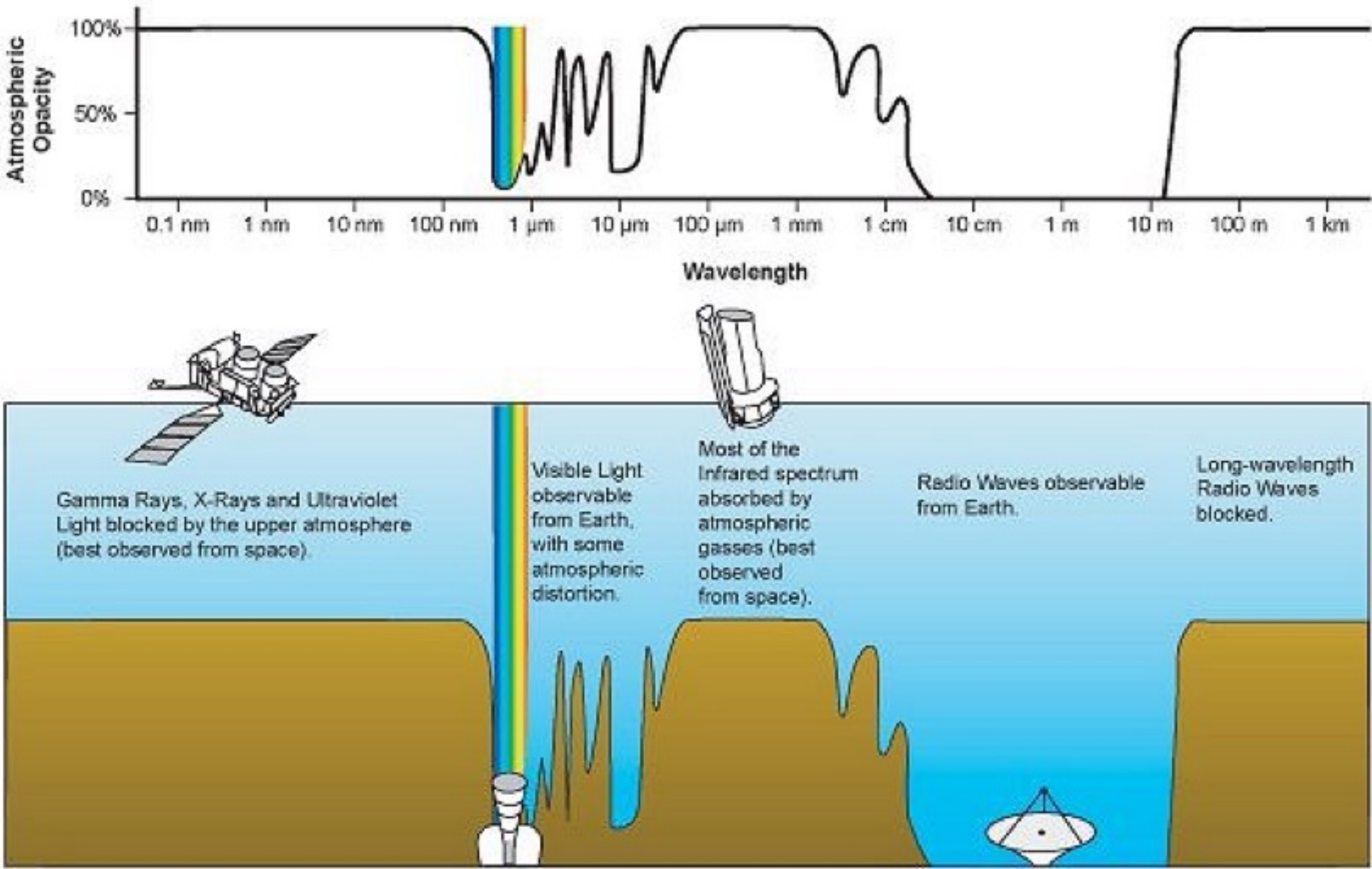
The Earth's Atmosphere



Space and ground

- From the ground, we can observe in the :
  - visible,
  - the near- and mid-infrared windows
  - Sub-mm and mm –waves from very dry sites
  - Radio above ~10MHz

And indirectly through Cerenkov radiation, gamma rays, cosmic rays,

Plus gravitational waves, neutrinos and, perhaps eventually, direct detection of dark matter

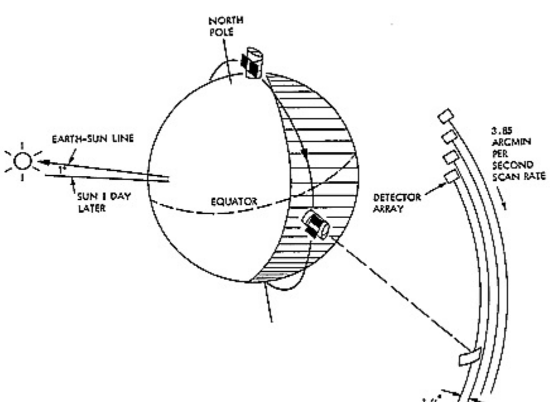
- Other wavebands need to be observed from high in or above the atmosphere

Space

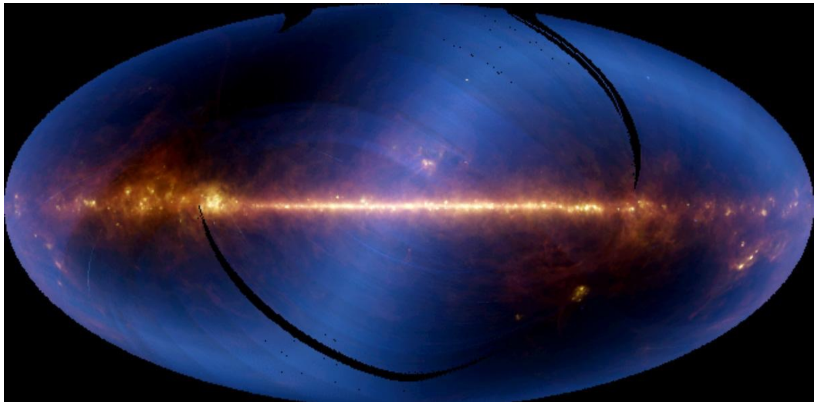
- Eliminate atmospheric absorption, scattering, phase variations & emission
- Access to the full electromagnetic spectrum
- Expensive, risky, size and power limitations
- Used where necessary
  - γ rays, X-rays, UV
  - Far-IR, Low frequency radio
  - High stability, extended monitoring,
  - Low background, distortion-free, high-resolution observations

Orbital Constraints

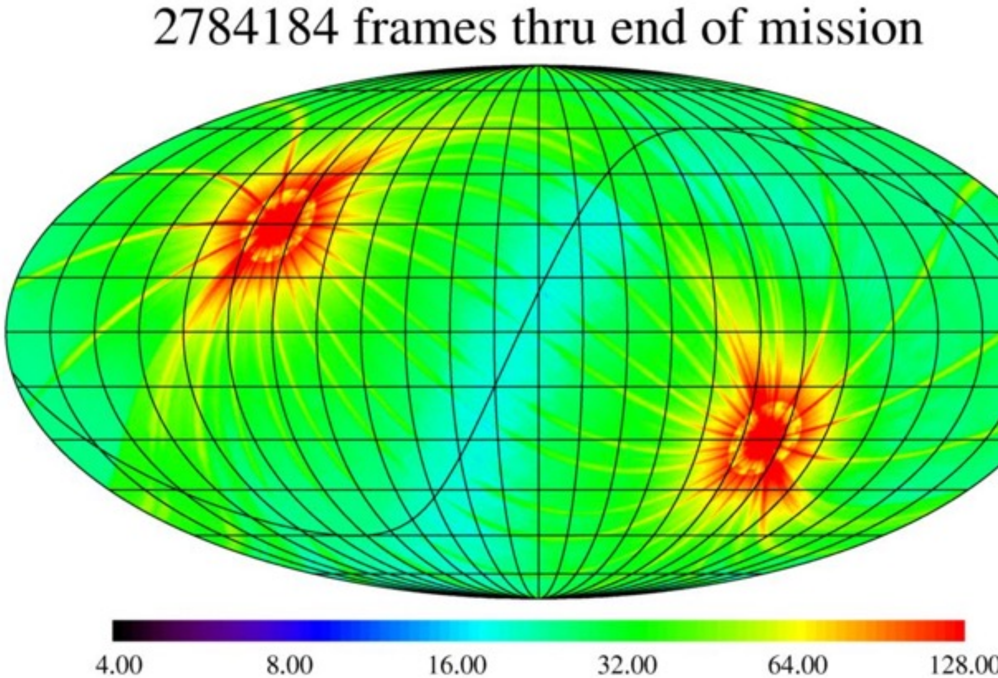
- Sun, Moon, Earth avoidance, especially heat load for cryogenic instruments
- Low-Earth orbit (e.g. HST) 90 min orbit with pointing constraints
- Survey satellites typically map out strips of the sky, building up to complete the survey
  - Some areas may have many passes (e.g. polar caps)

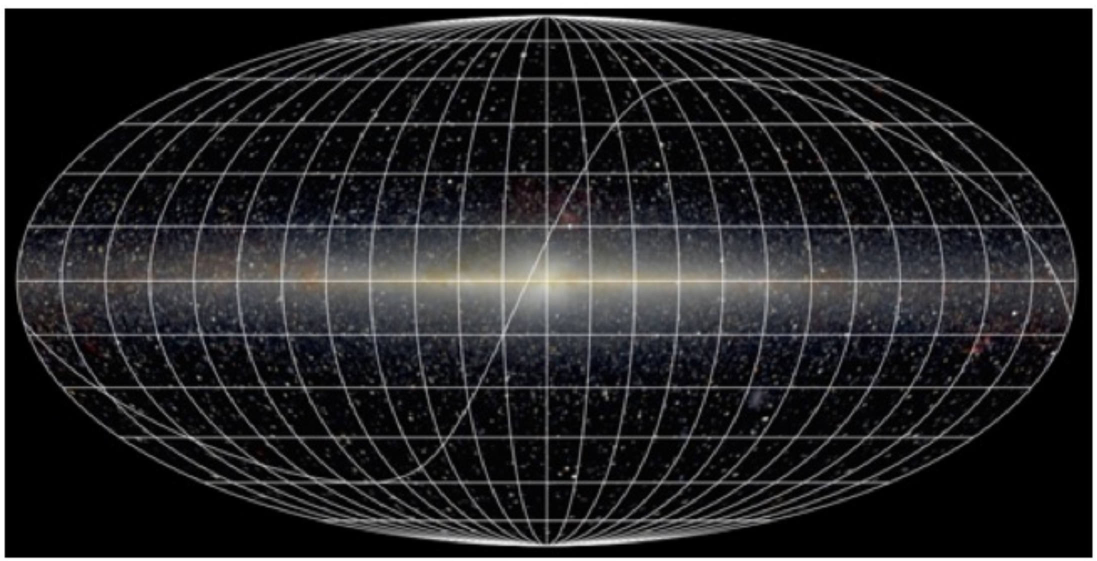


IRAS satellite orbit and (nearly) all-sky map at 12, 25,60 &, 100 μm



How much of the sky did WISE see?



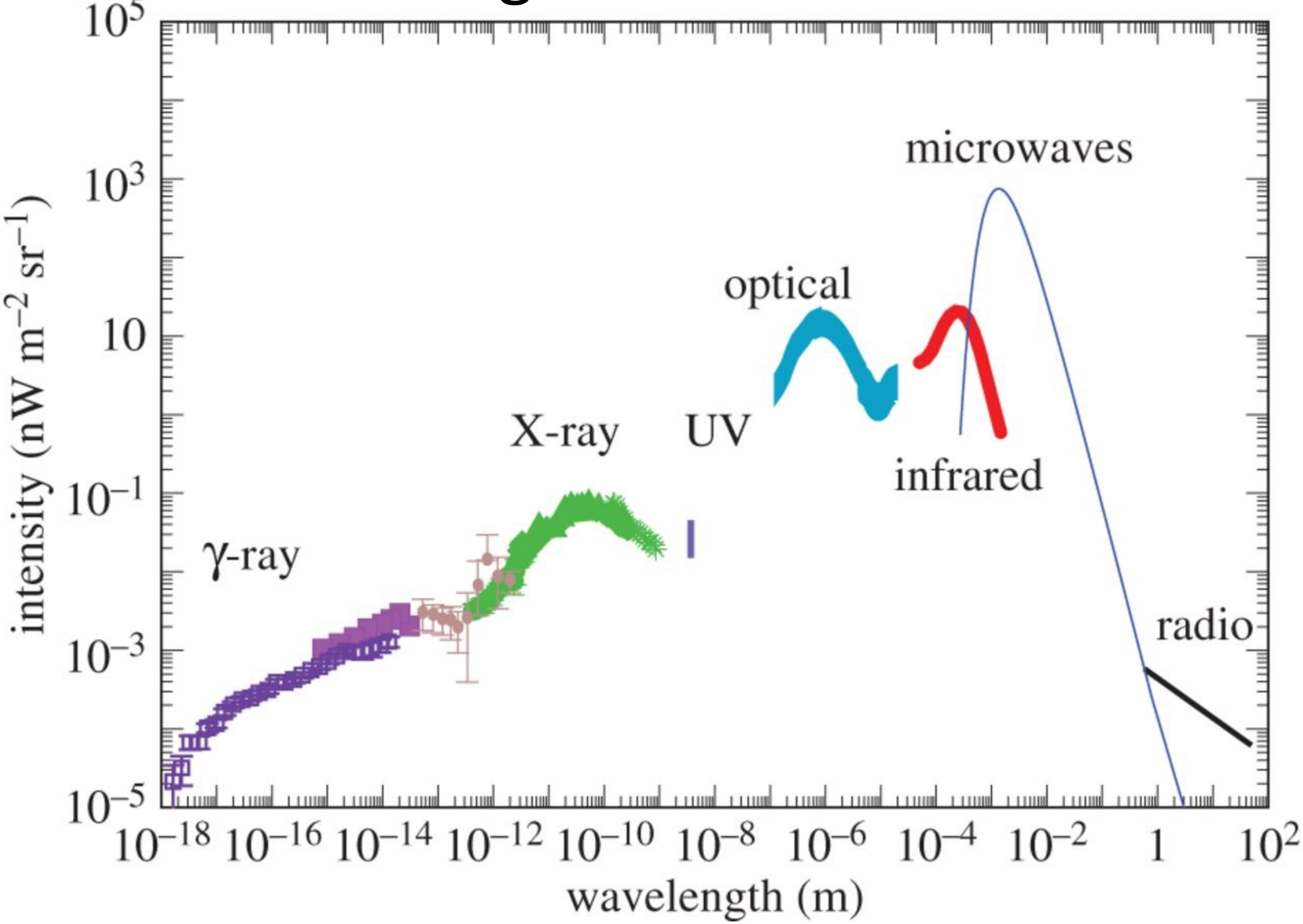


The top image shows the overall coverage of the WISE all-sky survey, as measured by successfully processed frames. The scale on the bottom shows the density of the coverage. The red portions indicate heavy coverage whereas blue portions indicate a lighter coverage. The poles received the most coverage because WISE orbits Earth around the poles, and scanned out strips of sky as Earth moved around the Sun. The green-yellow lines between the poles show areas that received extra coverage because of the mission's strategy to avoid the Moon. This resulted in overlapped coverage for certain slices of sky. The image is a map of the sky in a Mollweide projection centered on the Milky Way Galaxy. See the image of the sky below from COBE/DIRBE for reference.

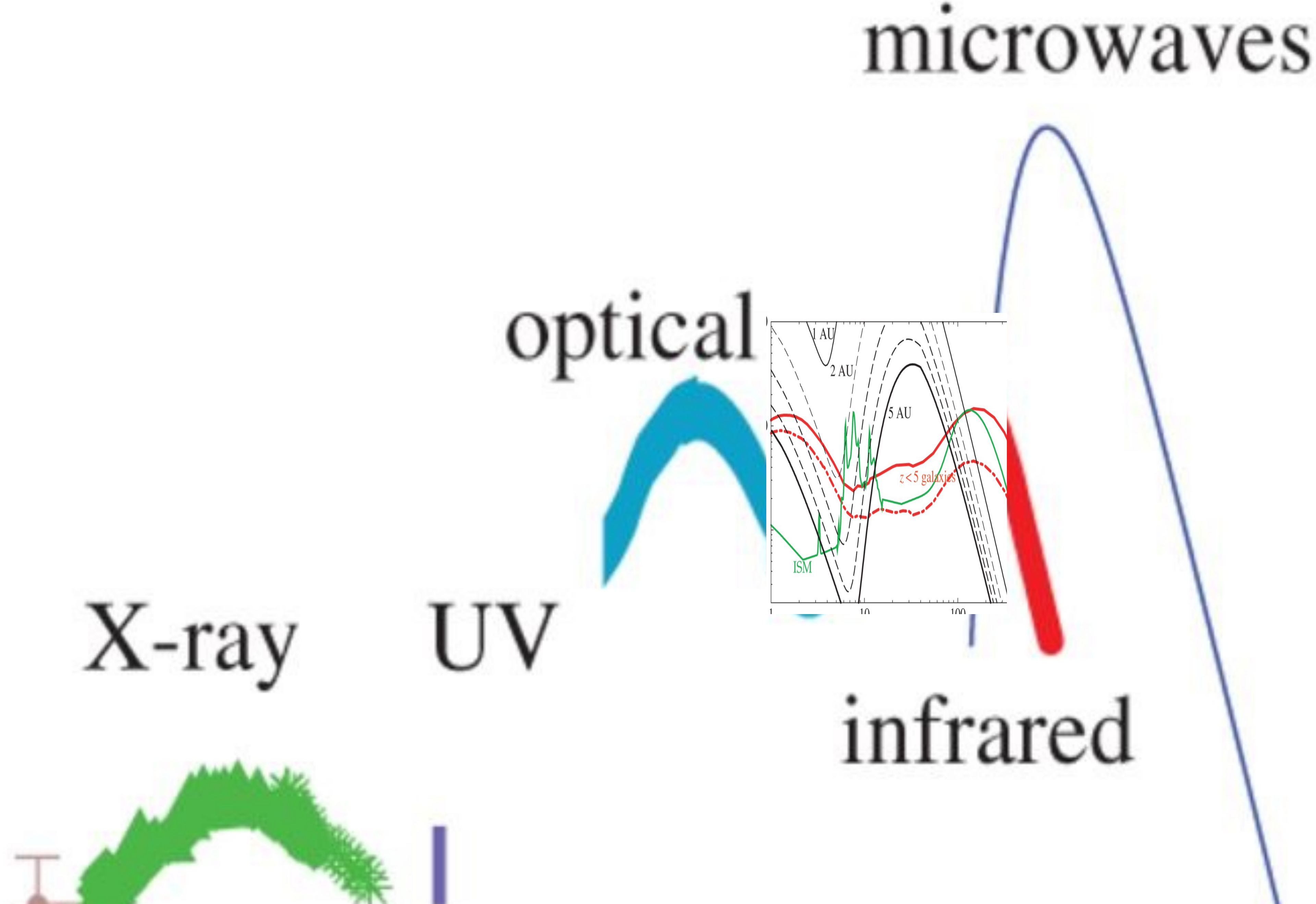
Foregrounds

- Galactic emission dominates at long wavelengths : dust and synchrotron radiation
- Solar system emission is important near the ecliptic plane
  - Scattered light at visible wavelengths
  - Dust emission at thermal IR wavelengths
  - Effects can be minimised by observing at high latitude
- Understanding of polarization as well as intensity may be important, e.g. for CMB studies

Sensitivity ultimately limited by diffuse background emission



Extragalactic background emission (A Cooray 2016) : Intensity of the extragalactic background (*νIν* in units of nW m−2 sr−1) as a function of the wavelength. We combine the existing measurements from the literature to highlight the best determined estimates for the background from γ-ray to radio. The CMB is best determined as the spectrum is determined to better than 1%. COB has large uncertainties involving direct measurements due to uncertain removal of the zodiacal light foreground. Here we show the indirect estimate of EBL at optical wavelengths based on the TeV/γ-ray absorption spectra of distant blazars. The UV/soft X-ray background at a wavelength of 10–100 nm remains unexplored


microwaves
optical
1 AU
2 AU
5 AU
z < 5 galaxies
ISM
10
100
X-ray
UV
infrared

Background

- Even at dark sites on Earth, the sky background emission is significantly brighter than the cosmic background
- At infrared wavelengths, thermal emission from the sky & telescope dominates and can be a million times greater than the background in space
- Space is cold and a shielded, passively cooled satellite can reach temperatures <40K via radiative cooling, compared to >280K at most terrestrial observatories
- Low Earth orbit suffers from high thermal heatloads and significant geocoronal Hydrogen Lyman emission, so most sensitive missions are positioned further away

Ground

- Select best sites – Hawaii, Chile, South Pole
  - Remote mountain tops
  - Dark skies
  - Clear, photometric nights (or days for solar observations!)
  - Low water vapour, low temperatures for IR, mm
  - Stable atmosphere, moderate wind
- Sites at +/-30 deg latitude access most of the sky and are away from geomagnetic poles
- South Pole is very cold and dry, ideal for IR and mm observations, and offers long nights for monitoring, but has limited sky visibility

Usable observing time

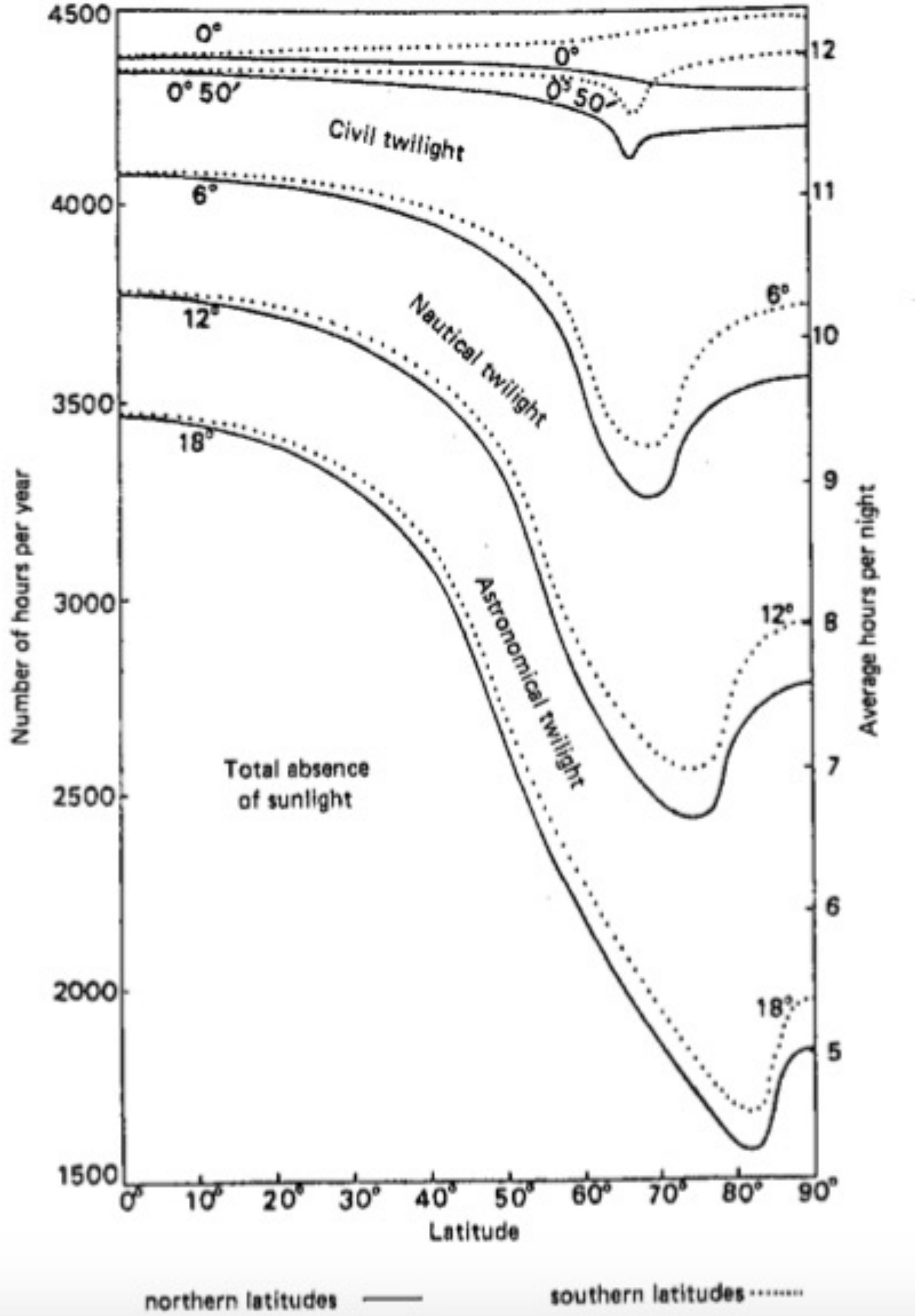
The variation in the number of dark hours in the year as a function of geographic latitude and twilight definition

Sites within +/- 30 deg of the equator provide the largest number of dark hours and also provide access to the greatest fraction of the sky

Astronomical twilight – where the sky is truly dark- ends when the sun is 18 deg below the horizon

The asymmetry between the north and south latitudes is because the sun is at perigee during the northern winter.

(B Yallop et al 1976)



Atmospheric Windows

- The accessible parts of the spectrum from the ground are the
  - Visible 0.3 – 0.8 um from the UV cut-off at 310nm
  - Infrared 0.8 to 25 um in windows of good to fair transmission at dry sites
  - mm/sub-mm in windows with transmission critically dependent on atmospheric water column
  - Radio down to ionospheric cut-off

Visible Window

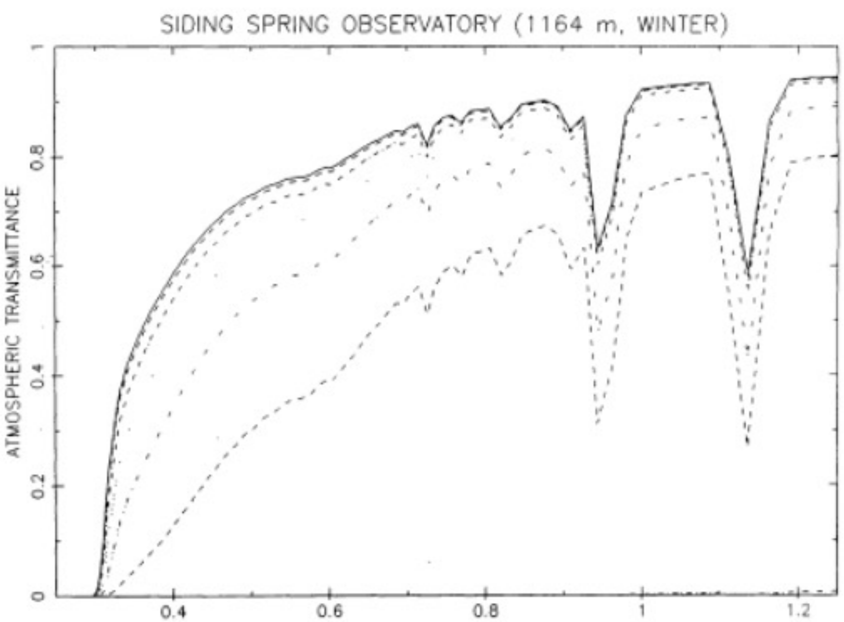


FIGURE 4. — Siding Spring Observatory transmittance between 0.25 μ and 1.25 μ during the Fall-Winter season (1164 m).

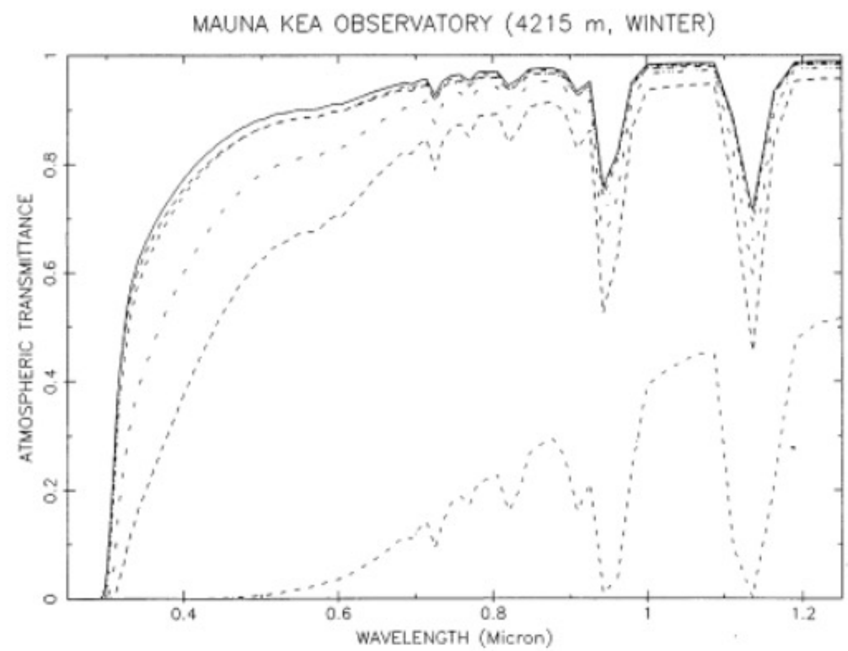


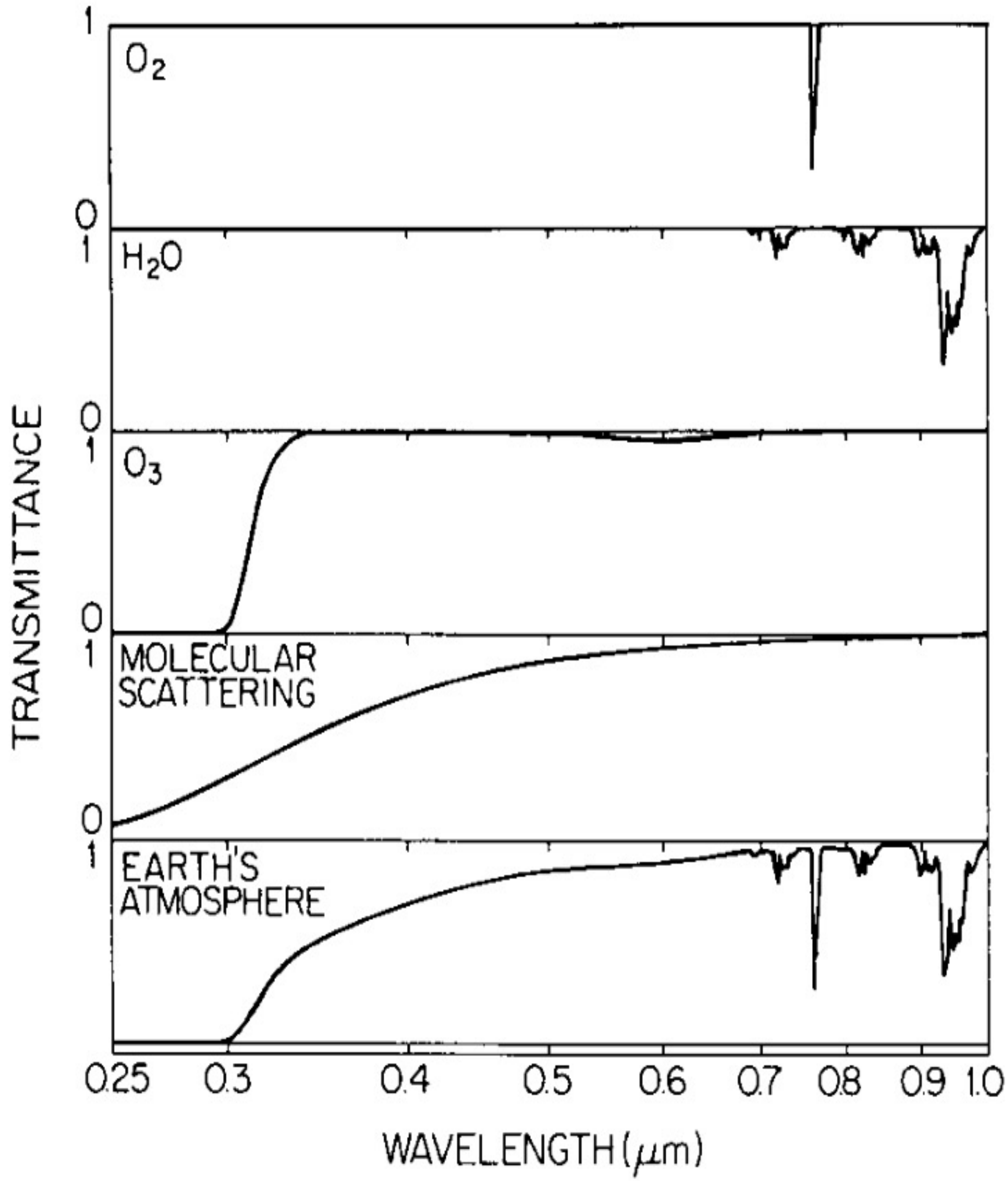
FIGURE 10. — Hawaii Mauna Kea Observatory transmittance between 0.25 μ and 1.25 μ during the Fall-Winter season (4215 m).

C. Nitschelm

Mauna Kea and Siding Spring visible/NIR atmospheric transmission curves.
The plots are for zenith angles of 0, 15, 30, 45, 60, 75, 90 degrees

Visible Transmission

- UV cutoff at 300nm due to stratospheric O_3 : by 290nm, attenuation is ~10^6.
- Fraunhofer A band absorption by O_2 at 760nm is often the sharpest and strongest telluric spectral feature
- Water bands absorption increasing with wavelength beyond 700nm



The region around the UV cutoff is an important spectral region for stellar and extragalactic astrophysics
e.g. see the science case for CUBES at the VLT by B Barbuy et al (ApSpSci 2014)

Instrument and telescope design can be driven by UV requirements

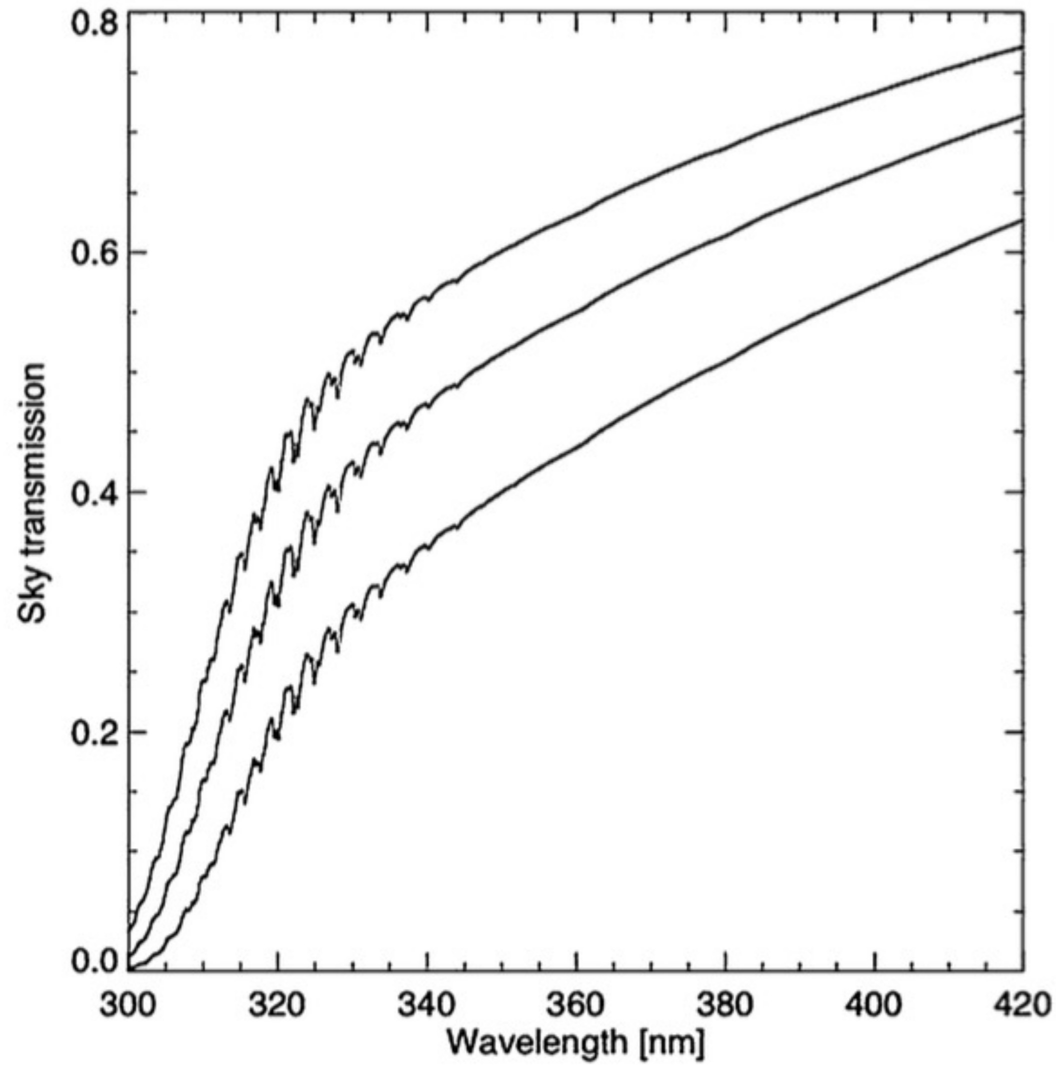
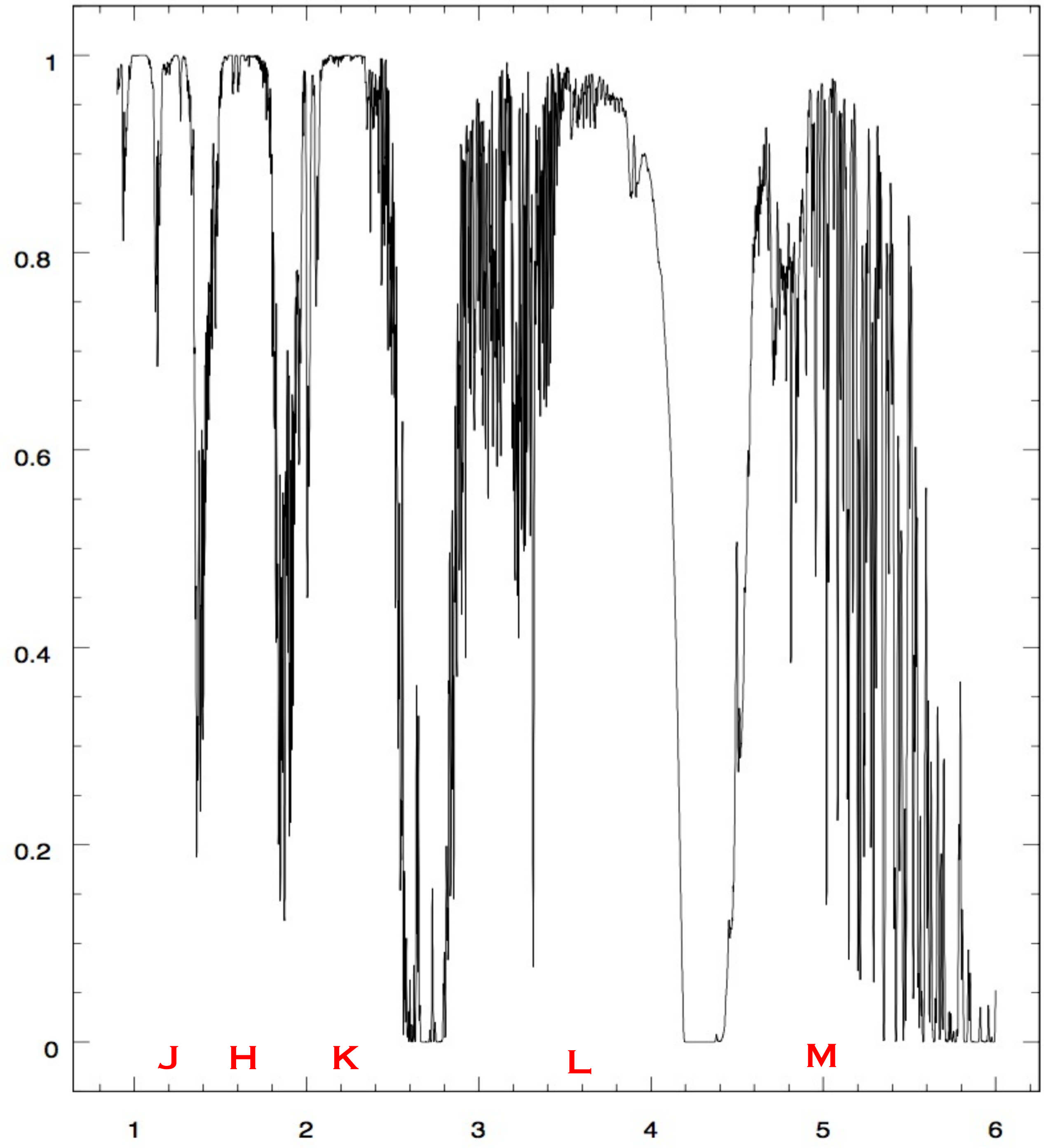


Fig. 3 Atmospheric transmission at the Paranal VLT platform (Noll et al. 2012). From top to bottom, the curves correspond to airmass = 1.0, 1.3 and 1.8. Note that the transmission drops sharply with wavelength below 330 nm and is 15–20 % lower at airmass = 1.8 than at zenith across most of the wavelength range in the plot

Infrared Windows

- Zenith atmospheric transmission calculated for Mauna Kea with HITRAN (Glass & Roche 1990)
- Near-IR windows defined by H_2O and CO_2 absorption bands designated J,H,K,L,M
- Note there are many sharp absorption features that can affect transmission on fine scales - effects of doppler shifts can be significant for some lines
- This is especially the case in the L and M bands and at the edges of the windows

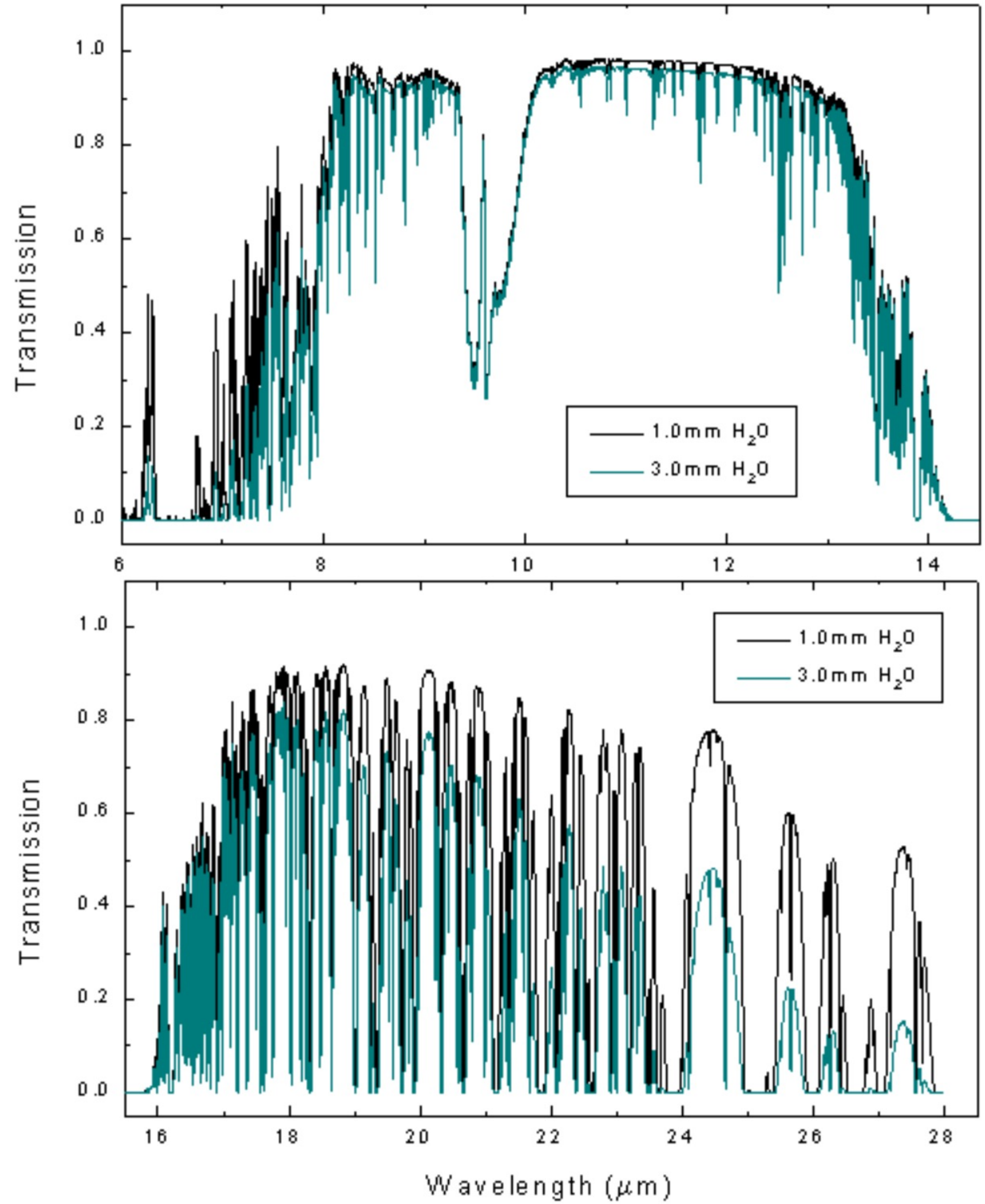


Mid-Infrared, N and Q band transmission for Mauna Kea.

The prominent absorption at 9.5–10um is by stratospheric O_3 and so does not depend on the water column

A water column of 1mm represents the lowest water vapour column expected on the best nights at Mauna Kea

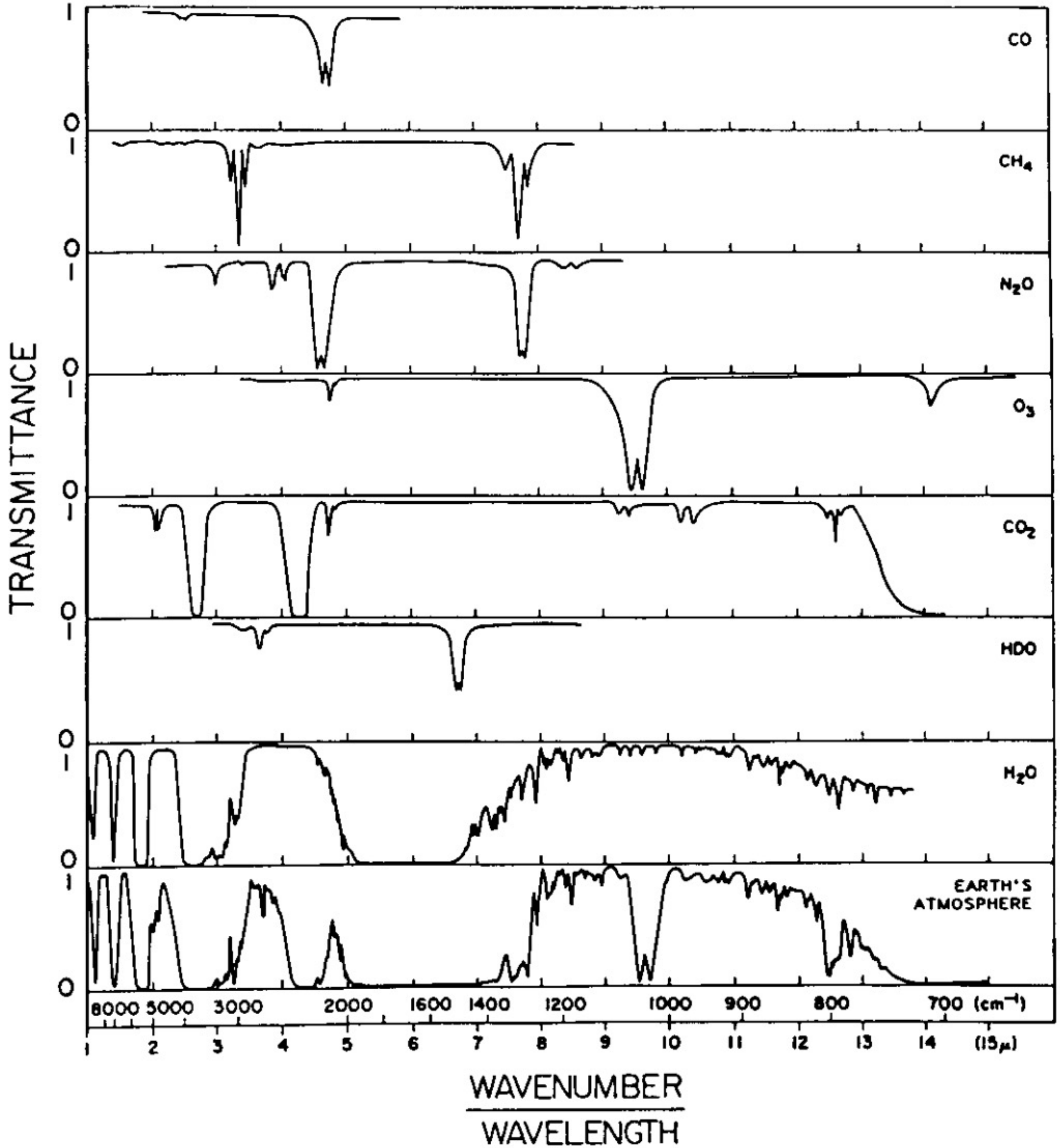
Transmission in the Q-band is more like a venetian blind than a window!



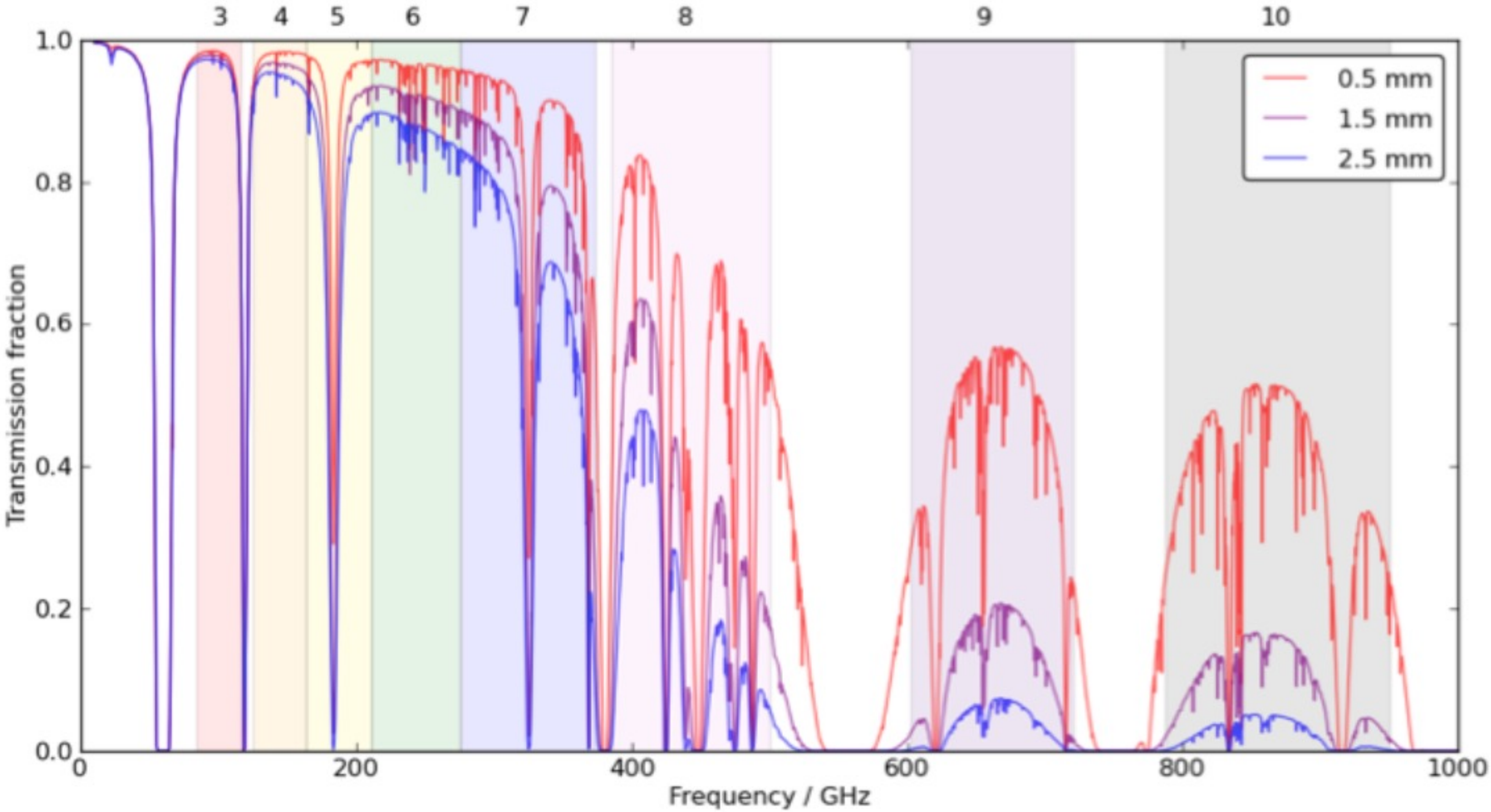
Atmospheric Absorption

Dominant absorbing species are water, carbon dioxide,
but methane & ozone are also important.

High dry sites have improved transmission and bandwidth in the windows



mm/sub-mm



ALMA and APEX are at 5000m elevation on the Chajnantor plateau in the Atacama desert. The low pressure and low water column give good transmission at mm/sub-mm wavelengths. Observation at the highest frequencies require the best observing conditions – stable atmosphere and low water. The South Pole offers significantly lower water columns (~0.1mm) and may enable Terahertz observations.

Protected Radio Frequencies

Radio Quiet Zones around Observatories

US246 : No station shall be authorized to transmit in the following bands:

- 73-74.6 MHz,
- 608-614 MHz, except for medical telemetry equipment,
- 1400-1427 MHz,
- 1660.5-1668.4 MHz,
- 2690-2700 MHz,
- 4990-5000 MHz,
- 10.68-10.7 GHz,
- 15.35-15.4 GHz,
- 23.6-24 GHz,
- 31.3-31.8 GHz,
- 50.2-50.4 GHz,
- 52.6-54.25 GHz,
- 86-92 GHz,
- 100-102 GHz,
- 109.5-111.8 GHz,
- 114.25-116 GHz,
- 148.5-151.5 GHz,
- 64-167 GHz,
- 182-185 GHz,
- 190-191.8 GHz,
- 200-209 GHz,
- 226-231.5 GHz,
- 250-252 GHz.

UNITED STATES FREQUENCY ALLOCATIONS

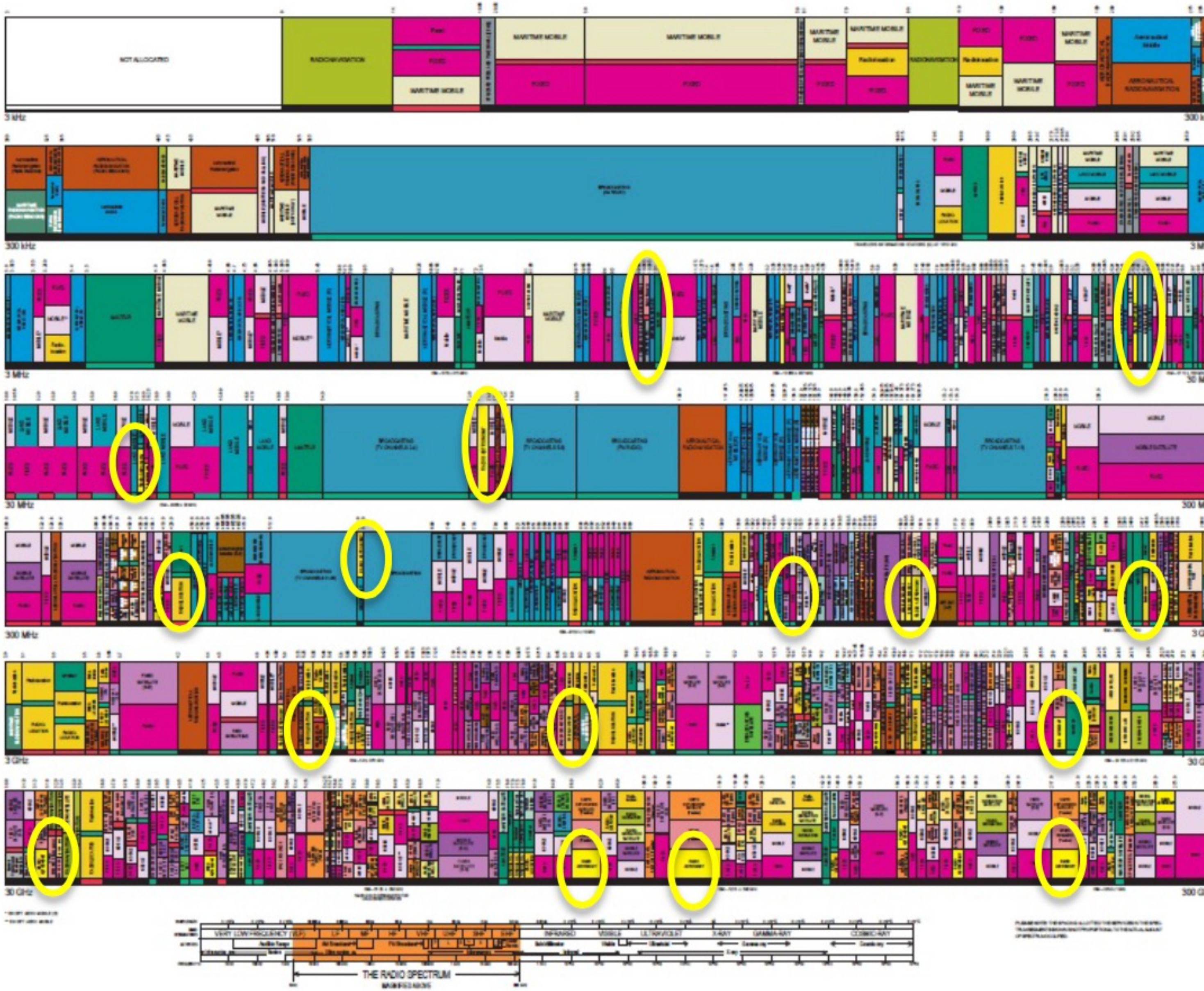
THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

ACTIVITY CODE

ALLOCATION USAGE DESIGNATION

U.S. DEPARTMENT OF COMMERCE



Long Wavelength Limit

The refractive index of a cold neutral plasma is given by

$$\mu(\nu) = \sqrt{1 - \frac{\nu_p^2}{\nu^2}}, \quad (16.1.1)$$

where ν_p the "plasma frequency is given by

$$\nu_p = \sqrt{\frac{n_e e^2}{\pi m_e}} \simeq 9\sqrt{n_e} \ \text{kHz} \quad (16.1.2)$$

where e is the charge on the electron, m_e is the mass of the electron and n_e is the electron number density (in cm^{-3}). At frequencies below the plasma frequency ν_p the refractive index becomes imaginary, i.e. the wave is exponentially attenuated and does not propagate through the medium. The earth's ionosphere has electron densities $\sim 10^4 - 10^5 \text{ cm}^{-3}$, which means that the plasma frequency is $\sim 1 - 10$ MHz. Radio waves with such low frequencies do not reach the earth's surface and can be studied only by space based telescopes. The plasma between the planets is called the Interplanetary Medium (IPM) and has electron densities $\sim 1 \text{ cm}^{-3}$ (at the earth's location); the corresponding cut off frequency is ~ 9 kHz. The typical density in the Interstellar Medium (ISM) is $\sim 0.03 \text{ cm}^{-3}$ for which the cut off frequency is ~ 1 kHz. Waves of such low frequency from extra solar system objects cannot be observed even by spacecraft since the IPM and ISM will attenuate them severely.

Rao, AP

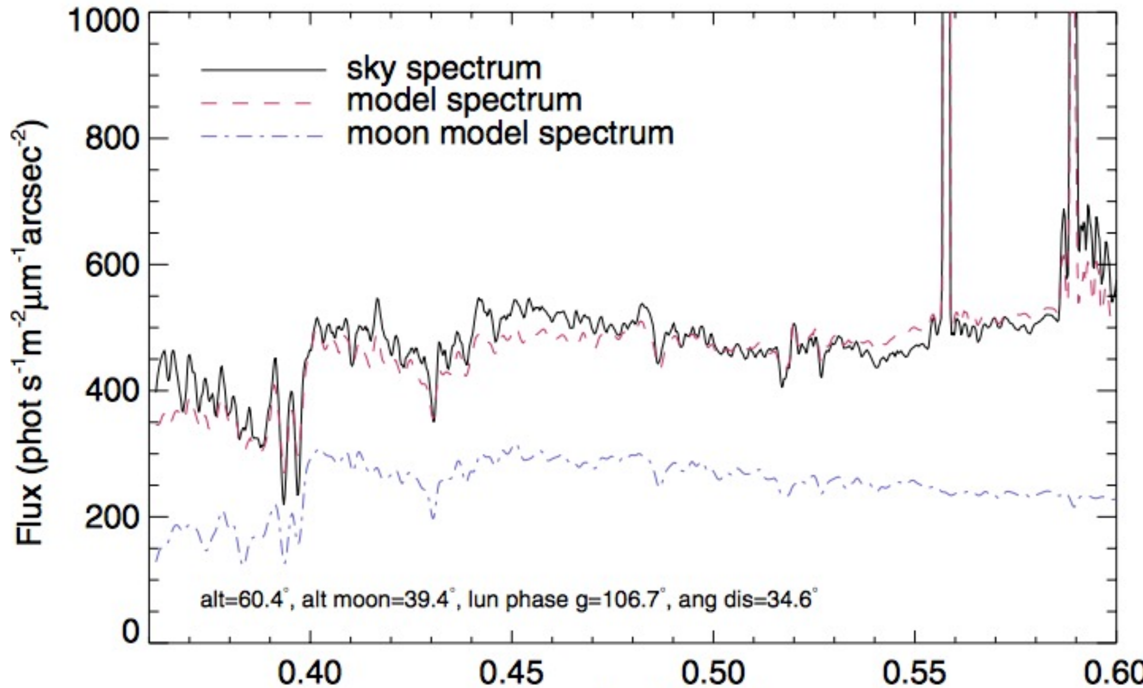
Atmospheric Background

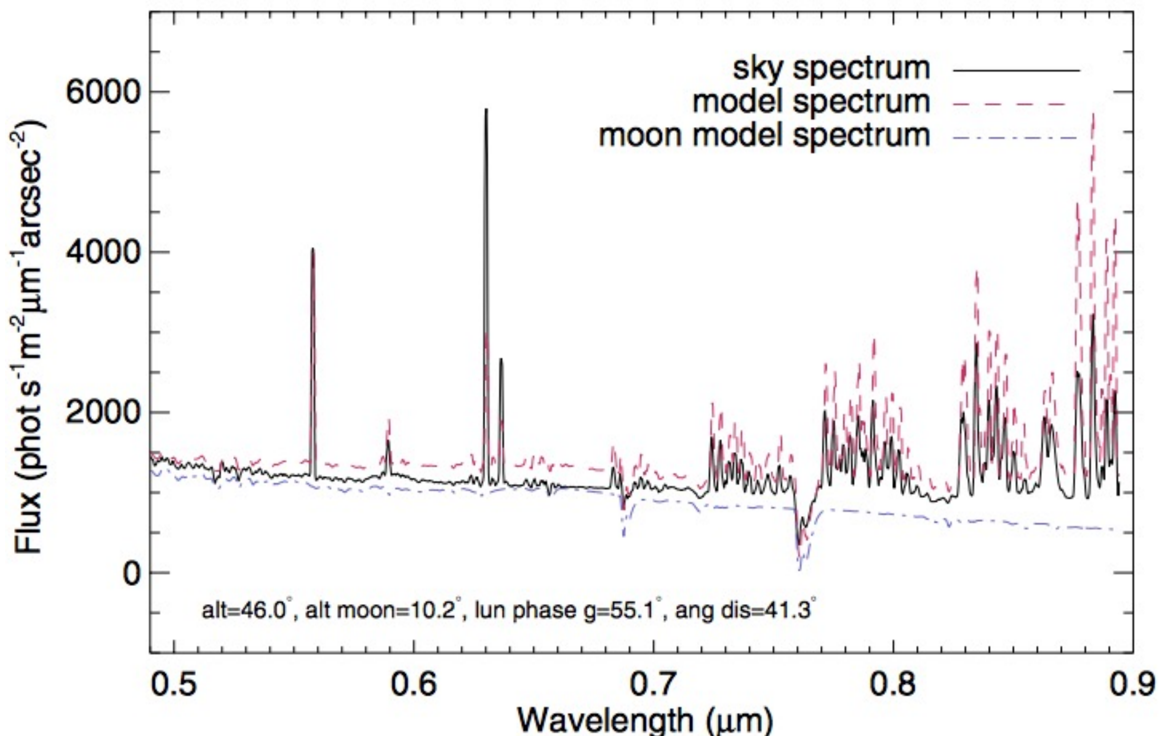
Calculated sky brightness model compared with observations from FORS 1 at Paranal (A Jones et al 2013)

The two plots compare models with different contributions from scattered moonlight, which is the dominant source of background under bright sky conditions

The strong narrow features are OI] and NI airglow lines, which are variable, so intensities will not match a general model. OH emission becomes prominent longwards of 700nm

Note that the scattered light background is quite strongly polarized





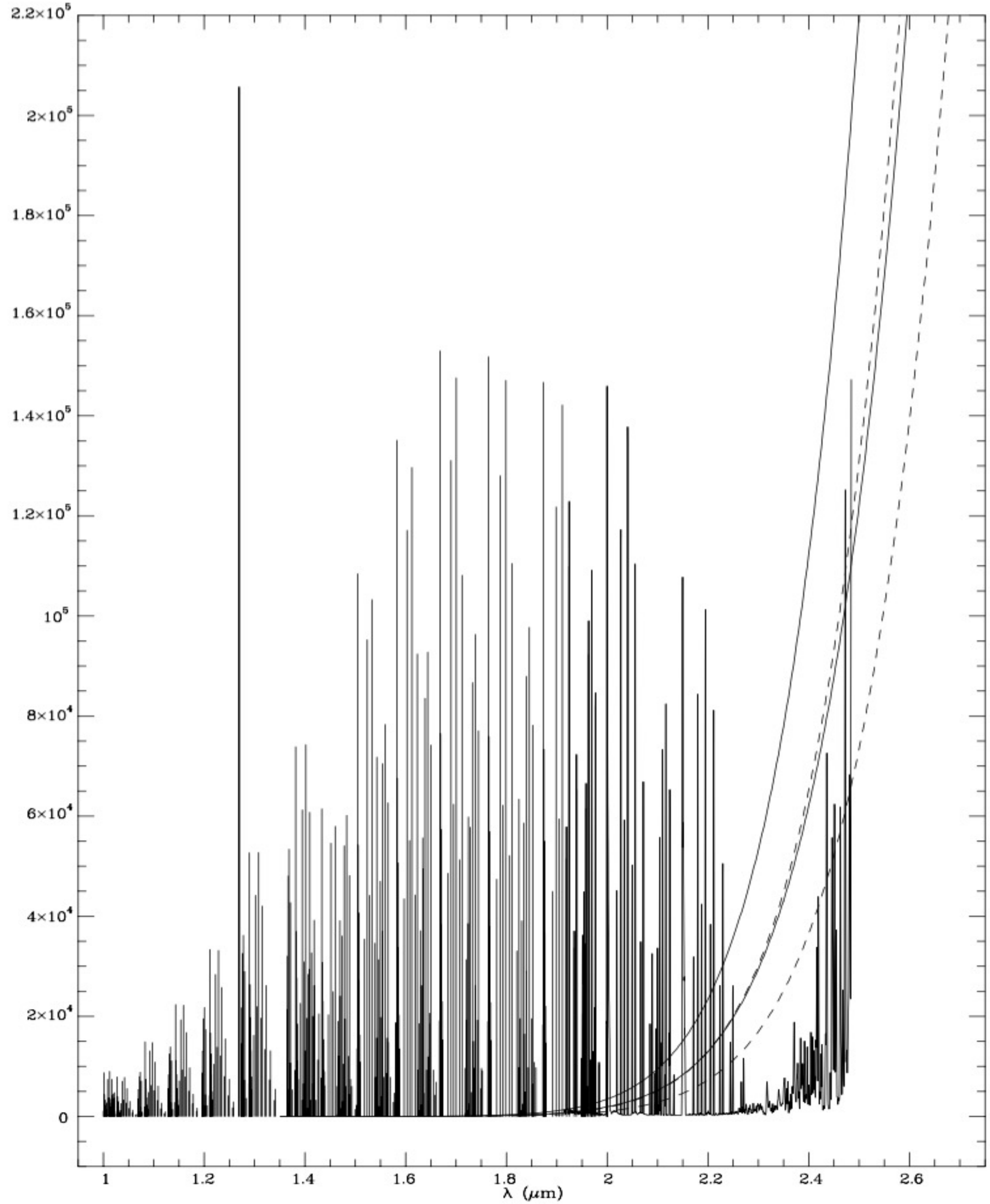
Near Infrared Sky Emission

Airglow lines from OH $+O_2$ emit strongly at far-red and near-IR wavelengths.

They are temporally and spatially variable and reduce sensitivity markedly.

Sites away from the geomagnetic poles are preferred

Model sky spectrum including airglow lines, thermal emission from the atmosphere with thermal emission from the telescope indicated by the continuous and dashed lines in summer and winter for high and low emissivities



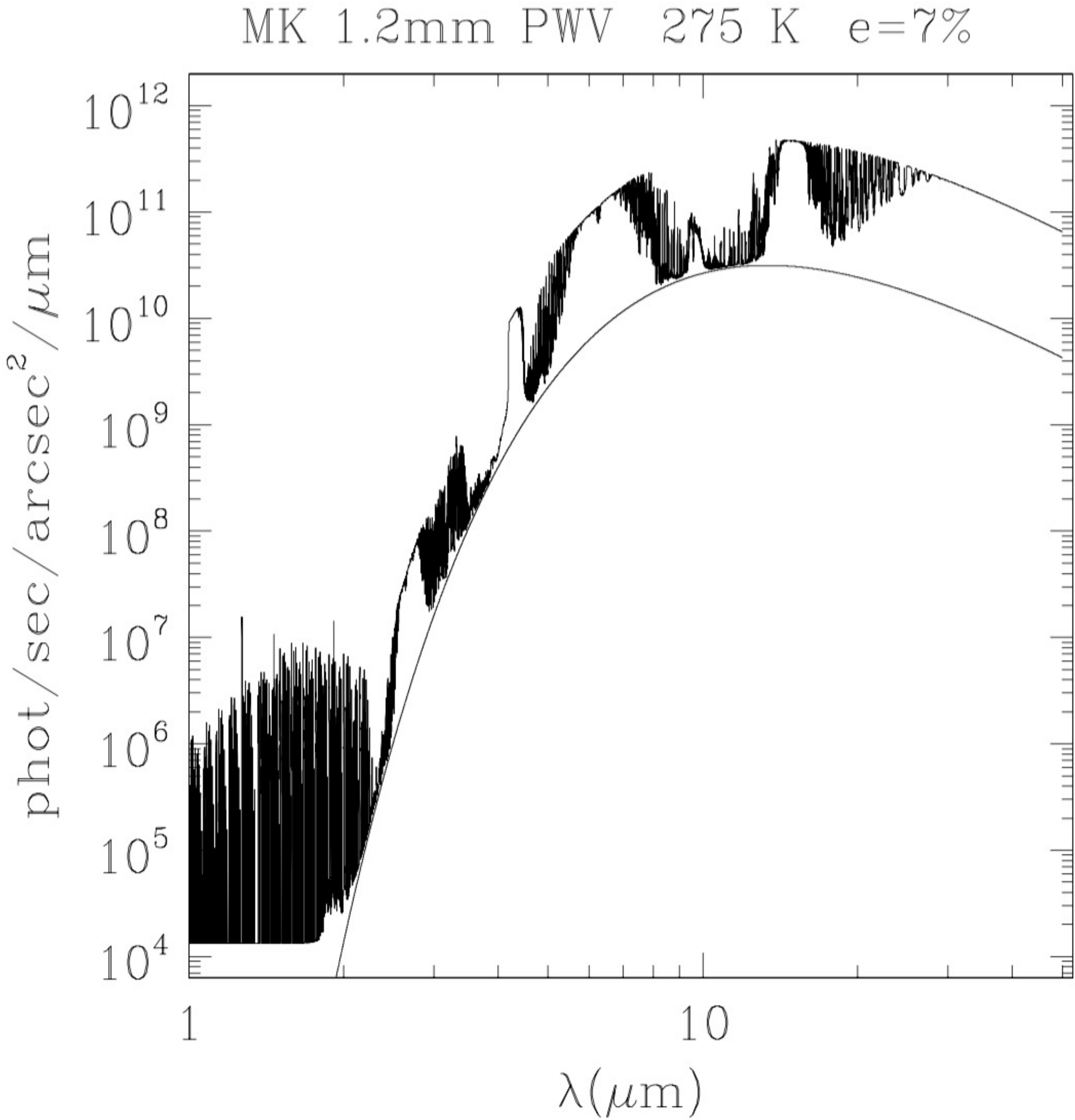
Mid- Infrared Emission

At mid-infrared wavelengths, the thermal emission from the sky and dominates

It peaks at ~12μm and leads to an enormous photon flux

Careful control of telescope emissivity and cold, dry sites are preferred.

In this model a telescope and sky temperature of 275K (winter on MK) is used with a system emissivity of 7%

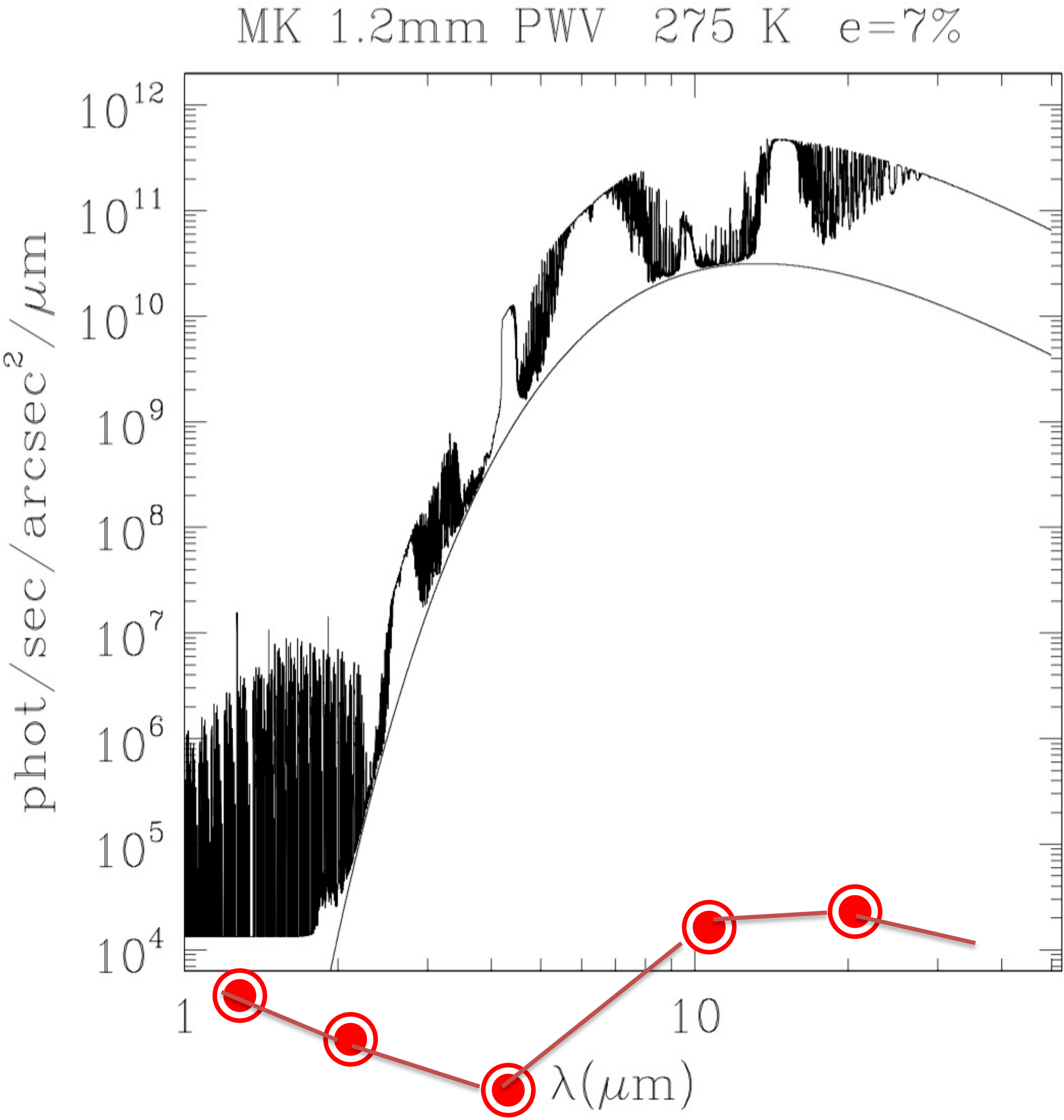


Mid- Infrared in Space

JWST will be a cool telescope at L2, due for launch in 2018

It is optimised for IR observations, taking advantage of the low sky background, and should be limited by zodiacal light from the solar system at λ <10μm

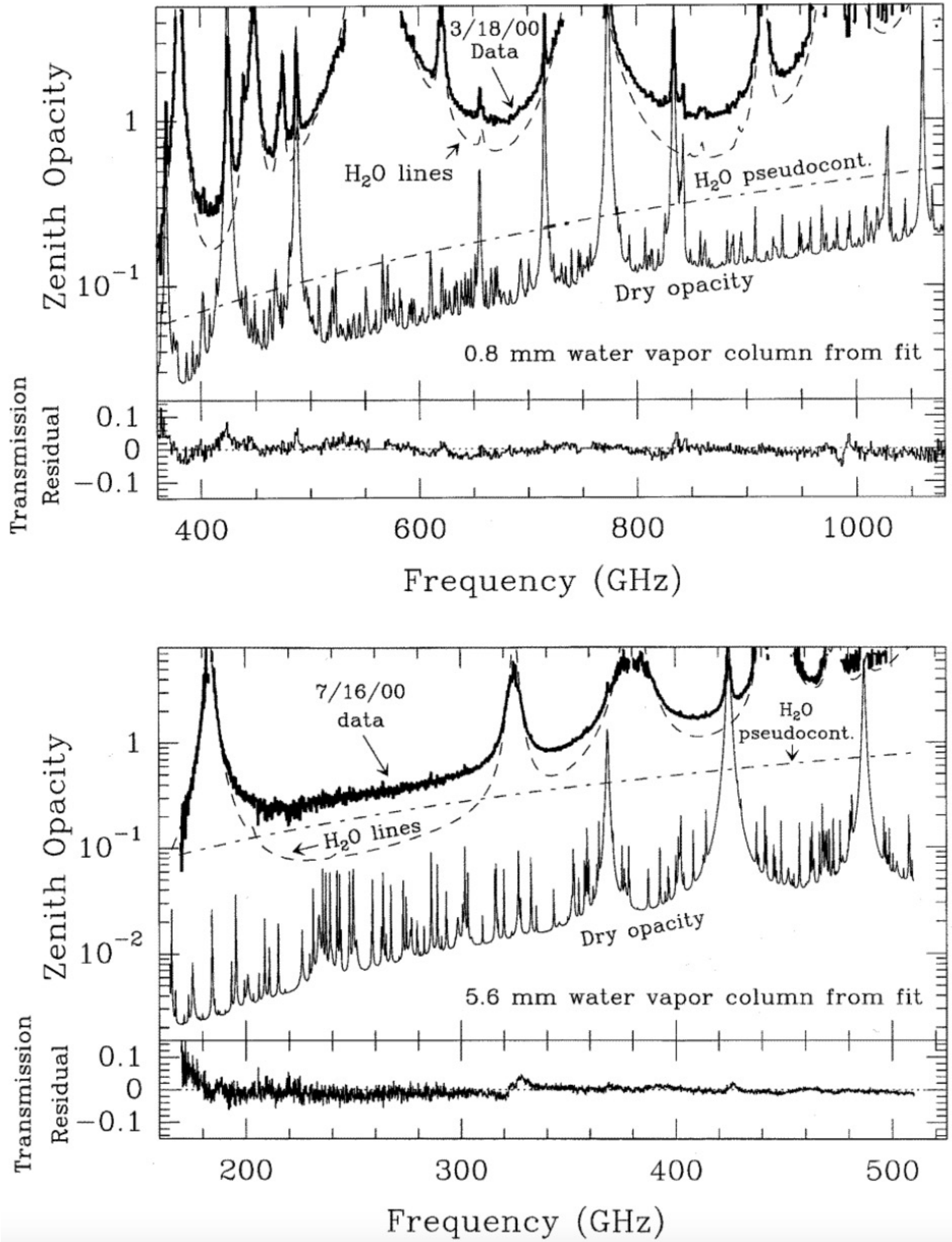
The photon background from the ZL at L2 is indicated by ◉



Sub-mm Sky Emission at MK

- FTS zenith atmospheric opacity spectra obtained on Mauna Kea in March and July 2000 and best fit opacity contributions
- The fitting routine that produced these results is based on the radiative transfer code and uses only the precipitable water vapor column as a free parameter

(J R Pardo et al 2001)



Artificial Backgrounds

- City Lights,
- Dust
- Radio Frequency Interference
  - Broadcasts, mobile phones, microwaves, other equipment on site
- Satellites – reflected sunlight & comms
- Aircraft con trails etc
- Laser light from LGS
- + cosmic rays

- Plus Volcanic aerosols, Saharan dust etc

Optical/NIR Sky brightness values

Filter	Continuum brightness [γ/s/μm/m²/arcsec²]	[mag/arcsec²]
U	190	21.5
B	150	22.4
V	210	21.7
Rc	340	20.8
Ic	500	19.9
J	1200	18.0
H	2300	16.5
K	2300	15.7

Sky Brightness (mag/arcsec2)					
lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

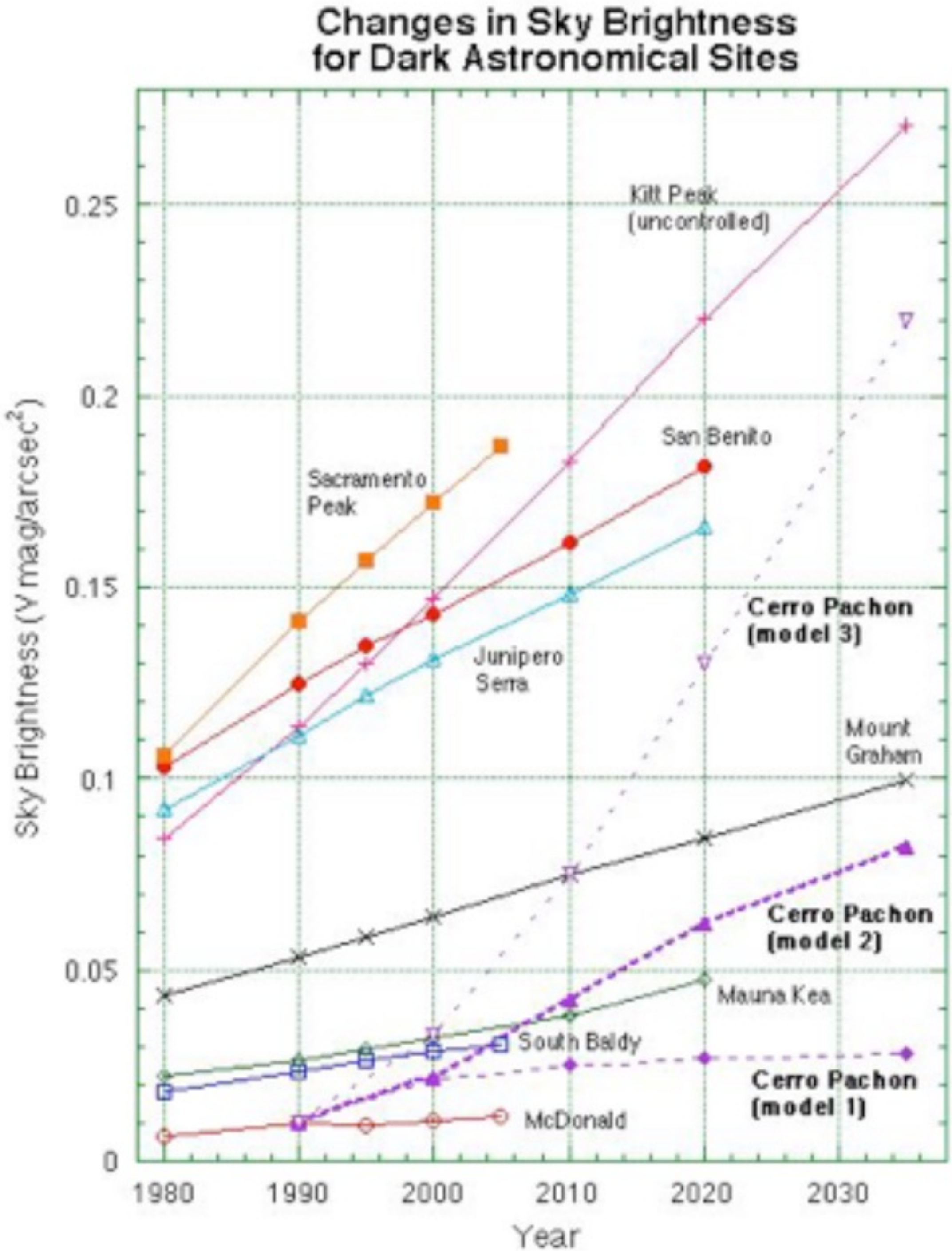
Paranal Sky Brightness at 3 days and variation with lunar phase

Dark Sky Protection

Threats from increasing populations, urban sprawl and
Industrial developments

Education and Implementation and enforcement of Lighting Ordinances

- Installation of light shields
- Low pressure sodium lighting



Atmospheric Extinction under good conditions (Mauna Kea CFHT)

wavelength (nm)	mag/airmass
300	4.90
310	1.37
320	0.82
330	0.57
340	0.51
350	0.42
360	0.37
370	0.33
380	0.30
390	0.27
400	0.25

wavelength	mag/airmass
425	0.21
450	0.17
475	0.14
500	0.13
525	0.12
550	0.12
575	0.12
600	0.11
650	0.11
700	0.10
800	0.07
900	0.05

IR Atmospheric Extinction under good conditions (Mauna Kea UKIRT)

Wavel/Filter	mean (mag/air mass)		median (mag/air mass)
(0.36) U	0.358		0.358
(0.44) B	0.198	+/- 0.008	0.194
(0.55) V	0.119	0.005	0.111
(1.25) J	0.114	0.007	0.102
(1.65) H	0.068	0.006	0.059
(2.2) K	0.096	0.005	0.088
(3.4) L	0.203	0.030	0.150
(3.8) L'	0.112	0.009	0.093
(4.8) M	0.244	0.016	0.220
(10) N	0.184	0.017	0.151
(20) Q	0.503	0.030	0.451
(32) Z	1.398	0.313	1.14

Extinction Variations

- Mean or median extinction values are a useful guide, but the values to be used on a given night generally have to be calculated for the night.
- Thin cloud, dust etc can have a marked effect even on a usable night.

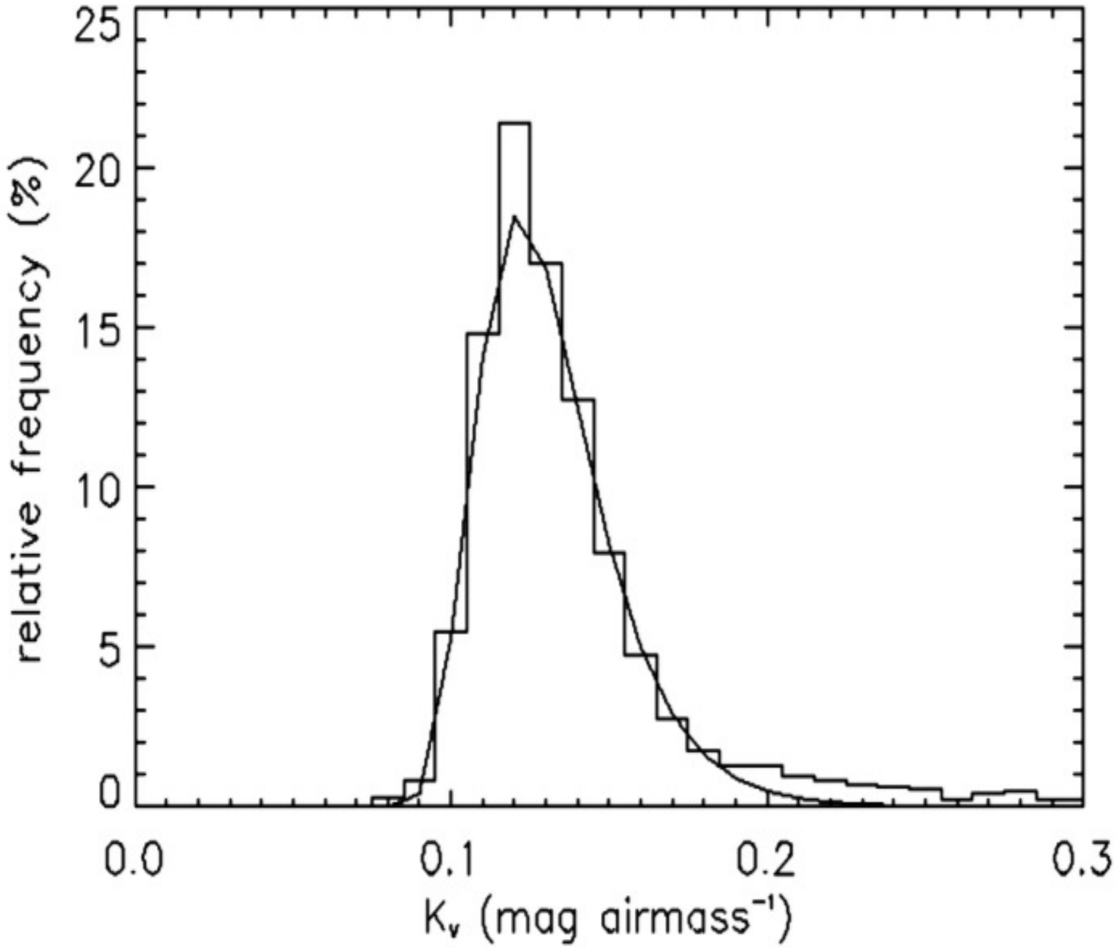


FIG. 7.—Histogram of the relative frequency of k_V for nonsummer nights

V Band opacity for LaPalma over 20yr (A Garcia-Gil 2010)