# Astronomical Observing Techniques

## Lecture 2: Earth Atmosphere

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# Outline

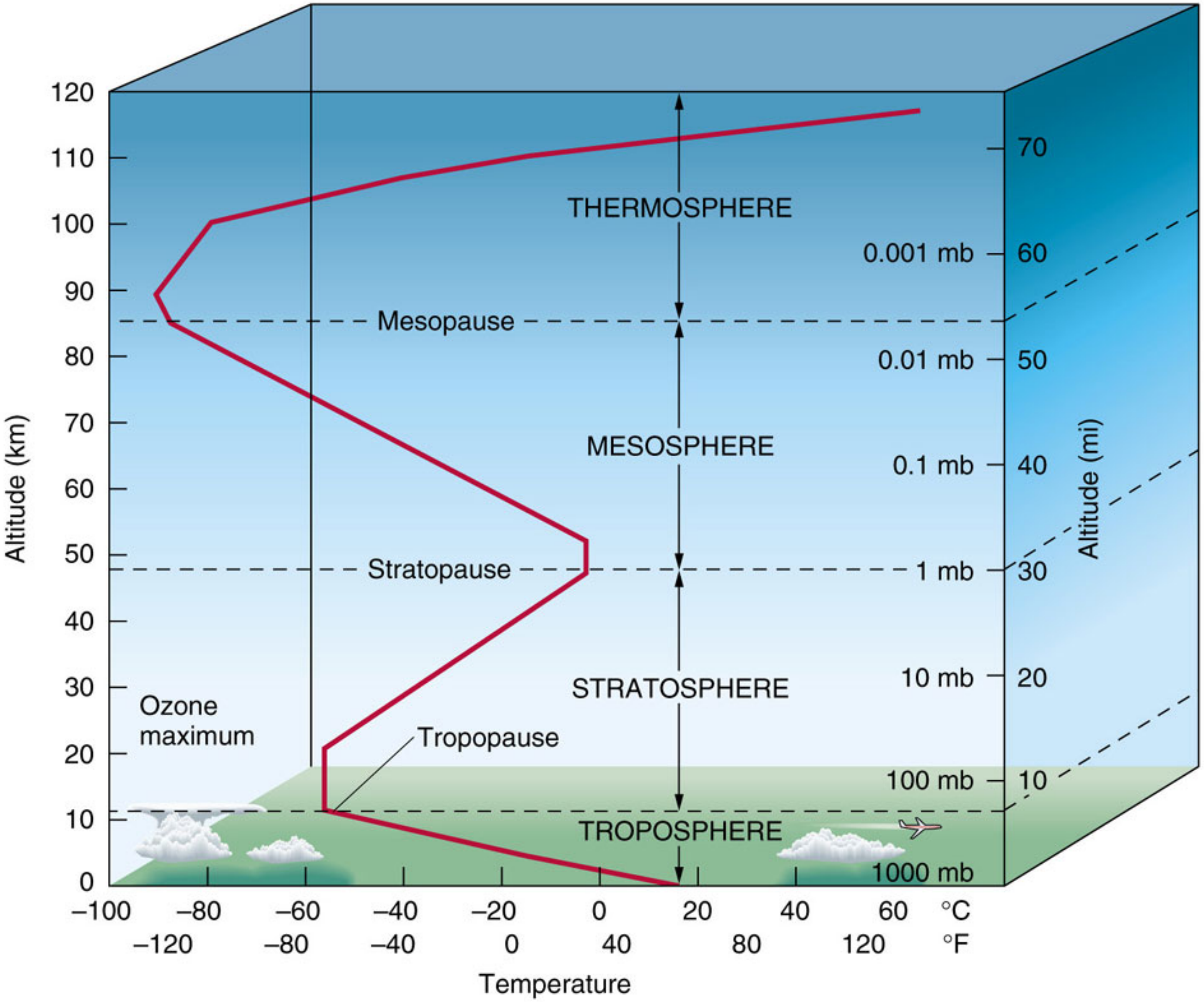
1. Atmospheric Structure
2. Absorption
3. Emission
4. Scattering, Refraction & Dispersion
5. Turbulence & Seeing

# 1. Atmospheric Structure

- Assumptions:
  - atmosphere in local radiative equilibrium
  - homogeneous composition
- Hydrostatic equilibrium structure described by:
  - altitude *z*
  - temperature *T(z)*
  - density *ρ(z)*
- Pressure *P(z)* described by: $P(z) = P_0 e^{-\frac{z}{H}}, \quad H = \frac{kT}{\mu g}$

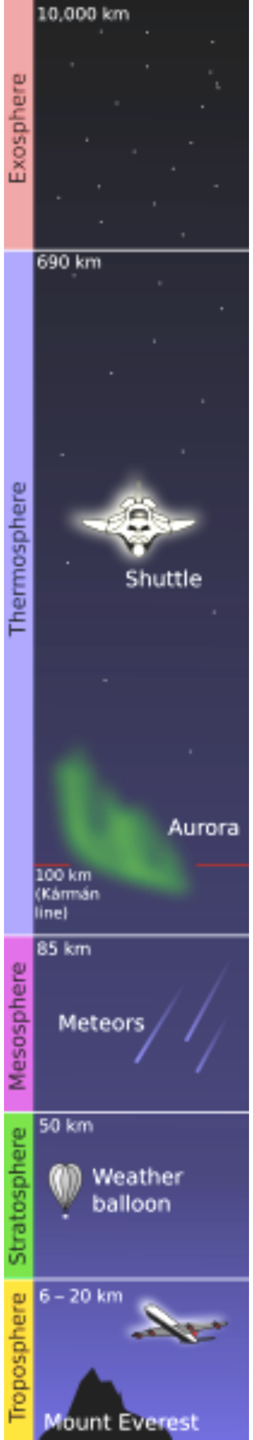
*H* = scale height (~ 8km), μ = mean molecular weight

# Vertical Profile

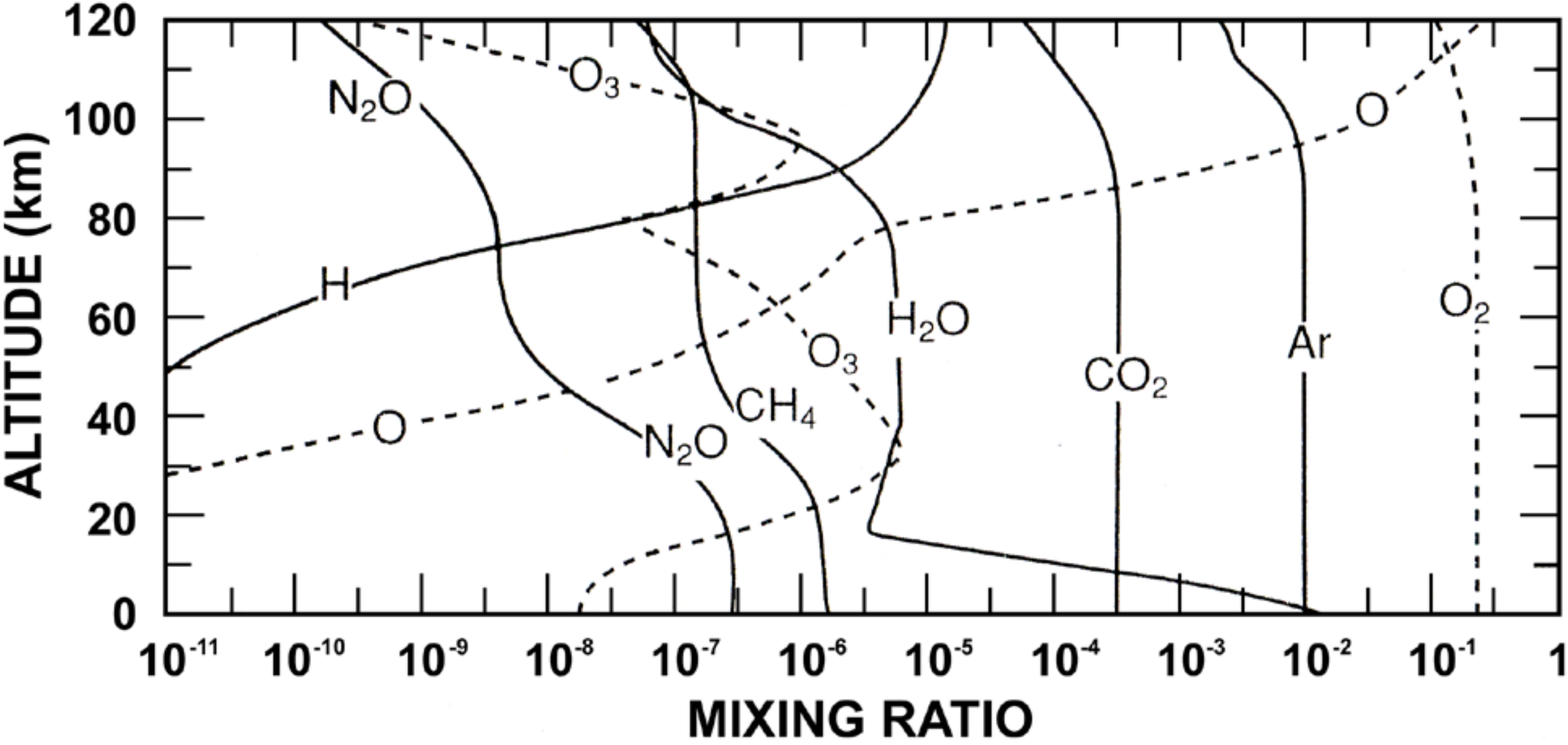


www.geog.ucsb.edu/~joel/g110_w08/lecture_notes/stability/agburt01_09.jpg

Ionosphere



# Mixing Ratio of Atmospheric Gases



ruc.noaa.gov/AMB_Publications_bj/2009%20Schlatter_Atmospheric%20Composition%20and%20Vertical%20Structure_eae319MS-1.pdf

# Atmospheric Composition

- $O_2$, $N_2$ main constituents, constant proportions up to 100 km (78.1% $N_2$, 20.9% $O_2$)
- Ozone – mainly absorbs in UV
  - distribution depends on latitude, season
  - maximum concentration around 16 km height
- $CO_2$ – important component for (mid)IR absorption
  - mixing independent of altitude
- Ions – varies strongly with altitude and solar activity
  - relevant > 60km (reactions with UV photons)

$$O_2 + h\nu \rightarrow O_2^{+*} + e^- \quad \text{and} \quad O_2 + h\nu \rightarrow O^+ + O + e^-$$

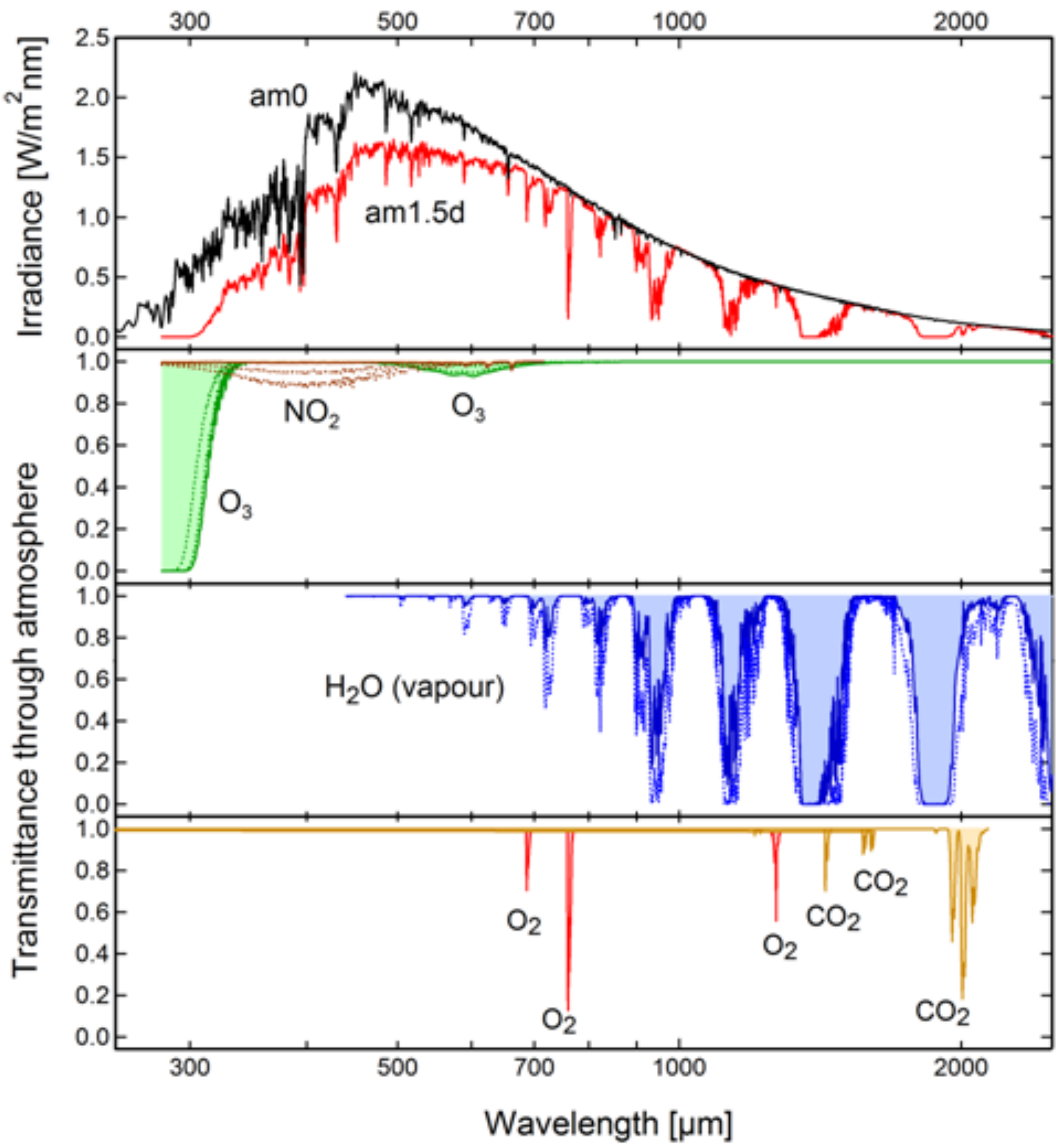
  - electron showers along magnetic fields cause Aurora
  - at 100 – 300 km height: $n_e \sim 10^5 - 10^6\ \mathrm{cm}^{-3}$
- $H_2O$ – highly variable, very strong absorption bands

# 2. Absorption

- Atomic, molecular transitions -> absorption features:
  - pure rotational molecular transitions: $H_2O$, $CO_2$, $O_3$,
  - rotation-vibrational molecular transitions: $CO_2$, NO, CO
  - electronic molecular transitions: $CH_4$, CO, $H_2O$, $O_2$, $O_3$, OH
  - electronic atomic transitions: O, N, ...
- Attenuation at altitude *$z_0$*: $$I(z_0) = I_0(\infty) \cdot \exp\left[ -\frac{1}{\cos\theta} \sum_i \tau_i(\lambda, z_0) \right]$$
- for *i* absorbing species with optical depth $\tau_i$

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

θ is the zenith distance; κ is the absorption coefficient; $\rho_0$ is the mass density of air, and $r_i(z)$ the mixing ratio



www.pvlighthouse.com.au/resources/courses/altermatt/The%20Solar%20Spectrum/figures/Sources%20of%20absorption%20in%20AM1-5d.png

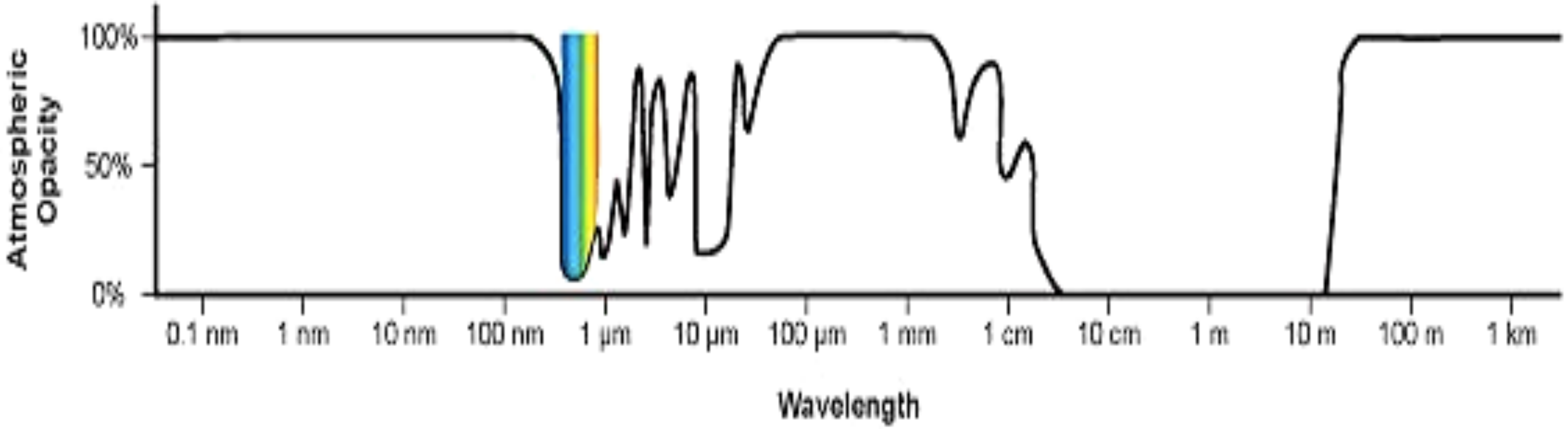
# Atmospheric Bands

Two cases of absorption:

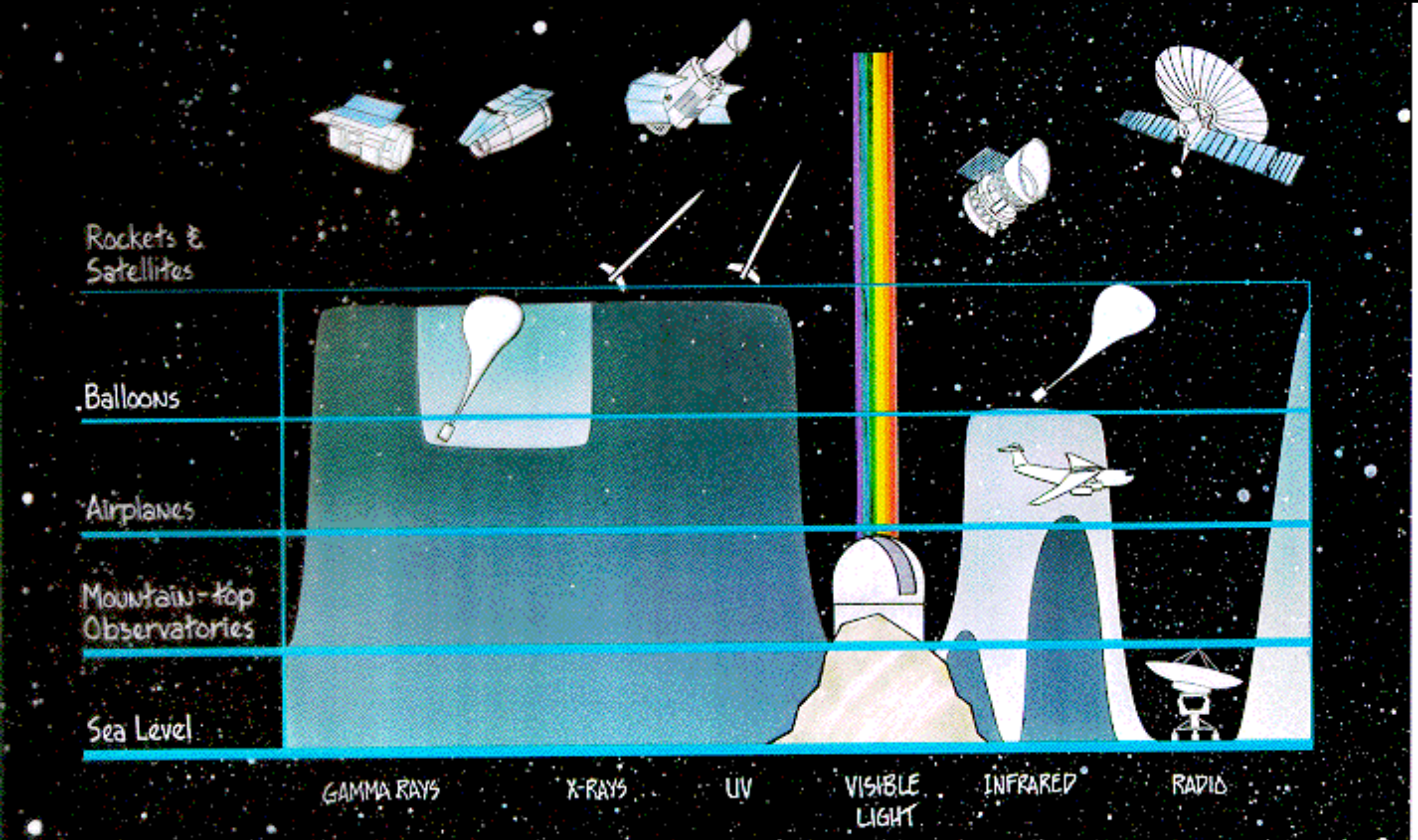
total absorption → atmospheric transmission windows

partial absorption → reduced transmission due to narrow telluric lines of terrestrial origin

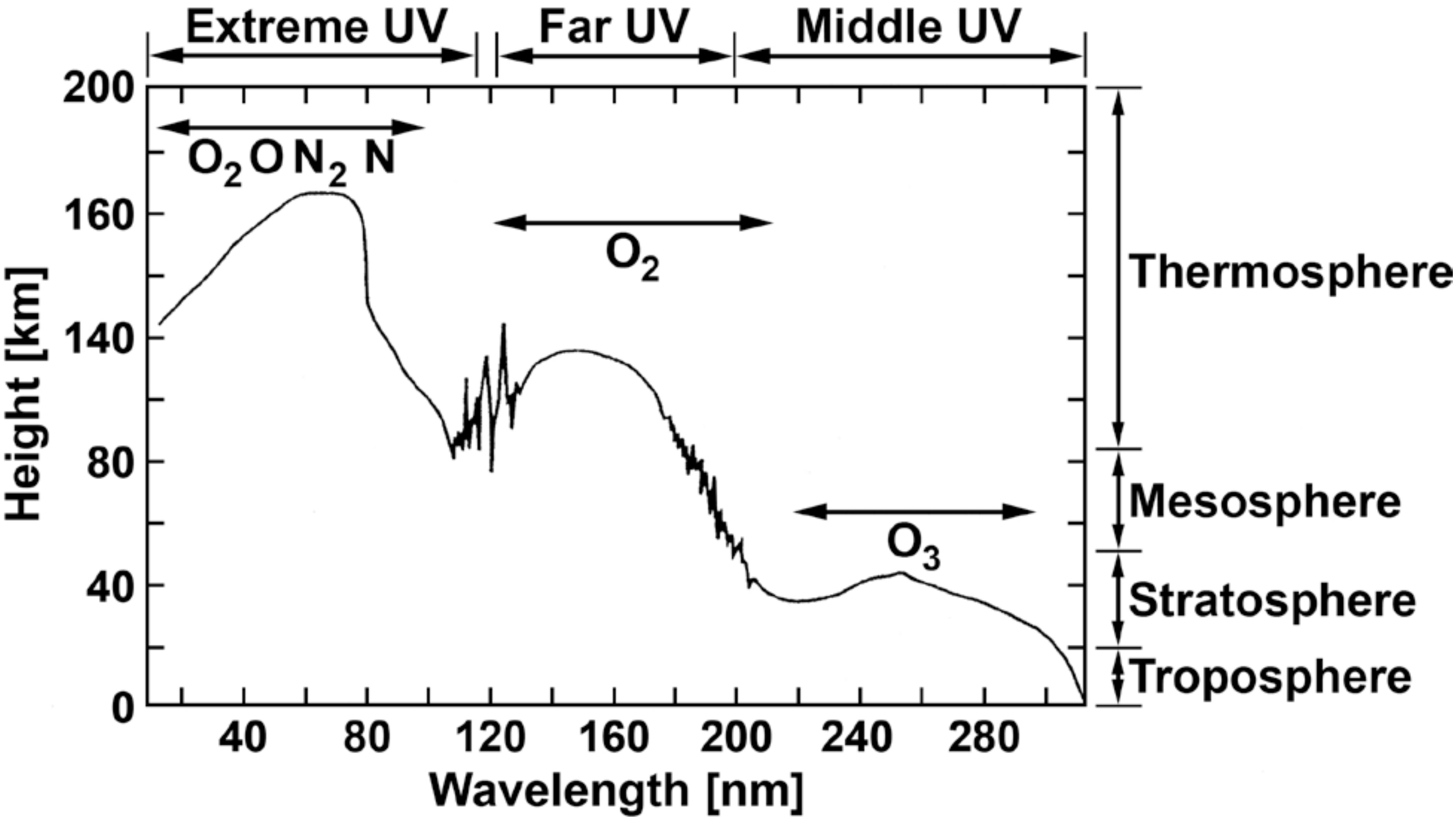
Atmospheric opacity defines atmospheric transmission bands (wavelengths accessible to ground-based observations)



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



# UV Absorption



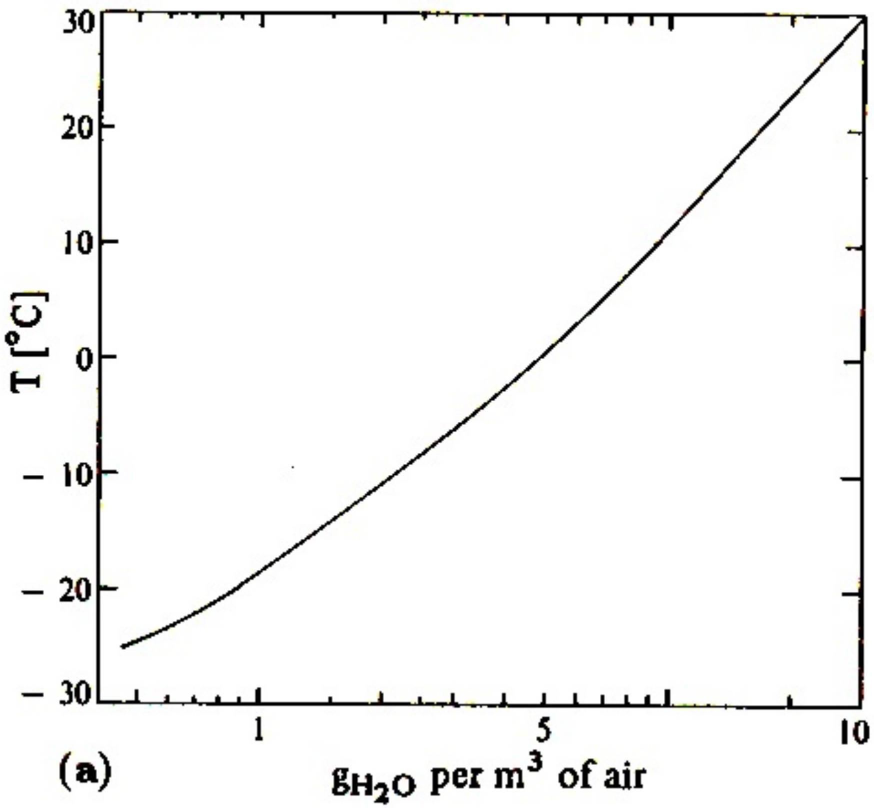
ruc.noaa.gov/AMB_Publications_bj/2009%20Schlatter_Atmospheric%20Composition%20and%20Vertical%20Structure_eae319MS-1.pdf

# Absorption by Water Vapour

- Water vapor strong function of *T* and *z*
- Precipitable water vapor (PWV) = depth of water in column of atmosphere (if liquid)
- PWV *w* above altitude $z_0$

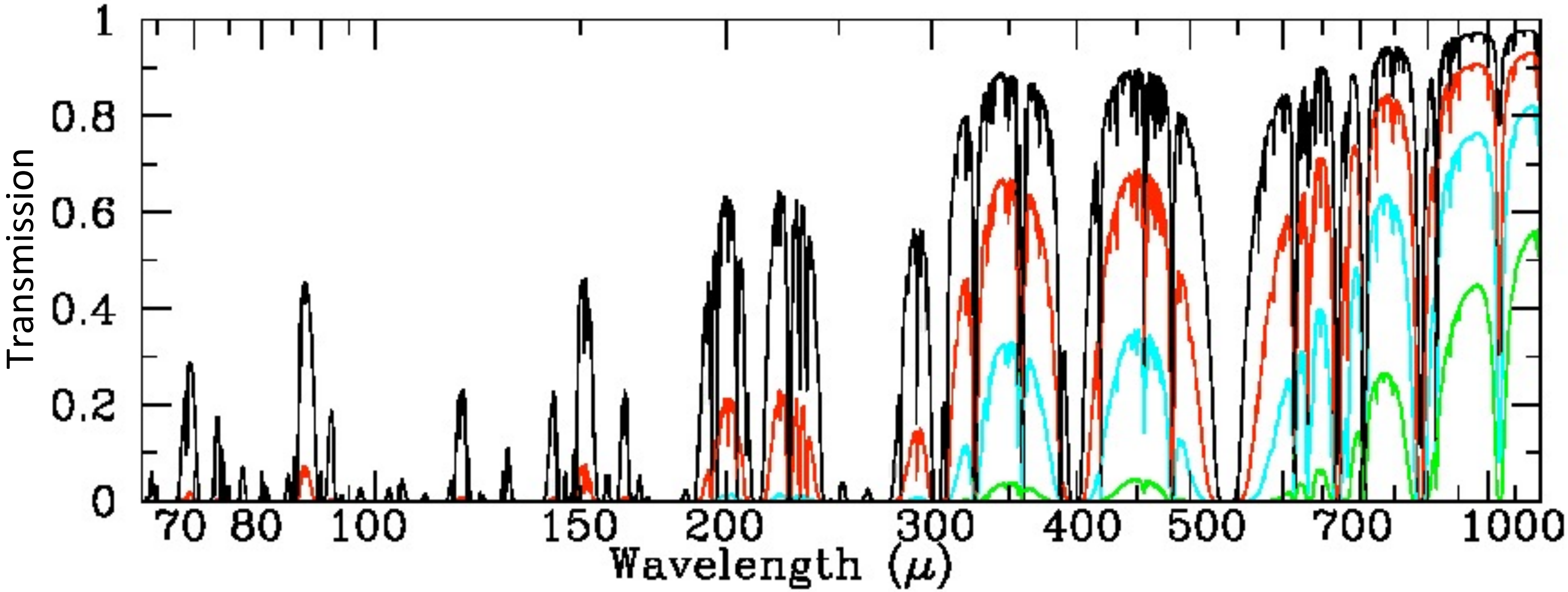
$$w(z_0) = \int_{z_0}^{\infty} N_{H_2O} dz \ ,$$

$$N_{H_2O}\left[\mathrm{m}^{-3}\right] = 4.3 \times 10^{25} \frac{P}{P_0}\frac{T}{T_0} r(z)$$



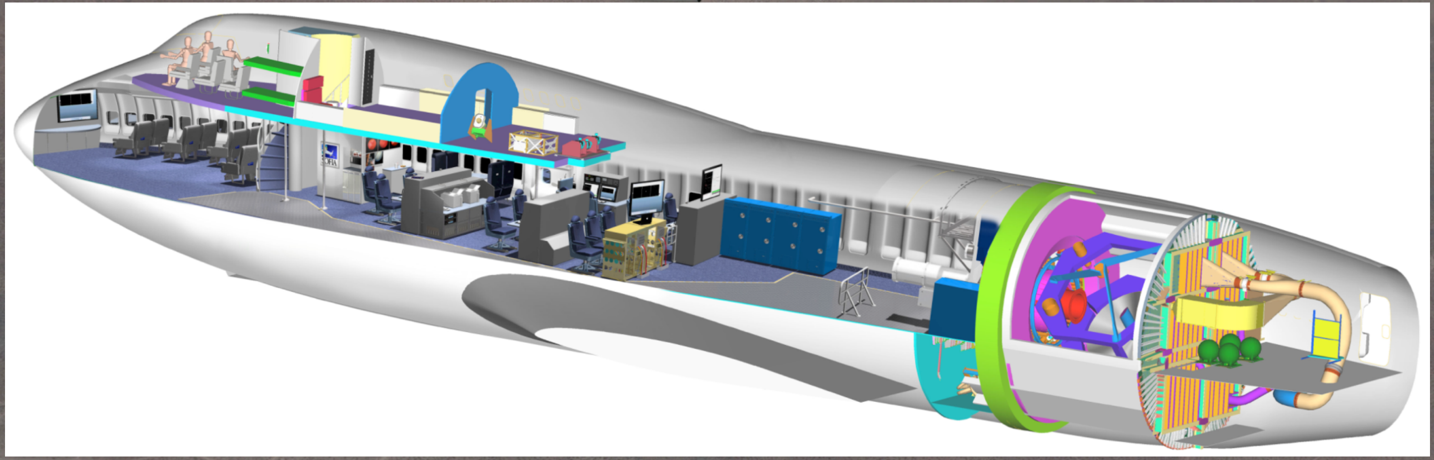
# Absorption by Water Vapour

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



0.1 mm PWV, 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)

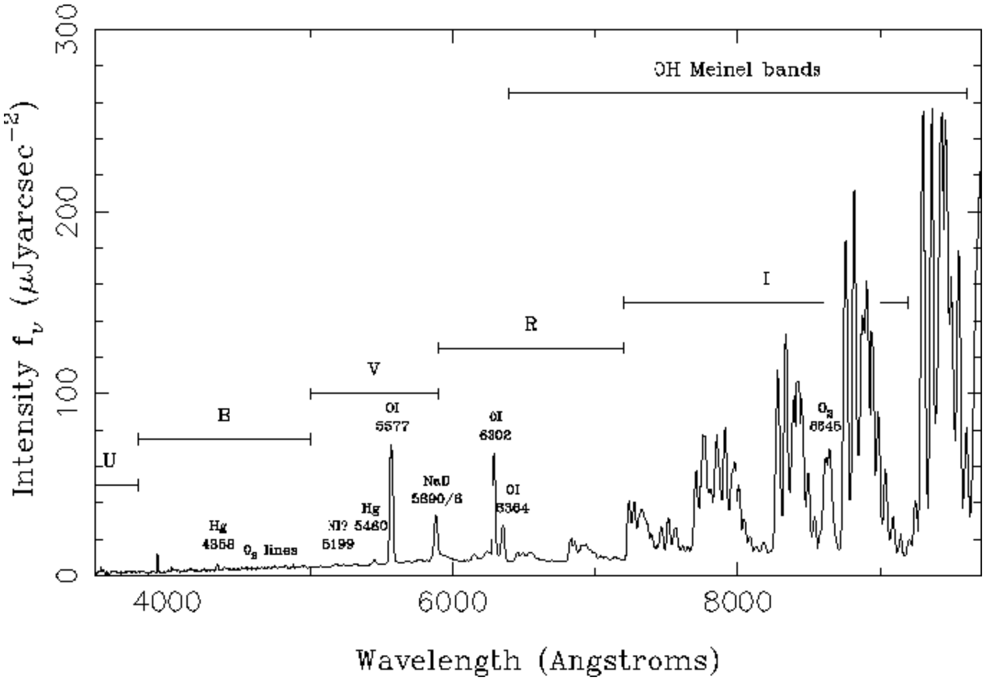


# 3. Fluorescent Atmospheric Emission

- Fluorenscence = recombination of electrons with ions
- Recombination probability low; takes several hours → part of night
  - Produces both continuum + line emission = airglow
  - Occurs mainly at ~ 100 km height
  - Main sources of emission: O I, Na I, $O_2$, OH (←NIR), H
- Emission intensity measured in Rayleigh:

$$1\,\text{Rayleigh} = 10^{6}\,\text{photons cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1} = \frac{1.58\cdot 10^{-11}}{\lambda[\text{nm}]}\,\text{W cm}^{-2}\,\text{sr}^{-1}$$

# Airglow



http://www.ing.iac.es/astronomy/observing/conditions/skybr/skybr.html

NASA/Dan Burbank - http://spaceflight.nasa.gov/gallery/images/station/crew-30/html/iss030e015472.html

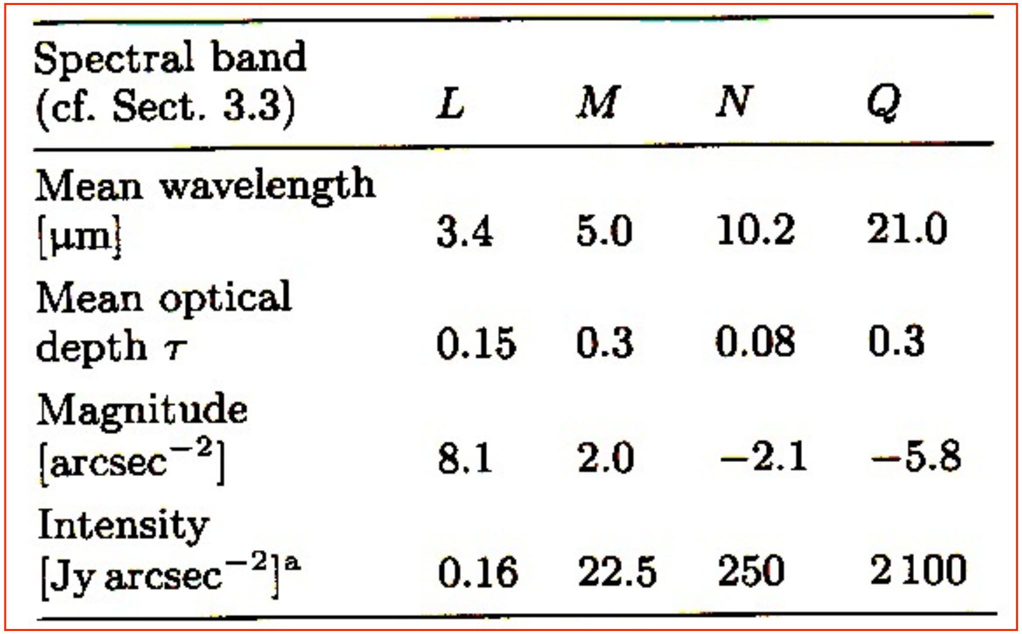
# 3. Thermal Atmospheric Emission

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

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

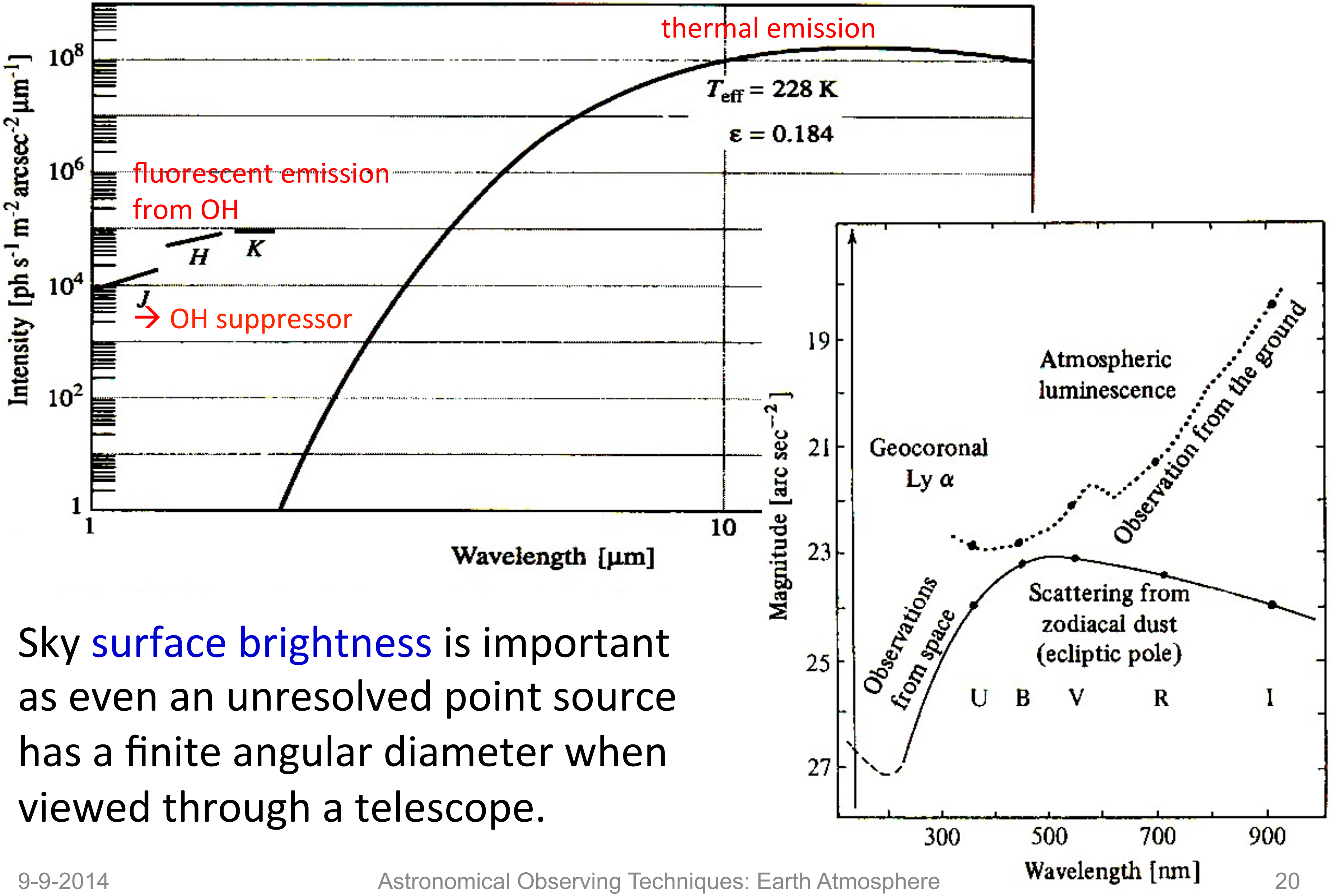
$B_\lambda(T_{mean})$: Planck function at mean temperature $T_{\text{mean}}$ of atmosphere

For T = 250 K and θ = 0



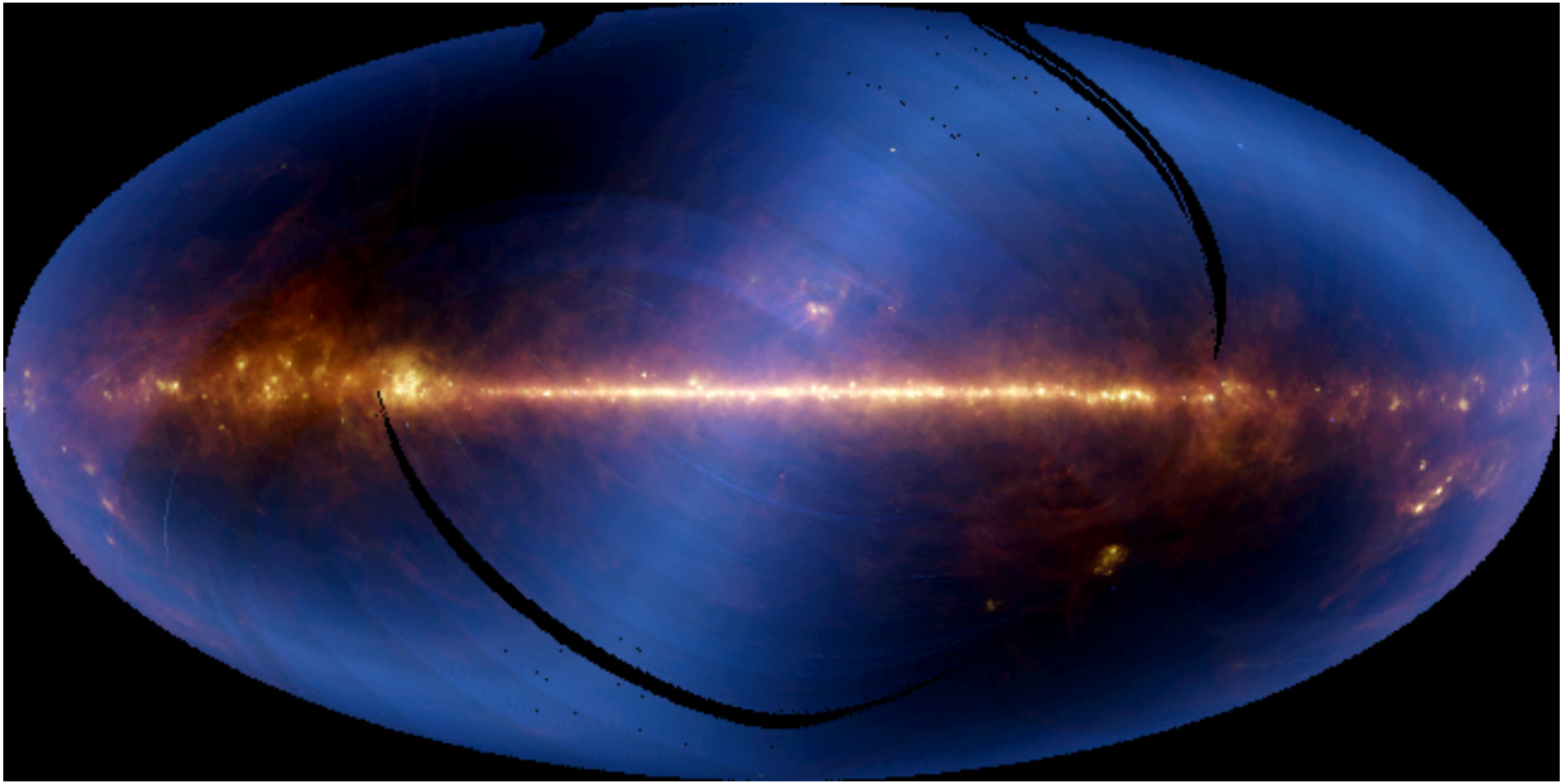
| Spectral band (cf. Sect. 3.3) | *L* | *M* | *N* | *Q* |
|---|---|---|---|---|
| Mean wavelength [μm] | 3.4 | 5.0 | 10.2 | 21.0 |
| Mean optical depth $\tau$ | 0.15 | 0.3 | 0.08 | 0.3 |
| Magnitude [arcsec$^{-2}$] | 8.1 | 2.0 | −2.1 | −5.8 |
| Intensity [Jy arcsec$^{-2}$]$^a$ | 0.16 | 22.5 | 250 | 2 100 |

# Fluorescent and Thermal Emission



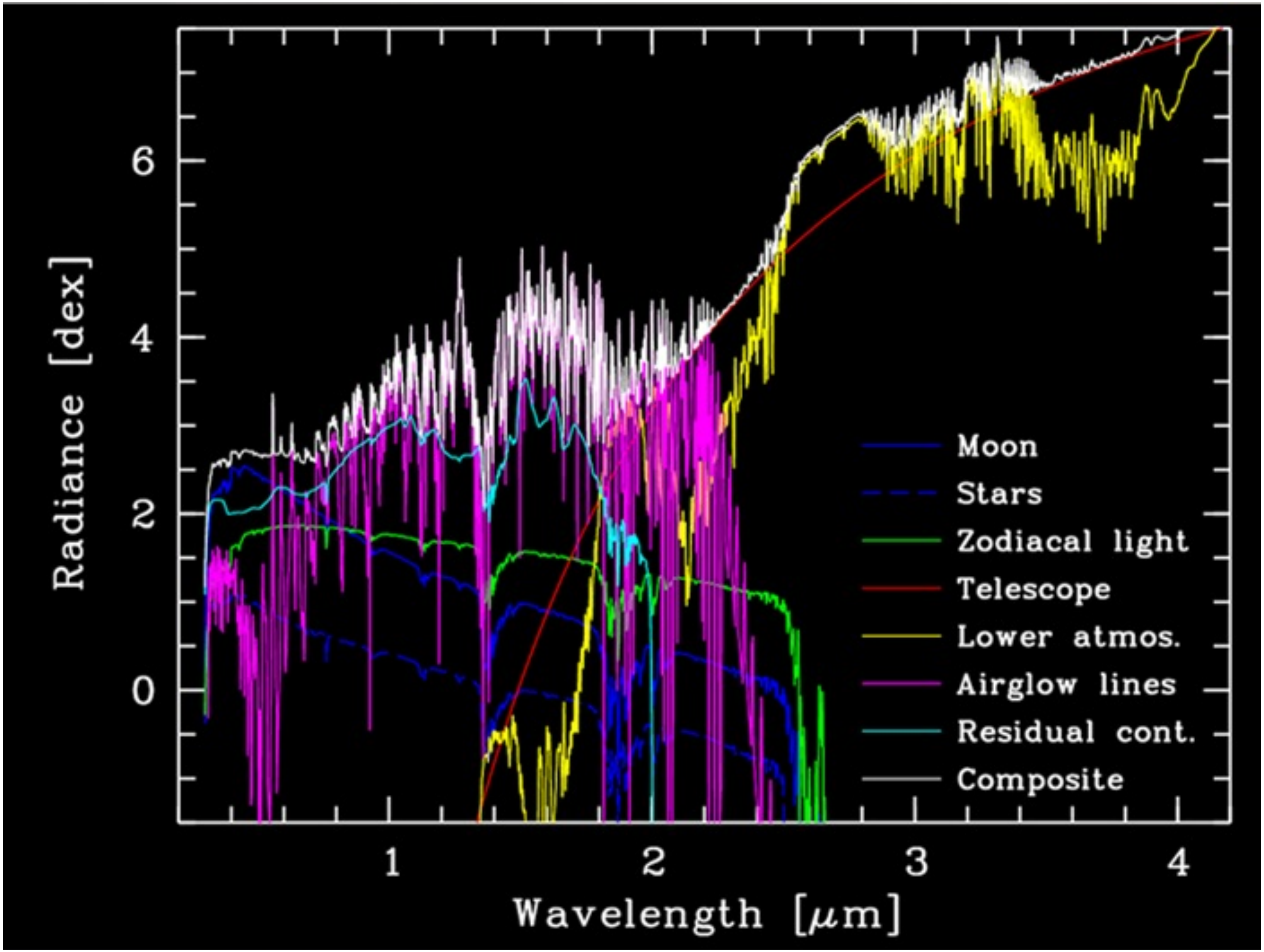
Sky surface brightness is important as even an unresolved point source has a finite angular diameter when viewed through a telescope.

# Emission from Space



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

# Total Emission in Near-Infrared



# Molecular Scattering

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

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

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

- Rayleigh scattering is not isotropic:

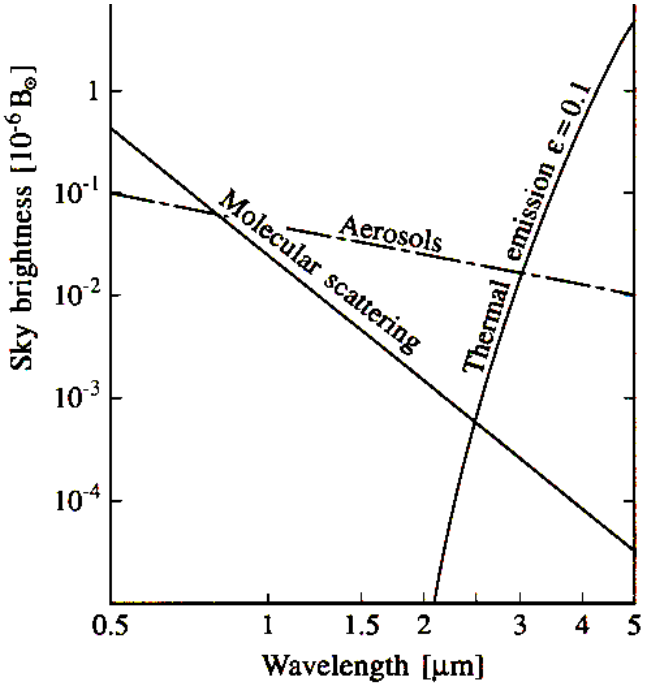
$$I_{scattered} = I_0 \frac{3}{16\pi}\sigma_R\left(1+\cos^2\theta\right)d\omega$$

# Aerosol Scattering

- Aerosols (sea salt, hydrocarbons, volcanic dust) much bigger than air molecules → Rayleigh scattering does *not* apply
- Aerosol scattering described by Mie theory (classical electrodynamics, “scattering efficiency factor” Q):

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

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



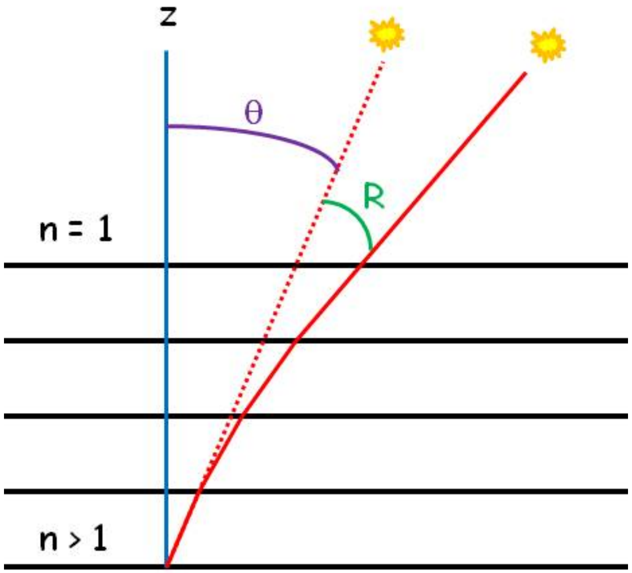
# Refraction

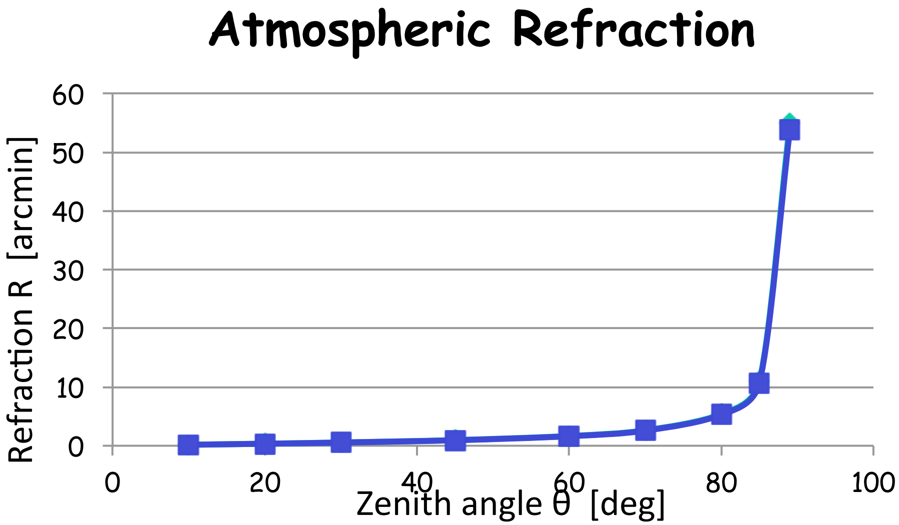
# Atmospheric Refraction

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

Refraction

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



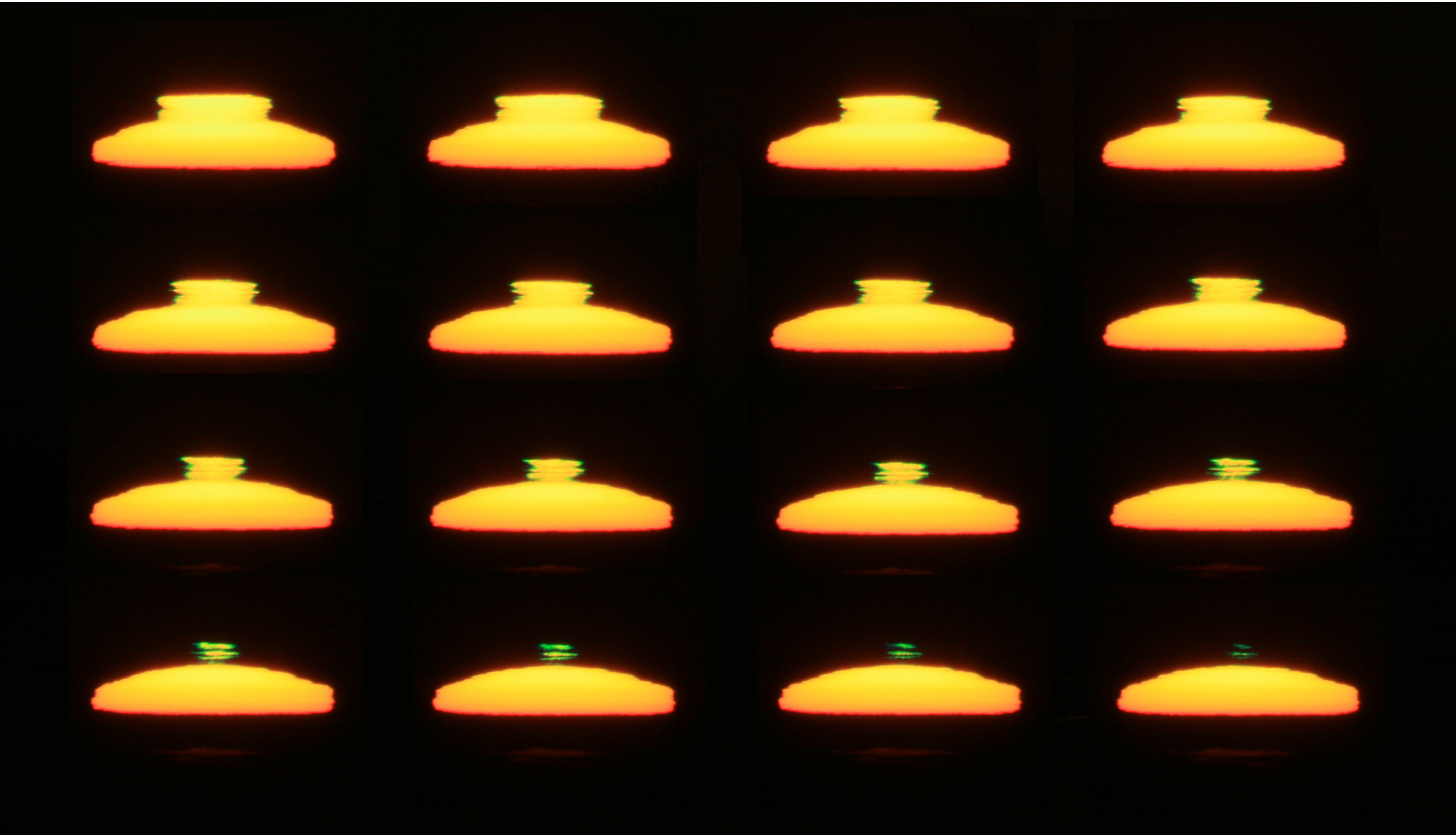


Refractive index of air depends on wavelength λ:

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

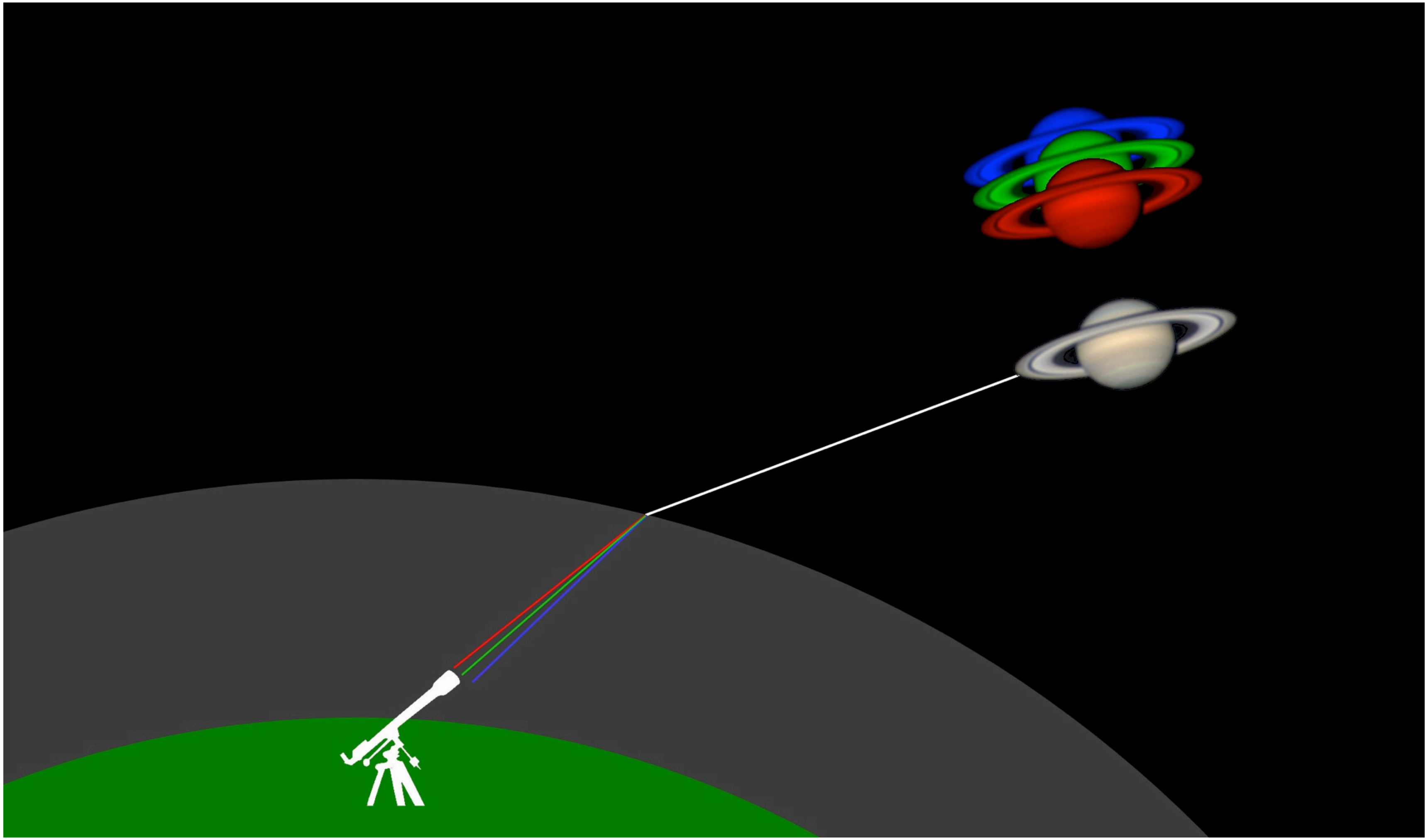
(dry air, 1 atm pressure, T ~ 290K, $\lambda_0$ in [µm])

# Green Flash



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

# Atmospheric Dispersion

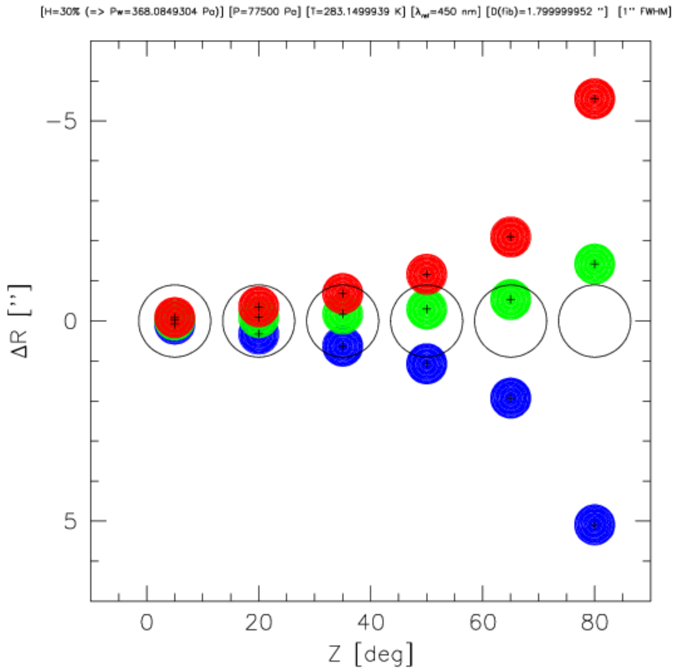


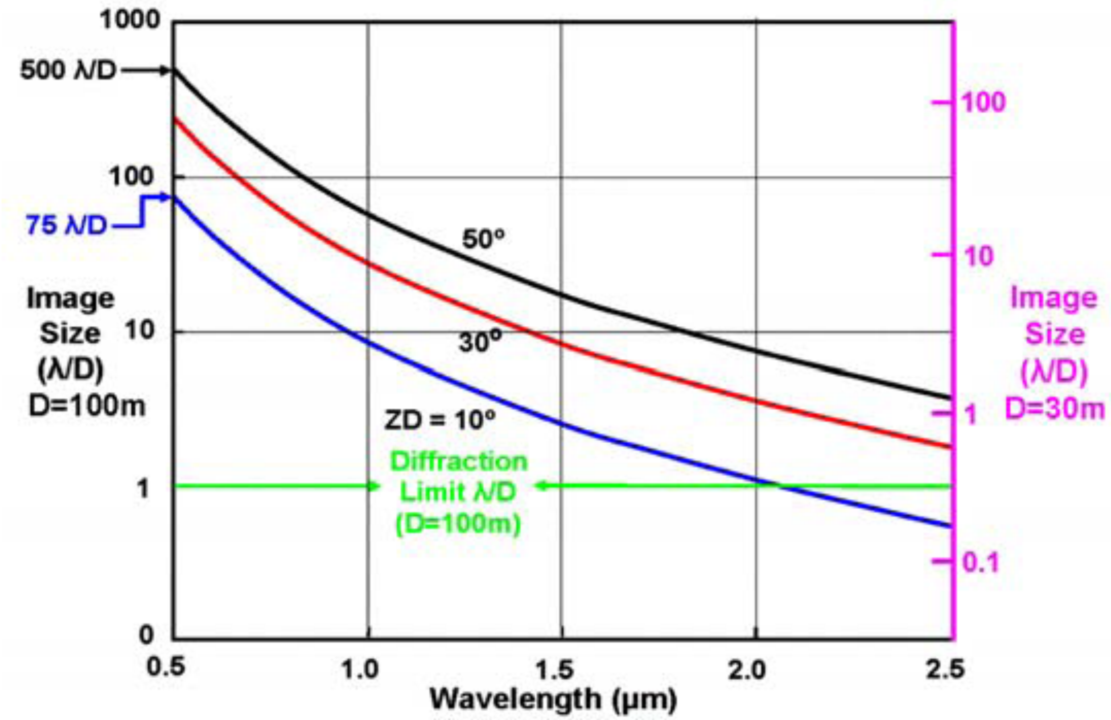
http://www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm

# Atmospheric Dispersion

Dispersion: Elongation of points in broadband filters due to n(λ) [→ "rainbow"]. The magnitude of the dispersion is a strong function of airmass and wavelength.

No problem if dispersion < λ/D ← o.k. for small or seeing limited telescopes, but big problem for large, diffraction limited telescopes

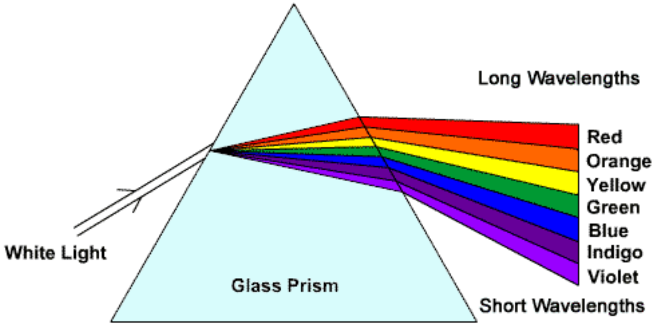


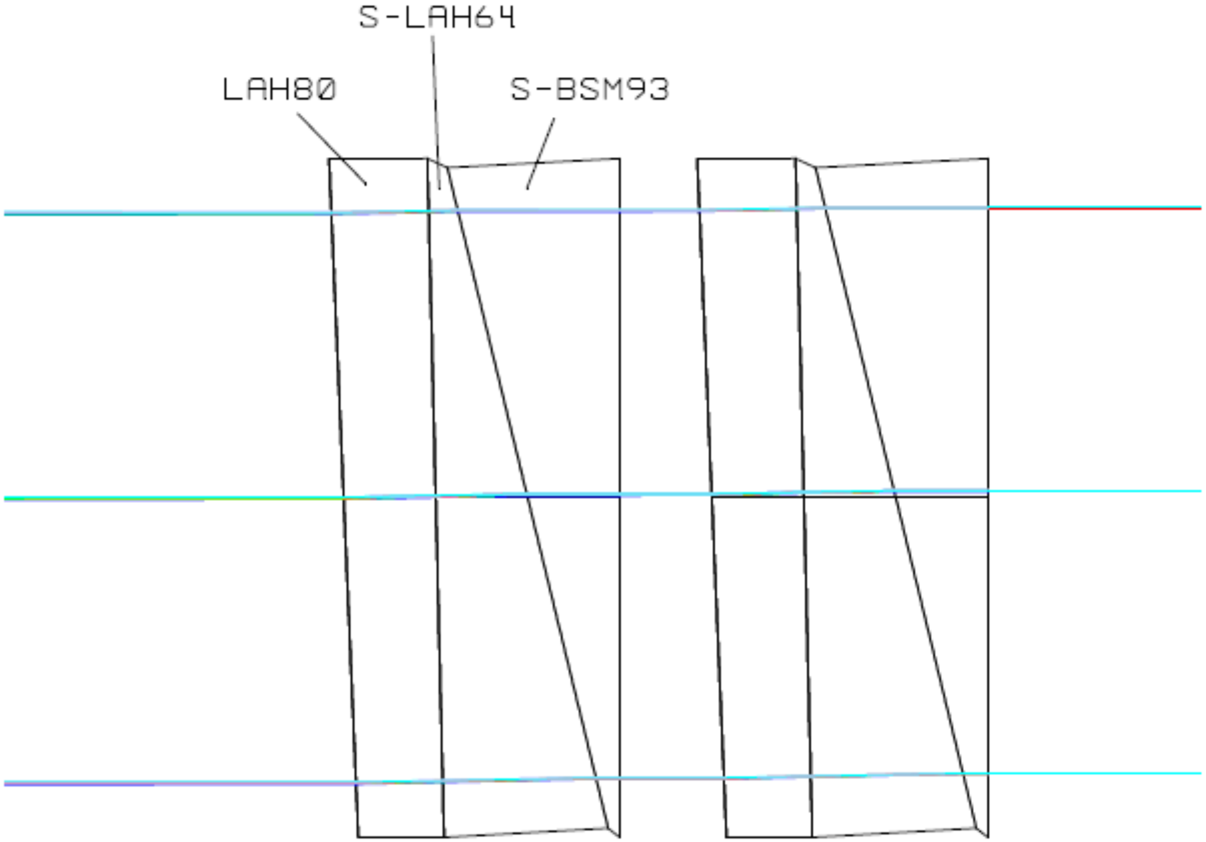


# Atmospheric Dispersion Corrector

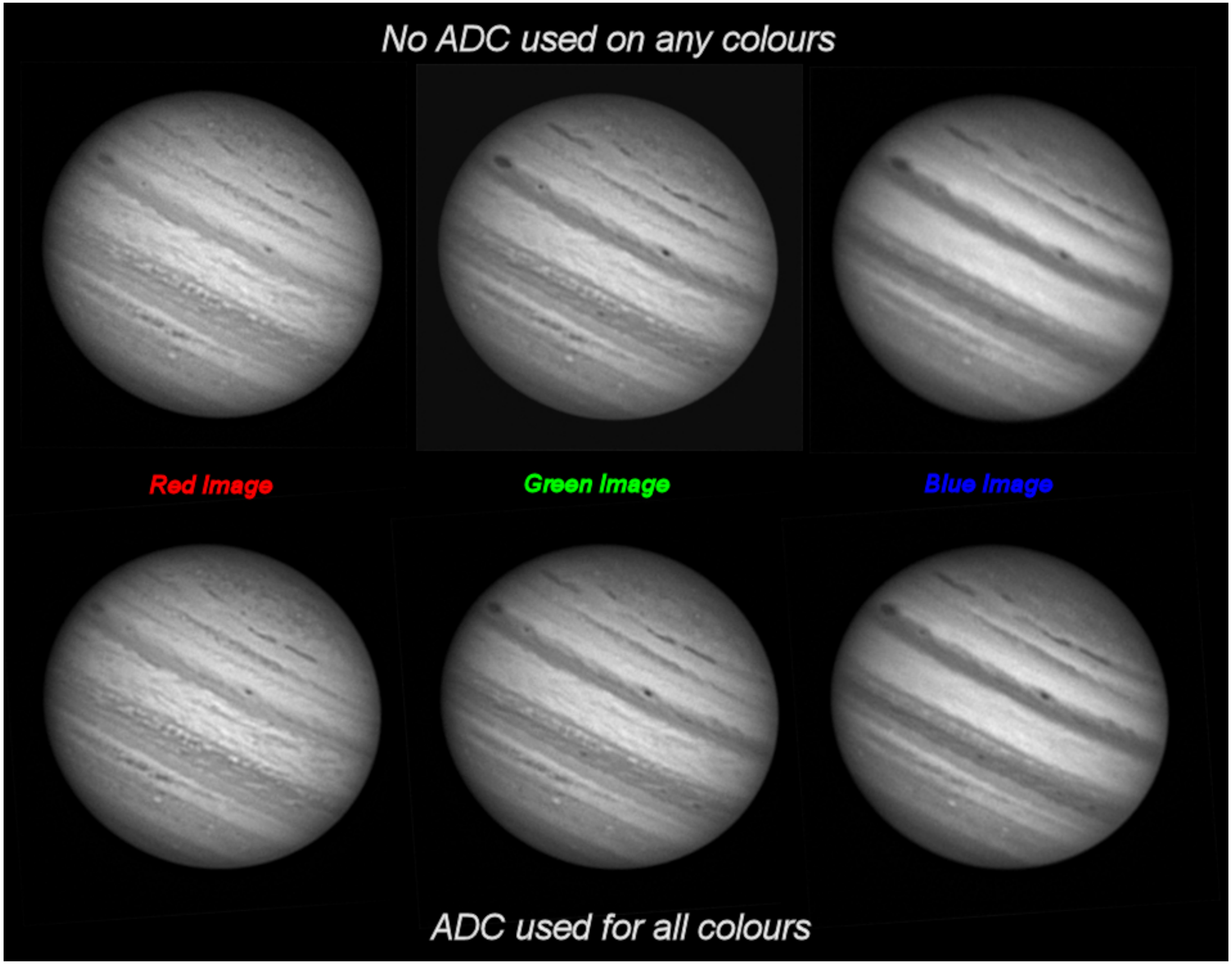
To counterbalance atmospheric dispersion use:

1. a refractive element (e.g., prism)
2. a second prism (different material with different dispersion) to maintain the optical axis
3. use a second (identical) double prism assembly to adjust the strength of the correction for different



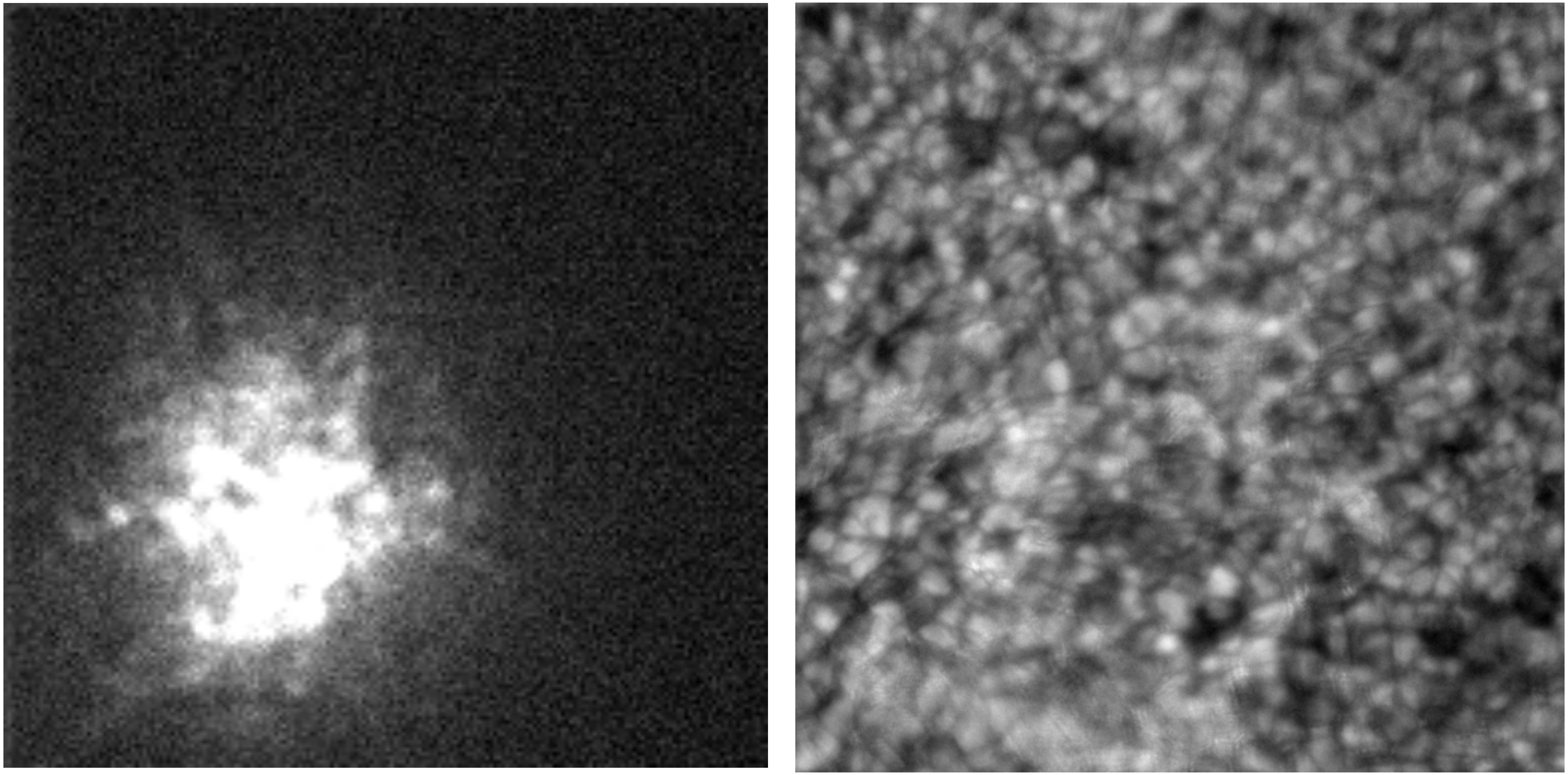


# Benefits of ADC

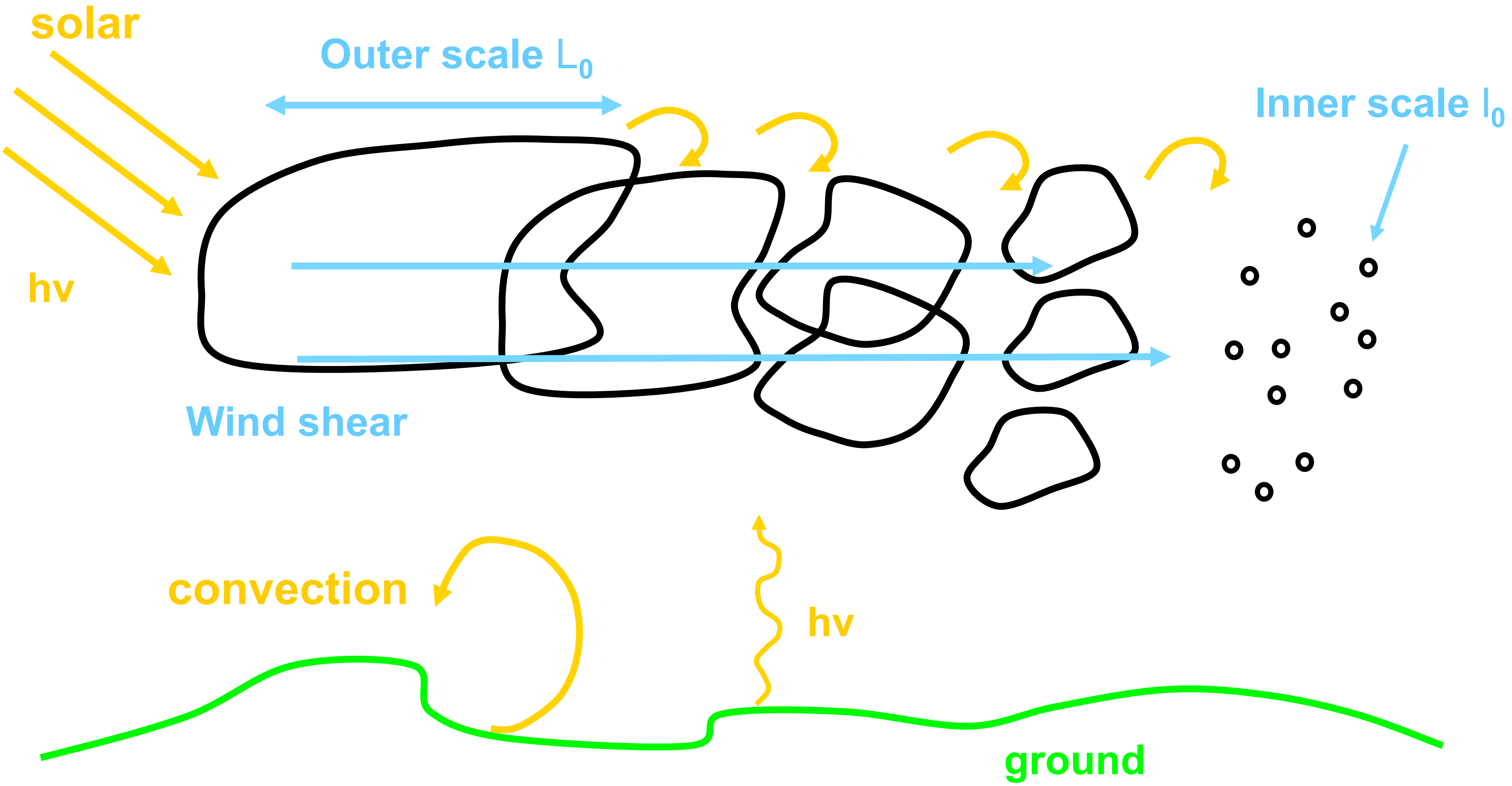


http://www.skyinspector.co.uk/Atm-Dispersion-Corrector-ADC(2587060).htm

# Seeing



# 5. Atmospheric Turbulence



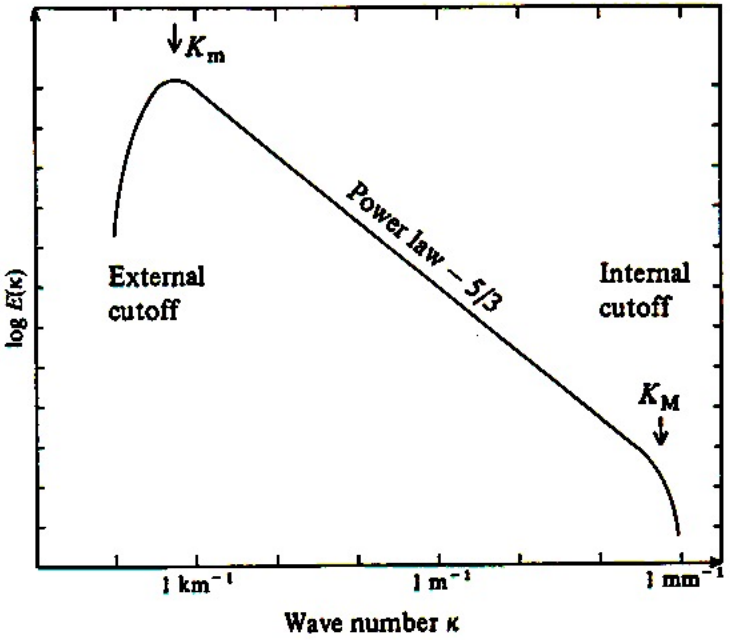
# Komogorov Turbulence

- kinetic energy of large scale (~*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/*κ* is length scale under consideration
- mean spectrum of kinetic energy (Kolmogorov spectrum)

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

- $l_0$ = inner scale, $L_0$ = outer scale with

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

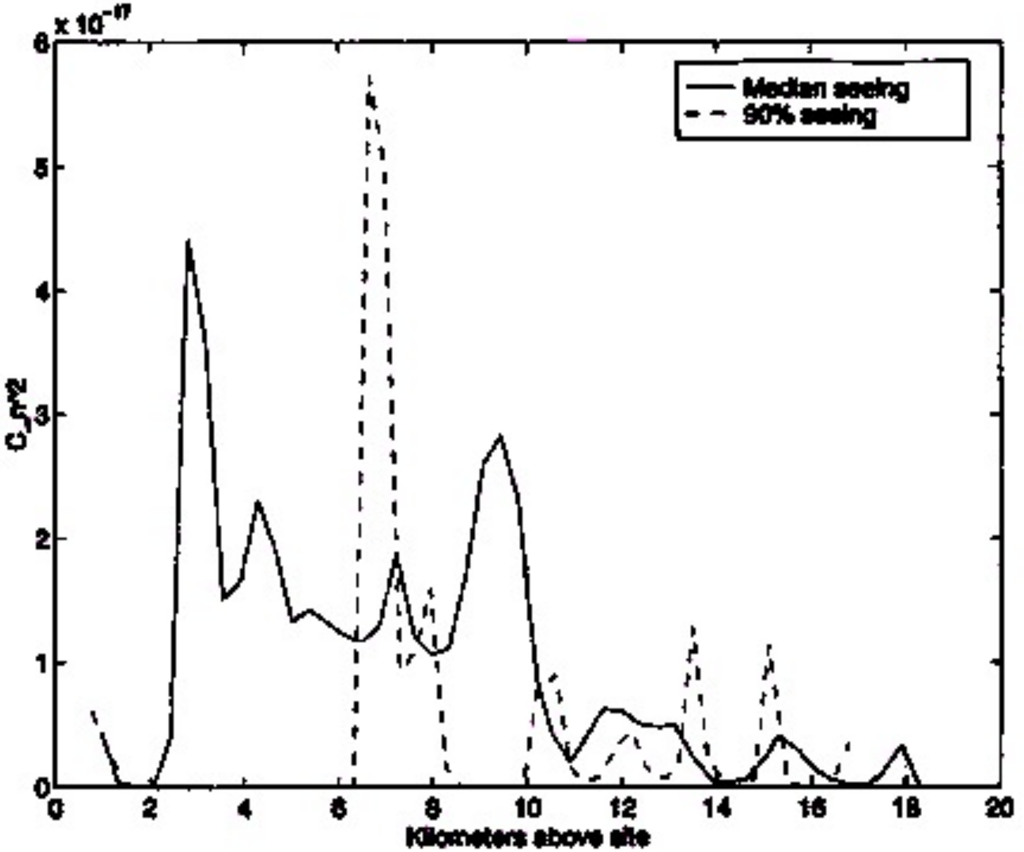


# Air Refractive Index Fluctuations

- Winds mix layers of different temperature → fluctuations of temperature T → fluctuations of density ρ→ fluctuations of refractive index *n*
- 1K temperature difference changes *n* by $1\times10^{-6}$
- variation of 0.01K along path of 10km:
  $10^4$ m × $10^{-8}$ = $10^{-4}$ m = 100 waves at 1µm
- refractive index of water vapour is less than that of air
  ➔ moist air has smaller refractive index

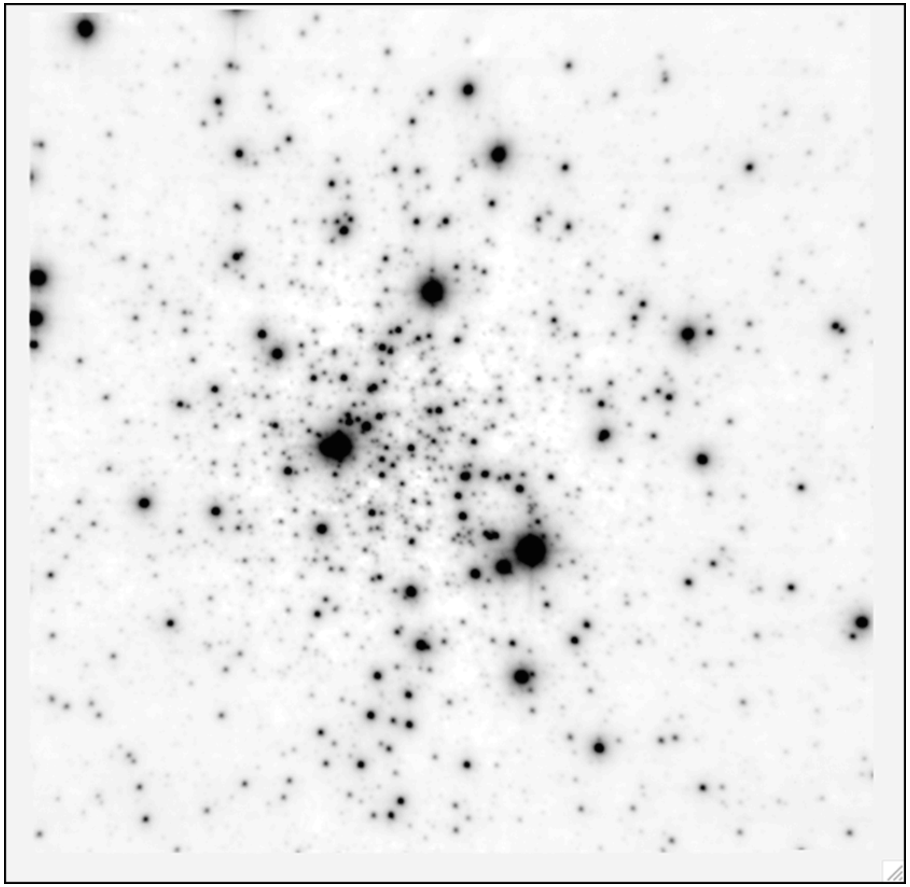
# Index Fluctuations with Altitude

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

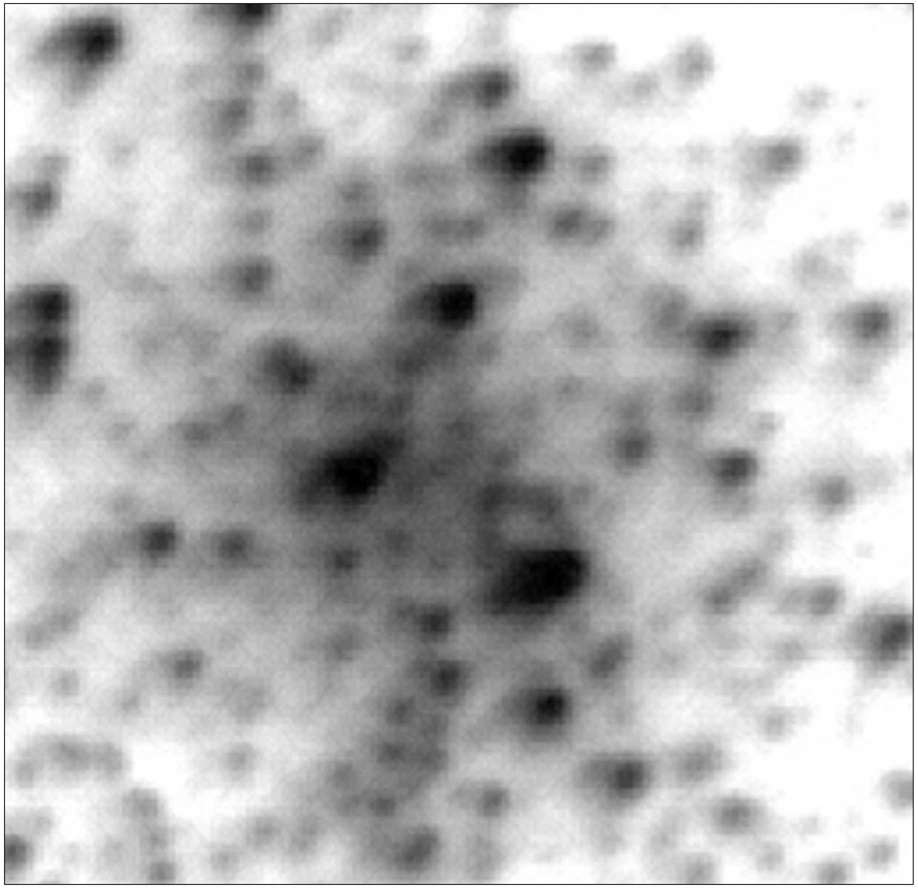


Median seeing conditions on Mauna Kea are taken to be $r_o \sim 0.23$ meters at 0.55 microns. The 10% best seeing conditions are taken to be $r_o \sim 0.40$ meters. Figure taken from a paper by Ellerbroek and Tyler (1997).

# Atmosphere and Image Quality

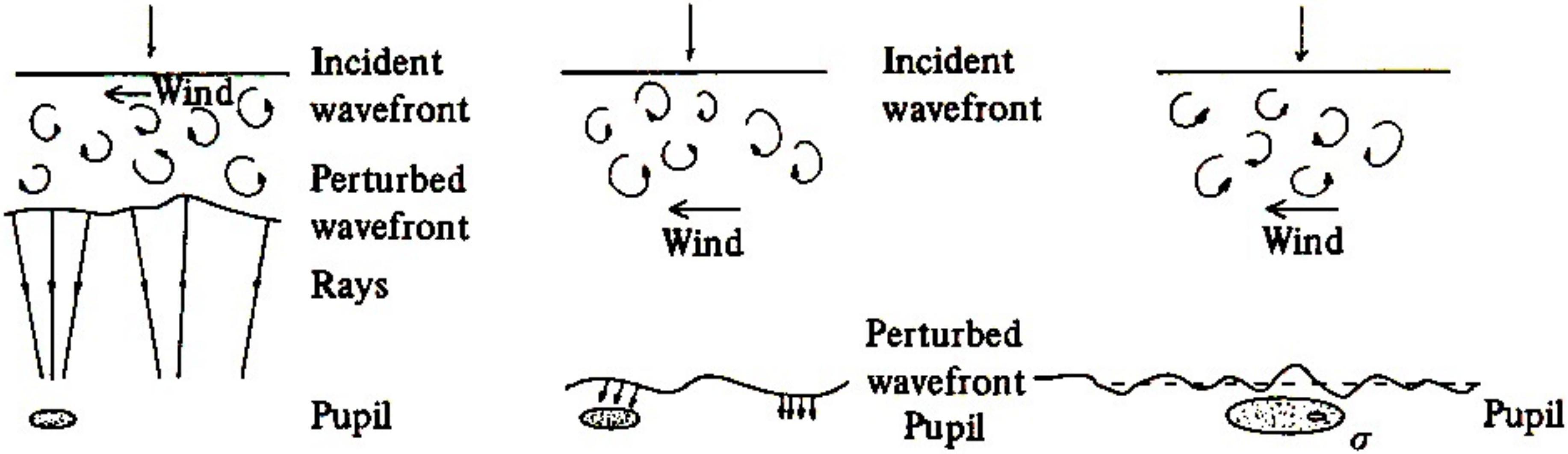


PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM



WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

# 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")

# Fried Parameter $r_0$

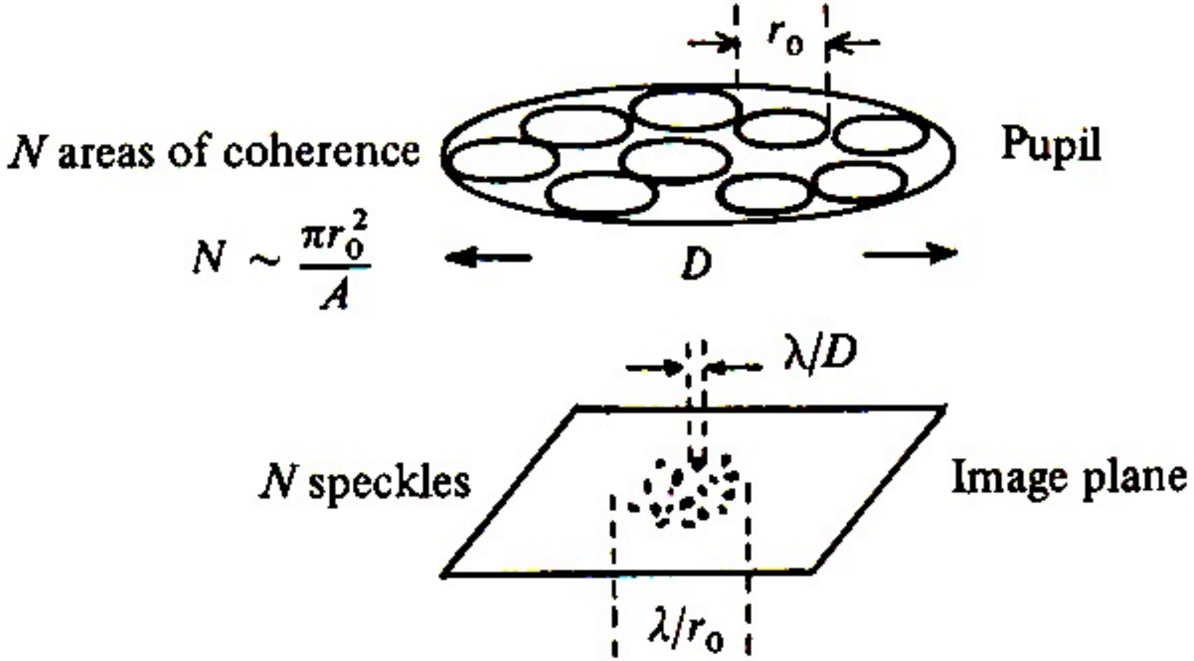
- radius of spatial coherence area (of wavefront) given by Fried parameter $r_0$ :

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

- $r_0$ increases as 6/5 power of wavelength
- $r_0$ decreases as -3/5 power of air mass
- $r_0$ is average scale over which rms optical phase distortion is 1 rad
- angle $\Delta\theta=\lambda/r_0$ is the seeing in arcsec
- seeing is roughly equivalent to FWHM of long-exposure image of a point source (Point Spread Function)

# Short Exposure through Turbulence

Random intensity distribution of speckles in focal plane

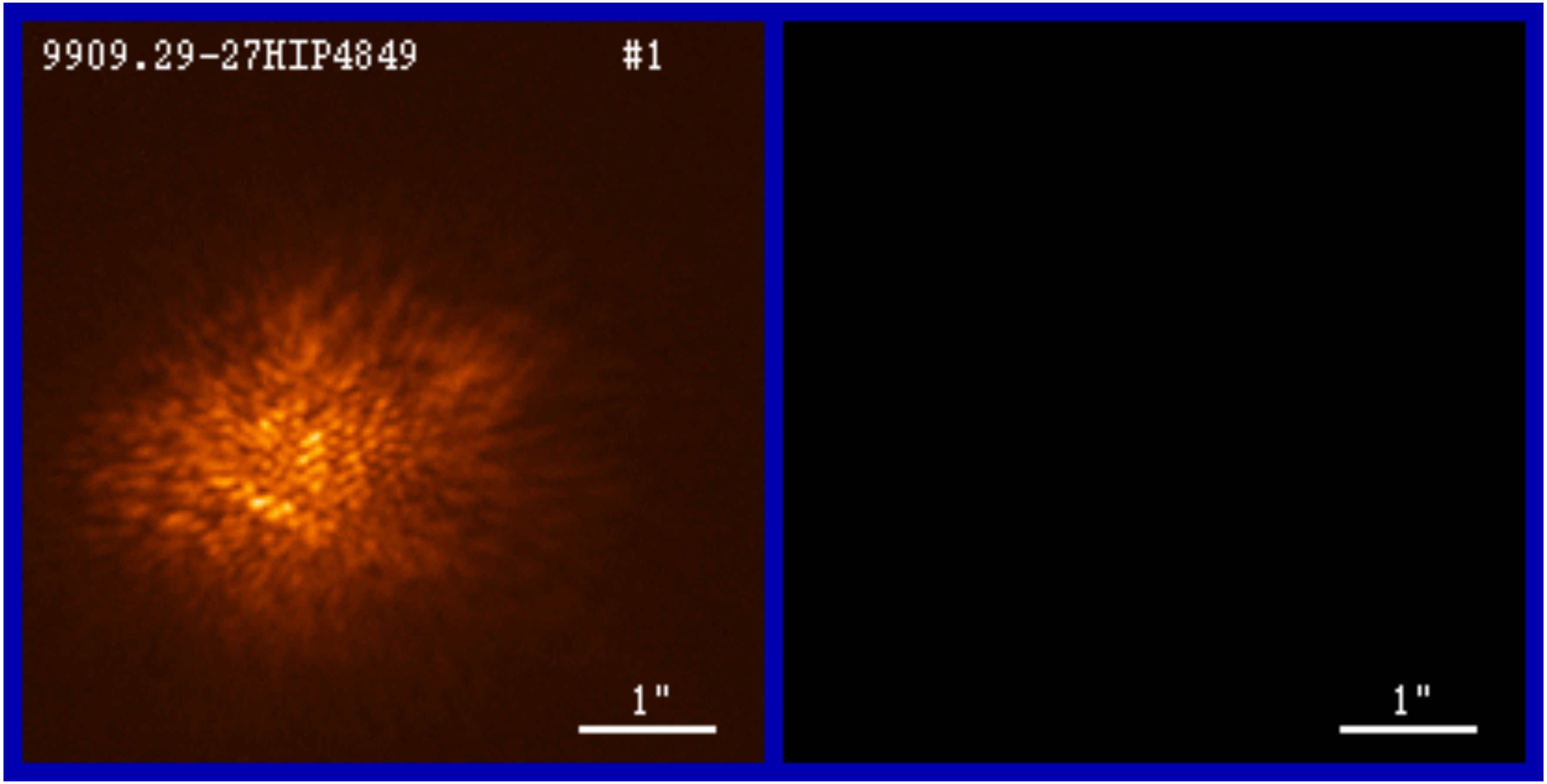


Observed image given by convolution of $I_0$ (object without seeing) with Point Spread Function (PSF) T(θ,t):

$$I(\theta,t) = I_0(\theta) * T(\theta,t)$$

# Speckle Interferometry

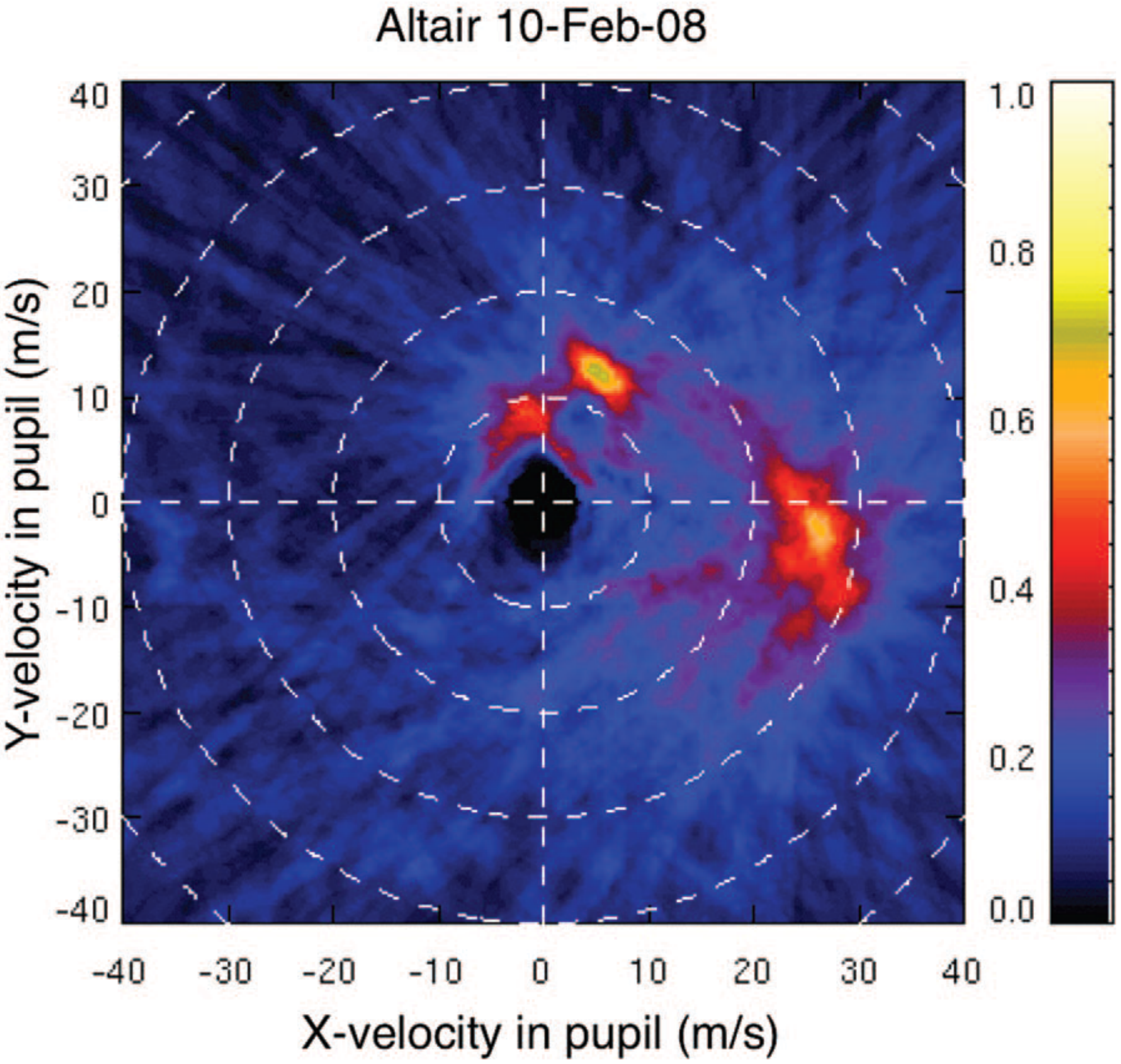
Example: Real-time bispectrum speckle interferometry: 76 mas resolution.
http://www3.mpifr-bonn.mpg.de/div/ir-interferometry/movie/speckle/specklemovie.html



Different but related techniques, e.g., Shift-and-Add, Lucky Imaging, Bispectrum analysis, Aperture masking, …

# Turbulence Correlation Time $\tau_c$

Wind map showing likelihood (0 to 1) of a layer of frozen flow existing at a specific velocity vector (Poyneer et al. 2009, J. Opt. Soc. Am. A 26, pp 833



1. Turbulence does not change arbitrarily fast but with correlation time or coherence time $\tau_c$
2. Often turbulent time scales >> time for the turbulent medium to pass the telescope aperture (wind speed) → frozen turbulence

# Seeing: $r_0$, $\tau_0$, $\theta_0$

- Fried parameter $r_0$: average turbulent scale over which RMS optical phase distortion is 1 rad

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

- $r_0$ increases as $\lambda^{6/5}$
- Seeing $\Delta\theta$ at good sites at 0.5μm: 10 - 30 cm

$$\Delta\theta = \frac{\lambda}{r_0} \sim \lambda^{-1/5}$$

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

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

- Isoplanatic angle $\theta_0$: angle over which RMS wavefront error is smaller than 1 rad

$$\theta_0 = 0.314\cos\zeta\frac{r_0}{\bar{h}}$$

# Long Exposure through Turbulence

- $t_{int} >> \tau_c$ -> image is mean of instantaneous intensity:

$$I(\theta) = \langle I_0(\theta) * T(\theta,t) \rangle = I_0(\theta) * \langle T(\theta,t) \rangle$$

- long-exposure image is smeared or spatially filtered (loss of high spatial frequencies)

- angular resolution $\sim\lambda/r_0$ instead of $\sim\lambda/D$

- As long as $D > r_0$, bigger telescopes will *not* provide sharper images