Adaptive Optics Follow-up

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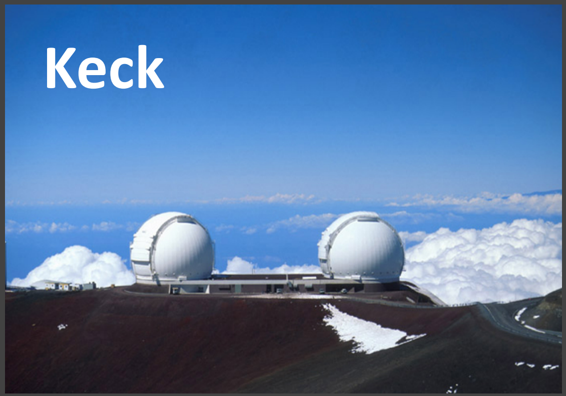
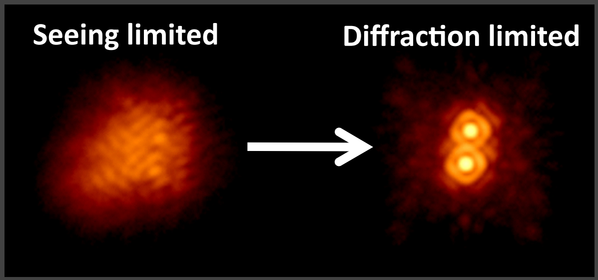
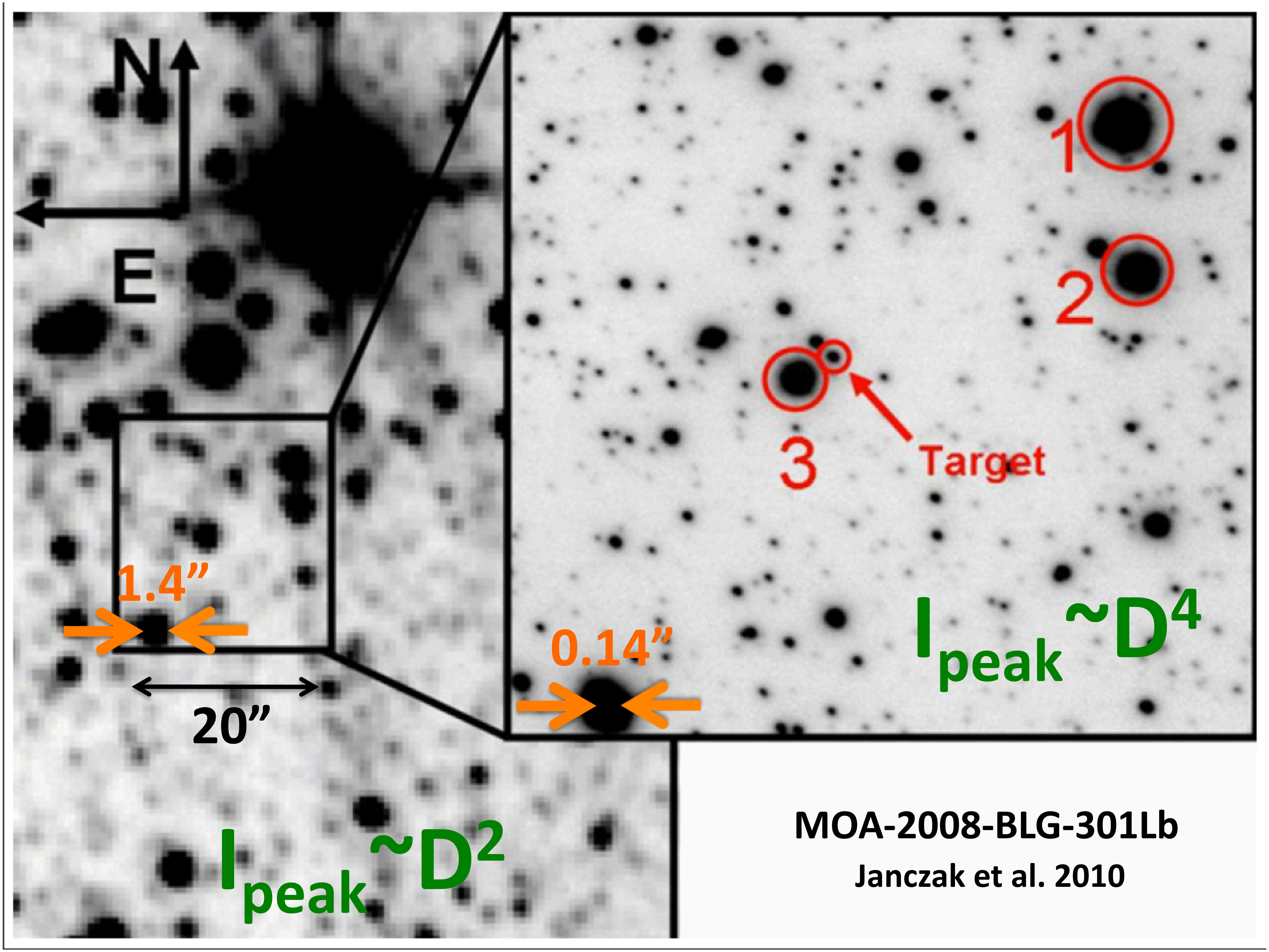


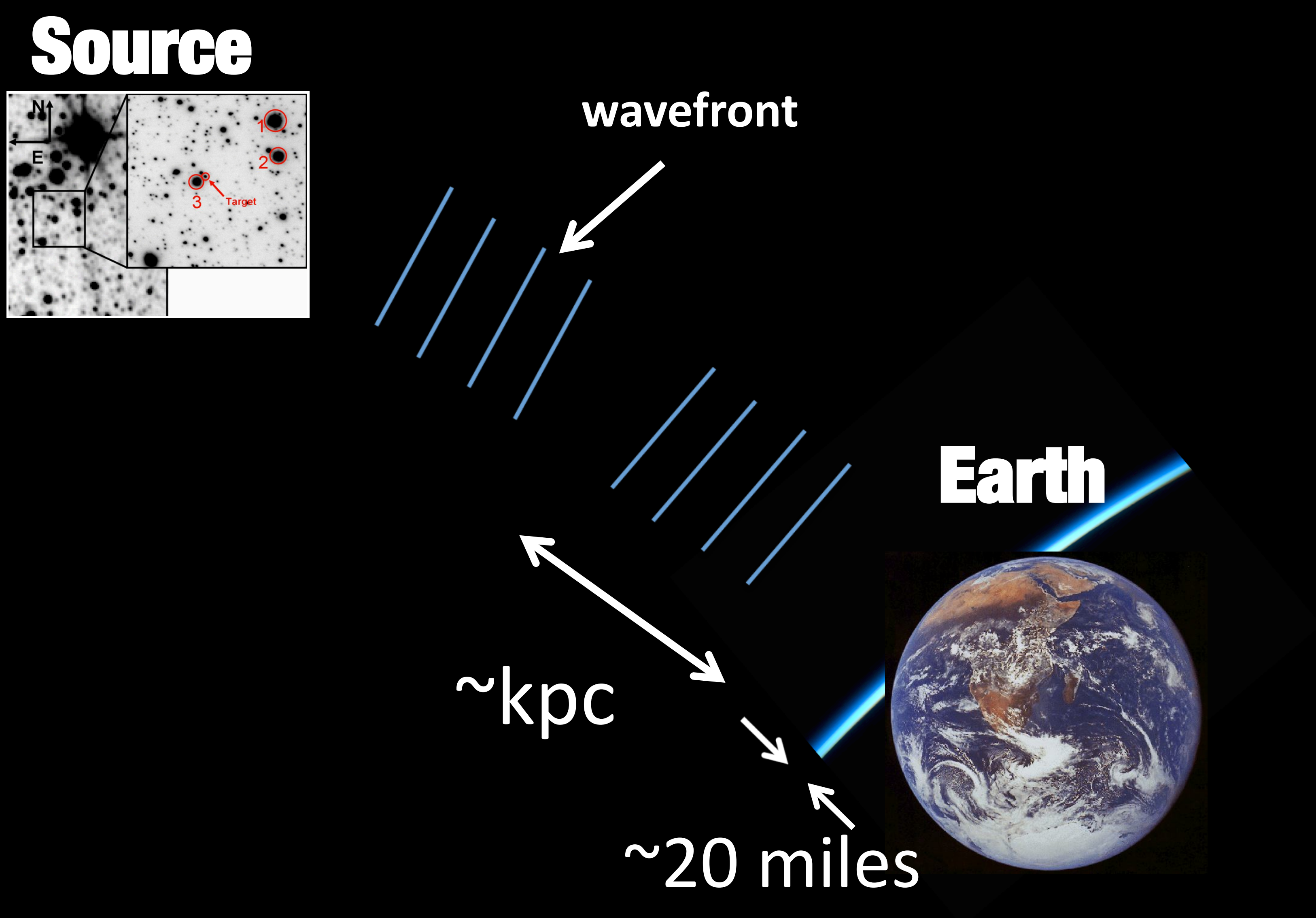


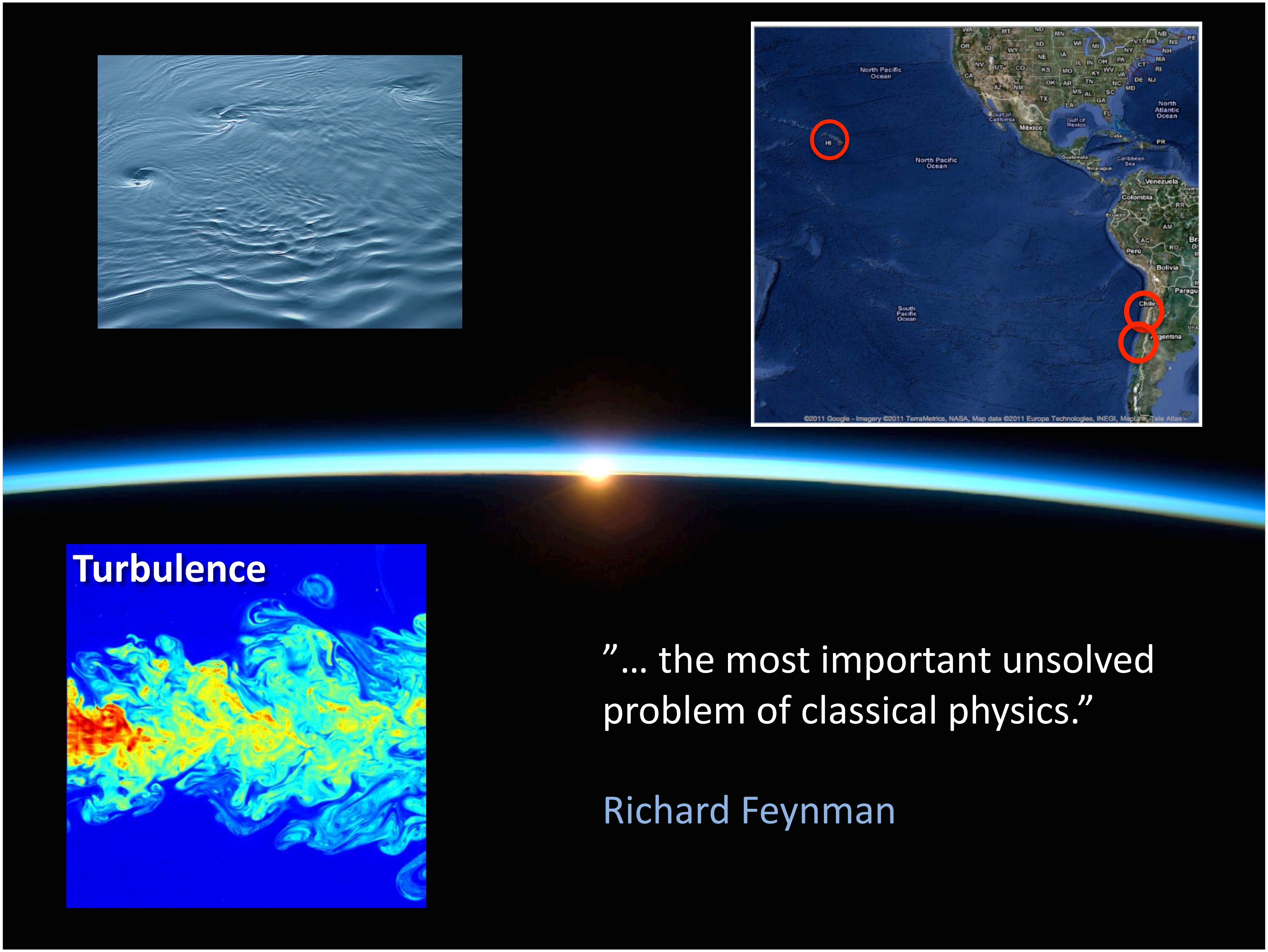


MOA-2008-BLG-301Lb

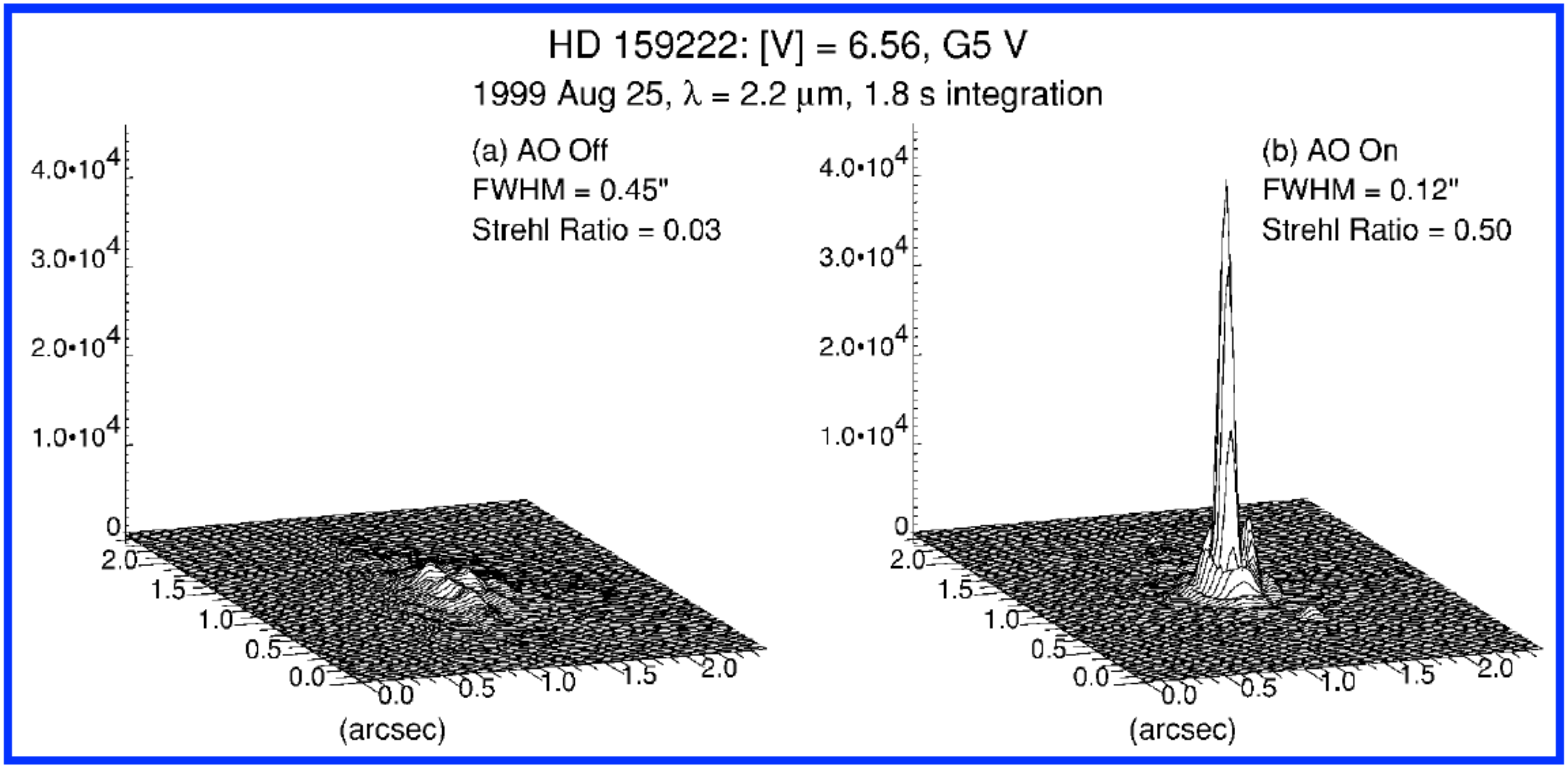
Janczak et al. 2010

Lost Information




Turbulence
”… the most important unsolved problem of classical physics.”
Richard Feynman

Principle of AO



We correct: phase aberrations, not amplitude.

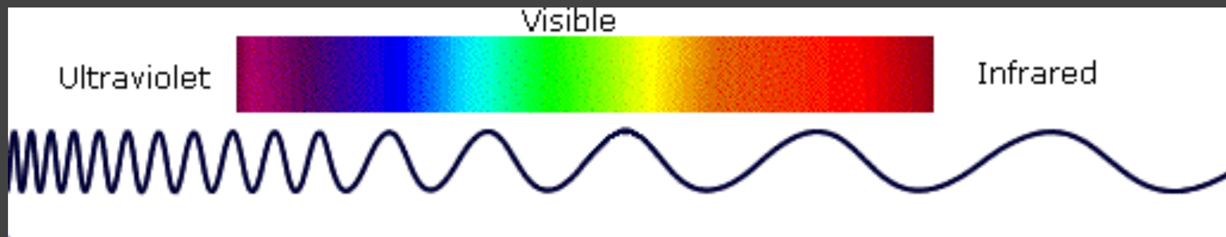
What You Need to Know

General AO concepts

Relation to Planet Finding

Data Processing

General AO Concepts



Fried Parameter (r_0)

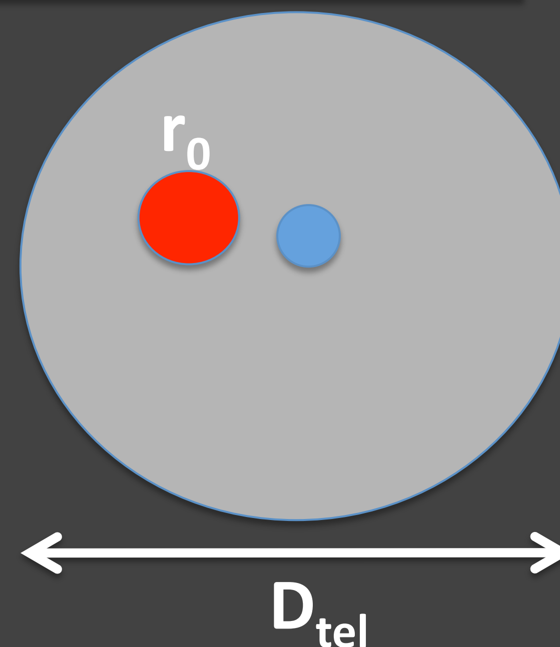
$$<| n(r) - n(r+\varepsilon) |^2> = C_N{}^2 \varepsilon^{2/3}$$

FWHM = $0.98\, \lambda / r_0$

$$r_0 = [0.432\, k^2 \sec(z) \int C_N{}^2(h)\, dh\,]^{-3/5}$$

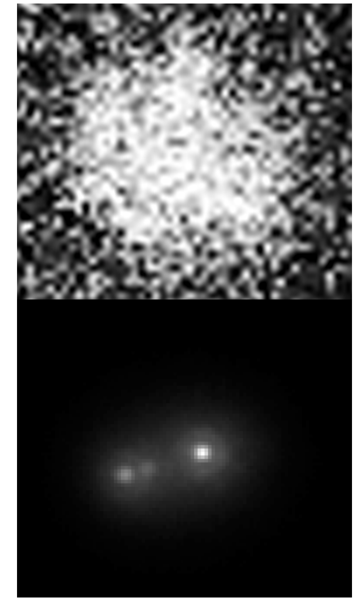
$r_0 \sim \lambda^{6/5}$ (~20 cm in visible)

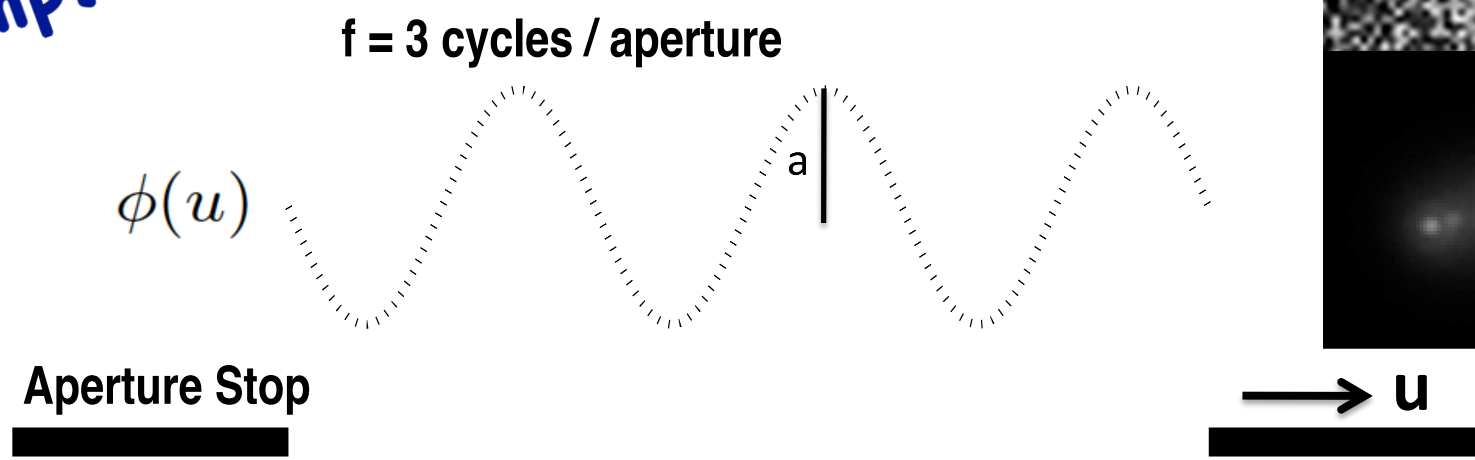
$t_0 \sim r_0 / v_{wind}$ (~1 ms)



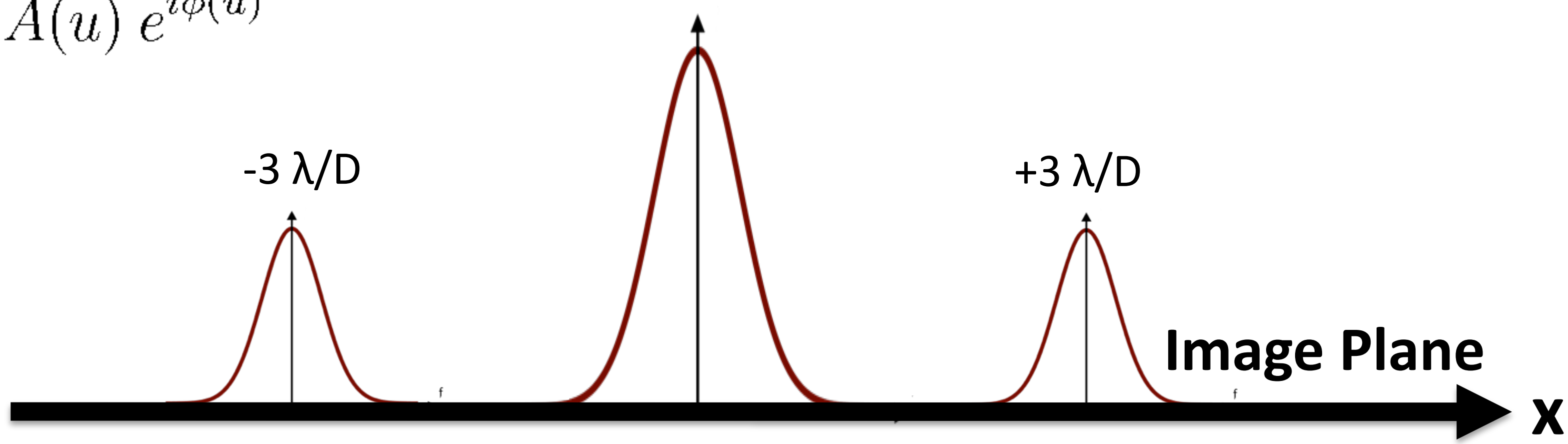
Consider for Example ...

Sine–wave Phase Ripple





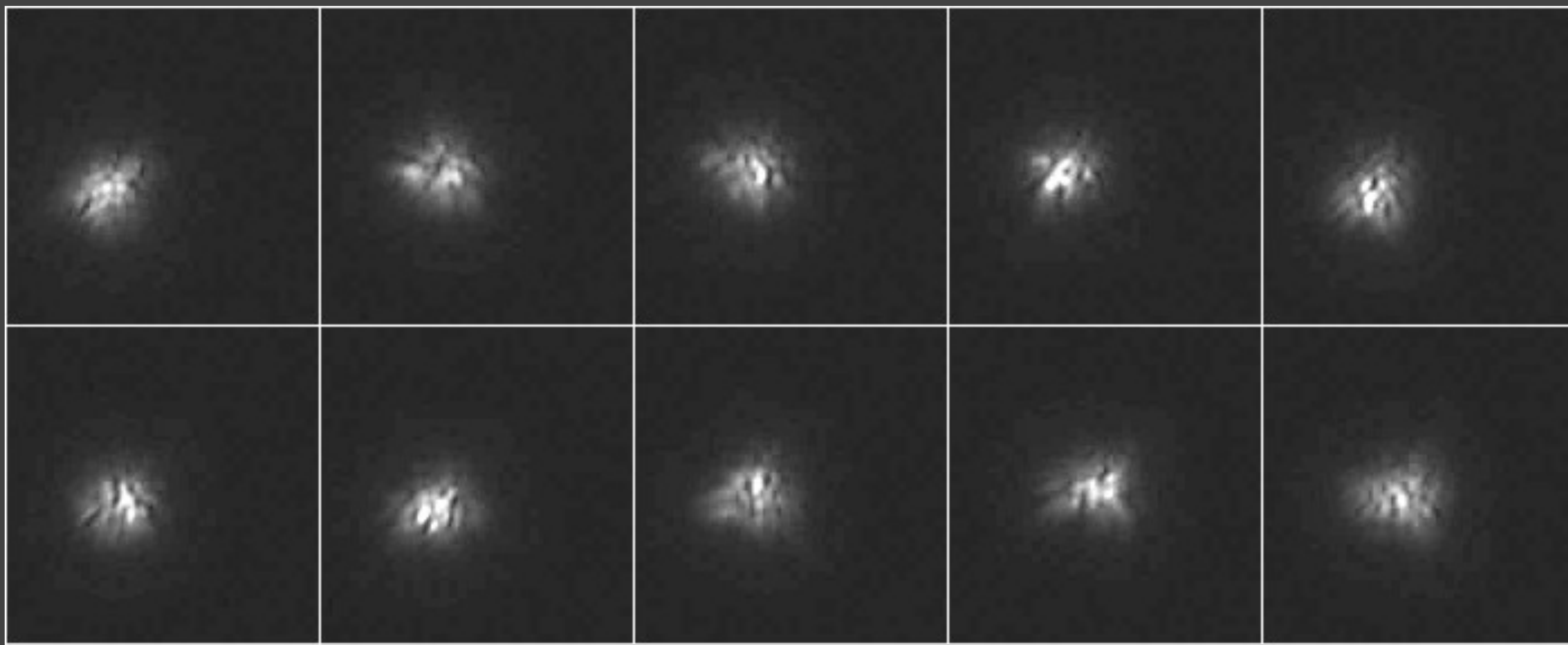
$$E(u) = A(u)\, e^{i\phi(u)}$$



$$\hat{E}(x) = \mathrm{FT}\{E(u)\} = \mathrm{FT}\{A(u)\} * (\delta(x) - a/2\,[\delta(x+f) - \delta(x-f)])$$

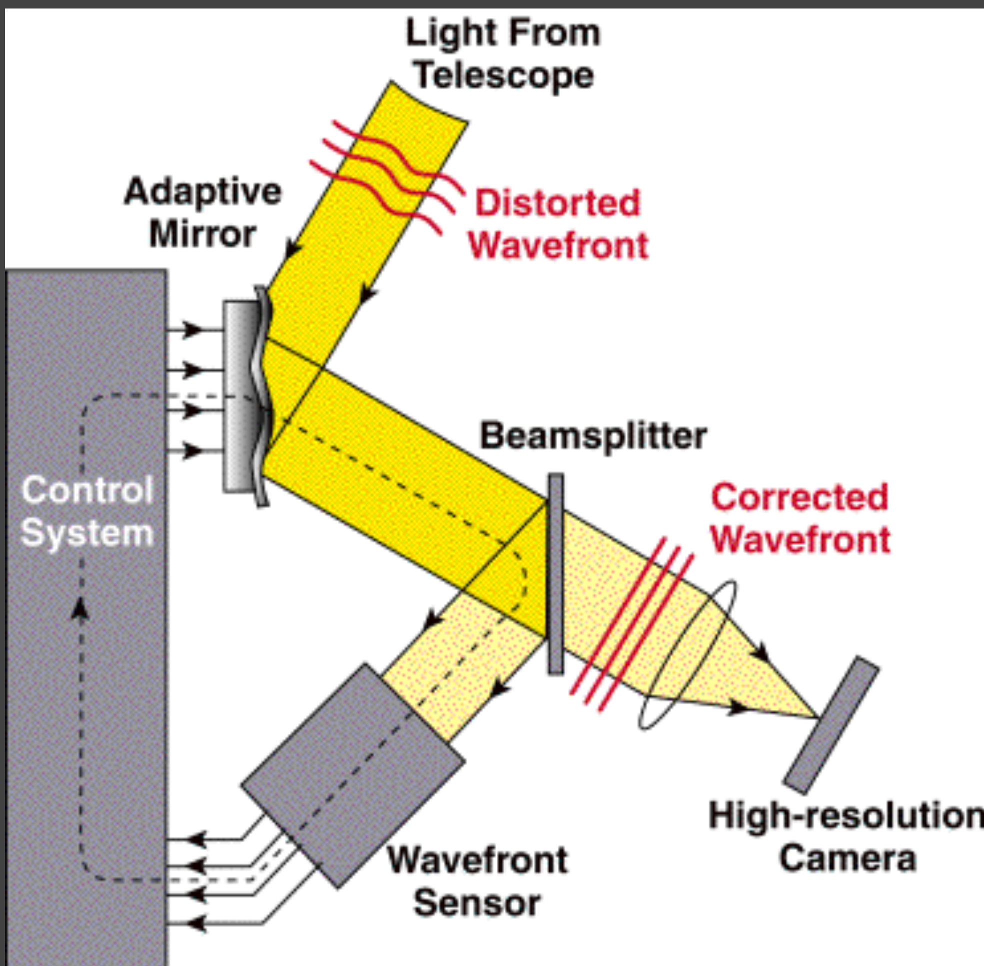
$$= \hat{A}(x) - a/2\,\hat{A}(x+f) + a/2\,\hat{A}(x-f)$$

Atmospheric Seeing



$$\Phi(f) \propto f^{-11/3}$$

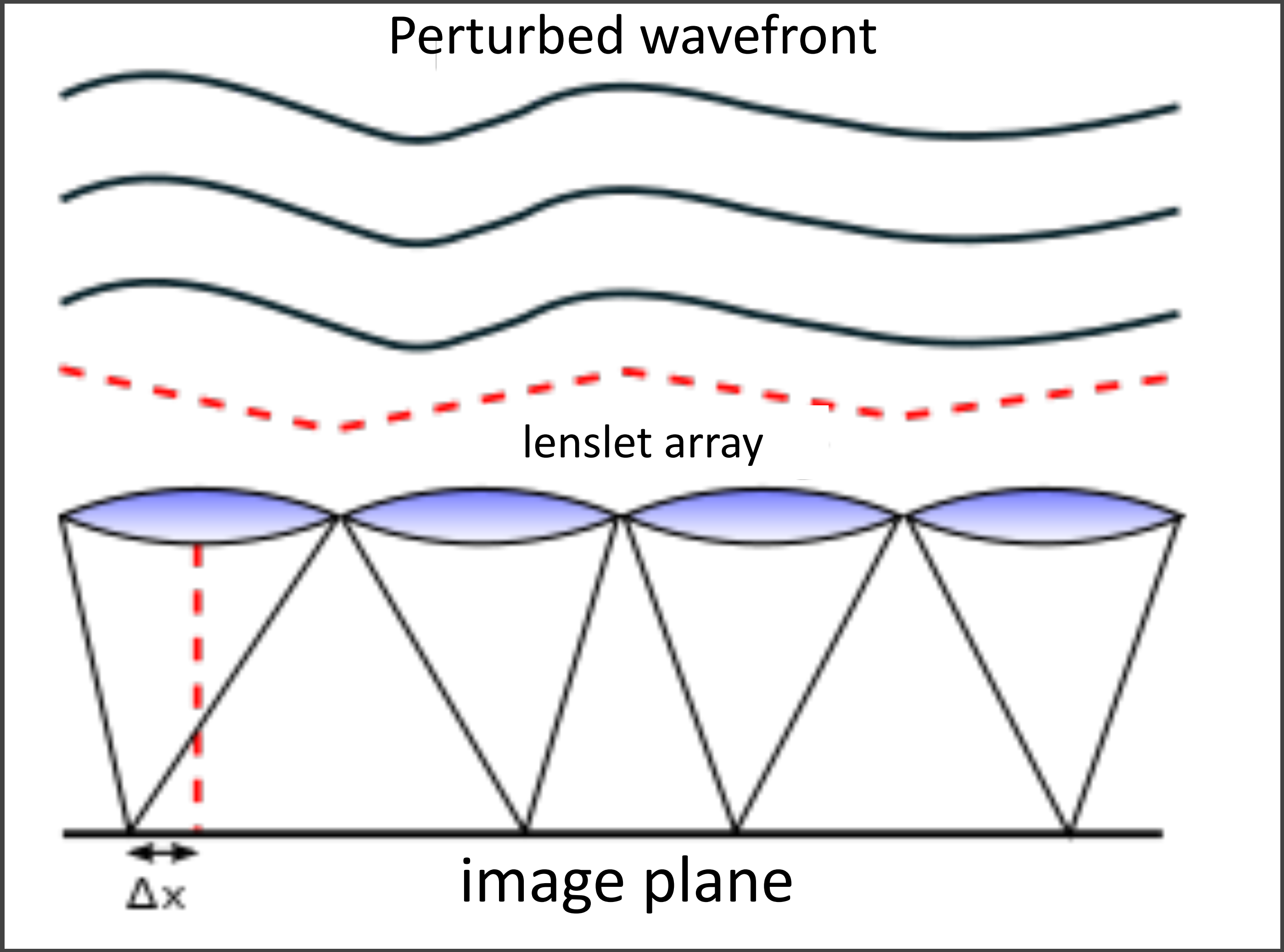
AO System Components



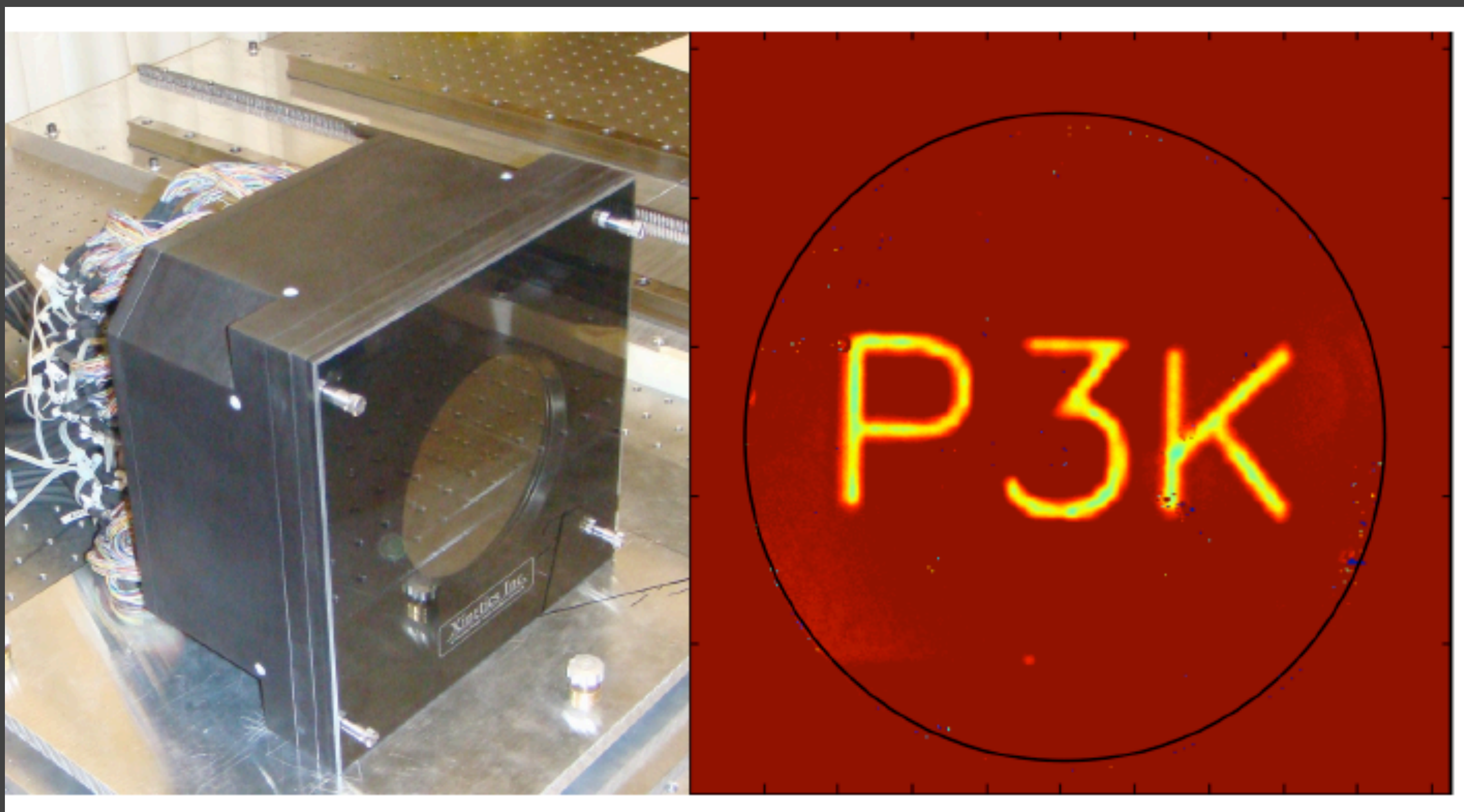
Hardware Required

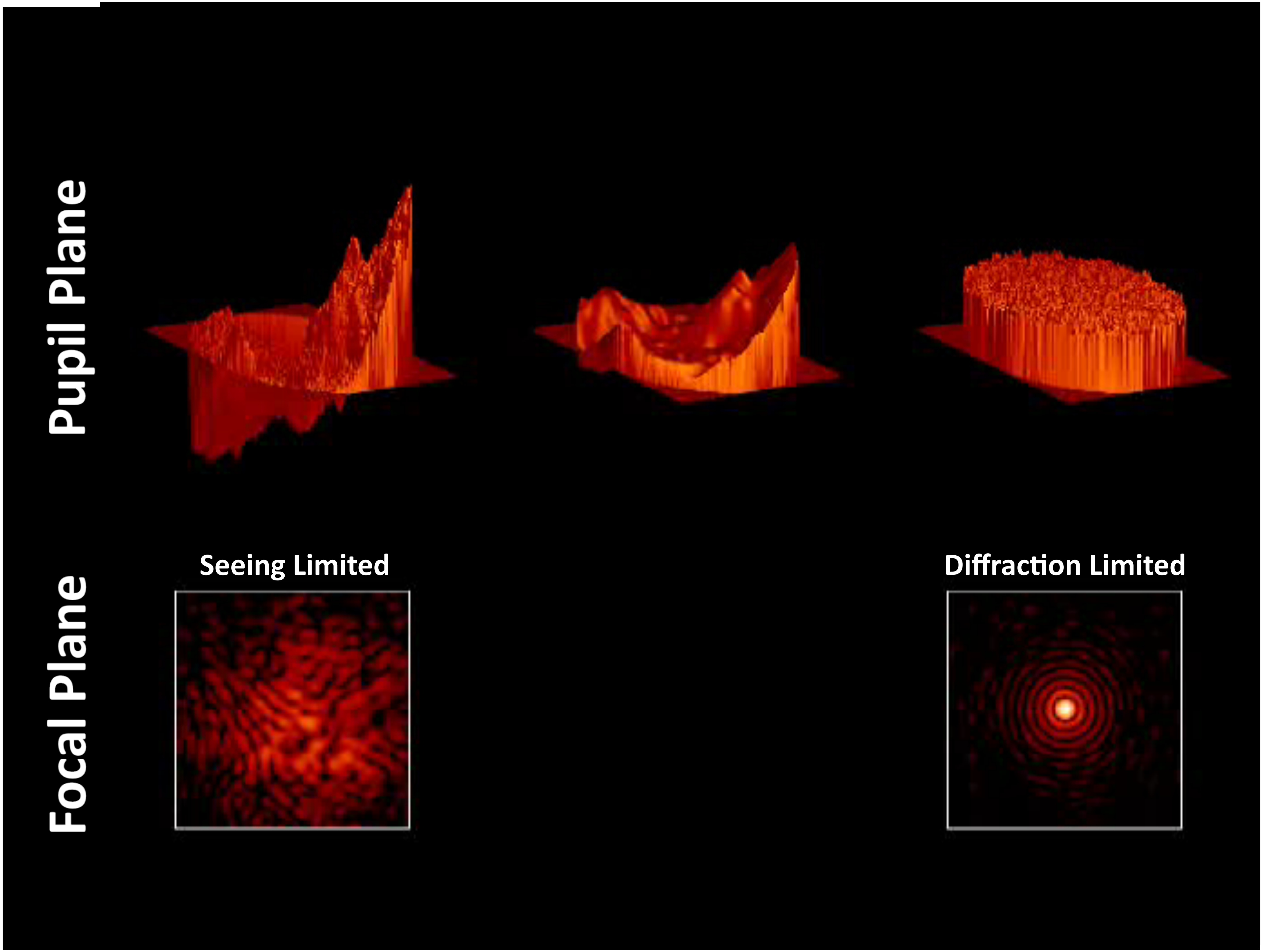
1) Deformable Mirror
2) Wavefront Sensor
3) Fast computer

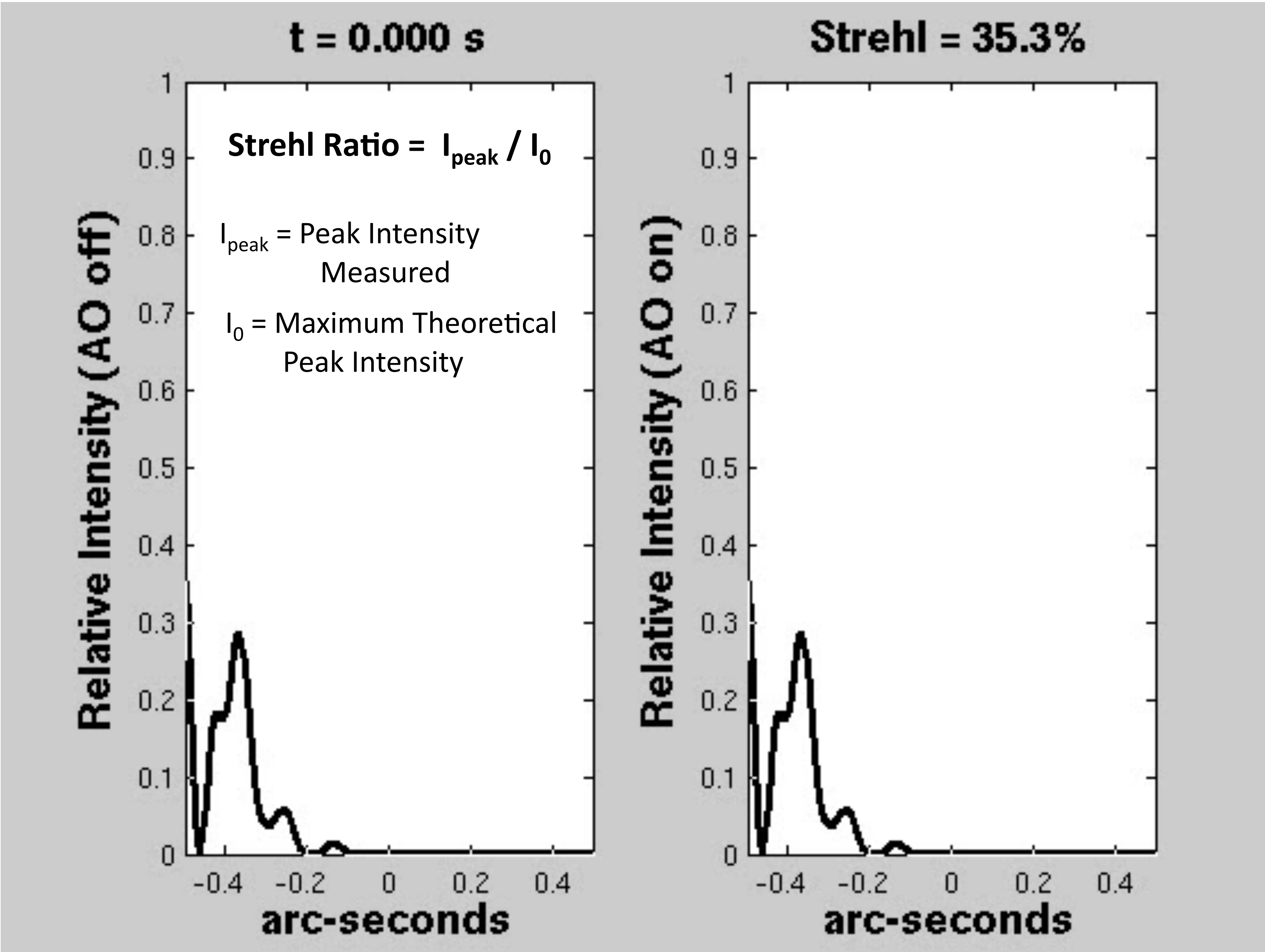
Shack-Hartmann WFS



Deformable Mirrors

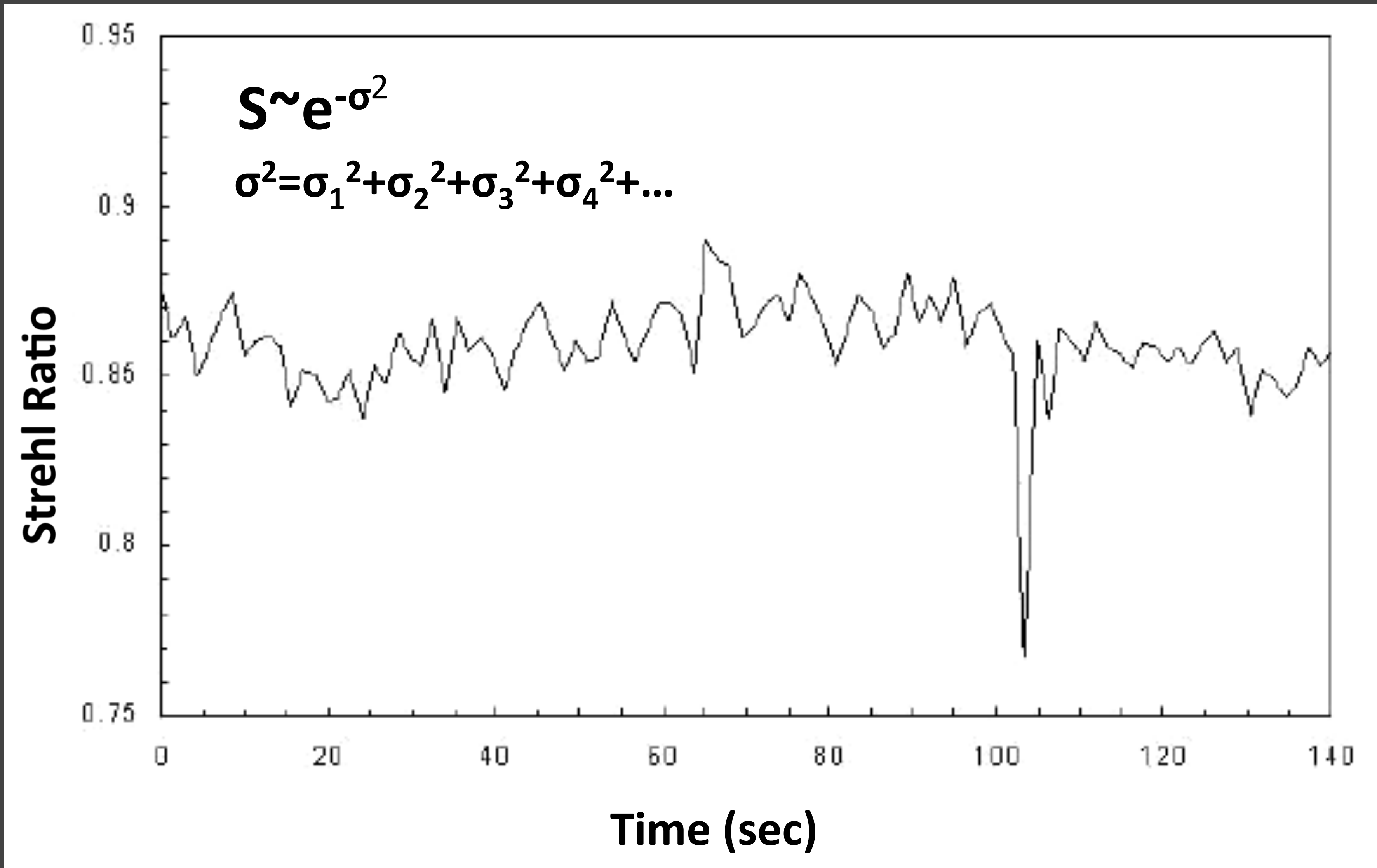



Pupil Plane
Focal Plane
Seeing Limited
Diffraction Limited



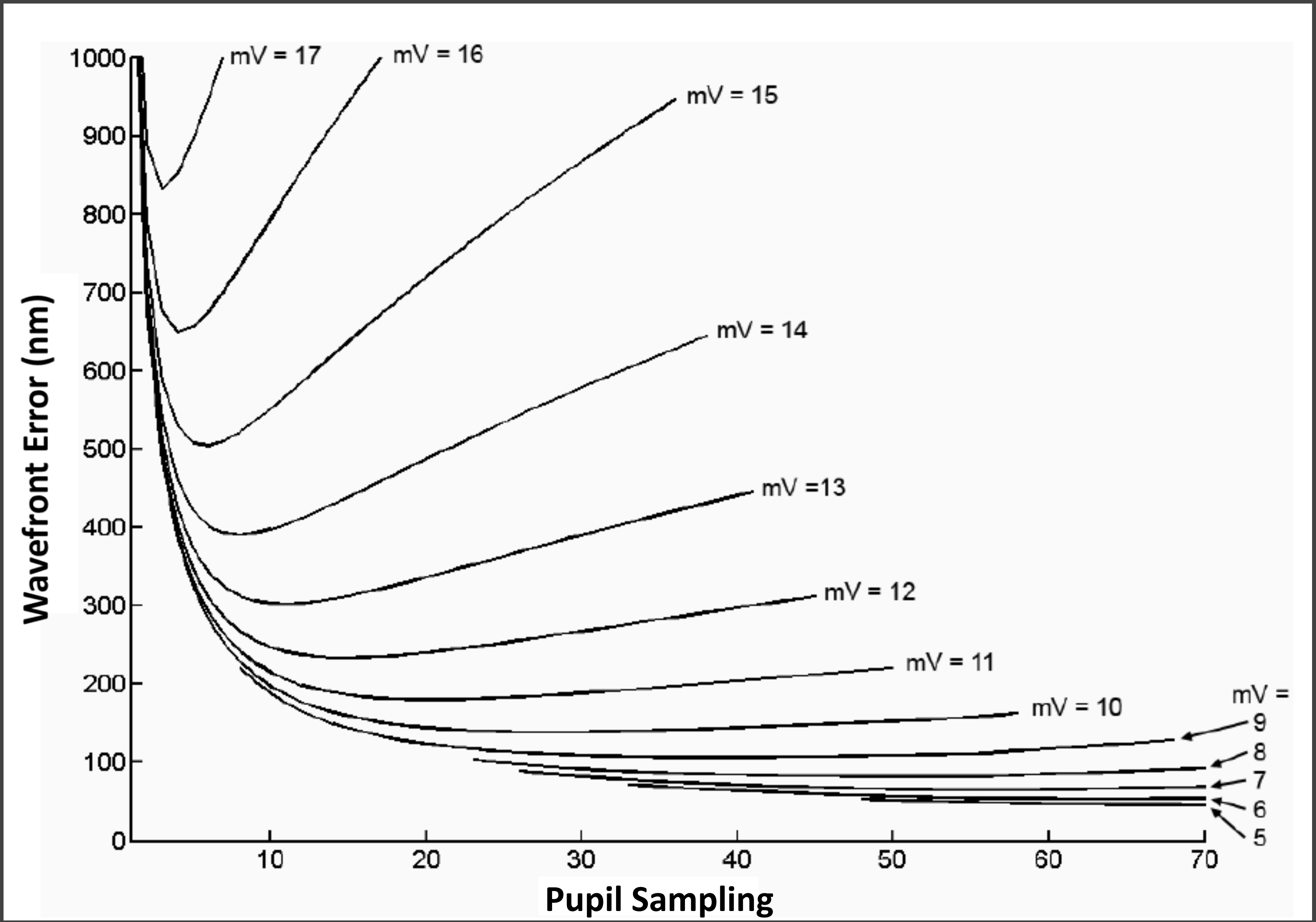
t = 0.000 s
Strehl = 35.3%
Strehl Ratio = I_{peak} / I_0
I_{peak} = Peak Intensity Measured
I_0 = Maximum Theoretical Peak Intensity
Relative Intensity (AO off)
Relative Intensity (AO on)
arc-seconds
arc-seconds

Temporal Variations



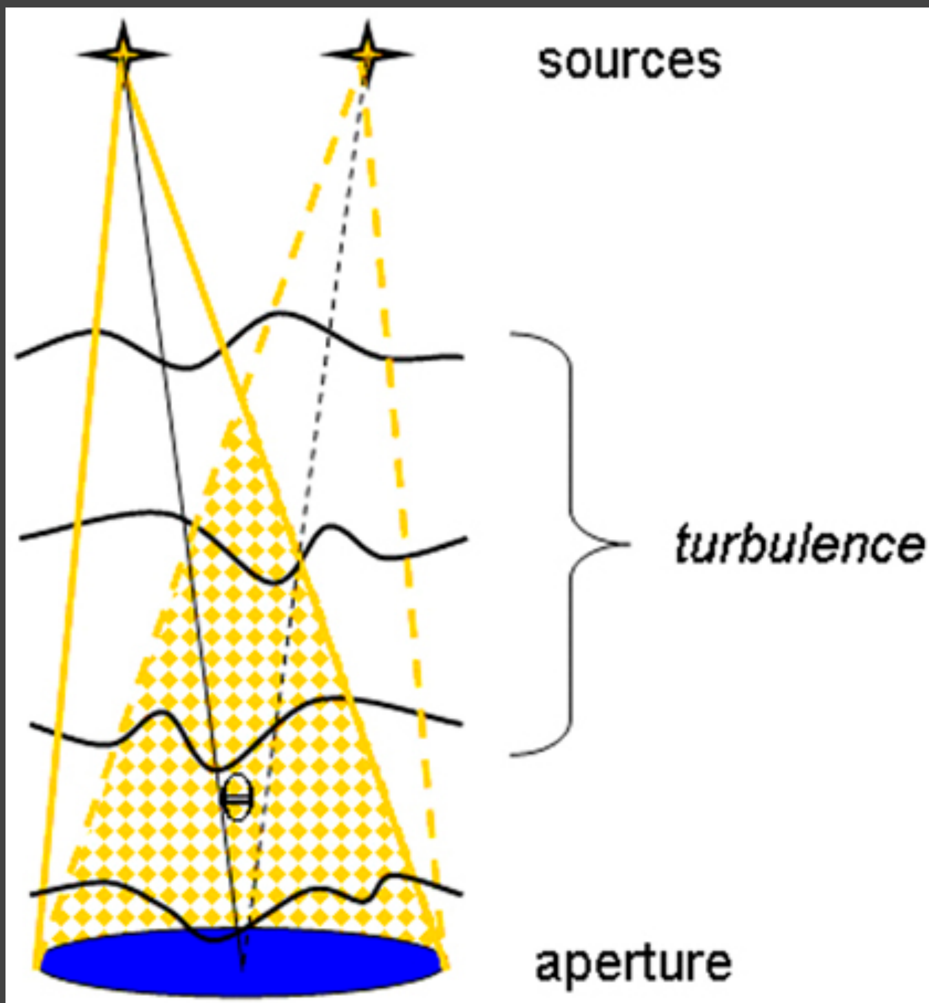
Serabyn et al. 2007

Wavefront Error



Baranec et al. 2008

Tilt Anisoplanatism



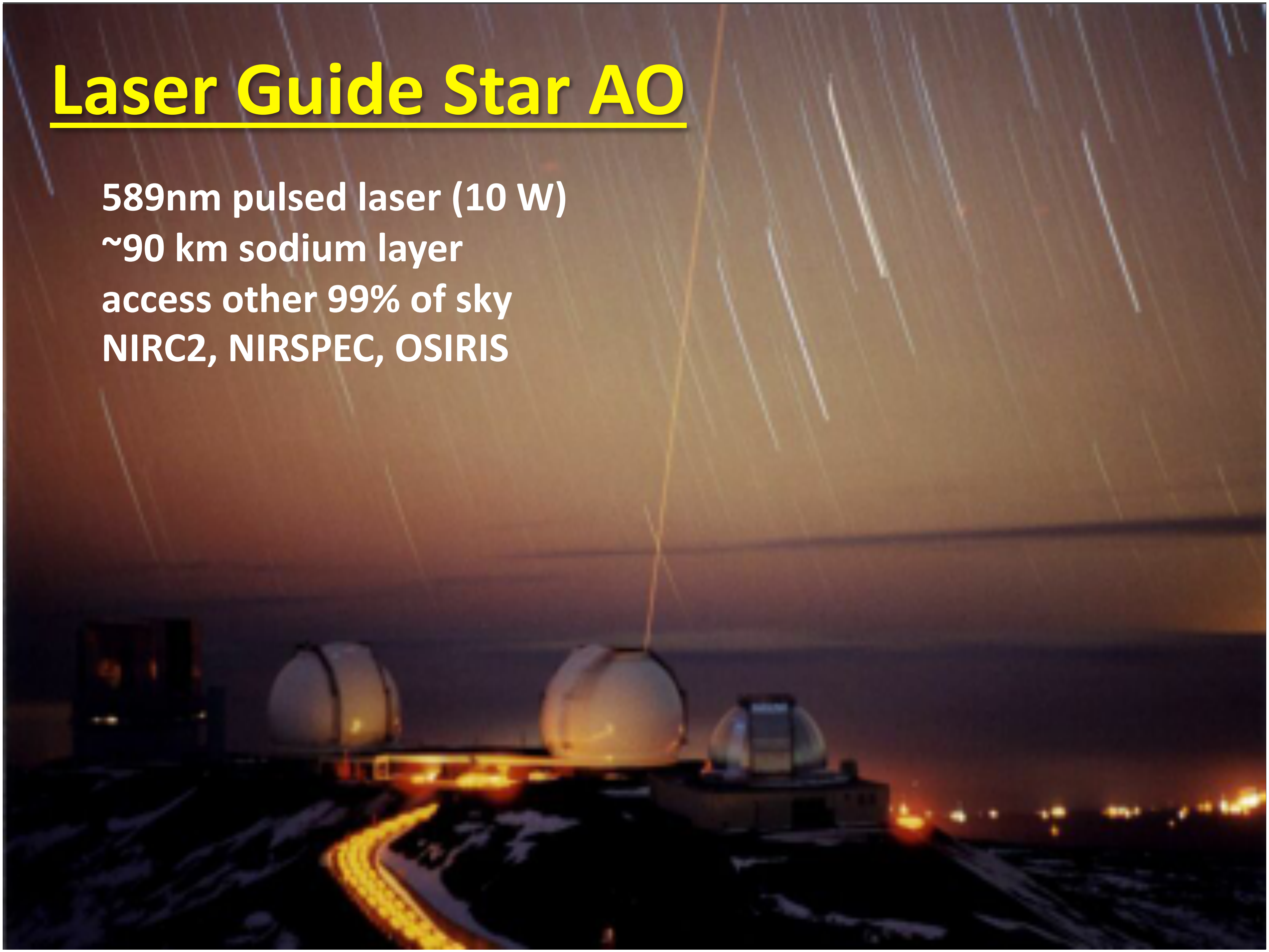
Sources at different angles experience different wavefront aberrations

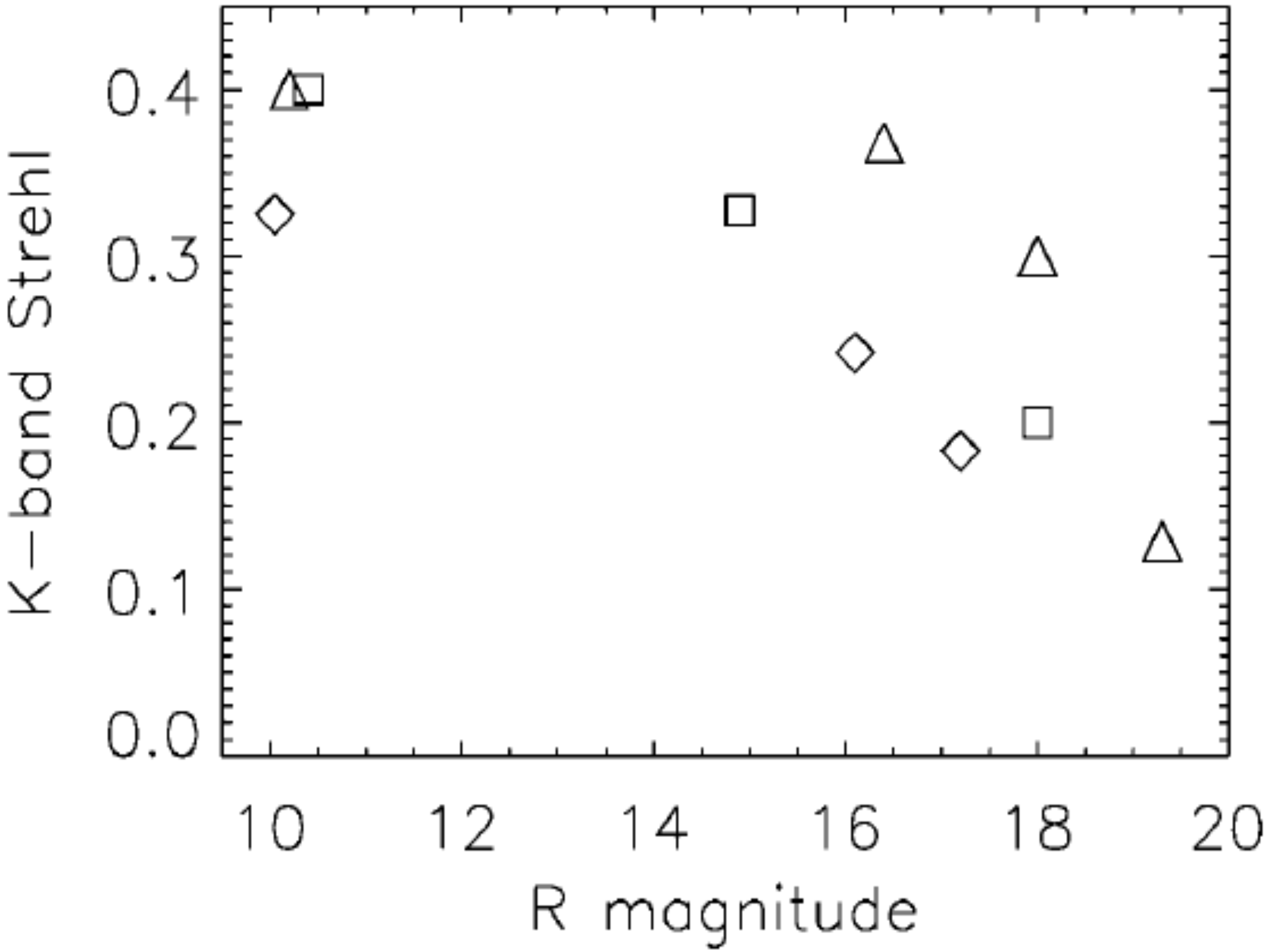
$$\sigma^2(\theta) = (\theta / \theta_0)^{5/3}$$

$$\theta_0 = 0.314 r_0 \sec(z)^{-1} h_{ave}^{-1}$$

Laser Guide Star AO

589nm pulsed laser (10 W)
~90 km sodium layer
access other 99% of sky
NIRC2, NIRSPEC, OSIRIS




K−band Strehl
0.0
0.1
0.2
0.3
0.4
10
12
14
16
18
20
R magnitude

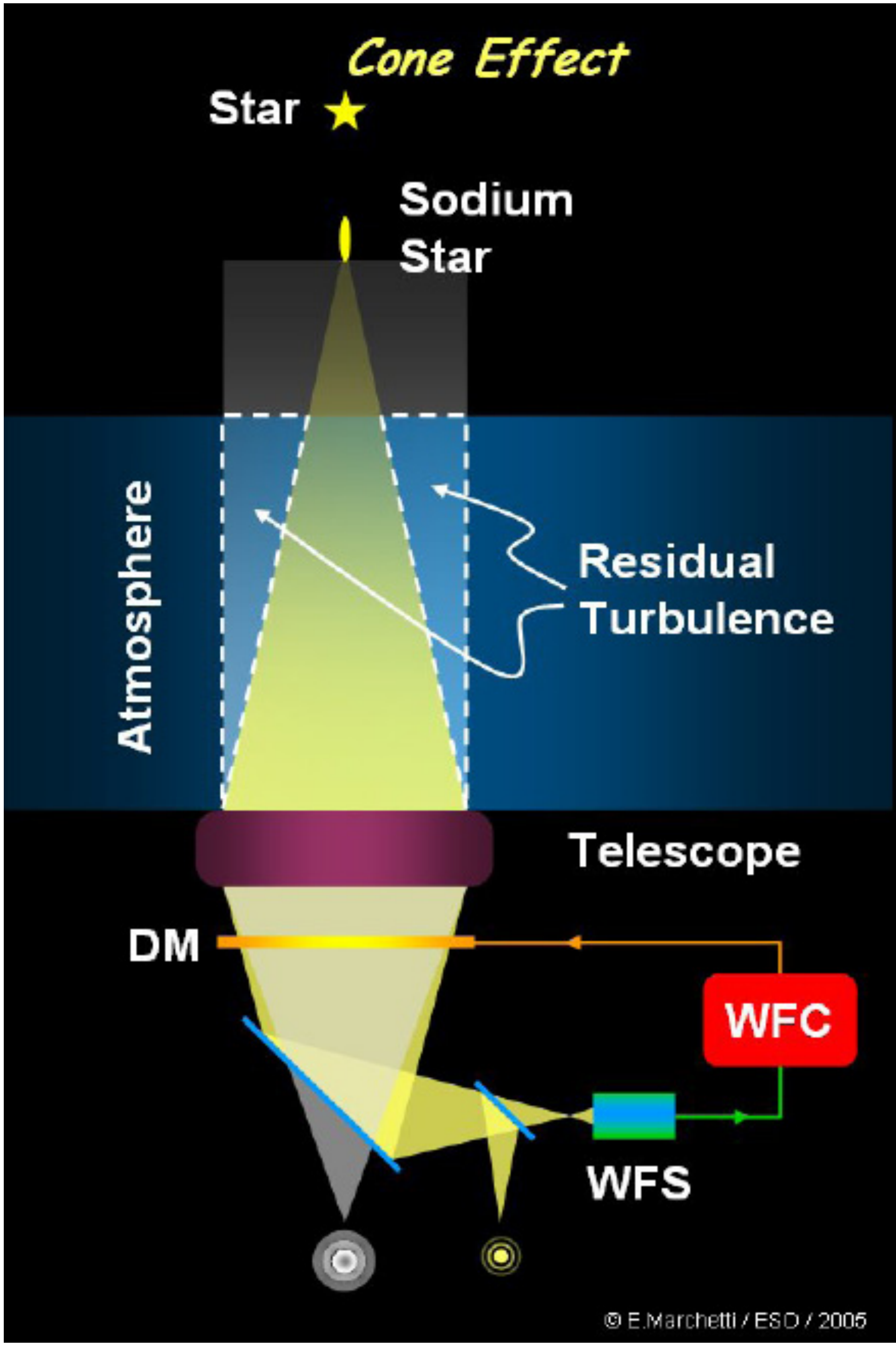


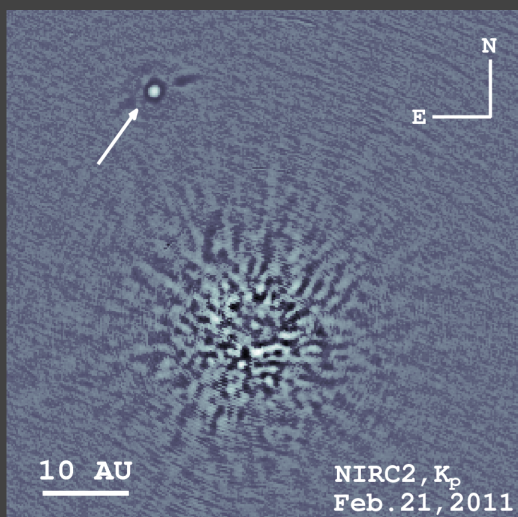
TABLE 1
BRIGHT STAR LGS AO ERROR BUDGET

Source	σ_W
Atmospheric fitting	128
Telescope fitting	60
Camera	50
DM bandwidth	157
DM measurement	142
TT bandwidth	109
TT measurement	23
LGS focus error	36
LGS high-order error	80
Focal anisoplanatism	175
Total wave-front error	357
Predicted Strehl (2.12 μm)	35%
Measured Strehl (2.12 μm)	35%

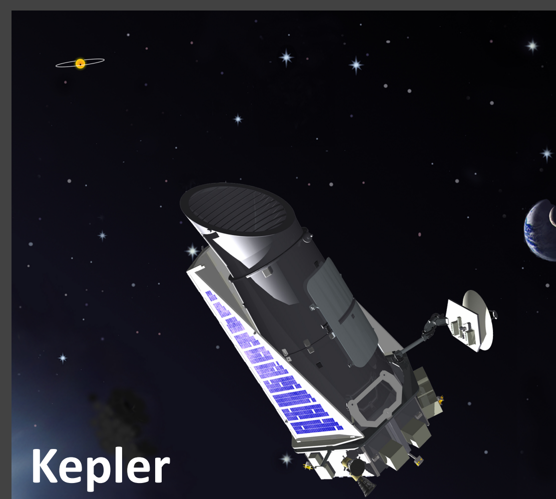
NOTE.—The rms wave-front errors σ_W are quoted in nanometers.

AO Relation to Planet Finding

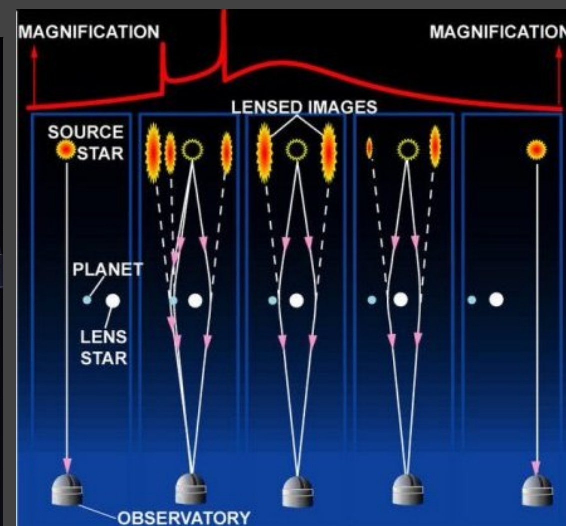
Direct Imaging



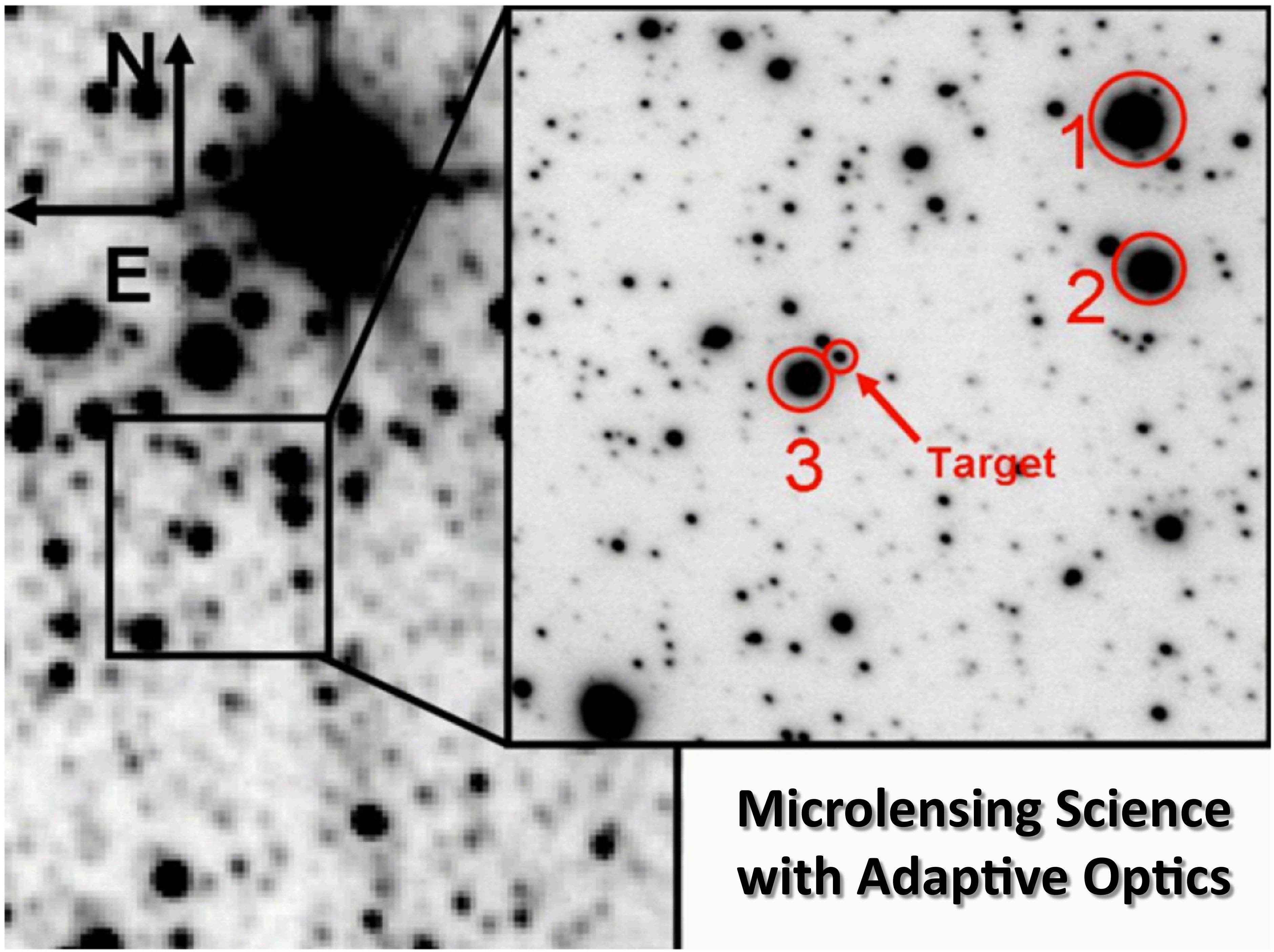
Transits



Microlensing

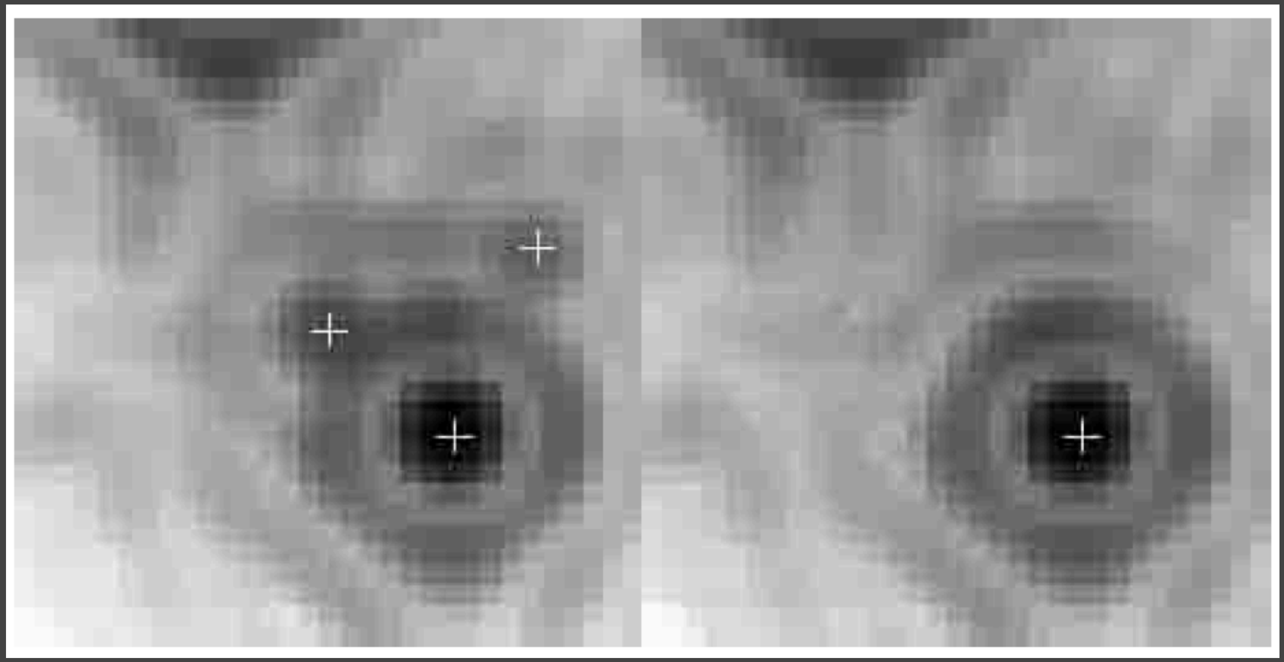


5 10 15 → V_{mag}



Microlensing Science with Adaptive Optics

Photometry & Astrometry

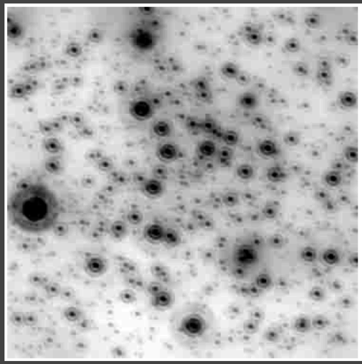


Data Characteristics

Nyquist sampling
PSF is complex with sharp peak
several (fragmented) Airy rings
extended irregular halo
isoplanatic if small FOV

Diolaiti et al. 2000

Example Procedure: "StarFinder"



Synthesize Image of Crowded Field

Clean hot pixels, subtract background, flat-field

Derive template PSF using bright isolated stars

Identify field stars using local intensity maxima (brightest to faintest)
estimate background halo

$$h(x,y) = s_0(x,y) + \sum_{n=1}^{N} f_n p(x - x_n, y - y_n) + b_0 + b_1 x + b_2 y$$

Iteratively fit sources (least-squares) using template to determine:
photometry and astrometry

http://ascl.net/starfinder.html

Example Capabilities

	Keck	Palomar	VLT
Dtel	10m	5m	8m
Instrument	NIRC2	PHARO	NACO
FOV	10"-40"	30"	14″-56″
NGS	V<17	V<15	V<17
Bands	JHKLM	(Y)JHK	JHKLM
LGS	~10 W	---	~5 W
plate scale	10-40 mas/pix	25 mas/pix	13-54 mas/pix

Summary of AO Concepts

- Most AO systems work with phase, not amplitude.
- Longer wavelengths result in better correction.
- High wind is bad. High Strehl is good.
- Run your AO system fast, but not too fast …
- More demanding observations generally require better seeing conditions, lower airmasses, more light.
- Choose your guide star(s) ahead of time.
- Be aware of tilt and focal anisoplanatism
- Images can provide instant gratification, but analysis should be rigorous.