Lecture locations

The revised plan is as follows (always 10 to 11 am)

24th April – Seminar Room
26th April – Fisher Room
29th April – Seminar Room
1st May – Fisher Room
3rd May – Fisher Room
6th May – no lecture, bank holiday
8th May – Fisher Room
10th May – Fisher Room

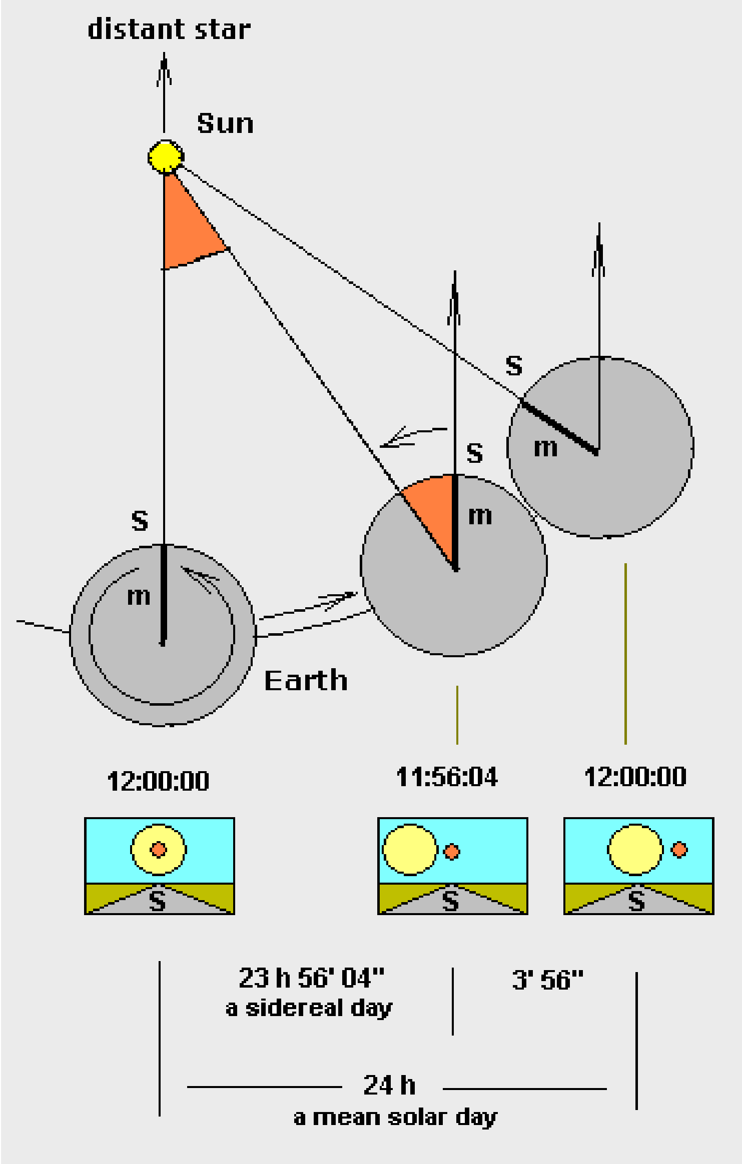
Coordinates

- Star and galaxy catalogues normally employ Equatorial coordinates with a rest frame tied to quasars.
- Recent data use ICRS equatorial J2000 (Epoch 2000), though older catalogues may be w.r.t to epoch 1950 (B1950). But note that the HD catalogue has epoch 1900!
  - J2000 Epoch 1 Jan 2000 at 12:00 UT = JD2455200.5
  - May need to take precession (and perhaps proper motion) into account for any other epoch.

- Expressed in Right Ascension (α in HMS) and Declination (δ in DMS) where RA is in the plane of the Earth's equator and Declination (latitude) is normal to it, reaching +/-90deg at the equatorial poles.
- Note that the RA coordinate may need to be compensated for cosine(δ) if true angles on the celestial sphere are required. 1 hour of RA = 15 degrees at the equator (δ=0)

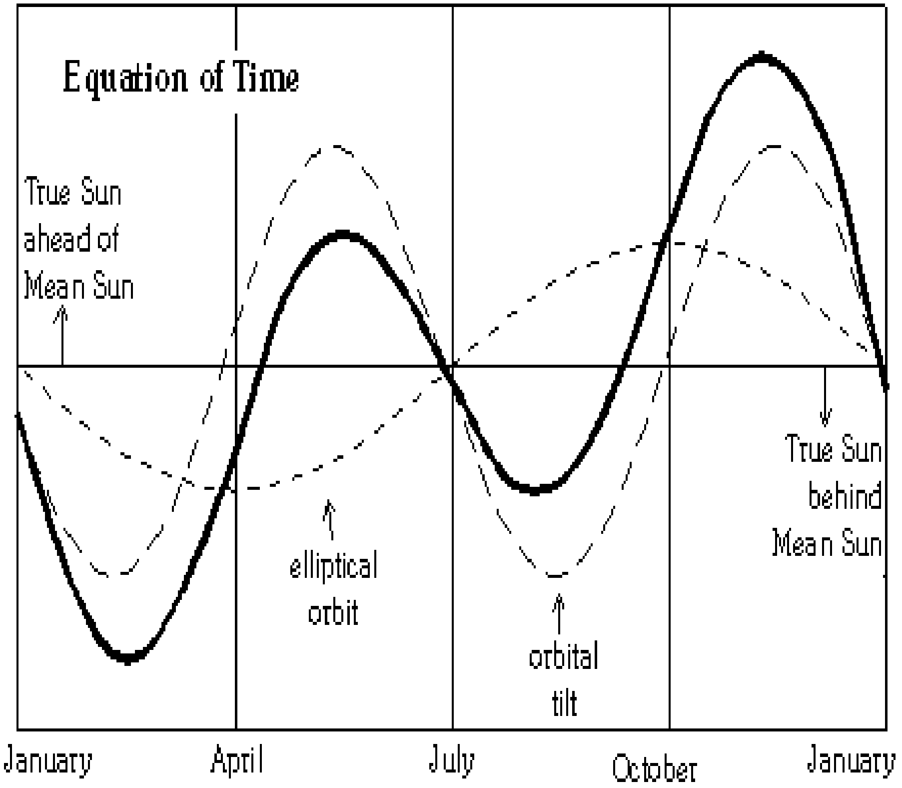
Equatorial Coordinates

- The zero point of the equatorial coordinate system is defined to be the intersection of the ecliptic and equatorial planes. (earth's orbital and rotational planes). This is not a fixed point, but changes because of precession and nutation. The annual vernal equinox precession is westward and northwards by :
  - $3.073 + 1.336 \sin\alpha \tan\delta$ seconds of time
  - $20.043 \cos\alpha$ arcsec
- Civil Time (e.g UTC) is based on the Earth's mean rotation around the sun, (the sun is at maximum elevation at mid-day) but it is more convenient in astronomy to use Sidereal Time, based on the Earth's rotation with respect to the fixed pattern of the stars.
- The solar day is ~4 min longer than the sidereal day.
- Local Sidereal Time is used for astronomical observatories and equals the Hour Angle of the vernal equinox, where HA = ST-α
- A star is on the meridian when the ST equals the star's RA



Time Systems

- Universal Time
  - mean solar time
  - ignore variations over the year
- Sidereal time
  - reference to the 'fixed pattern of the stars'
  - runs 1 day/year (~4min/day) faster than solar time
  - http://www.jgiesen.de/astro/astroJS/siderealClock/
- Julian Date
  - counted from Jan 1 4713BC
  - Changes at mid-day
  - Modified JD -2400000.5



The Observer's location, celestial coordinates (α, δ) and the sidereal time of observation give:
Hour Angle of observation Mm, where H.A. = (ST-α)
And the latitude of the observer, ϕ, is the arc ZM

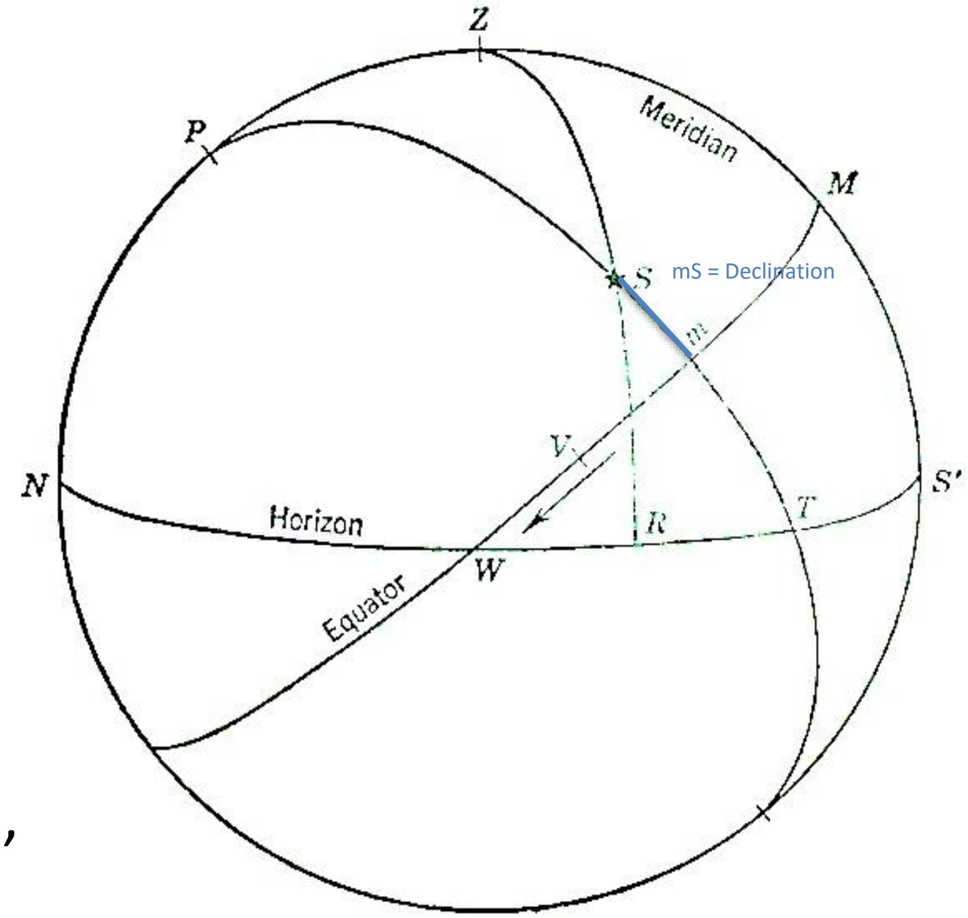


FIG. 20. The Sphere Seen from the Outside

The altitude, is given by :

$$\sin(h) = \cos(\phi-\delta) - 2\cos\phi \cos\delta \sin^2(HA/2)$$

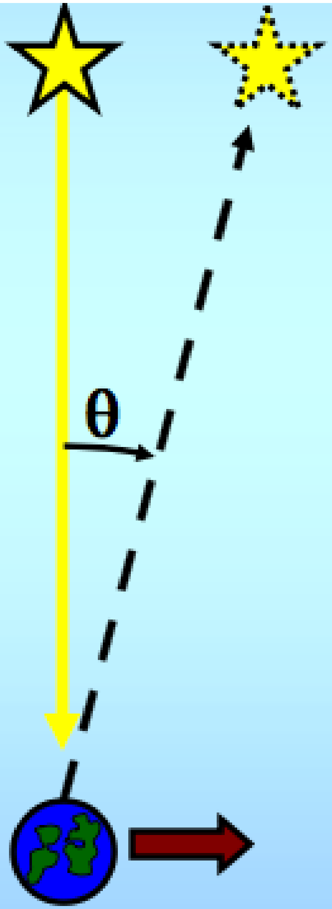
And the Zenith Distance, ZS = (90 – h) deg

Equatorial Coordinates

- Local Siderial Time calculator : http://www.jgiesen.de/astro/astroJS/siderealClock/
- Star catalogues may use barycentric equatorial (J2000)
  - Helio-centric equatorial coordinates may be used for planetary bodies
  - Apparent equatorial coordinates are referred to the location of the observer.
  - For distant objects, the differences become small, but for nearby, and particularly solar system objects they become very large due to parallax.
- Note that RA becomes undefined at the celestial pole

Other Effects

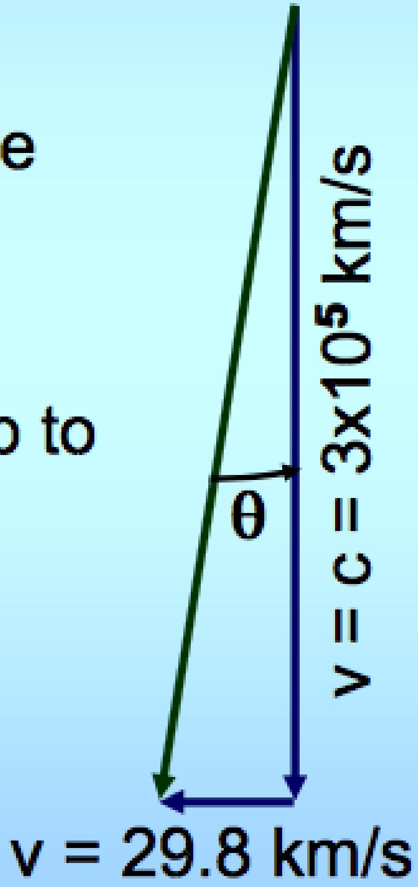
Stellar aberration – discovered by Bradley in 1727 when searching for stellar parallax



1. Light has a finite velocity
2. The Earth moves relative to the star
3. The combination of velocities “moves” the star position by up to 20”.49.

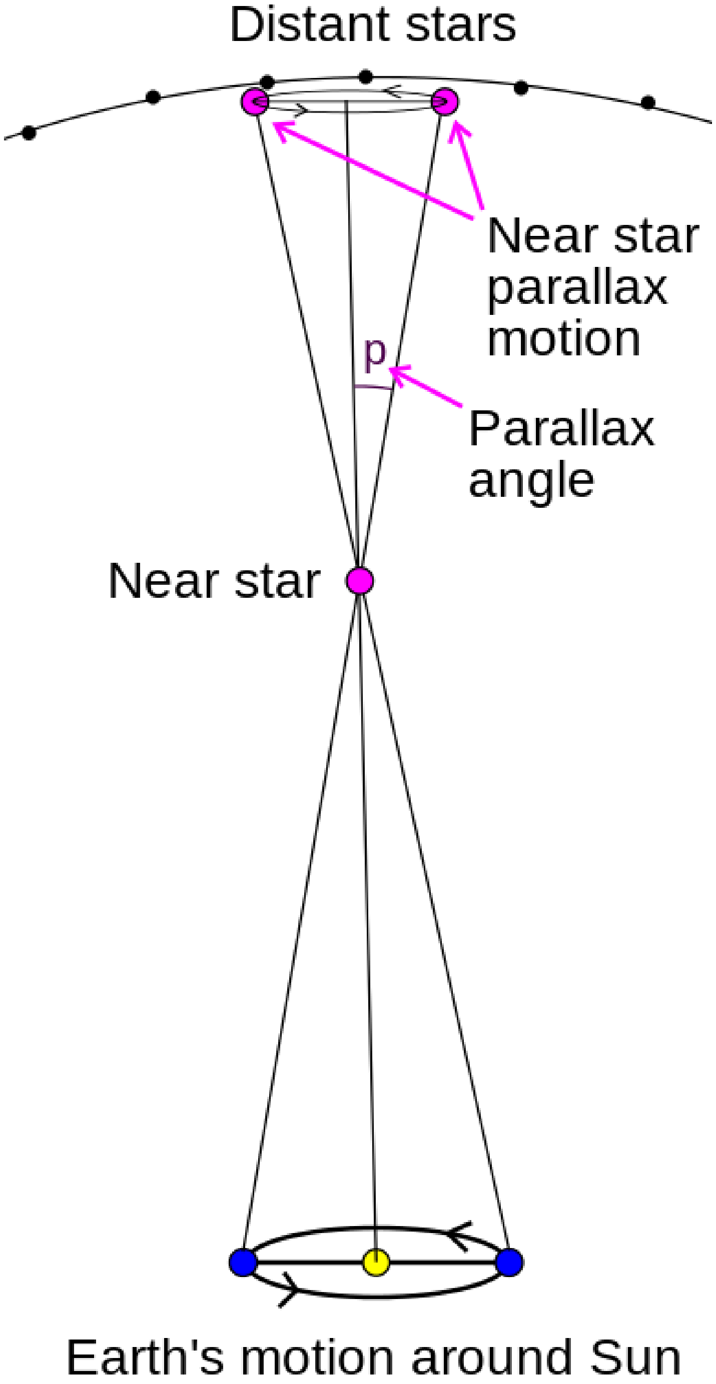
$$\tan\theta = \frac{29.8}{3\times10^{5}}$$

$$\Rightarrow \theta = 20''.49$$



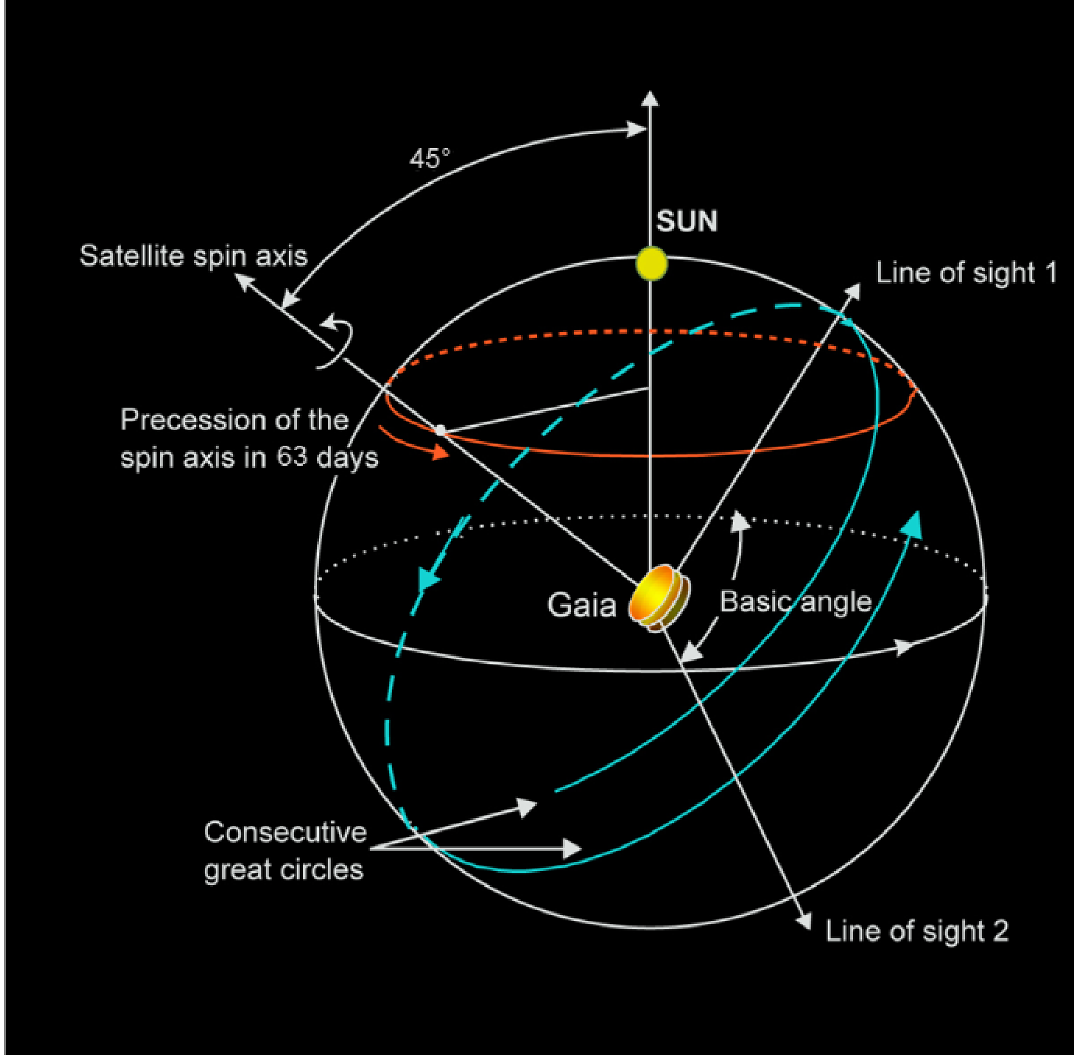
Parallax

- As the Earth orbits the sun, the angle at which stars are observed alters relative to the barycentre
- For nearby (solar system) objects, the effects of parallax are large and need to be taken into account
- The nearest star, Proxima Cen has a parallax of 0.76”   (d=1.3pc), and for most objects, the effect is small.
- But this is the basis of the Hipparcos and Gaia astrometric satellites which have and are providing accurate distances to large numbers of stars

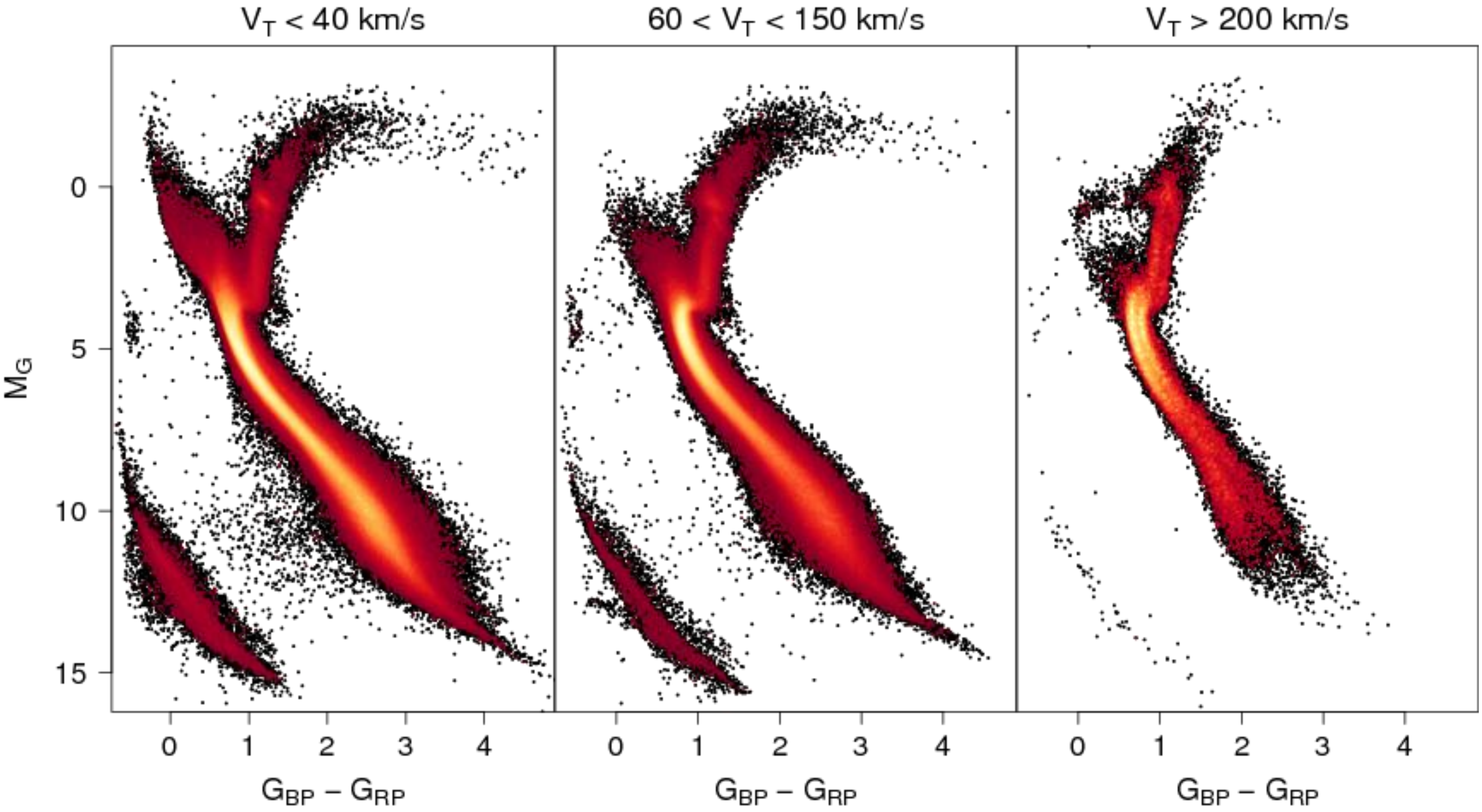


Gaia operations

- Gaia in routine operations since July 2014
- Scanning operations with observing strategy of continuous measuring
  - Dead-time: orbit maintenance, micrometeoroids, decontaminations, ground station weather
- Nominal 5-year mission ends mid-2019
- Estimated end of mission due to cold gas exhaustion in 2025



3rd data release occurred in June 2022 with 1.8 billion stars
Precisions will increase as more data are collected, but on-track to reach parallax measurements ranging from <10 μ-arcsec at V= 6 mag to 500 μ-arcsec at V~20, together with photometric accuracies of 4m-mag on bright (V<15) stars
Latest release includes 800,000 binary star system orbits and 33,000,000 radial velocities



Gaia H-R Diagrams for thin disk (low v_T), thick disk (mid v_T) and Halo populations

Gaia is on track to deliver the mission goals, revolutionising distance estimates and Galactic structure – as well as abundance estimates, Galactic archaeology etc…
https://www.gaia.ac.uk/data/gaia-data-release-3

Ecliptic Coordinates

- Instead of using the earth's rotation as the plane of longitude, ecliptic co-ordinates use the plane of the Earth's orbit around the sun, which is inclined by 23.5deg

Ecliptic coordinates are normally only used for solar system objects and can be obtained by spherical trigonometry transforms from α, δ to λ, β

JPL Horizons has ephemeris:
RA, Dec, Proper motion, Surf. Brightness, etc.
https://ssd.jpl.nasa.gov/horizons/app.html#/

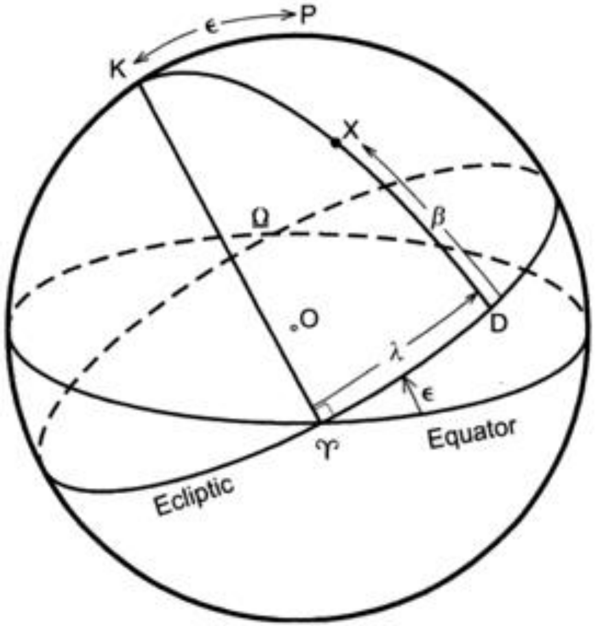
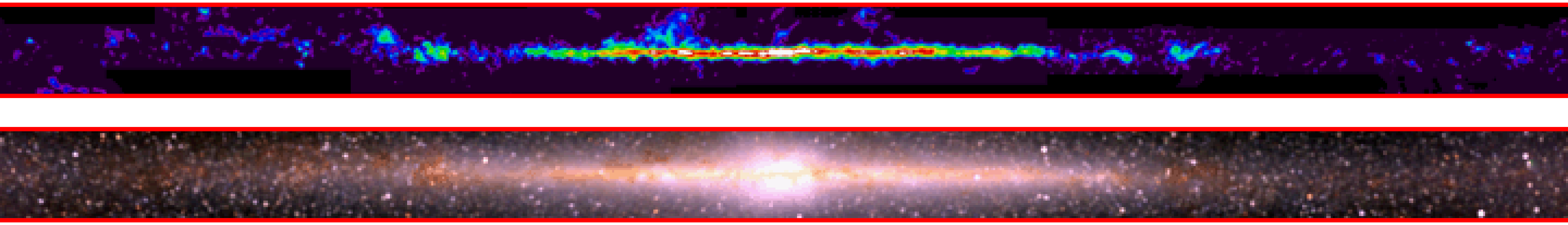


Figure 2.5

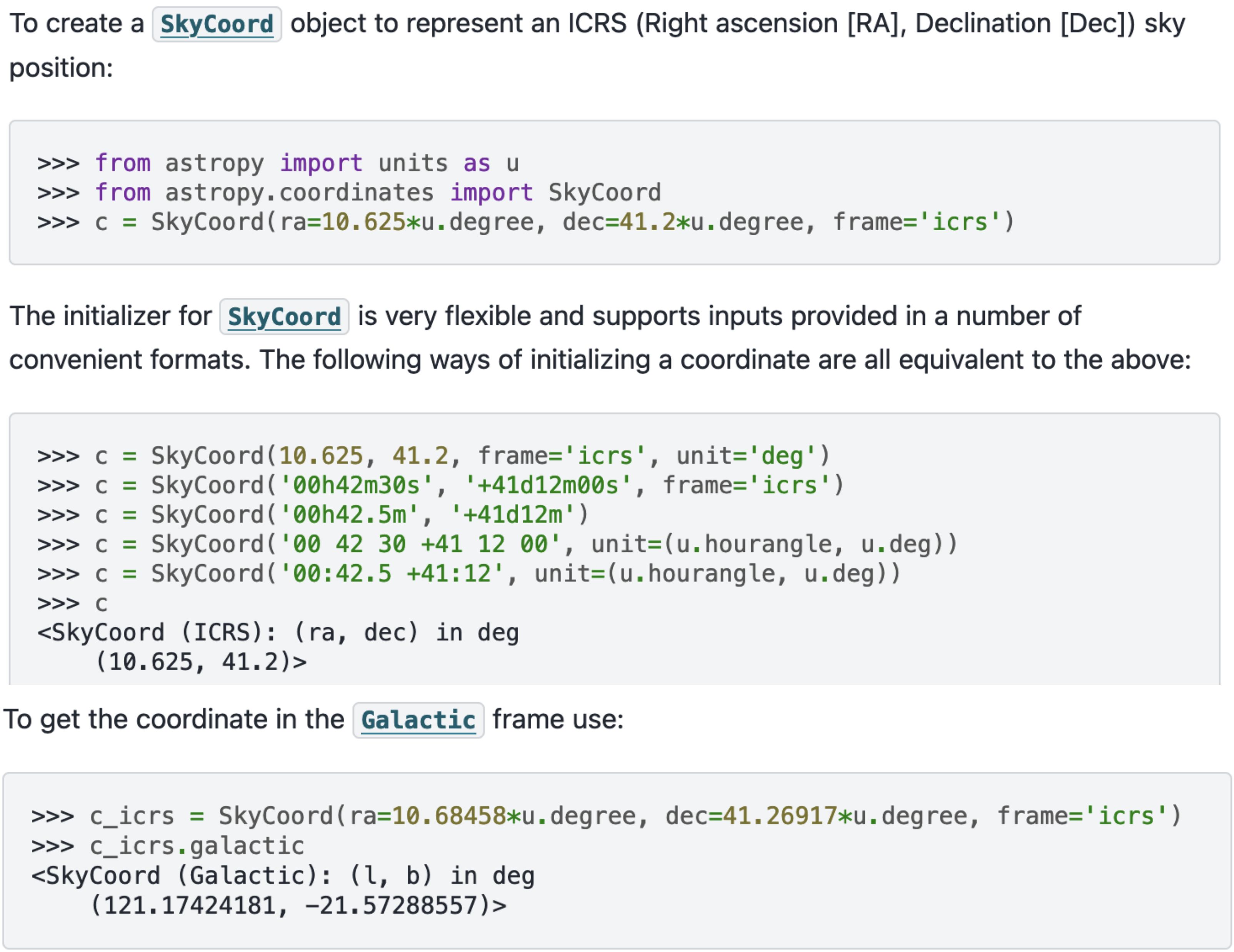
Galactic Coordinates

- Studies in the Milky Way may benefit from using Galactic coordinates, where longitude is measured along the Galactic plane with the origin at the Galactic Centre, and latitude normal to it. The north Galactic Pole is at α= 12h 51.4, δ= +27^{o} 07. The coordinates use *l, b for longitude and latitude* and may be in J2000, B1950 etc.



- There are many routines available to convert between Coordinate systems
  - e.g. coco in the Starlink collection -Converts between equatorial, ecliptic, Galactic with choice of epochs
  - Or a more user friendly site: http://ned.ipac.caltech.edu/forms/calculator.html

astropy.coordinates



To create a `SkyCoord` object to represent an ICRS (Right ascension [RA], Declination [Dec]) sky position:

```
>>> from astropy import units as u
>>> from astropy.coordinates import SkyCoord
>>> c = SkyCoord(ra=10.625*u.degree, dec=41.2*u.degree, frame='icrs')
```

The initializer for `SkyCoord` is very flexible and supports inputs provided in a number of convenient formats. The following ways of initializing a coordinate are all equivalent to the above:

```
>>> c = SkyCoord(10.625, 41.2, frame='icrs', unit='deg')
>>> c = SkyCoord('00h42m30s', '+41d12m00s', frame='icrs')
>>> c = SkyCoord('00h42.5m', '+41d12m')
>>> c = SkyCoord('00 42 30 +41 12 00', unit=(u.hourangle, u.deg))
>>> c = SkyCoord('00:42.5 +41:12', unit=(u.hourangle, u.deg))
>>> c
<SkyCoord (ICRS): (ra, dec) in deg
    (10.625, 41.2)>
```

To get the coordinate in the `Galactic` frame use:

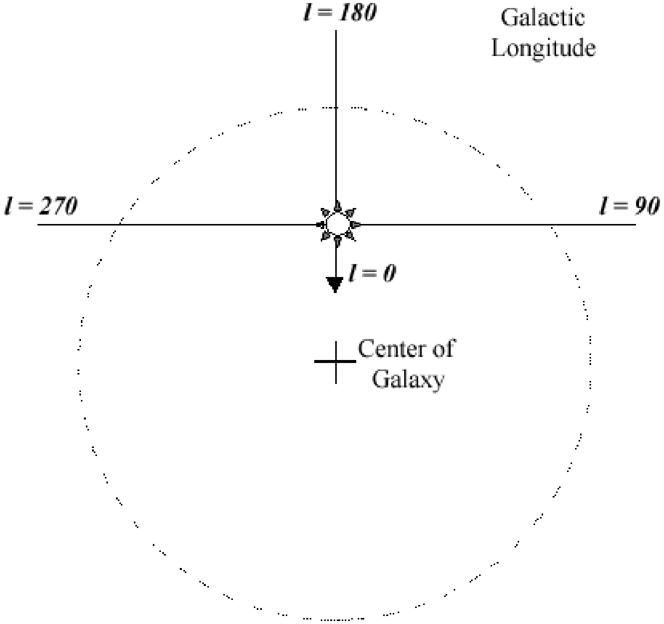
```
>>> c_icrs = SkyCoord(ra=10.68458*u.degree, dec=41.26917*u.degree, frame='icrs')
>>> c_icrs.galactic
<SkyCoord (Galactic): (l, b) in deg
    (121.17424181, -21.57288557)>
```

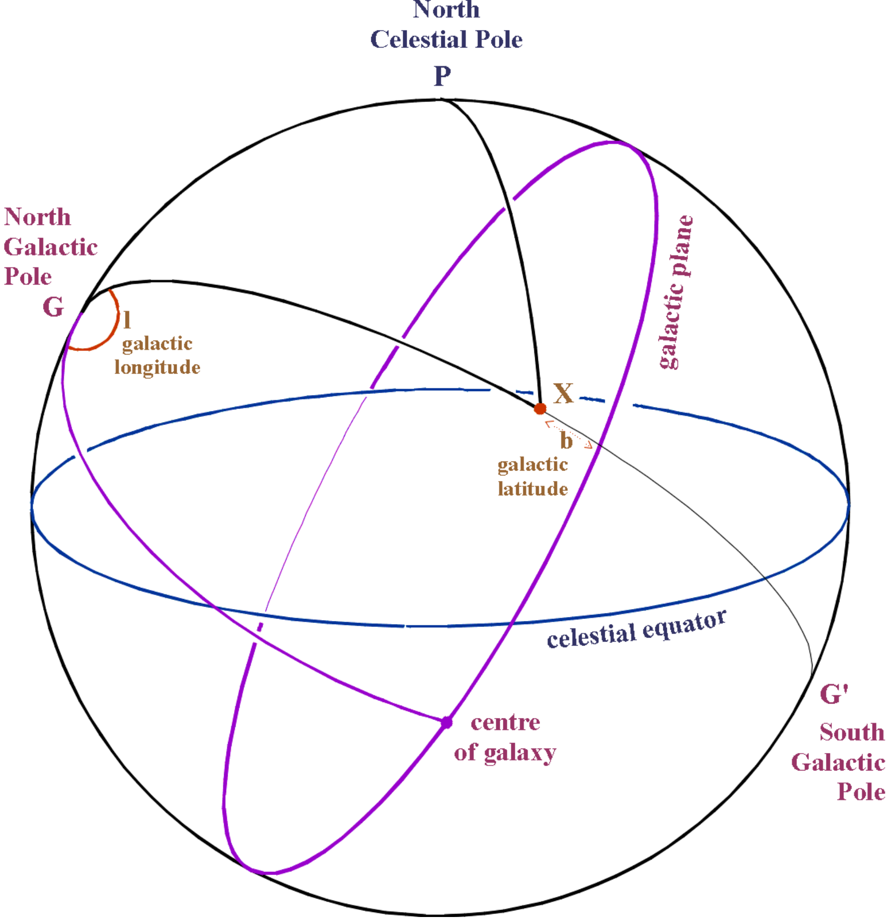
COCO

```
% coco
 *  Celestial Coordinate Conversions
 <- ?
    Input format:
        RA      Dec        PM        Px    RV
       h m s  d ' "  [s/y  "/y    ["  [km/s]]]
 <-   I 5
    Conversion is from:
       FK5, equinox J2000.0, epoch J2000.00 (barycentric)
 <- O G 2000
    Conversion is to:   Galactic, epoch J2000.00 (barycentric)

 <- 17 45 40.036 -29 00 28.17

  = 17 45 40.036 -29 00 28.17  J2000.00  J2000.00  FK5  0.000    0.0
 -> 359.94423   -0.04616  J2000.00  galactic (II)
```

A good reference for postional astronomy & coordinates is http://star-www.rl.ac.uk/docs/sun67.htx/sun67se4.html

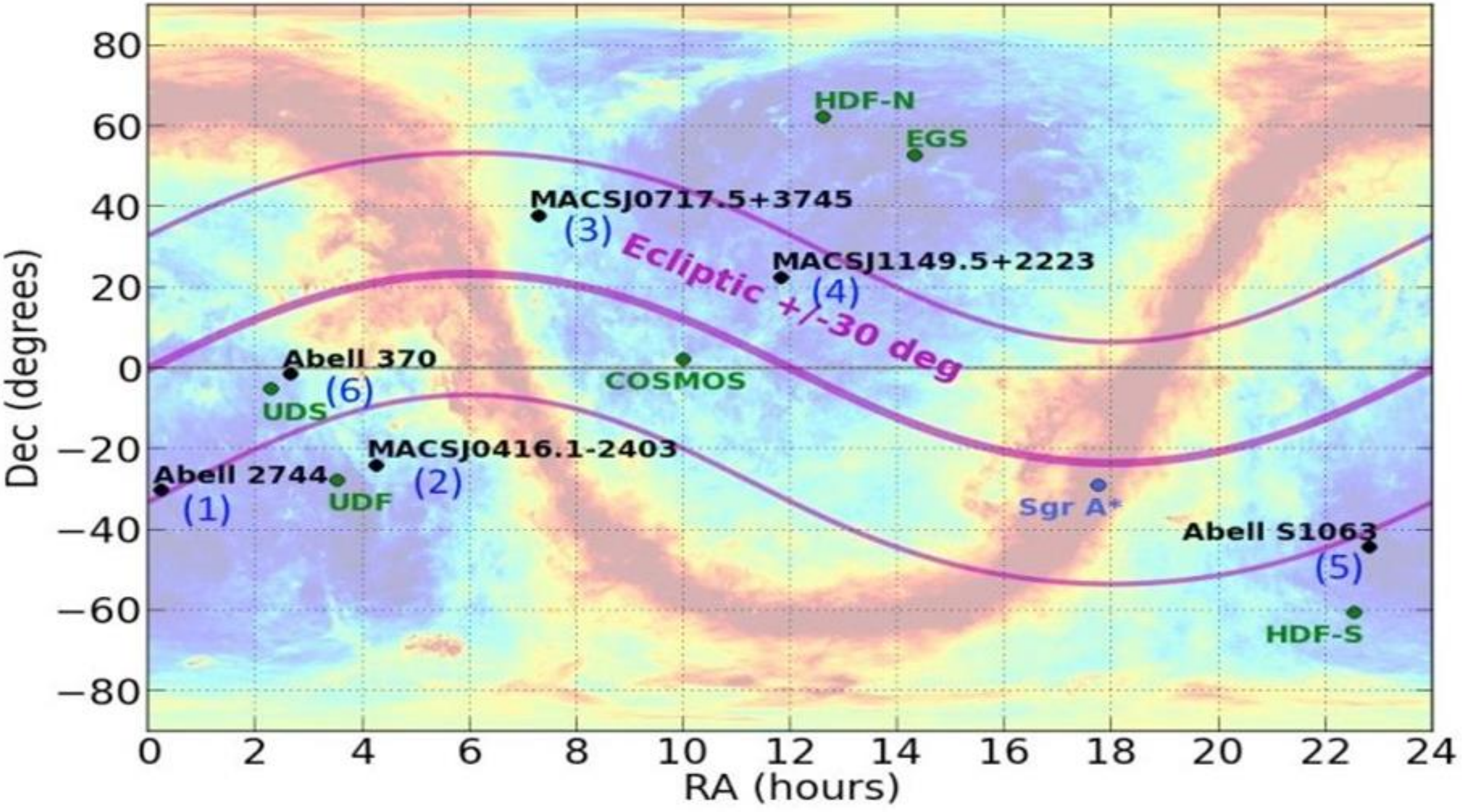
Galactic Coordinates



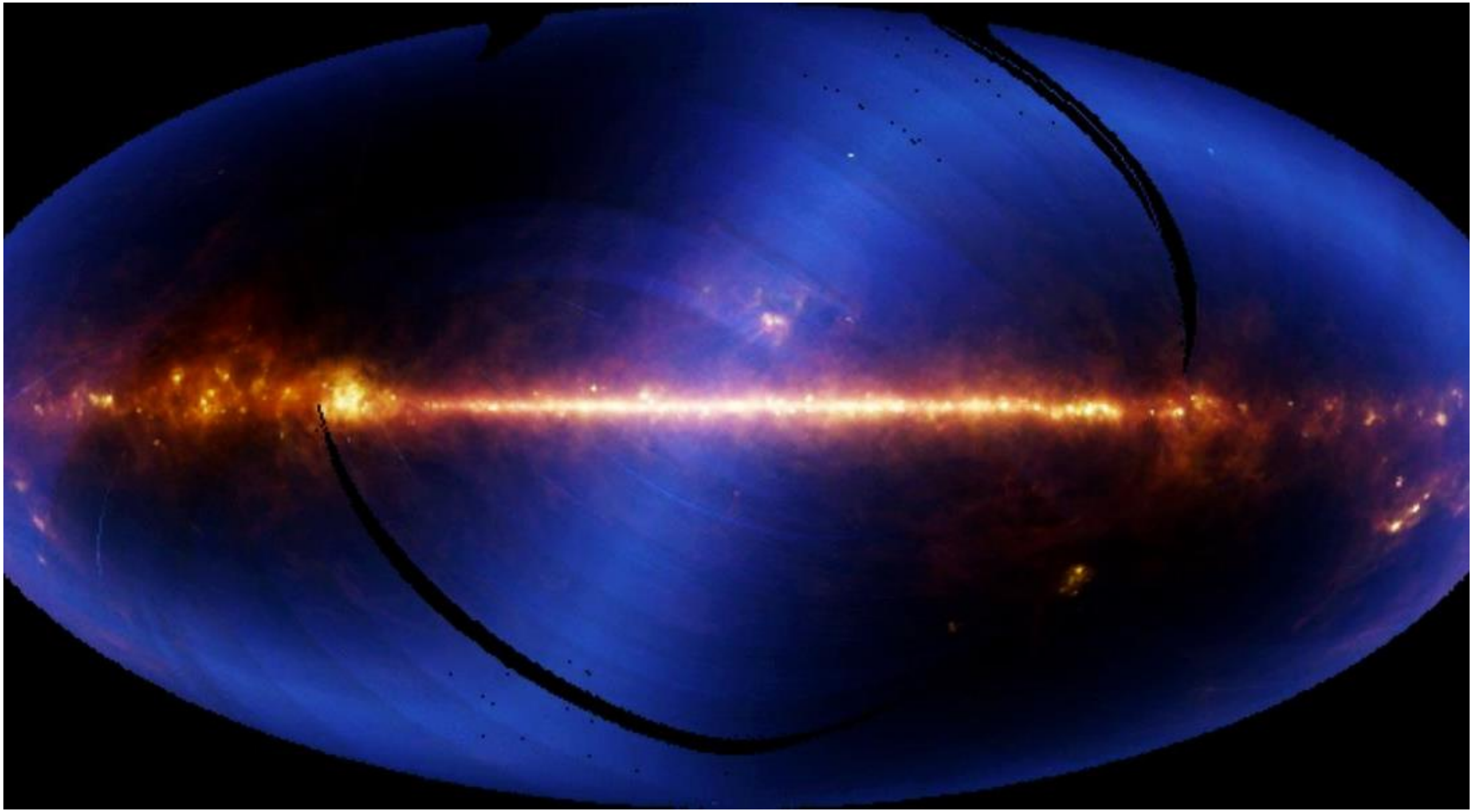


- Galactic coordinates (l^{II},b^{II}) with latitude $b^{II} = 0$ in the galactic plane, and l^{II}=0 toward the Galactic Center.
- Local Standard of Rest (LSR) moves with circular velocity about GC at Sun’s radius.

Equatorial Coordinates

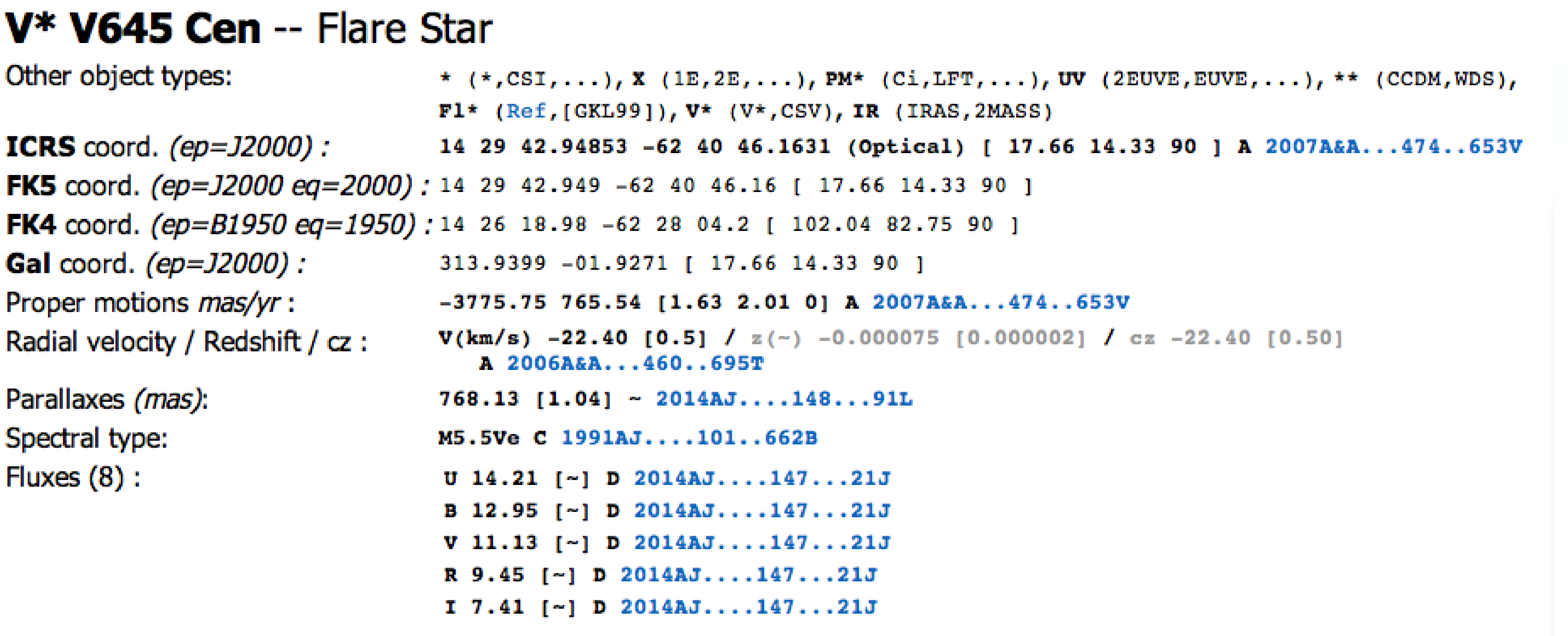


IRAS Survey



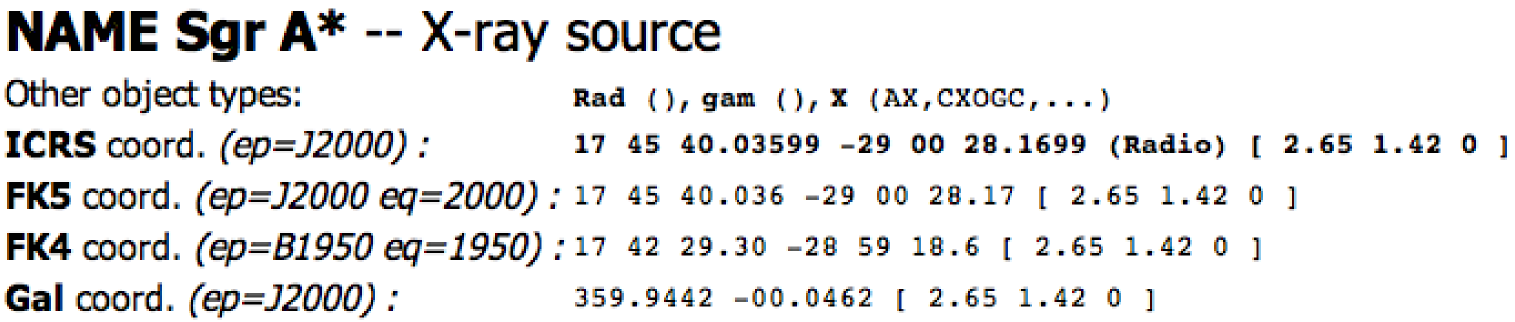
The Galactic Plane is the bright horizontal band, with Orion towards the right edge. The North and South celestial poles appear dark, as there is less dust emission while the faint blue haze represents warm dust emission from zodiacal light, tracing out the plane of the ecliptic

SIMBAD
http://simbad.u-strasbg.fr/simbad/



V* V645 Cen -- Flare Star

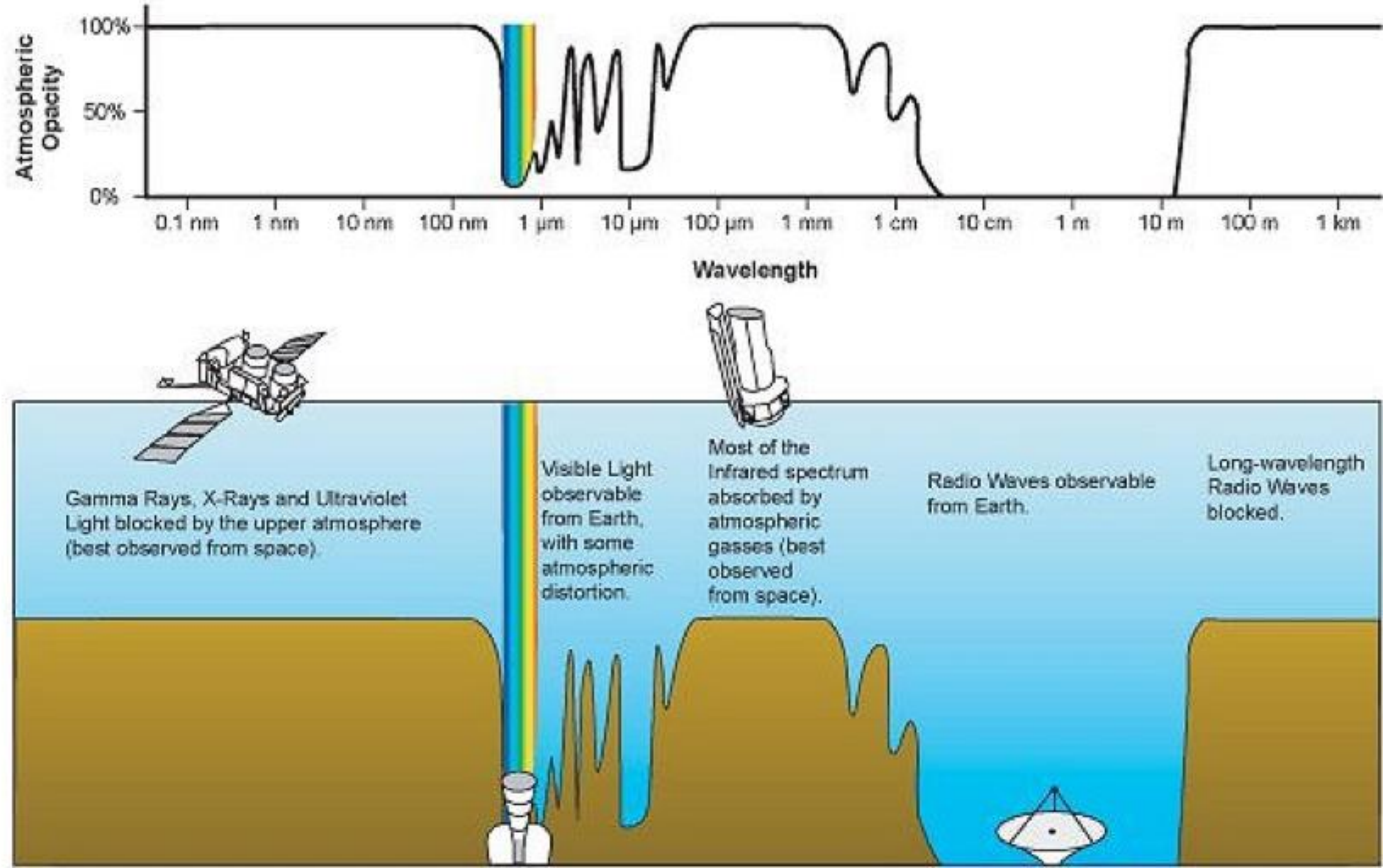
Other object types:	***** (*,CSI,...), **X** (1E,2E,...), **PM*** (Ci,LFT,...), **UV** (2EUVE,EUVE,...), ****** (CCDM,WDS), **Fl*** (Ref,[GKL99]), **V*** (V*,CSV), **IR** (IRAS,2MASS)
ICRS coord. *(ep=J2000) :*	**14 29 42.94853 -62 40 46.1631 (Optical) [17.66 14.33 90] A 2007A&A...474..653V**
FK5 coord. *(ep=J2000 eq=2000) :*	14 29 42.949 -62 40 46.16 [17.66 14.33 90]
FK4 coord. *(ep=B1950 eq=1950) :*	14 26 18.98 -62 28 04.2 [102.04 82.75 90]
Gal coord. *(ep=J2000) :*	313.9399 -01.9271 [17.66 14.33 90]
Proper motions *mas/yr* :	**-3775.75 765.54 [1.63 2.01 0] A 2007A&A...474..653V**
Radial velocity / Redshift / cz :	**V(km/s) -22.40 [0.5]** / z(~) -0.000075 [0.000002] / cz -22.40 [0.50] **A 2006A&A...460..695T**
Parallaxes *(mas)*:	**768.13 [1.04] ~ 2014AJ....148...91L**
Spectral type:	**M5.5Ve C 1991AJ....101..662B**
Fluxes (8) :	**U 14.21 [~] D 2014AJ....147...21J** **B 12.95 [~] D 2014AJ....147...21J** **V 11.13 [~] D 2014AJ....147...21J** **R 9.45 [~] D 2014AJ....147...21J** **I 7.41 [~] D 2014AJ....147...21J**



NAME Sgr A* -- X-ray source

Other object types:	**Rad** (), **gam** (), **X** (AX,CXOGC,...)
ICRS coord. *(ep=J2000) :*	**17 45 40.03599 -29 00 28.1699 (Radio) [2.65 1.42 0]**
FK5 coord. *(ep=J2000 eq=2000) :*	17 45 40.036 -29 00 28.17 [2.65 1.42 0]
FK4 coord. *(ep=B1950 eq=1950) :*	17 42 29.30 -28 59 18.6 [2.65 1.42 0]
Gal coord. *(ep=J2000) :*	359.9442 -00.0462 [2.65 1.42 0]

The Earth’s Atmosphere



Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).

Visible Light observable from Earth, with some atmospheric distortion.

Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio Waves observable from Earth.

Long-wavelength Radio Waves blocked.

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

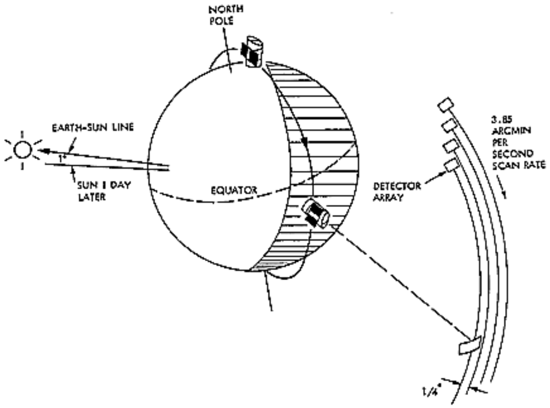
- Other wavebands need to be observed from high in or above the atmosphere

Space

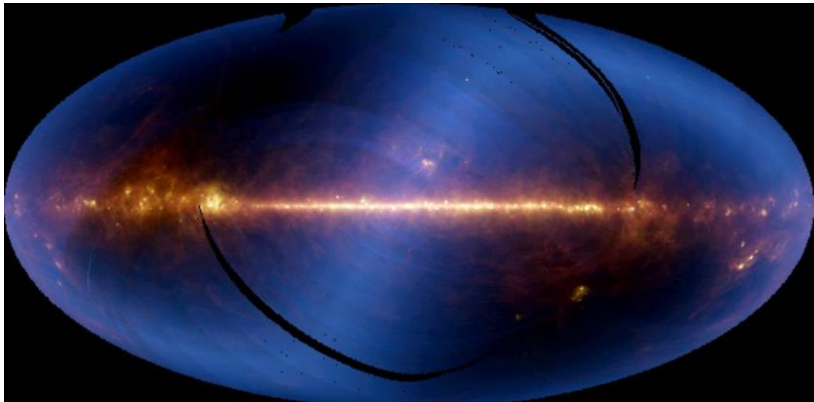
- Eliminate atmospheric absorption, scattering, phase variations & emission
- Access to the full electromagnetic spectrum
- Expensive, risky, size and power limitations
- Used where necessary
  - γ rays, X-rays, UV
  - Far-IR, Low frequency radio
  - High stability, extended monitoring,
  - Low background,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

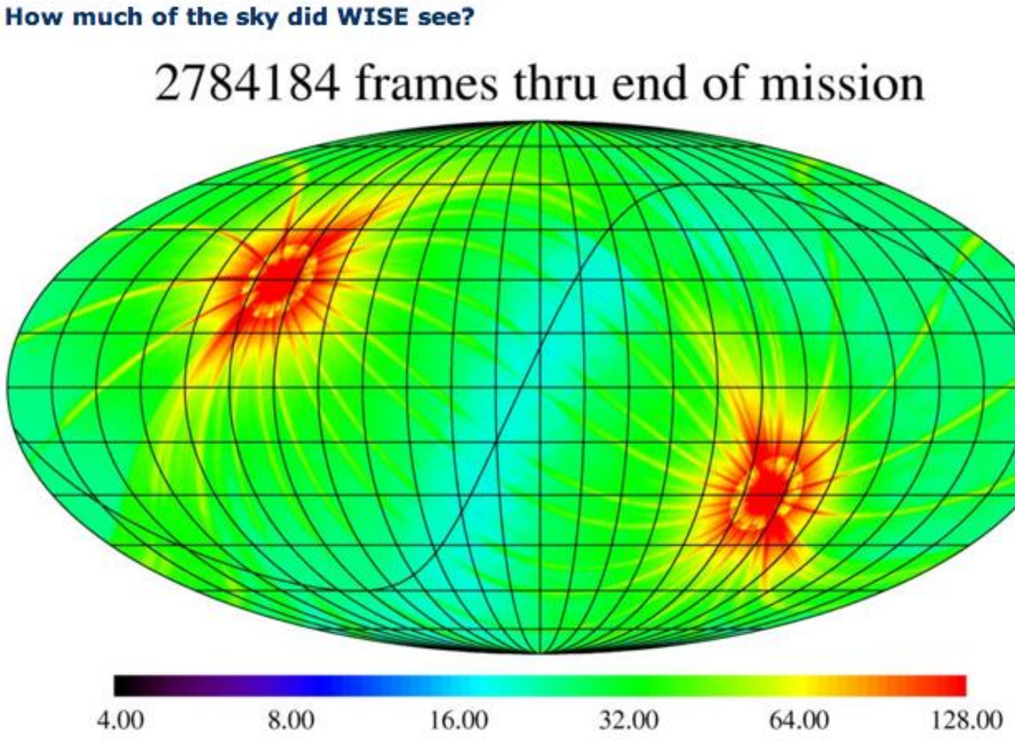
Orbital Constraints

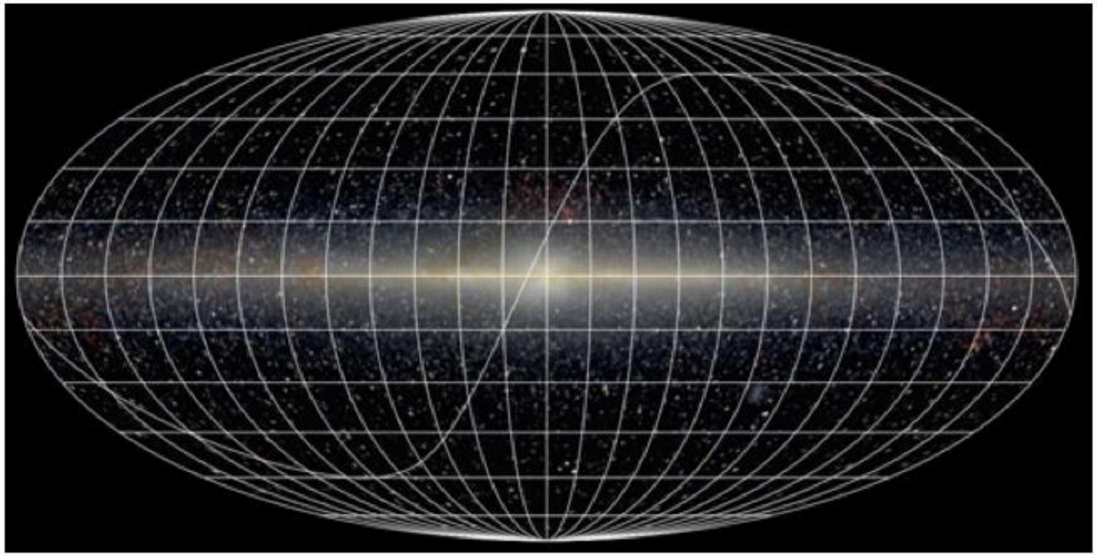
- Sun, Moon, Earth avoidance, especially heat load for cryogenic instruments
- Low-Earth orbit (e.g. HST) 90 min orbit with pointing constraints
- Survey satellites typically map out strips of the sky, building up to complete the survey
  - Some areas may have many passes (e.g. polar caps)



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





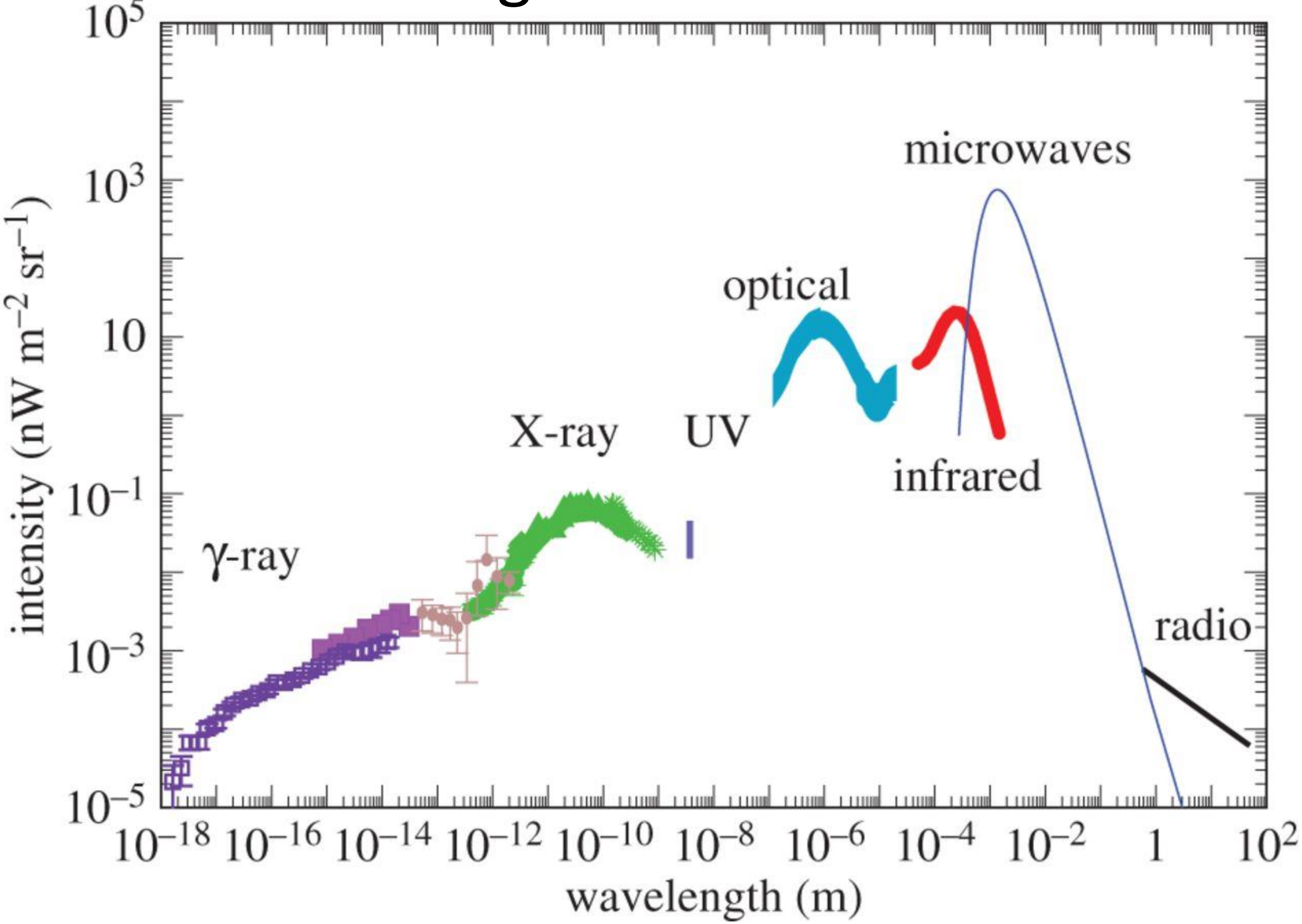


The top image shows the overall coverage of the WISE all-sky survey, as measured by successfully processed frames. The scale on the bottom shows the density of the coverage. The red portions indicate heavy coverage whereas blue portions indicate a lighter coverage. The poles received the most coverage 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

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

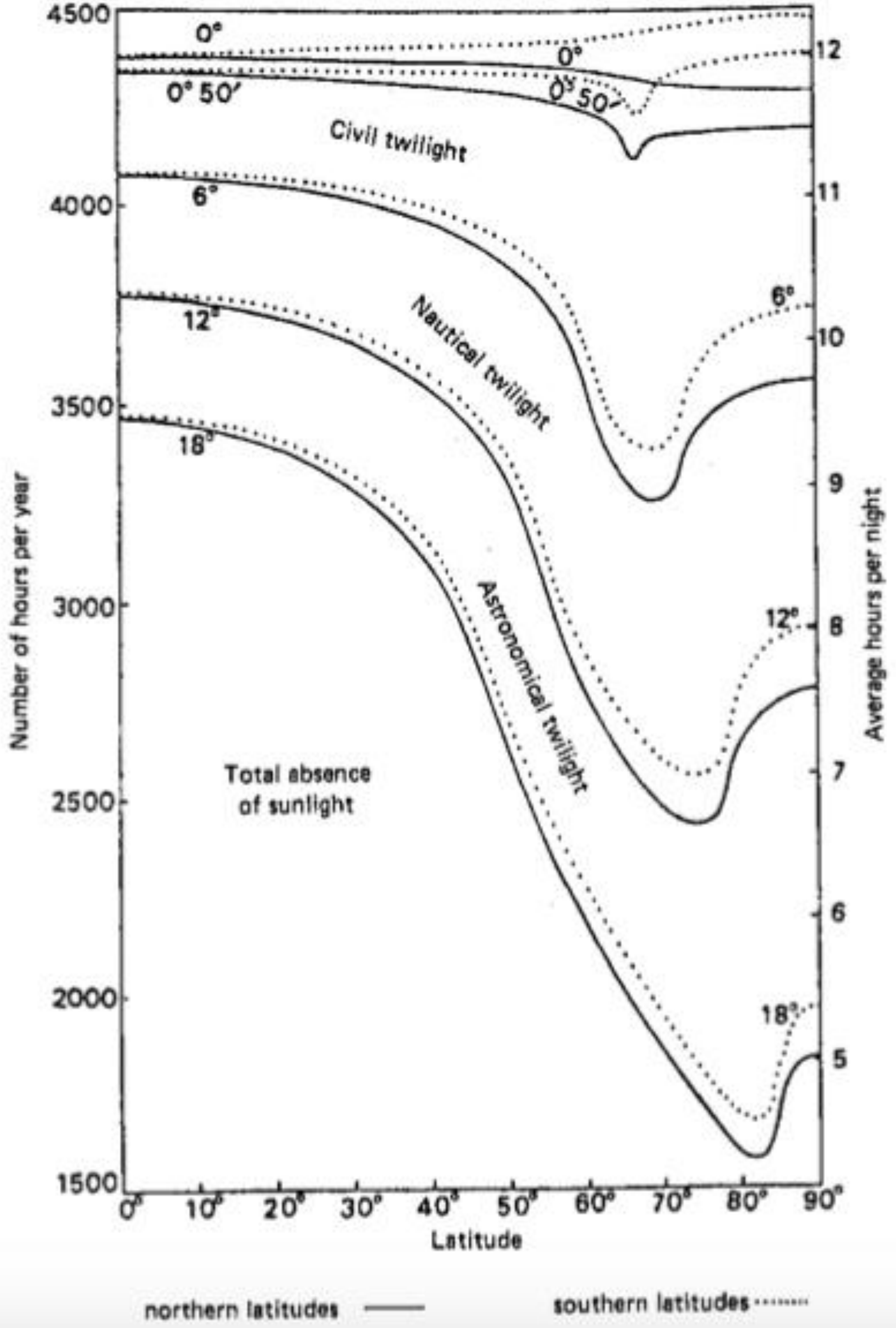
The variation in the number of dark hours in the year as a function of geographic latitude and twilight definition

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

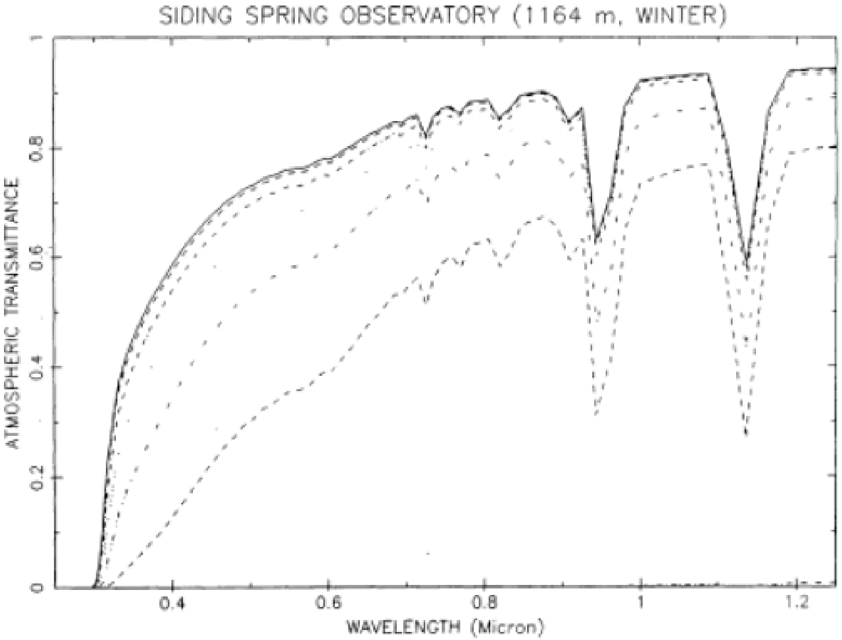


FIGURE 4. — Siding Spring Observatory transmittance between 0.25 μ and 1.25 μ during the Fall-Winter season (1164 m).

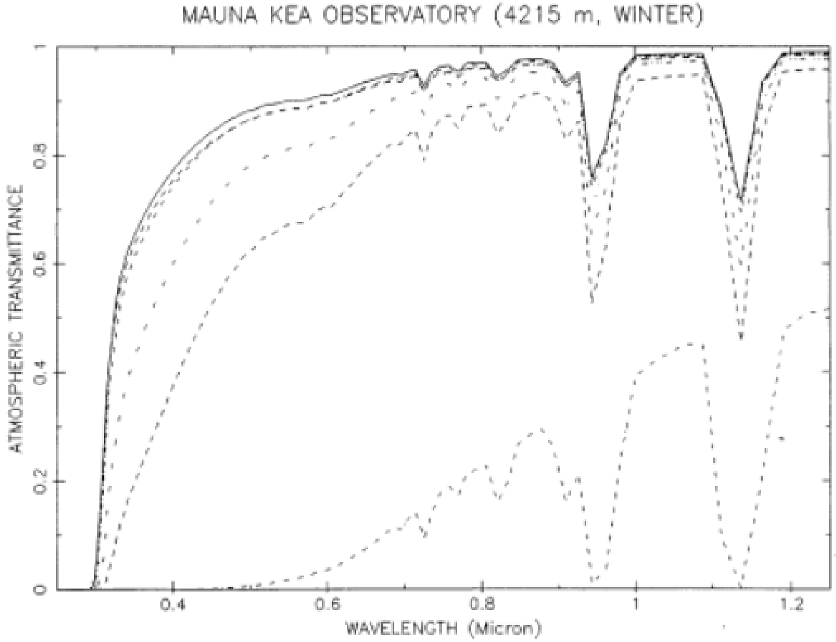


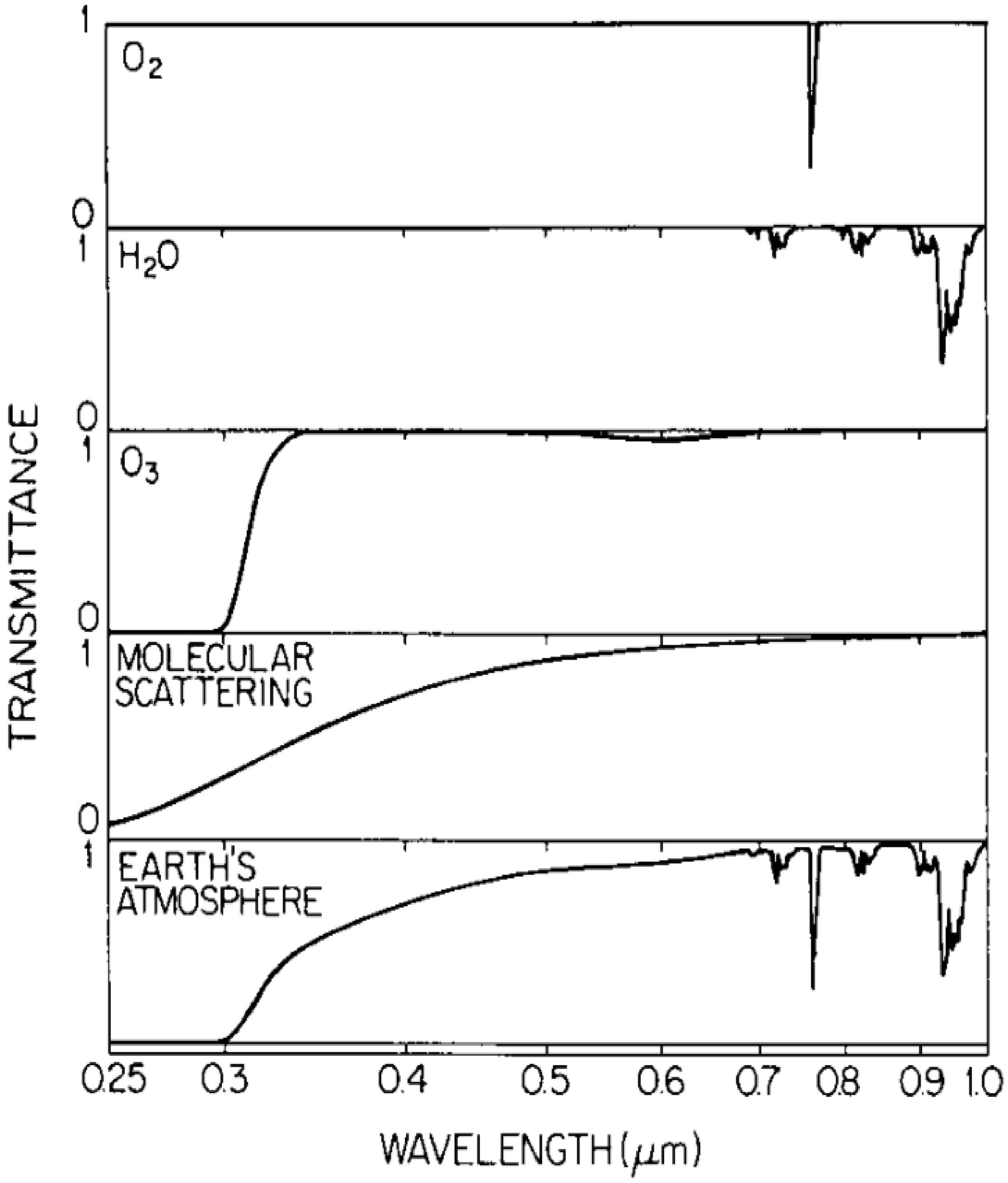
FIGURE 10. — Hawaii Mauna Kea Observatory transmittance between 0.25 μ and 1.25 μ during the Fall-Winter season (4215 m).

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

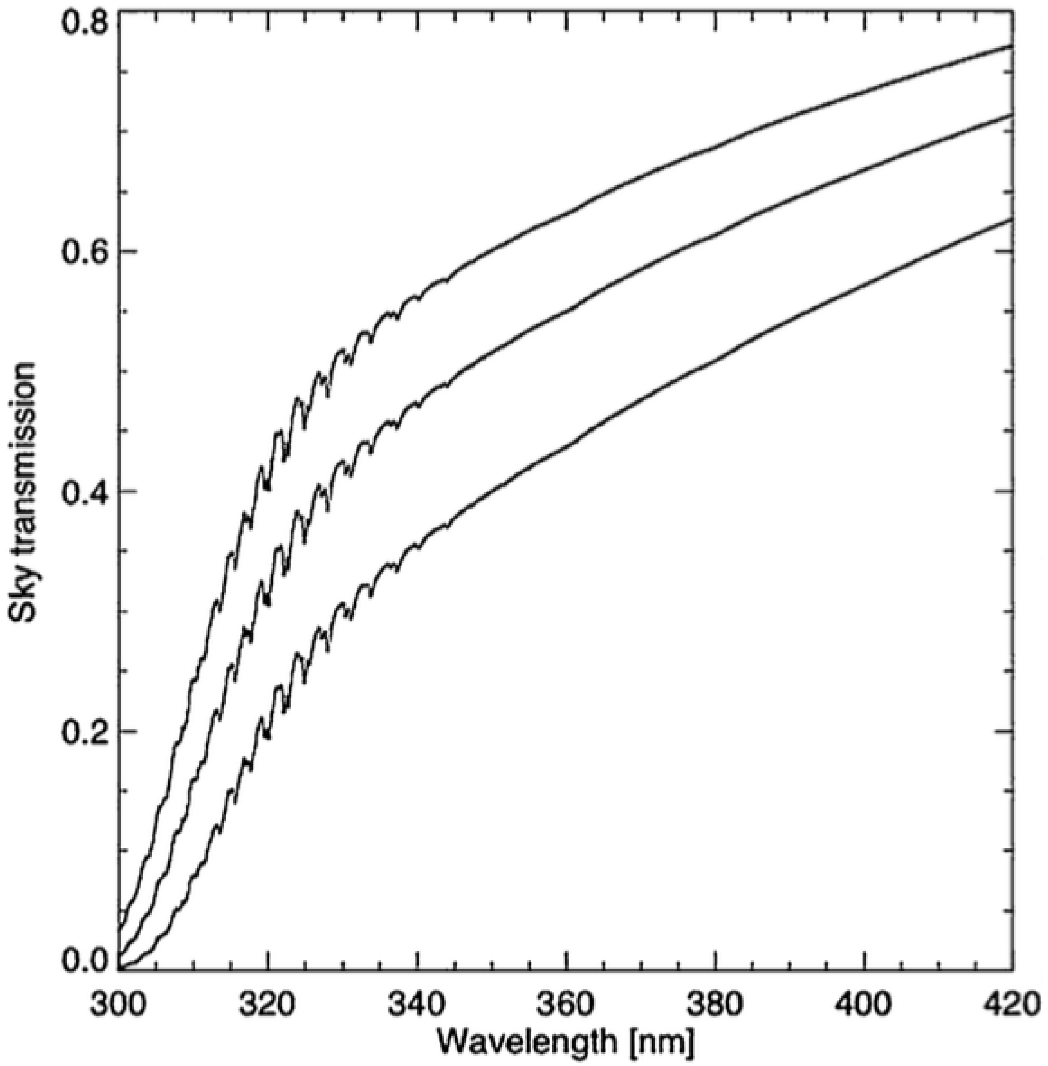
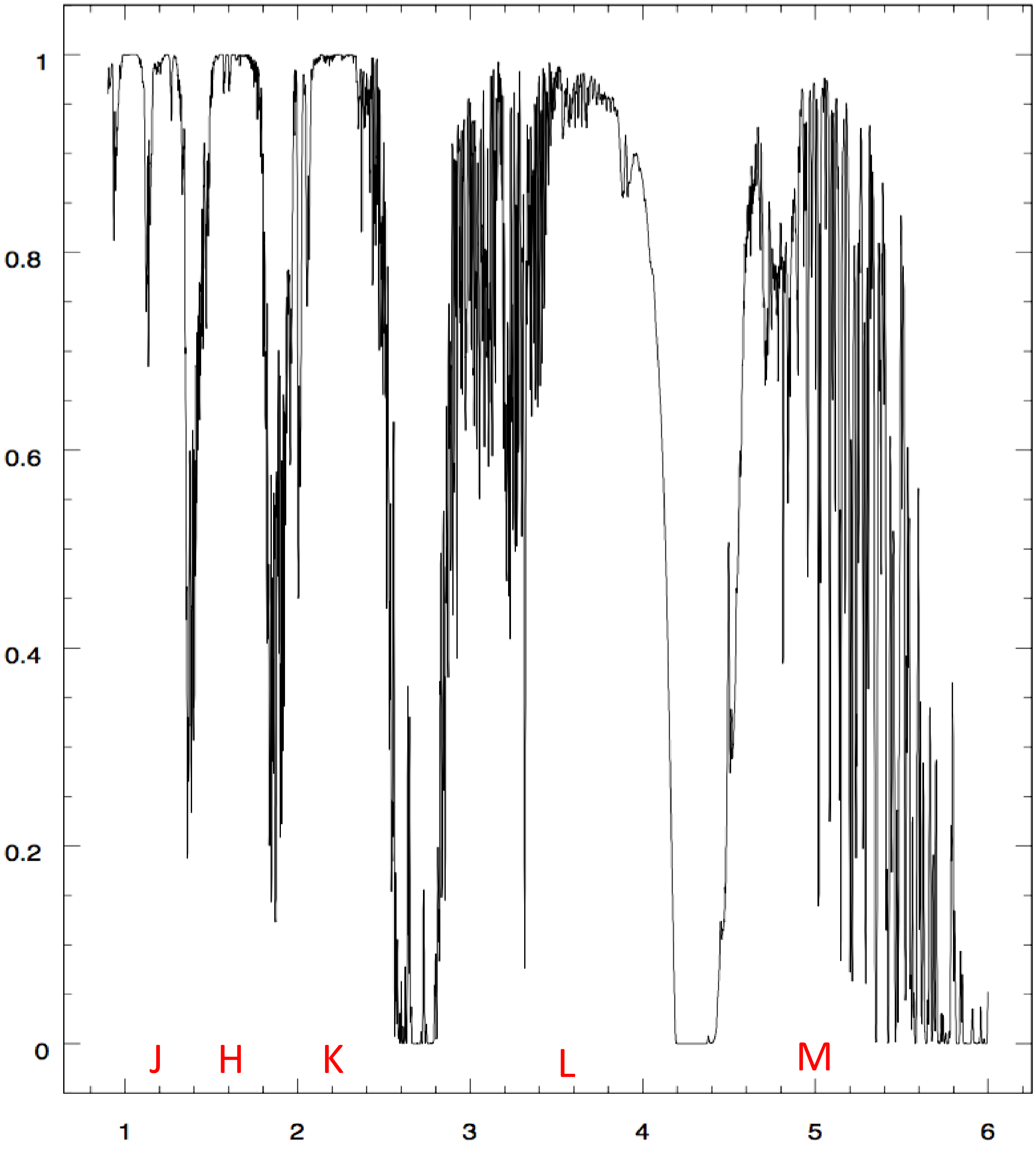


Fig. 3 Atmospheric transmission at the Paranal VLT platform (Noll et al. 2012). From top to bottom, the curves correspond to airmass = 1.0, 1.3 and 1.8. Note that the transmission drops sharply with wavelength below 330 nm and is 15–20 % lower at airmass = 1.8 than at zenith across most of the wavelength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

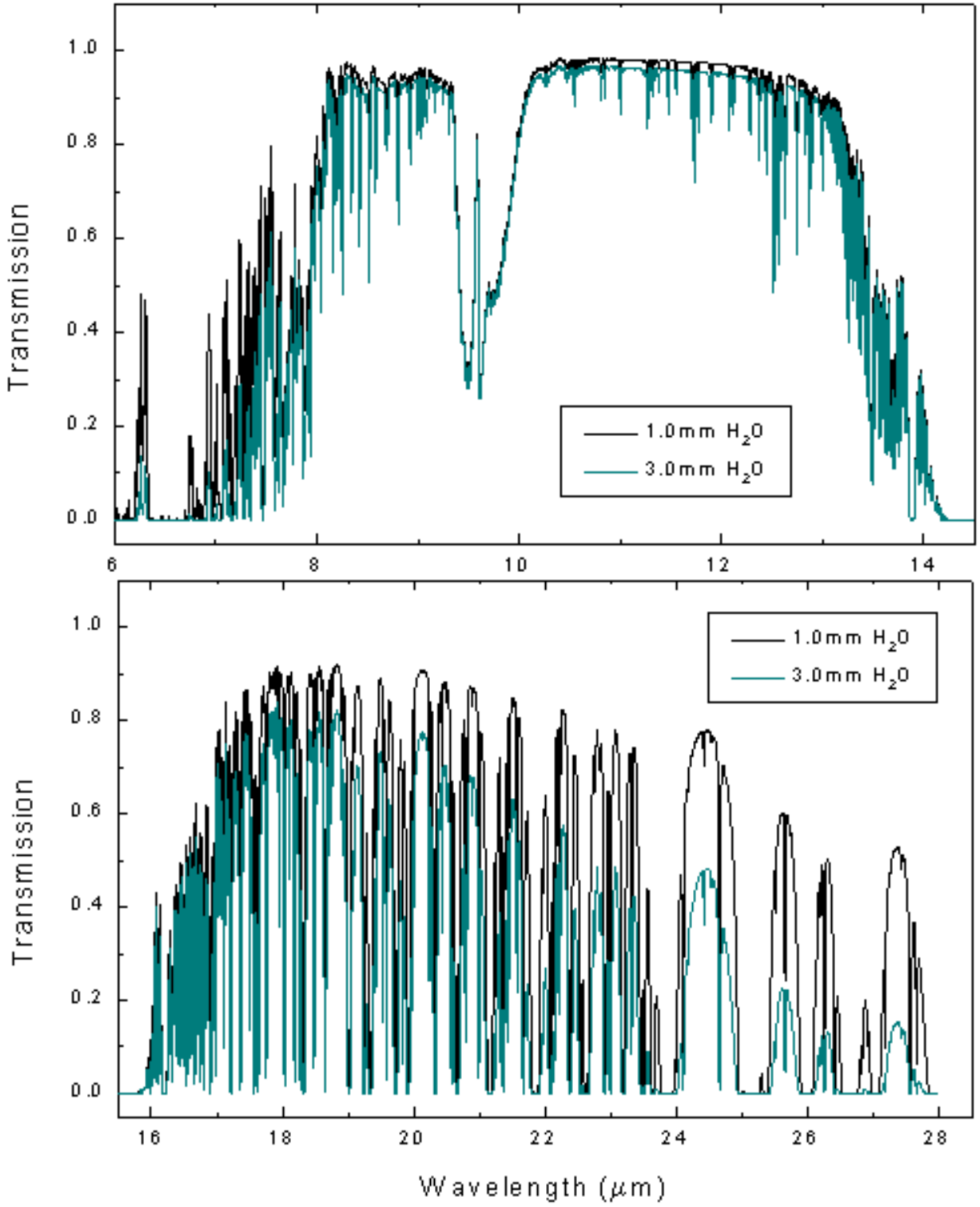


Mid-Infrared, N and Q band transmission for Mauna Kea.

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

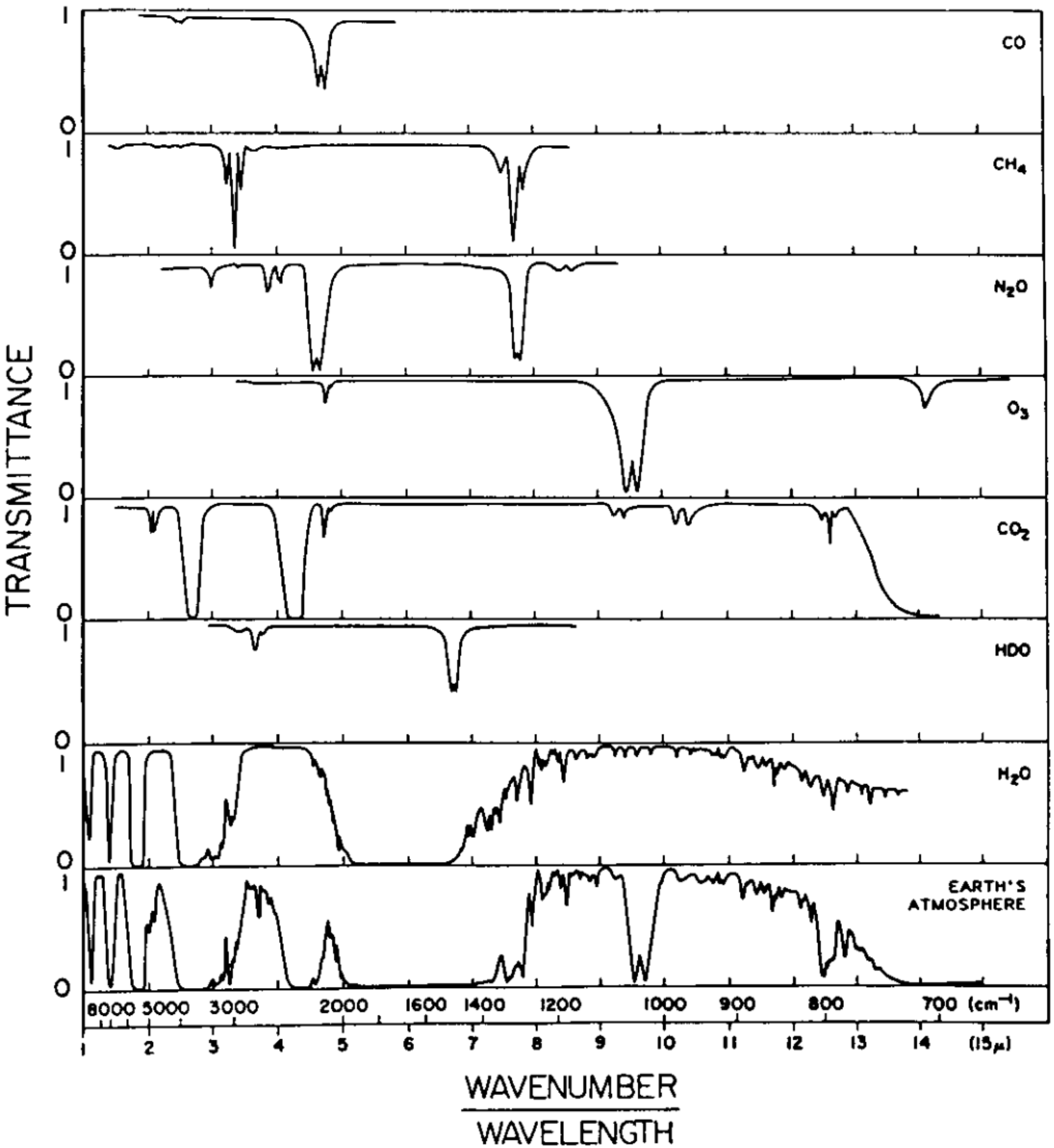
Transmission in the Q-band is more like a venetian blind than a window!



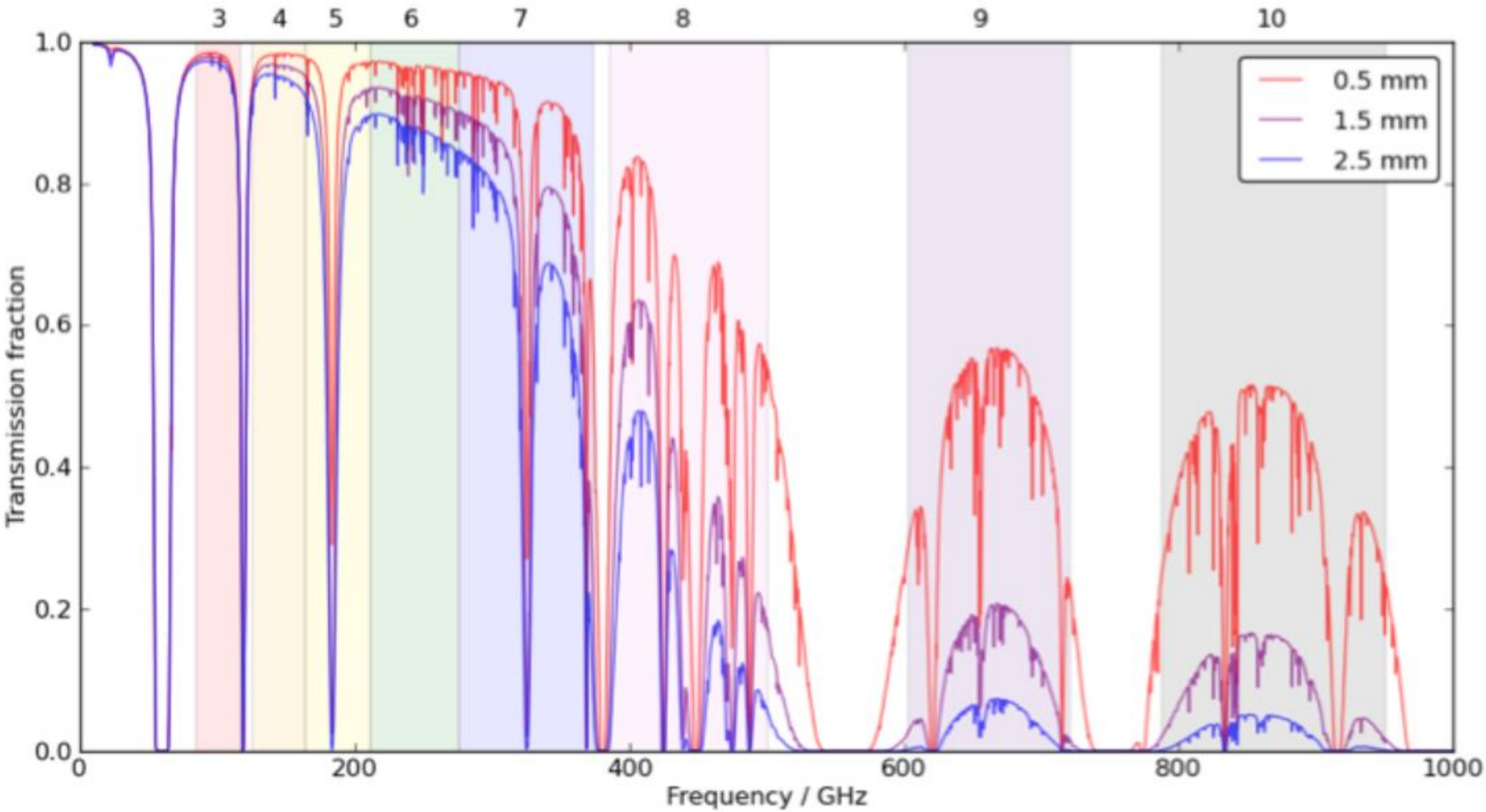
Atmospheric Absorption

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.