Lecture 12

Part 1: Lasers for Guide Stars

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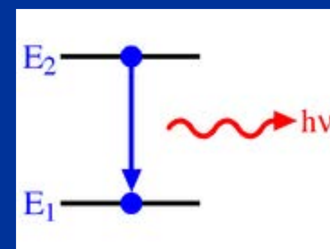
Outline of laser guide star topics

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

Atomic processes for two-level atom

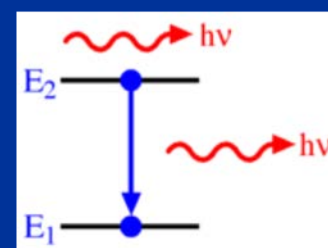
- Einstein, 1916: atom interacts with light in 3 ways
  - Spontaneous emission

$$\left(\frac{dN_1}{dt}\right)_{spont} = A_{21}N_2$$



  - Stimulated emission

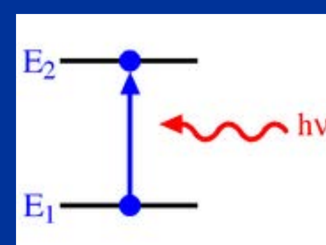
$$\left(\frac{dN_1}{dt}\right)_{stim} = B_{21}N_2U(\nu)$$



Graphics credit: Wikipedia

  - Absorption

$$\left(\frac{dN_1}{dt}\right)_{abs} = -B_{12}N_1U(\nu)$$



N_1, N_2 = density of atoms in states 1 and 2; $U(\nu)$ = radiation density

Saturation effects in the Na layer, from Ed Kibblewhite

- Consider a two level atom which initially has a ground state n containing N_n atoms and an empty upper state m. The atom is excited by a radiation field tuned to the transition

$$\nu = E_m - E_n/h, \qquad h\nu >> kT$$

- In equilibrium $B_{nm}\, U(\nu)\, N_n = A_{mn} N_m + B_{mn}\, U(\nu)\, N_m$

A_{mn} is Einstein's A coefficient (= 1/lifetime in upper state). $B_{nm} = B_{mn}$ = Einstein's B coefficient. $U(\nu)$ is the radiation density in units of Joules/cm^3 Hz

Check units:

(cm^3 Hz / erg) sec^{-1}

atoms

$$B_{nm}\ U(\nu)\ \ N_n = A_{mn}\ N_m + B_{mn}\ U(\nu)\ \ N_m$$

ergs / cm^3 Hz

sec^{-1} per atom

Saturation, continued

- Solve for $N_m = N_n B_{nm} U(\nu) / [B_{nm} U(\nu) + A_{mn}]$
- If we define the fraction of atoms in level m as f and the fraction in level n as (1 - f) we can rewrite this equation as

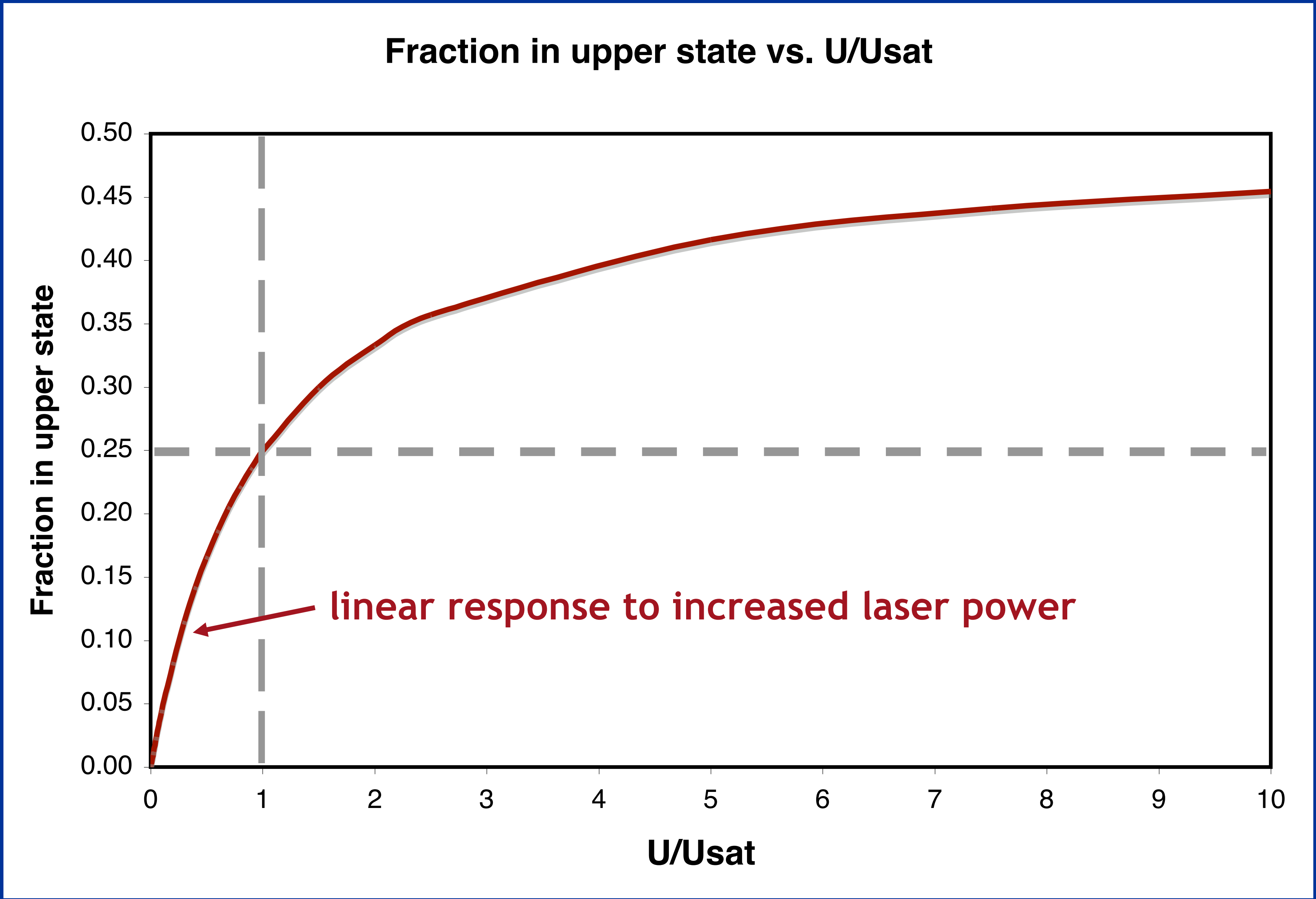
$$f = B_{mn} U(\nu) (1 - f) / (B_{mn} U(\nu) + A_{mn})$$

$$f = 1/[2 + A_{mn}/ B_{mn}U(\nu)]$$

- This equation shows that at low levels of radiation $U(\nu)$ the fraction of atoms in the upper level is $B_{mn} U(\nu) / A_{mn}$
- As the radiation density increases, fraction of atoms in upper level saturates to a maximum level of 1/2 for an infinite value of $U(\nu)$.
- Define a saturation level as radiation field generating 1/2 this max:

$$U_{sat}(\nu) = A_{mn}/2B_{mn}$$

U_{sat} is not a cliff: fraction in upper state keeps increasing for U >> U_{sat}



Saturation, continued

- The ratio A_{mn}/B_{mn} is known from Planck's black body formula and is equal to $8\pi h\nu^3/c^3$ joules cm^{-3} Hz
- The intensity of the radiation field I (ν) is related to U (ν) by

$$I(\nu) = U(\nu)\, c \text{ watts/cm}^2\text{ Hz}$$

$$I_{sat} \approx 9.48 \text{ mW/cm}^2 \text{ for linearly polarized light}$$

- In terms of photons N_{sat} = a few x 10^{16} photons/sec.
- CW (continuous wave) lasers produce more return/watt than pulsed lasers because of lower peak power

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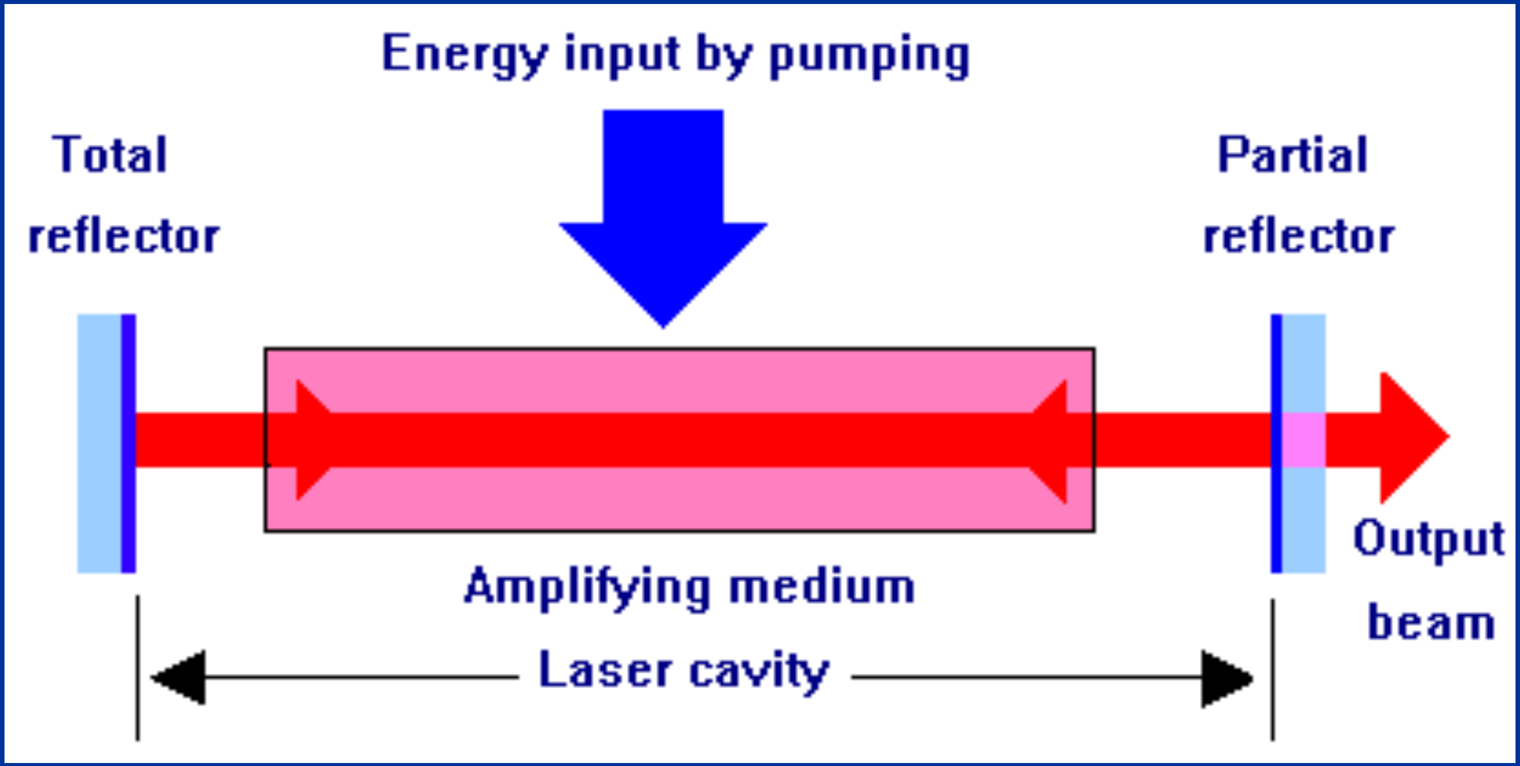
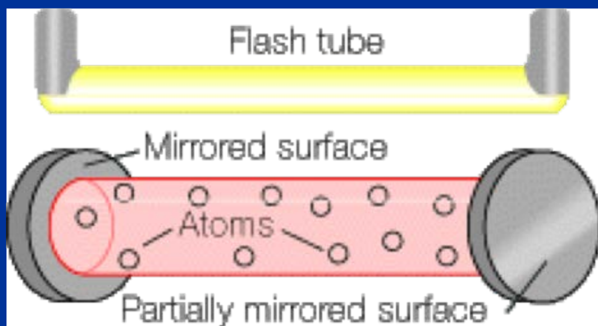
Types of lasers: Outline

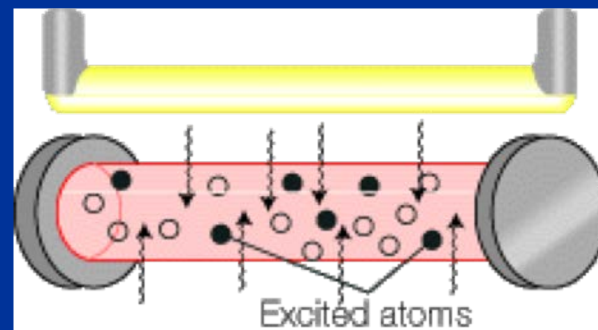
- Principle of laser action
- Lasers used for Rayleigh guide stars
- Lasers used for sodium guide stars

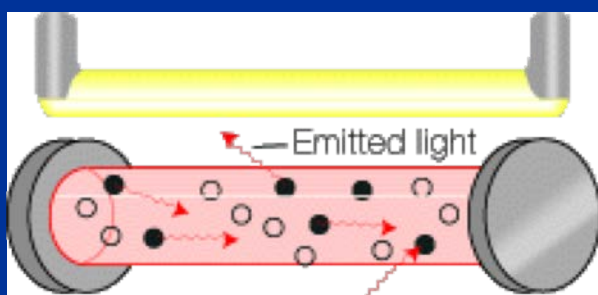
Overall layout (any kind of laser)

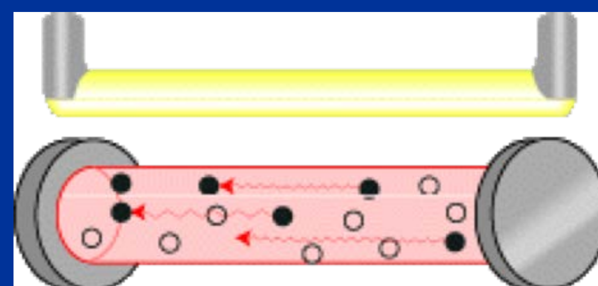


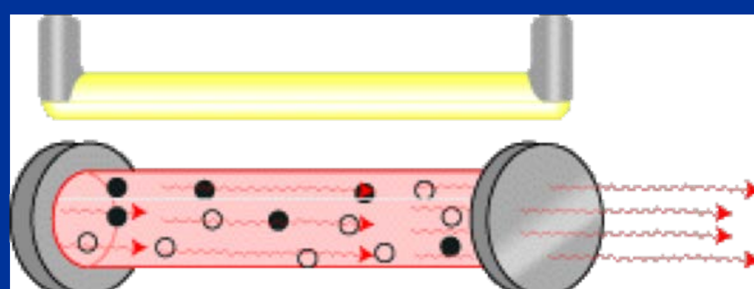
Principles of laser action











Stimulated emission

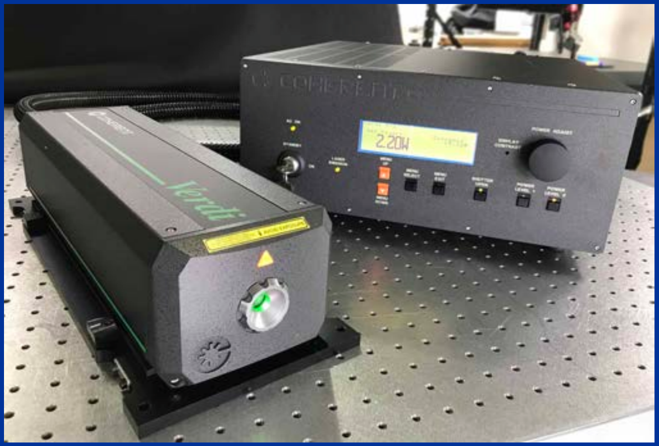
Mirror

Lasers used for Rayleigh guide stars

- Rayleigh x-section ~ λ^{-4} ⇒ short wavelengths better
- Commercial lasers are available
  - Reliable, relatively inexpensive
  - Green laser (532nm) - e.g. MMT
  - RoboAO uses 10W ultraviolet (λ = 355nm) laser pulsed at 10 kHz
    - Invisible to human eye.
    - Unable to flash-blind pilots; Class 1 laser (incapable of producing damaging radiation levels during operation and exempt from any control measures).
    - So no need for "laser spotters" as needed with Na lasers.

Example of laser for Rayleigh guide star: Frequency doubled Nd:YAG lasers

- Nd:YAG means "neodimium-doped yttrium aluminum garnet"
- Nd:YAG lases 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 18 Watts



Robo AO Error Budget on UC 88" Telescope

Percentile Seeing	25%	50%		75%
Atmospheric r0	22.1 cm	16.8 cm		10.3 cm
Effective seeing at zenith (with dome seeing)	0.69"	0.80"		1.00"
Zenith angle	15 degrees	15 degrees	45 degrees	35 degrees
High-order Errors	**Wavefront Error (nm)**			
Atmospheric Fitting Error	38	43	51	56
Bandwidth Error	36	42	49	54
High-order Measurement Error	24	27	30	34
LGS Focal Anisoplanatism Error	75	103	124	160
Multispectral Error	3	3	94	46
Scintillation Error	12	15	27	27
WFS Scintillation Error	10	10	10	10
Uncorrectable Tel / AO / Instr Aberrations	38	38	38	38
Zero-Point Calibration Errors	34	34	34	34
Pupil Registration Errors	21	21	21	21
High-Order Aliasing Error	13	14	17	19
DM Stroke / Digitization Errors	1	1	1	1
Total High Order Wavefront Error	**112 nm**	**136 nm**	**185 nm**	**198 nm**
Tip-Tilt Errors	**Angular Error (mas)**			
Tilt Measurement Error	11	11	13	14
Tilt Bandwidth Error	8	11	9	11
Science Instrument Mechanical Drift	6	6	6	6
Residual Telescope Pointing Jitter	2	2	2	2
Residual Centroid Anisoplanatism	1	1	2	2
Residual Atmospheric Dispersion	1	1	4	3
Total Tip/Tilt Error (one-axis)	**15 mas**	**16 mas**	**17 mas**	**19 mas**

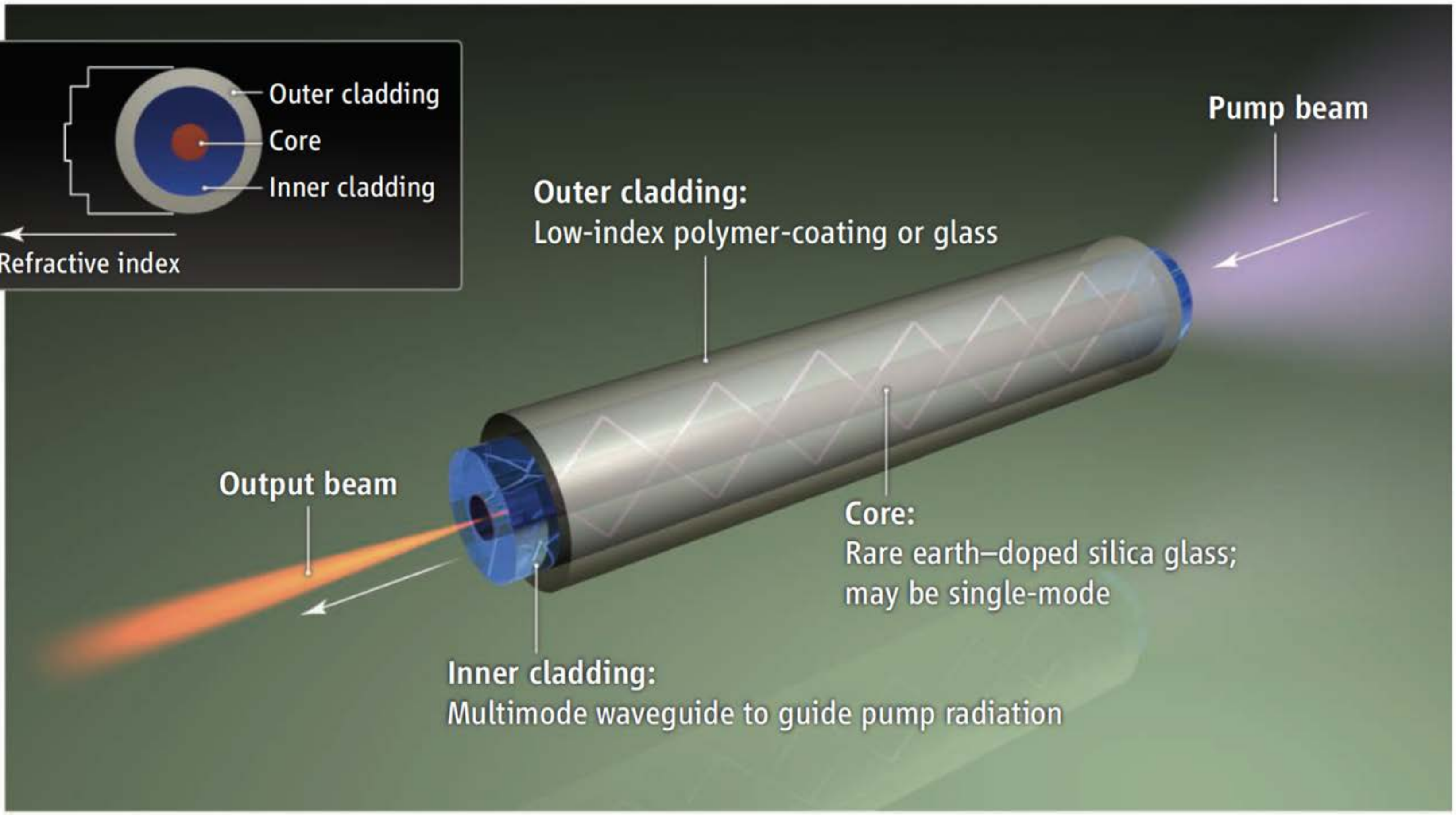
Total Effective Wavefront Error (IRTT)	**129 nm**	**155 nm**	**195 nm**	**208 nm**
Total Effective WFE (VISTT)	**124 nm**	**157 nm**	**195 nm**	**209 nm**

Spectral Band	λ	λ/D		Strehl	FWHM	Strehl	FWHM	Strehl	FWHM	Strehl	FWHM
g'	0.47 μ	0.044"		6%	0.06"	2%	0.07"	1%	0.11"	0%	0.49"
r'	0.62 μ	0.058"		18%	0.07"	9%	0.07"	6%	0.08"	1%	0.13"
i'	0.75 μ	0.070"		30%	0.08"	18%	0.08"	14%	0.08"	5%	0.10"
J	1.25 μ	0.117"		64%	0.12"	54%	0.12"	45%	0.13"	33%	0.13"
H	1.64 μ	0.153"		76%	0.16"	69%	0.16"	61%	0.16"	51%	0.16"

General comments on guide star lasers

- Typical average powers of a few watts to 20 watts
  - Much more powerful than typical laboratory lasers
- Na guide stars - 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"
- As a result, need to have interlocks on cabinets and doors, and avoid airplanes and satellites

Pump light propagates through cladding, pumps doped fiber all along its length



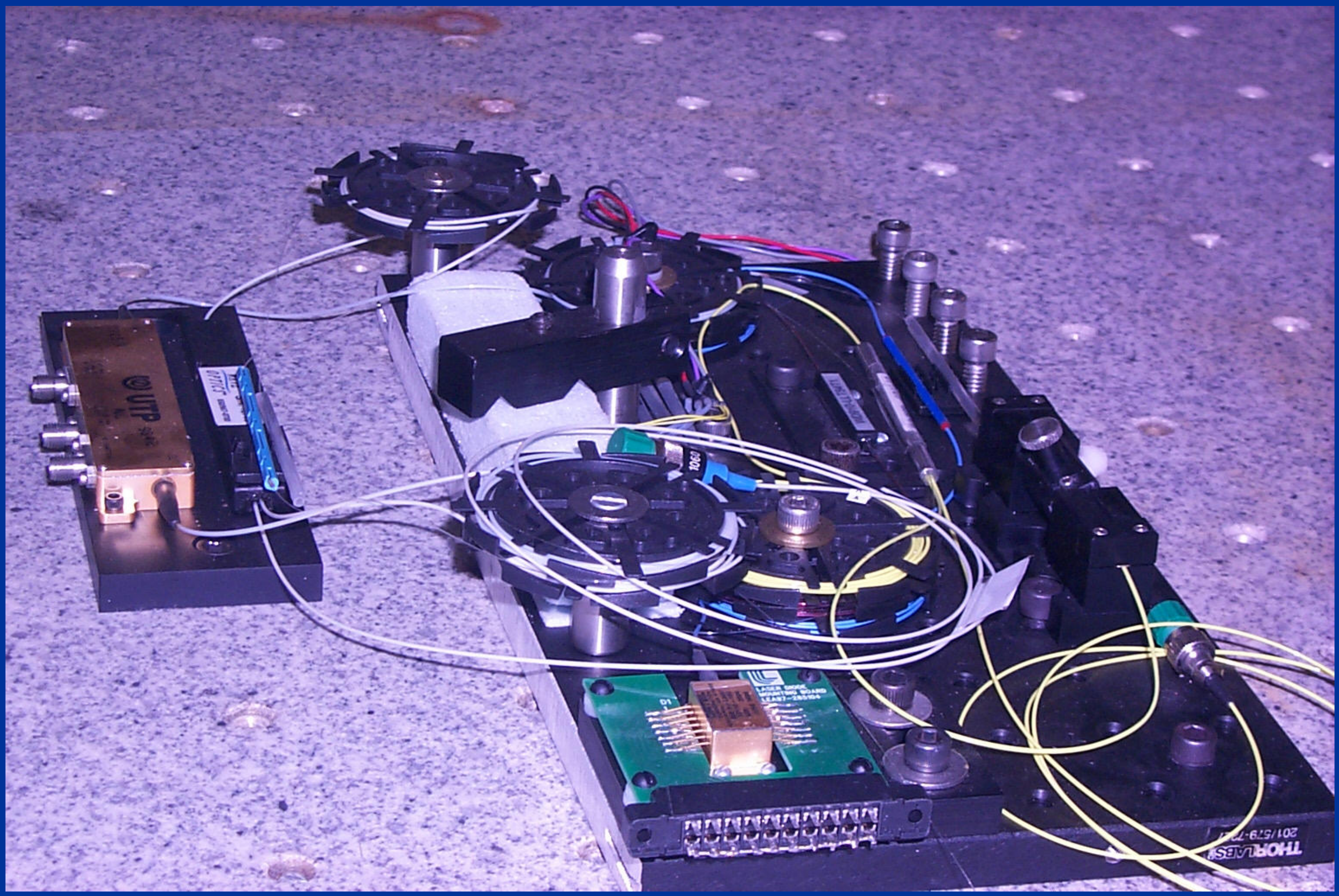
Fiber lasing. Schematic of a double-clad fiber laser in an end-pumped configuration (not to scale).

Credit: Nilsson and Payne, Science Magazine, 2011

Procuring lasers for sodium guide stars

- No known laser medium wants to lase directly at 589nm, the wavelength of the Na D_2 transition
- To make 589nm light, have to make use of <u>nonlinear</u> processes in the lasing medium
  - *Raman scattering:* shifts laser wavelength to a slightly longer one
  - *Frequency doubling:* two photons at frequency υ interact nonlinearly in a nonlinear crystal to produce a photon at frequency 2υ
  - *Sum frequency mixing:* $\upsilon_{out} = \upsilon_1 + \upsilon_2$ in a nonlinear crystal

Current generation of Na lasers: all-fiber laser (Toptica, LLNL and UCSC)



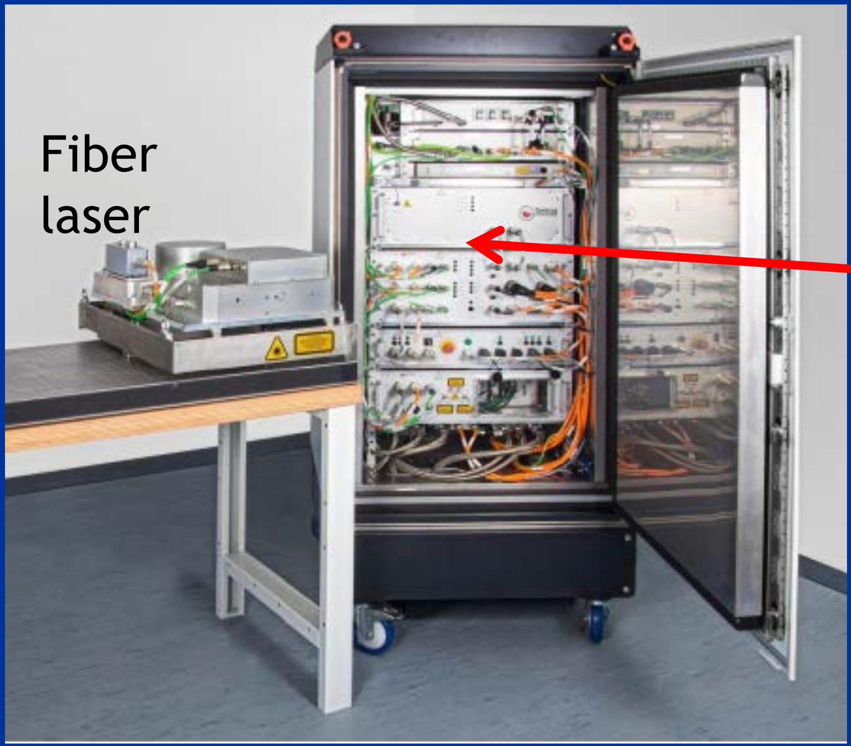
- Example of a fiber laser

Advantages of fiber lasers

- Very compact
- Commercial parts from telecommunications industry
- Efficient:
  - Pump with laser diodes - high efficiency
  - The doped fiber is in the core
  - Pump light goes thru fiber cladding 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, Daren Dillon at UCSC plus Jay Dawson at LLNL)

Toptica laser (concept developed by ESO)

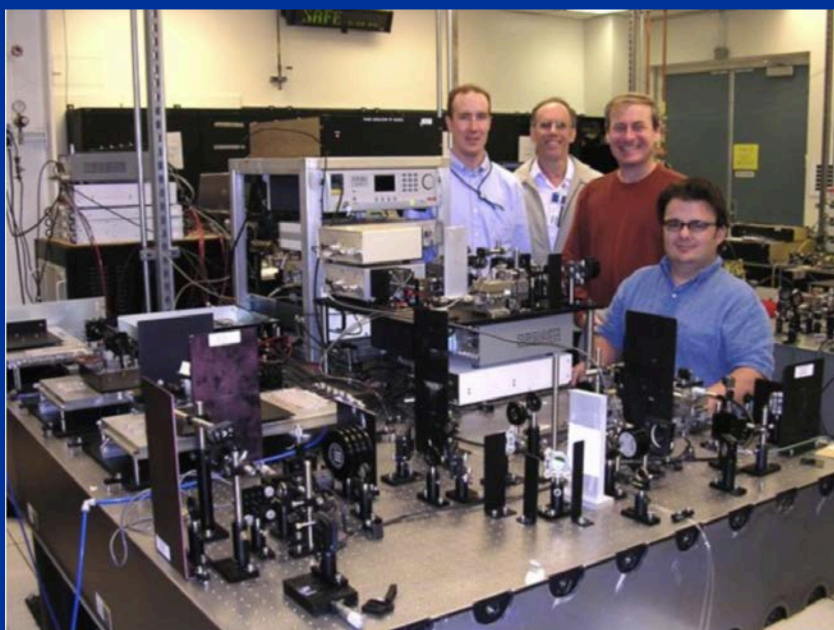
- Start with pump fiber laser at 1120 nm
- Raman shift to longer wavelength -- 1178 nm
- Then frequency-double to 589 nm



Keck Toptica Laser

CfAO Fiber laser concept developed by Daren Dillon (UCSC) and Jay Dawson (LLNL)

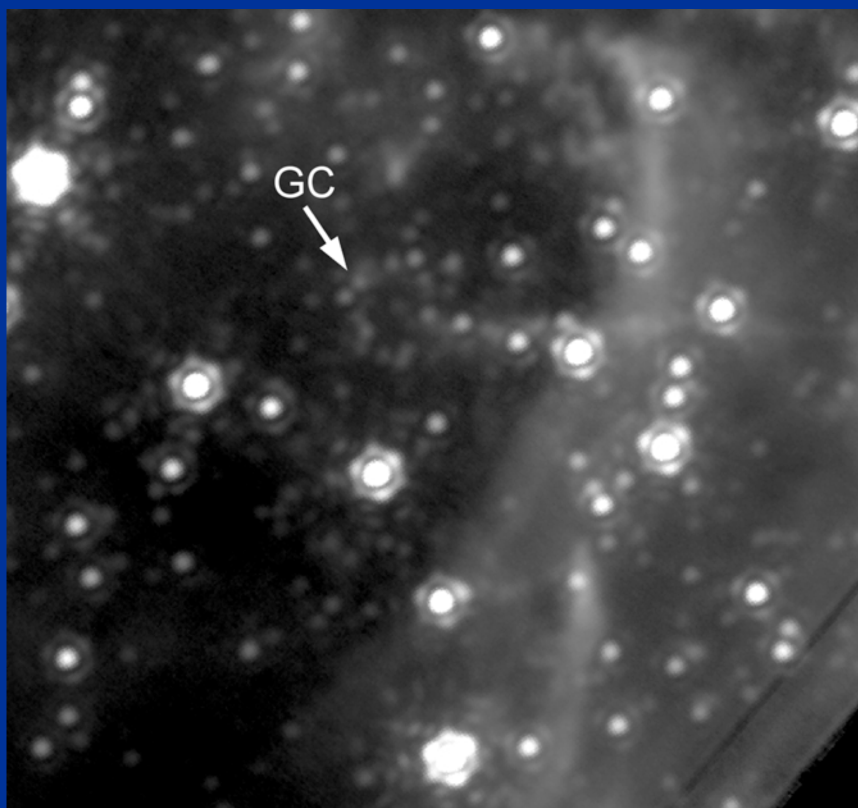
- Two separate fiber amplifiers, sum frequency mixing
- One at 938 nm, one at 1583 nm

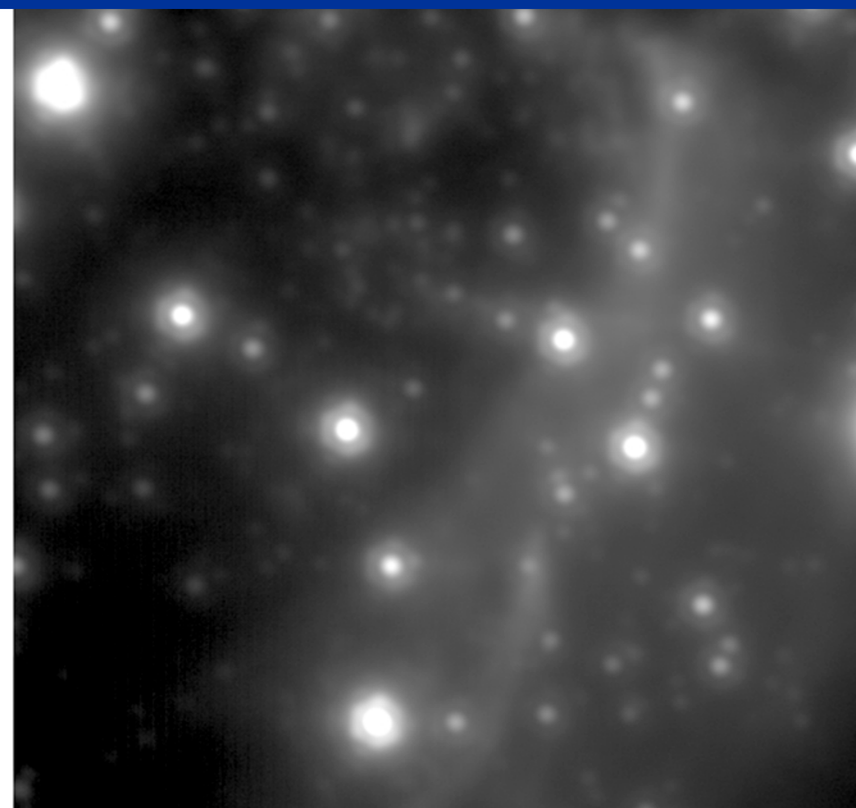


$$\frac{1}{938}+\frac{1}{1583}=\frac{1}{589}$$

Galactic Center with Keck laser guide star AO

Keck laser guide star AO **Best natural guide star AO**





Andrea Ghez, UCLA group

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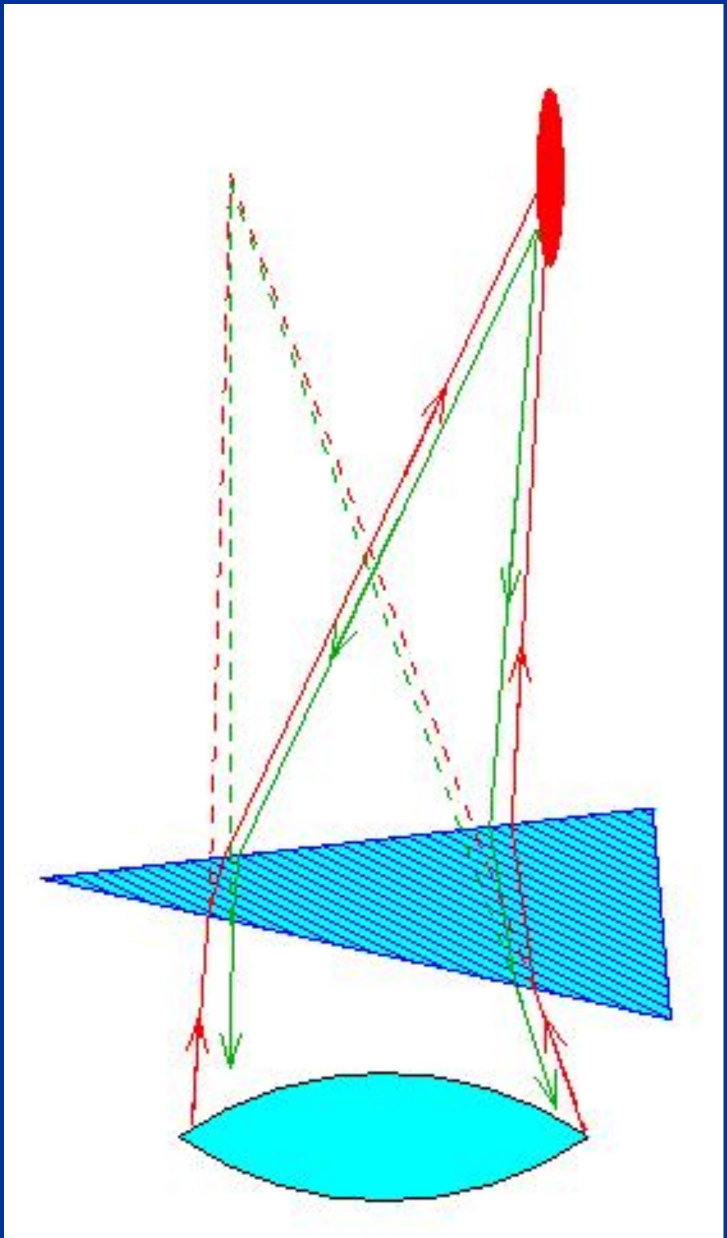
  - Stop here if we are running out of time

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



from A. Tokovinin

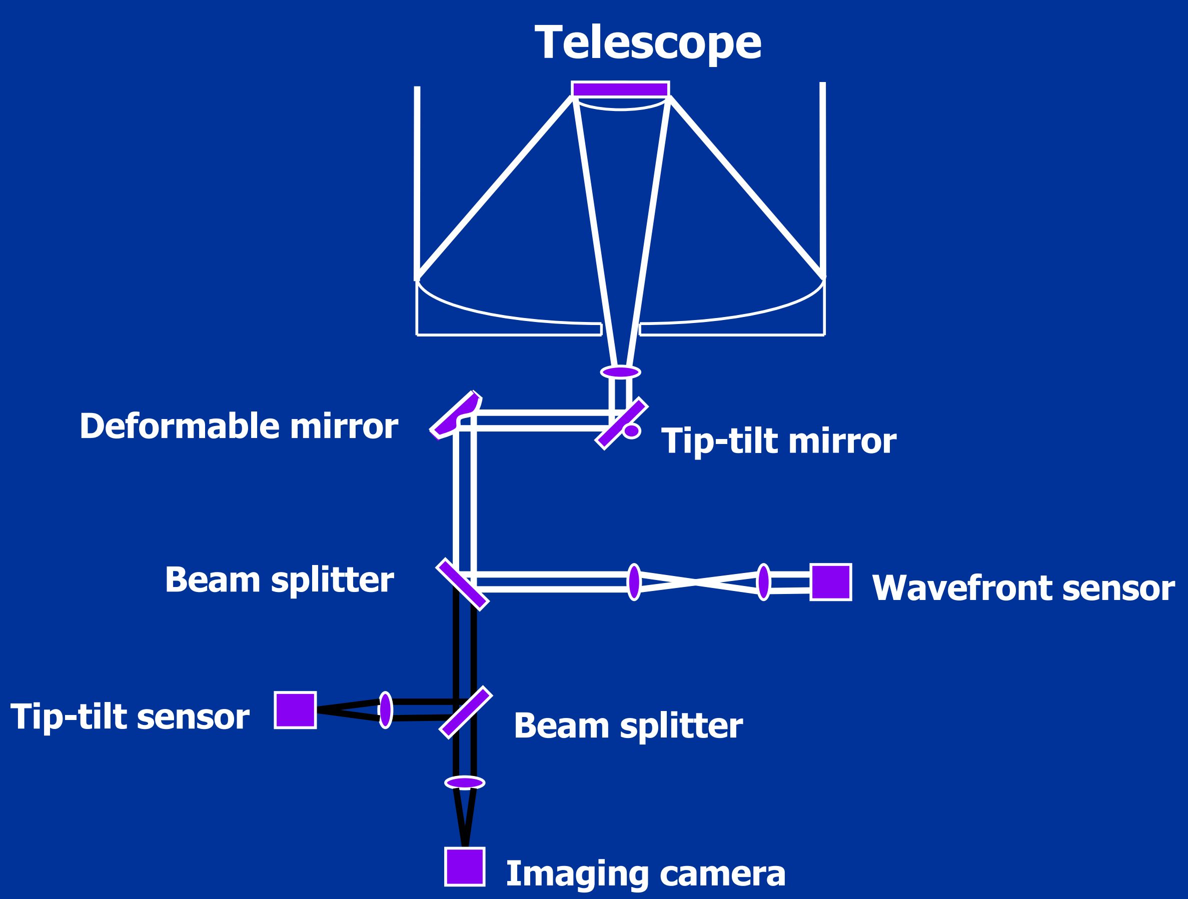
Effective isoplanatic angle for image motion: "isokinetic angle"

- 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

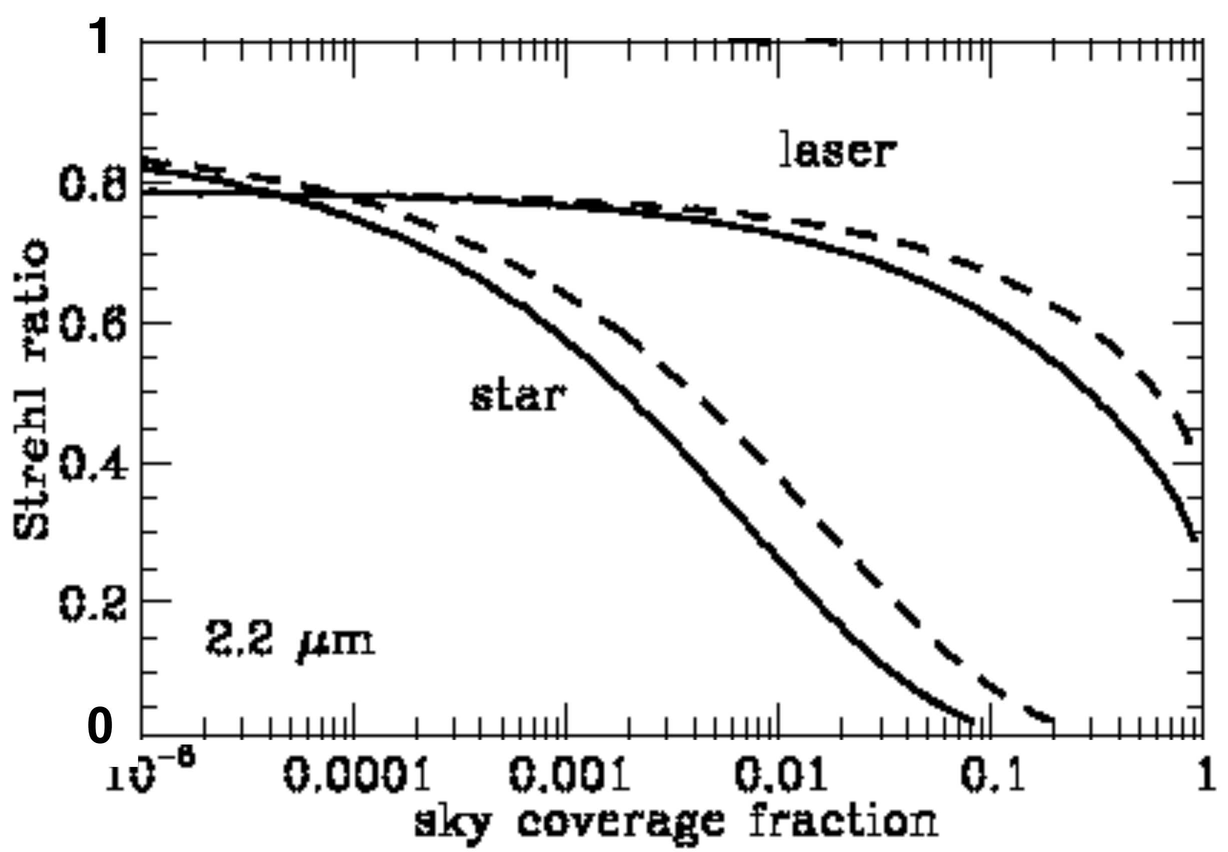
- "Isokinetic angle"
  - Analogue of isoplanatic angle, but for tip-tilt only
  - Typical values in infrared: of order 1 arc min

Tip-tilt mirror and sensor configuration



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

Sky coverage fraction: probability that your favorite galaxy will have a bright enough TT star nearby



From Keck AO book

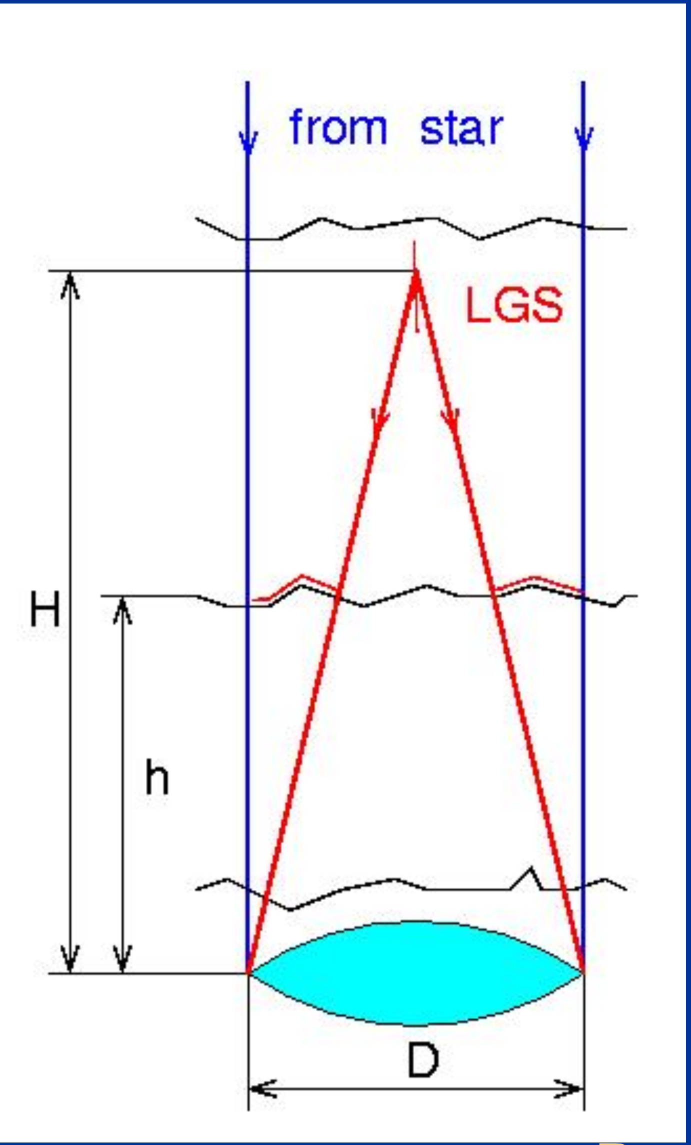
- Keck: >18th mag

—— Galactic latitude = 90˚
..... Galactic latitude = 30˚

Assumes:
271 deg of freedom
5 W cw laser

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

- "Real" star is at infinity, whereas laser is at finite height
- Two contributions:
  - Unsensed turbulence above height of guide star
  - Geometrical effect of unsampled turbulence at edge of pupil



from A. Tokovinin

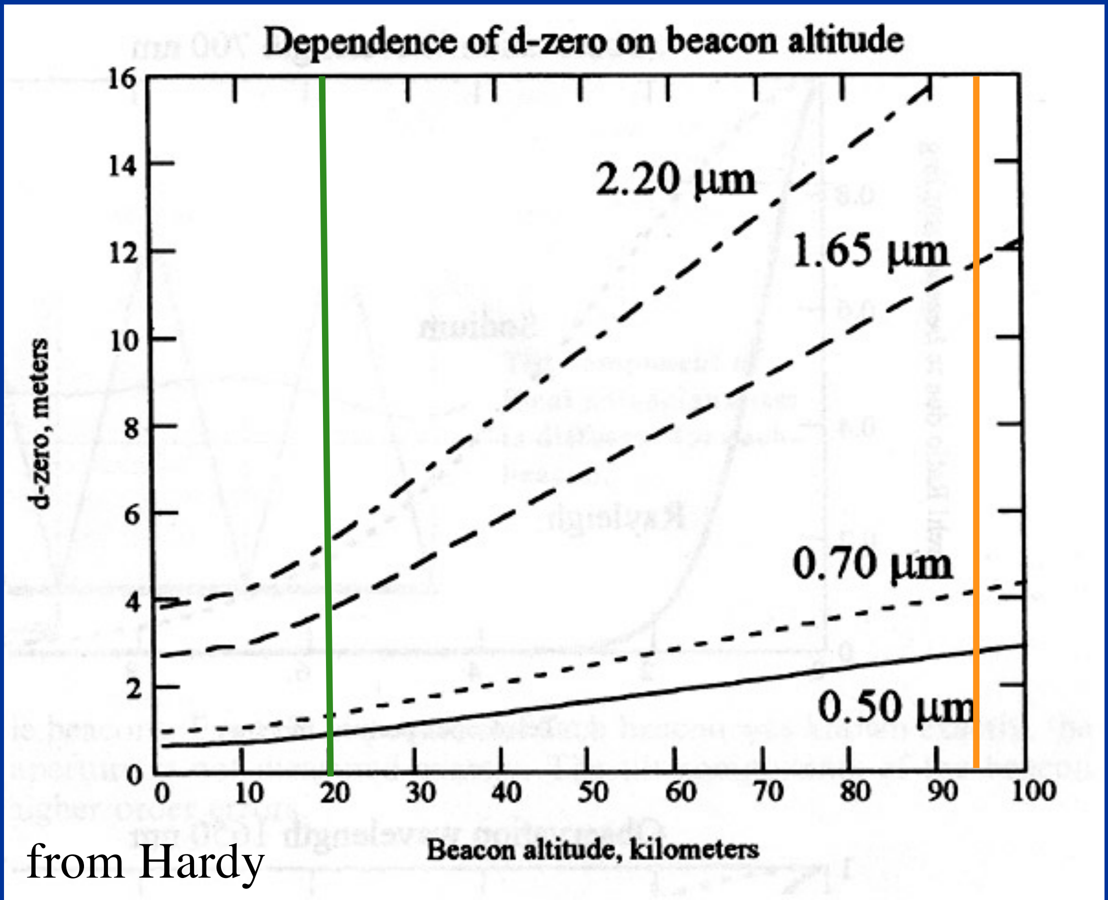
Cone effect, continued

- 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



- 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 $\sigma_{tilt}^2 = (\theta / \theta_{tilt})^{5/3}$
  - New: focus anisoplanatism $\sigma_{FA}^2 = (D / d_0)^{5/3}$
  - Laser spot larger than NGS $\sigma_{meas}^2 \sim (6.3 / SNR)^2$

Compare NGS and LGS performance

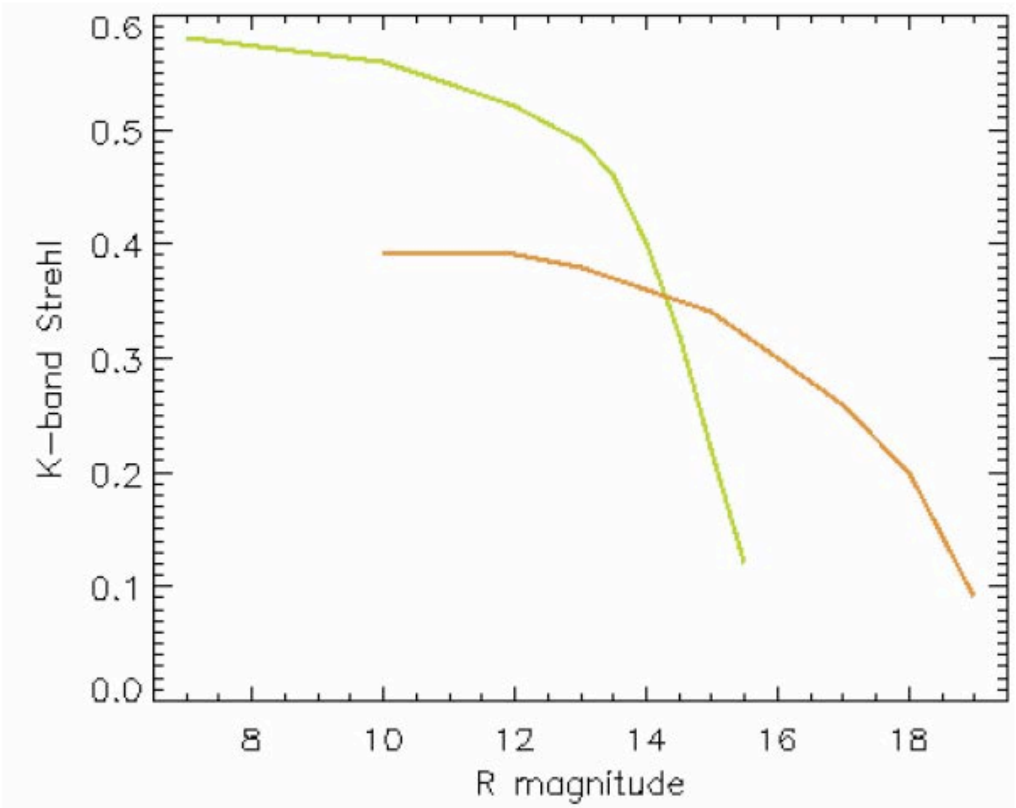


Figure 14: Strehl vs R-magnitude for NGS AO (green) and LGS AO (orange)

- **Schematic, for visible tip-tilt star**

Main Points

- Rayleigh beacon lasers are straightforward to purchase, but single beacons are limited to medium sized telescopes due to focal anisoplanatism
  - Can fix if you use multiple lasers
- Sodium layer saturates at high peak laser powers, so try to use long pulses or "CW" (continuous wave) lasers
- For Na guide stars, fiber lasers are the way to go (long pulses, low peak power)
- Added contributions to error budget from LGS's
  - Tilt anisoplanatism, cone effect, larger spot