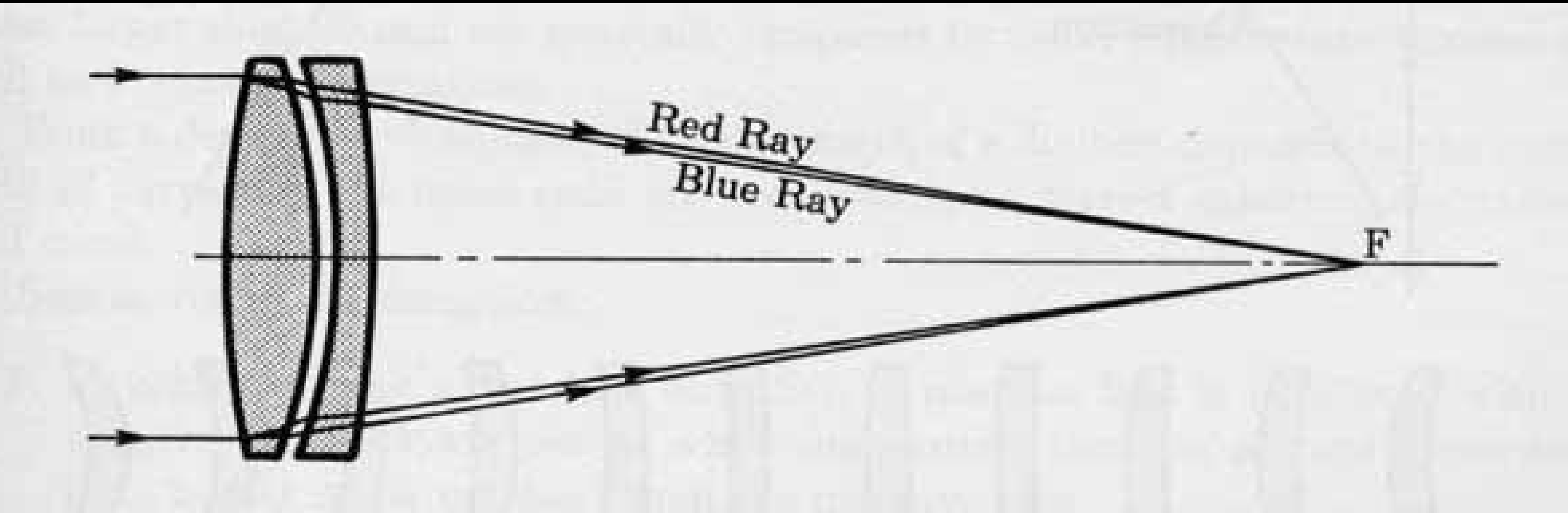
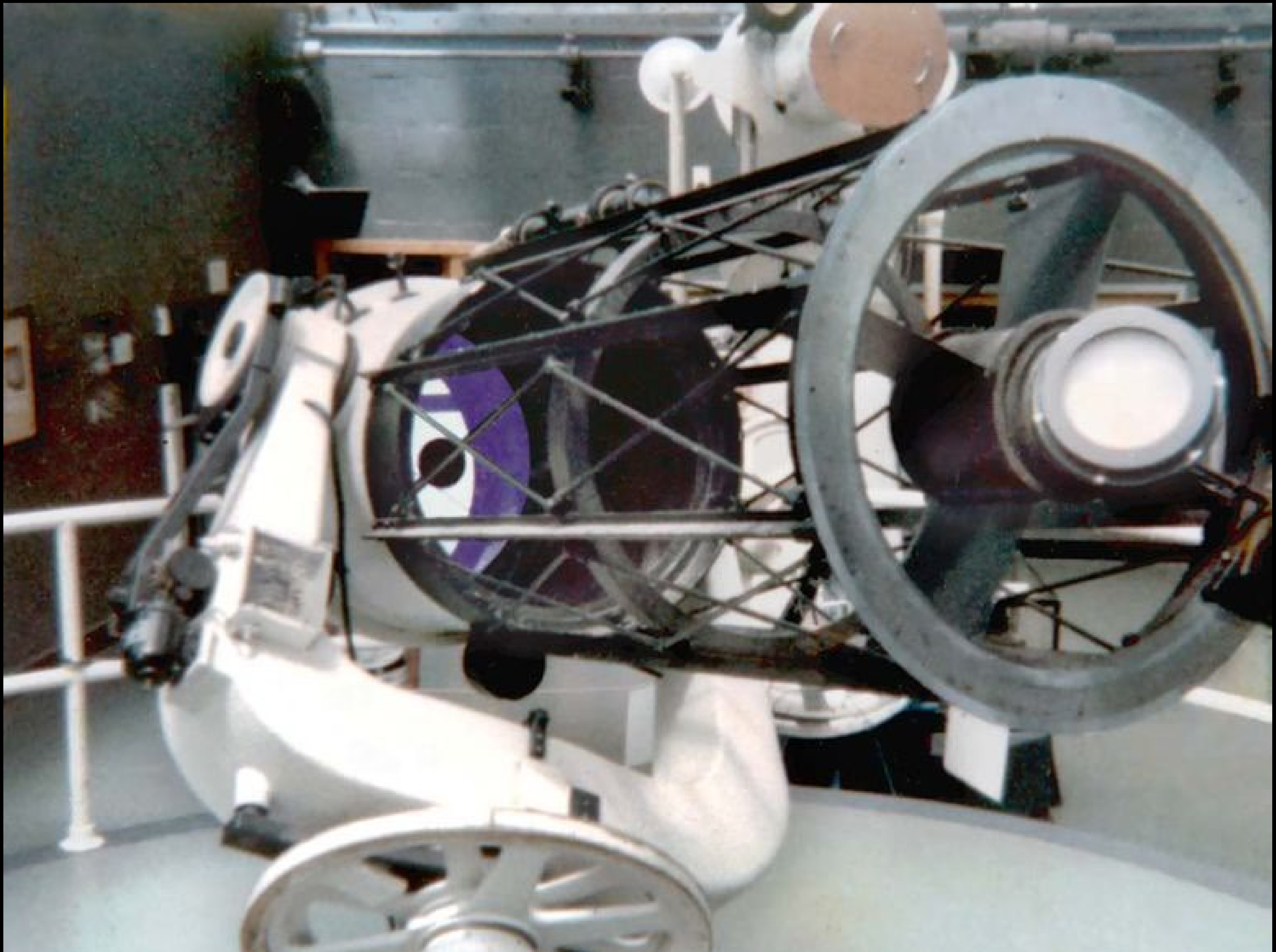
Chap 6: Telescopes and Detectors

- The most important property of a telescope?
- No, it's not it's "power" or magnifying ability, it is……
- It's the size of the ***Light Gathering area! So,*** the diameter of the mirror or lens is THE most important property
- You have to GATHER as much light as possible before you may consider magnifying it, and anyway, your purpose may instead be to take in a wide field of view (requiring low magnification)

Refracting Telescopes – uses lenses to bring parallel light to a focal point. Lots of problems with this design. Chromatic aberration, flexure due to support only at edge, expensive to make anti-reflection coated glass lenses which have no internal imperfections…



Reflecting Telescopes – use mirrors to bring light to a focus



Reflectors: ALL research level scopes are reflectors.

- **<u>Advantages are Many…</u>**
- They bring ALL light, no matter the color, to the same focal plane (lenses can do this only imperfectly, and at GREAT expense).
- Mirrors (not lenses) are cheap to make; light only touches one surface. You don't care about the interior glass or other surfaces
- They can be supported at many points on the back surface – lenses can only be supported at the edges. This is a HUGE issue for big scopes, since even glass has flexure at the level of concern.

The Single Most Important Reason to Launch Telescopes into Space?

- **It's to see wavelengths of light that don't make it to the ground through our atmosphere.**
- There's other advantages too (like no clouds), but not as vital as the wavelength argument

Which Wavelengths of Light Make it Down Through the Earth's Atmosphere?

- **You can't do anything unless the light makes it to you! In orbit, it ALL comes to you. At ground level though…**
- **Gamma Rays?** No – very high energy and will ionize any atmospheric atom they hit, getting absorbed.
- X-rays? No, same story
- UltraViolet (UV)? – No, same story

Visible light?

- <u>Yes!</u> (obviously. That's what we *SEE* with).
- Longer than ~350nm wavelength, light is low enough energy that it will not ionize most atoms and therefore only those rare wavelengths that can bump an electron to an allowed orbital can get absorbed.
- So most visible light makes it through our atmosphere just fine.
- (There are still advantages to going to space, even in visible light though… more later)

Visible Light: The Hubble Space Telescope, and now the James Webb Telescope too

Infra Red Light (IR)?

- The “near IR” (the IR that is closest to the visible band) does mostly make it through
- But longer wavelengths (“far infrared”) can be absorbed by molecules excited into vibrational, rotational, torsional, and more complex states, especially CO2 and…
- …**Water vapor** is a big absorber, and this is another reason that big observatories are on the highest possible mountains, above much of the atmosphere’s water vapor.

Microwaves?

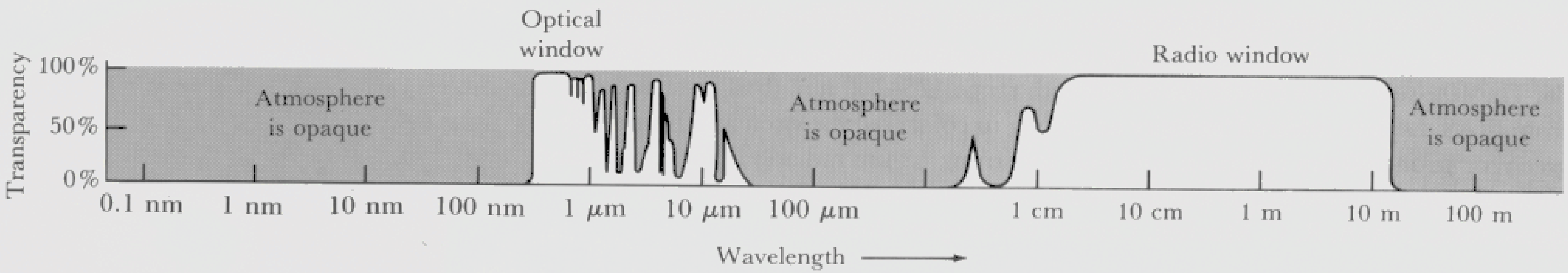
- Not really. Same story as for far infrared. Mostly chewed up by molecular absorption from water vapor and CO2. But some wavelengths in this band do make it through, especially at the long end.

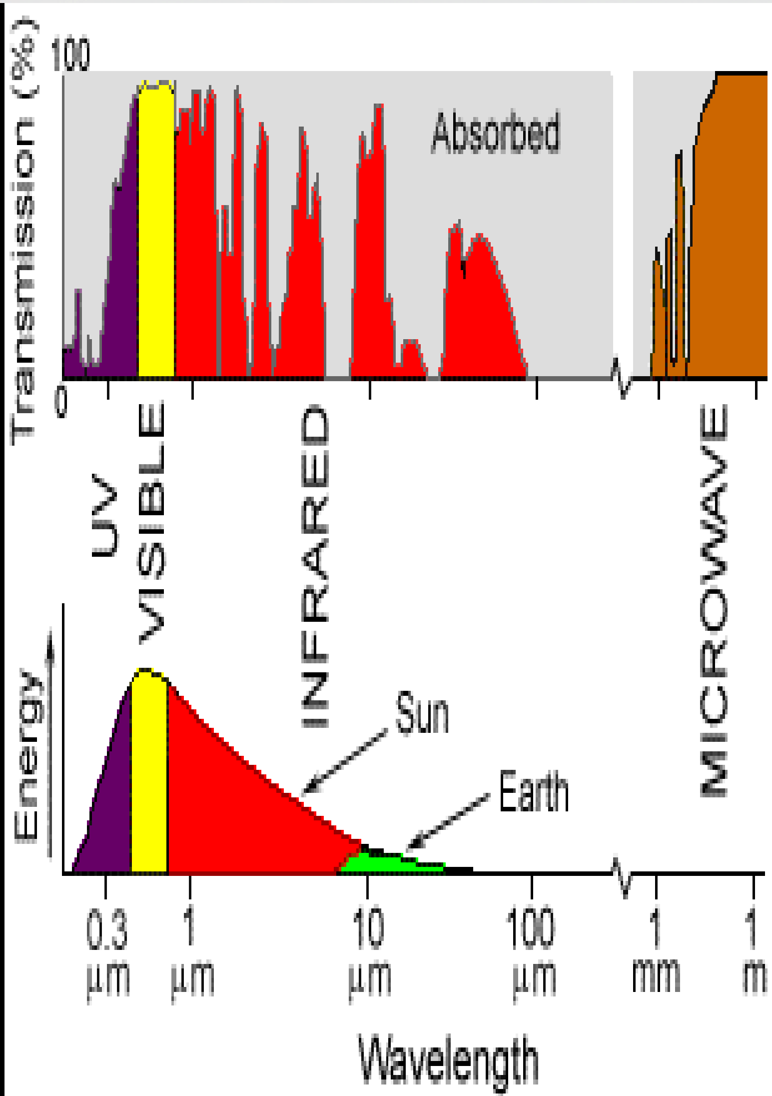
Radio?

- <u>**Yes!**</u> Wavelengths longer than 1 cm are too long to have much molecular absorption, and waay too long to move electrons between orbitals.
- However very long wavelengths (~15m or more) can scatter off of electrons and ions in the Earth's ionosphere (the ionosphere is ionized by cosmic rays and the solar wind) and so don't arrive to the ground from space very well.
- And shortward of 1 cm there is some molecular absorption.
- Radio astronomy is heavy, and done almost exclusively from the ground, and need not be at high elevation
- But, radio observatories should be in the boondocks – so you don't get interference from AM, FM and other human sources.

So There are Two Bands Which Can be Studied from Ground-based Observatories

- **The Visible band**
- **The Radio band**
- All others are, to a significant extent, partially or completely blocked by our atmosphere


Optical window
Radio window
Transparency
100%
50%
0%
Atmosphere is opaque
Atmosphere is opaque
Atmosphere is opaque
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 cm
10 cm
1 m
10 m
100 m
Wavelength


Transmission (%)
100
0
Absorbed
UV
VISIBLE
INFRARED
MICROWAVE
Energy
Sun
Earth
0.3 μm
1 μm
10 μm
100 μm
1 mm
1 m
Wavelength

Other Terms You'll Run Across

- Nowadays, technology continues to march on, and terms for specialty wavelength bands show up in the terminology
- Like – "submillimeter". It's on the border between microwave and infrared, and important for studying the Early Universe, when the first galaxies formed. They're the most distant, with light that is the most redshifted by the Hubble Expansion, and their visible light is shifted all the way to the far infrared and beyond.
- The new ALMA array is the premier instrument – best to be above ~all water vapor, in the Atacama Desert of Chile – driest desert on Earth

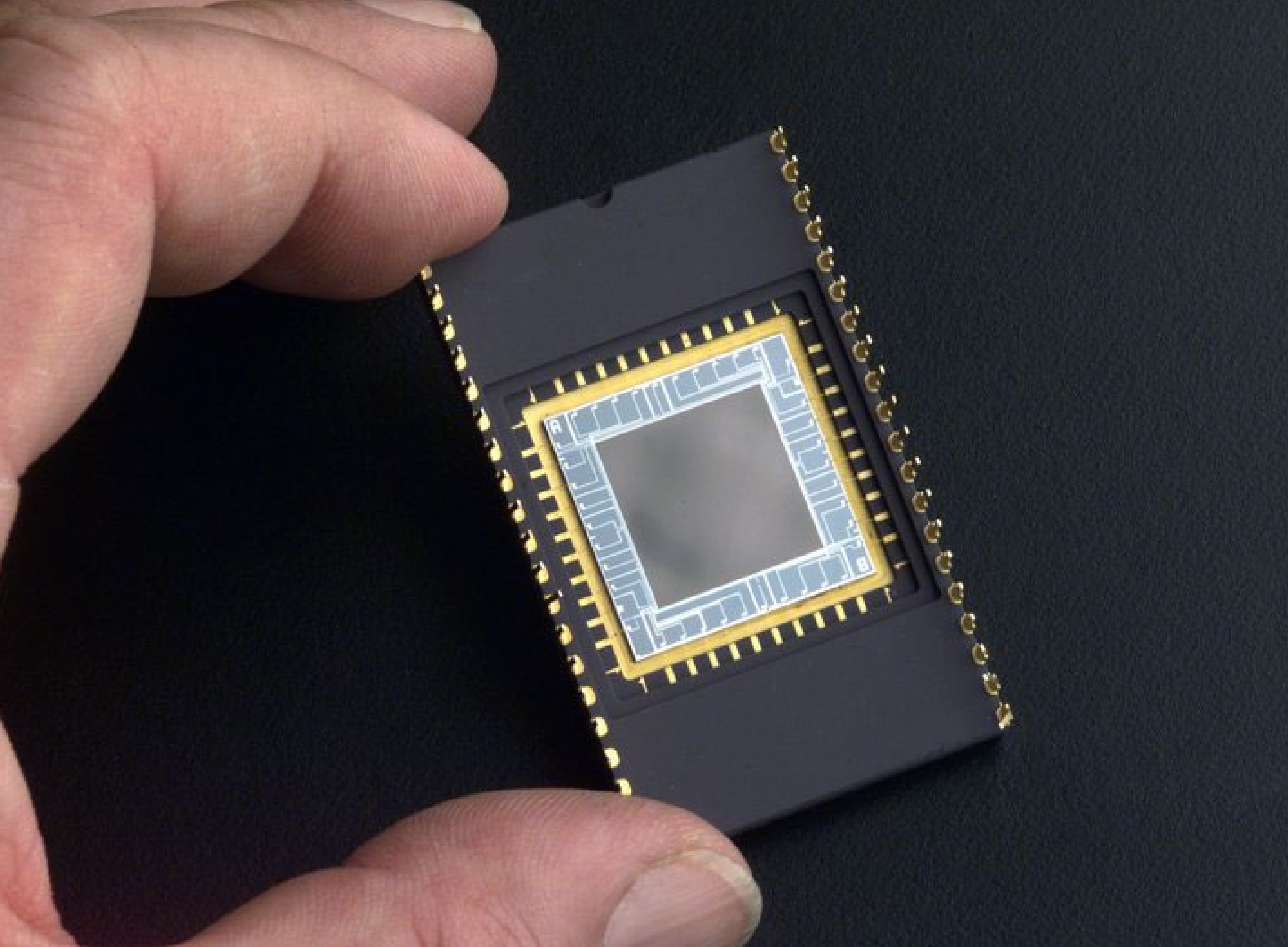
ALMA – **A**tacama **L**arge **M**illimeter/submillimeter **A**rray

How are Images Recorded at Modern Telescopes?

- Film and glass plate photography have now passed into history.
- Today, it’s CCD’s – **C**harge **C**oupled **D**evices. Astronomy’s “digital photography” then moved into consumer photography, in the 1980’s and 90’s.

What is a CCD Detector?

- A silicon chip divided finely into rows and columns, making “pixels”.
- A photon hits a pixel, knocks loose an electron where it stays in the pixel, but unbound to the atoms.
- Number of electrons knocked loose is **proportional to** the number of photons hitting the pixel. It would be perfectly **equal**, if the “quantum efficiency” were 100%. QE is good, but it’s not perfect in the real world



CCD's are MUCH Better than Photographic Film or Glass

- Their sensitivity is nearly perfect. One photon produces one electron, little light is wasted, upwards of 90% efficiency
- CCD's have **wide dynamic range**, much more so than film or glass photography. "dynamic range" means how wide a range of brightness it can capture in shades of gray
- Their response to light is **linear**, (meaning: 5 times as much light means 5 times the signal) whereas film gets "tired" as more light hits it
- They're re-usable over 'n over n' over. Film, glass, is not.
- Output is digital, computer software can do wonders. Glass plates? You got a piece of glass, unless you scan it into a computer later.

CCD vs CMOS

- CMOS = **C**omplimentary **M**etal **O**xide **S**emiconductor chip
- Your iPhone and other typical digital camera devices use CMOS chips, not CCD's.
- CMOS chips: Each pixel connects directly with the processor, so image downloading is much faster. CCD's must move electrons pixel-to-pixel across the array to get to the edge to download the electrons.
- CMOS is cheaper to make
- But, CCD's have lower read-out noise, and so for low-light situations (like astronomy), CCD's are preferred. But this advantage is rapidly disappearing.
- In daylight, CMOS is the way to go.

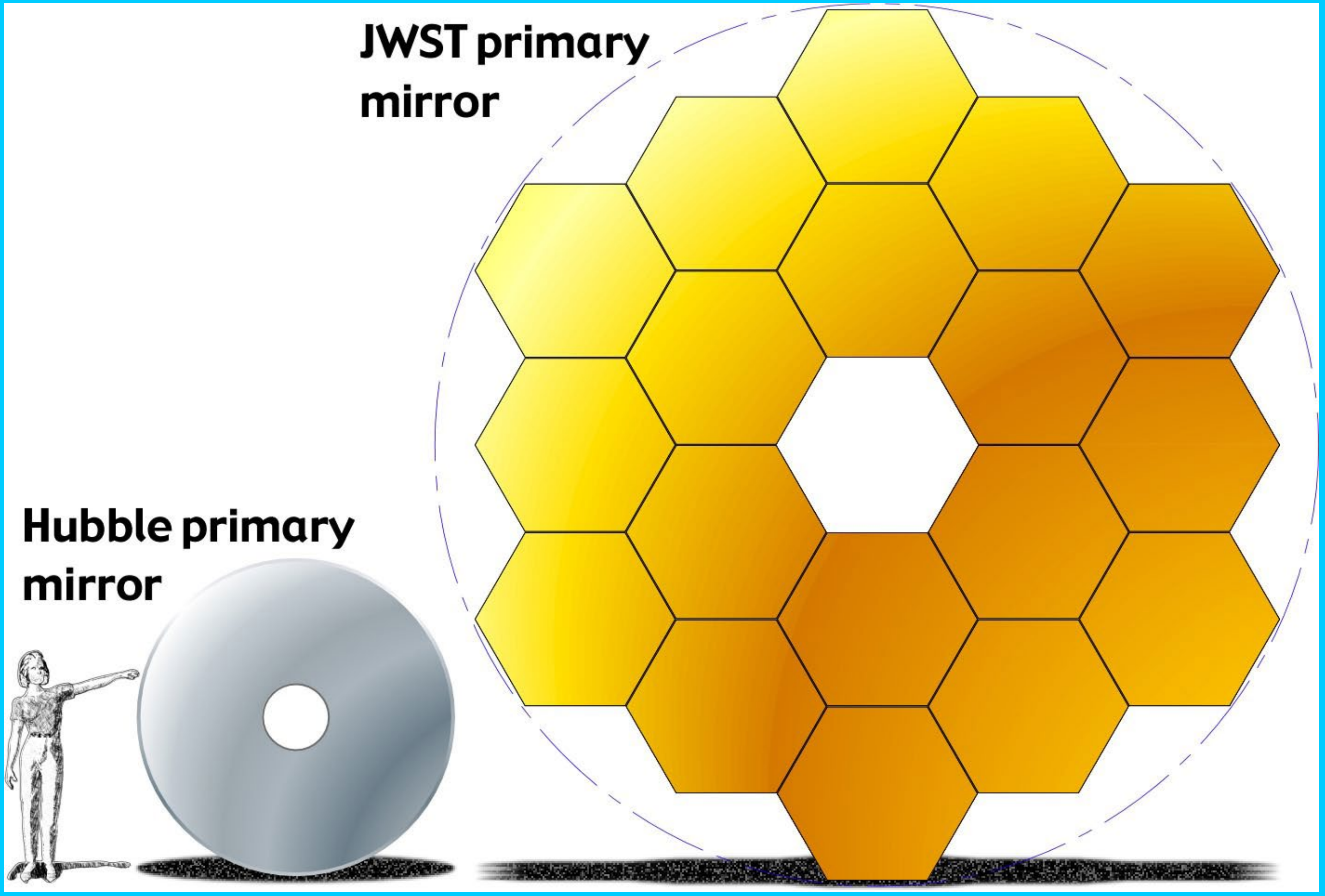
- But CCD chips are small, still, compared to old glass plates. For big research scopes, you get around this with tiling lots of them side-by-side at the focal plane
- Even serious amateur astronomers can take pictures with CCD's and small telescopes that just a couple of decades ago could only be taken with the largest telescopes in the world and all-night exposures
- **The following pictures were all taken by Astro 8 and Astro 9 students at Cabrillo College Observatory…**

Today's Best Space Telescopes…

- **James Webb** Telescope: Infrared
- 2nd place now is HST: Hubble Space Telescope (visible range, UV and near IR)
- Planck: Microwaves, especially the CMB
- Spitzer Telescope: Infra-red
- Fermi Gamma Ray Telescope
- Chandra: X-ray Astronomy

The James Webb is a 6.5m (21 ft) diameter behemoth!

James Webb Space Telescope is a big jump over the Hubble. The downside is, it was launched to the L1 gravitational stability point, which makes maintenance just about impossible. HST is in low Earth orbit. Fortunately, after 4 yrs, JWST is still working great!



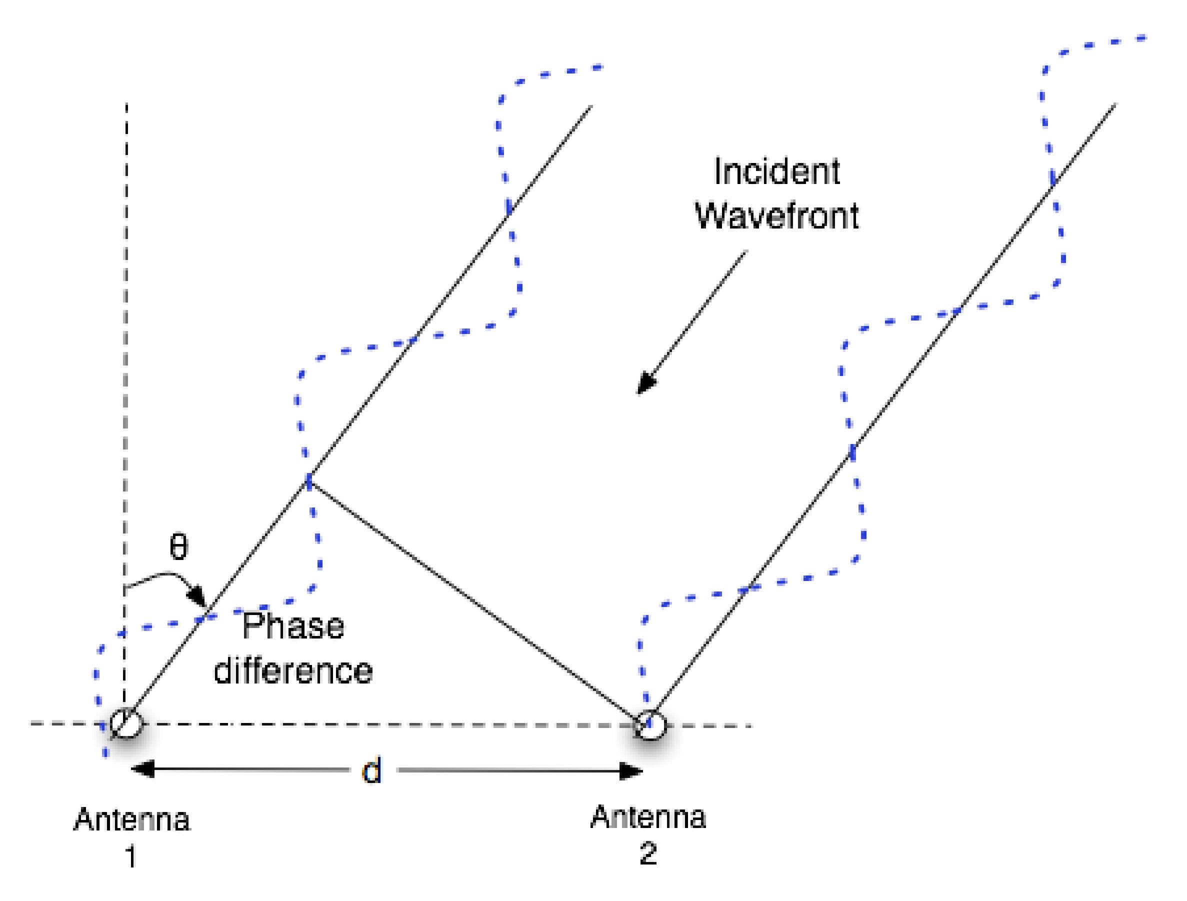
Why Send Telescopes into Space?

- **Most important reason – to "see" wavelengths which are absorbed by our atmosphere (gamma, X, UV, IR, Microwave wavelengths)**
- Secondarily, **Resolution**: to avoid blurring by the Earth's atmosphere. Also, avoid clouds
- However, recently we've developed ways to achieve high resolution comparable to that possible from space, from the ground: **Adaptive Optics**.
- An older, different method best radio and long wavelengths is…**Interferometry** - Using two or more telescopes which are separated, and optically combining the images to get the resolving power of a single telescope as large in diameter as the area spanned by the telescopes).

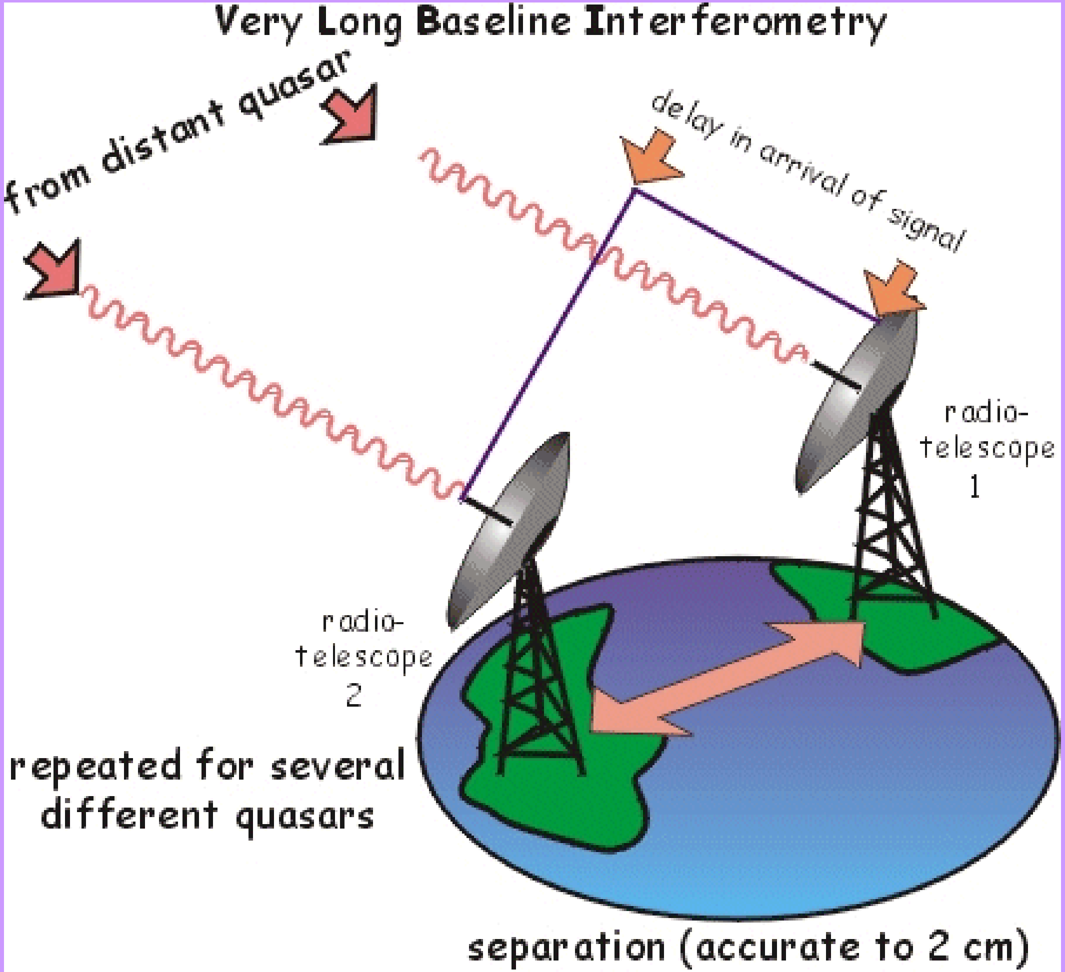
Resolving Power through Interferometry

- **Resolving power goes as D/wavelength, where D is the diameter of a single telescope, or if you can combine several, then the diameter of the outer boundary occupied by the telescopes.**
- **<u>So make D big to get sharper images.</u>**
- An interferometer will combine light waves from two separated telescopes to very finely determine the incoming direction, and reconstruct a sharp image.

Combining two incoming waves: Example; the "down" part of one wave will cancel the "up" part of the other wave, so the brightness of the combined waves tells you precisely the path difference, which, with a little geometry on-chip, tells you the precise arrival direction – voil'a! Sharp images!



From a perfect point source, like a quasar, whose position you know accurately already, you can even invert the process and **calculate** the separation of the two telescopes – This is how we can monitor “continental drift” between continents!



Keck Telescopes Interferometer on Mauna Kea, Hawaii

- We are now able to take images using interferometers which rival those seen from the Hubble (which has the advantage of being above the blurring effect of atmosphere)
- However, resolution increase is in only one direction if you only have two scopes like this.
- The wider the separation between scopes, **the better the resolution**

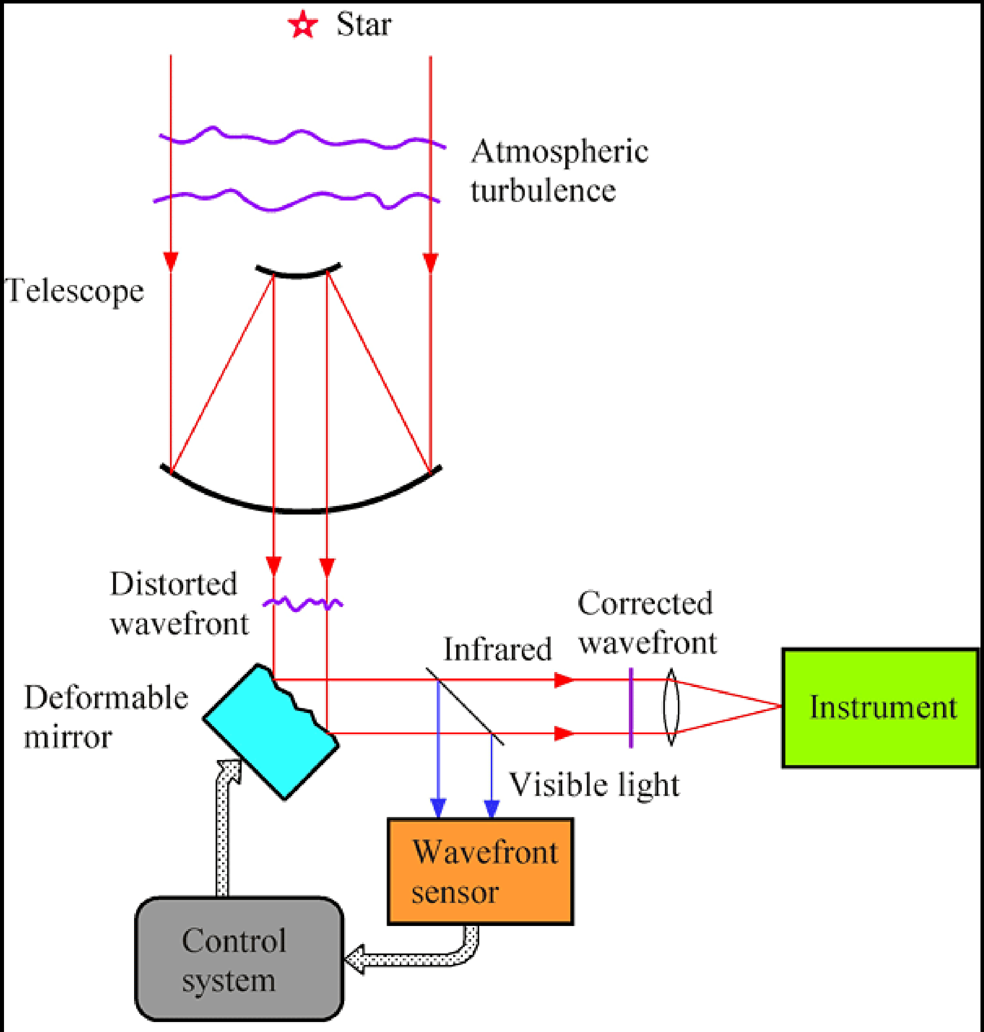
Adaptive Optics: Can correct for blurring caused by our atmosphere

- Light bends when it moves from a medium of one density to a medium of a different density.
- Colder air is denser than hotter air
- Therefore, when there is any air movement, especially convection, starlight will take slightly different wavering paths before arriving at the telescope, leading to blurring of the image.
- The time scale for this change is about 0.1 second, causing the “twinkling” so familiar for people looking up at bright stars

A Deformable Mirror and Very Fast Computer is the Key

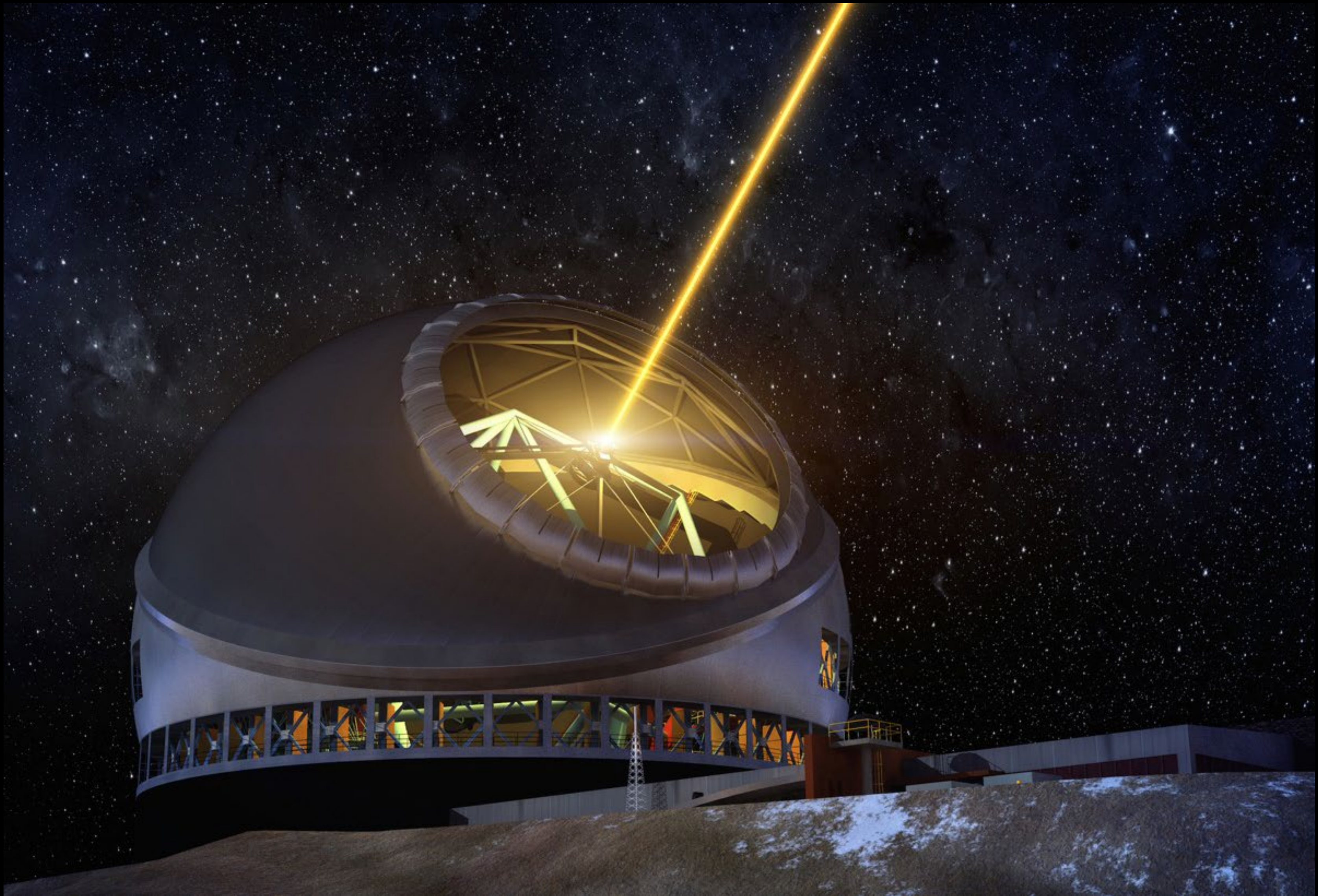
- Calculate how to change the shape of the deformable mirror so the reflected light rays are parallel, like they were in outer space before hitting our atmosphere.
- Requires an artificial point source "star" to accomplish this, and we typically use a powerful laser parallel to the telescope which ionizes the sodium layer high in the atmosphere to create a tiny **sodium light "star"**, which is in the same field of view as the object being imaged.
- The sodium star's twinkling tells a (very fast) computer how to deform the deformable mirror moment-to-moment to "de-twinkle" the whole picture

Adaptive Optics (AO): A fast computer deforms a small mirror to correct for the distortions from atmospheric "twinkling"



Schematic diagram of adaptive optics

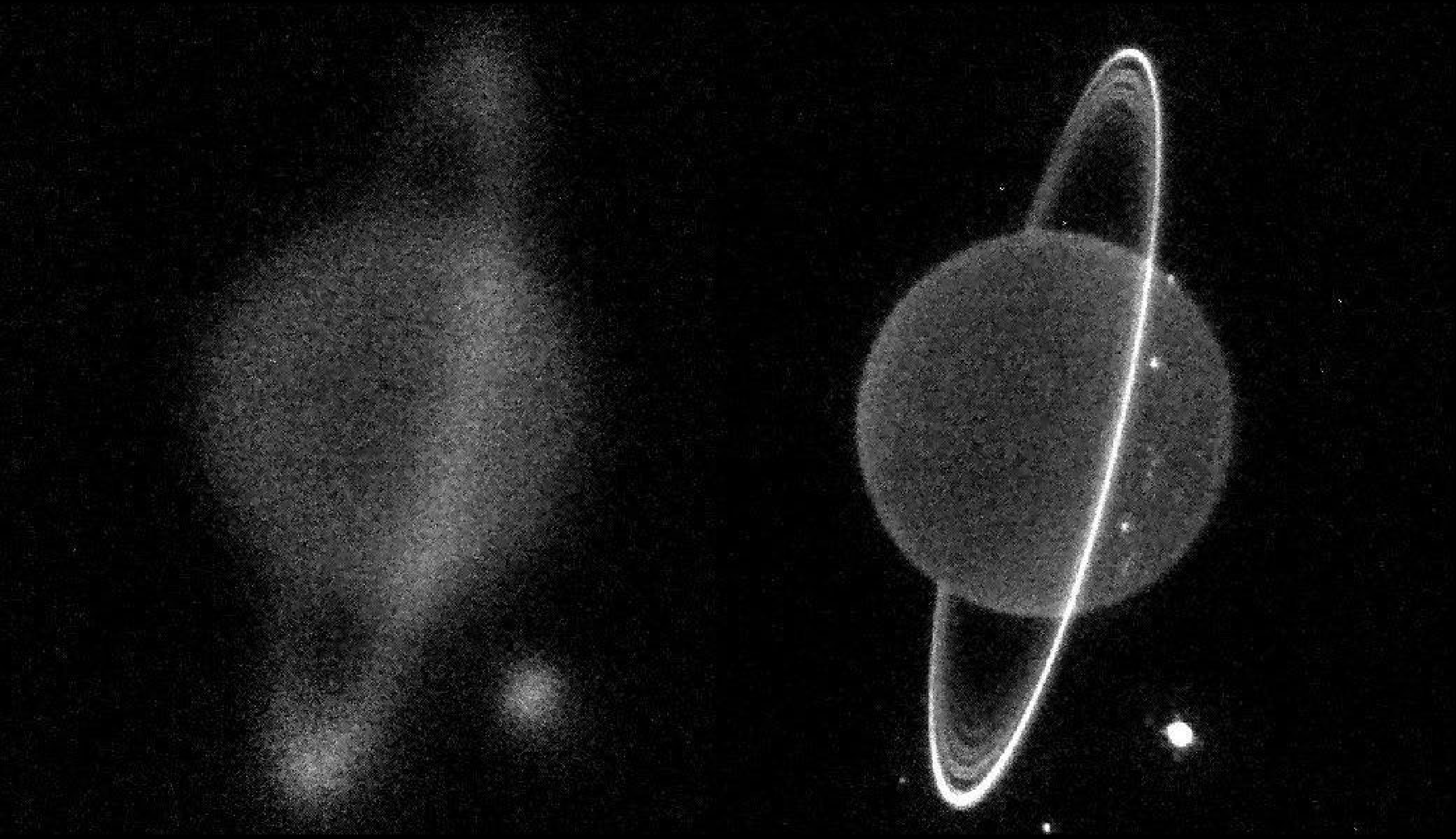
AO Requires a dependable “star” a true “point source”. We use a sodium laser to make a “star” out of sodium in the upper atmosphere



Hawaii's Keck Telescope AO laser at work

And at our own Lick Observatory on Mt. Hamilton (note the orange LP sodium lighting of San Jose?)

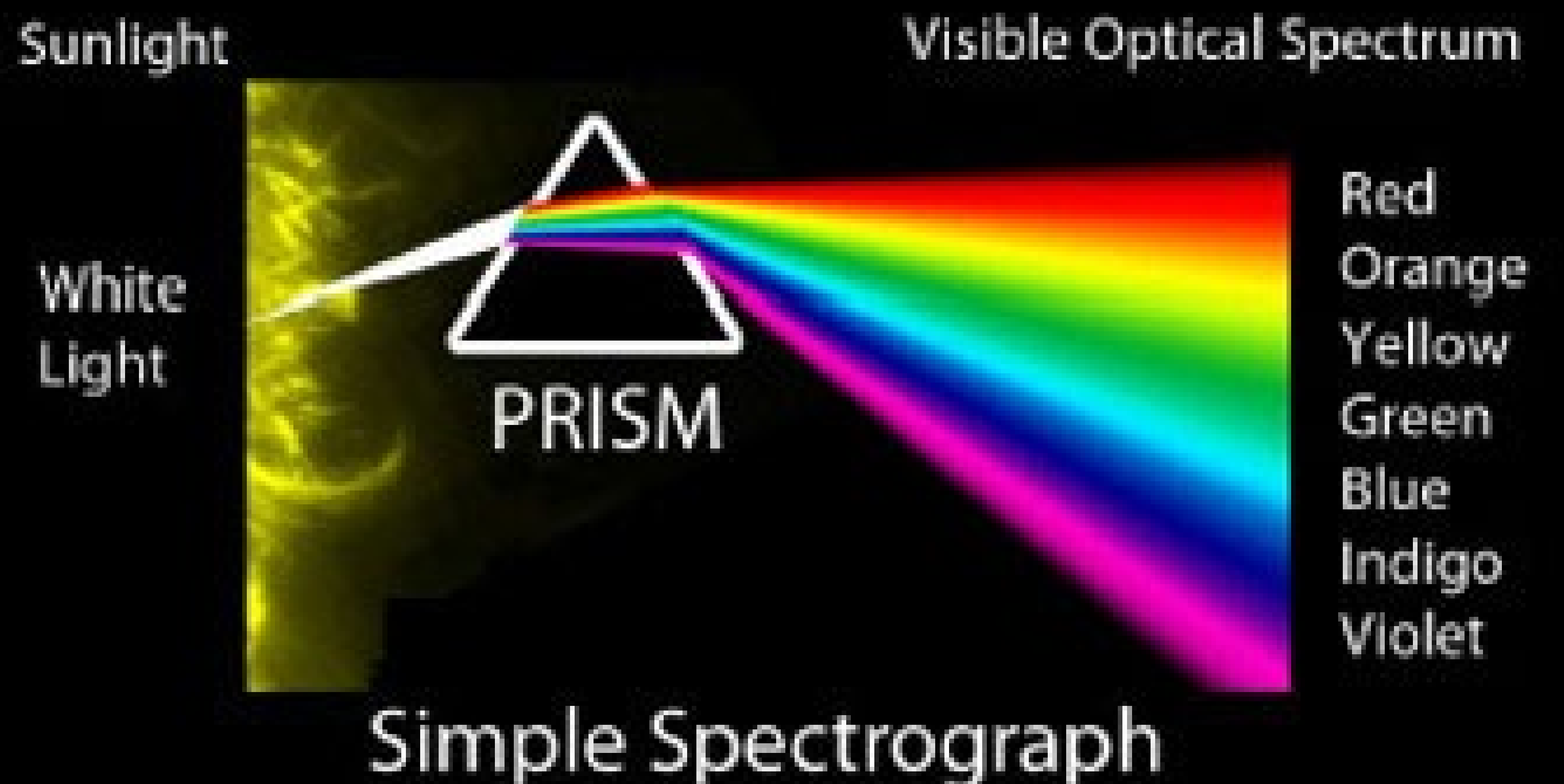
Ground-based images of Uranus: Without, and With Adaptive Optics



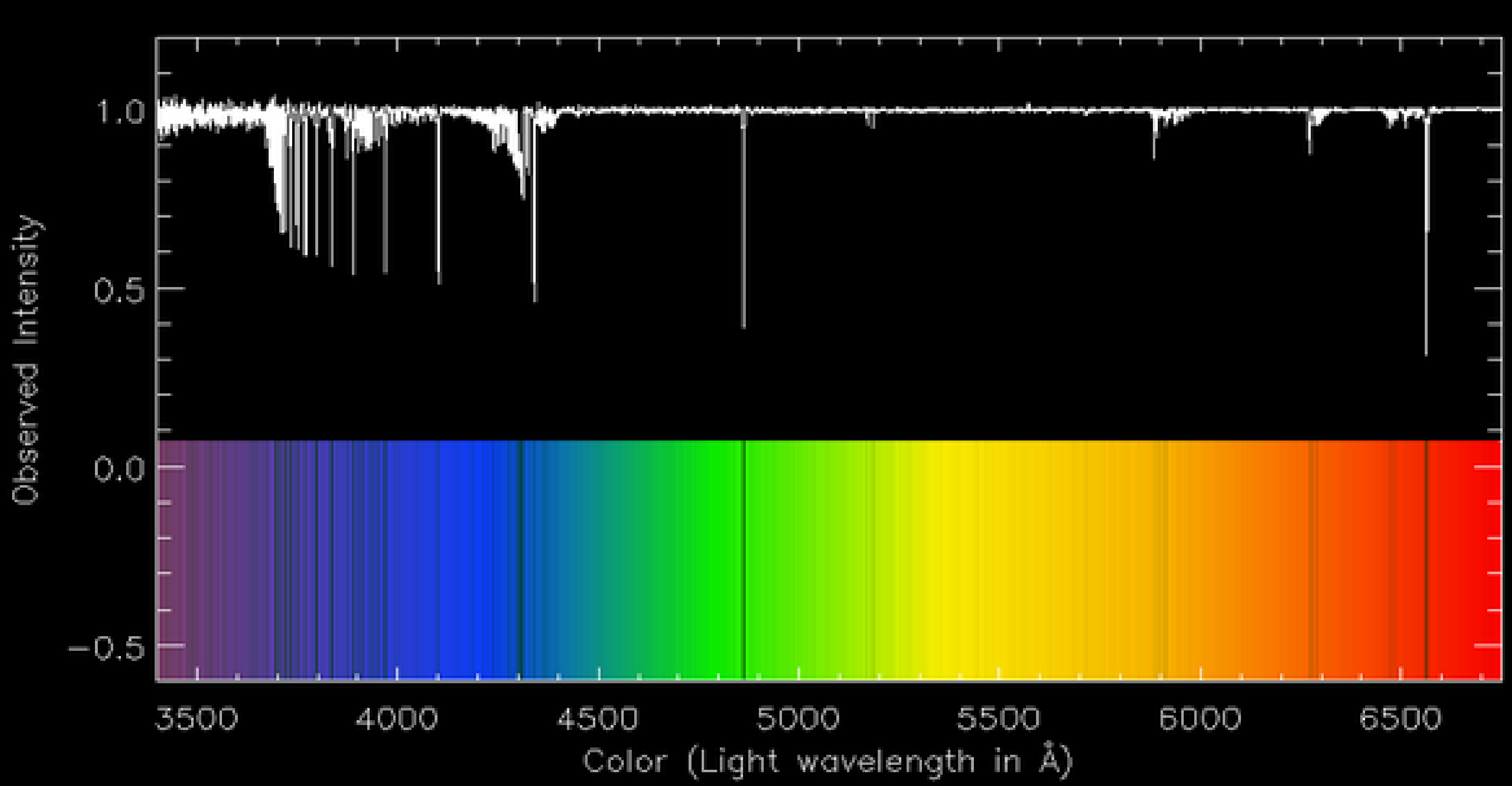
Spectrographs – Recording the Spectrum of an Object

- Together with CCD imagers, these two are the most important instruments in the Astronomer's toolbox.
- A spectrograph spreads a thin beam of light out into all the different wavelengths, and records it.
- A spectrograph image reveals the absorption and emission lines and thereby tells us the chemical composition, line-of-sight velocity, pressure, temperature, and rotation of the object we're studying

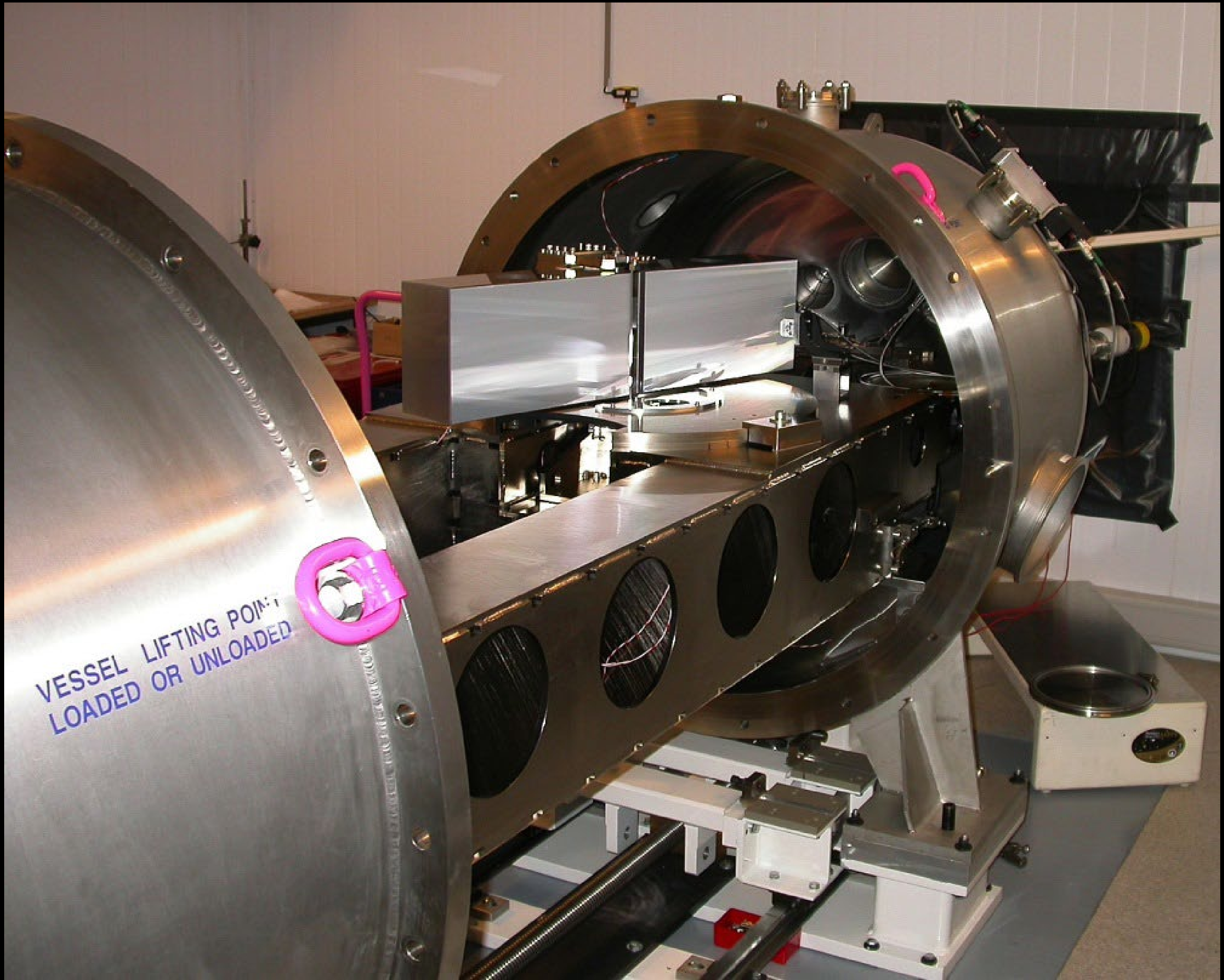
A Diffraction Grating, or sometimes a Prism, is used to spread the light



Spectrograph Image on Bottom, Graph of Intensity on Top



The HARPS Spectrograph at Keck Observatories in Hawaii



Next - Light Pollution

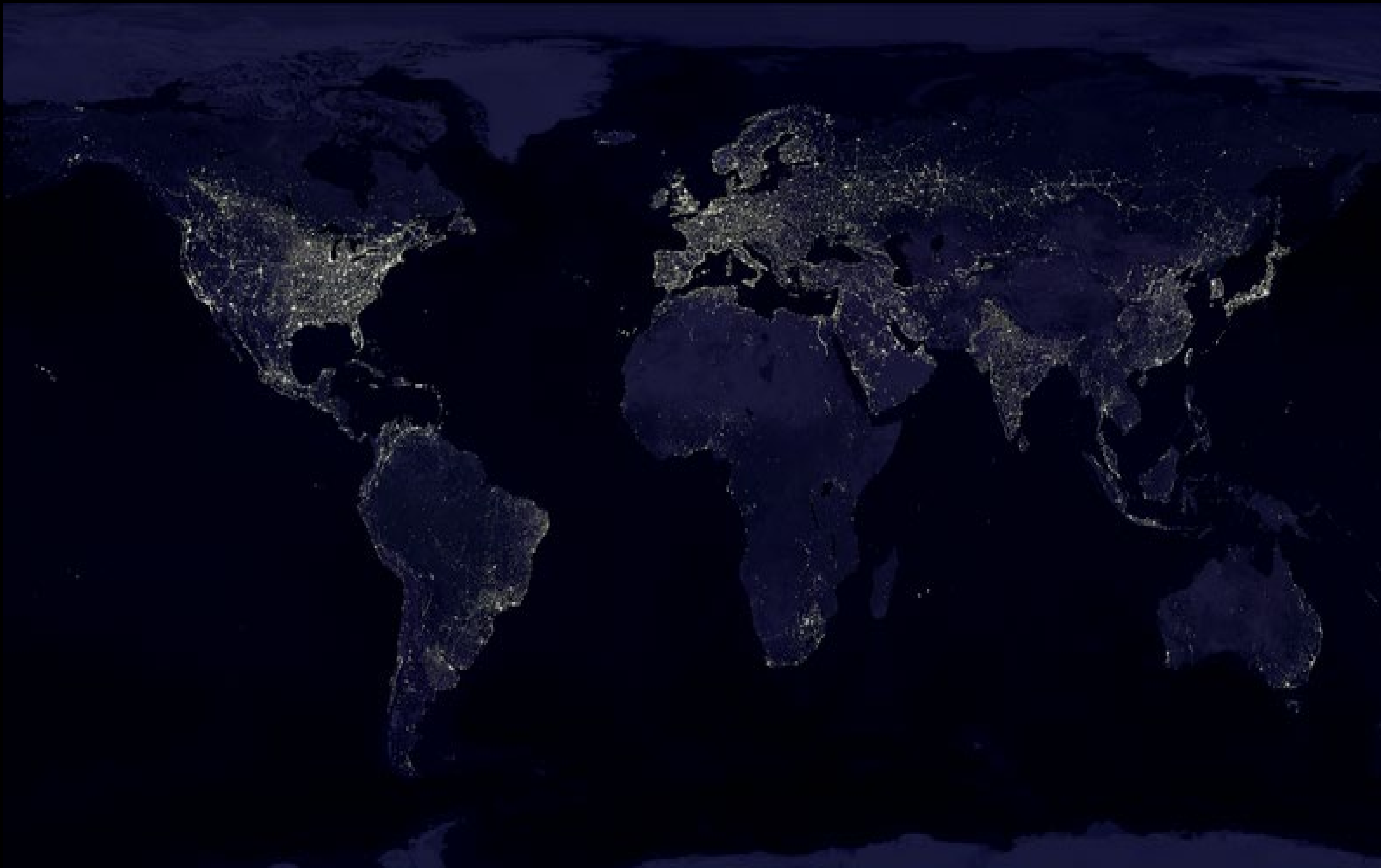
- Current night lighting is…
- -- damaging to astronomical observing
- -- wasteful of your dollars
- -- does not help inhibit crime
- -- Damages your health by interfering with hormone levels
- -- Puts money into the pockets of lawyers and insurance companies

- Five Strikes against it!
- Let's see why…

Compare: Rural sky scene (top) *vs.* same from a city.

The exposure length was forced to be much shorter in the city, when sky light became too strong

The Earth at Night: Lots of Wasted Energy



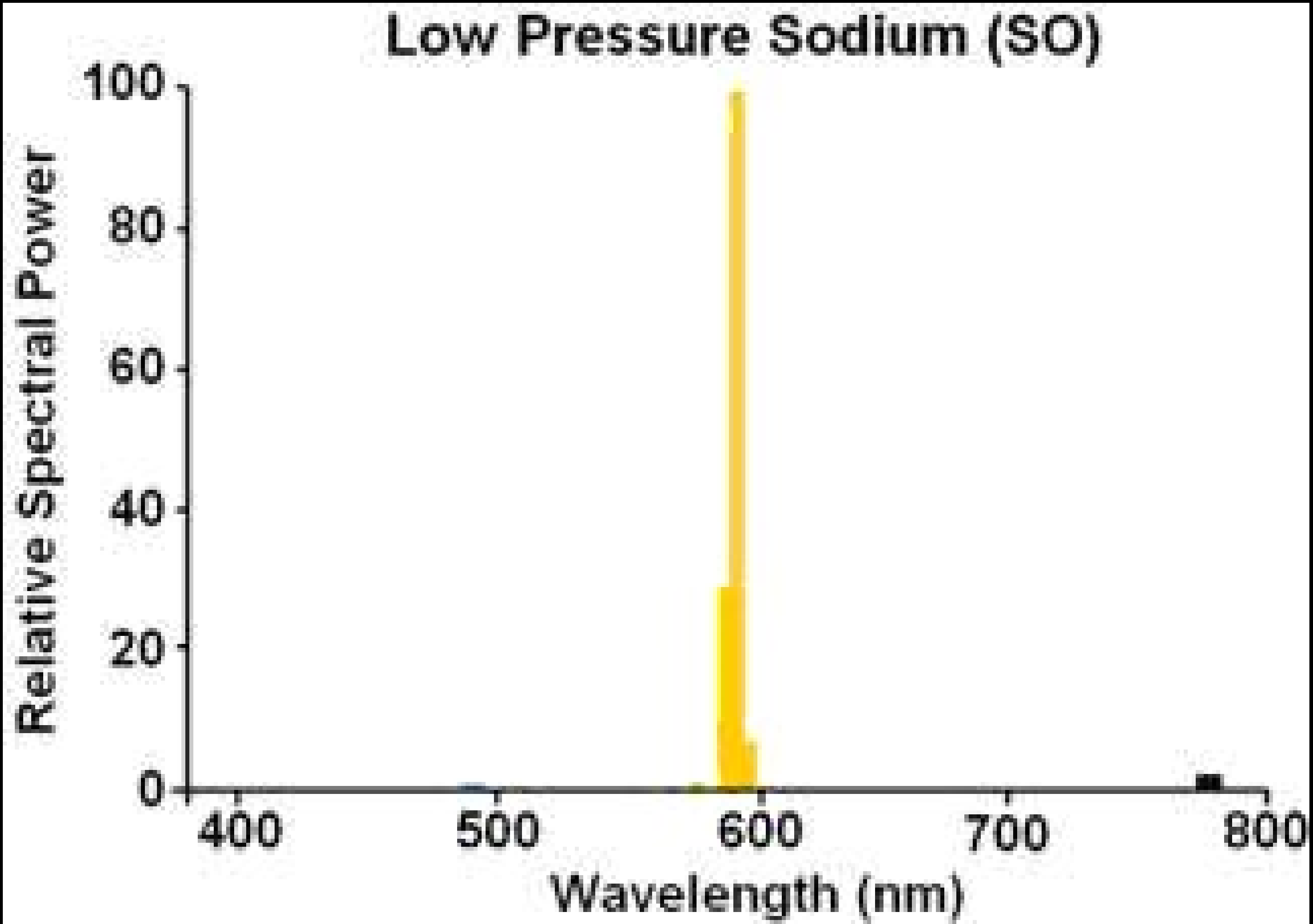
- **First Rule!: Light fixtures should direct ALL light downward, none sideways or upward**… so called **"Full Cutoff"** fixtures.
- Otherwise, upward light directly enters your eyes, making your pupil close down, making it harder, not easier, to see, AND wasting the cost of making that light.

2nd Rule: Use Low Pressure Sodium Lighting (LPS)!

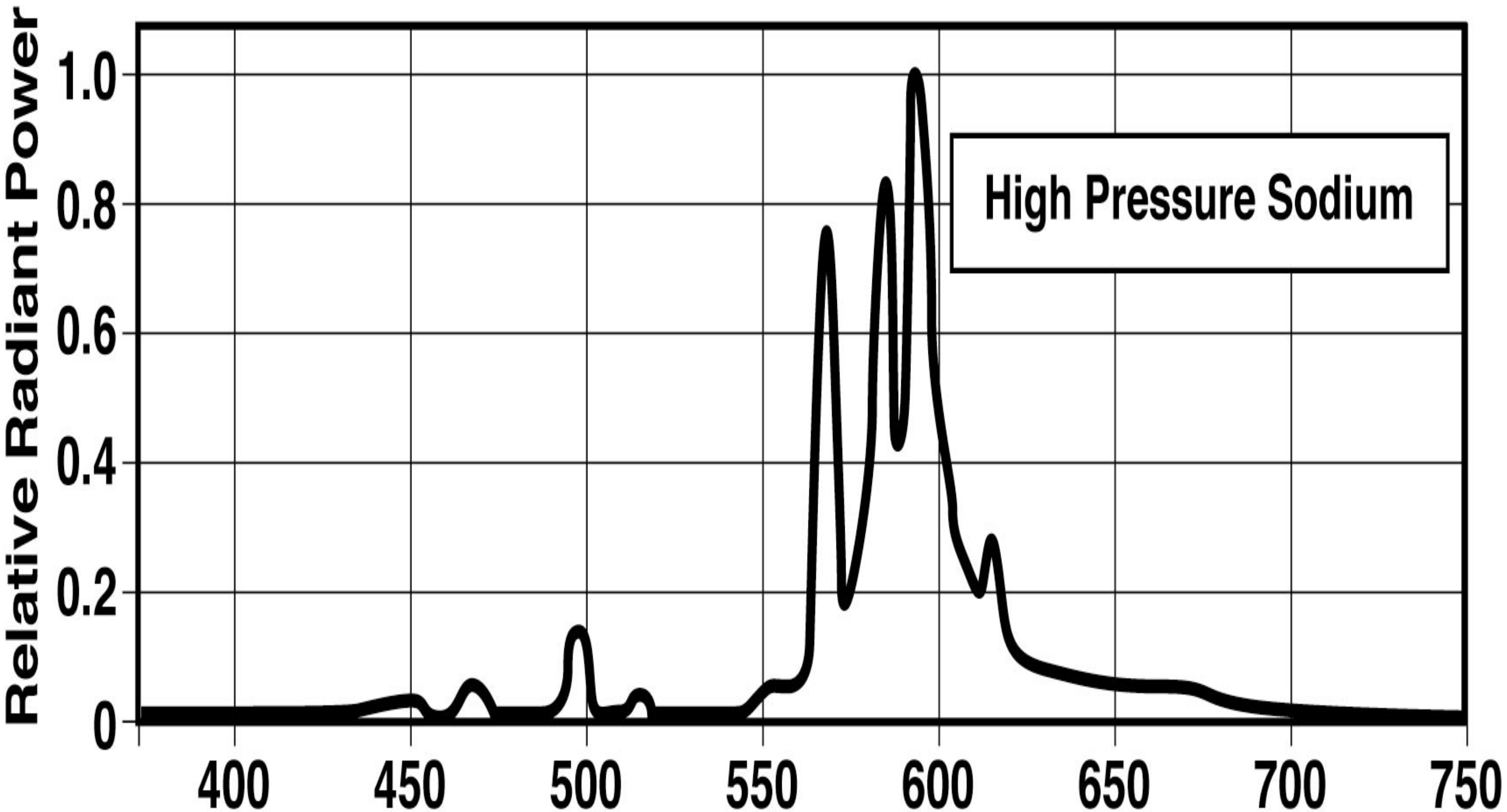
- **Good:** Low pressure sodium (LPS) only emits light at a few orange and red wavelengths. Astronomers can sacrifice study of these wavelengths if they can still do astronomy at the rest of the spectrum. Don't learn much about sodium in the universe but, it's a worthwhile compromise…

- **Bad:** High Pressure Sodium (HPS) spills over much more wavelength because of exactly that.
- **Bad:** Broadband lighting (like incandescent lights, high pressure sodium, mercury vapor lights) pollute very broad areas of the spectrum and not possible to filter out.

LPS only Wrecks One Wavelength



HPS Slops Over ~1/3 of the Visible Spectrum



Lights at Night Also Damage your Health

- Circadian (daily) rhythms involved in nearly ¼ of our genes. We are evolved to have darkness at night.
- Too much light, especially bluish light, shuts off our sleep mechanisms. A Public Health epidemic
- Melatonin initiates sleep, but its production is suppressed by light. Melatonin is a powerful and necessary hormone, involved for example in suppressing breast cancer.
- Interesting National Institute of Health article on light pollution and health
- Sleep deprivation is epidemic – it feeds corporate pockets, and it cripples your long term health, and it's no joke. **READ this from an expert**.

This is your eye/brain's sensitivity to different wavelengths', closely evolved to the arriving sun's thermal spectrum

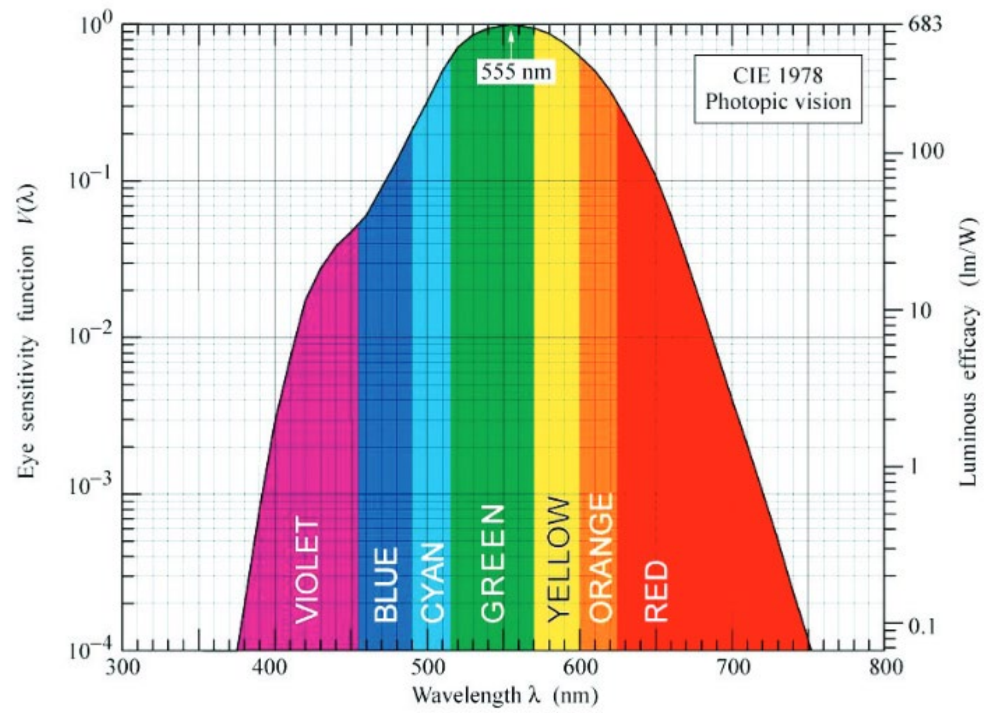


Figure 5.11 shows that one watt of energy in the form of green light results in 683 lm. This means that the absolute limit of a light device's efficiency is 683 lm/W. White, of course, is a mixture of many different colors and therefore seeing it requires eye receptors that are much less efficient than the green peak (Figure 5.11). There has been extensive analysis of what qualifies as an acceptable "white light."[61] The "white" that is acceptable depends on what is being illuminated (i.e., food, living areas, or streets), and there may be cultural differences.[62] Preferences for "warm" colors with more red or preferences for "cool" colors, which more closely match sunlight

LED lights have a friendlier more “thermal” spectrum *vs.* fluorescents, but with a big spike in blue light. OLED lights are a bit more efficient by trimming out more of the invisible IR, but are very non-thermal in distribution

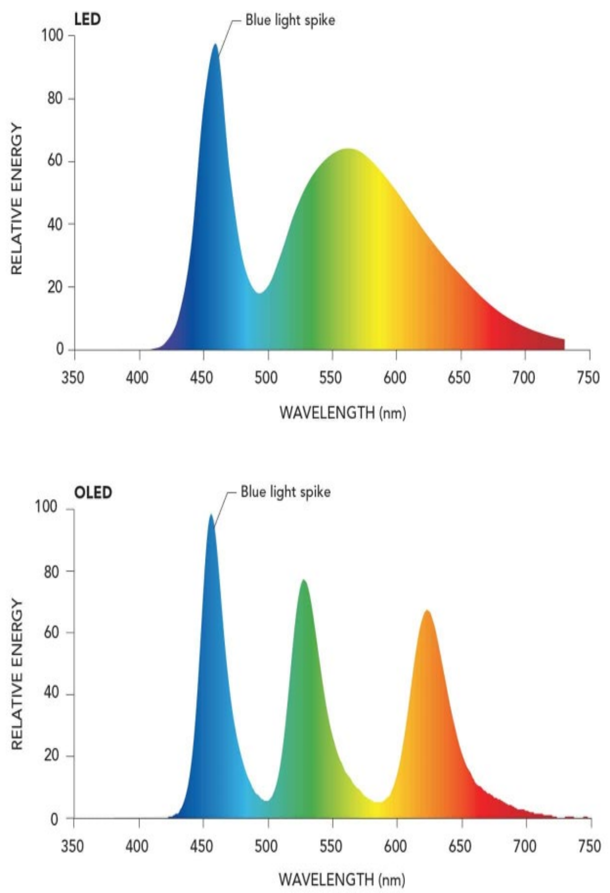
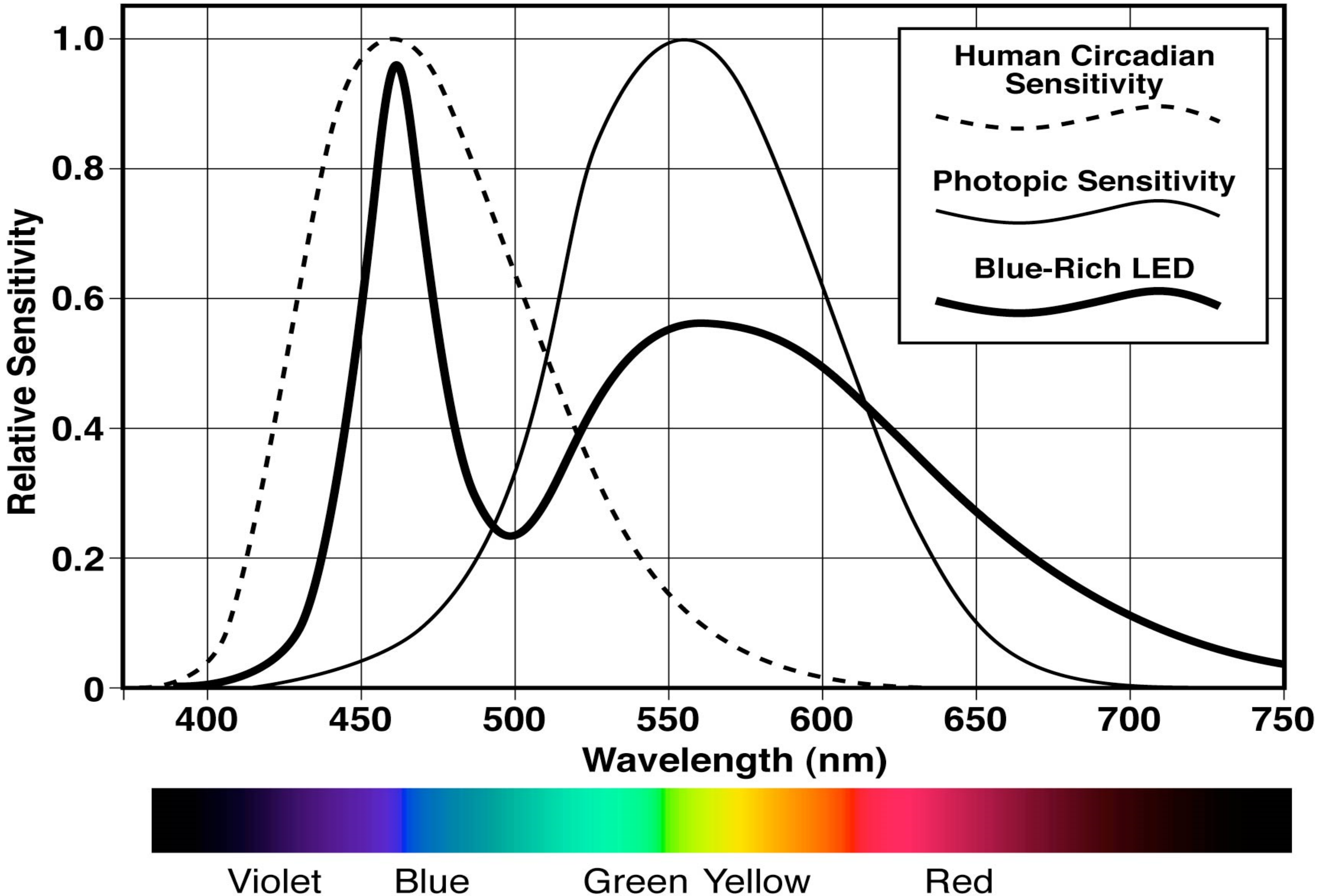


Figure 2-4. Wavelength compared to color temperature. Both LED and OLED technologies have a spike in the wavelength range of harmful blue light, and absolute energy, as measured by color temperature, can be 7500 K and higher.

HOW TO SAVE YOUR EYES IN THE DIGITAL AGE ©Healthe 2019 **eyesafe.com/handbook**

LED lights: Their blue wavelengths muck with our biology



From Sleep Scientist M. Walker (UC Berkeley)…

- *"In 1942, less than 8% of the population was trying to survive on six hours or less sleep a night; in 2017, almost one in two people is. The reasons are seemingly obvious. "First, we electrified the night," Walker says. "Light is a profound degrader of our sleep. Second, there is the issue of work: not only the porous borders between when you start and finish, but longer commuter times, too. No one wants to give up time with their family or entertainment, so they give up sleep instead. And anxiety plays a part. We're a lonelier, more depressed society."*

Walker continues…

- *“In the developed world, sleep is strongly associated with weakness, even shame. “We have stigmatised sleep with the label of laziness. We want to seem busy, and one way we express that is by proclaiming how little sleep we’re getting. It’s a badge of honor.”*

Without Light Pollution, the urban sky COULD look like this ☺

Not Rocket Science – So why has Eliminating Light Pollution been So Slow and Resisted?

- Lighting is designed to look *pretty*, not necessarily functional (you only know how functional it is AFTER you've bought it)
- Some people feel low pressure sodium lights are too red and makes skin tones not very *pretty*
- My reaction? Who cares about how pretty skin tones are when you're outside at night? You're probably wearing lots of clothes anyway (or should be!).
- Advertisers WANT to out-dazzle the competition with ever brighter, more wasteful lights. Searchlights, flashing billboards, Salinas Auto Mall expensive; expensive and absurdly bright lighting
- What about lawyers, liability insurance, and crime prevention?

Bright floodlights Cause MORE Crime, not less

- See this "New Yorker" article
- $1-2 billion a year is wasted on needless lighting
- San Antonio School District experimented with **eliminating** night lighting, and found vandalism dramatically **dropped**
- Chicago raised the wattage of alley lighting from 90W to 250W per fixture - and yet saw crime INCREASE by 21% compared to a control area.
- Easy to understand – When lighting is flooded everywhere, you stop noticing people and what they're doing. If it were dark, then seeing someone with an irregularly moving flashlight would catch your eye. Criminals need lights too!
- Also, more lighting only causes your pupil to close down, requiring even brighter lights to compensate.

Key Ideas – Chap 6: Instruments of Astronomy

- Top goal of a telescope – gather as much light as possible, not necessarily to magnify it. So maximize size of mirror!
- Reflectors, not refractors, much better and cheaper
- Modern imagers are CCD cameras with silicon CCD chip. Know advantages over old-style photography.
- Important instruments: Spectrograph. Less often and specialized use: high speed photometer, polarimeter
- Interferometer connecting adjoining telescopes will produce much sharper images. Wider spacing is harder to do but sharper if you can do it.
- Adaptive optics can correct for blurring by Earth's convective atmosphere and deliver sharp images.
- Vast amounts of energy wasted on expensive light which inhibits night vision, creates light pollution hurting all major observatories.
- **The two best solutions: full cut-off fixtures to direct all light downward, and narrow wavelength lights (low pressure sodium lights, not high pressure)**
- Know which wavelength bands can be studied from the ground, make it through our atmosphere: **visible, and radio**
- **Observing in blocked wavelengths, is the most important reason to launch space-based observatories**.