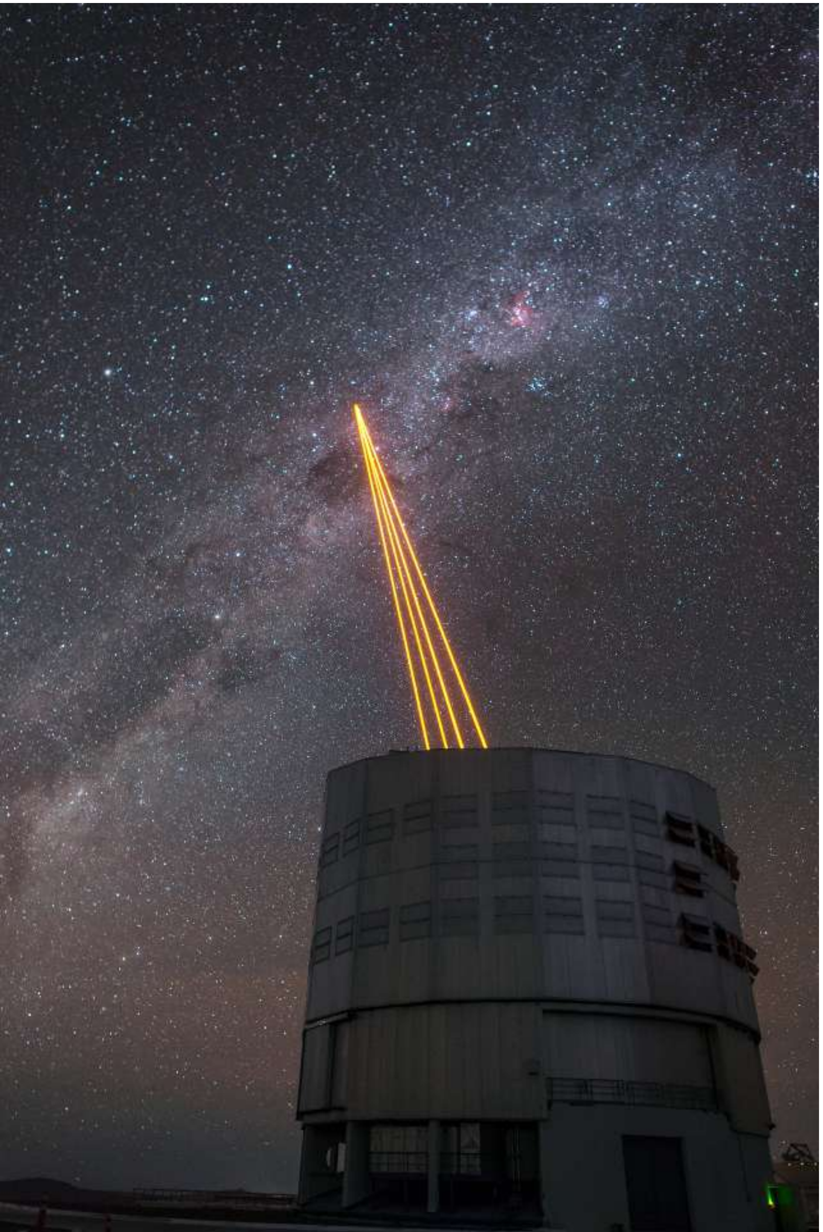
Lecture 12: Diffraction-Limited Imaging with Adaptive Optics



Rutgers Physics 346: Observational Astrophysics
April 13, 2021

Homework for Thursday, April 15

Due: Quiz #11 will appear on Canvas Assignments at 4:20pm, due at noon tomorrow (April 14).

Do: Be ready to work with your 2nd project group during Thursday's Project Meeting.

Due: Presentations will take place during class on April 27 & 29.

Due: Project reports will be due on Thursday, May 6.

Quiz #10: Describe two differences between ground-based observing with (a) a CCD camera at optical wavelengths, and (b) an InSb or HgCdTe detector at near-IR wavelengths.

Answer: Here are three possible answers, although only two accurate differences were required to receive full credit:

(1) CCD reads are destructive, while IR detector reads are non-destructive.

(2) IR detectors need to be operated at cryogenic temperatures, while CCDs do not.

(3) IR observing requires chopping and nodding to mitigate backgrounds, which is not generically the case for optical observing.

Atmospheric turbulence: the problem

A space telescope can deliver diffraction-limited images with resolution ~ 1.22 λ/D (in radians), where D = telescope diameter and λ = observing wavelength

– for an 8m diameter telescope observing at $\lambda = 2\ \mu$m, the diffraction limit is ~ 3.05×10^{-7} radians = 0.06 arcsec

A ground-based telescope can only deliver seeing-limited images, since atmospheric turbulence above the telescope will limit the resolution to ~ 1 arcsec at optical wavelengths, with a wavelength dependence $\propto \lambda^{-1/5}$

– for an 8m diameter telescope observing at $\lambda = 2\ \mu$m, the seeing limit is ~ 0.76 arcsec (12 times worse!)

Astronomers would love to overcome the effects of turbulence and obtain diffraction-limited images...

Atmospheric turbulence: r_0

The **Fried parameter** r_0 is the diameter of a telescope whose diffraction limit would equal the seeing limit at a given λ.

– at optical ($\lambda \sim 5500$ Å) wavelengths, $r_0 \sim 10$–20 cm

– build a telescope with $D < r_0$, and it will deliver diffraction-limited images! – but it won't be able to observe faint targets…

Atmospheric turbulence: t_0

Atmospheric turbulence also has a characteristic timescale, which we can approximate as $t_0 \sim r_0/v_{wind}$ (where v_{wind} is the characteristic speed at which turbulent fluctuations are blown over the telescope)

– this is the "frozen screen" model for turbulence

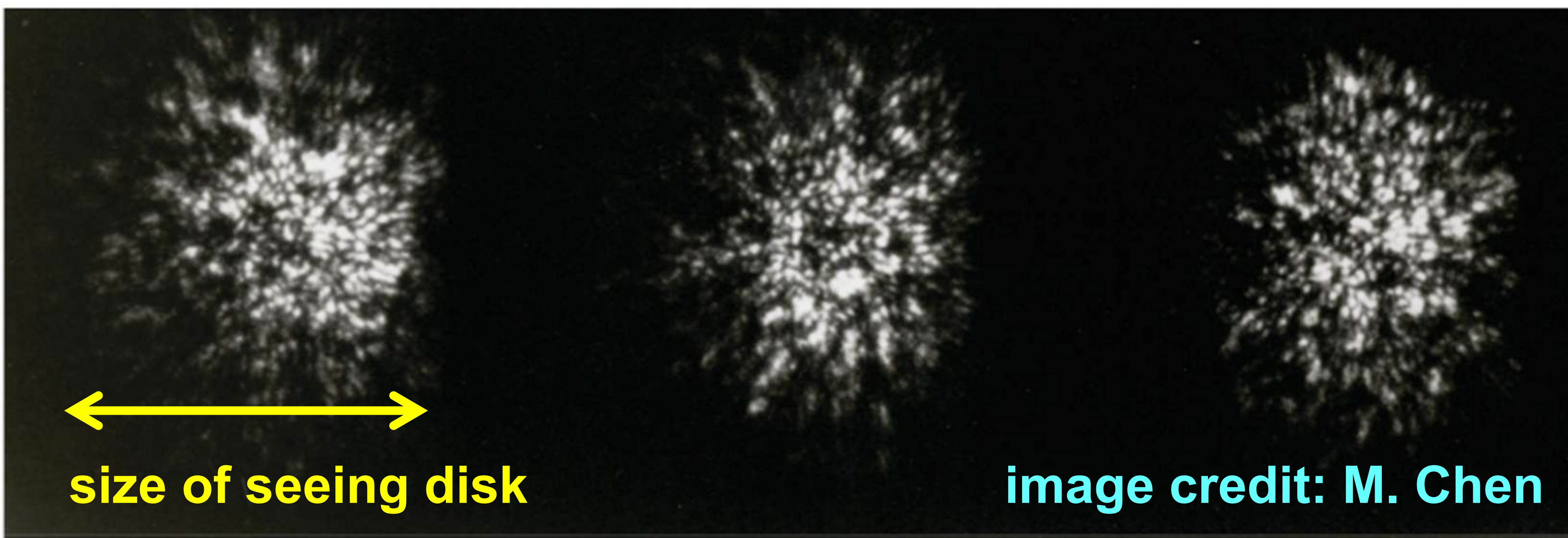
– since $r_0 \propto \lambda^{6/5}$, $t_0 \sim$ 100 ms at near-IR wavelengths, and significantly shorter at optical wavelengths

– in order to beat turbulence, we need to image faster than t_0 and/or adjust the telescope faster than t_0

Strategy # 1: speckle imaging

What happens if we image faster than t_0?

- each individual exposure will contain a pattern of speckles scattered over the area that *would* be the seeing disk if we imaged longer
- each speckle has size ~ 1.22 λ/D



Strategy # 1: speckle imaging

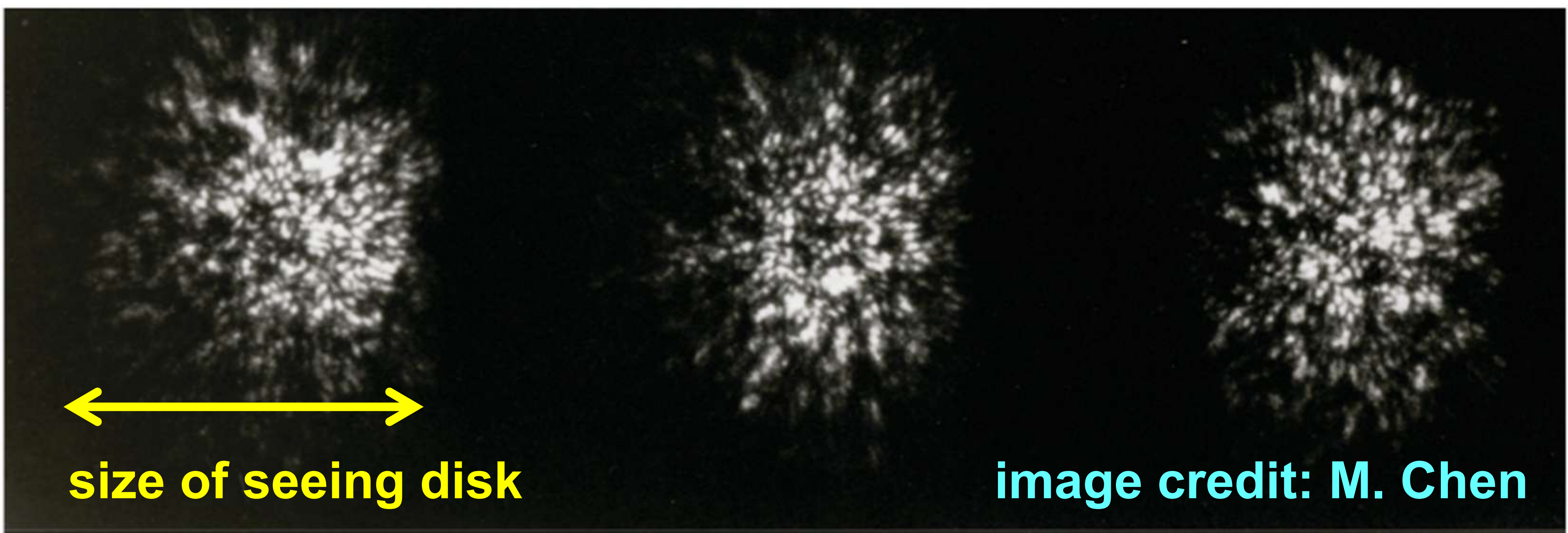
What happens if we image faster than t_0?

- light from source passes through many atmospheric cells that introduce phase delays, *some* of which will be similar, allowing for constructive interference
- the longest "baseline" between cells above the telescope will have length D, making smallest speckle ~ λ/D

Strategy # 1: speckle imaging

What happens if we image faster than t_0?

- various approaches to extracting diffraction-limited info…
  - shift-and-add: pick the brightest speckle in each image, and stack all images (or: only the best images) after aligning at these positions
  - full Fourier analysis, a.k.a. speckle interferometry



Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

- if we include a deformable mirror in the optical path, and adjust it faster than the turbulence changes above the telescope, we can correct for the effects of turbulence before the light from the target arrives at the detector
- to know which adjustments to make, we need a wavefront sensor to measure distortions of light from a bright star

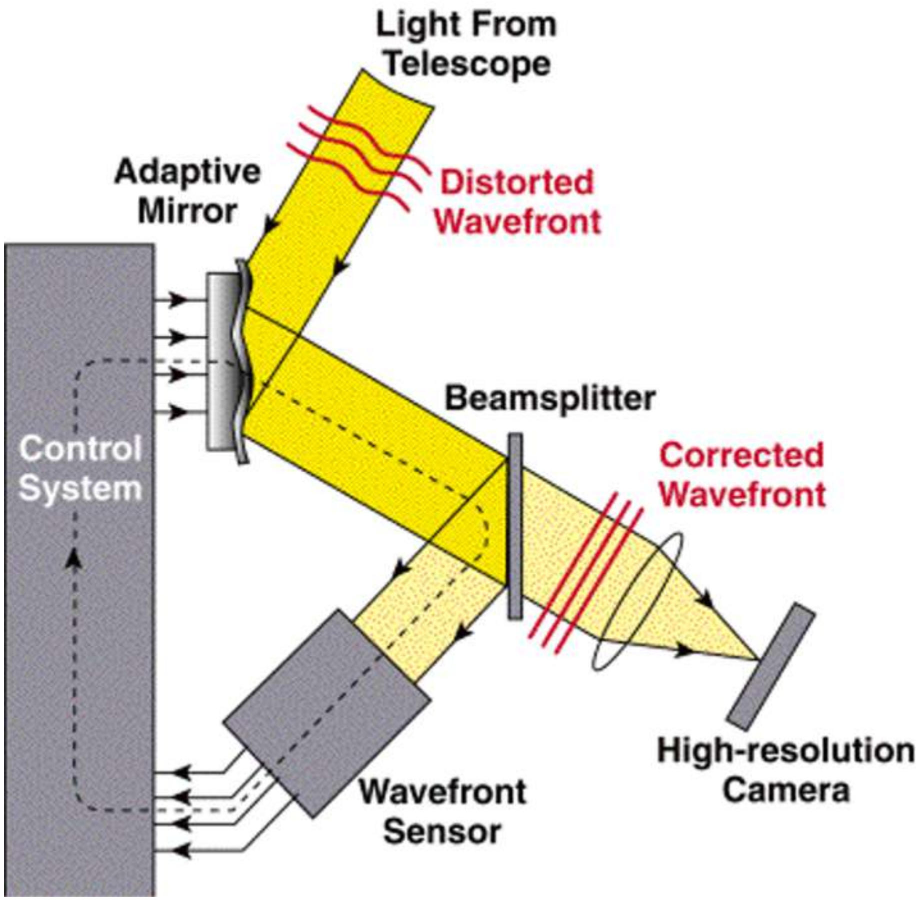


image credit: C. Max

Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

Step 1: telescope observes a bright star and a faint target

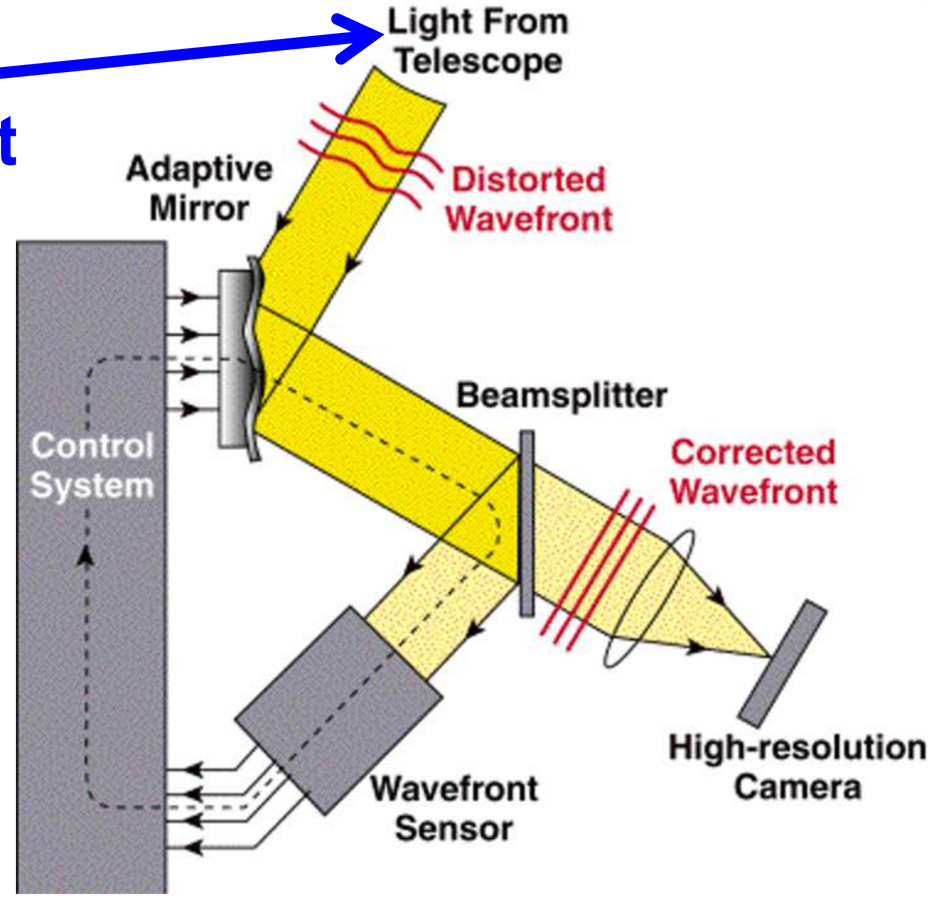


image credit: C. Max

Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

Step 1: telescope observes a bright star and a faint target

Step 2: light bounces off a deformable mirror that was just adjusted

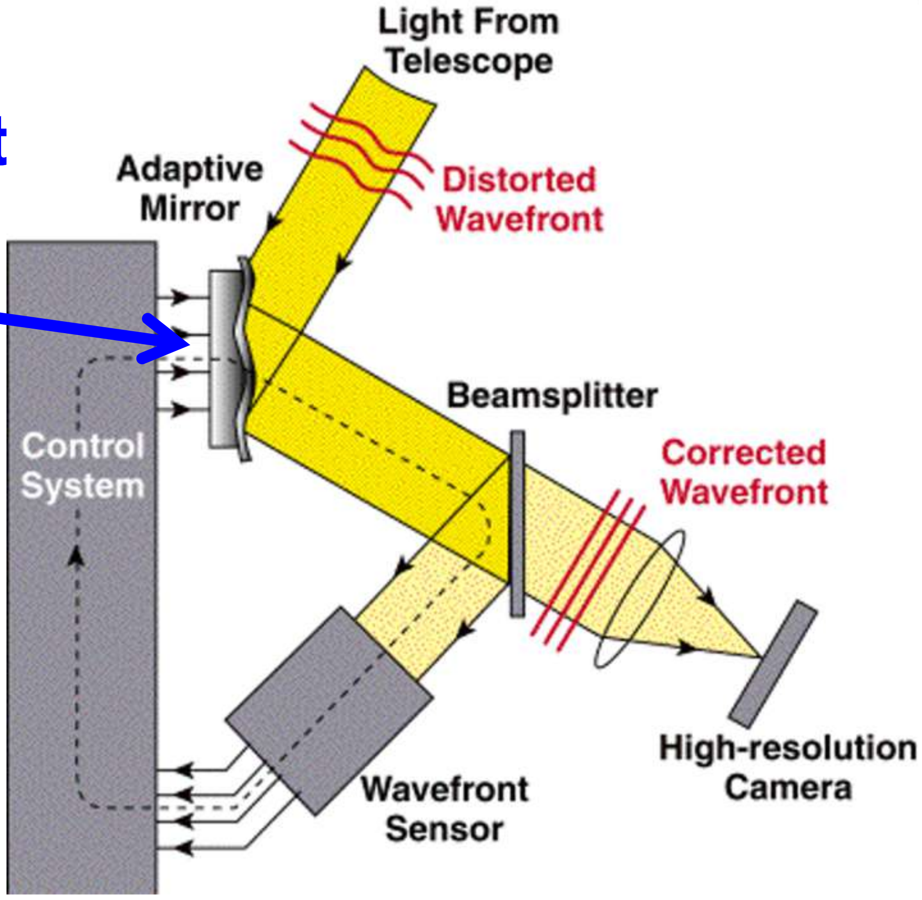


image credit: C. Max

Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

Step 1: telescope observes a bright star and a faint target

Step 2: light bounces off a deformable mirror that was just adjusted

Step 3: light is divided

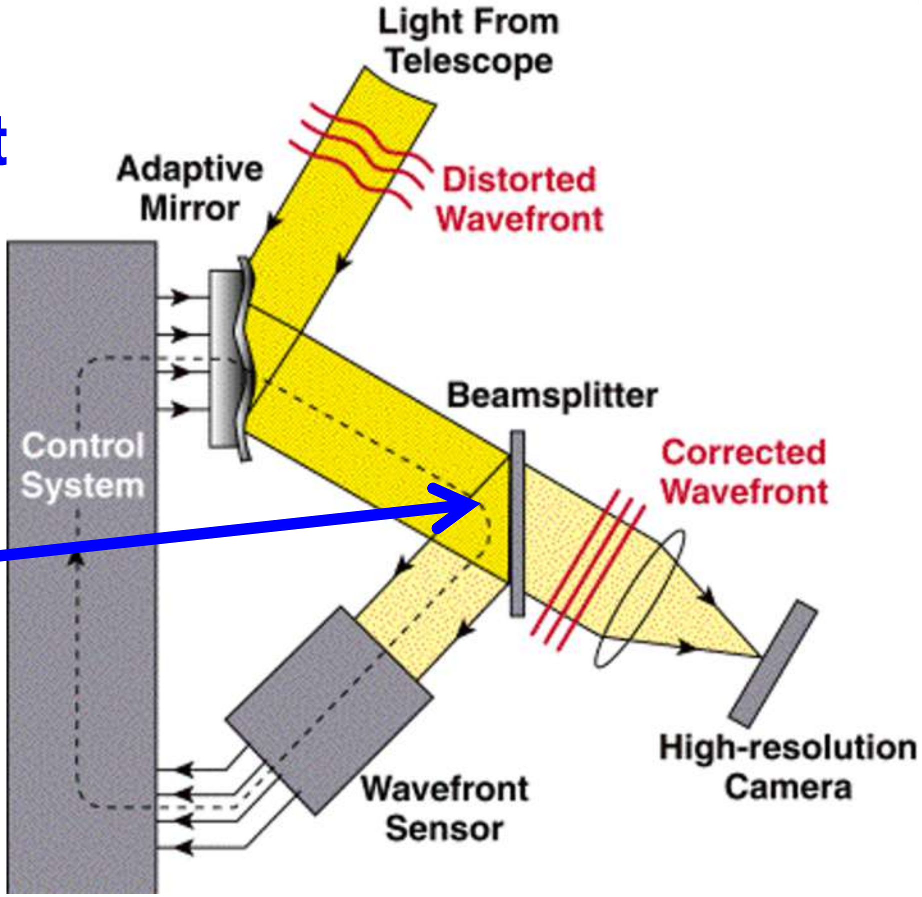


image credit: C. Max

Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

Step 1: telescope observes a bright star and a faint target

Step 2: light bounces off a deformable mirror that was just adjusted

Step 3: light is divided

Step 4a: wavefront sensor measures light from bright star, to determine next set of adjustments

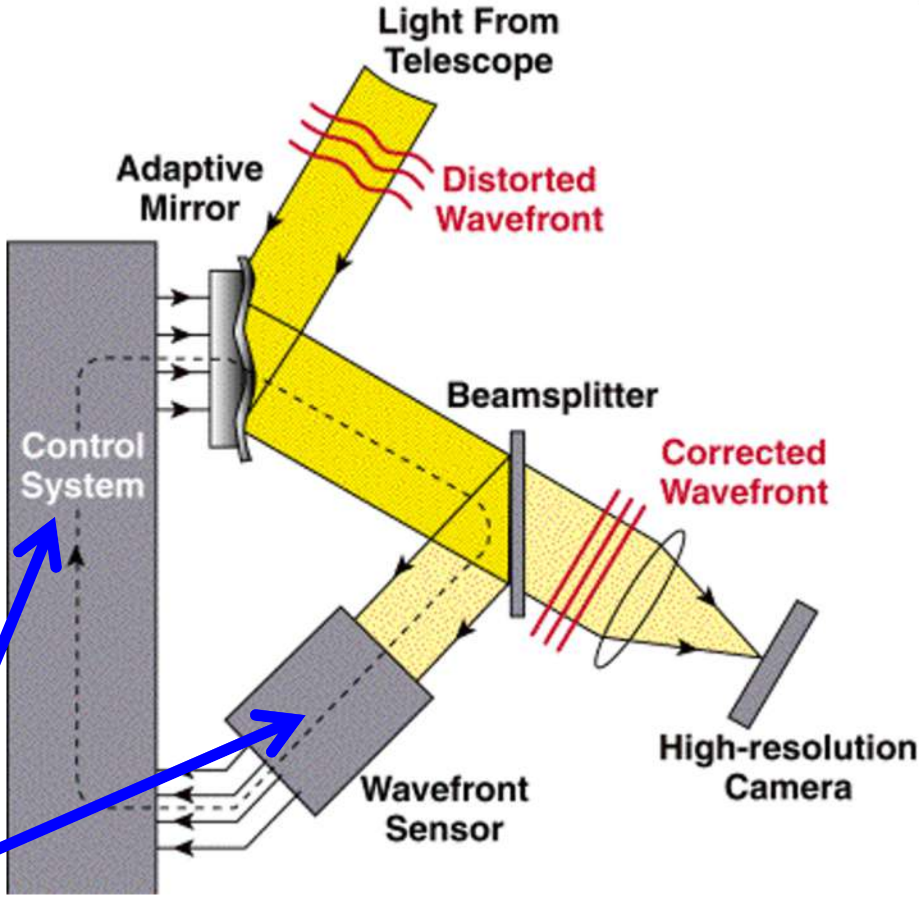


image credit: C. Max

Strategy # 2: adaptive optics

What happens if we adjust the telescope faster than t_0?

Step 1: telescope observes a bright star and a faint target

Step 2: light bounces off a deformable mirror that was just adjusted

Step 3: light is divided

Step 4b: science detector records the corrected light from the faint target

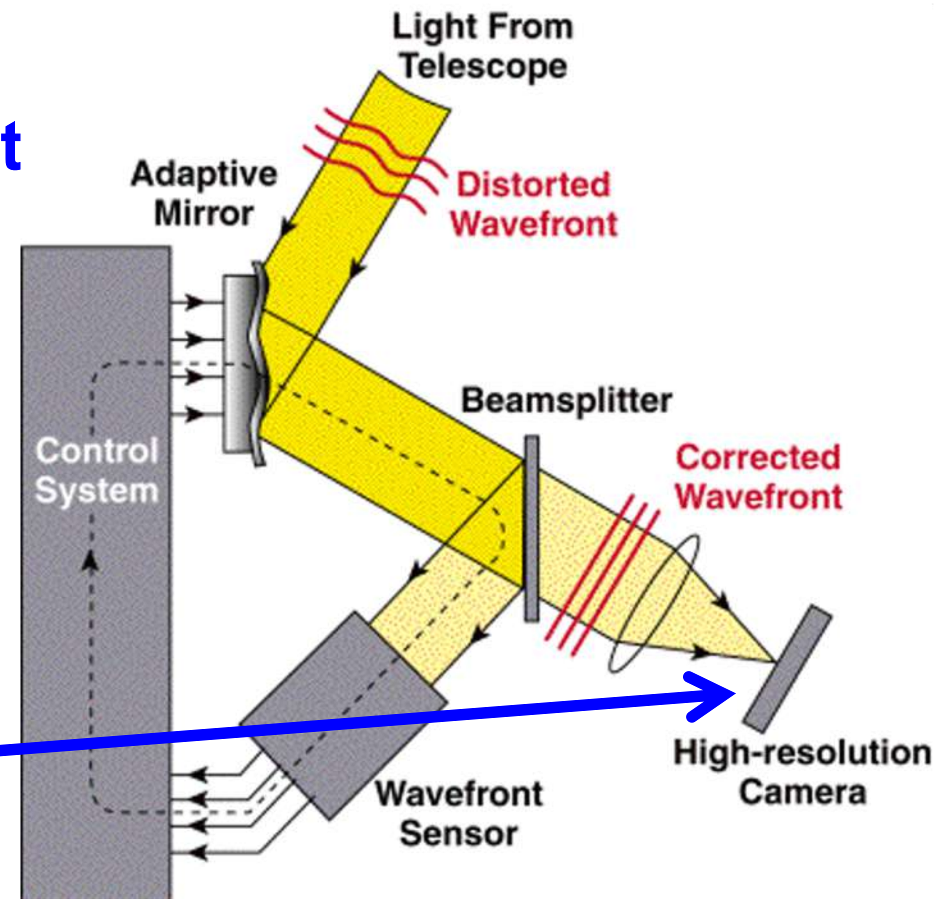
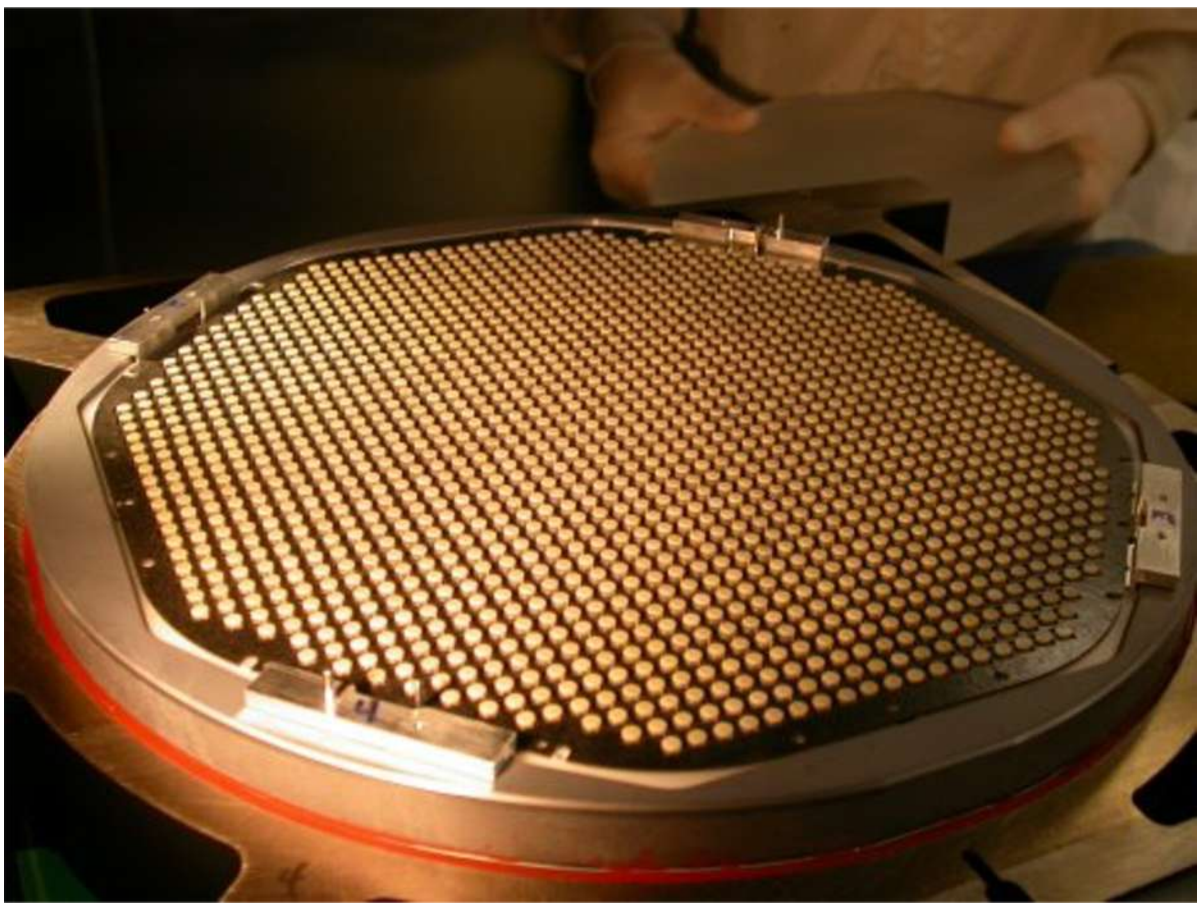


image credit: C. Max

The whole cycle must be fast!

Deformable mirrors

Deformable mirror = thin sheet of reflective material
mounted on a large number of actuators (i.e., pistons)
that can push/pull parts of surface many times per second



Daniel K. Inouye
Solar Telescope:
1600 actuators!

image credit:
NSO/DKIST

Wavefront sensors

Wavefront sensor = one of several designs that can measure the distortions of a bright reference star

– Shack-Hartman sensor = lenslet array, where positions of image centers are used to reconstruct (and then correct for) wavefront slopes

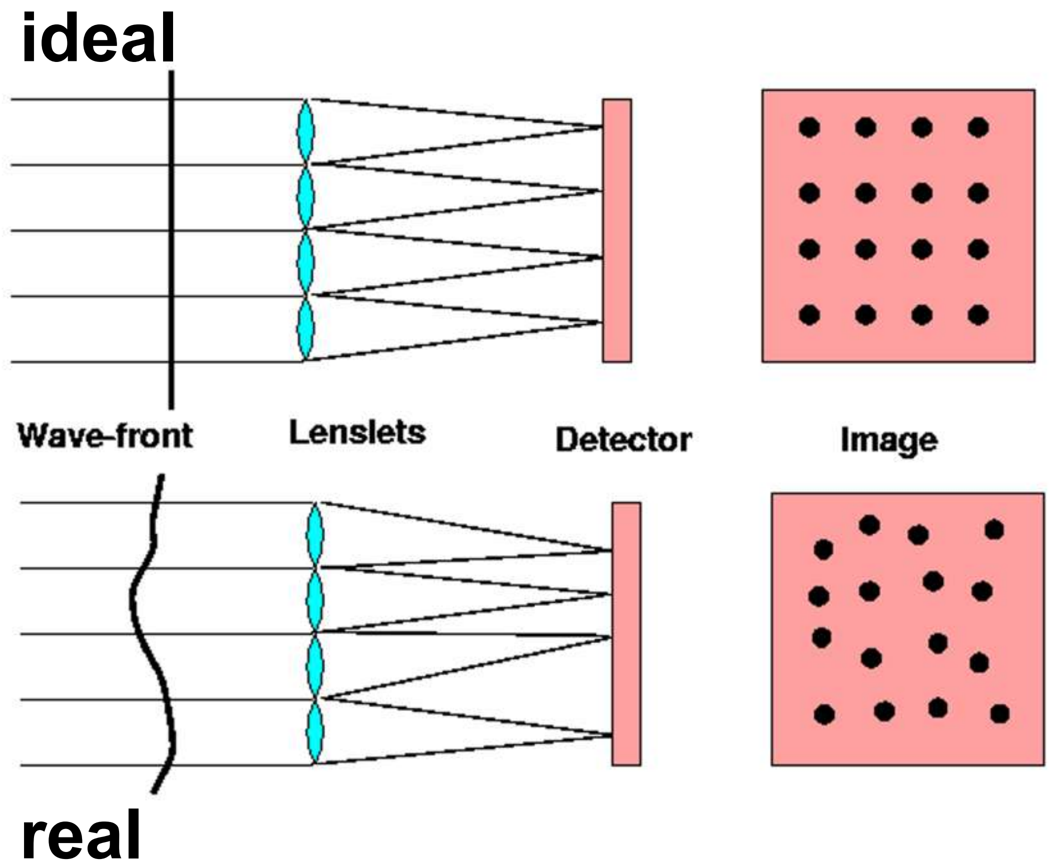


image credit: NOIRLab/CTIO

– curvature sensor

– pyramid sensor

The more "zones" measured, the better the correction.

Strehl ratio

No adaptive optics system is perfect…but we can characterize performance in terms of the Strehl ratio, which is the fraction of light from a star that is concentrated in the diffraction-limited core rather than the seeing-limited halo.

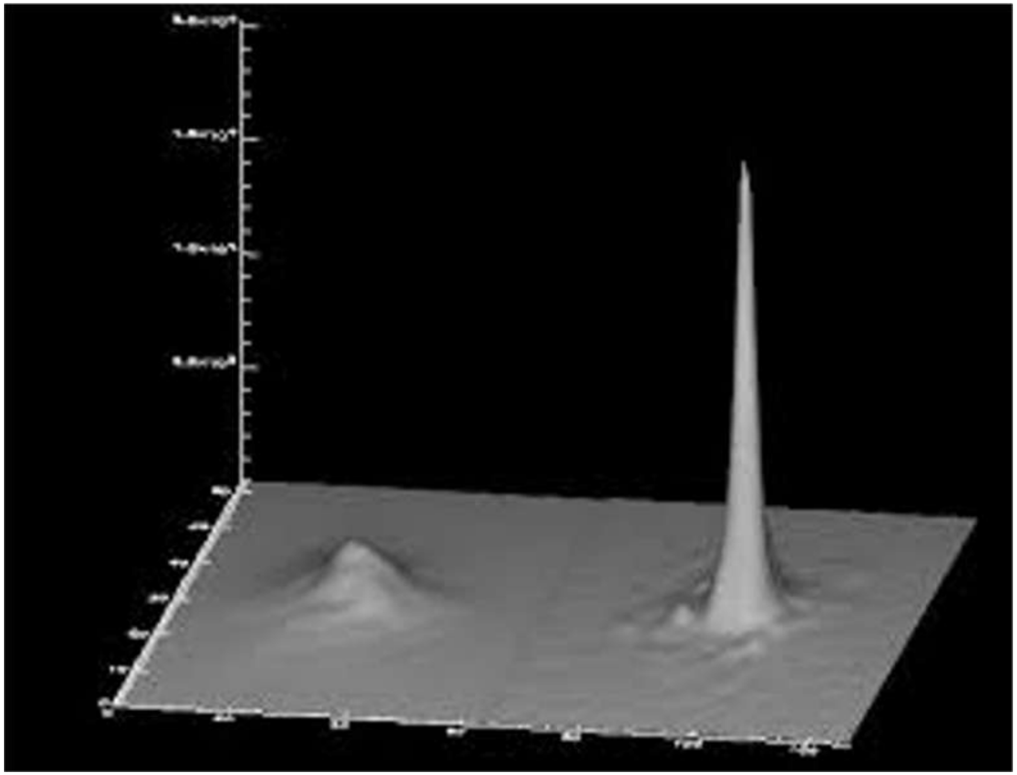


image credit: IfA

without AO with AO

Guide stars

Two key underlying assumptions of adaptive optics:

(1) a bright guide star is available (needs to be bright to enable wavefront sensing)

(2) the wavefront corrections that are derived for the guide star can legitimately be applied to the light from the science target

Can these assumptions be met?

Natural guide stars

Two key underlying assumptions of adaptive optics:

(1) a bright guide star is available (needs to be bright to enable wavefront sensing)

(2) the wavefront corrections that are derived for the guide star can legitimately be applied to the light from the science target

Ideal situation: there happens to be a bright ($V < 13$) star within 30 arcsec of our faint science target.

- **this allows for natural guide star AO**
- **not as unlikely as one might think (e.g., if the "faint science target" is an exoplanet, which orbits a star!)**

Laser guide stars

Two key underlying assumptions of adaptive optics:

(1) a bright guide star is available (needs to be bright to enable wavefront sensing)

(2) the wavefront corrections that are derived for the guide star can legitimately be applied to the light from the science target

Non-ideal situation: the nearest bright ($V < 13$) star is more than 30 arcsec from our faint science target, so corrections from former can't be applied to latter (sampling different atmospheric turbulence).

– this requires laser guide star AO – we make our own!

Laser guide stars

Two types of laser guide stars:

(1) Rayleigh beacon – short-wavelength laser fires pulses into the sky, and light is backscattered by molecules in the atmosphere

(2) sodium beacon – layer of sodium atoms at 80–105 km above the Earth (higher = ionized, lower = in molecules) will absorb and re-emit light at 5892 Å, creating a spot

Two caveats:

- **still need a bright-ish star (*V* < 16 within 90 arcsec) to measure low-order “tip-tilt” corrections, since these are cancelled out during up/down travel of laser light**
- **laser guide star measures turbulence in a cone, not a cylinder (Strehl ratios less than for natural guide stars)**

Laser guide stars

The "cone effect" means performance gets worse farther from the laser guide star spot… but we can access a larger sky area by using multiple laser guide stars. This approach is known as multi-conjugate adaptive optics (MCAO).

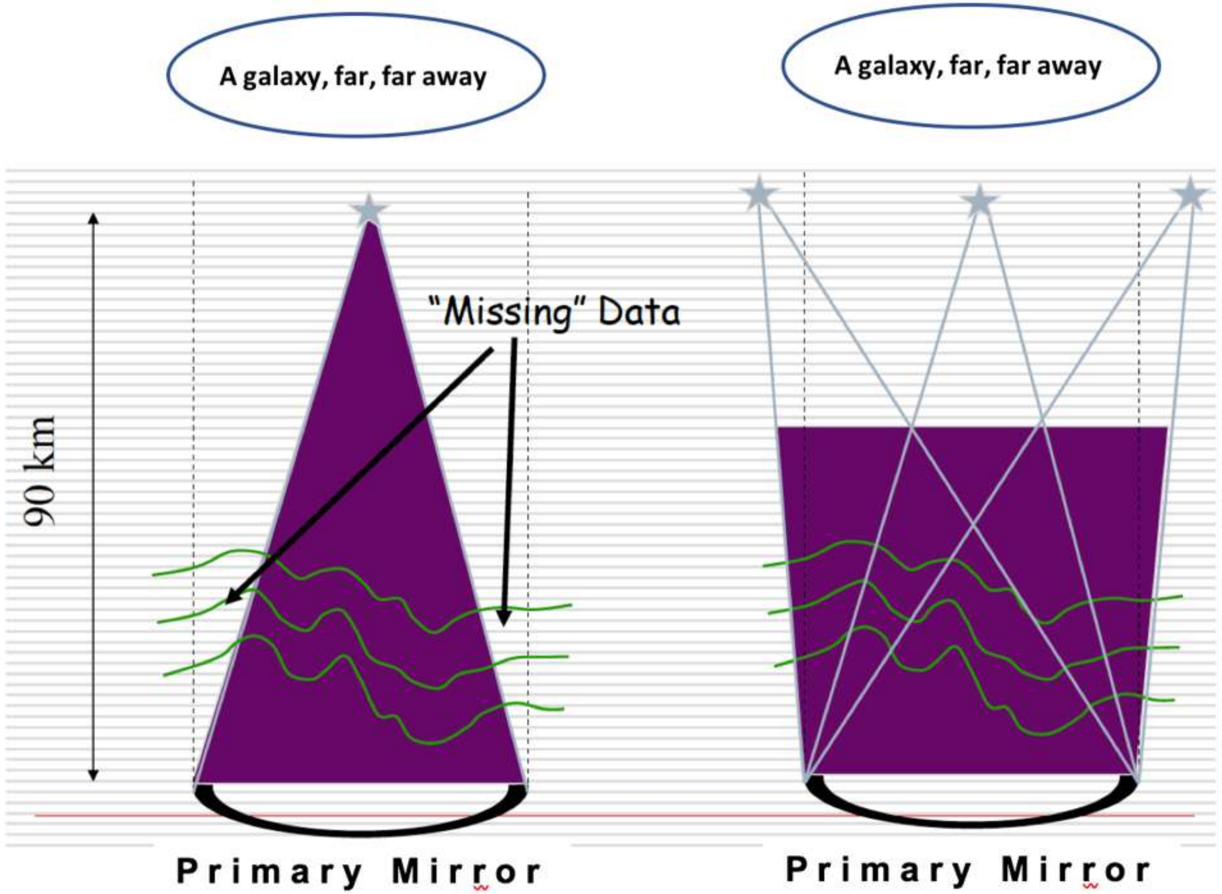


image credit: TMT

See video of Mauna Kea
and accompanying description