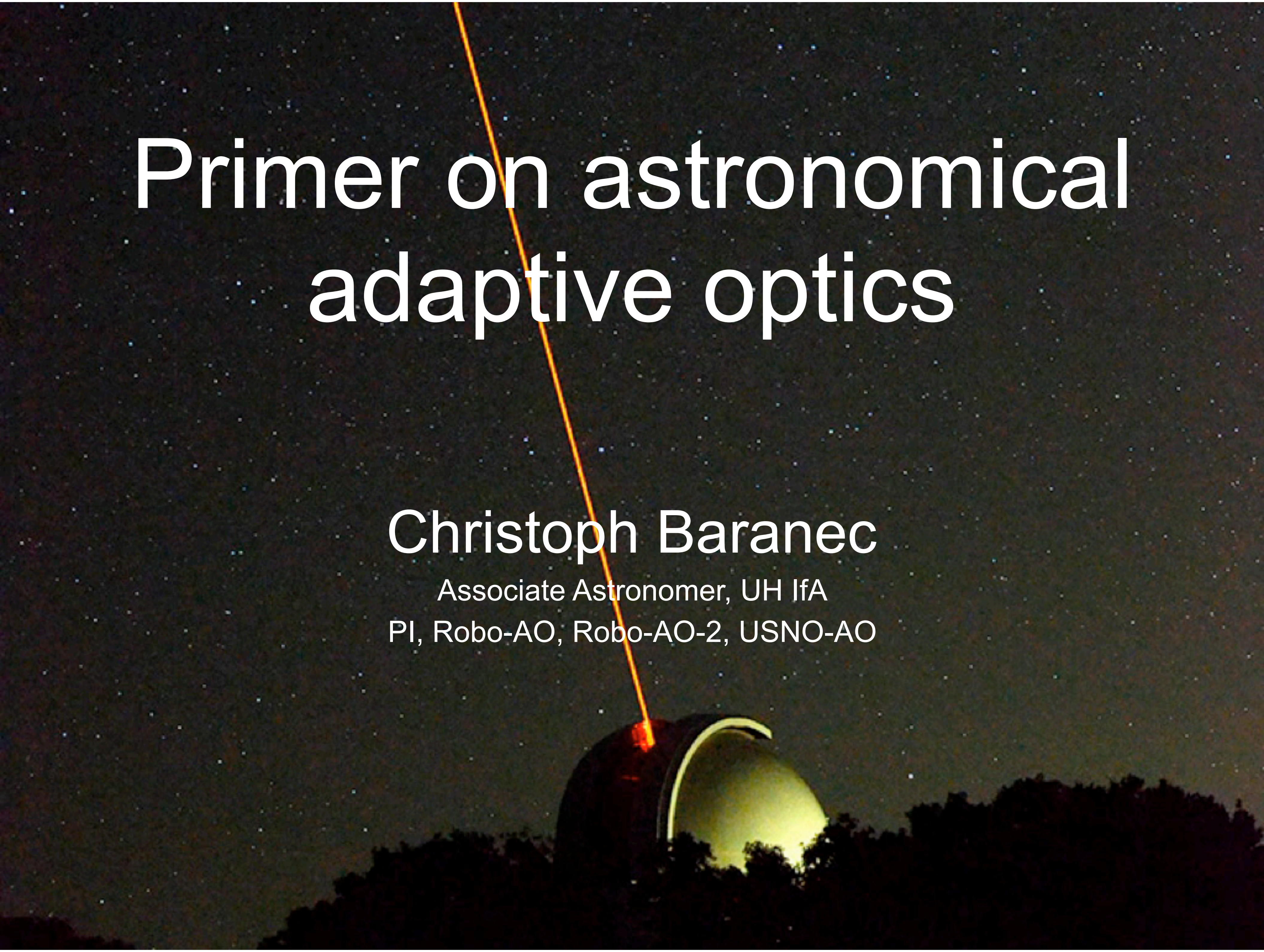


Primer on astronomical adaptive optics

Christoph Baranec

Associate Astronomer, UH IfA

PI, Robo-AO, Robo-AO-2, USNO-AO

My story…

Career path

Highs and Lows

Primer outline

Why do we need Adaptive Optics?

How does an AO system work?

What are the technologies used?

Designing an AO system with an error budget

Example AO systems: Robo-AO(-2)

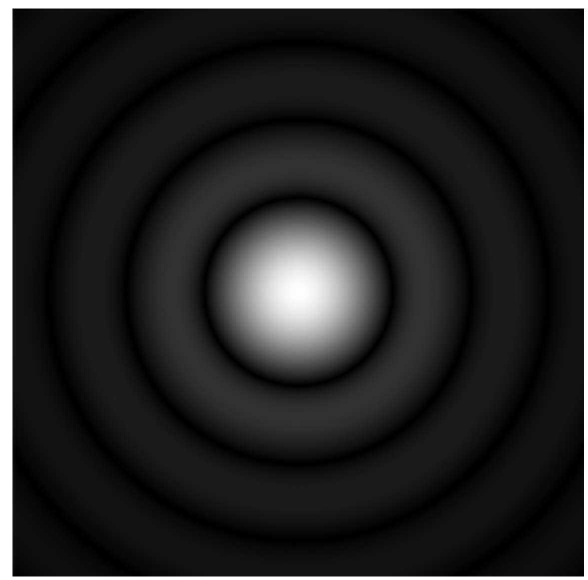
* This is not a comprehensive course in AO

Telescope image formation

Acuity/angular resolution set by diffraction: wavelength of light, λ, divided by aperture diameter, D. (For a circular aperture)

Full Width at Half Max

$\sim (1.03)\ \lambda/D$



Examples of λ/D

Visible wavelengths ~400-750 nm (λ=500 nm)

Thumb at arm's length is	~1-1.5 degrees
1 degree = 60 arcminutes	= 3600 arc sec
Eye (D~4mm): 7.2E-3 deg	= 0.5 arc min
Hubble (D=2.4m): 1.2E-5 deg	= 0.043 arc sec

Stars look blurry from down here.

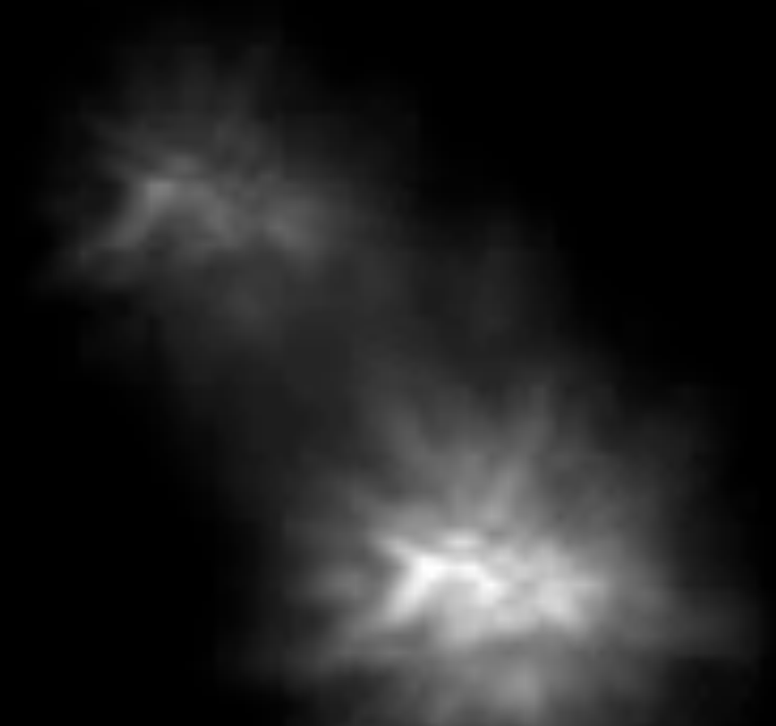
"For the Air through we look upon the Stars, is in perpetual Tremor …cause the Star to appear broader than it is…"

Sir Isaac Newton

Christiaan Huygens

Newton and Huygens were on to something!

Astronomers have adopted the term ‘**seeing**’
to describe this effect.



Typical seeing from a good astronomical site is 1 arc second, or 1/1800 the angular size of the moon.

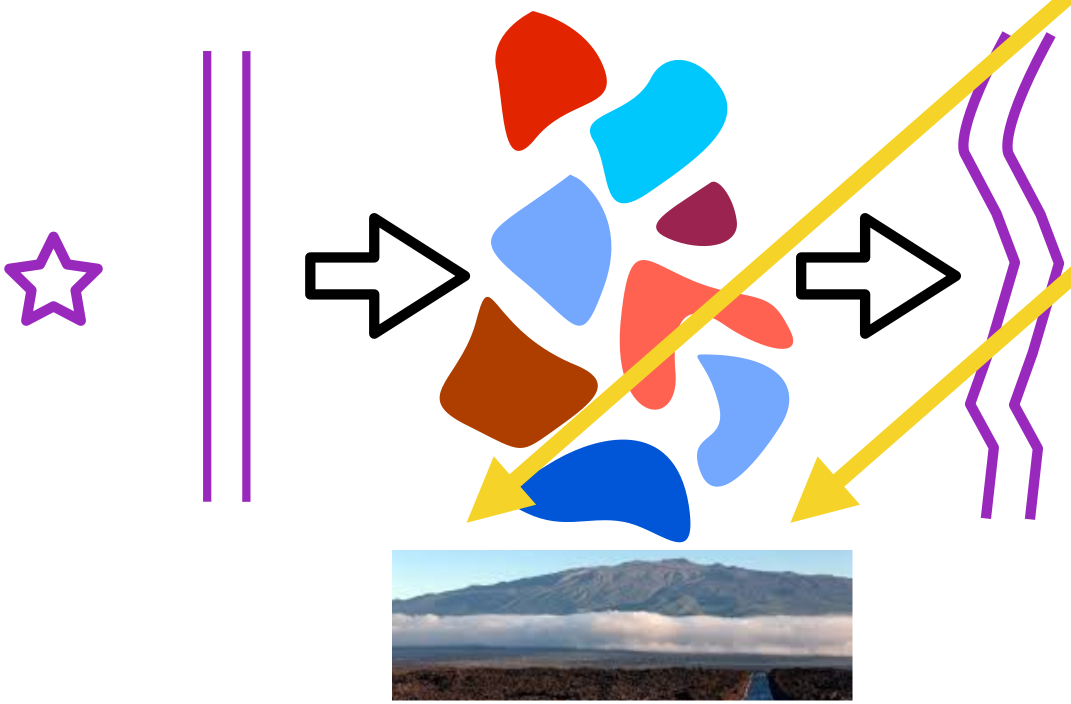
So what's going on with the atmosphere?

- The sun heats the ground.
- Hot air rises and mixes with cold air.
- Light from stars is passing through a dynamic lens.

Light from object

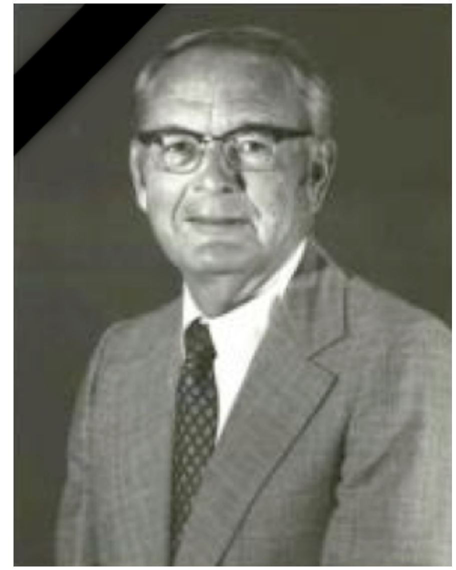
Hot and cold air mixing, variations in refraction

Rays come out distorted, images become blurry



Solutions proposed in the 1950s

Horace Babcock (U.S.A.)



MIT, Caltech, then director of Mt. Wilson and Palomar Observatories

Seminal Paper: “The Possibility of Compensating Astronomical Seeing,” *PASP*, 1953.

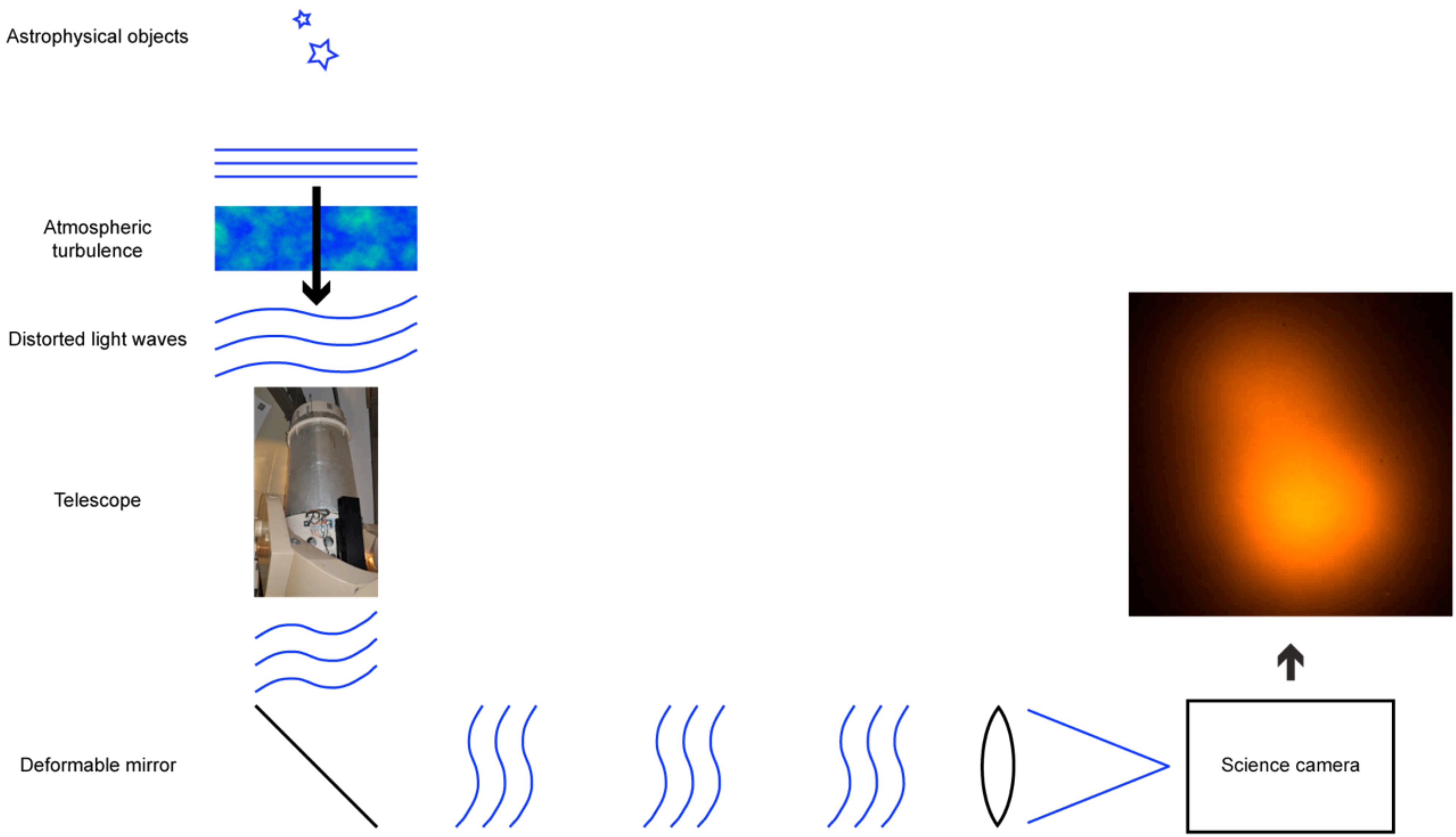
V. P. Linnik (U.S.S.R.)

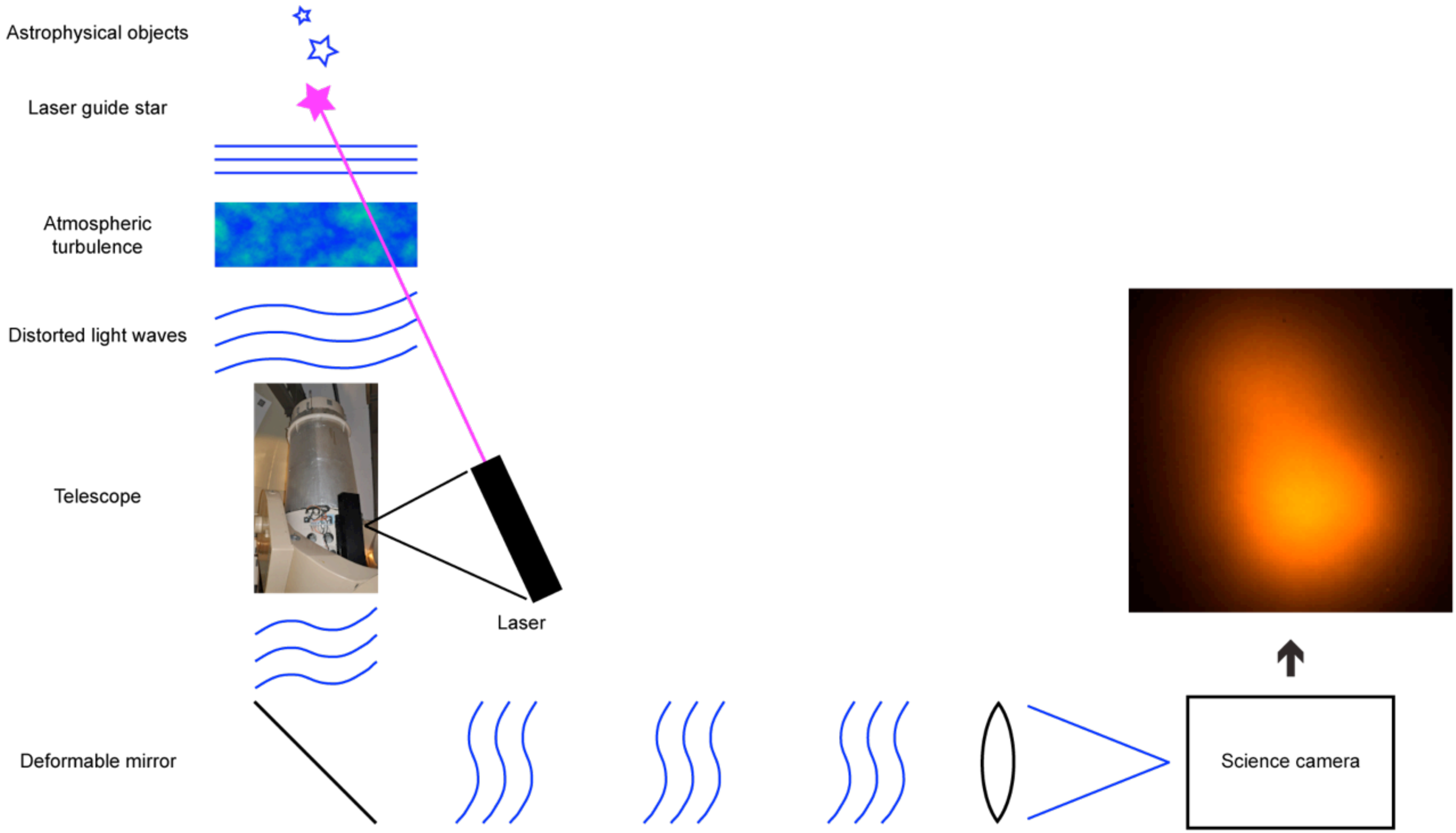
Independent proposal for adaptive optics systems and their limitations, and artificial stars, *Opt. Spectrosc.*,1957.

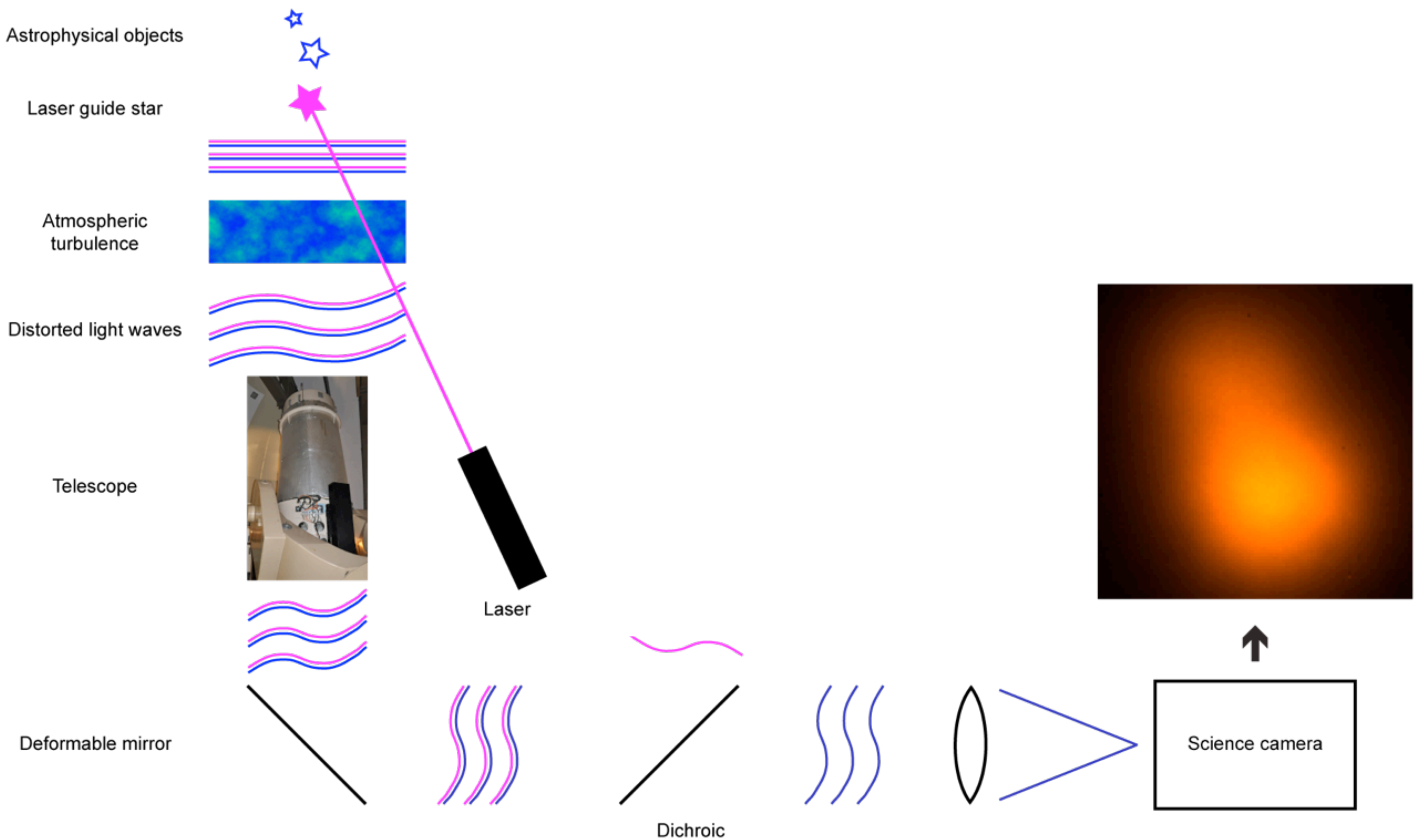
Modern Adaptive Optics

Baranec, et al., JoVE, 2013.

Modern Adaptive Optics




Astrophysical objects
Laser guide star
Atmospheric turbulence
Distorted light waves
Telescope
Laser
Deformable mirror
Science camera


Astrophysical objects
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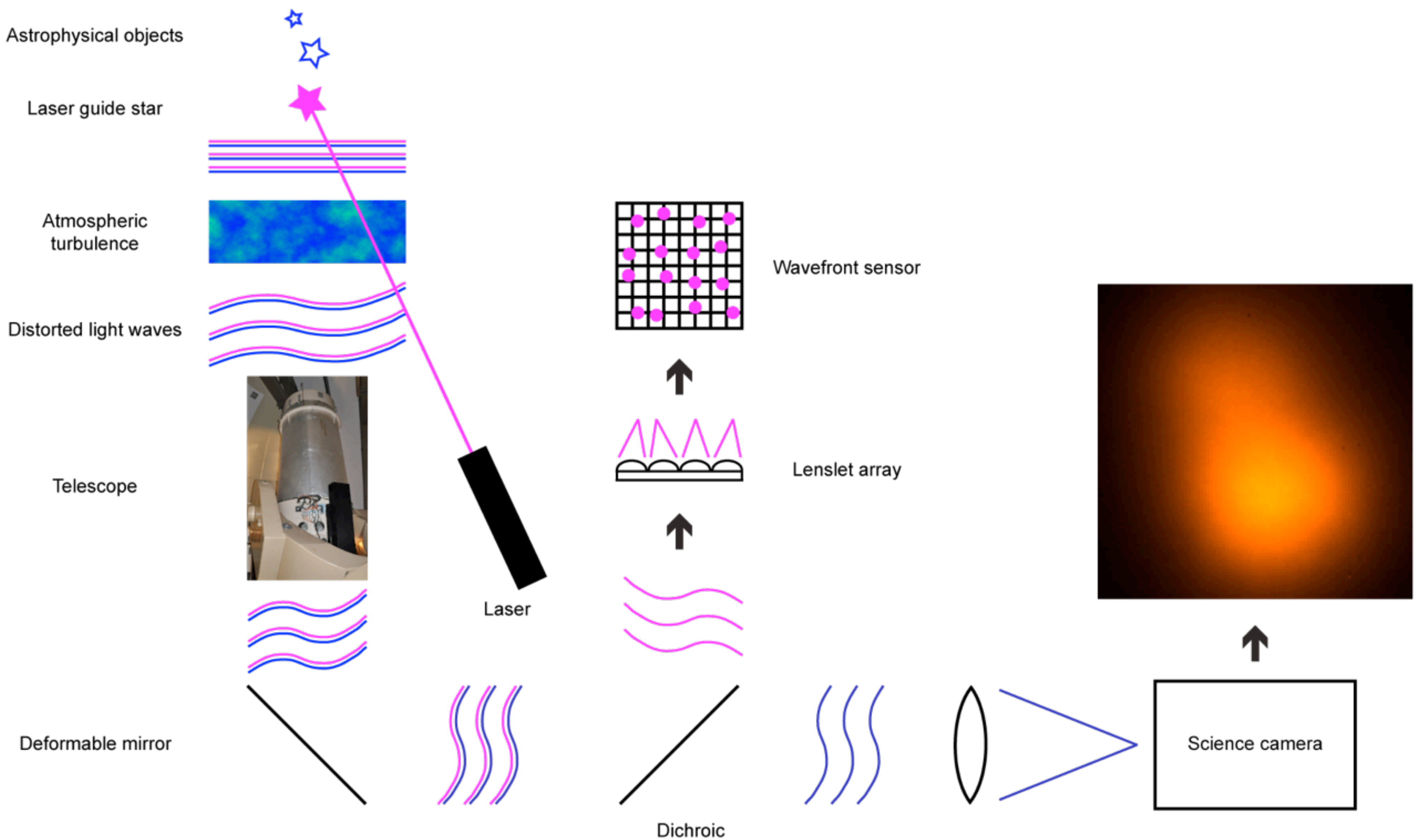
Deformable mirror
Dichroic
Science camera


Astrophysical objects
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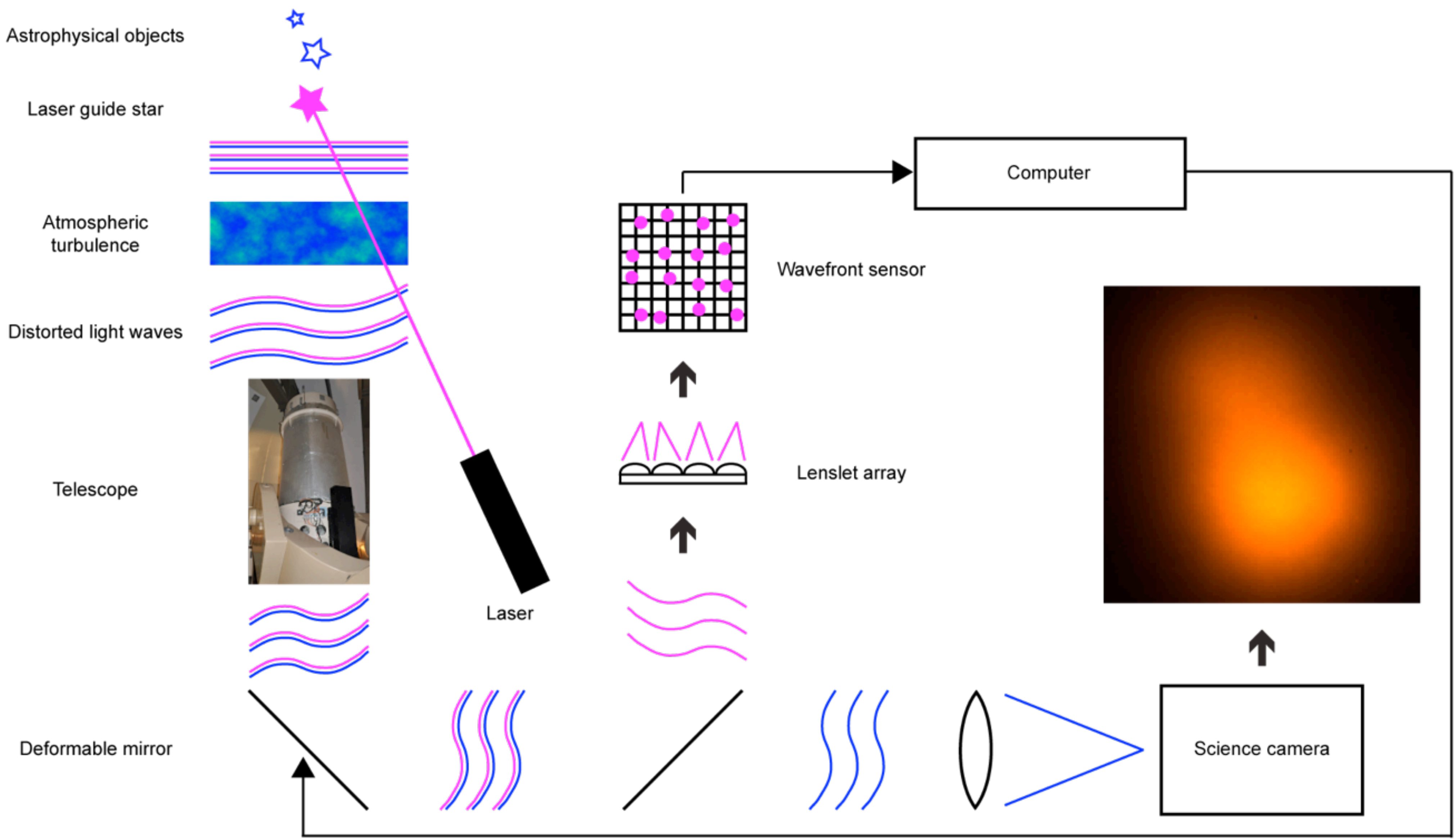
Distorted light waves
Telescope
Laser
Deformable mirror
Dichroic
Wavefront sensor
Lenslet array
Science camera


Astrophysical objects
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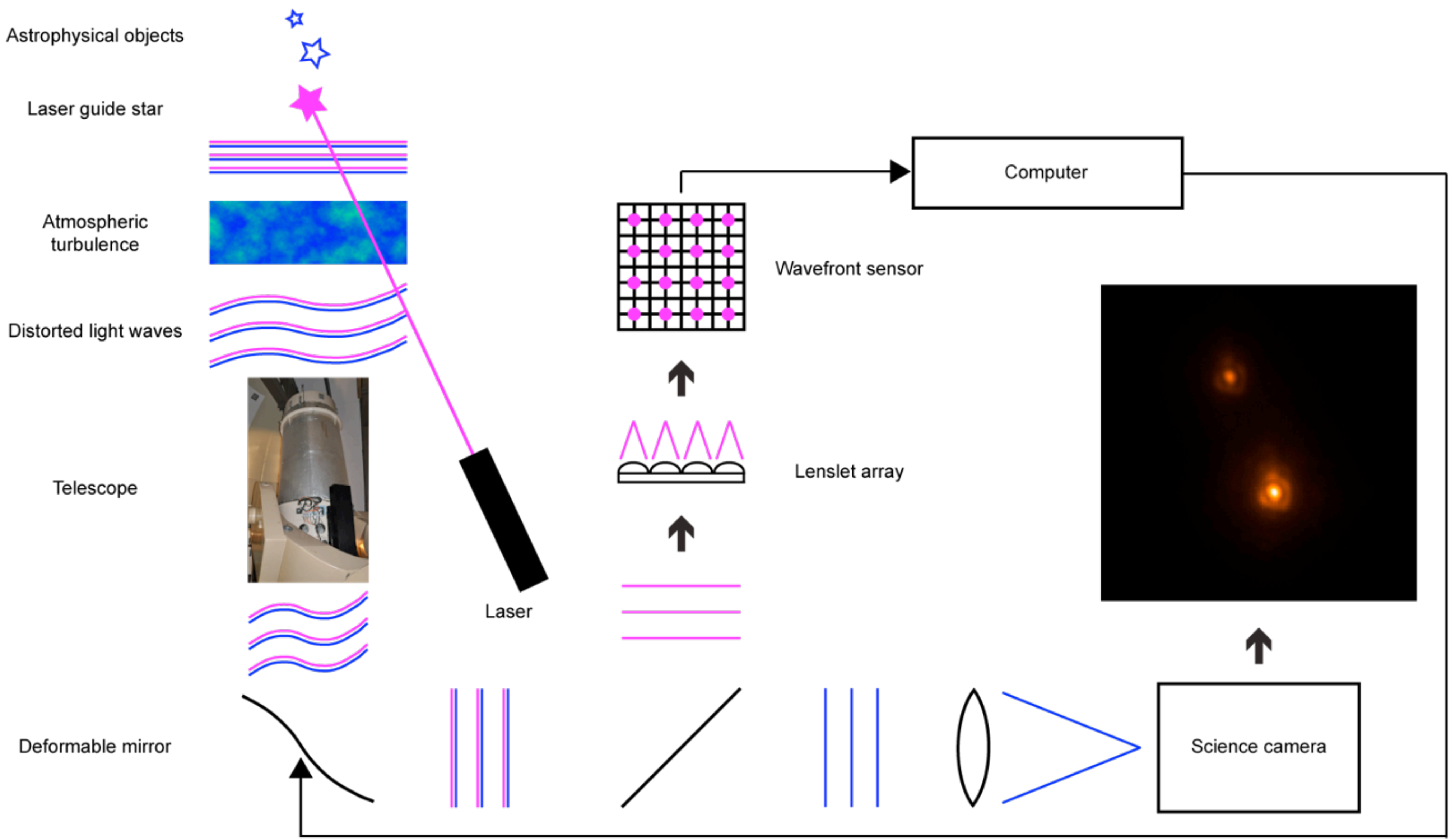
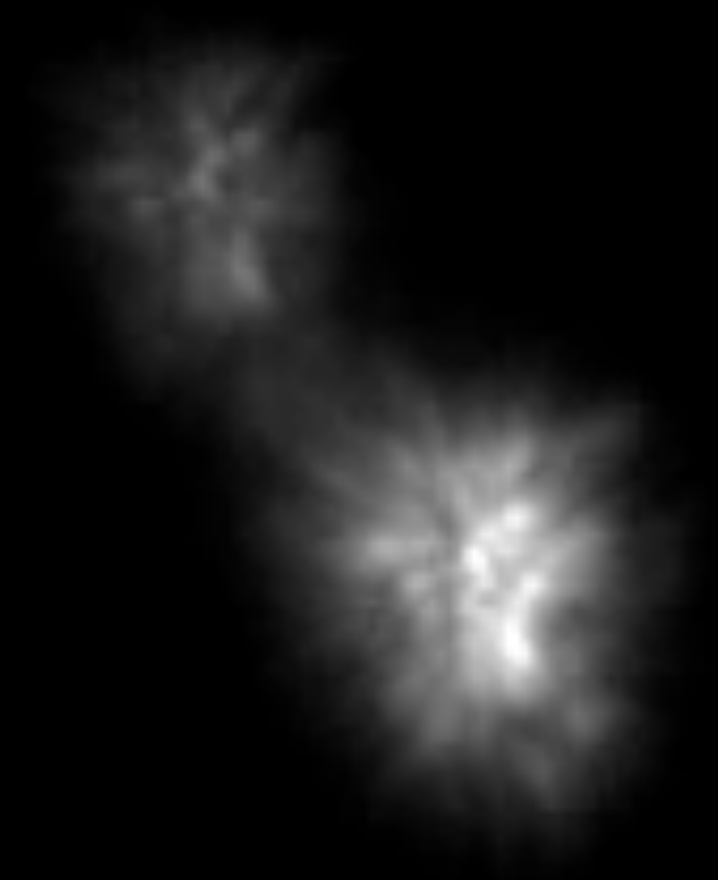
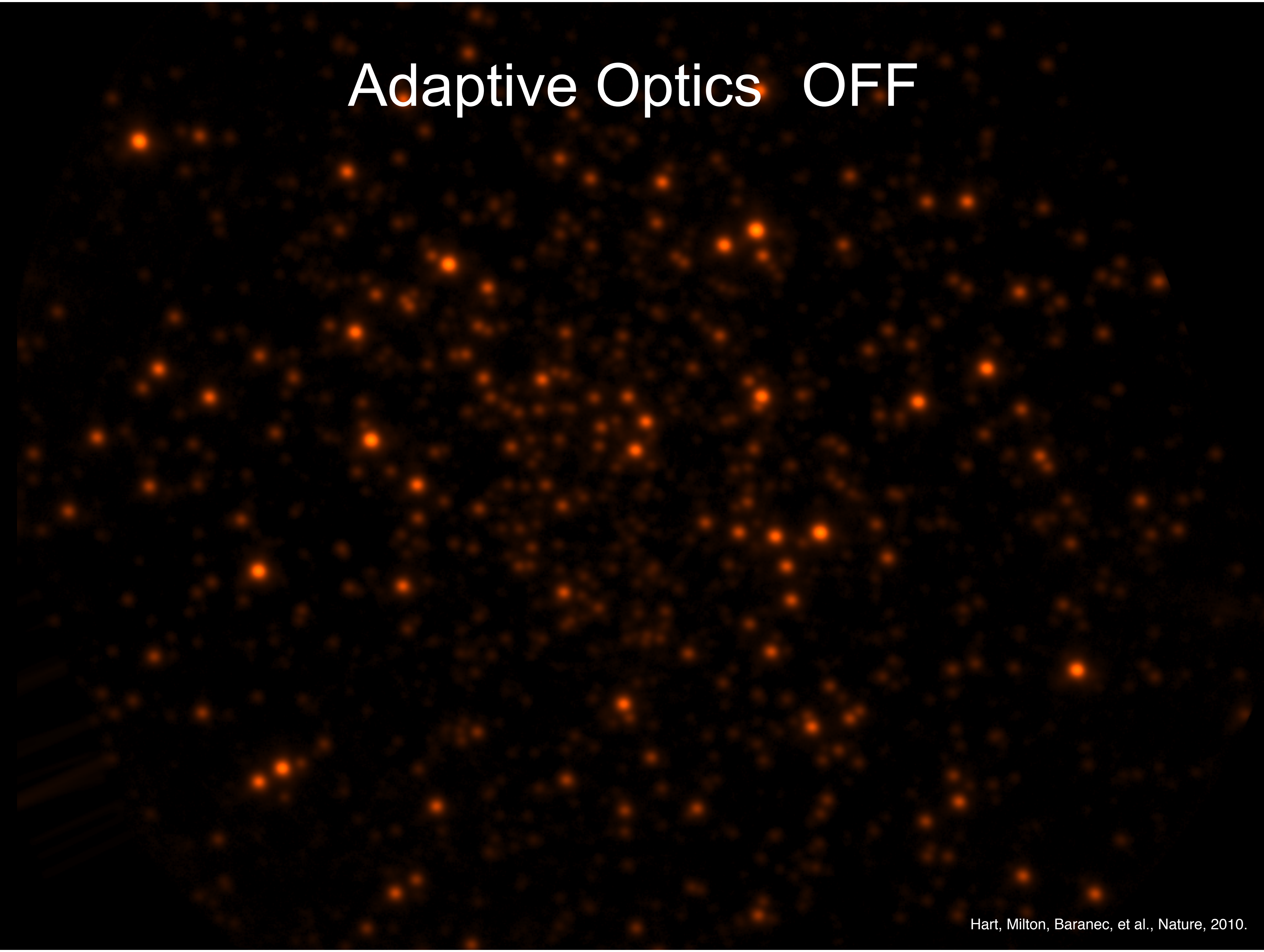
Computer
Wavefront sensor
Lenslet array
Science camera

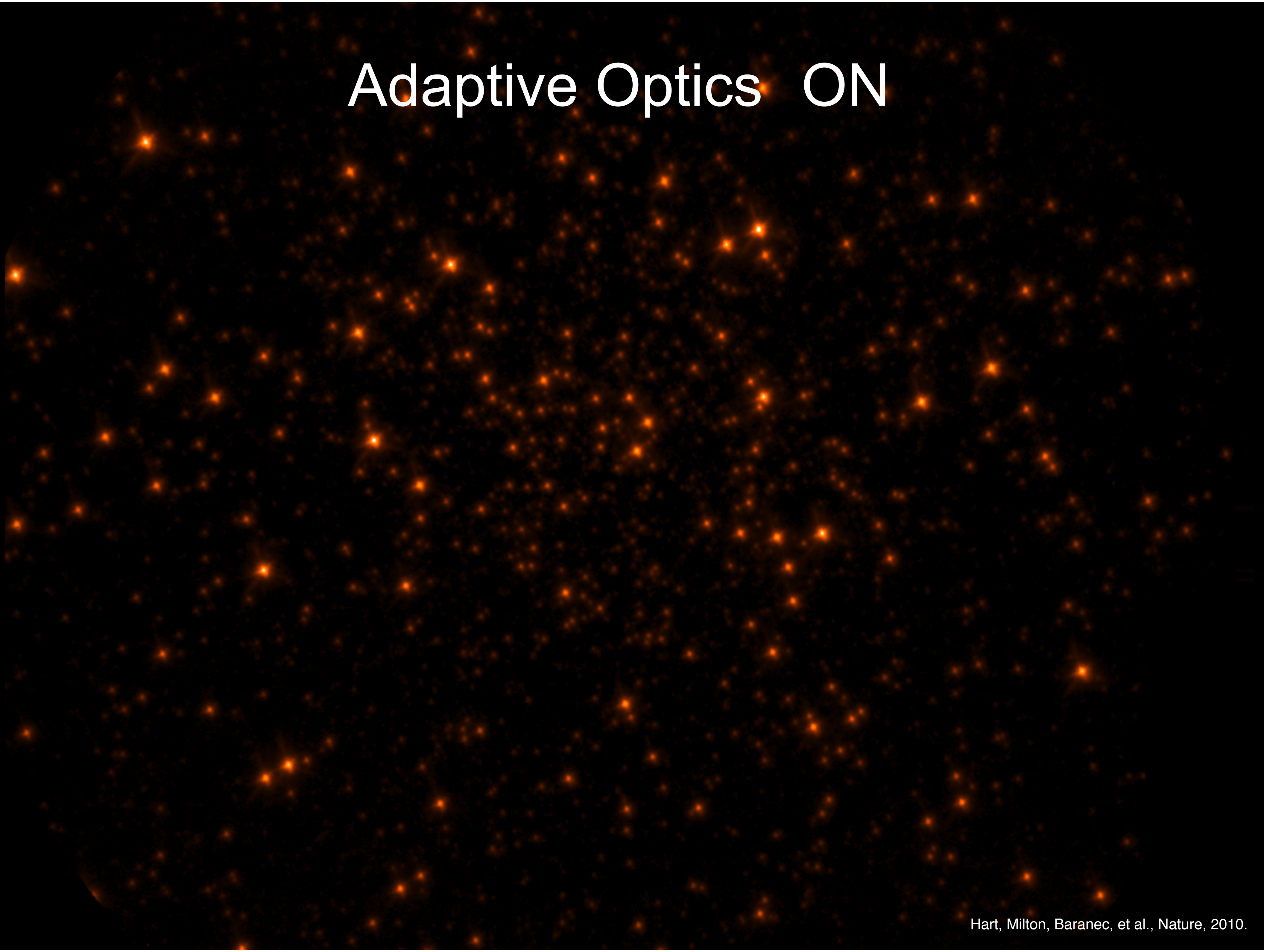

Astrophysical objects
Laser guide star
Atmospheric turbulence
Distorted light waves
Telescope
Deformable mirror
Laser
Computer
Wavefront sensor
Lenslet array
Science camera

Adaptive Optics OFF



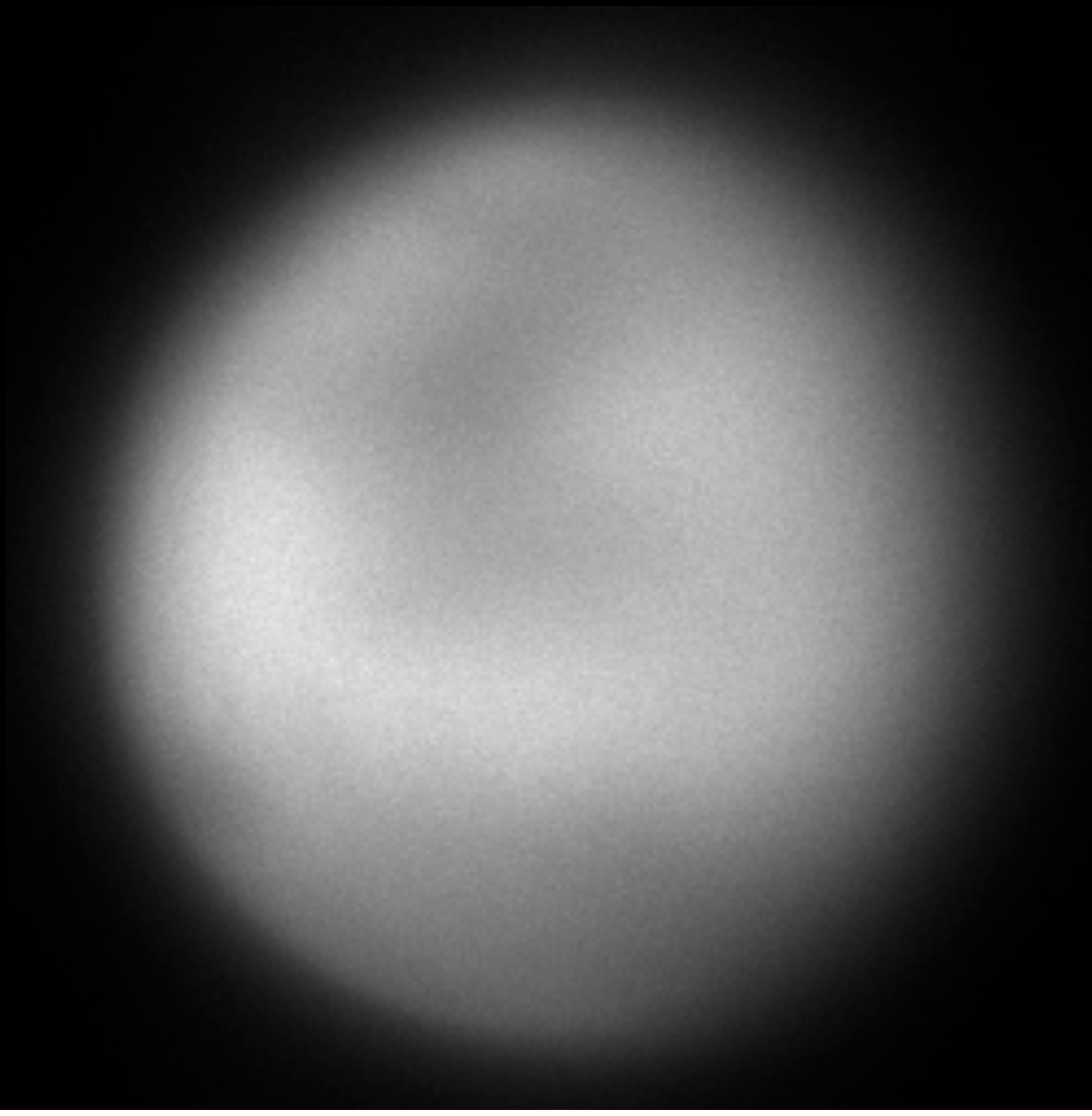

Adaptive Optics OFF
Hart, Milton, Baranec, et al., Nature, 2010.

Adaptive Optics ON

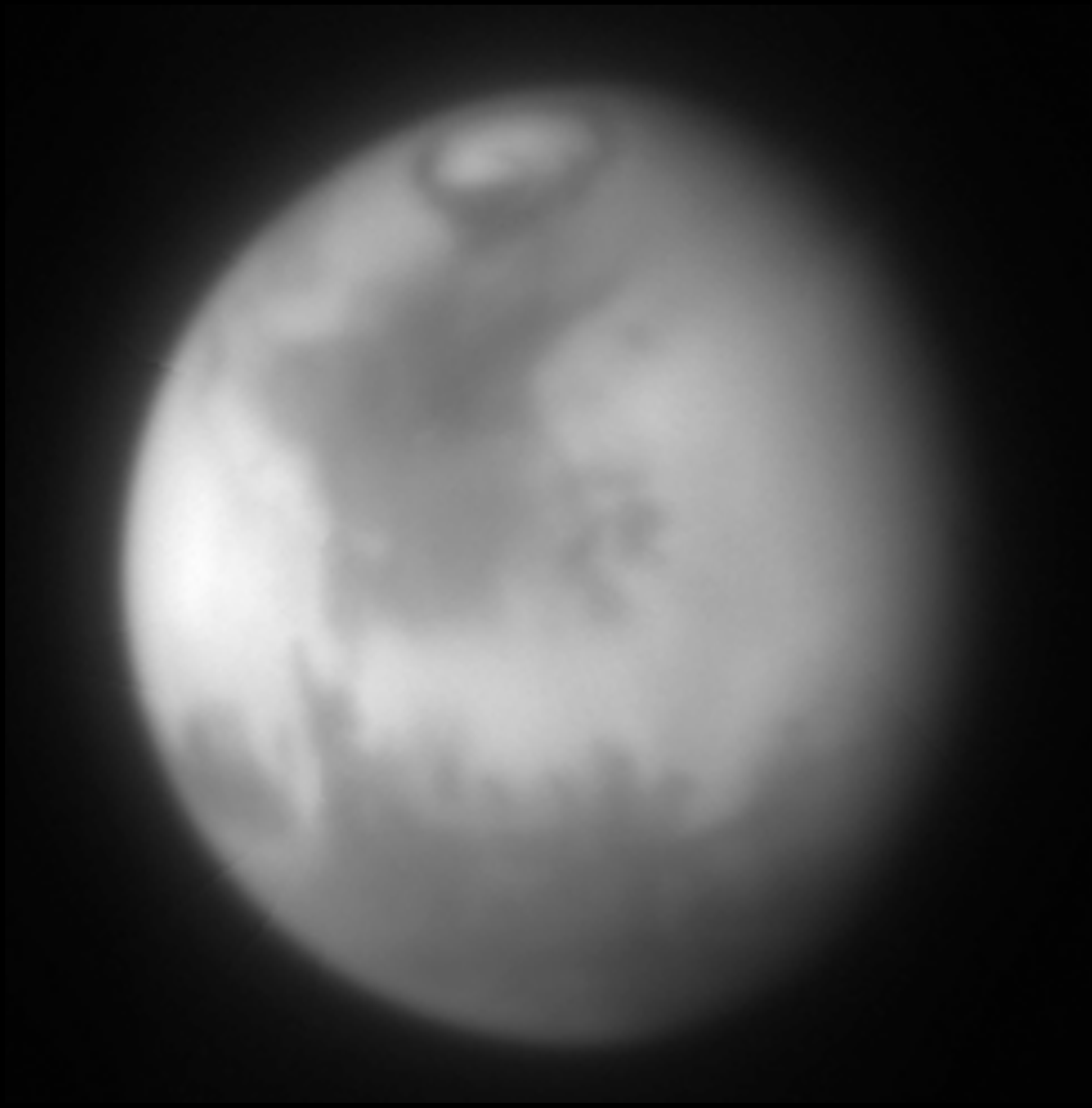


Hart, Milton, Baranec, et al., Nature, 2010.

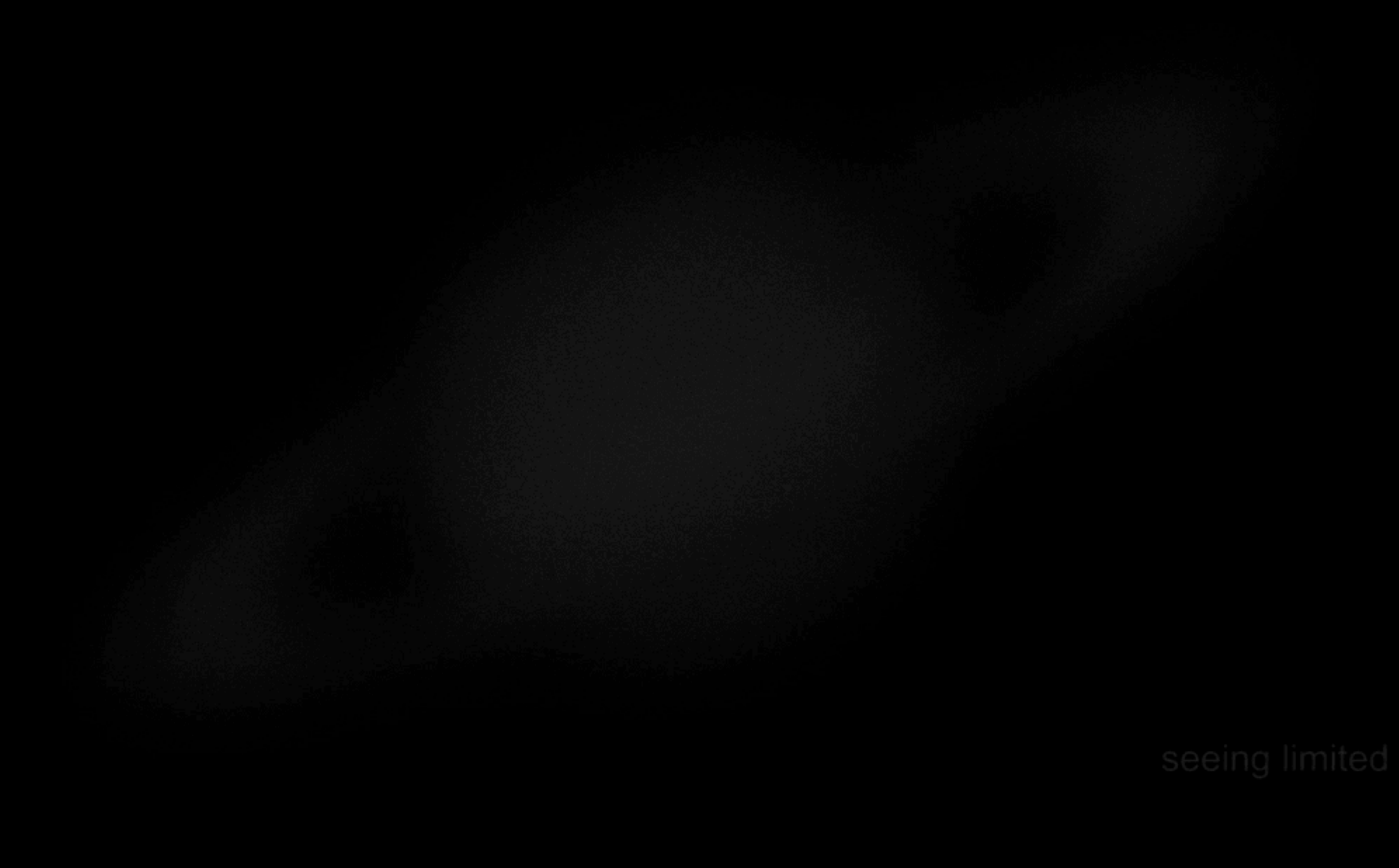
Adaptive Optics OFF



Adaptive Optics ON

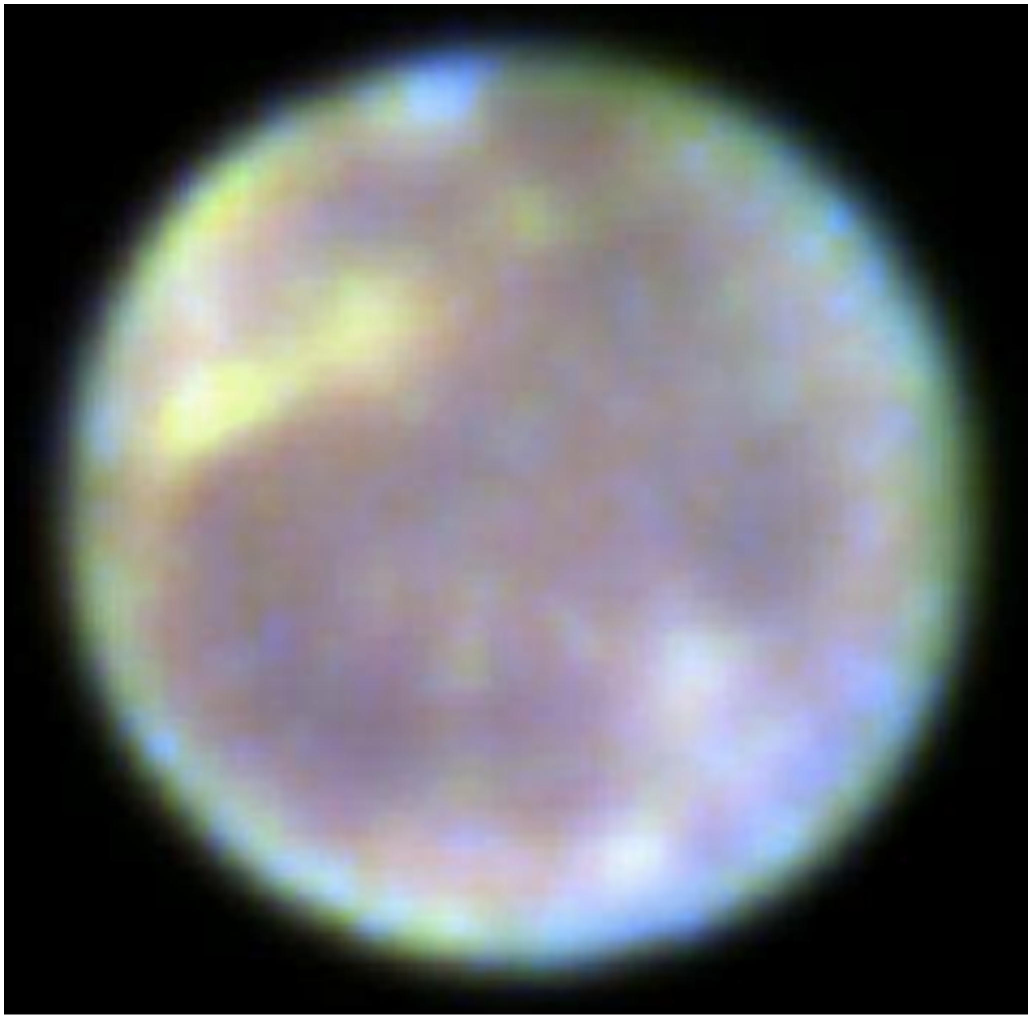


Saturn

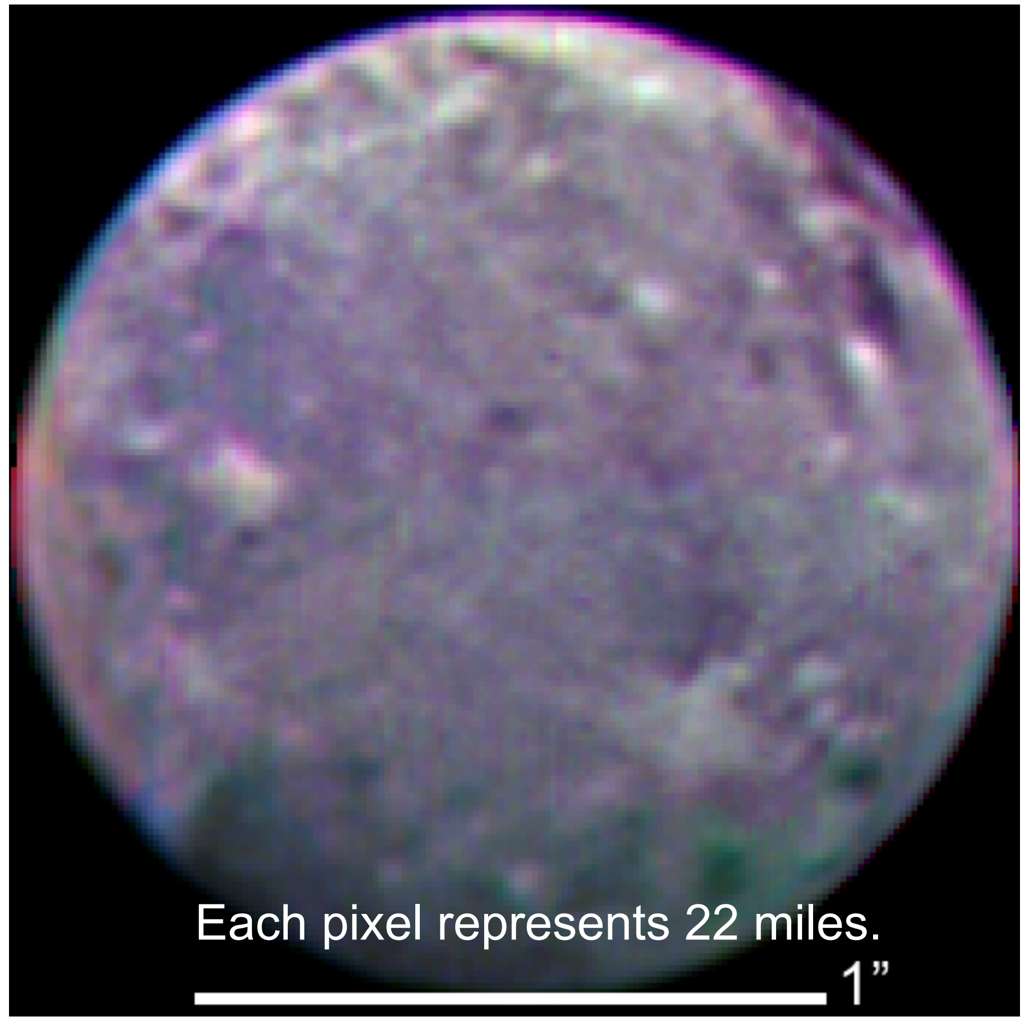


Jupiter's Moon Ganymede

2.4-m Hubble Space Telescope

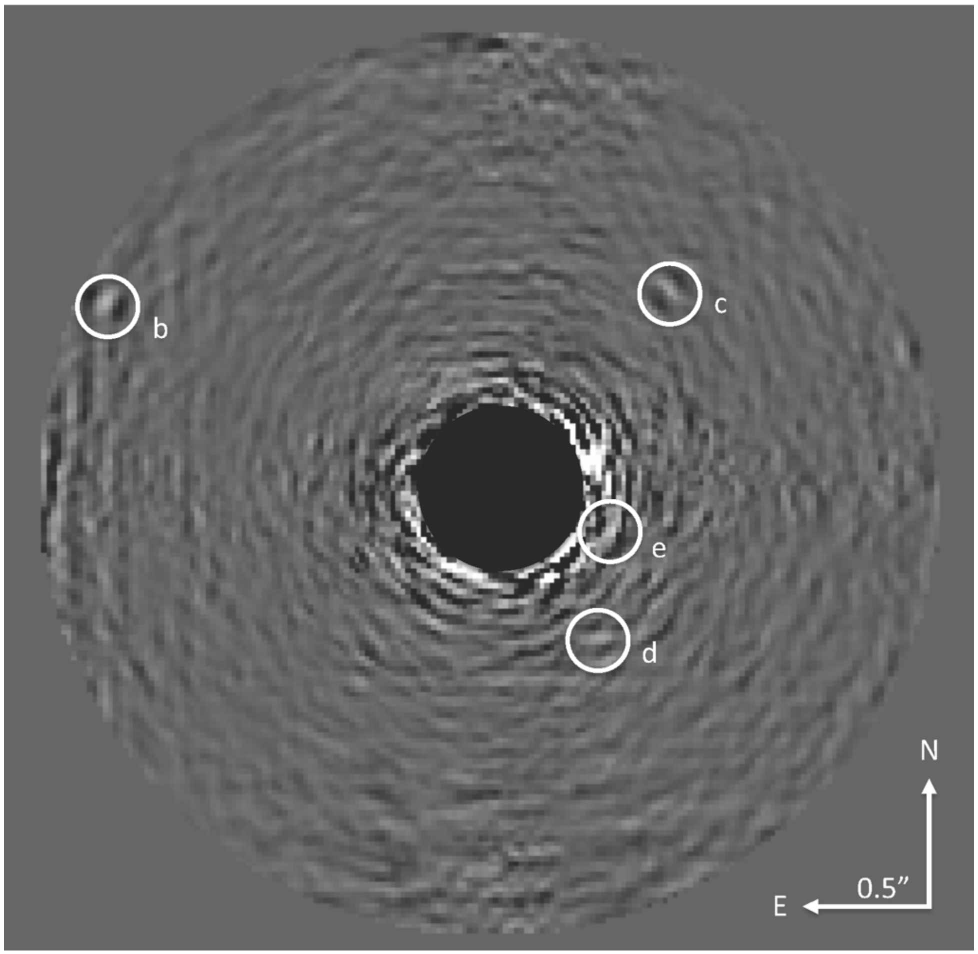


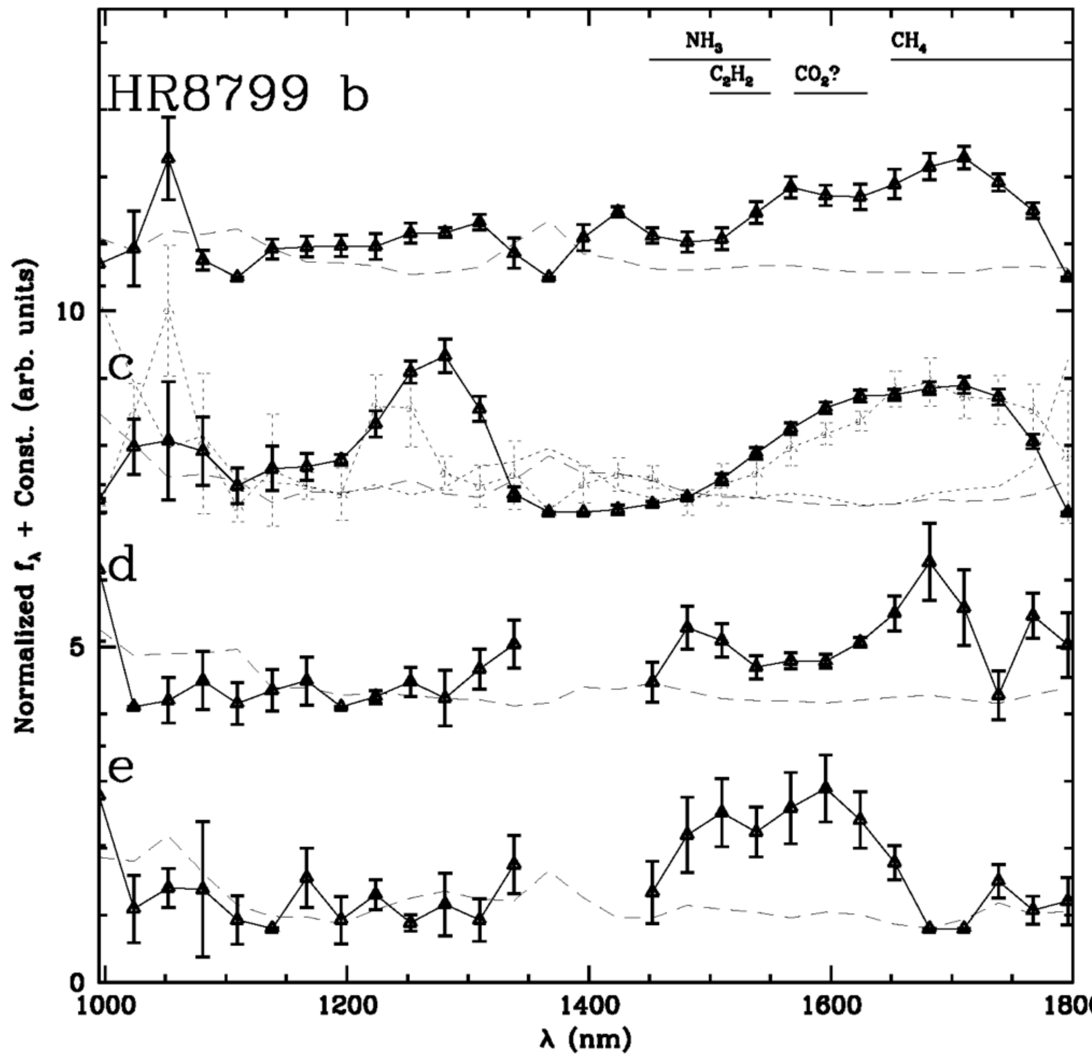
Adaptive Optics
on 5.1-m Hale Telescope



Dekany, …, Baranec, et al., ApJ, 776, 130, 2013.

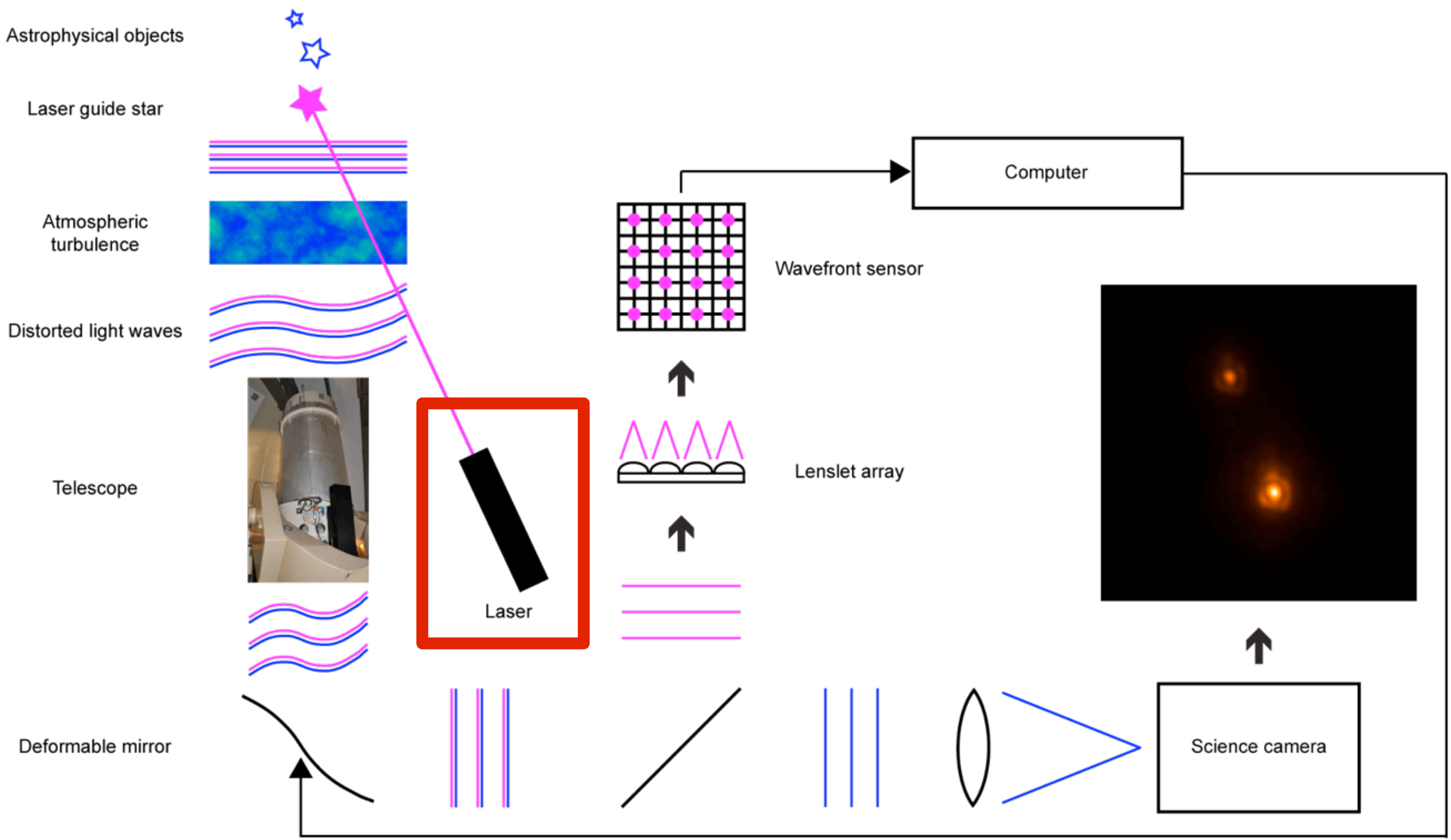
P3K + P1640 imaging spectroscopy





Oppenheimer, Baranec, et al., ApJ, 768, 2013

Adaptive Optics Components



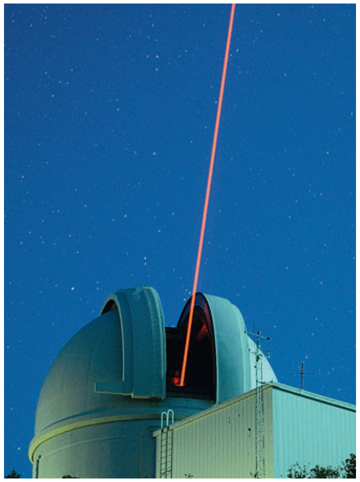
There are two types of laser beacons used in adaptive optics.

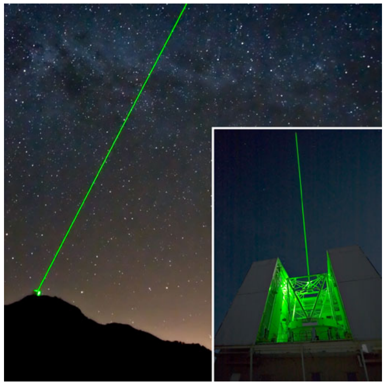
‘Sodium’

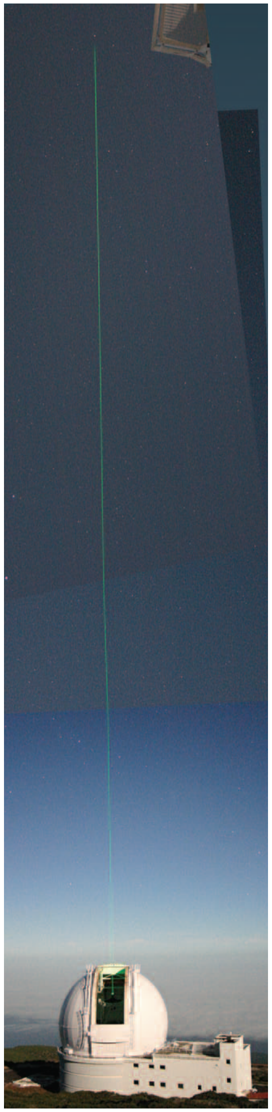
excite the D2 transition of mesospheric (**~90km**) Sodium ions

Rayleigh

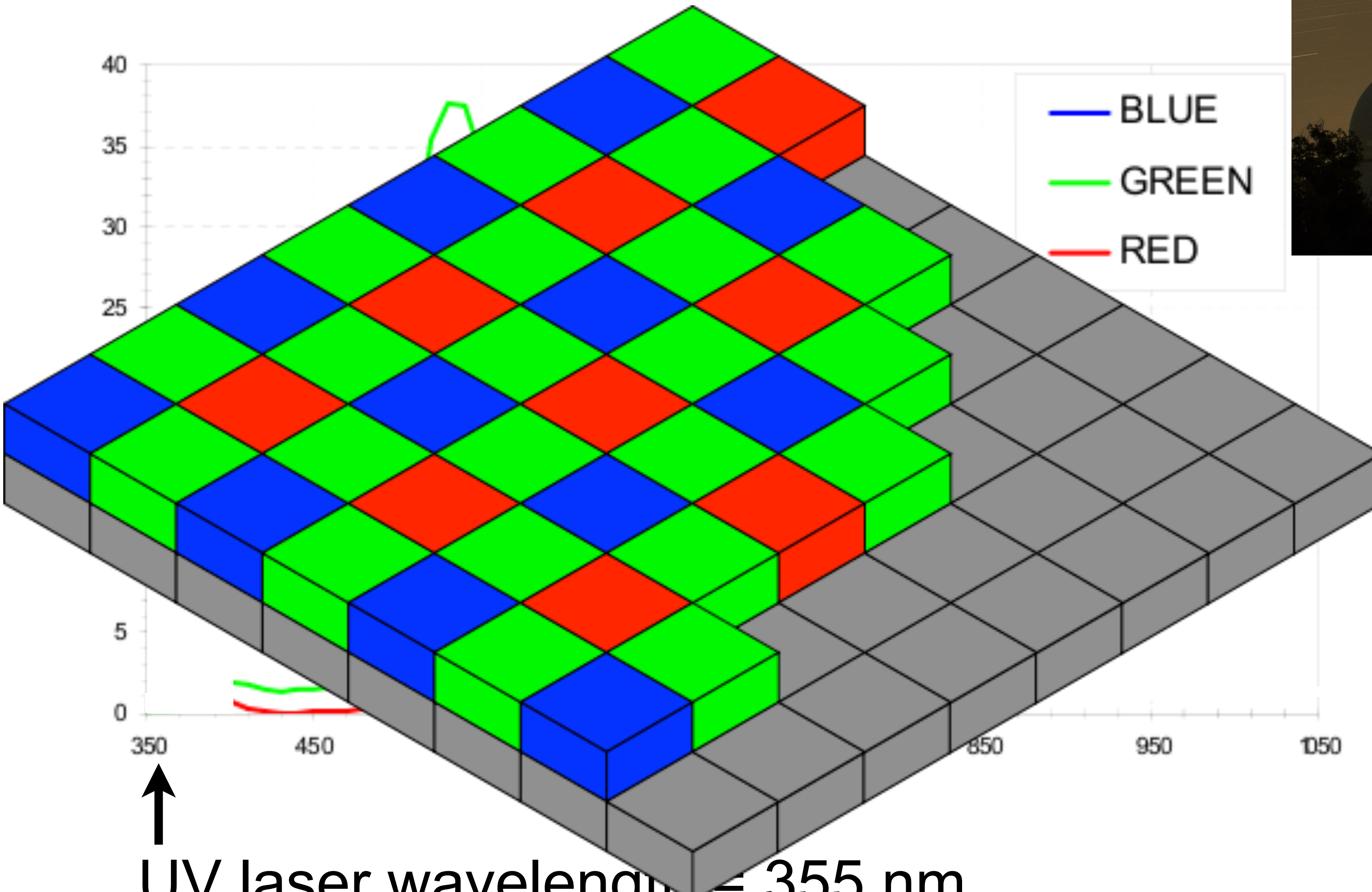
rely on the backscatter off of air molecules, up to **10-15km**



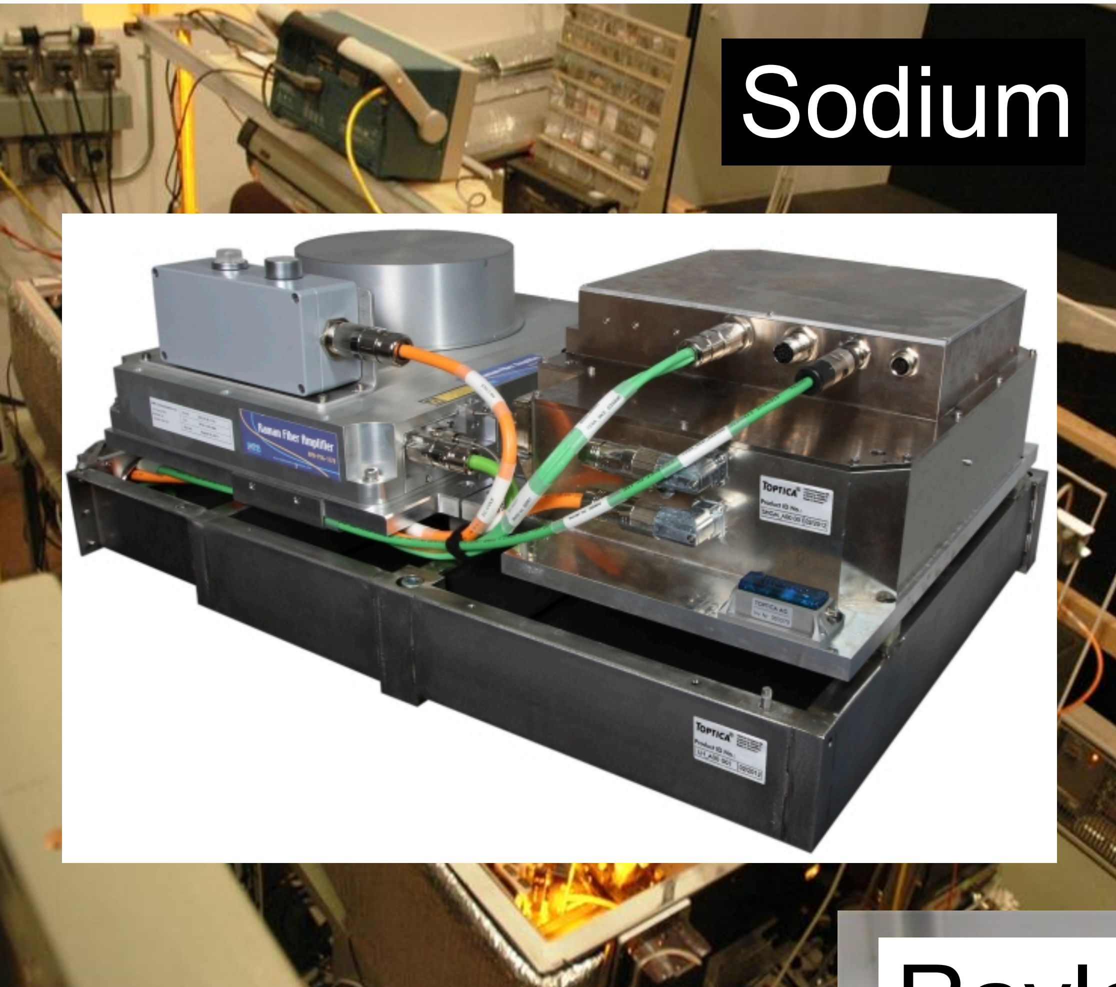




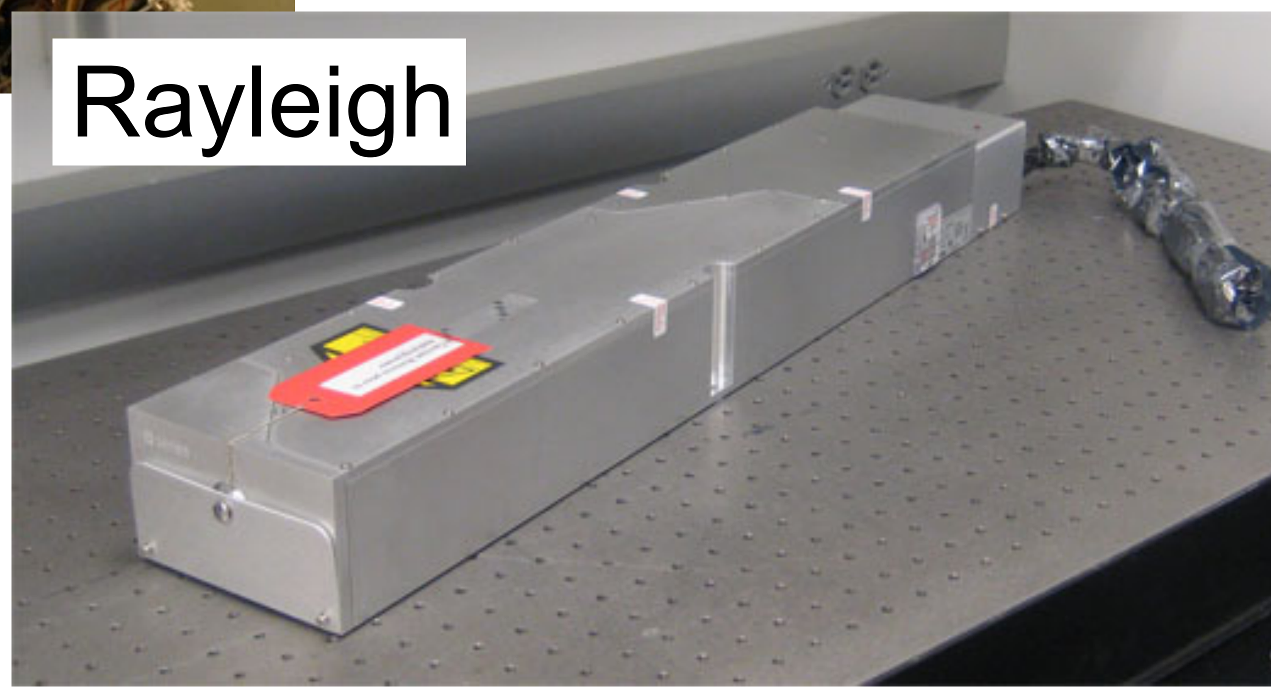
Why does the ultraviolet laser look orange?



UV laser wavelength = 355 nm

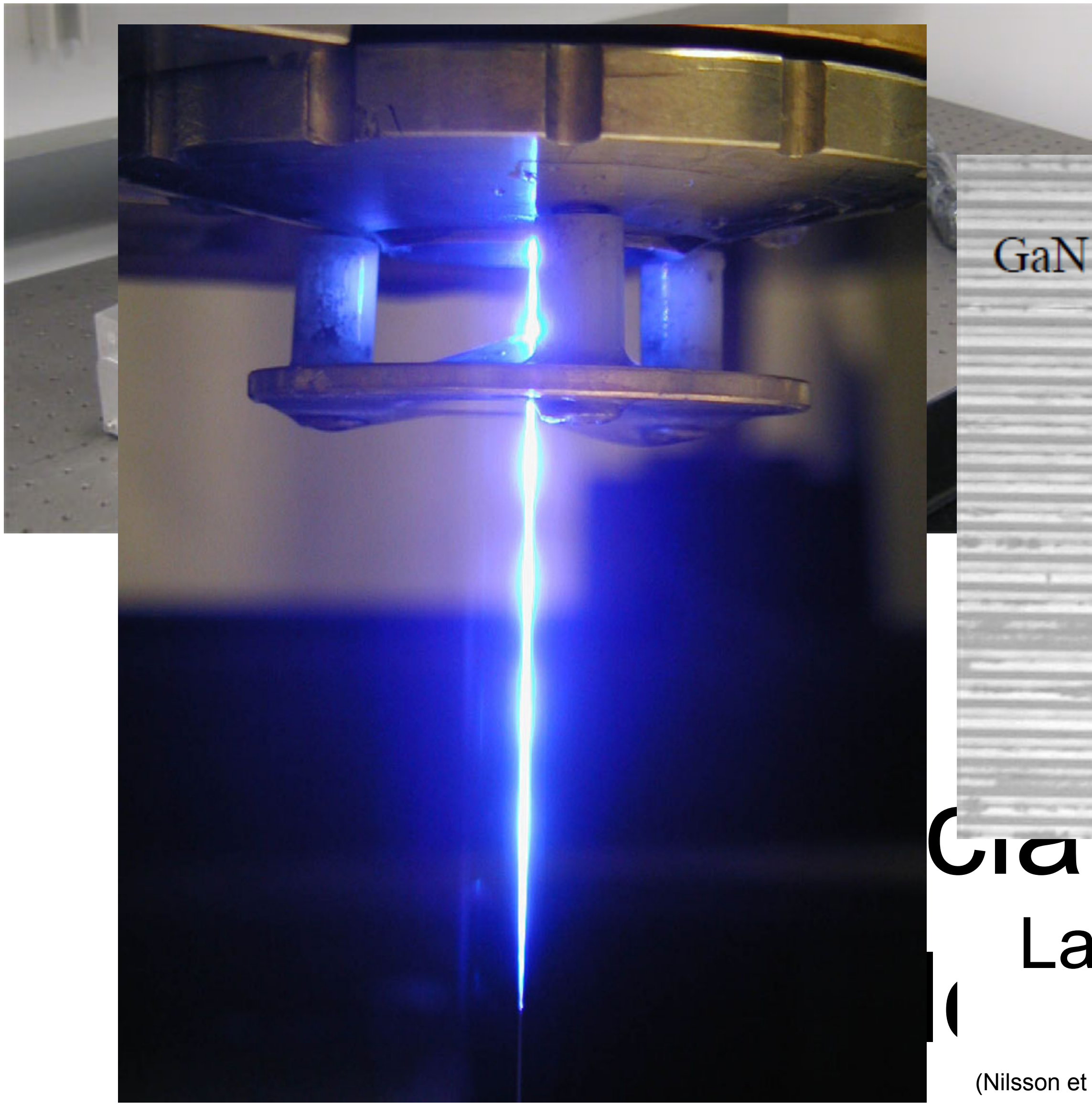


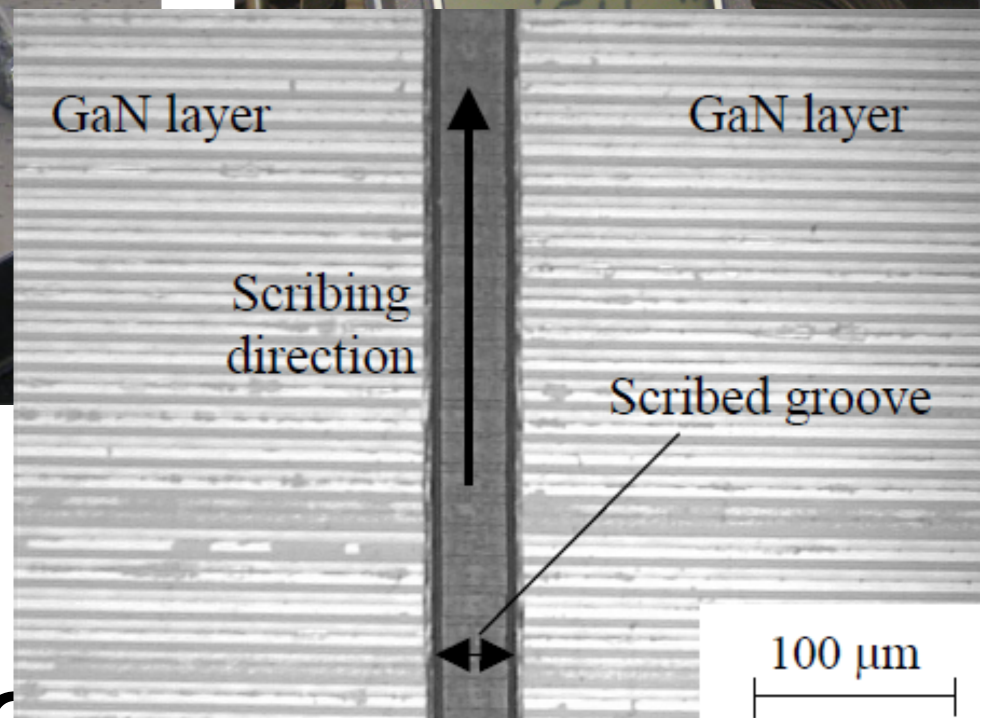
Na D2-line laser
~$100K/Watt
Required for > 3m



Commercial laser
$5K-$10K/Watt
Works for < 3m

Example Rayleigh Laser





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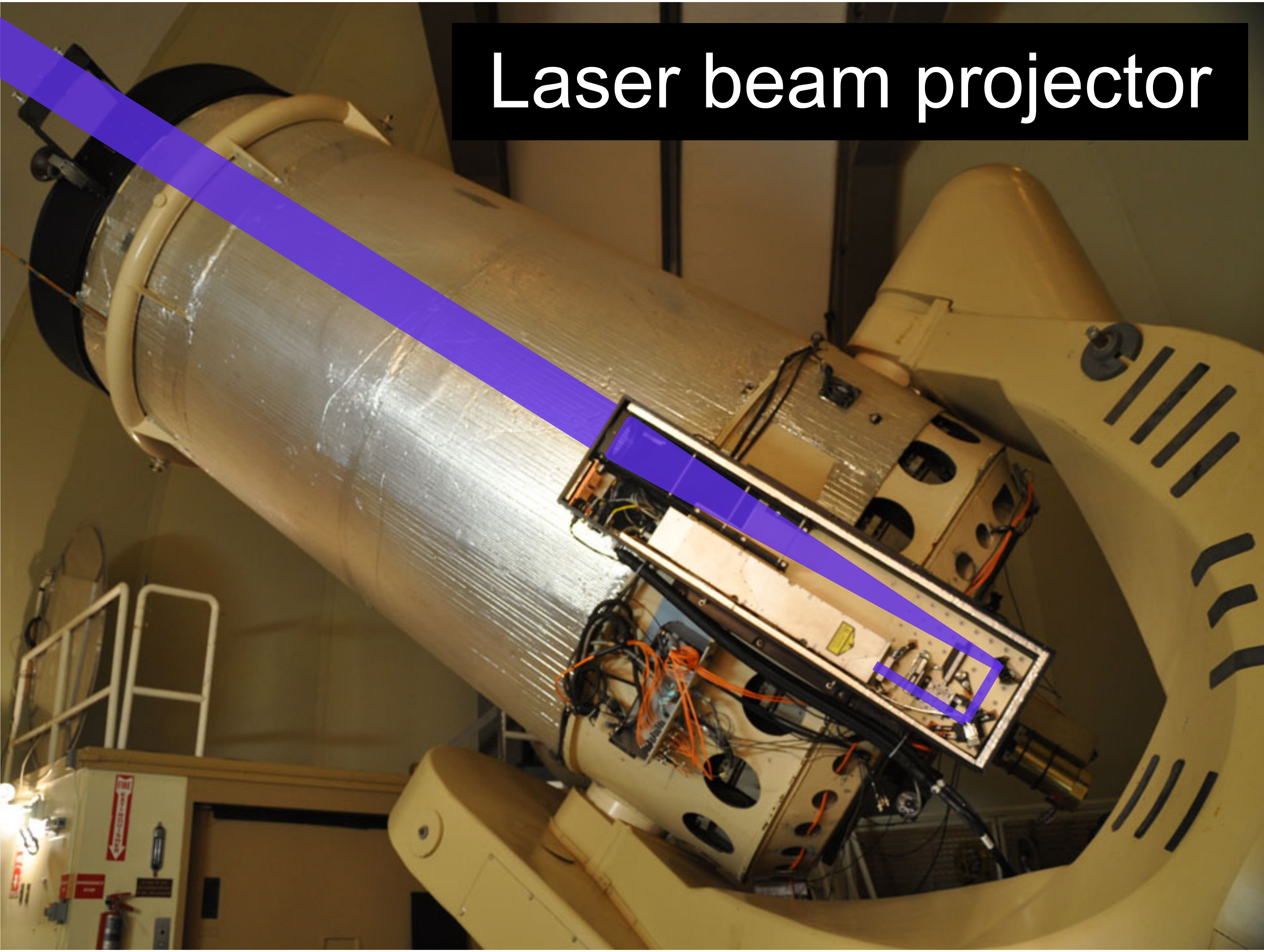
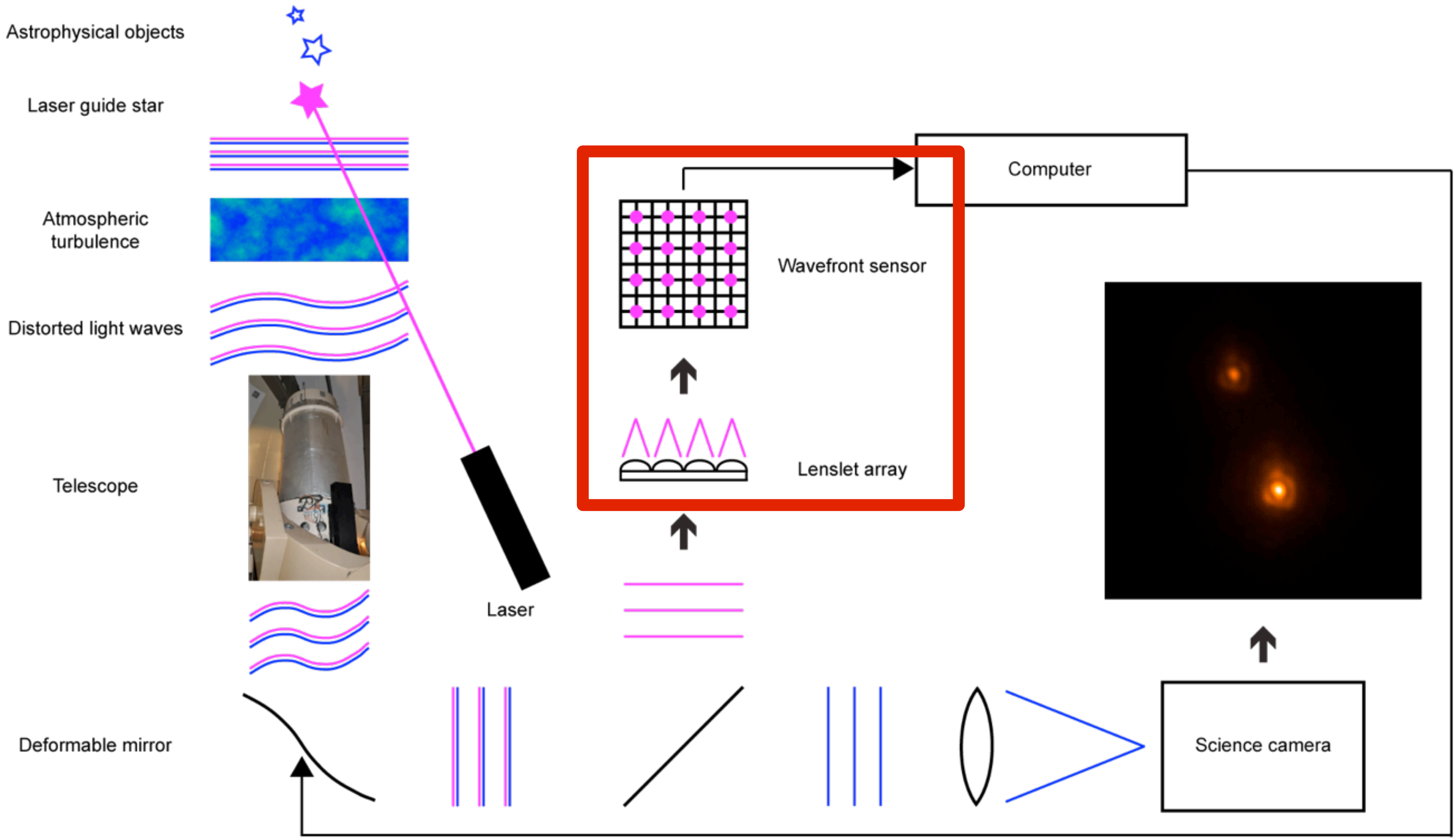
Laser drilling and scribing

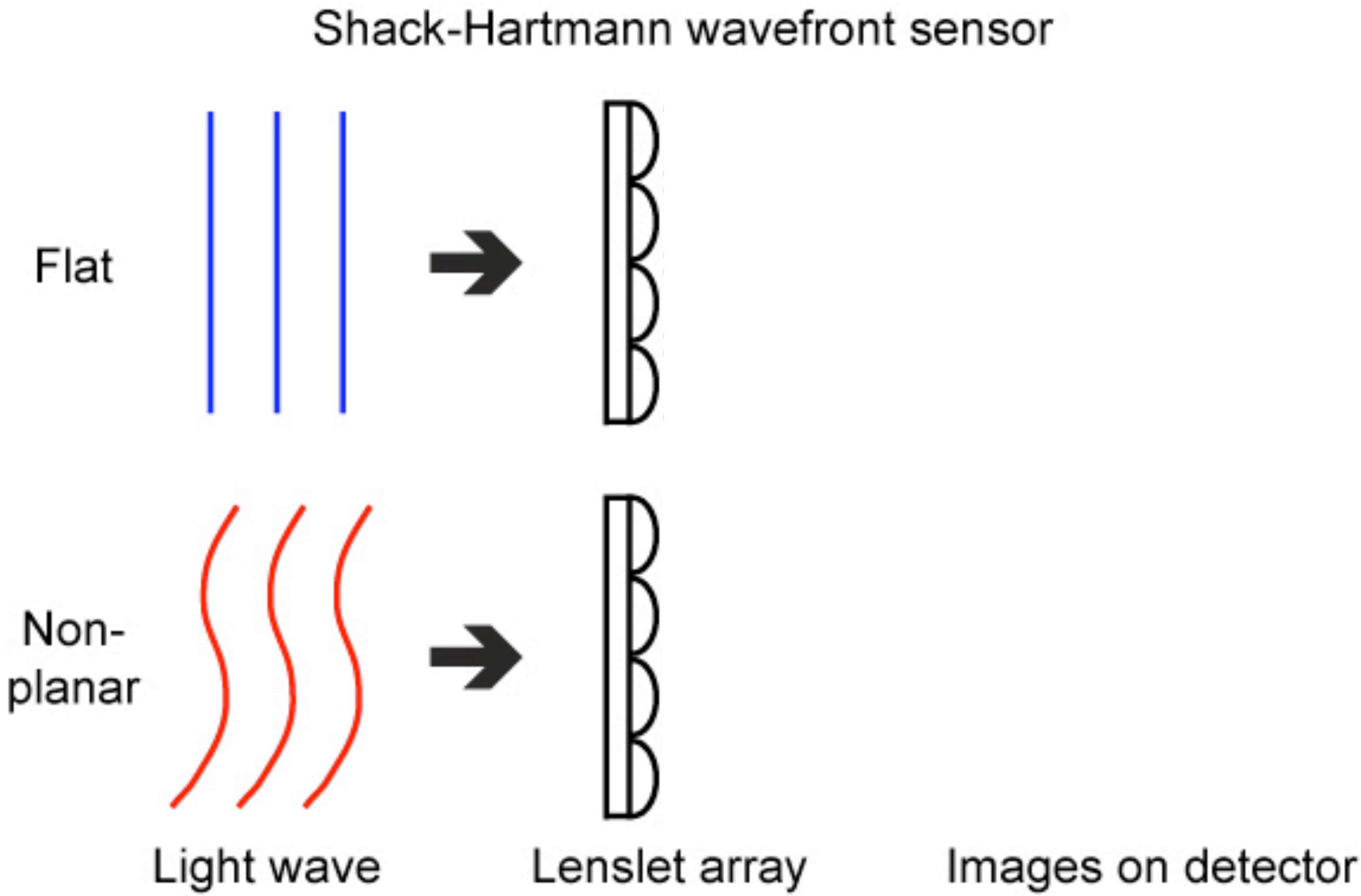
(Nilsson et al., 2004)


Laser beam projector

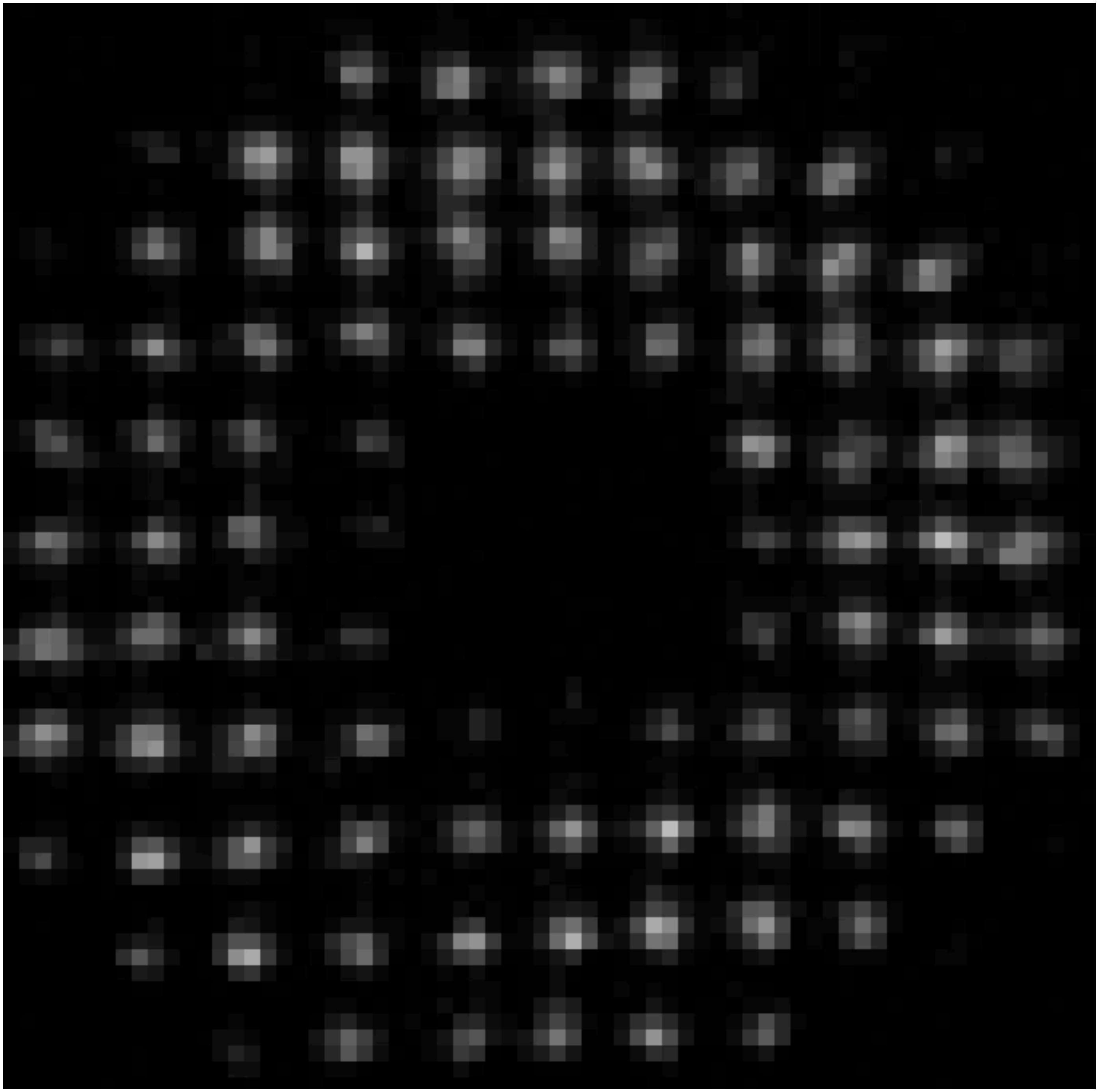
Adaptive Optics Components



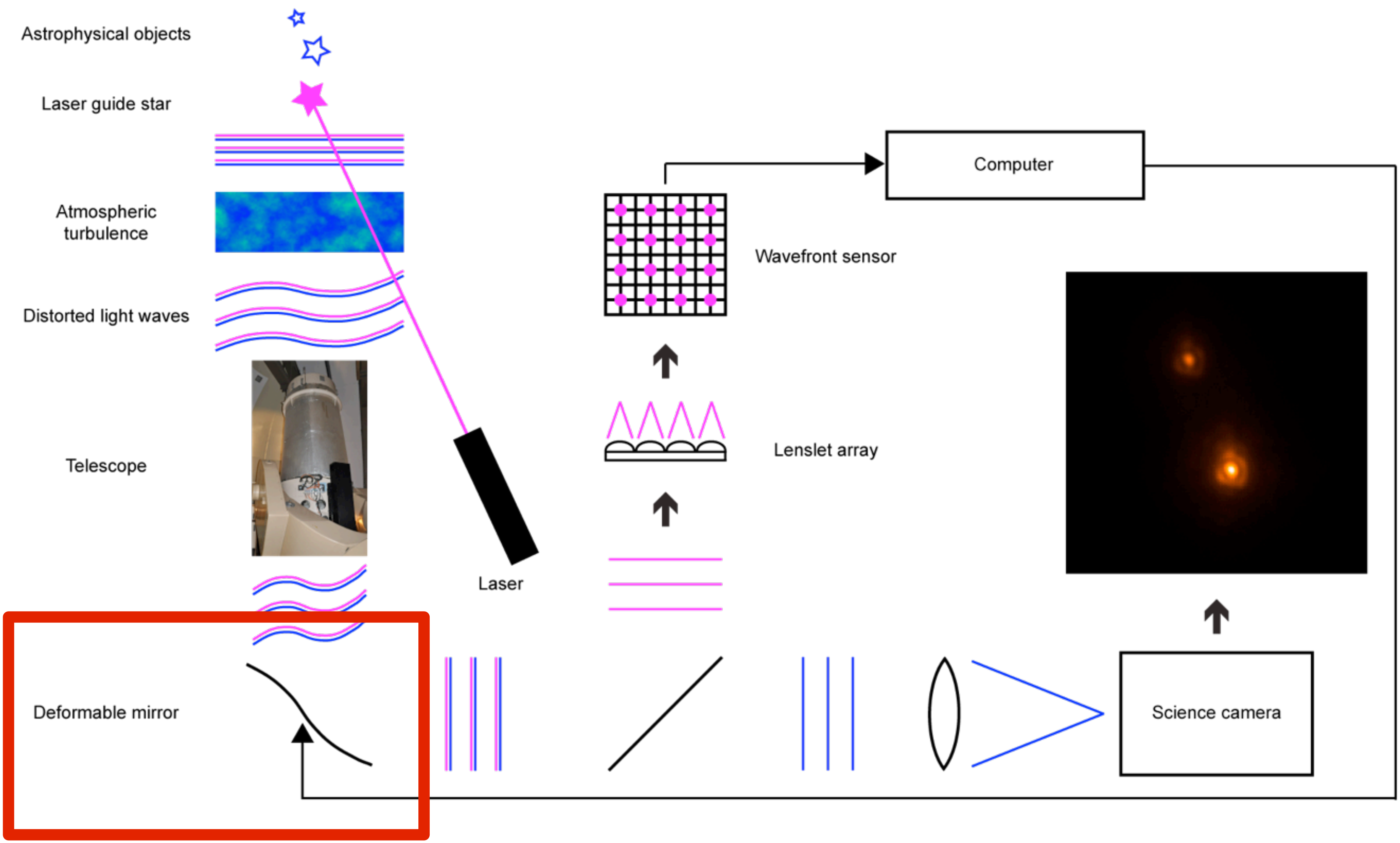
Measuring the shape of light



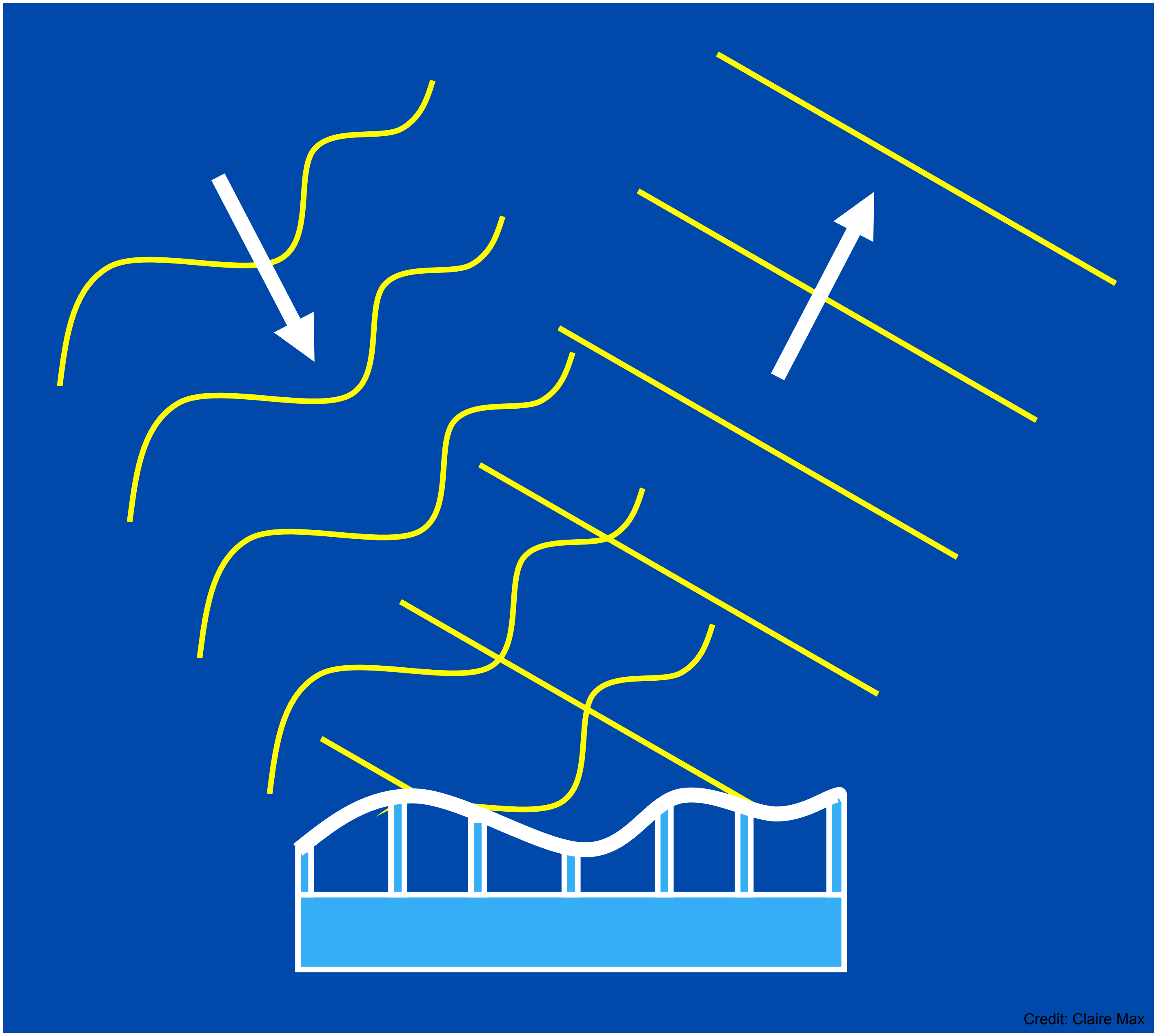
High-order Wavefront Sensor



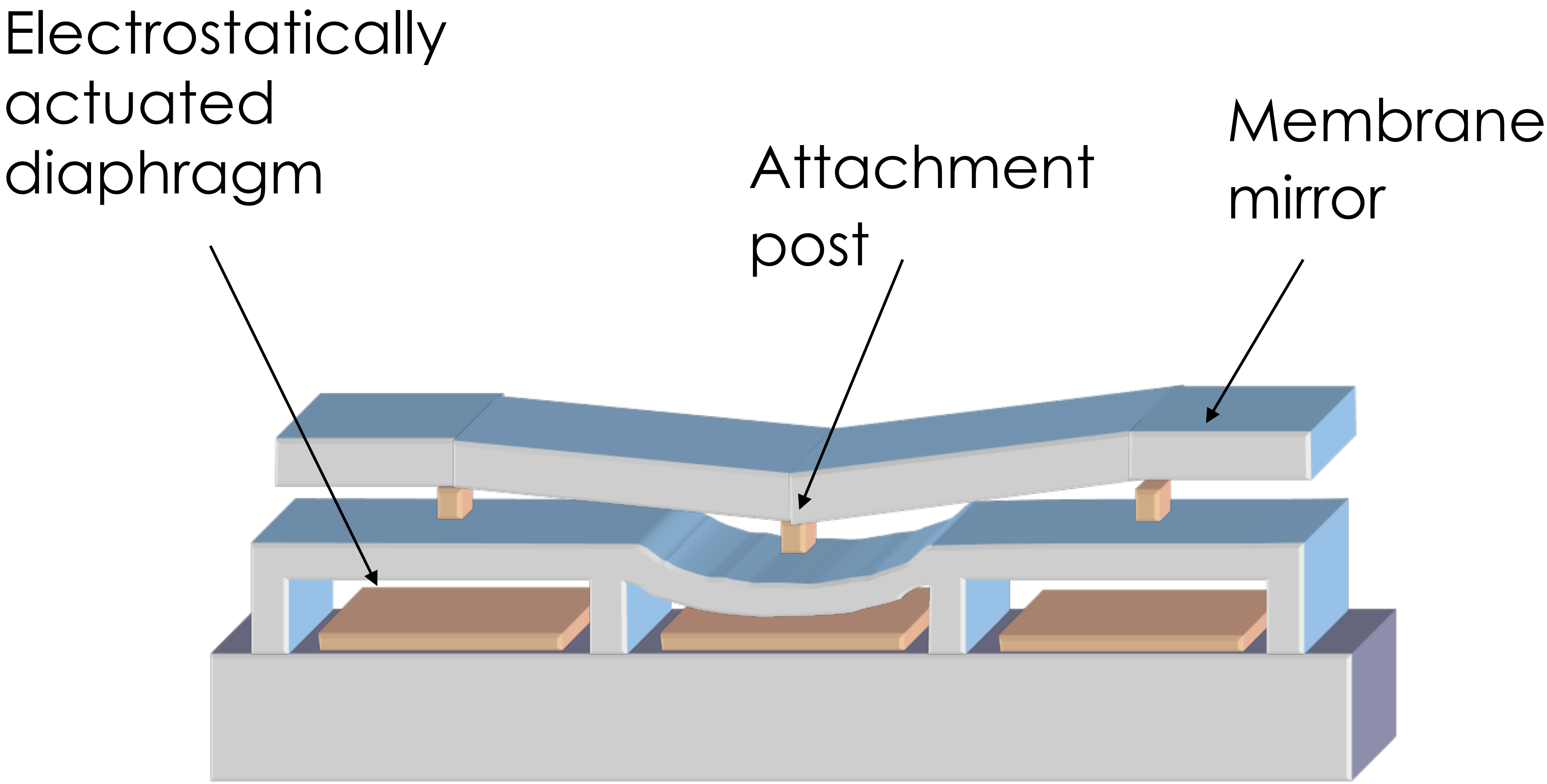
Adaptive Optics Components



Deformable mirrors affect light waves

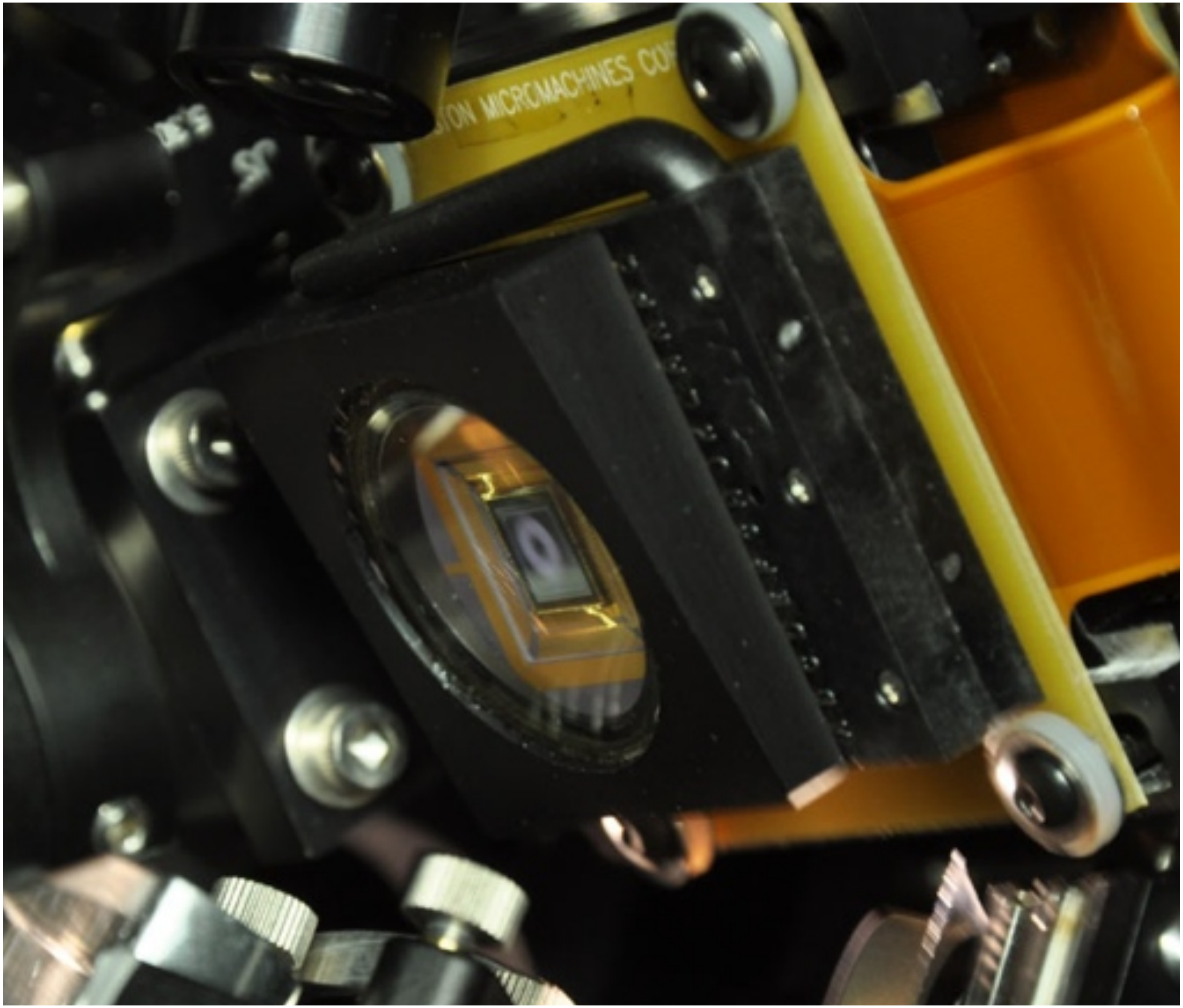


Deformable mirrors

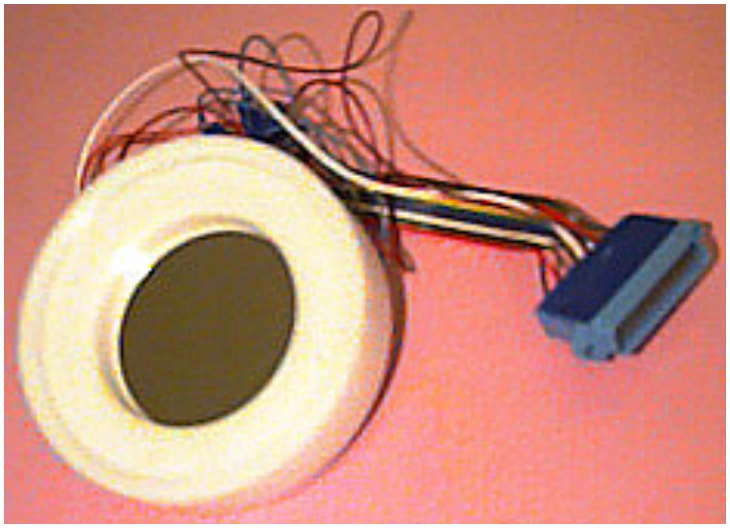


(Bifano, 2011)

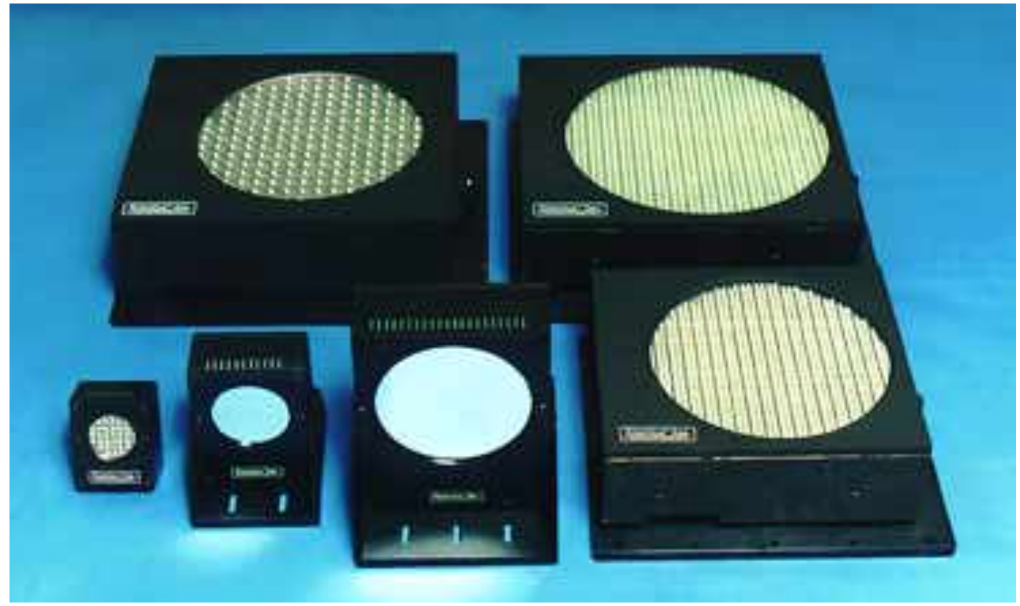
Silicon deformable mirror



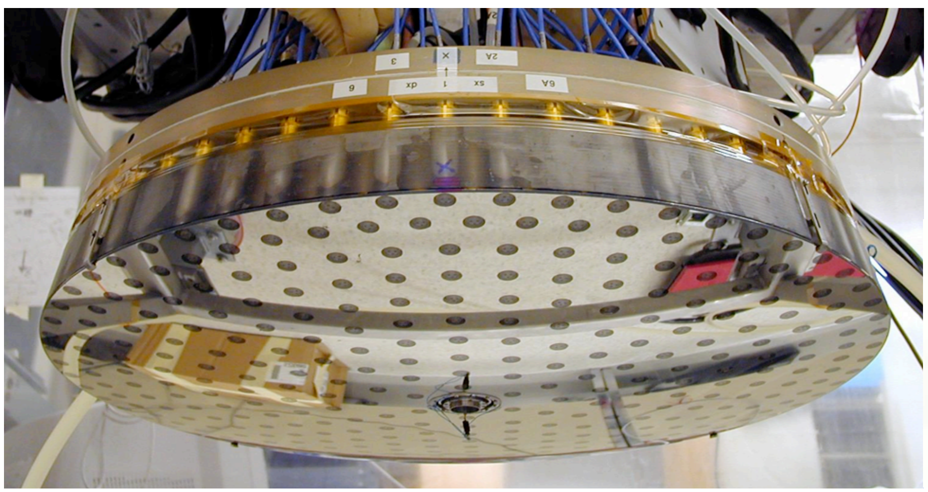
Other deformable mirrors



Uni/bi-morph DMs made from PZT wafers



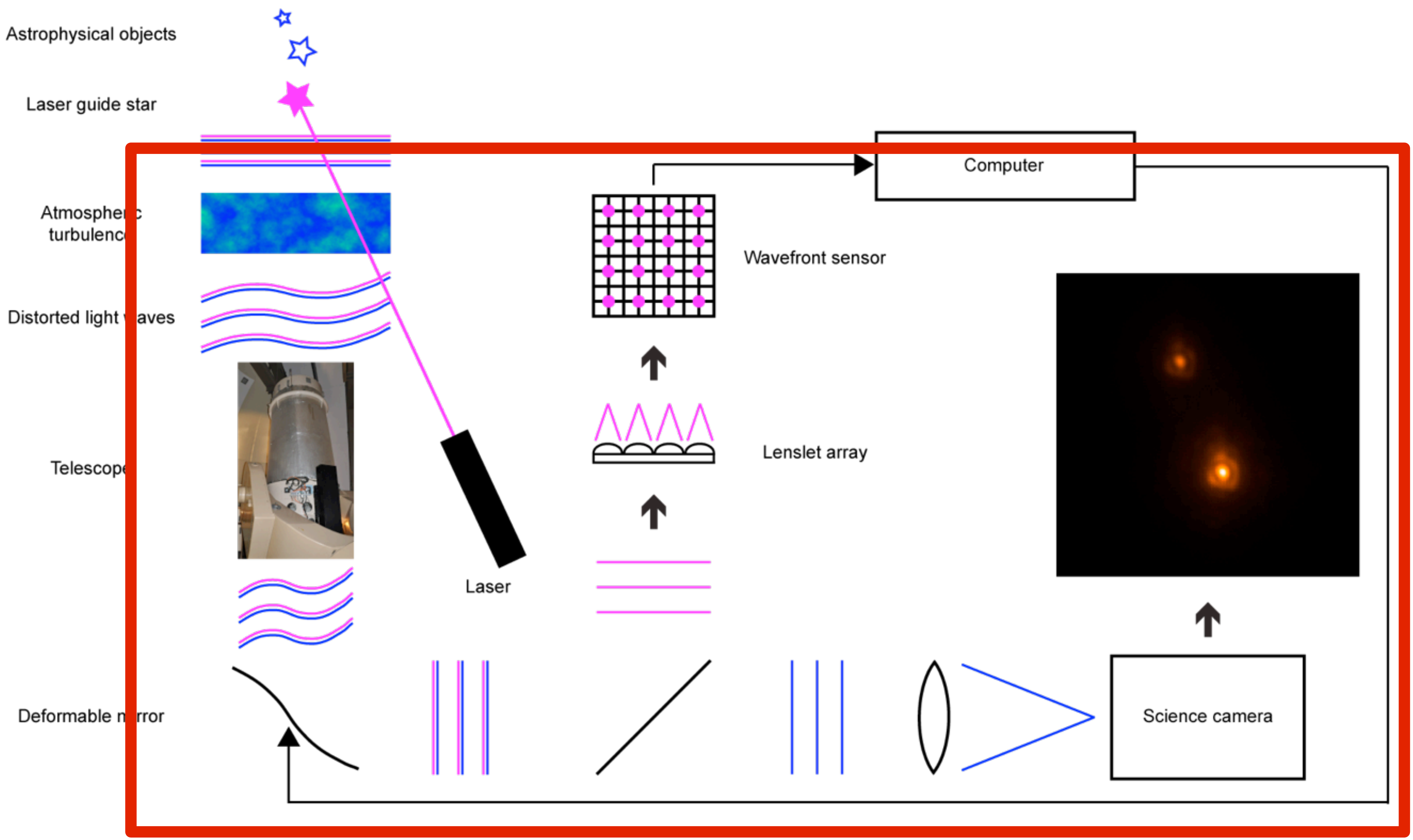
Piezo stack array DMs with glass factsheets



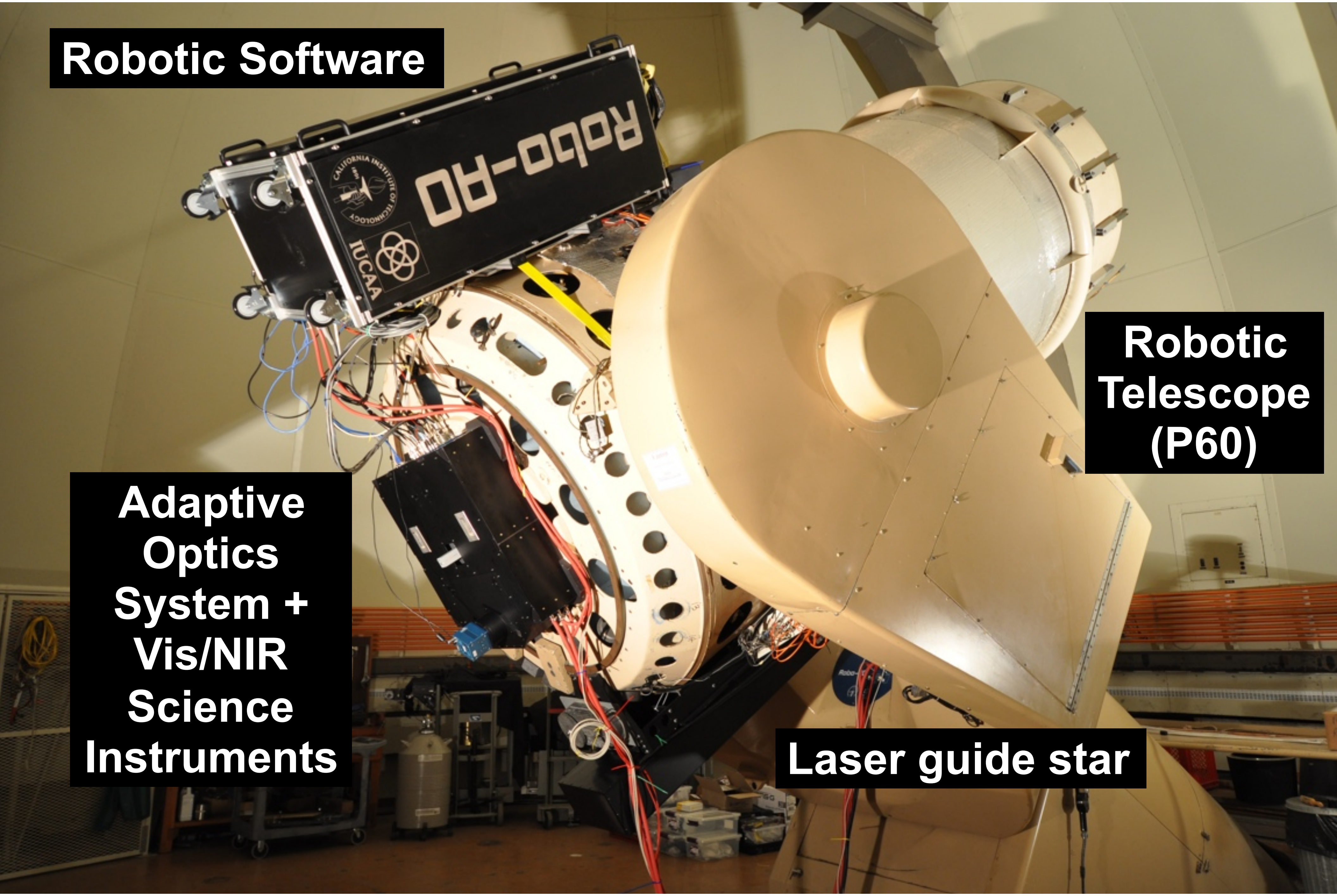
Voice coil deformable mirrors
(we’ll be testing a new ASM technology in a few years at UH88”)

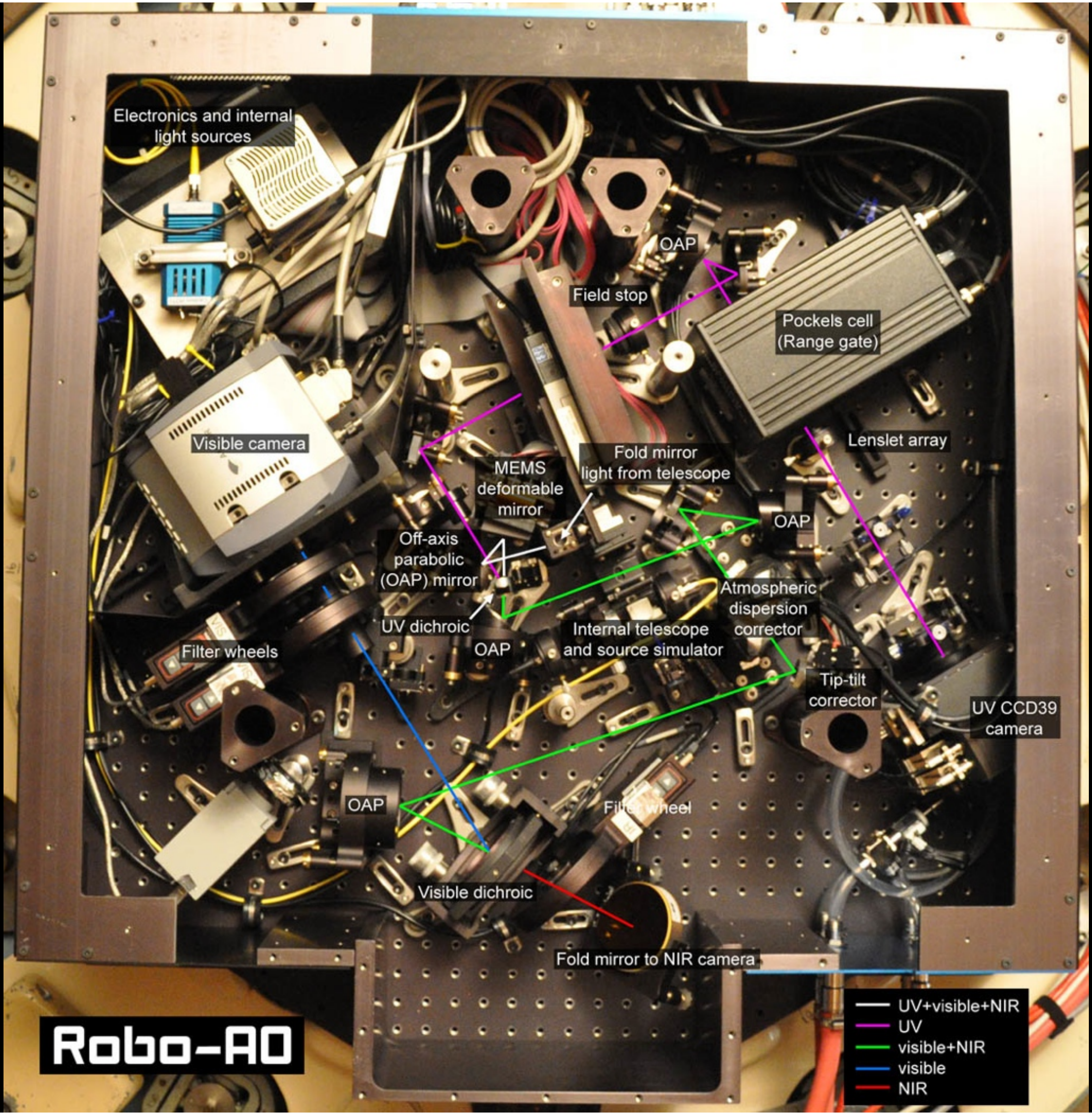
Even liquid crystal arrays (for narrow bandwidth and phase)

The entire system



Robo-AO on the Palomar 60" telescope

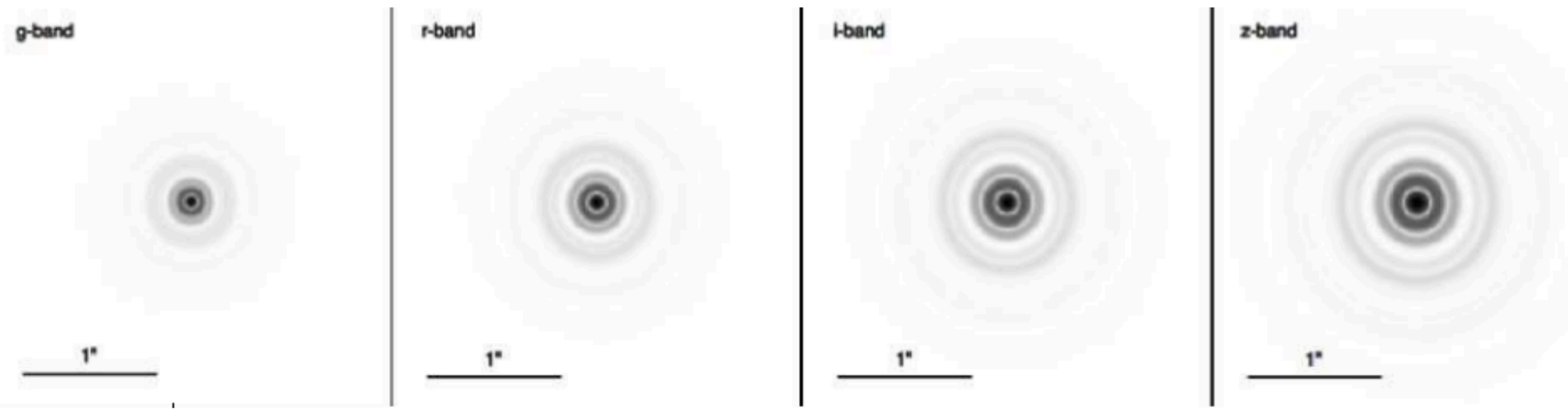




Electronics and internal light sources
OAP
Field stop
Pockels cell (Range gate)
Visible camera
Lenslet array
MEMS deformable mirror
Fold mirror light from telescope
OAP
Off-axis parabolic (OAP) mirror
Atmospheric dispersion corrector
UV dichroic
OAP
Internal telescope and source simulator
Filter wheels
Tip-tilt corrector
UV CCD39 camera
OAP
Filter wheel
Visible dichroic
Fold mirror to NIR camera
Robo-AO
UV+visible+NIR
UV
visible+NIR
visible
NIR

Strehl ratio - a measure of image quality

The ratio of peak intensity of the aberrated point-spread function (PSF) to an aberration-free PSF.



Model aberration-free PSFs for the Kitt-Peak 2.1-m telescope.

Salama, et al., SPIE 2016

The Maréchal Approximation

Strehl Ratio ~ $\exp(-\sigma^2) = \exp(-(2\pi[\mathrm{nm}]/\lambda)^2)$

- σ^2 - phase variance in square radians
- RMS wavefront error often expressed in nm

- This approximation does not take into account obscuration or frequency spectrum of phase variance.

r_0 and other useful relations

r_0 - Fried parameter / coherence length

– An aperture over which there is 1 radian^2 of phase variance.

Diffraction limited FWHM ~ λ/D

Seeing limited FWHM ~ λ/r_0

Total seeing phase variance = 1.03 $(D/r_0)^{5/3}$

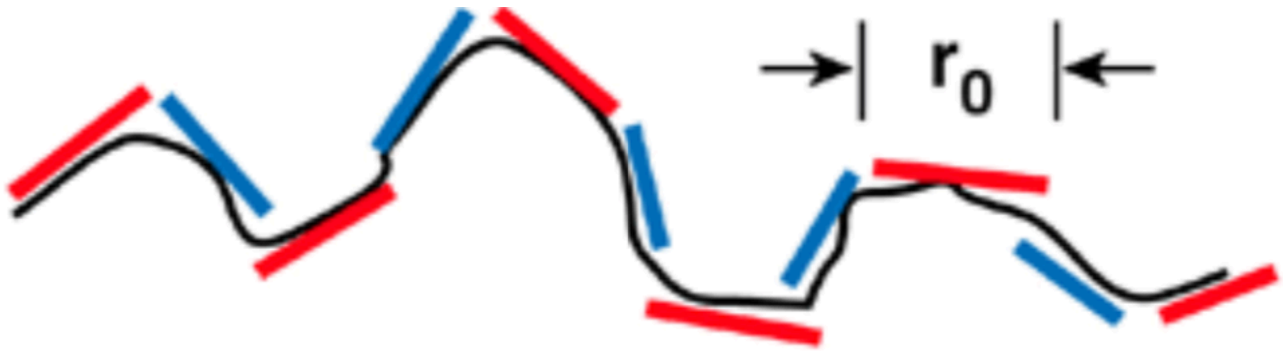
(Assuming Kolmogoroff power spectrum)

Error sources are added in quadrature.

Residual phase error:

$$\sigma^2_{\mathrm{total}} = \sigma^2_{\mathrm{fit}} + \sigma^2_{\mathrm{measure}} + \sigma^2_{\mathrm{delay}} + \sigma^2_{\mathrm{FA}} + \sigma^2_{\mathrm{other}}$$

Fitting error



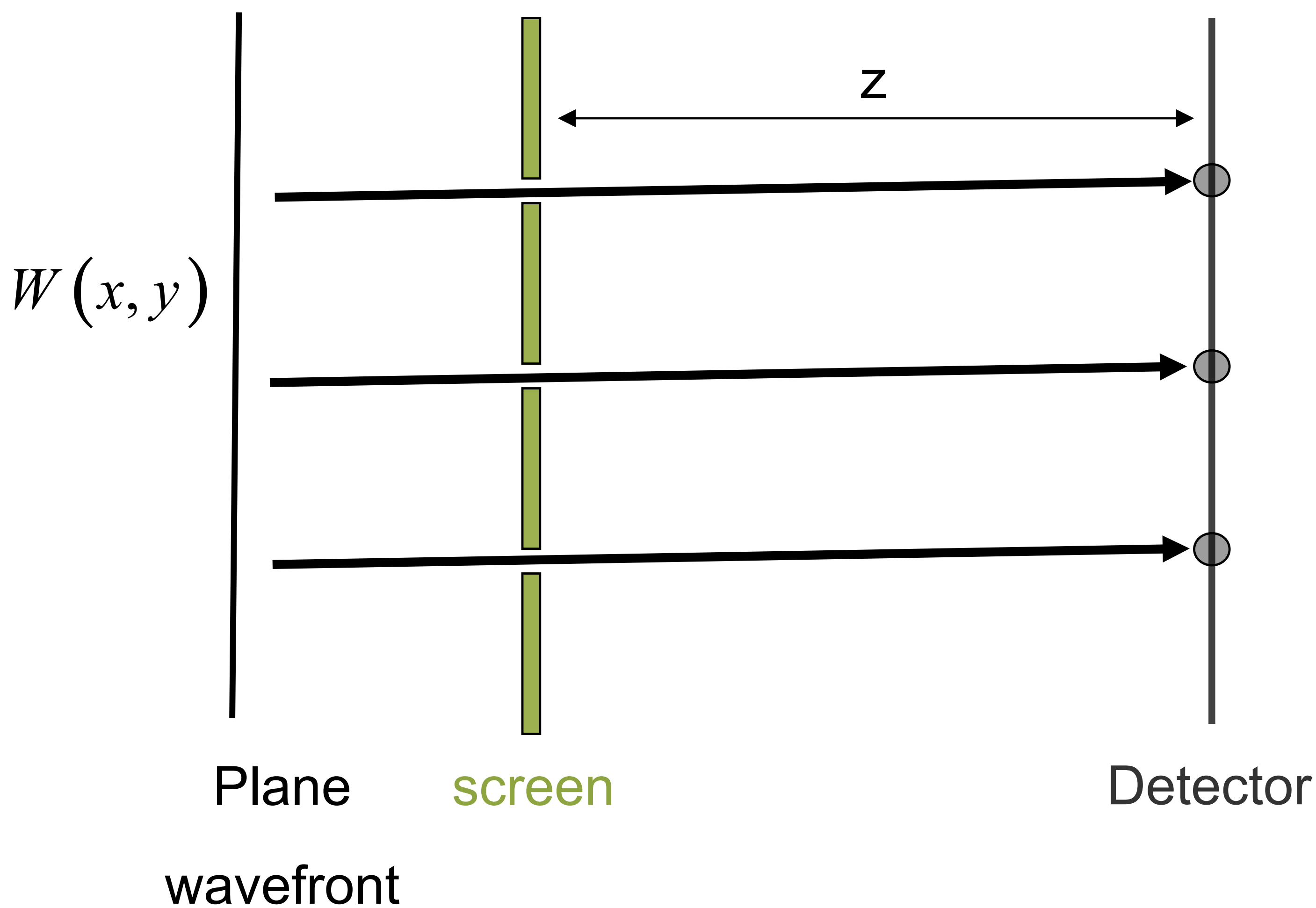
Credit: C. Max

$$\sigma^2_{\text{fit}} = a_F(d/r_0)^{5/3}$$

- a_F - constant based on geometry and control
- d - actuator spacing / sub aperture size*
- r_0 - Coherence length / Fried parameter

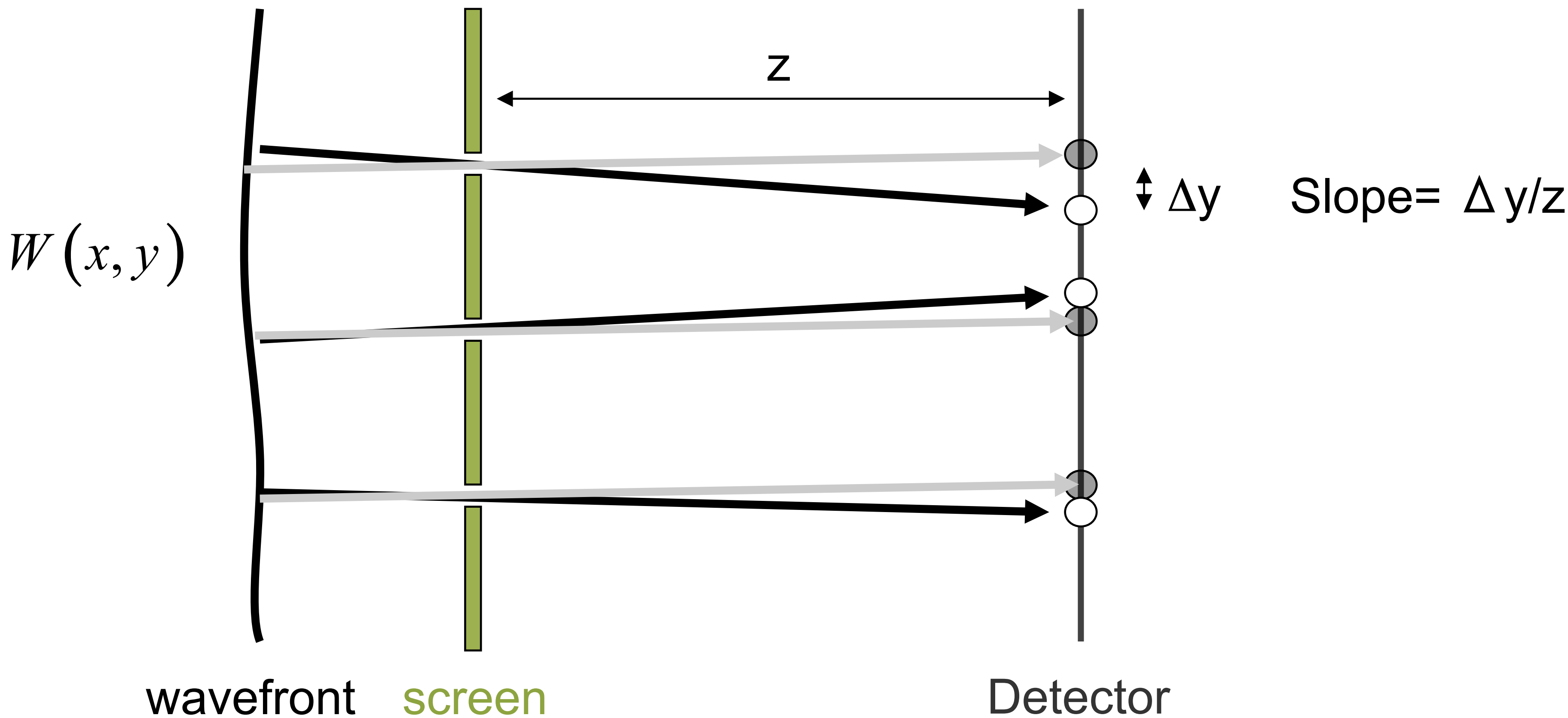
Measuring a light wave

- The Hartmann test (developed 1900):



Measuring a light wave

•

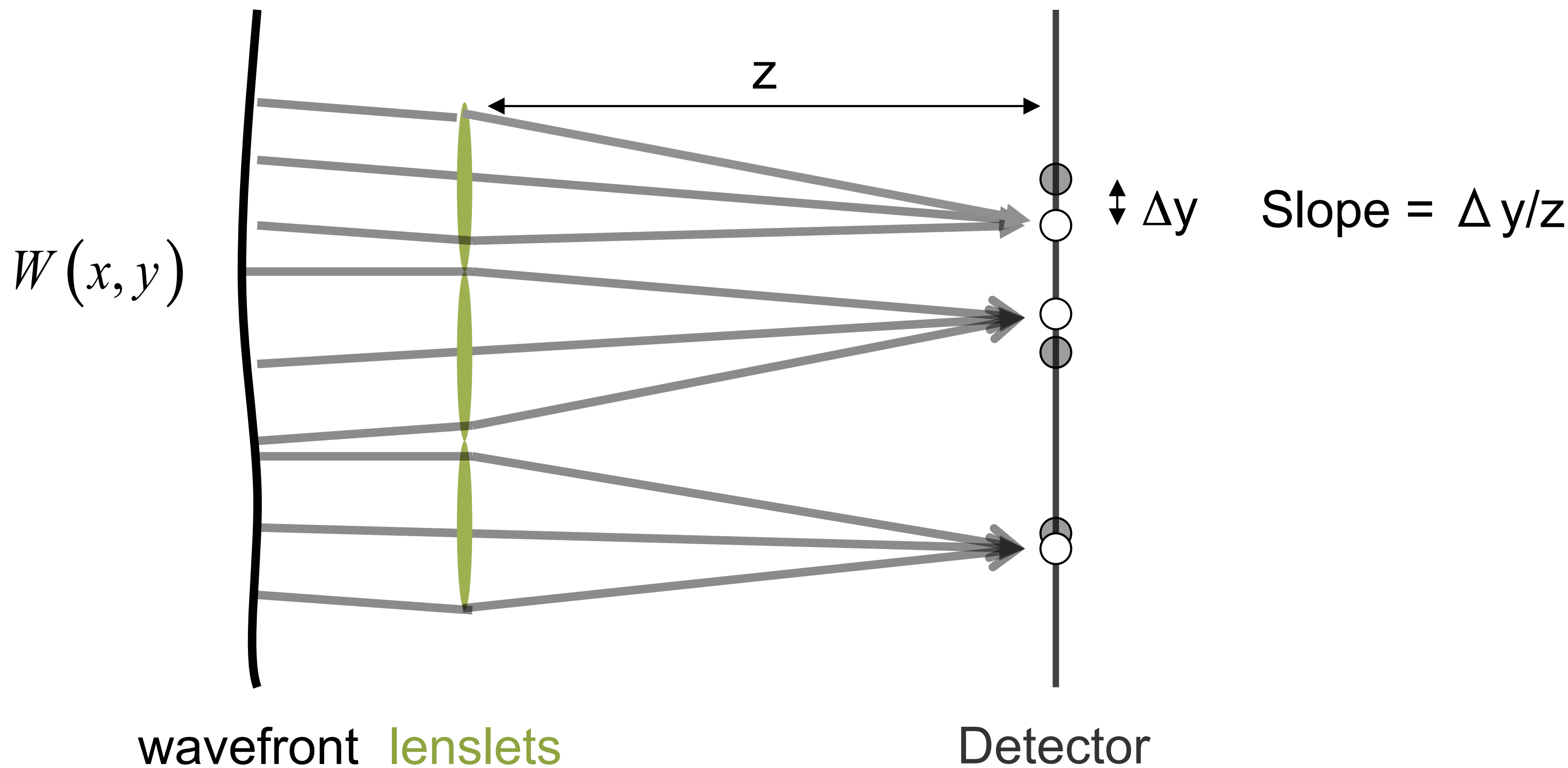


Measuring a light wave

- Main drawback to Hartmann test is the loss of light.
- Most stars aren’t that bright.
- More than 60 years for a real improvement.

Measuring a light wave

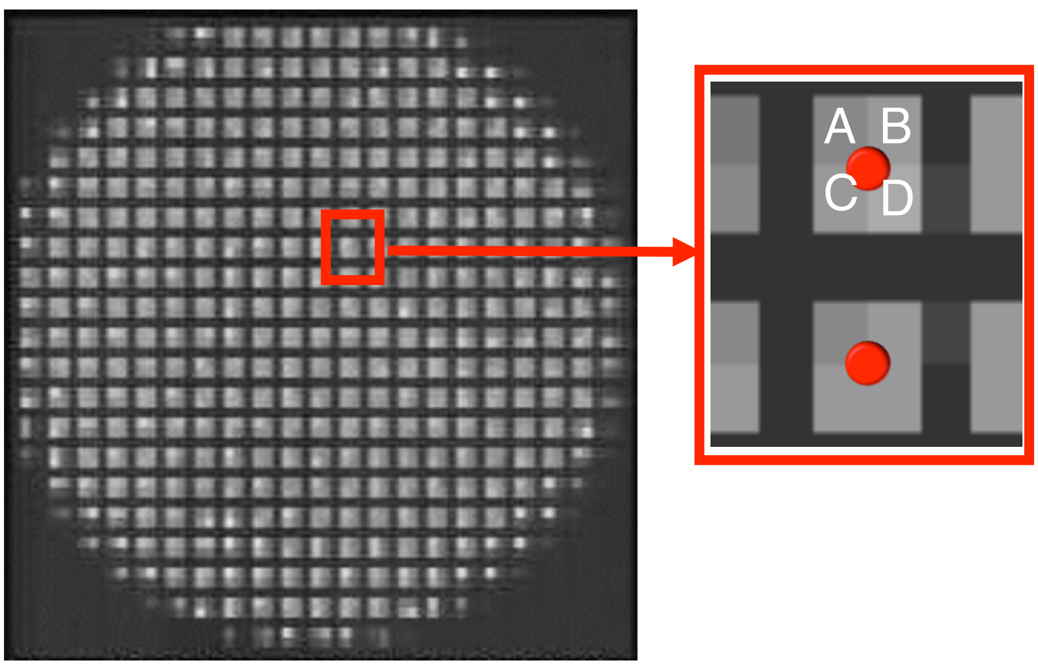
- Roland Shack (late 60's) proposed a grid of lenses instead of holes:



Locating Shack-Hartmann spots

- For each spot, measure its relative position.

Center-of-mass:



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

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

Signal/Noise of centroid

$$\mathrm{SNR} = \frac{n_{\mathrm{phot/sub}}}{(n_{\mathrm{phot/sub}} + n_{\mathrm{pix}}^2 e^2)^{1/2}}$$

- $n_{\mathrm{phot/sub}}$ - number photons per sub aperture
- n_{pix} - num. pixels per centroid measurement
- e - total noise from each pixel (read, dark, …)

Measurement error

$$\sigma_{\mathrm{me}}^2 = \begin{cases} \left(\frac{\pi^2}{4\mathrm{SNR}}\right)^2 \left(\left(\frac{3d}{2r_0}\right)^2 + \left(\frac{\theta d}{\lambda}\right)^2\right)\boldsymbol{E}, \mathrm{for}\, r_0 < d \\ \left(\frac{\pi^2}{4\mathrm{SNR}}\right)^2 \left(\left(\frac{3}{2}\right)^2 + \left(\frac{\theta d}{\lambda}\right)^2\right)\boldsymbol{E}, \ \mathrm{for}\, d < r_0 \end{cases}$$

- E - Error propagator, dependent on geometry of the wavefront sensor (slowly varies with d)
- θ - angular size of guide source (0 for NGS)
- d - subparture size
- SNR - Signal/noise for single measurement

Time delay error

$$\sigma_{\mathrm{td}}^2 = (\tau_s/\tau_0)^{5/3}$$

- τ_s - Time between measurement and application of correction. (Not frame rate)
- τ_0 - Atmospheric time constant. Typically 1-3 ms.
- There are other ways to determine this error.
- Partial mitigation with predictive control.

Balancing these errors

- Start with:
  - r_0, D, $\boldsymbol{\tau}_0$, guide star brightness
- You pick:
  - ***s* - d/D - spatial sampling of wavefront**
  - ***f* - frame rate / AO loop rate**
  - And to a lesser extent, WFS noise, geometry, QE of coatings, latency of computer, etc.

As $\boldsymbol{s}$ ⇧: σ^2_{fit} ⇩ and $\sigma^2_{\text{measure}}$ ⇧

As $\boldsymbol{f}$ ⇧: σ^2_{delay} ⇩ and $\sigma^2_{\text{measure}}$ ⇧

Analytical/brute force optimization

$$s_{\mathrm{opt}} = 0.529 \frac{a_F^{12/35} d_{\mathrm{tele}}^{4/7} \tau_0^{3/14} \Phi^{3/14}}{r_0^{4/7} n_{f\mathrm{delay}}^{3/14}}$$

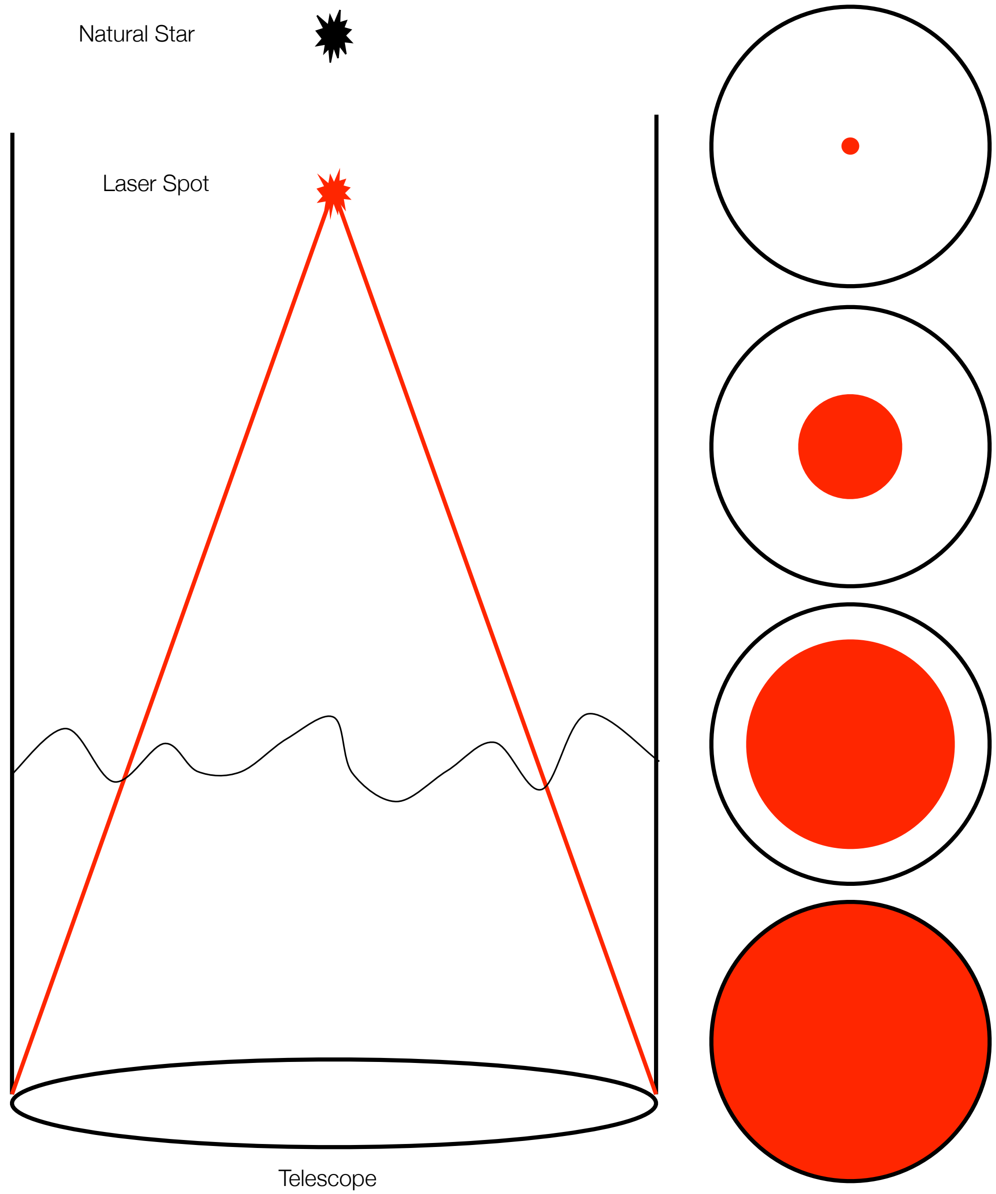
$$f_{\mathrm{opt}} = 0.801 \frac{n_{f\mathrm{delay}}^{1/14} r_0^{3/7} \Phi^{3/14}}{a_F^{9/35} d_{\mathrm{tele}}^{3/7} \tau_0^{11/14}}$$

ϕ - total radiant flux time system quantum efficiency

$n_{f\mathrm{delay}}$ - num. frames delay in CCD readout

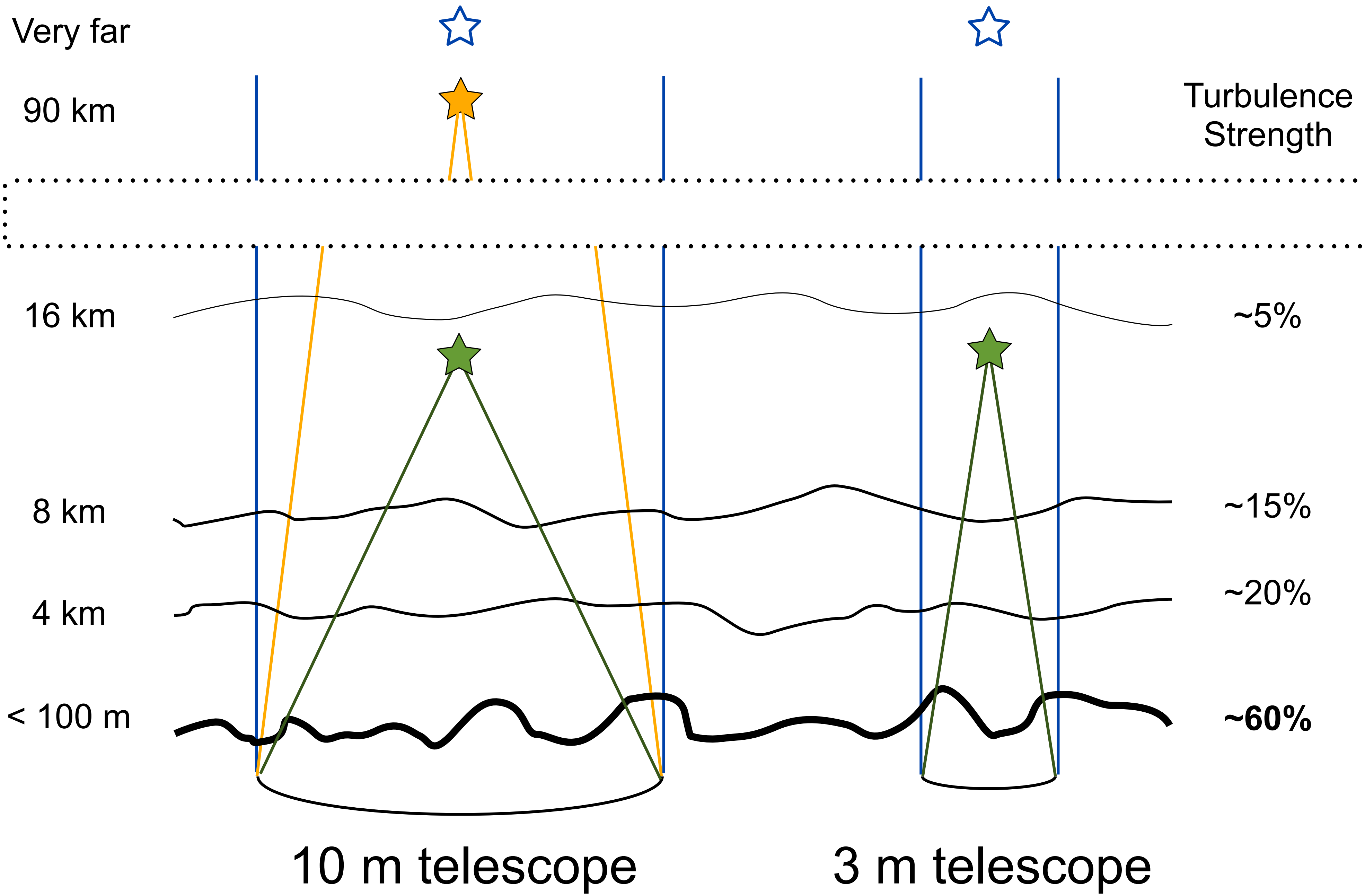
Baranec & Dekany, Ap. Opt. 2008

‘Focal Anisoplanatism’



Credit: Stalcup

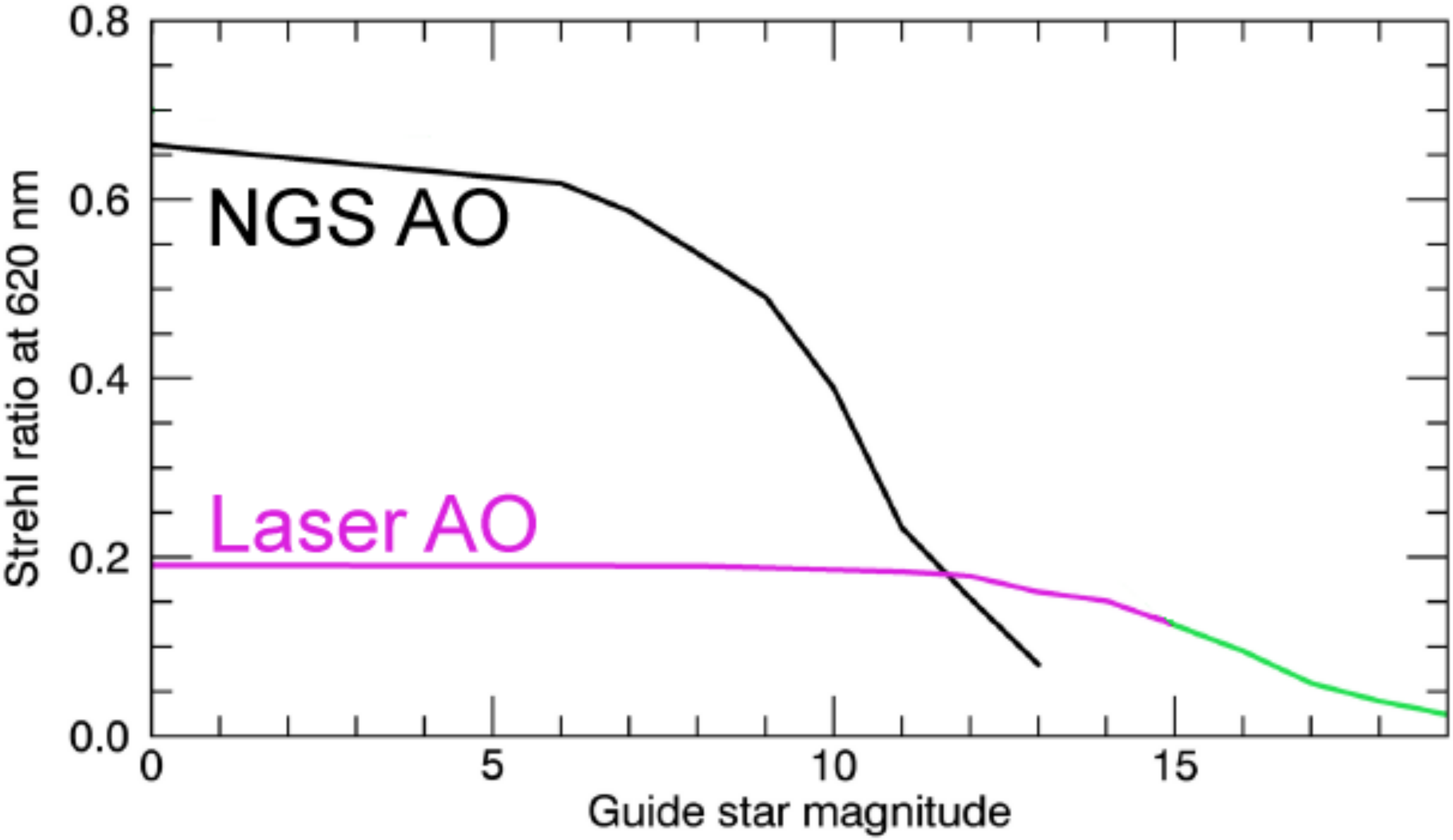
‘Focal Anisoplanatism’



Supplemental NGS wavefront sensing

- Lasers are insensitive to atmospheric tip/tit.
- Require supplemental tip/tilt sensing.
- Rayleigh always at exact same range.
- The Sodium layer and profile fluctuate requiring the use of a NGS to track focus.

Representative correction of NGS vs. LGS AO



How does one design an AO system?

- Can the objects you want to look at be used as their own guide star (NGS), or do you need a laser?
- Do you need high contrast? Bright NGS
- Do you need high sky coverage? Laser
- Do you need a wide field? Multiple NGS/laser
- Do you need something else?
- Build an error budget spreadsheet.

Percentile Seeing				10%		25%		50%		75%	
				0.67" @ z=0° r_0 = 15 cm		1.02" @ z=40° r_0 = 9.8 cm		1.12" @ z=20° r_0 = 8.9 cm		1.69" @ z=10° r_0 = 5.9 cm	
High-order Errors				**Wavefront Error (nm)**							
Atmospheric Fitting Error				39		56		61		85	
Bandwidth Error				47		52		65		92	
High-order Measurement Error				41		46		57		81	
LGS Focal Anisoplanatism Error				60		102		96		131	
Multispectral Error				0		74		11		3	
Scintillation Error				13		26		22		29	
WFS Scintillation Error				10		10		10		10	
Uncorrectable Tel / AO / Instr Aberrations				38		38		38		38	
Zero-Point Calibration Errors				34		34		34		34	
Pupil Registration Errors				21		21		21		21	
High-Order Aliasing Error				13		19		20		28	
DM Stroke / Digitization Errors				5		5		5		5	
Total High Order Wavefront Error				**112 nm**		**168 nm**		**156 nm**		**219 nm**	
Tip-Tilt Errors				**Angular Error (mas)**							
Tilt Measurement Error				19		24		27		39	
Tilt Bandwidth Error				14		18		21		30	
Science Instrument Mechanical Drift				6		6		6		6	
Residual Telescope Pointing Jitter				2		3		2		2	
Residual Centroid Anisoplanatism				1		2		2		2	
Residual Atmospheric Dispersion				0		1		0		0	
Total Tip/Tilt Error (one-axis)				**24 mas**		**30 mas**		**35 mas**		**50 mas**	
Total Effective Wavefront Error				**137 nm**		**176 nm**		**185 nm**		**241 nm**	
Spectral Band	**λ**	**λ/D**		**Strehl**	FWHM	**Strehl**	FWHM	**Strehl**	FWHM	**Strehl**	FWHM
r'	**0.62 μ**	**0.08"**		**17%**	0.09"	**5%**	0.14"	**4%**	0.15"	**0%**	0.59"
i'	**0.75 μ**	**0.10"**		**28%**	0.10"	**12%**	0.15"	**10%**	0.15"	**2%**	0.21"
H	**1.64 μ**	**0.22"**		**75%**	0.22"	**63%**	0.23"	**59%**	0.24"	**38%**	0.26"

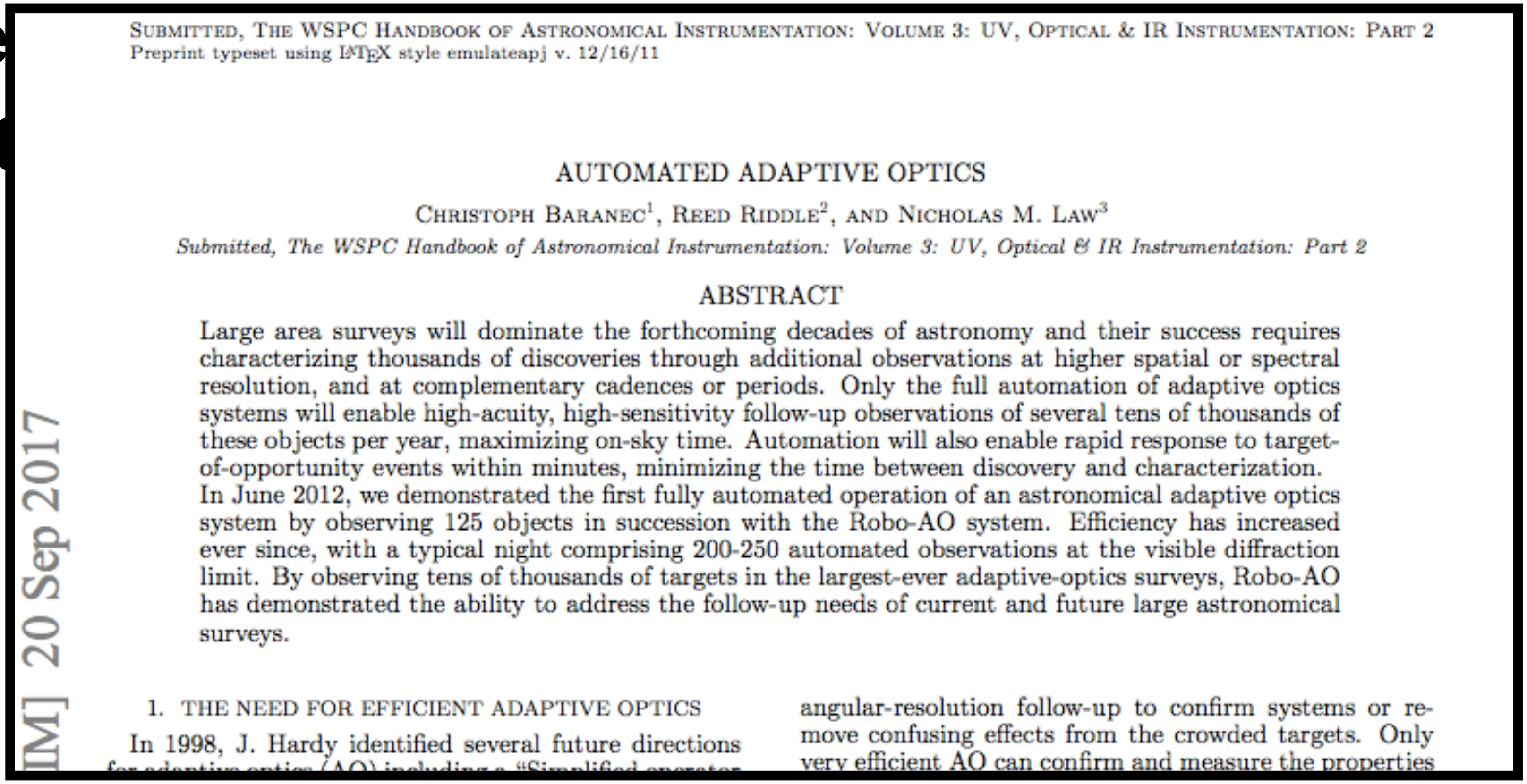
c/o Dekaney, et al.

There is a growing need for very efficient adaptive optics.

- Large surveys, large data sets
  - E.g., Kepler, TESS, Gaia, Pan-STARRS, …
  - Binary stars, exoplanet host vetting, …
- Rapid-response (transients)
  - E.g., ATLAS, ZTF, LSST, your favorite TDA project
  - Crowded fields, location in host galaxy, SNR boost
- Monitoring
  - E.g., planetary weather, lensed quasar dynamics

Efficient AO Design Philosophy

- Most large telescopes have (laser) AO.
- Primarily focused on very detailed studies of few inte
- Met



Submitted, The WSPC Handbook of Astronomical Instrumentation: Volume 3: UV, Optical & IR Instrumentation: Part 2
Preprint typeset using LaTeX style emulateapj v. 12/16/11

AUTOMATED ADAPTIVE OPTICS

Christoph Baranec[1], Reed Riddle[2], and Nicholas M. Law[3]

Submitted, The WSPC Handbook of Astronomical Instrumentation: Volume 3: UV, Optical & IR Instrumentation: Part 2

ABSTRACT

Large area surveys will dominate the forthcoming decades of astronomy and their success requires characterizing thousands of discoveries through additional observations at higher spatial or spectral resolution, and at complementary cadences or periods. Only the full automation of adaptive optics systems will enable high-acuity, high-sensitivity follow-up observations of several tens of thousands of these objects per year, maximizing on-sky time. Automation will also enable rapid response to target-of-opportunity events within minutes, minimizing the time between discovery and characterization. In June 2012, we demonstrated the first fully automated operation of an astronomical adaptive optics system by observing 125 objects in succession with the Robo-AO system. Efficiency has increased ever since, with a typical night comprising 200-250 automated observations at the visible diffraction limit. By observing tens of thousands of targets in the largest-ever adaptive-optics surveys, Robo-AO has demonstrated the ability to address the follow-up needs of current and future large astronomical surveys.

IM] 20 Sep 2017

1. THE NEED FOR EFFICIENT ADAPTIVE OPTICS

In 1998, J. Hardy identified several future directions

angular-resolution follow-up to confirm systems or remove confusing effects from the crowded targets. Only very efficient AO can confirm and measure the properties

Baranec, Riddle & Law: arXiv:1709.07103

Robo-AO

Fully robotic laser AO

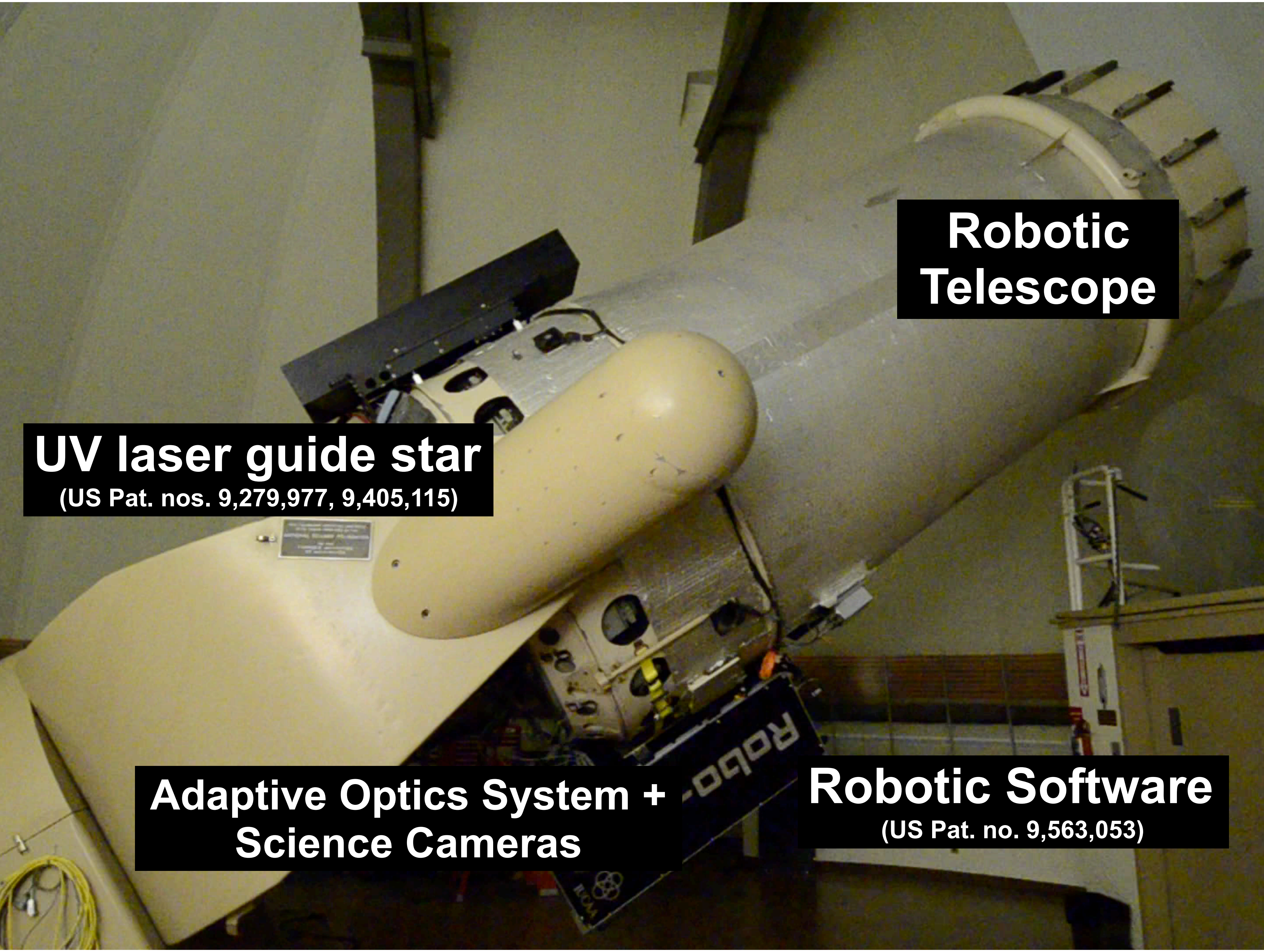
Sub-minute overheads

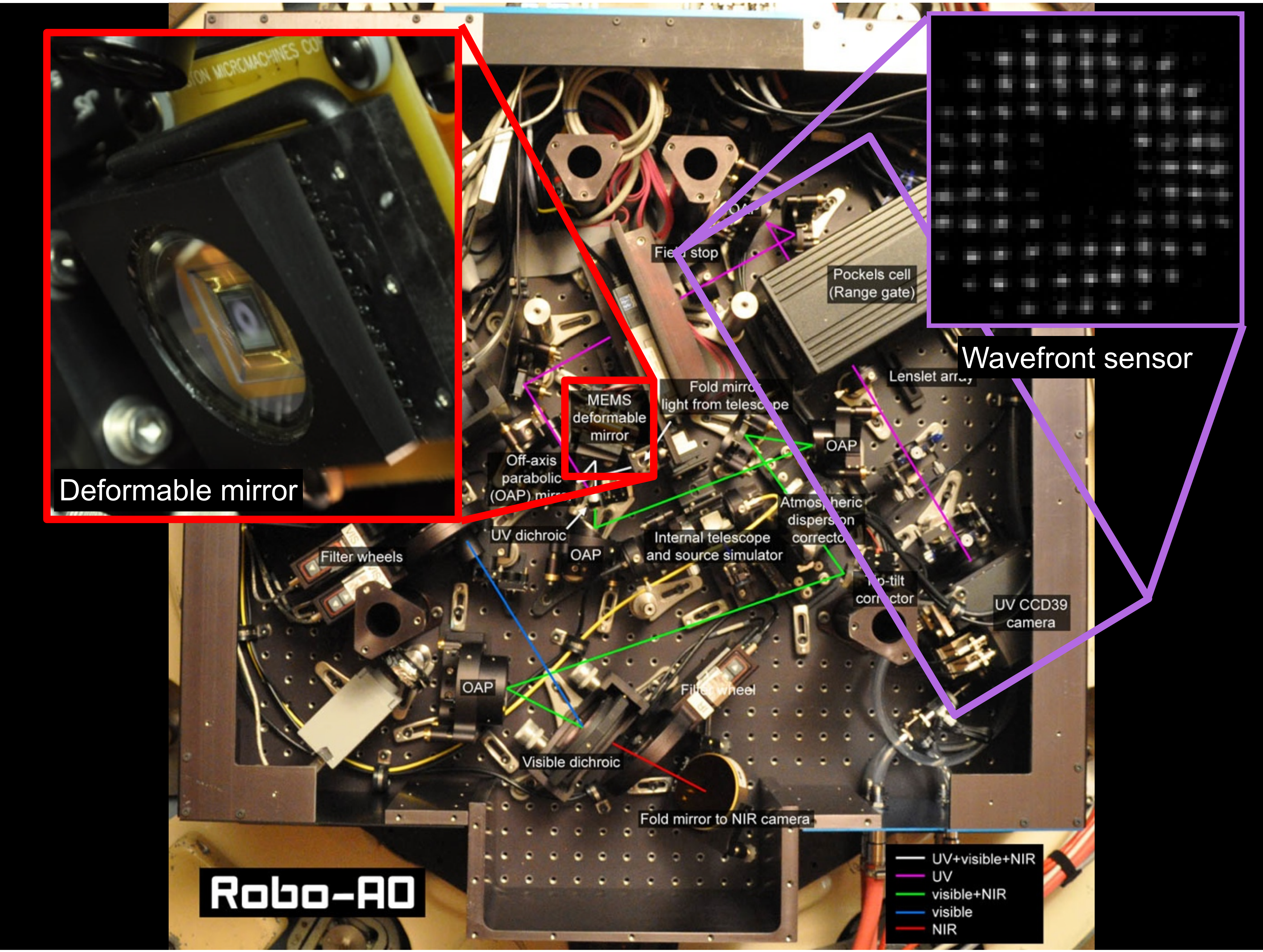
Performing previously infeasible AO surveys, N>1,000

Diffraction limited on V<16 point sources

Detects Δm~5 at 0.5”

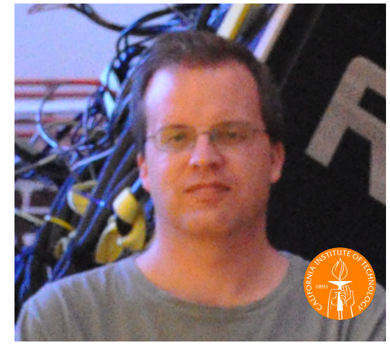
Baranec, Riddle, Law, et al., 2013, 2014


Robotic Telescope
UV laser guide star
(US Pat. nos. 9,279,977, 9,405,115)
Adaptive Optics System +
Science Cameras
Robotic Software
(US Pat. no. 9,563,053)
Robo-



Deformable mirror
Wavefront sensor
MEMS deformable mirror
Field stop
Pockels cell (Range gate)
Lenslet array
Fold mirror light from telescope
OAP
Off-axis parabolic (OAP) mirror
Atmospheric dispersion corrector
UV dichroic
OAP
Internal telescope and source simulator
Filter wheels
Tip-tilt corrector
UV CCD39 camera
OAP
Filter wheel
Visible dichroic
Fold mirror to NIR camera
Robo-AO
UV+visible+NIR
UV
visible+NIR
visible
NIR

Robo-AO is fully automated.

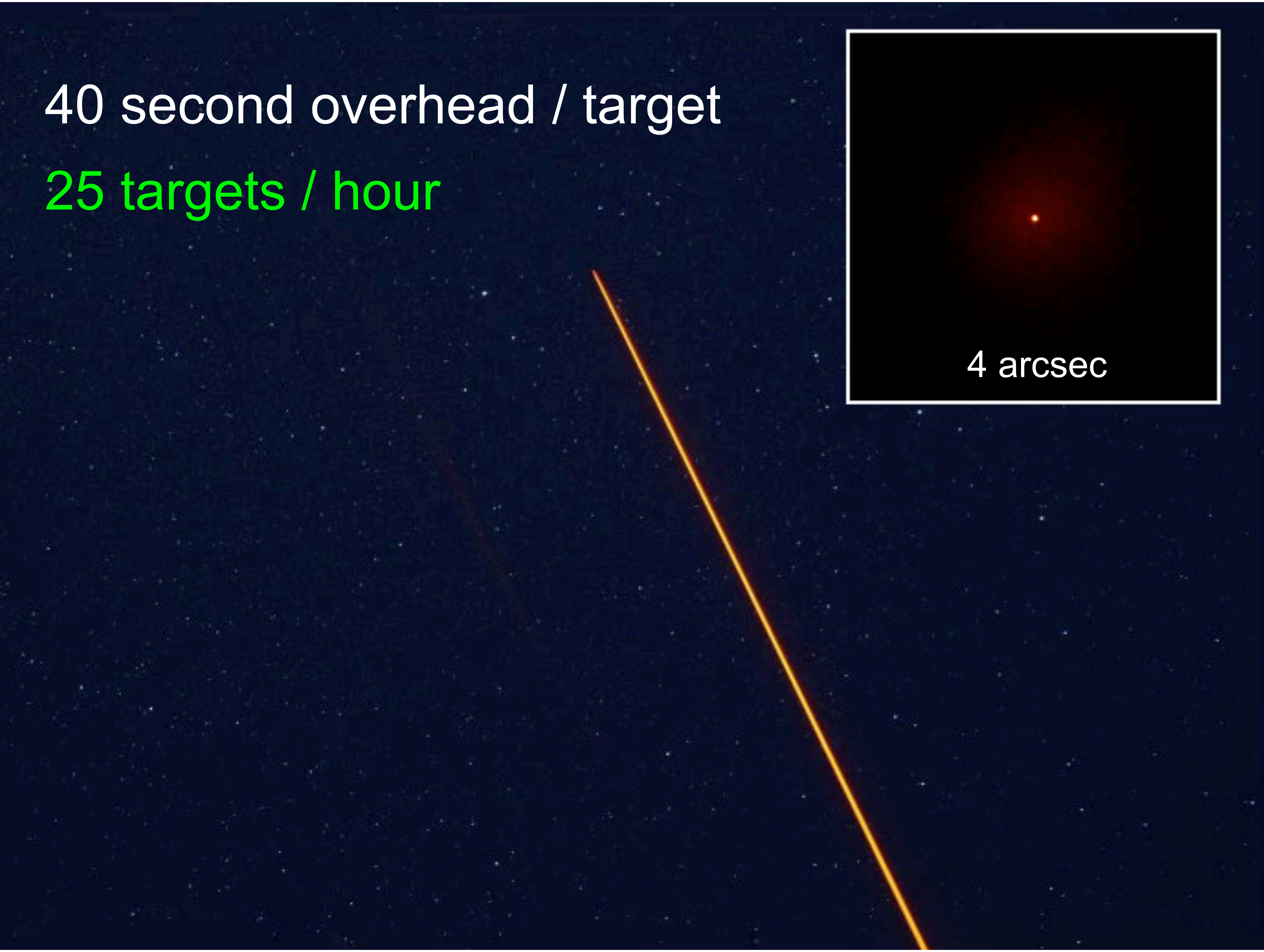


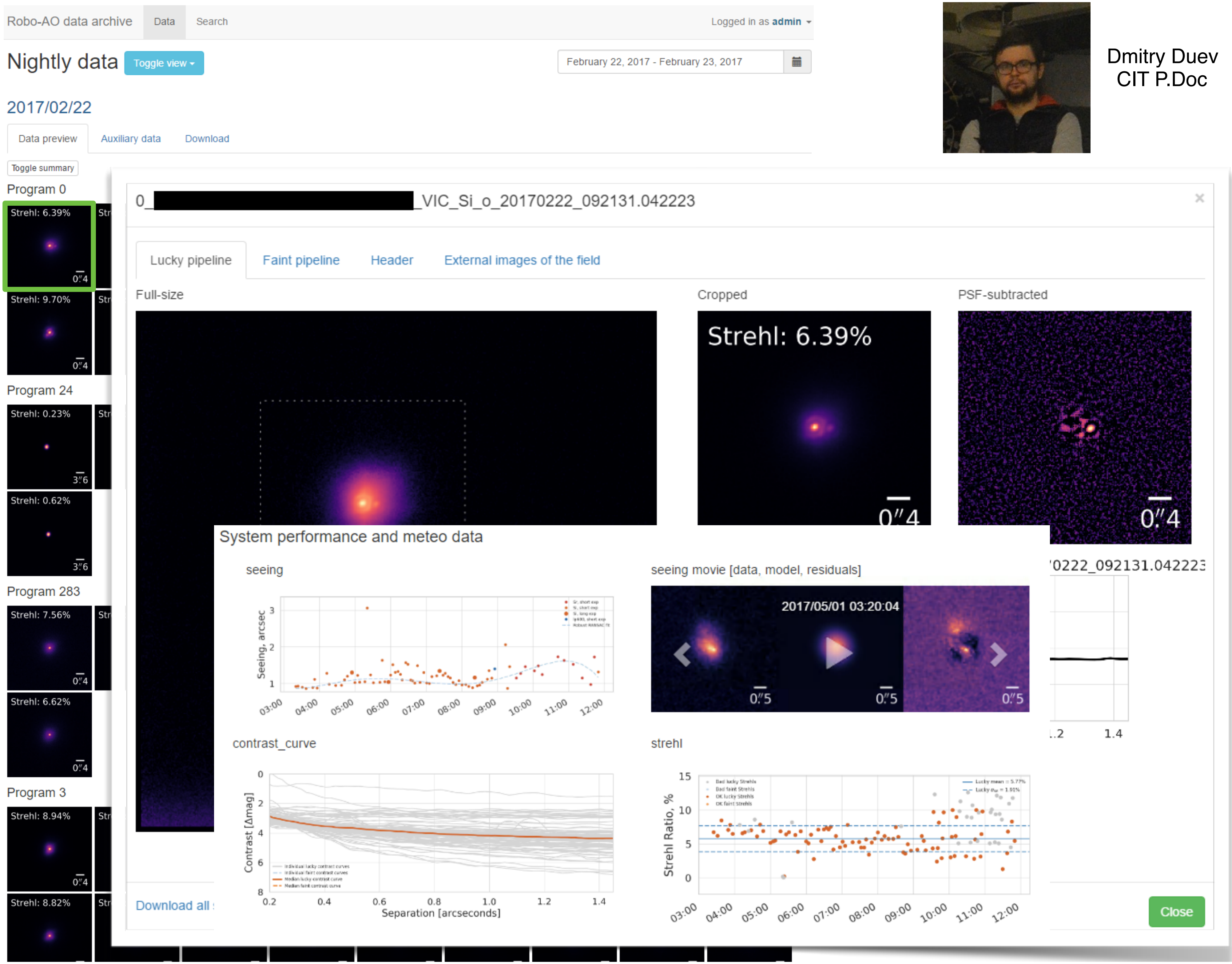
Reed Riddle, Robotic software Guru

- A master sequencer runs the show.
- Subsystems run as daemons.
- Auto-recovery from unexpected errors
- Observations loaded into database via .xml.
- Intelligent obs. queue, mixes science programs
  - Automatic satellite/laser deconfliction (TBD Keck)
- Automatic data reduction and analysis pipeline (images ready the next day)

40 second overhead / target

25 targets / hour





Dmitry Duev
CIT P.Doc

Robo-AO General Observing

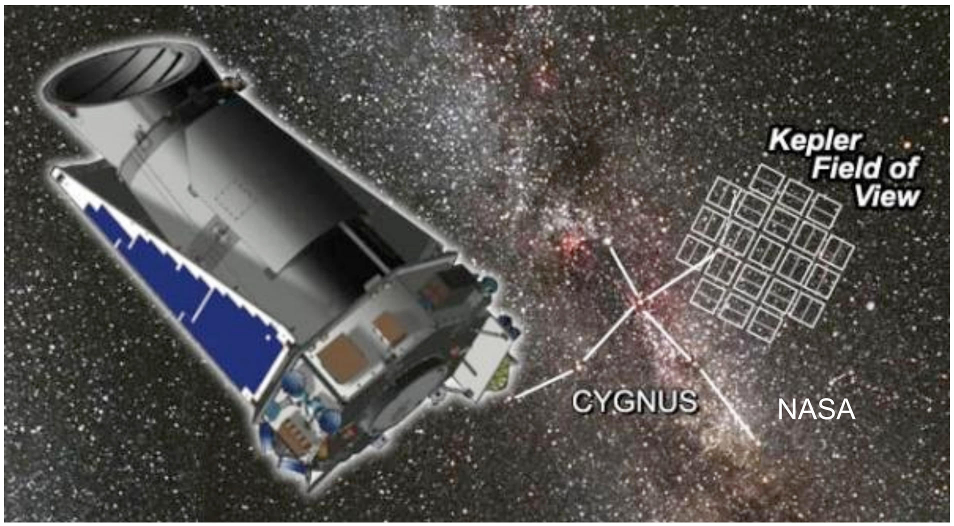
- **Nearby exoplanets & planetary formation:**
  - Stellar companions around K2 exoplanet hosts (Open c.o. Templeton Fnd.)
  - Verifying debris-disk stars (S. Hinkley)
  - Transit candidates from PTF/M-dwarfs survey (N.Law)
- **Field stellar multiplicity:**

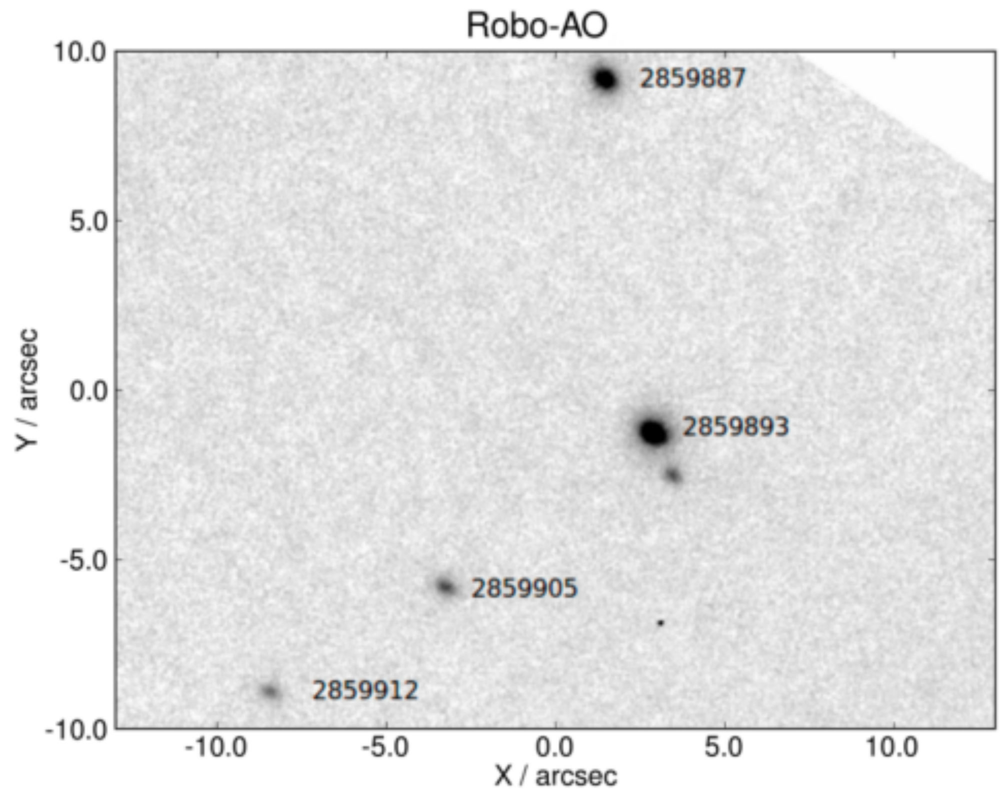
Robo-AO: 40 refereed scientific papers
6 refereed technical papers
12,500 targets (published and in sub.)

- **Solar system science:**
  - Monitoring of outgassing from Comet ISON (M. Drahus)
  - Solar system imaging (R. Hueso, et al.)
  - Search for binary asteroids (D. Duev)
- **Extragalactic & high-energy:**
  - AGN nuclei binarity (S. Tendulkar)
  - High-precision astrometry for globular cluster black holes (S. Hildebrand)
  - Lensed Quasar discovery and monitoring (E. Ofek, R. Griffiths)

Robo-AO Kepler survey

NASA XRP grant NNX15AC91G (Law, Baranec & Morton)

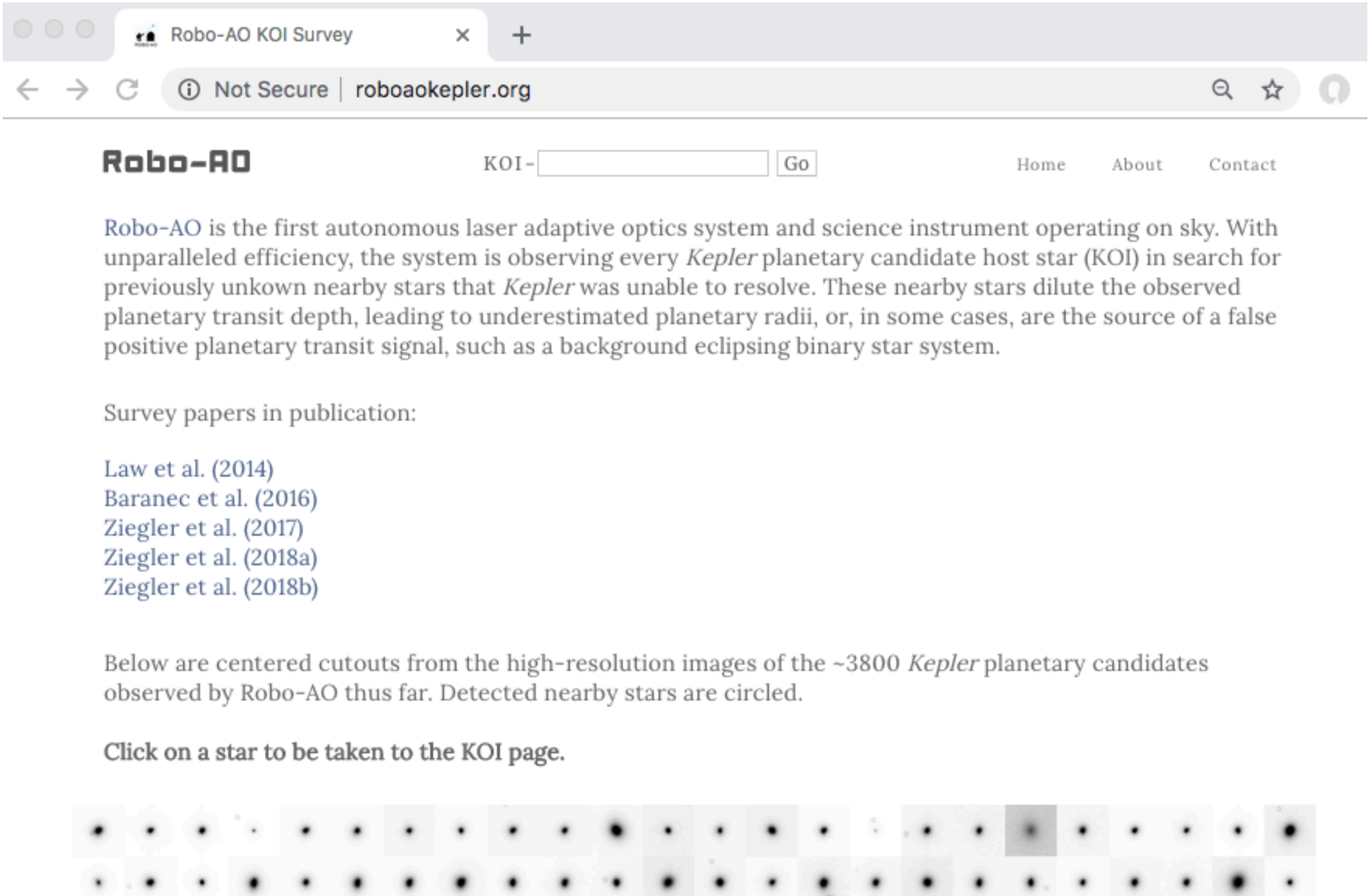




Kepler pixels are ~4”…

and stellar blends contaminate transits.

We imaged all ~3,800 candidate host stars (KOIs).
Public access to reduced images at roboaokepler.org



Robo-AO KOI- Go Home About Contact

Robo-AO is the first autonomous laser adaptive optics system and science instrument operating on sky. With unparalleled efficiency, the system is observing every *Kepler* planetary candidate host star (KOI) in search for previously unkown nearby stars that *Kepler* was unable to resolve. These nearby stars dilute the observed planetary transit depth, leading to underestimated planetary radii, or, in some cases, are the source of a false positive planetary transit signal, such as a background eclipsing binary star system.

Survey papers in publication:

Law et al. (2014)
Baranec et al. (2016)
Ziegler et al. (2017)
Ziegler et al. (2018a)
Ziegler et al. (2018b)

Below are centered cutouts from the high-resolution images of the ~3800 *Kepler* planetary candidates observed by Robo-AO thus far. Detected nearby stars are circled.

Click on a star to be taken to the KOI page.

Robo-AO KOI Survey

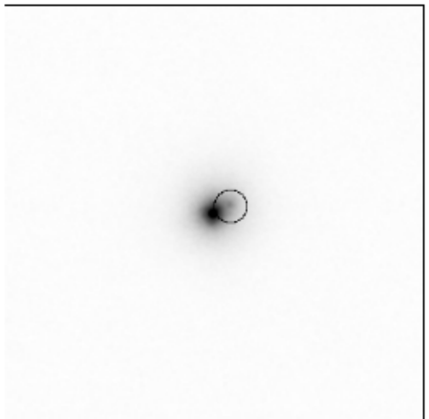
roboaokepler.org/koi_pages/KOI-1150.html

Robo-AO   KOI- [ ] Go   Home   About   Contact

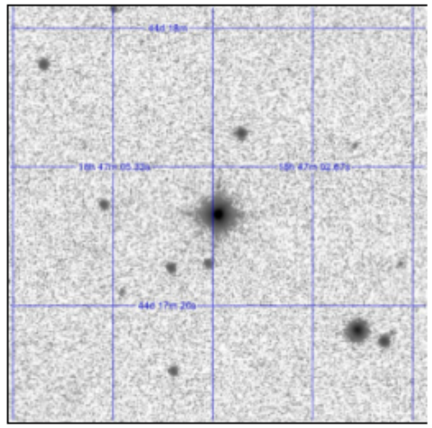
KOI-1150

Confirmed planet

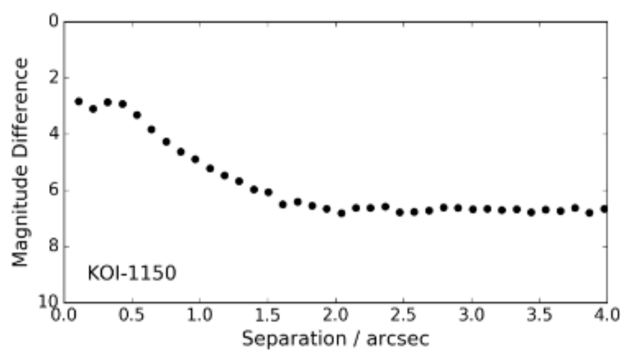
Kepler-780 b



Robo-AO 8-arcsec centered cutout image of KOI-1150 with any detected nearby stars circled (Law et al. 2014)



UKIRT 1-arcmin field centered on KOI-1150



Robo-AO 5-sigma detection sensitivity for KOI-1150

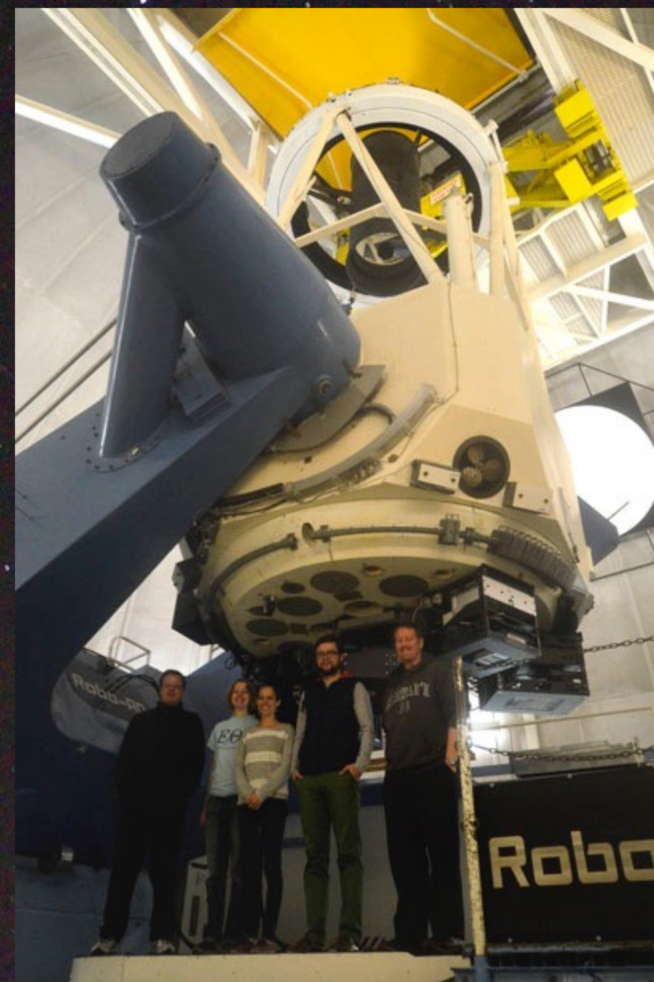
Nearby star properties

Separation (")	Position Angle (deg)	LP600 Contrast (mags)	Reference
0.39	322	2.41	Law et al. (2014)

Planet properties (Kepler DR25)

Planet	Disposition	Period (days)	Radius (R_Earth)	Epoch (BJD)	Transit duration (hrs)	Transit depth (ppm)	Eq. Temp. (K)

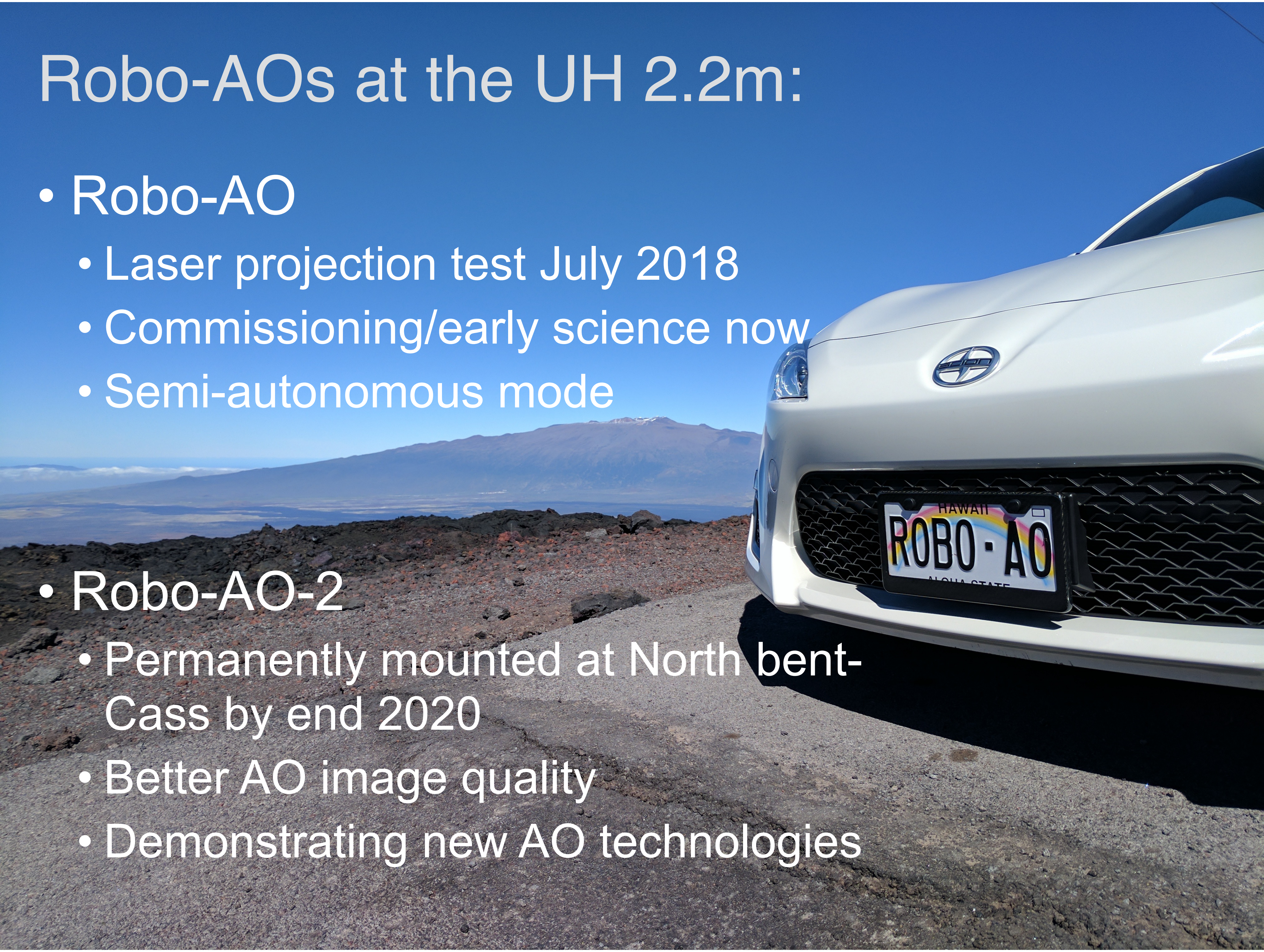
Robo-AO was moved to
the 2.1 m telescope at
Kitt Peak, AZ in Nov. 2015.



R. Jensen-Clem, et al., 2018
arXiv:1703.08867

Robo-AOs at the UH 2.2m:

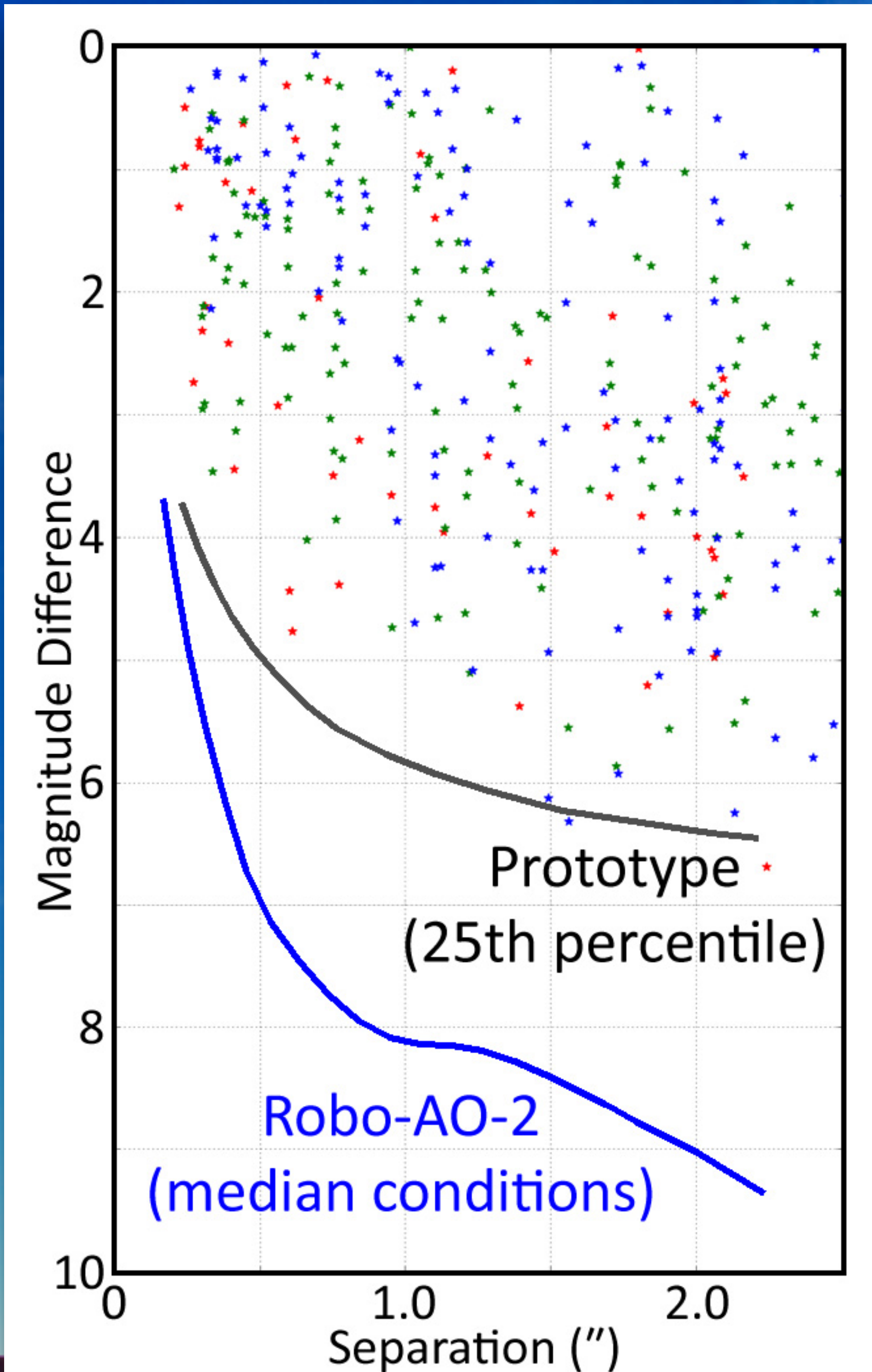
- Robo-AO
  - Laser projection test July 2018
  - Commissioning/early science now
  - Semi-autonomous mode
- Robo-AO-2
  - Permanently mounted at North bent-Cass by end 2020
  - Better AO image quality
  - Demonstrating new AO technologies



Robo-AO-2

Faster WFS, more photons, less read noise, more actuators, better site

				Percentile Seeing	25%		50%		50%		75%	
Atmospheric r_0					22.1 cm		16.8 cm				10.3 cm	
Effective seeing at zenith (inc. dome seeing)					0.69"		0.80"				1.00"	
Zenith angle					15 degrees		15 degrees		40 degrees		40 degrees	
High-order Errors					**Wavefront Error (nm)**							
Atmospheric Fitting Error					35		39		44		53	
Bandwidth Error					32		37		42		49	
High-order Measurement Error					32		35		36		41	
LGS Focal Anisoplanatism Error					74		102		118		164	
Other High-order Errors					58		59		69		74	
Total High Order Wavefront Error					**110 nm**		**134 nm**		**154 nm**		**198 nm**	
Tip-Tilt Errors					**Angular Error (milli arcseconds - mas)**							
Tilt Measurement Error					10		11		12		14	
Tilt Bandwidth Error					8		9		9		10	
Other Tip-Tilt Errors					6		7		10		12	
Total Tip/Tilt Error (one-axis)					**14 mas**		**16 mas**		**18 mas**		**21 mas**	
Total Wavefront Error (NIR TT)					**123 nm**		**146 nm**		**163 nm**		**206 nm**	
Total Wavefront Error (Visible TT)					**122 nm**		**146 nm**		**163 nm**		**207 nm**	
Spectral Band	**λ**	**λ/D**			**Strehl**	**FWHM**	**Strehl**	**FWHM**	**Strehl**	**FWHM**	**Strehl**	**FWHM**
g'	**0.47 μ**	**0.044"**			**7%**	0.06"	**2%**	0.07"	**1%**	0.13"	**0%**	0.49"
r'	**0.62 μ**	**0.058"**			**19%**	0.07"	**10%**	0.07"	**5%**	0.08"	**1%**	0.14"
i'	**0.75 μ**	**0.070"**			**30%**	0.08"	**19%**	0.08"	**13%**	0.08"	**4%**	0.10"
J	**1.25 μ**	**0.117"**			**65%**	0.12"	**55%**	0.12"	**47%**	0.12"	**31%**	0.13"
H	**1.64 μ**	**0.153"**			**77%**	0.16"	**70%**	0.16"	**64%**	0.16"	**50%**	0.16"



Robo-AO-2 on the UH 2.2-m

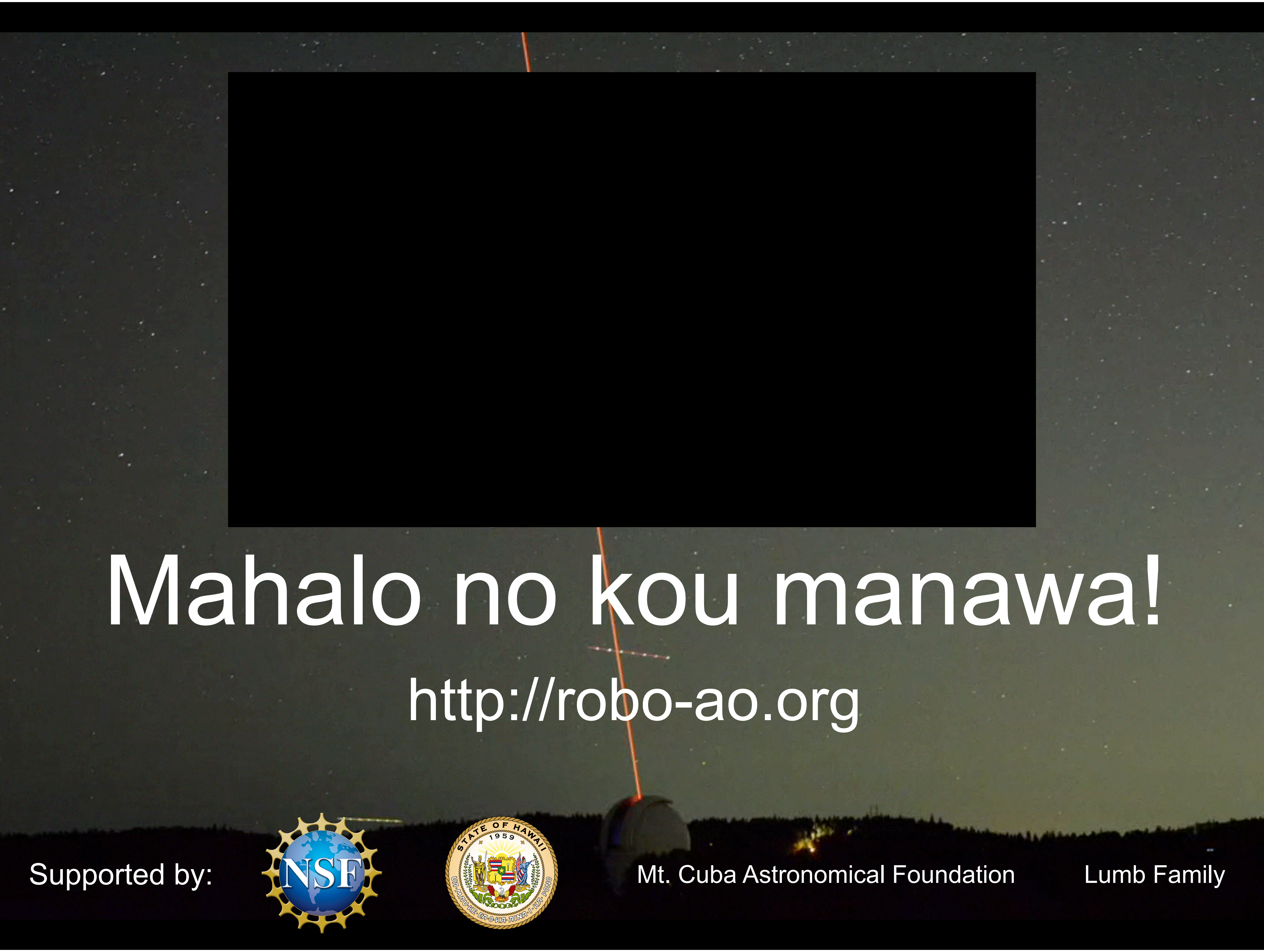
Moving to a 3 instrument automated facility

Respond to transients

~1 mag fainter (better image quality, larger aperture)

NGS for bright targets, and hybrid AO demonstrations

ETA end-2020



Mahalo no kou manawa!
http://robo-ao.org
Supported by:
Mt. Cuba Astronomical Foundation
Lumb Family

Further reading

1. **Adaptive Optics for Astronomical Telescopes**, Hardy (1998)
2. **SPIE Field Guide to Adaptive Optics**, Tyson & Frazier (2004)
3. **Recent Advances in Adaptive Optics**, Hart, Appl. Opt. 49, D17-29 (2010)
4. **Adaptive Optics for Astronomy**, Davies & Kasper, Annu. Rev. Astron. Astrophys. (2012)
5. https://www.jove.com/video/50021/bringing-the-visible-universe-into-focus-with-robo-ao
6. **Astronomical Adaptive Optics**, Rigaut, PASP 127, 958 (2015)
7. **Extreme Adaptive Optics**, Guyon, Annu. Rev. Astron. Astrophys. (2018)