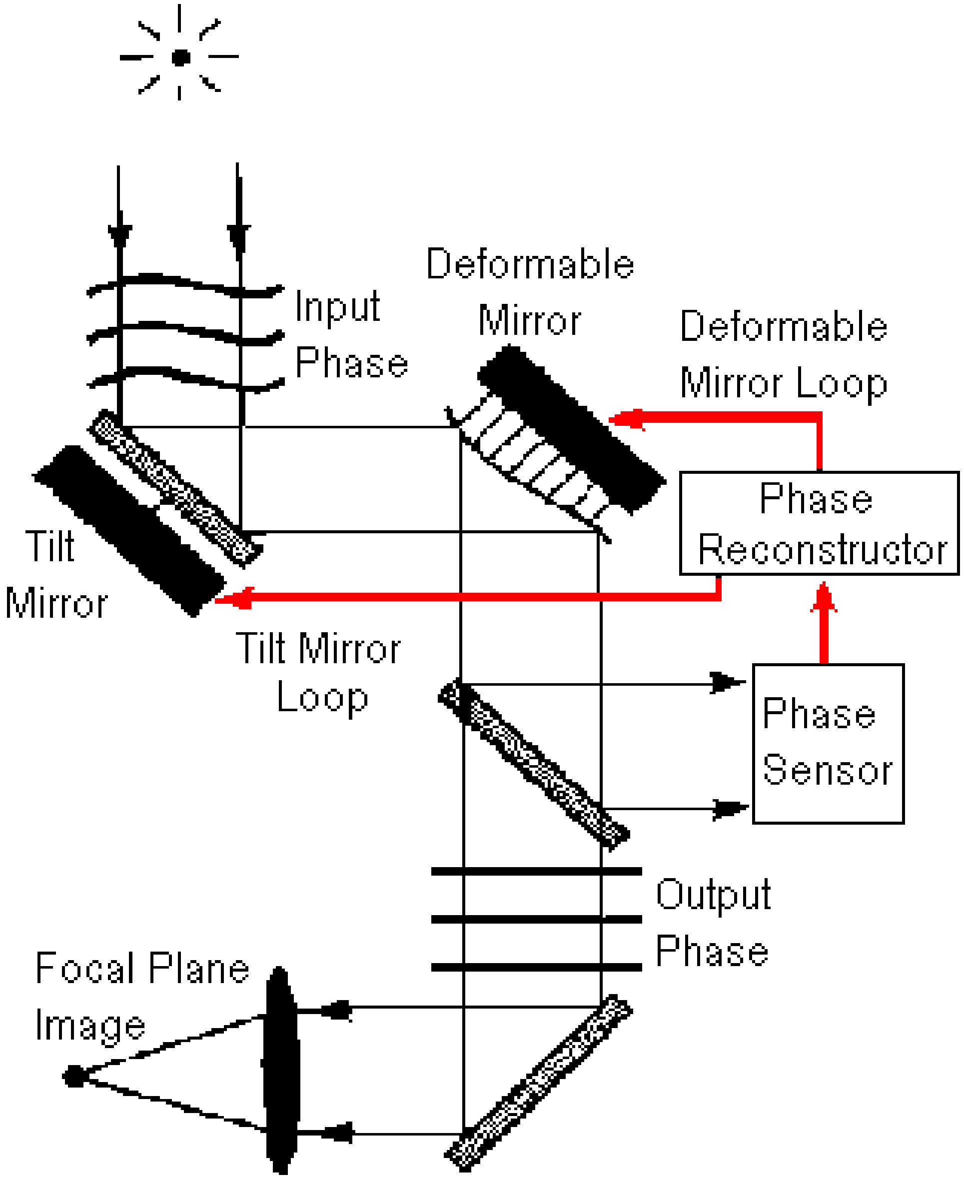
# What is Adaptive Optics ?




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

# Adaptive Optics

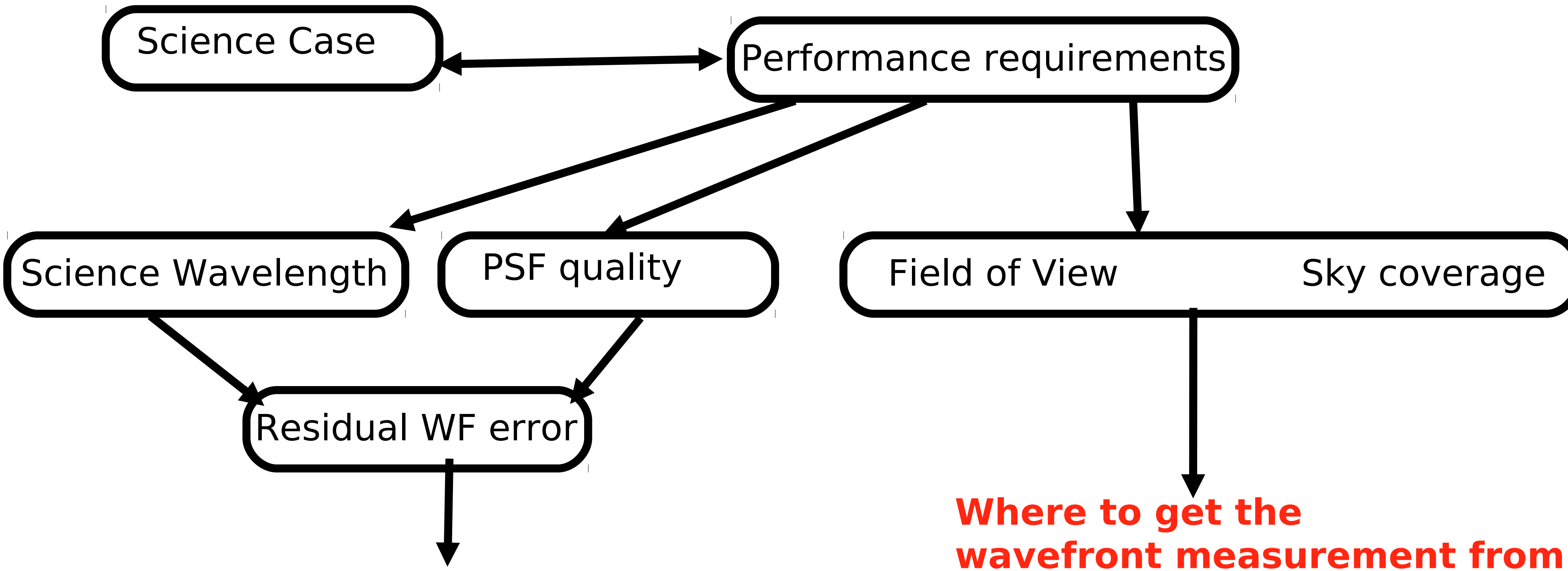
**System design**
General considerations
Laser guide star systems

**Software, algorithms & control**
Wavefront reconstruction and control:
translating wavefront sensor signals to DM commands

- Response and control matrix
- Loop gain
- Zonal and Modal control

Transfer functions
Simulating AO systems for design and performance estimation
Telemetry
Practical considerations: computing power, data transfer

# Choosing the wavefront sensing strategy is the most fundamental step in the design of an AO system




**Wavefront sensor(s) choice**

SH, Curv, PYR, other ?
How many elements ?

It is important to understand the physics of WFS well, avoid bad/inefficient combinations

**Where to get the wavefront measurement from ?**

NGS ? LGS ?
How many guide stars, where ?
WFS wavelength ?

**Where to get the wavefront measurement ?**

(1) Are there suitable natural guide star(s) ?

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

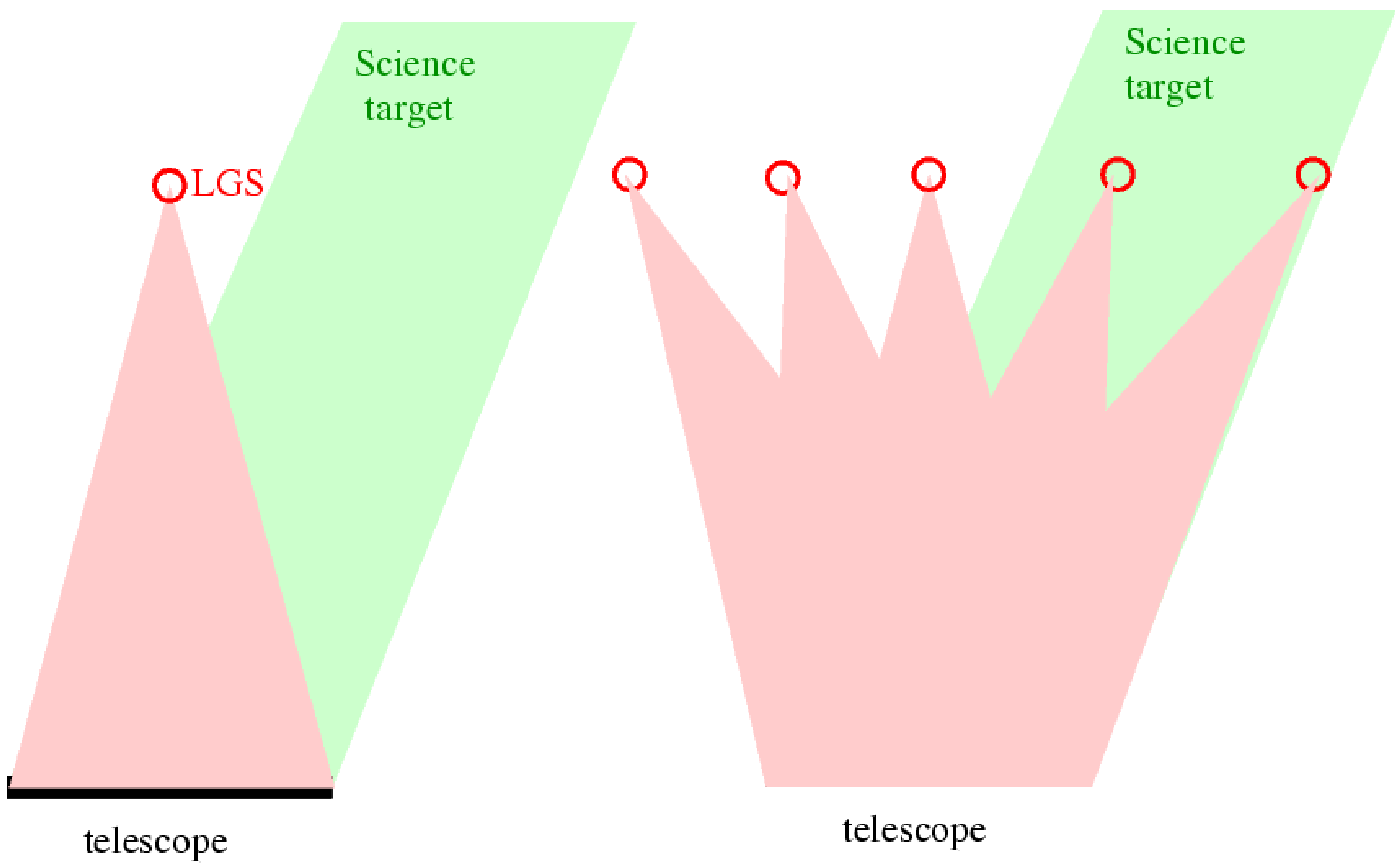
which laser ?

- 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**

**Where to get the wavefront measurement ?**

(2) Need several guide stars ?
(for field of view, tomography ?)
Multiple LGS ?
Multiple NGS ?

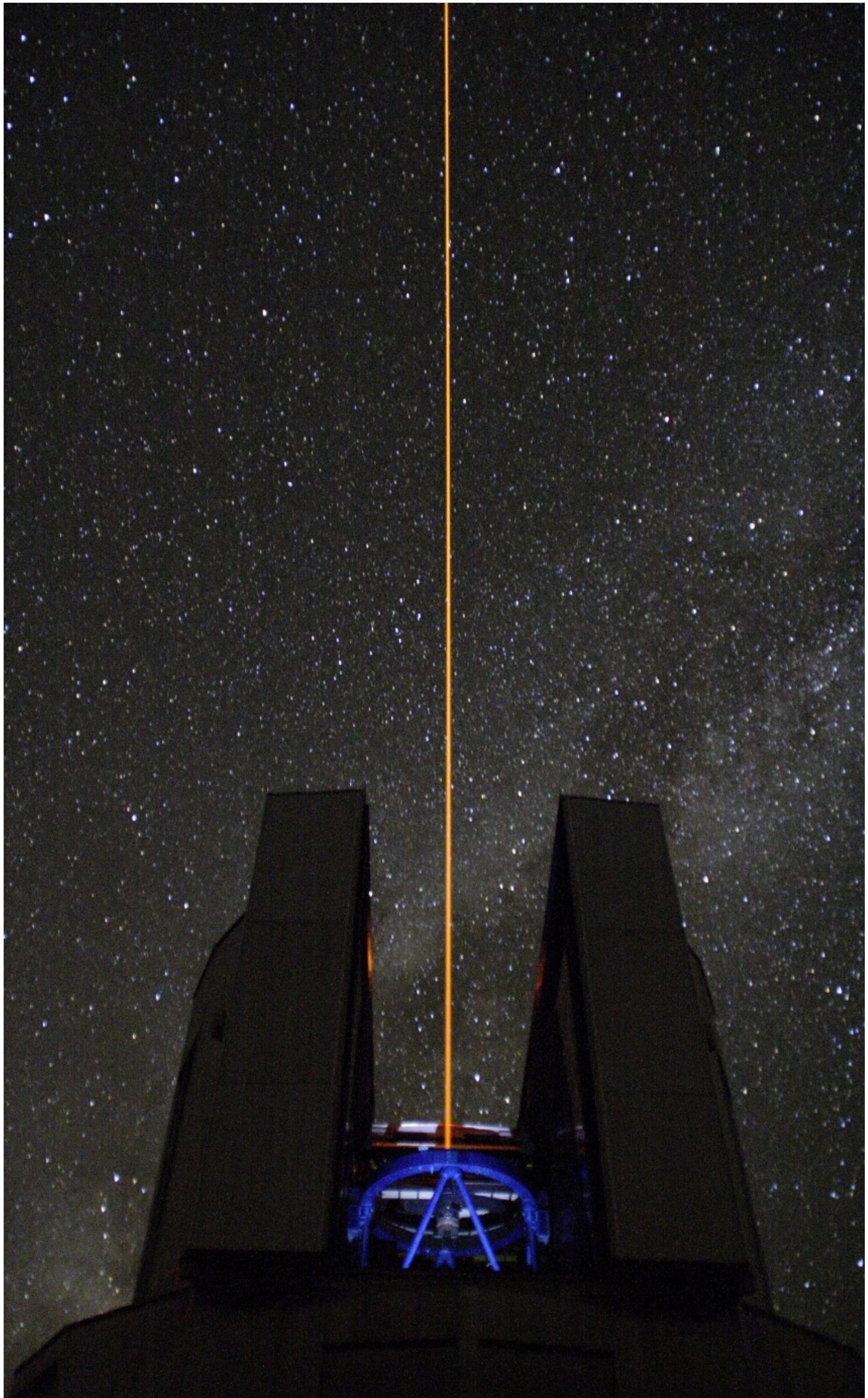


**Some challenges of LGS AO**

**Spot elongation**

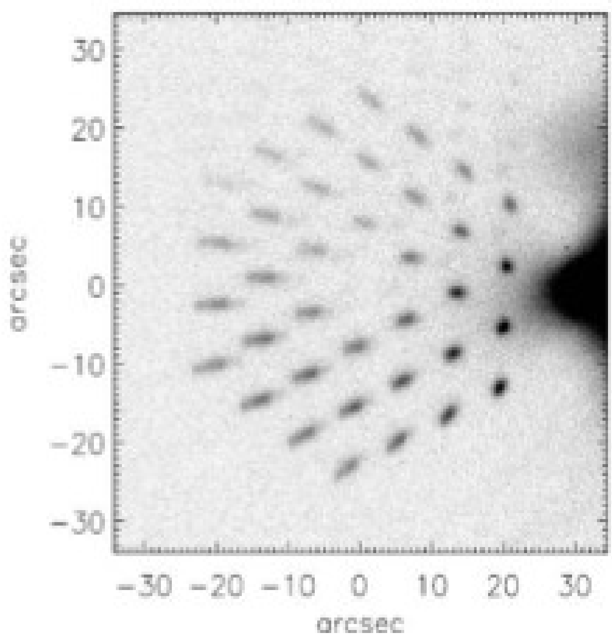
**Cone effect** due to finite altitude of LGS (90km sodium, few km for Rayleigh)
-> can be solved by using several lasers and tomography

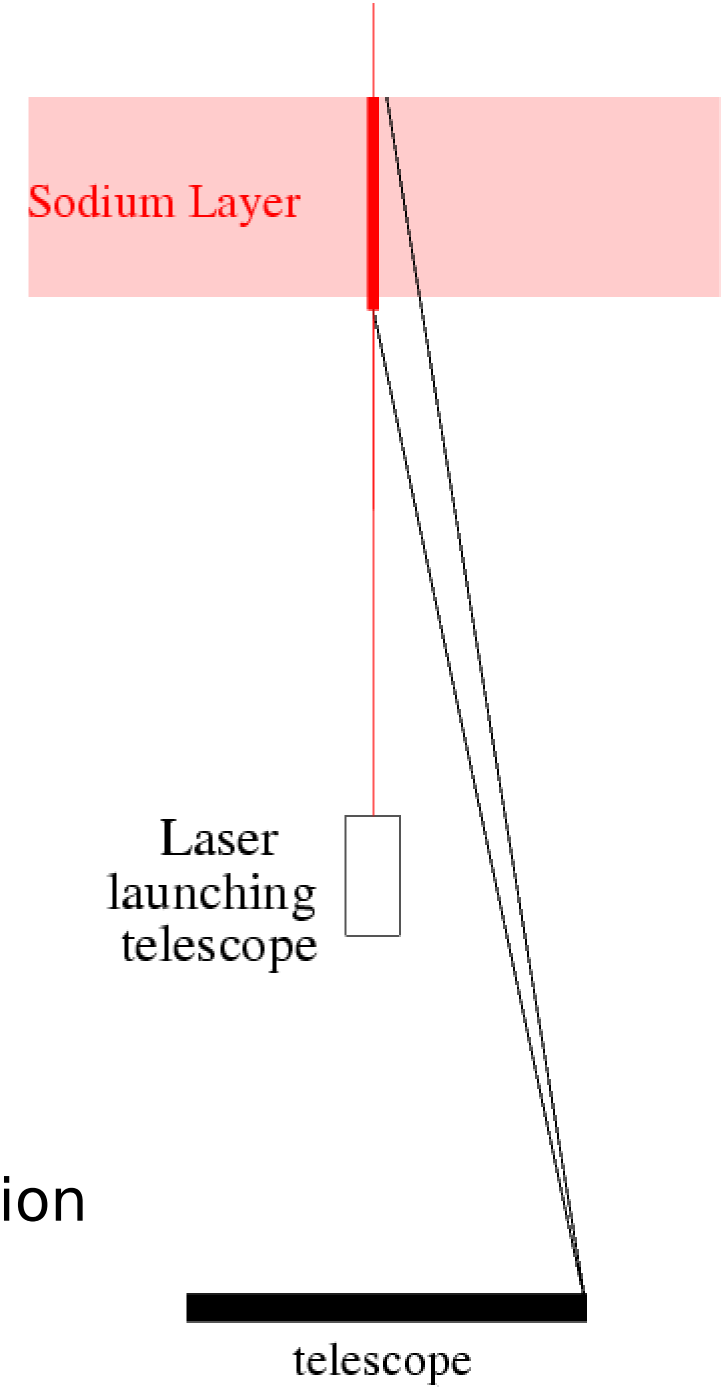
**Tip/Tilt & Focus sensing**
Upstream & downstream paths are the same: tip/tilt not seen
Sodium layer altitude not fixed: LGS focus info is incomplete (can be used to sense fast focus)
-> **Still need NGS(s) for tip/tilt & Focus**
**-> polychromatic laser (not quite mature yet)**



## Some challenges of LGS AO

**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

**LGS spot 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

# Cone effect

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

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

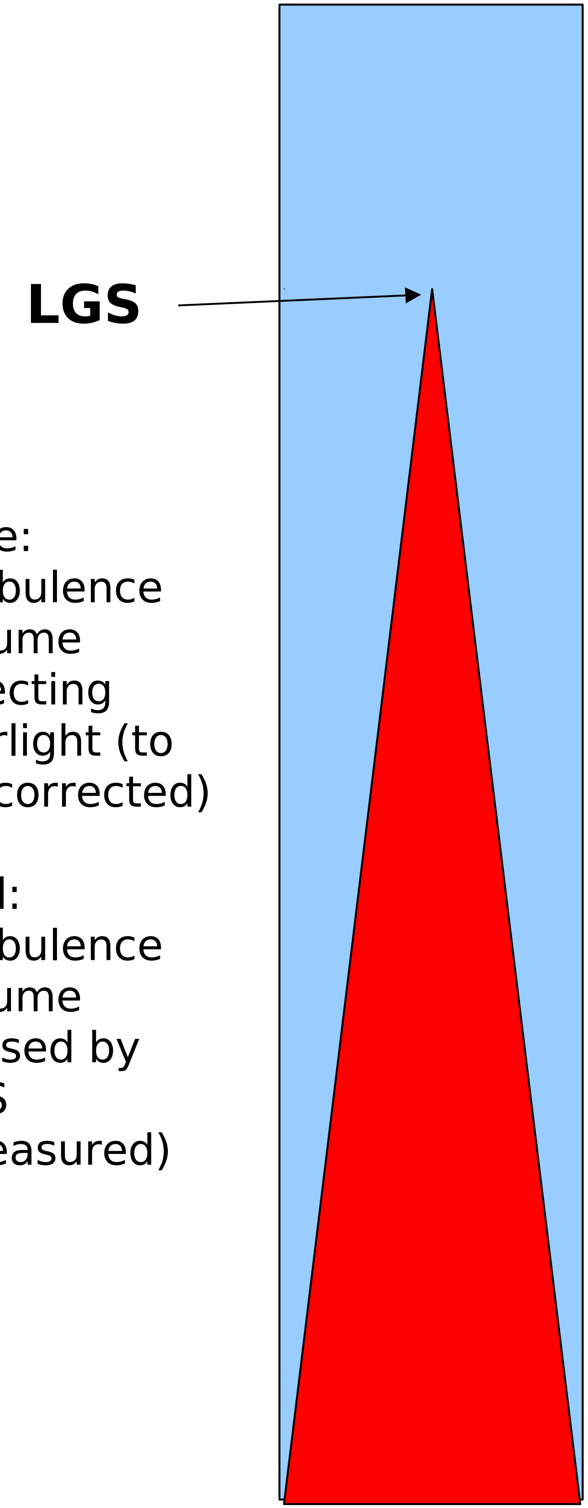
$\theta_0$: isoplantic angle

H : LGS altitude

D : Telescope diameter

→ impact is smaller for sodium LGS
→ larger effect for large telescopes

Mitigated by using several LGSs



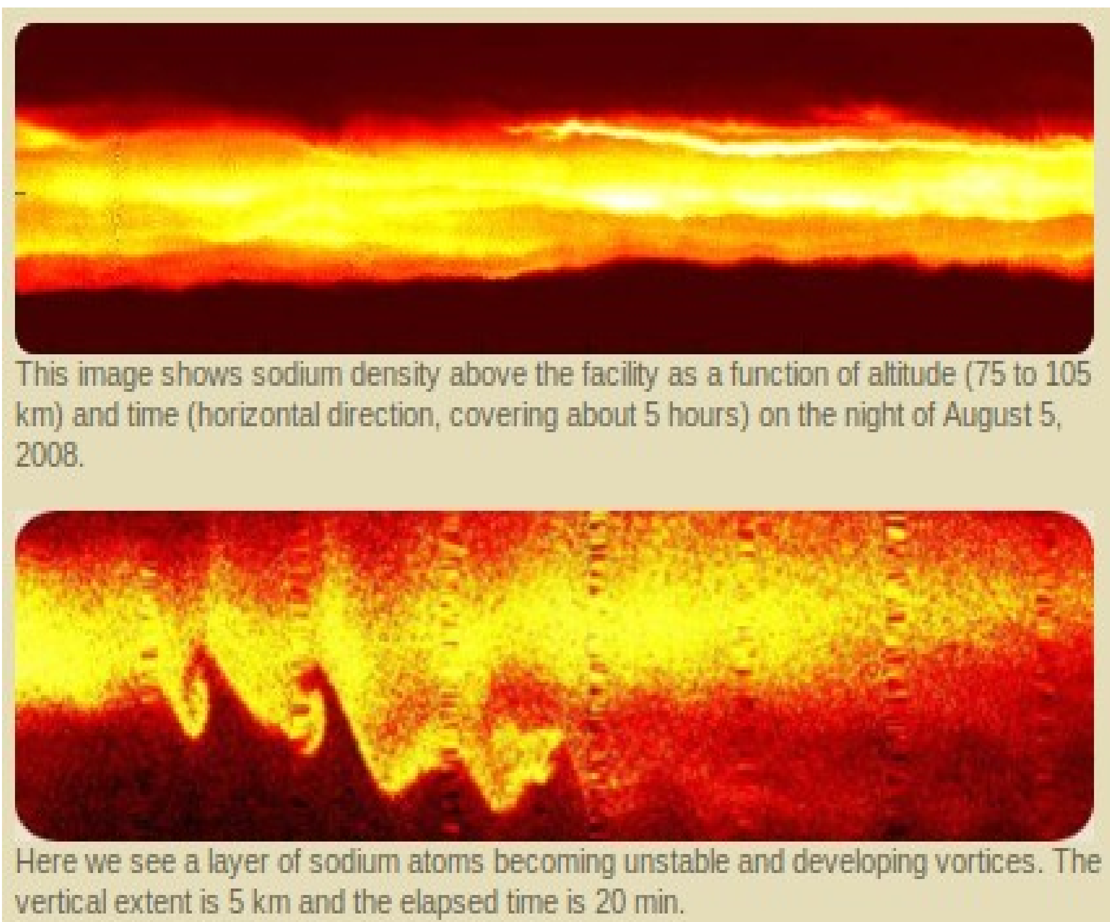

Blue: Turbulence volume affecting starlight (to be corrected)

Red: Turbulence volume sensed by LGS (measured)

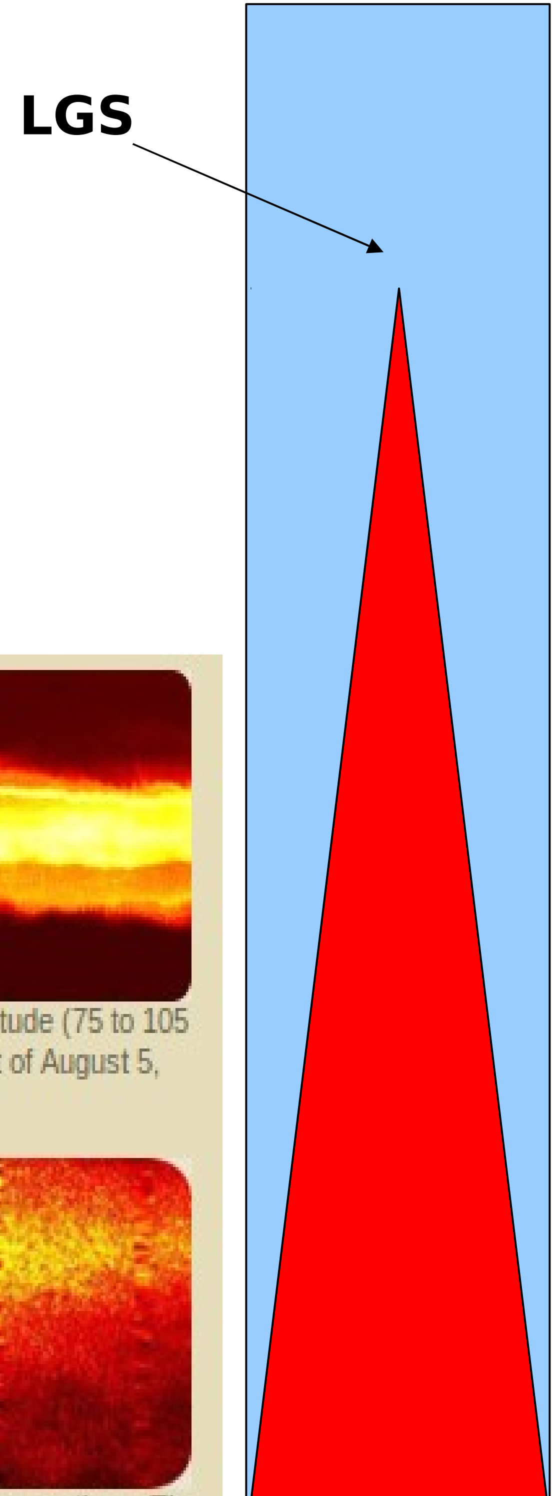
**Focus sensing**

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)




LIDAR measurements
Pfrommer & Hickson 2009



**Tip-tilt sensing**

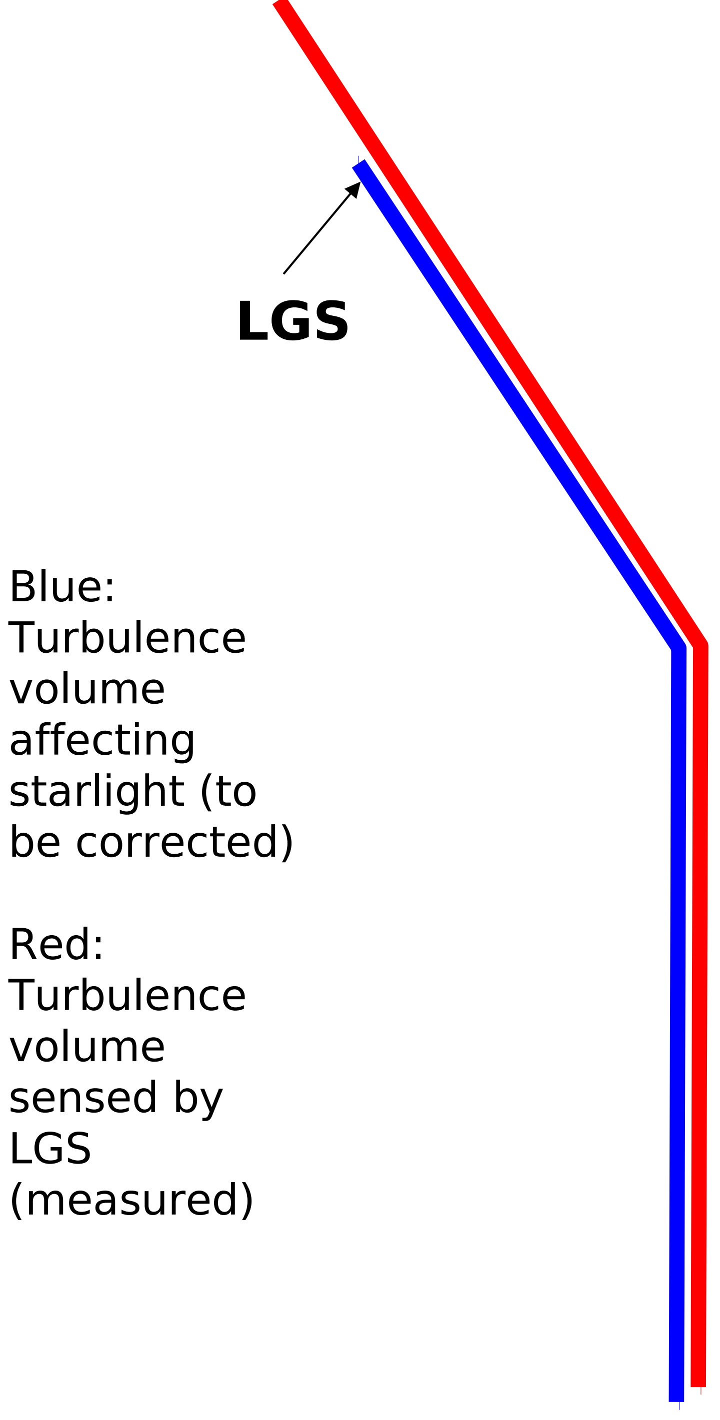
LGS light goes from telescope to LGS, and then back from LGS to telescope (double pass)

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.)



# LGS AO system

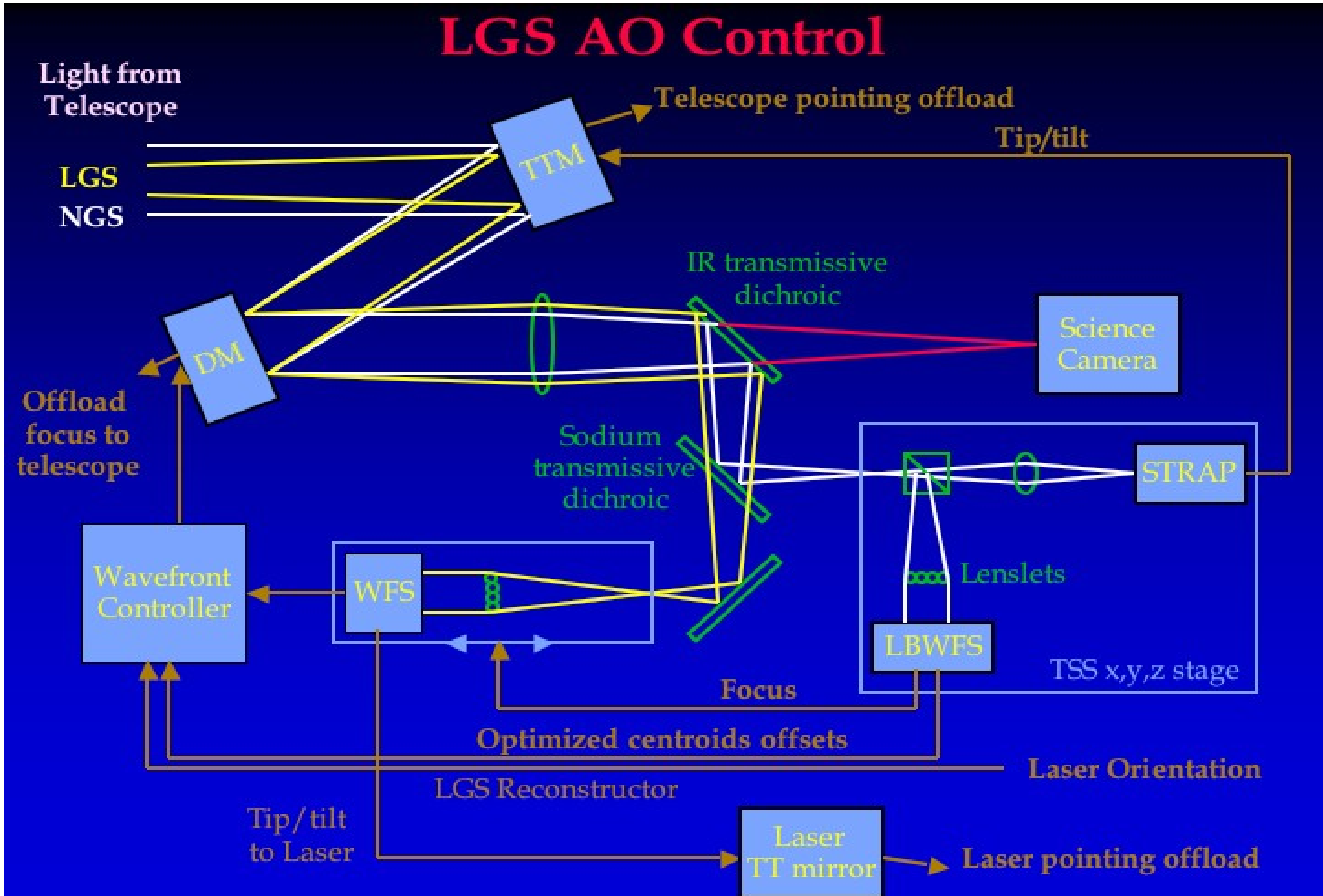
Must combine signals from several WFS sensors:

- 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)

# AO error budget terms :

**1 Fitting error**

**2 Speed**

**3 Limited # of photons**

These 3 fundamental errors usually need to be traded against each other

**4 AO guide "star" size & structure, sky background**

**5 Non-common path errors**

- chromaticity
- cone effect (LGS) & anisoplanetism

**6 Calibration, nasty "practical" things**

- vibrations, instabilities between control loops
- DM hysteresis / poor calibration (generally not too serious in closed loop)

**Useful references:**

**Adaptive Optics in Astronomy (2004)**, by Francois Roddier (Editor), Cambridge University Press

**Adaptive Optics for Astronomical Telescopes (1998)**, by John W. Hardy, Oxford University Press

# Science wavelength choice

**IR is "easy", visible is "very very hard"**

Things that get worse as lambda gets small:

- $r_0$ gets small: more actuators needed

  $r_0$ goes as $\lambda^{6/5}$ -> N goes as $\lambda^{-12/5}$

- speed gets high ($\tau_0 = 0.314\ r_0/v$) -> $\tau_0$ goes as $\lambda^{6/5}$
- anisoplanatism gets small (FOV, sky coverage go down)

  $\theta_0$ goes as $\lambda^{6/5}$

- chromaticity gets worse (refraction index of air varies more in visible than near-IR), ADC is needed
- instrumental non-common path errors get more serious

But diffraction limit is small in visible

# AO control

**How should the AO system drive the DM from WFS measurements ?**

**“standard” solution (fast, linear):**

- Measure/model how WFS measures DM commands
- If relationship is linear, this is stored as a “response matrix”
“response matrix” is inverted -> “control matrix” (this step usually includes some filtering – see next slides)
- WFS measurements x control matrix = DM commands

**This could also be done by computing explicitly the wavefront:**

WFS measurements -> wavefront -> DM commands

Good AO control now allows to separate WFS choice from DM choice: example: Curvature WFS could run with a MEMs DM

# Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear:

*If DM command increased by factor x, WFS signal multiplied by x*

*WFS signal to sum of 2 DM commands = sum of the 2 WFS signals*

→ Relationship can be written as matrix multiplication:

$A = M_{resp}\ B$

Assuming m actuators, n sensing elements

$A_{i=0...n-1}$: WFS signal vector (for example, x,y centroids for SH)

$B_{j=0...m-1}$: DM commands (can be voltages, displacements)

$M_{resp}$: m x n Response matrix (usually not a square matrix !)

**AO control problem:**

Given A (WFS measurement), and knowing $M_{resp}$, what is the DM command B which will produce the WFS signal -A ?

How to do this in a robust way, in the presence of noise, and with $M_{resp}$ which is generally not inversible ?

## Linear control of AO system: response and control matrix

Wavefront sensor response to DM commands is linear
→ DM commands to produce a given WFS signal is obtained by multiplication of A (WFS signal) by the control matrix $M_{contr}$

$B = M_{contr} A$

With $M_{contr}$ the pseudo-inverse of $M_{resp} = M_{resp}^{+} = (M_{resp}^{T} M_{resp})^{-1} M_{resp}^{T}$

If $M_{resp}$ is an inversible square matrix, $M_{contr} = M_{resp}^{-1}$

$M_{contr}$ can be computed by Singular Value Decomposition (SVD) of $M_{rest}$

Singular Value Decomposition:

$M = U \Sigma V^{*}$

U: Unitary matrix

Σ: diagonal matrix (Eigenvalues $a_i$)

V: Unitary matrix, $V^{*}$ its conjugate transpose ($=V^{T}$ if V real)

Pseudo-inverse :

$M^{+} = V \Sigma^{+} U^{*}$

With $\Sigma^{+} = 1/a$ if $|a|>0$, and 0 if $a=0$

# Linear control of AO system: response and control matrix

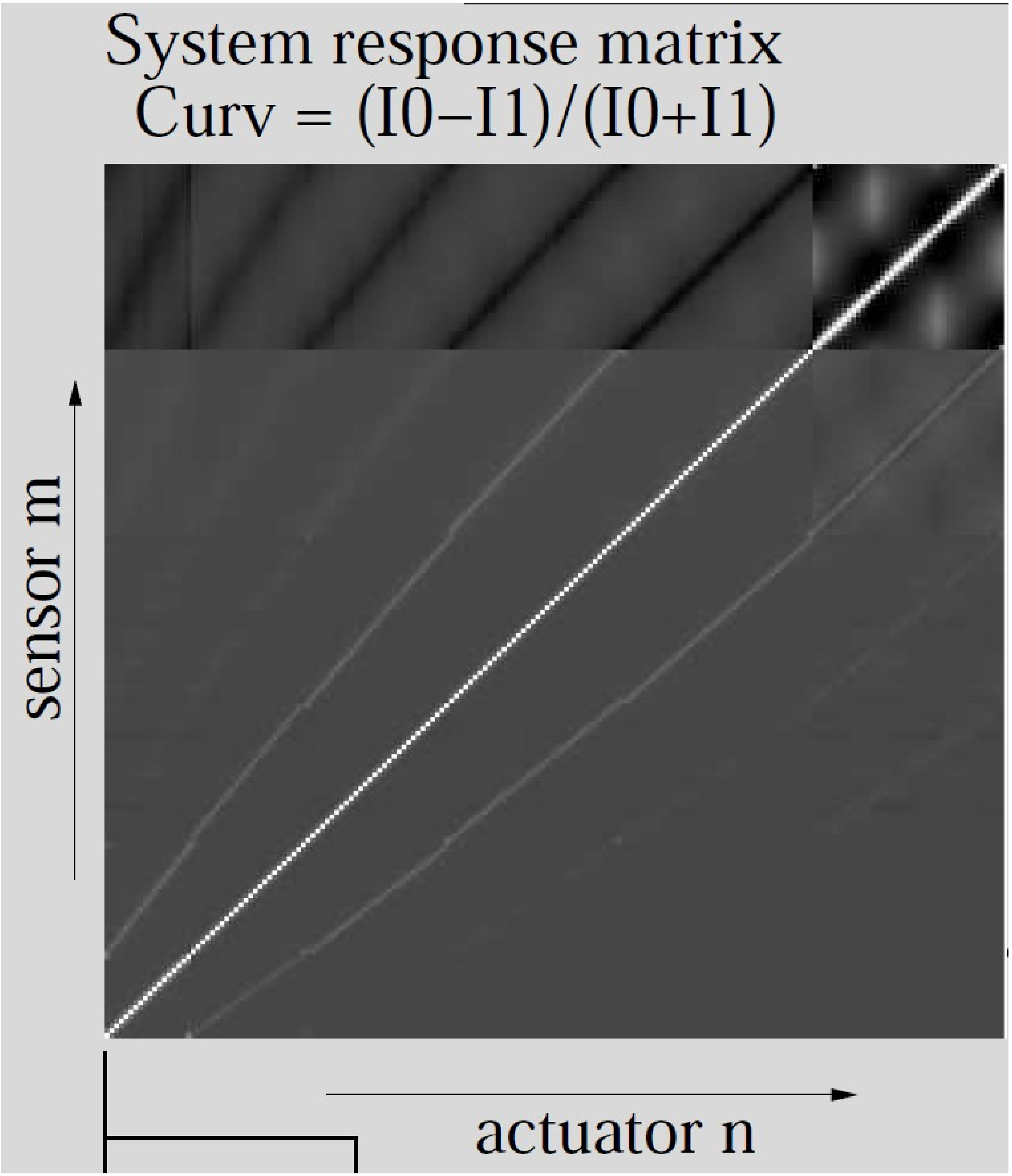
In practice:

- Although $M_{resp}$ could be in theory computer, $M_{resp}$ is usually measured by poking DM actuators and measuring the corresponding change in the WFS signal

- $M_{resp}$ can be mesured quickly by driving simultaneously several actuators if $M_{resp}$ is a sparse matrix (each DM actuator has an effect on a small number of sensors)

- $M_{contr}$ is usually computed by SVD, and presence of noise in the measurement forces modes of $M_{resp}$ with small eigenvalues to be discarded from the control loop (1/a considered =0 in the pseudo-inverse computation)

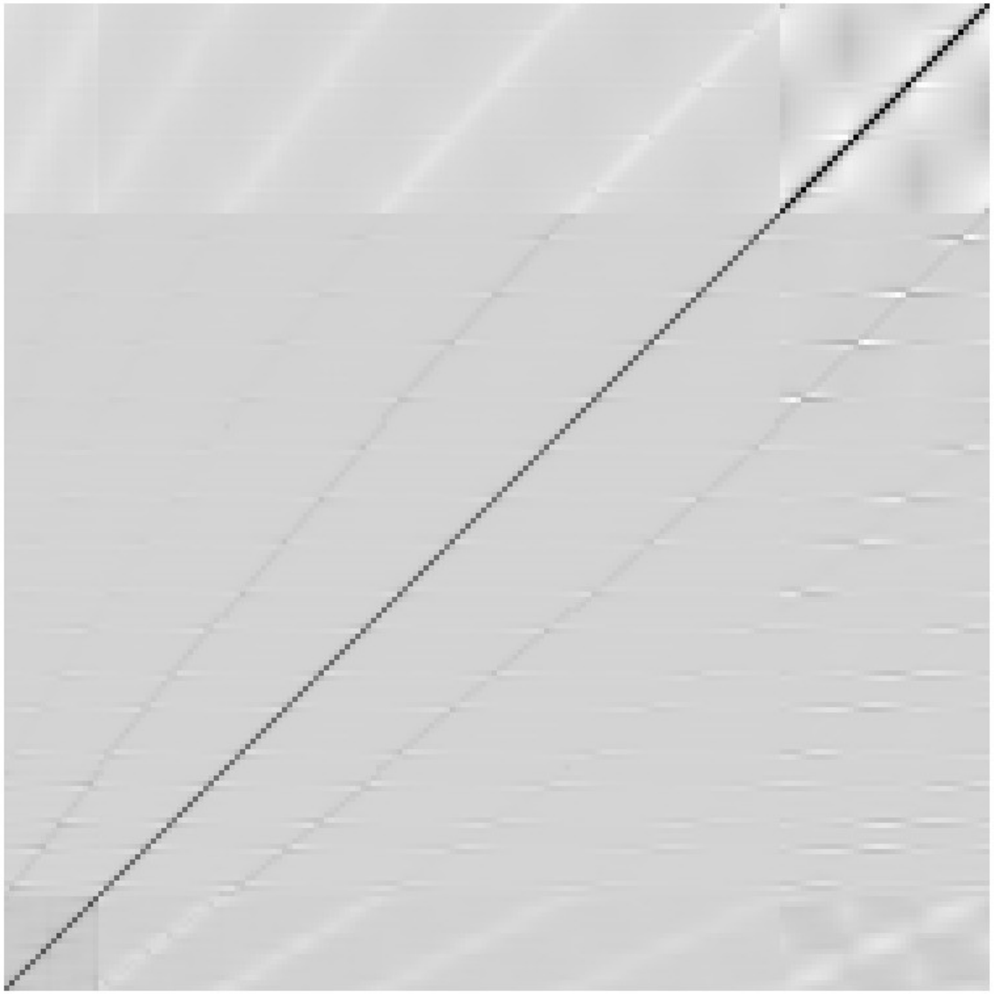
# System response matrix: example (simulation)



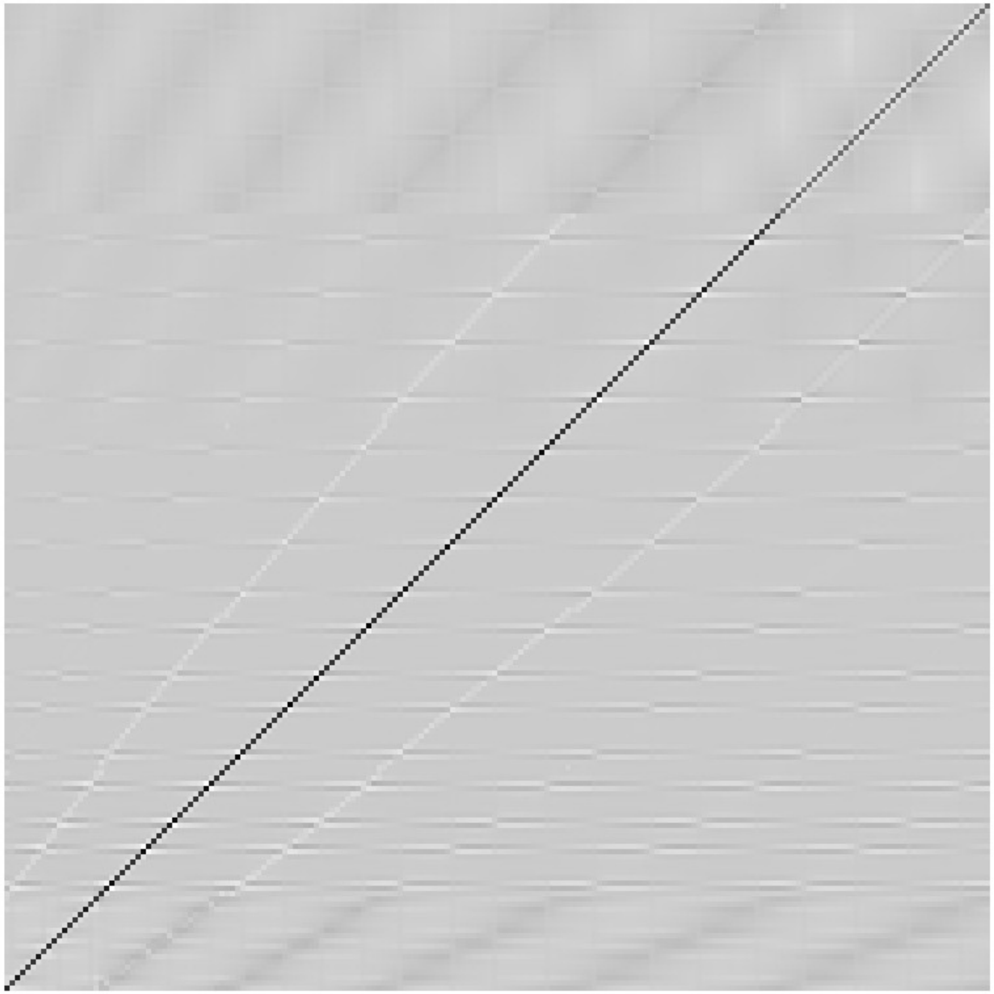

Measured response matrix includes system defects/imperfections, such as :
- alignment errors
- defective sensor(s)
- defective actuator(s)
- crosstalk

Mesuring response matrix is very good system diagnostics

# System response and control matrix: example (simulation)



Response matrix



Control matrix

## AO loop control: loop gain

At each step of the loop, offset dDM (= $-M_{contr}$ A ) required to cancel WFS signal is computed. Ideally, with k the loop step (= time) :
$DM_k = DM_{k-1} + dDM$

Problem: with above equation, loop would likely be unstable
Effective time lag in the measurement is 1/sampling time
→ some temporal frequencies are amplified
Measurement is noisy, and several consecutive measurements should be averaged

Solution: use loop gain < 1:

$DM_k = DM_{k-1} + g\ dDM$
With $0<g<1$
Noisy WFS measurement (faint guide star) → small g
High quality WFS measurement (bright guide star) → large g

# AO control: Modal control/filtering

Concept: Run AO loop at different speed for each mode, depending upon mode strength & WFS sensitivity for the mode
Gain becomes different for each mode

$M_{contr} = M_{resp}{}^{+} = V\ \Sigma^{+}\ U^{*}$
With $\Sigma^{+} = g_i/a_i$ if $|a_i|>0$, and 0 if $a_i=0$
Modal gains = $g_i$

Instead of thinking about AO control as relationship between individual sensors and actuators ("zonal" control), AO control is done mode per mode ("modal" control). Choice of modes is very important.

If $|a_i|$ is small (= WFS is not very sensitive to mode I), then
$1/a_i$ is large → noise can be amplified (noise/$a_i$ is big)
If $|a_i|$ is small and corresponding mode in atmosphere is weak, then $g_i$ should be small

**AO control: Modal control/filtering**

Modal control is very useful to:

- reject “bad modes” which can be produced by DM but not well sensed by WFS
- attenuate known vibrations
- powerful tool for system diagnostic

Modes poorly seen (noisy) by WFS & weak in the atmosphere should be prevented from feeding strong signals to DM. Powerful & well sensed mode should be rapidly driving the DM.

Modal control can continuously tune the system for optimal performance, adjusting gains $g_i$ in real time (see next slide for transfer function description).

Transfer function $H_g(f)$ known as a function of $g_i$, and WFS signals measures WFS(f) = $H_g(f)$*Atm(f), with Atm(f) the input disturbance. Simplified description (without noise):

→ Atm(f) can be computed (= WFS(f)/$H_g(f)$)

→ WFS(f) can be estimated for other values of $g_i$

→ best $g_i$ is adopted to minimize WFS(f)

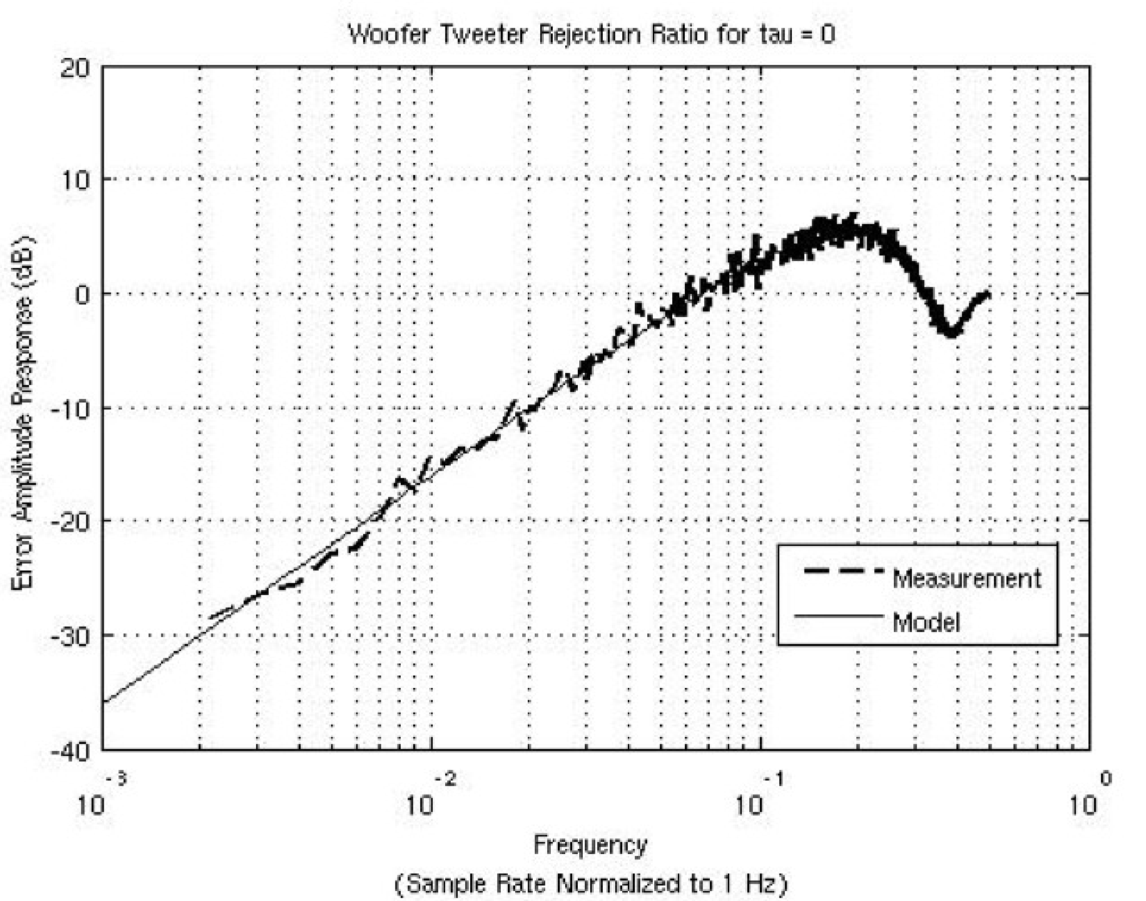
# AO control: transfer function

AO control loop can be considered as a linear temporal filter. For each mode and each temporal frequency f, the AO system attenuates incoming errors by H(f), the AO error transfer function

H(f) < 1 : attenuation
H(f) > 1 : amplification

H(f) → 0 for f → 0 in a closed loop system

Notes:
- H(f) is complex :
    ampl = attenuation
    phase = delay
- analytical tools can express H(f) in amplitude and phase according to loop characteristics (gain, delay)




Hampton et al. (University of Victoria)

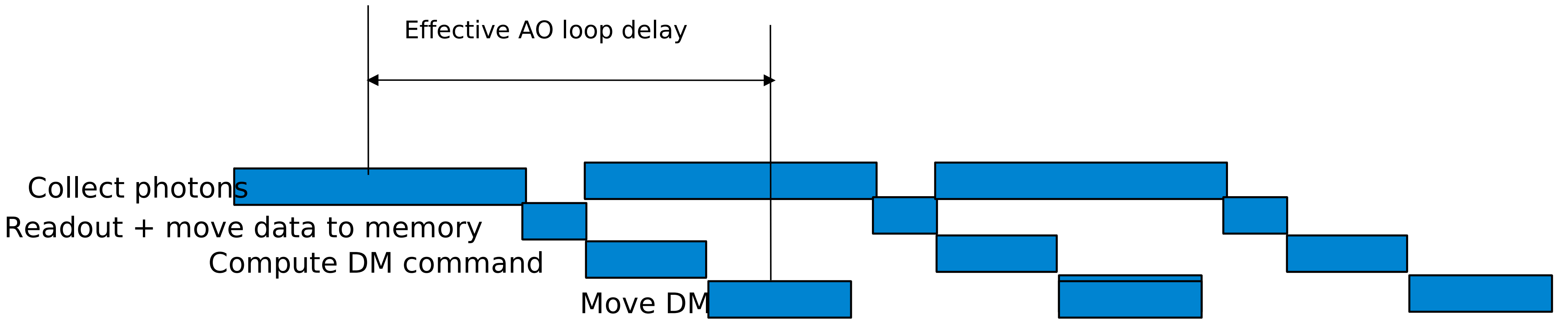
**Optimizing AO control speed**

→ High speed means fewer photons / sample need high SNR in WFS (optimal use of photons)

→ need fast hardware (see below)

- DM: good time response, low vibration
- Detector: fast readout / low readout noise
- computer, software & electronics need to be fast

→ Clever, predictive control can help a lot: anything that could be predicted should be !



## Realistic simulations of AO systems are extremely useful

AO simulations are relatively accurate, as input and outputs are well known:

- seeing properties are fairly well known (Kolmogorov layers)
- WFS behavior & properties are usually very well known
- Control algorithm identical in simulations & on the sky

**AO simulations can investigate:**

-> performance vs. # of actuators, DM type/geometry

-> loop instabilities & mode filtering

-> hardware trade-off:

WFS detector readout noise
DM hysteresis
speed of electronics & computer
Laser power for LGS
On-axis vs. off-axis LGS

-> alignment tolerance

# Telemetry is also very important

Recording WFS and DM data allows:

- seeing estimation & logging
- self-tuning of system
- diagnostics

**If a strange behaviour is observed in the AO loop, it is very hard to identify it without being able to “play back” the time when it occurs.**

Issues:

Disk space (2 kHz x 5000 single precision floats = 38MB/sec = 1 TB / night)

File management, archiving, sorting, searching