Lectures 9
Laser Guide Stars

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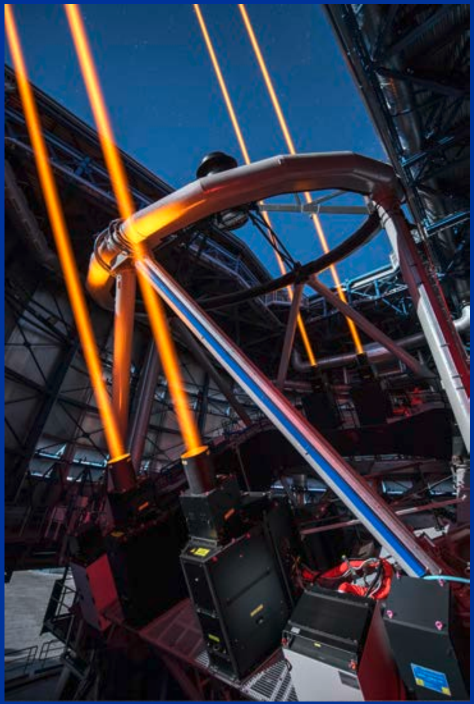
First, some pretty pictures

Lick Observatory

ESO VLT



Credit: Laurie Hatch

Credit: ESO/G. Hüdepohl

- Movie of 3 lasers in operation on Mauna Kea, HI: https://vimeo.com/24338510

Outline of lectures on laser guide stars

- Why are laser guide stars needed?
- Principles of laser scattering in the atmosphere
  - Rayleigh scattering, resonant scattering from sodium
- 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

Laser guide stars: Main points

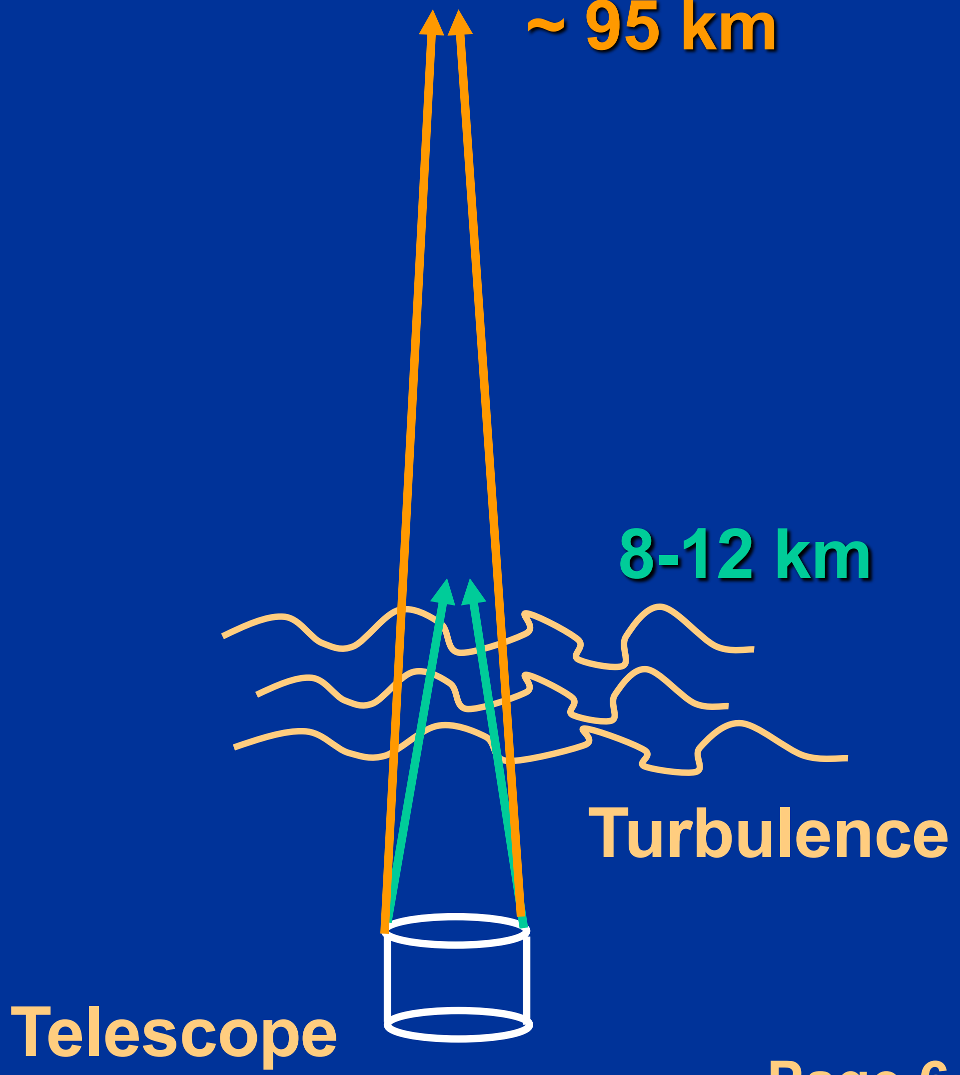
- Laser guide stars are needed because there aren't enough bright natural guide stars in the sky
  - Hence YOUR favorite galaxy probably won't have a bright enough natural guide star nearby

- Solution: make your own guide star using lasers
  - Nothing special about coherent light - could use a flashlight hanging from a "giant high-altitude helicopter"
  - Size on sky has to be $\lesssim$ diffraction limit of a WFS sub-aperture

- Laser guide stars have pluses and minuses:
  - Pluses: can put them anywhere, can be bright
  - Minuses: NGS give better AO performance than LGS even when both are working perfectly. High-powered lasers are tricky to build and work with. Laser safety is added complication.

Two types of laser guide stars in use today: "Rayleigh" and "Sodium"

- **Sodium guide stars:** excite atoms in "sodium layer" at altitude of ~ 95 km
- **Rayleigh guide stars:** Rayleigh scattering from air molecules sends light back into telescope, h ~ 10 km
- Higher altitude of sodium layer is closer to sampling the same turbulence that a star from "infinity" passes through



Reasons why laser guide stars can't do as well as bright natural guide stars

1) Laser light is spread out by turbulence on the way up.
   - Spot size is finite (0.5 - 2 arc sec)
   - Can increase measurement error of wavefront sensor
     - Harder to find centroid if spot is larger

2) For Rayleigh guide stars, some turbulence is above altitude where light is scattered back to telescope.
   - Hence it can't be measured.

3) For both kinds of guide stars, light coming back to telescope is spherical wave, but light from "real" stars is plane wave
   - Some turbulence around edges of the pupil isn't sampled well

Laser beacon geometry causes measurement errors

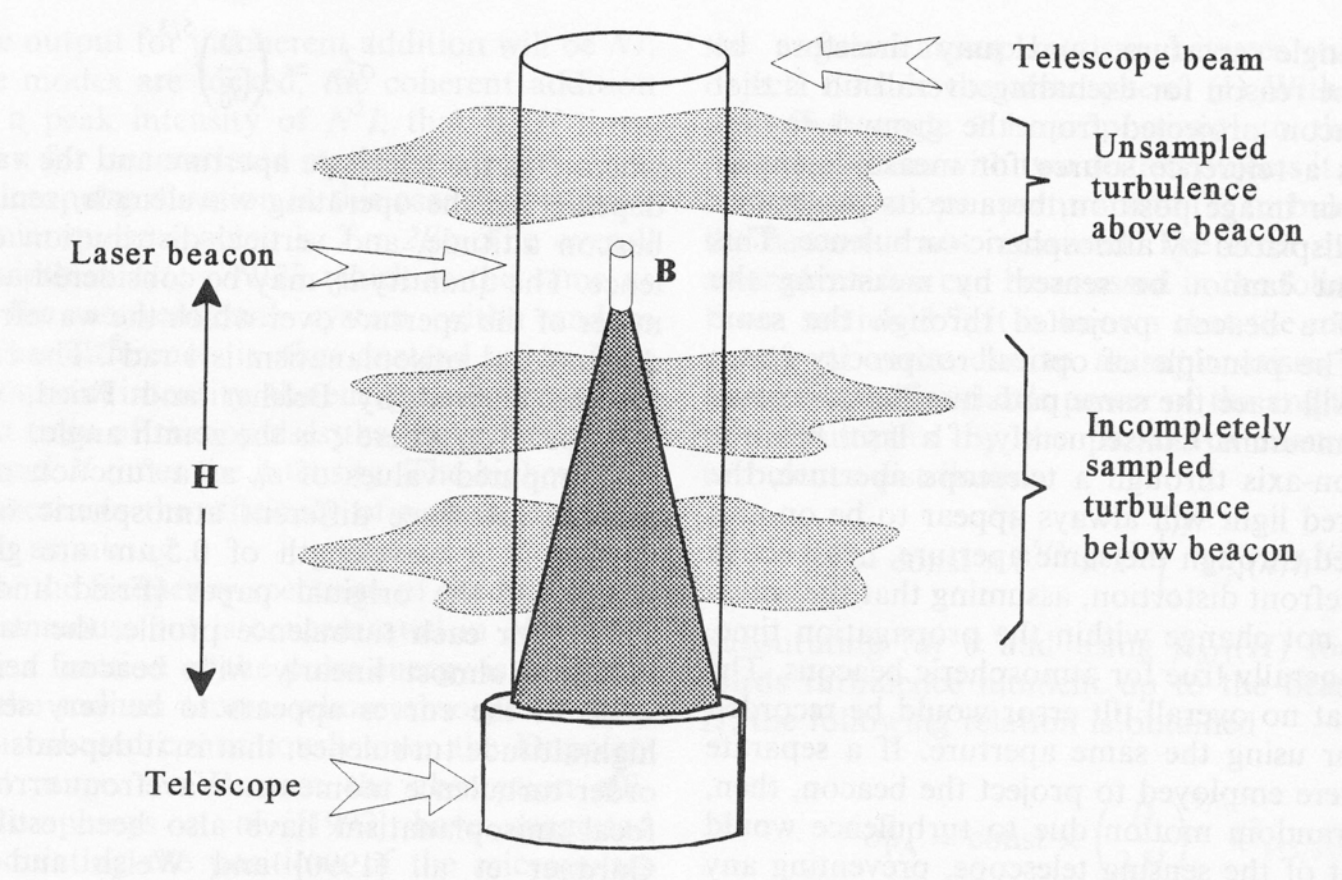


Figure 7.14 Laser beacon measurement errors.

Credit: Hardy

Why are laser guide stars needed?

- **Wavefront error due to anisoplanatism:**

$$\sigma_\phi^2 = \left(\frac{\theta}{\theta_0}\right)^{5/3} \qquad \theta_0 \cong 0.314\left(\frac{r_0}{\bar{h}}\right)$$

$$\bar{h} \equiv \left(\frac{\int z^{5/3}\, dz\, C_N^2(z)}{\int dz\, C_N^2(z)}\right)^{3/5}$$

Example: At Keck θ_0 ~ 10 arc sec x (λ / 0.5 micron)$^{6/5}$

What is σ_ϕ^2 for $\theta = 40$ arc sec at $\lambda = 1$ micron?

What is Strehl loss due to anisoplanatism?

Answers: $\sigma_\phi^2 = 2.52$ rad^2, Strehl = 0.08 x Strehl at $\theta = 0$

How many bright stars are there?

- There are about 6 million stars in the whole sky brighter than 13th magnitude
- Area of sky = $4\pi \; r^2 = 4\pi \; (360 / 2\pi)^2$

  sky contains $(360 \text{ deg})^2 / \pi$ sq deg = 41,253 sq deg
- Question: How many stars brighter than 13th mag are there per square arc sec on the sky?

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- Question: How many stars brighter than 13th mag are there per square arc sec on the sky?

Answer: 10^{-5} stars per square arc sec (!)

If we can only use guide stars closer than ~ 40 arc sec, sky coverage is low!

- High-order Shack-Hartmann AO systems typically need guide stars brighter than magnitude V ~ 13.5
  [V band: central wavelength ~ 0.54 μm]
- Surface density of these stars on the sky is
  $\Sigma \sim 10^{-5} / (\text{arc sec})^2$
- So probability *P* of finding bright enough guide star w/in radius of 40 arc sec of an arbitrary place in the sky is

$$P = \Sigma \pi (40)^2 = 10^{-5} \pi (40)^2 = 0.05$$

- Magnitude V ~ 13.5 stars only have 5% sky coverage, at least for Shack Hartmann sensors!

Solution: make your own guide star using a laser beam

- Point the laser beam directly at YOUR favorite astronomical target

- Use scattering of laser light by the atmosphere to create an "artificial" guide star
  - Sometimes called "synthetic beacon" or "artificial beacon"

- What physical mechanism causes the laser light to scatter back down into your telescope's wavefront sensor?

Scattering: 2 different physical processes

- Rayleigh Scattering (Rayleigh beacon)
  - Elastic scattering from atoms or molecules in atmosphere. Works for broadband light, no change in frequency
- Resonance Scattering (Sodium Beacon)
  - Line radiation is absorbed and emitted with no change in frequency.

Regardless of the type of scattering…

Number of photons detected =

(number of transmitted photons

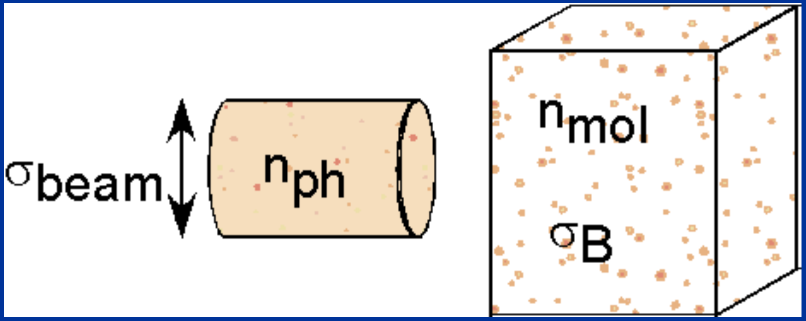
x probability that a transmitted photon is scattered

x probability that a scattered photon is collected

x probability that a collected photon is detected)

+ background photons (noise)

Amount of Photon Scattering



n_{ph} = # of photons

σ_{beam} = laser beam cross-section

n_{mol} = density of scatterers

σ_B = scattering cross-section

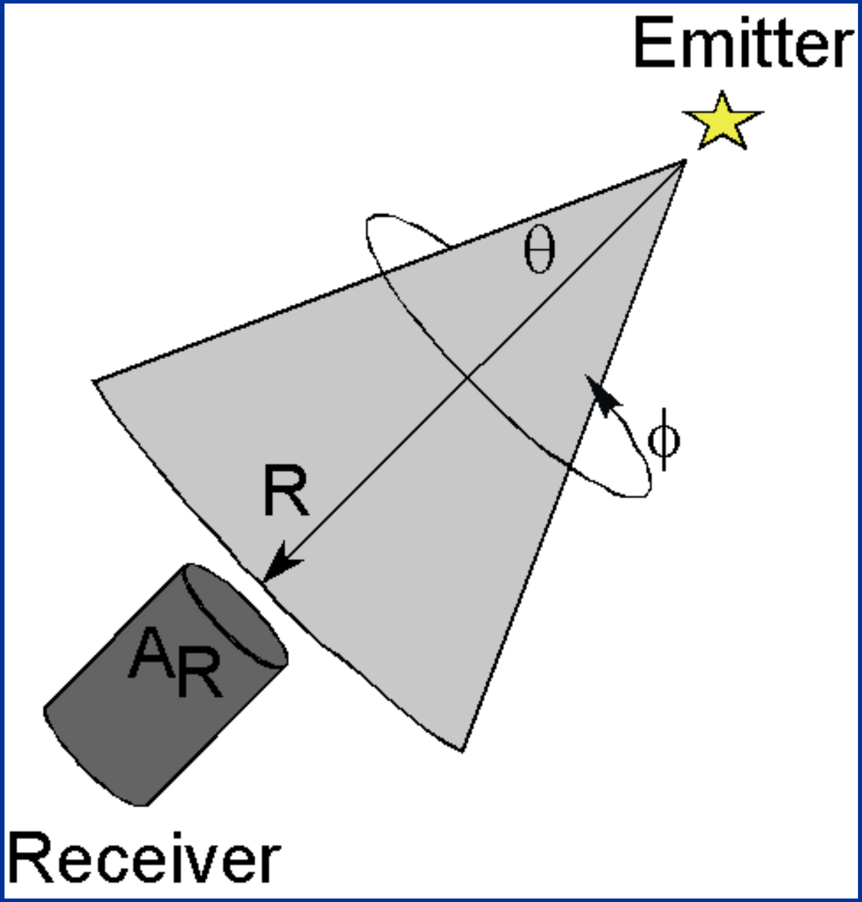
- # molecules hit by laser beam in volume $\sigma_{beam}\ \Delta z = n_{mol}\ (\sigma_{beam}\ \Delta z\ )$
- Percentage of beam scattered = $[\ n_{mol}\ (\ \sigma_{beam}\ \Delta z\ )\ ]\ \sigma_B\ /\sigma_{\ beam}$
- Total number of photons scattered = $(\ E_L\ /\ h\nu\ )\ (\ n_{mol}\sigma_B\ \Delta z\ )$
- E_L and ν are laser's energy and frequency, h is Planck's constant

Percentage of photons collected

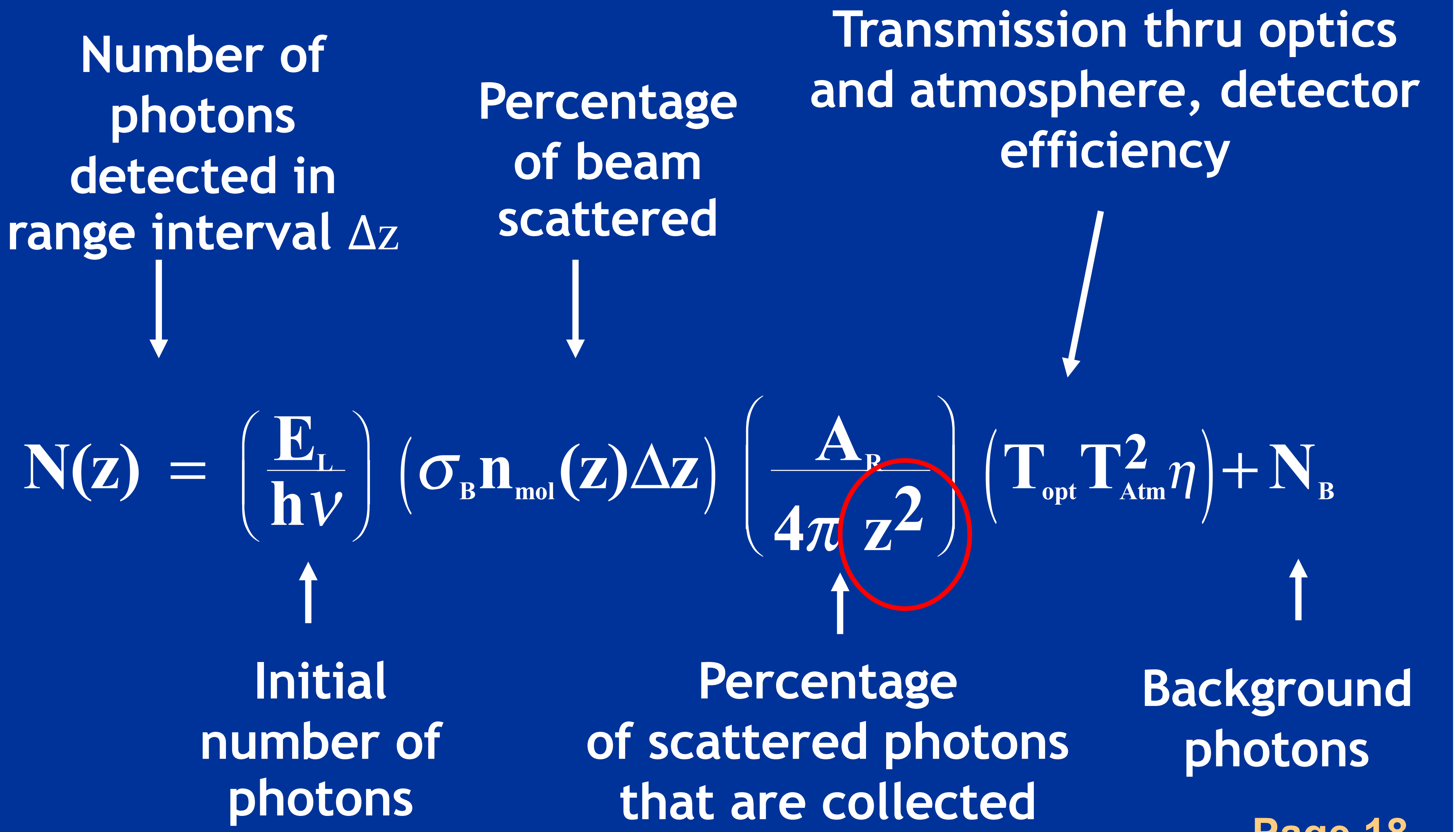
- Assuming uniform emission over 2π steradians, scattered photons are uniformly distributed over area

$$\int_0^{2\pi}\int_0^{\pi} R^2 \sin\theta \, d\theta \, d\phi = 4\pi R^2$$

- Percentage of photons collected = $A_R / (4 \pi R^2)$ where A_R is receiver area



LIDAR Equation
(LIght Detection And Ranging)



Number of photons detected in range interval Δz

Percentage of beam scattered

Transmission thru optics and atmosphere, detector efficiency

$$N(z) = \left(\frac{E_L}{h\nu}\right)\left(\sigma_B n_{mol}(z)\Delta z\right)\left(\frac{A_R}{4\pi z^2}\right)\left(T_{opt}T_{Atm}^2\eta\right) + N_B$$

Initial number of photons

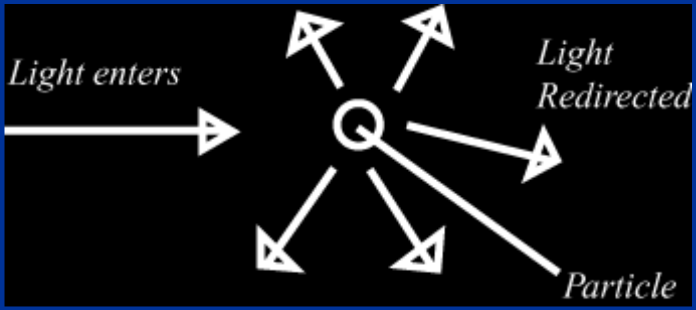
Percentage of scattered photons that are collected

Background photons

Rayleigh Scattering

- Due to interactions of the electromagnetic wave from the laser beam with molecules in the atmosphere.

- The light's electromagnetic fields induce dipole moments in the molecules, which then emit radiation at same frequency as the exciting radiation (elastic scattering).



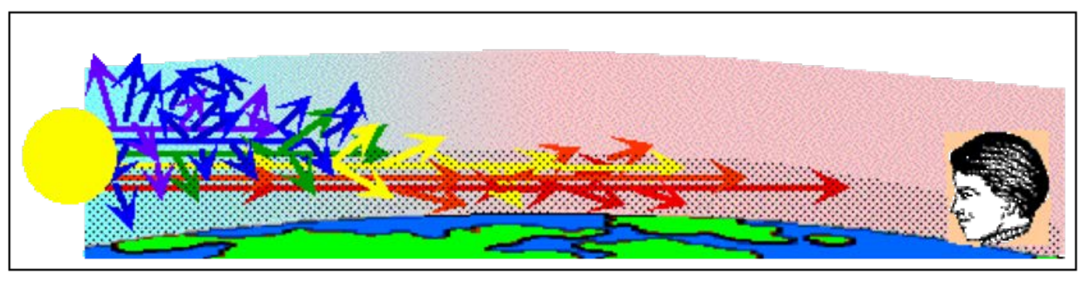
Rayleigh Scattering cross section

- Rayleigh **back**scattering cross section is

$$\sigma_B^R = \frac{d\sigma^R(\theta=\pi)}{d\Omega} \cong \frac{5.5\times10^{-28}}{\left(\lambda/0.55\mu m\right)^4} \quad cm^2 sr^{-1}$$

where λ is laser wavelength

- Scattering $\propto \lambda^{-4}$ ⇒ use shorter wavelength lasers for better scattering efficiency
- Why sunsets look red:



Dependence of Rayleigh scattering on altitude where the scattering occurs

- Product of Rayleigh scattering cross section with density of molecules is

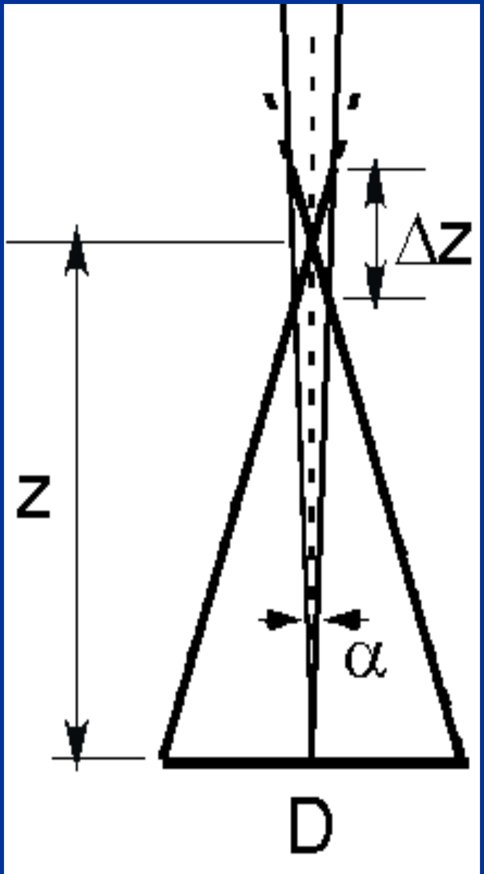
$$\sigma_B^R n_{mol} \cong 3.6 \times 10^{-31} \frac{P(z)}{T(z)} \lambda^{-4.0117} \quad \mathrm{m}^{-1}\ \mathrm{sr}^{-1}$$

where *P(z)* is the pressure in millibars at altitude z, and *T(z)* is temperature in degrees K at altitude z

- Because pressure *P(z)* falls off exponentially with altitude, Rayleigh beacons are generally limited to altitudes below 8 - 12 km

Rayleigh laser guide stars use timing of laser pulses to detect light from Δz

- Use a pulsed laser, preferably at a short wavelength (UV or blue or green) to take advantage of λ^{-4}
- Cut out scattering from altitudes lower than z by taking advantage of light travel time z/c
- Only open shutter of your wavefront sensor when you know that a laser pulse has come from the desired scattering volume Δz at altitude z



Rayleigh laser guide stars

- LBT ARGOS laser guide star

MMT laser guide star, Arizona

- Starfire Optical Range, NM. Quite a few years ago.

Robo-AO UV laser

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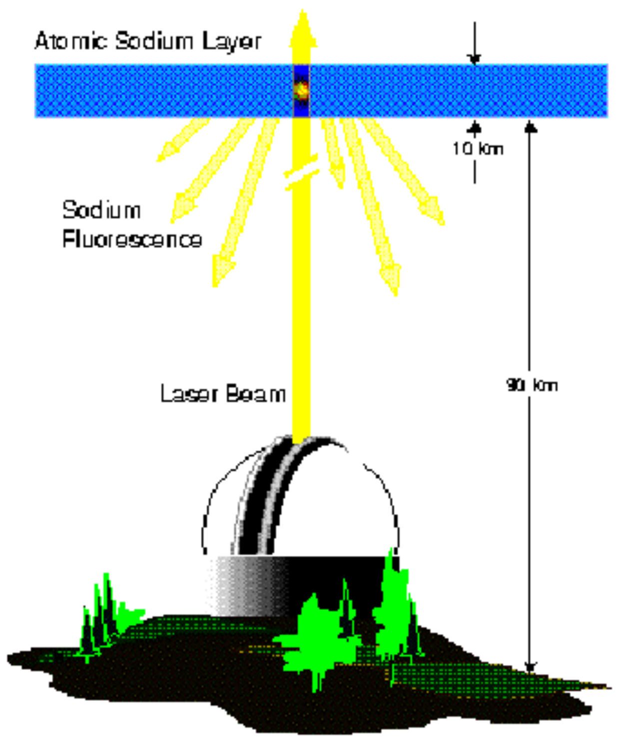
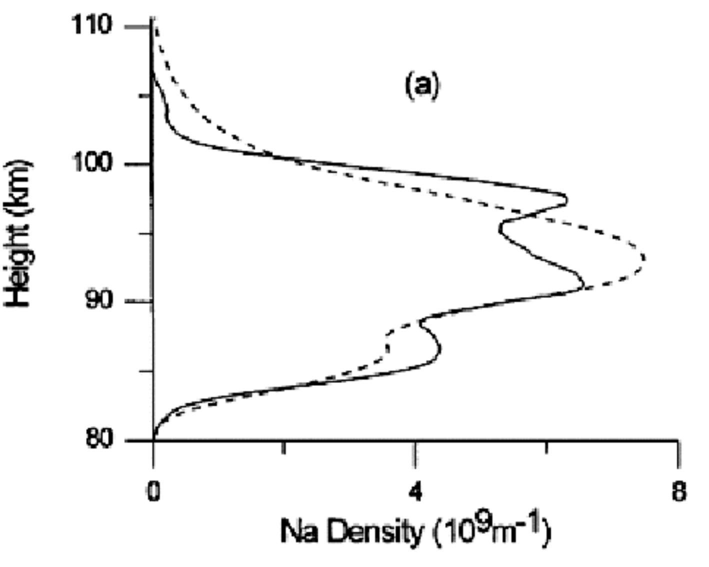
Sodium Resonance Fluorescence

- Resonance scattering occurs when incident laser is tuned to a specific atomic transition.
- Absorbed photon raises atom to excited state. Atom emits photon of same wavelength via spontaneous or stimulated emission, returning to original lower state.
- Large absorption and scattering cross-sections.
- Layer in mesosphere ($h \sim 95$ km, $\Delta h \sim 10$ km) containing alkali metals, sodium (10^3 - 10^4 atoms/cm^3), potassium, calcium
- Strongest laser return is from D_2 line of Na at 589 nm.

The atmospheric sodium layer: altitude ~ 95 km , thickness ~ 10 km



Credit: Milonni, LANL



Credit: Clemesha, 1997

- Layer of neutral sodium atoms in mesosphere (height ~ 95 km)
- Thought to be deposited as smallest meteorites burn up

Rayleigh scattering vs. sodium resonance fluorescence

- Atmosphere has ~ exponential density profile:

$$-\nabla(nkT) = nMg \Rightarrow n(z) = n_o \exp\text{-}\left(\frac{Mg\,z}{kT}\right)$$

- M = molecular mass, n = no. density, T = temperature, k = Planck's constant, g = gravitational acceleration
- Rayleigh scattering dominates over sodium fluorescence scattering below h = 75 km.

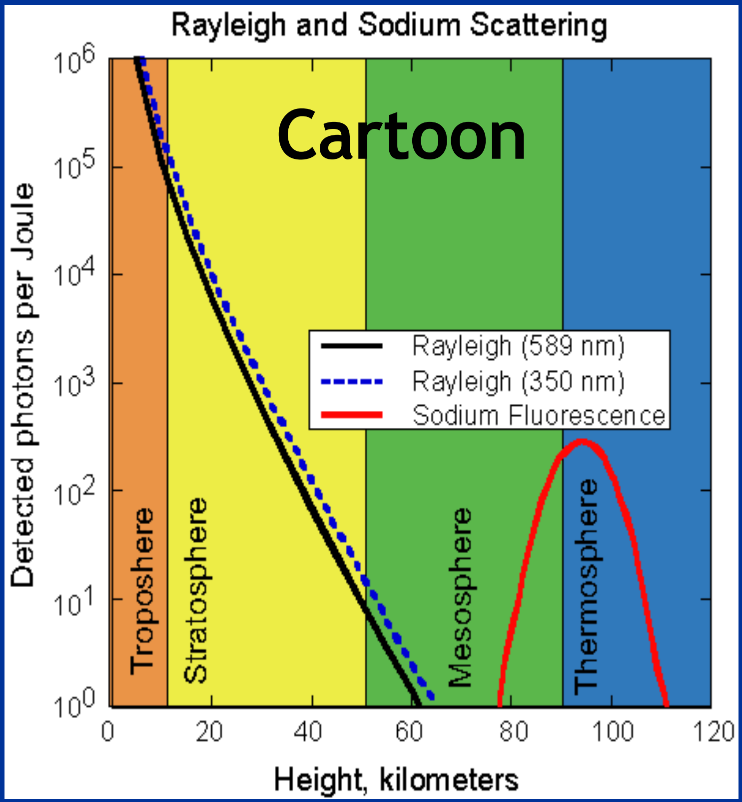
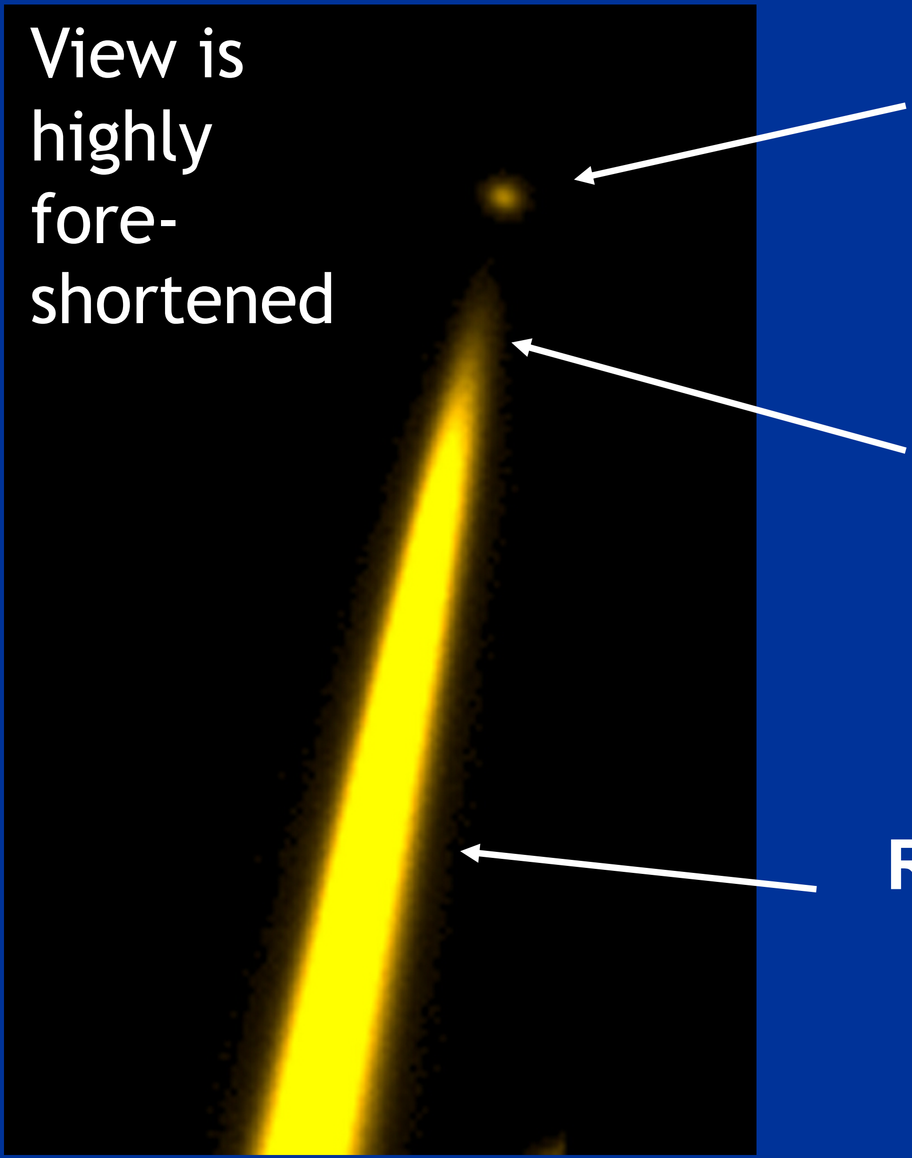


Image of sodium light taken from telescope very close to main telescope

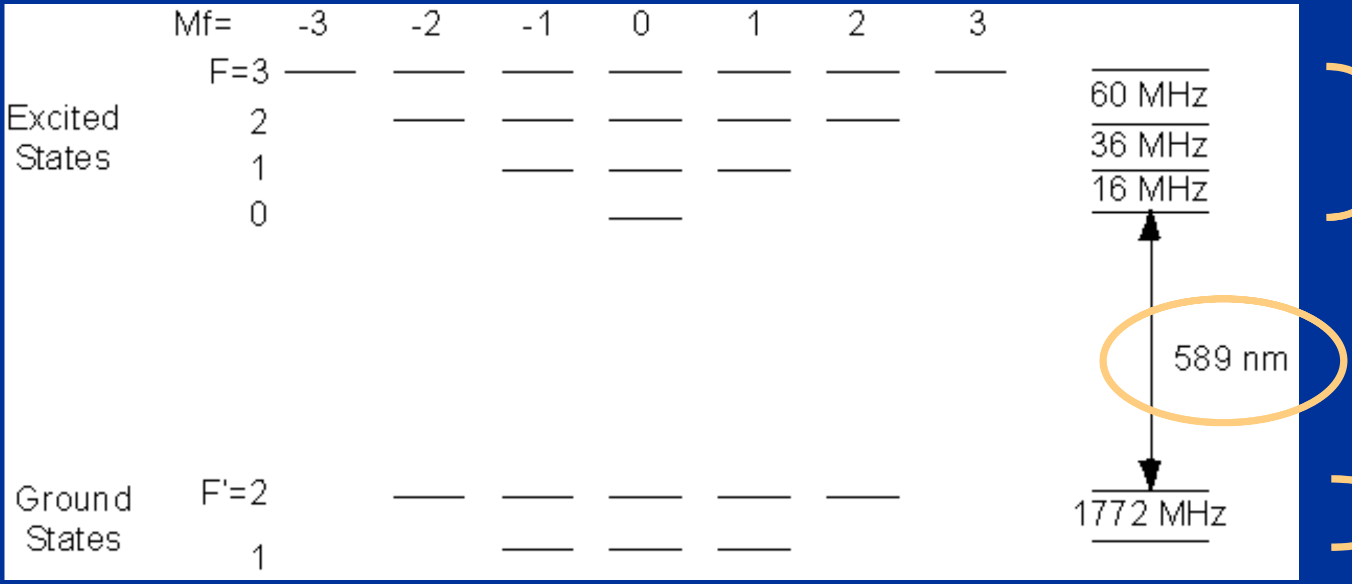


Light from Na layer at ~ 100 km

Max. altitude of Rayleigh ~ 35 km

Rayleigh scattered light from low altitudes

Can model Na D_2 transition as a two-level atom (one valence electron)



Hyperfine splitting

Hyperfine splitting (not to scale)

- Hyperfine splitting: spins of valence electron and nucleus are (or are not) aligned
- Separation between upper three hyperfine states is small
- Separation bet. two ground states is large: 1.8 GHz

Overview of sodium physics

- Column density of sodium atoms is relatively low
  - Less than 600 kg in whole Earth's sodium layer!

- When you shine a laser on the sodium layer, the optical depth is only a few percent. Most of light just keeps on going upwards.

- Natural lifetime of D_2 transition is short: 16 nsec

- Can't just pour on more laser power, because sodium D_2 transition saturates:
  - Once all the atoms that CAN be in the excited state ARE in the excited state, return signal stops increasing even with more laser power

Origin of sodium layer

- Layer 10 km thick, at an altitude of 90 km - 105 km in the Earth's "mesosphere"

- Thought to be due to meteorites: at this altitude, small meteorites aimed toward the Earth first get hot enough to evaporate
  - Deposit their elements in atmosphere in atomic state: iron, potassium, sodium, lithium, ...
  - Atomic layer is "eaten away" at its bottom by chemical reactions (e.g. oxidation reactions)

Sodium abundance varies with season

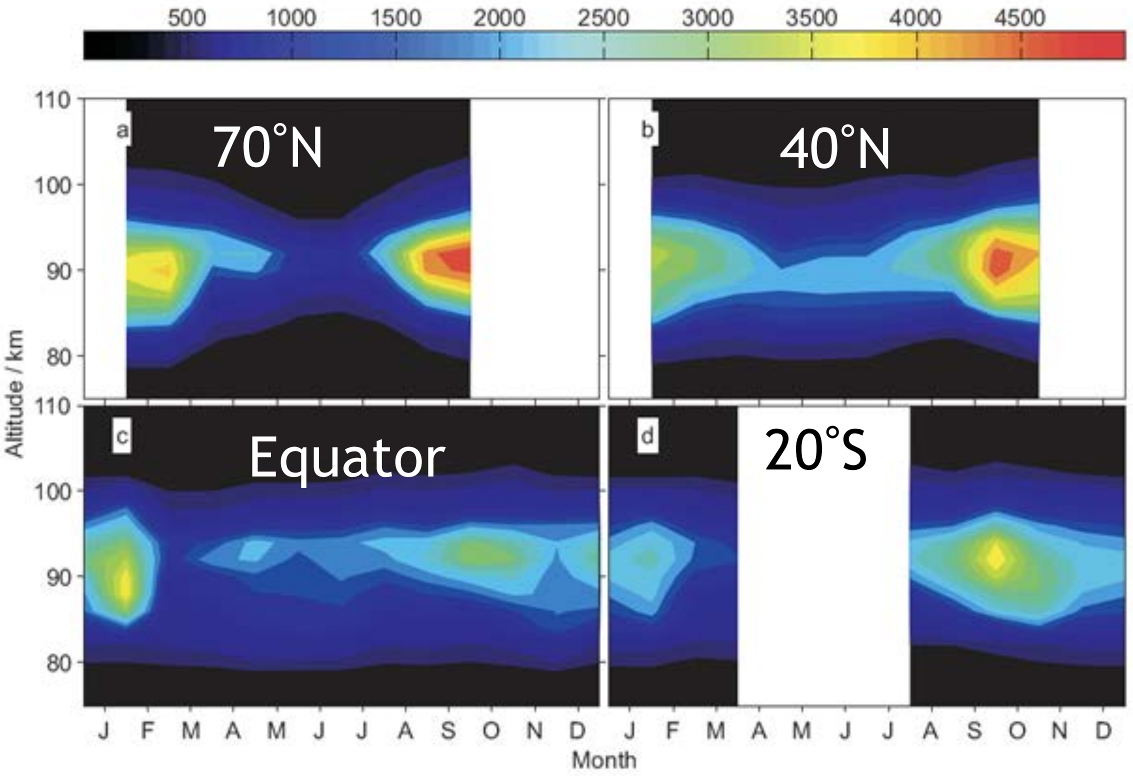


Fig. 3. Seasonal variation of the zonally- averaged Na density profile (units: atom cm^{-3}) at four latitude bands centred at **(a)** 70° N, **(b)** 40° N, **(c)** the equator, and **(d)** 20° S.

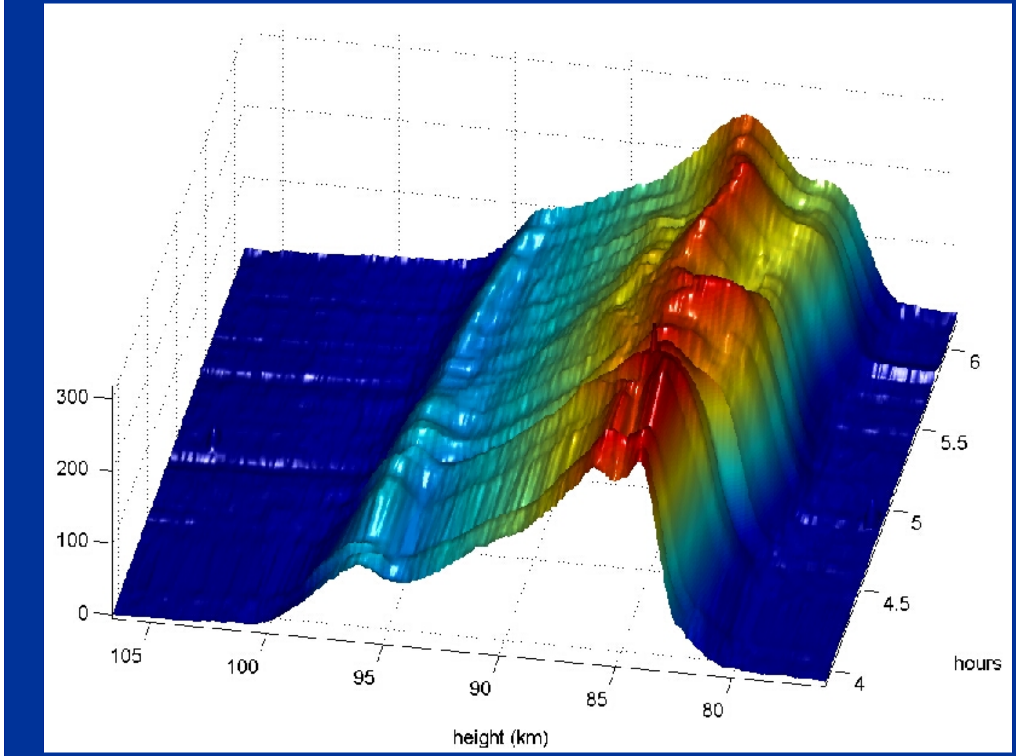
Satellite measurements of the global mesospheric sodium layer

Z. Y. Fan[1], J. M. C. Plane[2], J. Gumbel[3], J. Stegman[3], and E. J. Llewellyn[4]

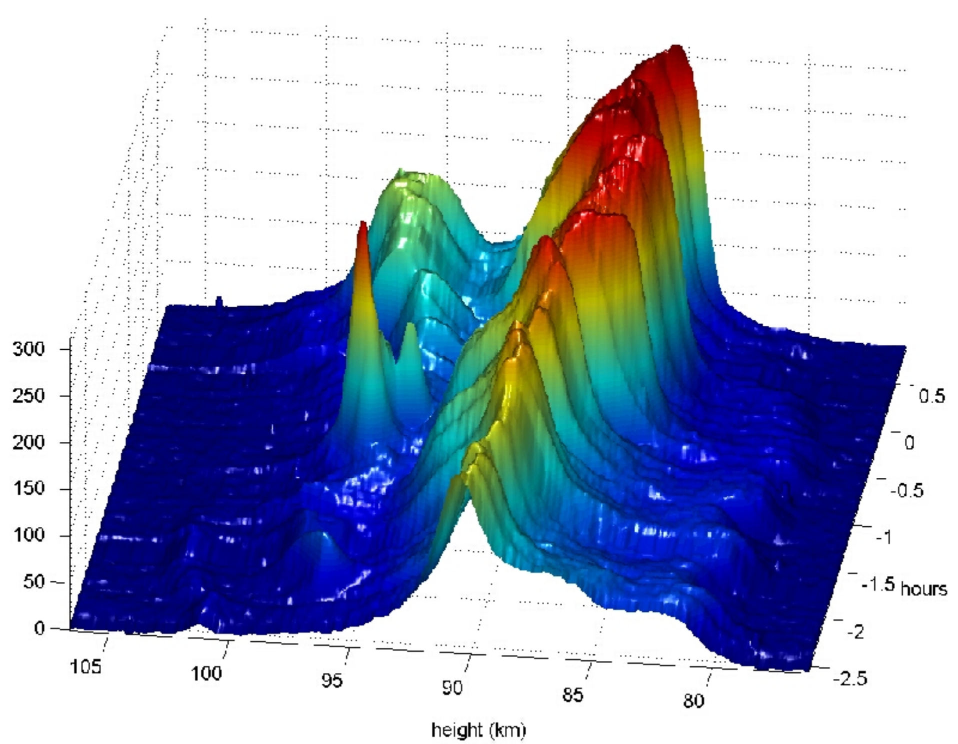
- Equatorial regions: density is more constant over the year, but peak is lower
- Temperate regions: lowest density in summer
  - Chemical reactions at bottom of layer

Time variation of Na density profiles over periods of 4 - 5 hours

Night 1: single peaked



Night 2: double peaked



At La Palma, Canary Islands

Outline of laser guide star topics

- ✓ Why are laser guide stars needed?
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- Physics of sodium atom excitation
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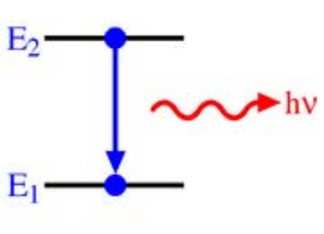
Atomic processes for two-level atom

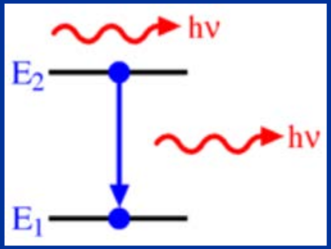
- Einstein, 1916: atom interacts with light in 3 ways
  - Spontaneous emission

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



  - Stimulated emission

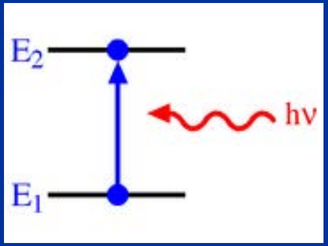
$$\left(\frac{dN_1}{dt}\right)_{stim} = B_{21}N_2U(\nu)$$



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

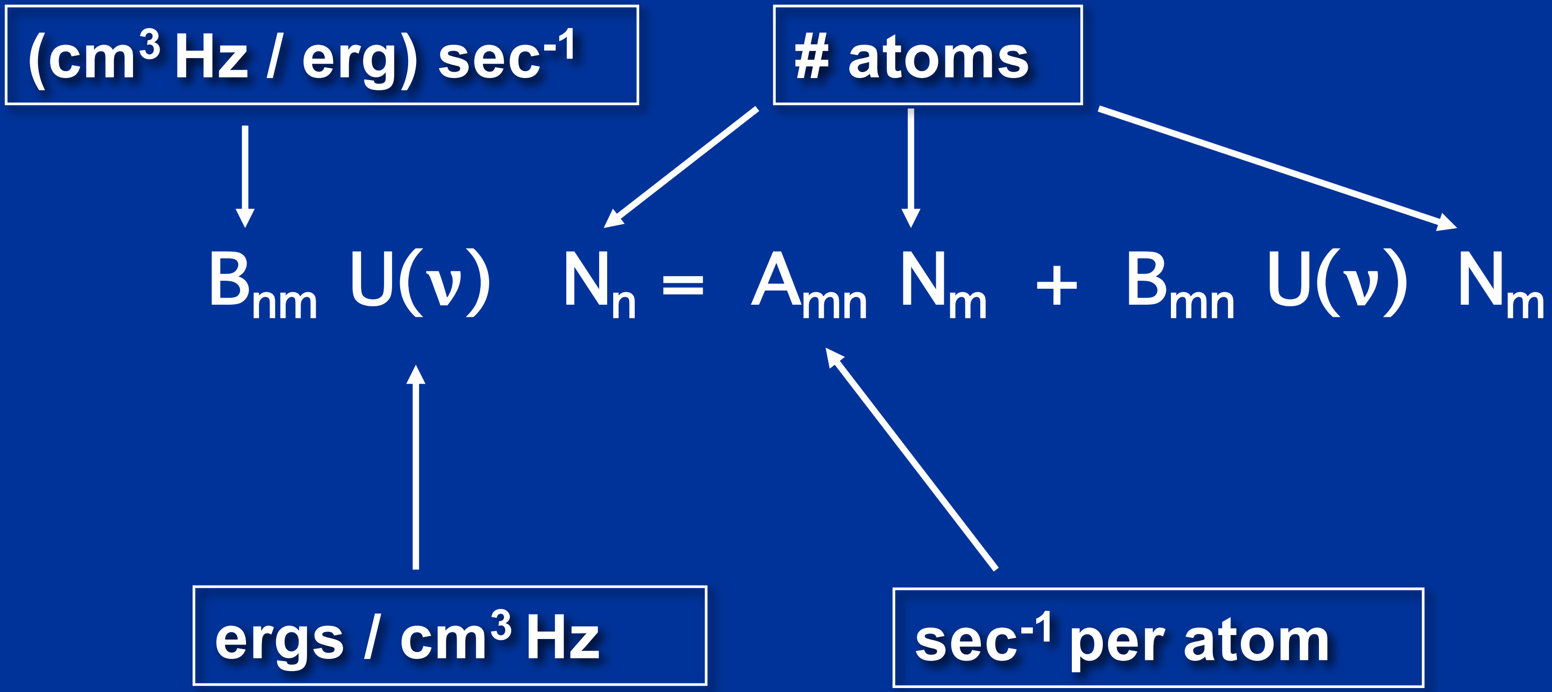
- Consider a two level atom which initially has a ground state n containing N_n atoms and an empty upper state m. The atom is excited by a radiation field tuned to the transition

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

- 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

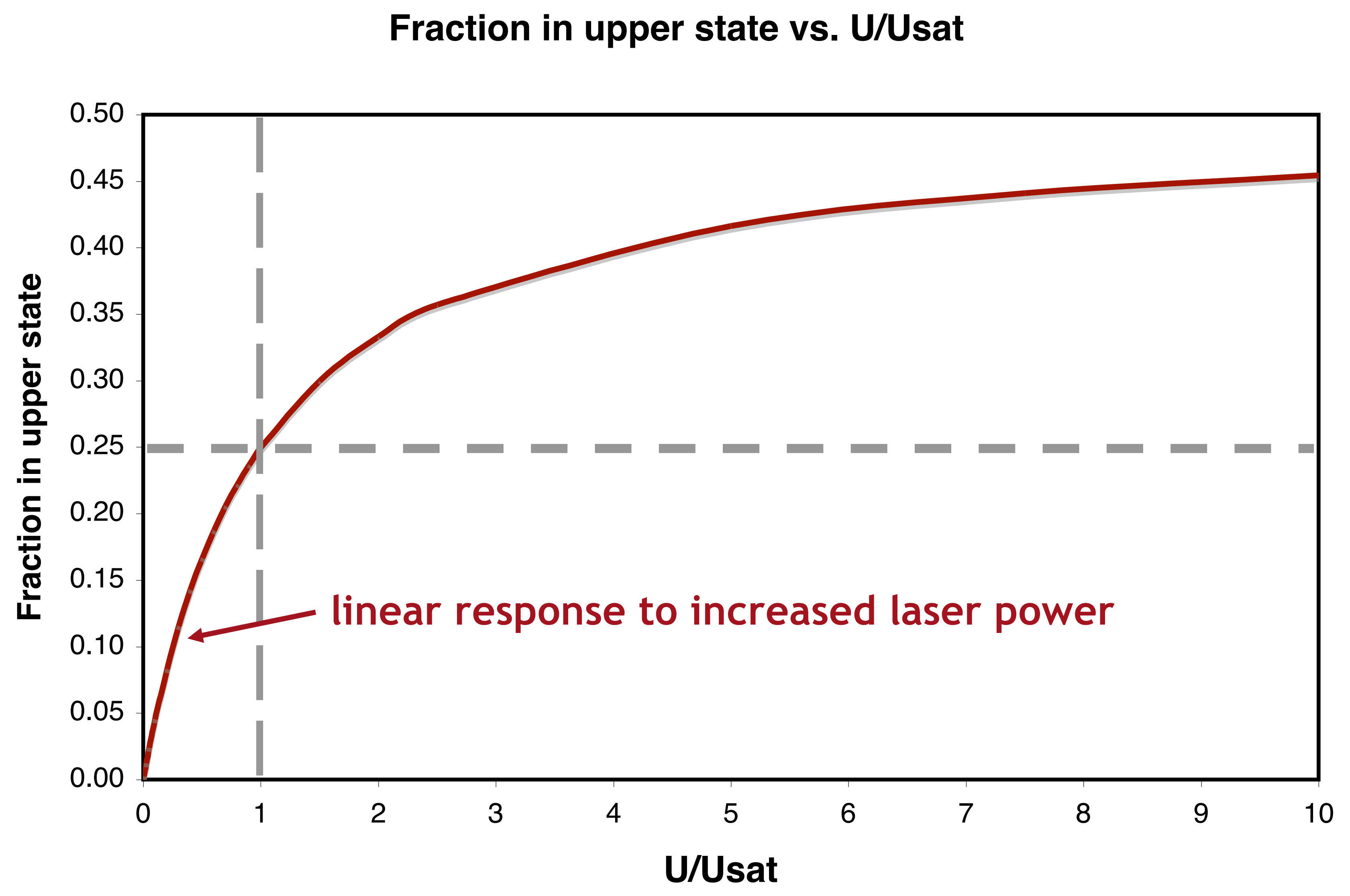
$$f = B_{mn} U(\nu) (1 - f) / (B_{mn} U(\nu) + A_{mn})$$

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

- 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

Laser guide stars: Main points so far

- Laser guide stars are needed because there aren't enough bright natural guide stars in the sky
- Solution: make your own guide star
  - Using lasers
  - Nothing special about coherent light
  - Size on sky has to be ≲ diffraction limit of a WFS sub-aperture
- Rayleigh scattering: from ~10-15 km:
  - Doesn't sample turbulence as well as resonant scattering from Na layer at ~100 km. Lasers are cheaper, and easier to build.
- Sodium laser guide stars:
  - Sodium column density varies with season, and within a night
  - Need to sense variation and follow it

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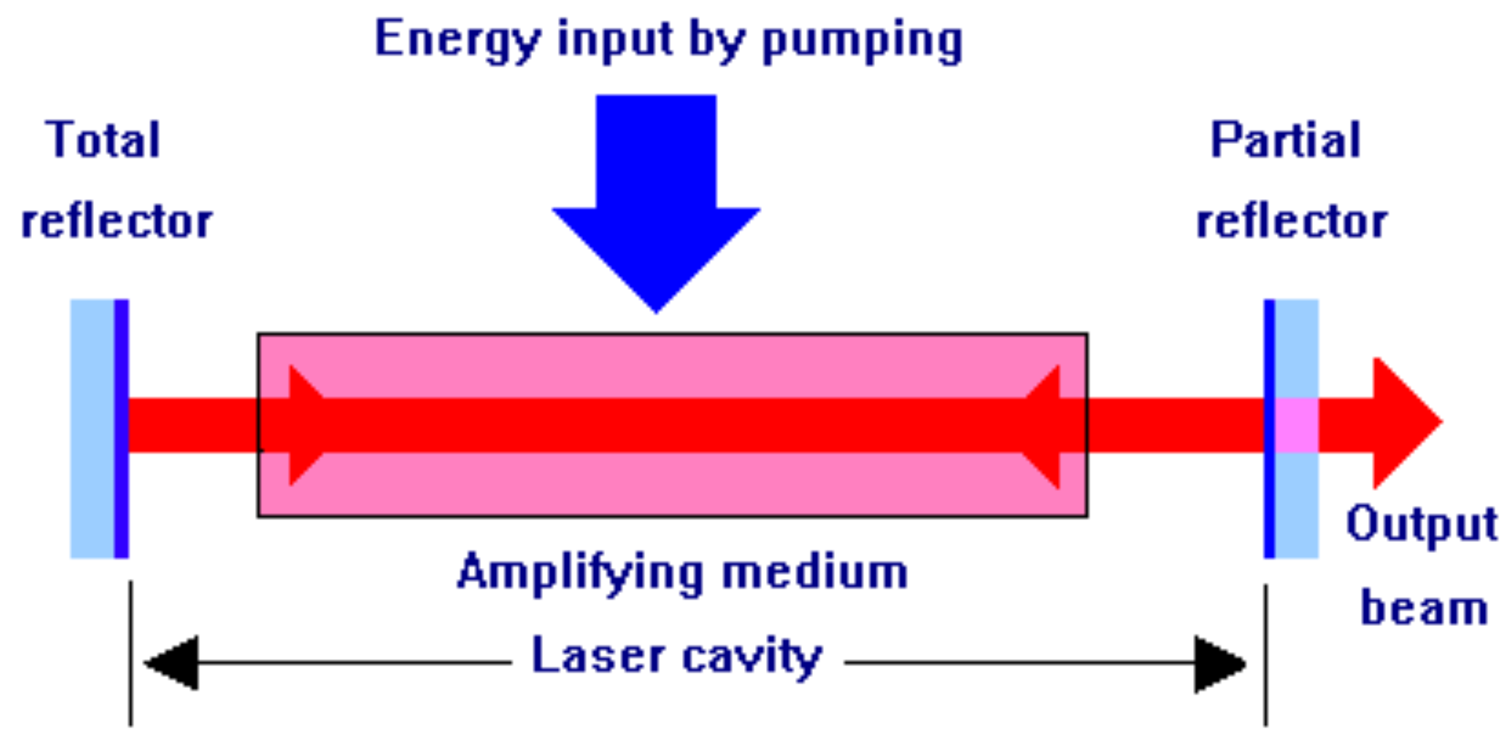
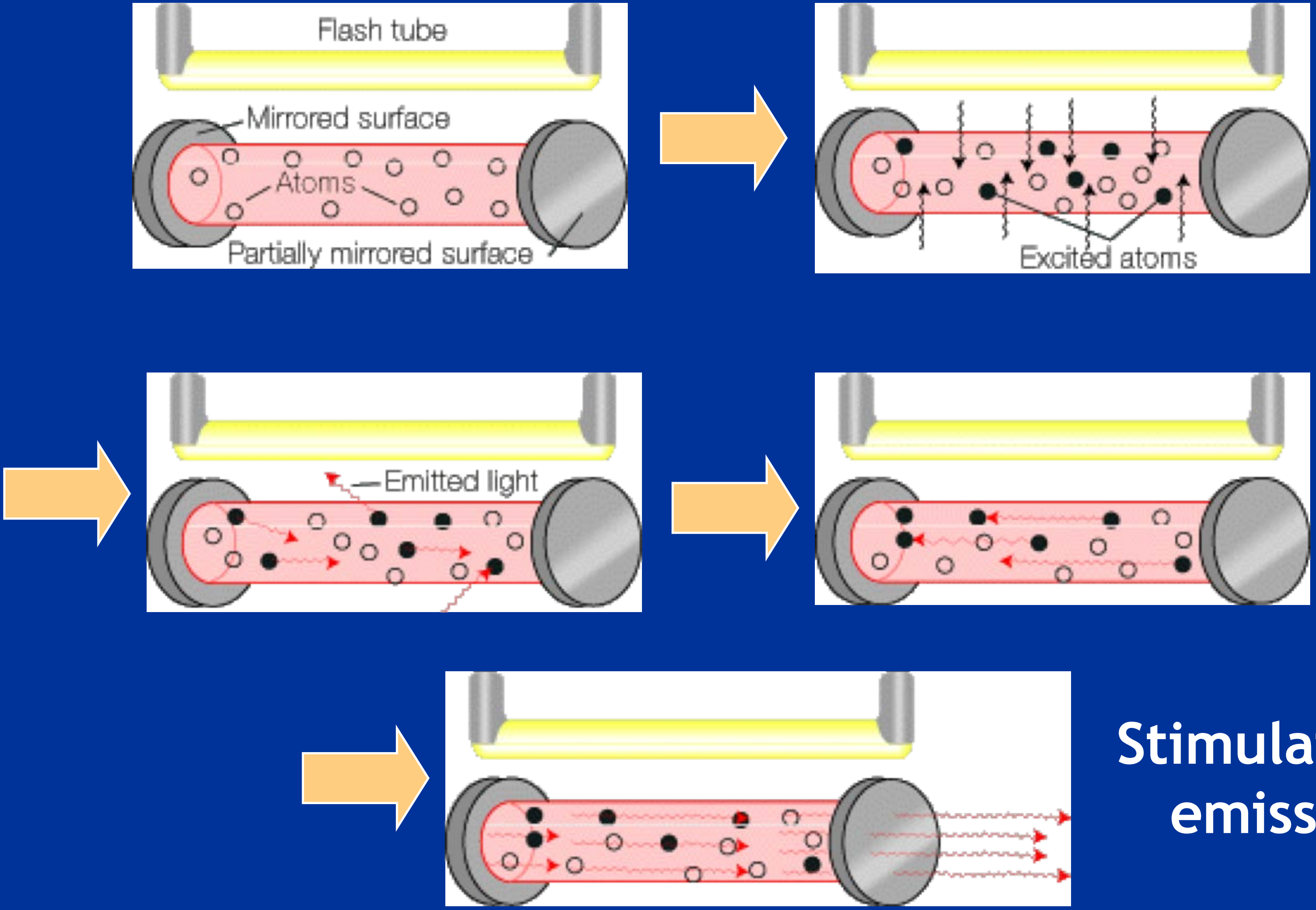
Types of lasers: Outline

- 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

General comments on guide star lasers

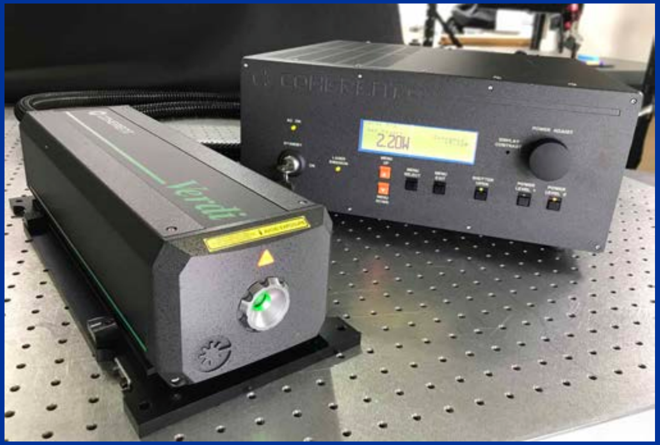
- Typical average powers of a few watts to 20 watts
  - Much more powerful than typical laboratory lasers
- Na guide stars - Class IV lasers (a laser safety category)
  - "Significant eye hazards, with potentially devastating and permanent eye damage as a result of direct beam viewing"
  - "Able to cut or burn skin"
  - "May ignite combustible materials"
- As a result, need to avoid airplanes and satellites

Lasers used for Rayleigh guide stars

- Rayleigh x-section ~ λ^{-4} ⇒ short wavelengths better

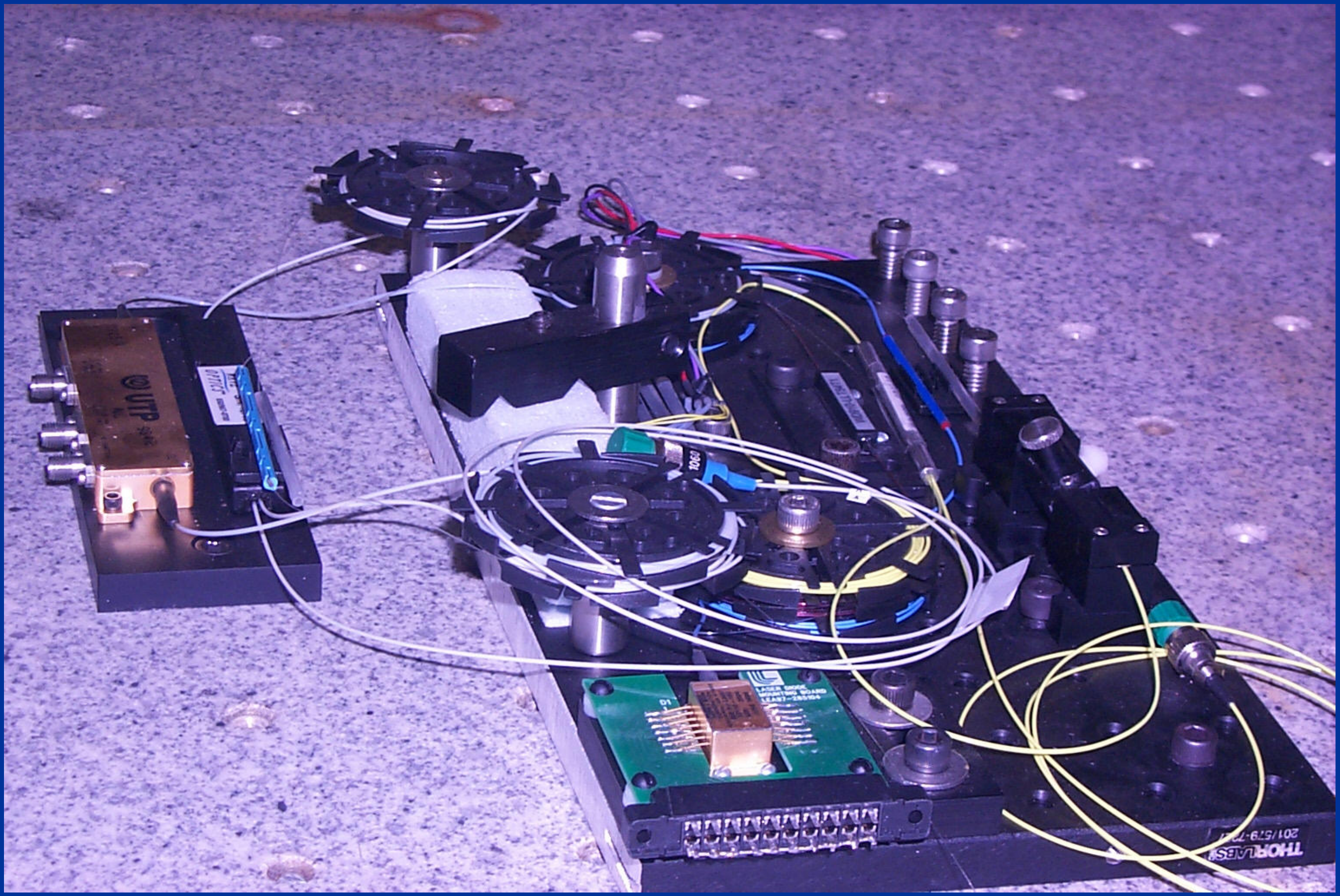
- Commercial lasers are available
  - Reliable, relatively inexpensive
  - Green laser (532nm) - e.g. MMT
  - RoboAO uses 10W ultraviolet (λ = 355nm) laser pulsed at 10 kHz
    - Invisible to human eye. Unable to flash-blind pilots; considered a Class 1 laser (incapable of producing damaging radiation 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 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 18 Watts
  - Pretty expensive
    - It's always worrisome when price isn't listed on the web!

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

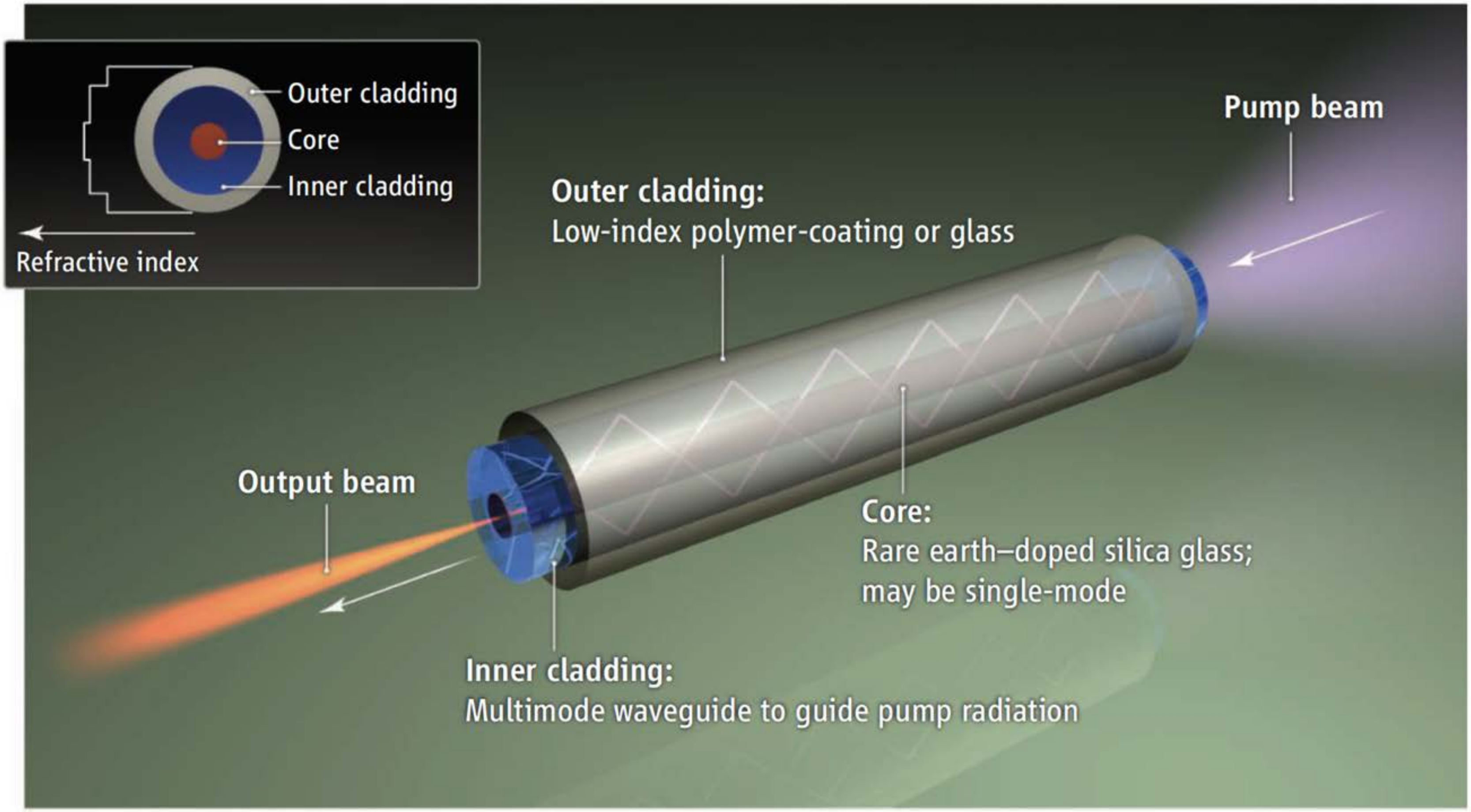


- Example of a fiber laser

Advantages of fiber lasers

- Very compact
- Commercial parts from telecommunications industry
- Efficient:
  - Pump with laser diodes - high efficiency
  - Pump 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)

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).

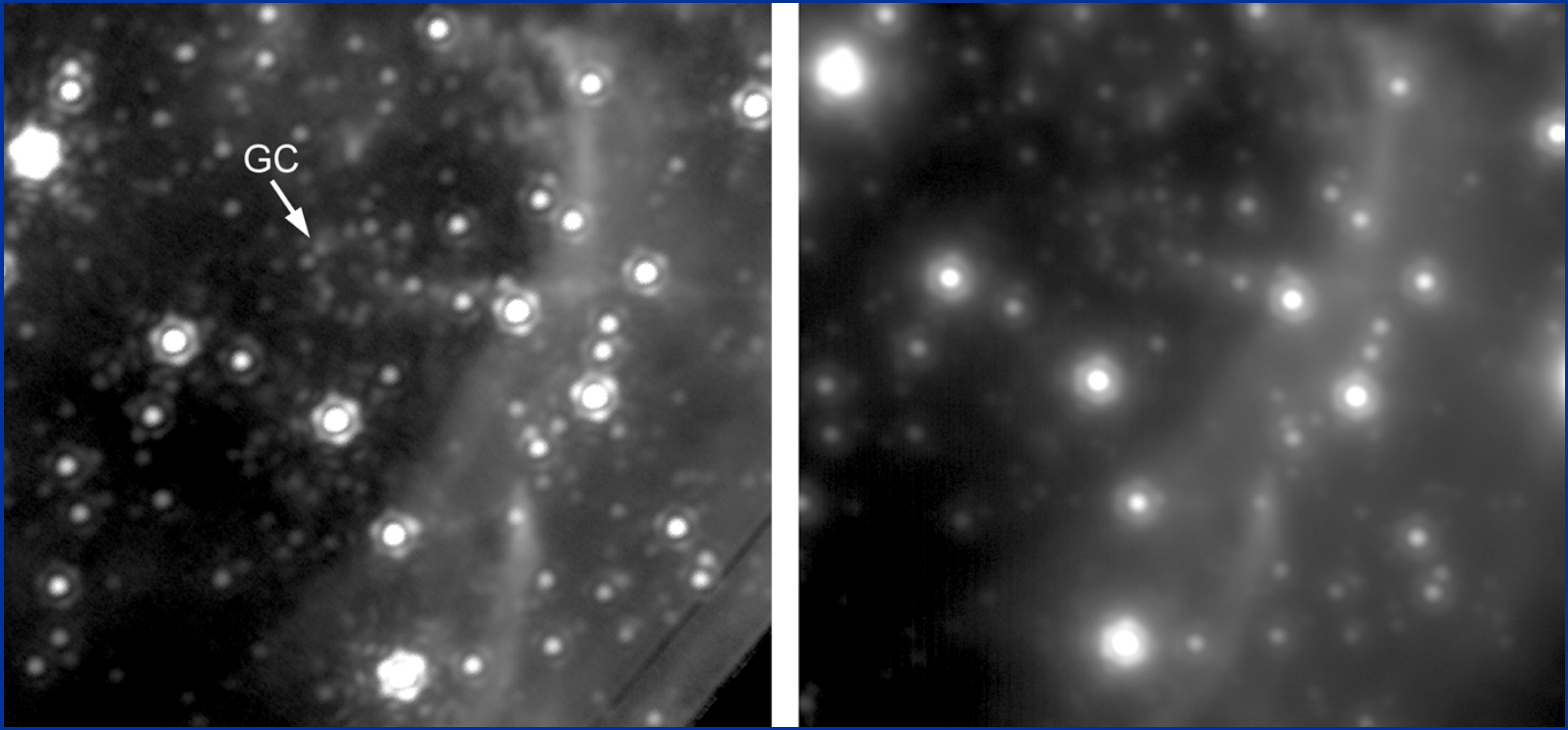
Credit: Nilsson and Payne, Science Magazine, 2011

Toptica fiber laser (ESO, Keck 2, Gemini)

Electronics
and cooling

Galactic Center with Keck laser guide star AO

Keck laser guide star AO   Best natural guide star AO

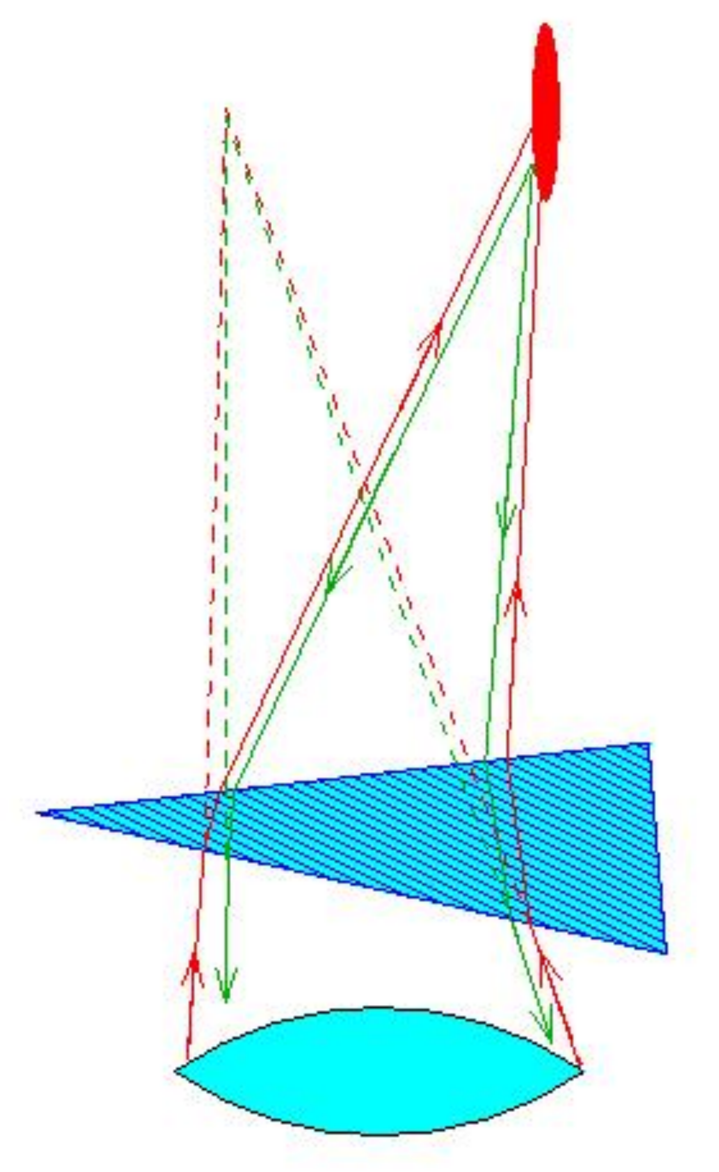


Andrea Ghez, UCLA group

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

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



from A. Tokovinin

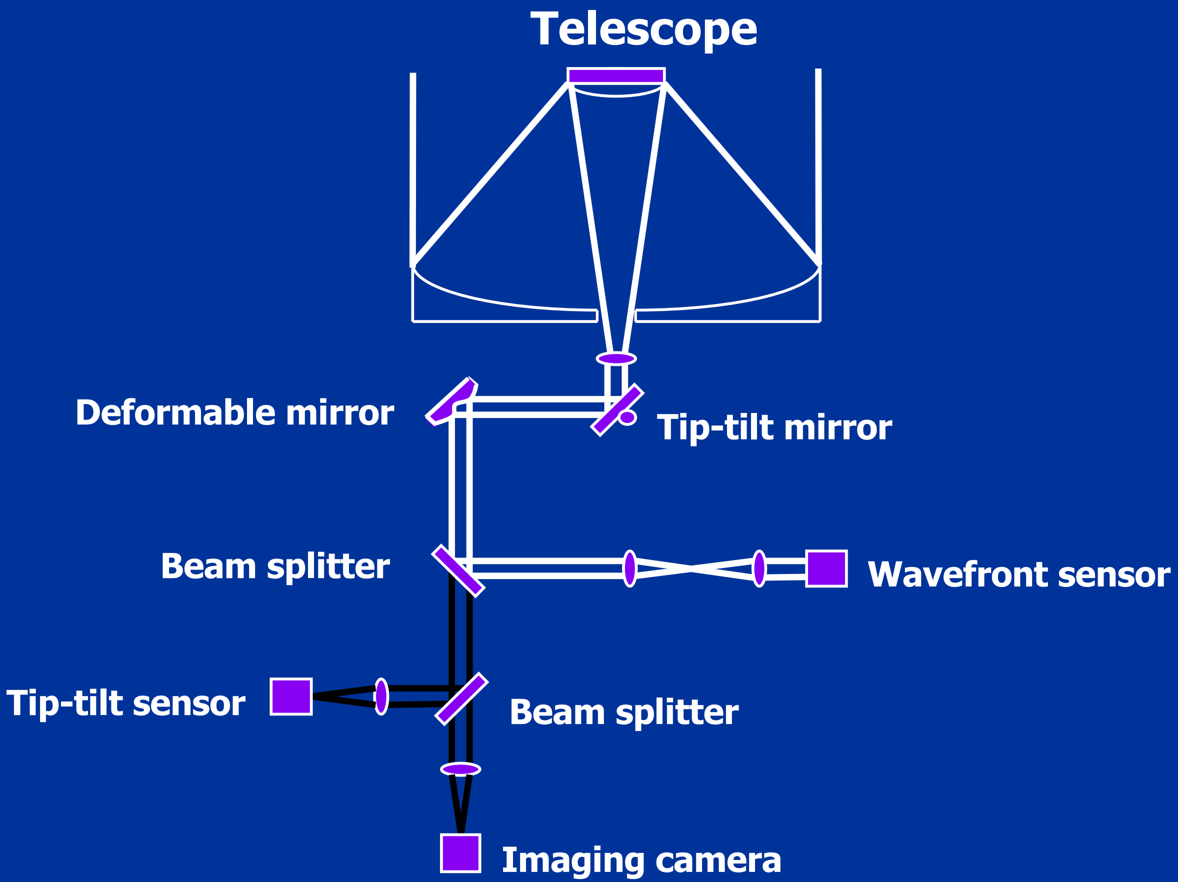
Effective isoplanatic angle for image motion: "isokinetic angle"

- 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

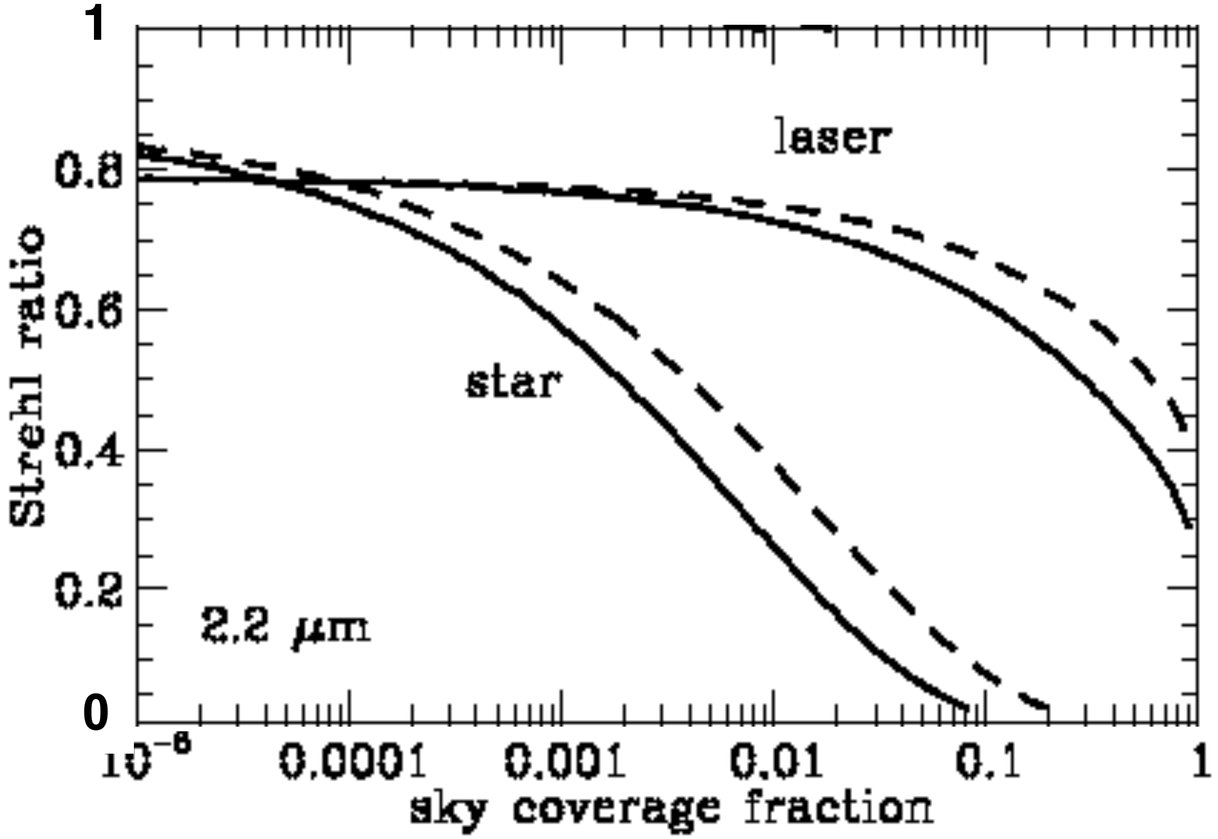
- "Isokinetic angle"
  - Analogue of isoplanatic angle, but for tip-tilt only
  - Typical values in infrared: of order 1 arc min

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˚

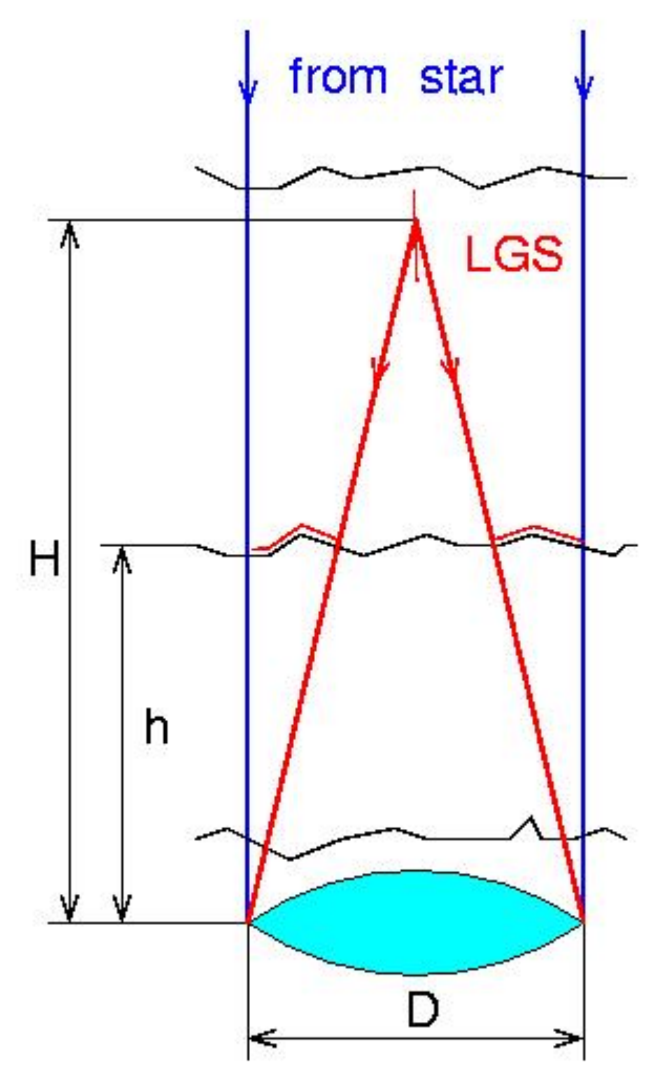
---- Galactic latitude = 30˚

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

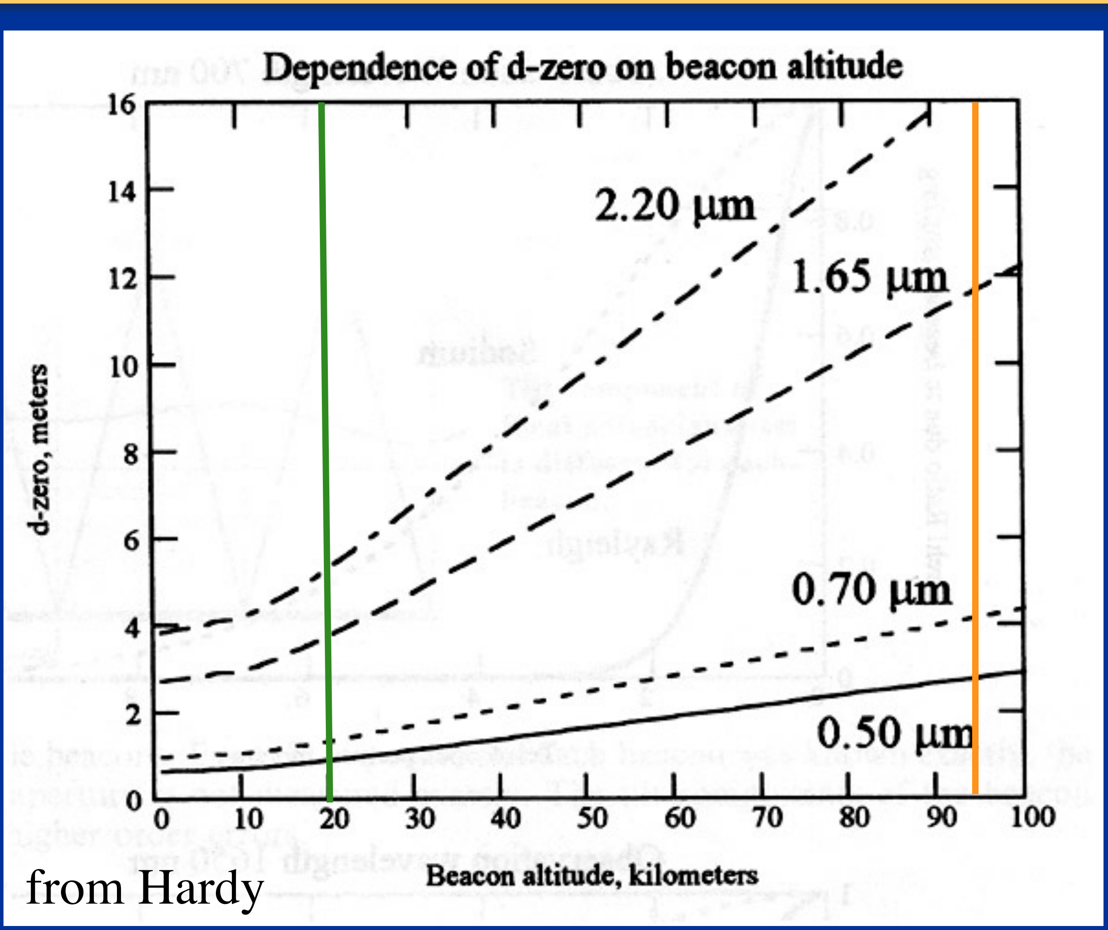
Cone effect, continued

- 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 tilt 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

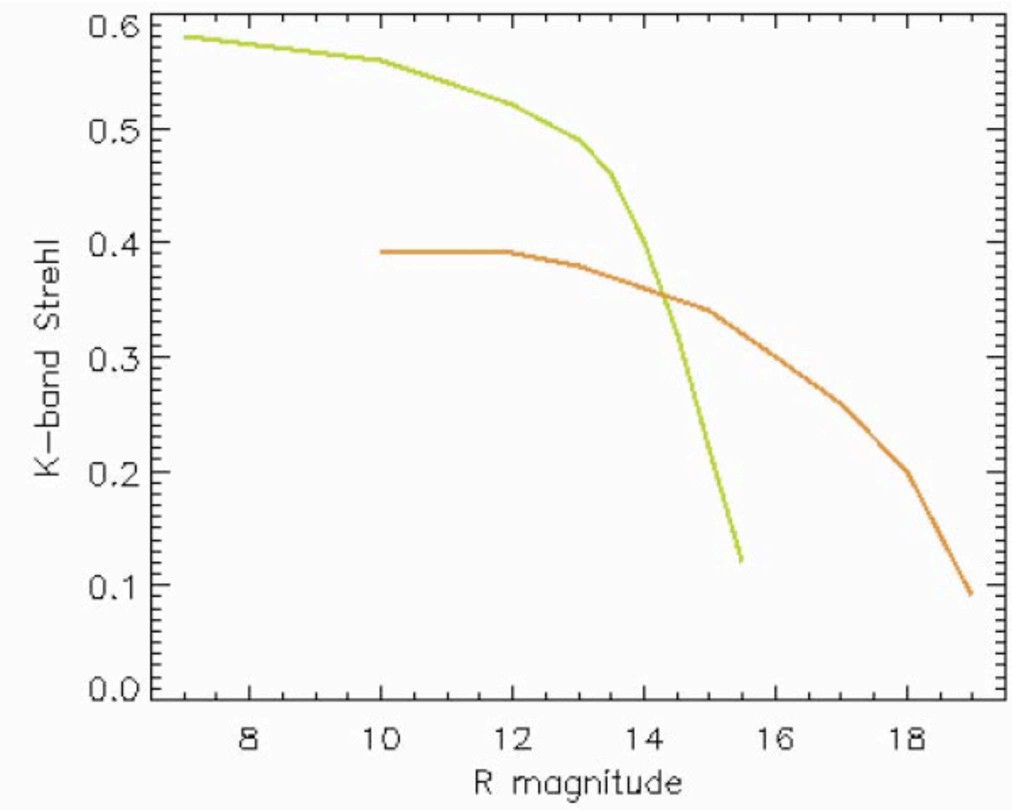


Figure 14: Strehl vs R-magnitude for NGS AO (green) and LGS AO (orange)

- 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
- Sodium layer saturates at high peak laser powers
- 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