Shower development and Cherenkov light propagation

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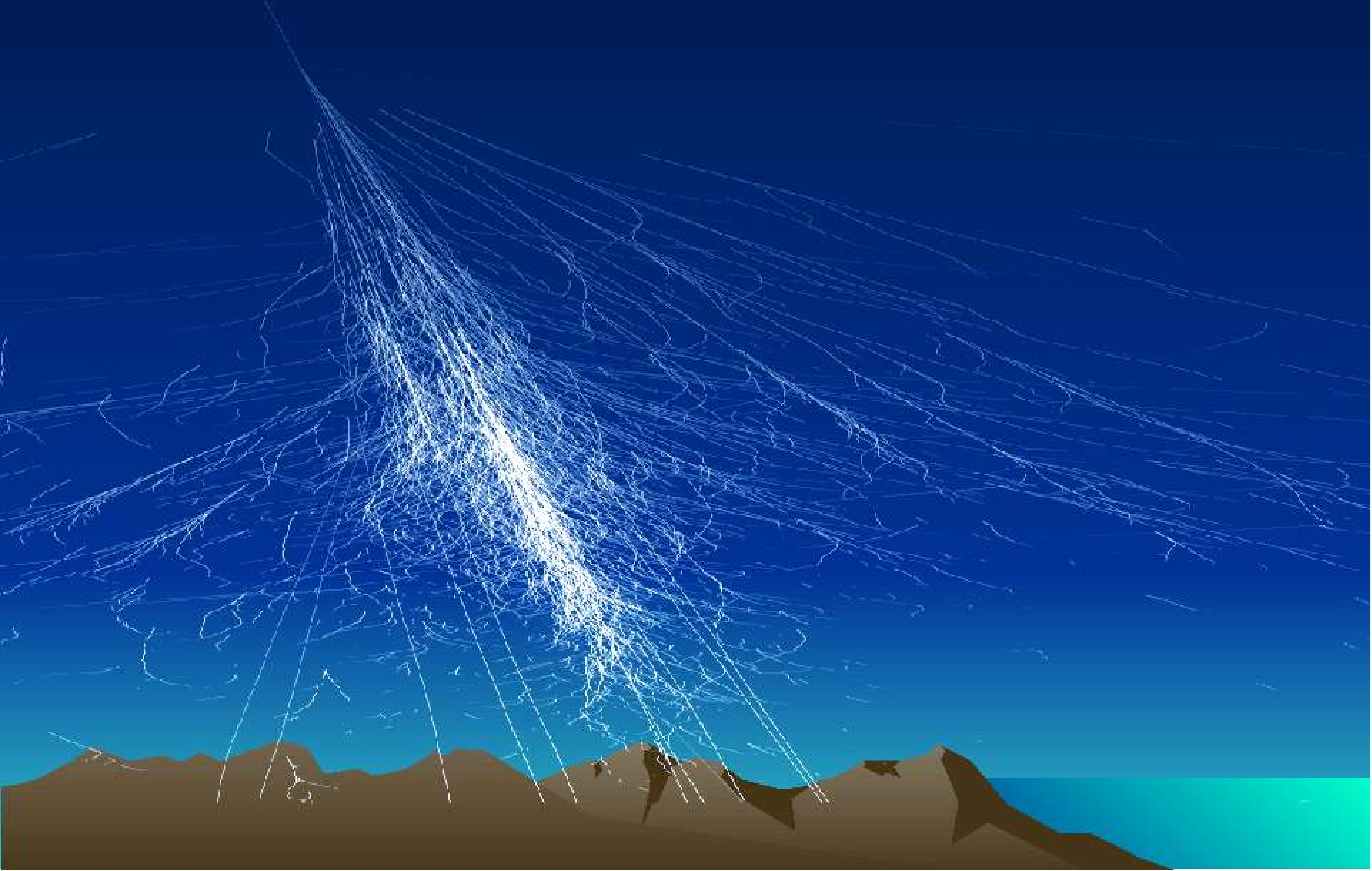
Shower development and Cherenkov light propagation

- Development of air showers (focusing on low-energy gamma-ray showers ...).
- Simulation packages and interaction models.
- Emission of Cherenkov light.
- Atmospheric profiles:
  - Impact of geographic latitude and seasons.
  - How to get the profiles relevant for your site.
- Propagation of light in the atmosphere:
  - Absorption and scattering processes.
  - Modelling of transmission tables.
  - Inputs needed to check transmission tables.
  - Relevance of scattered light.
  - Refraction.

Shower development

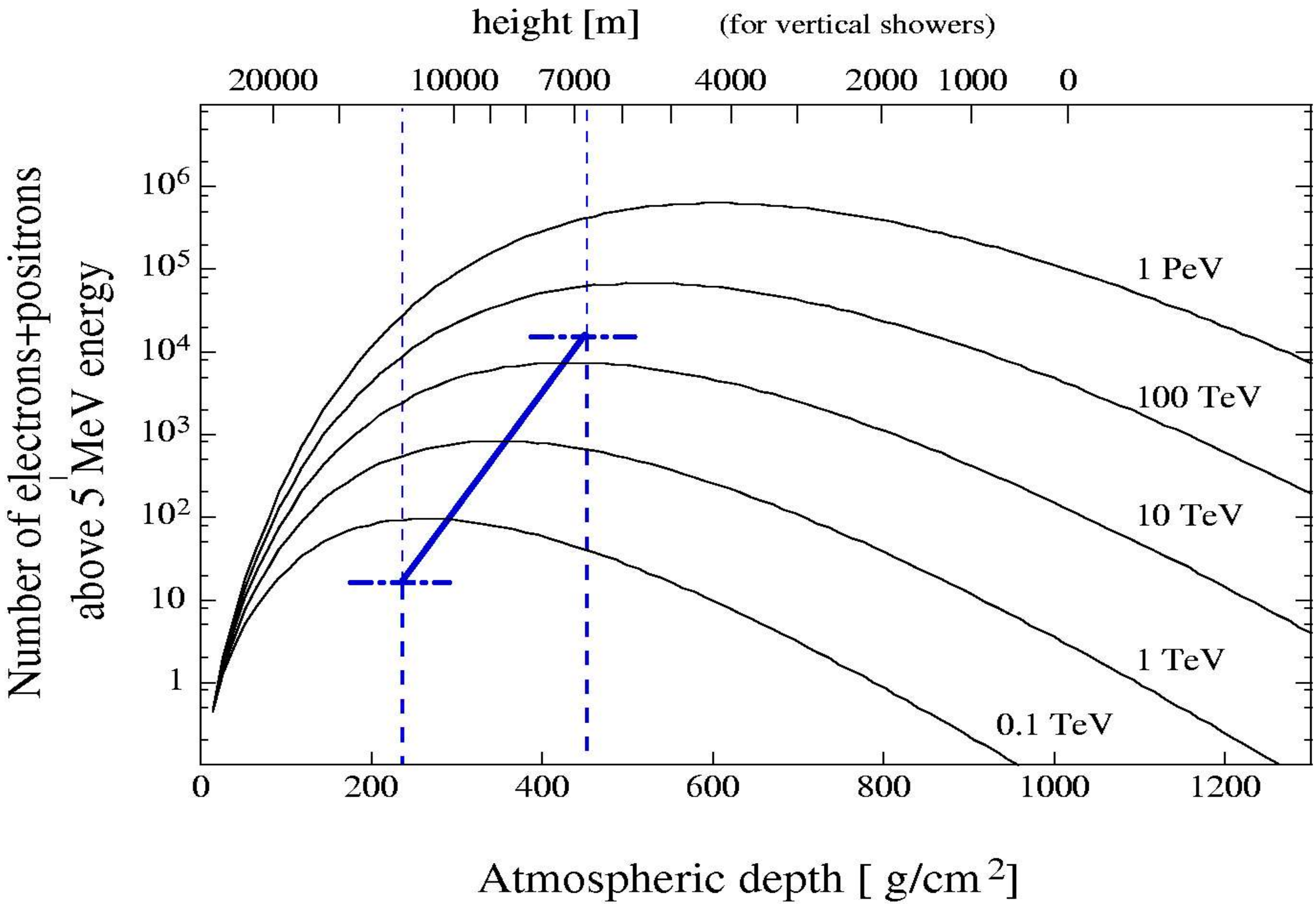


Shower development

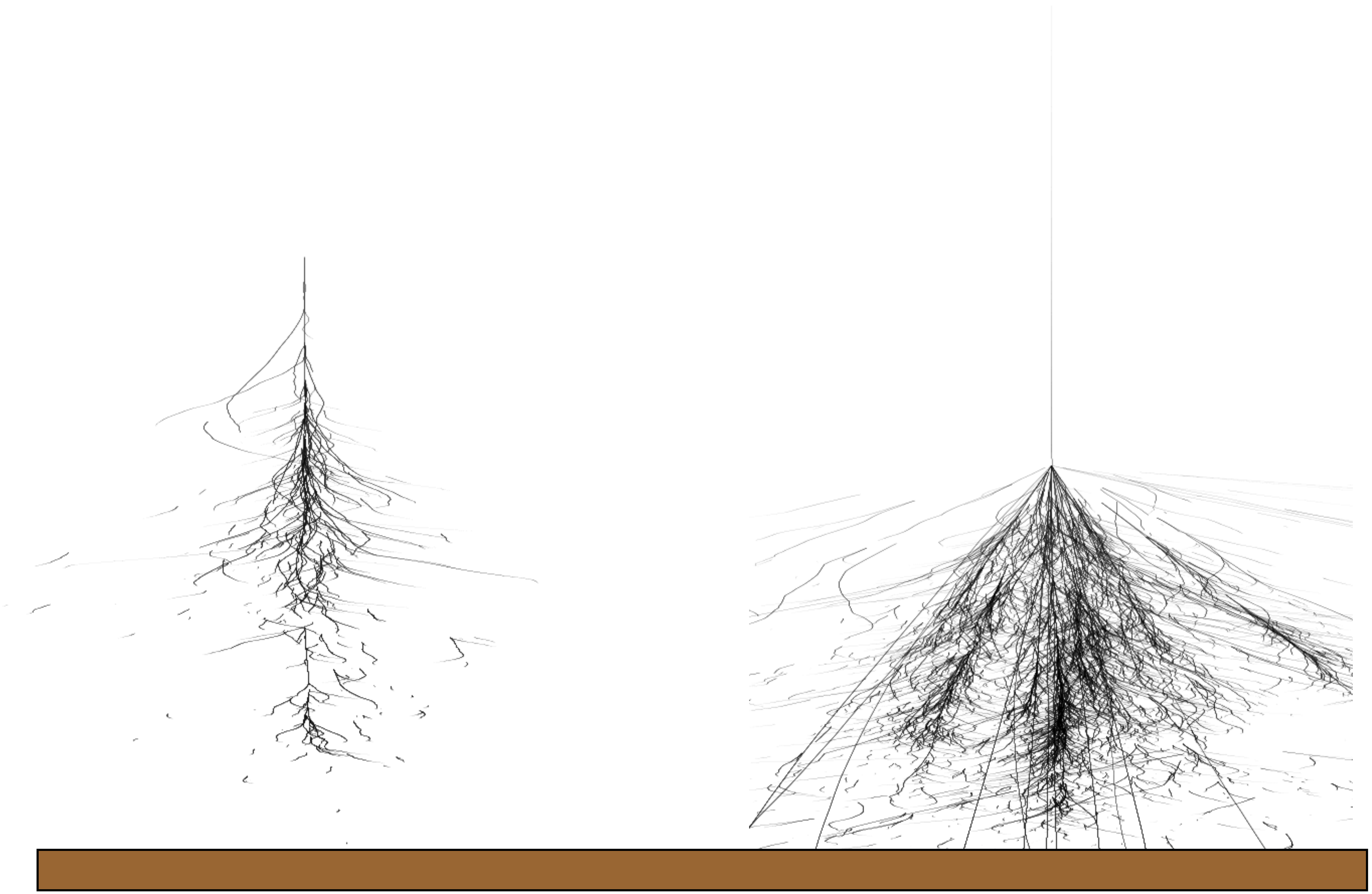
Analytical formulae (Bethe and Heitler 1934, Rossi and Greisen, 1941) tell us that:

- Shower maximum is reached (on average) at atmospheric depths of ~250 to 450 g/cm˜ for gamma rays of 20 GeV to 20 TeV, corresponding to altitudes of about 7 to 12 km.
- At the lower end of that energy range, we have only a few particles.

Shower development



Examples of shower development



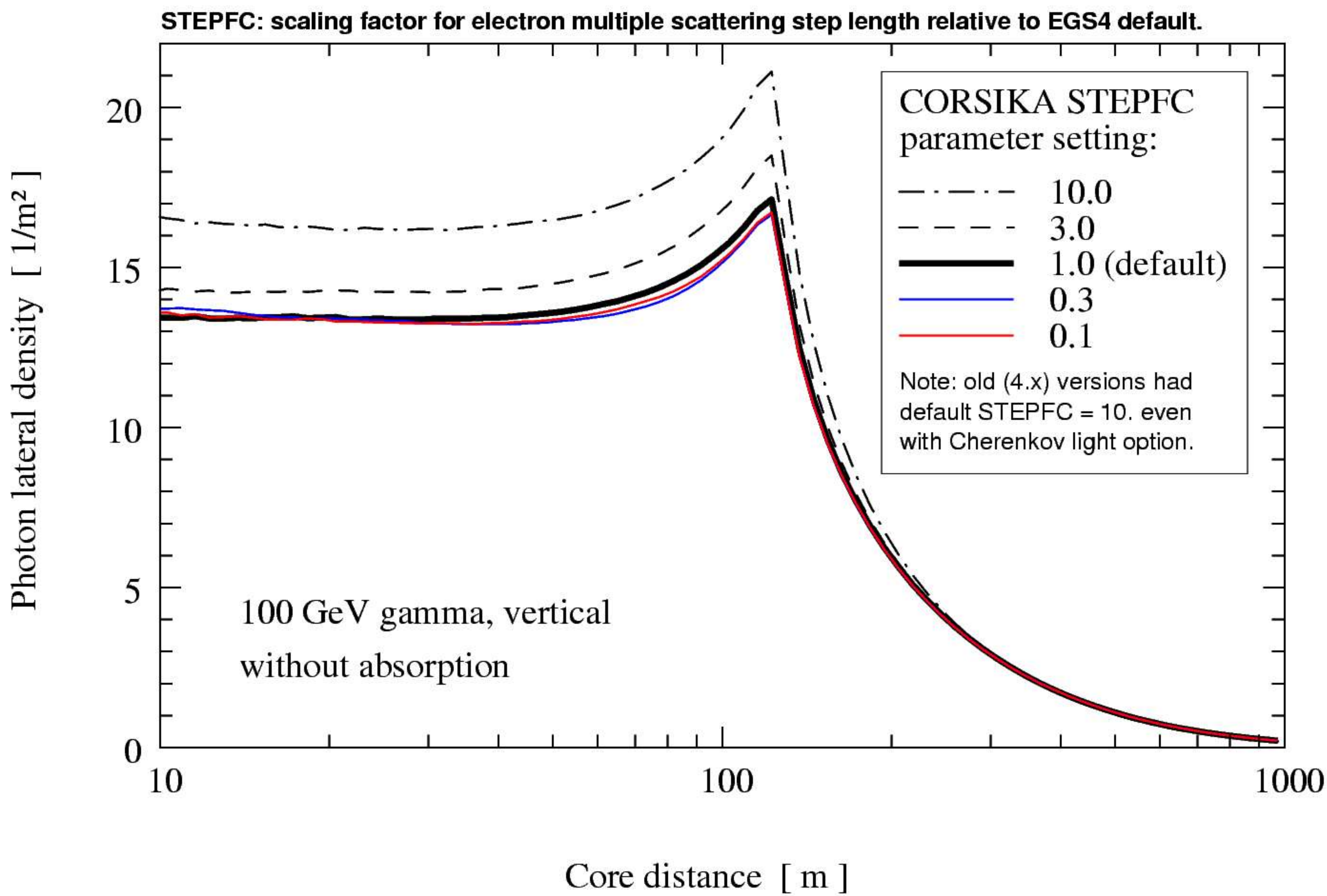
Simulation packages

- A number of specialized packages are available for both gamma-ray and cosmic-ray shower simulations. In use within H.E.S.S. are, for example:
  - CORSIKA, ALTAI, KASCADE, Mocca
- Packages developed for particle physics experiments (GEANT) are also possible but inefficient.

Simulation packages

- For gamma-ray showers, agreement between different packages is generally good, although they differ for example in
  - radiation length of air,
  - treatment of multiple scattering,
  - other step lengths, e.g. in geomagnetic field,
  - photo-nuclear and other reactions,
  - inclusion of atmospheric refraction,
  - inclusion of atmospheric transparency and detector efficiency already in the shower simulation package (or done later in a separate detector package).

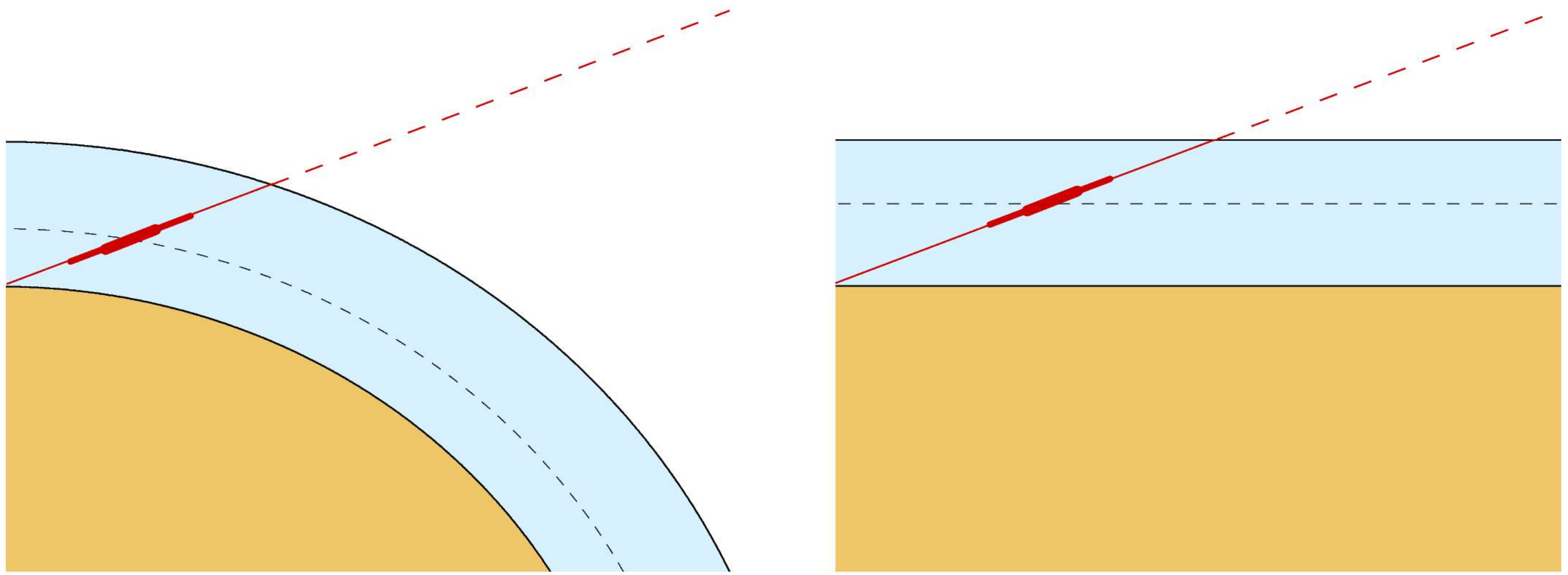
Simulation: step size



Simulation packages

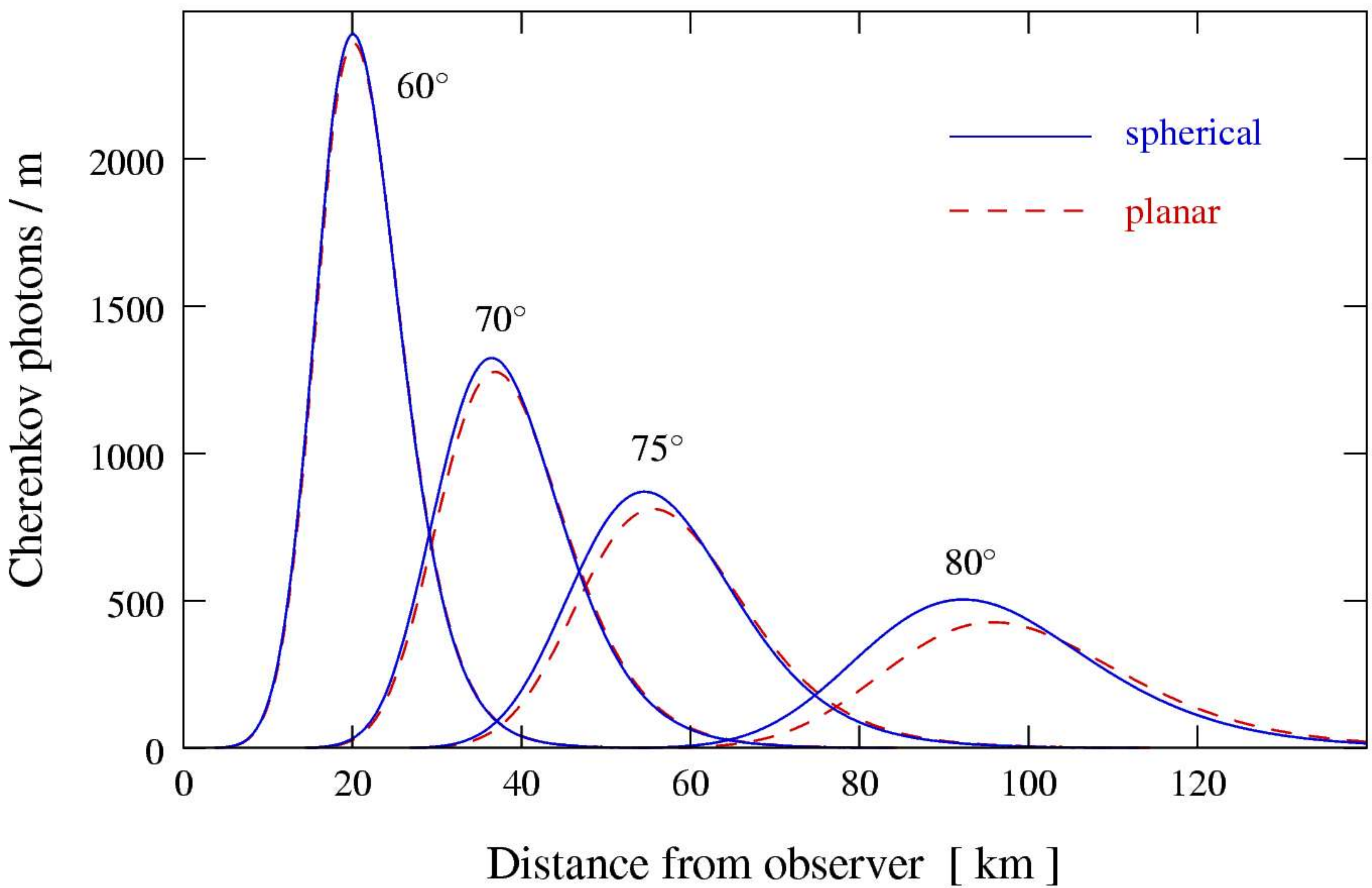
- For hadronic showers, the differences are typically larger since interaction models are often quite different.
- In recent years more effort was put into improving interaction models for the highest energies than into low-energy models.

Shower development: spherical versus planar atmosphere

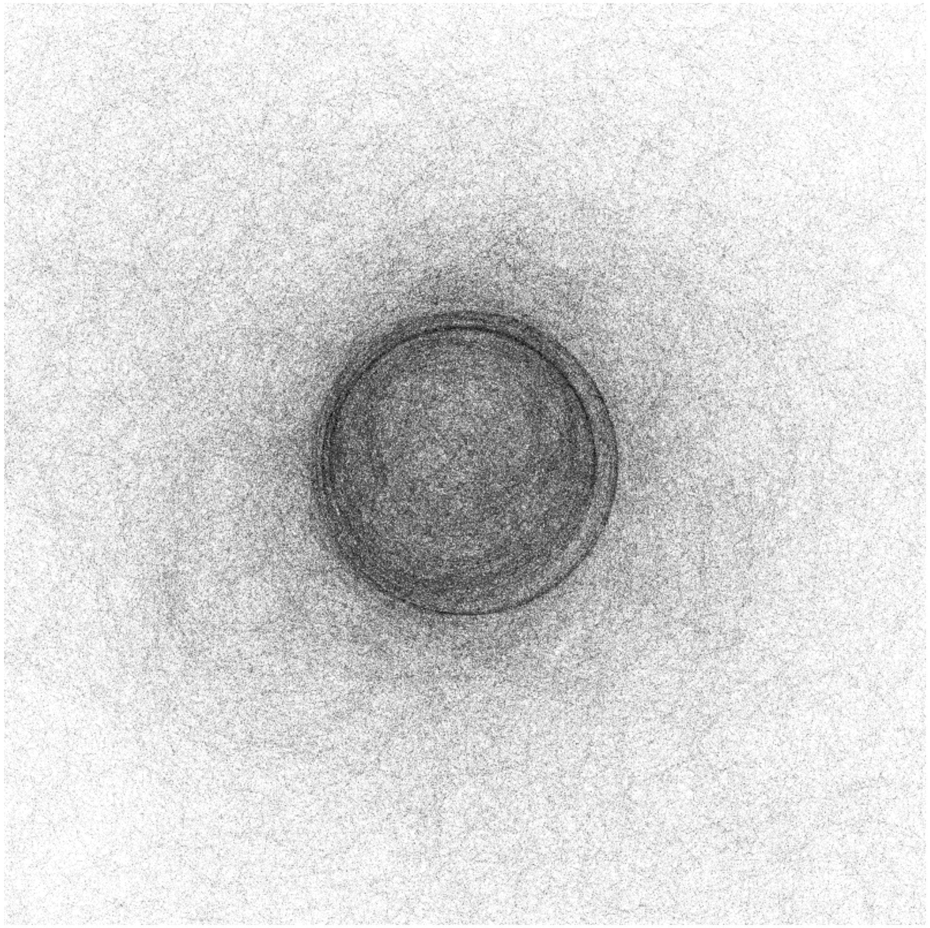


At large zenith angles, the planar atmosphere approximation results in shower maxima in too large altitude and at too large distance. Since more efficient to implement, most MC codes use the planar approximation.

Shower development: spherical versus planar atmosphere

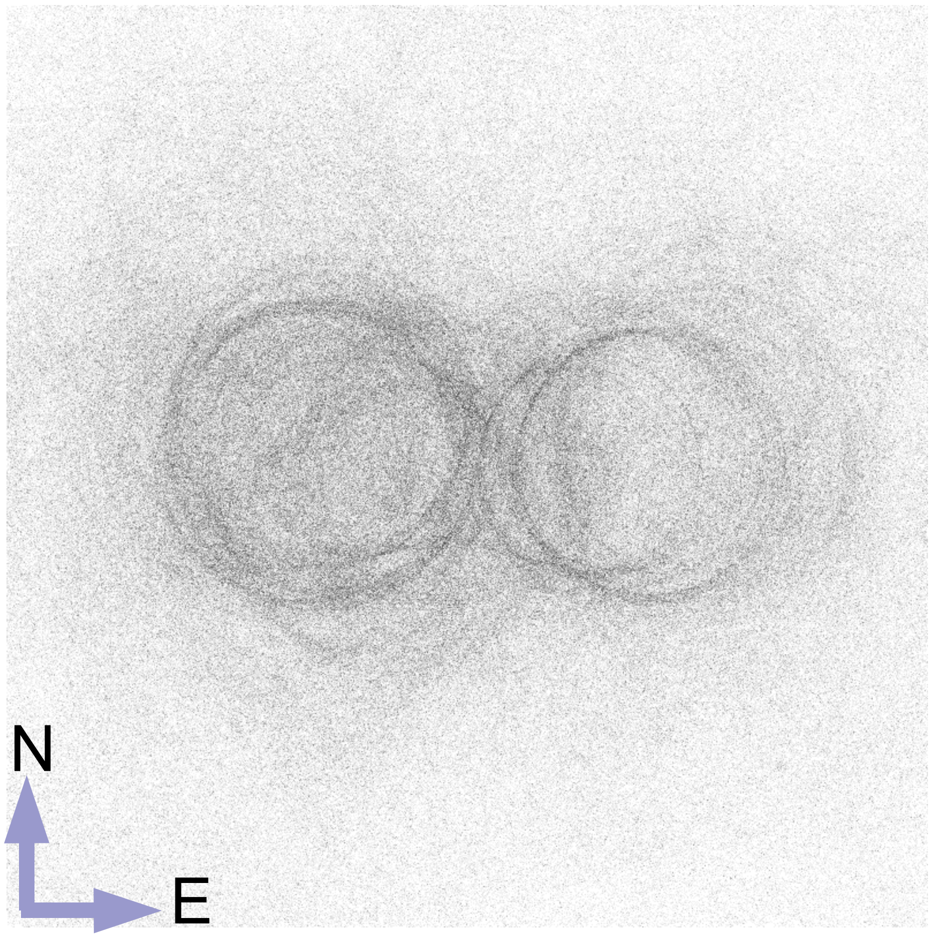


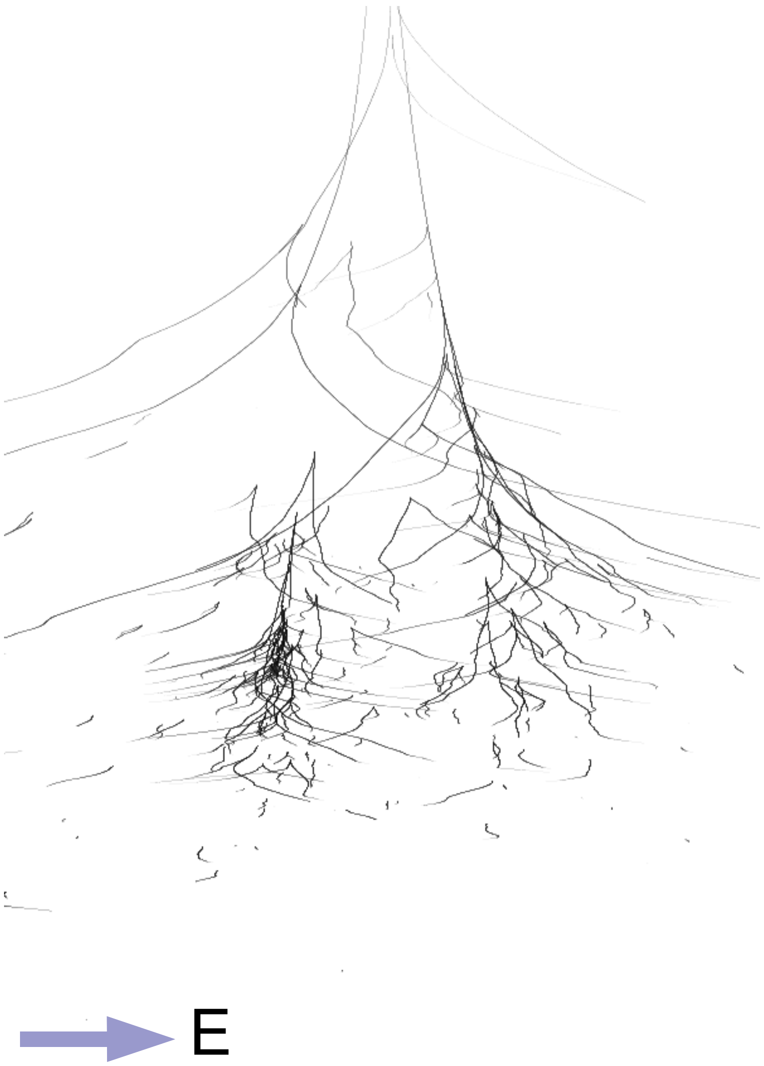
Shower development and geomagnetic field



- Without geomagnetic field showers tend to look quite symmetric. (see image to the left).
- With field, there can be a quite significant separation in east-west direction ...

Shower development and geomagnetic field





Cherenkov light emission

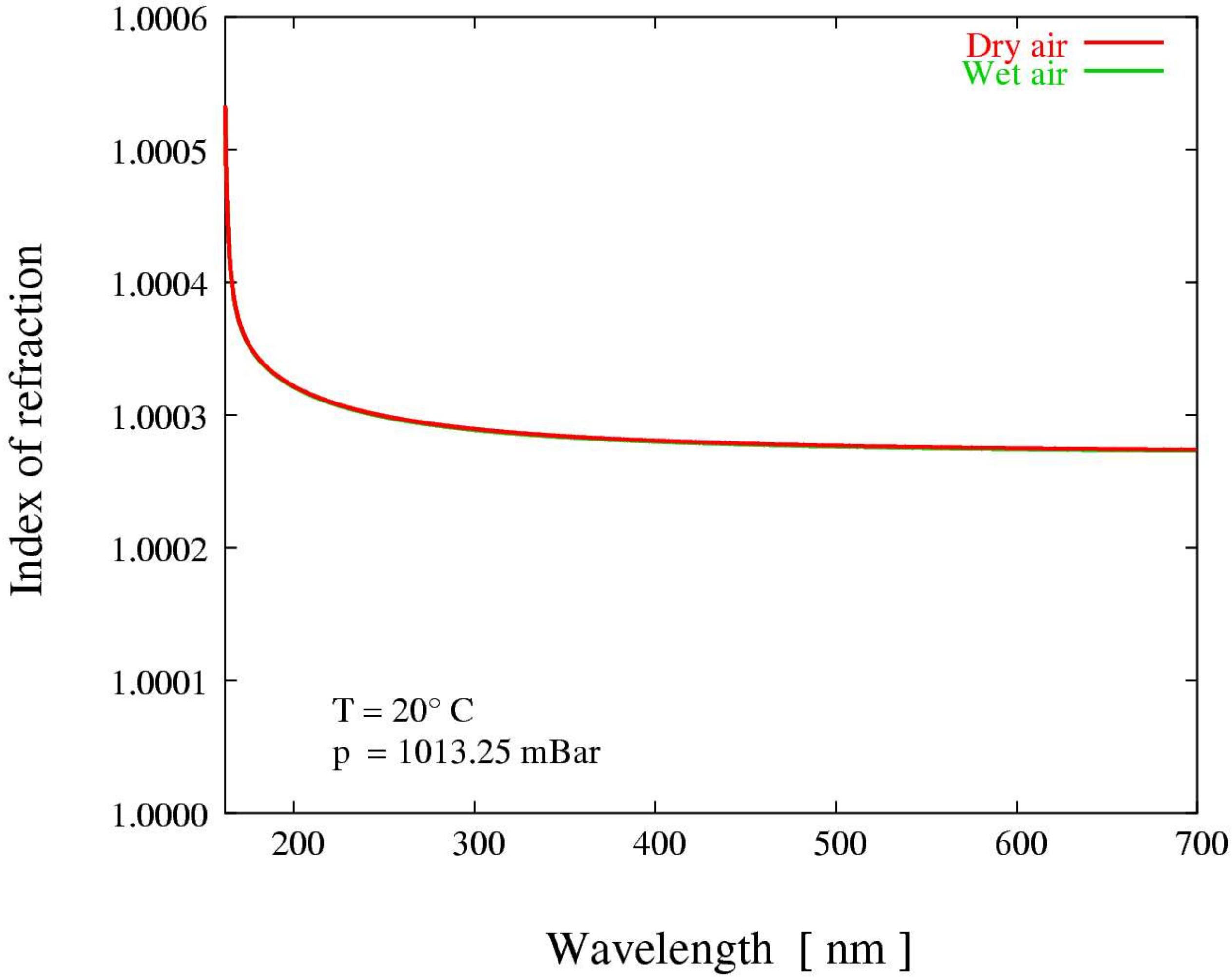
- Basic formulae:

$$\cos\theta = \frac{1}{n\beta} + \frac{\hbar}{2p}\left(1 - \frac{1}{n^2}\right) \approx \frac{1}{n\beta}$$

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2(\lambda)\beta^2}\right) \frac{d\lambda}{\lambda^2}$$

- Recoil can be safely neglected.
- Wavelength dependence of index of refraction is often neglected (for efficiency reasons).

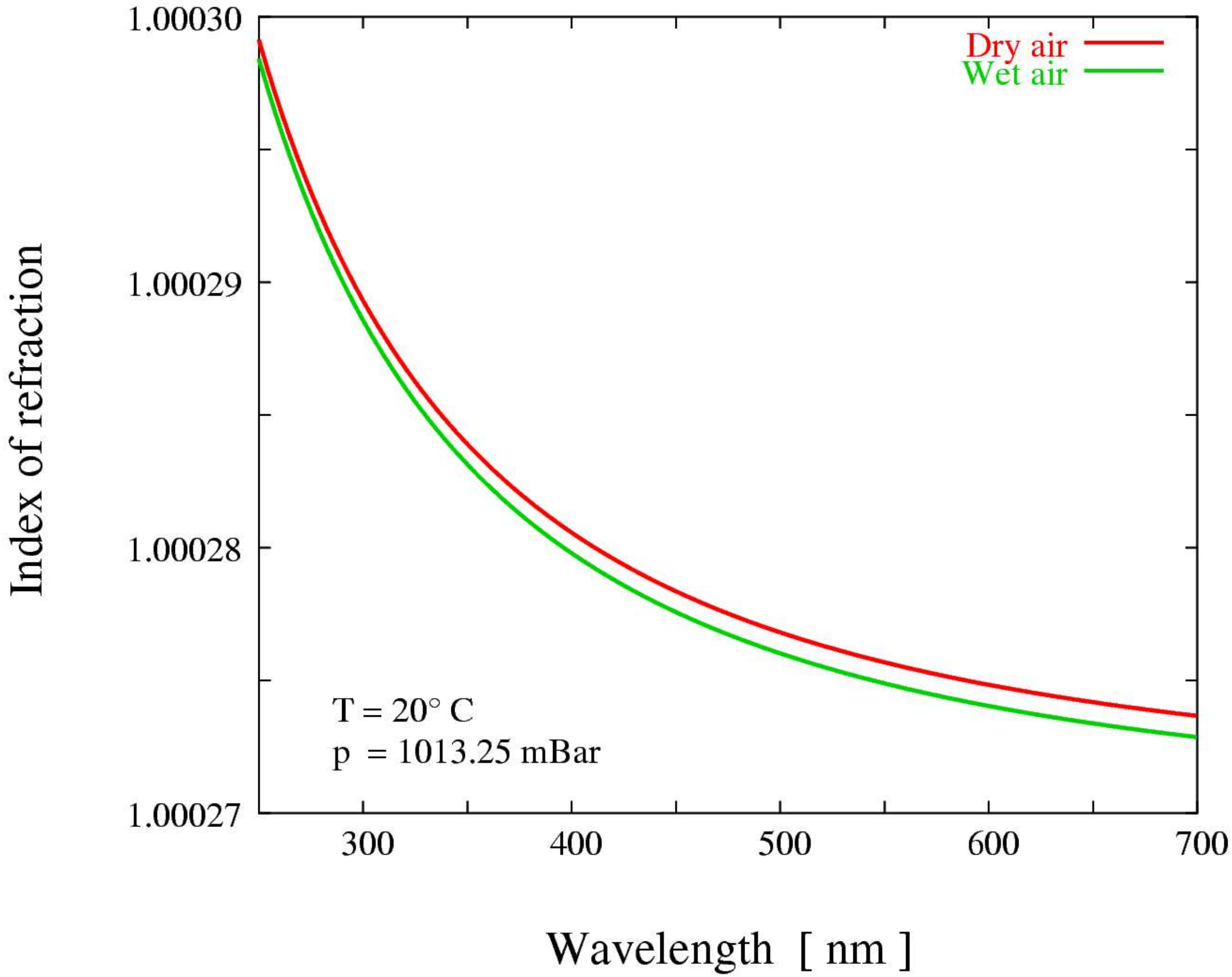
Index of refraction



Formula:
MODTRAN

Wavelength dependence highly significant only below 250 nm.

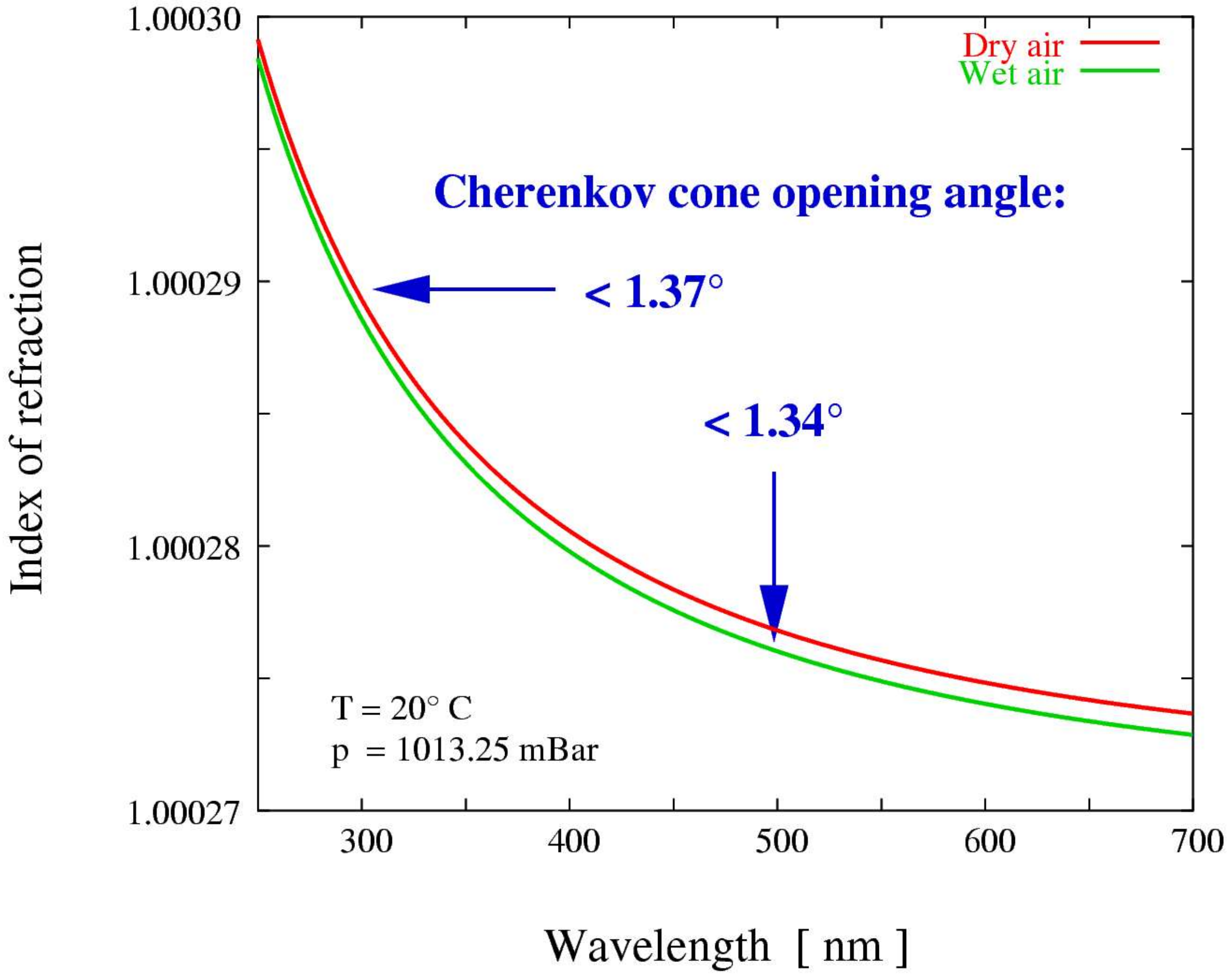
Index of refraction



Formula:
MODTRAN

Between 300 nm and 700 nm only rather small change.

Index of refraction



Formula: MODTRAN

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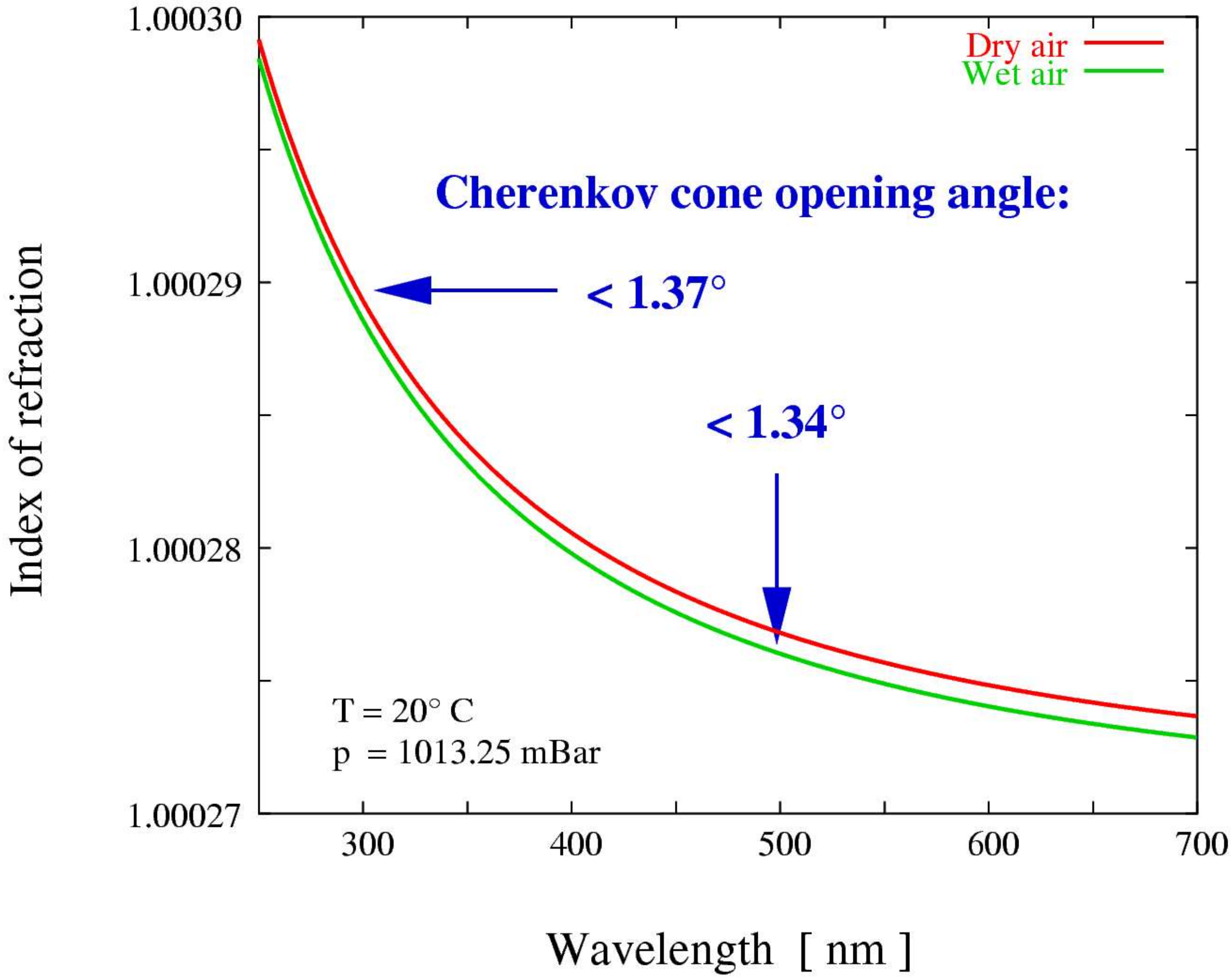
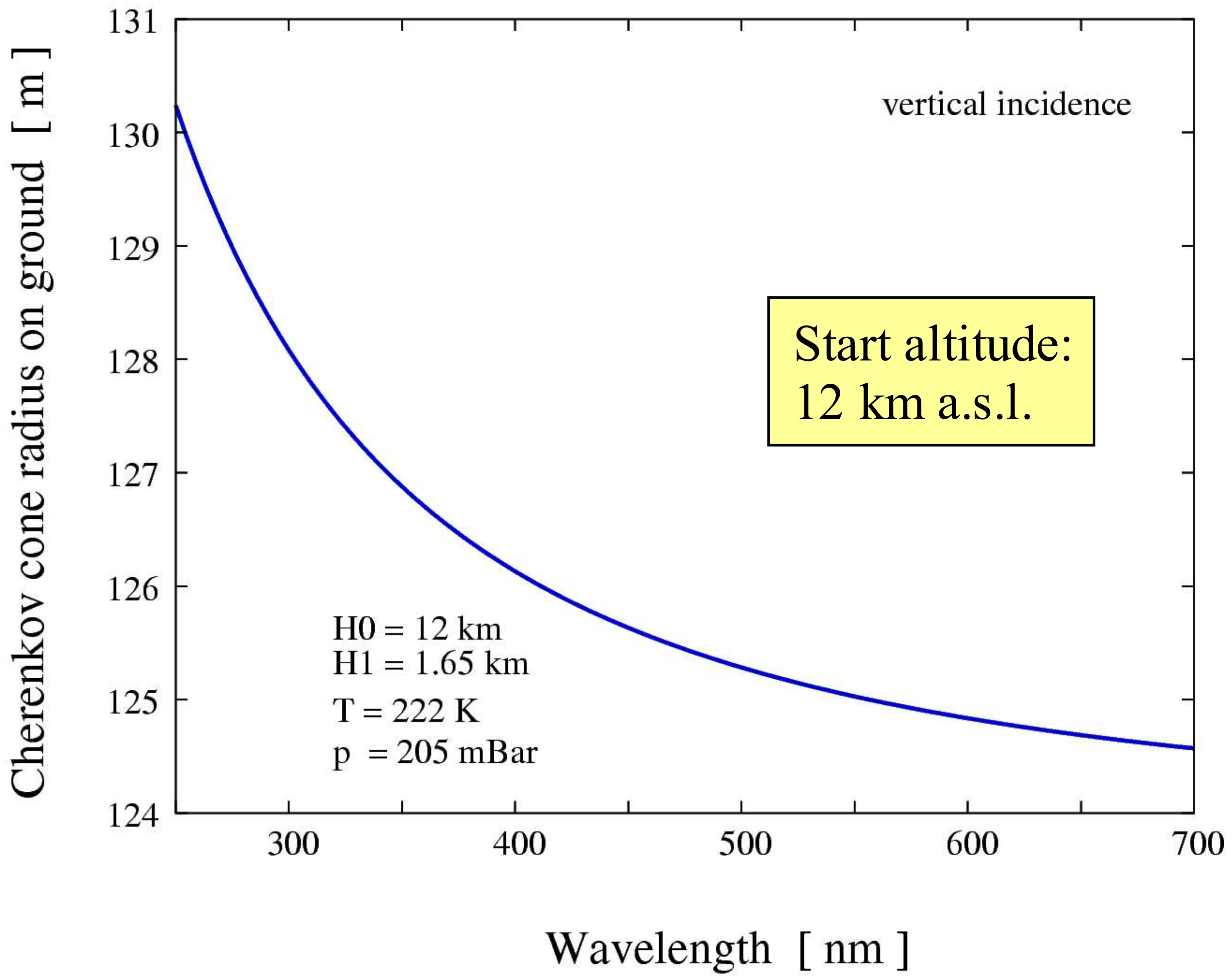
Index of refraction

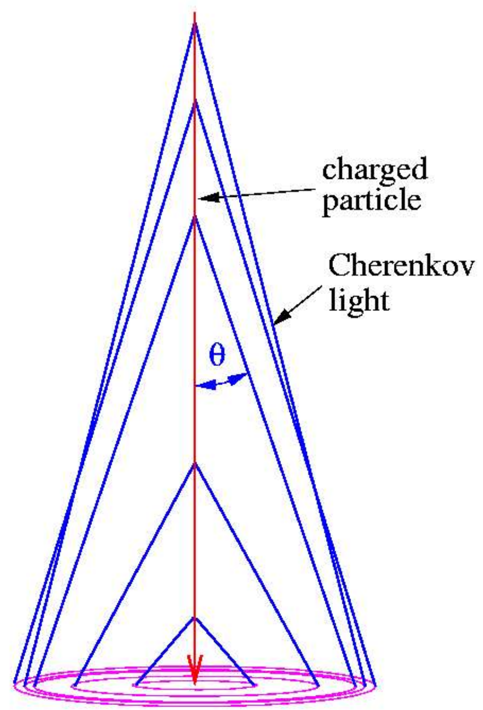


Formula: MODTRAN

Impact of humidity on index of refraction is of little relevance.

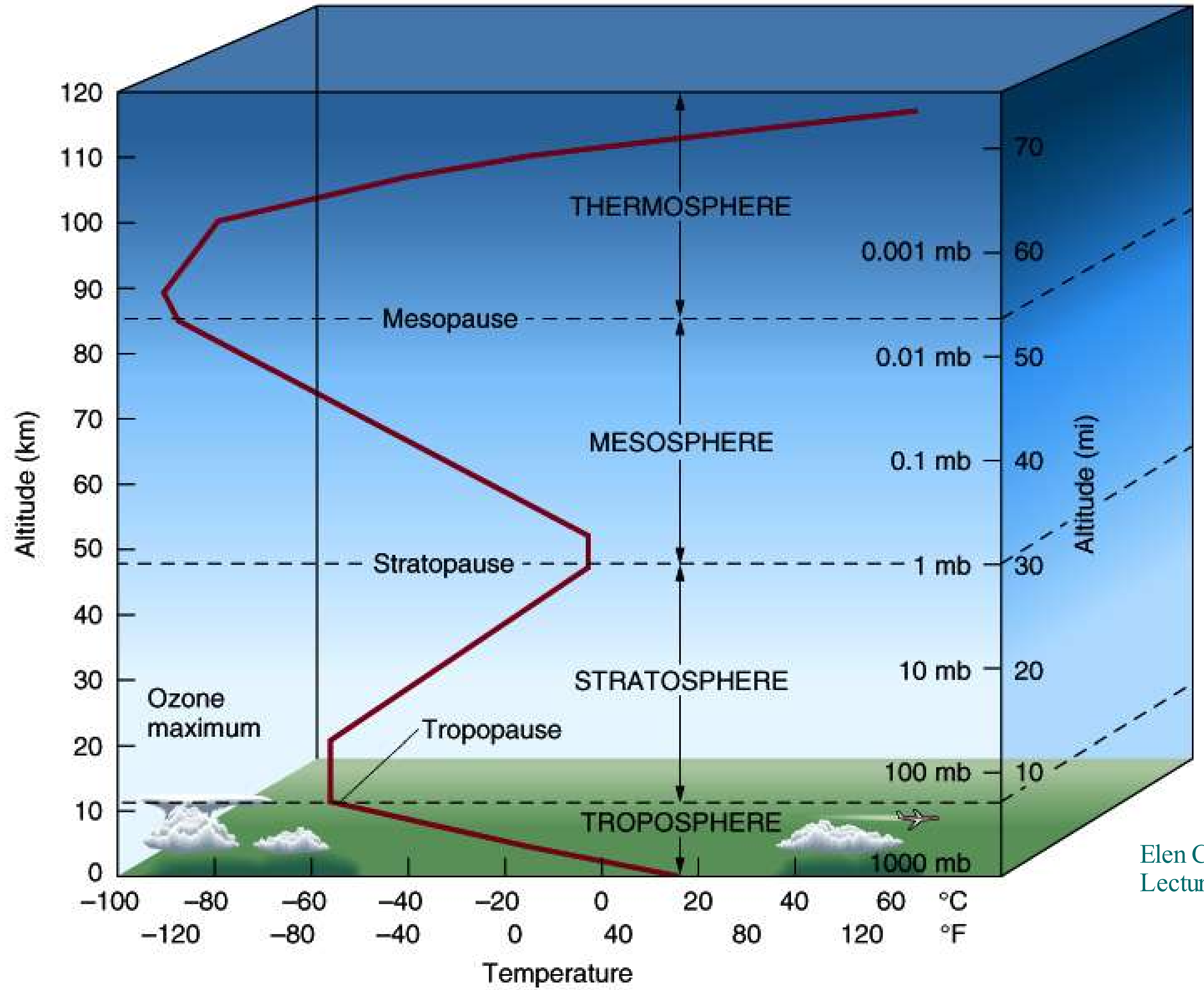
Example for Themis site: Cone radius on ground





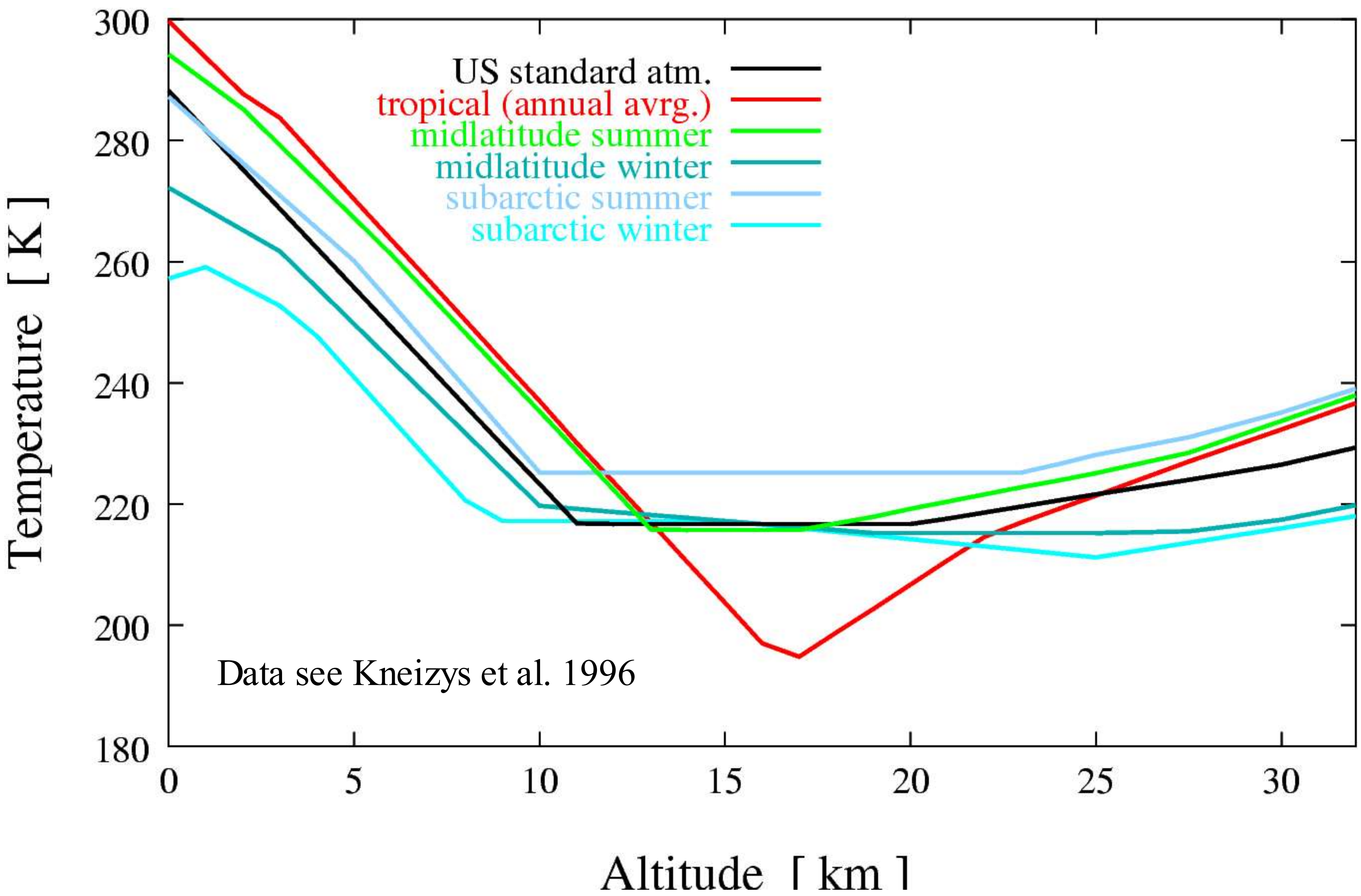
Between 300 and 700 nm the cone radius changes by up to 3 m.

Atmospheric profiles



Elen Cutrim, Lecture Notes

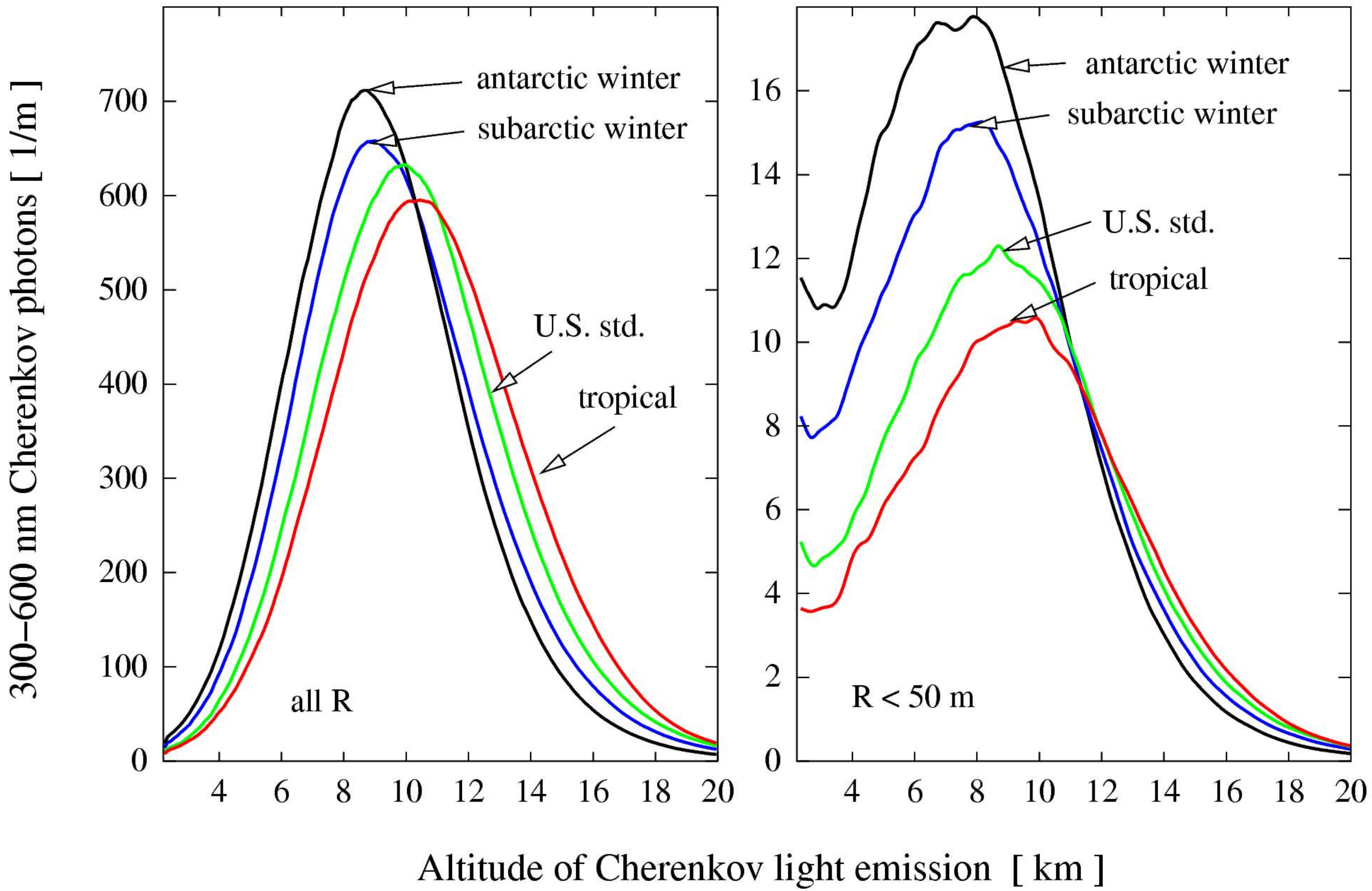
Atmospheric profiles



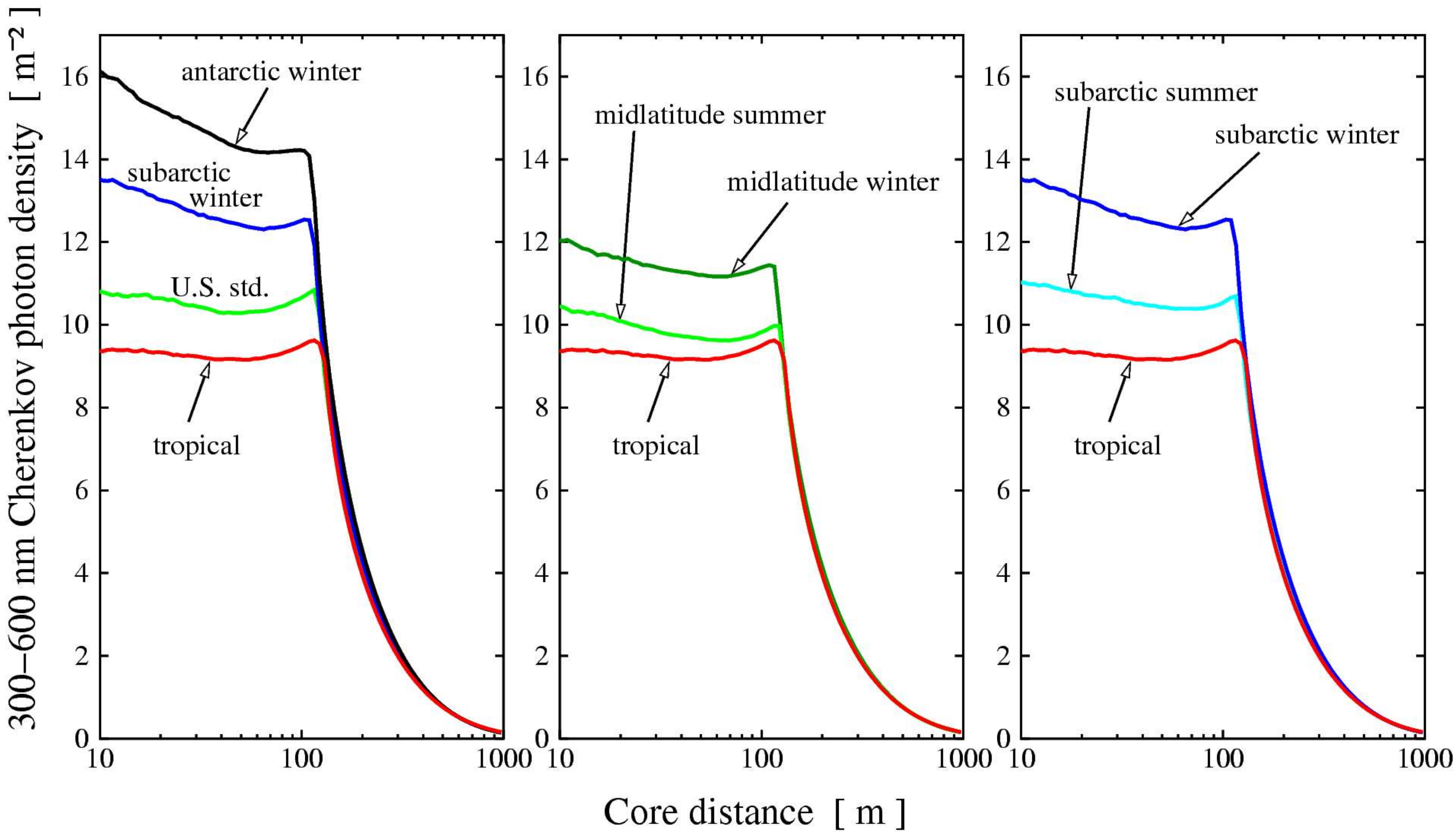
Atmospheric profiles

- Different temperature profiles result in different density profiles and different relations between atmospheric depth *X* and altitude *H*.
- Lower temperatures mean smaller density scale height:
  - Fixed X (for example X_0) is at lower *H.*
  - The shower maximum is then closer to the observer.
  - The atmospheric density at the shower maximum is larger, and therefore also the index of refraction. More Cherenkov light gets emitted at larger opening angles.

Impact of atmospheric profiles: longitudinal distribution

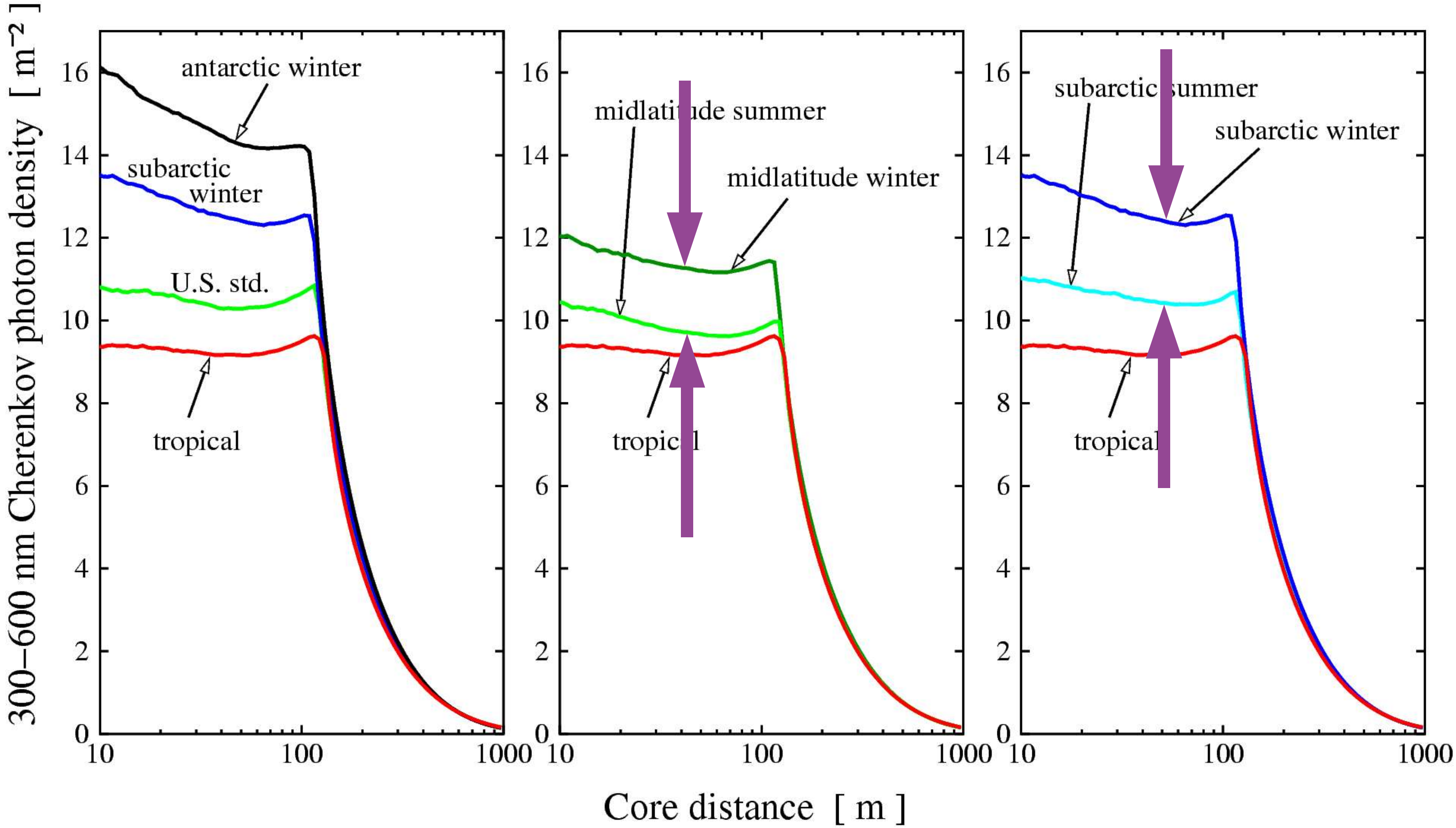


Impact of atmospheric profiles: lateral distribution



Impact of atmospheric profiles: lateral distribution

Seasonal variations !

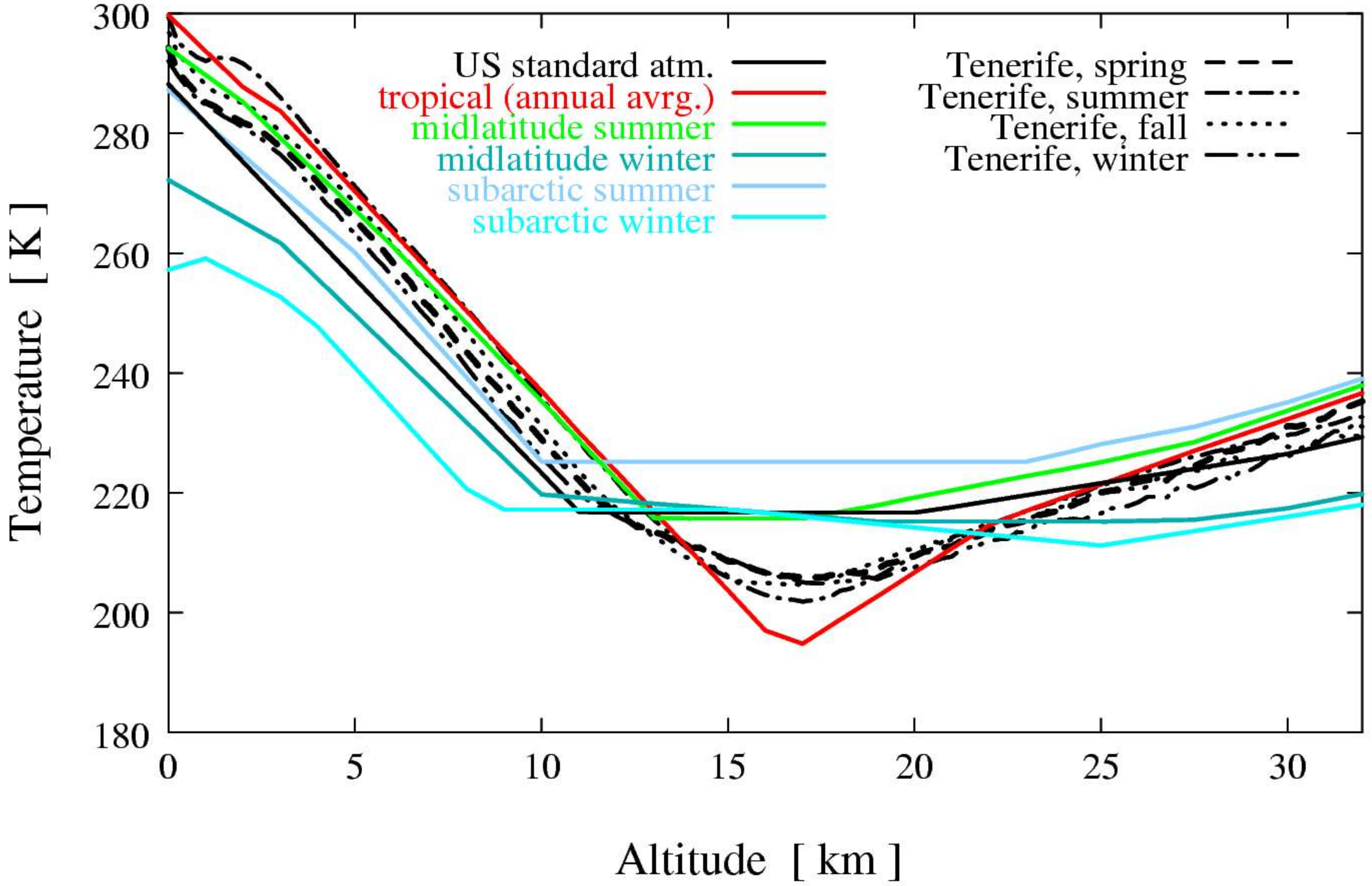


How to get the right atmospheric profile for your site?

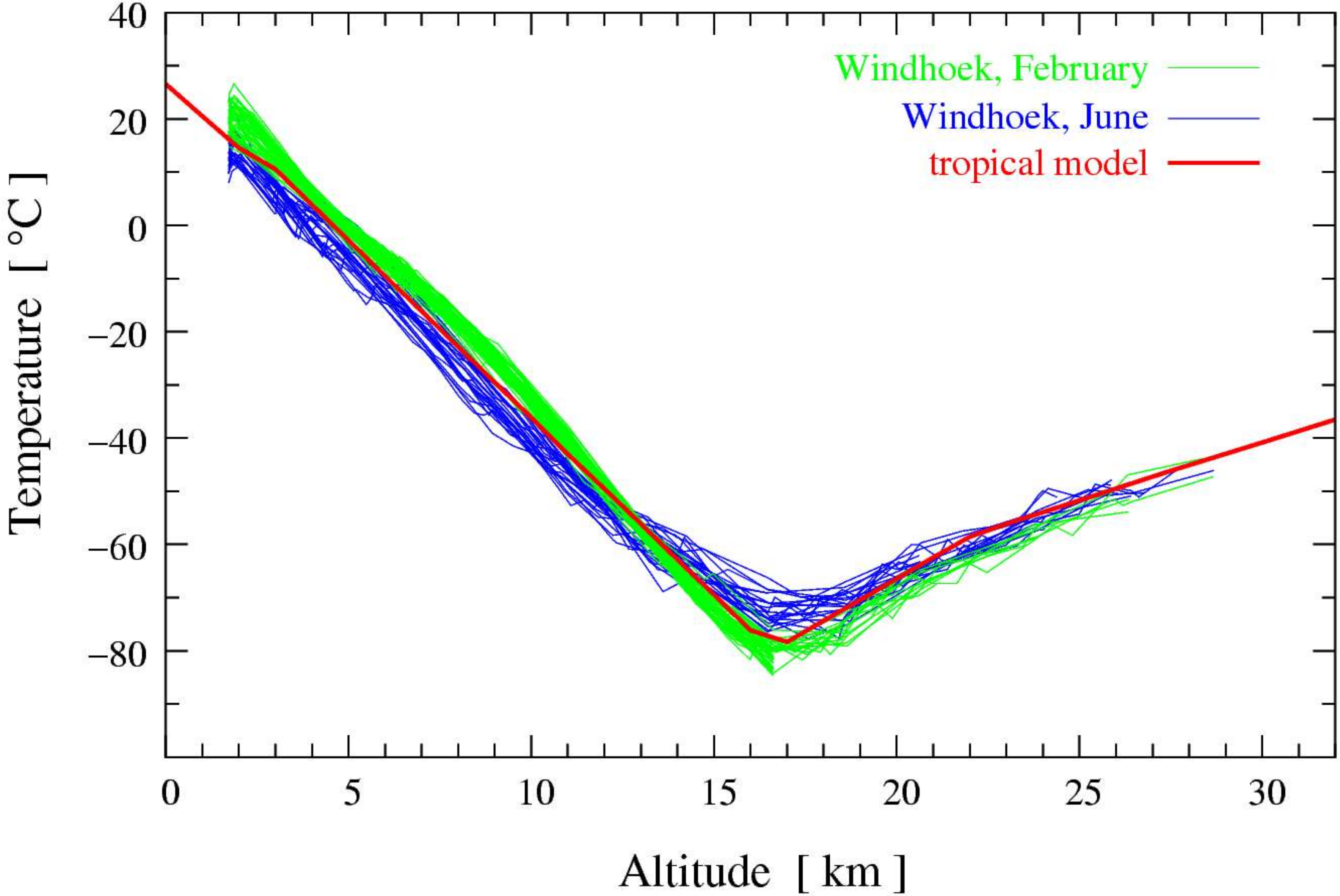
In order of improving accuracy:

- Take U.S. Standard Atmosphere 1976 (poor).
- Take an available table corresponding to your climate zone (e.g. from MODTRAN report, see also CORSIKA IACT/ATMO package).
- Calculate model profiles with MSIS-E 90, see `http://nssdc.gsfc.nasa.gov/space/model/models/msis_n.html`
- Use available measurements from radiosondes launched at nearby sites, see `http://raob.fsl.naoo.gov/` or `http://www.weather.uwyo.edu/upperair/sounding.html`
- Or you could launch your own radiosondes ...

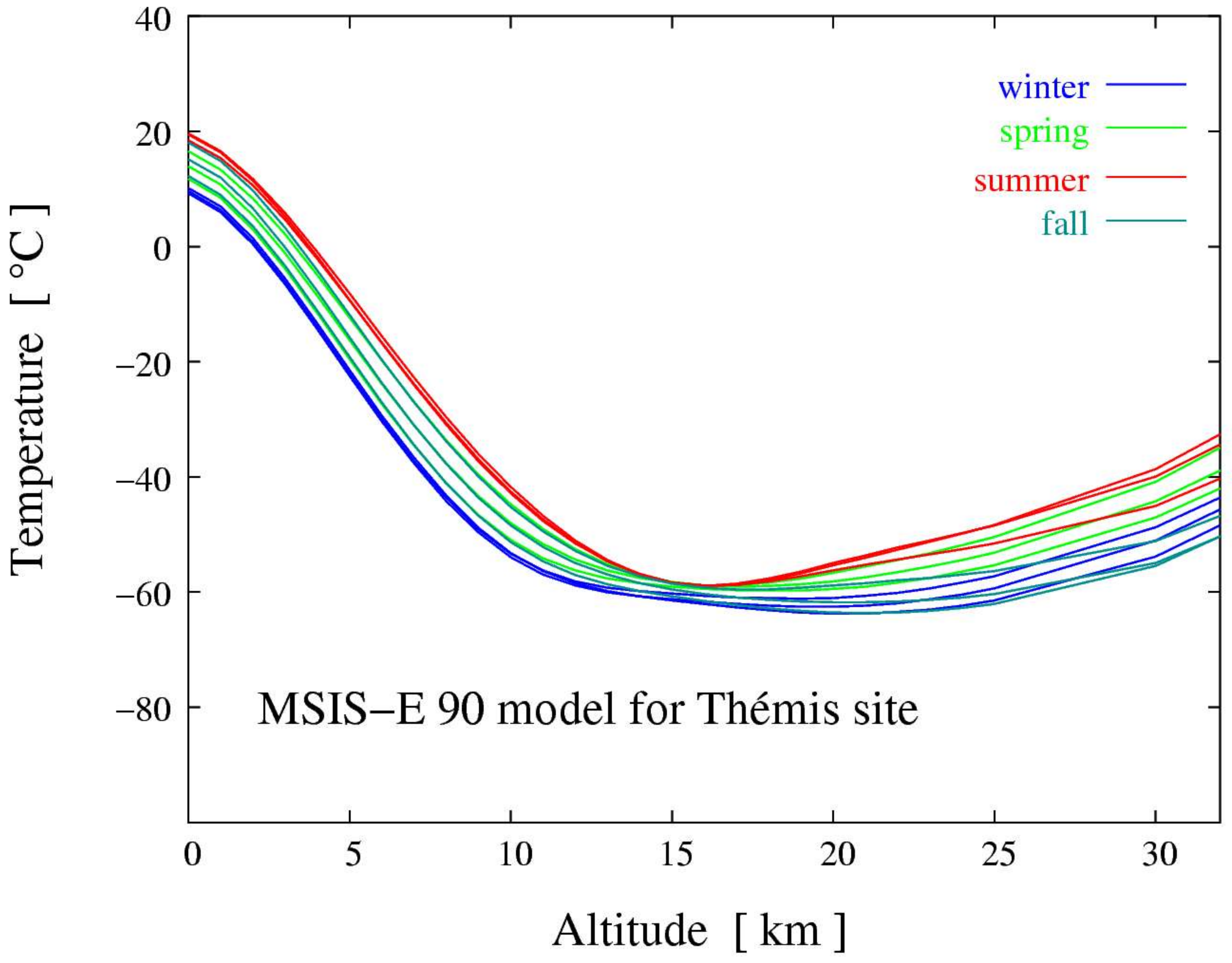
Atmospheric profiles: La Palma



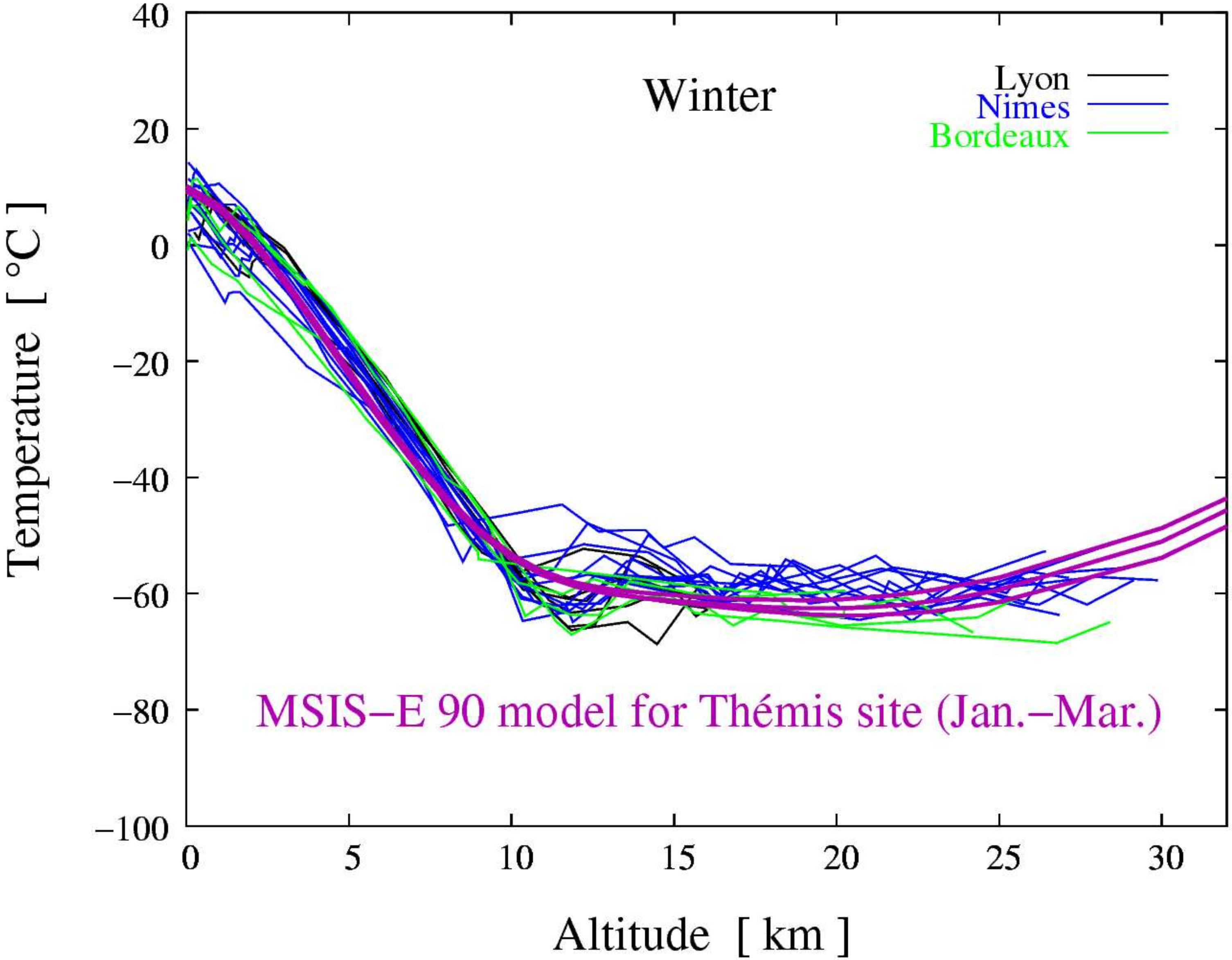
Atmospheric profiles: Namibia



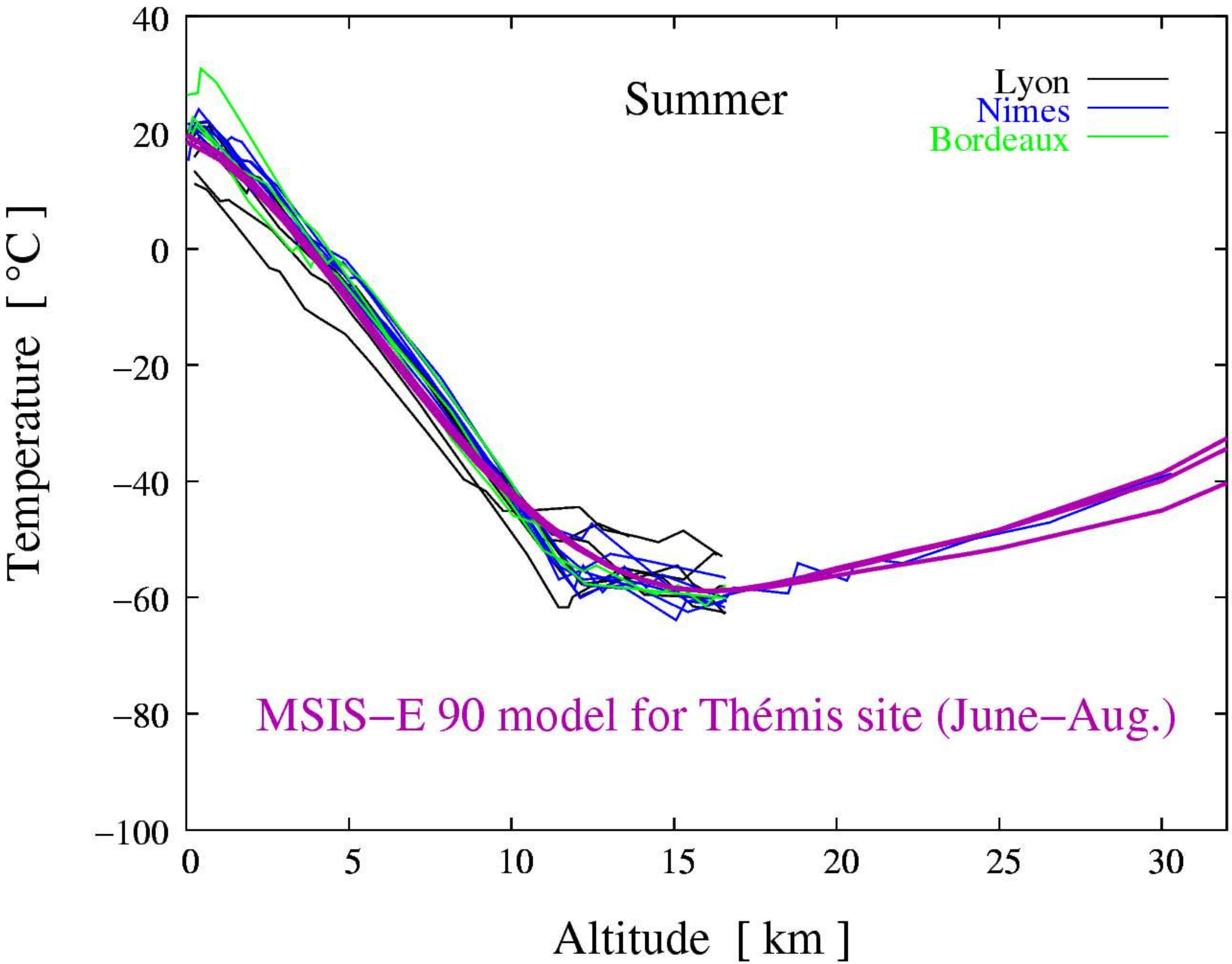
Atmospheric profiles: Thémis



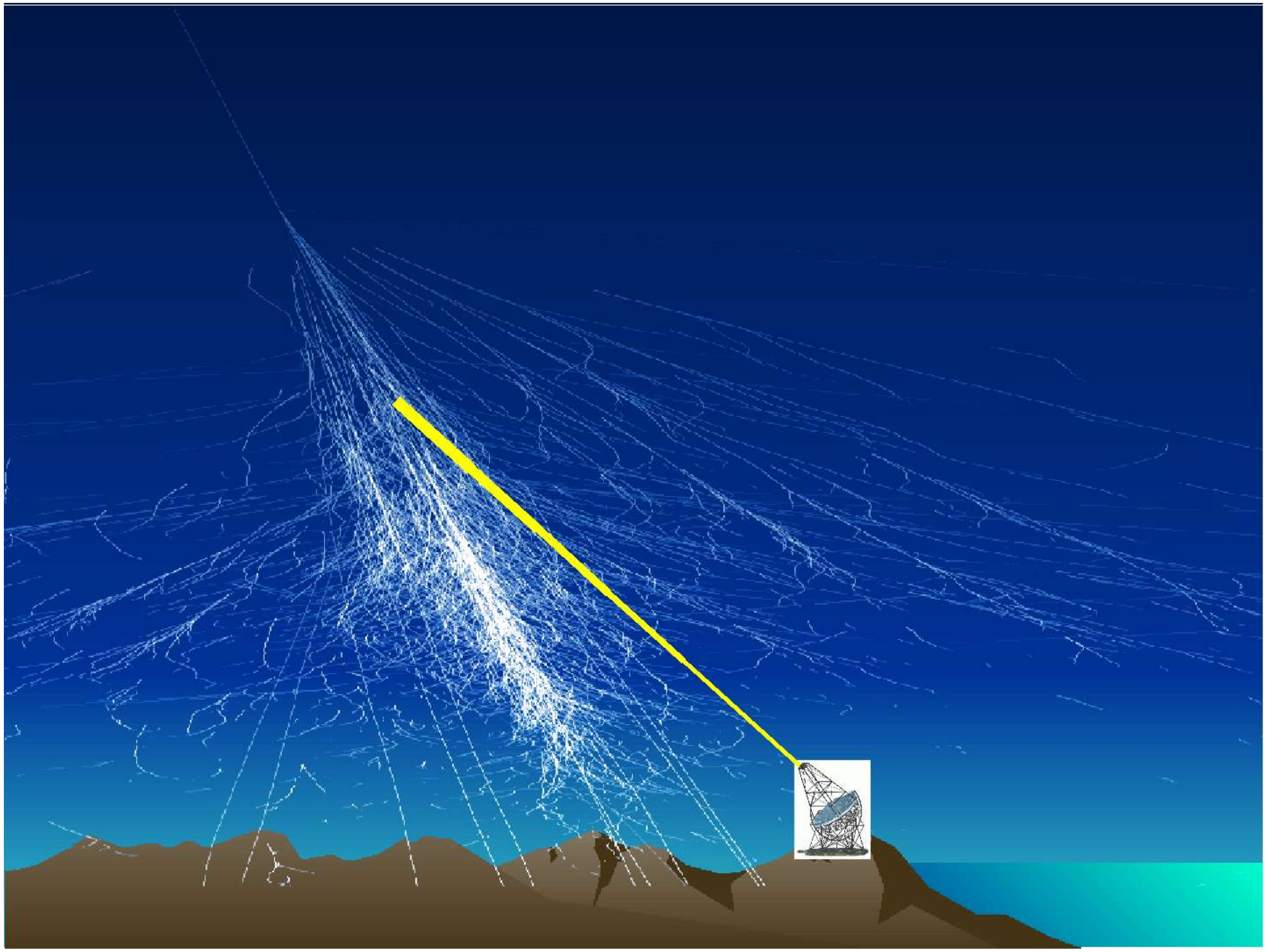
Atmospheric profiles: Thémis



Atmospheric profiles: Thémis



Extinction of Cherenkov light



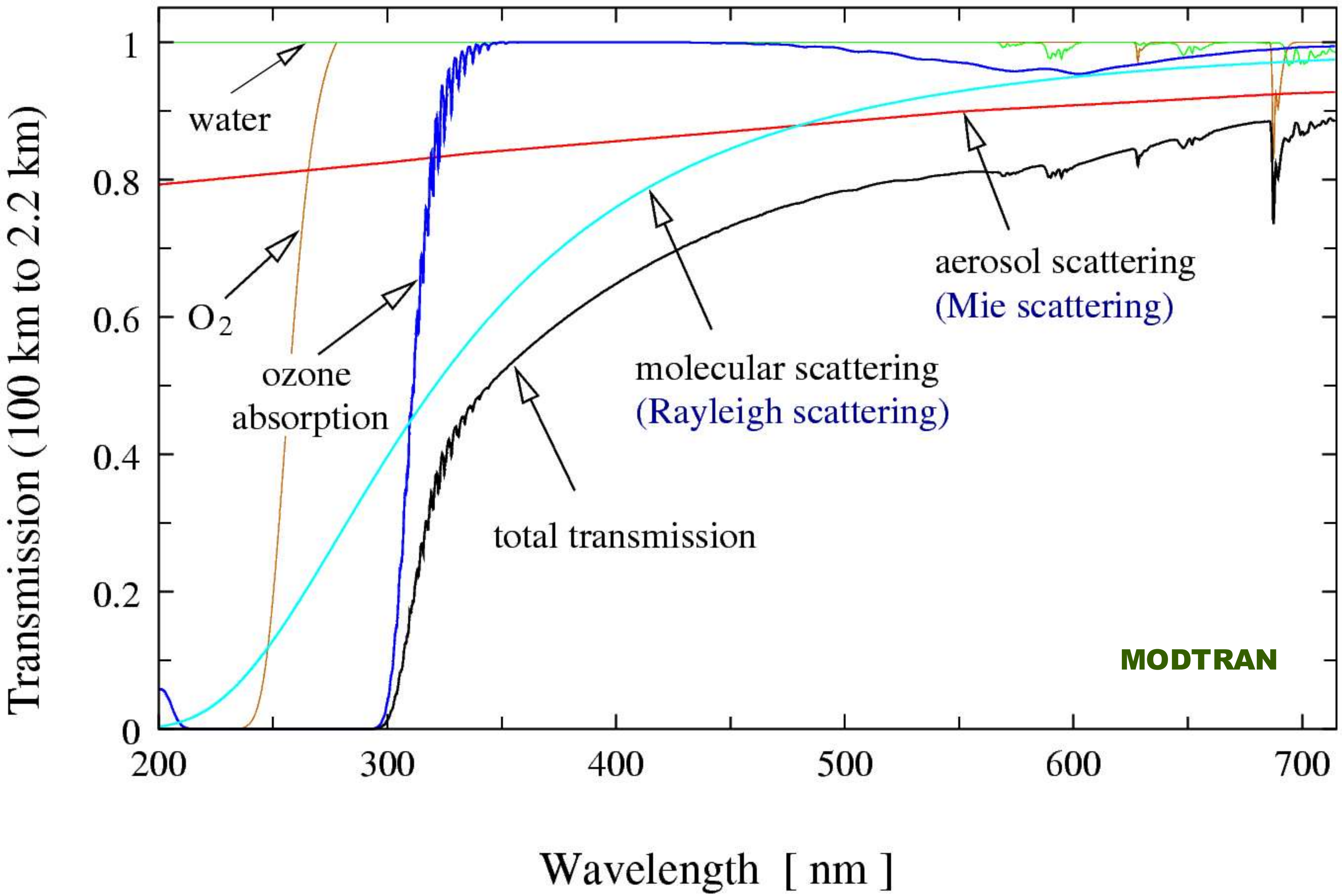
Due to different processes, Cherenkov light gets lost along the line of sight to the observer.

Extinction of Cherenkov light

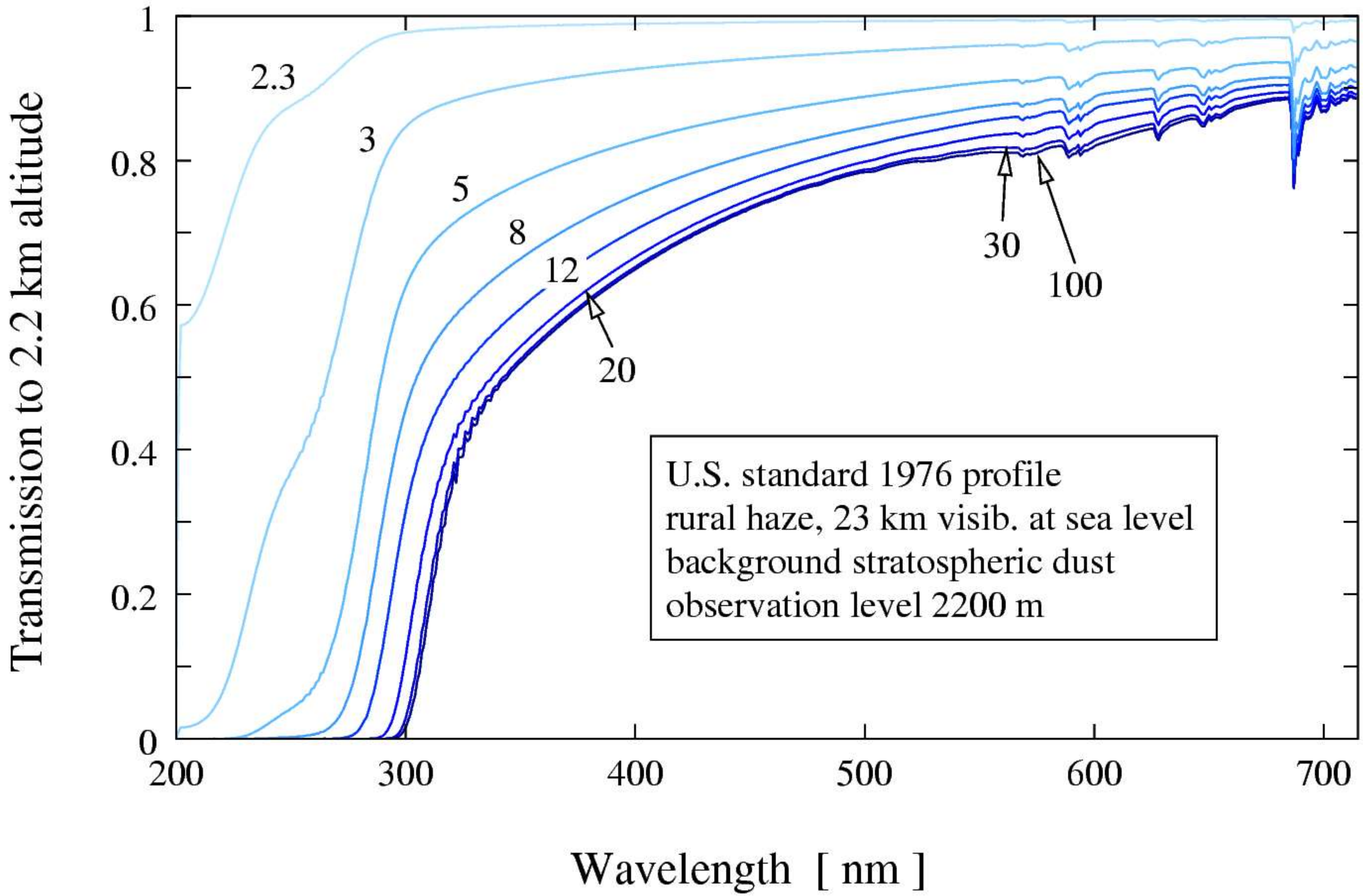
Extinction of Cherenkov light due to:

- Molecular (Rayleigh) scattering
- Aerosol (Mie) scattering and absorption
- Molecular absorption on ozone:
  - Hartly bands (200-300 nm)
  - Huggins bands (up to 340 nm)
  - Chappuis bands (near 600 nm, weak: few %)
- Molecular absorption on oxygen:
  - Herzberg continuum (below 242 nm)
  - Herzberg band (~260 nm) and others below 190 nm
- Absorption by water vapour (weak)

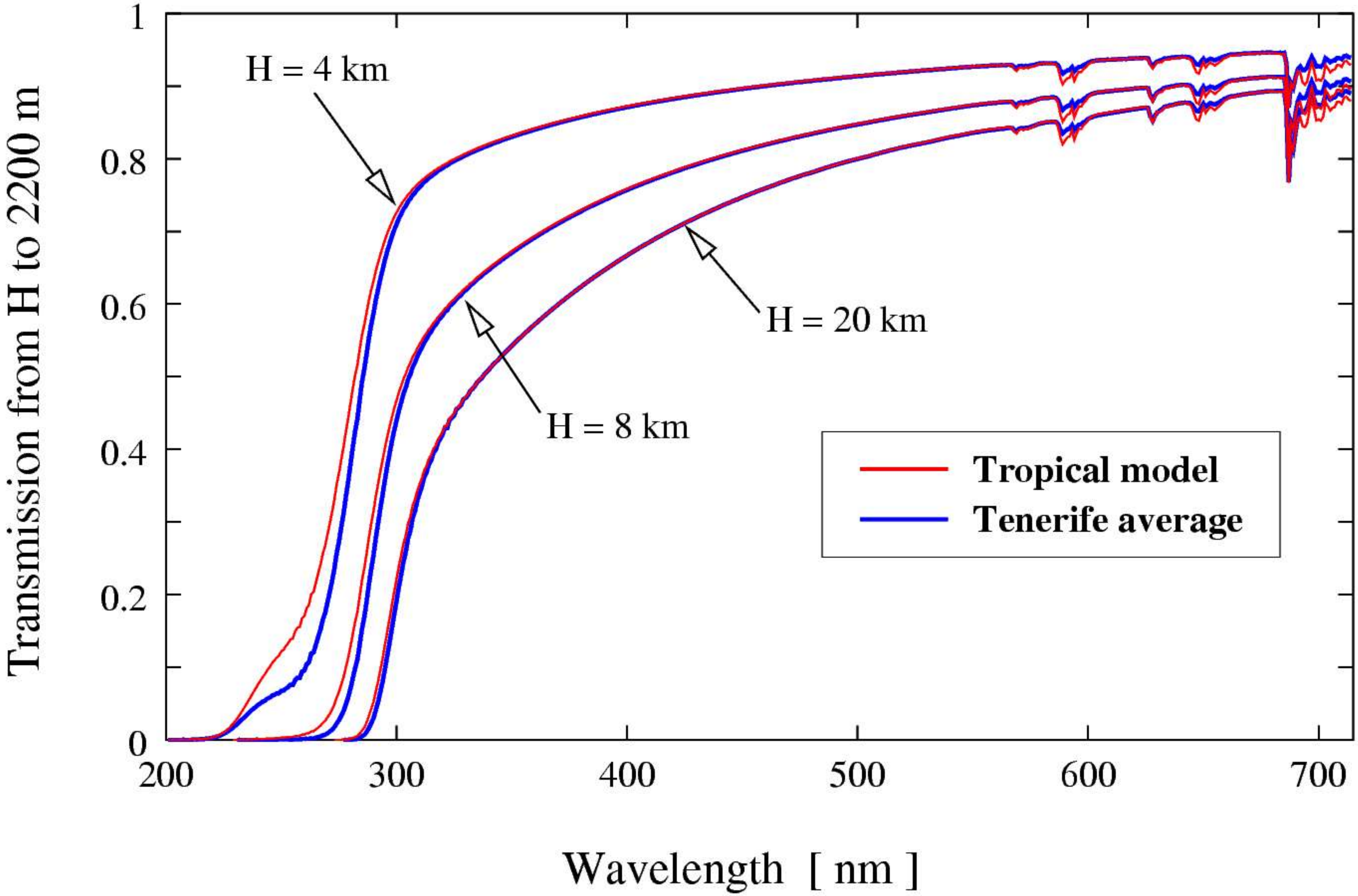
Extinction processes



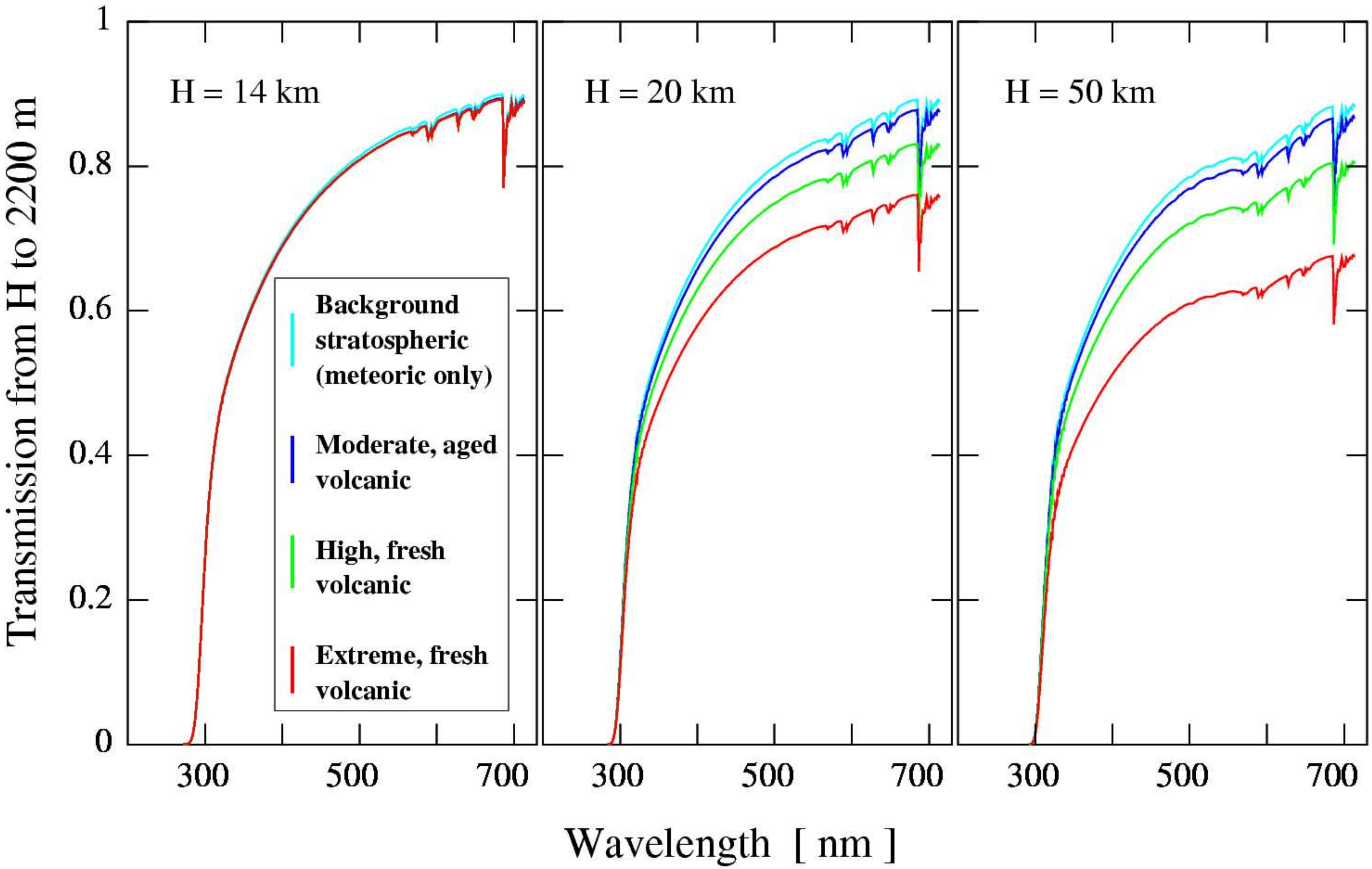
Transmission from different altitudes to the experiment



Individual extinction sources: Tropospheric ozone

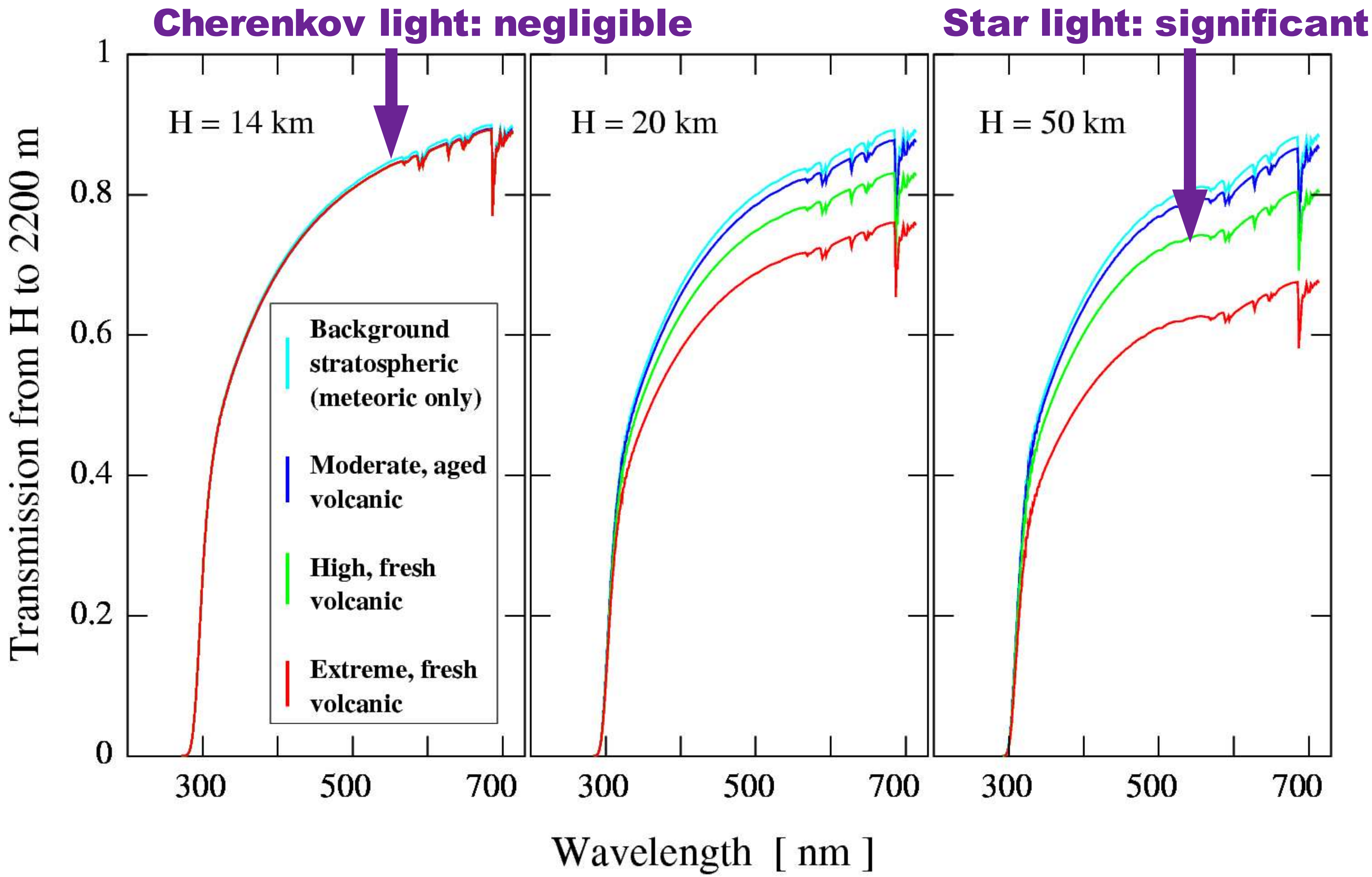


Individual extinction sources: volcanic dust



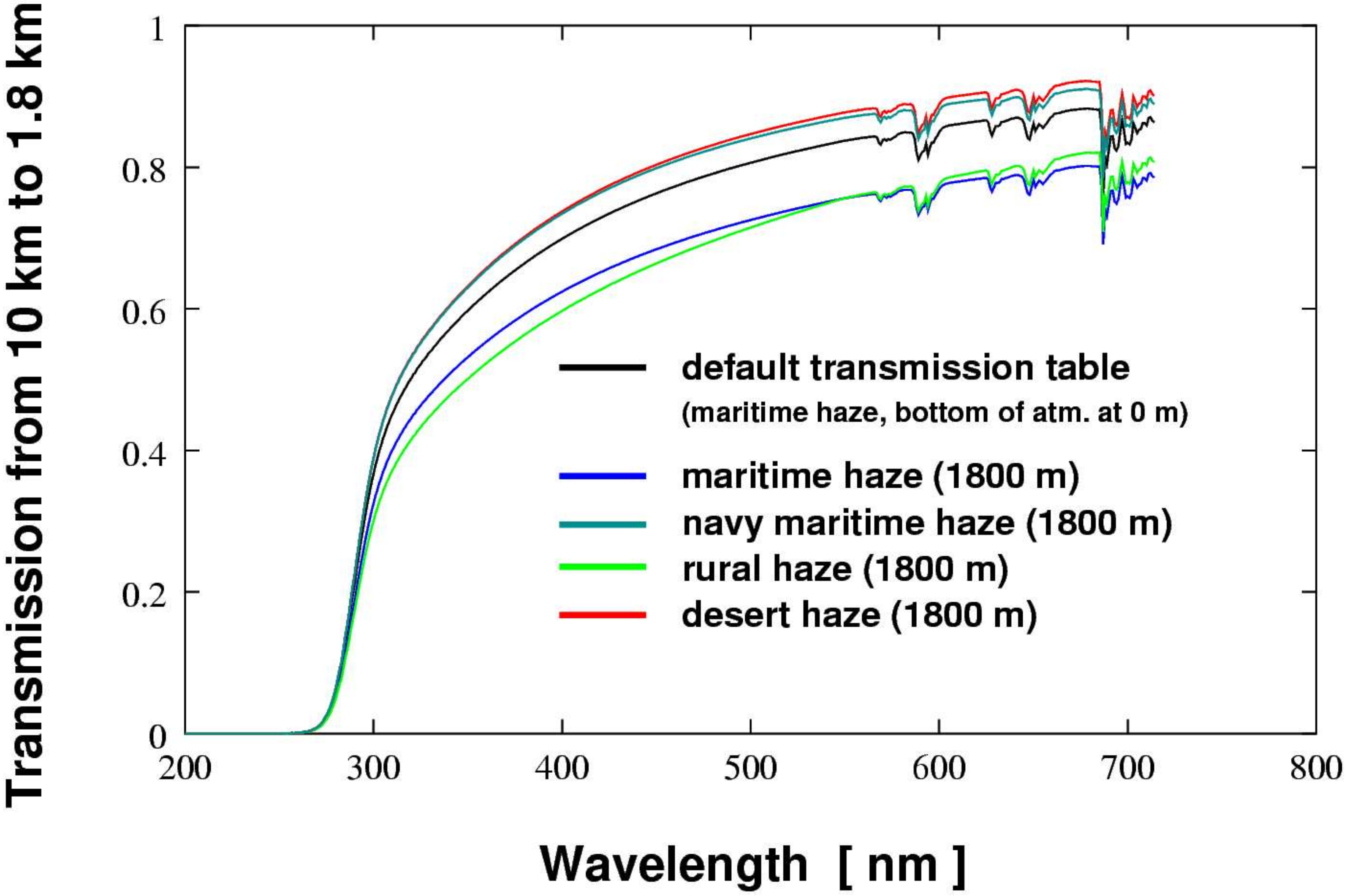
Pinatubo eruption: 'high' even on northern hemisphere for more than 1 year

Individual extinction sources: volcanic dust



Pinatubo eruption: 'high' even on northern hemisphere for more than 1 year

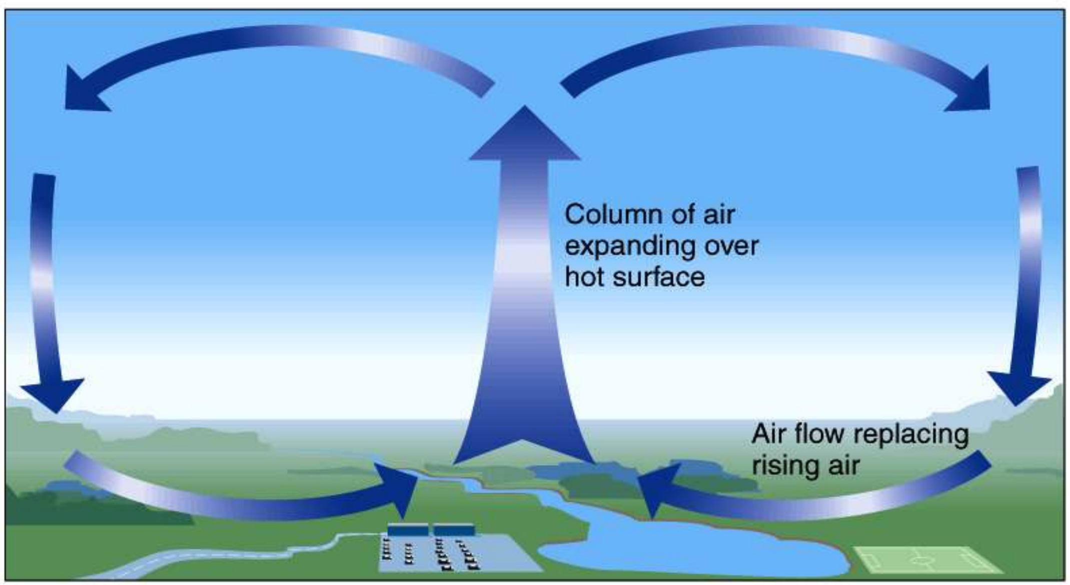
Individual extinction sources: the real trouble: aerosols

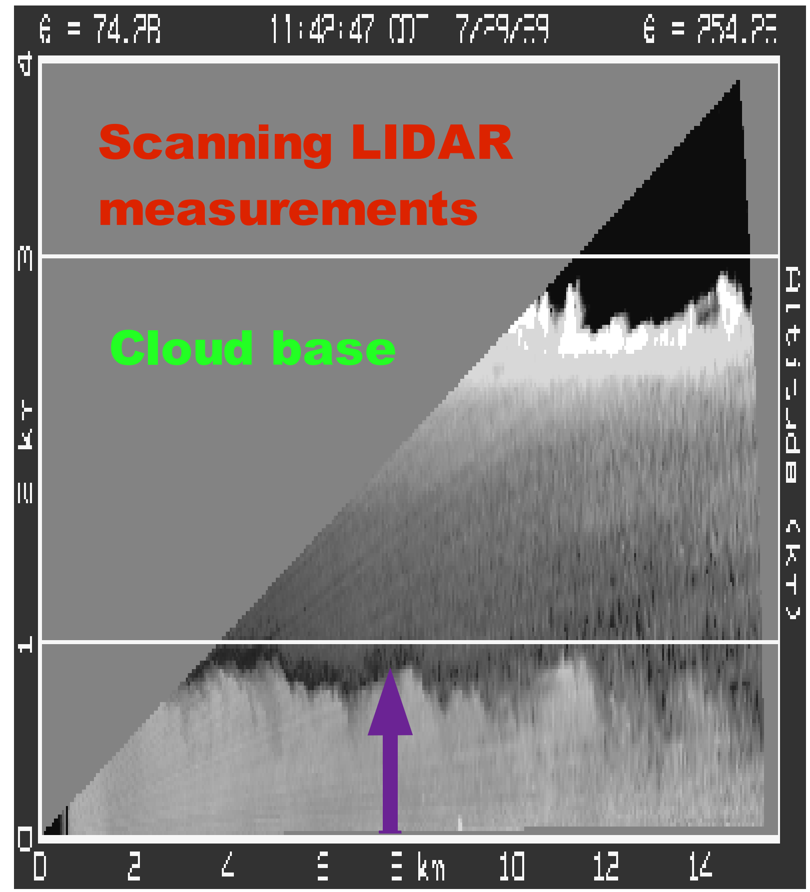


You need measurements to decide which model is most appropriate!

Aerosols and the boundary layer

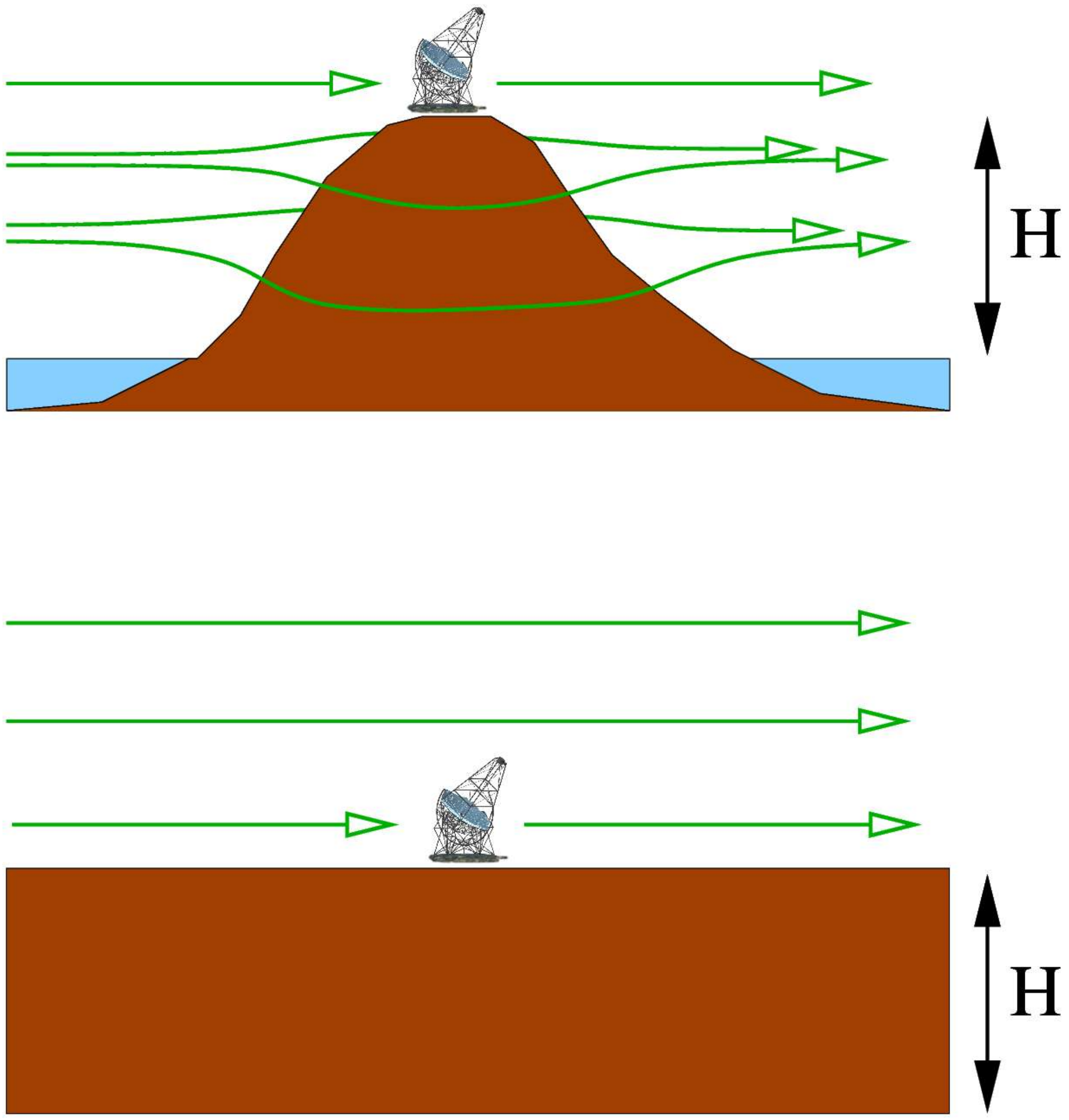
Diurnal convection and turbulence raises aerosols from ground.





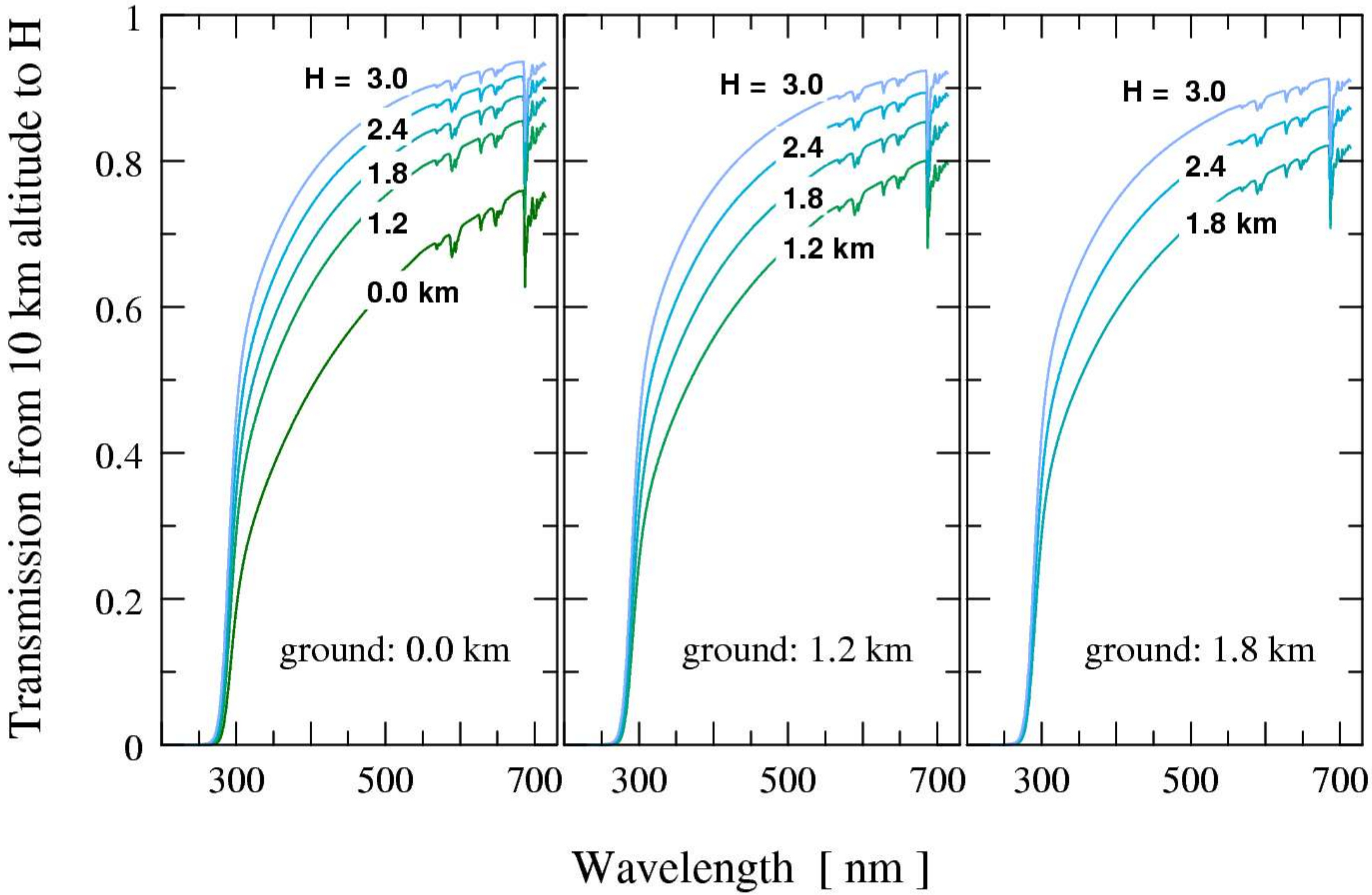
A **boundary layer** of 1 to 2 km thickness has a higher aerosol content than the air above.

Importance of air flow



Aerosol content above observer not just a function of altitude *H* but also of the air flow, where it came from etc.

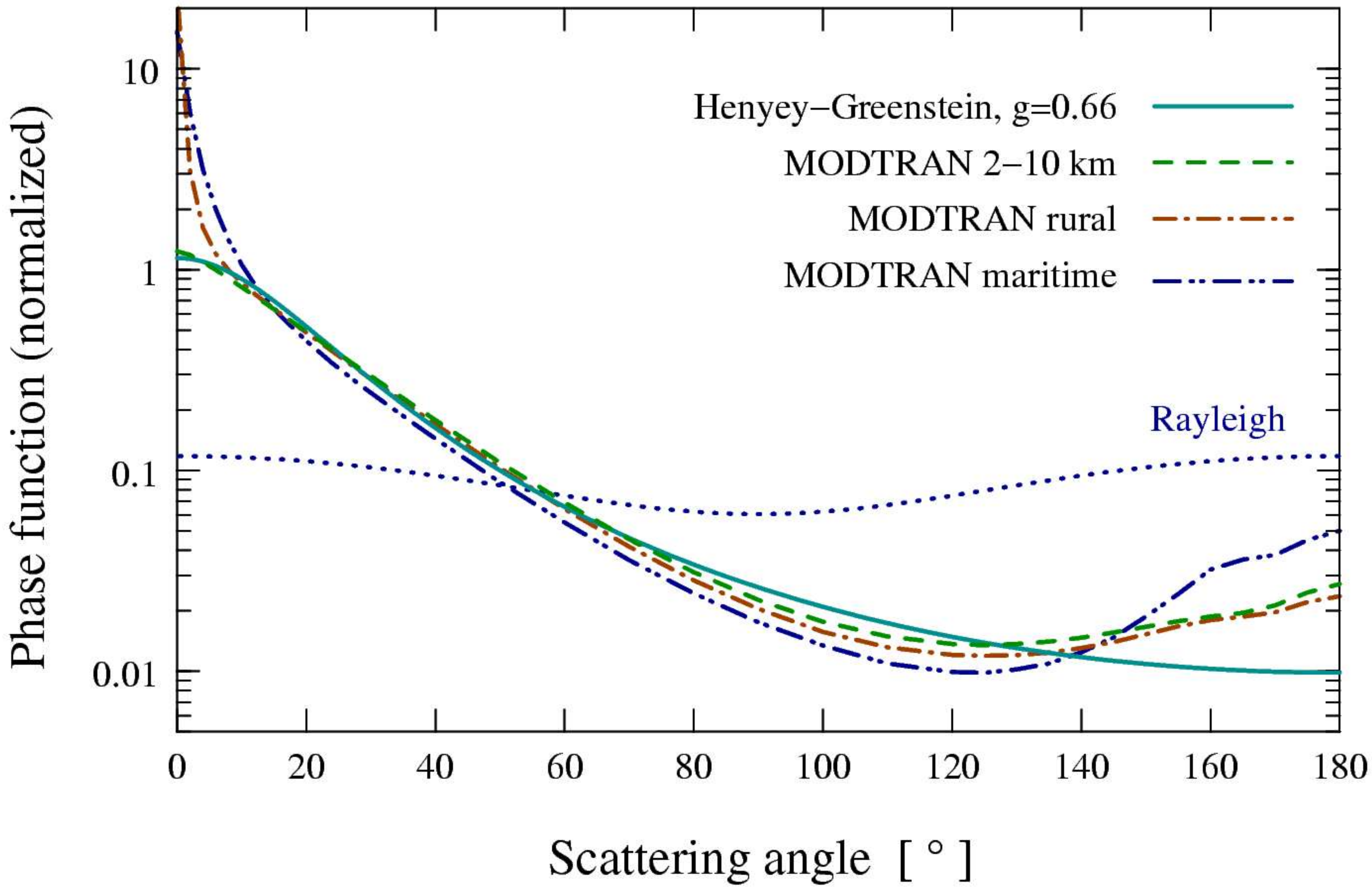
Altitude and base of atmosphere



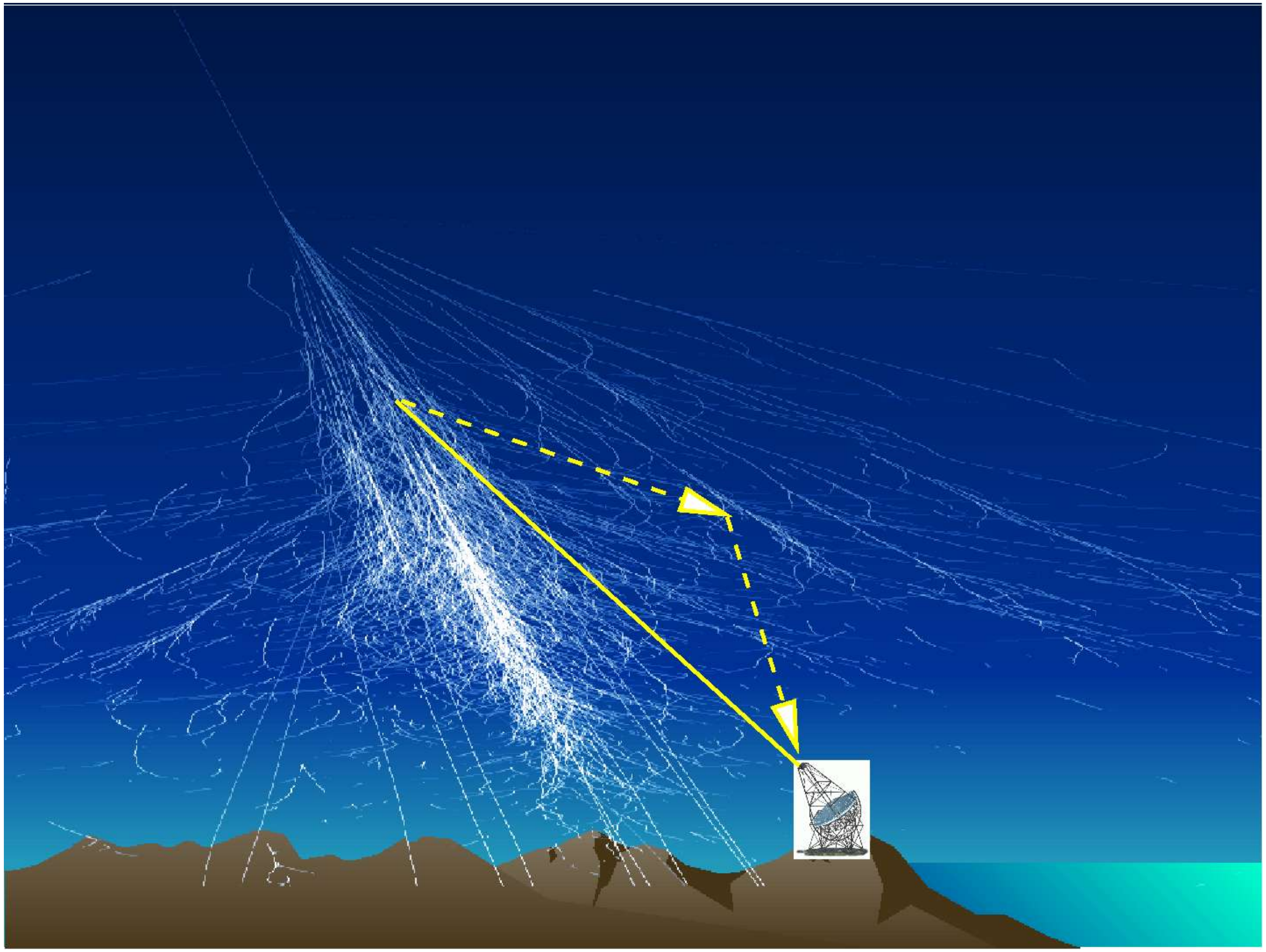
Aerosols in the boundary layer

- Aerosol content and composition in the boundary layer depends on the history of the air during the last several days: over which surface, wind speed, turbulence, precipitation ...
- Aerosols (including hydrosols) can change with temperature/humidity.
- Models can be adapted to reality with
  - Observations of star light extinction (stable nights).
  - Backscatter LIDAR measurements of vertical structure of aerosols.
  - Use of multi-wavelength and/or Raman LIDAR.
  - Measurements of scattering phase function.

Scattering phase functions

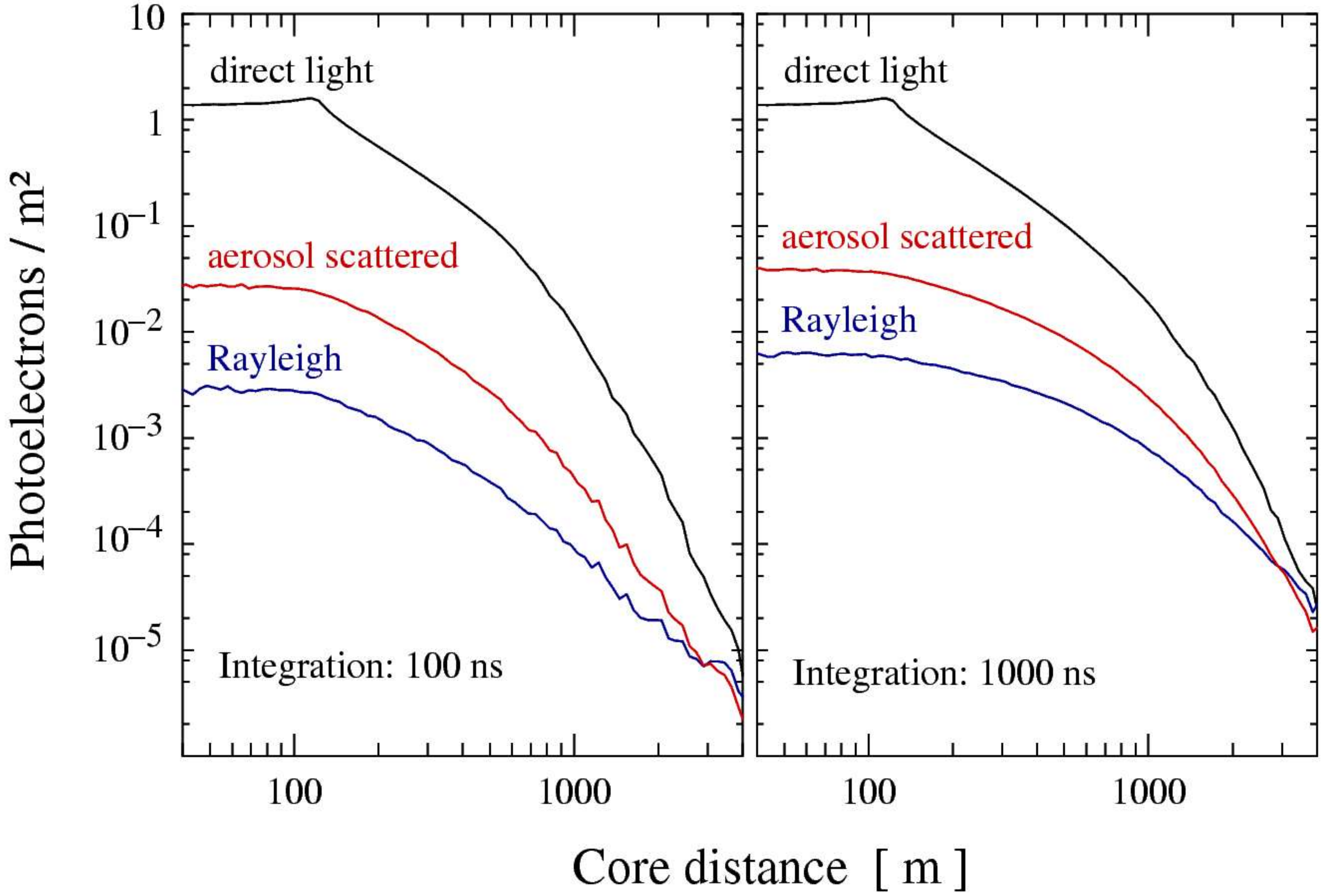


Scattered Cherenkov light

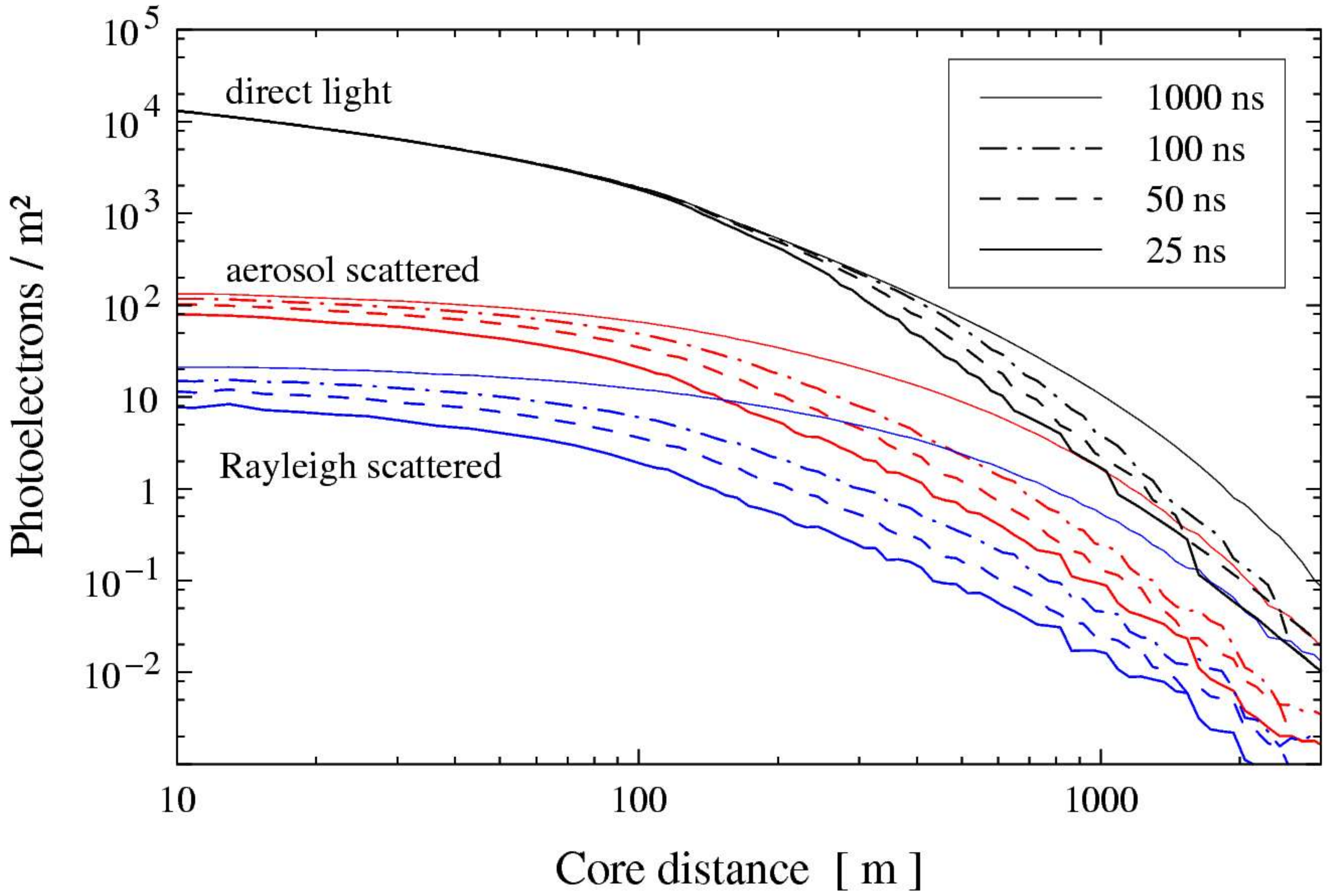


Scattered light may fall into the field of view – but typically later than direct light from the shower. Integration time matters.

Relevance of scattered Cherenkov light



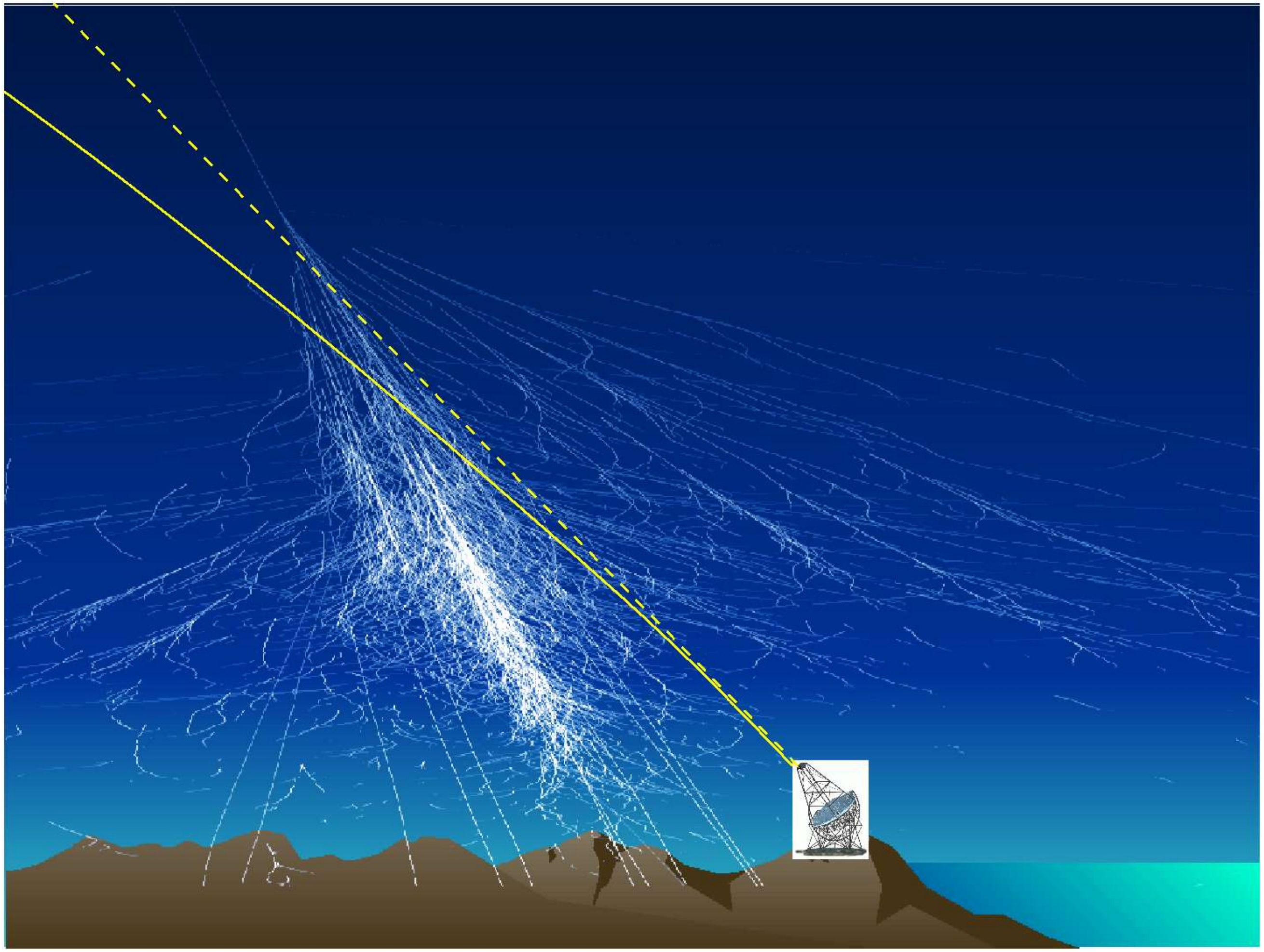
Relevance of scattered Cherenkov light



Relevance of scattered Cherenkov light

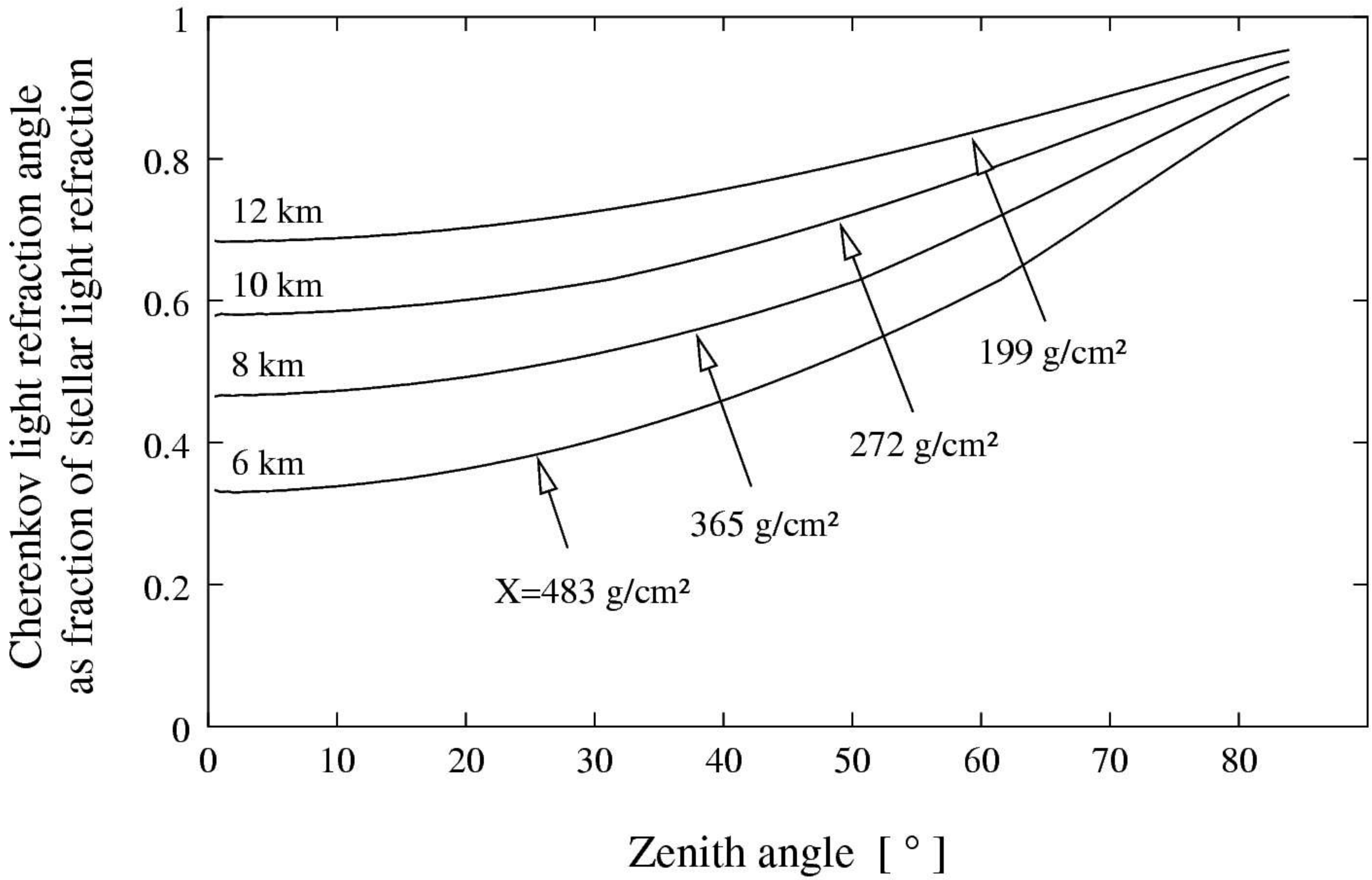
- For Cherenkov experiments, scattered Cherenkov light is insignificant since
  a) Integration times are short ($\ll$ 100 ns)
  b) Gamma-showers only observed at distances below 1000 m due to small field of view.
- For fluorescence experiments (observing at large core distances, large integration times), the scattered light can exceed the direct light and Rayleigh scattering can exceed Mie scattering.

Atmospheric refraction



Accurate source locations require correction for atmospheric refraction (~1' at 45° for star light).

Atmospheric refraction



Conclusions

- Development of air showers depends on the atmospheric density profile.
- Showers developing deeper in the atmosphere result in more intense Cherenkov light at the observer being closer to shower maximum.
- Seasonal variations: 10-15% at mid latitudes.
- At zenith angles beyond 65°, the curvature of the earth atmosphere gets important.
- For measuring and modelling of transmission, aerosols are the critical component.
- Scattered light is only for fluorescence folks.
- Refraction corrections for accurate positions.

The End