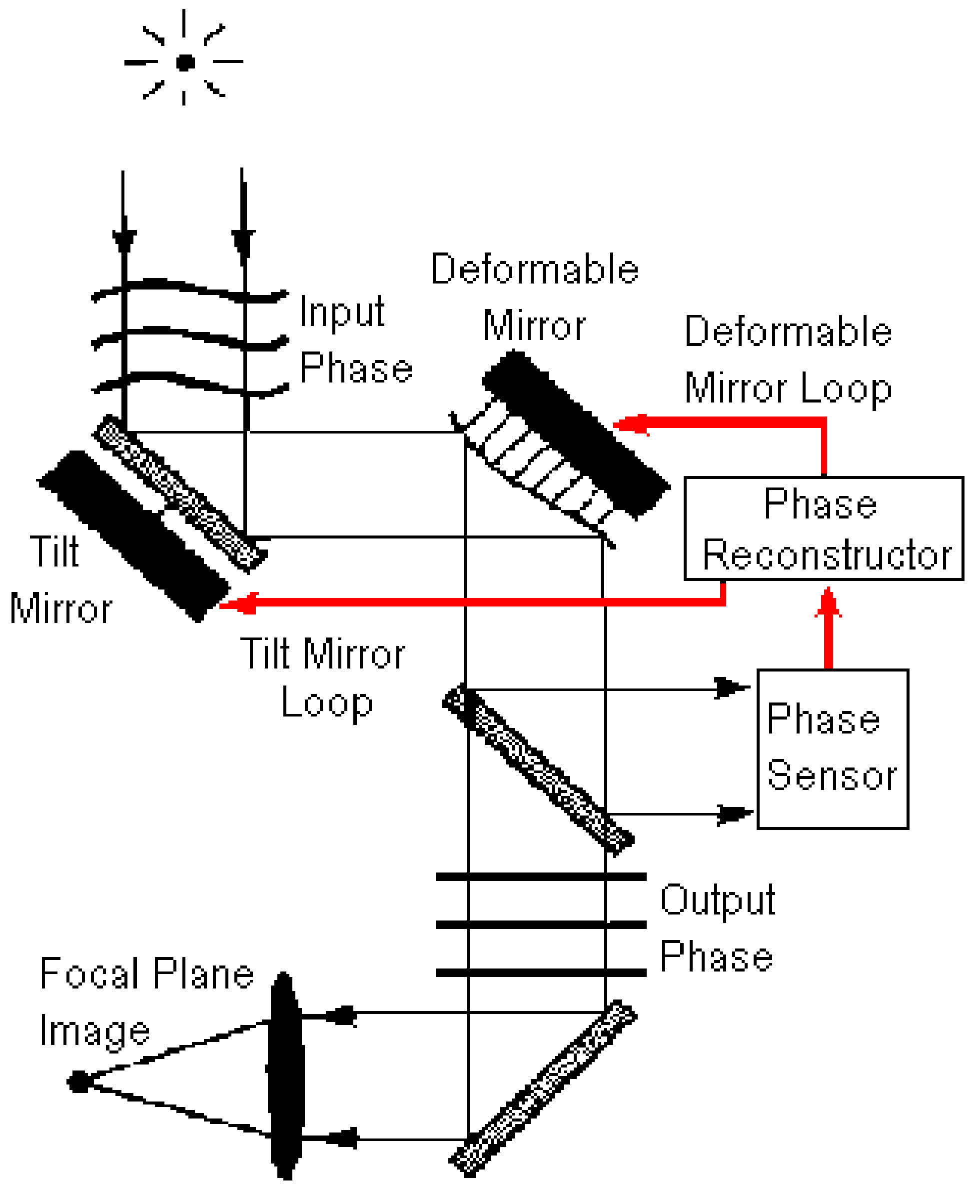
What is Adaptive Optics ?



Main components of an AO system:

Guide star(s): provides light to measure wavefront aberrations, can be natural (star in the sky) or laser (spot created by laser)

Deformable mirror(s) (+ tip-tilt mirror): corrects aberrations

Wavefront sensor(s): measures aberrations

Computer, algorithms: converts wavefront sensor measurements into deformable mirror commands

5. Adaptive Optics

5.5. Laser Guide Stars (LGS) for Astronomical Adaptive Optics

Motivation
- Isoplanatic angle
- Required number of photon from guide star

LGS Principle
- Rayleigh LGS
- Sodium LGS

Limitations, challenges
- LGS angular size
- Cone effect
- Tip-tilt, Focus

LGS AO system design

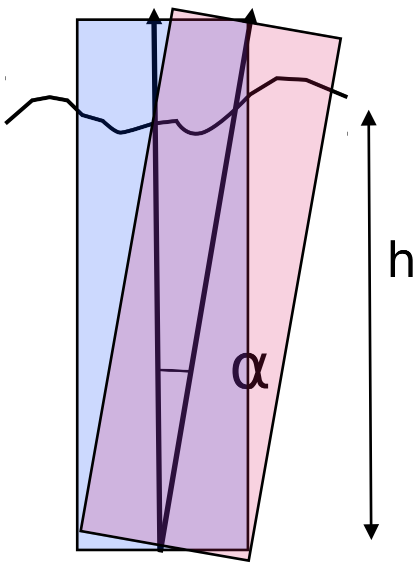
Isoplanatic Angle: guide stars far away from science target and not very good for wavefront measurement

If we assume perfect on-axis correction, and a single turbulent layer at altitude h, the variance (sq. radian) is :

$\sigma^2 = 1.03\ (\alpha/\theta_0)^{5/3}$

Where α is the angle to the optical axis, θ_0 is the isoplanatic angle:

$\theta_0 = 0.31\ (r_0/h)$



D = 8 m, r_0 = 0.8 m, h = 5 km -> θ_0 = 10”

Good wavefront sensing requires a large number of photon

Relationship between optimal WFS exposure time and # of photon

Longer WFS “exposure time” -> better SNR but more time lag

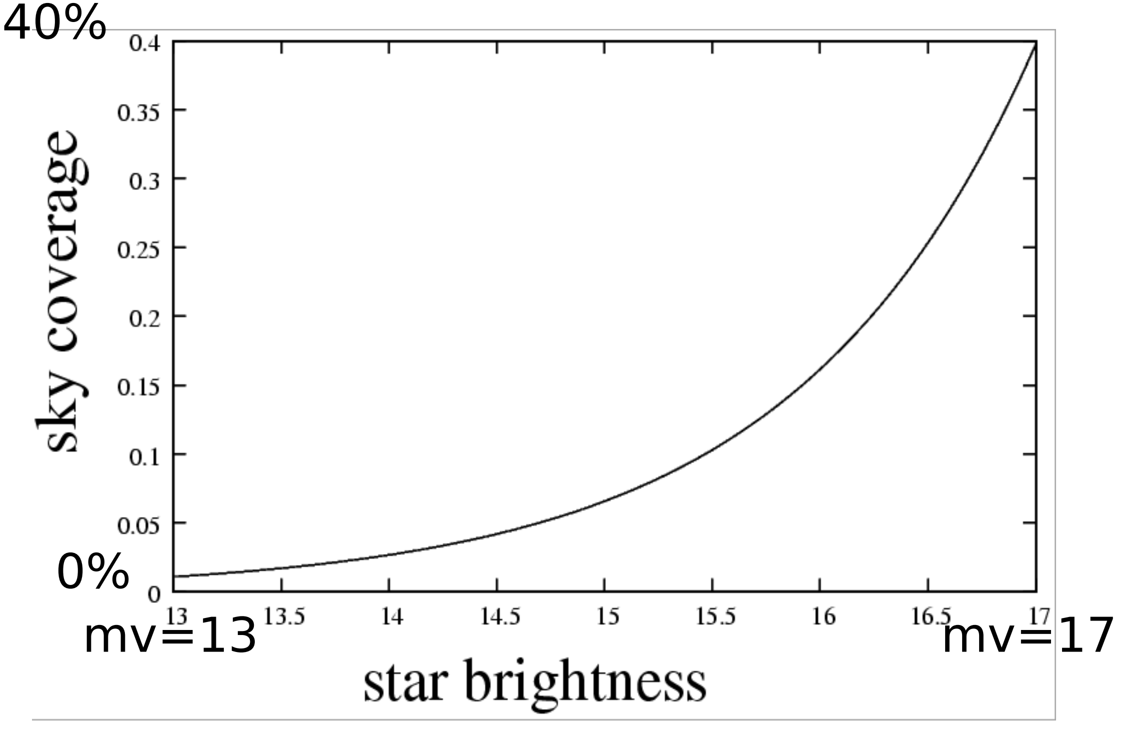
m_V=15 -> 400 ph/ms on 8m pupil in 0.5 µm band (20% efficiency)

Sky offers finite number of sufficiently bright stars !

Star brighter than m_v density ~ 9e-4 exp(0.9 m_v) per sq. deg (galactic pole)

ref: Parenti & Sasiela, 1994

Within a 20” radius:



Sky coverage = fraction of sky over which AO correction is possible

For Natural Guide Star systems, sky coverage is typically few %

OK for some science cases (eg: exoplanets around bright stars), but very constraining for others (eg: study of nearby galaxies)

Where to get the wavefront measurement ?

Are there suitable natural guide star(s) ?

If not -> **Laser Guide Star (LGS)**

which laser ?

- Rayleigh
  - low altitude (few km) Rayleigh scattering
  - same process makes the sky blue
  - works better at shorter wavelength
- Sodium
  - excitation of sodium layer at 90 km
- Polychromatic Sodium (not quite ready yet)
  - excitation of sodium layer to produce LGS
  - in 2 wavelengths -> can solve Tip/Tilt problem

LGS allows large (>50%) sky coverage

Laser types

Rayleigh

- Wavelength is not critical
- Laser can be high power and cheap

Sodium

- Wavelength needs to be accurately tuned to Sodium line
- More expensive, difficult to achieve high power
  - Typically 10 W to 50 W
  - Reliability is an issue (no market outside of astronomy)

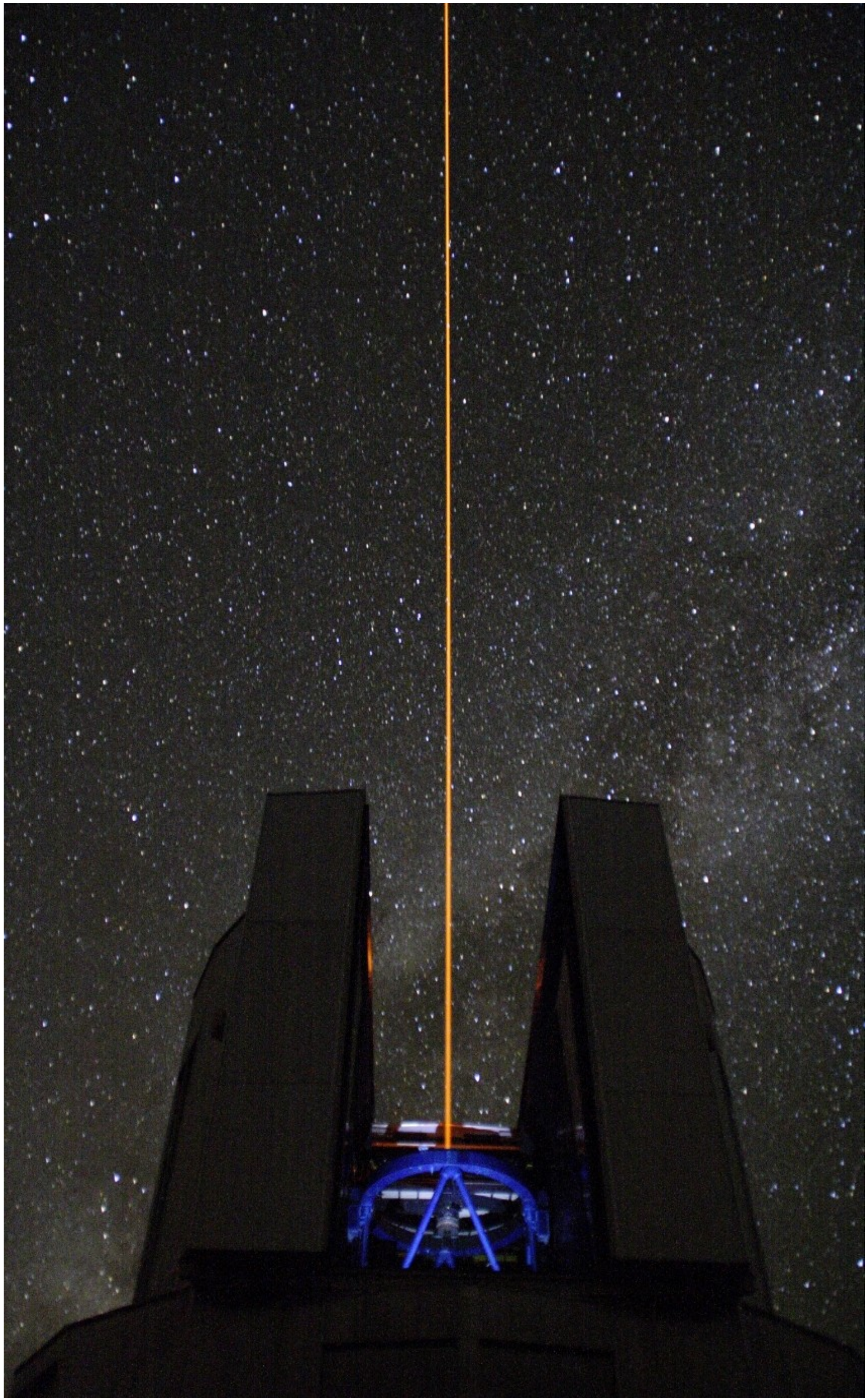
<u>Dye laser:</u> laser medium is liquid with organic dye, streaming at high speed in beam

<u>Solid state:</u> more robust, use non-linear crystal to frequency-sum two solid state near-IR lasers to 589 nm

Some challenges of LGS AO

Cone effect due to finite altitude of LGS (90km sodium, few km for Rayleigh)
-> can be solved by using several lasers and tomography

Tip/Tilt & Focus sensing
Upstream & downstream paths are the same: tip/tilt not seen
Sodium layer altitude not fixed: LGS focus info is incomplete (can be used to sense fast focus)
-> **Still need NGS(s) for tip/tilt & Focus**
-> polychromatic laser (not quite mature yet)



Cone effect

Cone effect due to finite altitude of LGS (90km sodium, ~10-20 km for Rayleigh)

$\sigma^2 = 1.03 \; (D \,/\, (2.91 \theta_0 H) \;)^{5/3}$

θ_0: isoplantic angle

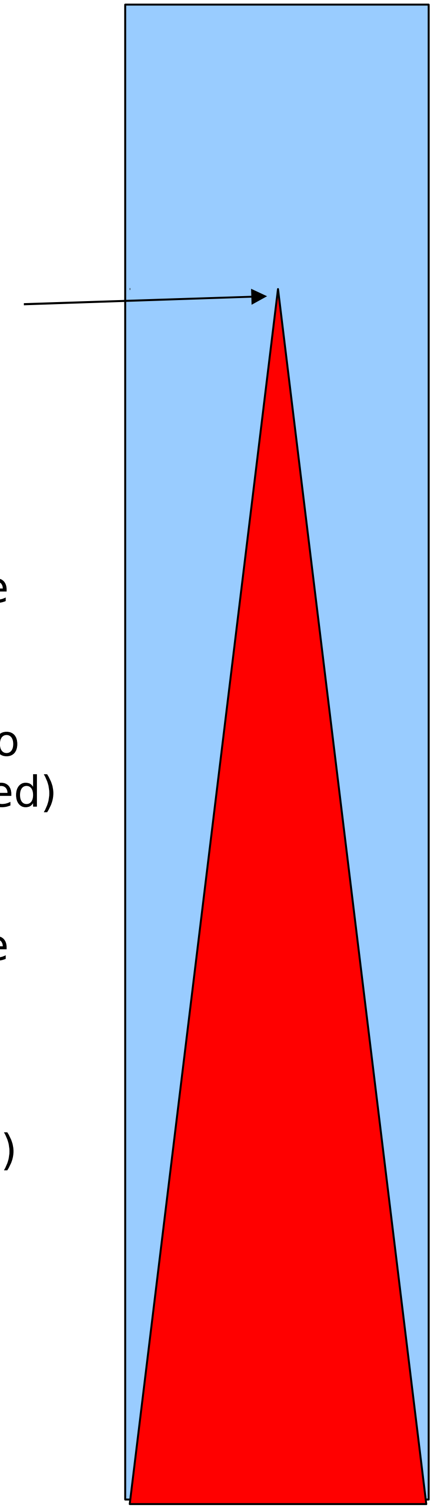
H : LGS altitude

D : Telescope diameter

→ impact is smaller for sodium LGS

→ larger effect for large telescopes

Mitigated by using several LGSs



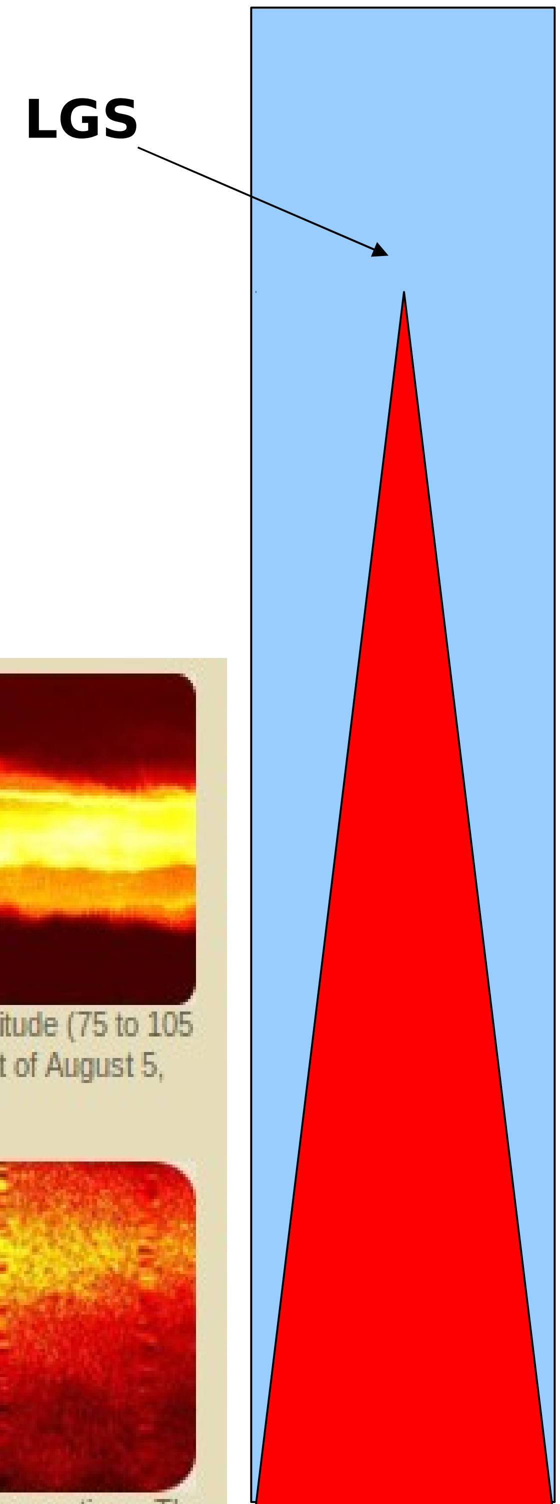
Blue: Turbulence volume affecting starlight (to be corrected)

Red: Turbulence volume sensed by LGS (measured)

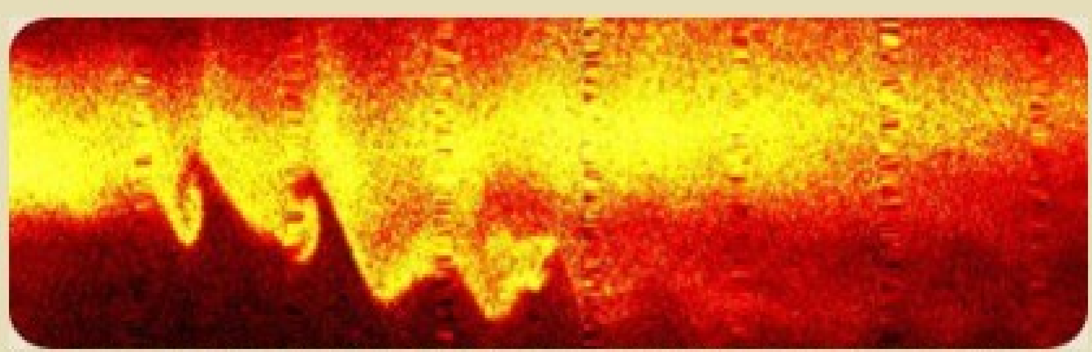
Focus sensing

Altitude of LGS is variable
(~90km sodium layer)
-> slow variations in measured
focus are introduced by sodium layer

Natural guide star is required to
measure slow focus
(fast focus can be measured by LGS)



This image shows sodium density above the facility as a function of altitude (75 to 105 km) and time (horizontal direction, covering about 5 hours) on the night of August 5, 2008.



Here we see a layer of sodium atoms becoming unstable and developing vortices. The vertical extent is 5 km and the elapsed time is 20 min.

LIDAR measurements
Pfrommer & Hickson 2009

Tip-tilt sensing

LGS light goes from telescope to LGS, and then back from LGS to telescope (double pass)

NGS light goes from star to telescope (single pass)

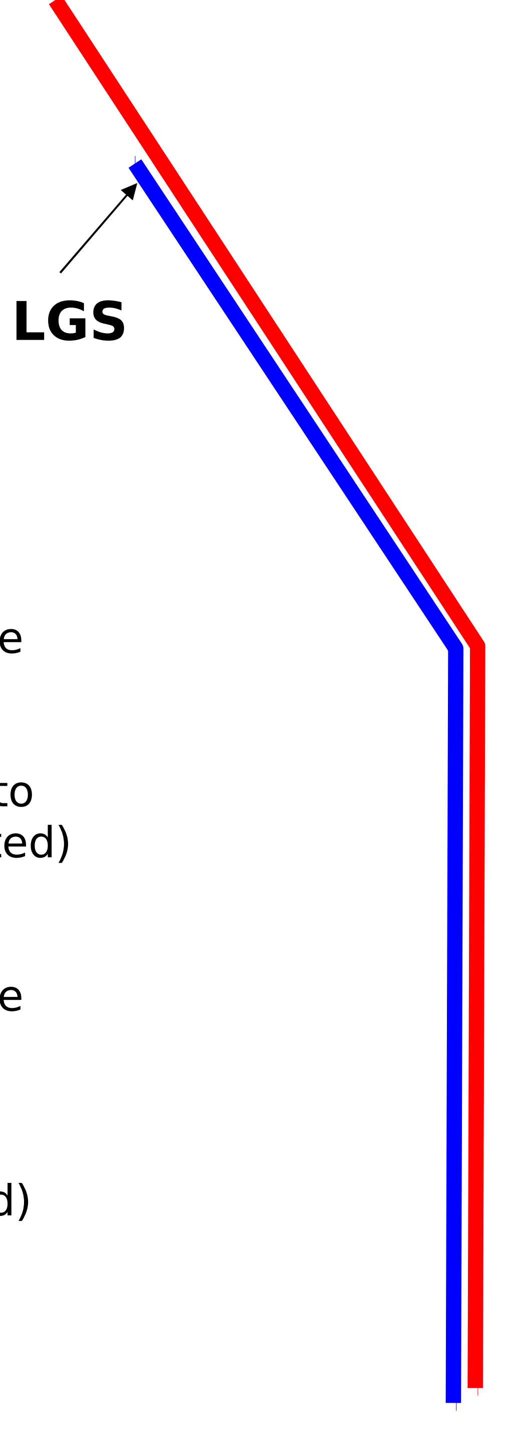
→ tip-tilt is not sensed by LGS

Solutions:

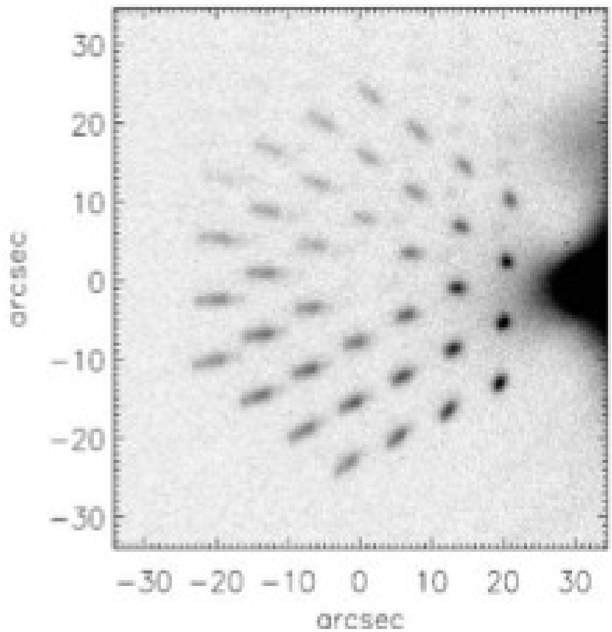
- use natural guide star(s) to measure tip-tilt
- polychromatic LGS (under dev.)

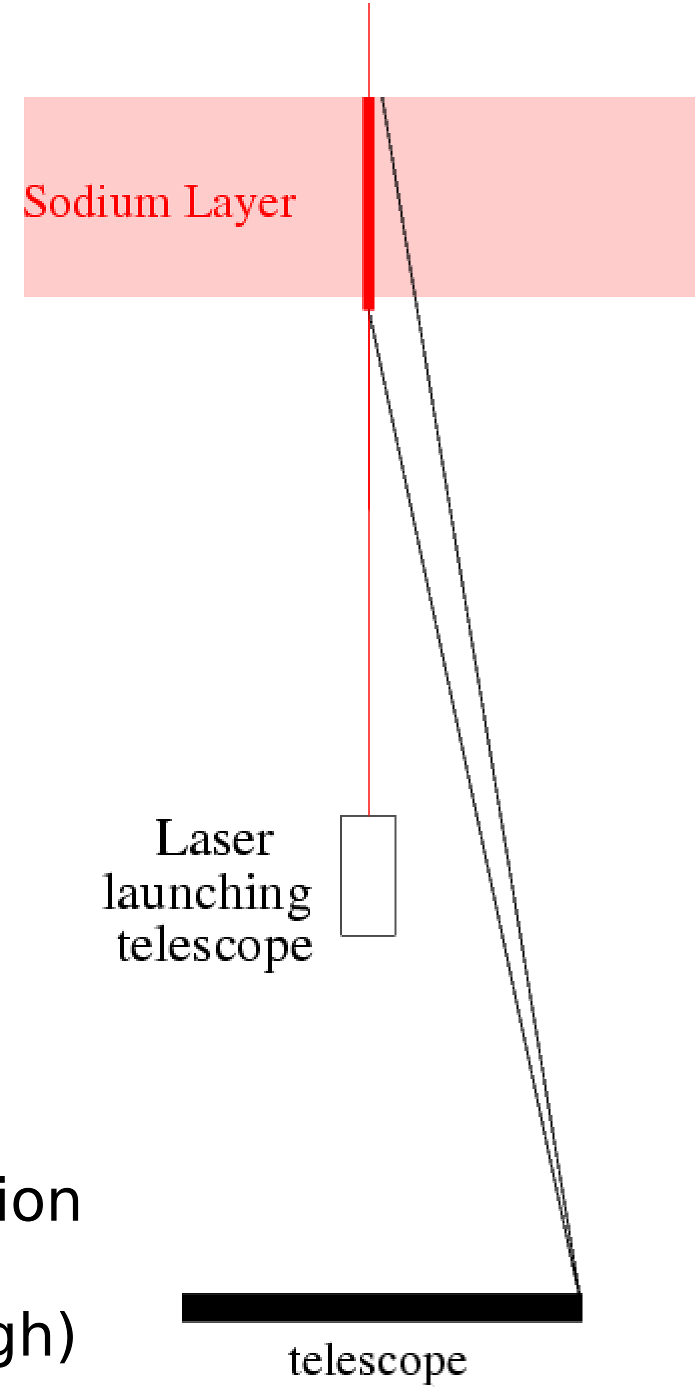
Blue: Turbulence volume affecting starlight (to be corrected)

Red: Turbulence volume sensed by LGS (measured)



Spot elongation
Sodium layer
is ~10km thick





4m off-axis = 1” elongation
15m off-axis = 4” elongation
→ if single LGS, better to launch from the center of pupil than the edge
→ if multiple LGSs, can launch from edges and combine signal to mitigate spot elongation
→ dynamic refocusing + pulsed laser can remove spot elongation (required for Rayleigh)

LGS spot fundamentally extended due to:

- Laser light has to go up through turbulence
- Diffraction from laser launching telescope aperture (usually << full telescope aperture)

-> it is very difficult to create a small size LGS

Spot size excludes some high sensitivity WFS options (fixed pyramid for example)

LGS AO system

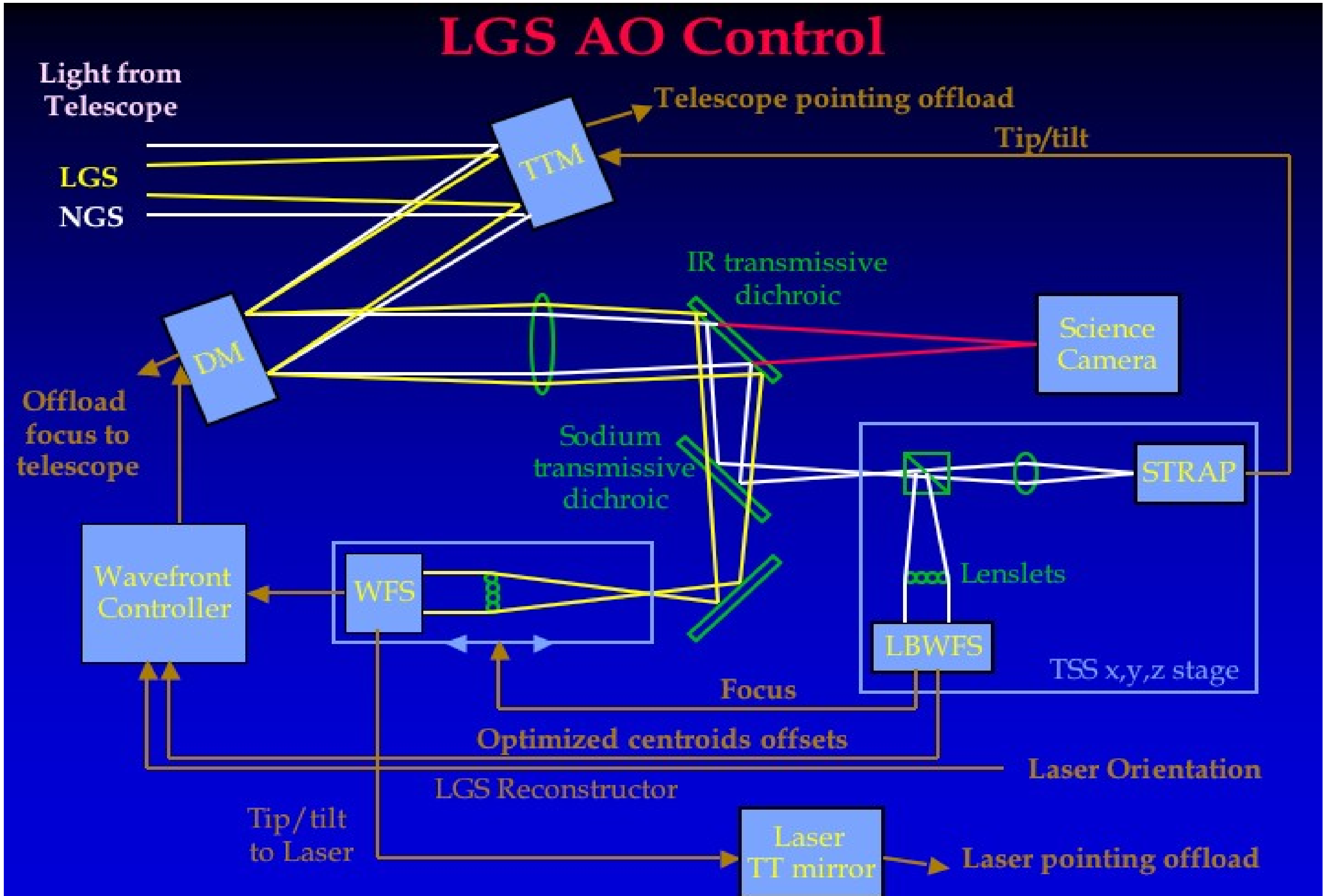
Must combine signals from several WFS sensors:

- Tip-tilt from NGS(s)
- Fast focus from LGS, slow focus from NGS
- High order modes from LGS
- (slow offset to some modes from NGS)

Needs mechanical focus stage for LGS

May need independent tip-tilt stage for LGS

Keck LGS system
Block diagram



Laser beam transport

Lasers are too large to be mounted at the top of the telescope
Need to launch beam from behind secondary mirror
→ laser beam has to be transported

Two options:

Relay optics (mirrors)
Difficult to align, needs active compensation of flexures
(eg: Gemini, laser beam behind telescope spider)

Fiber transport

High power density in fiber: new fiber technologies
Fiber injection is critical

(eg: Subaru, laser in dedicated room, fiber runs to top of telescope)