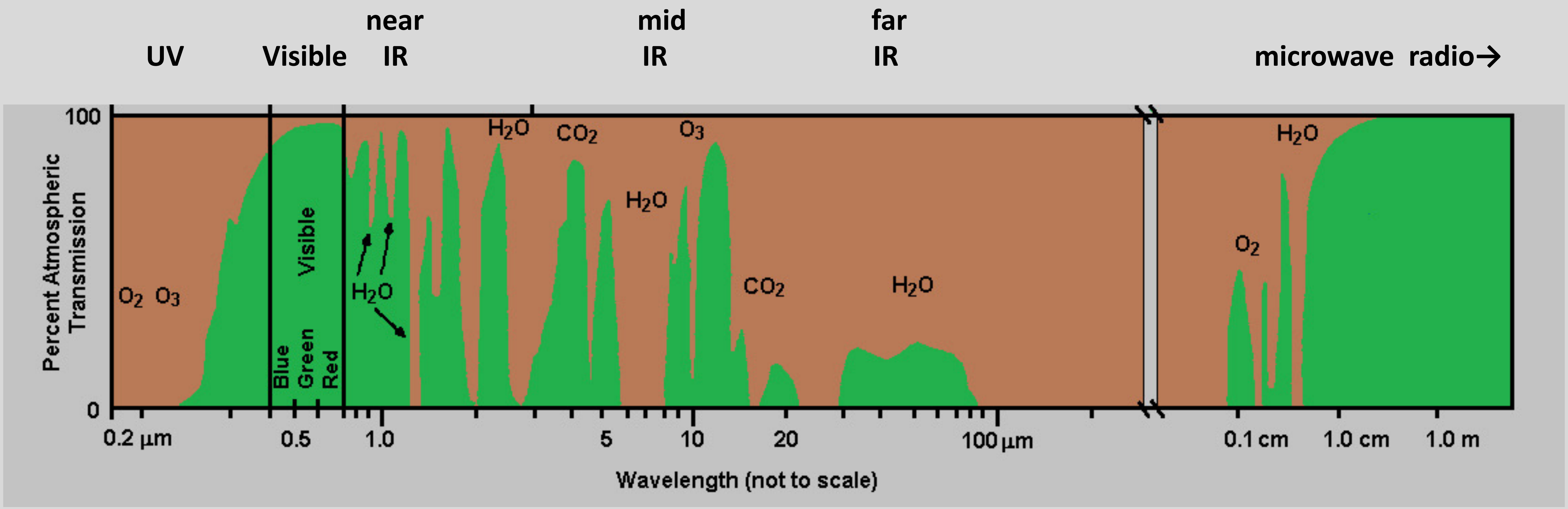
Transparency

The atmosphere absorbs at many wavelengths. There are two major "windows" for ground-based astronomy: optical/near-IR and radio. Observations at other wavelengths (X-ray, UV, mid/far-IR) must be done from space.



Transparency (in green) as a function of wavelength.

Atmospheric Extinction and Reddening

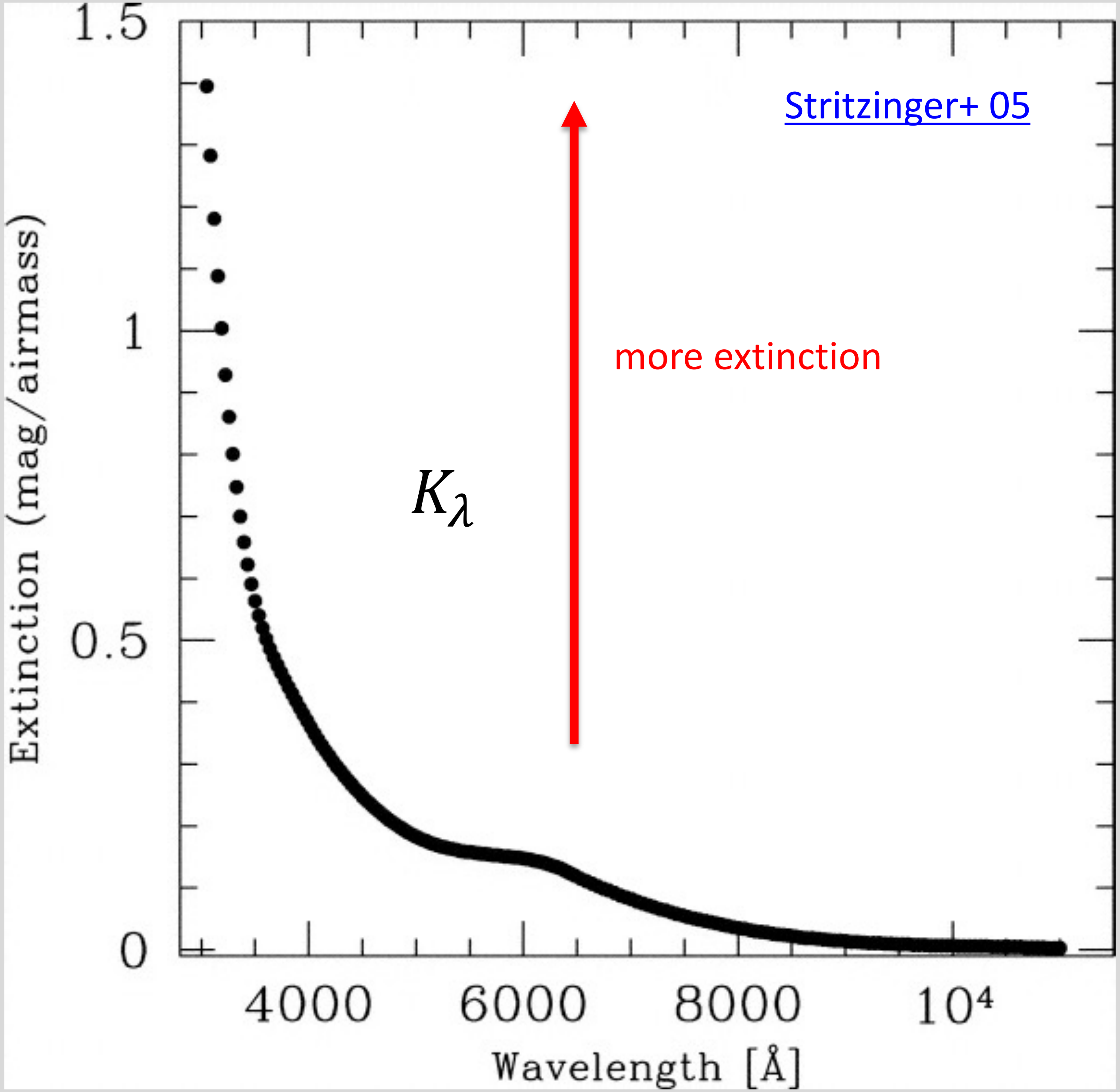
Even in the windows, the transmission can be significantly degraded. This extinction of starlight needs to be corrected, to get the magnitude of a star "at the top of the atmosphere":

$$m_{\lambda,obs} = m_{\lambda,true} + K_\lambda X$$

where X= airmass and the extinction coefficient K_λ is very wavelength dependent.

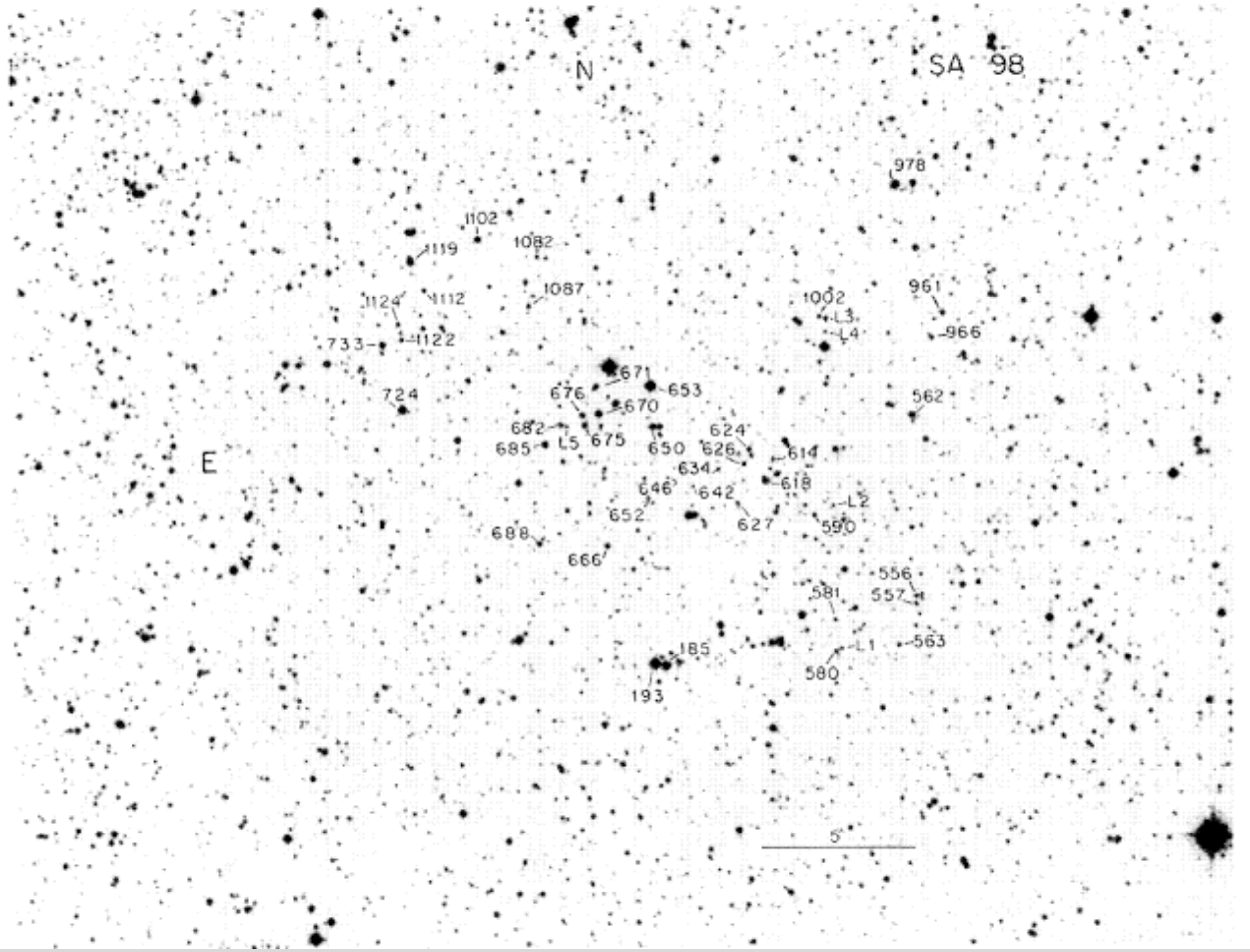
Sanity check: atmospheric extinction makes the star artificially fainter than true, so to correct for this we want the corrected magnitude to be brighter, i.e., numerically smaller. Hence the subtraction of the extinction term.

Stronger extinction in the blue means that the atmosphere **reddens** the light. (Think about sunset.....)



Extinction coefficients are also, unfortunately, time- and location-dependent! You need to measure them yourself as part of your observing run....

To measure extinction coefficient: take data for “standard stars” of known brightness (and color) at a range of airmasses and fit the slope and uncertainties.



Simple Photometric Solutions

For stars of known true magnitude, measure the instrumental magnitude as a function of airmass, fit slope and zeropoint to measure extinction term and photometric calibration.

Instrumental magnitude

An *uncalibrated magnitude-like measure* of how many photons are detected each second from the star.

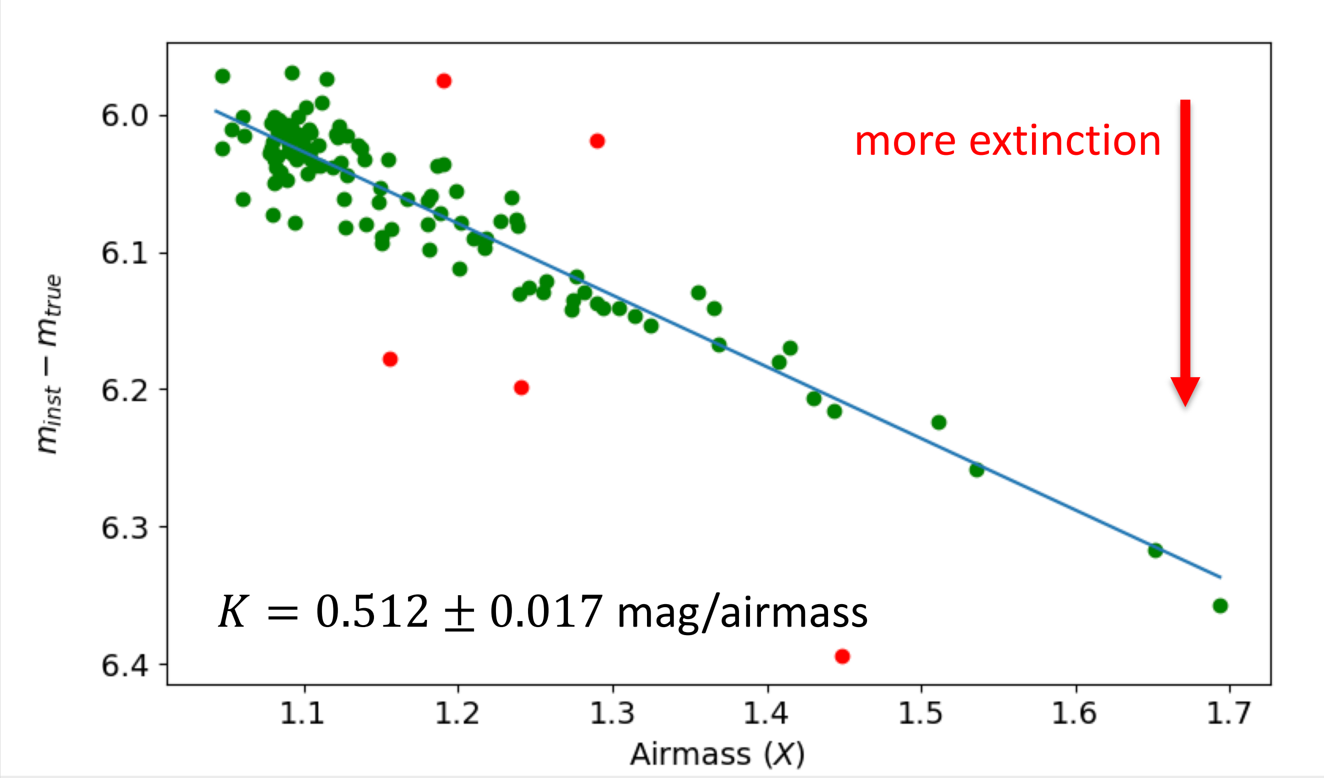
$$m_{inst} = -2.5 \log_{10} I + C$$

I: counts per second
C: arbitrary constant

Simple Photometric solution:

$$m_{inst} = m_{true} + KX + ZP$$

X: Airmass
K: Extinction Term (slope of line)
ZP: Photometric Zeropoint (y-intercept)



Burrell Schmidt 2021
[OII]λ3727 on-band imaging

Night Sky Brightness

Scattering (moonlight, artificial lights)
Strong function of lunar phase:

Night sky surface brightness in mag/arcsec^2 in blue (B) and red (R) wavelengths:

	Lunar age (days)	μ(B)	μ(R)
Dark Time	0	22.7	20.9
Grey Time	7	21.6	19.7
Bright Time	14	19.5	19.9

KPNO, approximate

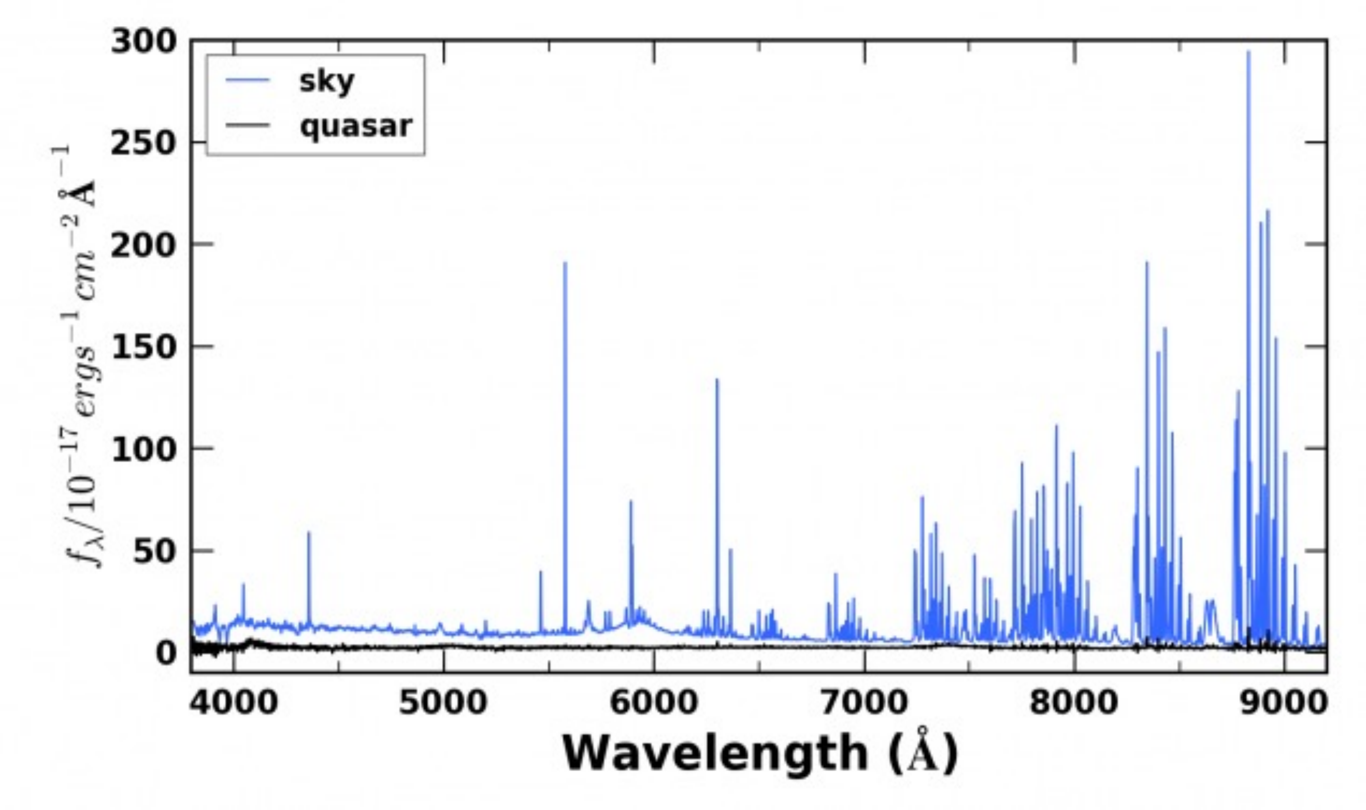
At R, the difference is 1 mag/arcsec^2, or a factor ≈ of 2.5
At B, the difference is 3.2 mag/arcsec^2, or a factor of ≈ 20

Dark time: work on faint things and/or at blue wavelengths.
Bright time: work on bright things and/or red/IR wavelength.

Night Sky Brightness

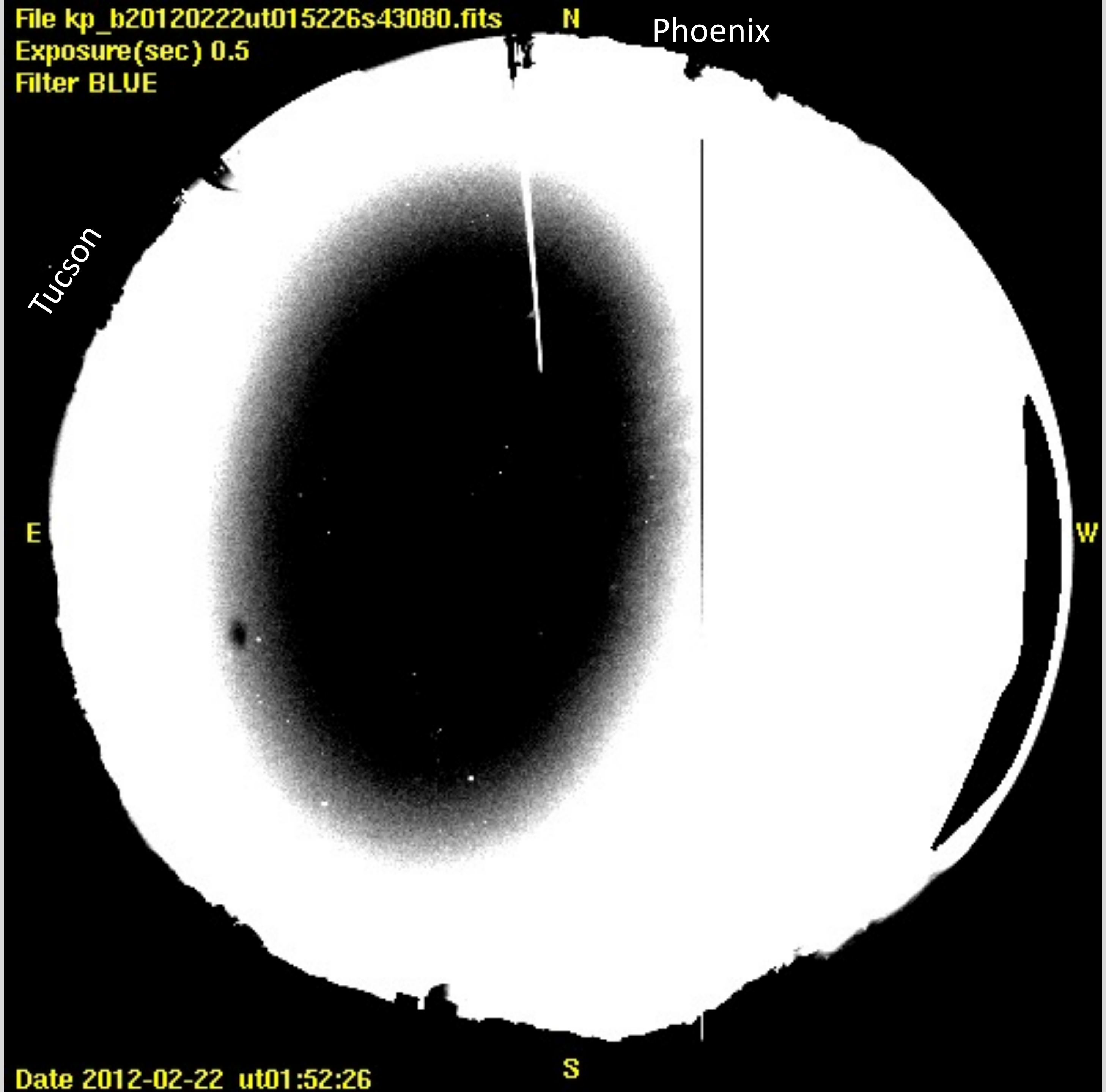
Emission
- Natural sky emission: Oxygen, Nitrogen, OH molecules
- Artificial lights: Mercury, Sodium, etc

Depends on time of night, solar activity, etc.



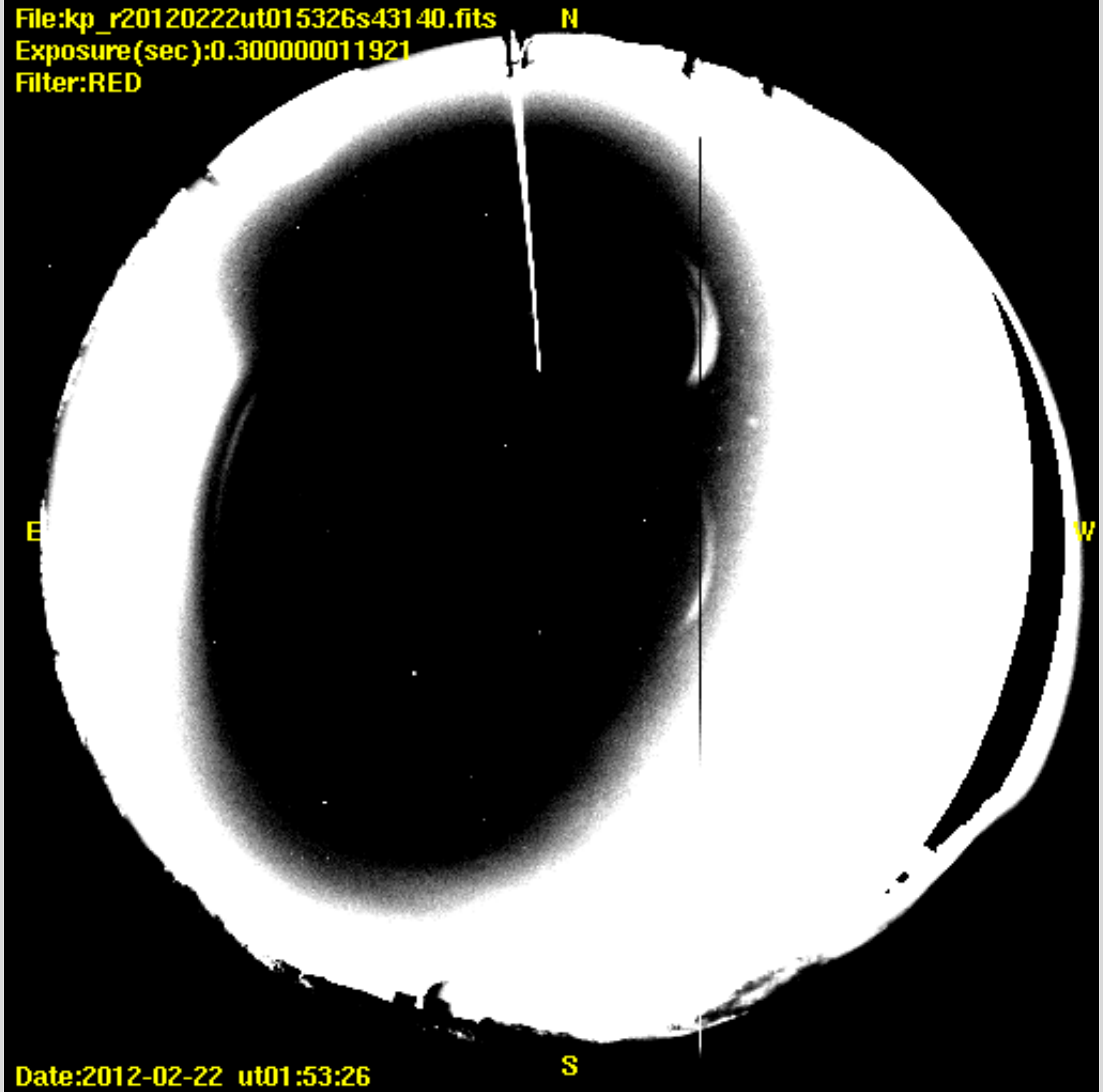
Kitt Peak Night Sky Brightness

(Blue wavelengths)



Kitt Peak Night Sky Brightness

(Red wavelengths)

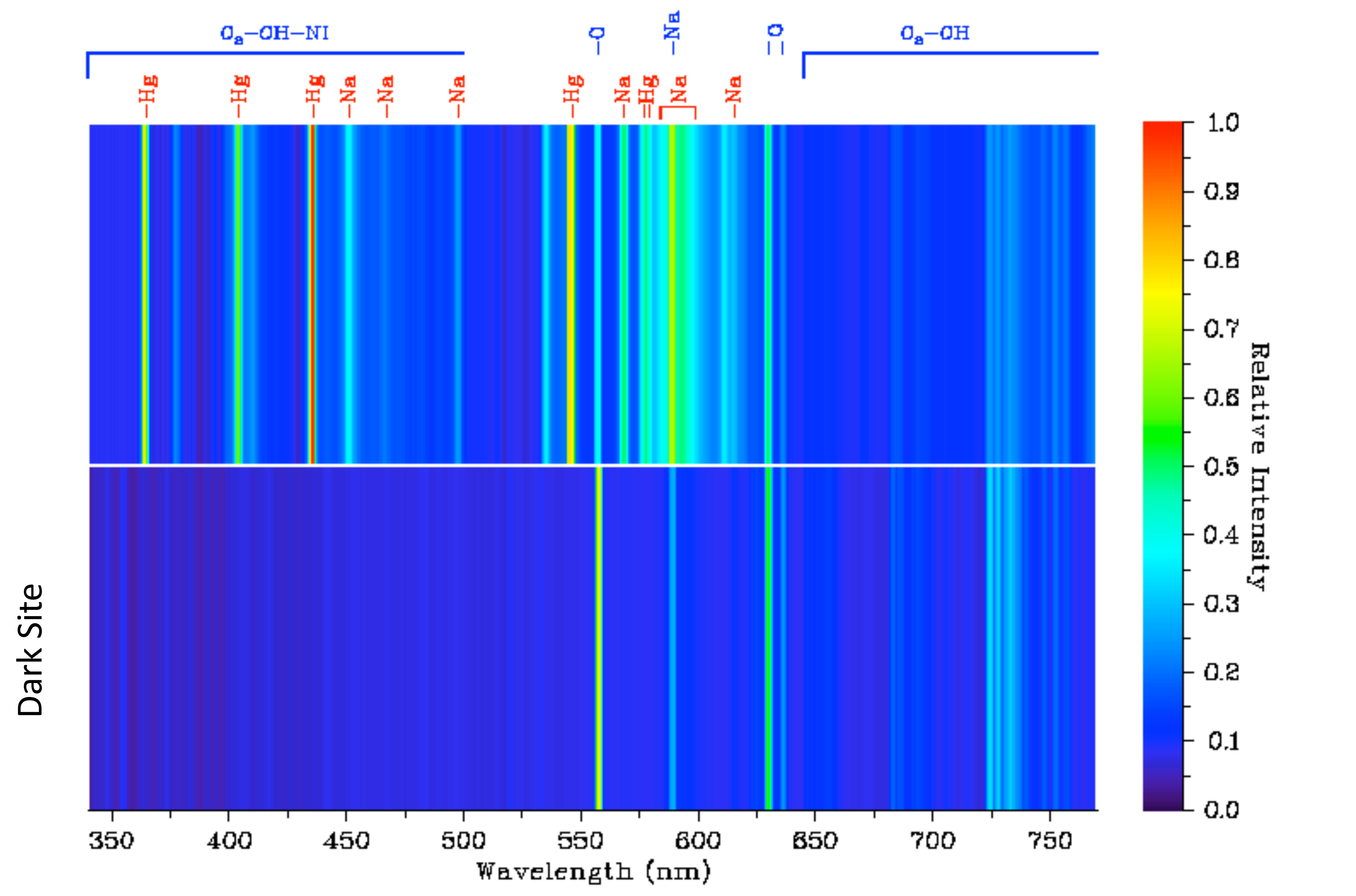


City Sky

Many sodium and mercury emission lines due to light pollution

Dark site

”Natural” night sky lines, mostly oxygen and OH molecules.

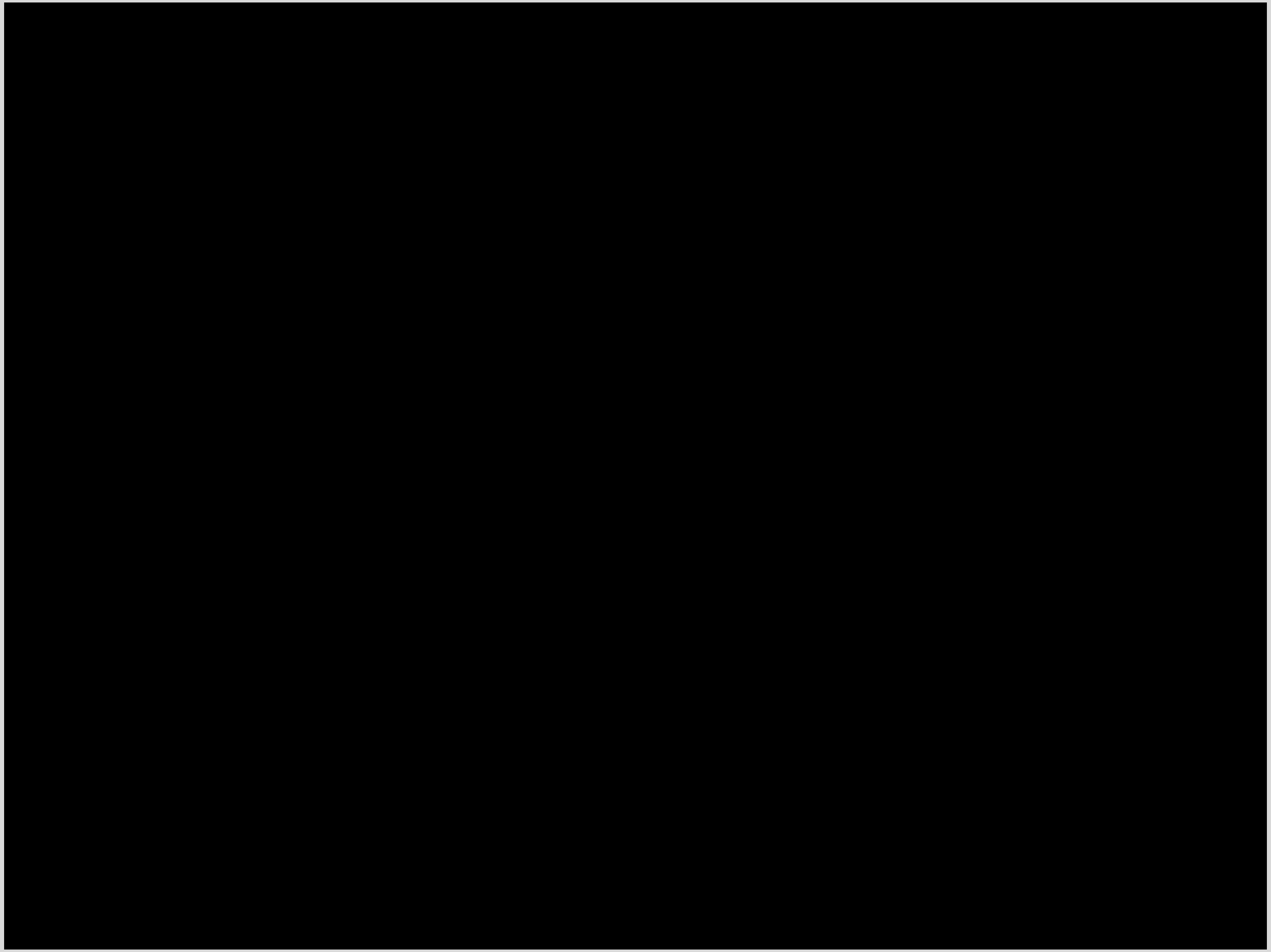


Comparison between a night sky spectrum taken at Cerro Paranal-Chile during dark time (lower panel) and one taken in Asiago-Italy (upper panel). Light pollution is clearly visible in the form of Sodium (Na) and Mercury (Hg) emission lines in the blue/visible part of the spectrum.

Night Sky variability

The night sky varies in intensity, depending on atmospheric conditions, time of night, solar activity, etc.

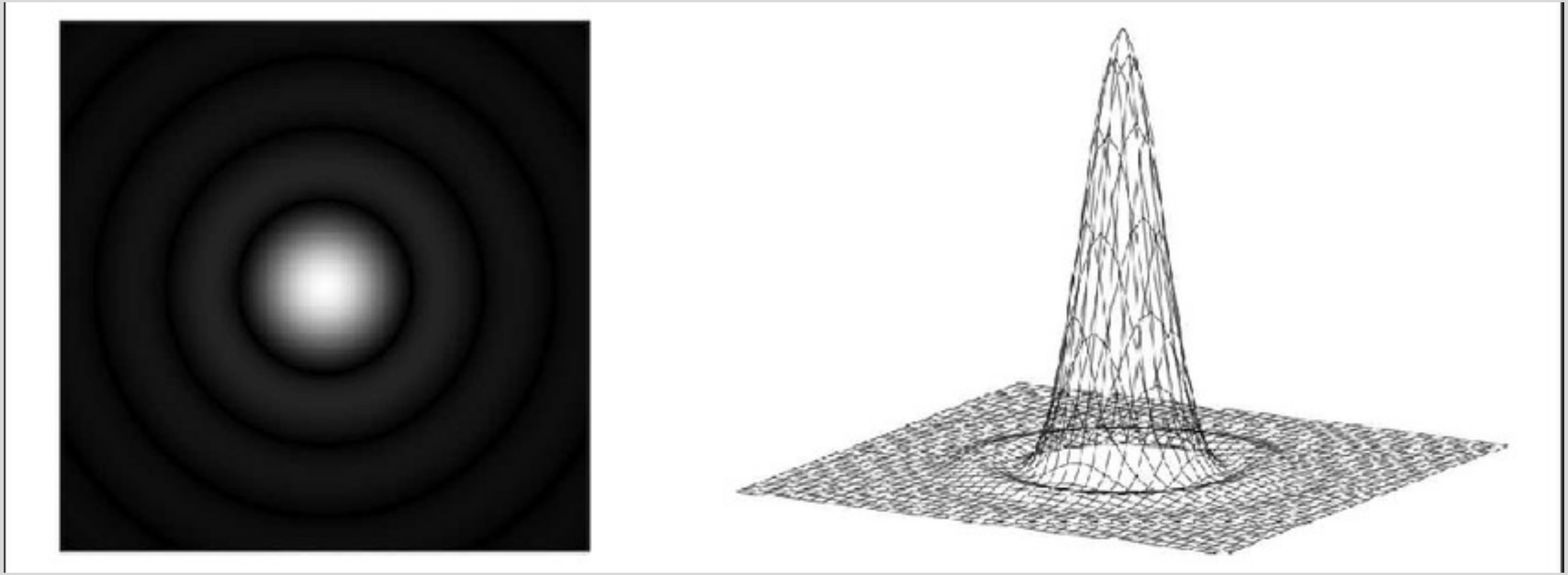
Must always make a concurrent measurement of the sky to “subtract” from and correct the observations of your target.



Media courtesy Nando Patat (ESO); taken from
http://www.eso.org/~fpatat/science/skybright/

Resolution and the Point Spread Function (PSF)

Telescope produces (at best) diffraction limited optics. A perfect telescope would show a point source as an **Airy profile**:



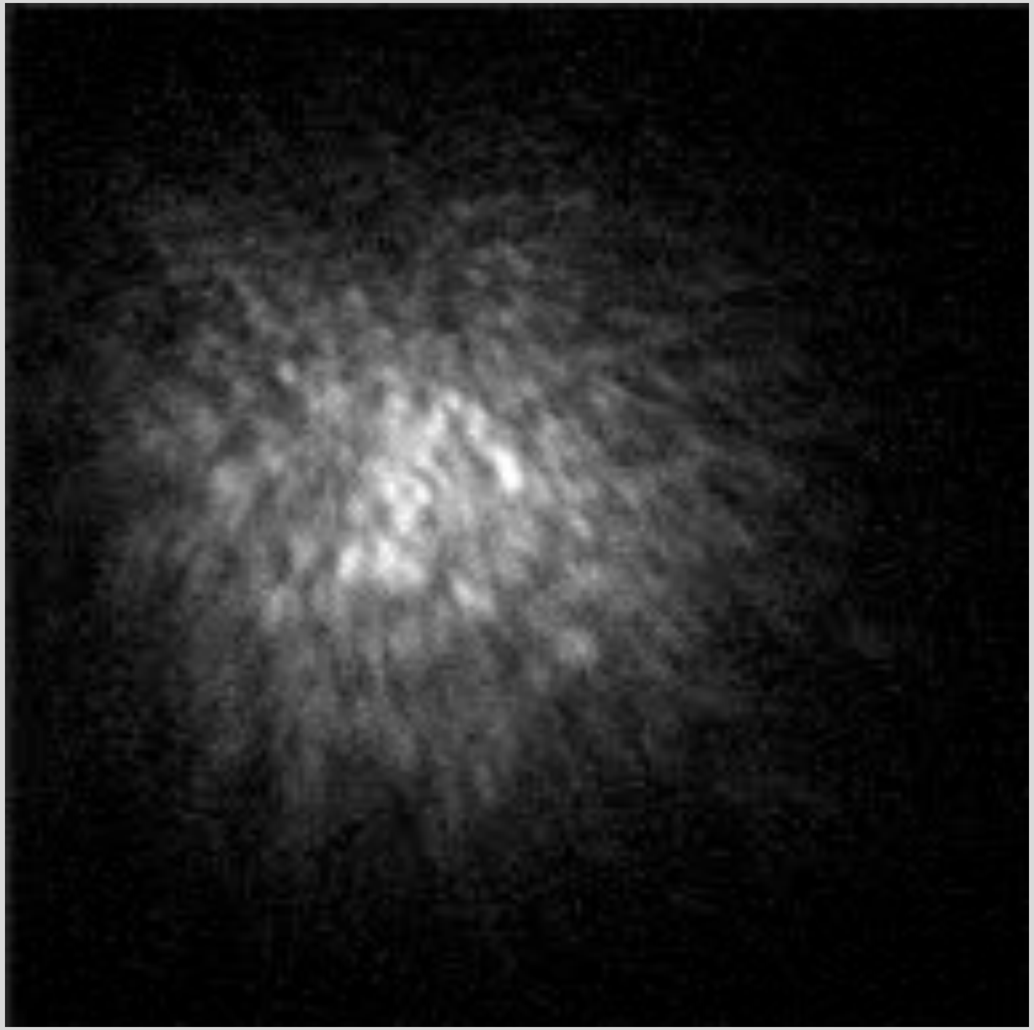
For a telescope of diameter D observing at a wavelength λ, full width at half max (FWHM) of peak is = 1.22 λ/D

This is ≈ 0.05 arcsec for 2.4m telescope in the optical, but that resolution cannot be achieved from the ground due to the atmosphere.

Atmospheric Seeing

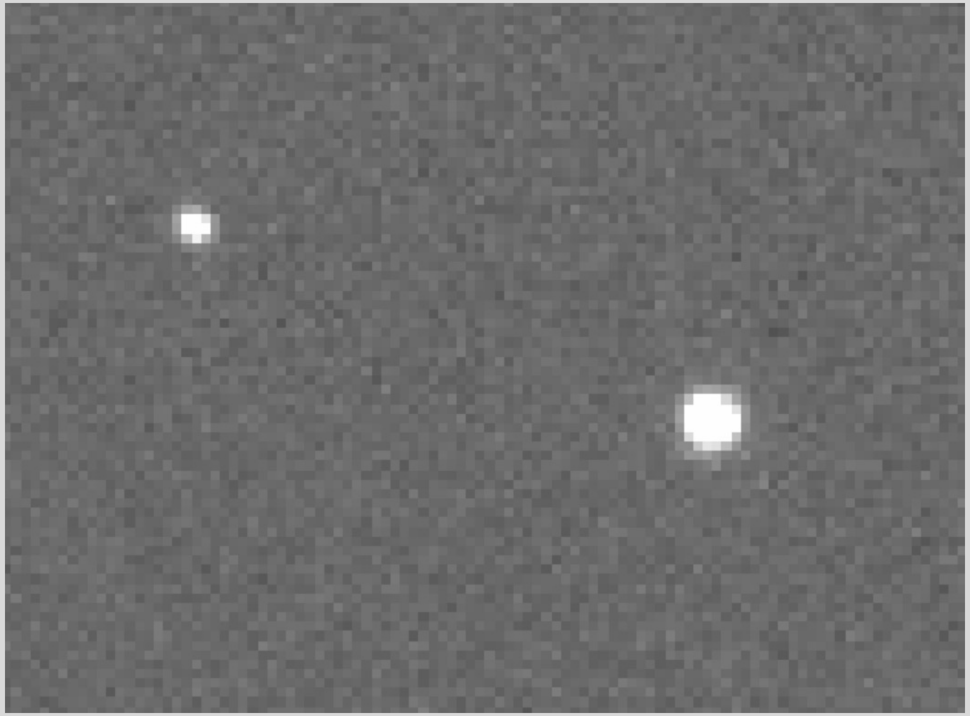
In a ground-based telescope, watching a star image in real time we see:

- Scintillation (brightness changes)
- Blurring (sharpness changes)
- Image motion (position changes)



30 msec images of Betelgeuse through the 4.2m INT telescope.

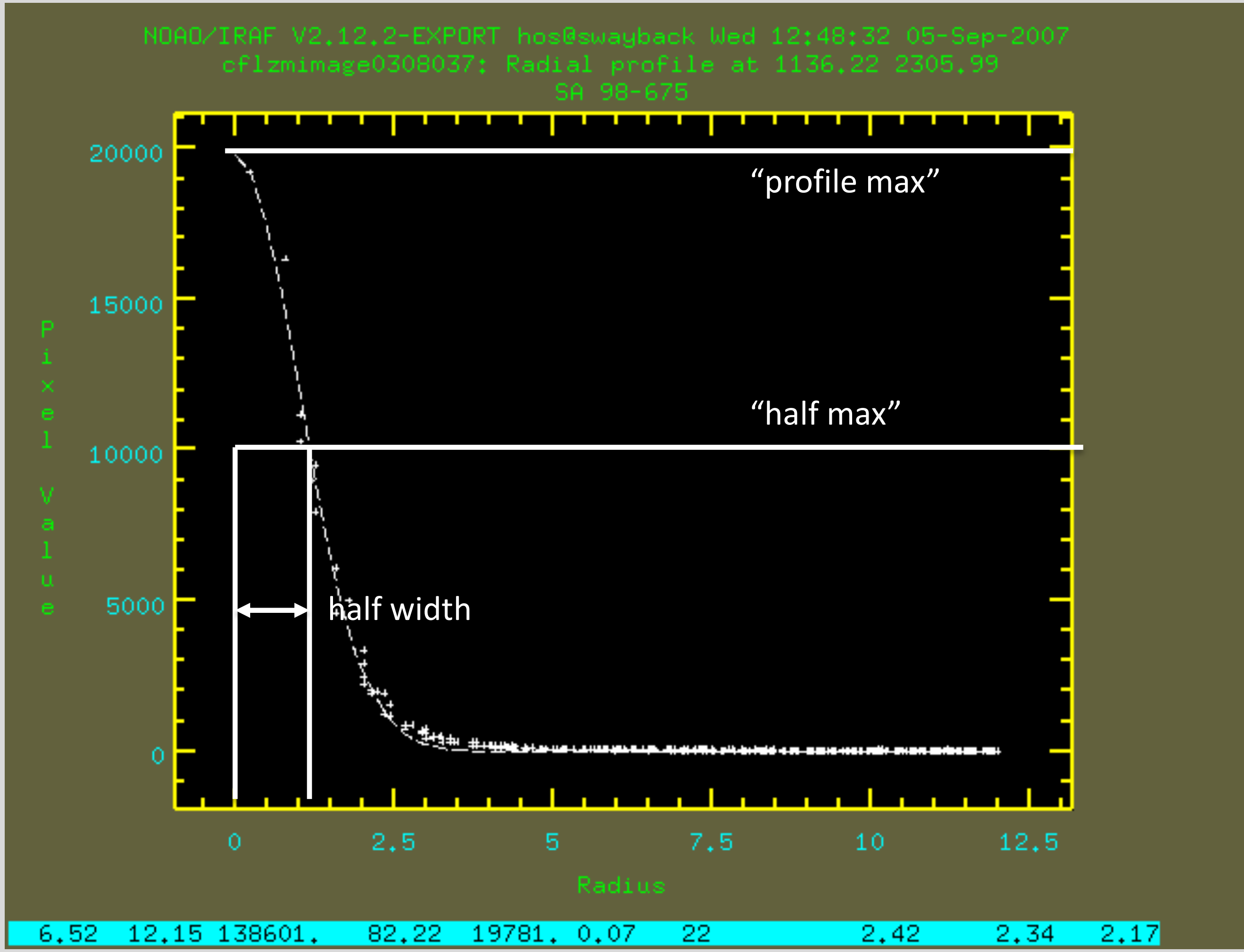
Atmospheric Seeing



In an extended exposure, all this jittering blurs the PSF out to a quasi-gaussian shape:

$$I(r) = I_0 e^{-(r^2/2\sigma^2)}$$

We typically characterize the seeing by "full width at half max" or FWHM. (*Note: FWHM is not the same as σ*)

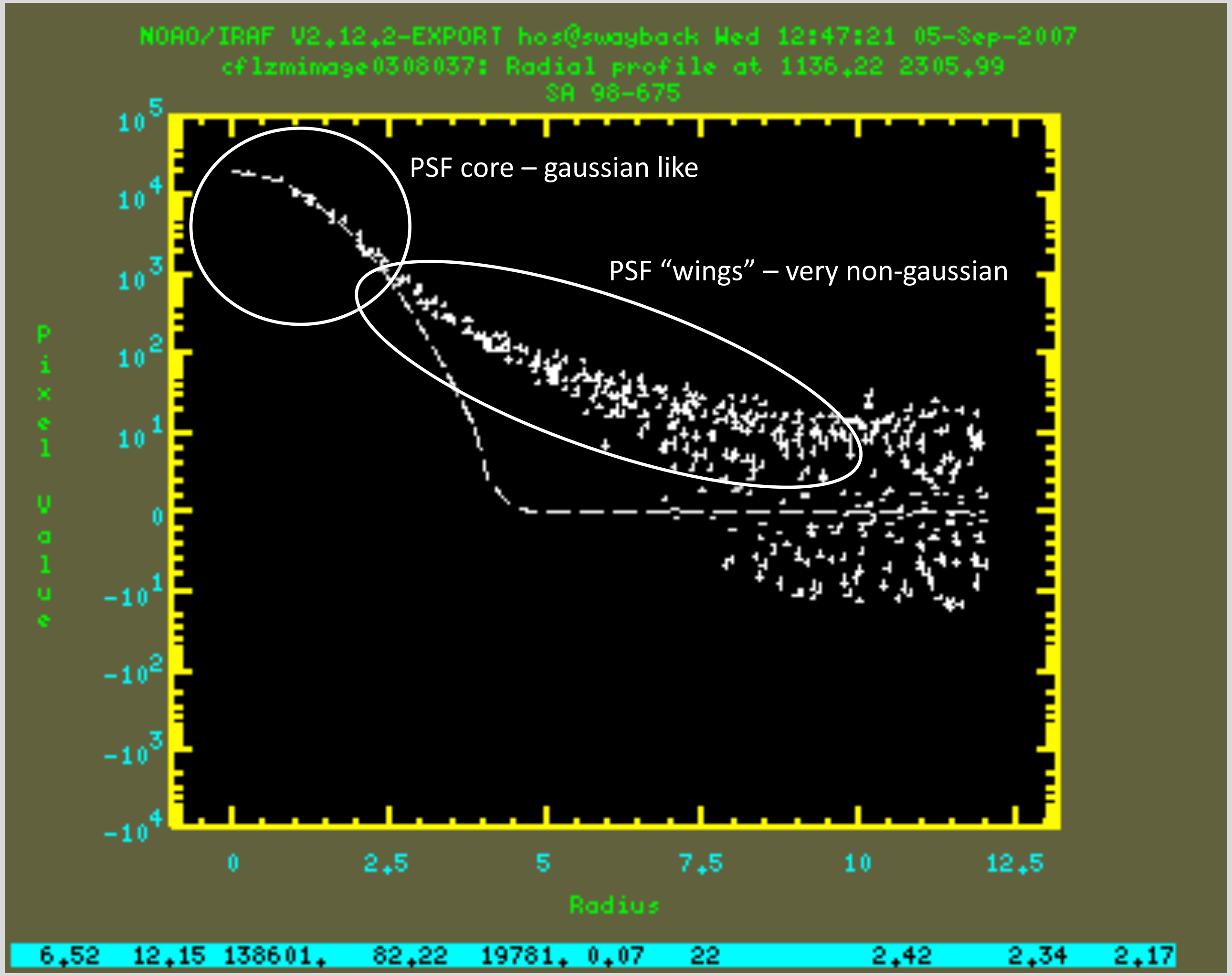


Radial profile of a star from the Burrell Schmidt telescope, plotted linearly in flux.

- Points are measured intensity.
- Dotted line is gaussian profile fit to the inner parts.

PSF core vs PSF wings

On larger scales, the PSF typically shows broad extended wings arising from a variety of sources, including diffraction and reflection from the telescope optics, scattering inside the telescope and in the atmosphere, tracking errors, etc...



Radial profile of a star from the Burrell Schmidt telescope, plotted logarithmically in flux.

- Points are measured intensity.
- Dotted line is gaussian profile fit to the inner parts.

PSF core vs PSF wings

Deep imaging often shows extended halos of light around bright stars, due to reflections between optical elements.

Introduces two problems:

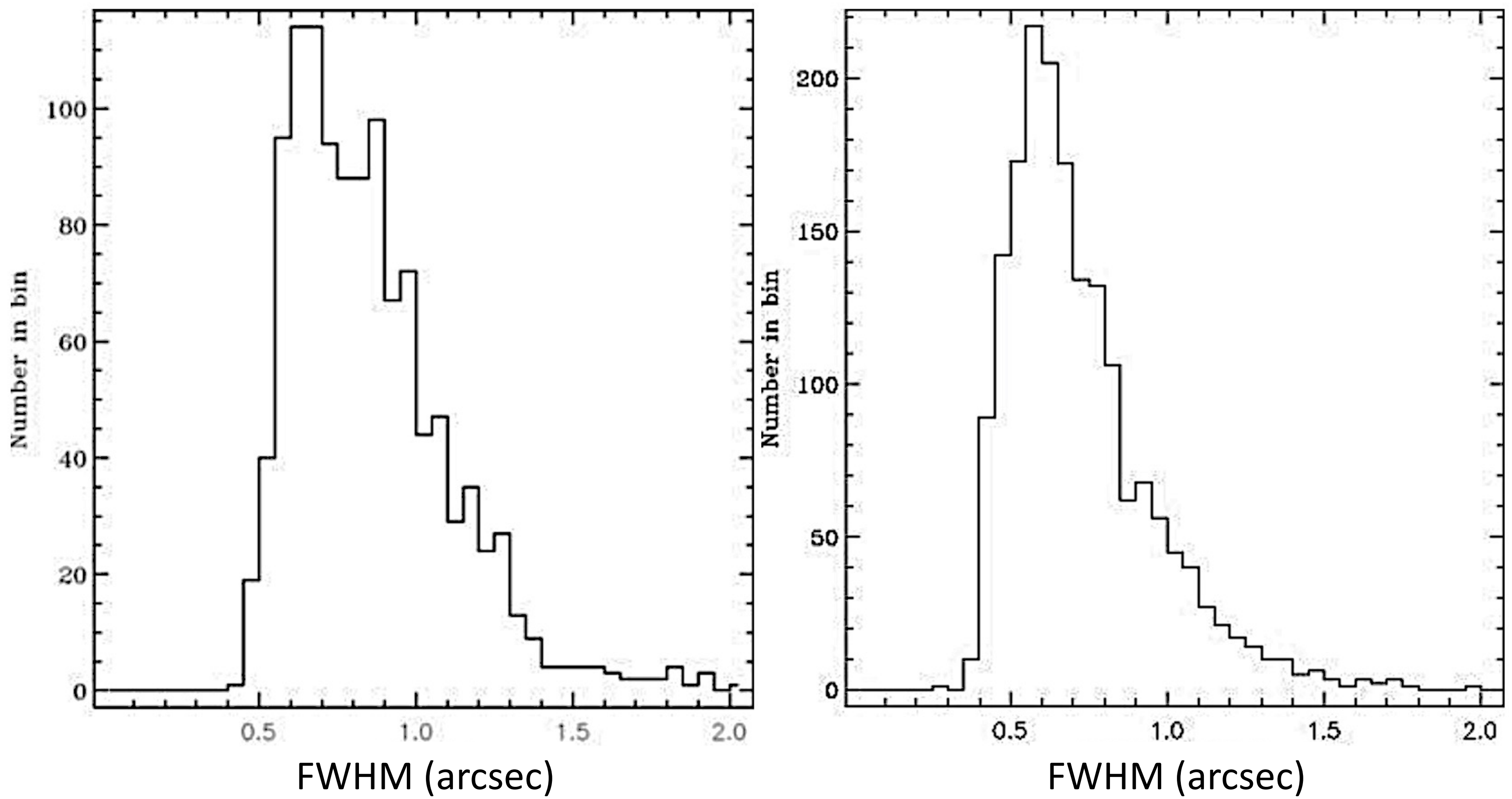
1. scatters light into surrounding objects (contamination)

2. scatters light out of the core PSF, star is measured too faint.

For example: CFHT imaging of M25:

(see also Duc et al 2015, MNRAS, 446, 120)

Ground-based seeing measurements (in arcsec, over the course of many nights)



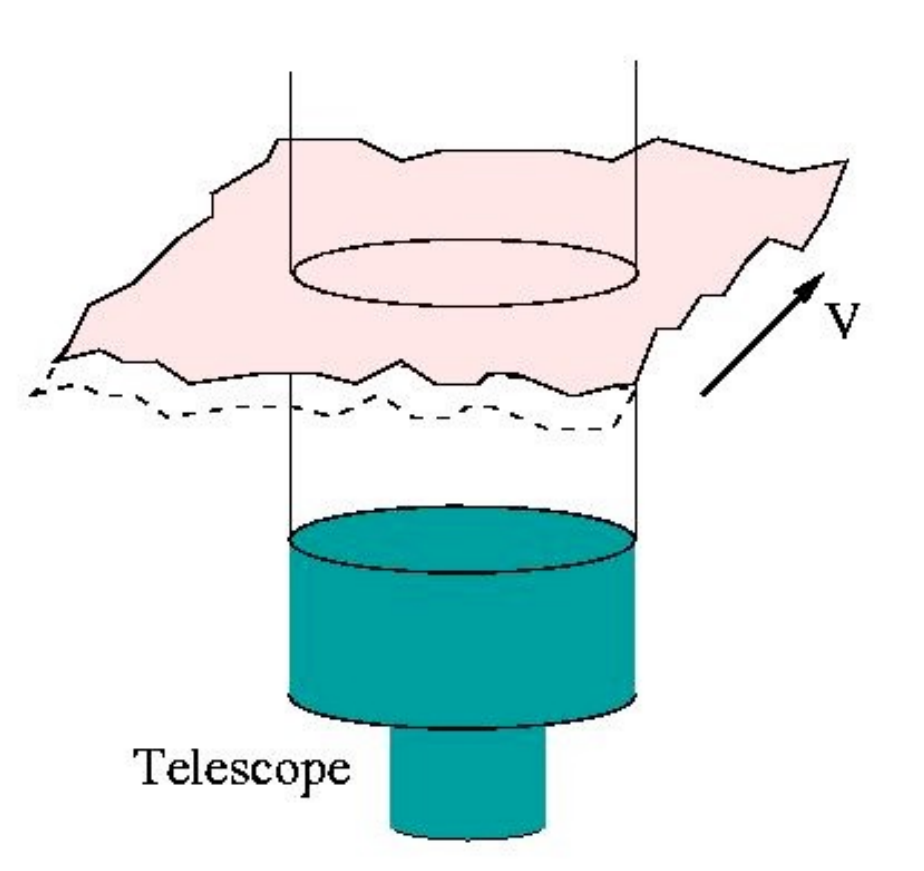
Seeing quality from Gemini South (Chile, left) and Gemini North (Mauna Kea, right). From http://www.gemini.edu/metrics/seeing.html.

from Majewski notes, at
http://www.faculty.virginia.edu/ASTR5110/lectures/atmos1/turbulence.html

Seeing: Atmospheric turbulence.

Think of the atmosphere as being composed of individual cells of calm air; as these cells move around, they distort the image.

Larger cell size (quiet atmosphere) == better images.
Smaller cell size (turbulence) == poor images.



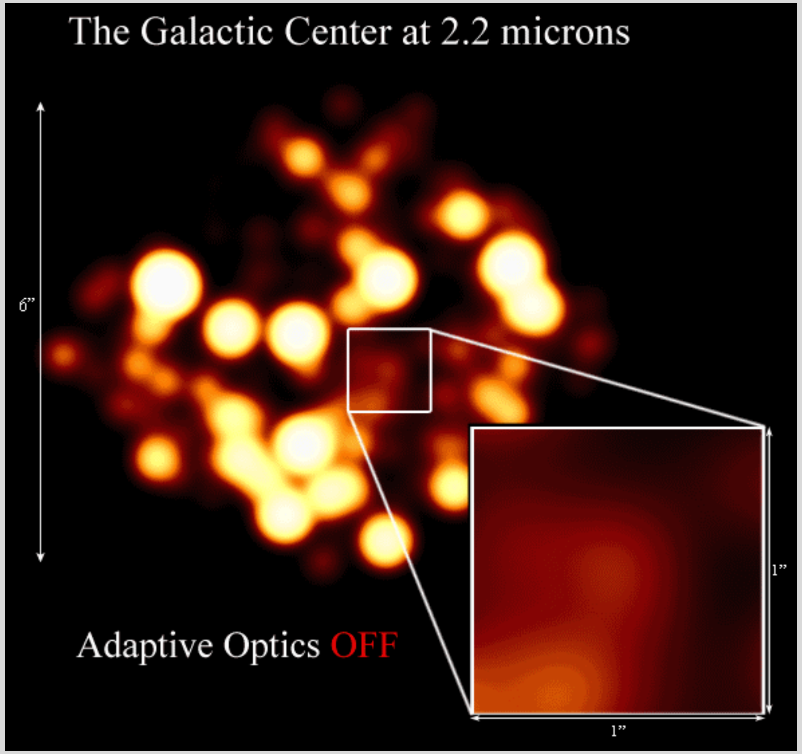
Qualitatively, we can consider three sources of seeing:

- Upper atmosphere (5-10 km)
- Local atmosphere (atmospheric flow around the observatory). Choose your site carefully before building an observatory.
- "Dome seeing" (conditions inside the dome and at the dome/outside interface). Keep the telescope dome cool, like the outside air.

Adaptive Optics

Many modern telescopes use adaptive optics to obtain sharper images.

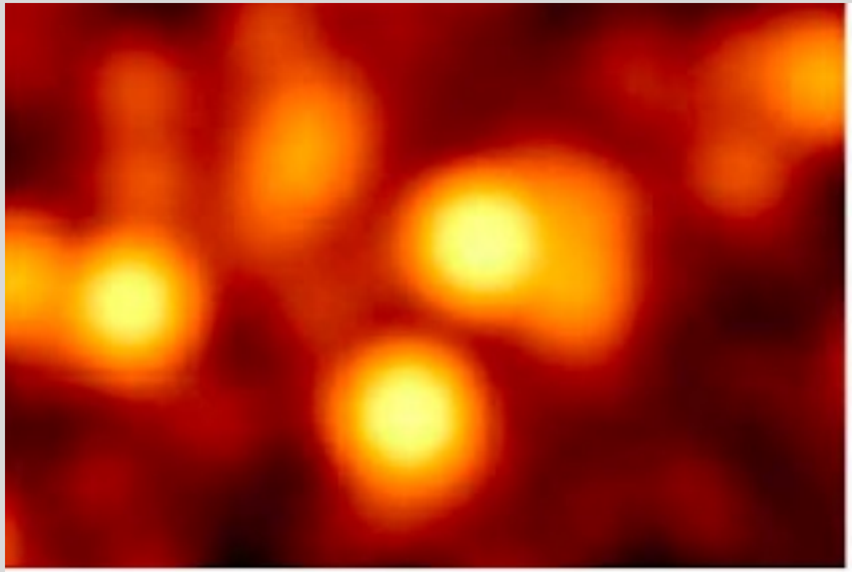
- Shoot laser into sky, excite atoms in the ”sodium layer” of the Earth’s atmosphere (~ 90km high). Creates a bright artificial guide star.
- Monitor the position of the guide star on very short timescales (milliseconds)
- Adjust the alignment of the secondary or primary mirror to follow the jittering laser guidestar.

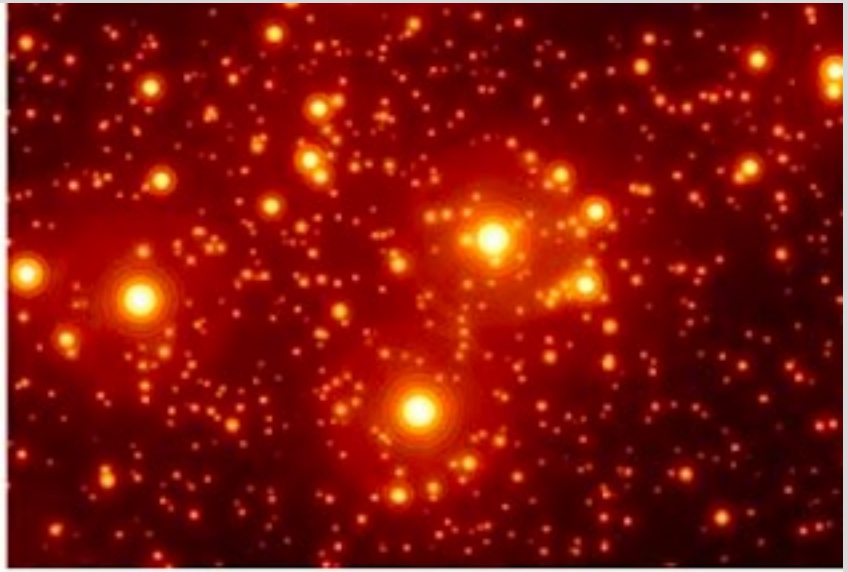


Keck AO system

ESO laser guide star system

Without Adaptive Optics

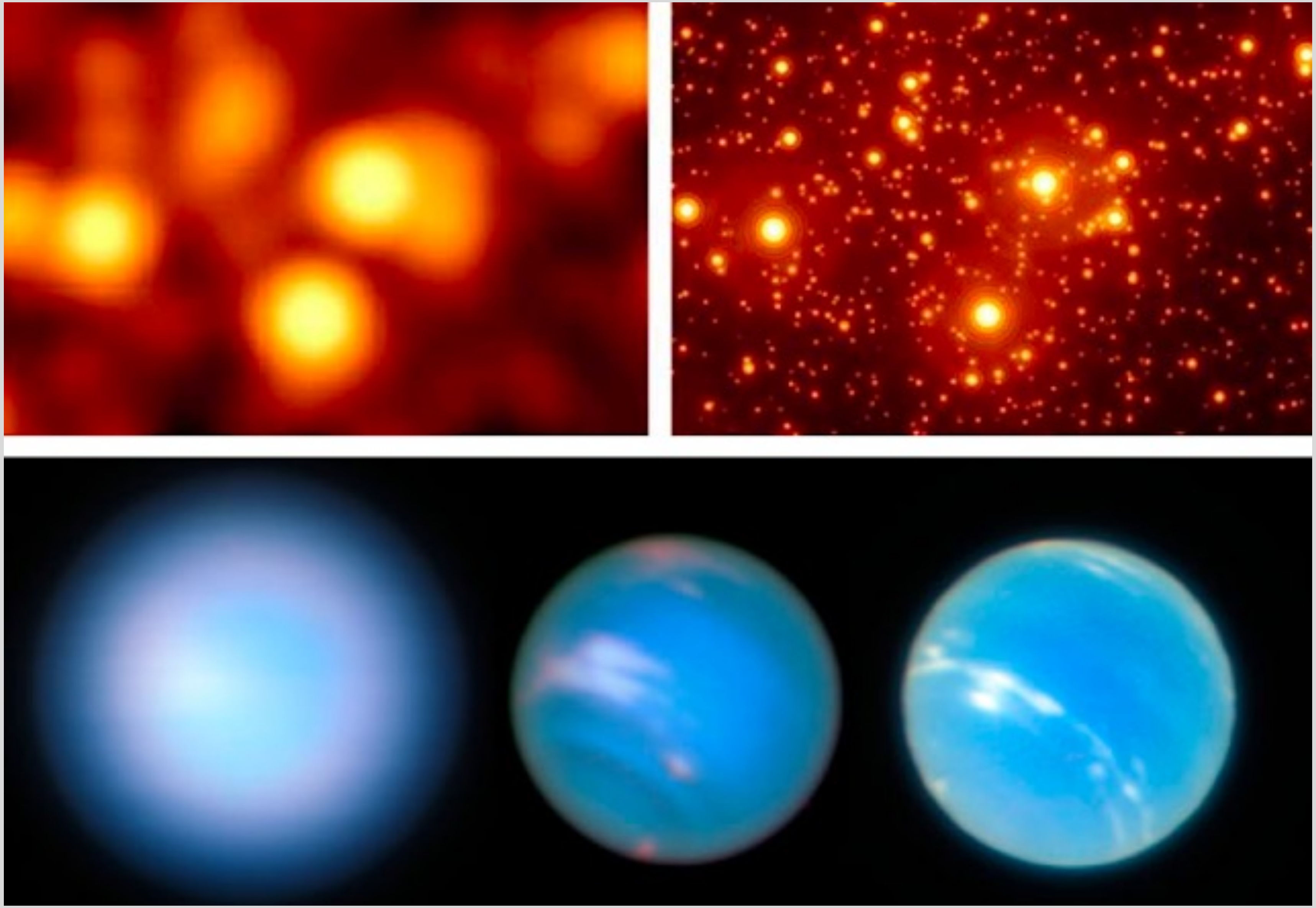




With Adaptive Optics

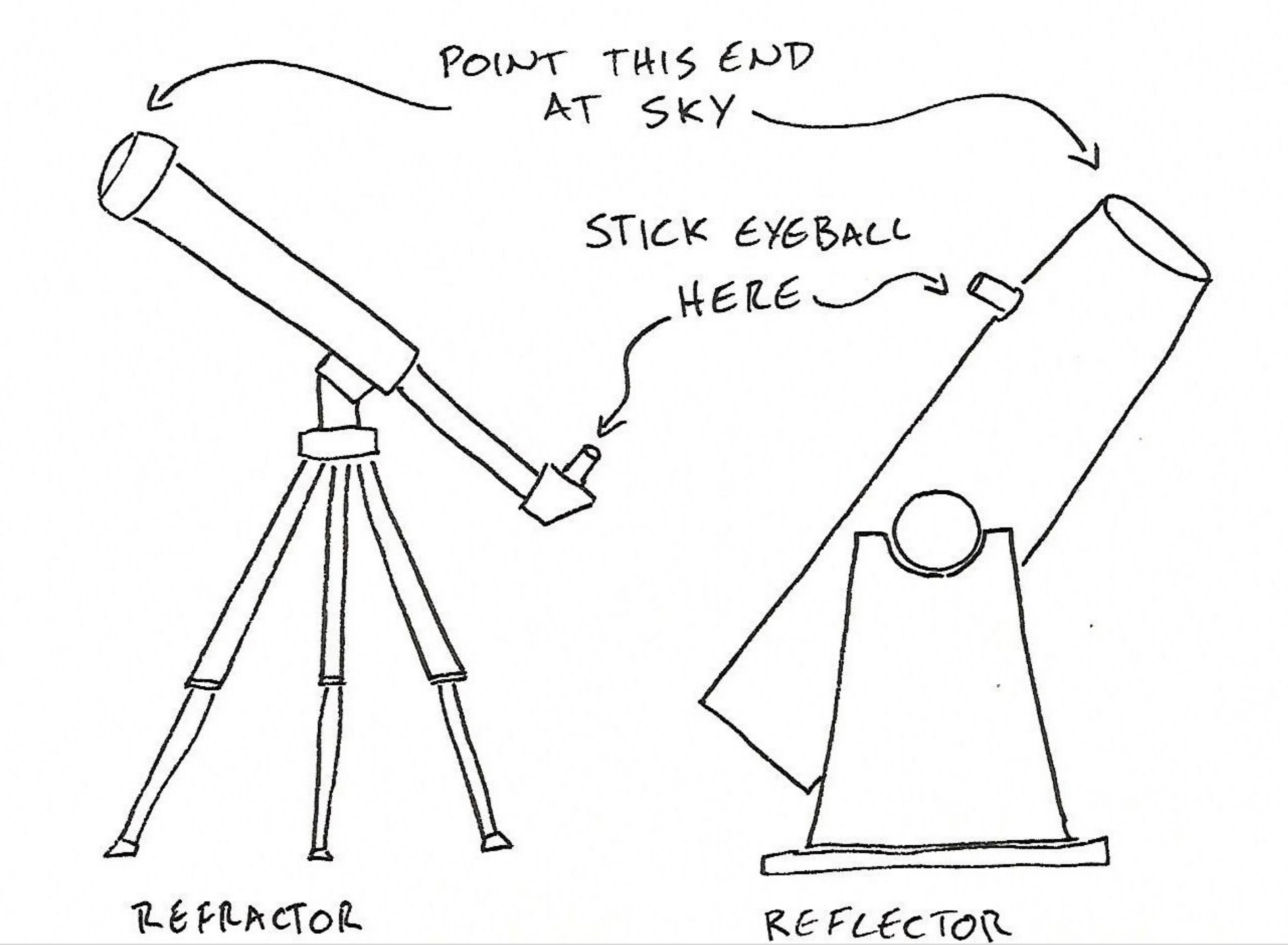
Without Adaptive Optics

With Adaptive Optics



Without Adaptive Optics | Hubble Image | With Adaptive Optics

Telescopes

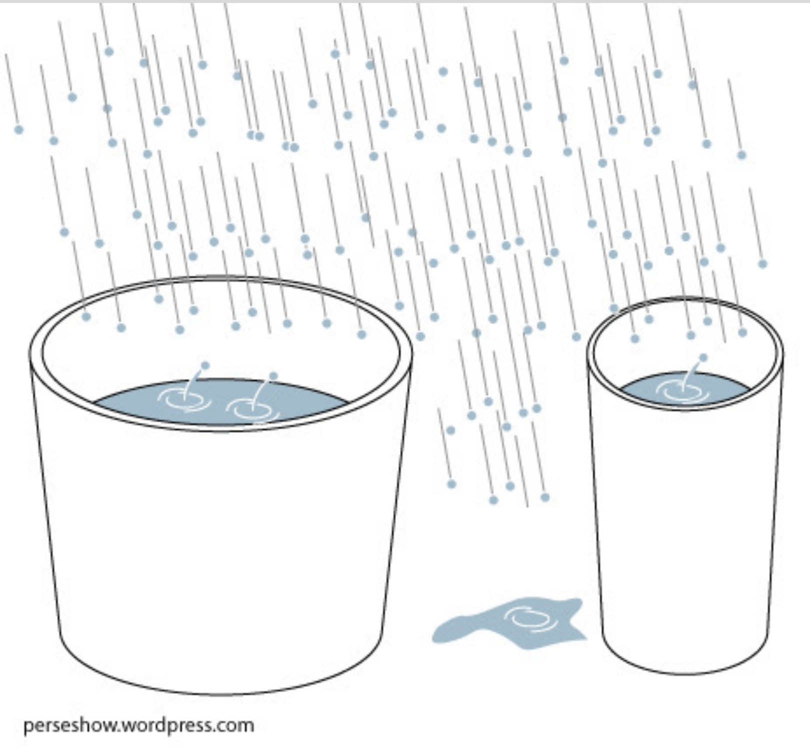


courtesy [Zach Dickeson]

Telescopes: why so big?

1. Collecting area: Telescopes are light buckets.

The amount of light at telescope collects scales as the area of the primary lens or mirror. Bigger telescopes collect more light. When an astronomer talks about the size of a telescope, they almost always are refering to the diameter of the primary.



Telescopes: why so big?

2. Angular Resolution: Bigger telescopes can (in principle) produce sharper images.

The interaction of light waves with an aperture leads to interference patterns: diffraction. In the case of a perfect circular aperture (like an unblocked lens or mirror), this leads to a point source (like a star) being imaged as an Airy pattern.

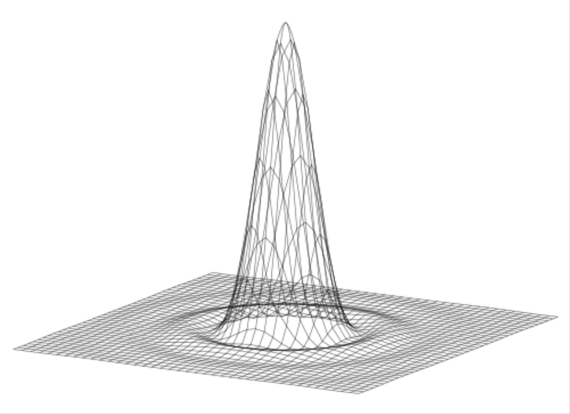
The "Rayleigh limit": once two point sources come closer than the angular size of their first Airy minimum, they are not resolved.

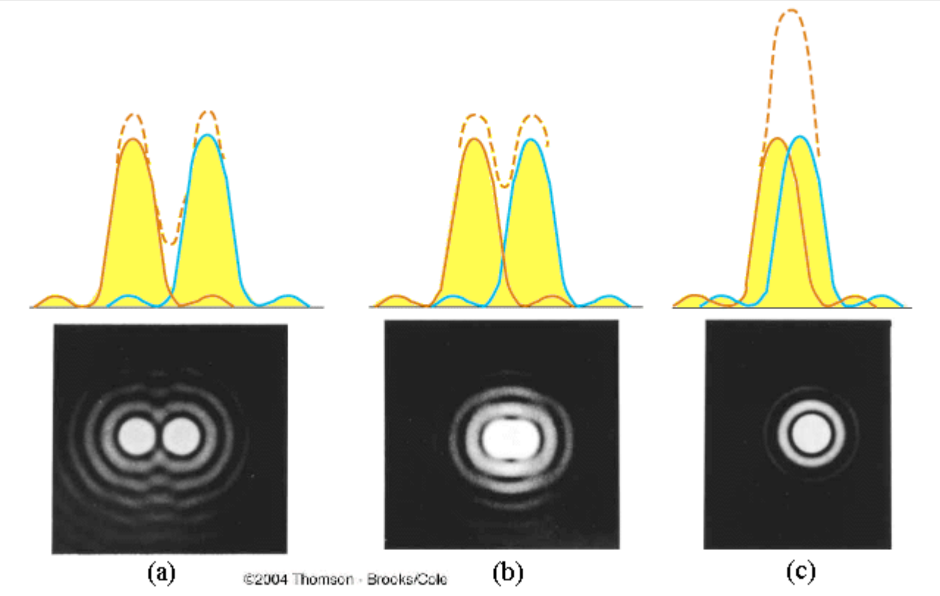
The first minimum of the Airy pattern comes at an angular size:

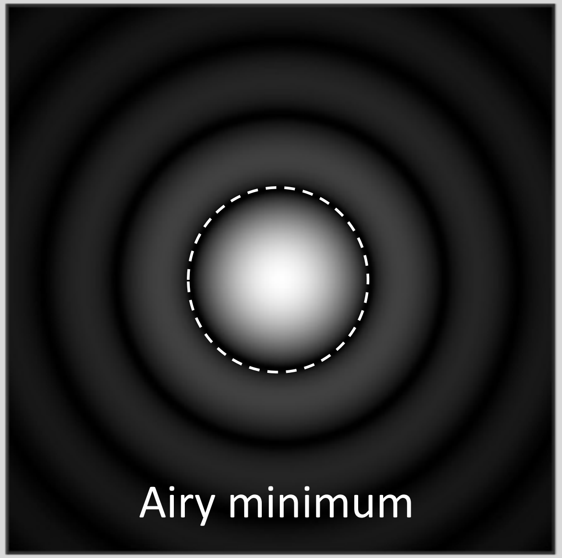
$$\theta_{min} = 1.22\,\lambda/D$$

where λ is the wavelength of the light and D is the diameter of the telescope.

Big telescope: smaller Airy disk, better resolution, *in principle.*

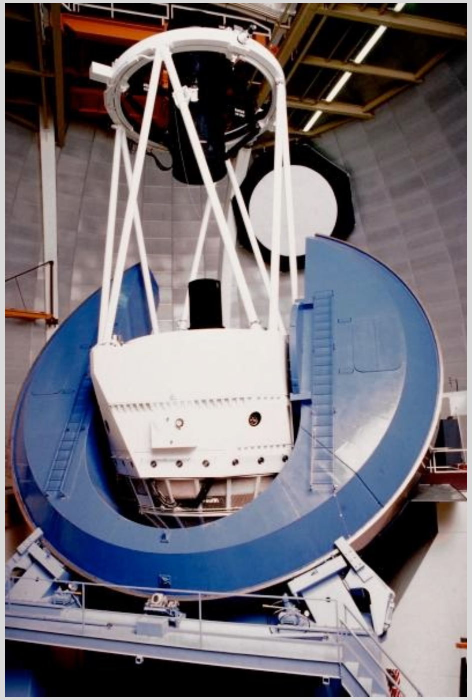






Diffraction limit of telescopes

"Diffraction limit" means that the angular resolution of the telescope is set by the Rayleigh criteria for diffraction: $\theta_{min} = 1.22\,\lambda/D$.



λ=5000Å (optical)

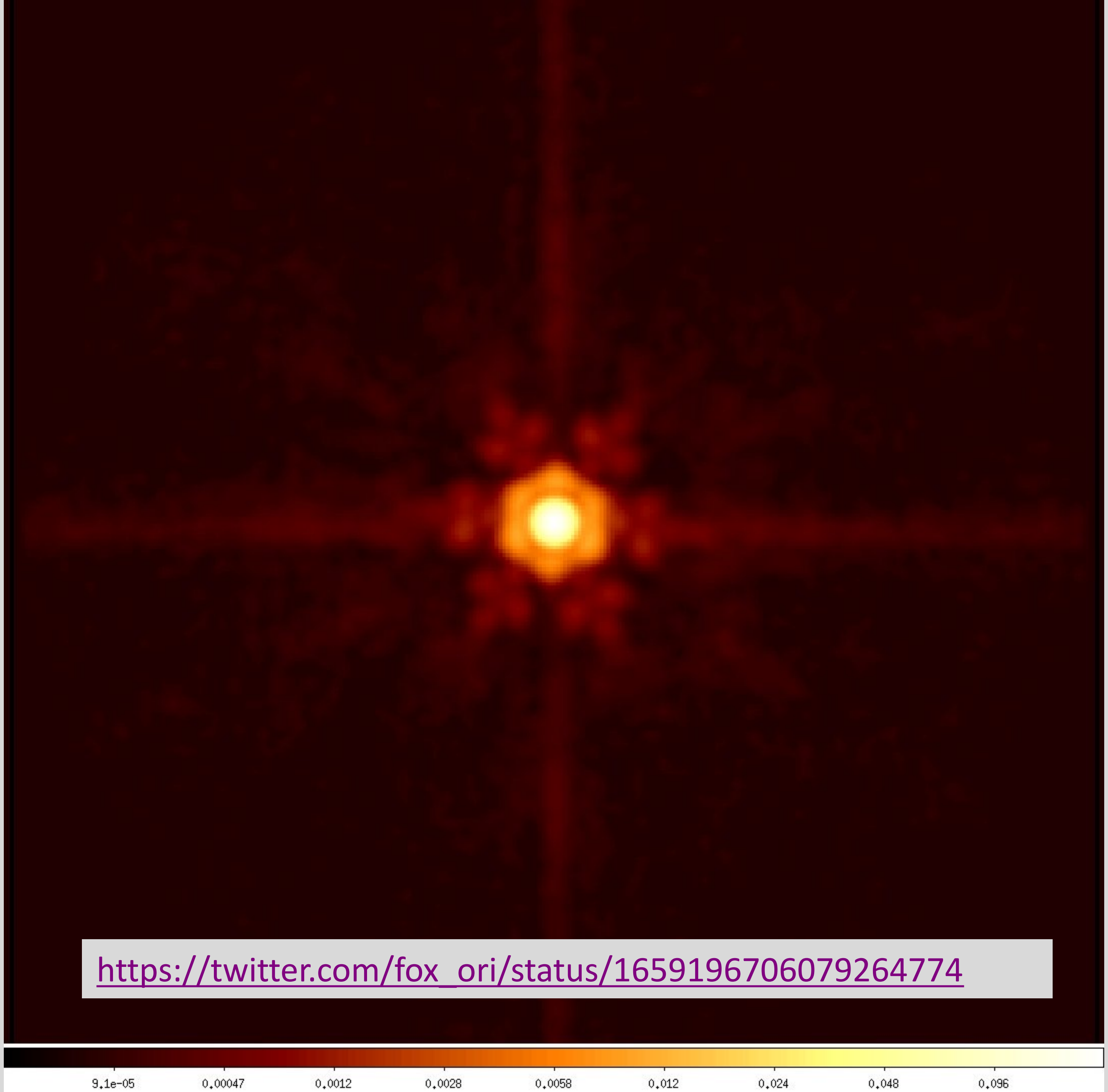
- D=10cm ➔ θ_{min}=1.2 arcsec
- D=4m ➔ θ_{min}=0.03 arcsec

λ=21cm (radio)

- D=20m ➔ θ_{min}=35arcmin
- D=100m ➔ θ_{min} = 7 arcmin

Two important caveats:

- To make a diffraction limited mirror, the surface must be polished to accuracy < λ
- From the ground, atmospheric blurring ("seeing") is typically 1 arcsec or so.



https://twitter.com/fox_ori/status/1659196706079264774