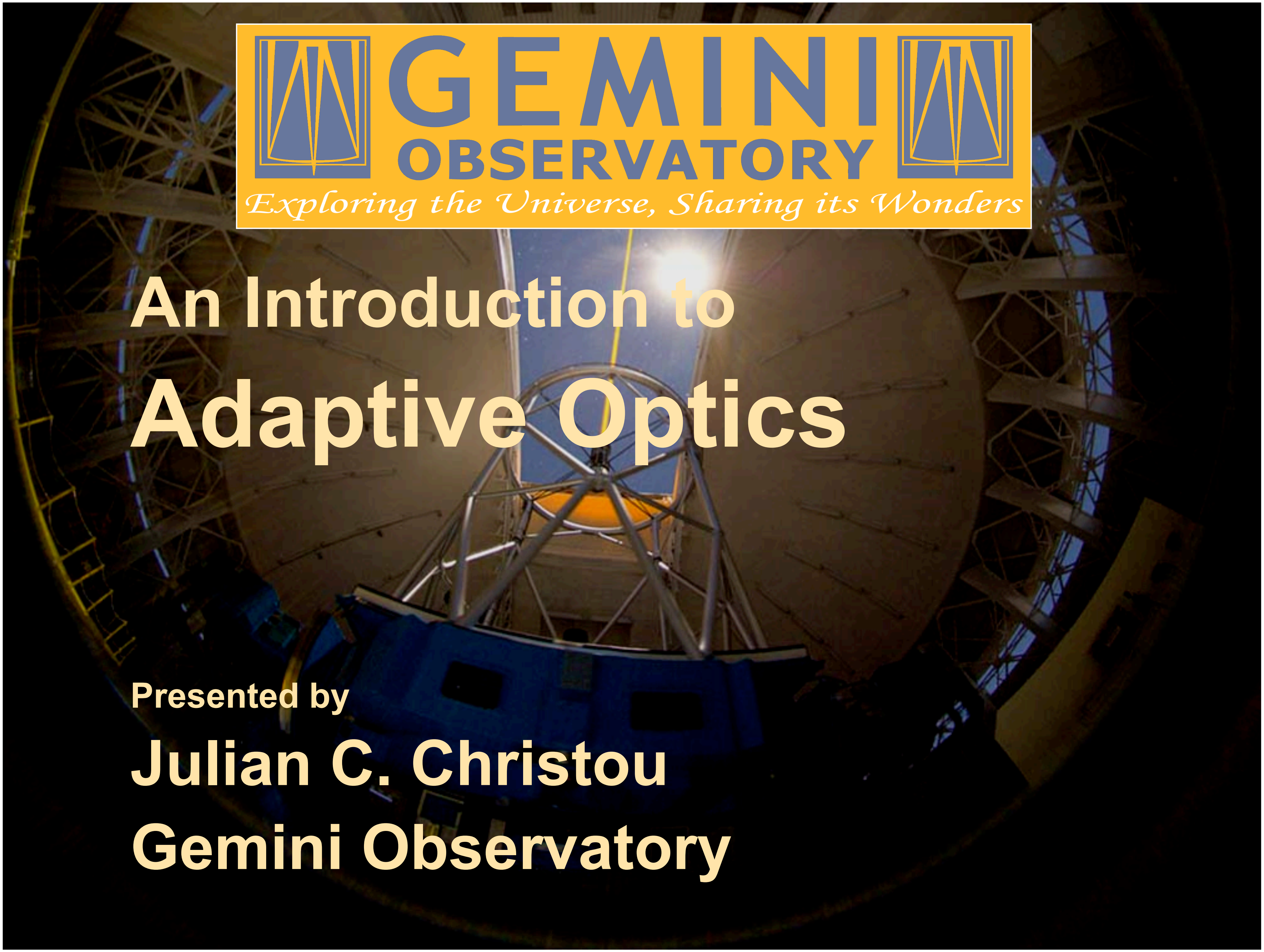


GEMINI OBSERVATORY

Exploring the Universe, Sharing its Wonders

An Introduction to
Adaptive Optics

Presented by

Julian C. Christou

Gemini Observatory

Gemini North in action

An AO Outline

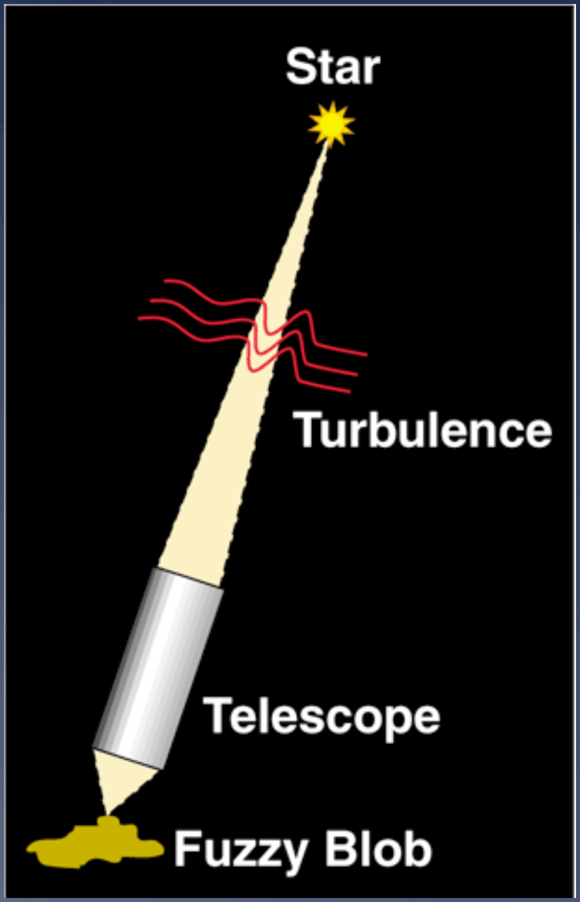
* Turbulence
  * Atmospheric turbulence distorts plane wave from distant object.
  * How does the turbulence distort the wavefront?
* Wavefront Sensing
  * Measuring the distorted wavefront (WFS)
* Wavefront Correction
  * Wavefront corrector – deformable mirror (DM)
* Real-time control
  * Converting the sensed wavefront to commands to control a DM
* Measuring system performance
  * Residual wavefront error, Strehl ratio, FWHM
* Characteristics of an AO Image/PSF

Some content courtesy Claire Max (UCSC/CfAO)

Why Adaptive Optics

- Turbulence in earth's atmosphere makes stars "twinkle".
  - Adaptive Optics (AO) takes the "twinkle out of starlight"
- Turbulence spreads out light.
  - A "blob" rather than a point
  - Seeing disk ~ 0.5 – 1.0 arcseconds
    - With AO can approach the diffraction-limit of the aperture.

$$\theta = \lambda / D$$



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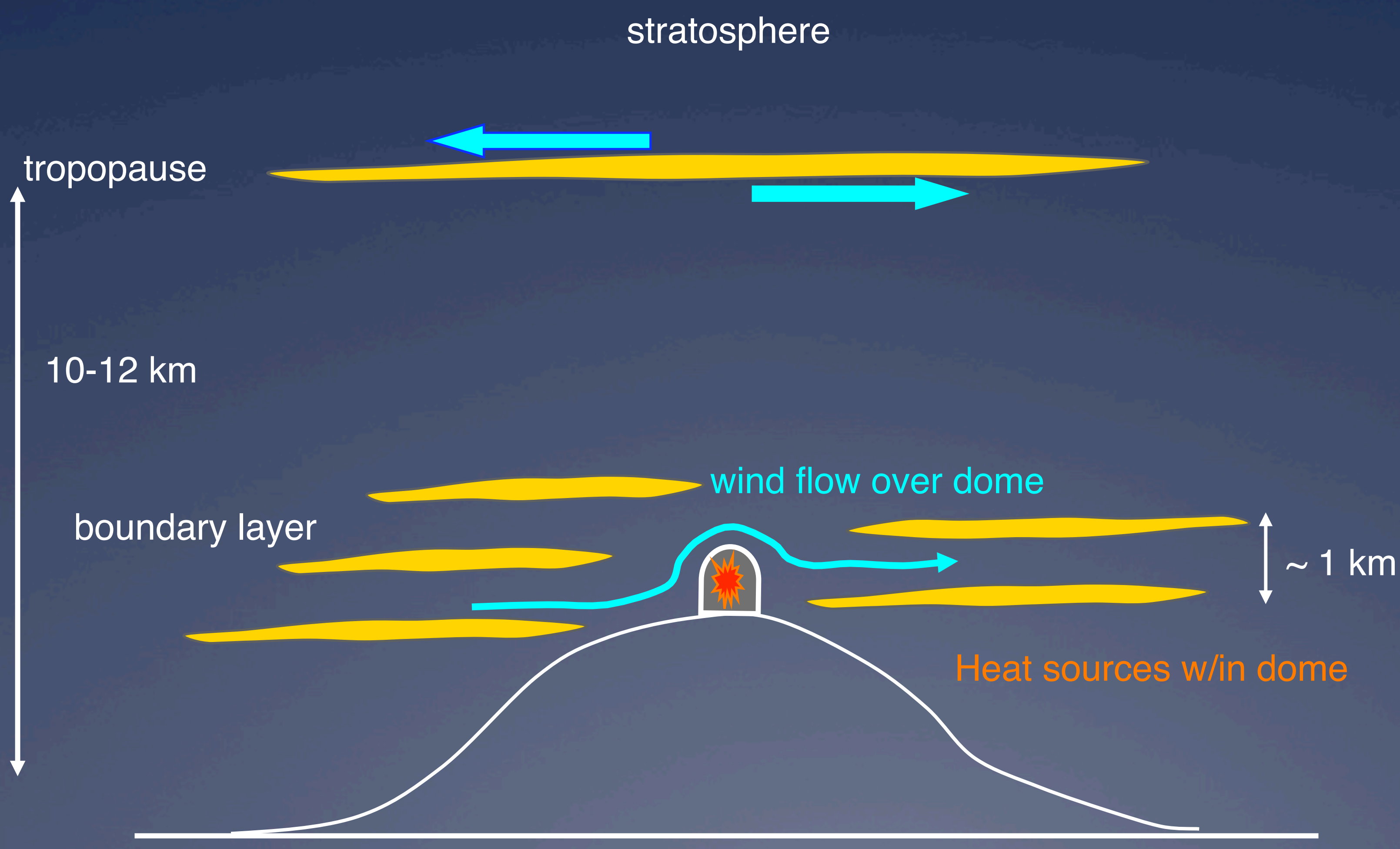
Sources of Turbulence



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Turbulent Cells

Rays not parallel

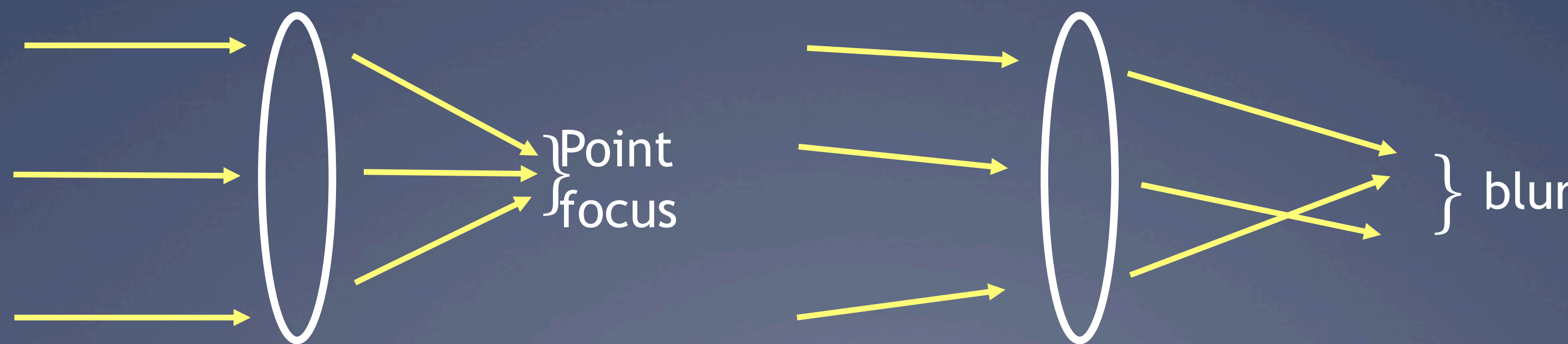
Plane Wave

Temperature variations lead to index of refraction variations

Distorted Wavefront

How Turbulence affects Imaging

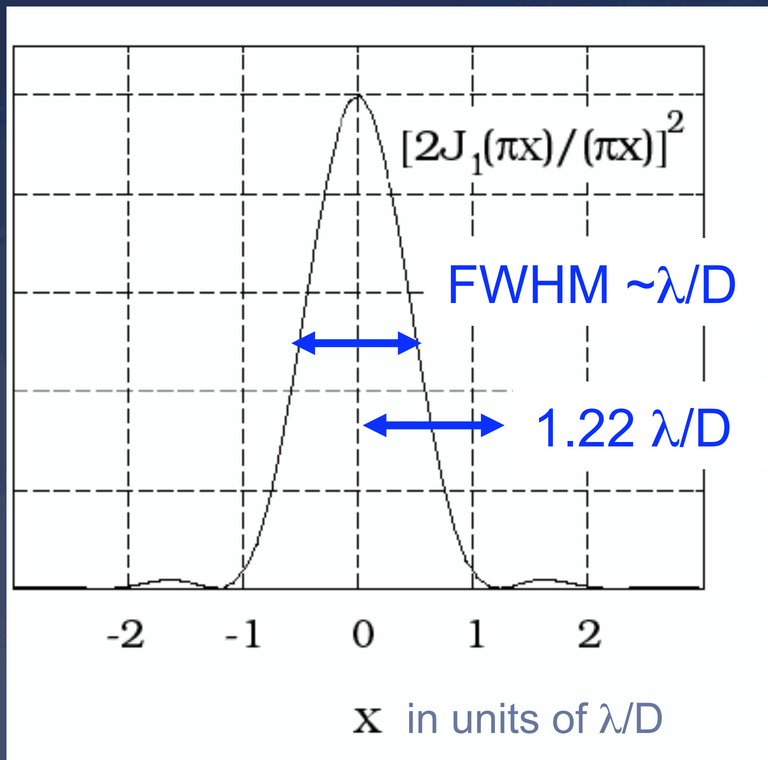
* Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
* Light rays are refracted many times (by small amounts)
* When they reach telescope they are no longer parallel
* Hence rays can't be focused to a point:



Parallel light rays

Light rays affected by turbulence

Imaging through a perfect telescope with no atmosphere



With no turbulence, FWHM is diffraction limit of telescope,

$$\vartheta \sim l / D$$

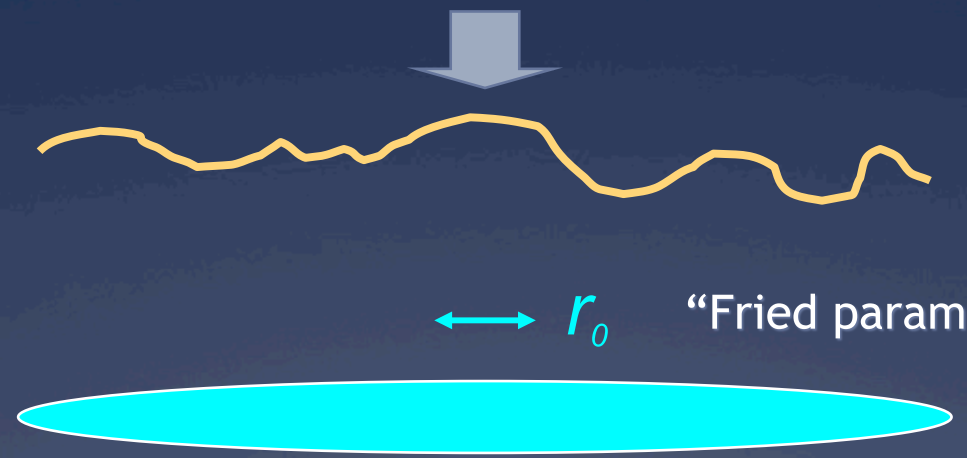
Example:

λ / D = 0.056 arc sec for λ = 2.2 μm, D = 8 m

With turbulence, image size gets much larger (typically 0.5 – 2.0 arc sec)

Point Spread Function (PSF): intensity profile from point source

Turbulence strength r_0



- "Coherence Length" r_0 : distance over which optical phase distortion has mean square value of 1 rad^2
  - r_0 ~ 15 - 30 cm at good observing sites
- r_0 = 10 cm ⇔ FWHM = 1 arcsec at $\lambda = 0.5\mu m$

The Coherence length – r_0

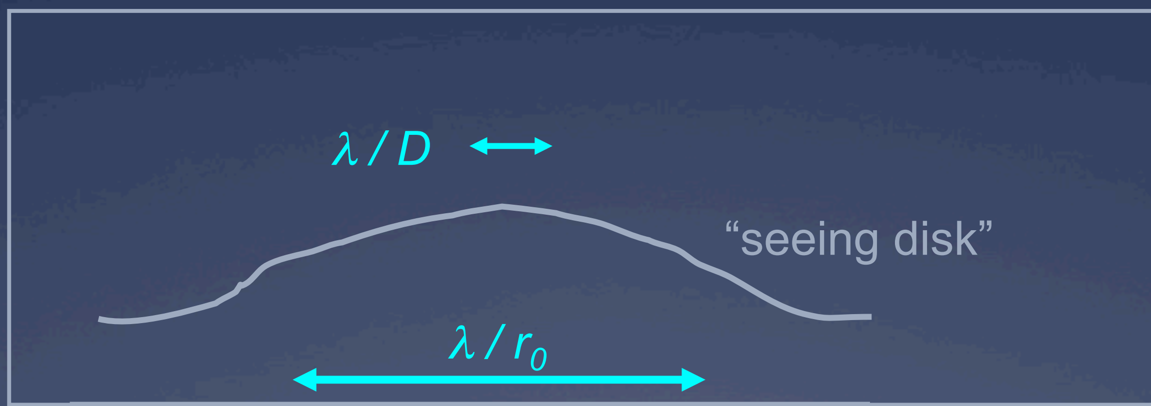
- r_0 sets the scale of all AO correction

$$r_0 = \left[0.423k^2 \sec\varsigma \int_0^H C_N^2(z)\,dz\right]^{-3/5} \propto \lambda^{6/5} \left(\sec\varsigma\right)^{-3/5} \left[\int C_N^2(z)\,dz\right]^{-3/5}$$

- r_0 decreases when turbulence is strong (C_N^2 large)
- r_0 increases at longer wavelengths
  - AO is easier in the IR than with visible light
- r_0 decreases as telescope looks toward the horizon (larger zenith angles ζ)
- At excellent sites such as Mauna Kea in Hawaii, r_0 at $\lambda = 0.5$ micron is 10 - 30 cm.
- A large range from night to night, and also during a night.

Image Size and Turbulence

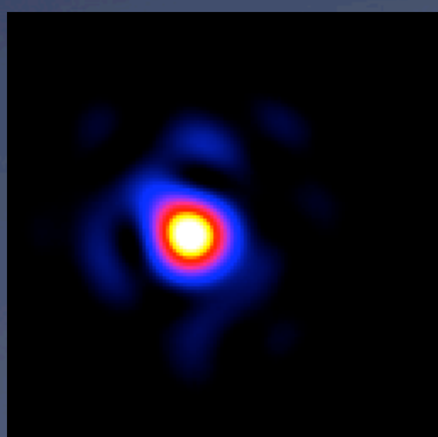
- If telescope diameter $D >> r_0$, image size of a point source is $\lambda / r_0 >> \lambda / D$



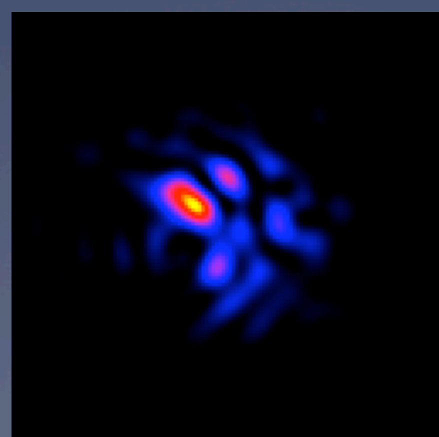
- r_0 is diameter of the circular pupil for which the diffraction limited image and the seeing limited image have the same angular resolution.
- r_0 (λ = 500 nm) $\approx$ 25 cm at a good site. So any telescope larger than this has no better spatial resolution!

r_0 & the telescope diameter D

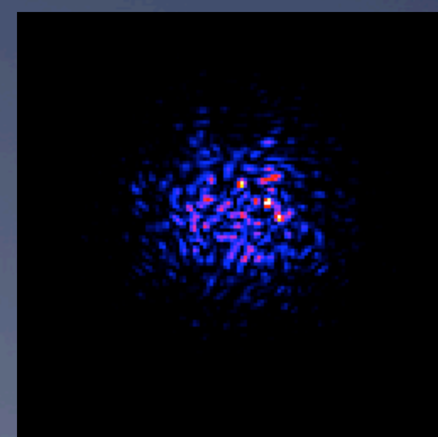
- Coherence length of turbulence: r_0 (Fried’s parameter)
- For telescope diameter $D < (2 - 3) \times r_0$
  - Dominant effect is "image wander”
- As D becomes >> r_0
  - Many small "speckles" develop
    - N ~ (D/r_0)
  - Speckle scale ~ diffraction-limit



***D* = 1 m**



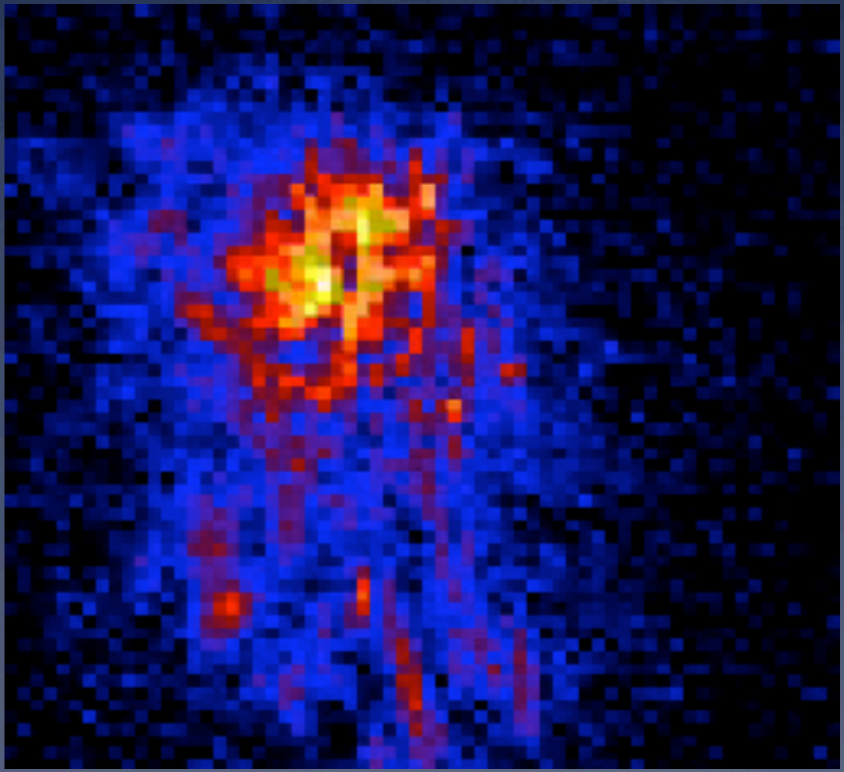
***D* = 2 m**



***D* = 8 m**

Real-time Turbulence

Image is spread out into speckles



Centroid jumps around (image motion)

"Speckle images": sequence of short snapshots of a star

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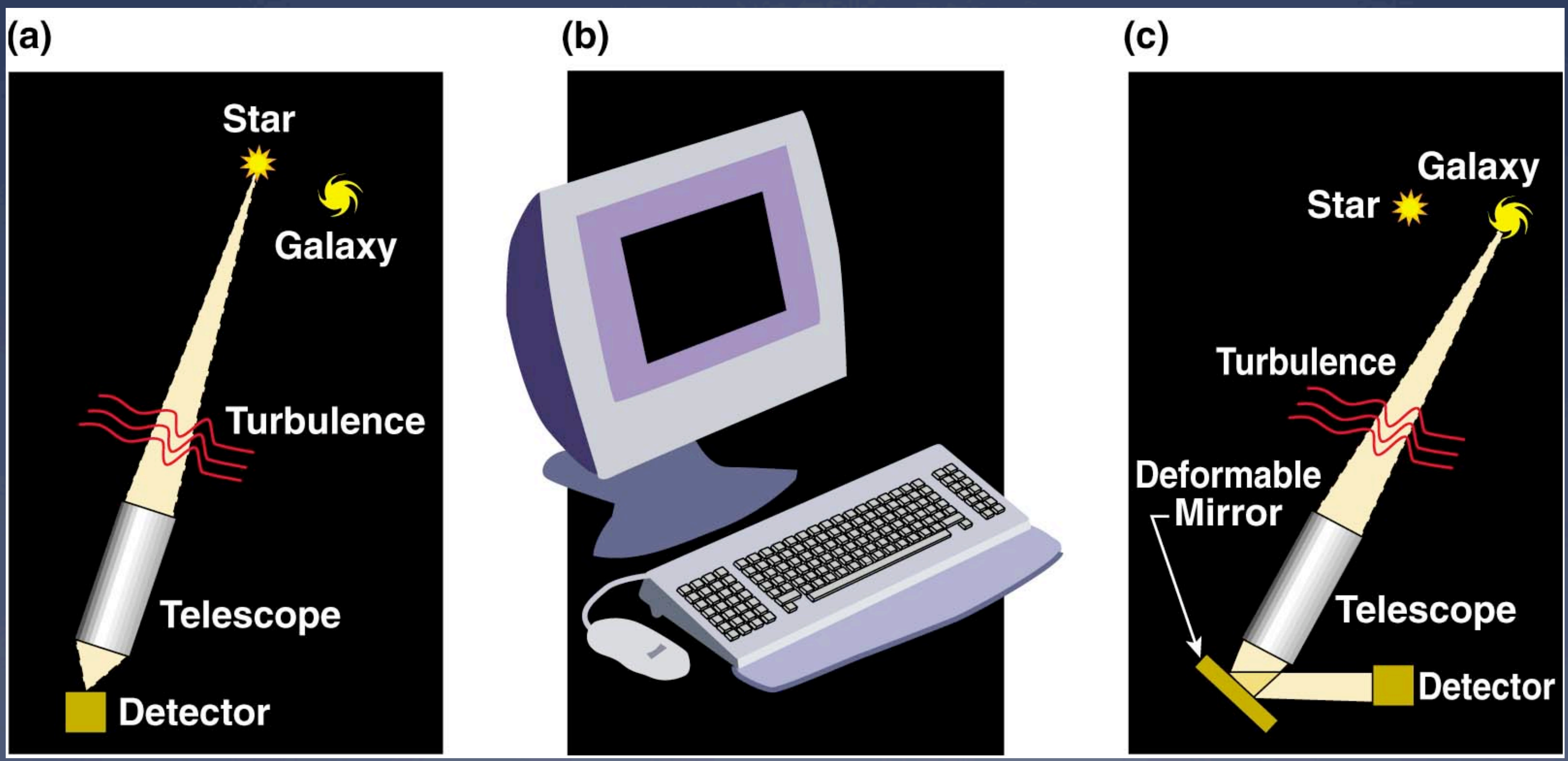
Concept of Adaptive Optics

Measure details of blurring from "guide star" at or near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



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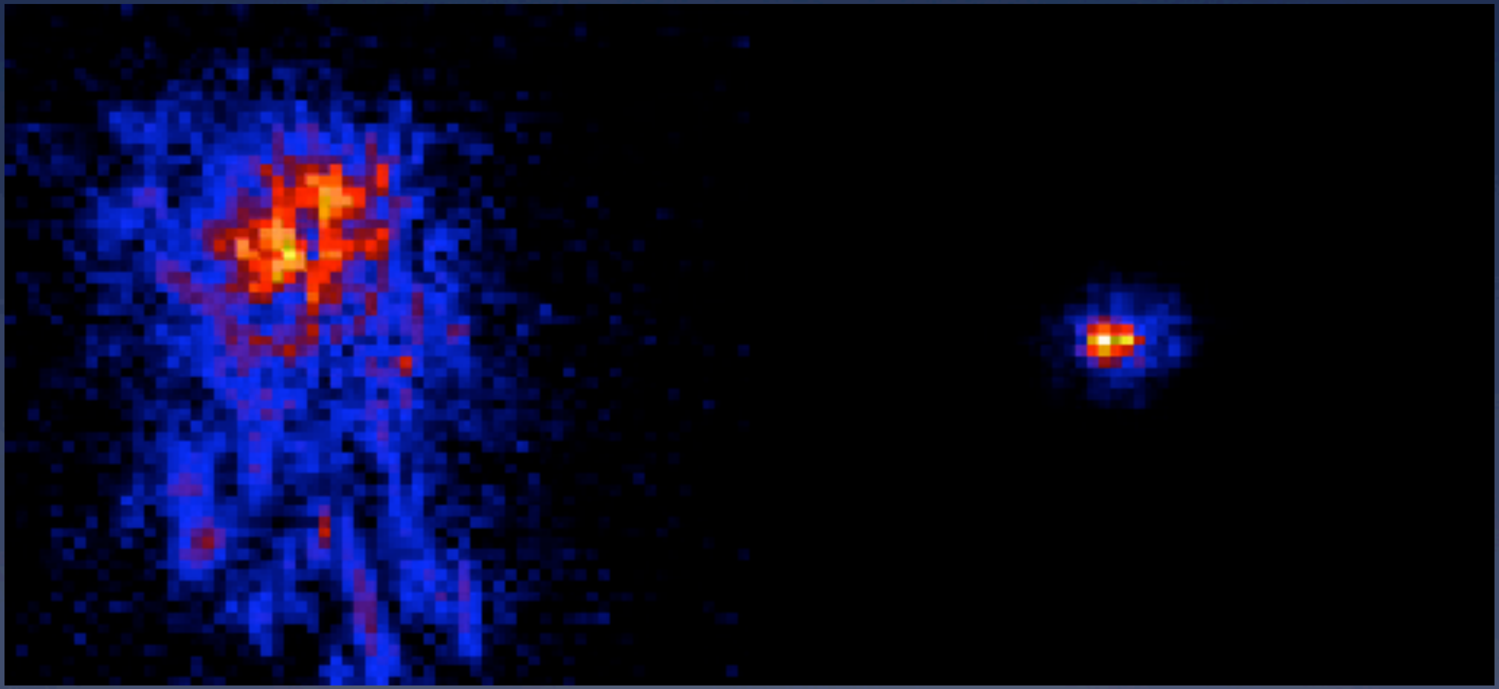
Adaptive Optics in Action



No adaptive optics | With adaptive optics

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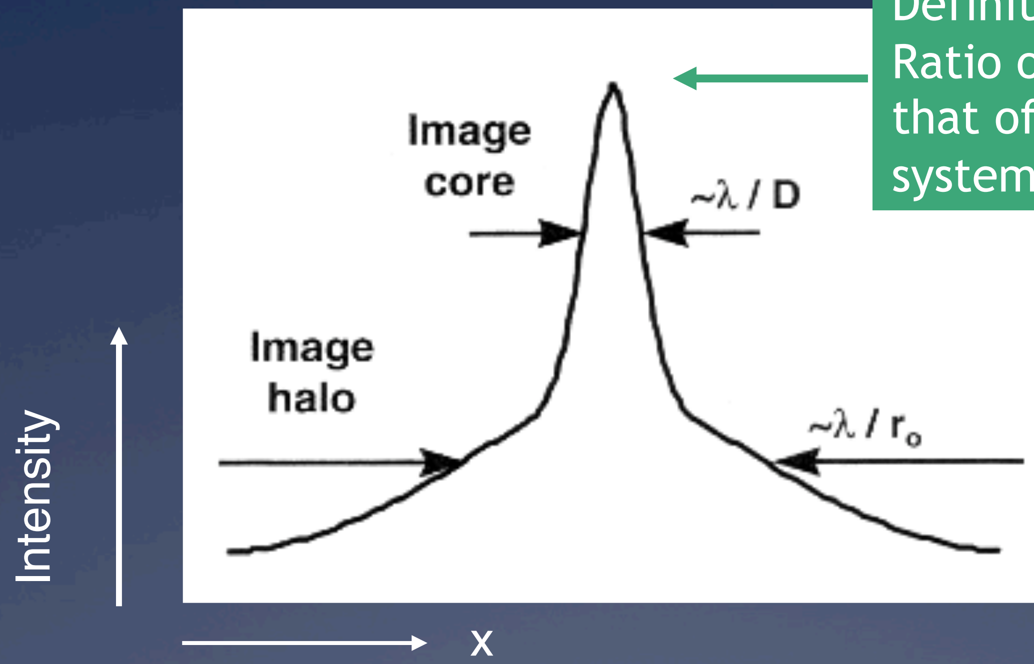
The Adaptive Optics PSF



Definition of "Strehl": Ratio of peak intensity to that of "perfect" optical system

- When AO system performs well, more energy in core
- When AO system is stressed (poor seeing), halo contains larger fraction of energy (diameter ~ r_0)
- Ratio between core and halo varies during night

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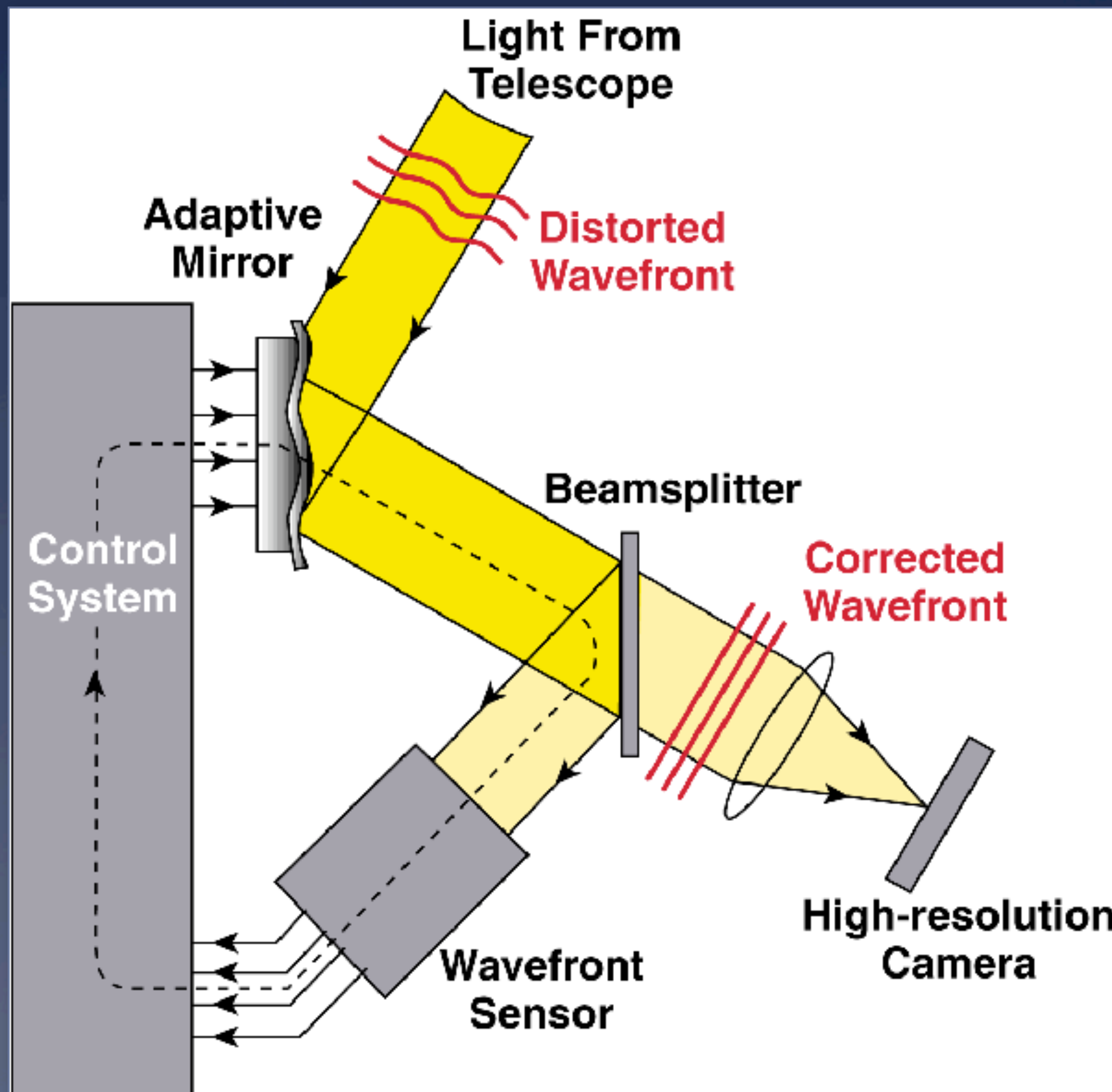
Adaptive Optics

- How does Adaptive Optics Work?
  - Sense the wavefront errors produced by the atmosphere.
    - Wavefront sensor (WFS) technology
  - Correct the wavefront, i.e. convert the corrugated wavefront to a flat wavefront.
    - Wavefront Corrector – Deformable Mirror (DM) technology
  - Real Time Controller.
    - How to convert the WFS measurements to signals to control the shape of the DM and adjust it ~ 100-200 Hz.
  - Guide Stars
    - Natural Guide Star
    - Laser Guide Star
      - Rayleigh Beacon
      - Sodium Beacom

Closed-loop AO System

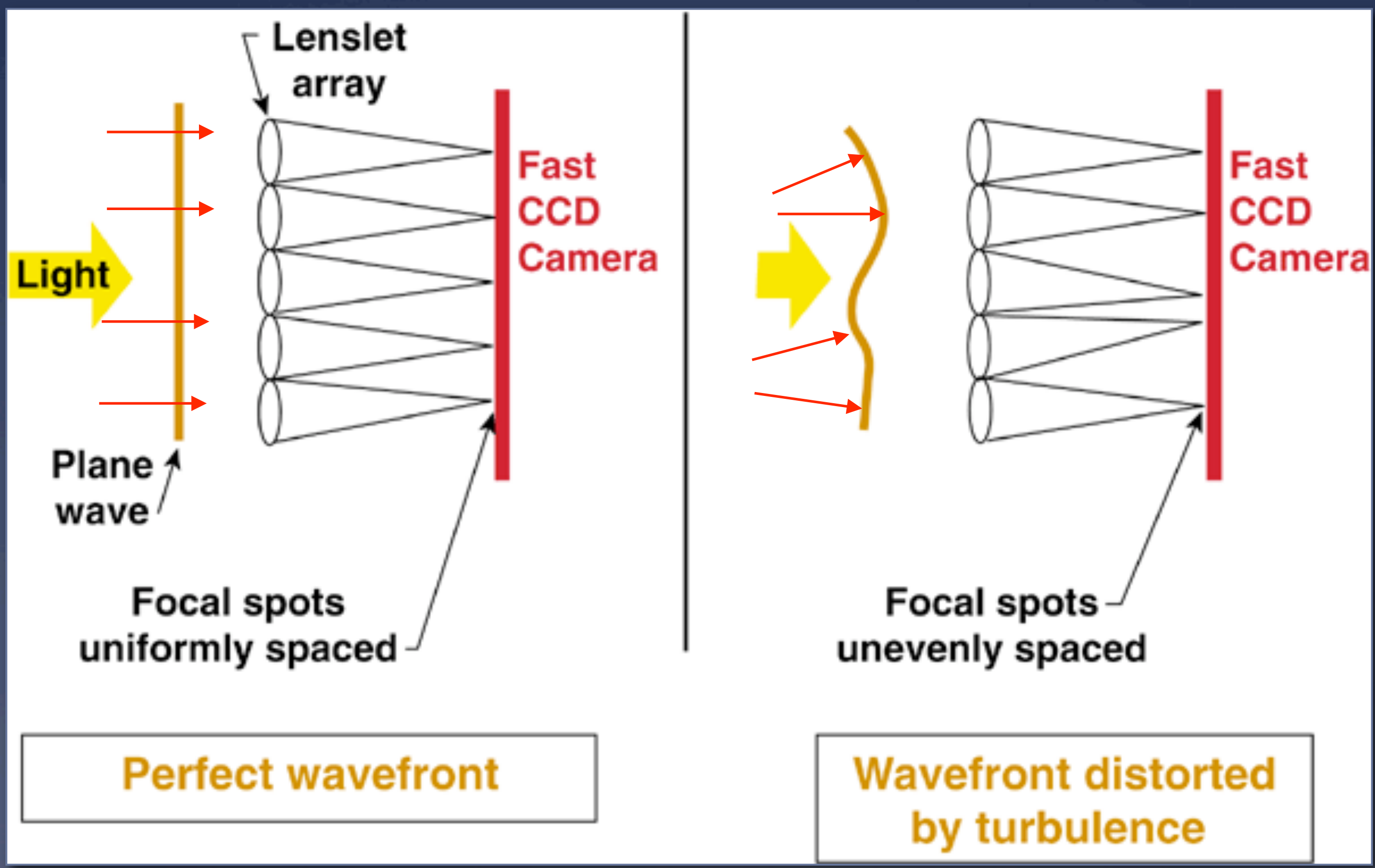
Feedback loop: next cycle corrects the (small) errors of the last cycle



Wavefront Sensing

Wavefront Sensing

Shack-Hartmann wavefront sensor



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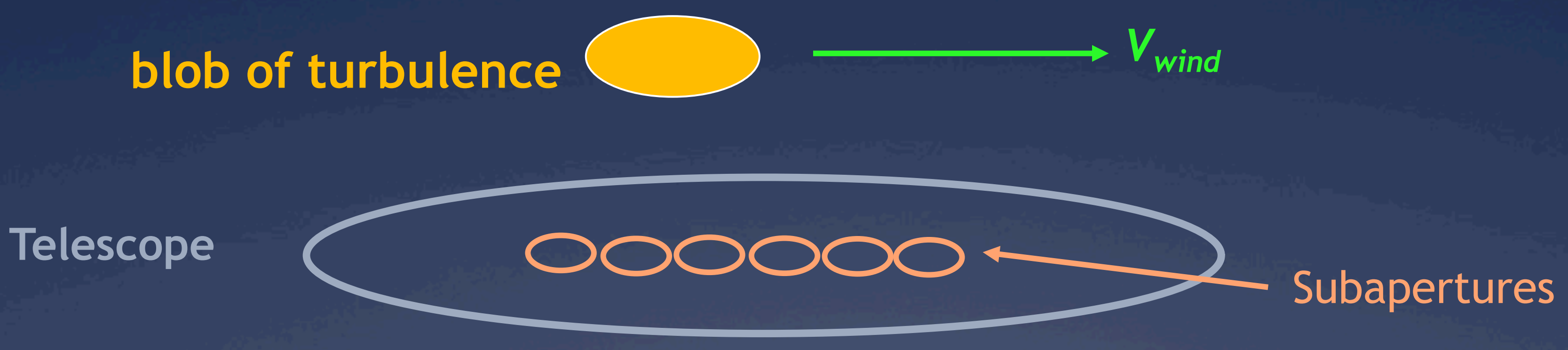
Wavefront Sensing

- Shack-Hartmann WFS
  - Divide pupil into subapertures of size ~ r_0
  - Number of subapertures ~ $(D / r_0)^2$
  - Lenslet in each subaperture focuses incoming light to a spot on the wavefront sensor's CCD detector
  - Deviation of spot position from a perfectly square grid measures shape of incoming wavefront
  - Wavefront reconstructor computer uses positions of spots to calculate voltages to send to deformable mirror

WFS sensitivity to r_0

- For smaller r_0 (worse turbulence) need:
  - Smaller sub-apertures
    - More actuators on deformable mirror
    - More lenslets on wavefront sensor
  - Faster AO system
    - Faster computer, lower-noise wavefront sensor detector
  - Much brighter guide star (natural star or laser)

Temporal behaviour of WFS



- Timescale over which turbulence within a subaperture changes is

$$\tau \sim \frac{subaperture\ diameter}{V_{wind}} \sim \frac{r_0}{V_{wind}}$$

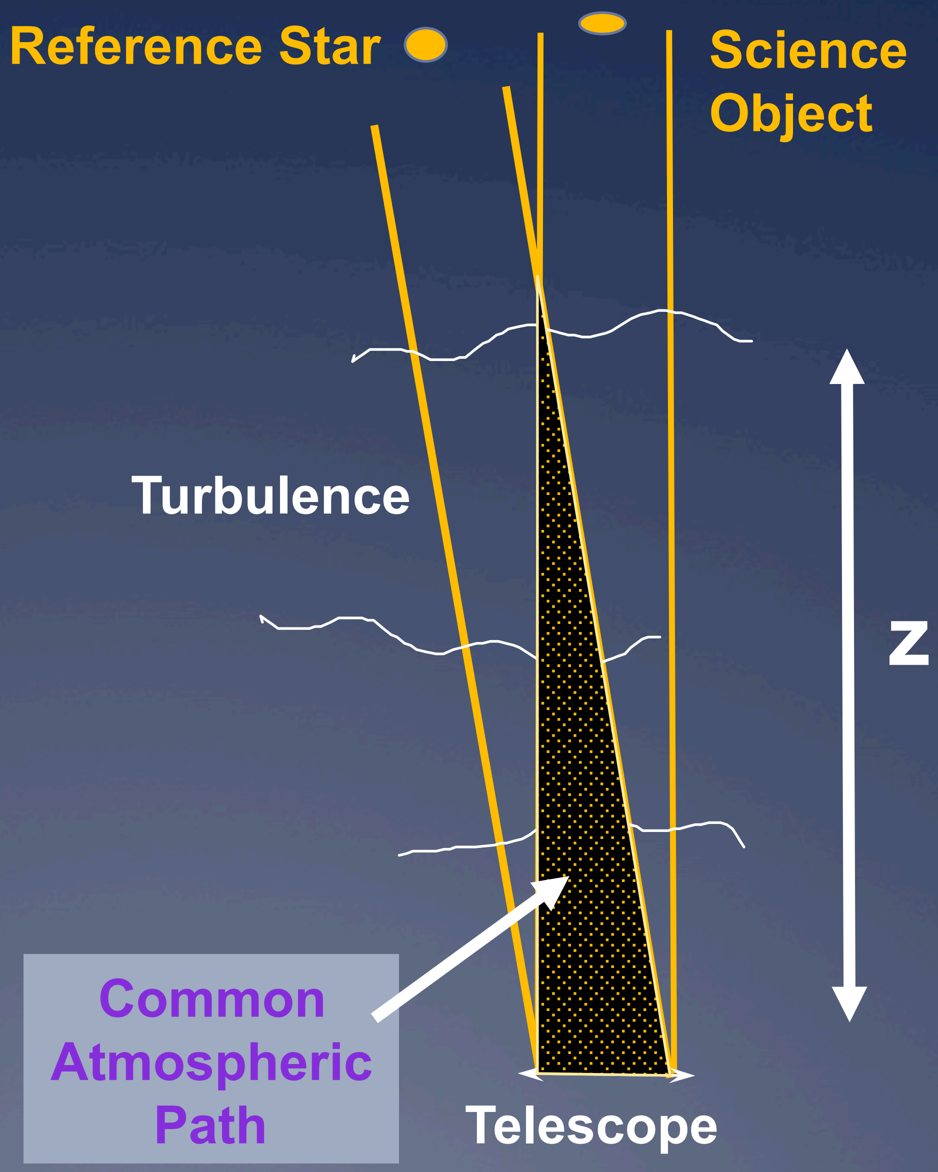
- Smaller r_0 (worse turbulence) ⇒ need faster AO system
- Shorter WFS integration time ⇒ need brighter guide star

The Isoplanatic angle

Turbulence has to be similar on path to reference star and to science object

Common path has to be large

Anisoplanatism sets a limit to distance of reference star from the science object

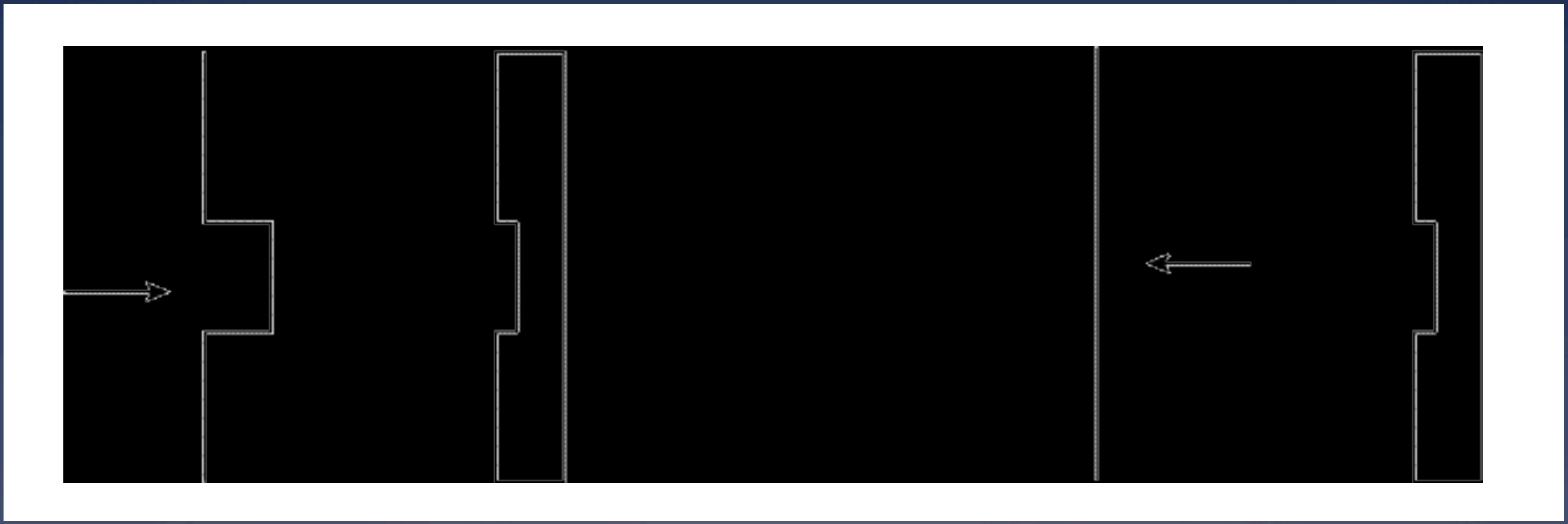


Wavefront Correction

Wavefront Correction Concept

BEFORE

AFTER



Incoming Wave with Aberration

Deformable Mirror

Corrected Wavefront

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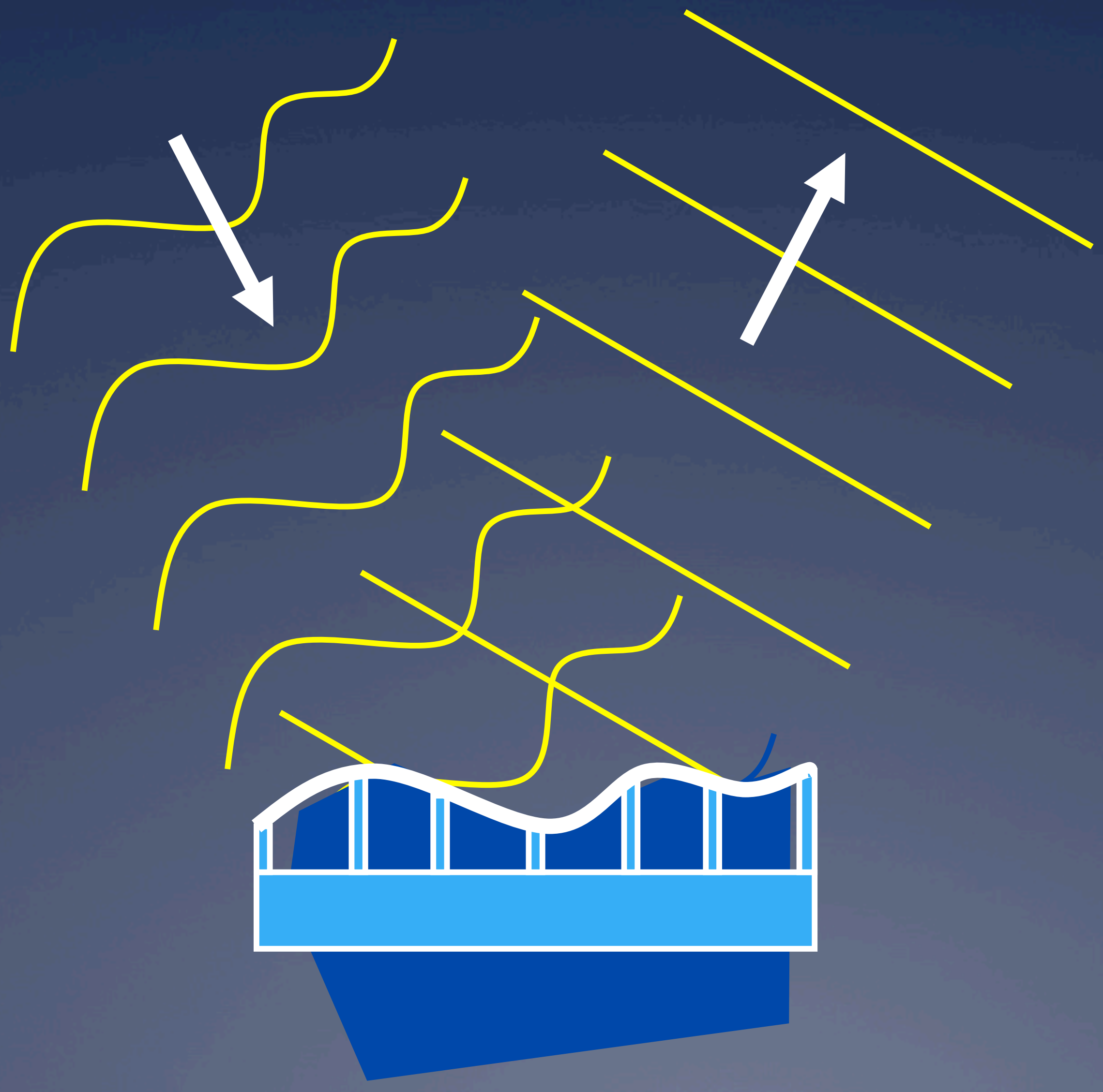
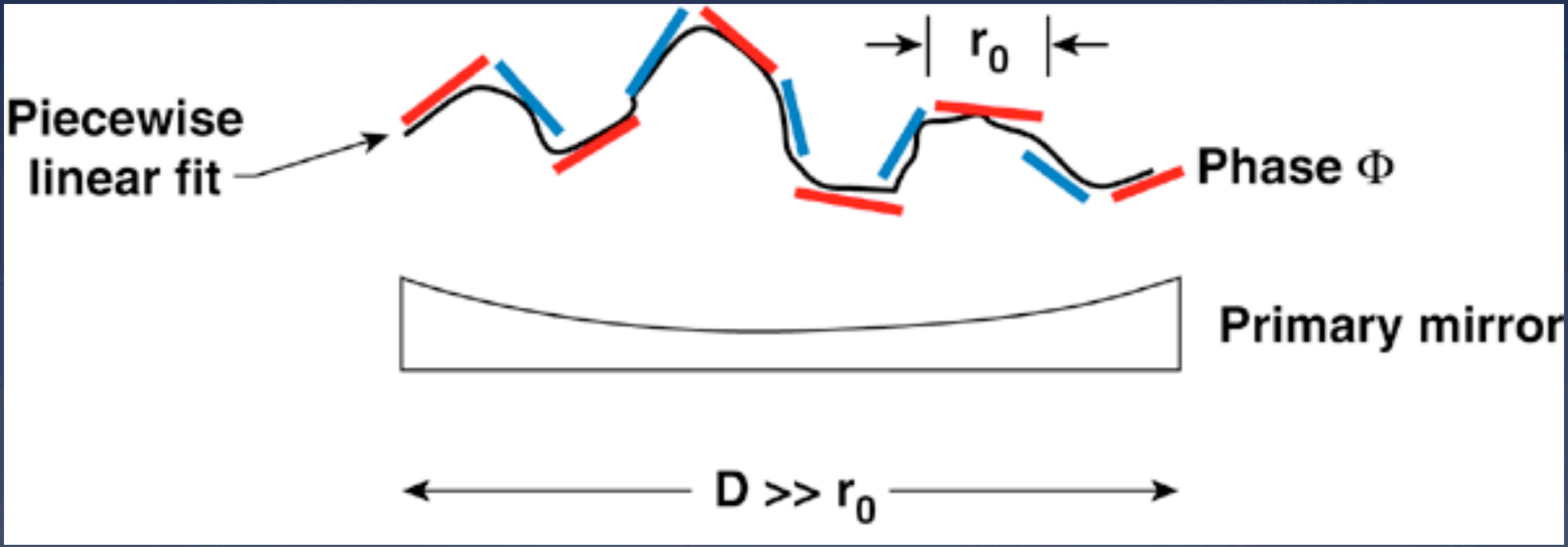
Wavefront Correction

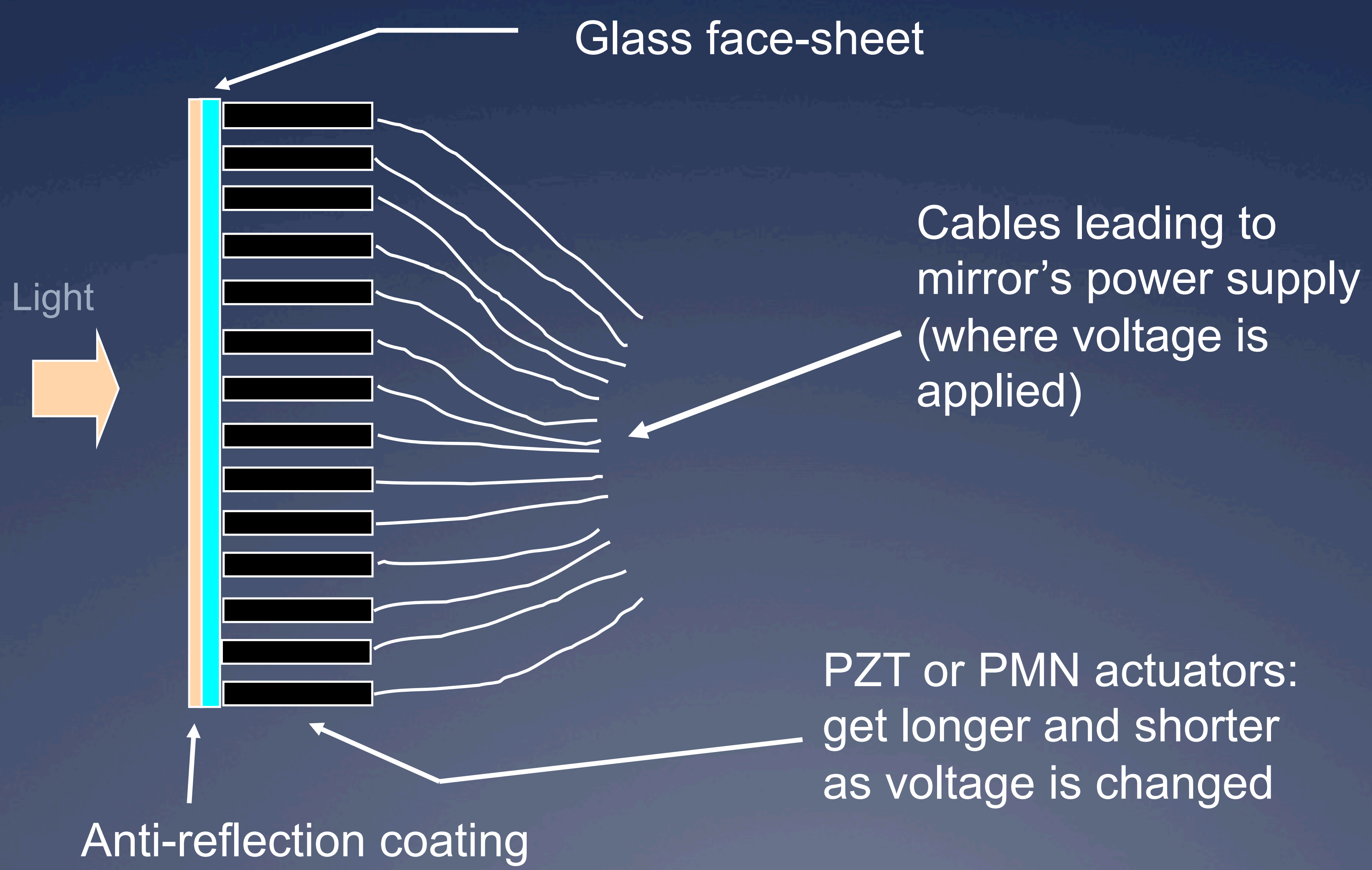


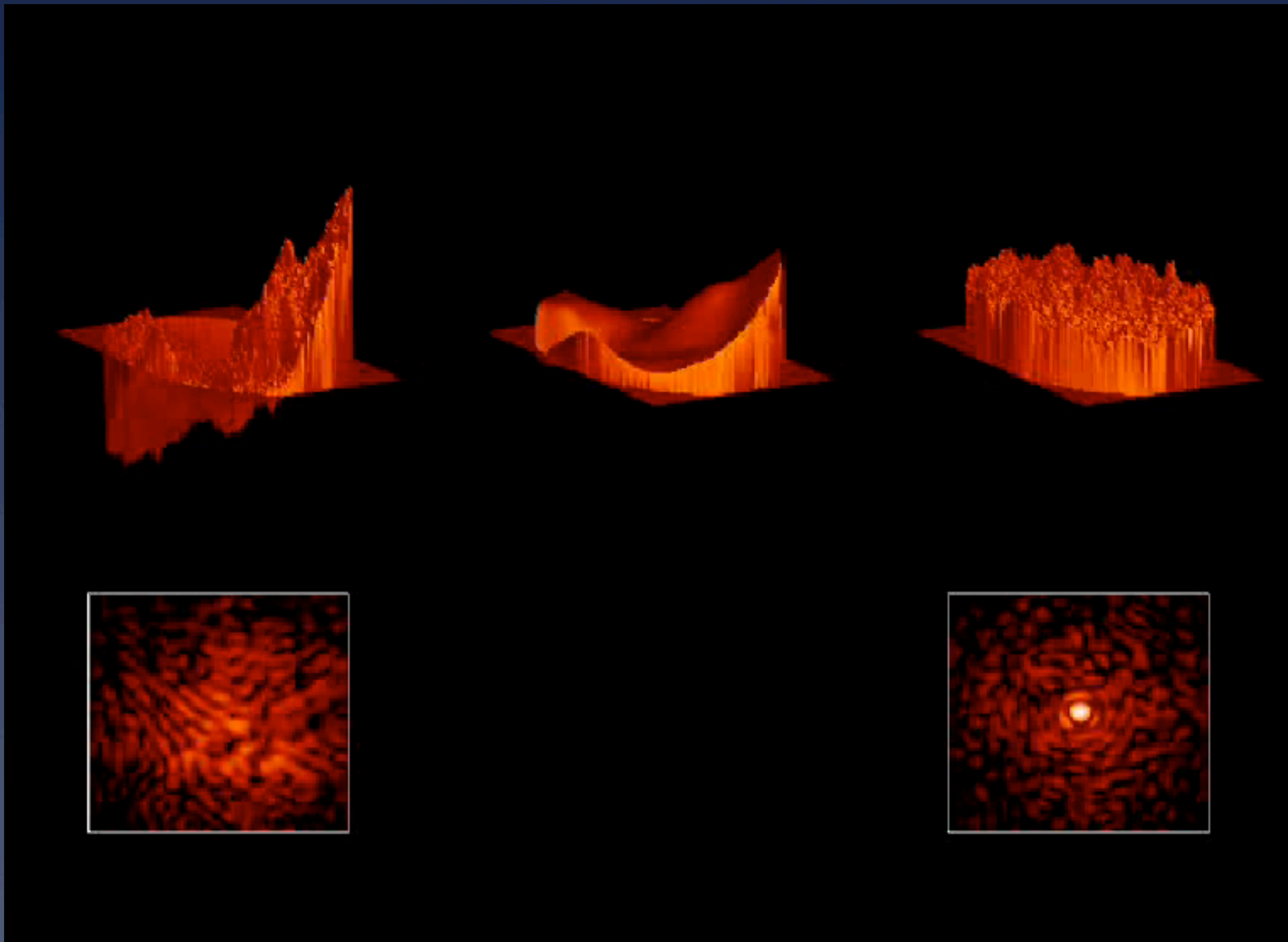
Wavefront Correction



- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed <u>after</u> the main telescope mirror

Typical Deformable Mirror





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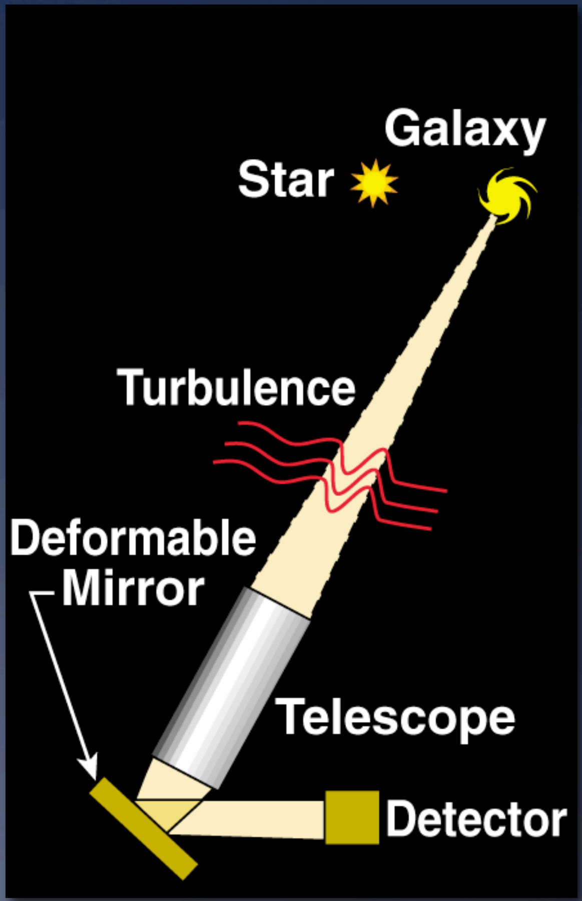
Guide Stars

"Guide" Stars

- The WFS requires a point-source to measure the wavefront error.
- A natural guide star (*V* < 11) is needed for the WFS.
  - Limited sky coverage and anisoplanatism
- Create an artificial guide star
  - Rayleigh Beacon ~ 10 - 20 km
  - Sodium Beacon ~ 90 km



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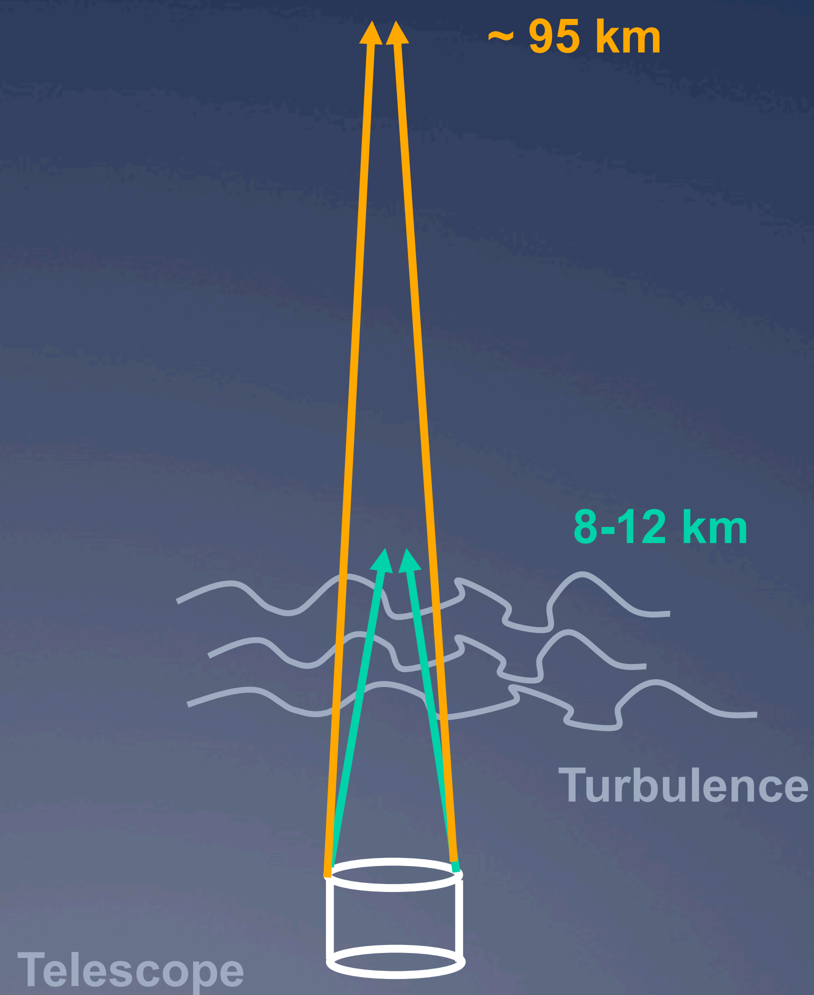
Rayleigh and Sodium "Guide" Stars

* Sodium guide stars: excite atoms in "sodium layer" at altitude of ~ 95 km
* Rayleigh guide stars: Rayleigh scattering from air molecules sends light back into telescope, h ~ 10 km
* Higher altitude of sodium layer is closer to sampling the same turbulence that a star from "infinity" passes through



Focal Ansioplanatism

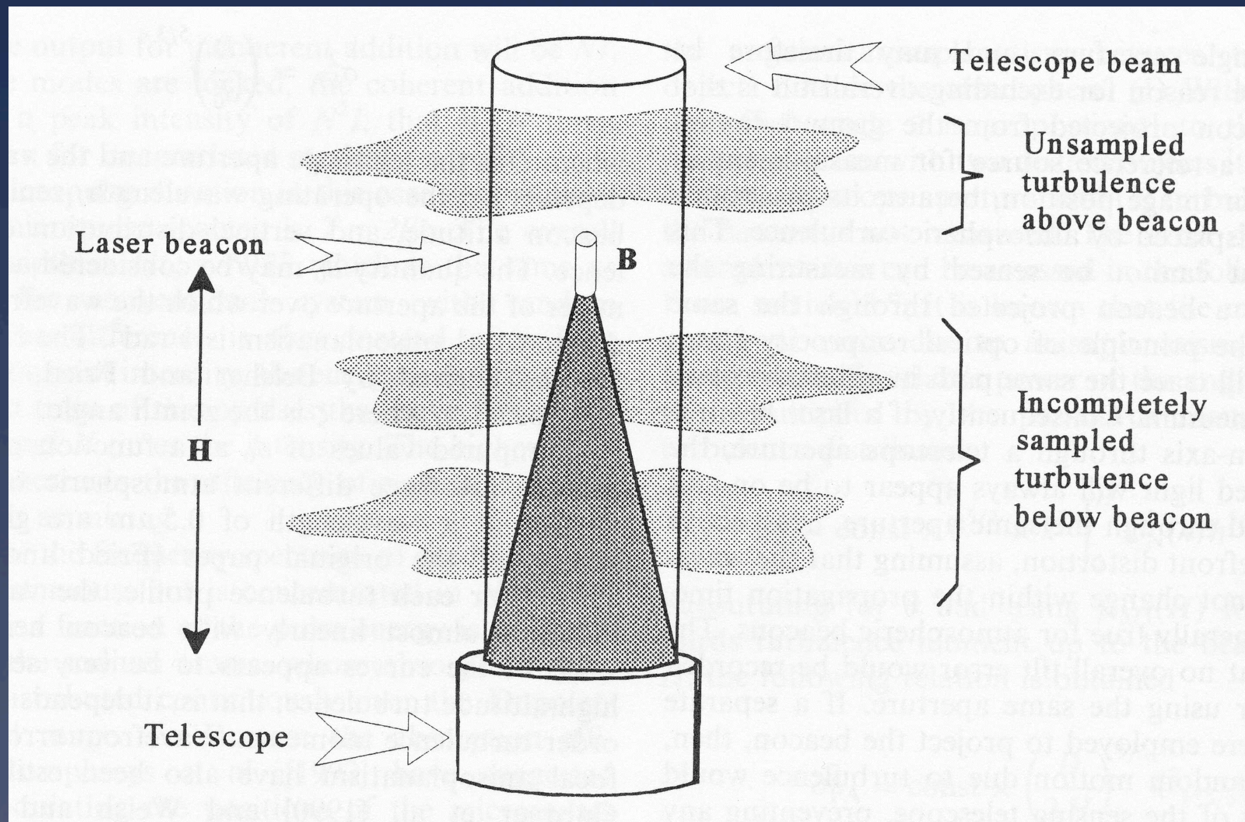
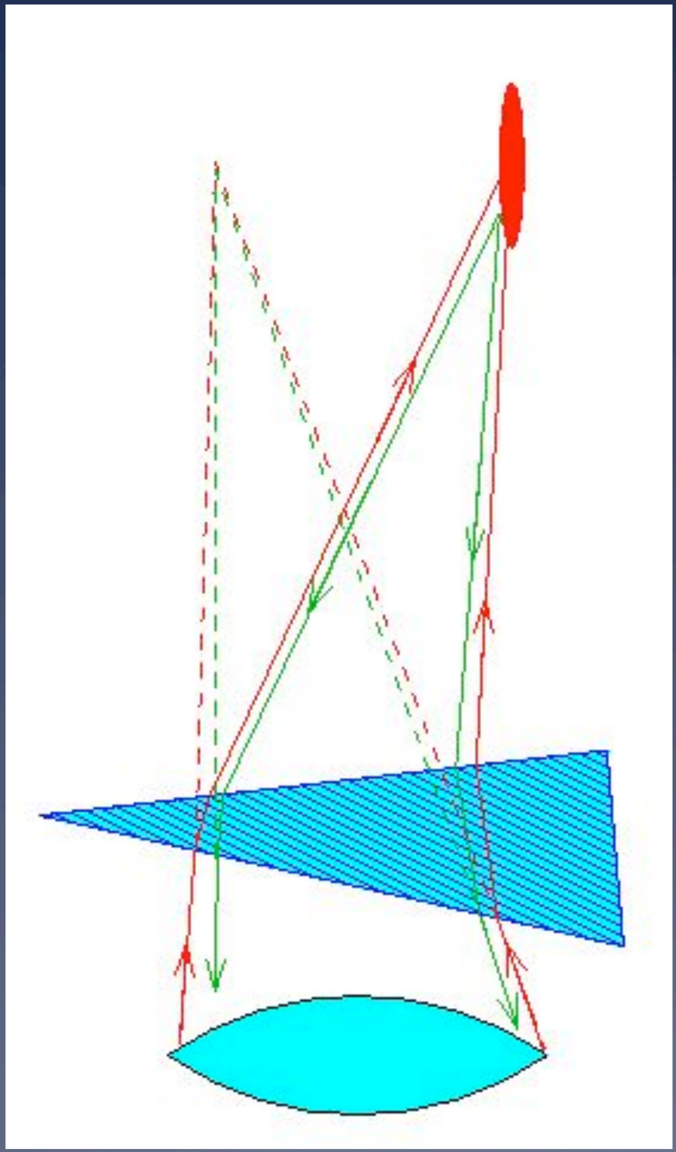


Figure 7.14 Laser beacon measurement errors.

Credit: Hardy

TT Natural Guide Star



from A. Tokovinin

AO Performance

- AO delivers improved Focal Plane performance.
  - How to measure this performance?
    - Residual wavefront error
      - Phase variance
    - Strehl ratio
    - Full width at half-maximum
    - Encircled energy
  - All are related

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Phase variance and Strehl ratio

- "Maréchal Approximation"

$$\text{Strehl} \cong \exp\left(-\sigma_\phi^2\right)$$

where σ_ϕ^2 is the total wavefront variance

- Valid when Strehl > 10% or so
- Under-estimate of Strehl for larger values of σ_ϕ^2

Gemini AO Instruments

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Gemini AO Instrumentation

AO System	Instrument	FoV (")	Strehl Ratio (H-Band)	R_{lim} (full/limit)	Sky Coverage (%)
UH36	QUIRC	20	15	15	1
Altair NGS	NIRI / NIFS	20	35	12/15	< 1
Altair LGS	NIRI / NIFS	20/50	20	15/18	~ 30
NICI	Coronograph Imager	14	45	12/15	< 1
GeMS (MCAO)	GSAOI Flamingos-2	83	40	15/18	~ 30
GPI	Coronograph IFU	? / 4	90	8/11	< 0.1
GLAO	all instruments	up to 360	5*	>15	100

Past | Present | In Development | Possible Future Instrument

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Altair Overview

Altair - **<u>ALT</u>**titude conjugate **<u>A</u>**daptive optics for the **<u>I</u>**nfra**<u>R</u>**ed)

* Facility natural/laser guide star adaptive optics system of the Gemini North telescope.

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Altair Overview

- Shack-Hartmann WFS – 12 × 12 lenslet array – visible light.
- 177 actuator deformable mirror (DM) and a separate tip-tilt mirror (TTM)
- Closed loop operation at ≤ 1 KHz
- Initially single conjugate at 6.5km
- 87-92% *J* - *K* optical throughput
- NGS operation since 2004
  - Strehl ratio – typically 0.2 to 0.4 (best at *H*, *K*)
  - FWHM = 0.07''
- LGS commissioned in 2007
- LGS Strehl ratio ~0.3 at 2.2 μm (FWHM = 0.083'')
- LGS sky coverage ~ 40% (4% for NGS)
- NGS tip-tilt star ≤ 25''
- LGS science operations ~1 to 2 weeks/month

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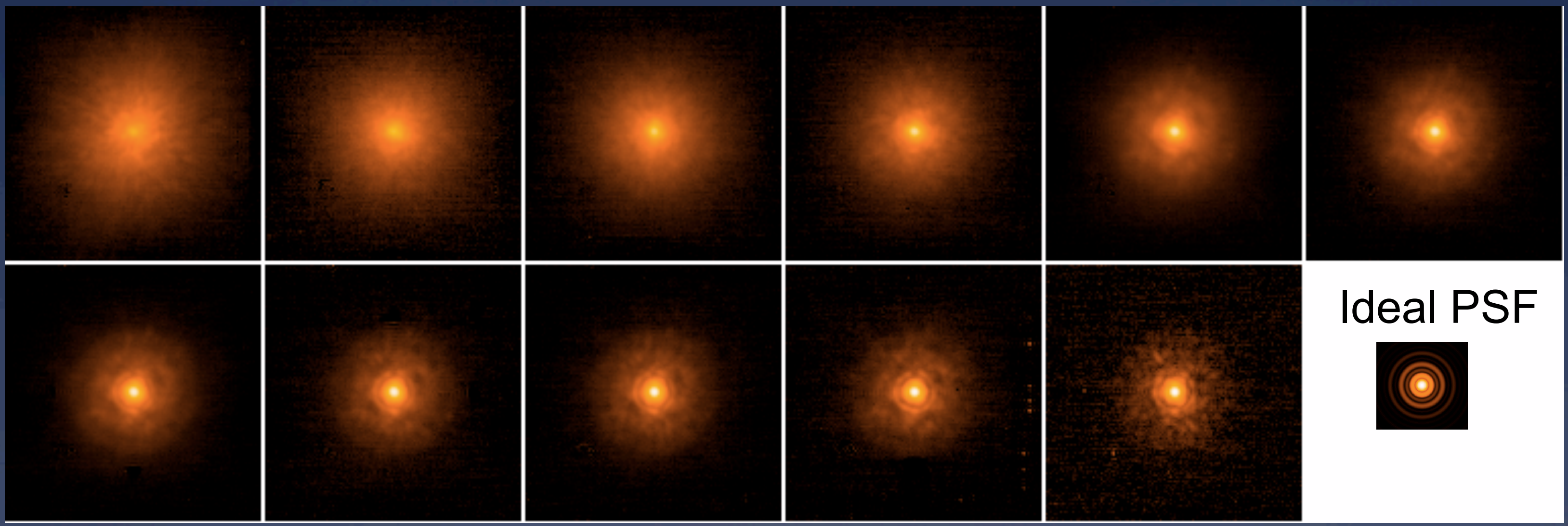
Altair PSFs (*K*)

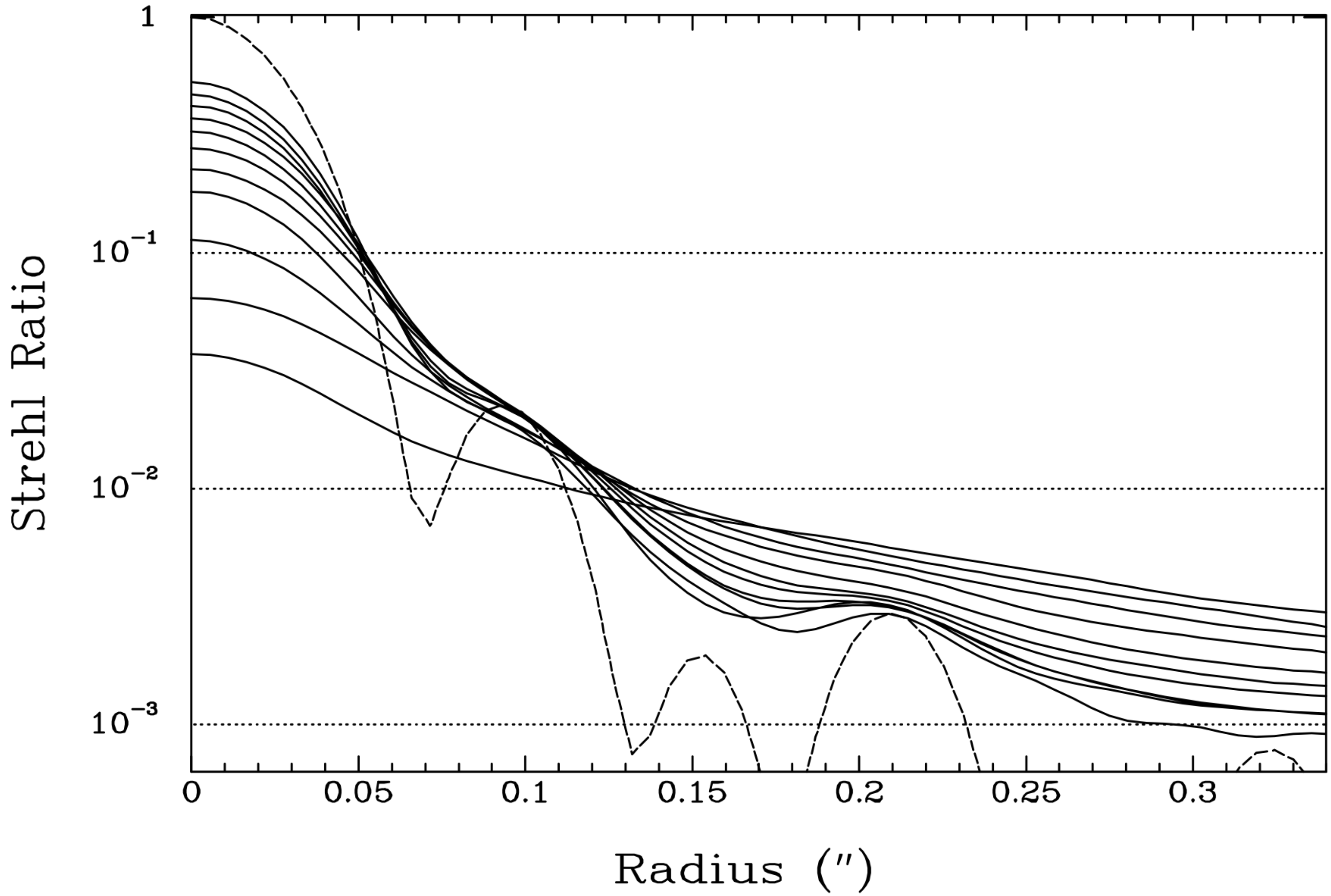
Variability of the Altair NGS PSF with seeing.



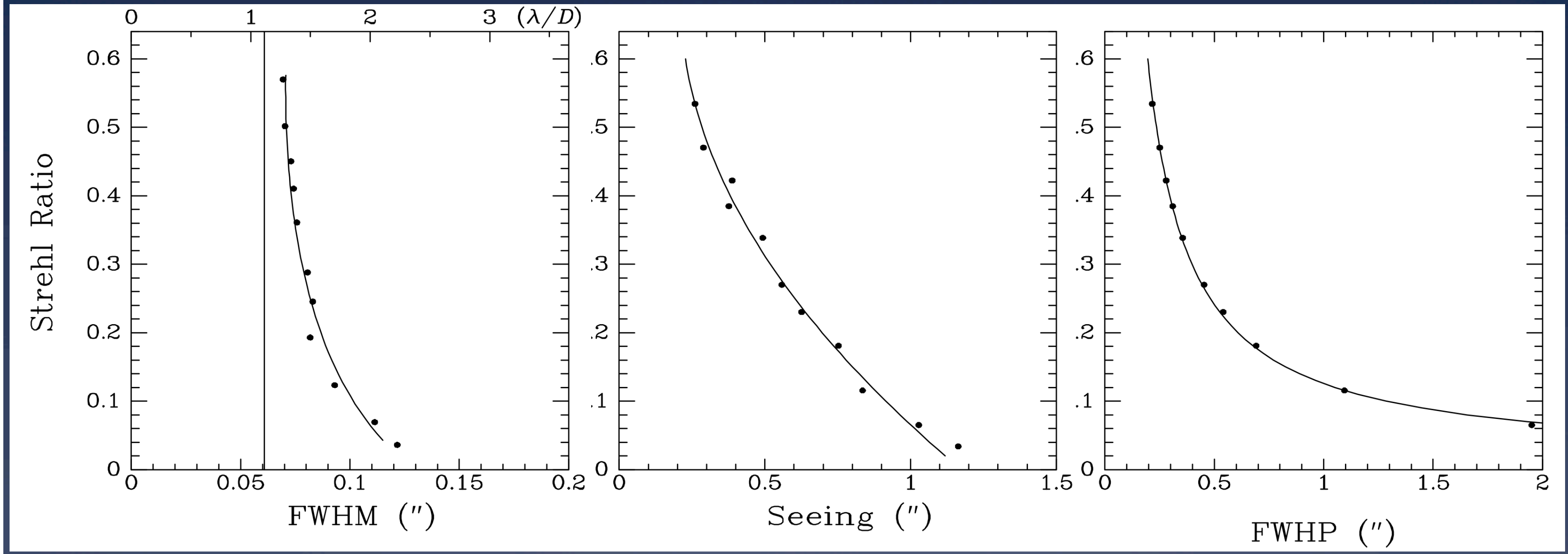
- PSF depends upon conditions

- Photometry/Astrometry difficult in crowded fields:
  - Overlapping PSFs
  - SNR problems
  - Require good PSF estimate
    - Model Fitting (StarFinder)
    - Deconvolution

Altair PSFs (*K*)



PSF Metrics (*K*)



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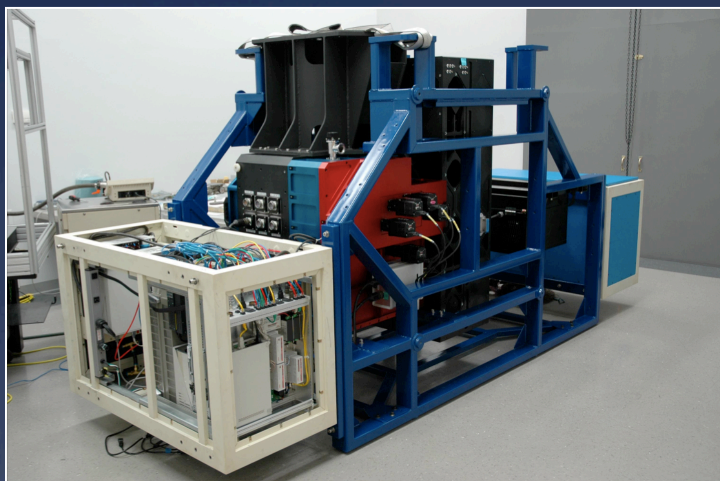
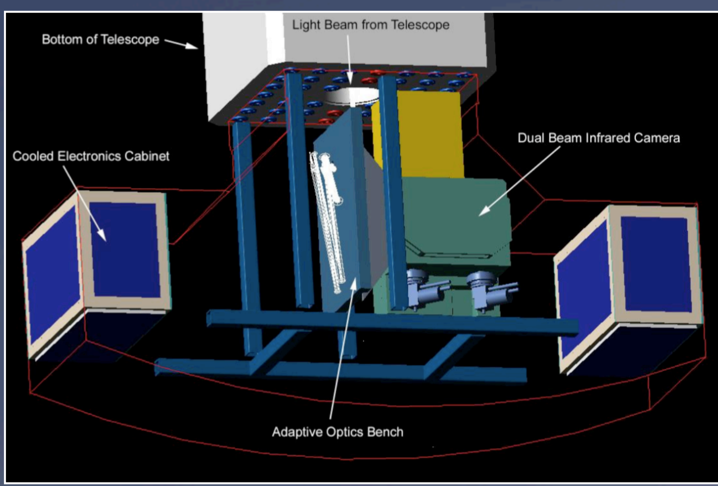
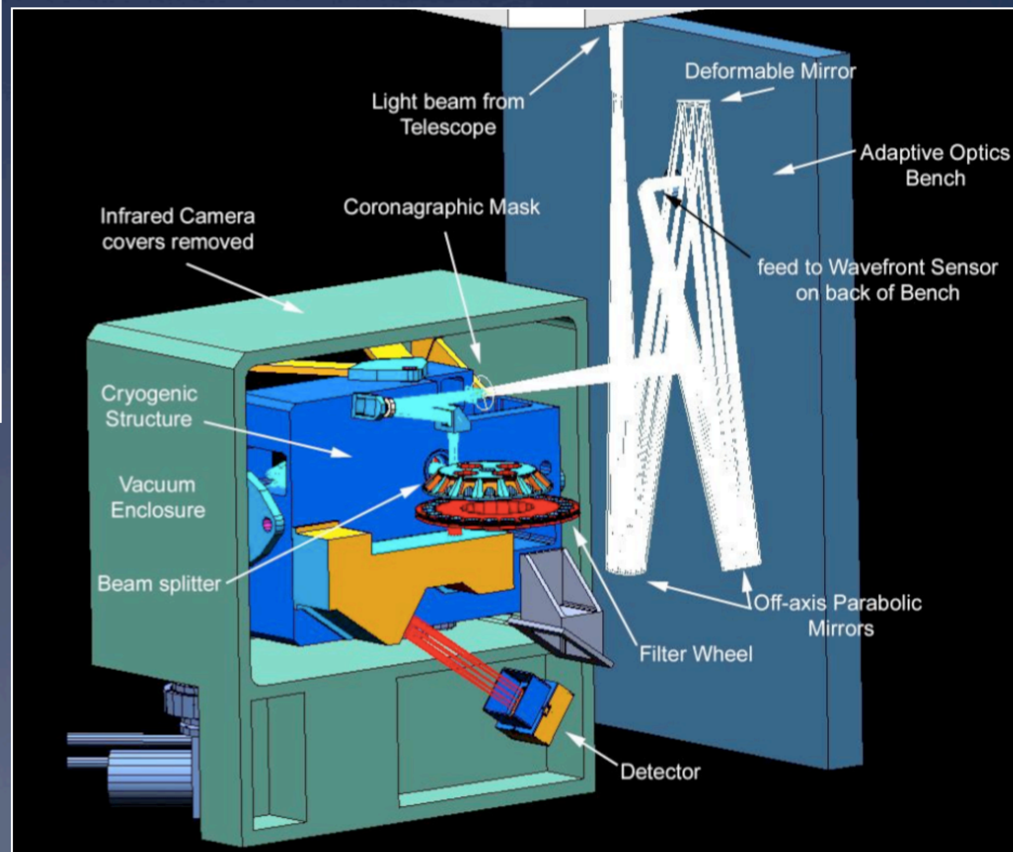
Near Infrared Coronographic Imager - NICI







Near Infrared Coronagraphic Imager - NICI

- AO System + Lyot Coronograph + Dual Channel Near-IR Camera
  - Optimized for High-Contrast Imaging
    - Lensless
    - Minimum static aberrations
    - Differential Imaging
- 85-element curvature system
  - Natural Guide Star (on-axis)
  - H-Band Strehl ratio:
    - 20% for V = 13
    - 40% for bright stars
- Dual channel InSb
  - $1\ \mu m \leq \lambda \leq 2.5\ \mu m$ ($J-K$ bands)
  - Focal plane and Pupil plane masks
  - Beamsplitting elements
  - Filters in each channel

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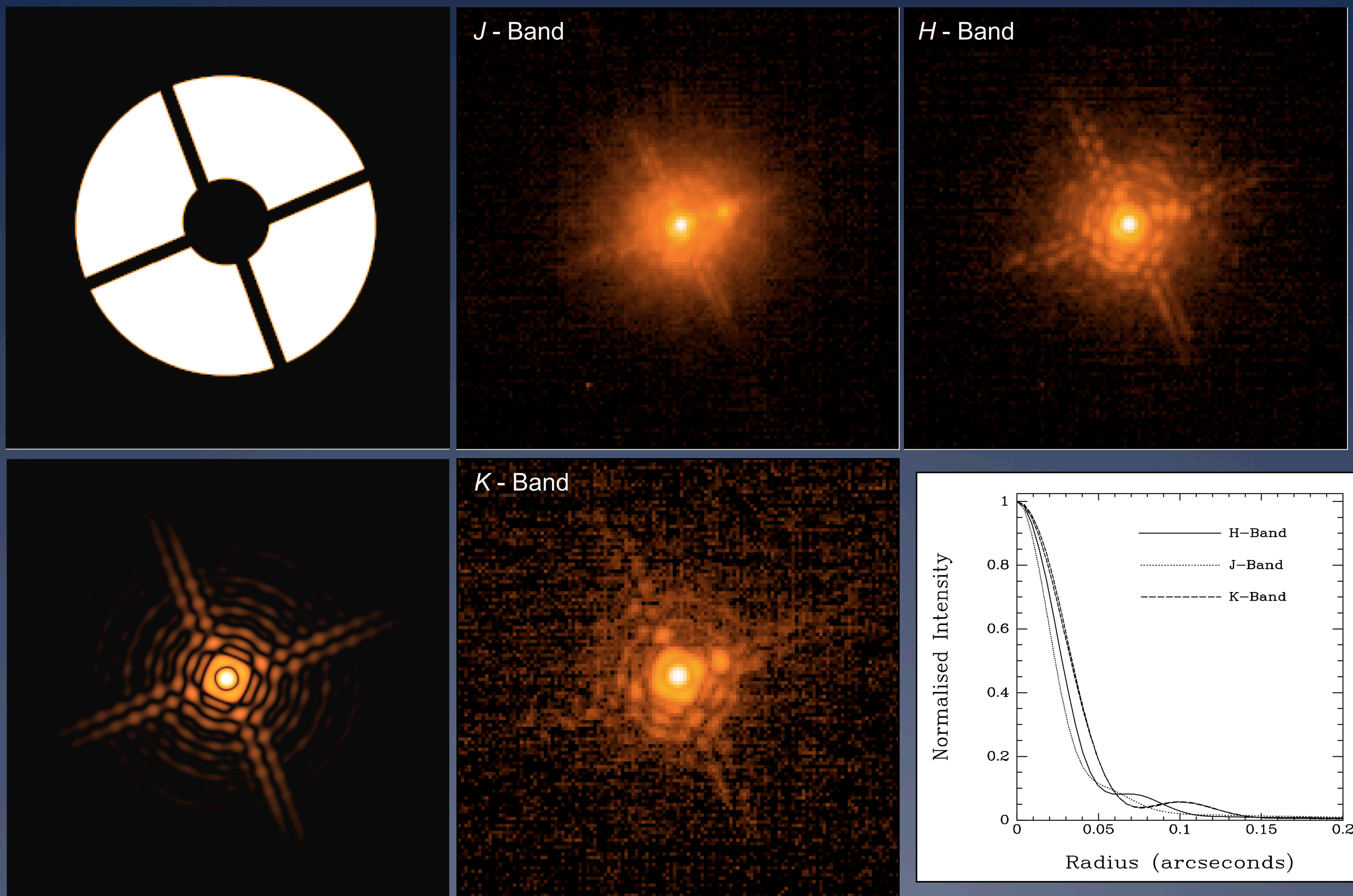
The NICI Point Spread Function



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NICI Data Reduction

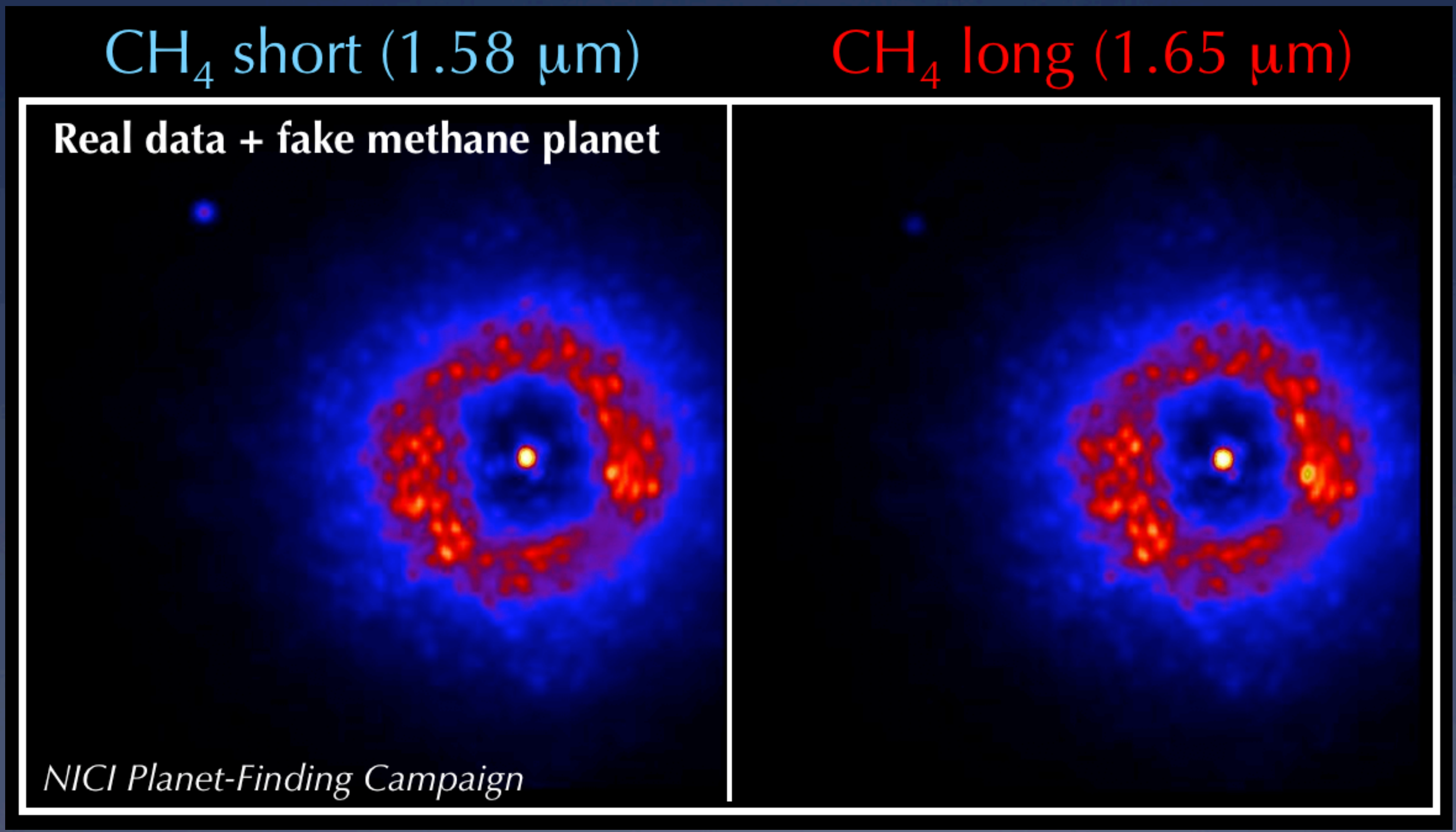
ADI Reduction (using field rotation)

- For Red and Blue Arms separately:
  - Standard Calibration – Flats, Darks, Bad Pixels etc.
  - Register (sub-pixel shift) to central star.
  - Highpass filter – look for point sources
  - Match speckles – simplex minimization – scale intensity
  - Median ADI cube for PSF
  - Subtract PSF from data cube matching speckles of individual frames.

SDI Reduction

- Cancels primary retaining methane band object
  - Shift images, adjust image scale for wavelength
  - Subtract final results

Spectral Differential Imaging



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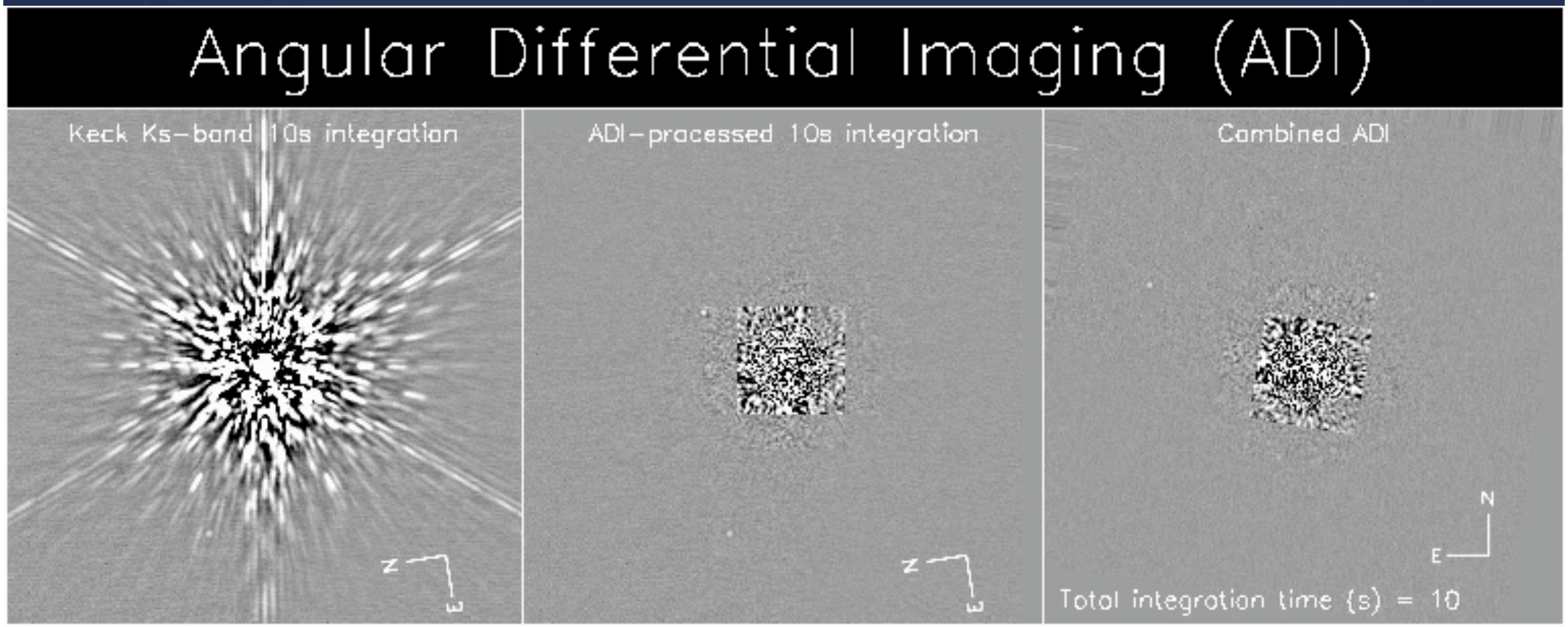
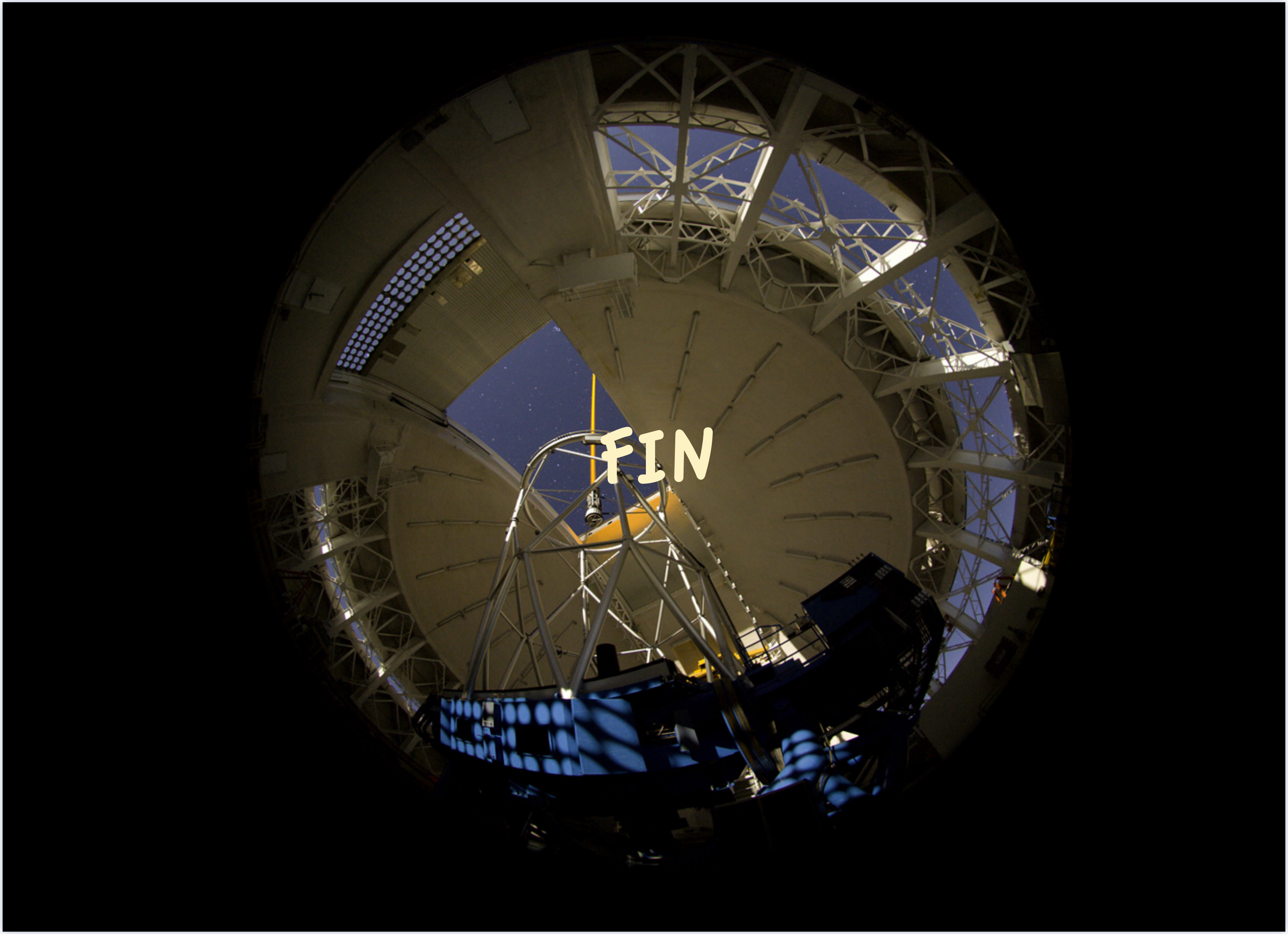
Angular Differential Imaging

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