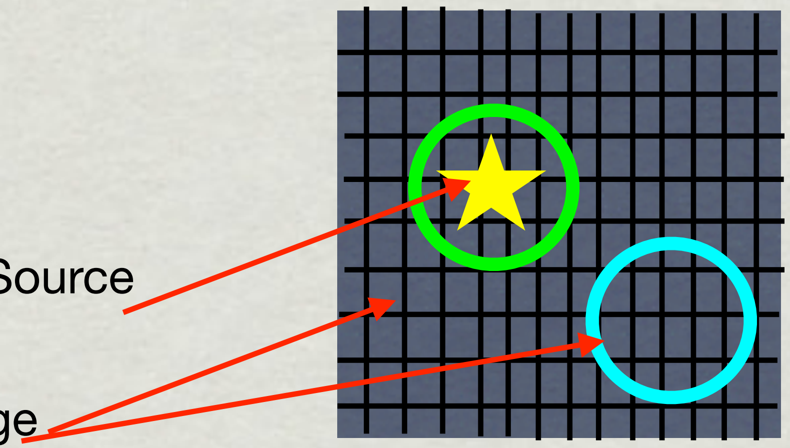
Observables and Detectors

Source

Regions of image that collects only "empty" sky background



N total photons collected in the green circle come from the source plus sky.

Project an image of the sky onto detector and record it

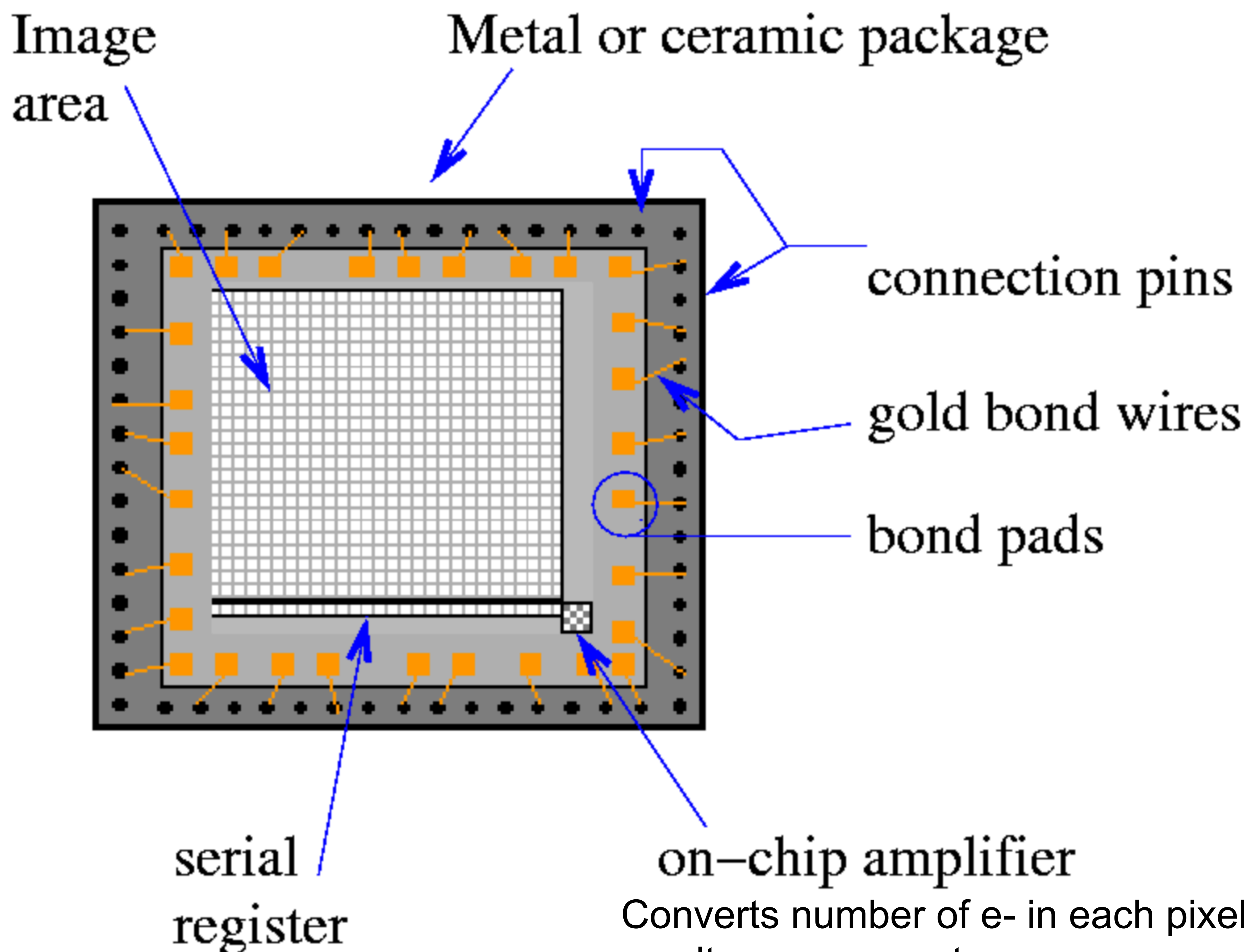
- telescope and instrument: optics, filters, detector
- stars, galaxies, all astronomical objects emit (or reflect, in the case of planets and asteroids) photons
- detectors converts photons into something we can measure, like volts or amps. We will use a detector called a "charged coupled device", CCD for short. They convert one photon to one electron, regardless of the wavelength of the photon
  - other kinds of detectors: photographic film, bolometers, radio antennae
- Observe a source: measure the number of photons that arrive from our source and get converted into e- in each pixel. We record that information as a 2-dimensional array of the number of e- in each pixel, write it to a file
- Those measurements have uncertainty, statistical and systematic

A Charged Coupled Device (CCD)
Made of silicon, detect photons as red as 1 micron

Near-infrared detectors are similar, use different materials to match the lower-energy photons

Pixels give 2-d spatial information

We will come back to pixel size

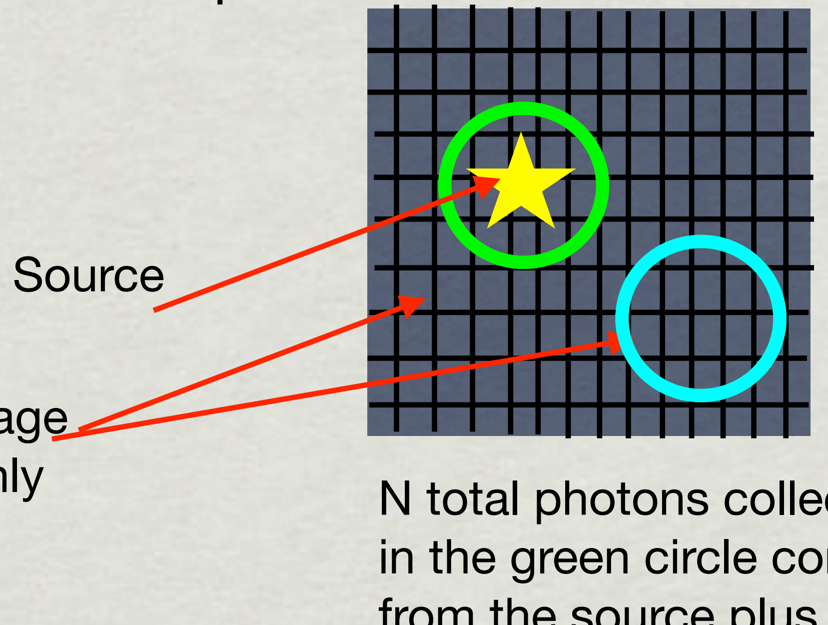


Converts number of e- in each pixel to a voltage or current we can measure. Adds Gaussian uncertainty “readnoise” to each pixel in the process.

Observables and Detectors

To use that image, we need to “process” or “reduce” it, and calibrate it

- measure and subtract the background contributed by the detector
- measure and subtract the sky background
- determine the fraction of photons from the source that were detected
- determine the uncertainty in the measurement of the number of photons from our source measured in each pixel



N total photons collected in the green circle come from the source plus sky.

“Signal” = some source of e- (and therefore DN in your image) you are trying to measure

- from an astronomical source, it will usually be the number of photons/second

“Noise” = uncertainty in the estimate of that measurement. Could be uncertainty in the measurement of the astronomical object itself, or in the background you need to measure and subtract

Observables

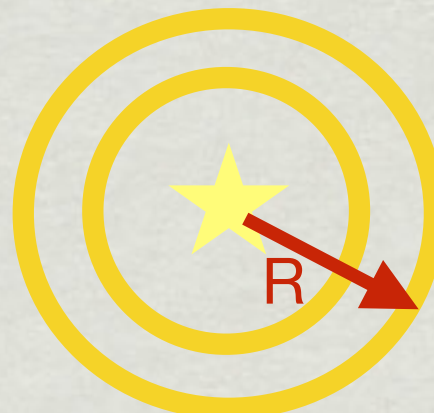
Total power output from some source (like a star), energy per unit time (Watts).
An intrinsic property of the source.

Specific (per unit frequency) **Luminosity** L_ν: Energy per second per frequency interval

Total energy per unit time: $dE = L_\nu \, dt \, d\nu$

Diameter of
collecting area

Sphere area A,
distance R from the star.
Collect flux over all of A, get L_ν



We observe **Flux** (flux density), the fraction of the luminosity intercepted by our collector (telescope, antenna, your eye, etc.)

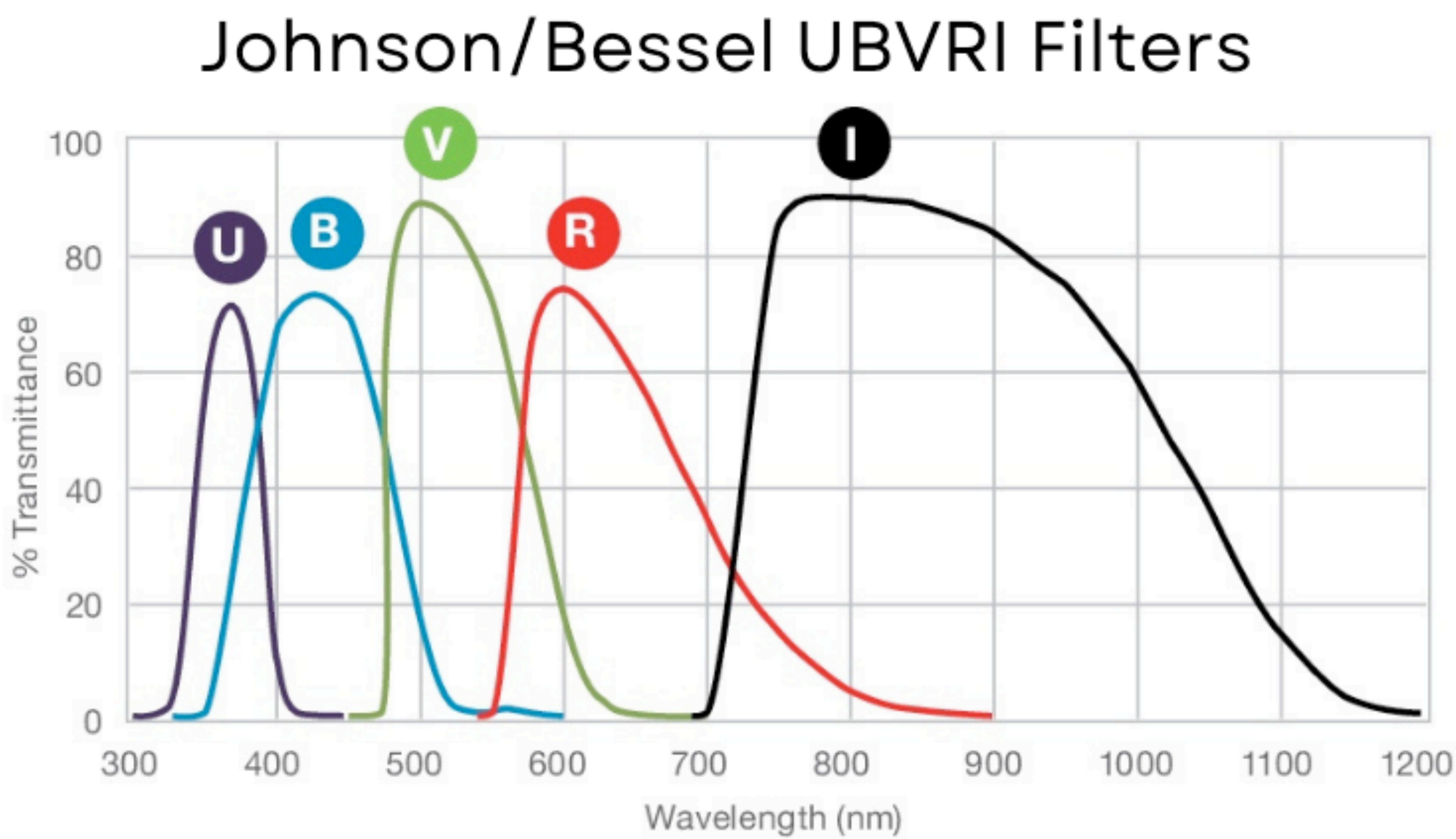
Flux F_ν; units of ergs/sec/cm^2/Hz
The SI unit of flux is the Jansky = 10^{-26} W/m^2/Hz

$$dE = L_\nu dt d\nu = \int F_\nu dA = 4\pi R^2 F_\nu$$

Flux depends on distance from the source.

Good reference for these Observables definitions: Rybicky and Lightman

Standard Optical Filters



Used to define the range of wavelengths passed through to the detector and recorded in the image

Note x-axis, often defined a as the “optical” region, UV cutoff to Si bandgap cutoff

Used to define the range of wavelengths passed through to the detector and recorded in the image

Observables

Magnitudes are measurements of flux:

$$m = -2.5 \log \frac{\int F_\nu S_\nu d(\log \nu)}{\int S_\nu d(\log \nu)} - zp$$

Fν is the flux from the source

Sν is the response function, e.g, a wavelength bandpass filter, the system sensitivity, etc. We almost always measure flux in a particular bandpass (wavelength range)

zp is the zero point, the calibration of the magnitude

We will talk more about magnitudes, magnitude systems and calibration later in the quarter

Observables

Radiation from a source with arbitrary shape and size: **specific intensity** I_ν
also "brightness" or "surface brightness"

I_ν is the energy received per second, from a patch of angle on the sky, per unit collecting area, per frequency interval

Units: W/m^2/Hz/Sr or ergs/cm^2/s/Hz/Sr

Sr = steradian, angle dΩ
Usually measure surface brightness in magnitudes per square arcsec

dΩ integrated over a sphere is 4π

solid angle
area of source dΩ
Units: steradians
or square arcsec

Diameter of
collecting area

Sphere area A,
distance R from the source.

Observables

Example of specific intensity:
a blackbody

$$I_{\nu,Planck} = \left(\frac{2h\nu^3}{c^2}\right)\frac{1}{\exp h\nu/kT - 1}$$

Flux is specific intensity integrated over solid angle of the source:

$$F_\nu = \int I_\nu \cos\theta d\Omega$$

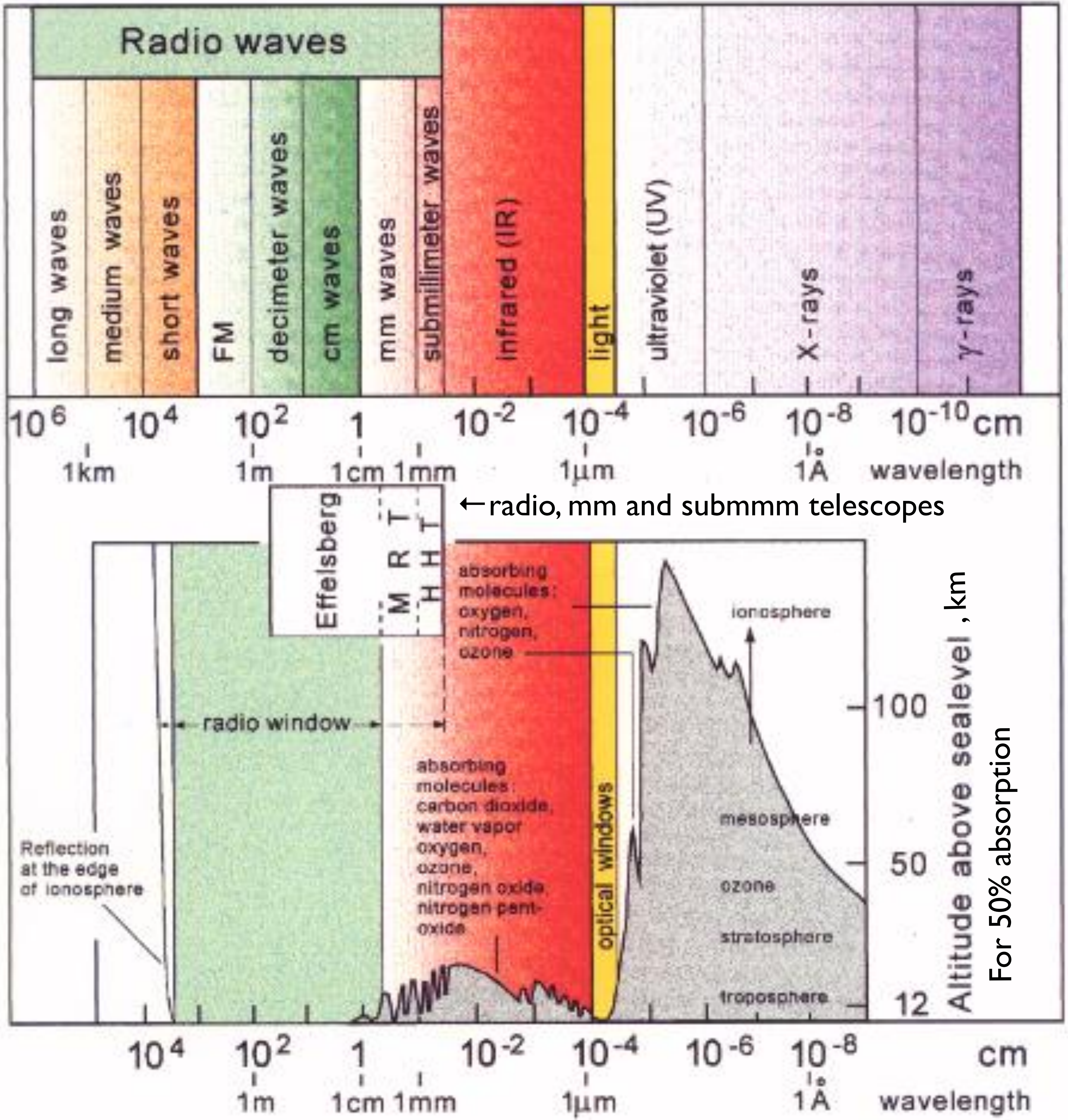
cos θ accounts for the photon direction

For an unresolved point source, we measure flux

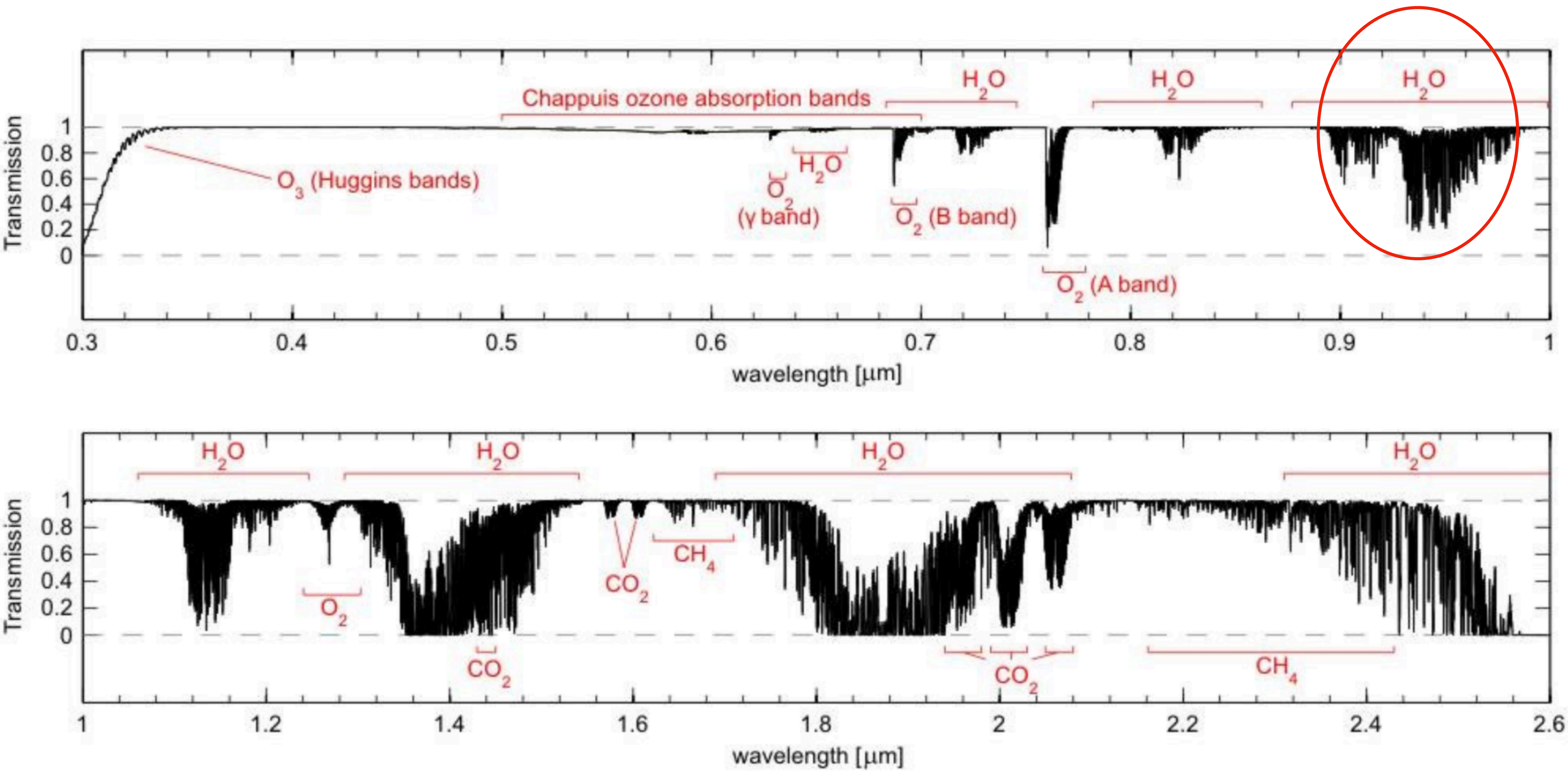
For an extended source, we can measure the flux per unit area, which is a surface brightness

Flux depends on distance from the source.

Surface brightness (intensity) does not, at least until cosmology changes the measurement geometry


Radio waves
long waves
medium waves
short waves
FM
decimeter waves
cm waves
mm waves
submillimeter waves
infrared (IR)
light
ultraviolet (UV)
X-rays
γ-rays
10^6 10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} cm
1km 1m 1cm 1mm 1μm 1Å wavelength
Effelsberg
MRT
HHT
←radio, mm and submmm telescopes
absorbing molecules: oxygen, nitrogen, ozone
ionosphere
radio window
absorbing molecules: carbon dioxide, water vapor oxygen, ozone, nitrogen oxide, nitrogen pent-oxide
optical windows
mesosphere
ozone
stratosphere
troposphere
Reflection at the edge of ionosphere
100
50
12
Altitude above sealevel , km
For 50% absorption
10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} cm
1m 1cm 1mm 1μm 1Å wavelength

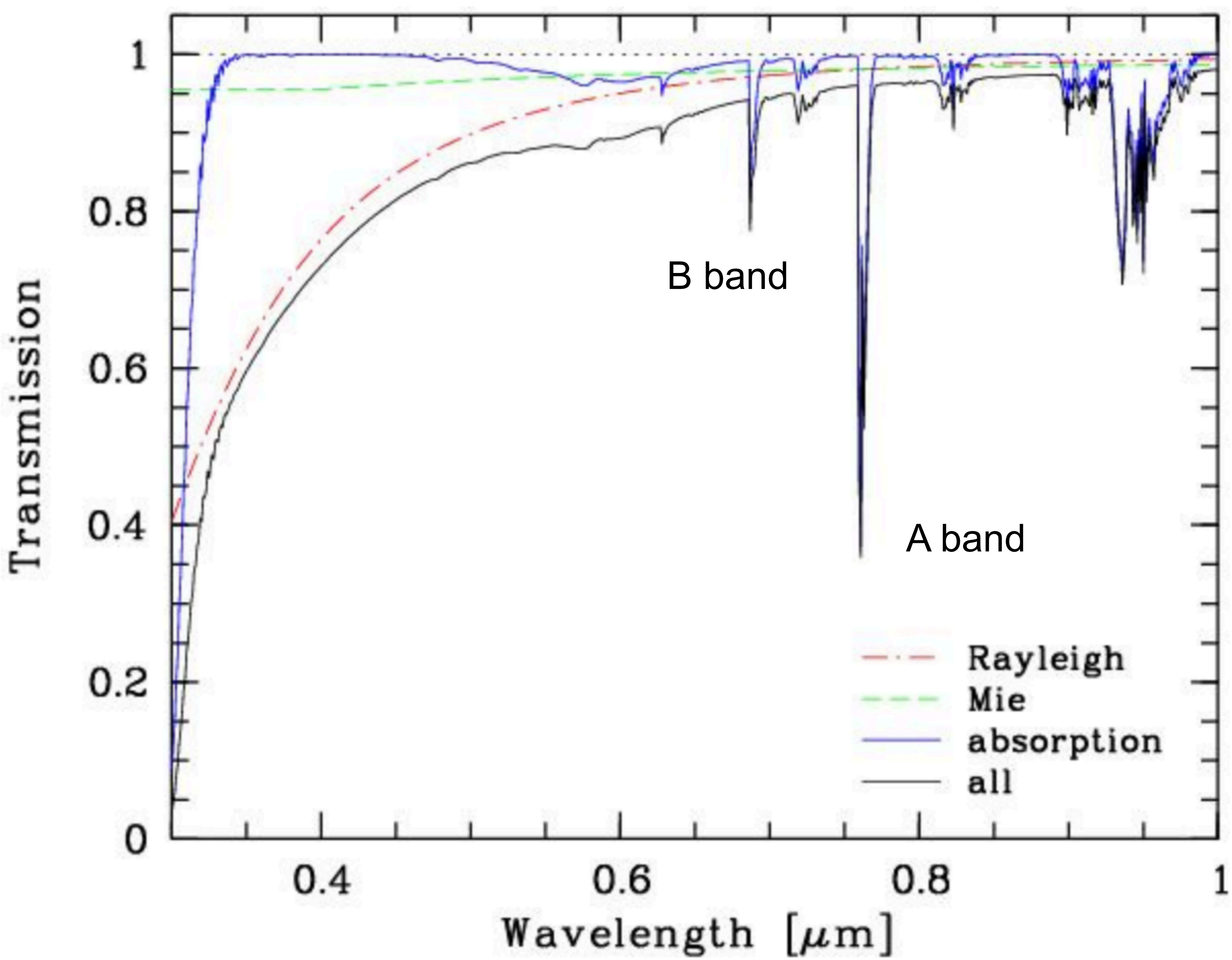
Atmospheric absorption, optical and near-IR



Smette et al. 2015, A&A, 576, A77

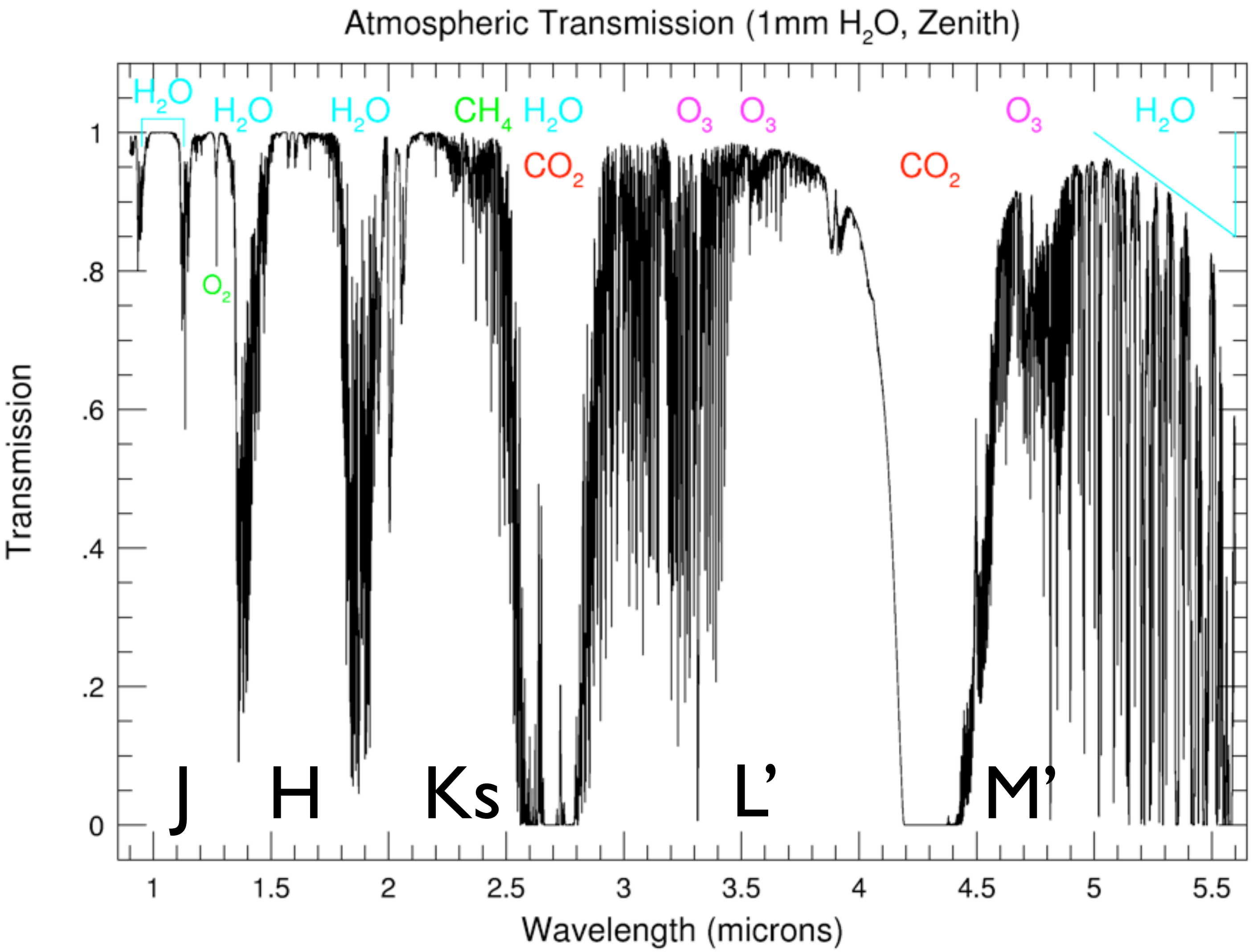
Atmosphere transmission, Zenith. ESO Cerro Paranal

H2O absorption bands
at λ > 9000A

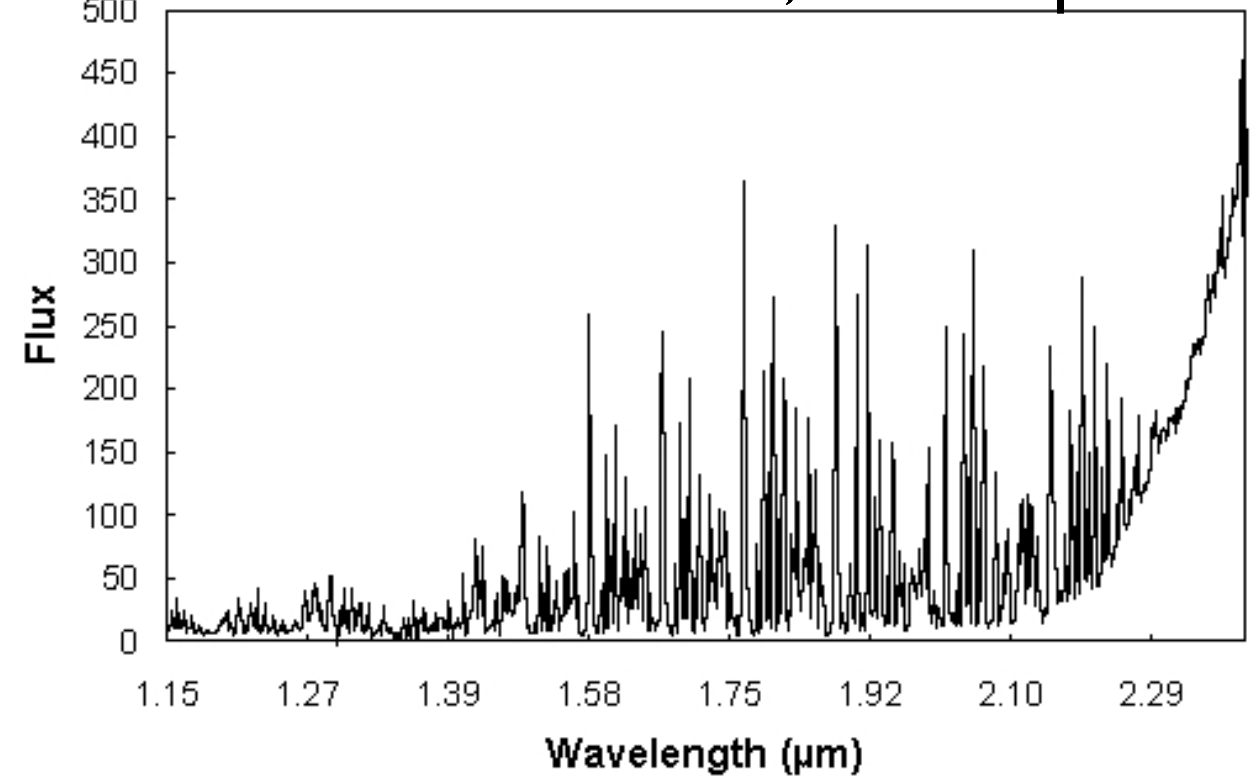


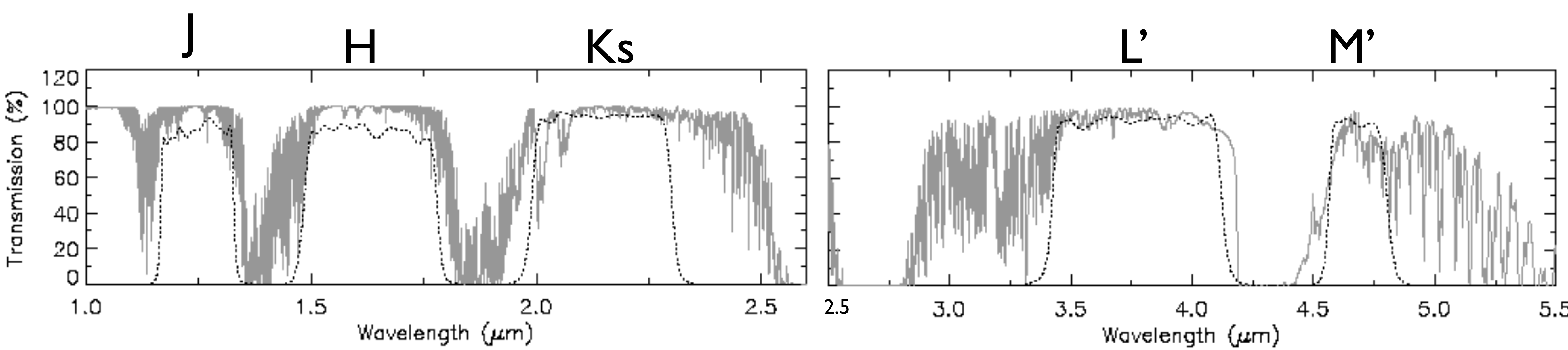
Noll et al. 2012

Near Infrared Absorption



And Near-IR emission, for comparison

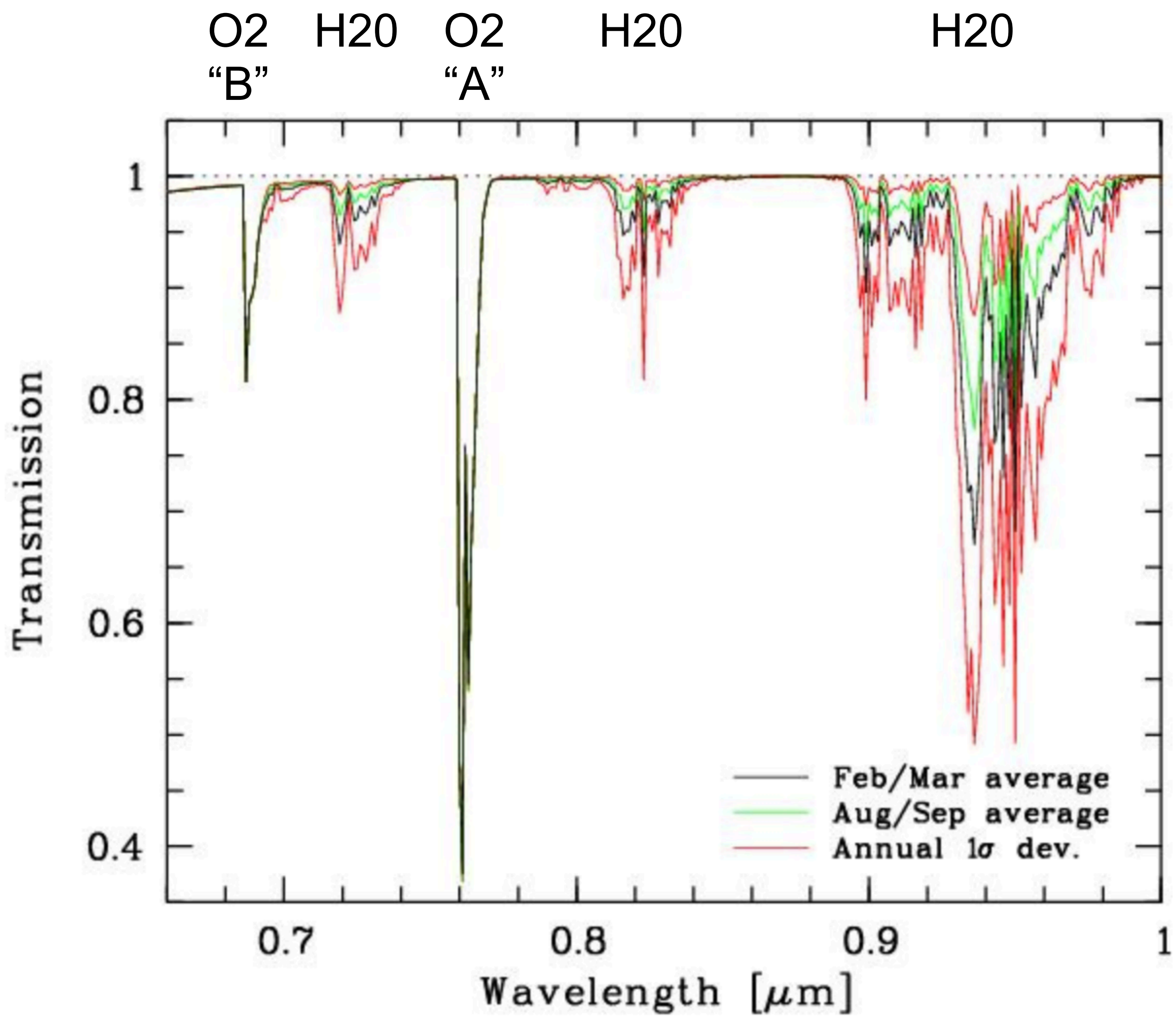


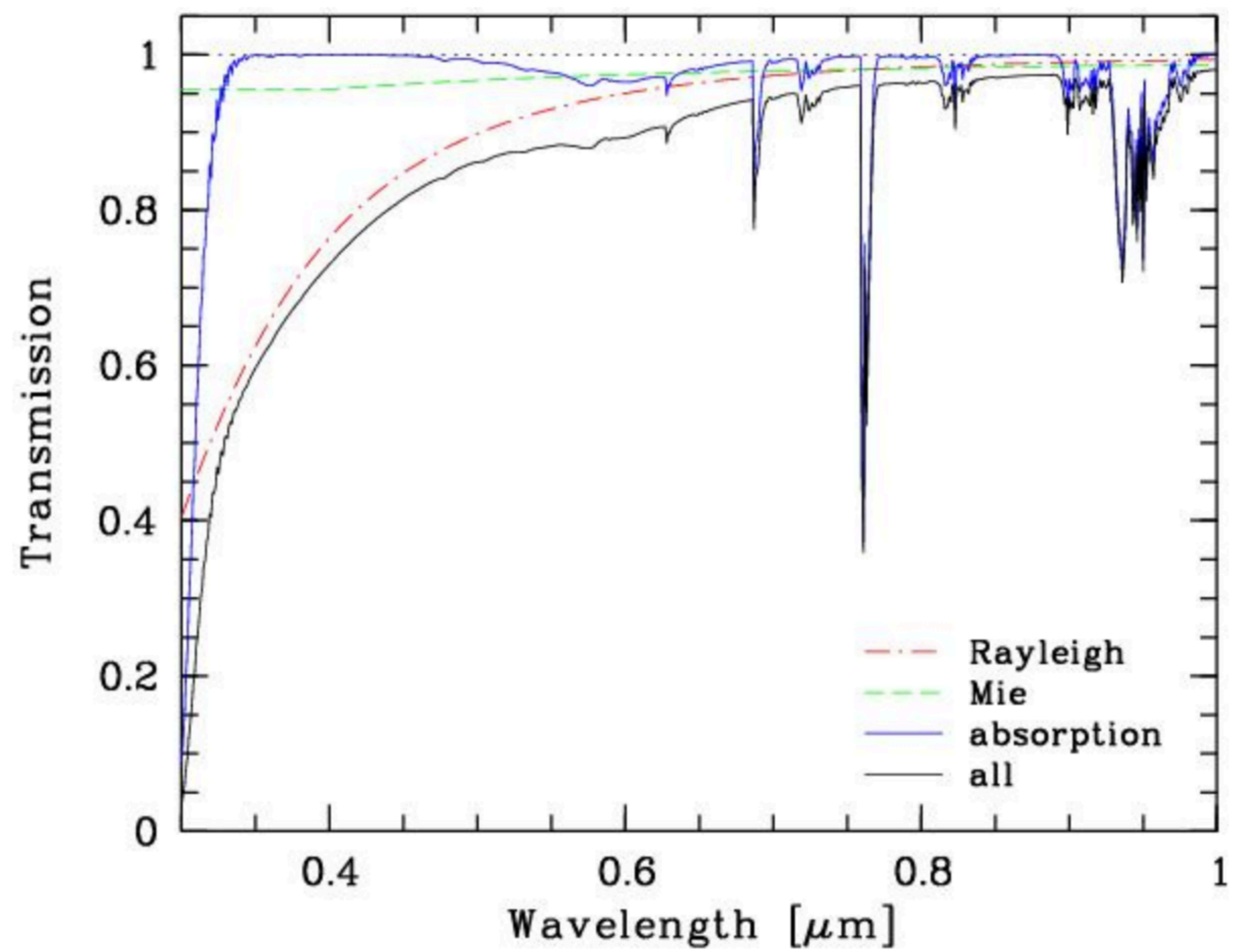


Mauna Kea Near-IR filters, Tokunaga et al. 2001, PASP, 114, 169

Average annual transmission variation, zenith. ESO Cerro Paranal

One reason you have to take calibration data when you observe!





Noll et al. 2012

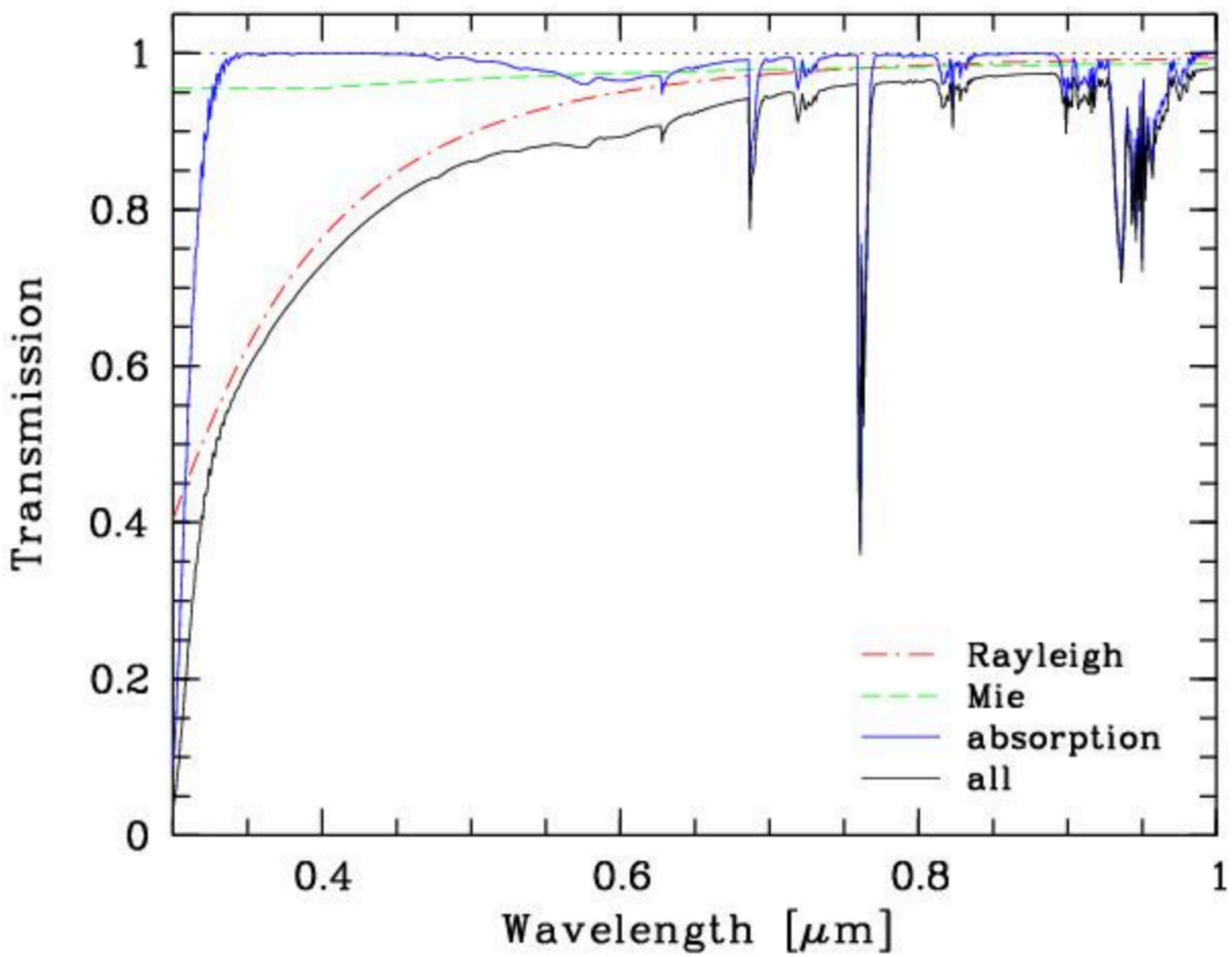
This figure shows transmission looking out through the atmosphere pointed at zenith.

As you point toward the horizon, your path length through the atmosphere increases.

More atoms and molecules to scatter and absorb light — transmission goes down

Approximate: aimass = $\sec z = \dfrac{1}{\cos z}$ where z is the angle of your line of sight, from zenith toward horizon

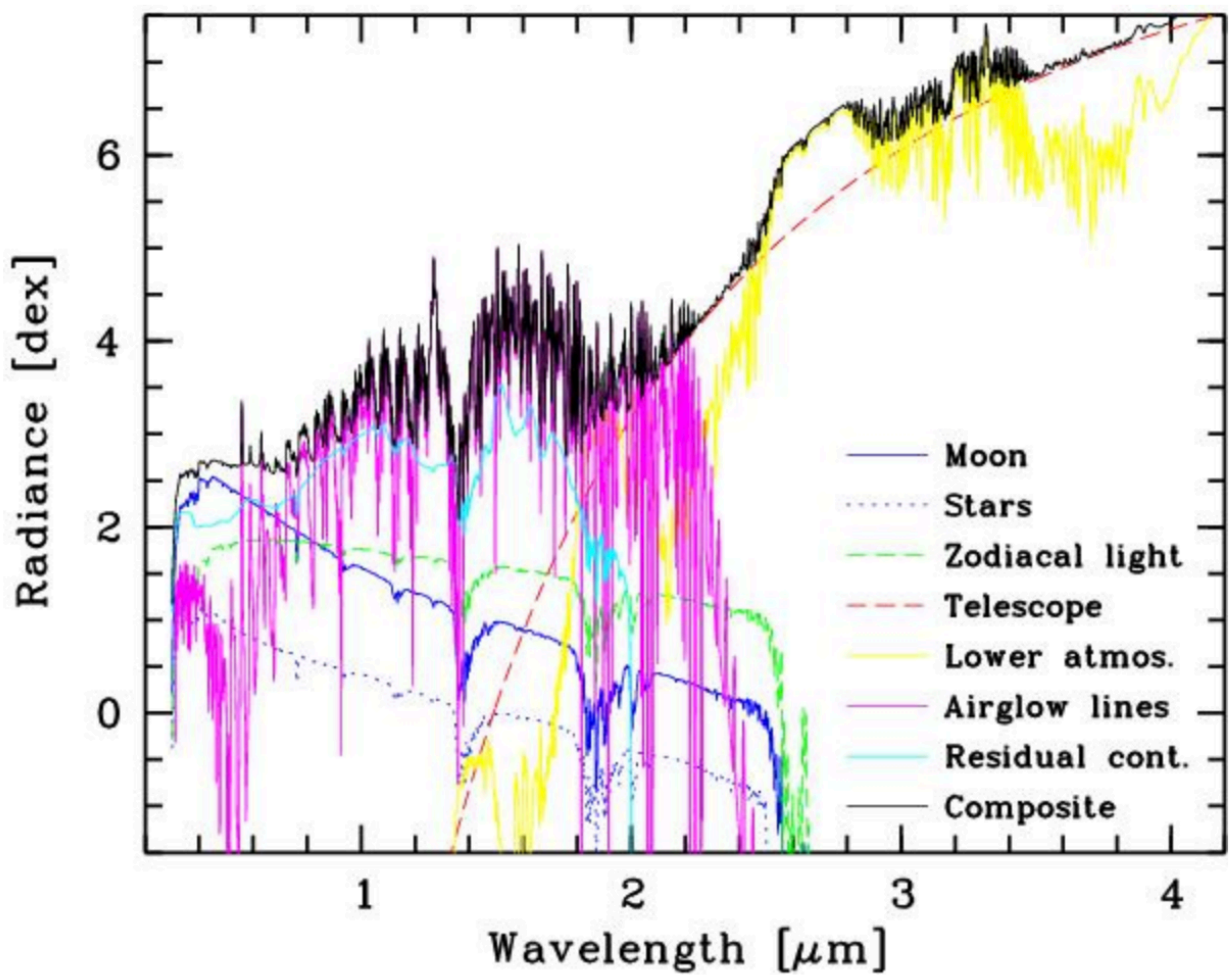
This is correct for a flat earth (!) and works well enough. You probably should not be observing where this approximation is not good!



Useful numbers:
airmass 2 = twice the path length through the atmosphere vs. zenith

airmass 2 is at zenith angle z = 60 degrees (30 degrees above the horizon)

Atmosphere Emission, Zenith. ESO Cerro Paranal



Noll et al. 2012

Why do we describe observations by wavelength range? Changing sky brightness is one reason

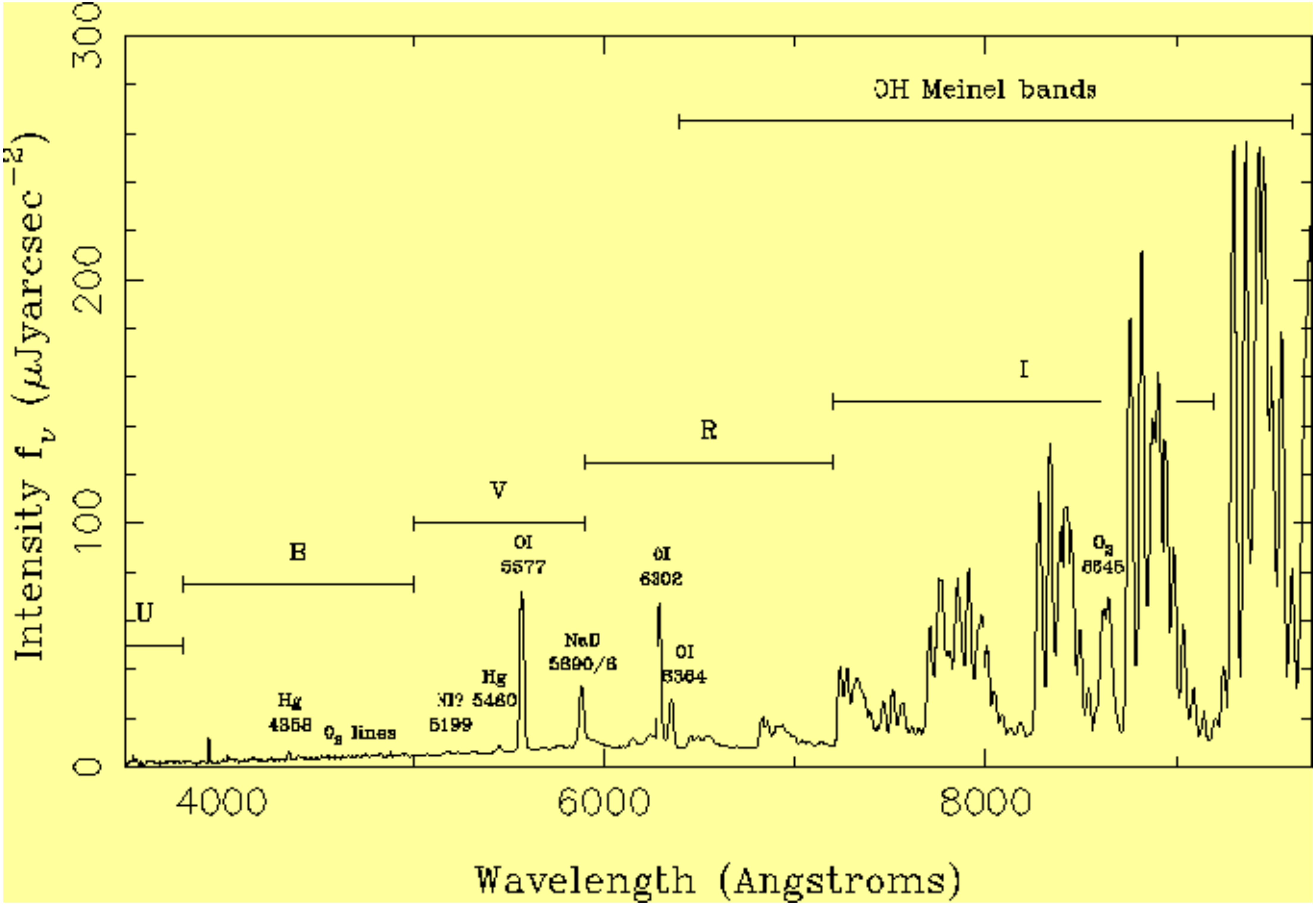
Typical sky brightness, Mauna Kea, mag per square arcsec:
B 22.3
V 21.1
I 19.2
J 14.8
H 13.4
K 12.6 = few milli-Janskys arcsec^{-2}

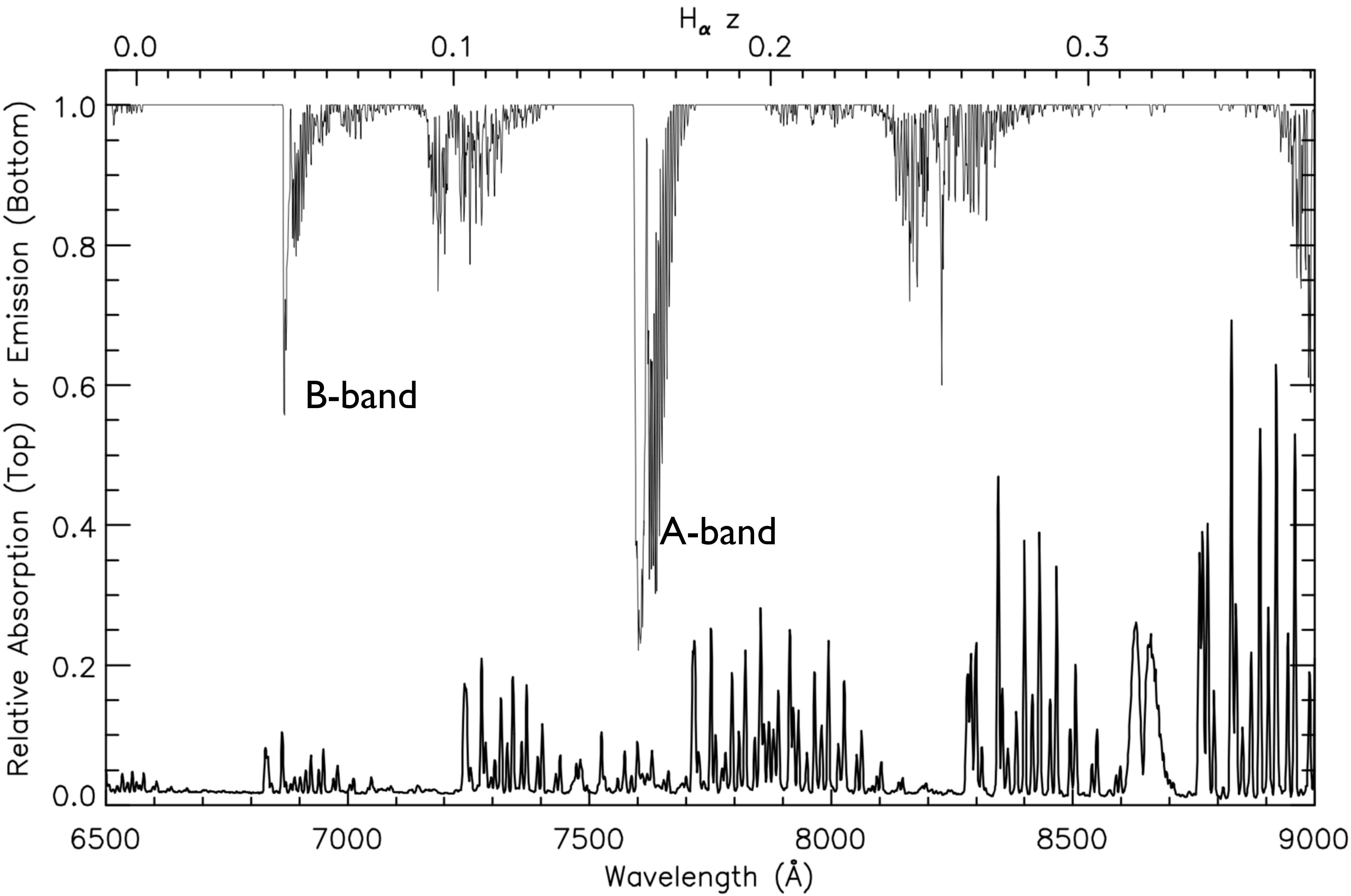
Sky brightness 10 magnitudes greater in K vs. B = 10,000x brighter in K than in B

Mid-IR 3.5 um (L-band): few Jy arcsec^{-2}
20 um: ~1000 Jy arcsec^{-2} (JWST!)
Far IR, few 100 microns: 100 Jy arcsec^{-2}
1mm: few Jy arcsec^{-2} (useful submm wavelength: 850 microns)

For a 1 arcsec source, the I-band sky magnitude integrated over the same aperture is 18
CFHT legacy survey limiting magnitude: 24.5
- 400x fainter than sky

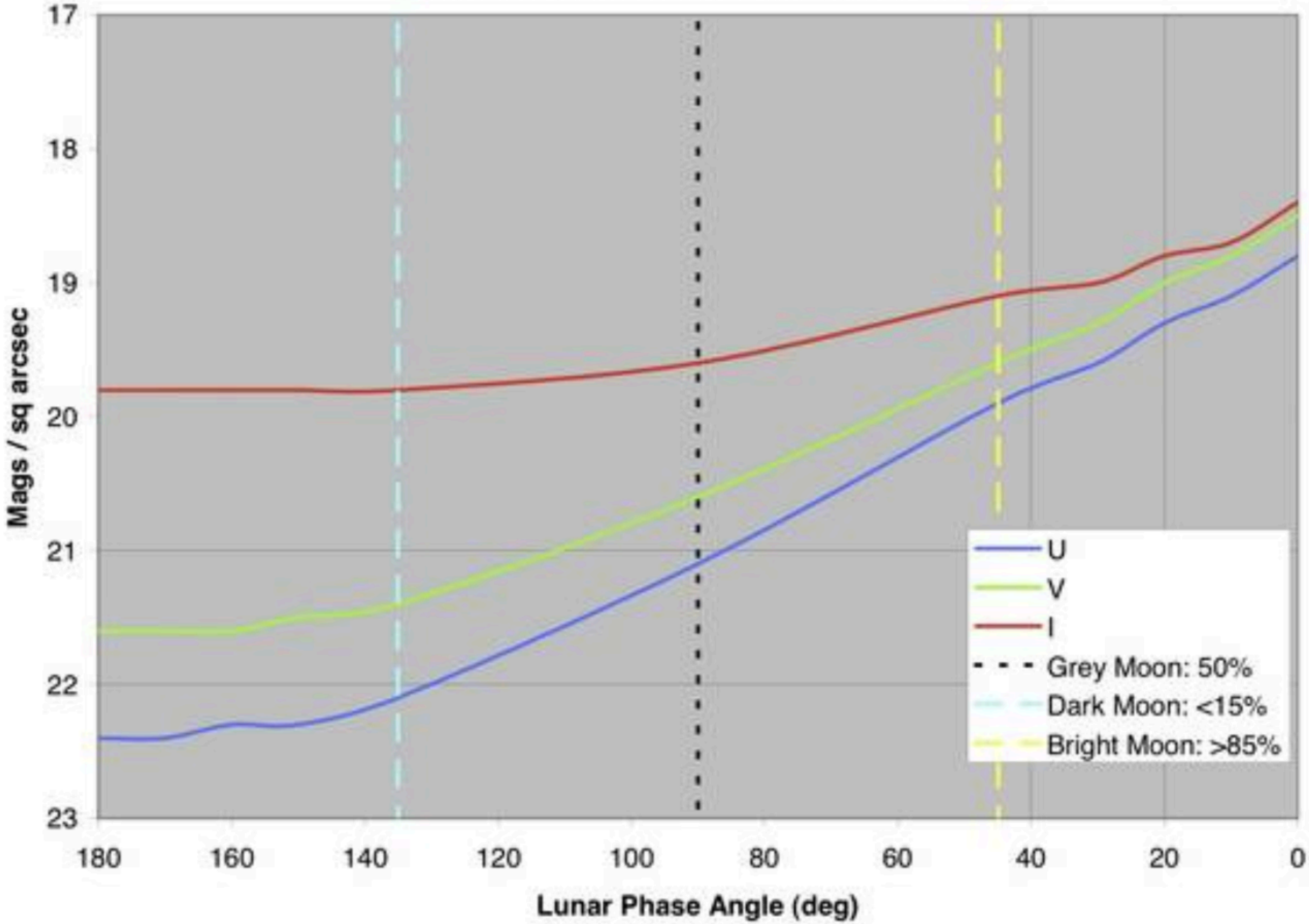
Sky Brightness, New Moon

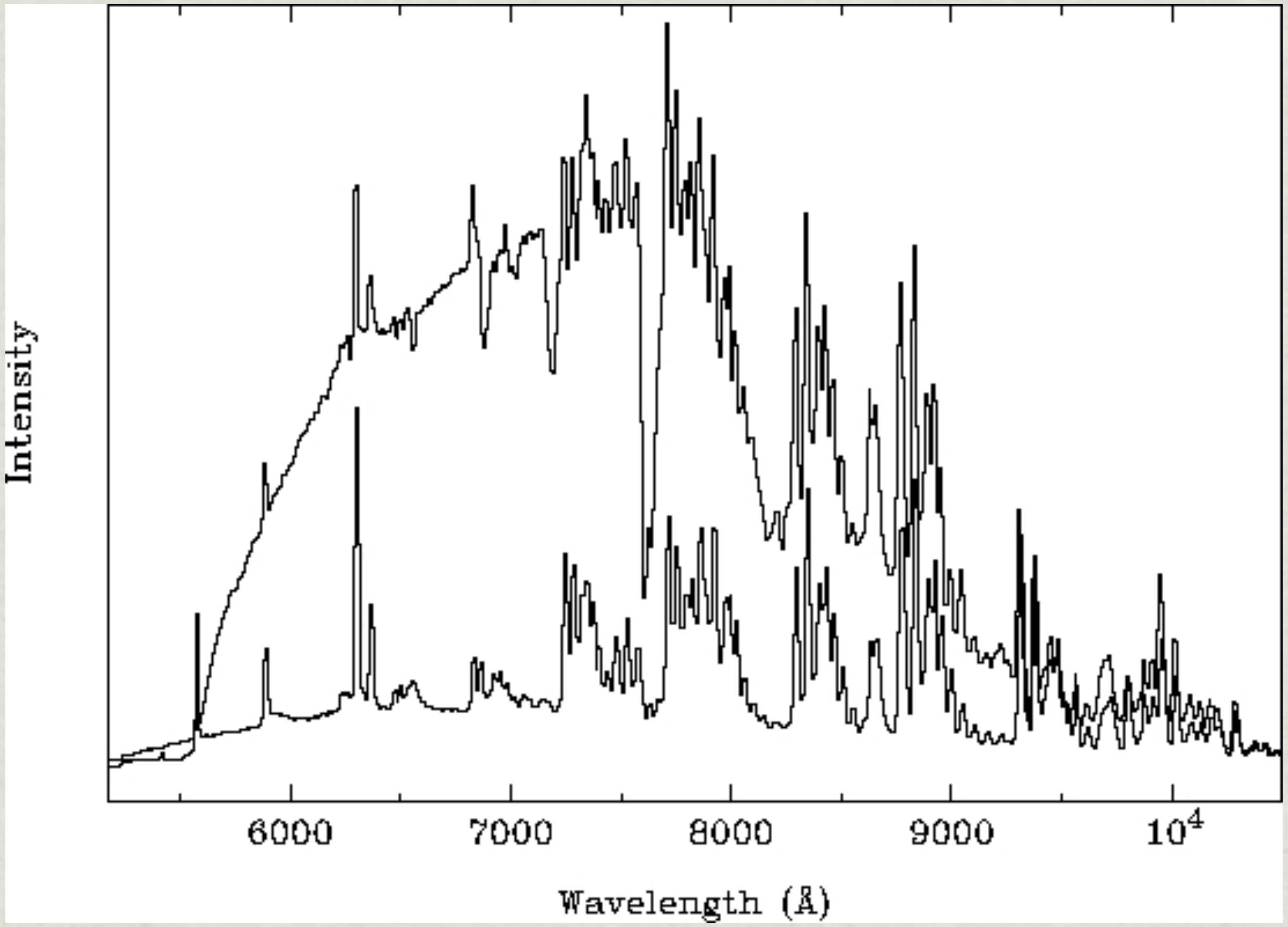




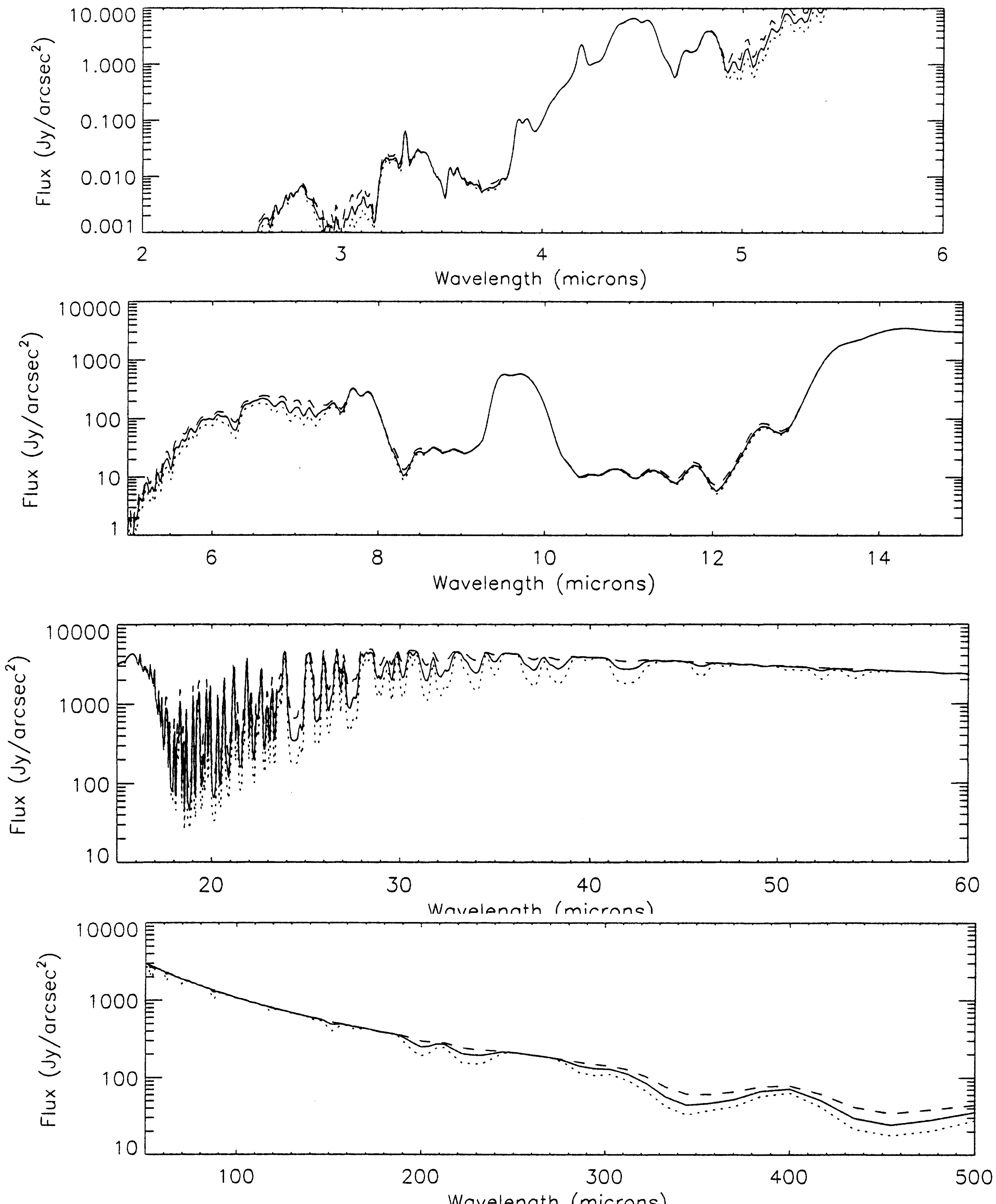
Kurtz et al. 2008

Night Sky Brightness, 90 degrees from the moon





Sky at new and full moon as seen by the FORS2 spectrograph, ESO



Flux (Jy/arcsec^2)
Wavelength (microns)
Flux (Jy/arcsec^2)
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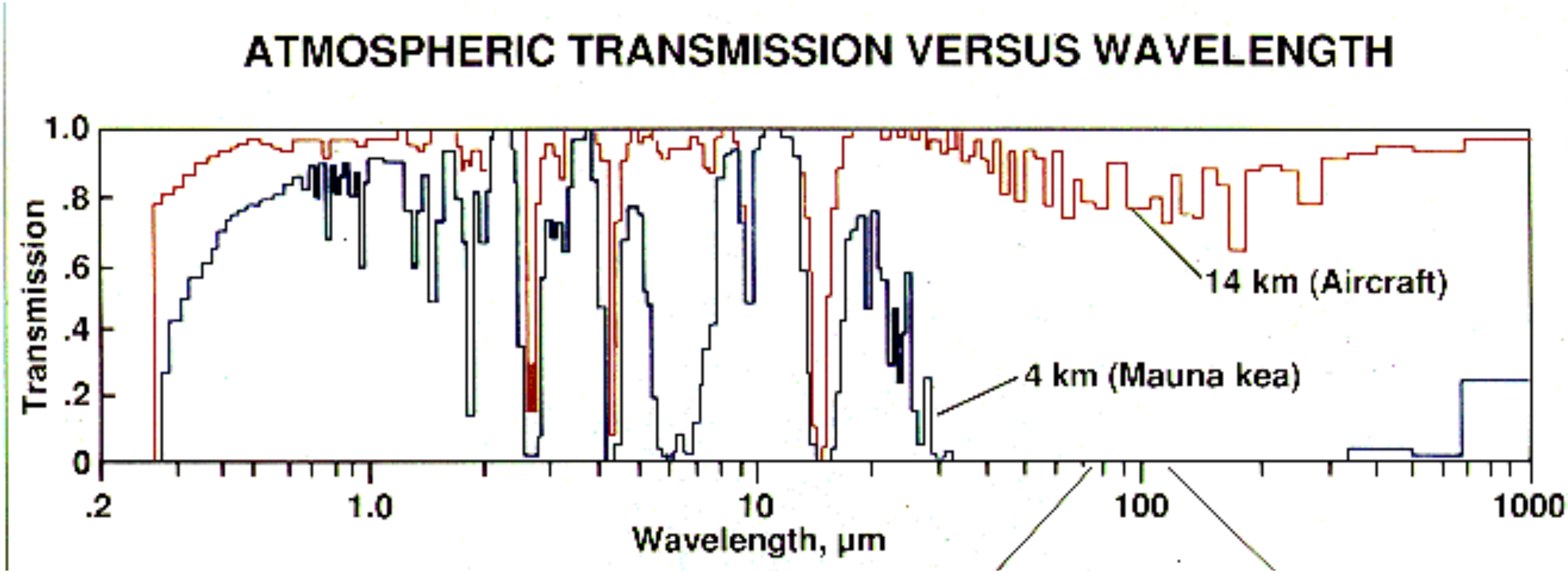
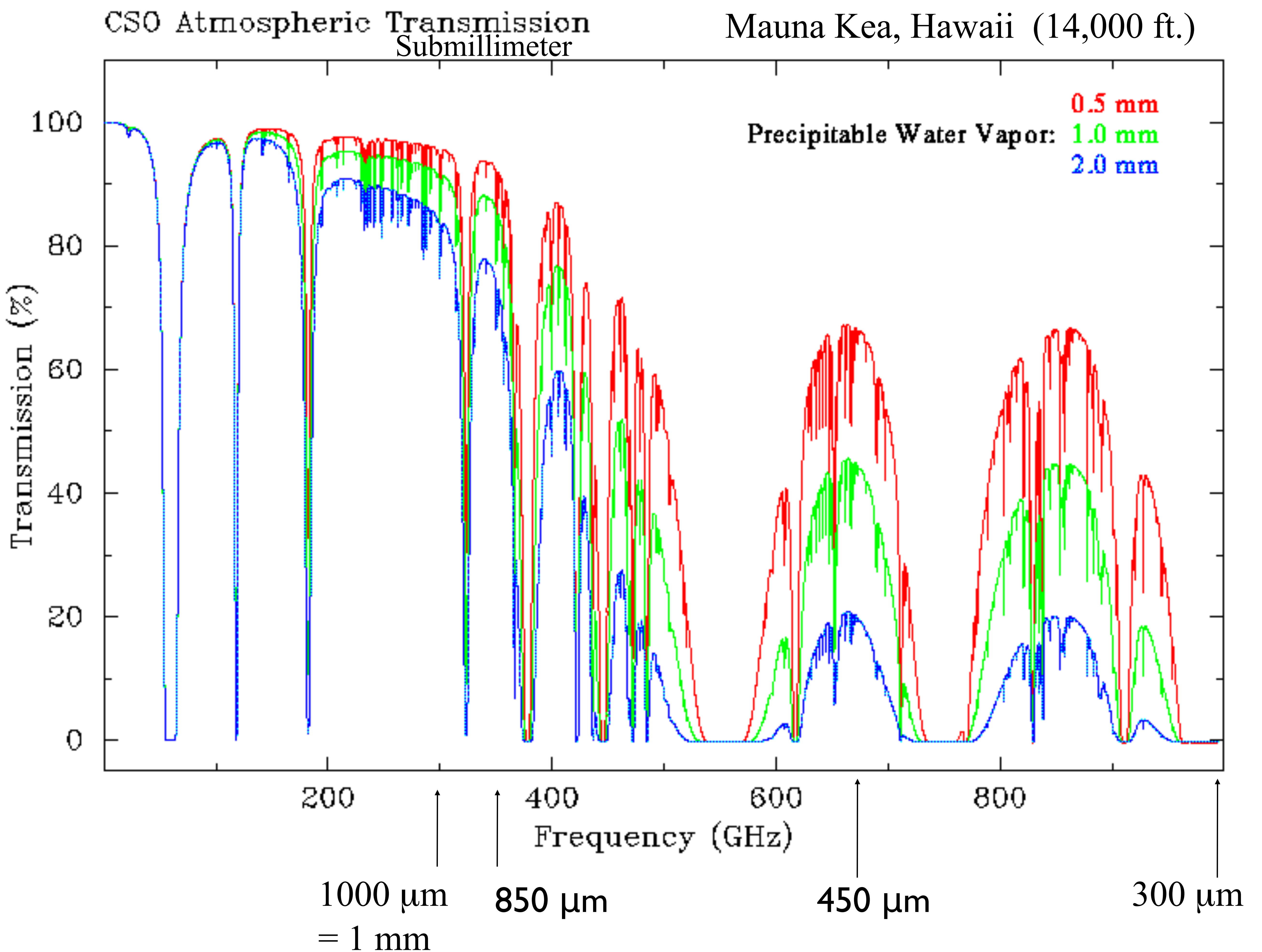
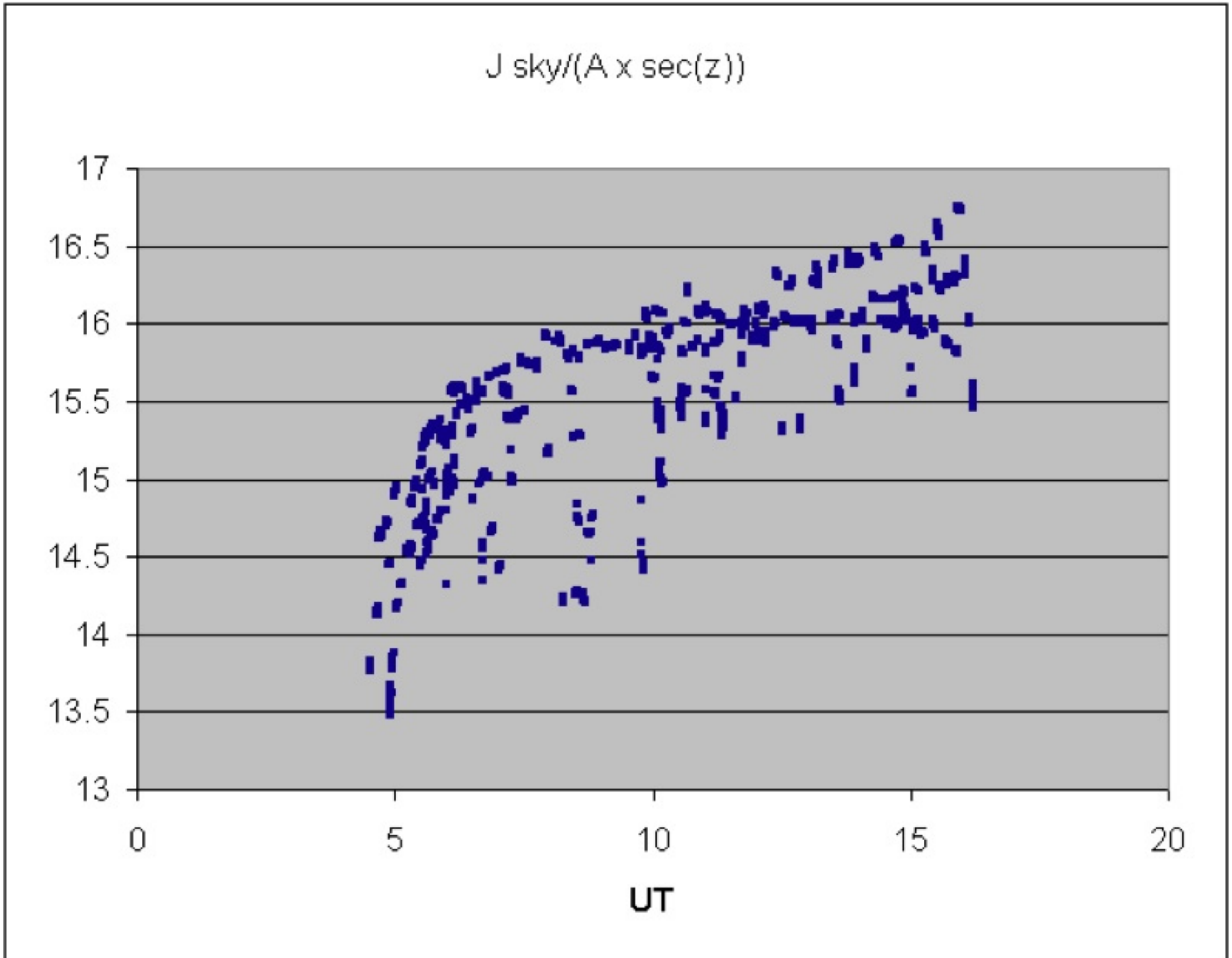


ATMOSPHERIC TRANSMISSION VERSUS WAVELENGTH
Transmission
1.0
.8
.6
.4
.2
0
14 km (Aircraft)
4 km (Mauna kea)
.2
1.0
10
100
1000
Wavelength, μm



CSO Atmospheric Transmission
Submillimeter
Mauna Kea, Hawaii (14,000 ft.)
Precipitable Water Vapor:
0.5 mm
1.0 mm
2.0 mm
Transmission (%)
100
80
60
40
20
0
200
400
600
800
Frequency (GHz)
1000 μm
= 1 mm
850 μm
450 μm
300 μm

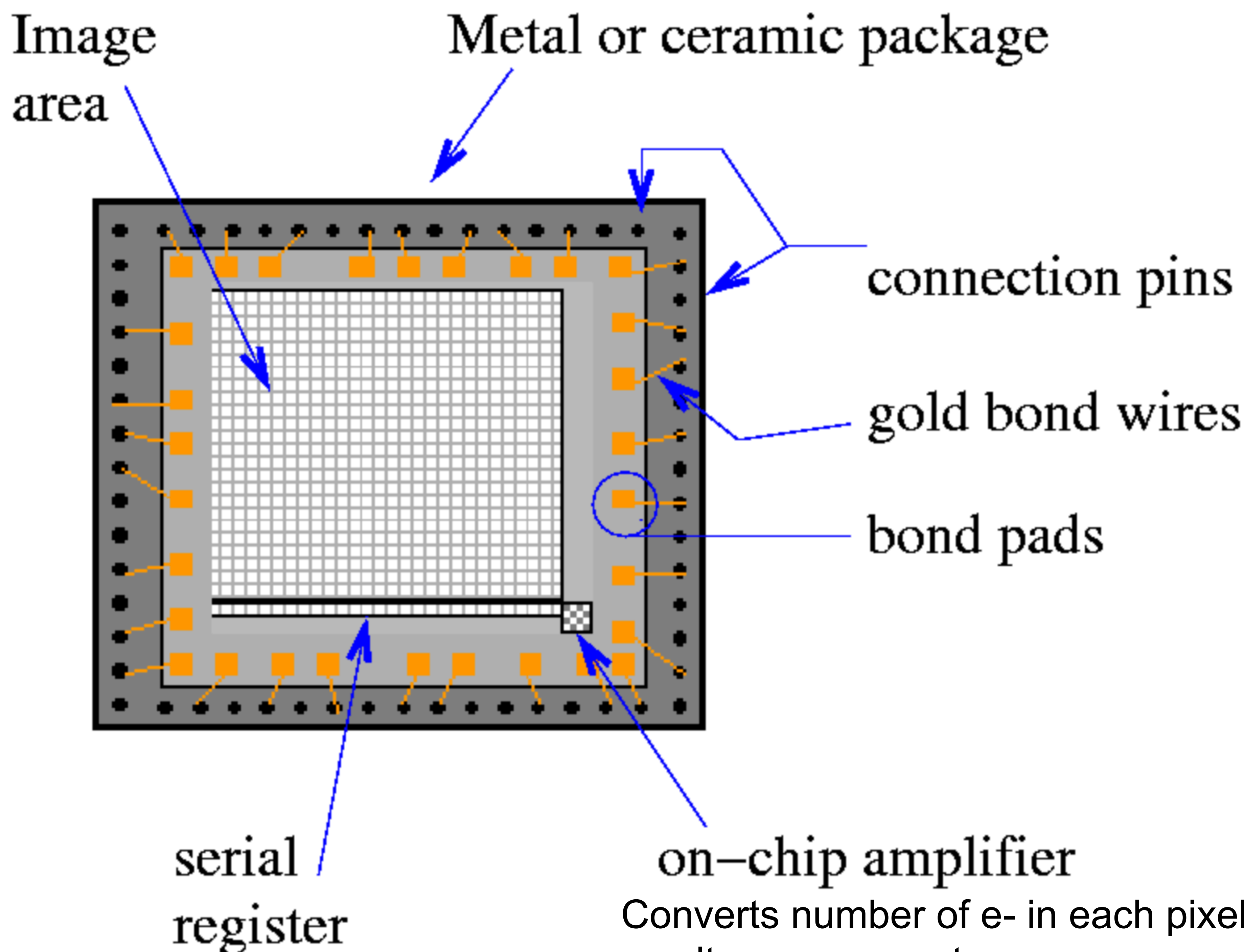
Airglow time variability
Data from JCMT



Another reason to take calibration data: night sky variations!

A Charged Coupled Device (CCD)
Made of silicon, detect photons as red as 1 micron

Near-infrared detectors are similar, use different materials to match the lower-energy photons



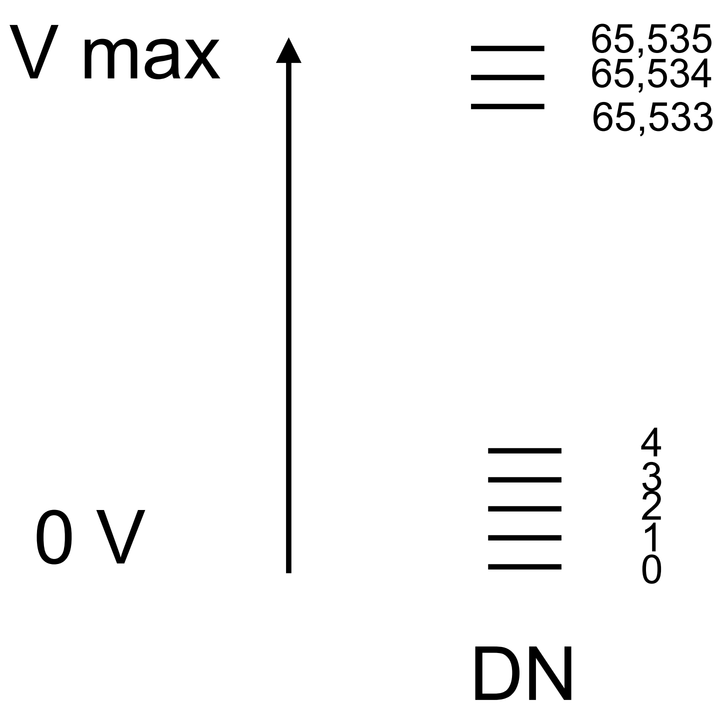
Converts number of e- in each pixel to a voltage or current we can measure. Adds Gaussian uncertainty “readnoise” to each pixel in the process.

Pixels give 2-d spatial information

We will come back to pixel size

- CCD collects e- in each pixel, output amplifier measures as volts
- Then convert that voltage to a number we can store
- 0 - Vmax (Vmax = maximum value of voltage that can be measures
  - also the maximum number of e- that can be measured in each pixel
- turn that into a set of discrete numerical values with an analog to digital converter
- Usually 16 bits = 65,535 discrete numerical values
  - steps are called **DN** = data numbers or **ADU** = analog-to-digital units
- Vmax/65535 = volts/DN

If Vmax = 5V: 5V / 65535 DN = 7.6×10^{-5} V/DN



What happens if the voltage on the CCD output is larger than 5V?

- detector system design choice: volts/DN and volts/e-
- user needs the **gain** of the detector system
  - measured in electrons/DN (or electrons/ADU)

Usually the gain gets measured by someone responsible for maintaining the instrument - should be available it in the documentation for the instrument, or you might have to measure it. We will use the documented values.