

Astronomical Observing Techniques 2019

Lecture 8: Trouble is in the Air

Huub Rottgering
rottgering@strw.leidenuniv.nl

Content

1. Layers in the atmosphere
2. Atmospheric absorption
3. Emission from the atmosphere and space
4. Scattering and dispersion in the atmosphere
5. Turbulence in the atmosphere and seeing
6. Low frequency radio astronomy and the ionosphere

Hydrostatic Equilibrium in the atmosphere

$$dm = \rho \cdot A \cdot dz$$

$$dF = -g \cdot dm = -\rho \cdot g \cdot A \cdot dz$$

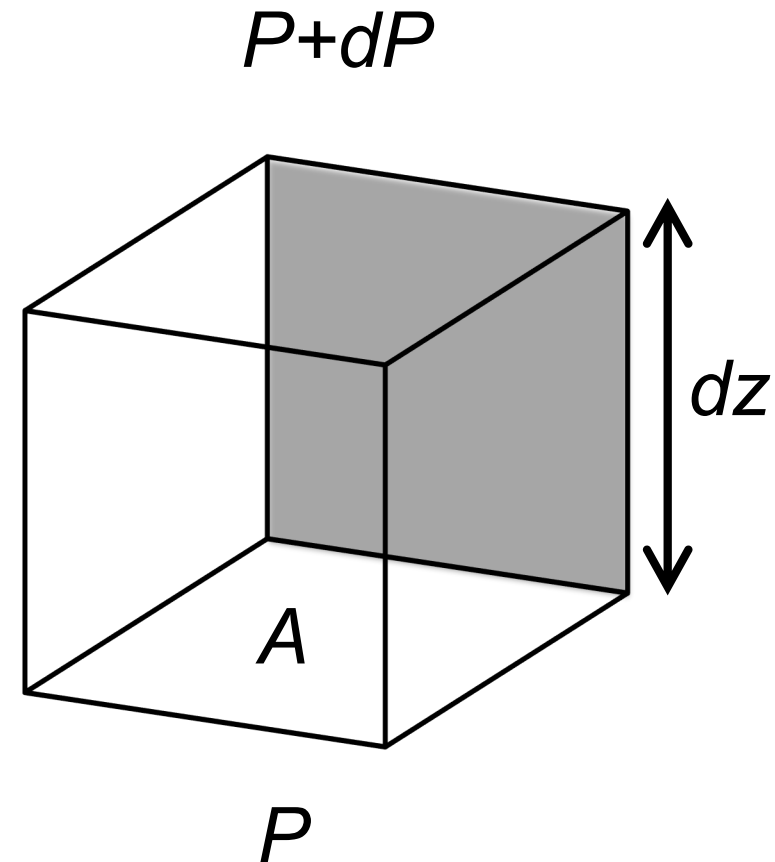
$$dP = dF / A = -\rho \cdot g \cdot dz$$

$$P = \rho \cdot k \cdot T / \mu, \quad \rho = P \cdot \frac{\mu}{kT}$$

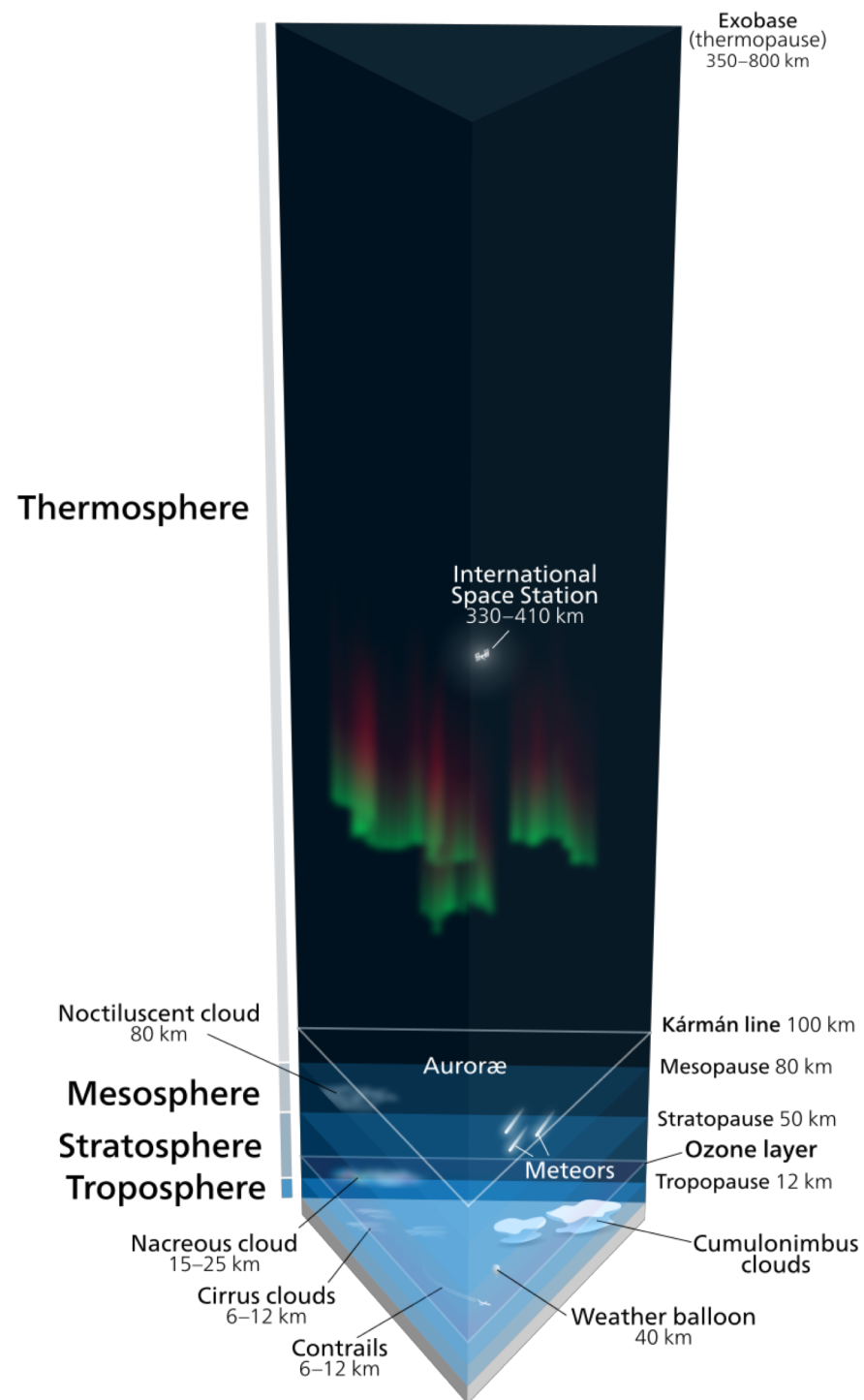
$$dP / dz = -P / H, \quad H = \frac{kT}{\mu g}$$

$$P(z) = P_0 \cdot e^{-\frac{z}{H}}$$

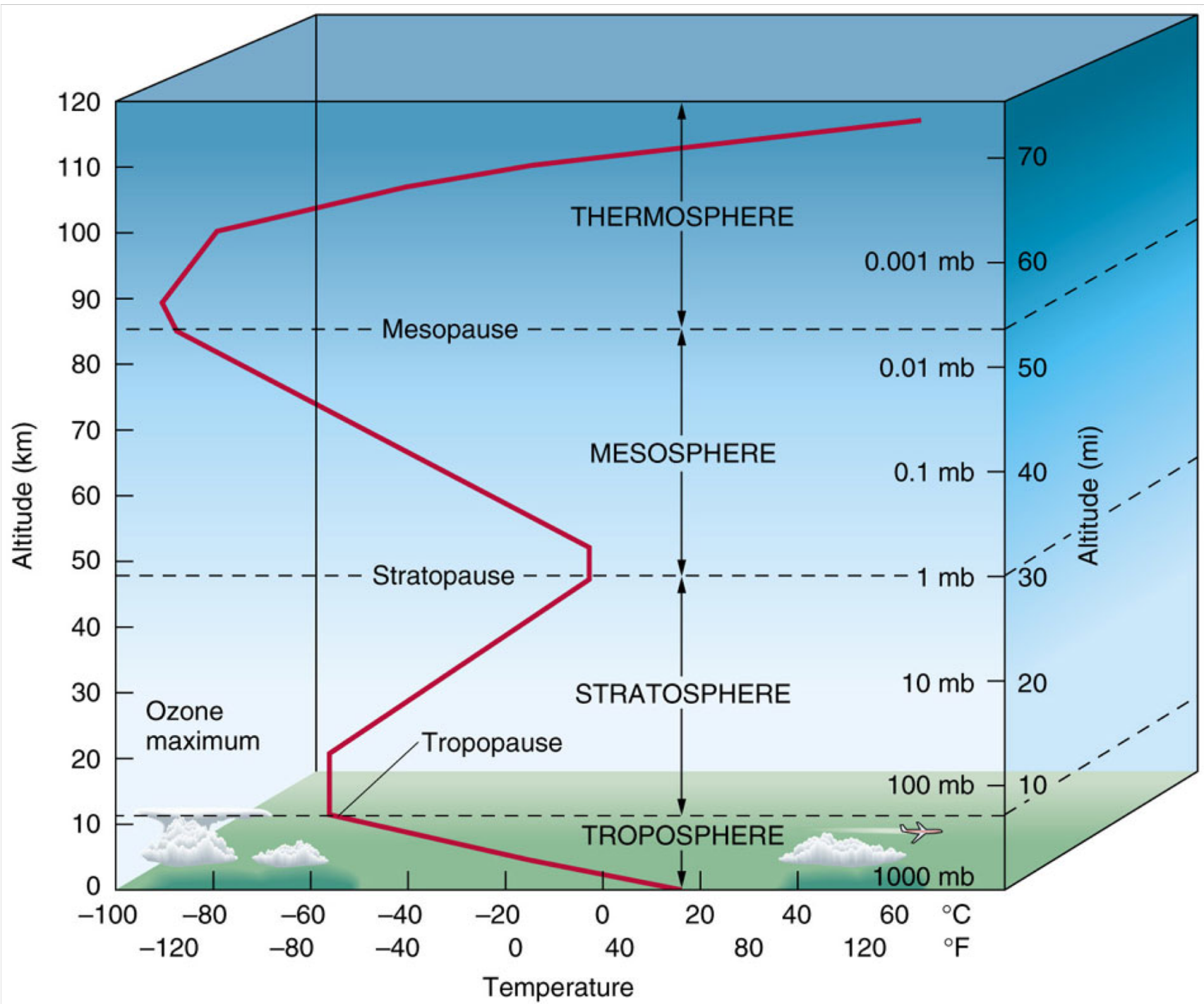
ρ : density, A : surface, g : gravitational acceleration,
 F : force, k : Boltzmann constant, T : temperature,
 μ : mean molecular weight. H : scale height ≈ 6 -8 km



Earth atmosphere



https://en.wikipedia.org/wiki/Atmosphere_of_Earth



Troposphere

The troposphere is the lowest layer of Earth's atmosphere. It extends from Earth's surface to an average height of about 12 km with some variation due to weather. The troposphere is bounded above by the [tropopause](#), a boundary marked by a [temperature inversion](#) (i.e. a layer of relatively warm air above a colder one), or by a zone which is [isothermal](#) with height.

The temperature usually declines with increasing altitude because the troposphere is mostly heated through energy transfer from the surface. Thus, the lowest part of the troposphere (i.e. Earth's surface) is typically the warmest section of the troposphere. This promotes vertical mixing (hence, the origin of its name in the Greek word *τρόπος*, *tropos*, meaning "turn"). The troposphere contains roughly 80% of the [mass](#) of Earth's atmosphere. Fifty percent of the total mass of the atmosphere is located in the lower 5.6 km of the troposphere.

Nearly all atmospheric water vapor or moisture is found in the troposphere, so it is the layer where most of Earth's weather takes place. It has basically all the weather-associated cloud genus types generated by active wind circulation, although very tall cumulonimbus thunder clouds can penetrate the tropopause from below and rise into the lower part of the stratosphere. Most conventional [aviation](#) activity takes place in the troposphere, and it is the only layer that can be accessed by propeller-driven aircraft.

Stratosphere

The stratosphere is the second-lowest layer of Earth's atmosphere. It lies above the troposphere and is separated from it by the [tropopause](#). This layer extends from the top of the troposphere at roughly 12 km above Earth's surface to the [stratopause](#) at an altitude of about 50 to 55 km. Although the temperature may be -60°C at the tropopause, the top of the stratosphere is much warmer, and may be near 0°C .

The atmospheric pressure at the top of the stratosphere is roughly 1/1000 the pressure at [sea level](#). It contains the ozone layer. The stratosphere defines a layer in which temperatures rise with increasing altitude. This rise in temperature is caused by the absorption of [ultraviolet radiation](#) (UV) radiation from the Sun by the [ozone layer](#). In this layer [ozone](#) concentrations are about 2 to 8 parts per million, which is much higher than in the lower atmosphere but still very small compared to the main components of the atmosphere. It is mainly located in the lower portion of the stratosphere from about 15–35 km though the thickness varies seasonally and geographically. About 90% of the ozone in Earth's atmosphere is contained in the stratosphere.

The stratospheric temperature profile creates very stable atmospheric conditions, so the stratosphere lacks the weather-producing air turbulence that is so prevalent in the troposphere. Consequently, the stratosphere is almost completely free of clouds and other forms of weather. However, polar stratospheric or [nacreous clouds](#) are occasionally seen in the lower part of this layer of the atmosphere where the air is coldest. The stratosphere is the highest layer that can be accessed by jet-powered aircraft.

Mesosphere

The mesosphere is the third highest layer of Earth's atmosphere, occupying the region above the stratosphere and below the thermosphere. It extends from the stratopause at an altitude of about 50 km to the mesopause at 80–85 km above sea level.

Temperatures drop with increasing altitude to the [mesopause](#) that marks the top of this middle layer of the atmosphere. It is the coldest place on Earth and has an average temperature around -85°C .

Just below the mesopause, the air is so cold that even the very scarce water vapor at this altitude can be sublimated into polar-mesospheric [noctilucent clouds](#). These are the highest clouds in the atmosphere and may be visible to the naked eye if sunlight reflects off them about an hour or two after sunset or a similar length of time before sunrise. The mesosphere is also the layer where most [meteors](#) burn up upon atmospheric entrance. It is too high above Earth to be accessible to jet-powered aircraft and balloons, and too low to permit orbital spacecraft. The mesosphere is mainly accessed by [sounding rockets](#) and rocket-powered aircraft.

Thermosphere

The thermosphere is the second-highest layer of Earth's atmosphere. It extends from the mesopause (which separates it from the mesosphere) at an altitude of about 80 km up to the [thermopause](#) at an altitude range of 500–1000 km. The height of the thermopause varies considerably due to changes in solar activity. The lower part of the thermosphere, from 80 to 550 kilometres above Earth's surface, contains the [ionosphere](#).

The temperature of the thermosphere gradually increases with height. Unlike the stratosphere beneath it, wherein a temperature [inversion](#) is due to the absorption of radiation by ozone, the inversion in the thermosphere occurs due to the extremely low density of its molecules. The temperature of this layer can rise as high as 1500 °C), though the gas molecules are so far apart that its [temperature in the usual sense](#) is not very meaningful. The air is so rarefied that an individual molecule (of [oxygen](#), for example) travels an average of 1 kilometre between collisions with other molecules. Although the thermosphere has a high proportion of molecules with high energy, it would not feel hot to a human in direct contact, because its density is too low to conduct a significant amount of energy to or from the skin.

This layer is completely cloudless and free of water vapor. However, non-hydrometeorological phenomena such as the [aurora borealis](#) and [aurora australis](#) are occasionally seen in the thermosphere. The [International Space Station](#) orbits in this layer, between 350 and 420 km.

Exo-sphere

- The exosphere is the outermost layer of Earth's atmosphere (i.e. the upper limit of the atmosphere). It extends from the [exobase](#), which is located at the top of the thermosphere at an altitude of about 700 km above sea level, to about 10,000 km where it merges into the [solar wind](#).
- This layer is mainly composed of extremely low densities of hydrogen, helium and several heavier molecules including nitrogen, oxygen and carbon dioxide closer to the exobase. The atoms and molecules are so far apart that they can travel hundreds of kilometers without colliding with one another. Thus, the exosphere no longer behaves like a gas, and the particles constantly escape into space. These free-moving particles follow [ballistic trajectories](#) and may migrate in and out of the [magnetosphere](#) or the solar wind.
- The exosphere is located too far above Earth for any meteorological phenomena to be possible. However, the [aurora borealis](#) and [aurora australis](#) sometimes occur in the lower part of the exosphere, where they overlap into the thermosphere. The exosphere contains most of the satellites orbiting Earth.

Ionosphere

The ionosphere is a region of the atmosphere that is ionized by solar radiation:



Electron showers along magnetic fields cause auroras. During daytime hours, it stretches from 50 to 1,000 km and includes the mesosphere, thermosphere, and parts of the exosphere.

At 100 – 300 km height: $n_e \sim 10^5 - 10^6 \text{ cm}^{-3}$ However, ionization in the mesosphere largely ceases during the night, so auroras are normally seen only in the thermosphere and lower exosphere.

The ionosphere forms the inner edge of the magnetosphere. It has practical importance because it influences, for example, radio propagation on Earth.

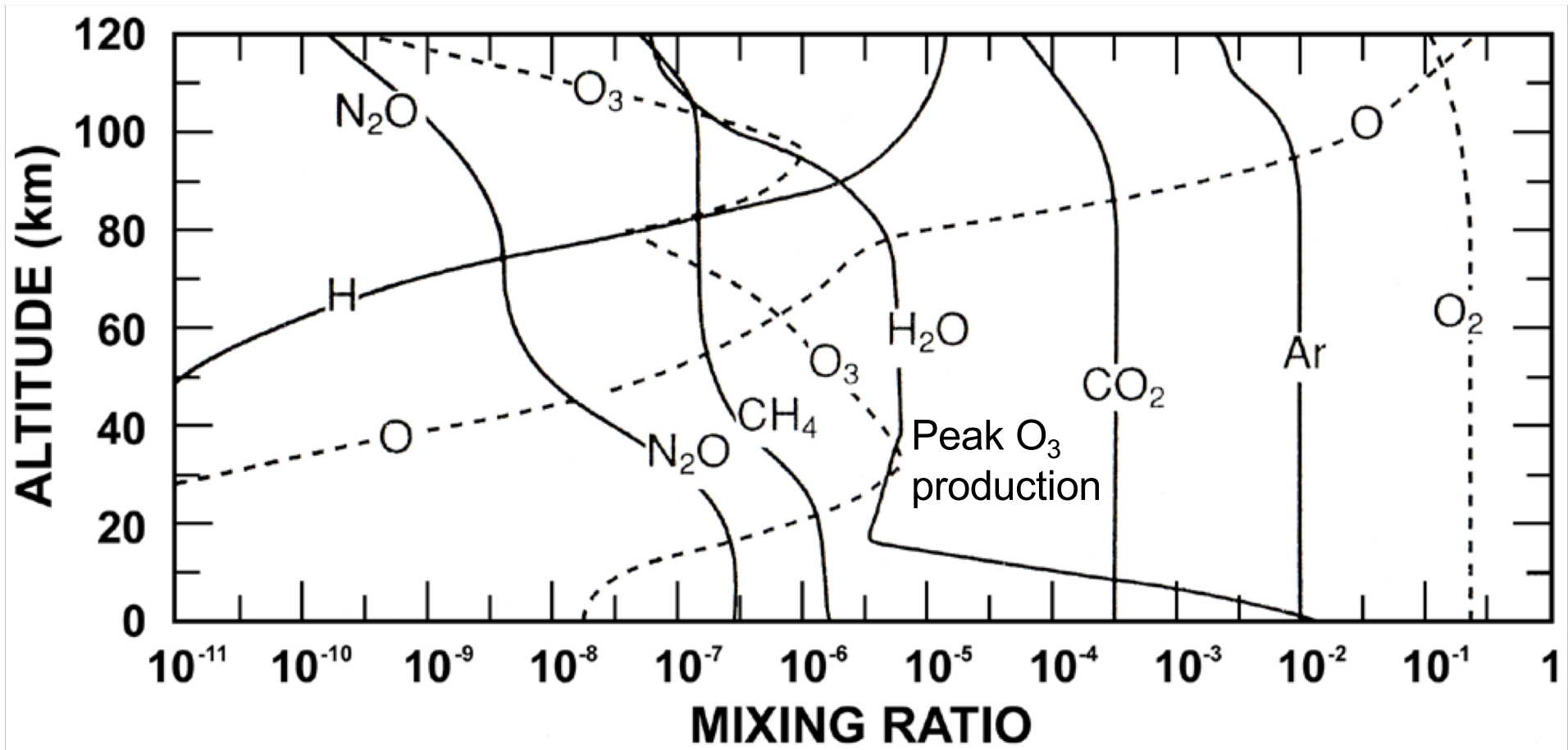


HR, March 15, 2018, Karasjok, Norway



HR, March 15, 2018, Karasjok, Norway

Atmospheric Composition: Mixing Ratios



The mixing ratio is the number density of the gas under consideration divided by number density of all gases in dry air. Not depicted are N_2 and the rare noble gases, whose mixing ratios are nearly constant up to 100 km because of their chemical stability. The N_2 mixing ratio curve would parallel the O_2 curve and lie to its right, starting at a sea-level value of 0.78.

Schatter 2009: Atmospheric Composition and Vertical Structure

Atmospheric Composition

- O_2 , N_2 main constituents, constant proportions up to 100 km
- Ozone – mainly absorbs in UV
 - distribution depends on latitude, season
- CO_2 – important component for (mid)-infrared absorption
 - mixing ratio independent of altitude
- H_2O – highly variable, very strong absorption bands

Atmospheric Absorption

- Absorption features due to
 - individual atomic absorption lines
 - molecular absorption bands
- Attenuation at altitude z_0 and zenith distance θ :
- for i absorbing species with optical depth τ_i

$$I(z_0) = I_0(\infty) \cdot \exp \left[-\frac{1}{\cos \theta} \sum_i \tau_i(\lambda, z_0) \right]$$

$$\tau_i(\lambda, z_0) = \int_{z_0}^{\infty} r_i(z) \rho_0(z) \kappa_i(\lambda) dz$$

κ : absorption coefficient; ρ_0 : mass density of air;

$r_i(z)$ the mixing ratio $r_i = n_i / (n_{\text{tot}} - n_i)$ where n is the number density

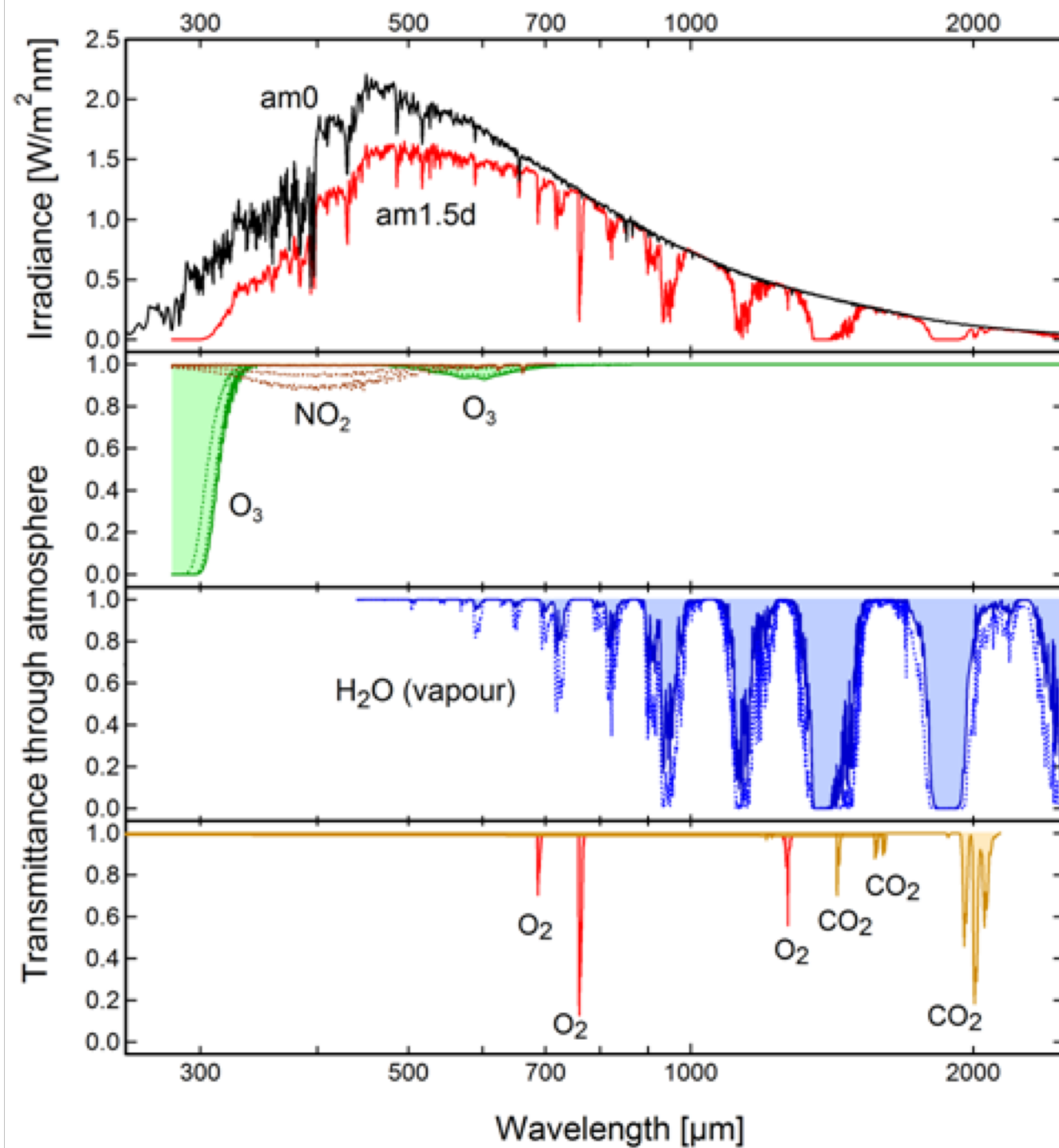
Atmospheric Absorption: Bands

No absorption → atmospheric **transmission windows/bands**
(wavelengths accessible to ground-based observations)

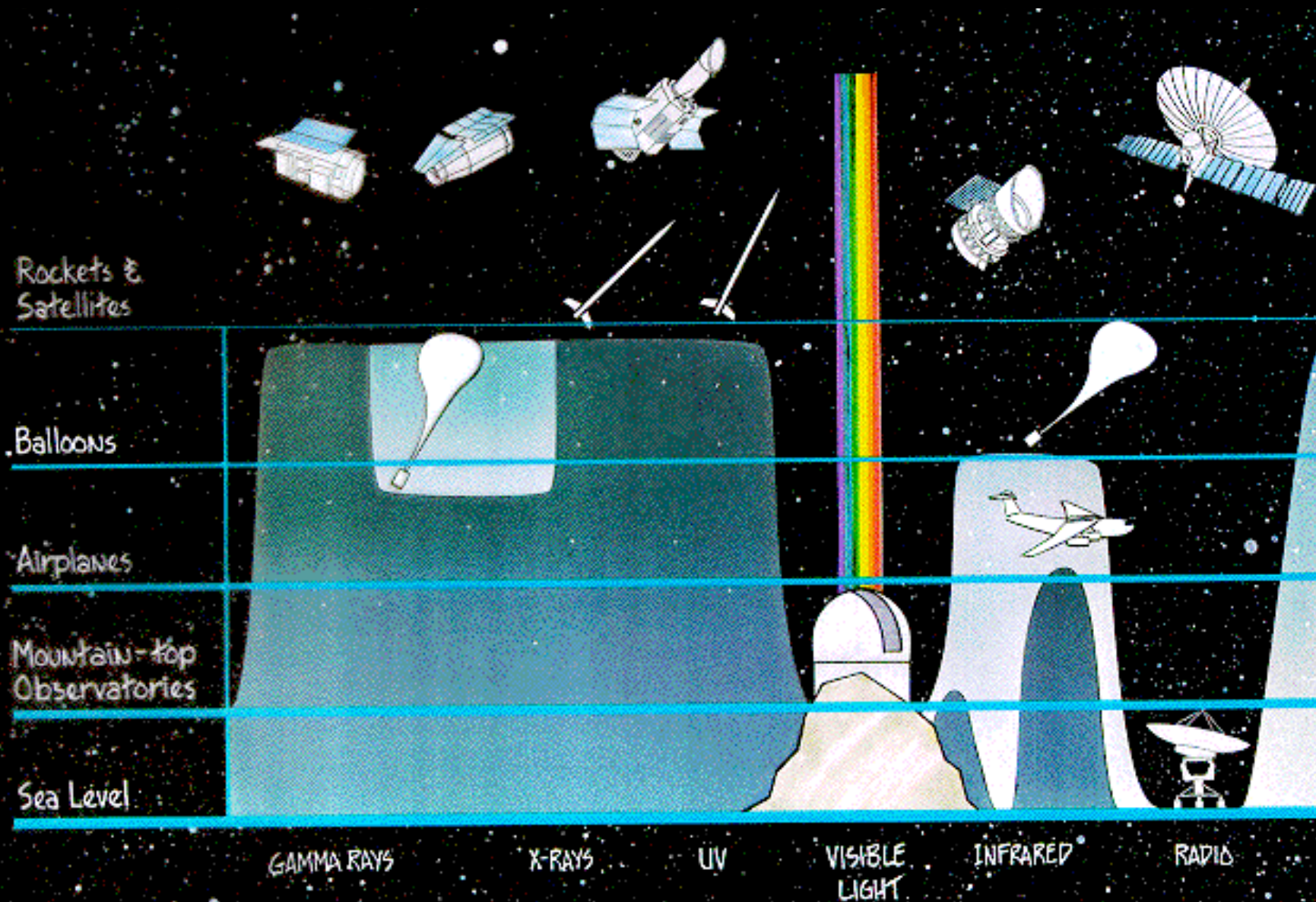
Partial absorption → reduced transmission

AM0 spectrum: air mass zero, meaning that the spectrum was measured with no air between the sun and the receiver.

The global standard spectrum (AM1.5g) is measured at an airmass of 1.5 under 'standard' conditions



Ground based astronomy is limited to visible, near/mid-IR and radio wavelengths.
Space astronomy provides access to γ -rays, X-rays, UV, FIR, sub-mm



Atmospheric Absorption: UV

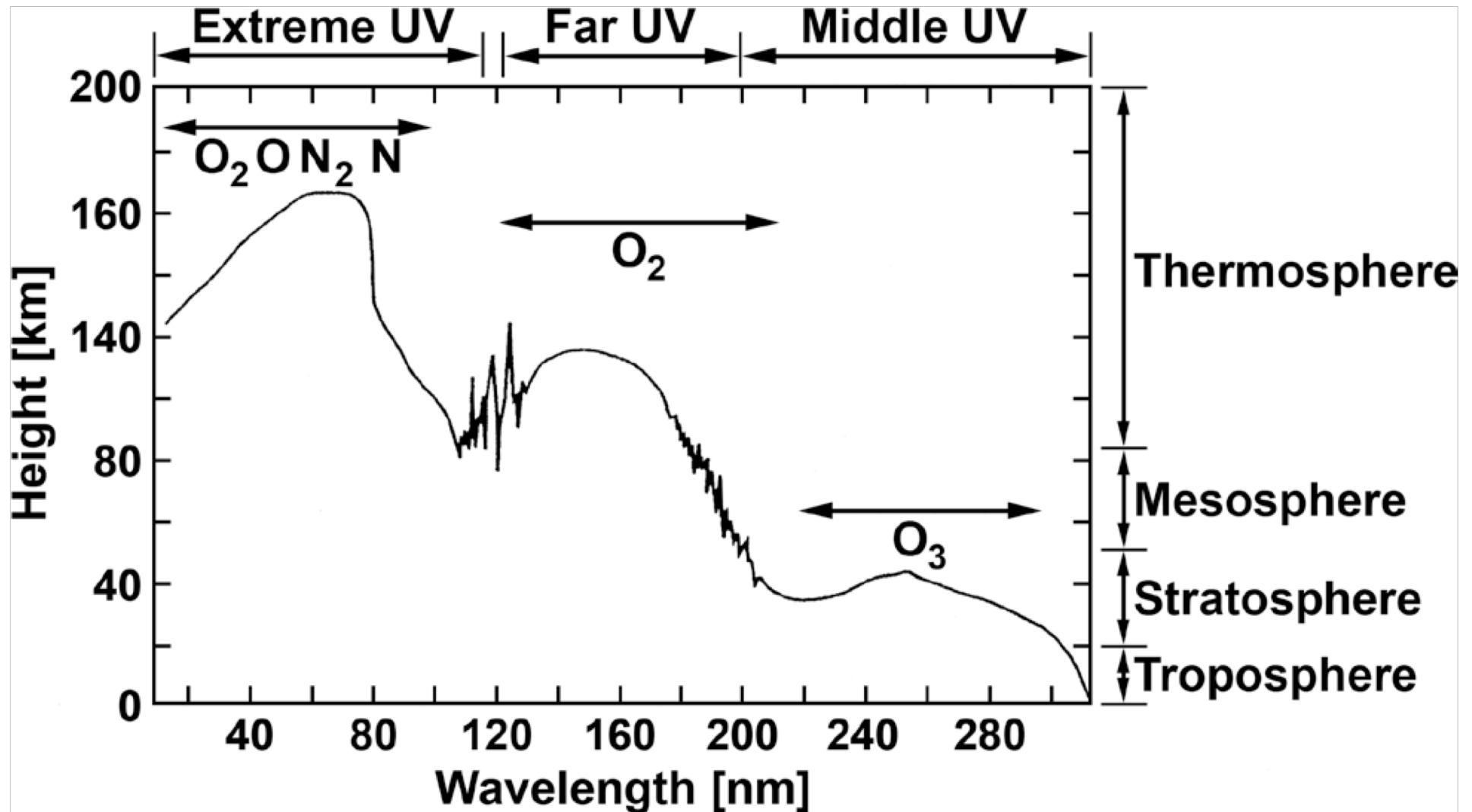
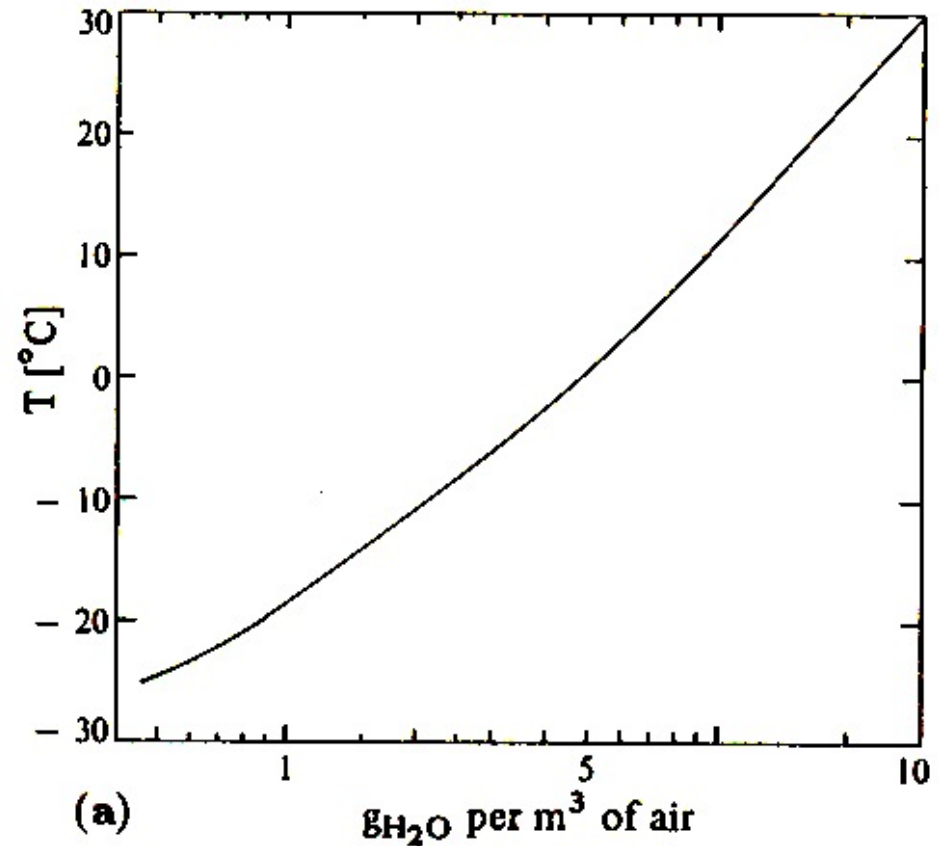


Figure shows the altitude at which absorption lowers the intensity of ultraviolet radiation to $1/e$ (37%) of its value at the top of the atmosphere (Schlatter 2009)

Atmospheric Absorption: Water Vapour

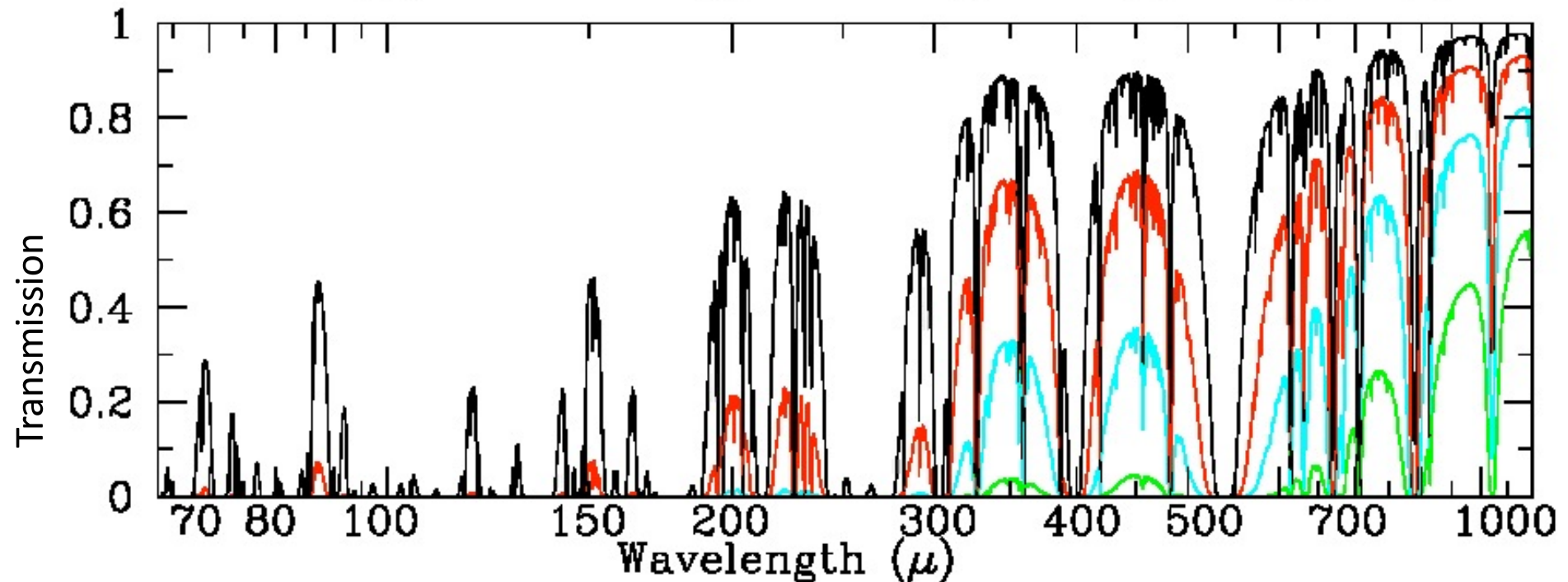
- Water vapor strongly depends on T and z
- Precipitable water vapor (PWV) = depth of liquid water in column of atmosphere
- PWV w above altitude z_0 given relative humidity $r(z)$

$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz ,$$



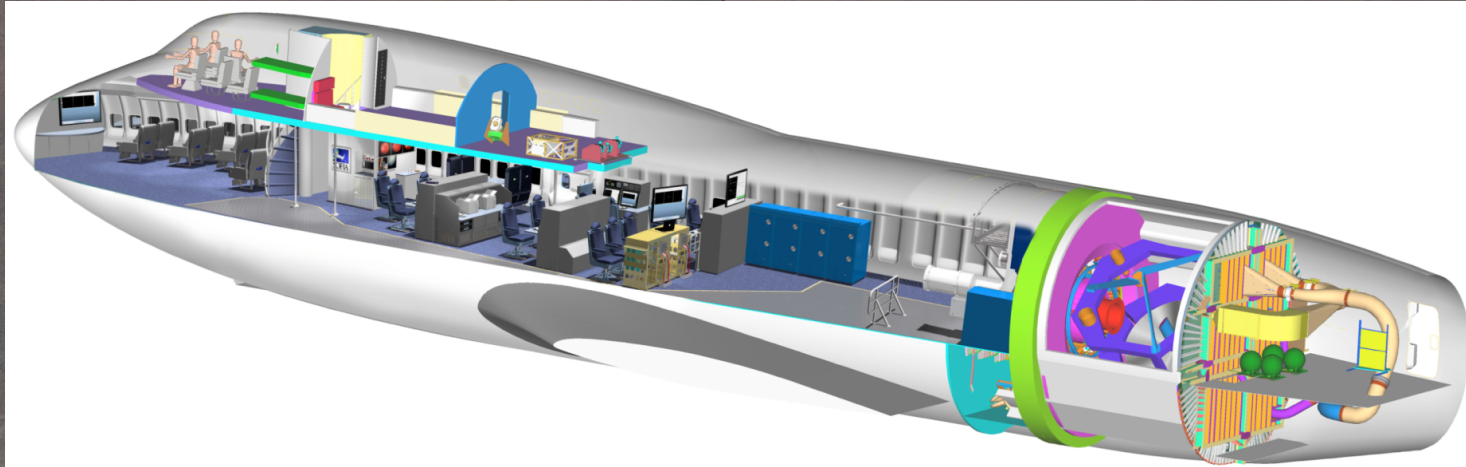
Absorption by Water Vapour

Scale height for PWV is only ~ 3 km
→ observatories at **high altitudes**



0.1 mm PWV (Hawaii/ALMA), 0.4 mm PWV, 1.0 mm
PWV, 3.0 mm PWV

FIR/sub-mm astronomy is also possible from airplanes, e.g. the Stratospheric Observatory for Infrared Astronomy (SOFIA)

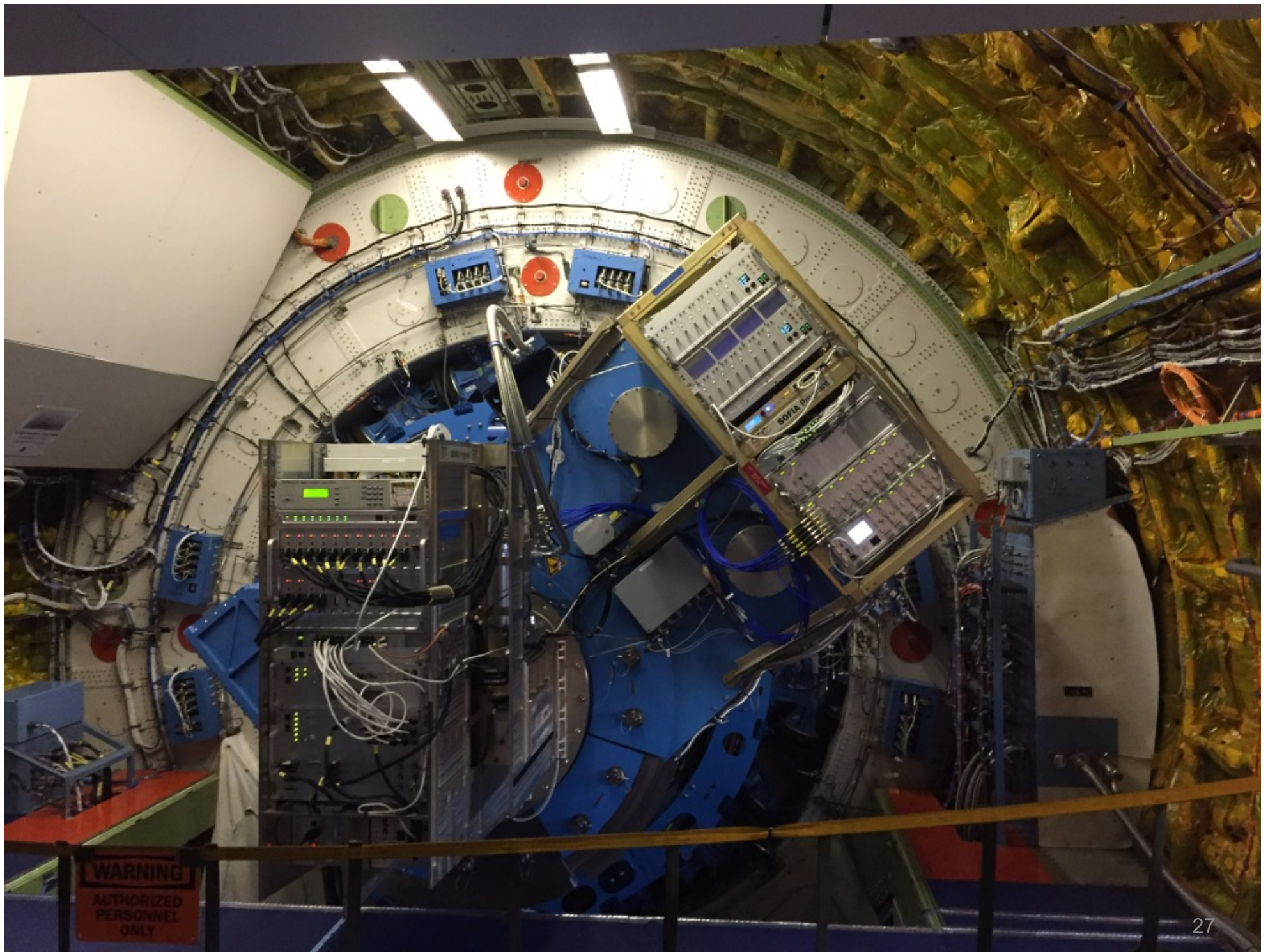




HR, Palmdale, CA, 15 Feb 2017







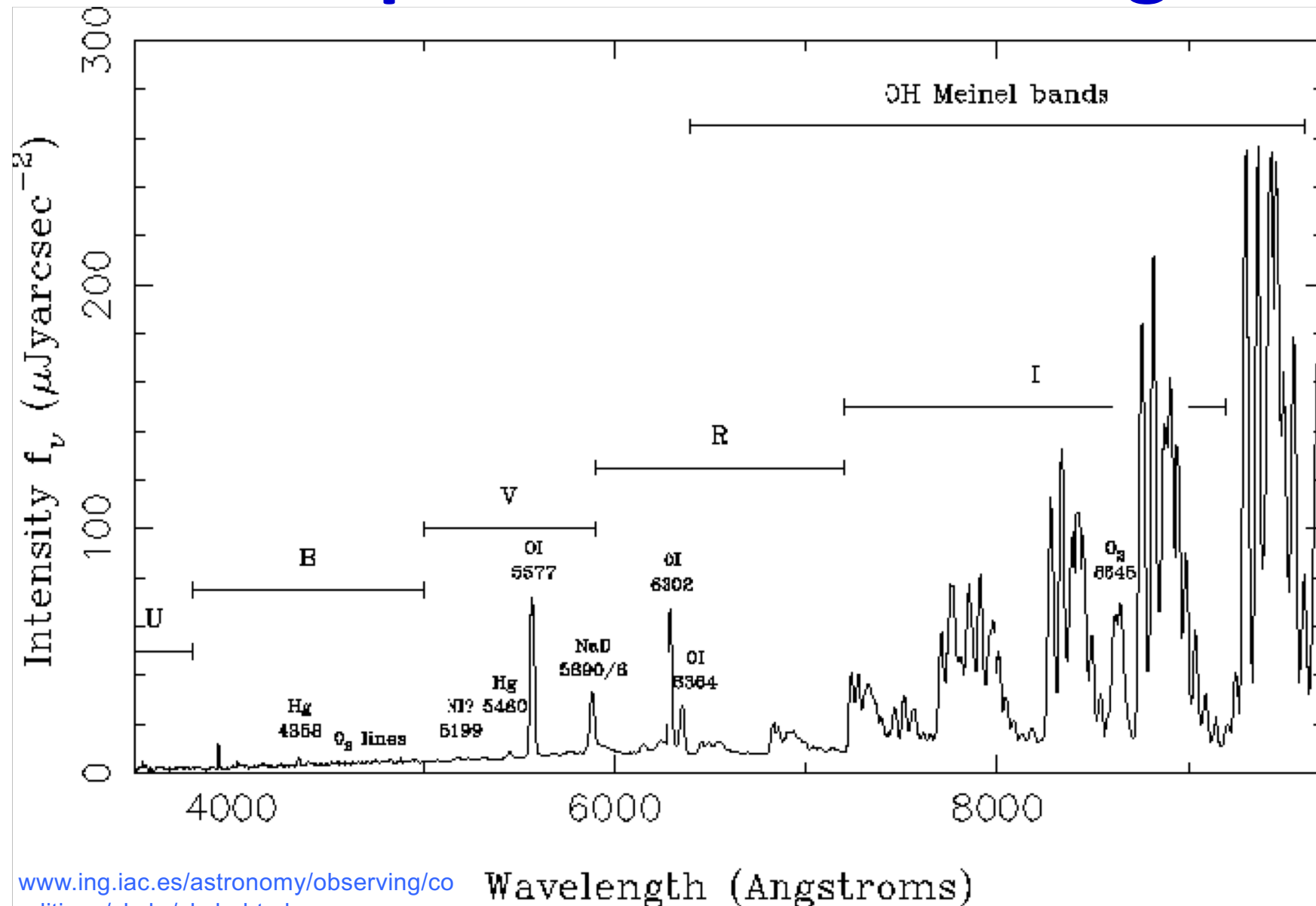
WARNING
AUTHORIZED
PERSONNEL
ONLY



Atmospheric Emission: Airglow

- **Fluorescence** = recombination of electrons and ions
- Recombination probability low; takes several hours
- Produces both continuum + line emission = **airglow**
 - Occurs mainly at ~ 100 km height
 - Main sources of emission: O I, Na I, O₂, OH (in NIR), H

Atmospheric Emission: Airglow



Thermal Atmospheric Emission

- Atmosphere in **local thermodynamic equilibrium** (LTE) <60 km, i.e. excitation levels are thermally populated
- **Full radiative transfer calculation** needed
- For $\tau \ll 1$ use **approximation**:

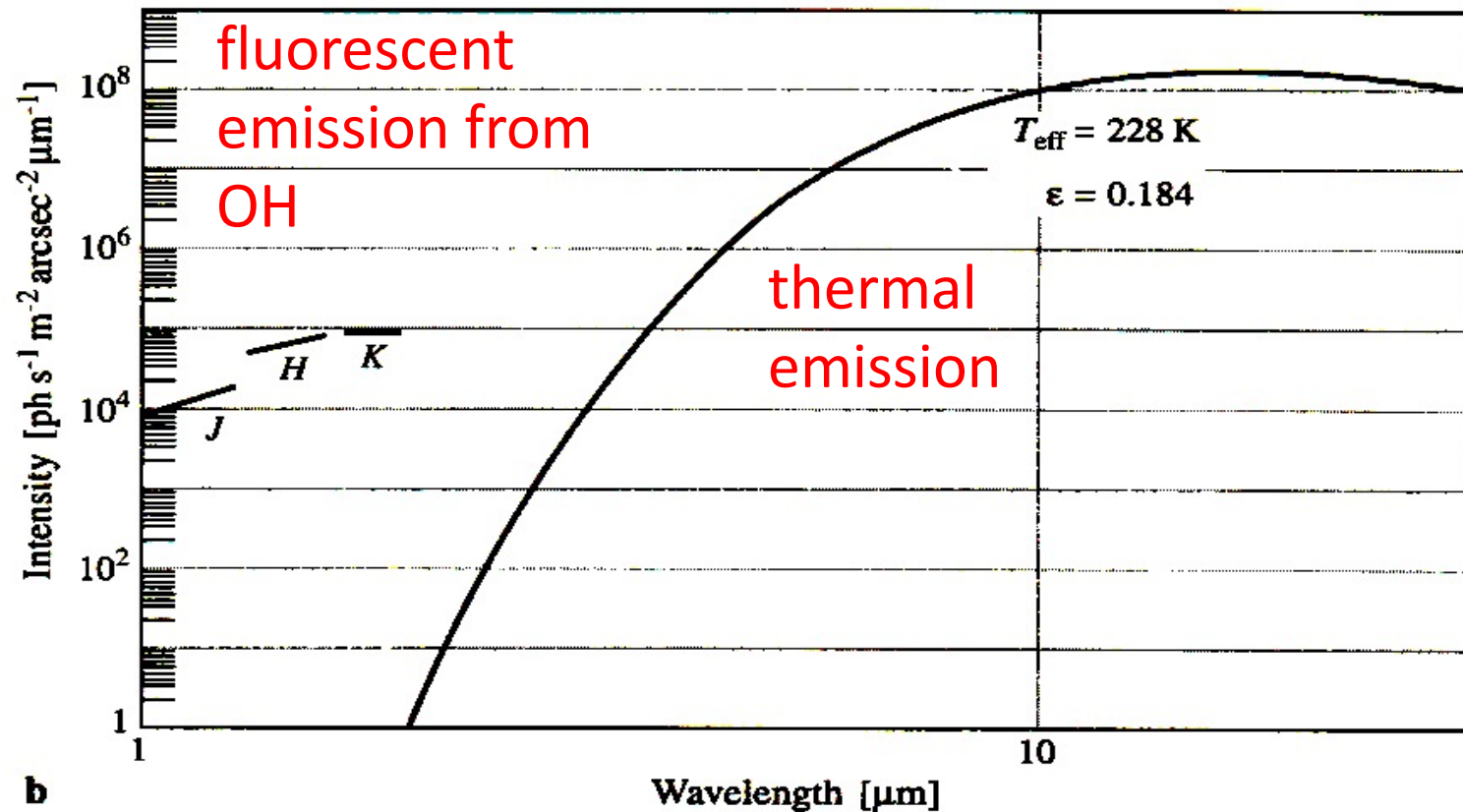
$$I_{\lambda}(z) = \frac{\tau_{\lambda} B_{\lambda}(T_{\text{mean}})}{\cos \theta}$$

$B_{\lambda}(T_{\text{mean}})$: Planck function at mean temperature T_{mean} of atmosphere

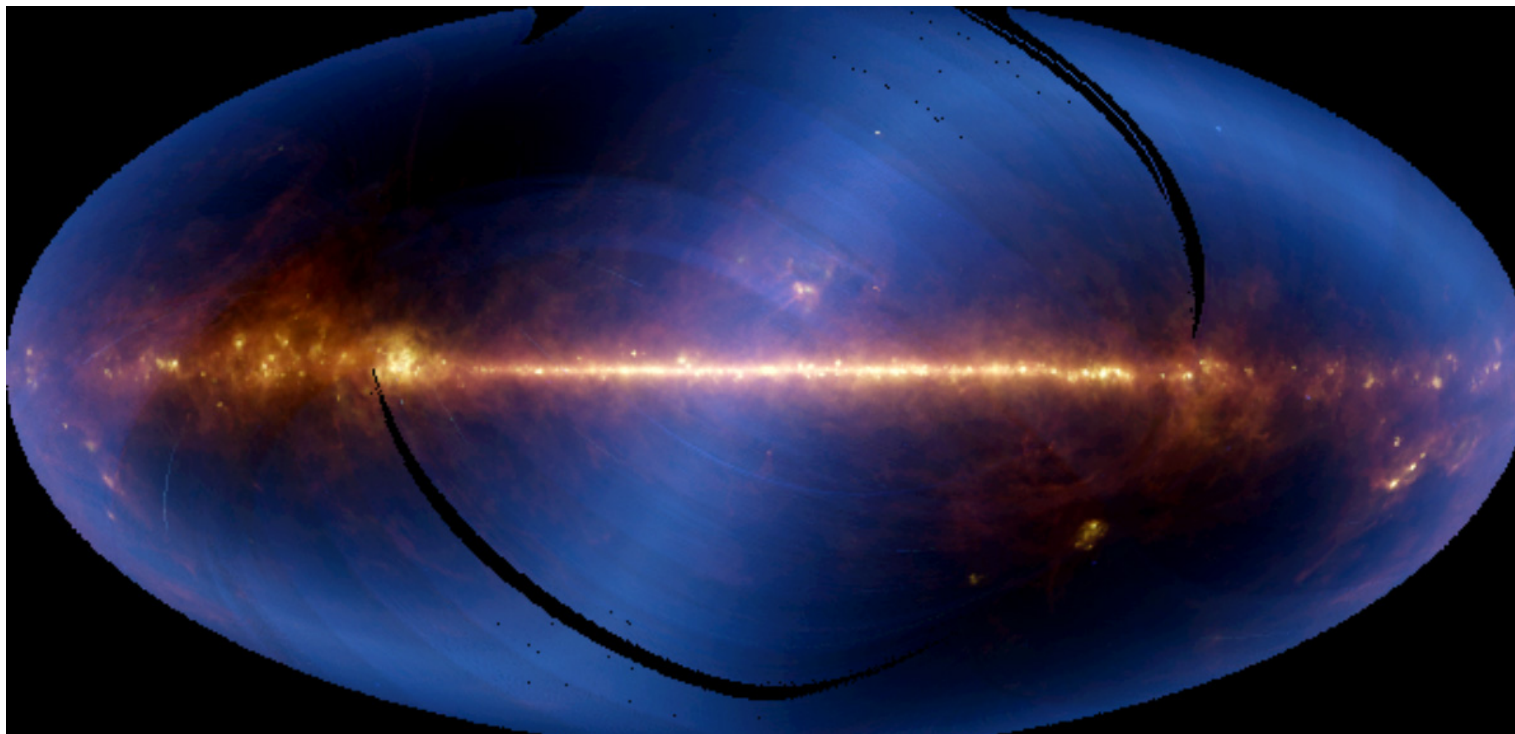
For $T = 250$ K and $\theta = 0$

Spectral band (cf. Sect. 3.3)	<i>L</i>	<i>M</i>	<i>N</i>	<i>Q</i>
Mean wavelength [μm]	3.4	5.0	10.2	21.0
Mean optical depth τ	0.15	0.3	0.08	0.3
Magnitude [arcsec ⁻²]	8.1	2.0	-2.1	-5.8
Intensity [Jy arcsec ⁻²] ^a	0.16	22.5	250	2100

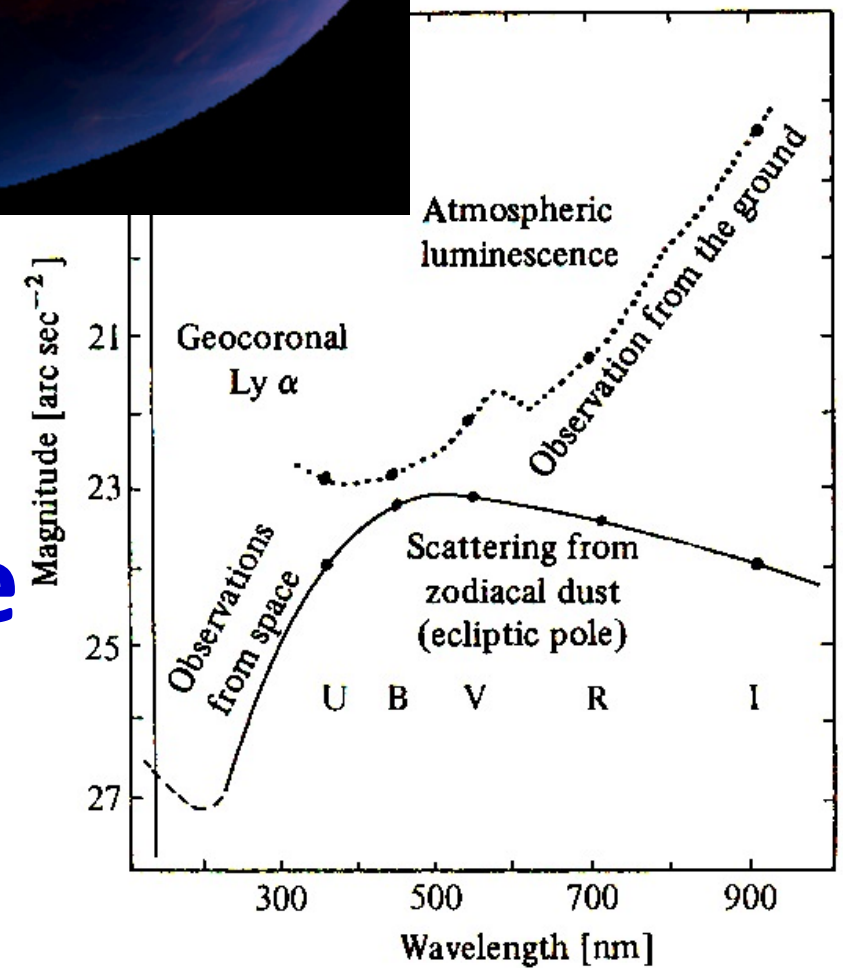
Fluorescent and Thermal Emission

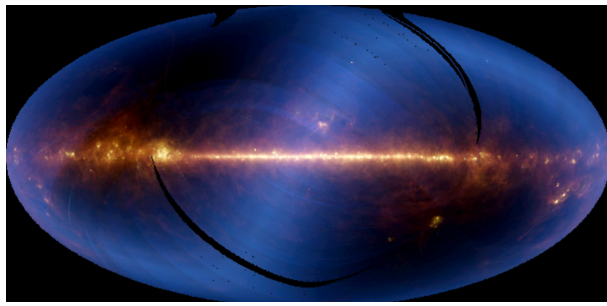


Sky **surface brightness** is important as even an unresolved point source has a finite angular diameter when viewed through a telescope.



Emission from Space





Emission from Space

Nearly the entire sky is shown in this image, assembled from six months of data from the Infrared Astronomical Satellite (IRAS). The bright horizontal band is the plane of the Milky Way, with the center of the Galaxy located at the center of the picture. The colors represent infrared emission detected in three of the telescope's four wavelength bands (blue is 12 microns; green is 60 microns, and red is 100 microns). Hotter material appears blue or white while the cooler material appears red. **The hazy, horizontal S-shaped feature that crosses the image is faint heat emitted by dust in the plane of the solar system.** Celestial objects visible in the photo are regions of star formation in the constellation Ophiucus (directly above the galactic center) and Orion (the two brightest spots below the plane, far right). The Large Magellanic Cloud is the relatively isolated spot located below the plane, right of center. Black stripes are regions of the sky that were not scanned by the telescope in its first six months of operation.

www.ipac.caltech.edu/Outreach/Gallery/IRAS/allsky.html



Molecular Scattering

- Molecular scattering in visible and NIR is Rayleigh scattering; scattering cross-section given by:

$$\sigma_R(\lambda) = \frac{8\pi^3}{3} \frac{(n^2 - 1)^2}{N^2 \lambda^4}$$

where N is the number of molecules per unit volume and n is the refractive index of air ($n-1 \sim 8 \cdot 10^{-5} P/T$).

- Rayleigh scattering is not isotropic:

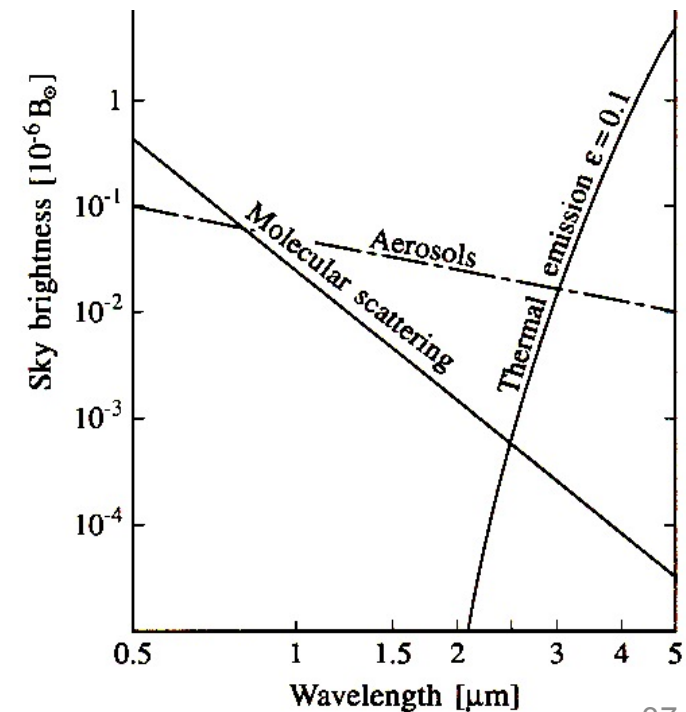
$$I_{scattered} = I_0 \frac{3}{16\pi} \sigma_R (1 + \cos^2 \theta) d\omega$$

Aerosol Scattering

- Aerosols (sea salt, hydrocarbons, volcanic dust) much larger diameter d than air molecules $\rightarrow$ NOT Rayleigh scattering
- Aerosol scattering described by **Mie theory** (classical electrodynamics, “scattering efficiency factor” Q):

$$Q_{\text{scattering}} = \frac{\sigma_M}{\pi a^2} = \frac{\text{scattering cross section}}{\text{geometrical cross section}}$$

- $d \gg \lambda$: $Q_{\text{scattering}} \sim Q_{\text{absorption}}$
 - scattered power equal to absorbed power
 - **effective cross section is twice the geometrical size**
- $d \sim \lambda$: $Q_s \sim 1/\lambda$ (for dielectric spheres):
 - **scattered intensity goes with $1/\lambda$**



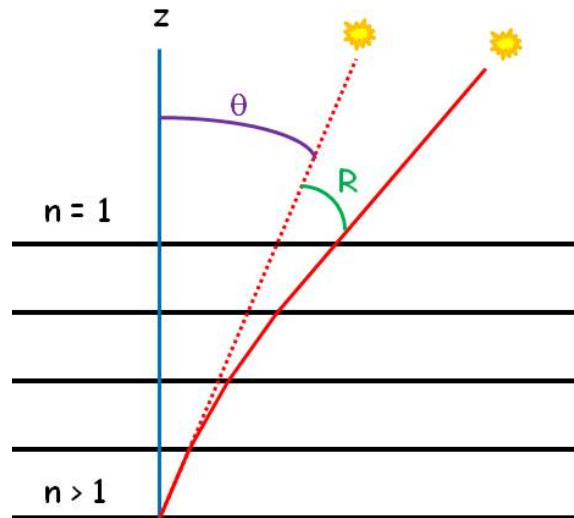
Atmospheric Refraction



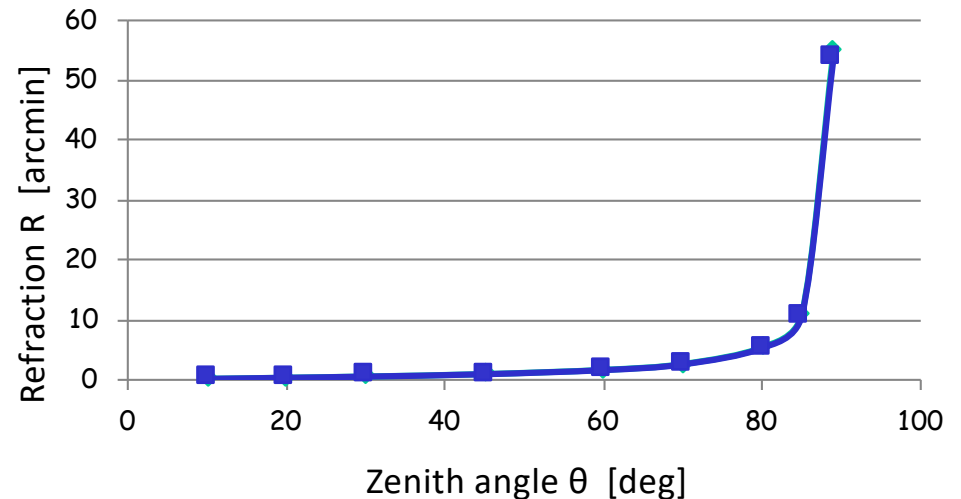
Atmospheric Refraction: Equations

Atmospheric refraction -> *apparent* location of source significantly altered (up to 0.5 degree near horizon) → telescope pointing must correct for refraction

Refraction $R = (n(\lambda) - 1) \tan \theta$



Atmospheric Refraction

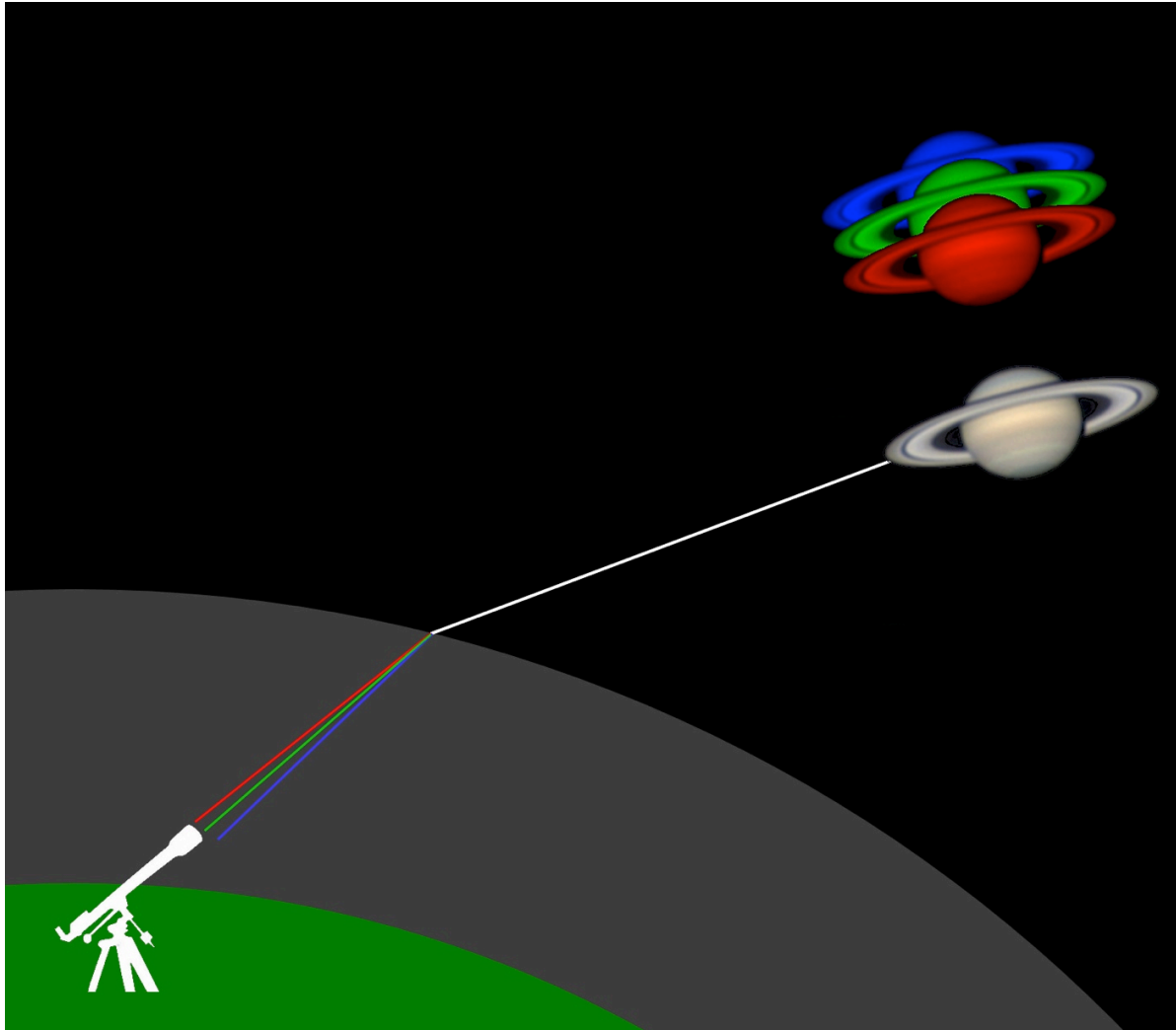


Refractive index of air depends on wavelength λ :

$$[n(\lambda) - 1] \times 10^6 = 64.328 + \frac{29498.1}{146 - \frac{1}{\lambda_0^2}} + \frac{255.4}{41 - \frac{1}{\lambda_0^2}}$$

(dry air, 1 atm pressure, $T \sim 290K$, λ_0 in $[\mu m]$)

Atmospheric Dispersion



[www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC\(2587060\).htm](http://www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm)

- **Dispersion:** Elongation of points in broadband filters due to $n(\lambda) \rightarrow$ “rainbow”
- Dispersion depends strongly on airmass and wavelength
- No problem if $\text{dispersion} < \lambda/D \leftarrow$ o.k. for small or seeing limited telescopes, but big problem for large, diffraction limited telescopes (e.g. E-ELT)

Green Flash

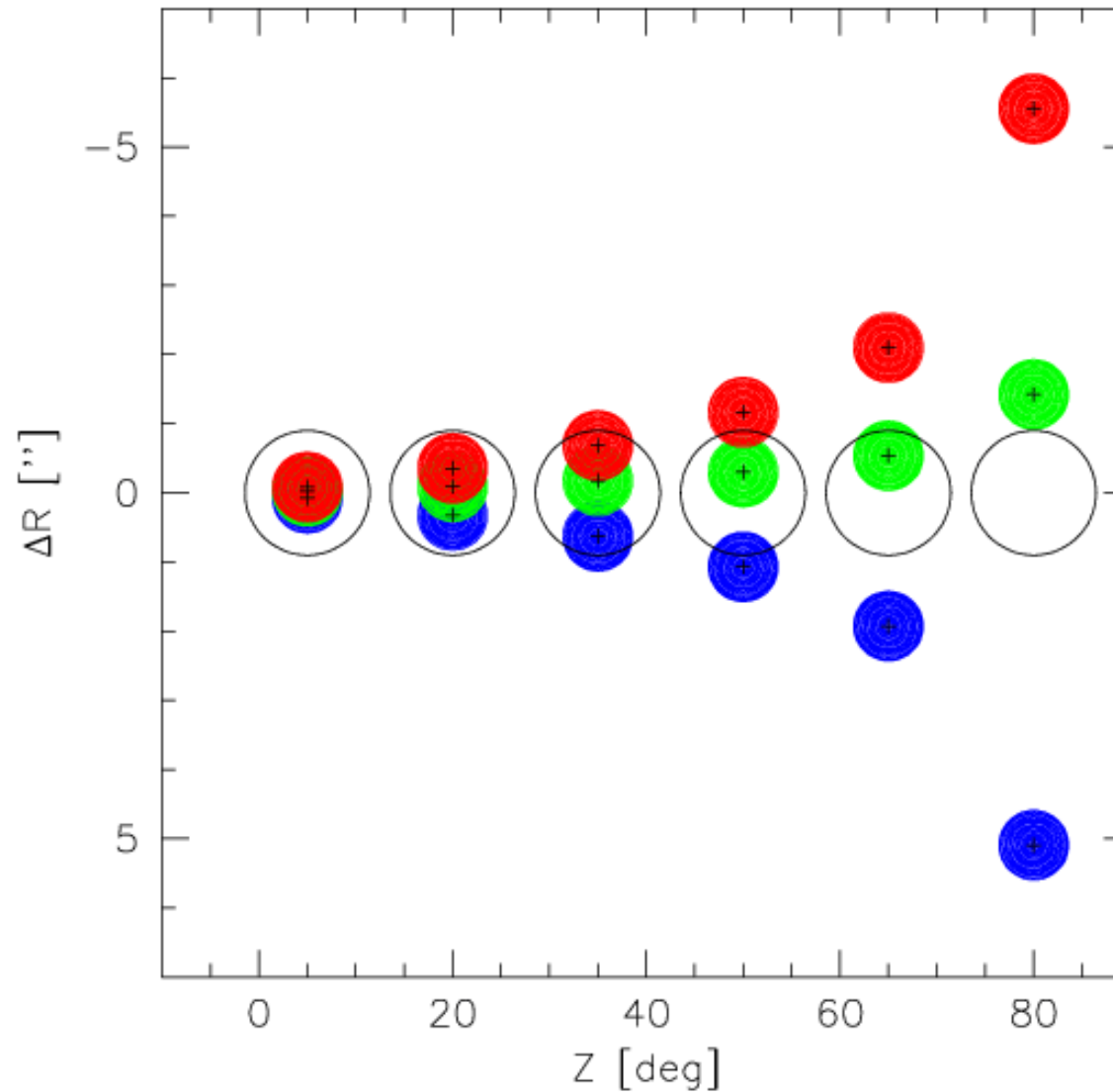


upload.wikimedia.org/wikipedia/commons/2/2b/Development_of_Green_Flash.jpg

A green flash is more likely to be seen in stable, clear air, when more of the light from the setting sun reaches the observer without being scattered. One might expect to see a blue flash, since blue light is refracted most of all, and the blue component of the sun's light is therefore the very last to disappear below the horizon, but the blue is preferentially scattered out of the line of sight, and the remaining light ends up appearing green.

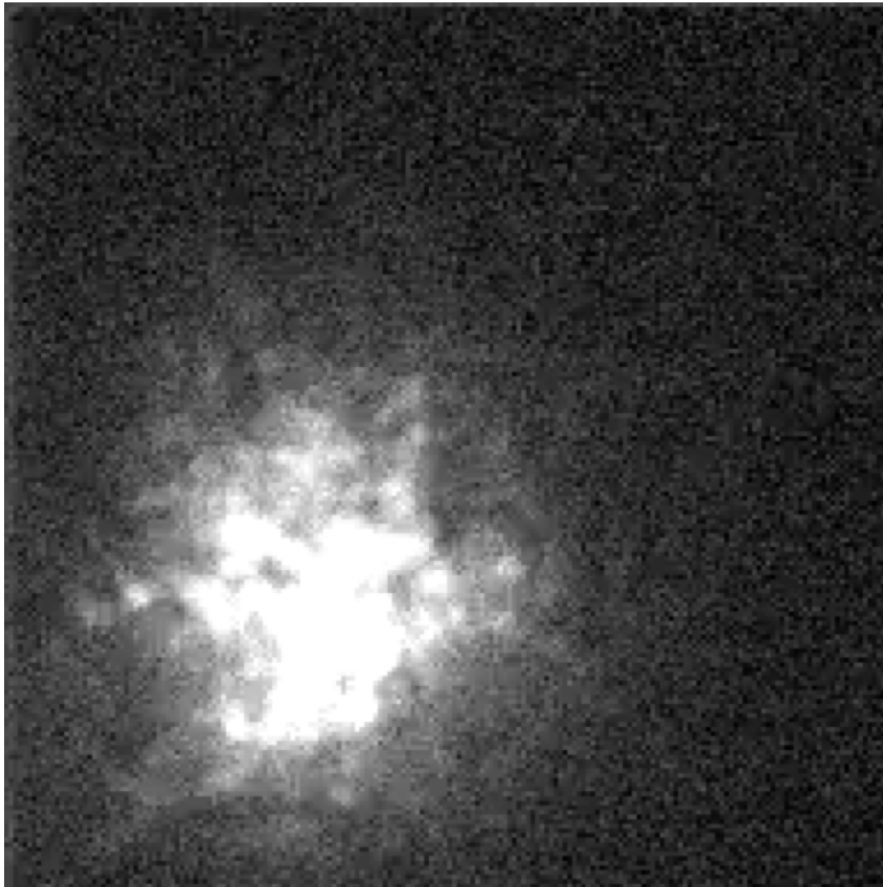
Atmospheric Dispersion

[H=30% ($\Rightarrow P_w=368.0849304 \text{ Pa}$)] [P=77500 Pa] [T=283.1499939 K] [$\lambda_{\text{ref}}=450 \text{ nm}$] [D(fib)=1.799999952 "] [1" FWHM]

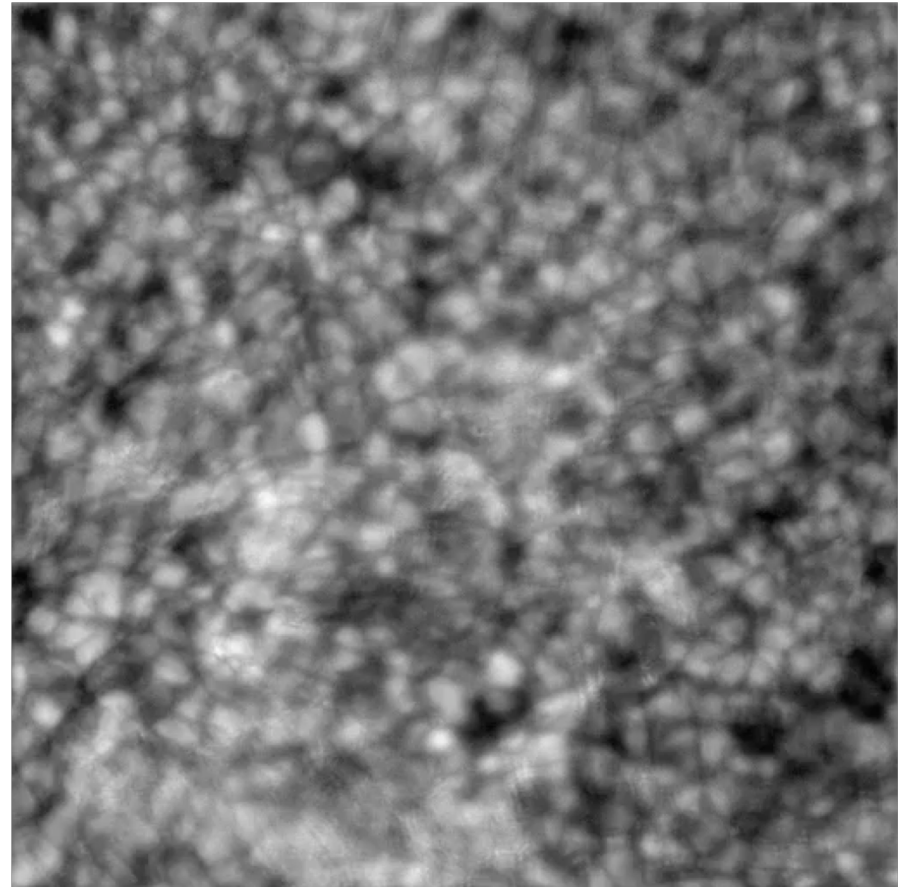


Solution: Atmospheric Dispersion Corrector: a set of prisms that correct for this

Atmospheric Turbulence: Seeing

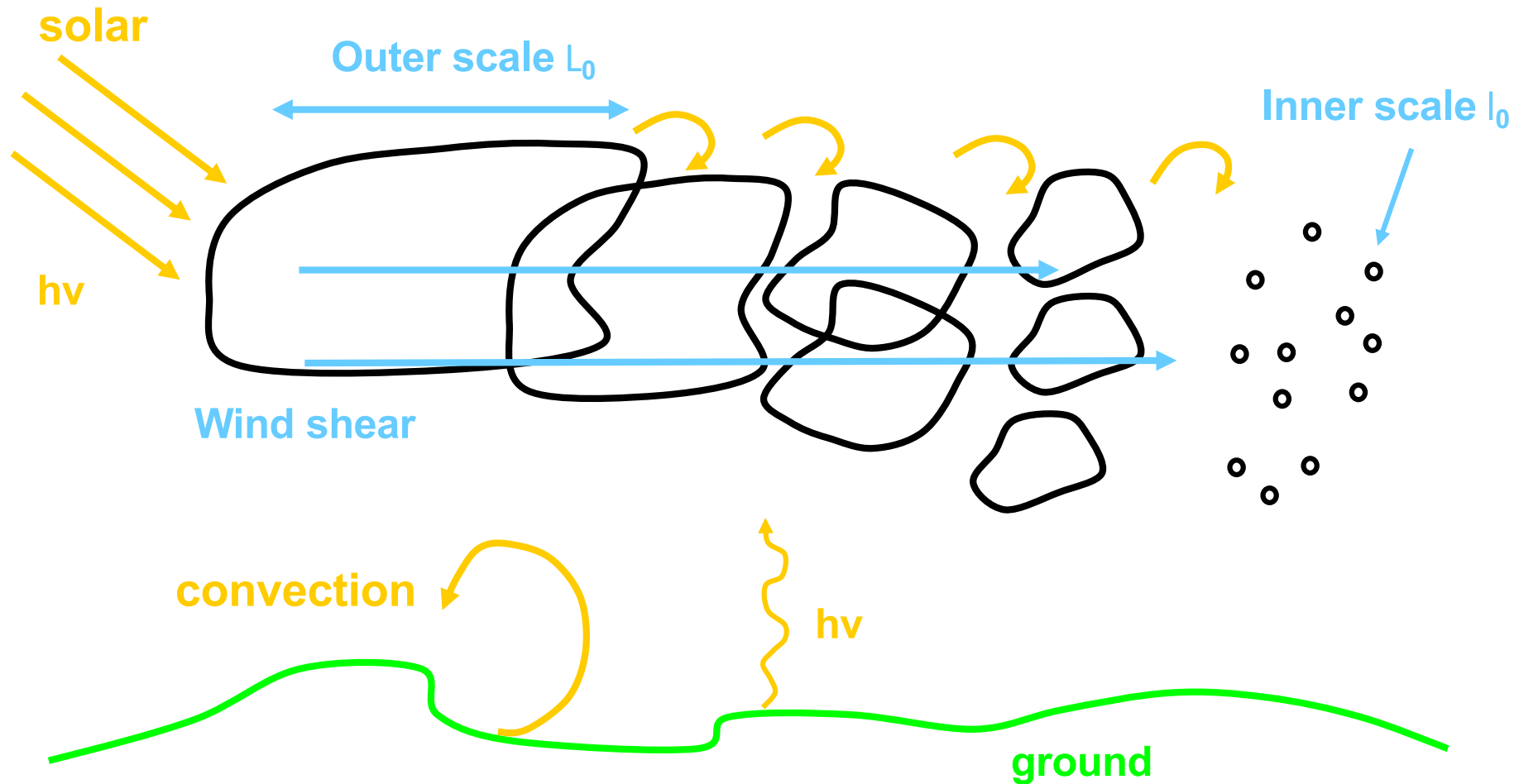


α Ori



solar photosphere

Atmospheric Turbulence: Origin



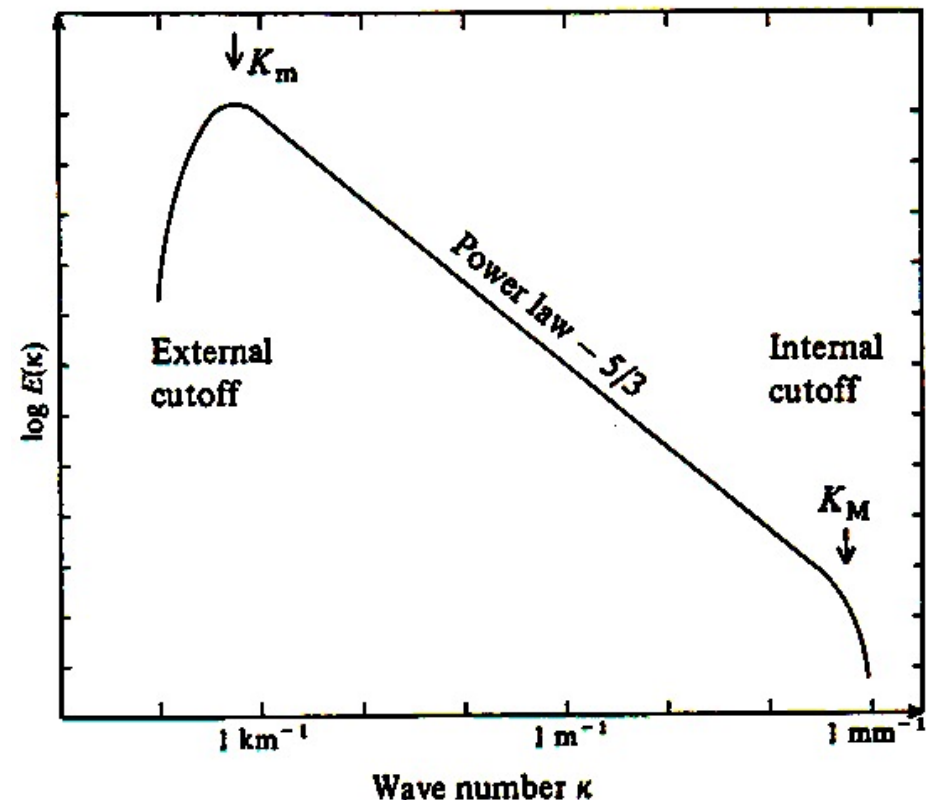
Kolmogorov Turbulence

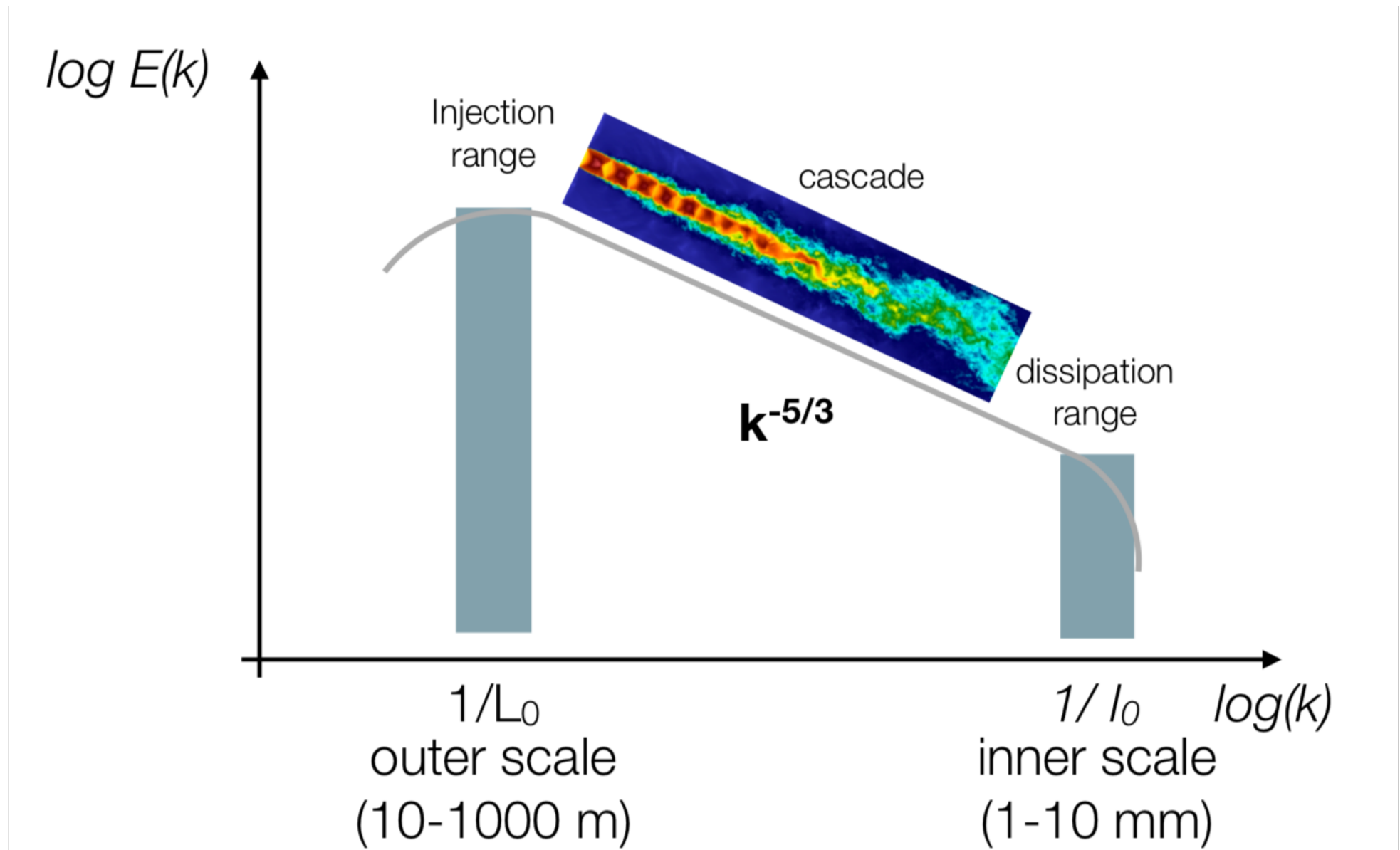
- kinetic energy of large scale ($\sim L$) movements transferred to smaller and smaller scales, down to minimum scale length l_0 , where energy is dissipated by viscous friction
- local velocity field decomposed into spatial harmonics of wave vector κ (Fourier domain)
- $1/\kappa$ is considered length scale
- mean spectrum of kinetic energy (Kolmogorov spectrum)

$$E(\kappa) \propto \kappa^{-5/3}$$

- l_0 = inner scale, L_0 = outer scale

$$L_0^{-1} < \kappa < l_0^{-1}$$



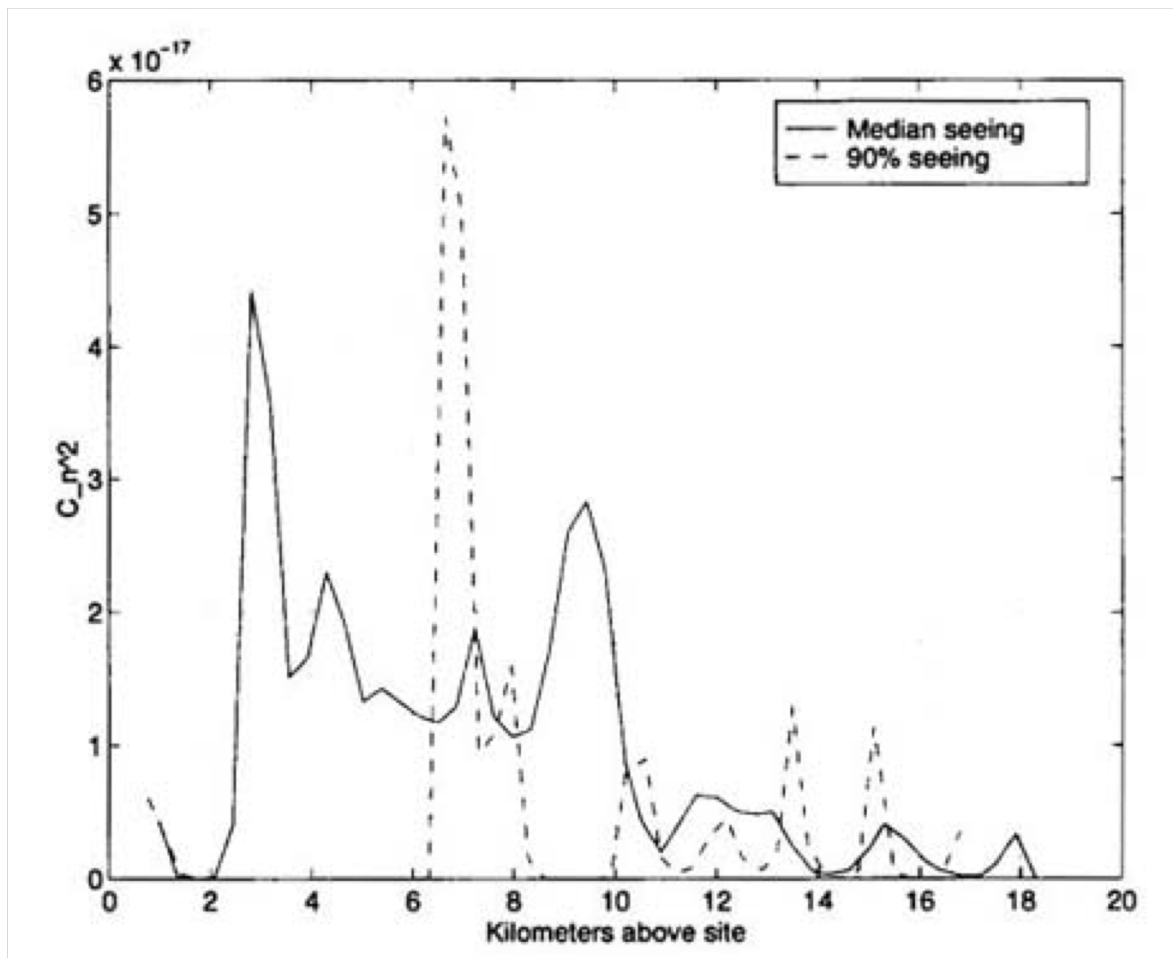


Air Refractive Index Fluctuations

- winds mix layers of different temperature $\rightarrow$ fluctuations of temperature $T \rightarrow$ fluctuations of density $\rho \rightarrow$ fluctuations of refractive index n
- 1K temperature difference changes n by 1×10^{-6}
- variation of 0.01K along path of 10km:
 $10^4 \text{ m} \times 10^{-8} = 10^{-4} \text{ m} = 100 \text{ waves at } 1\mu\text{m}$
- refractive index of water vapour is less than that of air
 $\rightarrow$ moist air has smaller refractive index

Index Fluctuations with Altitude

- $C_n^2(z) \cdot \Delta z$ indicates index fluctuation contributions from layer Δz
- typical value: $C_n^2 \cdot \Delta z \sim 4 \cdot 10^{-13} \text{ cm}^{1/3}$ for a 3 km altitude layer
- turbulence often occurs in layers



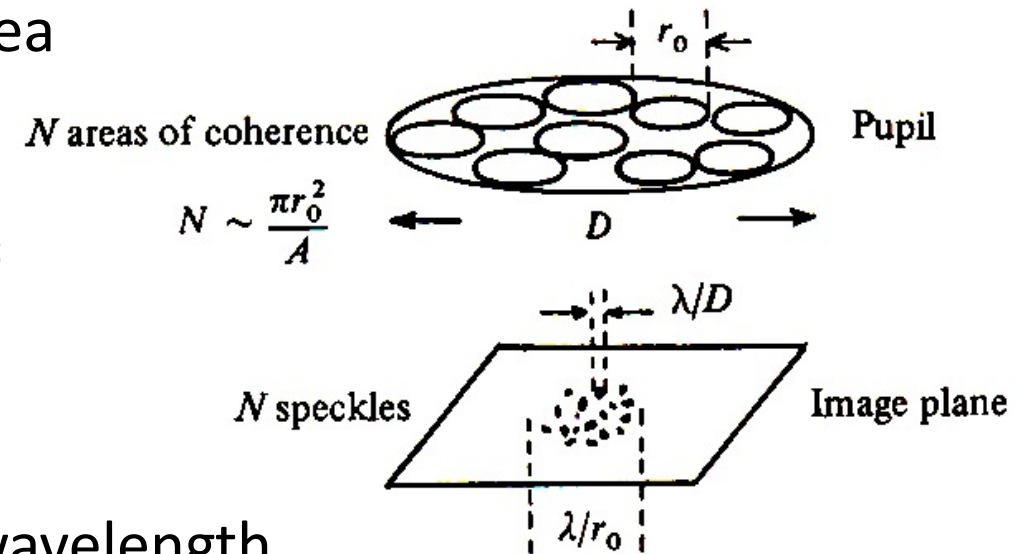
Median seeing conditions on Mauna Kea $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are $r_o \sim 0.40$ m.

www.gemini.edu/sciops/instruments/adaptiveOptics/mk_cn2.jpg

Fried Parameter r_0

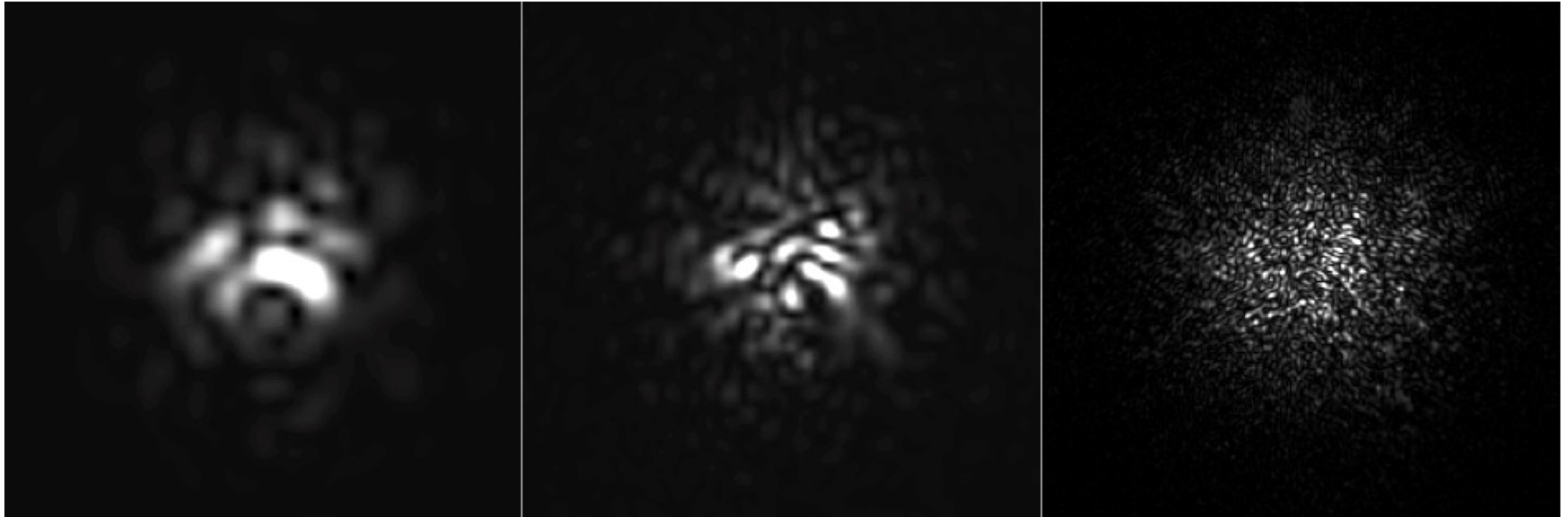
- radius of spatial coherence area
(of wavefront) given by
Fried parameter r_0 :

$$r_0(\lambda) = 0.185\lambda^{6/5} \left[\int_0^\infty C_n^2(z) dz \right]^{-3/5}$$



- r_0 increases as 6/5 power of wavelength
- r_0 is average scale over which rms optical phase distortion is 1 rad
- angle $\Delta\theta = \lambda/r_0$ is the seeing in arcsec
- r_0 at good sites: 10 - 30 cm (at $0.5\mu\text{m}$)
- seeing is roughly equivalent to FWHM of long-exposure image of a point source (Point Spread Function)

Speckles & Telescope Diameter



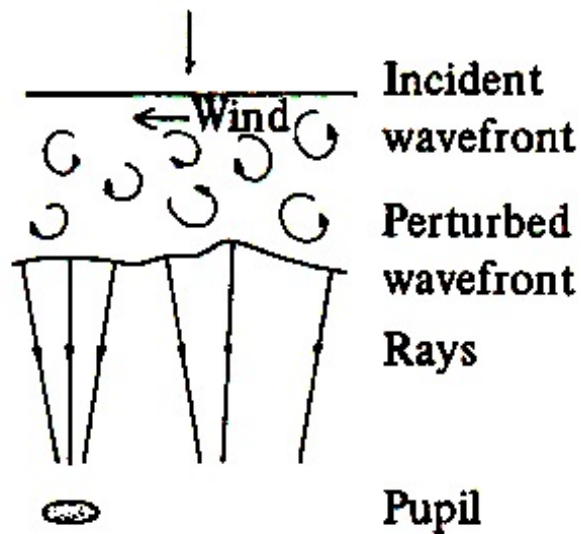
1 m

2 m

8 m

Telescope Diameter

Aspects of Image Degradation



Scintillation

energy received by pupil varies in time (stars flicker)

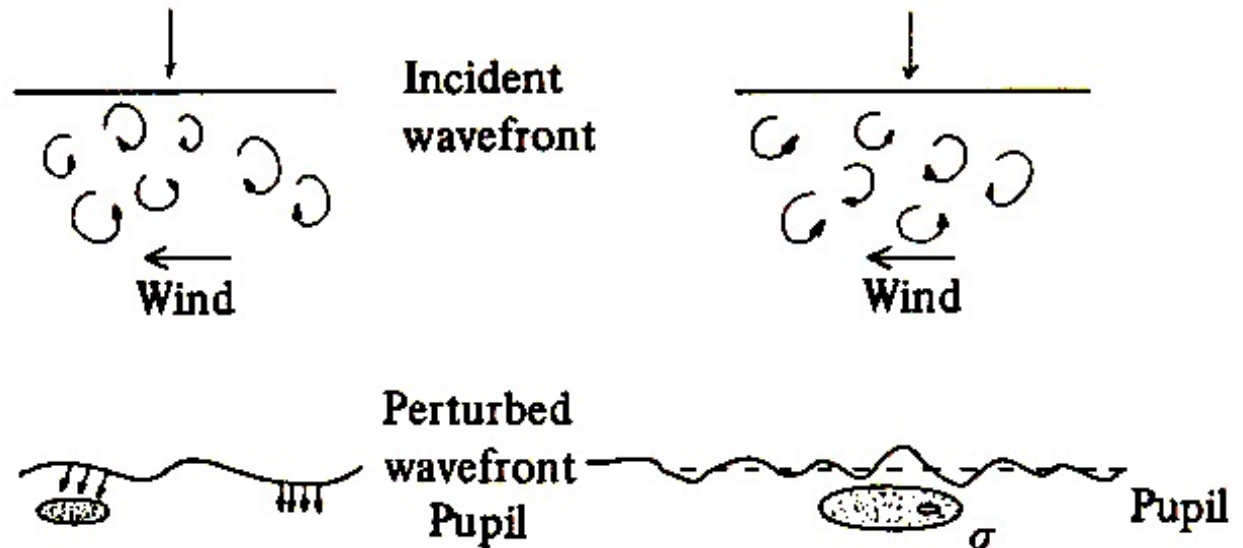


Image Motion

average slope of wavefront at pupil varies ("tip-tilt", stars move around)

Image Blurring

wavefront is not flat ("seeing")

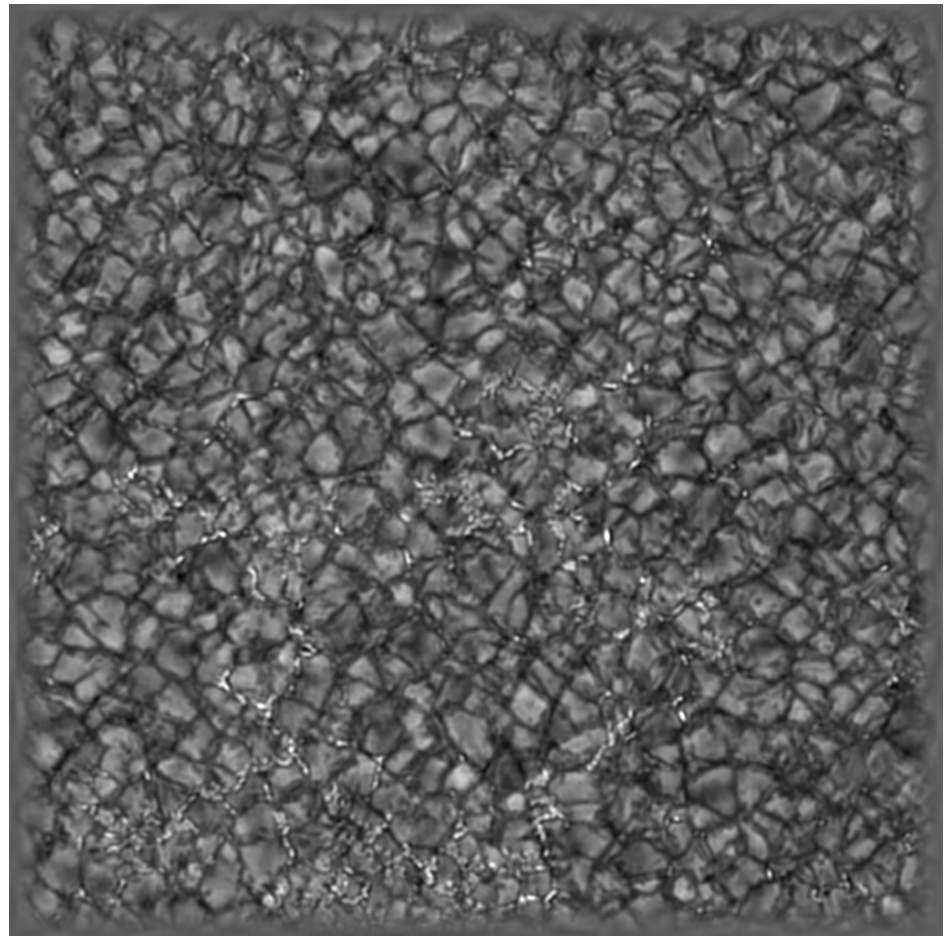
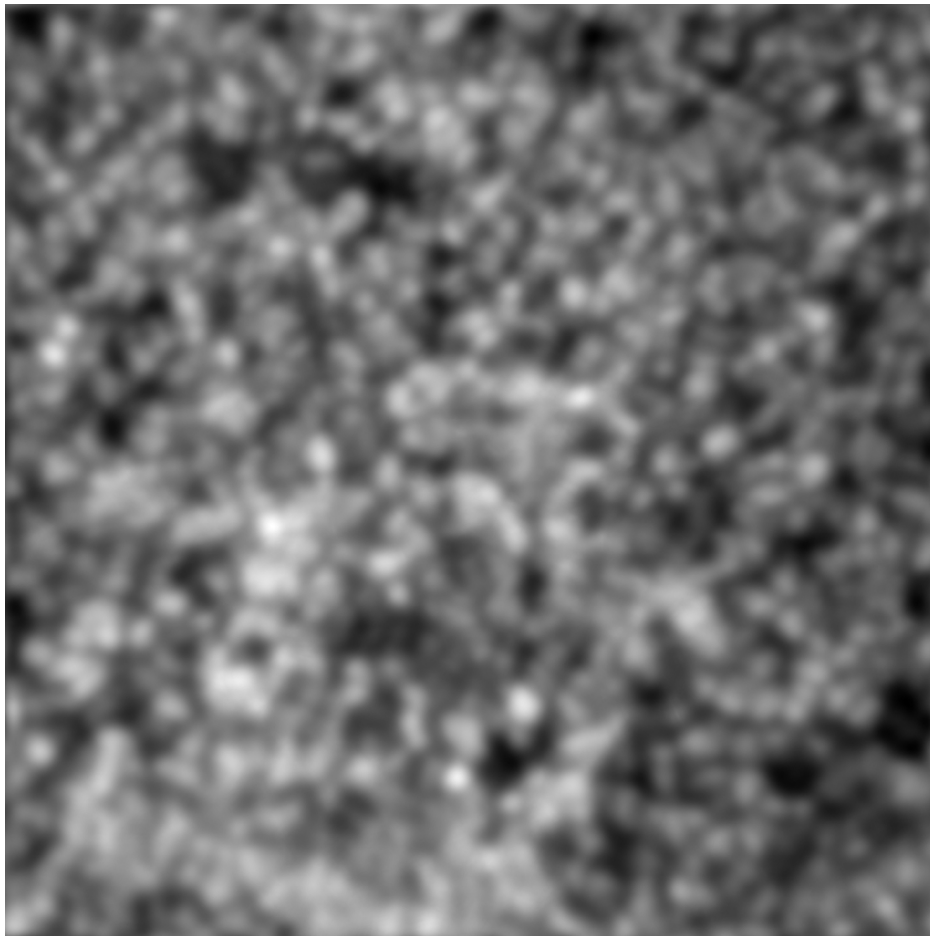
Long Exposure through Turbulence

- atmospheric coherence time:
maximum time delay for RMS wavefront error to be less than 1 rad (v is mean wind velocity)

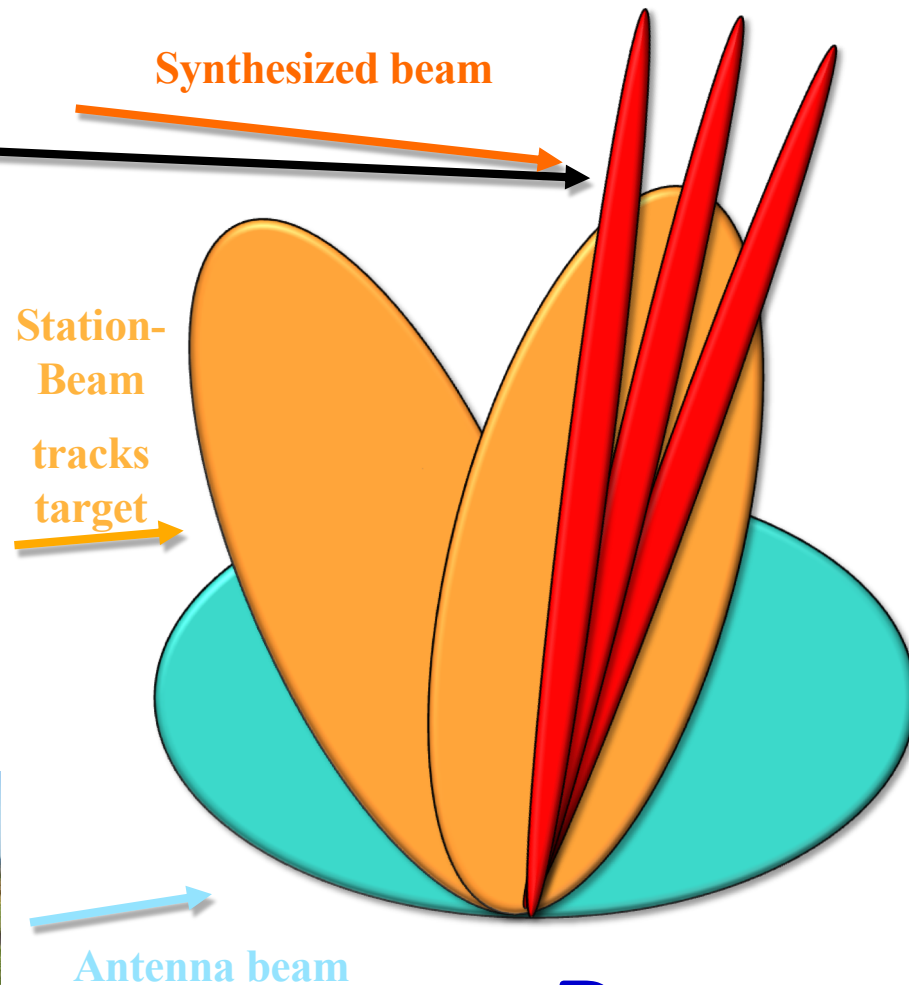
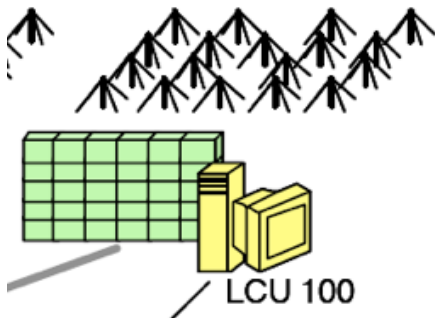
$$\tau_0 = 0.314 \frac{r_0}{\bar{v}}$$

- integration time $t_{\text{int}} \gg \tau_0$
→ image is mean of many instantaneous images
- angular resolution $\sim \lambda/r_0$ instead of $\sim \lambda/D$
- for $D > r_0$, bigger telescopes will *not* provide sharper images!

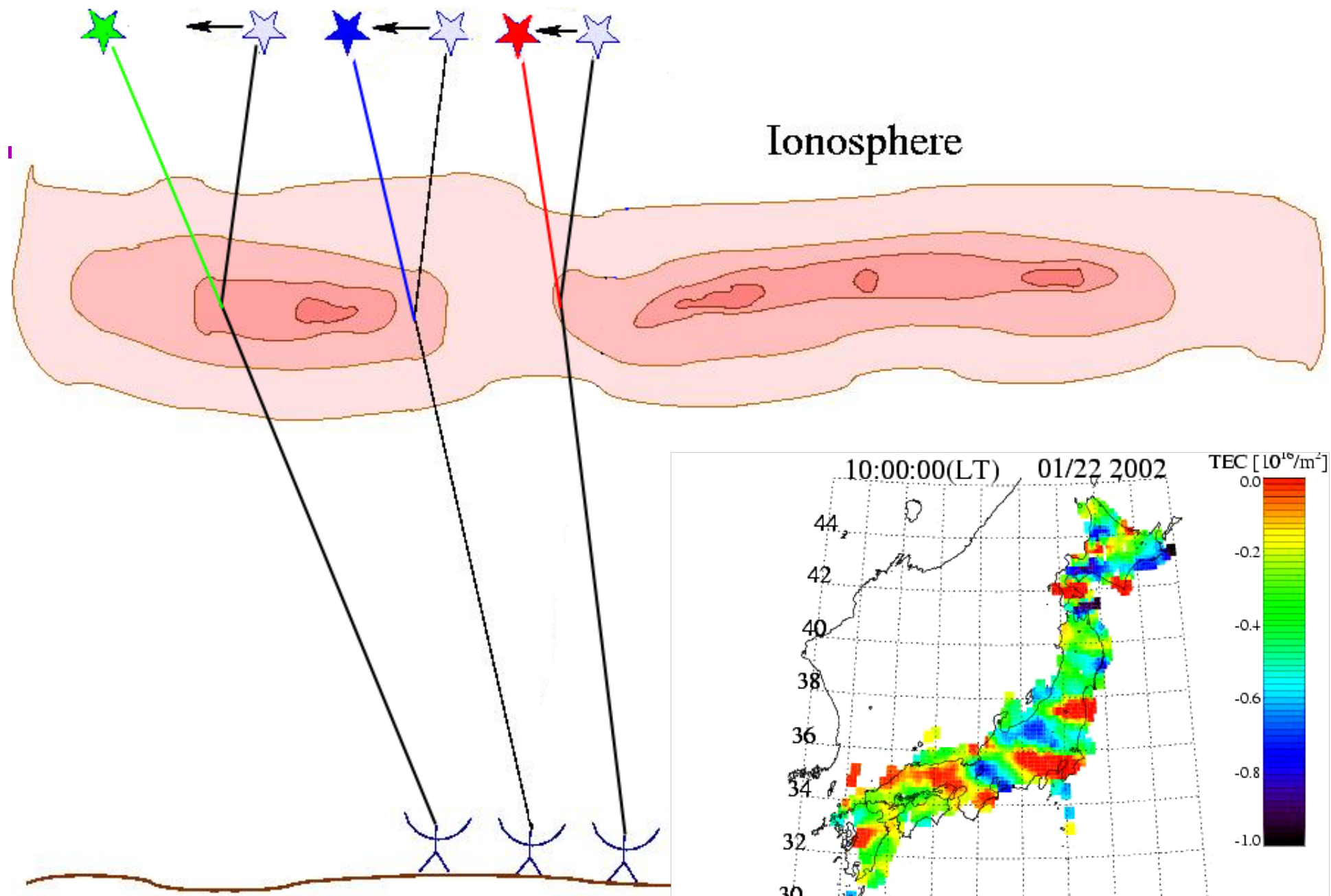
Long Exposure of Solar Photosphere



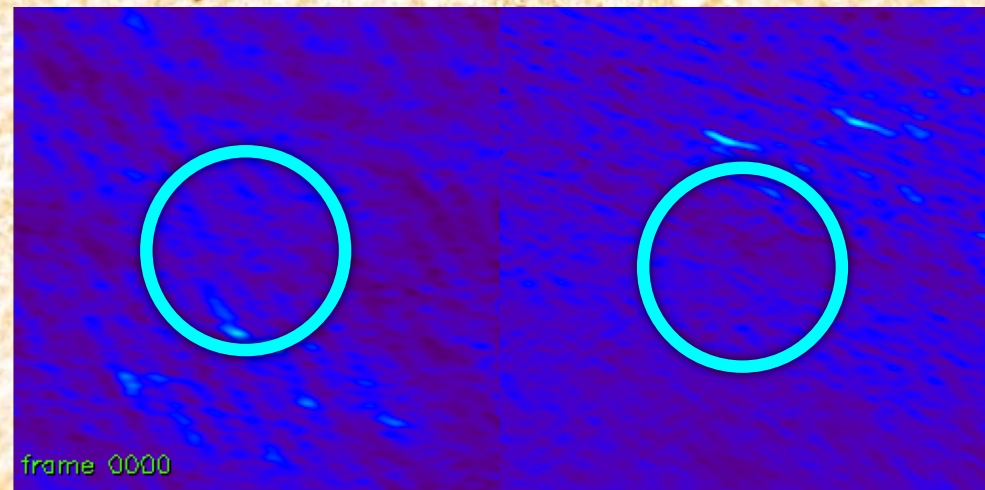
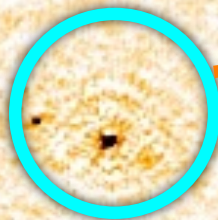
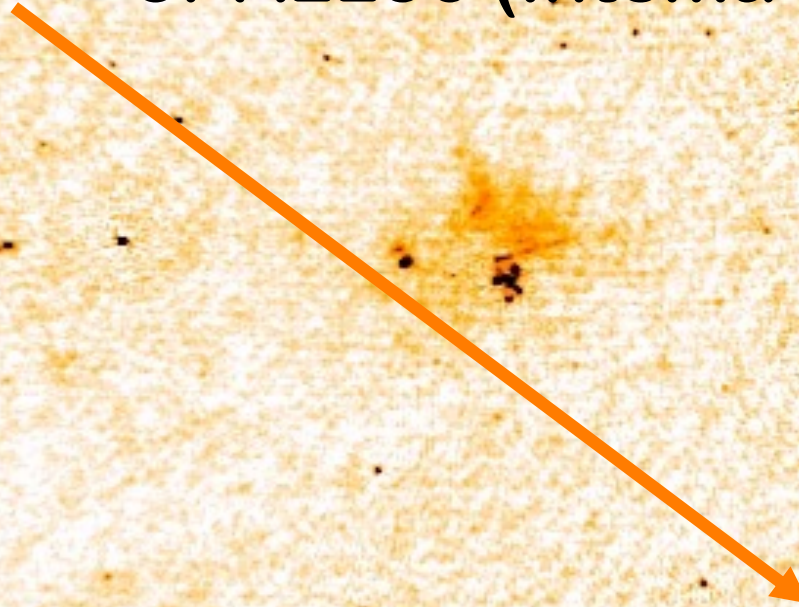
Low frequency radio astronomy and the ionosphere



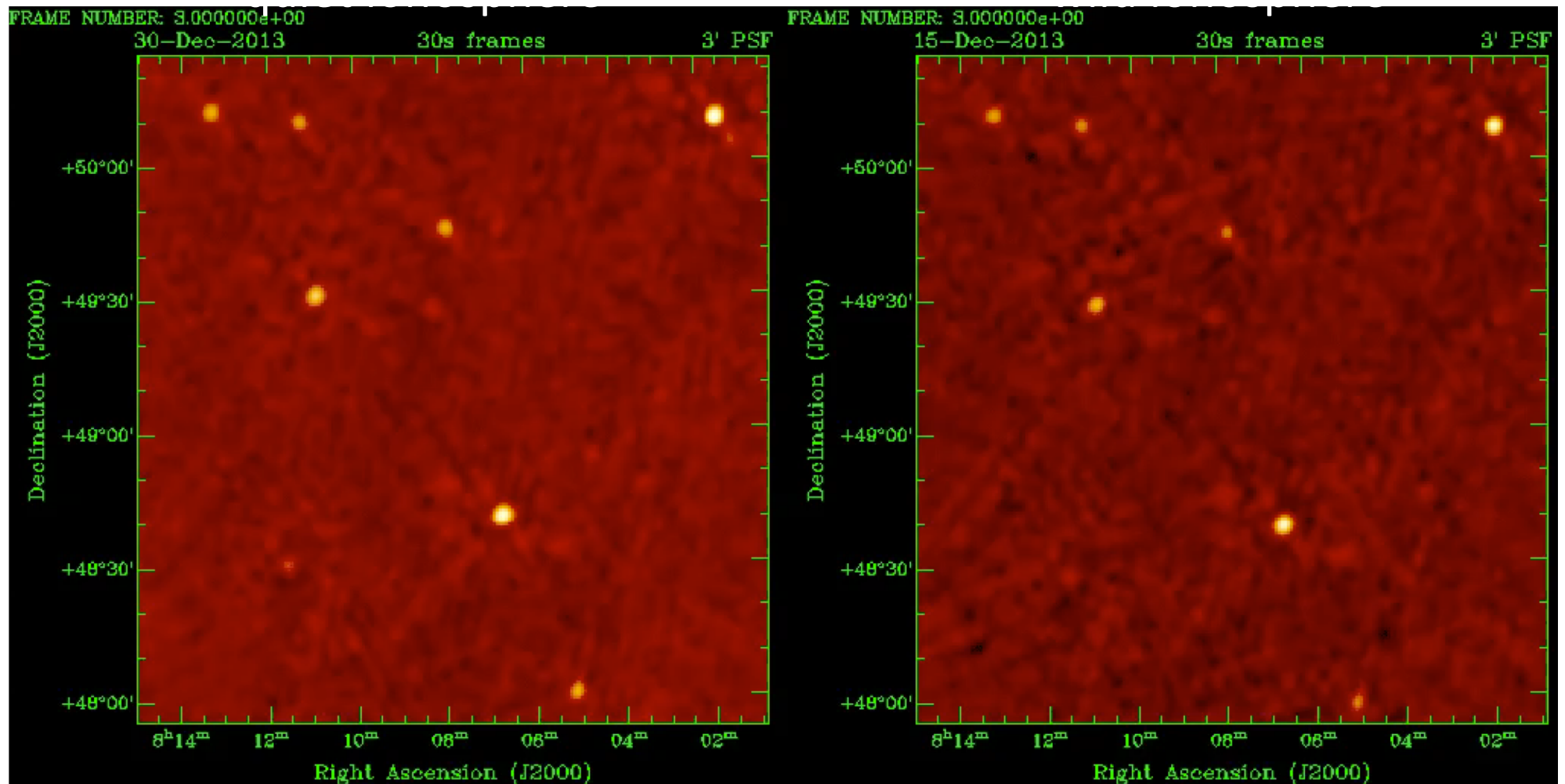
Beams of LOFAR



**150 MHz GMRT
radio observations
of A2256 (Intema et 2009)**

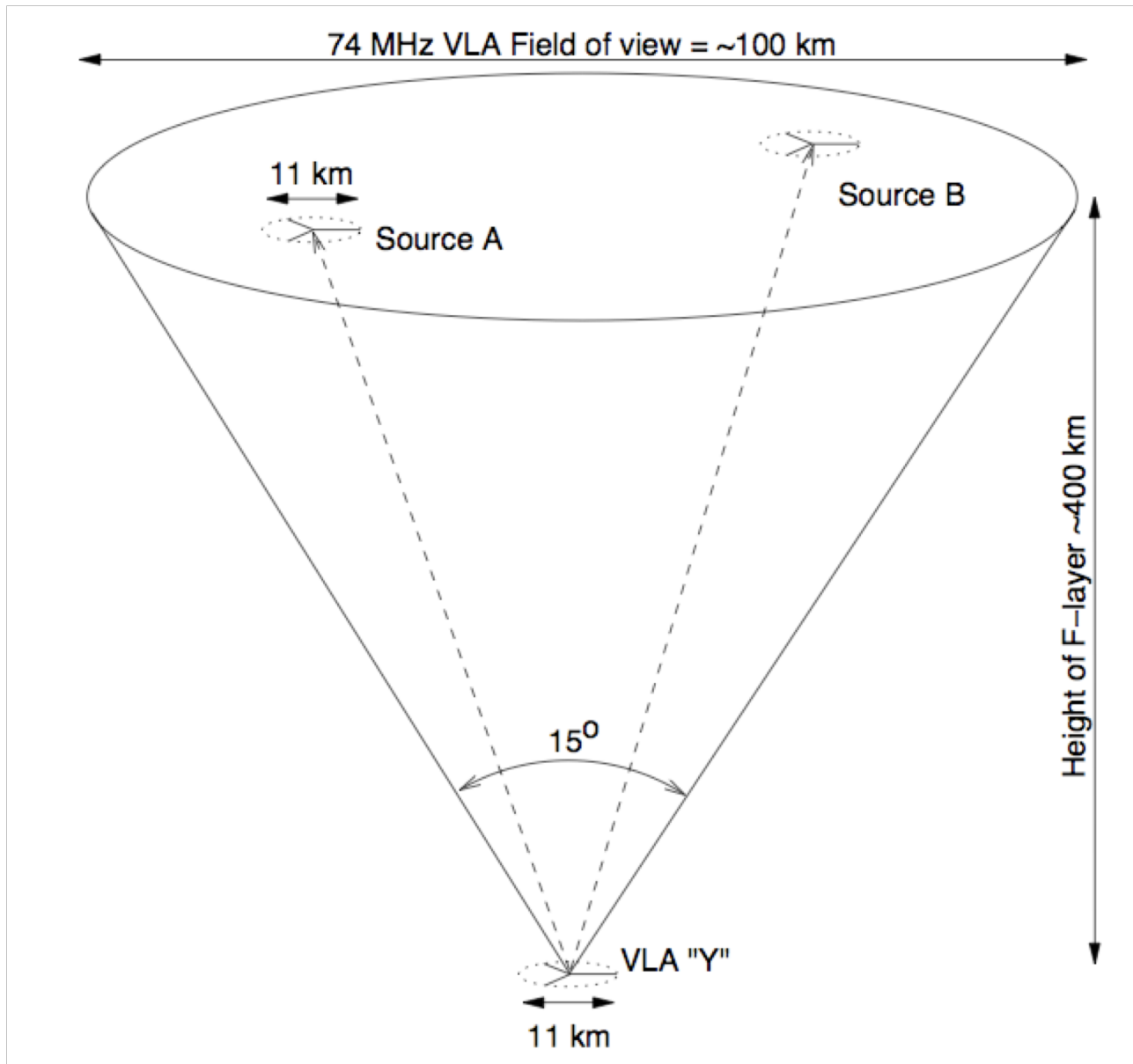


Ionosphere over LOFAR



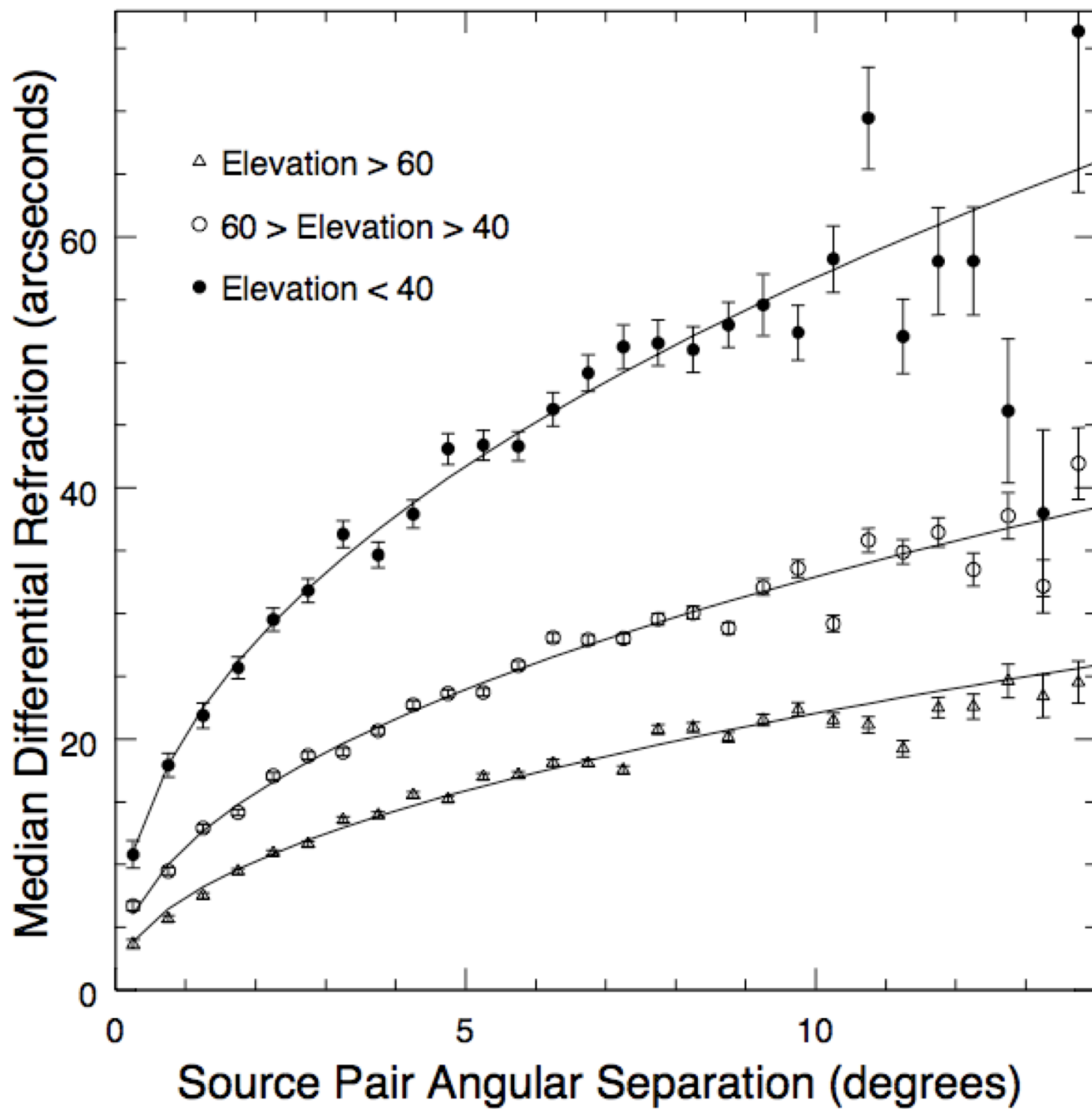
Seeing ~ 1 arcmin, variation time scale $\sim$ few sec

74 MHz VLA system

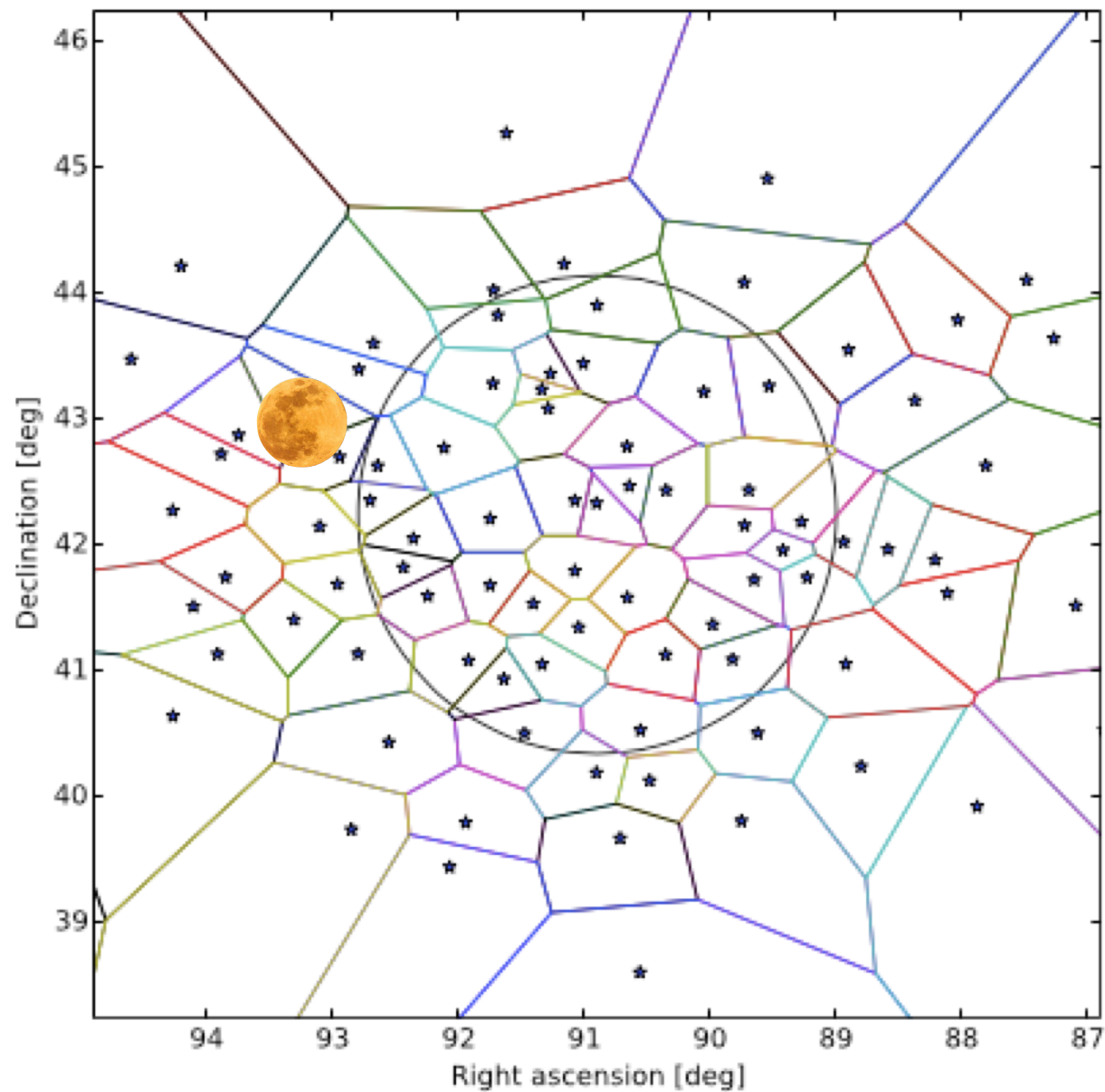


Consider differential refraction

$$r_{ij} = |\vec{r}_i - \vec{r}_j|$$



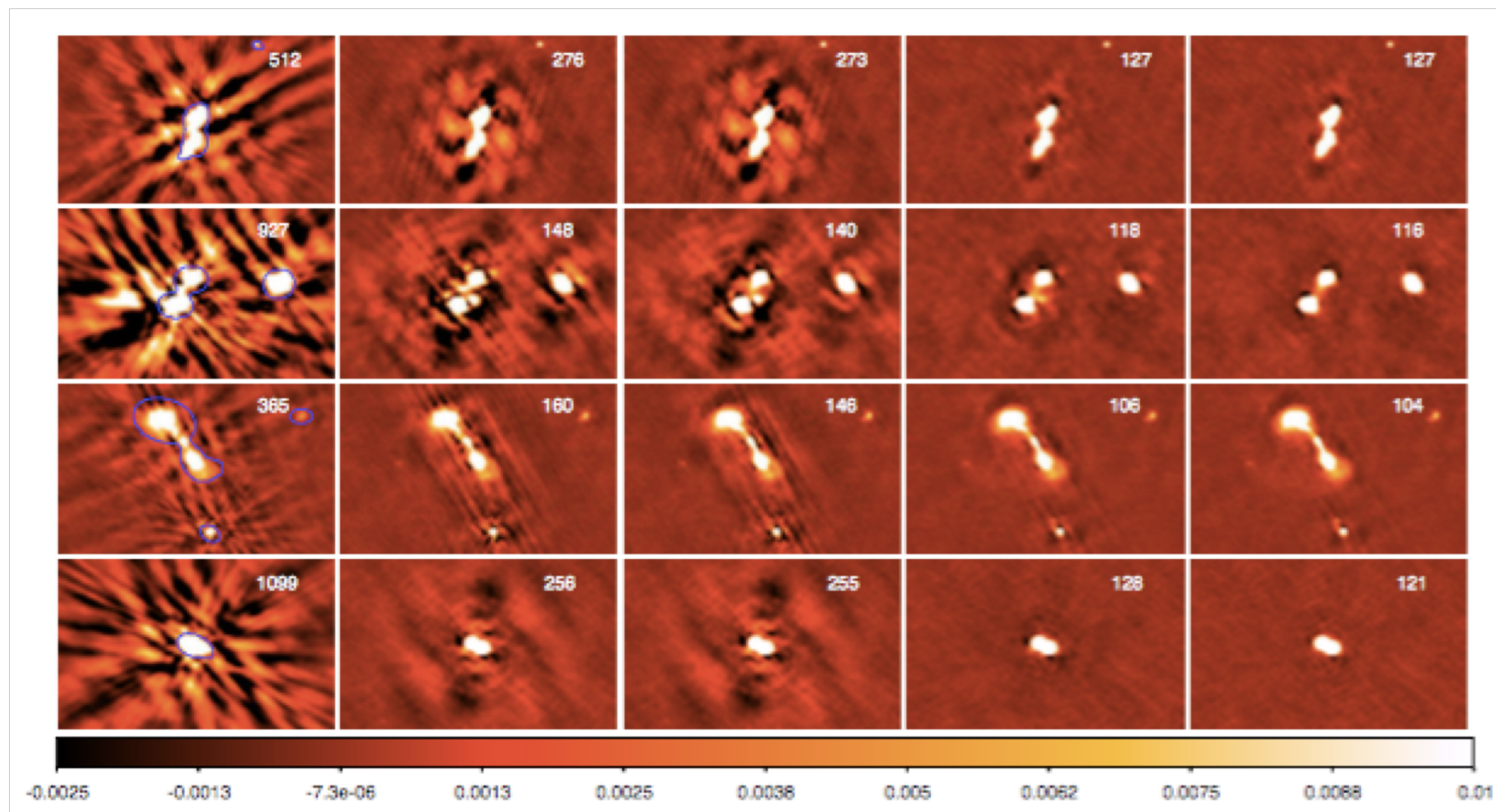
Solution: facet calibration

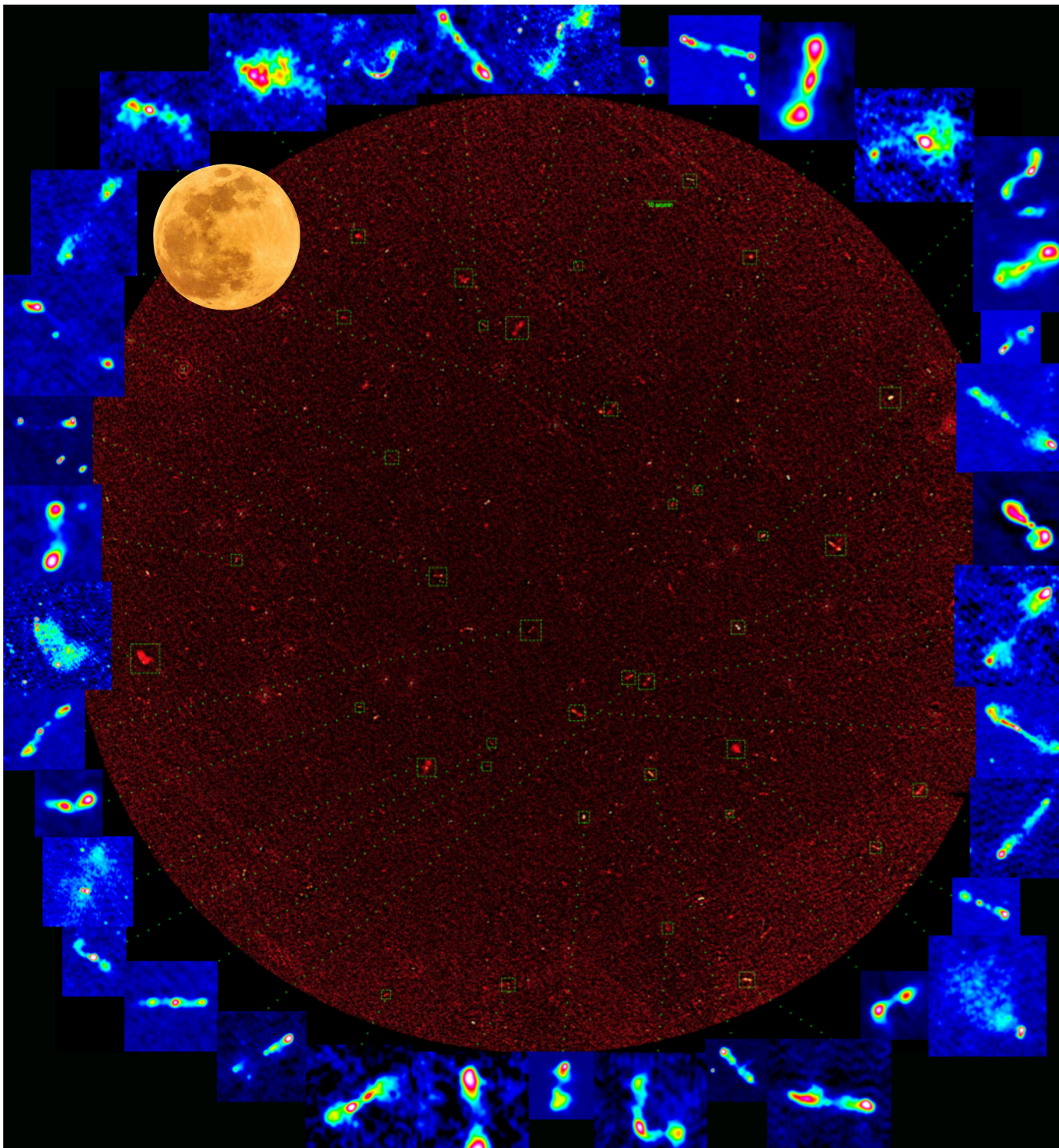


LOFAR FOV
at 150 MHz

Solve for the ionospheric phase distortions in patches
centered on bright sources

Improvements after each iteration





PhD
Wendy
Williams