Lectures 11
Lasers used for Guide Stars
Wavefront Errors from Laser Guide Stars
Projects: Discuss Performance Reqirements

Claire Max
Astro 289, UC Santa Cruz

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Outline of laser guide star topics

- ✔ Why are laser guide stars needed?
- ✔ Principles of laser scattering in the atmosphere
- ✔ What is the sodium layer? How does it behave?
- ✔ Physics of sodium atom excitation

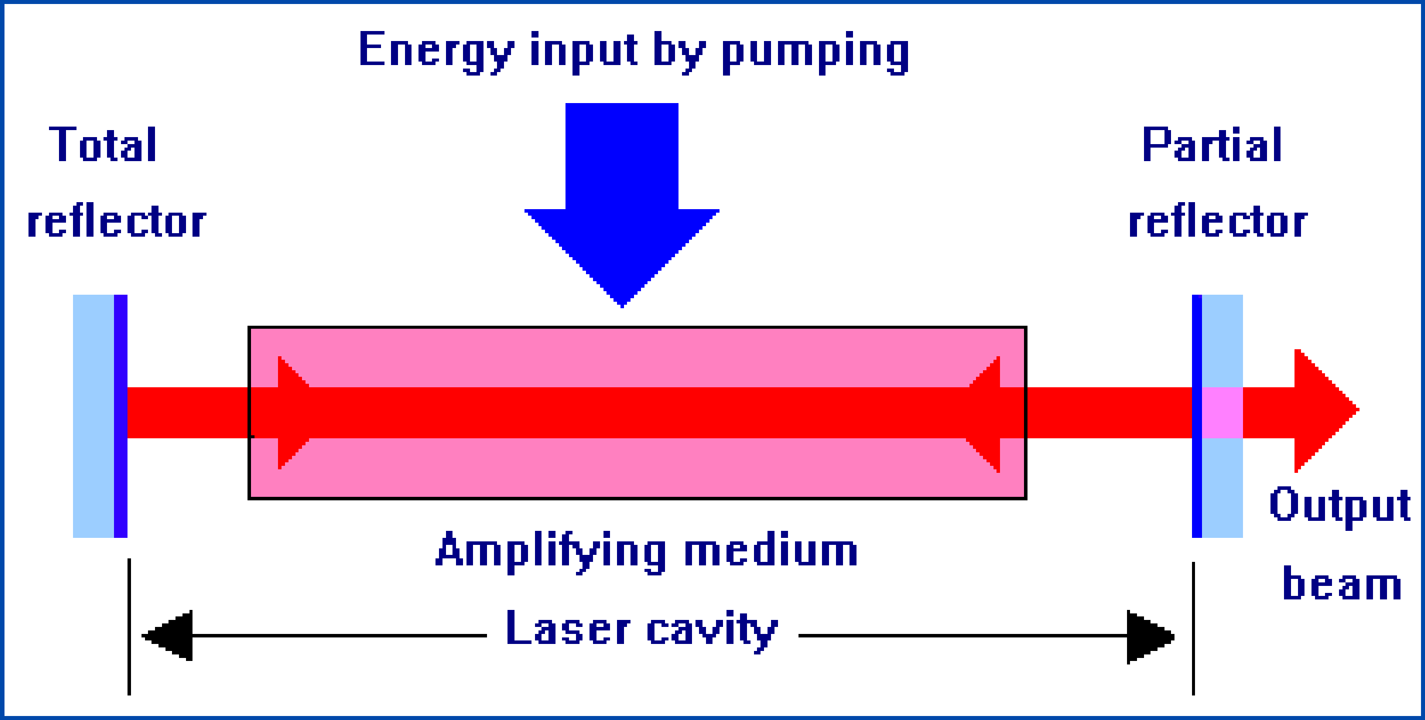
✔I stopped here last lecture

- Lasers used in astronomical laser guide star AO
- Wavefront errors for laser guide star AO

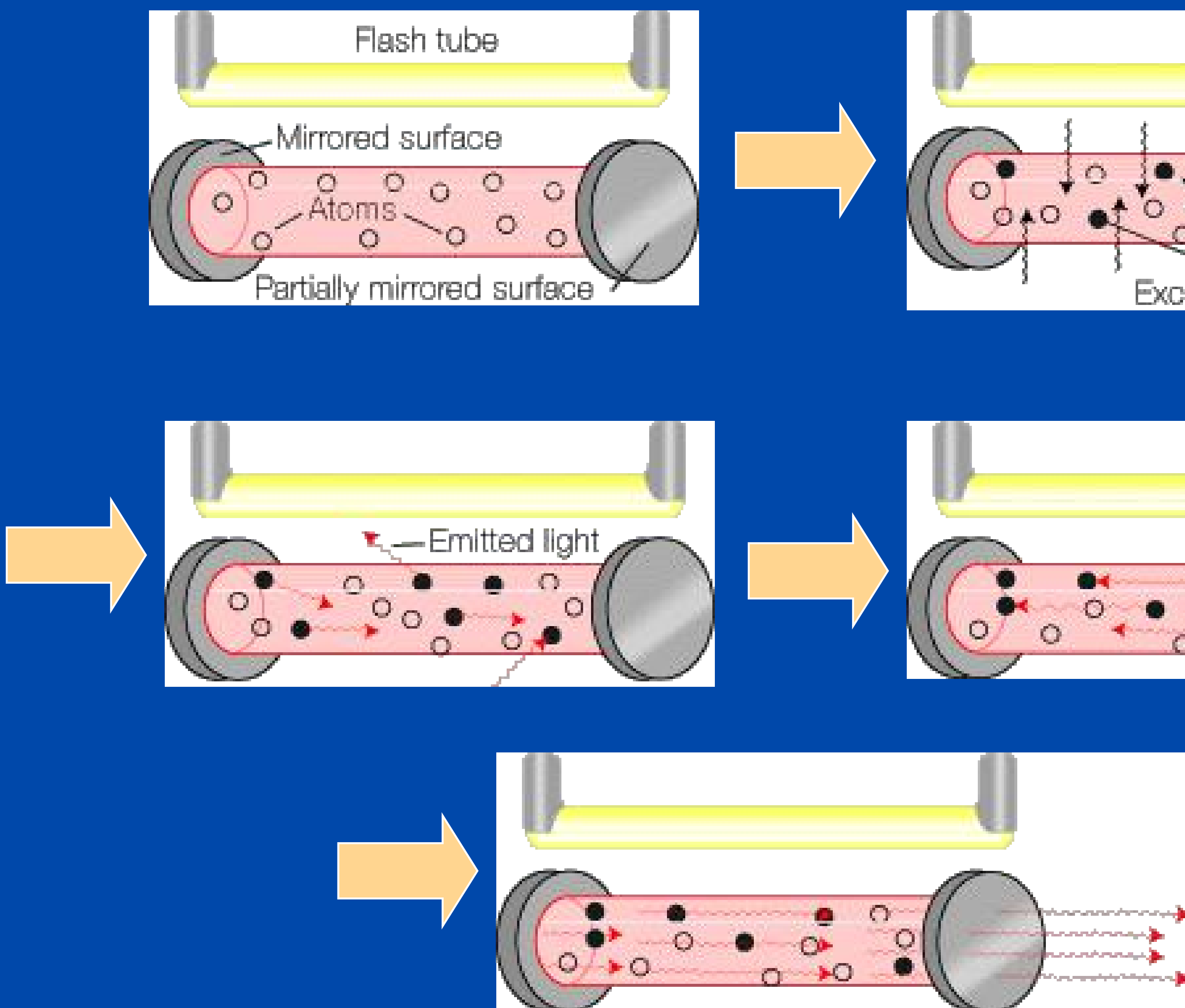
Types of lasers: Outline

- Principle of laser action
- Lasers used for Rayleigh guide stars
- Lasers used for sodium guide stars

Overall layout (any kind of laser)



Principles of laser action



Stimulated emission

Mirror

General comments on guide star lasers

- Typical average powers of a few watts to 20 watts
  - Much more powerful than typical laboratory lasers
- Class IV lasers (a laser safety category)
  - "Significant eye hazards, with potentially devastating and permanent eye damage as a result of direct beam viewing"
  - "Able to cut or burn skin"
  - "May ignite combustible materials"
- These are big, complex, and can be dangerous. Need a level of safety training not usual at astronomical observatories until now.

Lasers used for Rayleigh guide stars

- Rayleigh x-section ~ λ^{-4} $\Rightarrow$ short wavelengths better

- Commercial lasers are available
  - Reliable, relatively inexpensive

Example: Frequency doubled Nd:YAG lasers

- Nd:YAG means "neodimium-doped yttrium aluminum garnet"
- Nd:YAG emits at 1.06 micron
- Use nonlinear crystal to convert two 1.06 micron photons to one 0.53 micron photon (2 X frequency)
- Example: Coherent's Verdi laser
  - Pump light: from laser diodes
  - Very efficient
  - Available up to 20 Watts
  - Pretty expensive
    - It's always worrisome when price isn't listed on the web!

Types of Rayleigh guide star lasers

- SOAR: SAM
  - Frequency tripled Nd:YAG, λ = 0.35 μm, 8W, 10 kHz rep rate
- LBT:
  - Frequency doubled Nd:YAG, λ = 0.53 μm, 15 W each, 10 kHz rep rate
- William Herschel Telescope: GLAS
  - Yb:YAG "disk laser" at λ = 0.515 μm, 18 W, 5 kHz

Lasers used for sodium guide stars

- 589 nm sodium D_2 line doesn't correspond to any common laser materials
- So have to be clever:
  - Use a dye laser (dye can be made to lase at a range of frequencies)
  - Or use solid-state laser materials and fiddle with their frequencies somehow
    - Sum-frequency lasers (nonlinear index of refraction)
    - Raman scattering
  - Latest development: Fiber lasers that use either sum-frequency mixing or Raman shifting or both

Dye lasers

- Dye can be "pumped" with different sources to lase at variety of wavelengths
- Messy liquids, some flammable

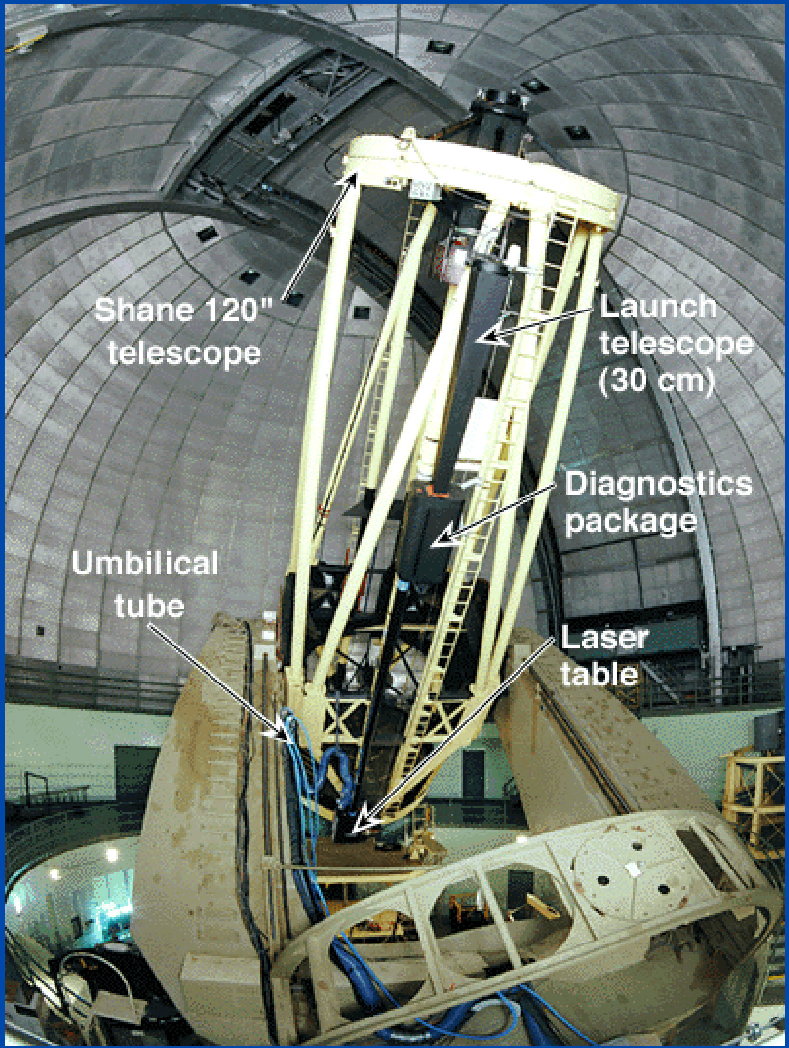
- Poor energy efficiency
- You can build one at home!
  - Directions on the web
- High laser powers require rapid dye circulation, powerful pump lasers

Dye lasers for guide stars

- Single-frequency continuous wave (CW): always "on"
  - Modification of commercial laser concepts
  - Subaru (Mauna Kea, HI); PARSEC laser at VLT in Chile (now retired)
  - Advantage: avoid saturation of Na layer
  - Disadvantage: hard to get one laser dye jet to > 3 watts

- Pulsed dye laser
  - Developed for DOE - LLNL laser isotope separation program
  - Lick Observatory, then Keck Observatory
  - Advantage: can reach high average power
  - Disadvantages: potential saturation, less efficient excitation of sodium layer
  - Use a lot of power

Lick Observatory



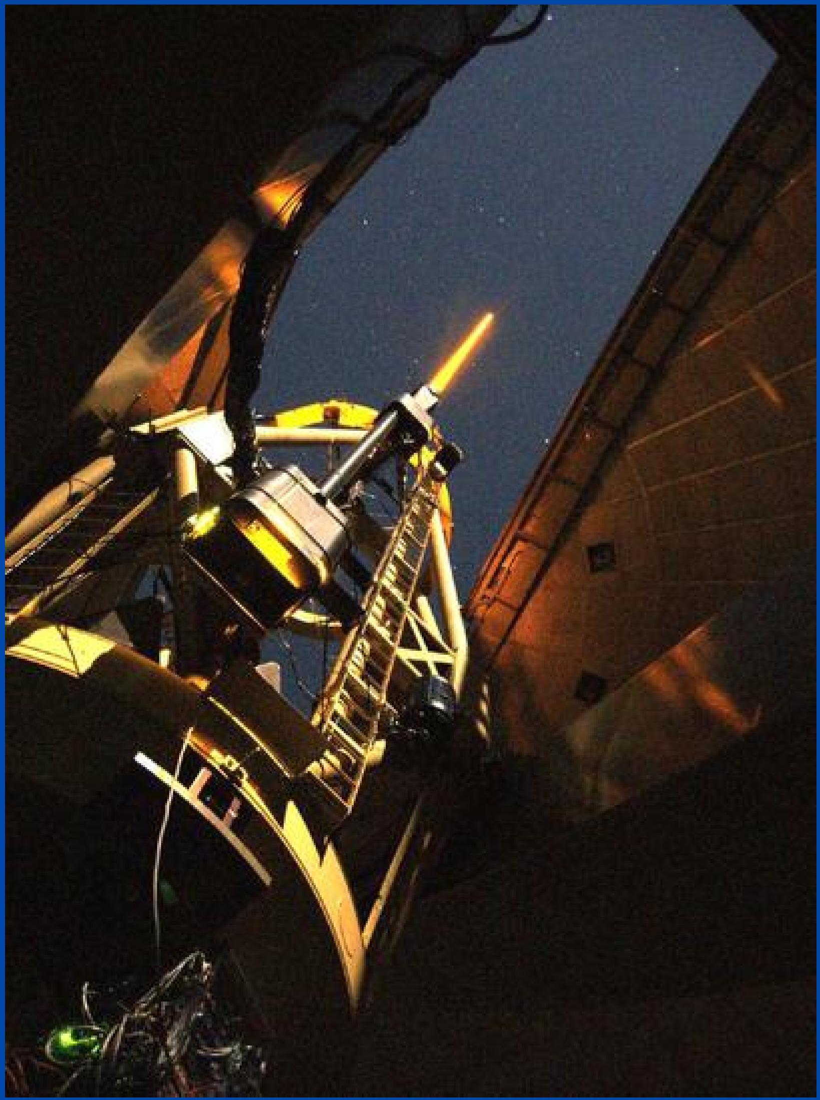
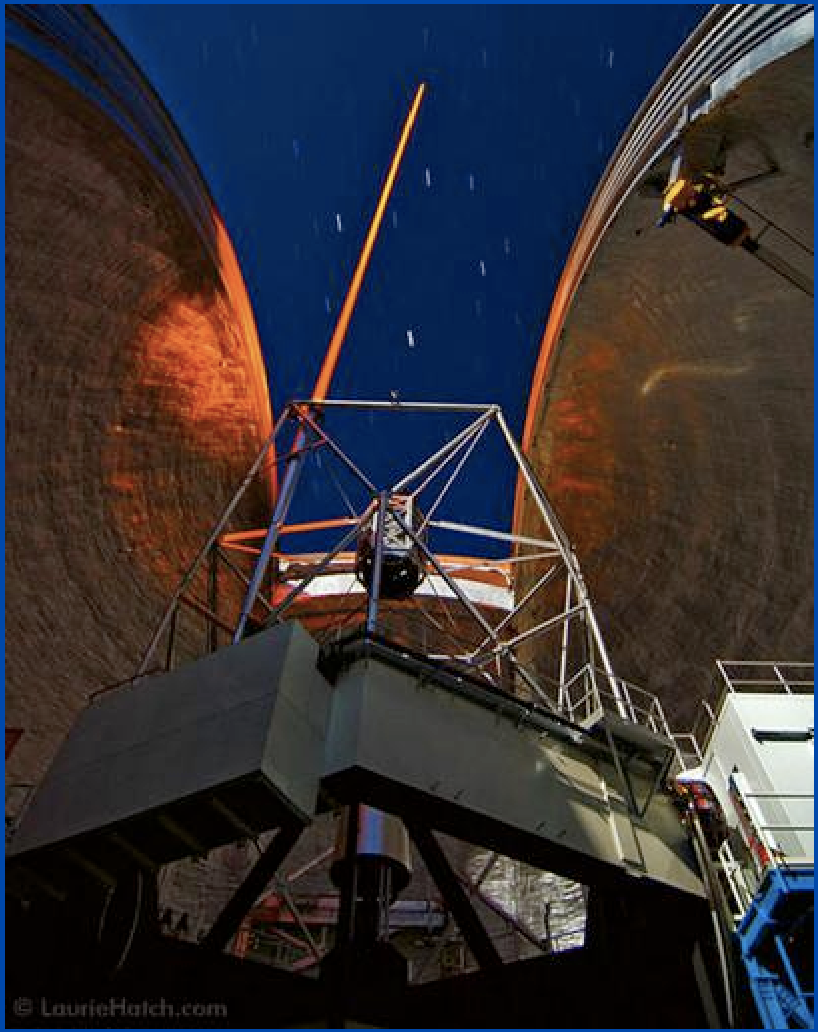


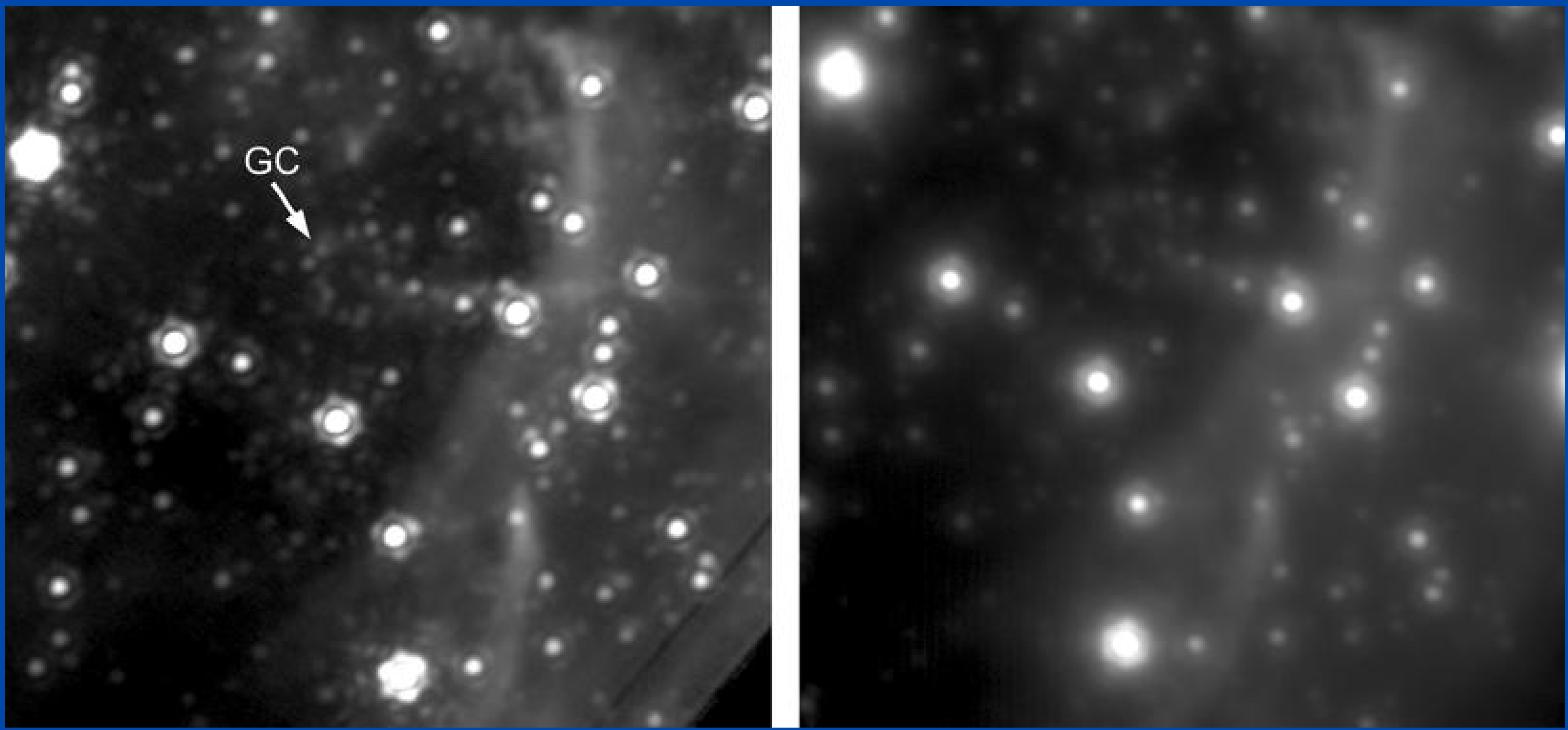
Photo by Dave Whysong, NRAO

Keck laser guide star



Galactic Center with Keck laser guide star AO

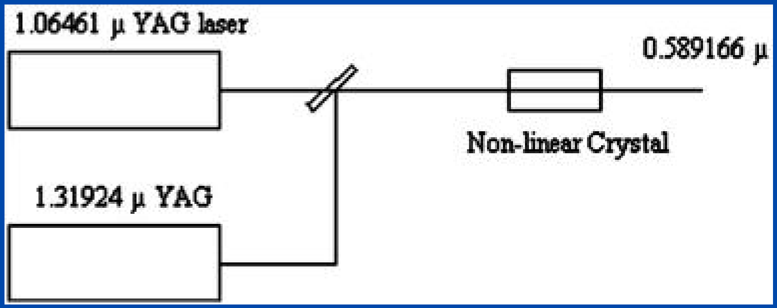
Keck laser guide star AO | Best natural guide star AO



Andrea Ghez, UCLA group

Solid-State Lasers for Na Guide Stars: Sum frequency mixing concept

- Example: two diode laser pumped Nd:YAG lasers are sum-frequency combined in a non-linear crystal

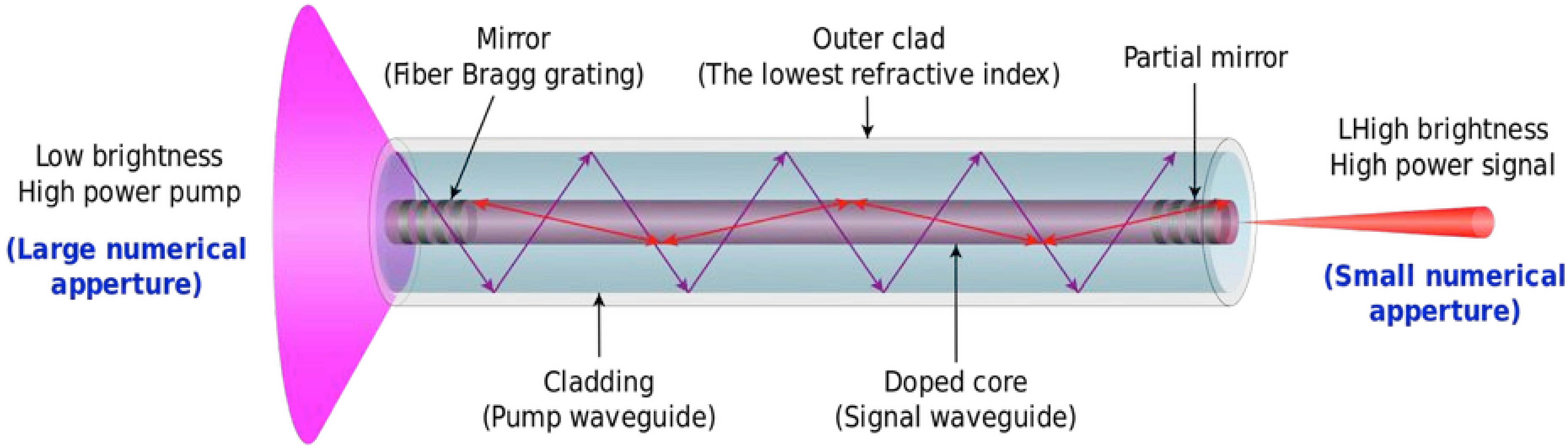


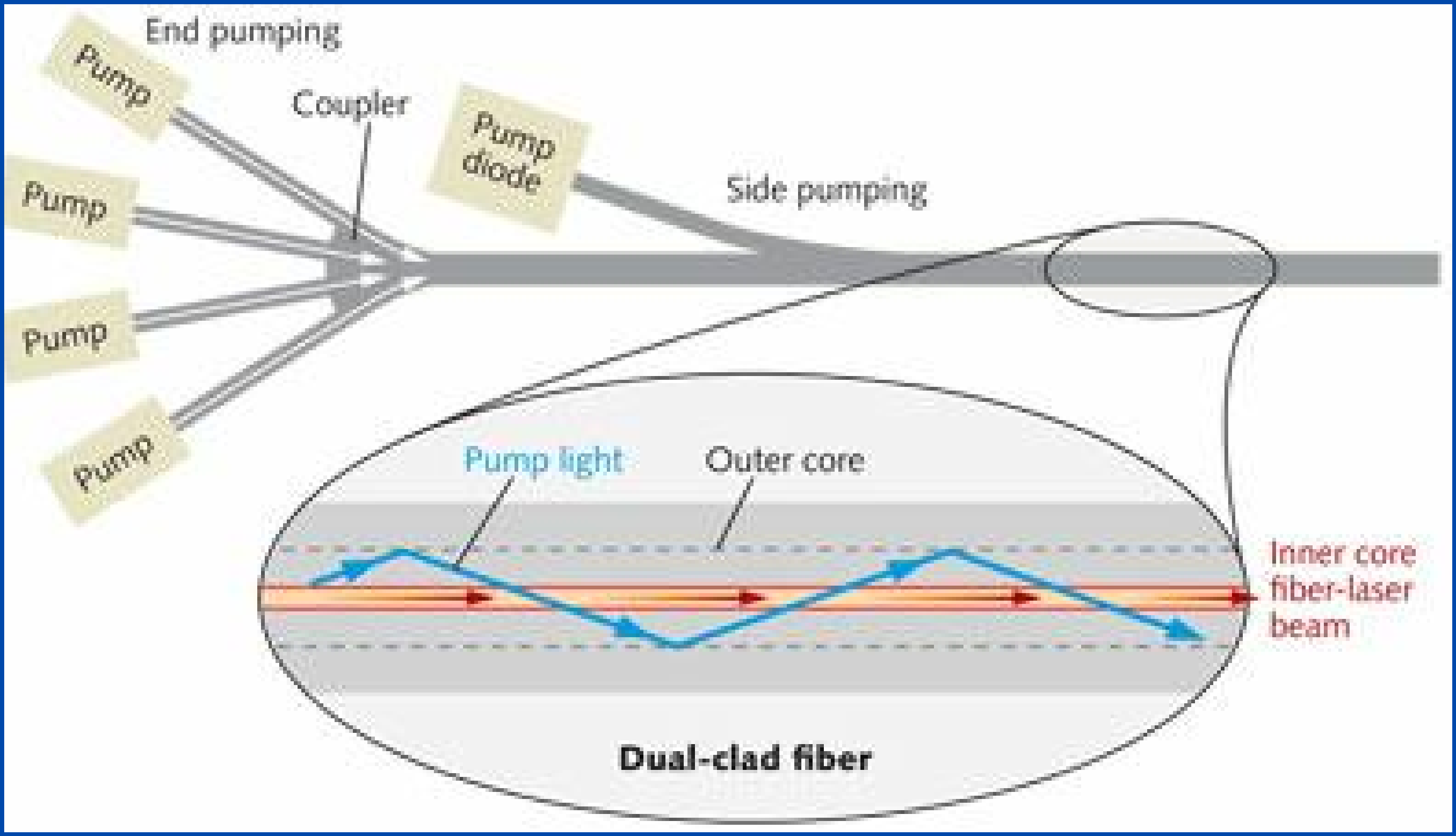
$$(1.06\ \mu m)^{-1} + (1.32\ \mu m)^{-1} = (0.589\ \mu m)^{-1}$$

- Kibblewhite (U Chicago and Mt Palomar), Telle and Denman (Air Force Research Lab), Coherent Technologies Incorporated (for Gemini N and S Observatories and Keck 1 Telescope)

Air Force laser at Starfire Optical Range

- **Built by Craig Denman**


Low brightness
High power pump
(Large numerical
apperture)
Mirror
(Fiber Bragg grating)
Outer clad
(The lowest refractive index)
Partial mirror
LHigh brightness
High power signal
(Small numerical
apperture)
Cladding
(Pump waveguide)
Doped core
(Signal waveguide)


End pumping
Pump
Pump
Pump
Pump
Coupler
Pump diode
Side pumping
Pump light
Outer core
Inner core fiber-laser beam
Dual-clad fiber

New generation of lasers: all-fiber laser (Toptica, Pennington and Dawson LLNL)

- **Example of a fiber laser**

Toptica fiber laser (ESO, Keck 2)

Electronics
and cooling

Advantages of fiber lasers

- Very compact
- Commercial parts from telecommunications industry
- Efficient:
  - Pump with laser diodes - high efficiency
  - Pump fiber all along its length - excellent surface to volume ratio
- Two types of fiber lasers have been demonstrated at the required power levels at 589 nm (Toptica in Europe, Jay Dawson at LLNL)

Questions about lasers?

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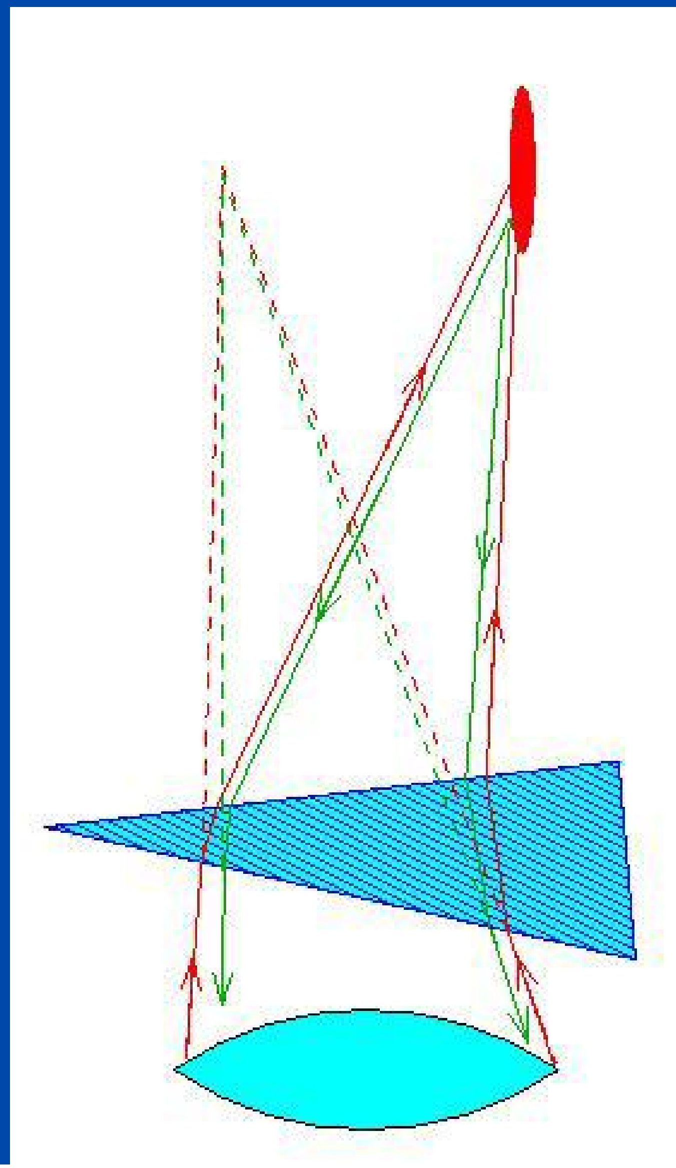
Laser guide star AO needs to use a faint tip-tilt star to stabilize laser spot on sky

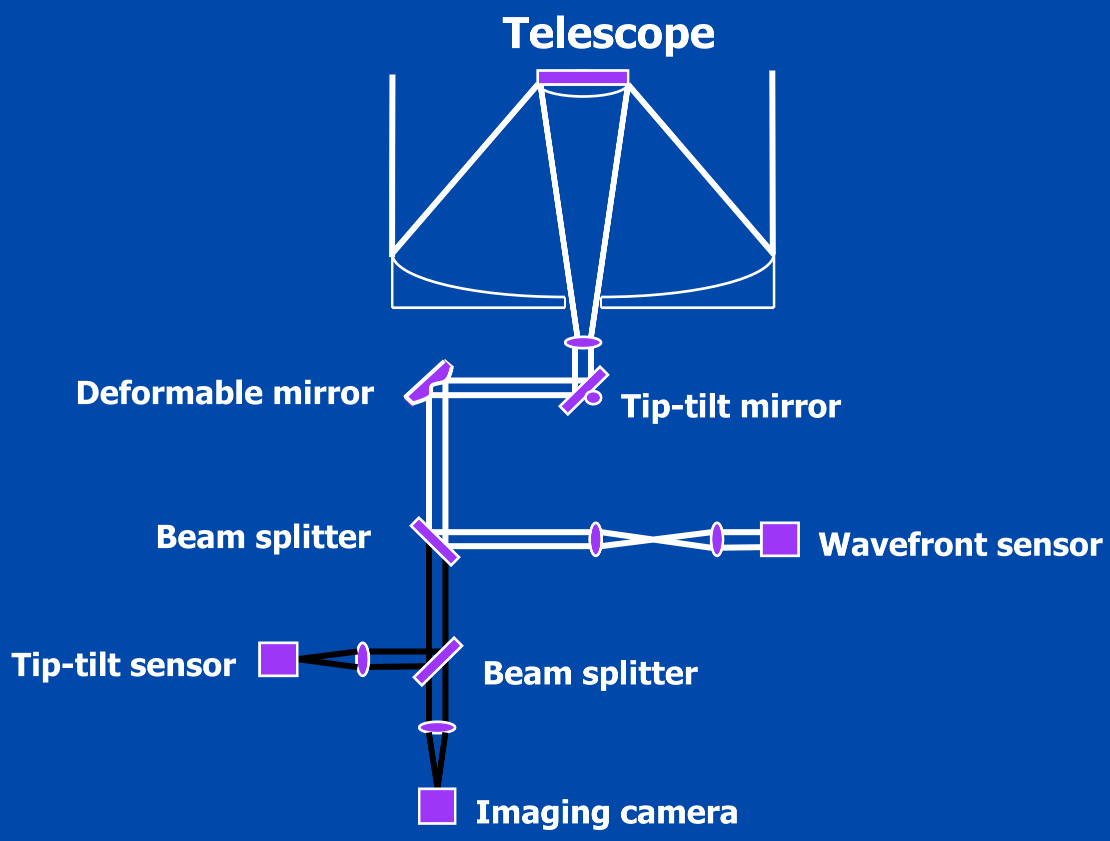


from A. Tokovinin

Effective isoplanatic angle for image motion: "isokinetic angle"

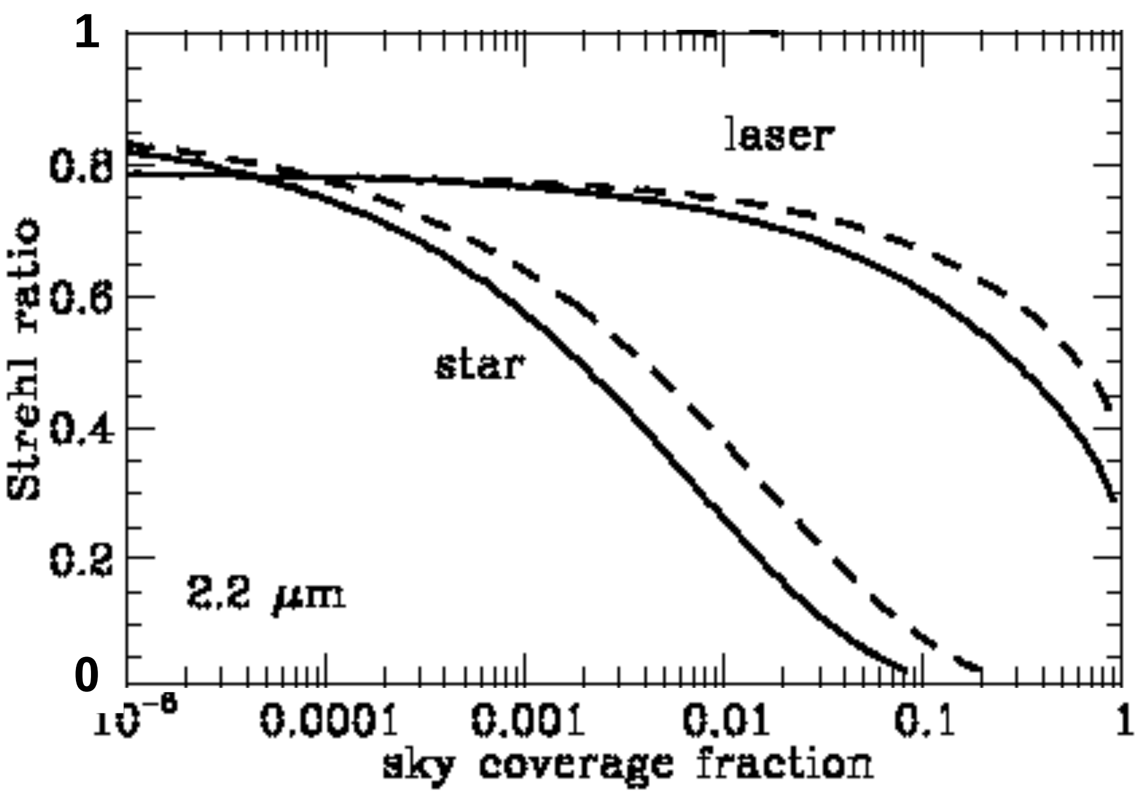
- Image motion is due to low order modes of turbulence
  - Measurement is integrated over whole telescope aperture, so only modes with the largest wavelengths contribute (others are averaged out)
- Low order modes change more slowly in both time and in angle on the sky
- "Isokinetic angle"
  - Analogue of isoplanatic angle, but for tip-tilt only
  - Typical values in infrared: of order 1 arc min

Tip-tilt mirror and sensor configuration



Sky coverage is determined by distribution of (faint) tip-tilt stars

- Keck: >18th magnitude



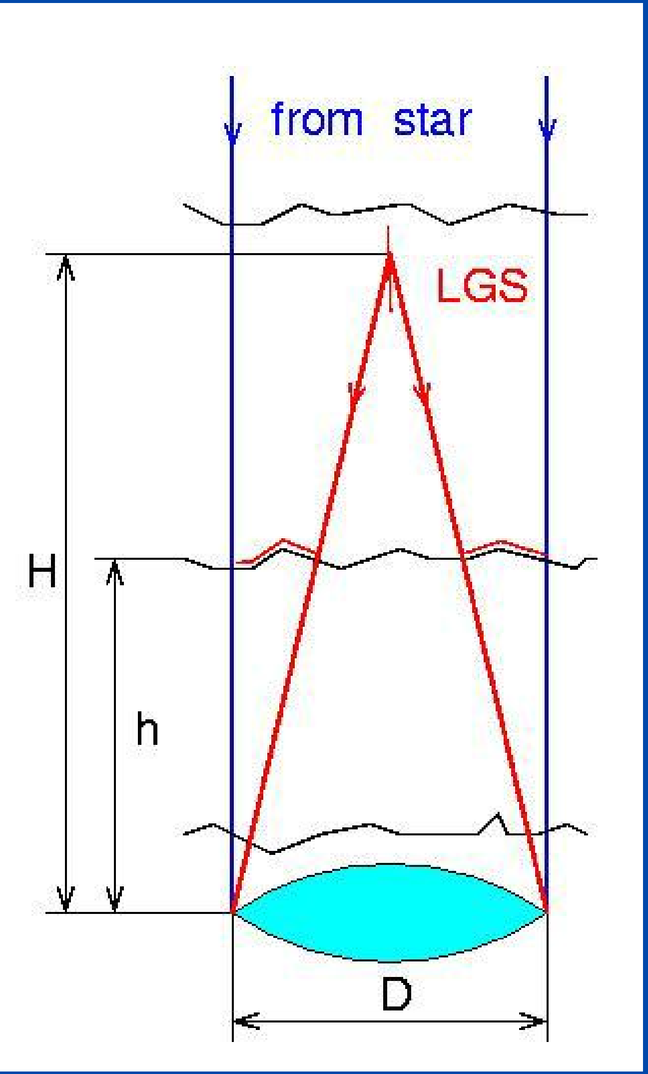
From Keck AO book

—— Galactic latitude = 90°
..... Galactic latitude = 30°

271 degrees of freedom
5 W cw laser

"Cone effect" or "focal anisoplanatism" for laser guide stars

- Two contributions:
  - Unsensed turbulence above height of guide star
  - Geometrical effect of unsampled turbulence at edge of pupil



from A. Tokovinin

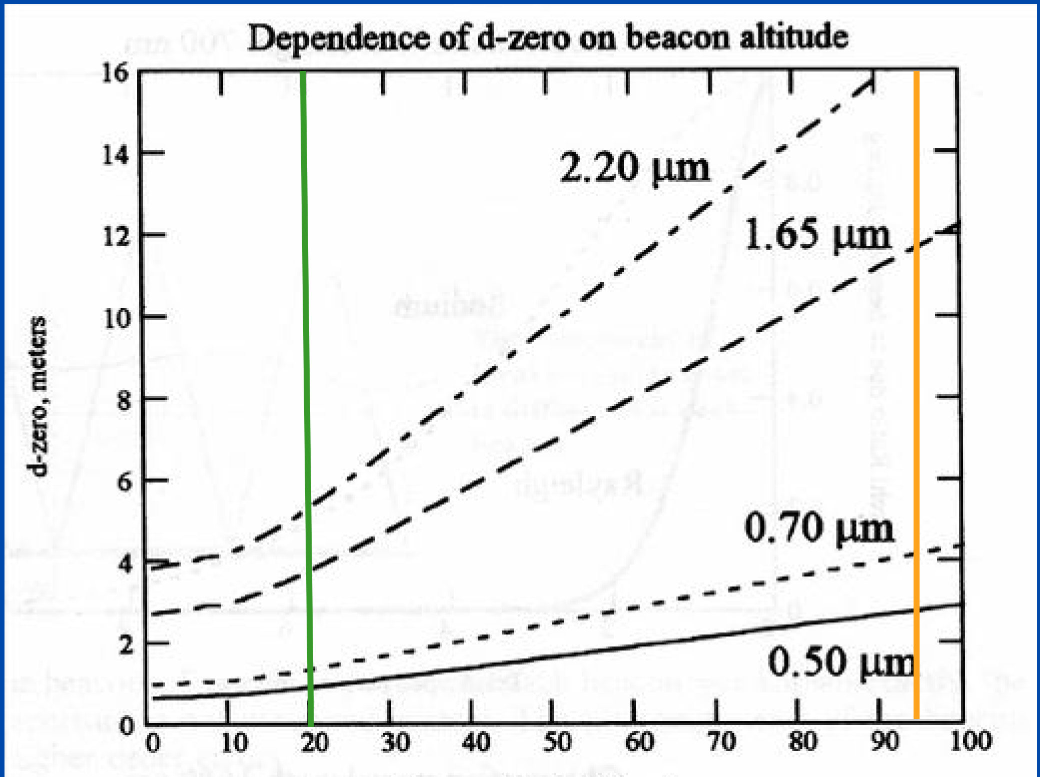
Cone effect, continued

- Characterized by parameter d_0
- Hardy Sect. 7.3.3 (cone effect = focal anisoplanatism)

$$\sigma_{FA}^2 = (D / d_0)^{5/3}$$

- Typical sizes of d_0 ~ a few meters to 20 meters

Dependence of d_0 on beacon altitude



from Hardy

- **One Rayleigh beacon OK for D < 4 m at λ = 1.65 micron**
- **One Na beacon OK for D < 10 m at λ = 1.65 micron**

Effects of laser guide star on overall AO error budget

- The good news:
  - Laser is brighter than your average natural guide star
    - Reduces measurement error
  - Can point it right at your target
    - Reduces anisoplanatism
- The bad news:
  - Still have <u>tilt</u> anisoplanatism
  - New: focus anisoplanatism
  - Laser spot larger than NGS

$$\sigma_{tilt}^2 = (\theta / \theta_{tilt})^{5/3}$$

$$\sigma_{FA}^2 = (D / d_0)^{5/3}$$

$$\sigma_{meas}^2 \sim (6.3 / SNR)^2$$

Compare NGS and LGS performance

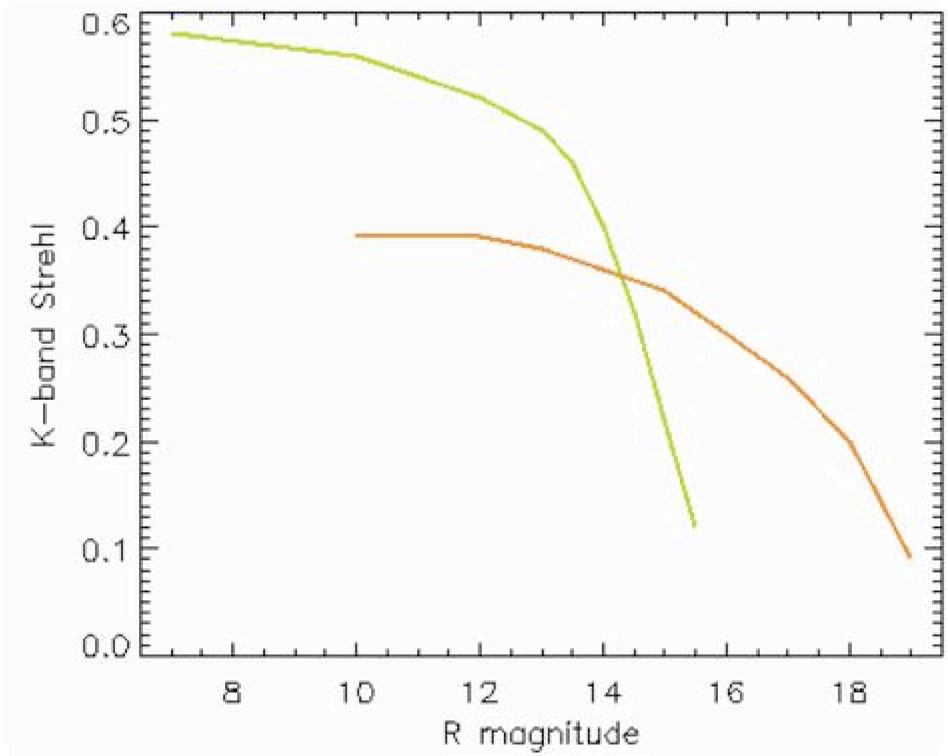


Figure 14: Strehl vs R-magnitude for NGS AO (green) and LGS AO (orange)

Main Points

- Rayleigh beacon lasers are straightforward to purchase, but single beacons are limited to medium sized telescopes due to focal anisoplanatism
- Sodium layer saturates at high peak laser powers
- Sodium beacon lasers are harder:
  - Dye lasers (today) inefficient, hard to maintain
  - Solid-state lasers are better
  - Fiber lasers may be better still
- Added contributions to error budget from LGS's
  - Tilt anisoplanatism, cone effect, larger spot

Projects:

- Investigable science questions
- Resulting performance requirements