Area
ε = efficiency (0.8 – 0.9 per mirror)
Ω = Field of view
θ = image size (flux concentration)

**Typical 75th percentile, R-band seeing.


θ=0.65”


GLAO: θ=0.25”

Full time AO: NGAO, LTAO, & GLAO

Telescope + planned instrument field of view:

	Keck	**GMT (2 mirrors)**	**GMT with GLAO**	**TMT (3 mirrors)**	**ELT (5 mirrors)**
$A\varepsilon$	1	6	6	9	14
Ω	81	50	50	24	11
θ^2 **	$(0.65'')^2$	$(0.65'')^2$	$\mathbf{(0.25'')^2}$	$(0.65'')^2$	$\mathbf{(0.25'')^2}$
$A\varepsilon\Omega/\theta^2$ (relative)	1	4	25	3	10

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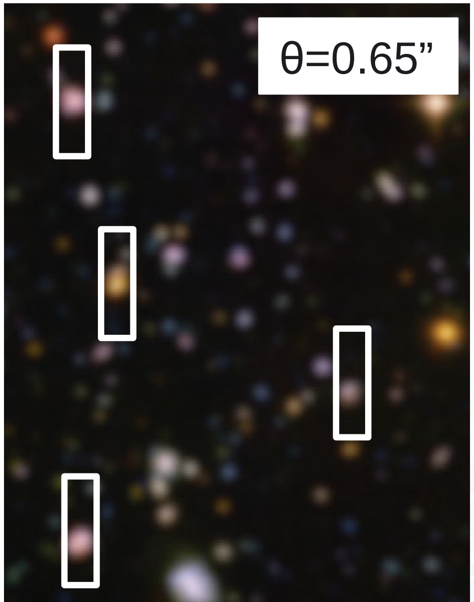
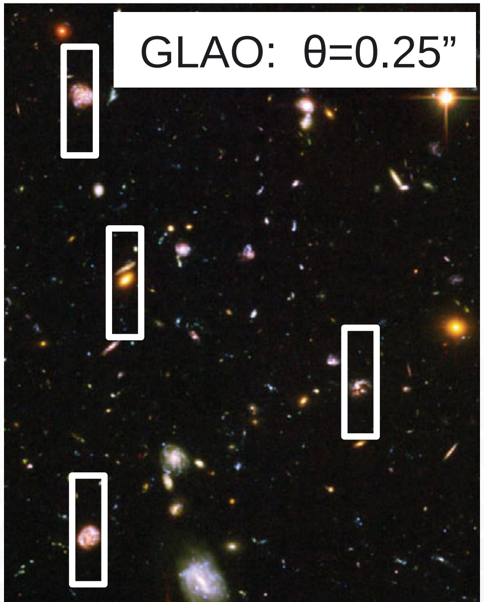
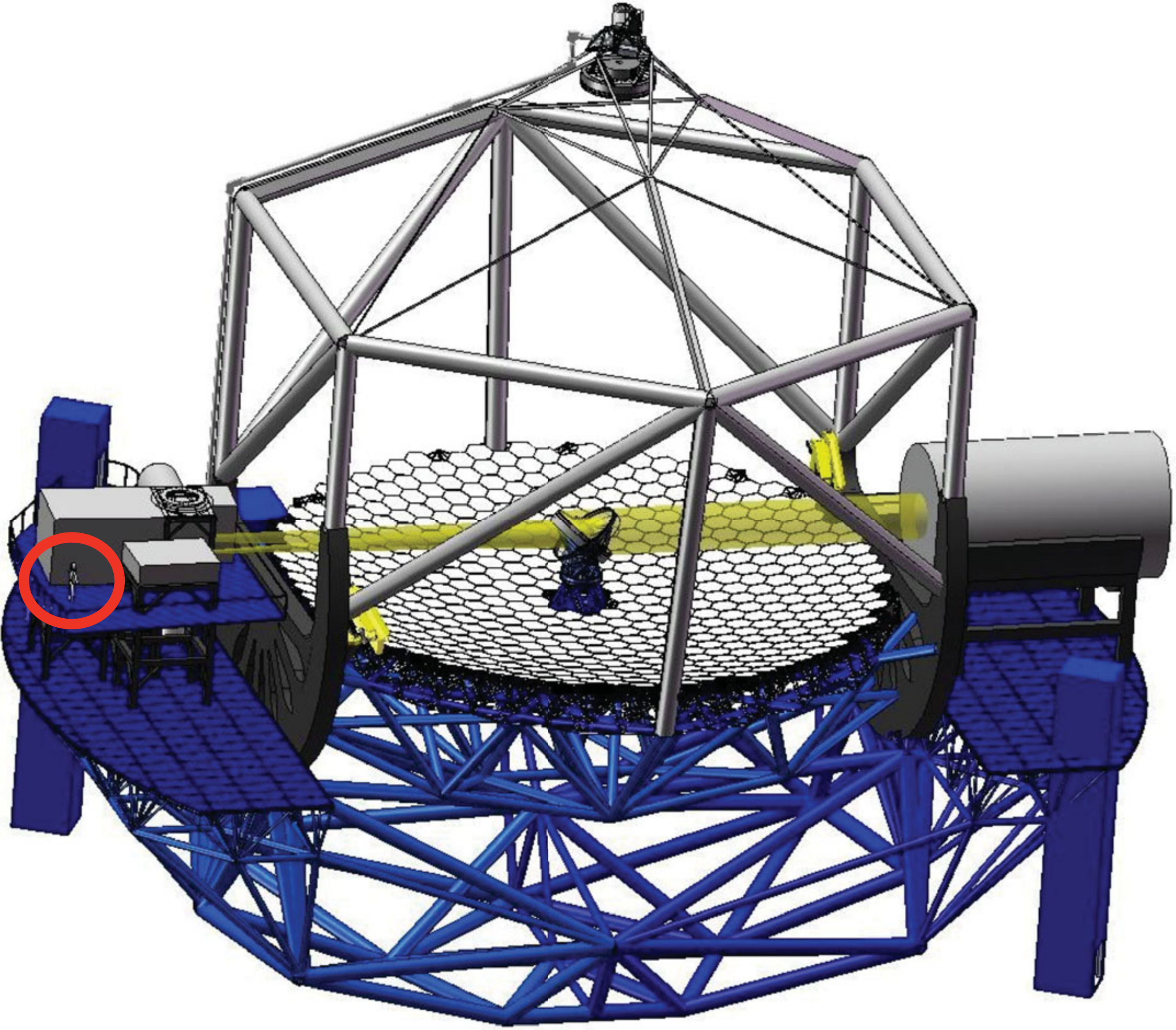


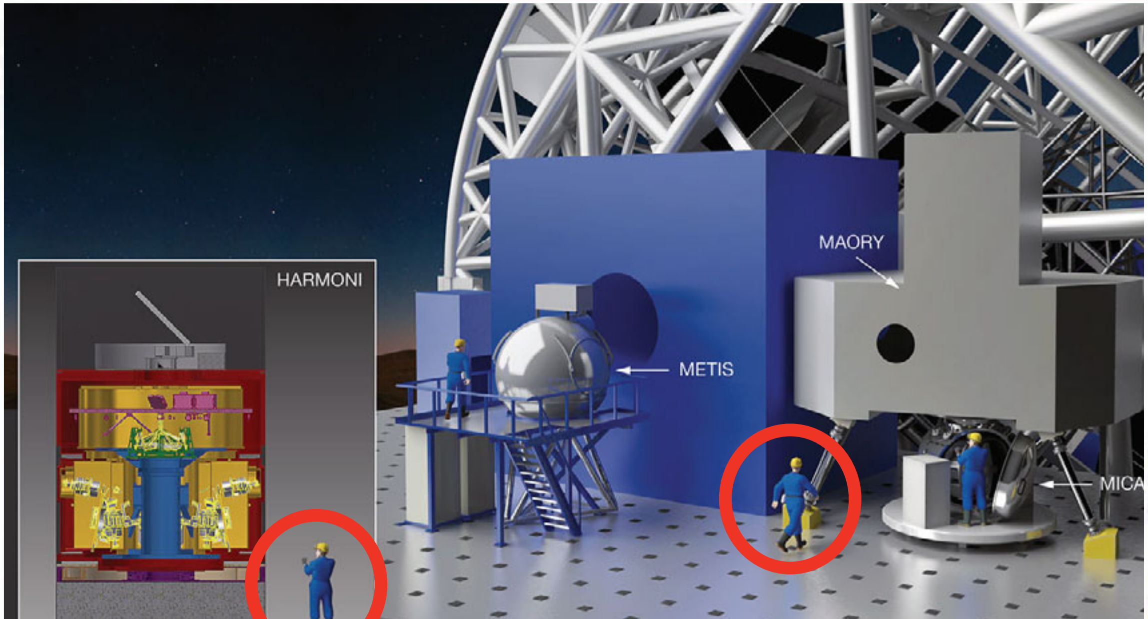


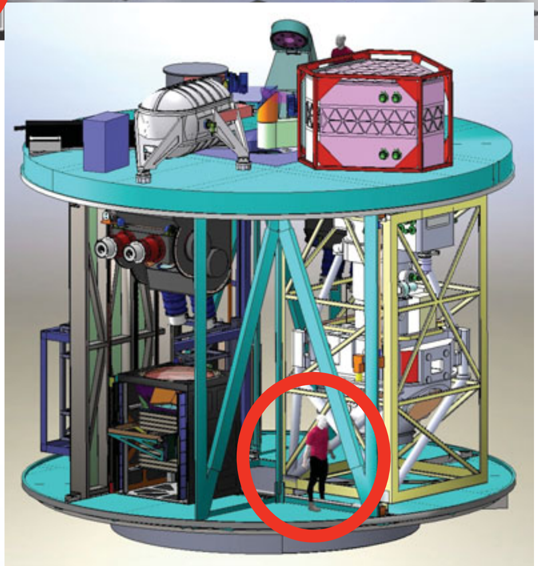
Instrument scale:

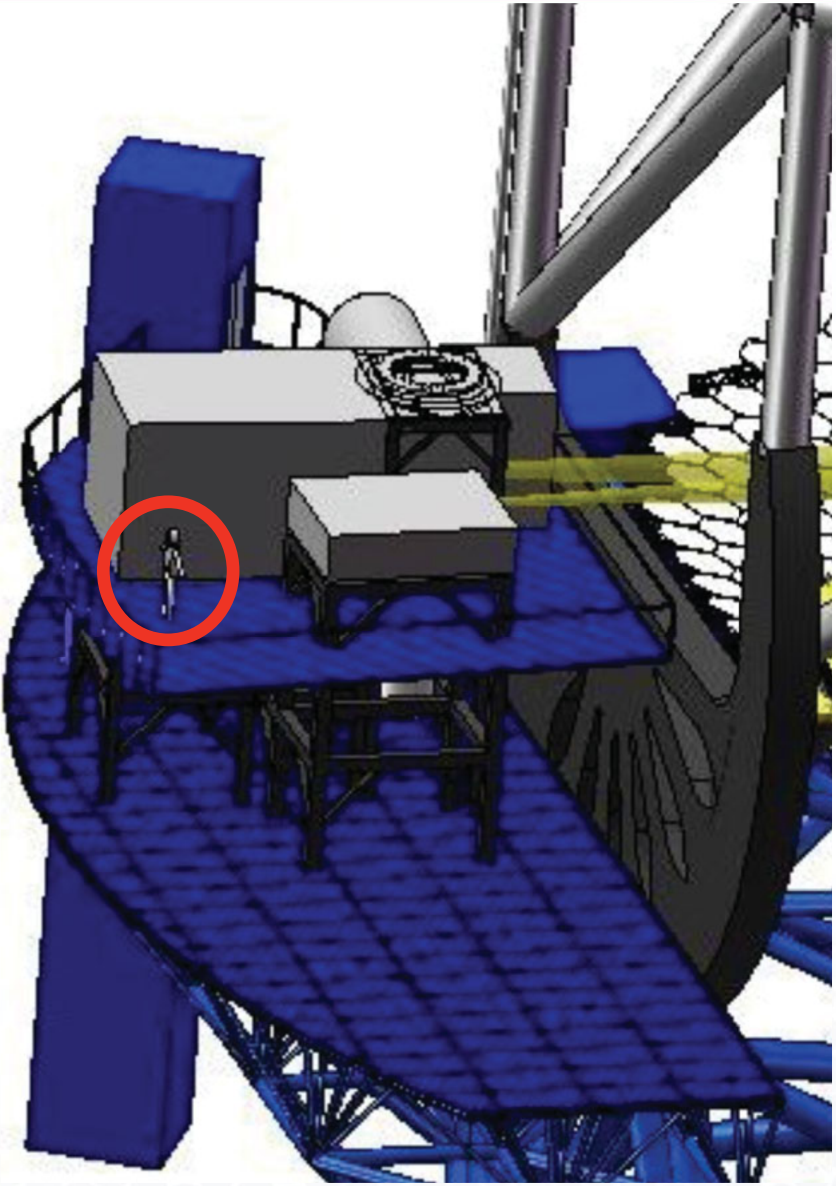
GMT



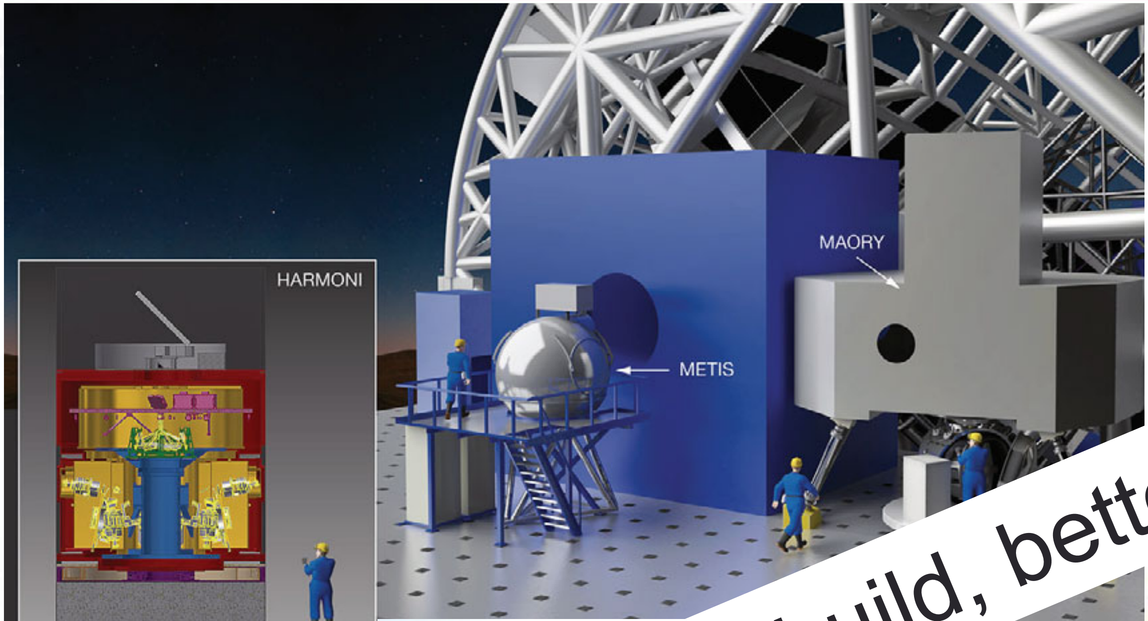
Instrument scale: smaller is better!

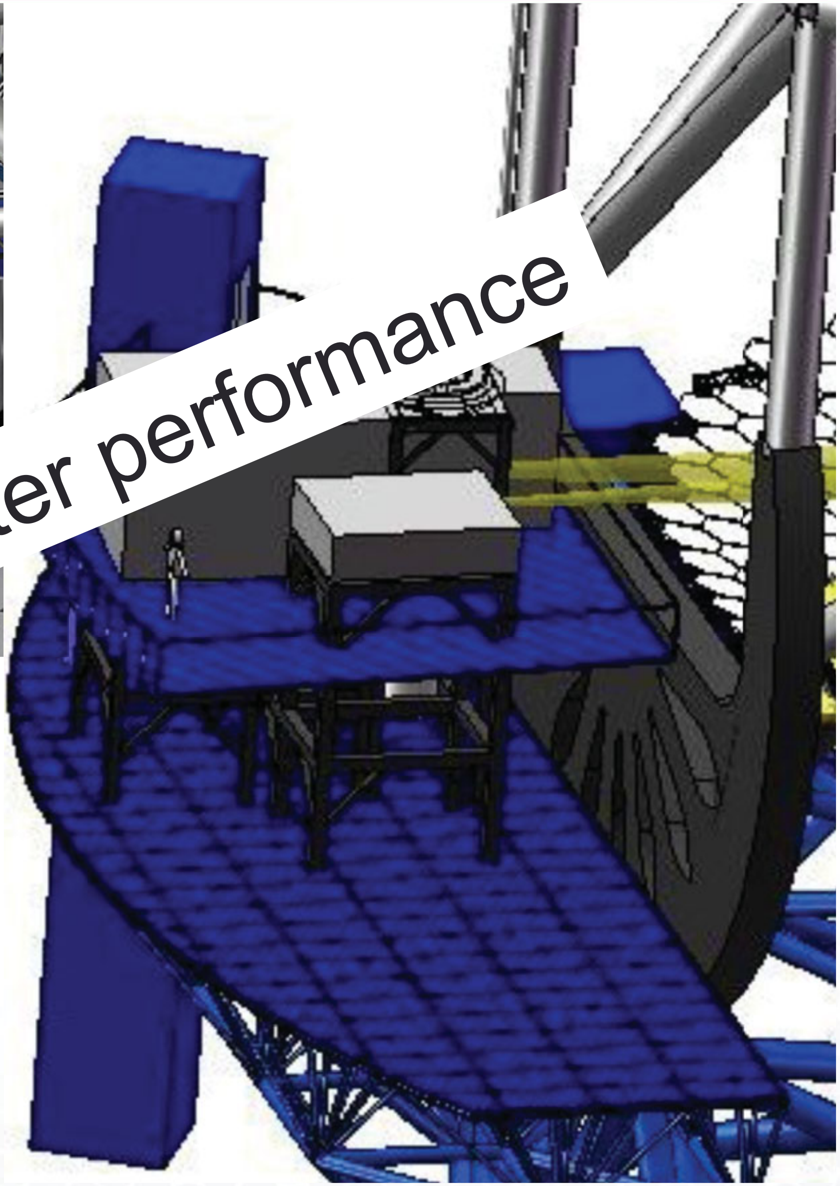




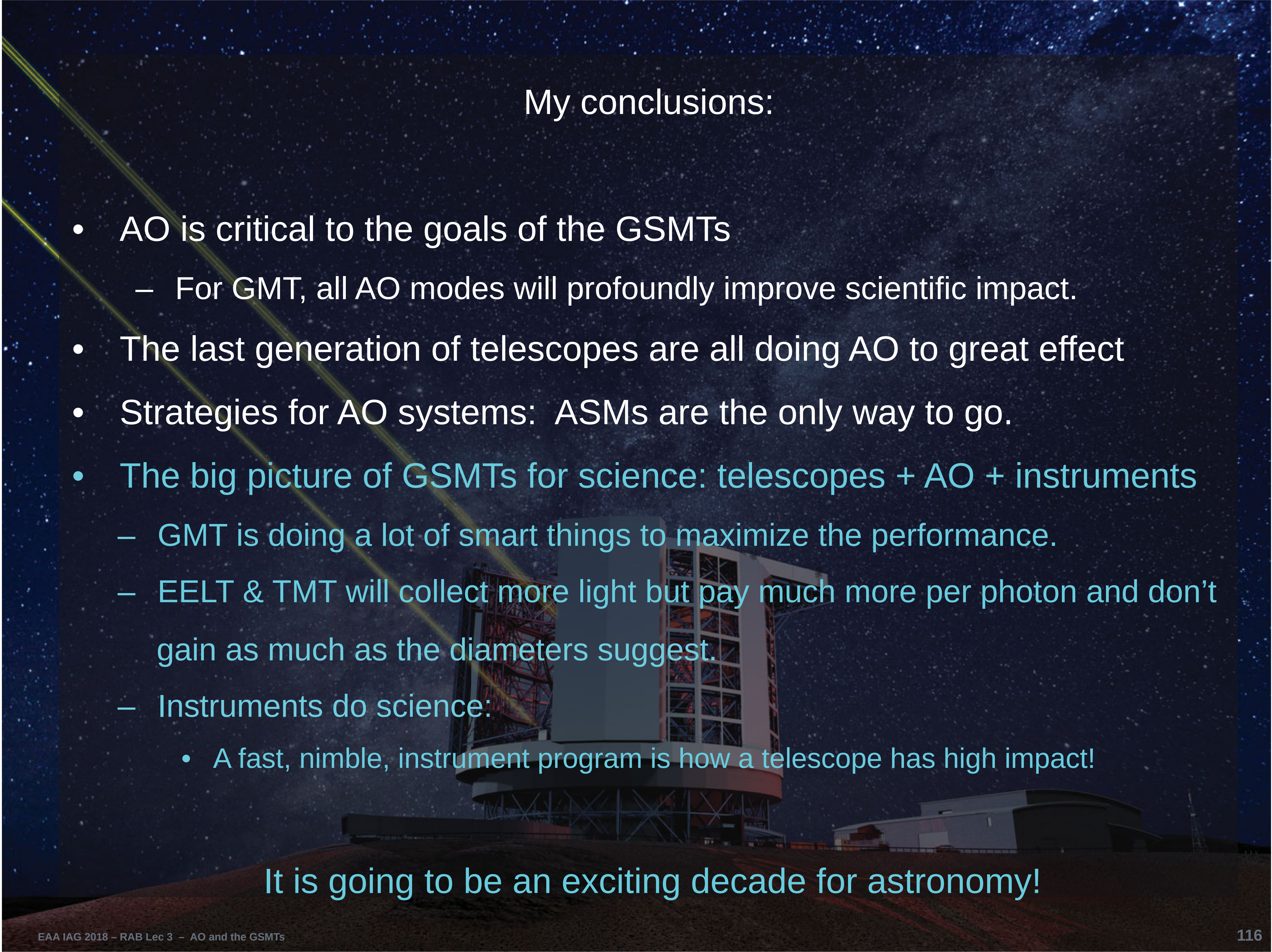


Instrument scale: smaller is better!





Better = faster to build, better performance



My conclusions:

- AO is critical to the goals of the GSMTs
  - For GMT, all AO modes will profoundly improve scientific impact.
- The last generation of telescopes are all doing AO to great effect
- Strategies for AO systems: ASMs are the only way to go.
- The big picture of GSMTs for science: telescopes + AO + instruments
  - GMT is doing a lot of smart things to maximize the performance.
  - EELT & TMT will collect more light but pay much more per photon and don’t gain as much as the diameters suggest.
  - Instruments do science:
    - A fast, nimble, instrument program is how a telescope has high impact!

It is going to be an exciting decade for astronomy!

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GMT Phasing Challenges

1. The doubly-segmented optical design

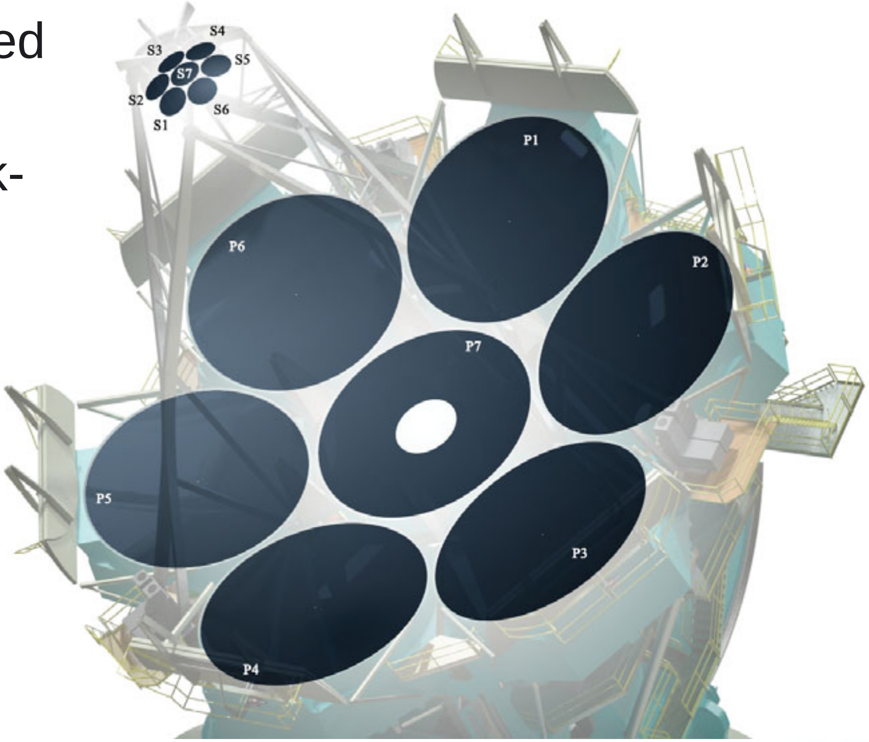
Tilt of an M1 segment can be perfectly cancelled by tilt of the matching M2 segment, causing a segment phase piston gradient to which Shack-Hartmann sensors are blind

2. M1 segment thermal stability

Ohara E6 Borosilicate non-zero thermal expansion (CTE = 2.8×10^{-6} /C) will cause edge sensors to drift on ~minute timescales

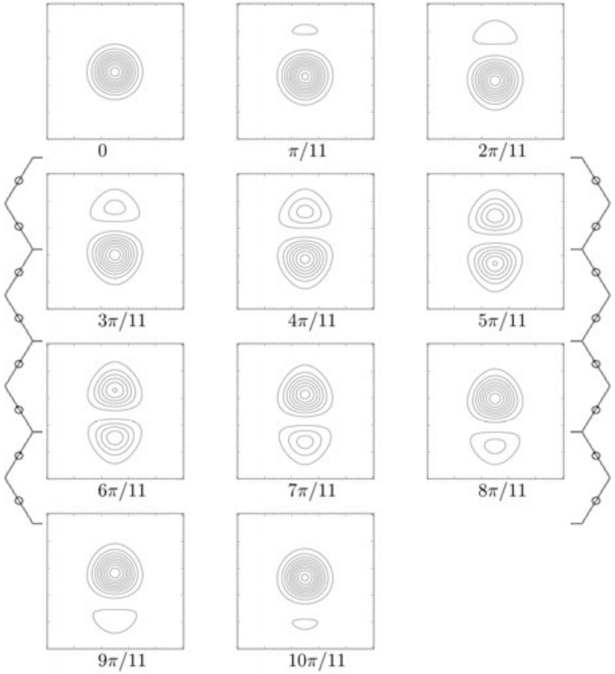
3. M1 segment gap size

30-35 cm gaps are larger than the atmospheric coherence length in the visible (10-20 cm), requiring phasing sensors in the infrared



Phasing of Segmented Telescopes

- Strategy 1: Optical Delay Lines
  - Used by all optical interferometers, MMT, and LBT
  - An optical control loop (generally requiring a bright star nearly on-axis) maintains drives a delay line in closed-loop to cancel telescope and atmospheric phase piston errors
- Strategy 2: Telescope phasing + Edge sensors
  - Used by the Keck and Gran Canarias telescopes
  - Planned for TMT and E-ELT
  - A specialized natural guide star wavefront sensor is used to initially phase the M1 segments
  - Edge sensors maintain the relative segment position vs. wind, gravity, and thermal effects over timescales of weeks



GMT Phasing Strategy

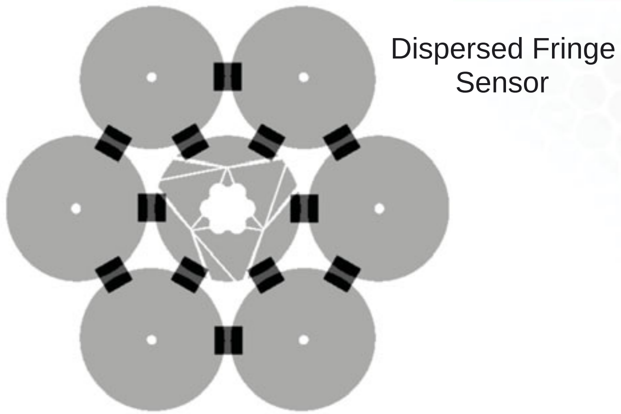
1. Absolute laser metrology truss aligns segment to ±20 µm
2. Telescope is phased across the full FOV using the light of 3 off-axis guide stars
   - Each AGWS probe includes a Dispersed Fringe Sensors (DFS) at 1.05-1.35 µm wavelength
   - Multiple guide stars enable phase piston and its gradients to be measured every 30 s

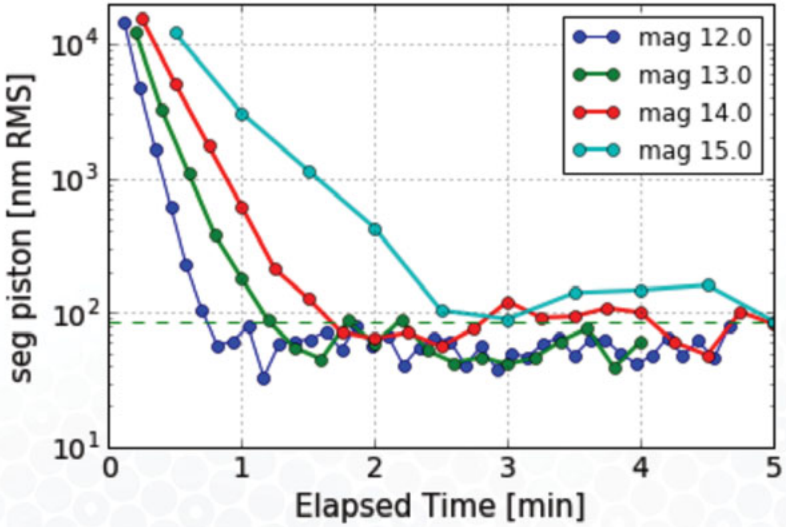
3a. Natural Guide Star AO

- Pyramid wavefront sensor controls telescope and atmospheric phase piston on-axis (1 kHz)
- AGWS controls phase piston gradients (0.03 Hz)

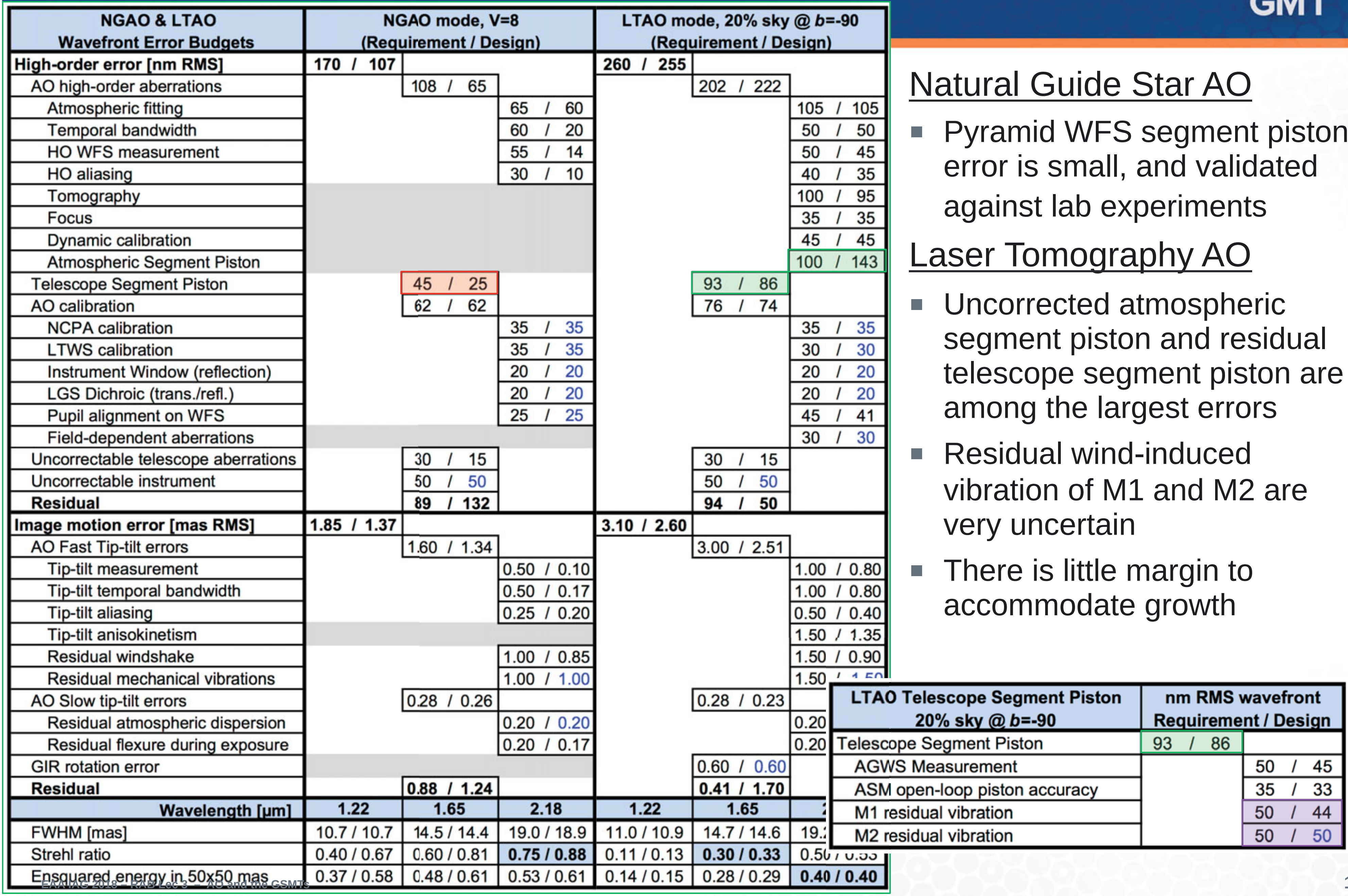
3b. Laser Tomography AO

- AGWS controls phase piston on-axis and gradients (0.03 Hz; provides sky coverage)
- Edge sensors maintain phased condition (500 Hz; provides vibration rejection)





AO Wavefront Error Budgets



NGAO & LTAO Wavefront Error Budgets	NGAO mode, V=8 (Requirement / Design)			LTAO mode, 20% sky @ *b*=-90 (Requirement / Design)		
High-order error [nm RMS]	**170 / 107**			**260 / 255**		
AO high-order aberrations		108 / 65			202 / 222	
Atmospheric fitting			65 / 60			105 / 105
Temporal bandwidth			60 / 20			50 / 50
HO WFS measurement			55 / 14			50 / 45
HO aliasing			30 / 10			40 / 35
Tomography						100 / 95
Focus						35 / 35
Dynamic calibration						45 / 45
Atmospheric Segment Piston						100 / 143
Telescope Segment Piston		45 / 25			93 / 86	
AO calibration		62 / 62			76 / 74	
NCPA calibration			35 / 35			35 / 35
LTWS calibration			35 / 35			30 / 30
Instrument Window (reflection)			20 / 20			20 / 20
LGS Dichroic (trans./refl.)			20 / 20			20 / 20
Pupil alignment on WFS			25 / 25			45 / 41
Field-dependent aberrations						30 / 30
Uncorrectable telescope aberrations		30 / 15			30 / 15	
Uncorrectable instrument		50 / 50			50 / 50	
Residual		**89 / 132**			**94 / 50**	
Image motion error [mas RMS]	**1.85 / 1.37**			**3.10 / 2.60**		
AO Fast Tip-tilt errors		1.60 / 1.34			3.00 / 2.51	
Tip-tilt measurement			0.50 / 0.10			1.00 / 0.80
Tip-tilt temporal bandwidth			0.50 / 0.17			1.00 / 0.80
Tip-tilt aliasing			0.25 / 0.20			0.50 / 0.40
Tip-tilt anisokinetism						1.50 / 1.35
Residual windshake			1.00 / 0.85			1.50 / 0.90
Residual mechanical vibrations			1.00 / 1.00			1.50 / 1.50
AO Slow tip-tilt errors		0.28 / 0.26			0.28 / 0.23	
Residual atmospheric dispersion			0.20 / 0.20			0.20
Residual flexure during exposure			0.20 / 0.17			0.20
GIR rotation error					0.60 / 0.60	
Residual		**0.88 / 1.24**			**0.41 / 1.70**	
Wavelength [µm]	**1.22**	**1.65**	**2.18**	**1.22**	**1.65**	**2**
FWHM [mas]	10.7 / 10.7	14.5 / 14.4	19.0 / 18.9	11.0 / 10.9	14.7 / 14.6	19.2
Strehl ratio	0.40 / 0.67	0.60 / 0.81	**0.75 / 0.88**	0.11 / 0.13	**0.30 / 0.33**	0.50 / 0.53
Ensquared energy in 50x50 mas	0.37 / 0.58	0.48 / 0.61	0.53 / 0.61	0.14 / 0.15	0.28 / 0.29	**0.40 / 0.40**

LTAO Telescope Segment Piston 20% sky @ *b*=-90	nm RMS wavefront Requirement / Design	
Telescope Segment Piston	93 / 86	
AGWS Measurement		50 / 45
ASM open-loop piston accuracy		35 / 33
M1 residual vibration		50 / 44
M2 residual vibration		50 / 50

Natural Guide Star AO

- Pyramid WFS segment piston error is small, and validated against lab experiments

Laser Tomography AO

- Uncorrected atmospheric segment piston and residual telescope segment piston are among the largest errors
- Residual wind-induced vibration of M1 and M2 are very uncertain
- There is little margin to accommodate growth

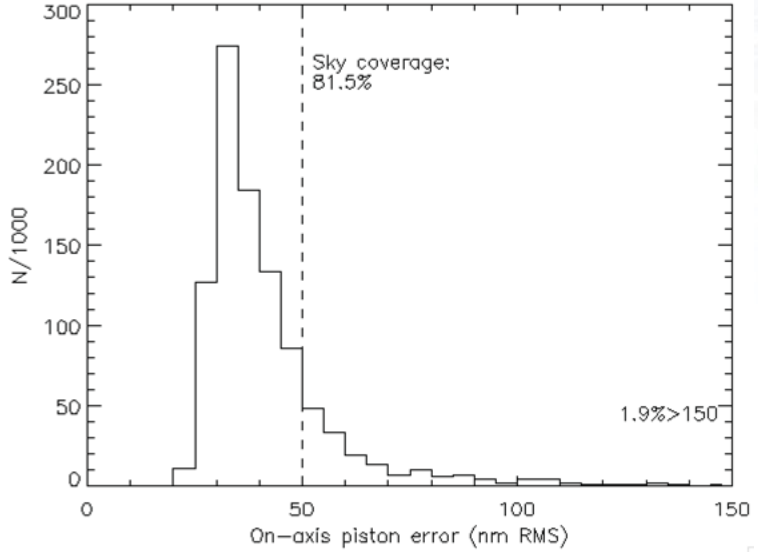
Simulations and Prototyping

Simulations

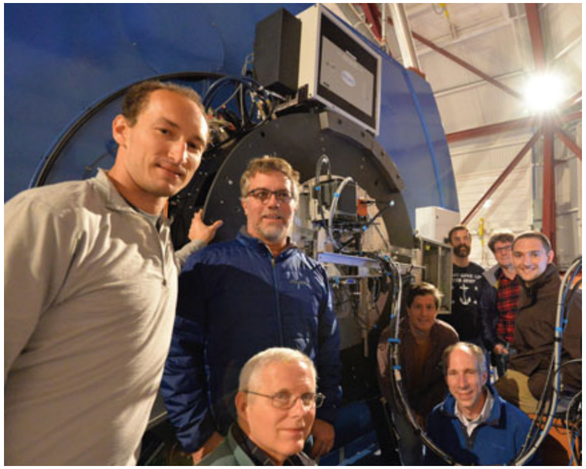
- High-fidelity simulations of the DFS indicate that currently-available detector performance will limit AGWS phasing sky coverage to ~80% (vs. 90% requirement)
- Wind buffeting and edge sensor performance simulations are still immature

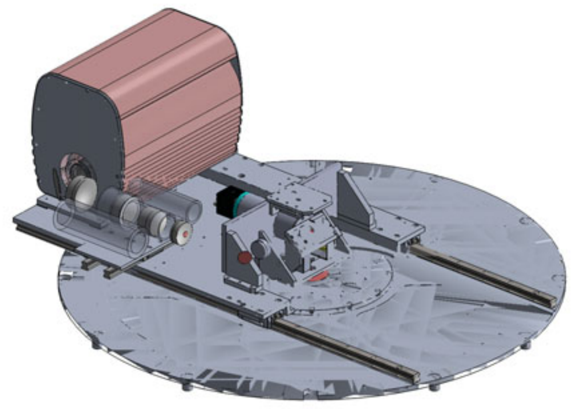
Prototyping

- Dispersed Fringe Sensor prototypes at Magellan have provided confidence in the design, and identified calibration issues (eg. real-time atmospheric dispersion calibration)


48 e-/s dark current, 4 guide stars


Infrared integrating phasing sensor prototype: July 2012


Visible high-speed phasing sensor prototype: Dec. 2015


Infrared high-speed phasing sensor prototype: Planned Mar. 2018

Maturing the Phasing Strategy and Design

AGWS Dispersed Fringe Sensor

- 3rd prototype DFS at Magellan will test the infrared camera, optical design, and calibration strategies in March 2018. It will validate the predicted phasing sky coverage in LTAO mode.

Edge Sensors and Wind Buffeting

- The GMT Integrated Model is maturing and should provide reliable wind disturbances by Q3 2017
  - Modeled wind disturbances will be validated against LBT and Magellan accelerometer measurements
- Edge sensor design will be advanced by a JPL trade study beginning August 2017, and lab prototyping in early 2018

Both major aspects of LTAO phasing
will be validated by mid-2018

8 June Wavefront Control Peer Review

The review committee:

- expressed support for the wavefront control strategies and algorithms presented
- had concern over the lack of margin in the current budgets, particularly given the uncertain telescope vibration environment
- recommended further prototyping and model validation using laboratory and on-sky experiments
- recommended deploying the AGWS Dispersed Fringe Sensors on the GMT at first light, to gain experience

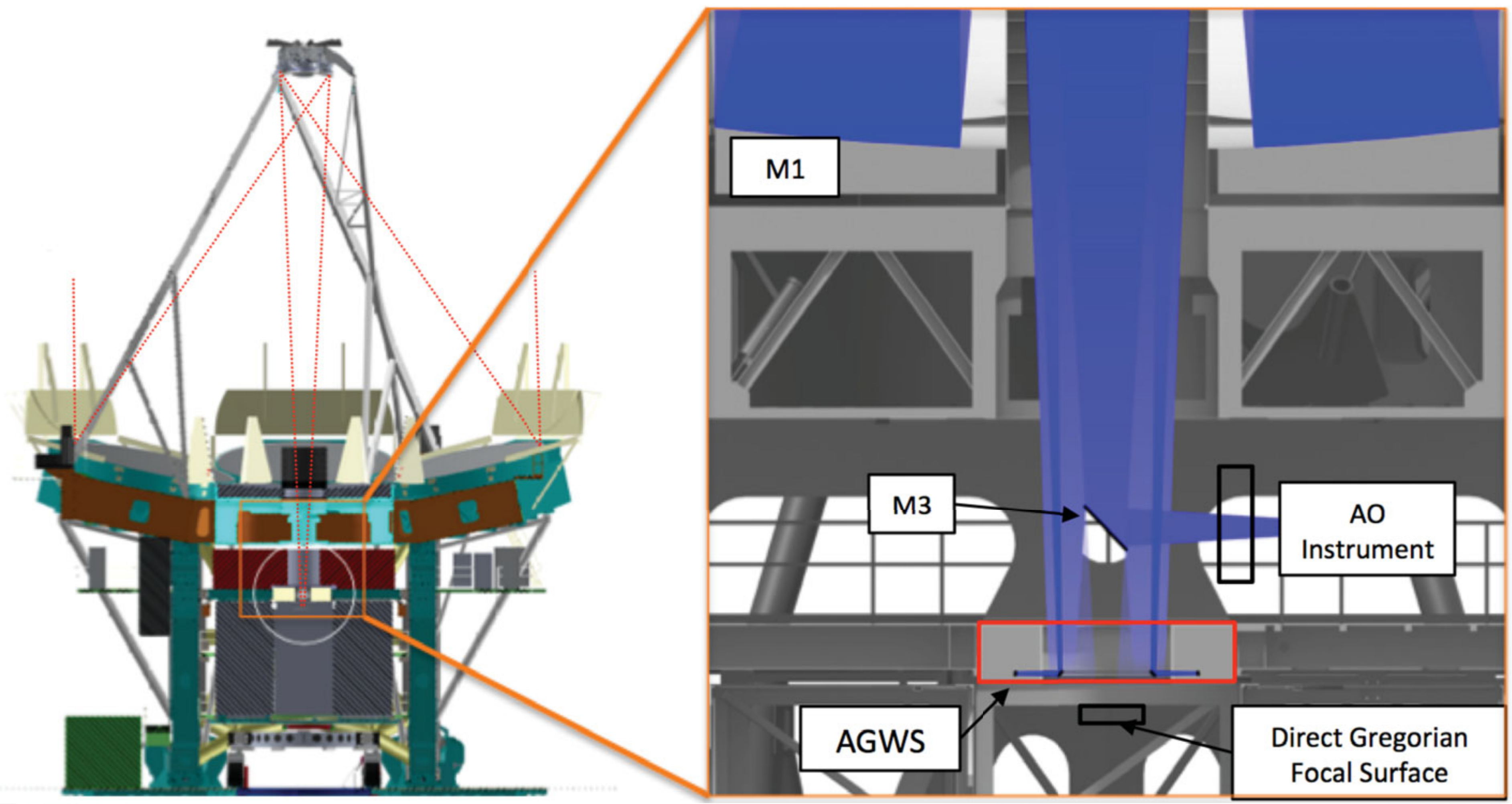
- Others?

Summary

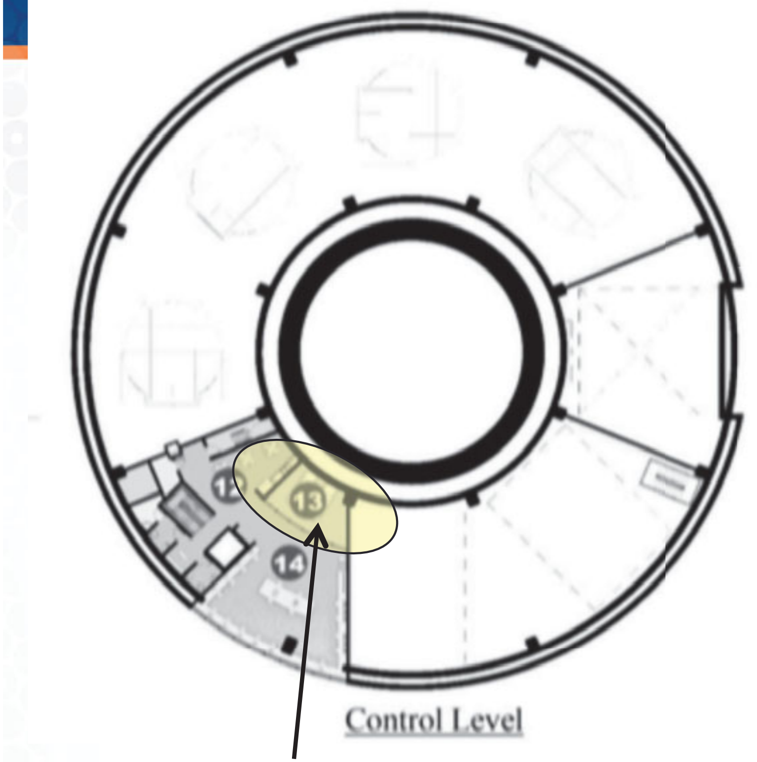
- The GMT phasing strategy is a variation on that of existing facilities:
    - In Natural Guide Star AO, the telescope and atmospheric are phased in closed loop on the Pyramid WFS, analogous to fringe tracking on optical interferometers
    - In Laser Tomography AO, the telescope is phased using edge sensors (similarly to Keck/TMT), but with continuous correction for thermal drift by three off-axis Dispersed Fringe Sensors
- The performance of the Dispersed Fringe sensor is well understood as a result of extensive prototyping on Magellan
- The ability of the edge sensor system to control wind shake has not yet been demonstrated
    - Higher-fidelity wind disturbance simulations and validation are planned
    - Edge sensors will be prototyped in early 2018

AGWS – carries phasing probes

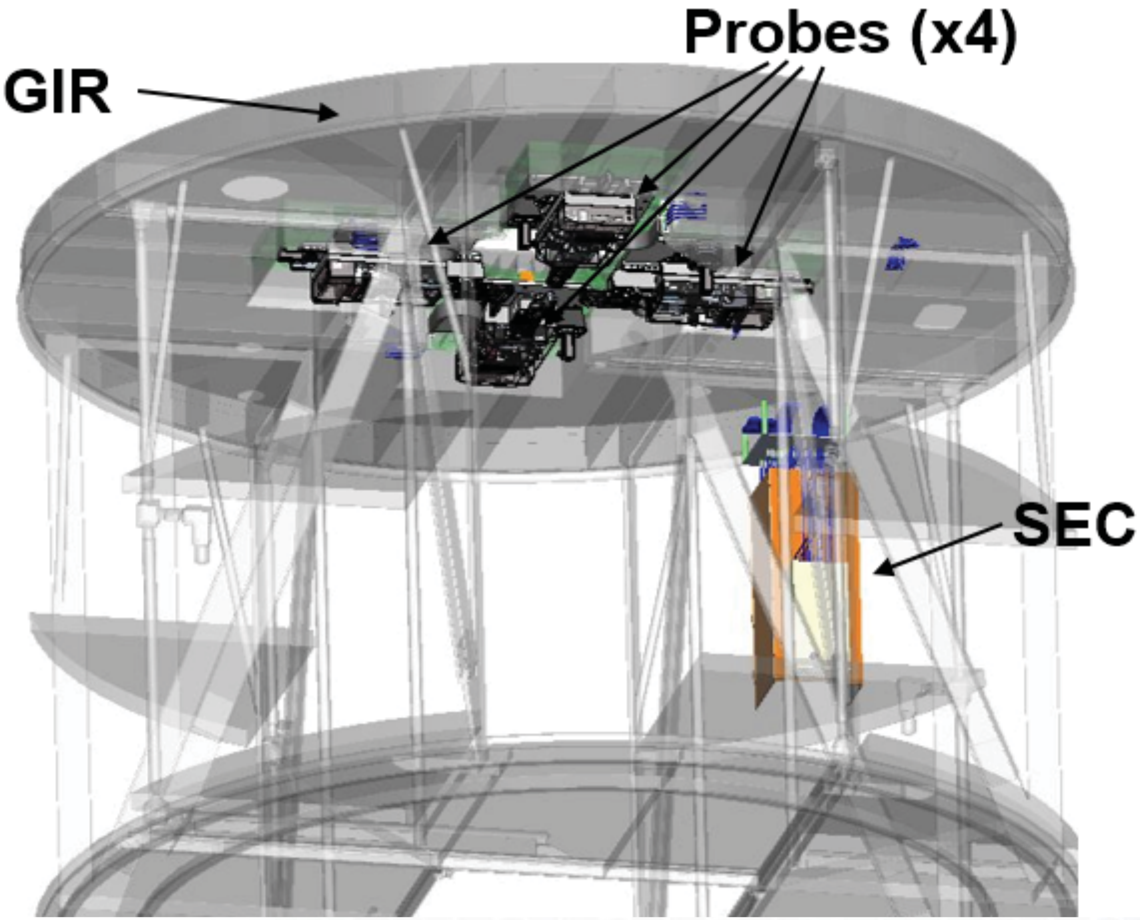
AGWS Located at Heart of GMT



Components of AGWS in Three Locations



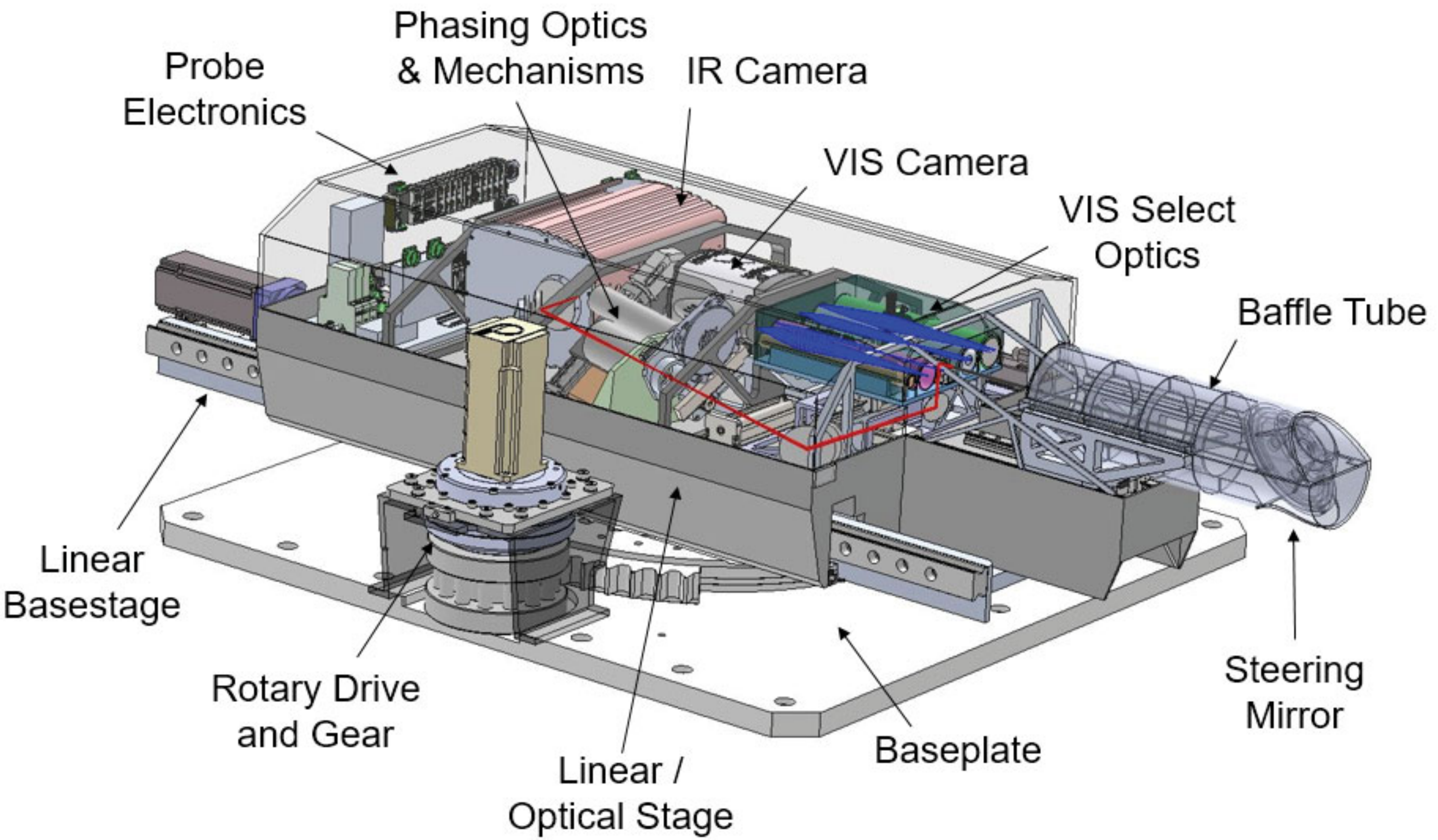
Electronics Room


GIR

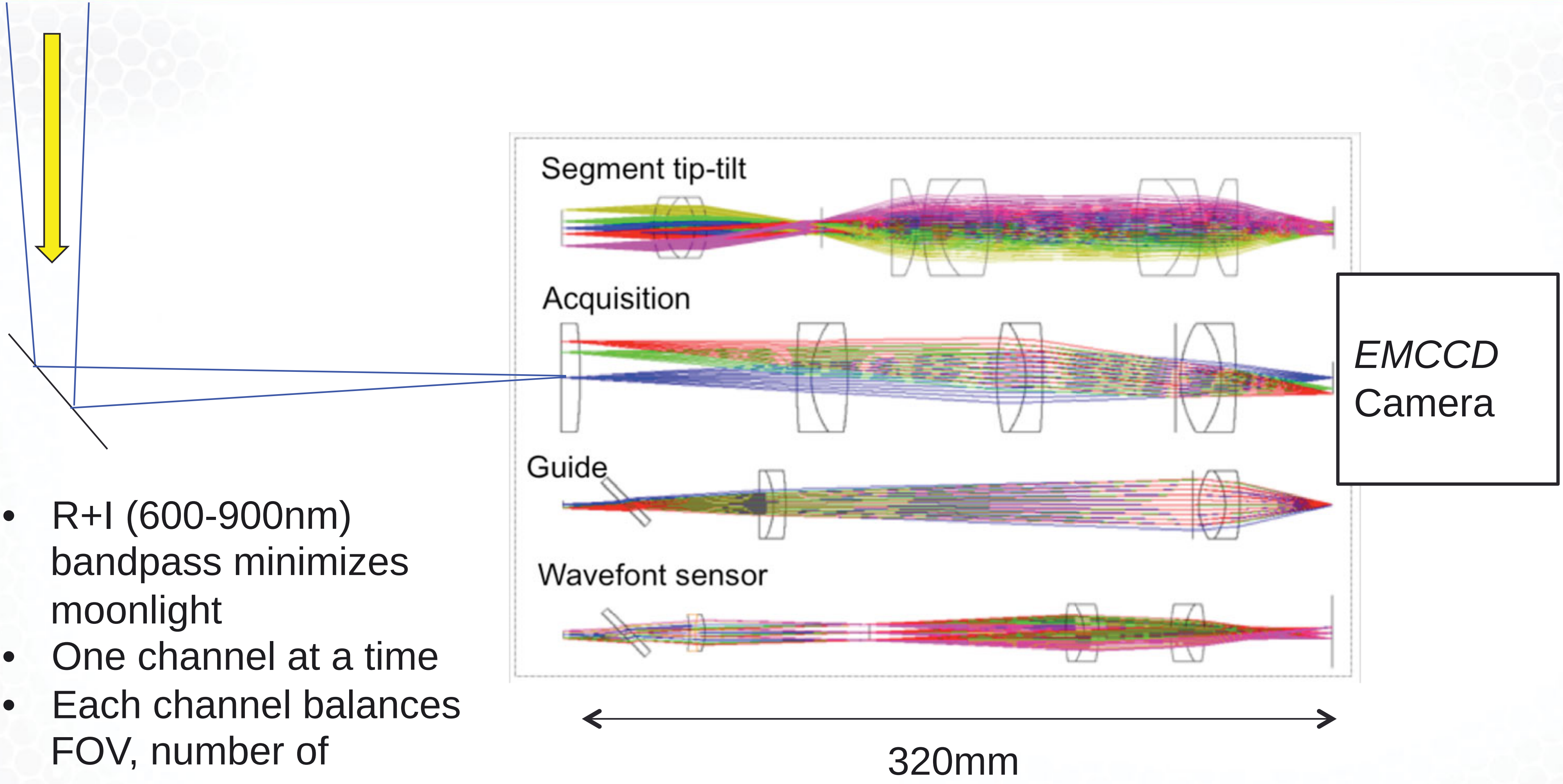
Probes (x4)

SEC

New Probe Includes Phasing And Reaches On-axis



Visible Channels (Everything But Phasing)

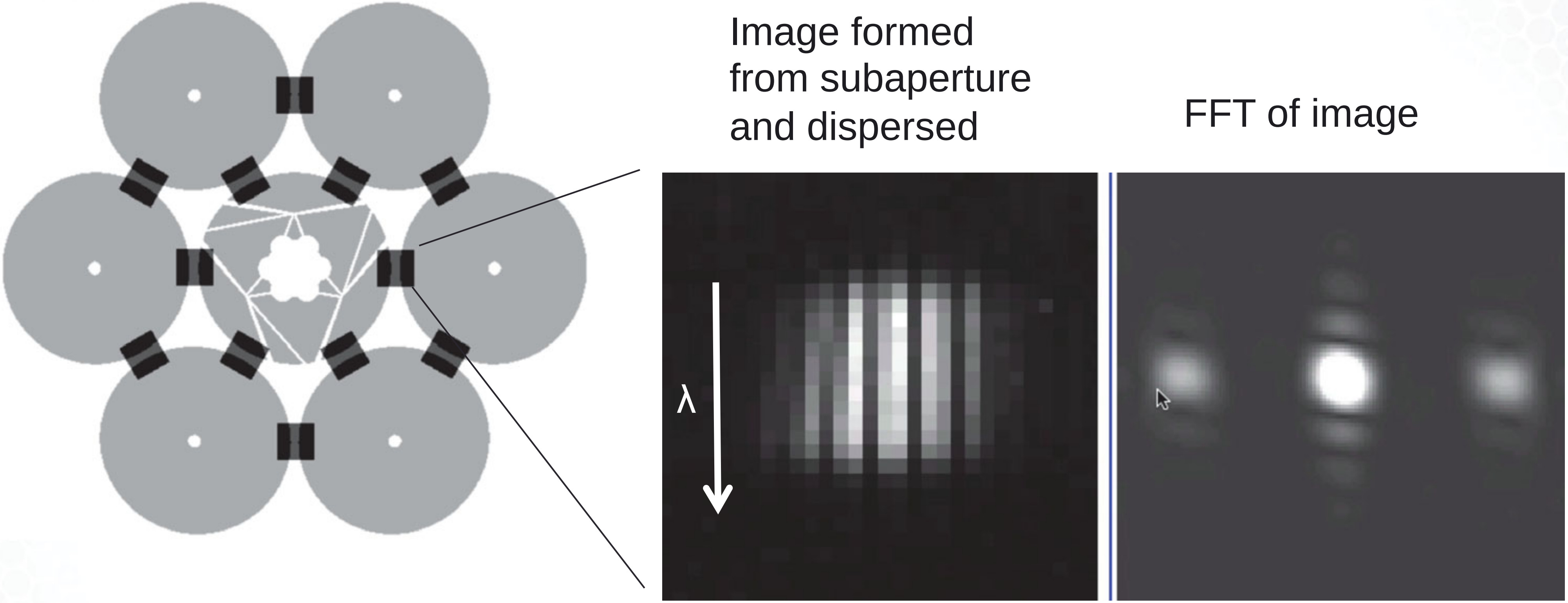


- R+I (600-900nm) bandpass minimizes moonlight
- One channel at a time
- Each channel balances FOV, number of subapertures and speed

Dispersed Fringe Sensor Measures Relative Piston Of The 7 Segments – Not Measured By Other Sensors

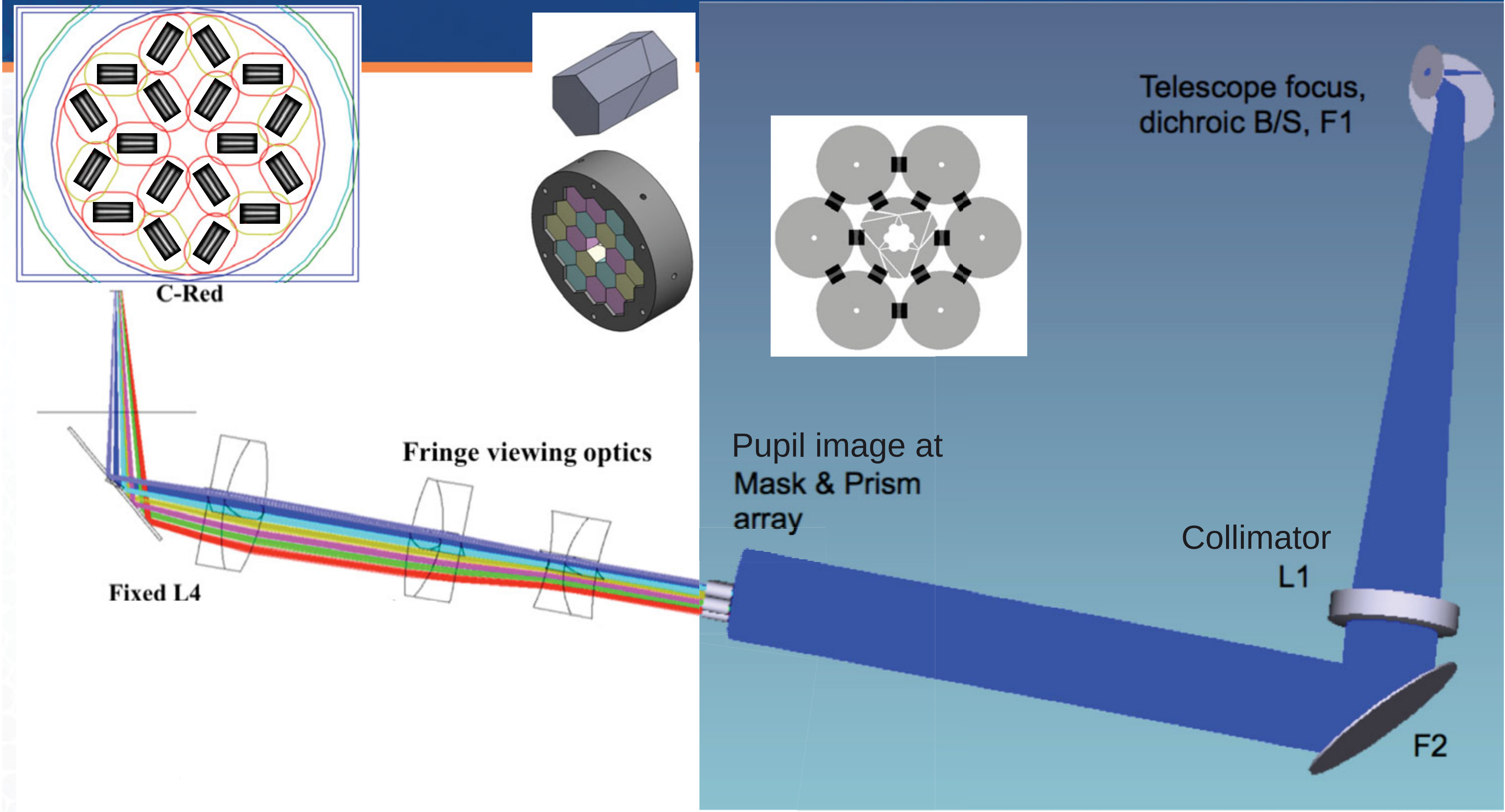
Image formed from subaperture and dispersed

FFT of image



Vertical position of peak by arrow depends linearly with piston error

Implementation of IR Dispersed Fringe Sensor

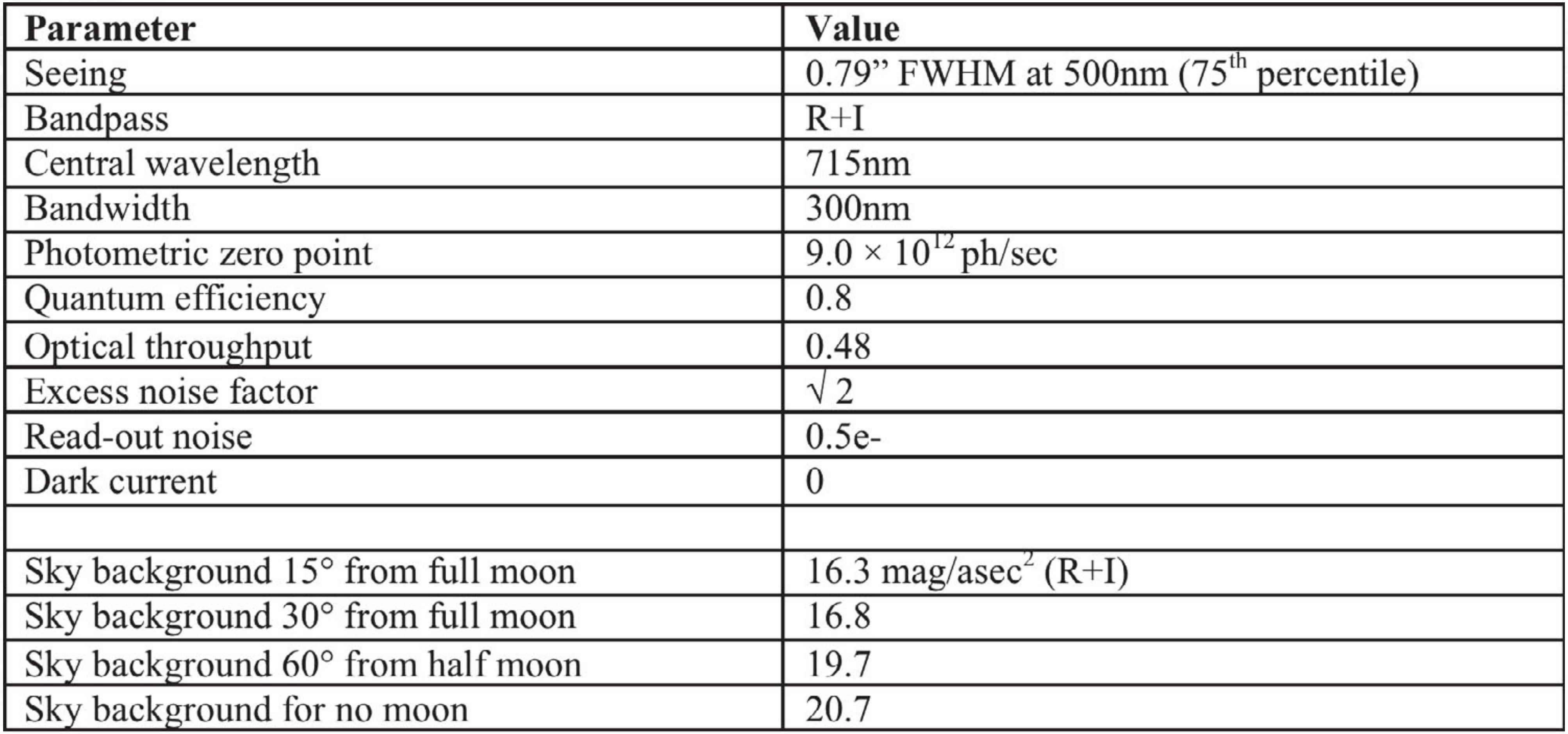


for initial
alignment

SKY COVERAGE SIMULATIONS

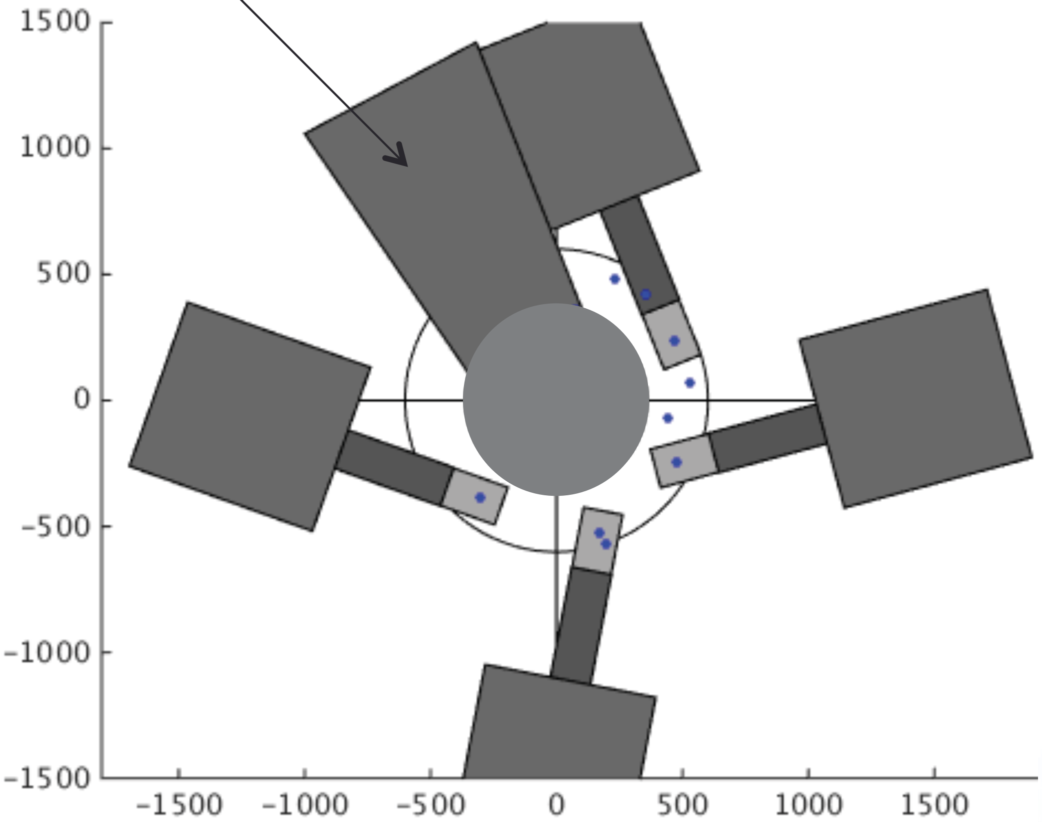
Brian McLeod

Visible Sky Coverage Calculation Assumptions



Parameter	Value
Seeing	0.79” FWHM at 500nm (75th percentile)
Bandpass	R+I
Central wavelength	715nm
Bandwidth	300nm
Photometric zero point	9.0×10^{12} ph/sec
Quantum efficiency	0.8
Optical throughput	0.48
Excess noise factor	$\sqrt{2}$
Read-out noise	0.5e-
Dark current	0
Sky background 15° from full moon	16.3 mag/asec^2 (R+I)
Sky background 30° from full moon	16.8
Sky background 60° from half moon	19.7
Sky background for no moon	20.7

Probe Geometry Combined With Star Catalogs



Shadow of M3

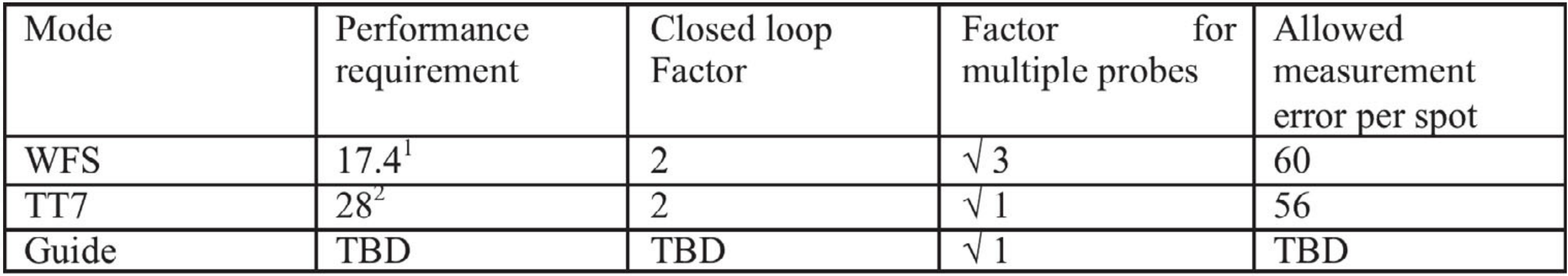
Example star field with R<15th mag

Error That Meets NSIQ Error Budget

- Error budget allocation is 25mas EE80 diameter
- Assumptions:
  - 48x48 subapertures
  - 48 Zernike terms
- Put in random centroid errors. Calculate and apply correction.
- Result: 17mas RMS centroid error is allowed.

Additional Factors Increase Allowed Error

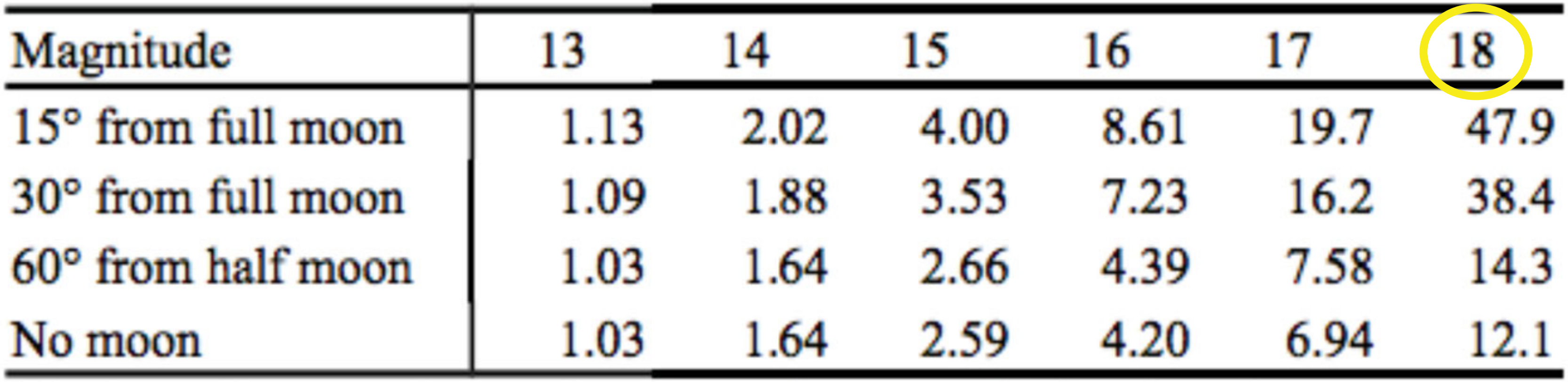
- 3 probes -> 1.7
- Gain of ~0.5 -> 2.0
- Additional aberrations in AGWS and telescope polishing errors -> 0.9



Mode	Performance requirement	Closed loop Factor	Factor for multiple probes	Allowed measurement error per spot
WFS	17.4[1]	2	$\sqrt{3}$	60
TT7	28[2]	2	$\sqrt{1}$	56
Guide	TBD	TBD	$\sqrt{1}$	TBD

Magnitude Limits are TT7: R=16.7, WFS: R>18

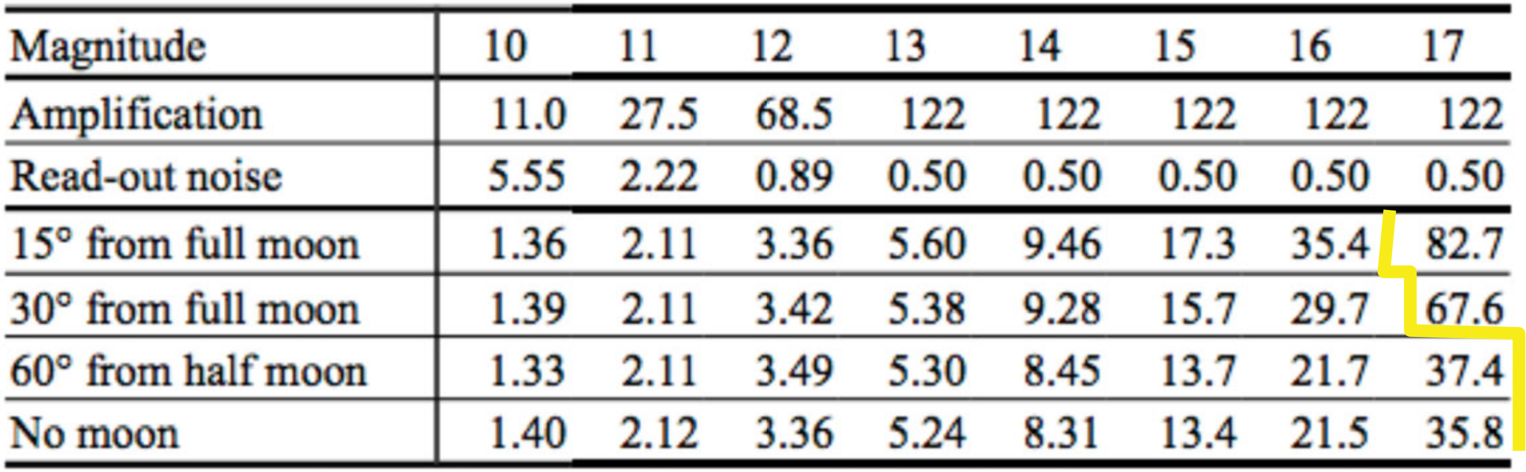
Wavefront sensing mode (req=60mas)



Magnitude	13	14	15	16	17	18
15° from full moon	1.13	2.02	4.00	8.61	19.7	47.9
30° from full moon	1.09	1.88	3.53	7.23	16.2	38.4
60° from half moon	1.03	1.64	2.66	4.39	7.58	14.3
No moon	1.03	1.64	2.59	4.20	6.94	12.1

Table 6: RMS centroid error (mas) as a function of R-band guide star magnitude

TT7 mode (req=56mas)

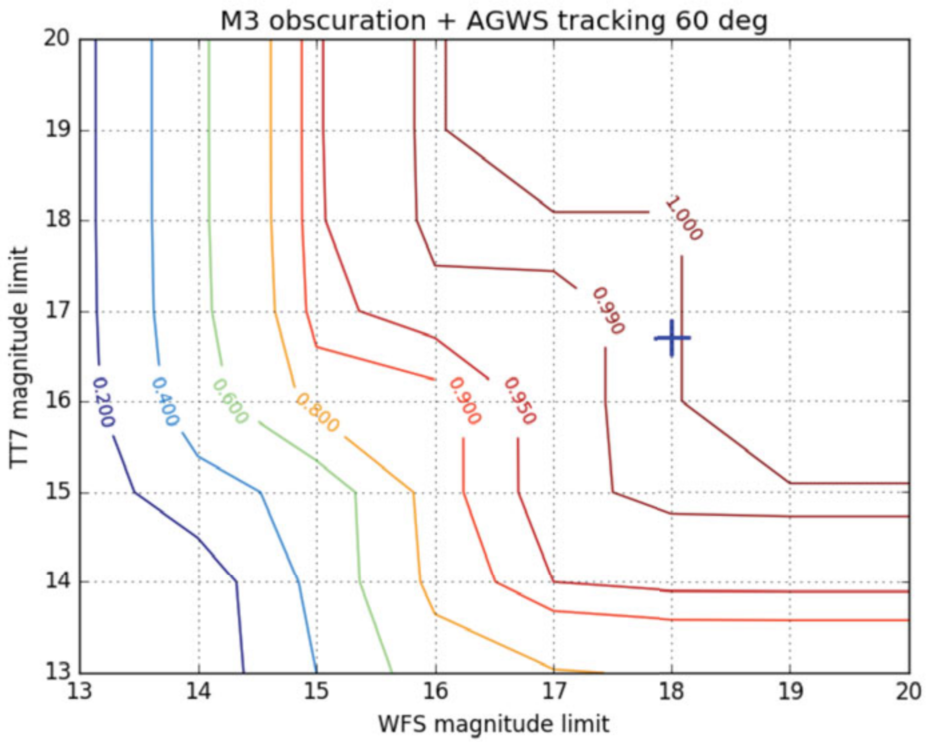


Magnitude	10	11	12	13	14	15	16	17
Amplification	11.0	27.5	68.5	122	122	122	122	122
Read-out noise	5.55	2.22	0.89	0.50	0.50	0.50	0.50	0.50
15° from full moon	1.36	2.11	3.36	5.60	9.46	17.3	35.4	82.7
30° from full moon	1.39	2.11	3.42	5.38	9.28	15.7	29.7	67.6
60° from half moon	1.33	2.11	3.49	5.30	8.45	13.7	21.7	37.4
No moon	1.40	2.12	3.36	5.24	8.31	13.4	21.5	35.8

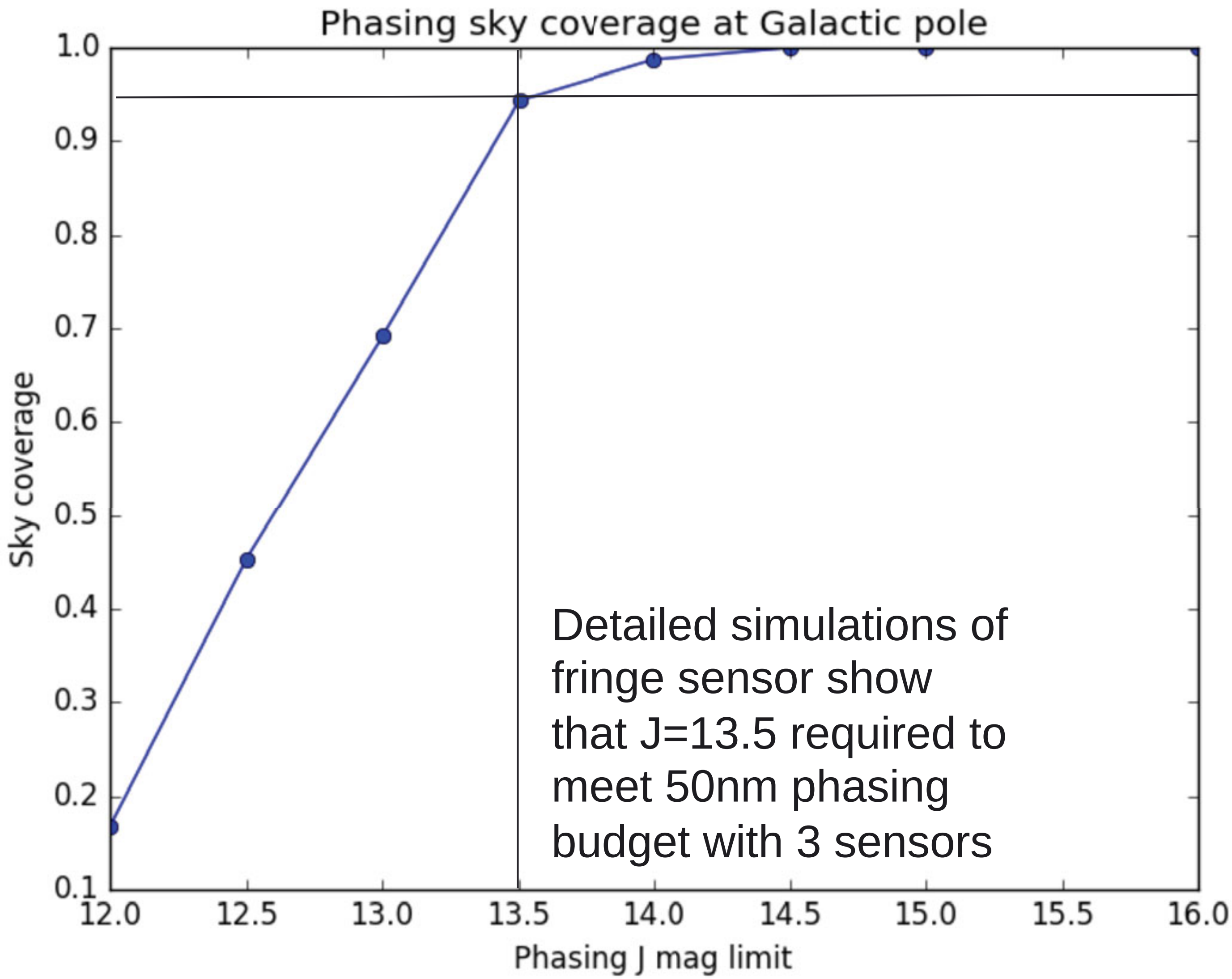
Table 8: RMS centroid error (mas) as a function of R-band guide star magnitude in TT7 mode

Natural Seeing Sky Coverage Is >99%

- At Galactic Pole
- With AGWS tracking
- 15 deg from full moon
- 75% seeing



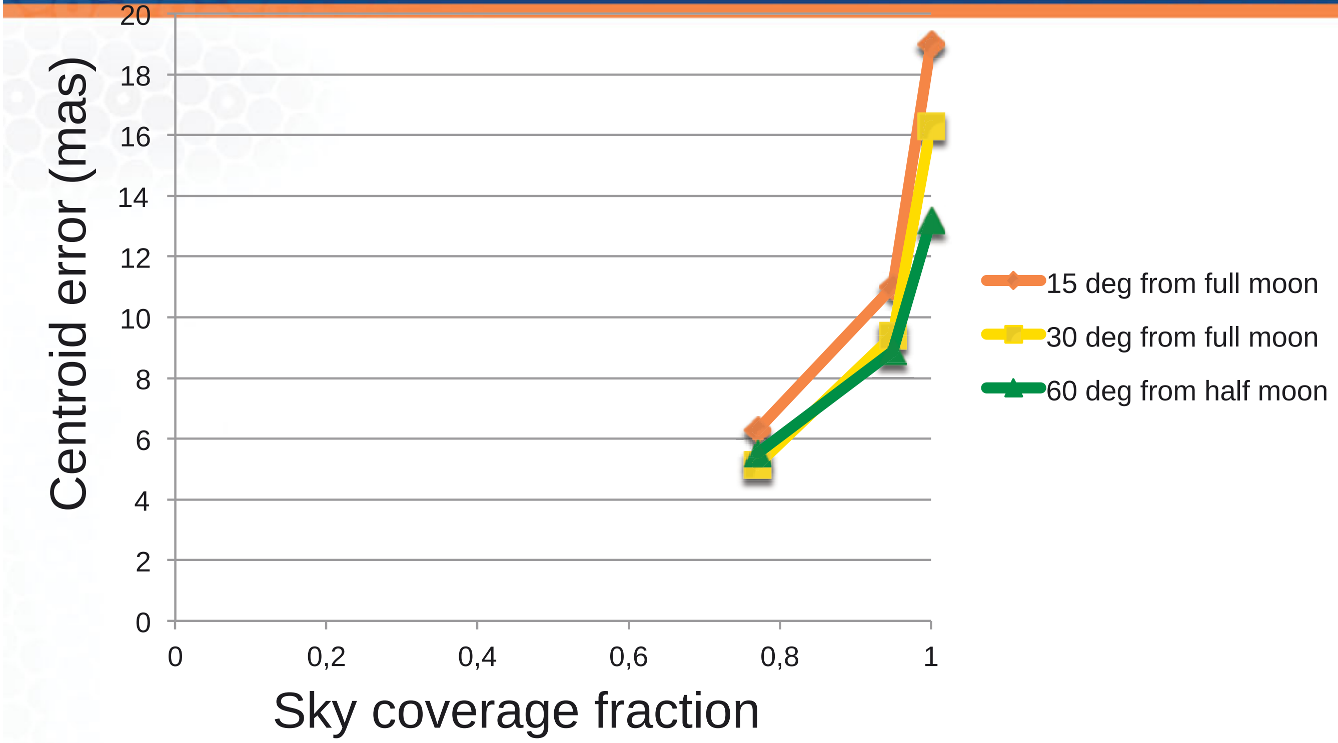
Phasing Sky Coverage Just Meets Requirement



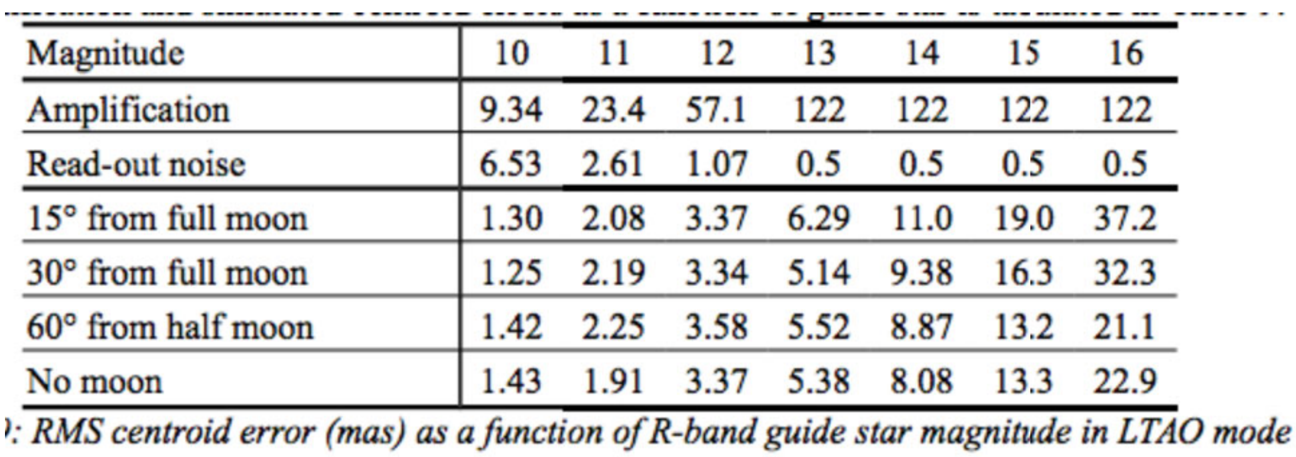
95% sky coverage required by AO specs

Detailed simulations of fringe sensor show that J=13.5 required to meet 50nm phasing budget with 3 sensors

Guide Mode Used to Mitigate LTAO Windshake

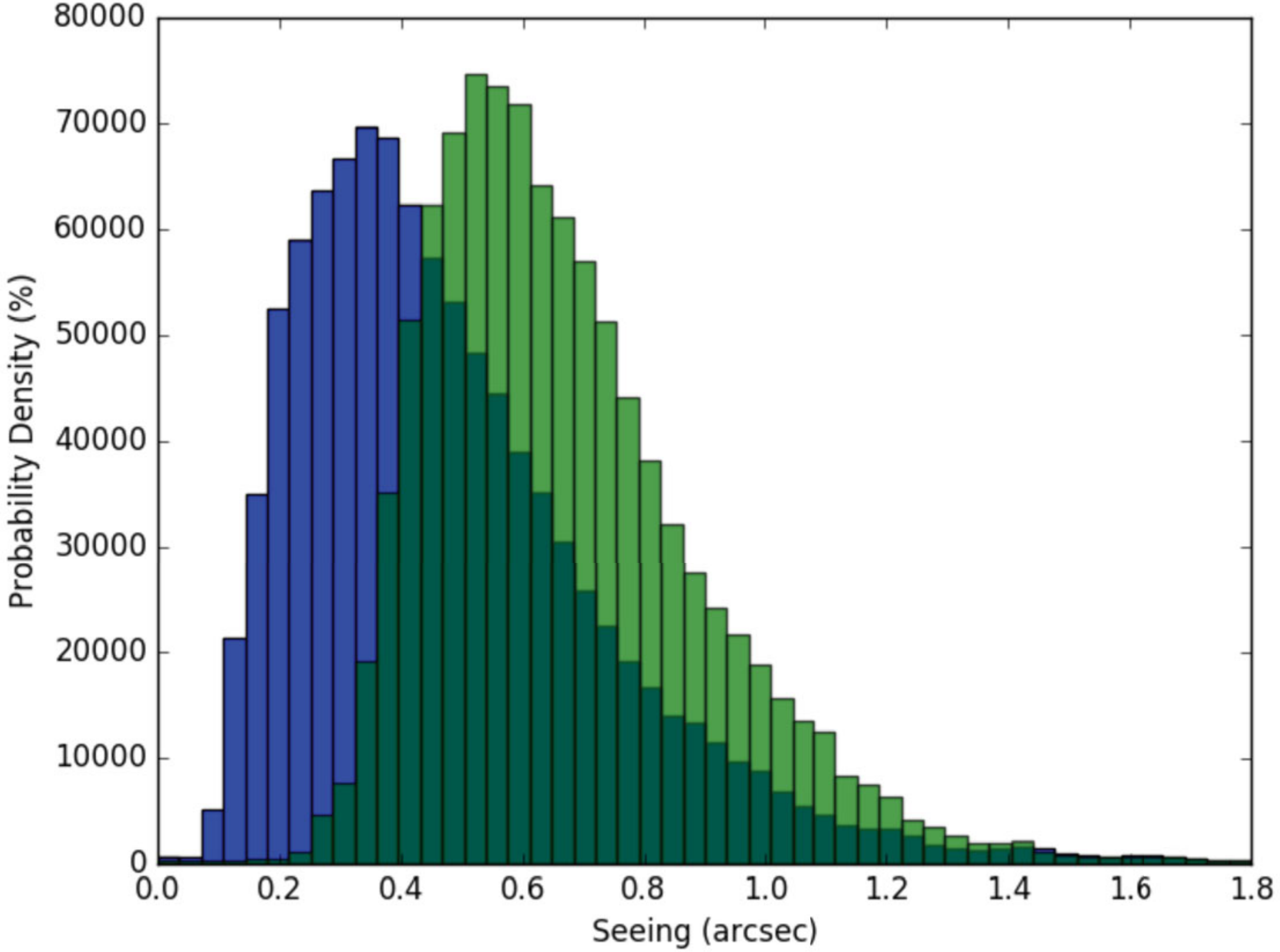


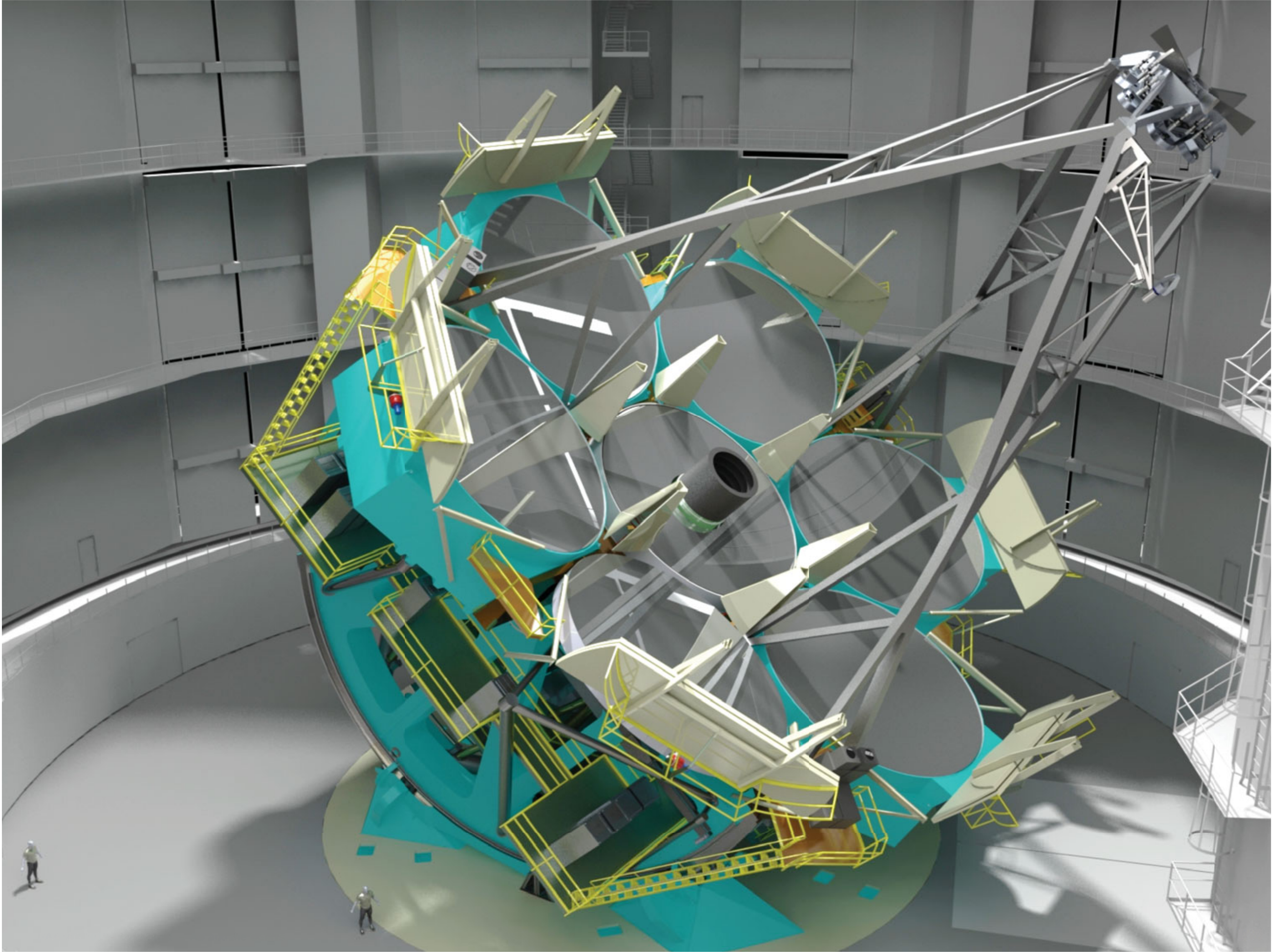
- Effective r_0=11cm due to anisoplanatism with actual r_0=15cm and on-axis AO
- Full aperture guider located 10’ off-axis
- 0.7msec integration time



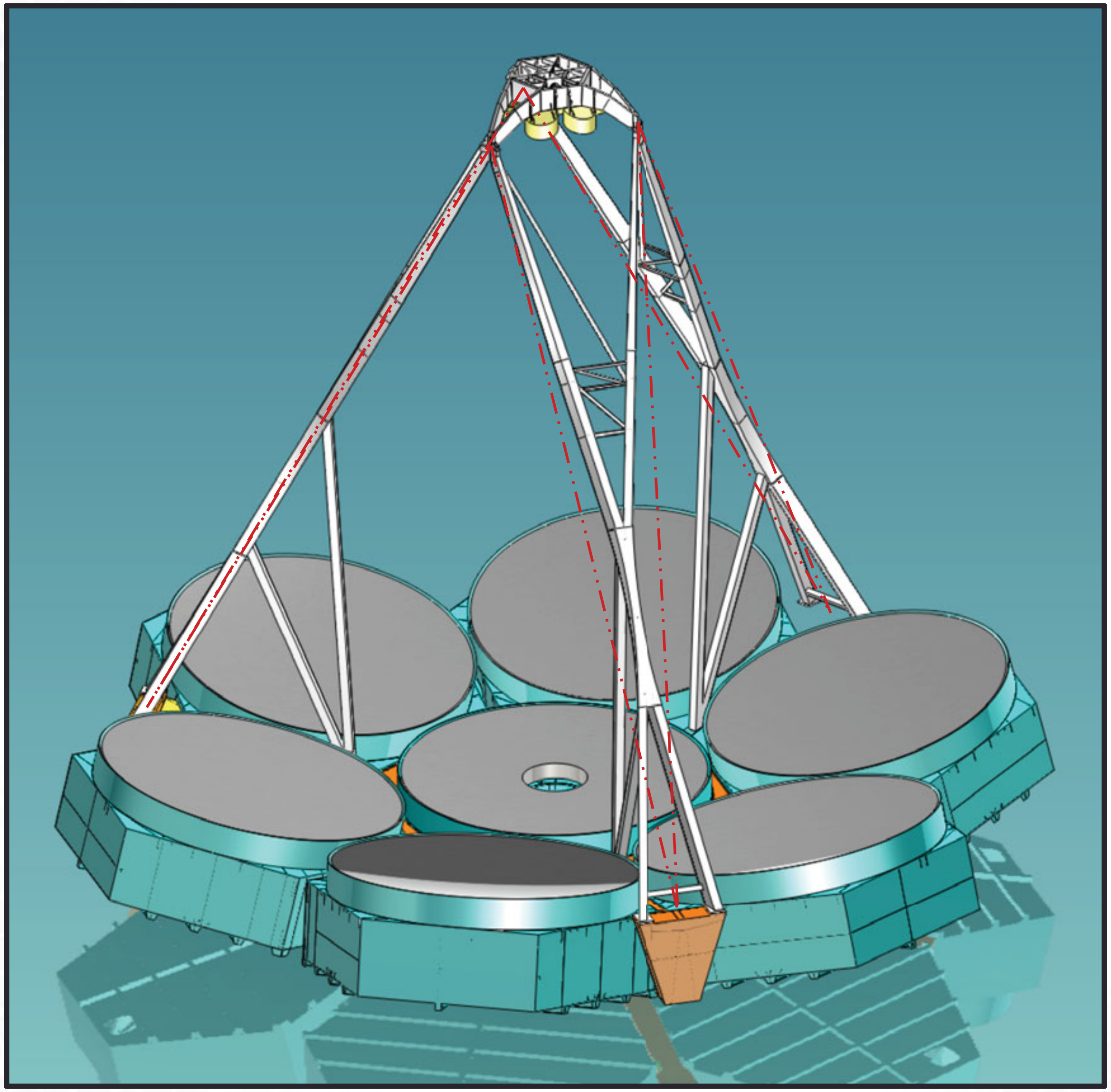
Magnitude	10	11	12	13	14	15	16
Amplification	9.34	23.4	57.1	122	122	122	122
Read-out noise	6.53	2.61	1.07	0.5	0.5	0.5	0.5
15° from full moon	1.30	2.08	3.37	6.29	11.0	19.0	37.2
30° from full moon	1.25	2.19	3.34	5.14	9.38	16.3	32.3
60° from half moon	1.42	2.25	3.58	5.52	8.87	13.2	21.1
No moon	1.43	1.91	3.37	5.38	8.08	13.3	22.9

: RMS centroid error (mas) as a function of R-band guide star magnitude in LTAO mode


Probability Density (%)
80000
70000
60000
50000
40000
30000
20000
10000
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
Seeing (arcsec)

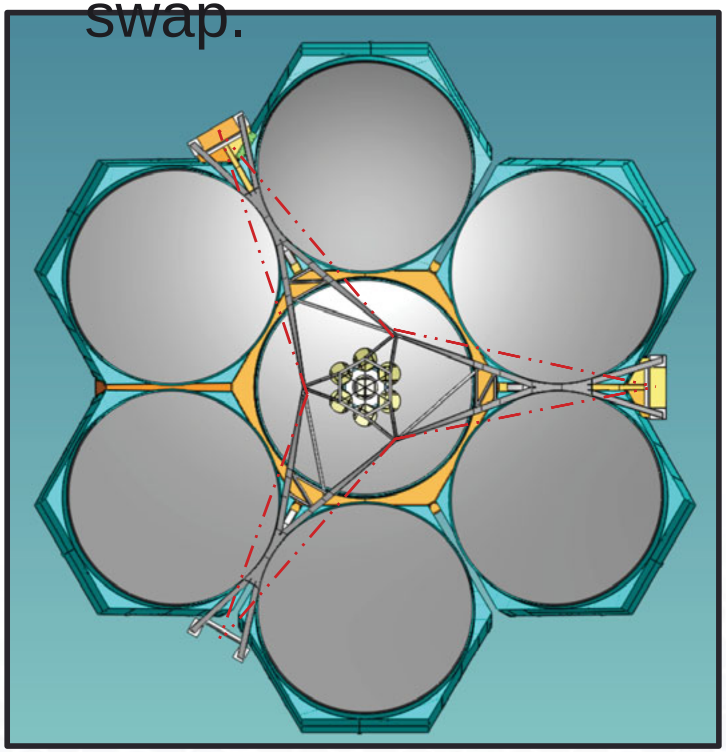


Secondary Truss



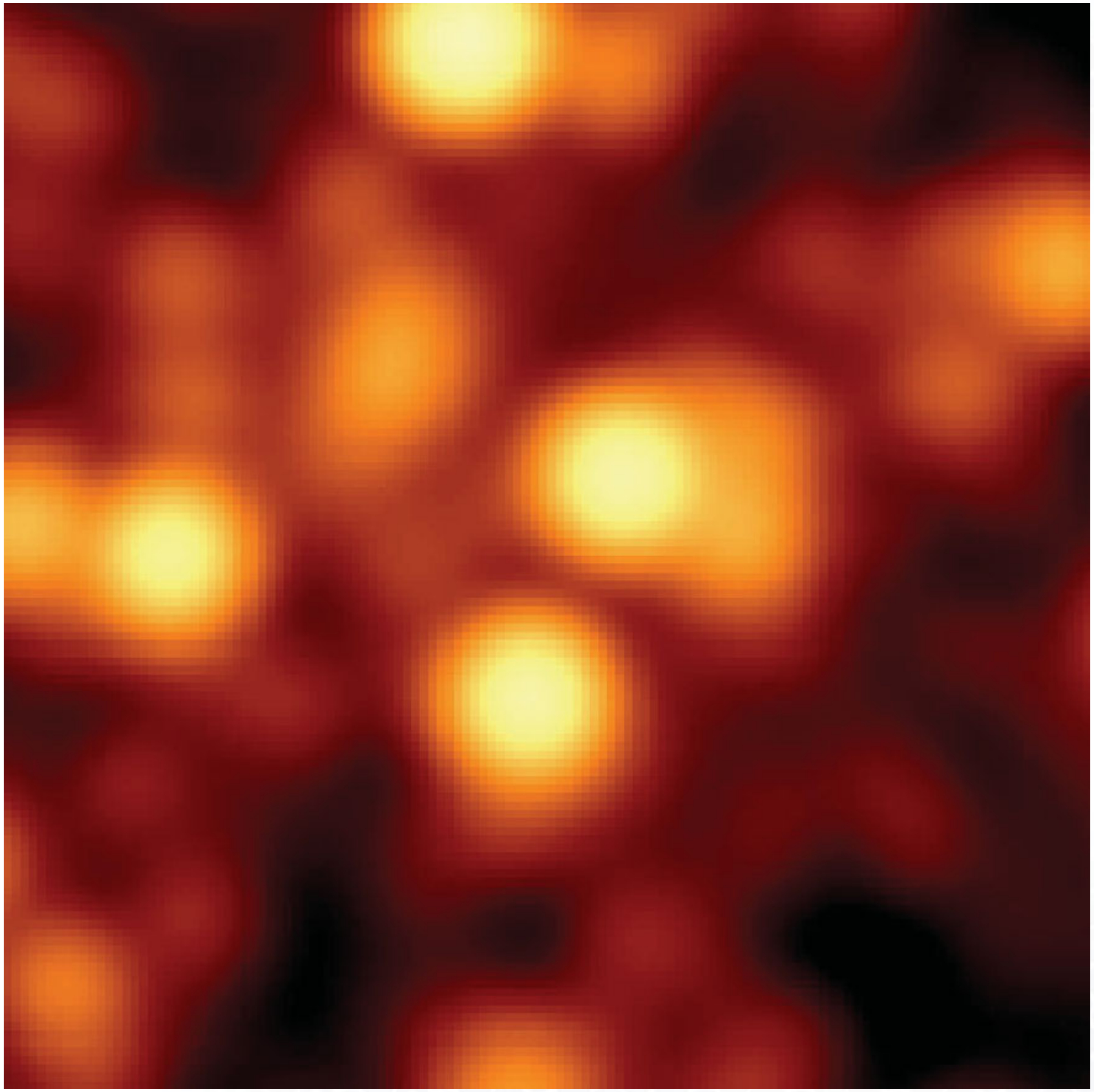
"Braced Hexapod"

- Supports M2 Assembly
- Stiff, lightweight,
- Low wind area,
- Blocks very little light
- Accommodates cell swap.



GMT Image Simulations

Natural Seeing 0.6”



Natural seeing at GMT site:

0.40 arcsec resolution (1.65 µm)

Diffraction-limited resolution:

0.013 arcsec resolution

- 30x higher resolution
- ~40x higher point-source sensitivity*
- >100x higher contrast near bright stars

C. Peng

GMT Image Simulations

Natural seeing at GMT site:

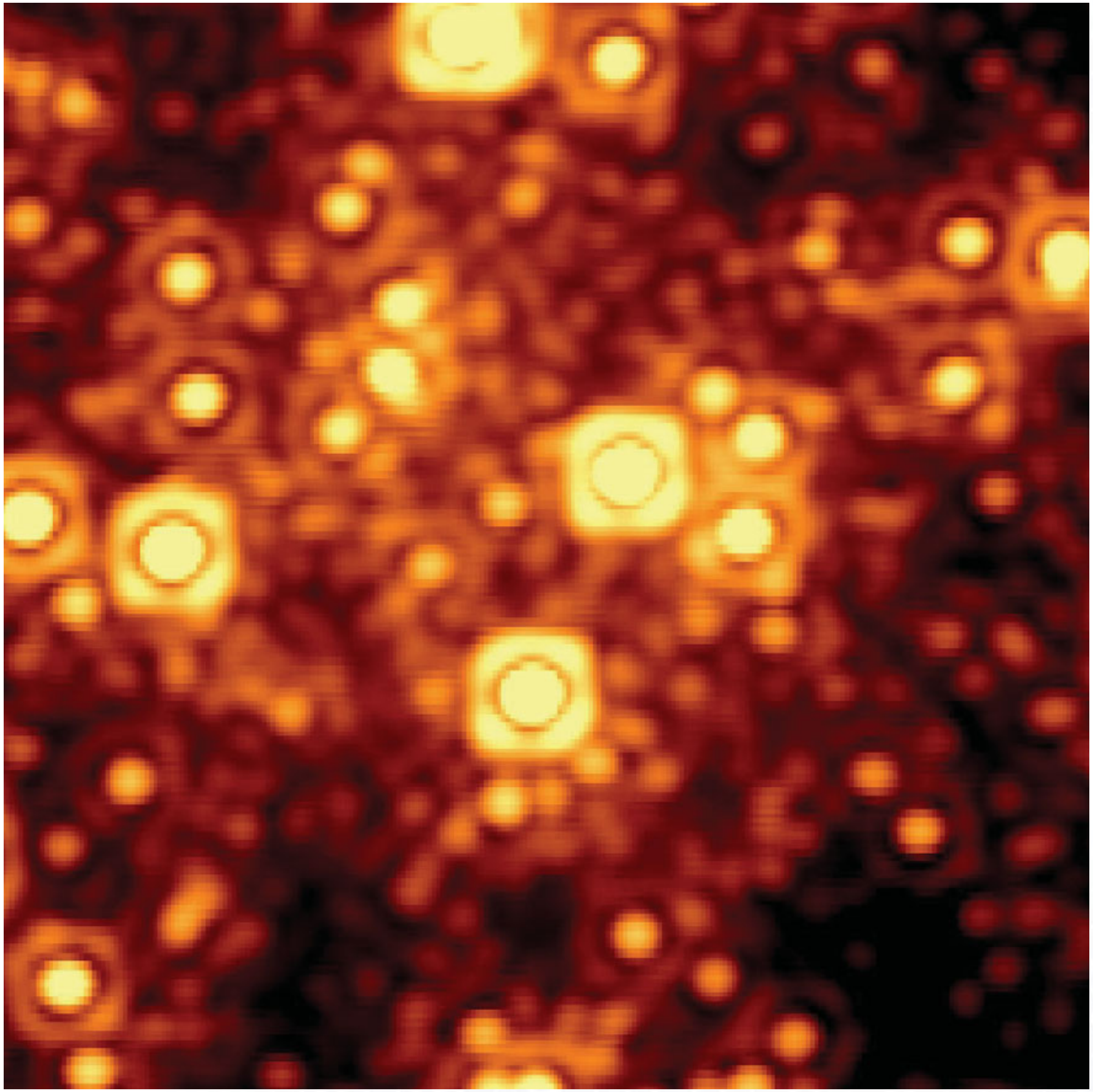
0.40 arcsec resolution (1.65 µm)

Diffraction-limited resolution:

0.013 arcsec resolution

- 30x higher resolution
- ~40x higher point-source sensitivity*
- >100x higher contrast near bright stars

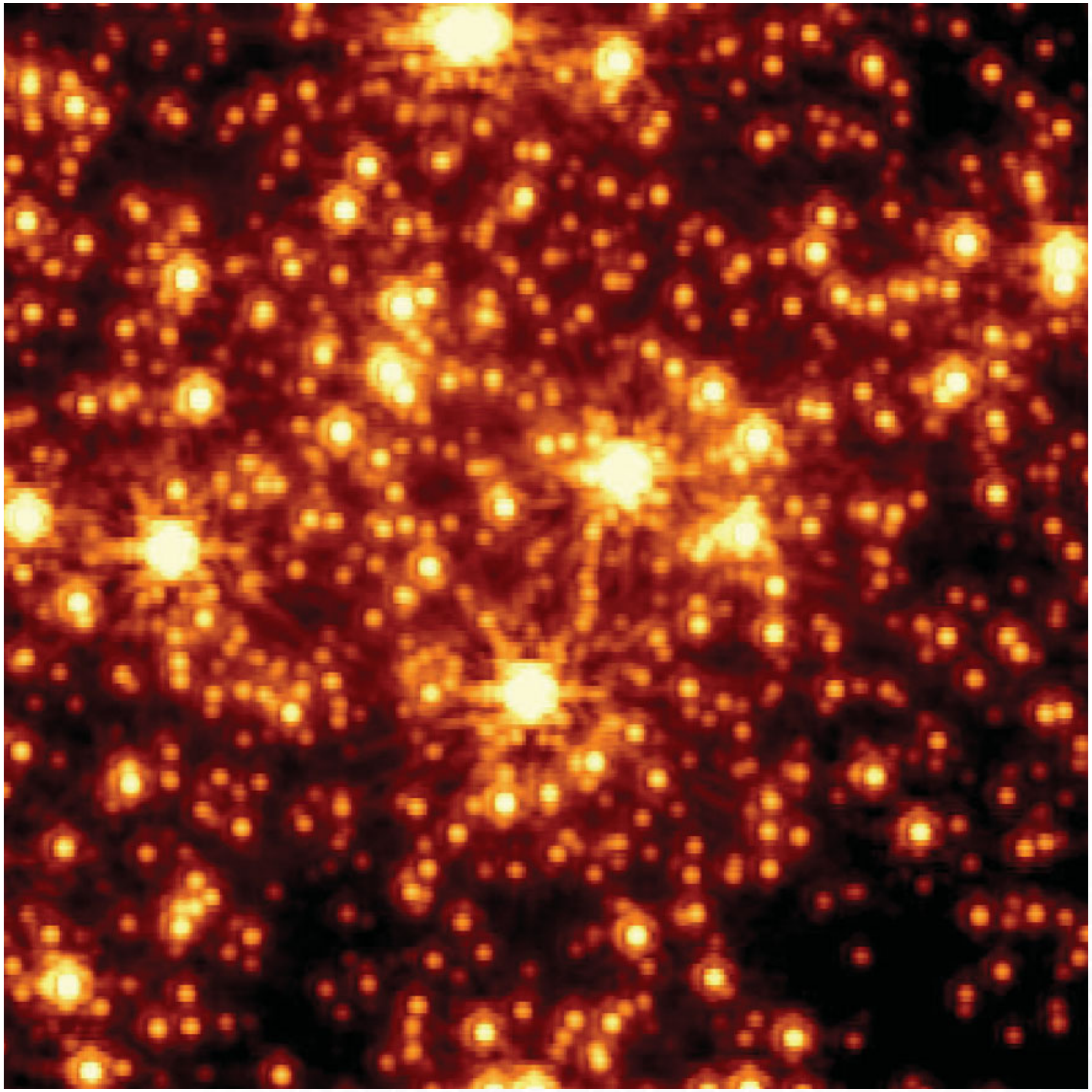
HST/NICMOS



C. Peng

GMT Image Simulations

JWST NIRCAM



Natural seeing at GMT site:

0.40 arcsec resolution
(1.65 µm)

Diffraction-limited resolution:

0.013 arcsec
resolution

- 30x higher resolution
- ~40x higher point-source sensitivity*
- >100x higher contrast near bright stars

C. Peng

GMT Image Simulations

Natural seeing at GMT site:

0.40 arcsec resolution
(1.65 µm)

Diffraction-limited resolution:

0.013 arcsec resolution

- 30x higher resolution
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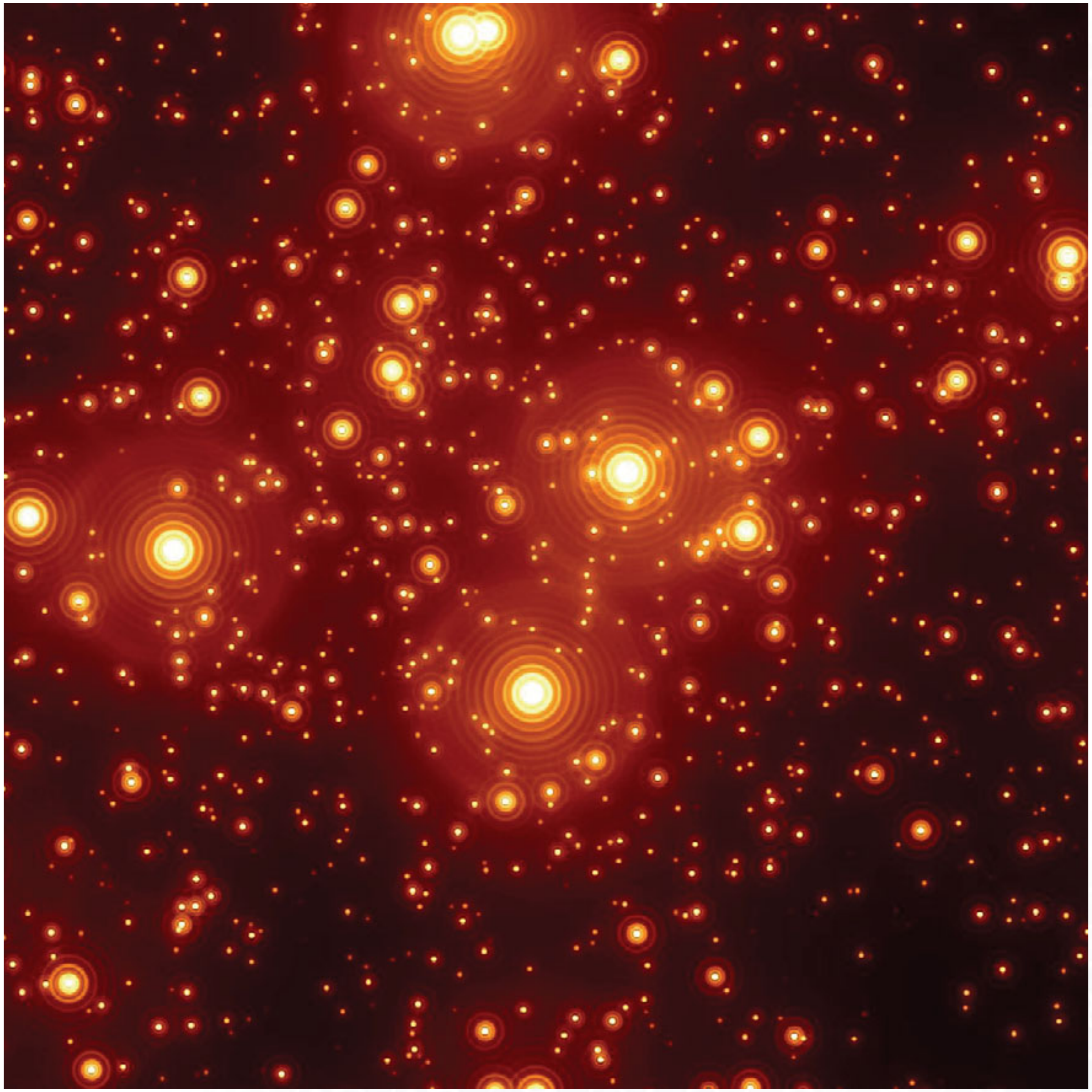
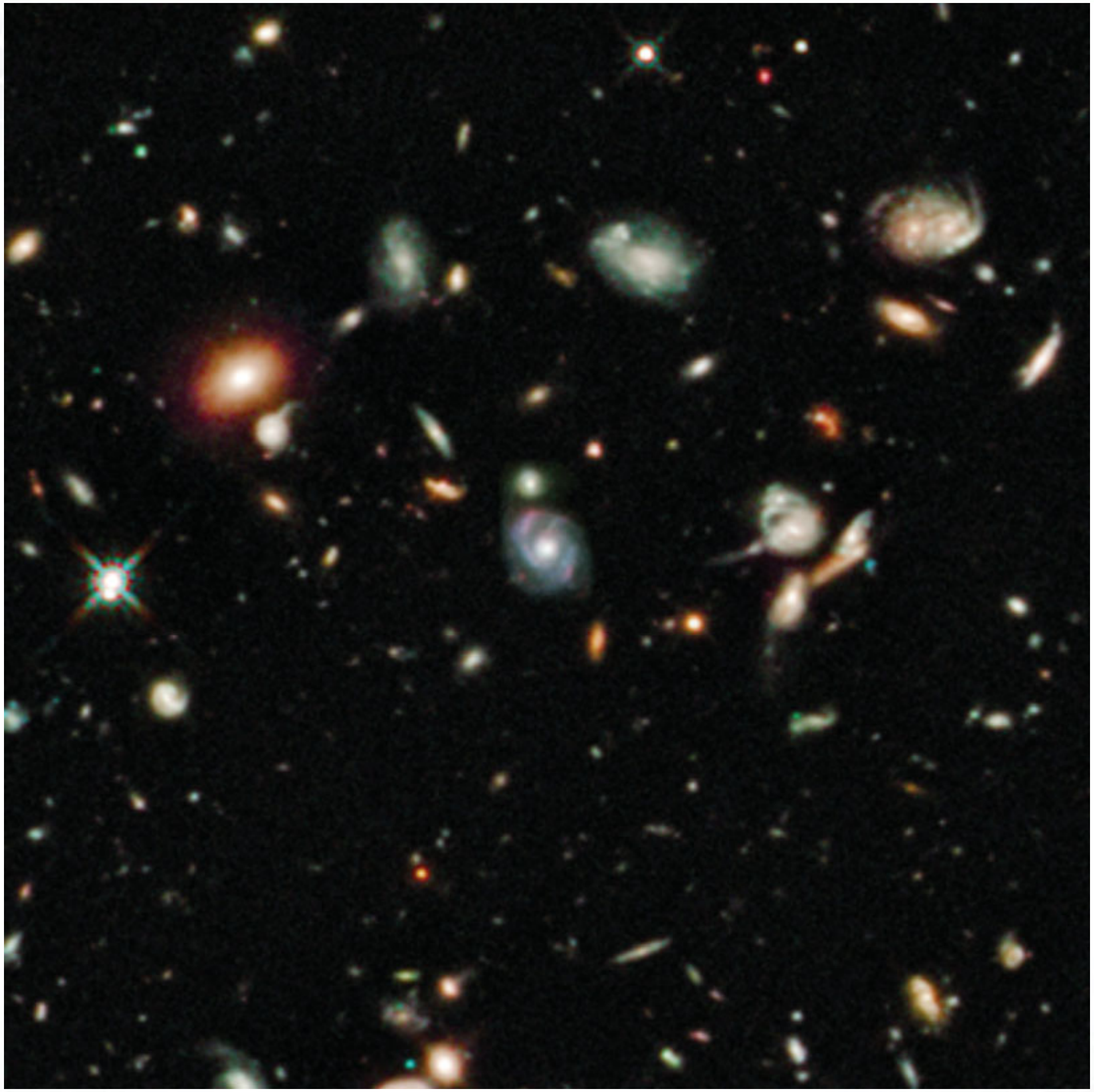
- >100x higher contrast near bright stars

C. Peng



GMT K-Filter, Strehl: 80%

GMT Image Simulations



For Harvard Magazine

Phasing Strategy
2) AGWS Dispersed Fringe Sensor

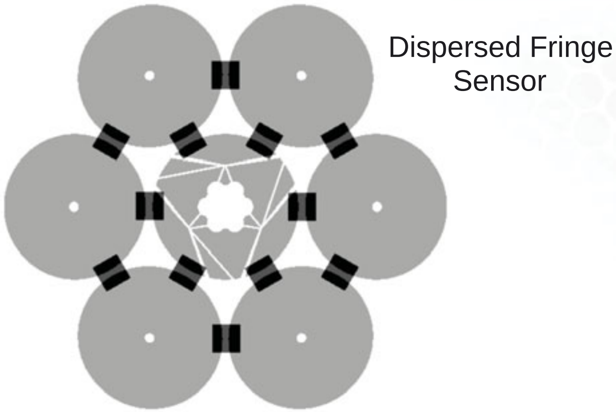
1. Telescope laser metrology truss provides initial alignment to ±10 μm (3σ) wavefront
2. Telescope is phased and maintained phased at low bandwidth (~0.01 Hz) by the AGWS
    - 30 s frame rate
    - ≤50 nm RMS accuracy at 90% sky coverage
    - ±40 μm wavefront capture range

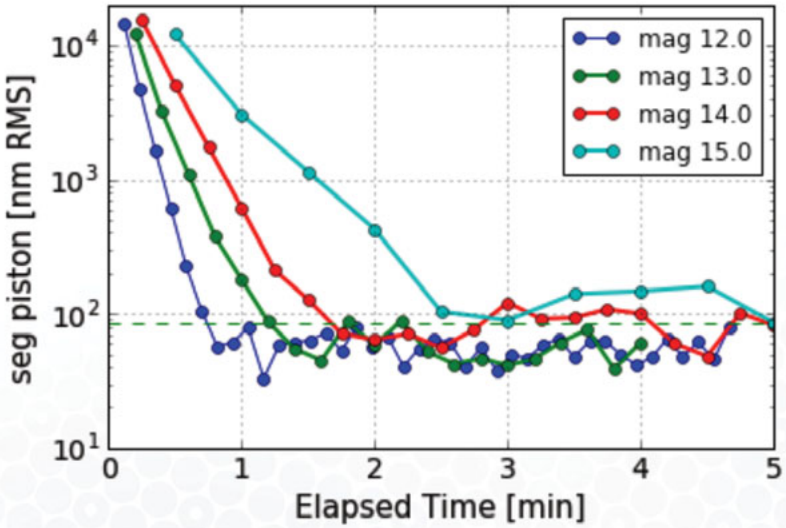
3a. NGAO Mode

- Pyramid WFS controls telescope and atmospheric segment piston error on-axis (~30 nm RMS)

3b. LTAO Mode

- Atmospheric piston error not controlled
- Wind buffeting and vibration are controlled by feed-forward from M1 and M2 edge sensors to ASM





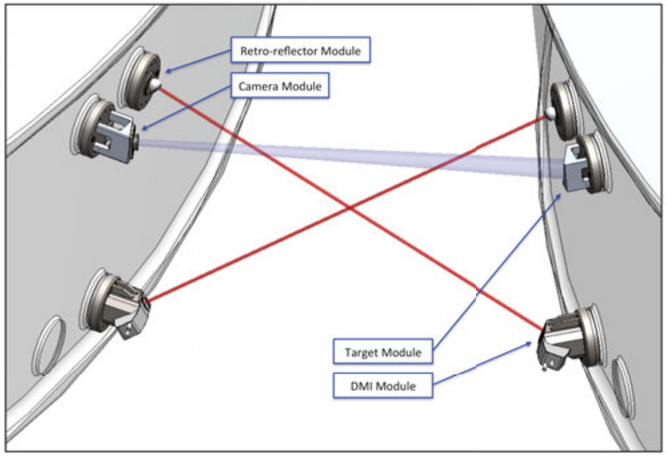
Phasing Strategy
3b) M1 & M2 Edge Sensors (LTAO)

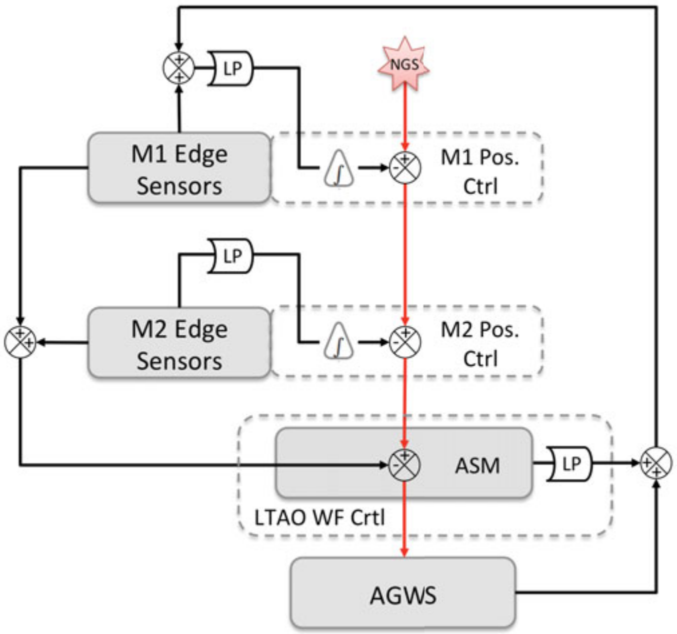
1. Telescope laser metrology truss provides initial alignment to ±10 μm (3σ) wavefront

2. Telescope is phased and maintained phased at low bandwidth (~0.01 Hz) by the AGWS
   - 30 s frame rate
   - ≤50 nm RMS accuracy at 90% sky coverage
   - ±40 μm wavefront capture range

3a. NGAO Mode
   - Pyramid WFS controls telescope and atmospheric segment piston error on-axis (~30 nm RMS)

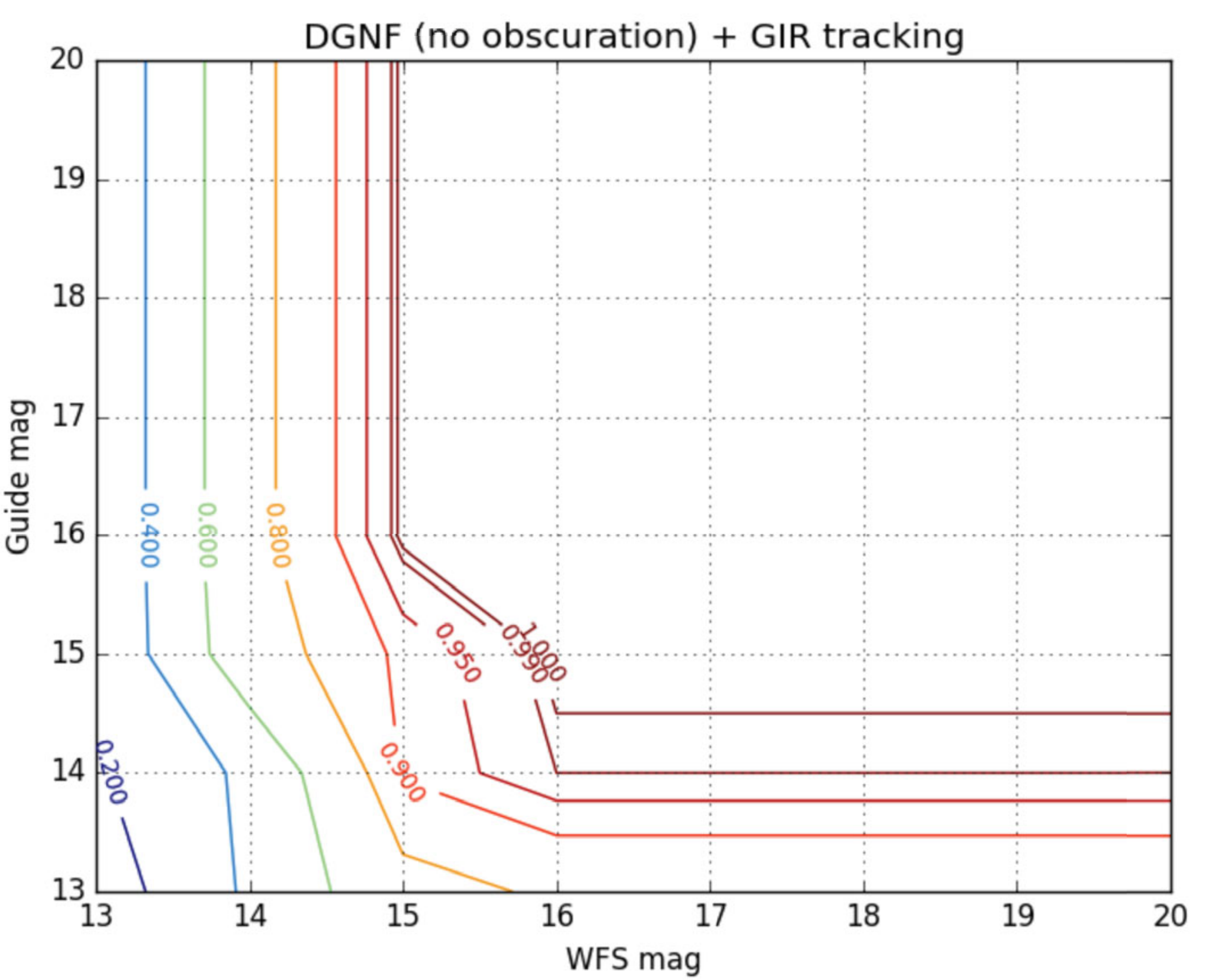
3b. LTAO Mode
   - Atmospheric piston error not controlled
   - Wind buffeting and vibration are controlled by feed-forward from M1 and M2 edge sensors to ASM


M1 Edge Sensor Unit



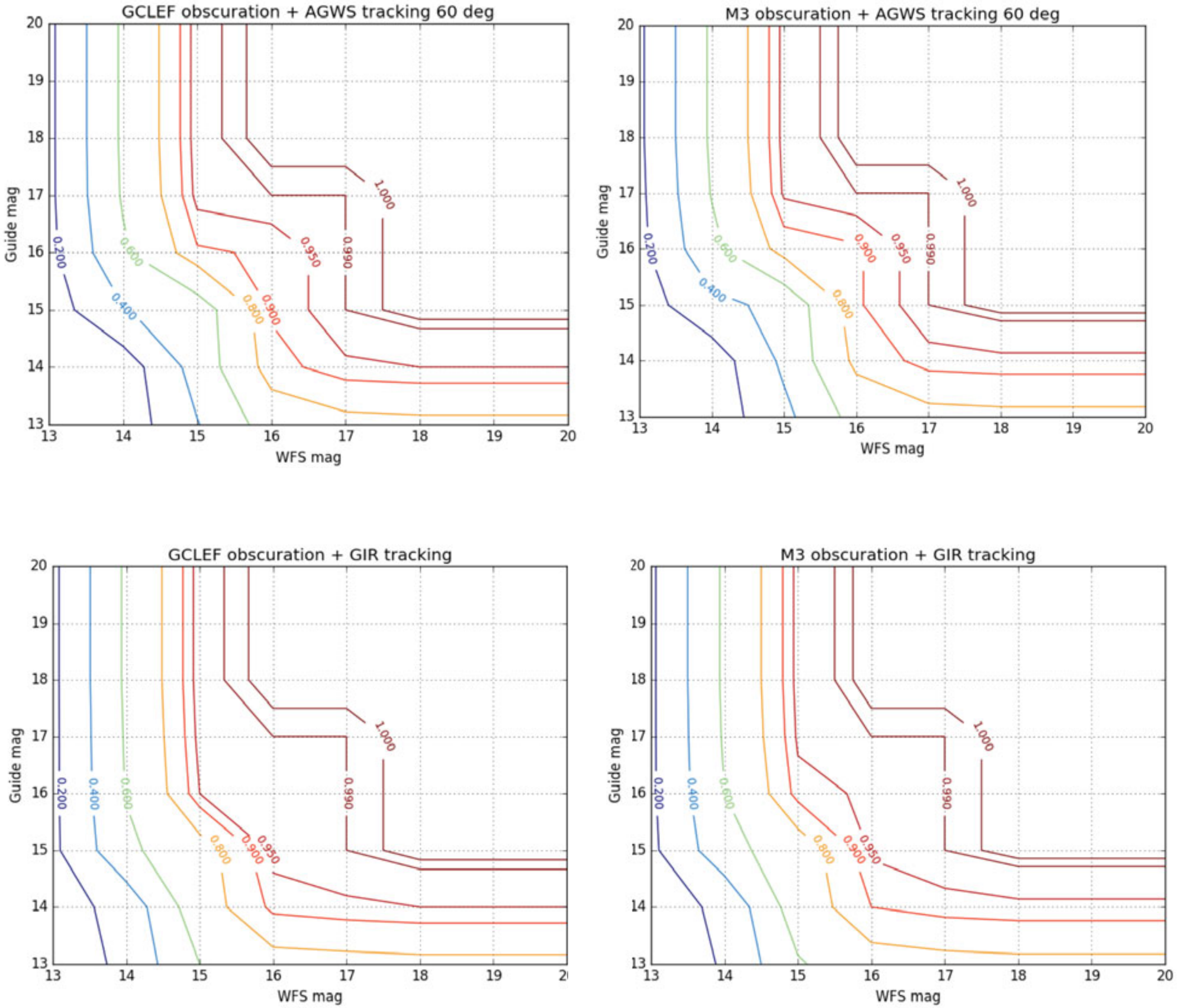
Probabi

One star of this magnitude for segment guiding



And three stars of this magnitude for wavefront sensing, at the South Galactic Pole

Sky Coverage Computed For Each Mode



Topics:

- What do telescopes do and how?
  - Mirrors (collect and focus light)
  - Structures (point and follow targets, support optics)
  - Challenges and limitations
    - Telescope optics 101
    - Strategies of the 3 GSMTs

    - Strategies of the 3 GSMTs
- What do instruments do and how?
  - Instruments optics 101
    - Basic scaling relations for instruments.
    - Challenges and limitations
  - Strategies of the 3 GSMTs

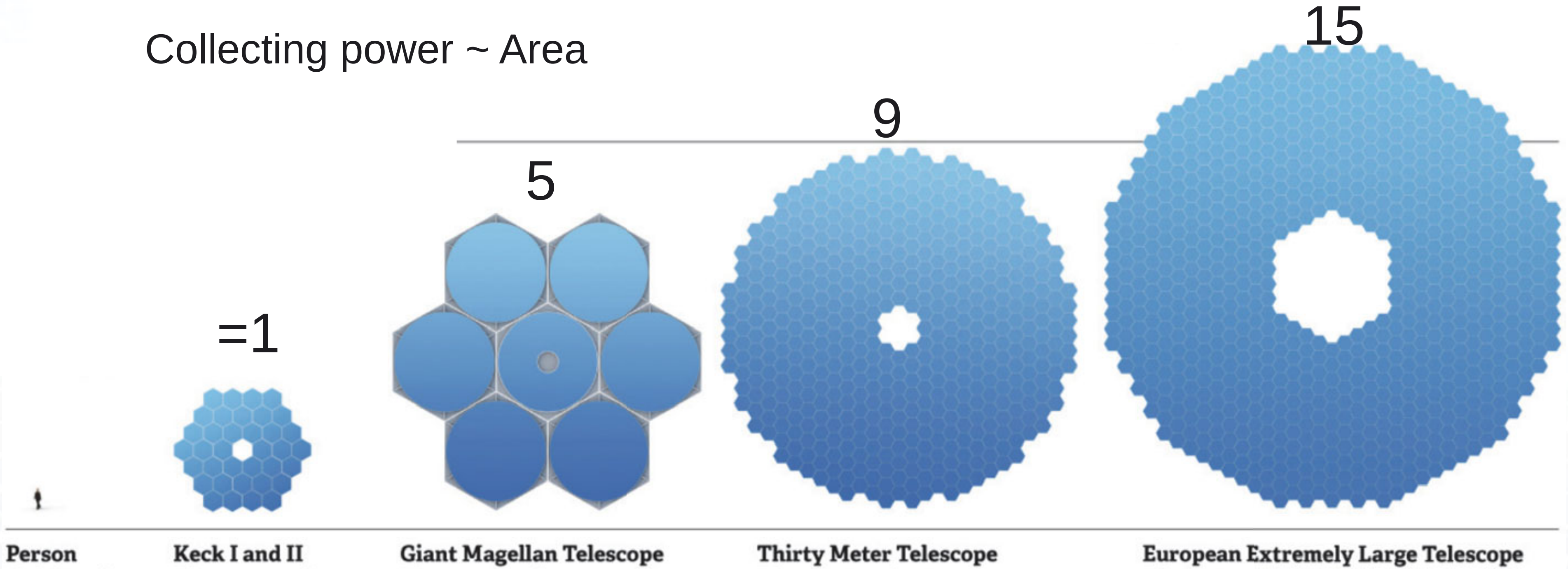
- GSMT Comparison

New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Collecting power: primary mirror area (~D^2)

    …but throughput goes *down* with the number of mirrors

Collecting power ~ Area



New science with new capabilities:

- Increased sensitivity: LIGHT!
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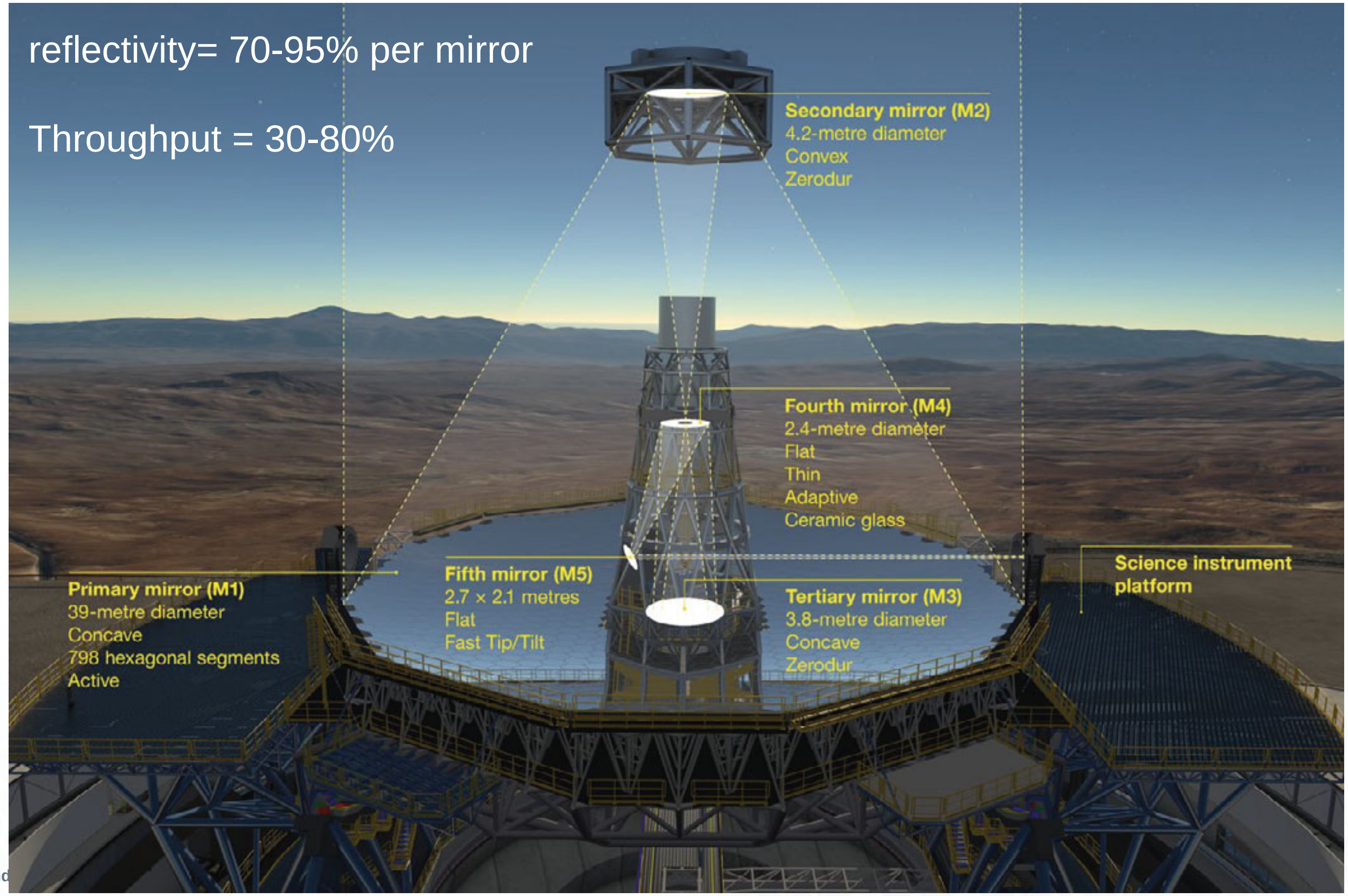
  …but throughput goes *down* with the number of mirrors



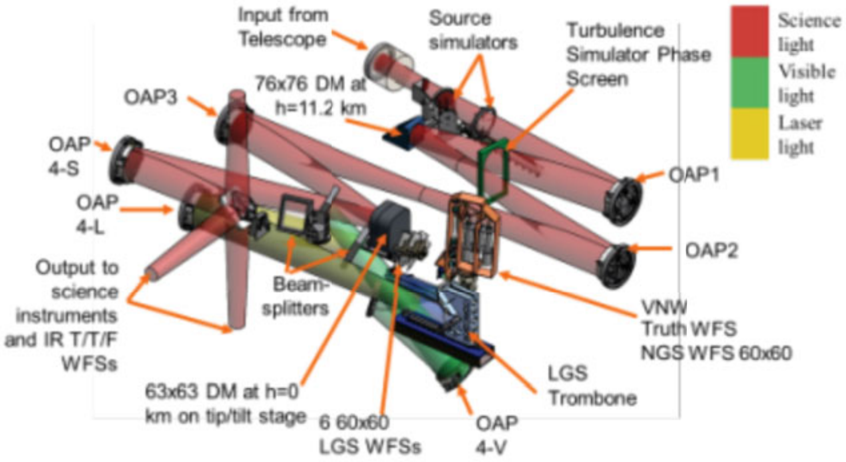
reflectivity= 70-95% per mirror

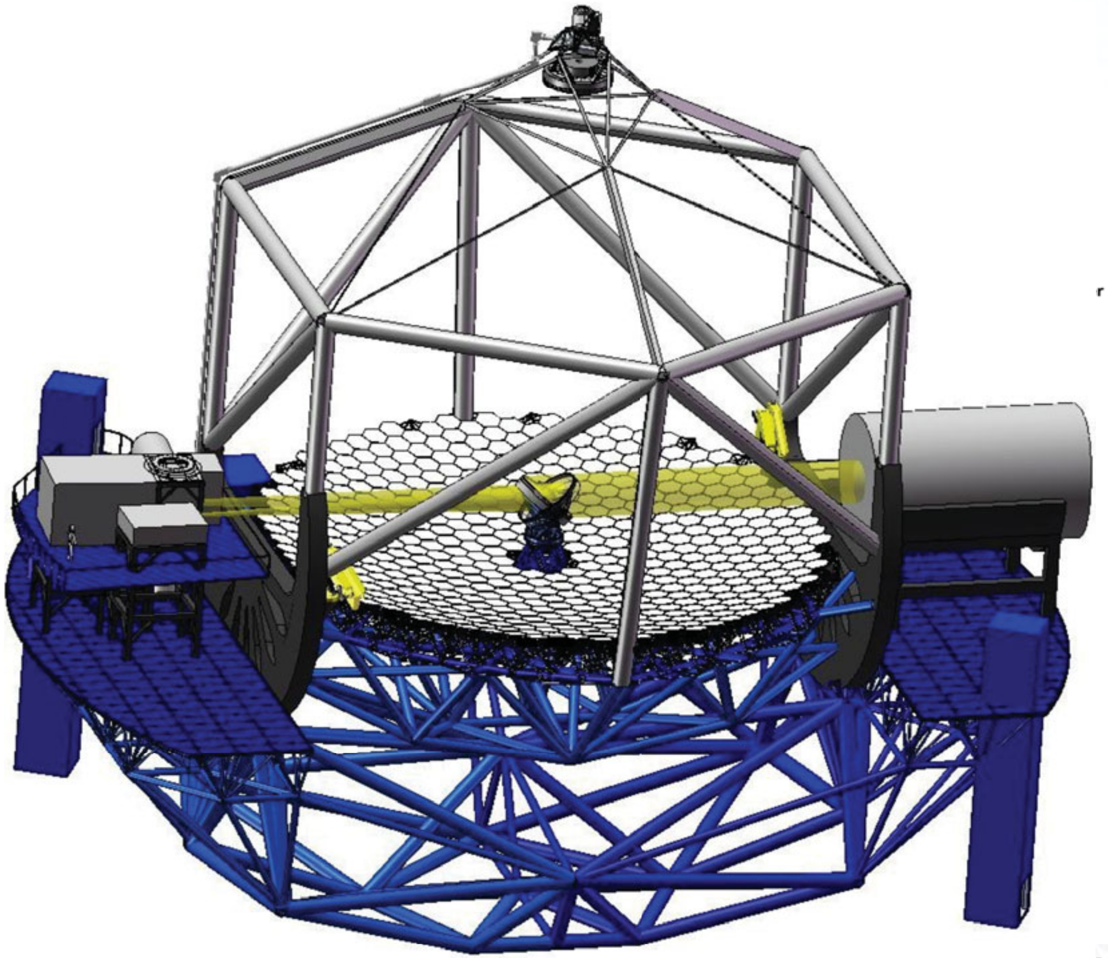
Throughput = 30-80%

New science with new capabilities:

- Increased sensitivity: LIGHT!
  - Collecting power: primary mirror area (~D^2)

    …but throughput goes *down* with the number of mirrors

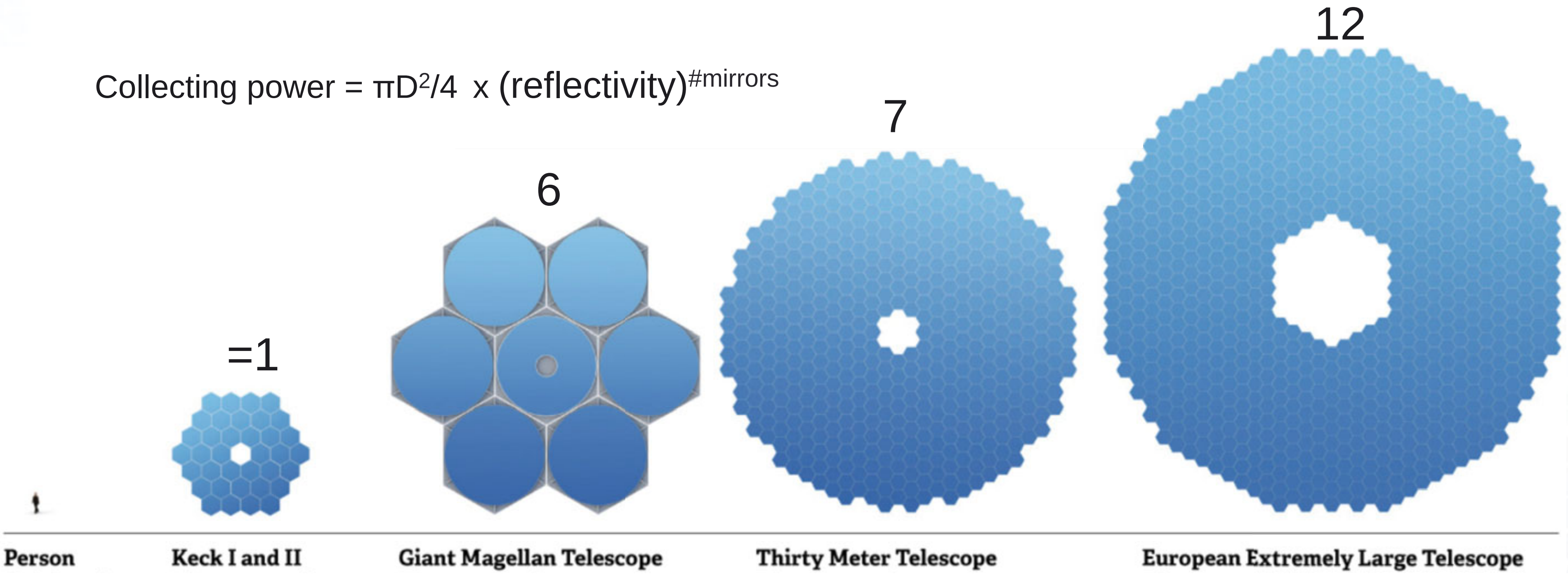




New science with new capabilities:

- Increased sensitivity: LIGHT!
  - ~~Collecting power: primary mirror area (~D^2)~~
  - Total collecting power: gets better with D^2, gets worse with # mirrors

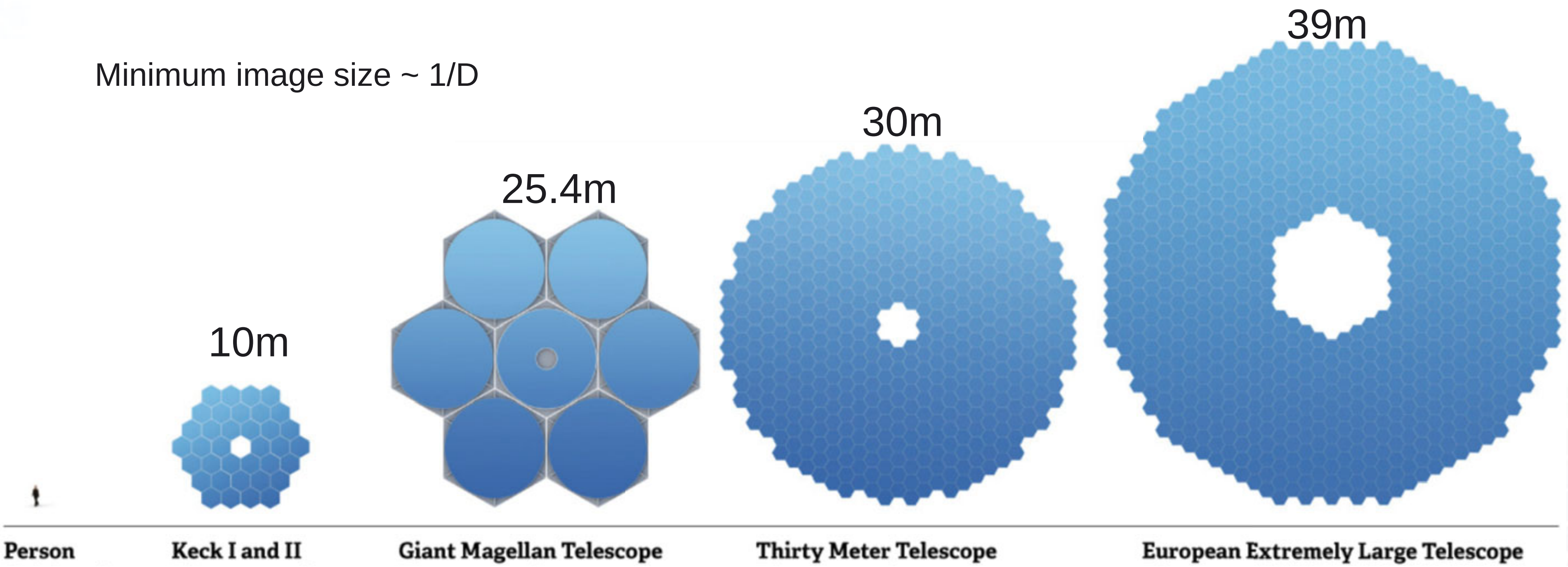
Collecting power = $\pi D^2/4$ x $(\text{reflectivity})^{\#\text{mirrors}}$



New science with new capabilities:

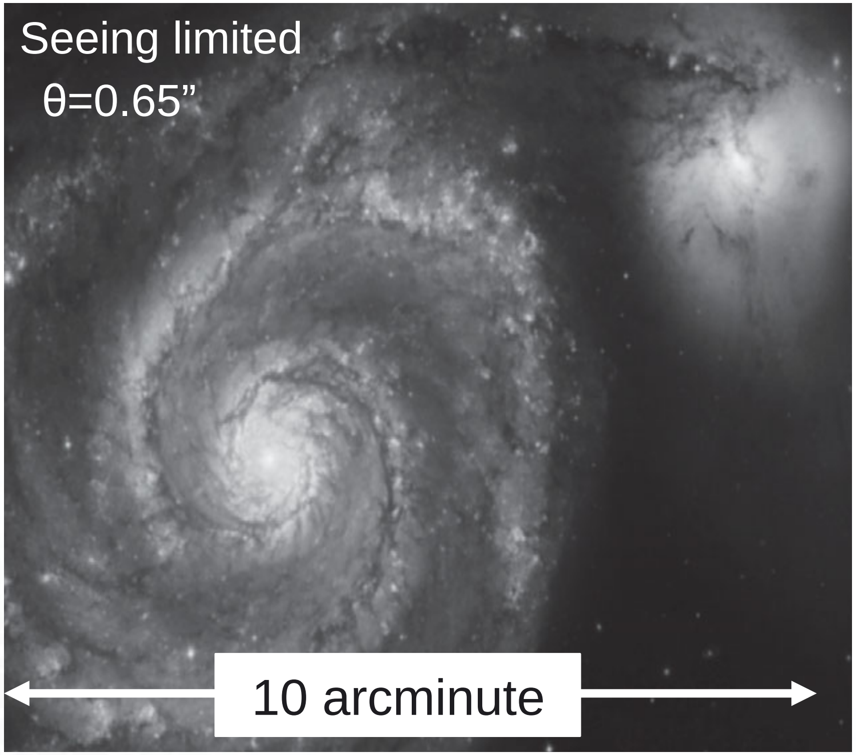
- Increased sensitivity: LIGHT!
  - Total collecting power: gets better with D^2, gets worse with # mirrors
- Increased angular resolution: sharper images
  - Diffraction limit (smallest possible image): gets better with D

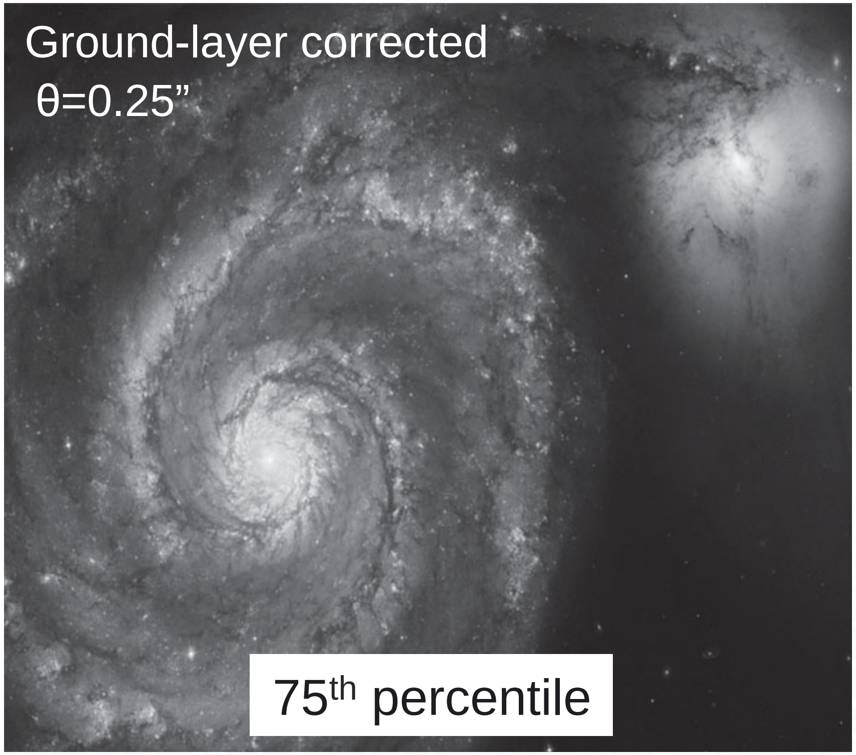
Minimum image size ~ 1/D



New science with new capabilities:

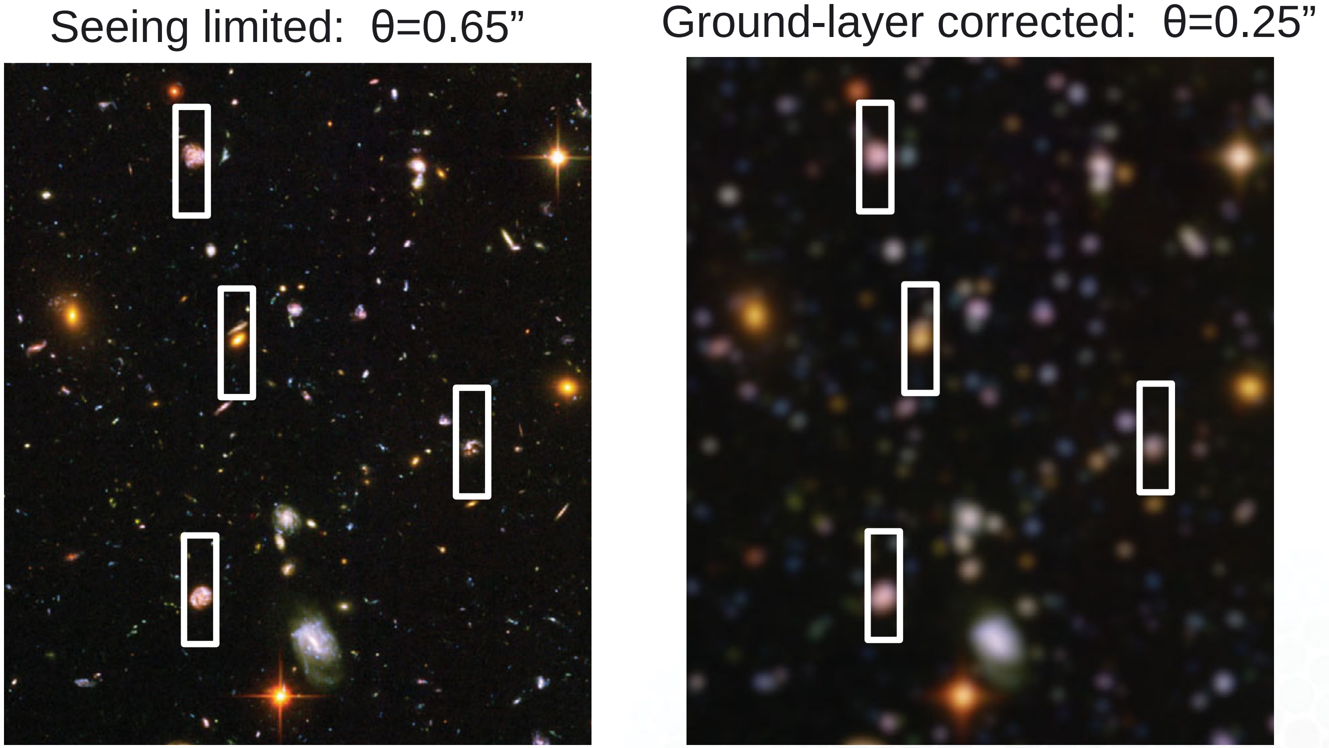
- Increased sensitivity: LIGHT!
  - Total collecting power: gets better with D^2, gets worse with # mirrors
- Increased angular resolution: sharper images
  - Diffraction limit (smallest possible image): gets better with D
  - *Full time AO and Ground layer AO*: enabled by telescope configuration and ASMs





New science with new capabilities:

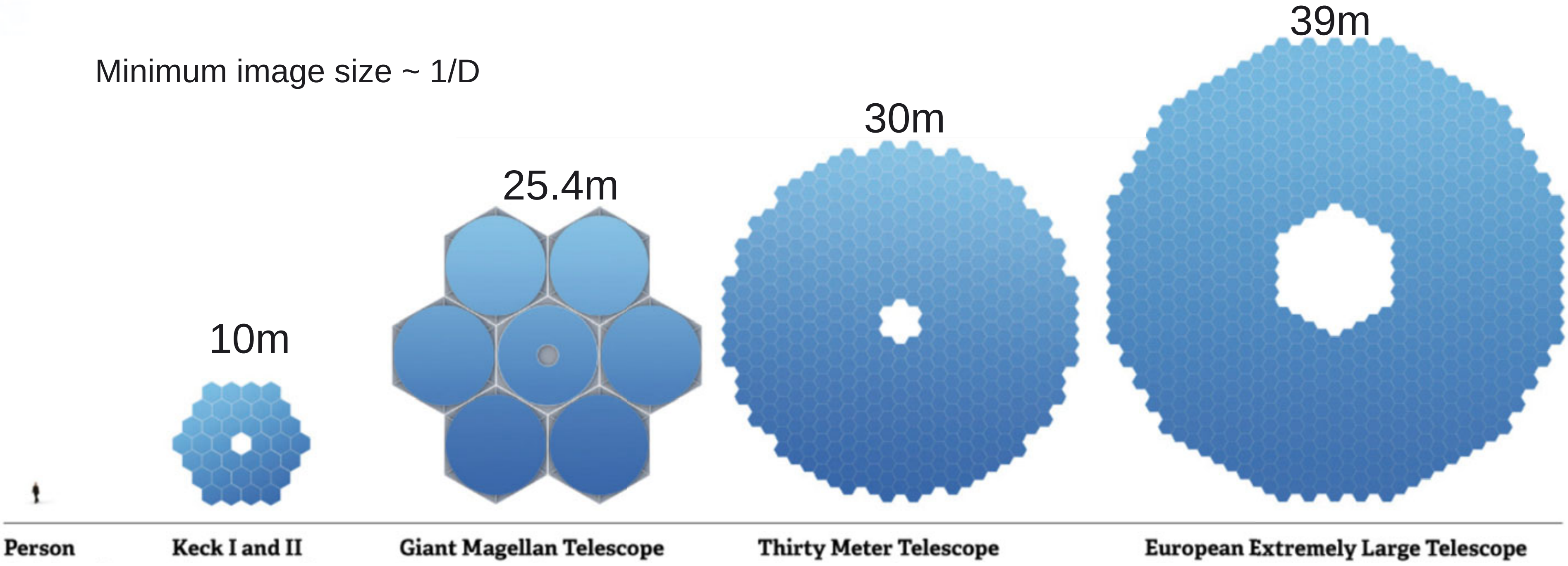
- Increased sensitivity: LIGHT!
  - Total collecting power: gets better with D^2, gets worse with # mirrors
- Increased angular resolution: sharper images
  - Diffraction limit (smallest possible image): gets better with D
  - *Full time AO and Ground layer AO*: enabled by telescope configuration and ASMs



New science with new capabilities:

- Increased sensitivity: LIGHT!
    - Total collecting power: gets better with D^2, gets worse with # mirrors
- Increased angular resolution: sharper images all the time
    - Diffraction limit (smallest possible image): gets better with D
    - *Full time AO and Ground layer AO*: enabled by telescope configuration and ASMs

Minimum image size ~ 1/D



GMT’s design strengths for science:

- Full time AO
  - Diffraction limited (w/ low background, high throughput — 2 mirrors to focal plane)
  - Full time *Ground Layer* AO (same)

- Wide, *useable* field of view: 10 arcmin (20 arcmin with field correctors)

- 1 arcsec/mm plate scale = smaller instruments = better performance
  - Availability of optical materials (glass and gratings)
  - Wider field of view accessible to slit masks (for faintest objects)
  - Wider field of view accessible to fibers (for higher multiplexing)
  - Faster concept-to-telescope — nimble instrumentation program

Full time AO: NGAO, LTAO, & GLAO

GMT

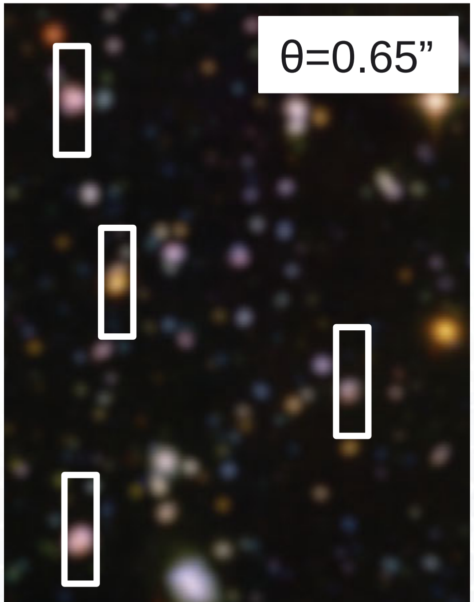
Telescope + planned instrument field of view:

	Keck	GMT (2 mirrors)	GMT with GLAO	TMT (3 mirrors)	ELT (5 mirrors)
Aε	1	6	6	9	14
Ω	81	50	50	24	11
θ^2 **	$(0.65'')^2$	$(0.65'')^2$	**$(0.25'')^2$**	$(0.65'')^2$	**$(0.25'')^2$**
$A\varepsilon\Omega/\theta^2$ (relative)	1	4	25	3	10

Metric for **wide field** science: **$A\varepsilon\Omega/\theta^2$**

A = Area
ε = efficiency (0.8 – 0.9 per mirror)
Ω = Field of view
θ = image size (flux concentration)

**Typical 75th percentile, R-band seeing.



Full time AO: NGAO, LTAO, & GLAO

Telescope + planned instrument field of view:

	Keck	**GMT (2 mirrors)**	**GMT with GLAO**	**TMT (3 mirrors)**	**ELT (5 mirrors)**
$A\varepsilon$	1	6	6	9	14
Ω	81	50	50	24	11
θ^2 **	$(0.65'')^2$	$(0.65'')^2$	**$(0.25'')^2$**	$(0.65'')^2$	**$(0.25'')^2$**
$A\varepsilon\Omega/\theta^2$ (relative)	1	4	25	3	10

Metric for **wide field** science: $\boldsymbol{A\varepsilon\Omega/\theta^2}$

A = Area
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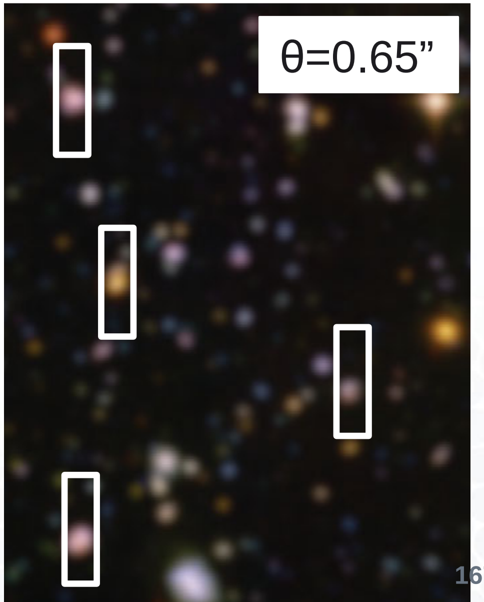
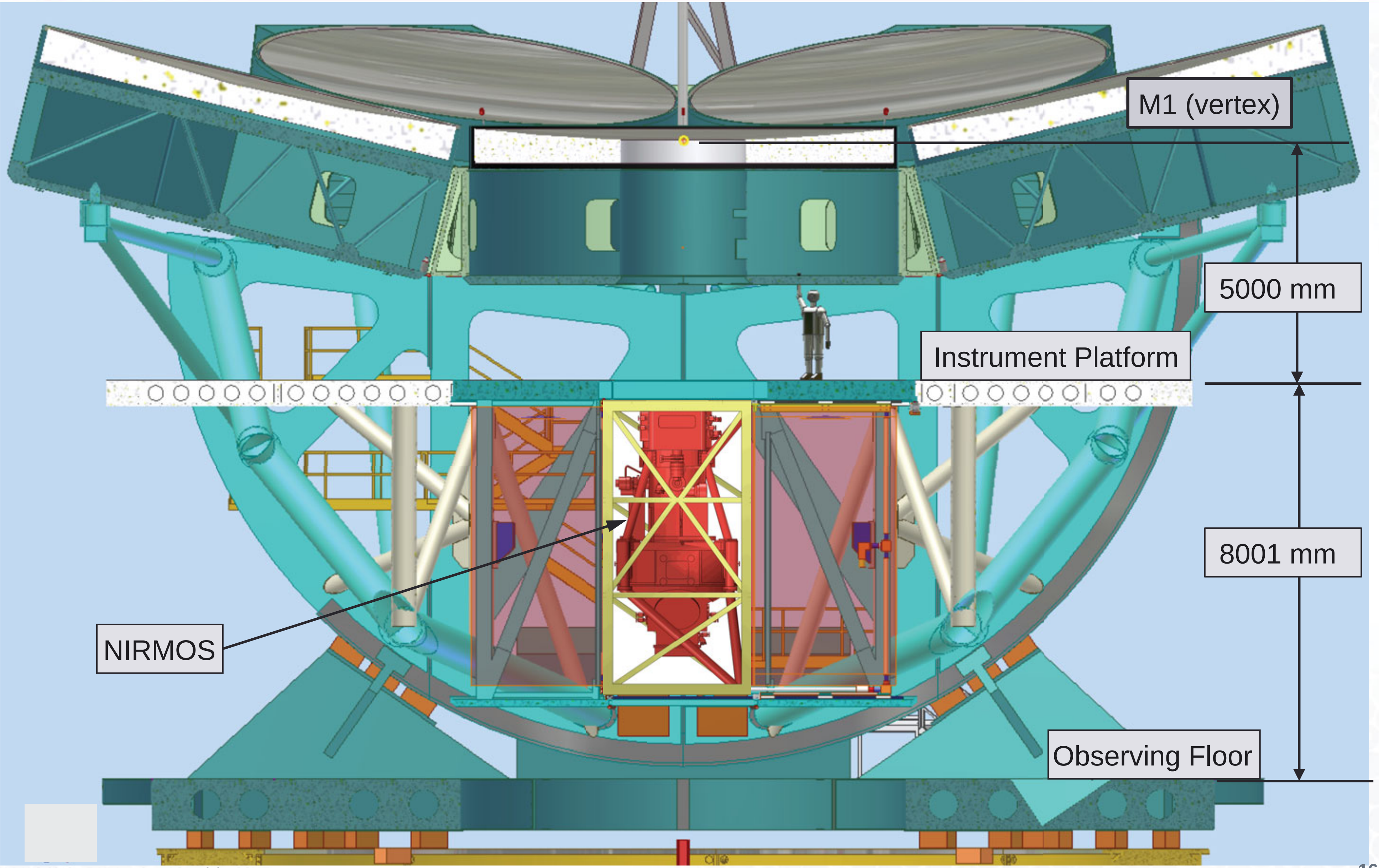
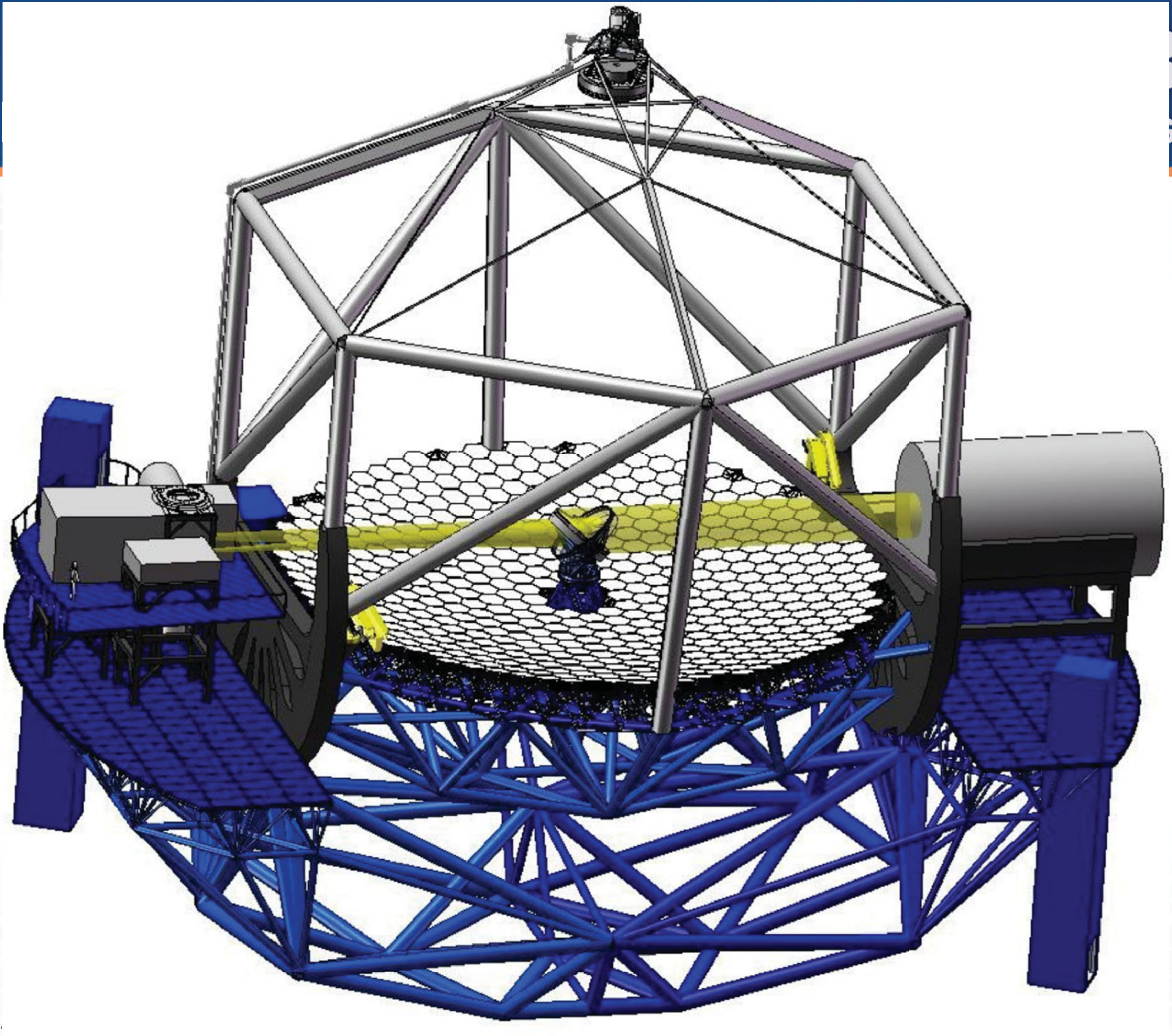
**Typical 75th percentile, R-band seeing.



Instrument scale: smaller = better



In



Instrument scale: smaller = better