Simulation of detector / telescope arrays and the impact of atmospheric parameters

by

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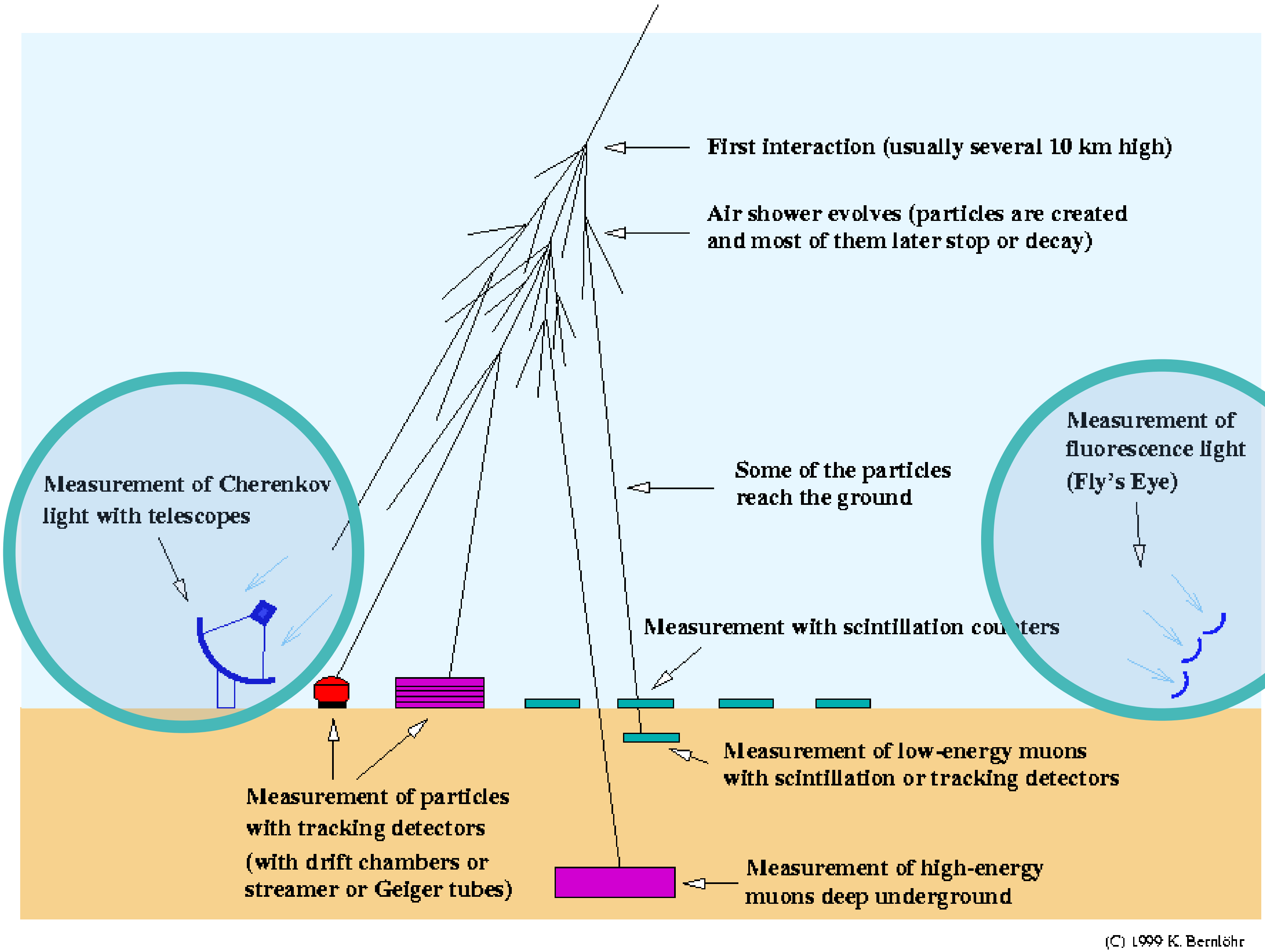
Some atmospheric parameters are hard to include in simulations. Simulations are often for simpler conditions than in real life.

Air showers and measurement methods

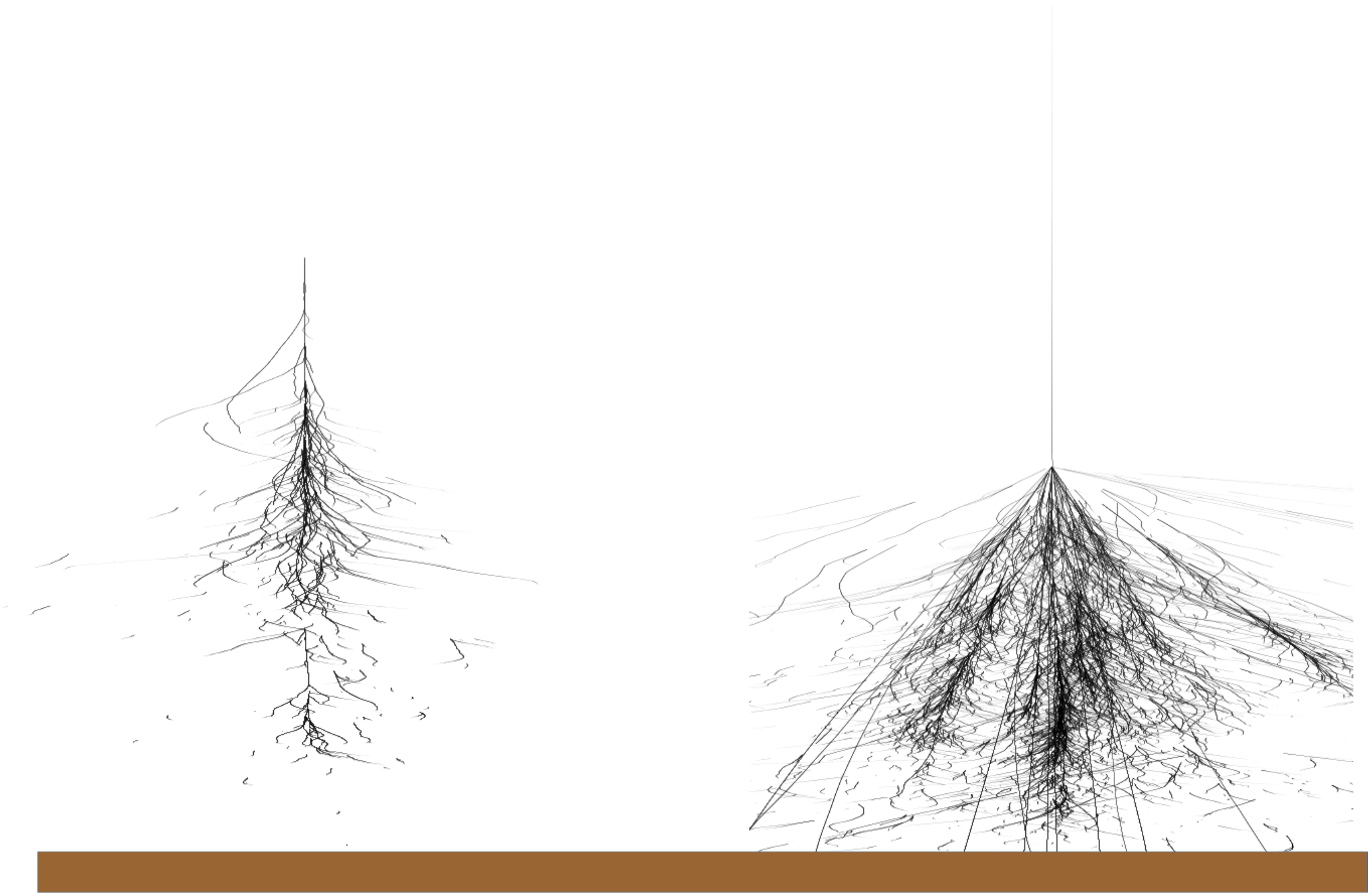


Particle detector array or telescopes

Different impact of atmospheric parameters on different detection techniques:

- Particle detectors: Only shower development:
  - Density profile is relevant
  - Composition not very relevant
- Light detectors (in particular telescopes):
  Shower development + light emission & propagation:
  - Density profile
  - Index of refraction (emission & refraction)
  - Composition important for absorption (e.g. ozone)
  - Aerosol distribution and properties (for extinction and scattering)
  - Nightsky background light

Examples of shower development



Shower development + density profile

- Ground level measurements (p, g) will tell you the total atmospheric overburden above a site.
- That will not be enough for a detailed simulation of a particle detector array because of
  - the competition between interaction and decay of unstable particles (pions, kaons) in the shower development (relevant e.g. for e/µ ratio),
    - ➔ with different profiles of identical ground-level pressure having different longitudinal shower development;
  - different heights of given atmospheric depths result in different lateral distributions;
  - differences also in multiple scattering, also resulting in different lateral distributions.

Assumptions in shower simulations

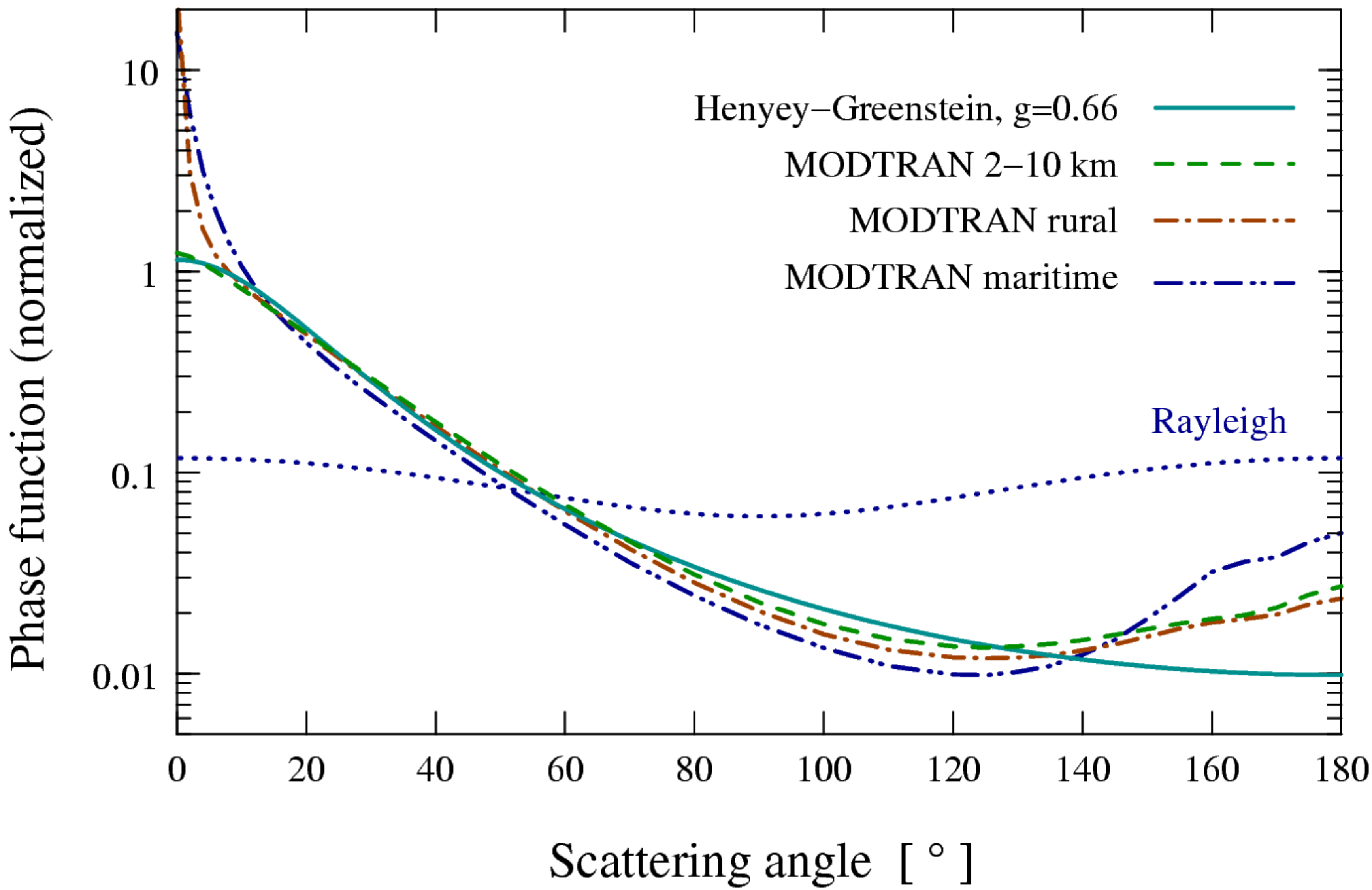
Typical shower simulation programs make assumptions (for efficiency or due to lack of knowledge) like

- piecewise exponential density profile,
- either using only an all-year average profile or at best a few seasonal average profiles,
- constant composition,
- (constant and uniform B field,)

and for Cherenkov & fluorescence light typically assume

- index of refraction assumed wavelength-independent,
- changes in absorption by trace gases (ozone etc.) often neglected,
- simplified scattering phase function for aerosols.

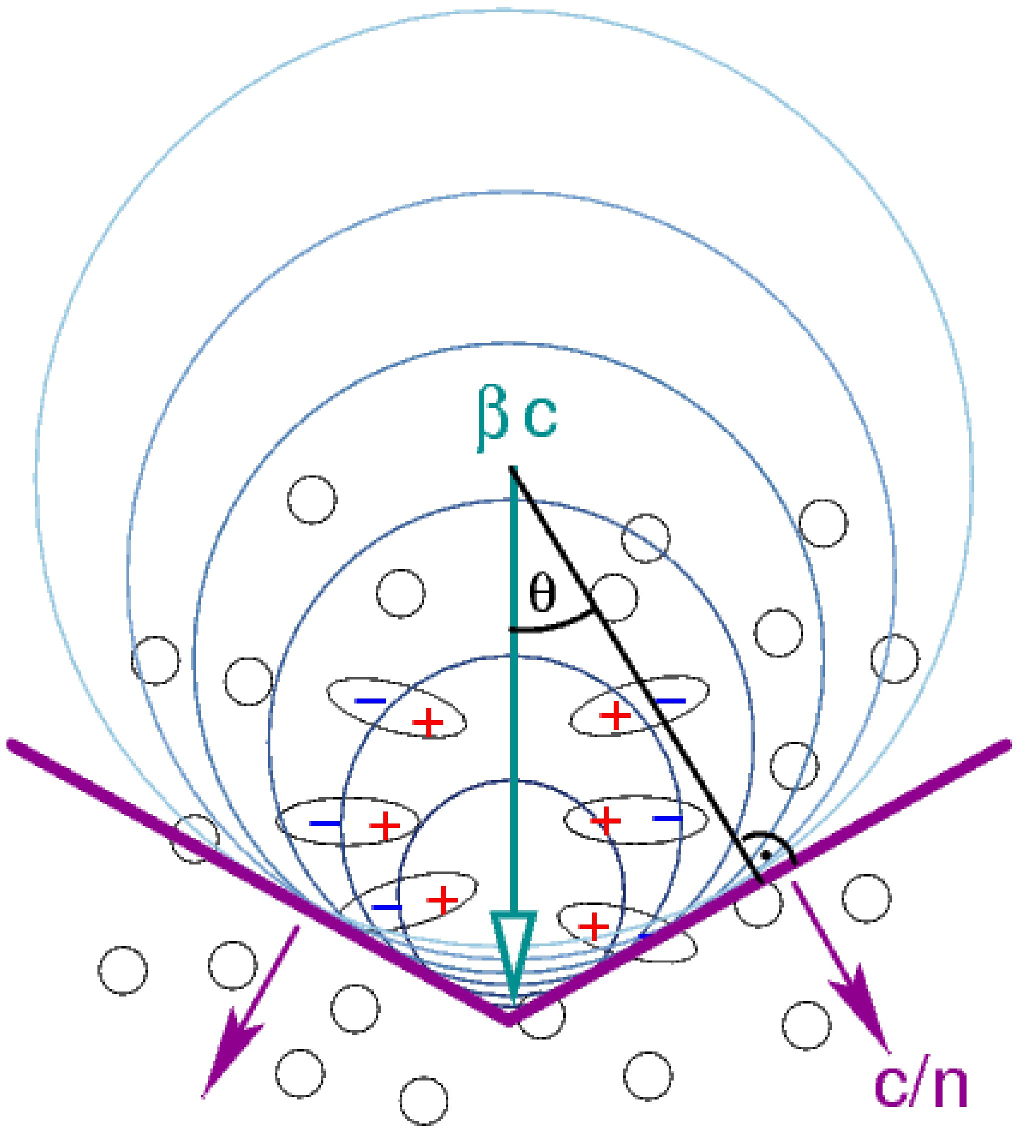
Scattering phase functions



Site-related parameters not discussed here in detail

- Night-sky background light
  - Air glow
  - Zodiacal light
  - Star light
  - Anthropogenic light pollution
- Geomagnetic field
  - Rigidity cutoff (θ,φ)
  - Separation of +/- charged particles
  - Spreading & asymmetry of lateral distribution
  - Image distortion (Cherenkov telescopes)
- Site altitude
  - Energy losses
  - Closeness to shower maximum

Cherenkov light emission



Cherenkov light emission

Basic formulae:

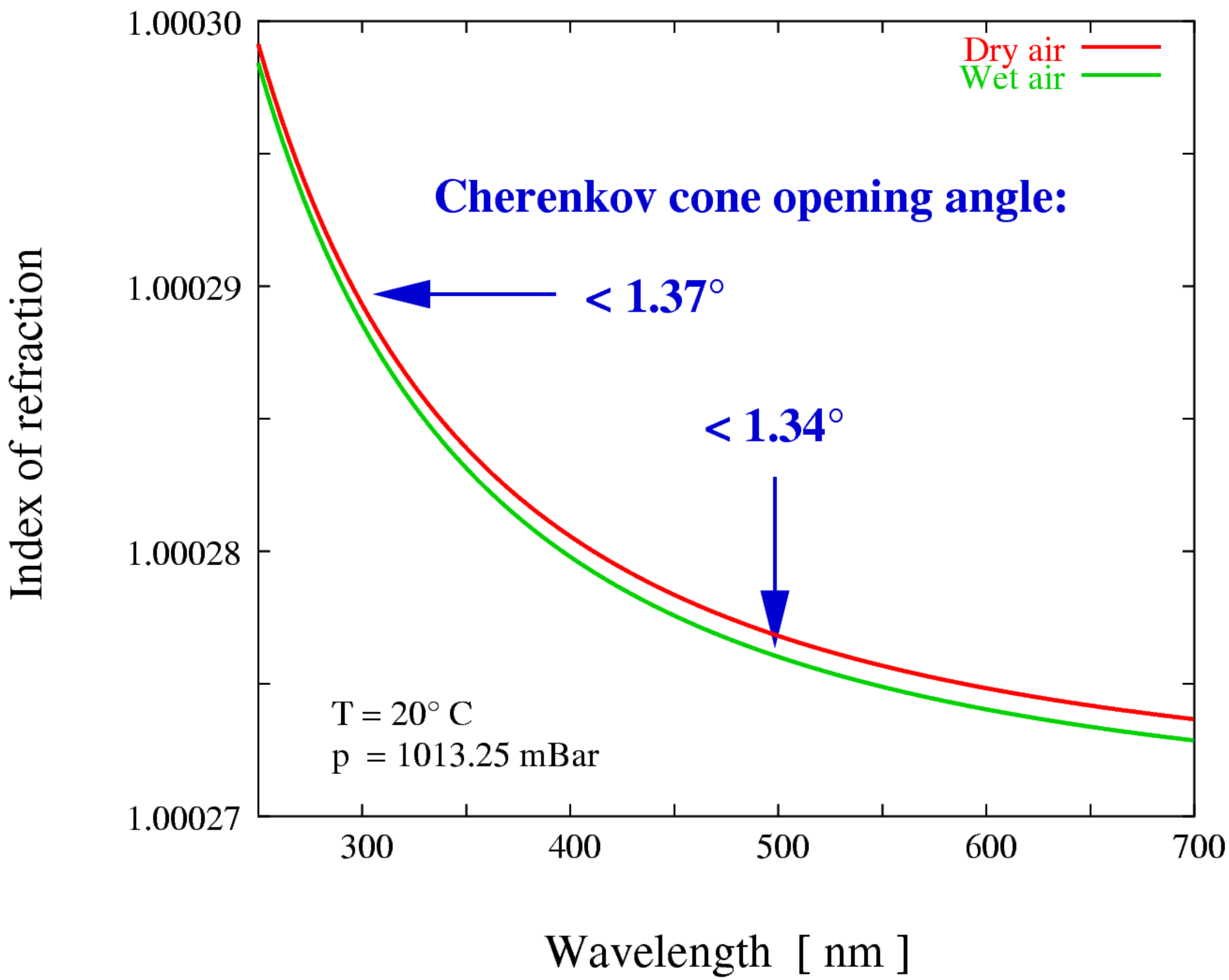
$$\cos\theta = \frac{1}{n\beta} + \frac{\hbar}{2p}\left(1 - \frac{1}{n^2}\right) \approx \frac{1}{n\beta}$$

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

Recoil can be safely neglected.

Wavelength dependence of index of refraction is often neglected (for efficiency reasons).

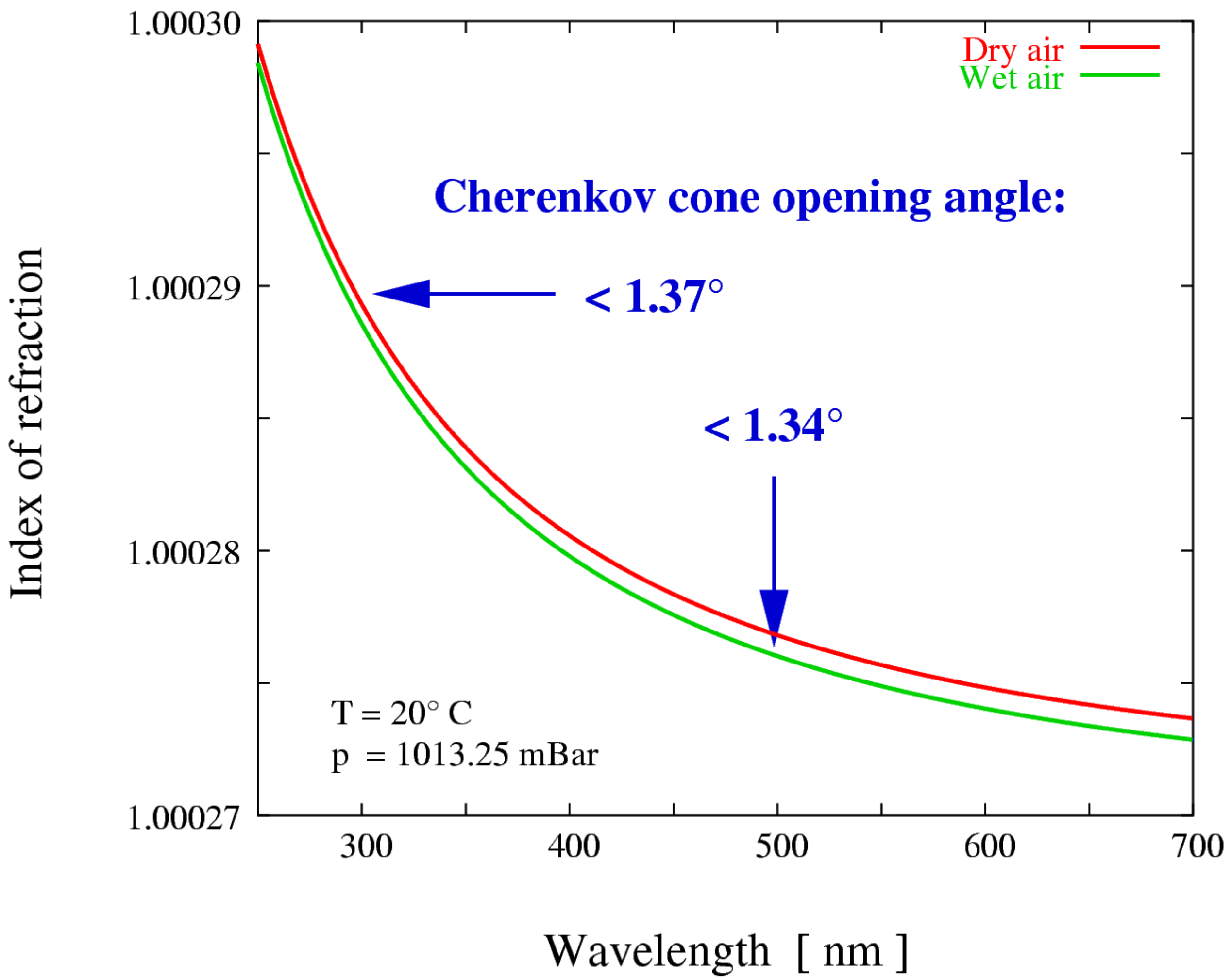
Index of refraction



Formula: MODTRAN

Between 300 nm and 700 nm only rather small change.

Index of refraction



Formula:
MODTRAN

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

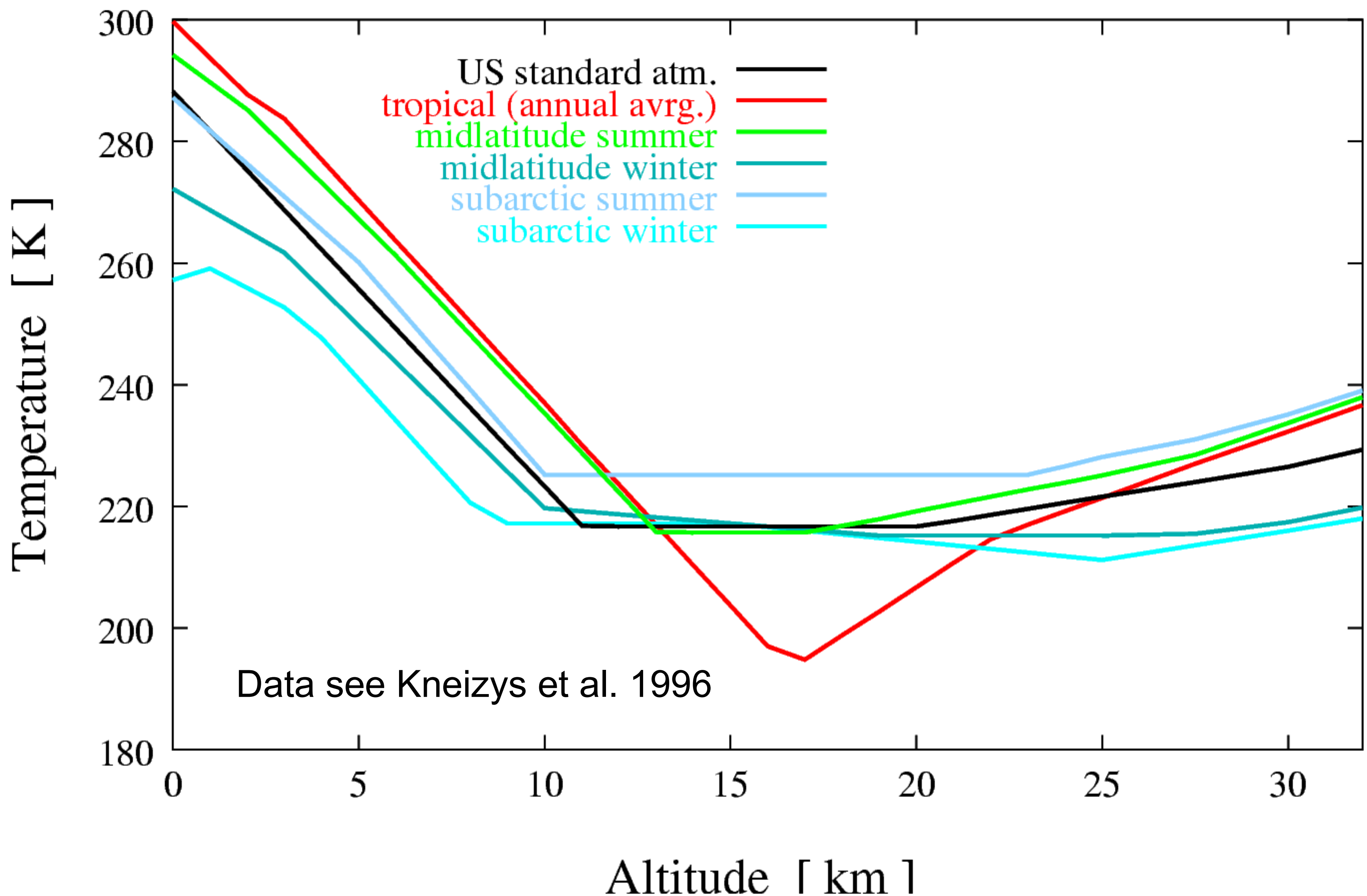
Atmospheric profiles

Different temperature profiles result in different density profiles and different relations between atmospheric depth *X* and altitude *H*.

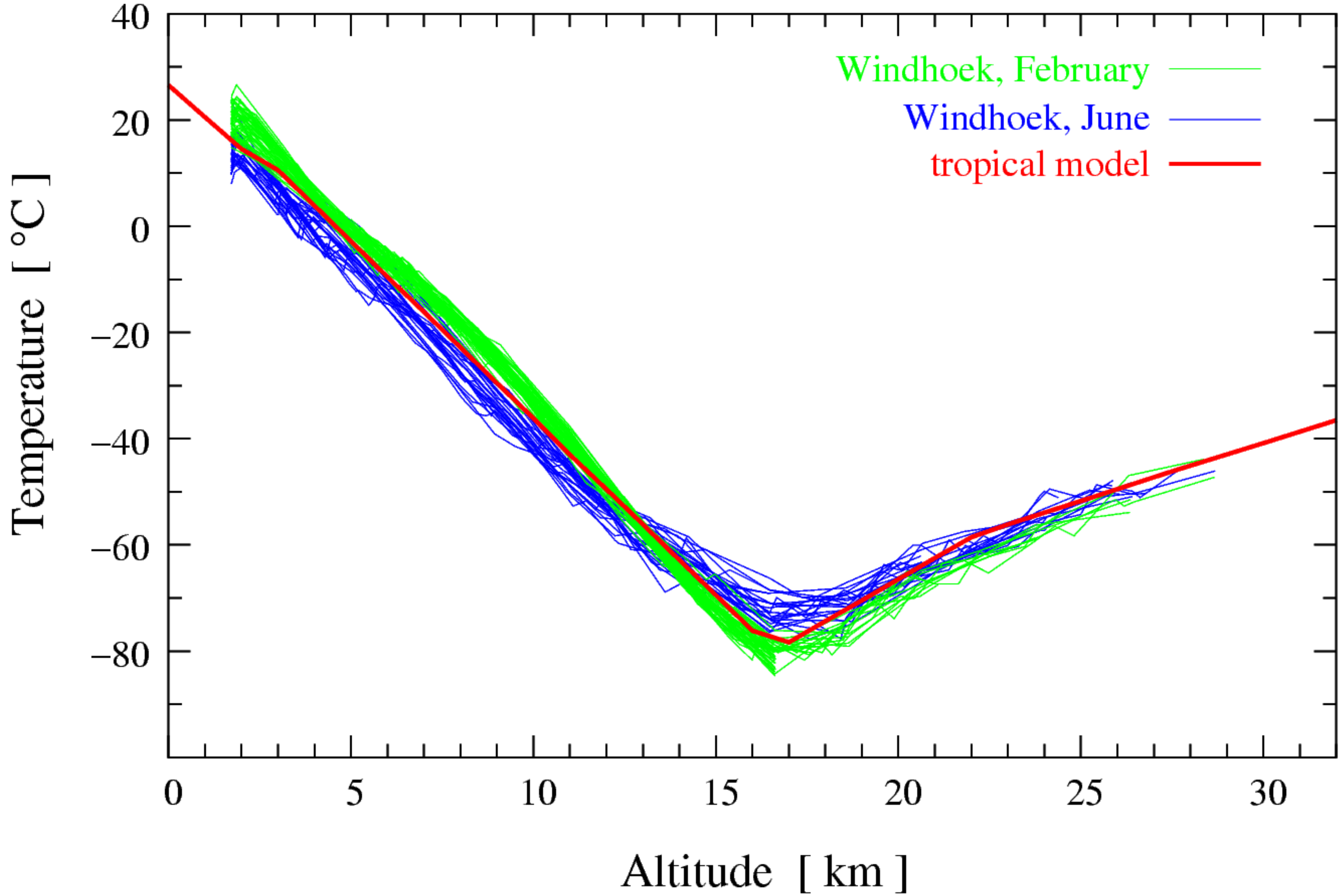
Lower temperatures mean smaller density scale height:

- 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. More particles above Ch. emission threshold.

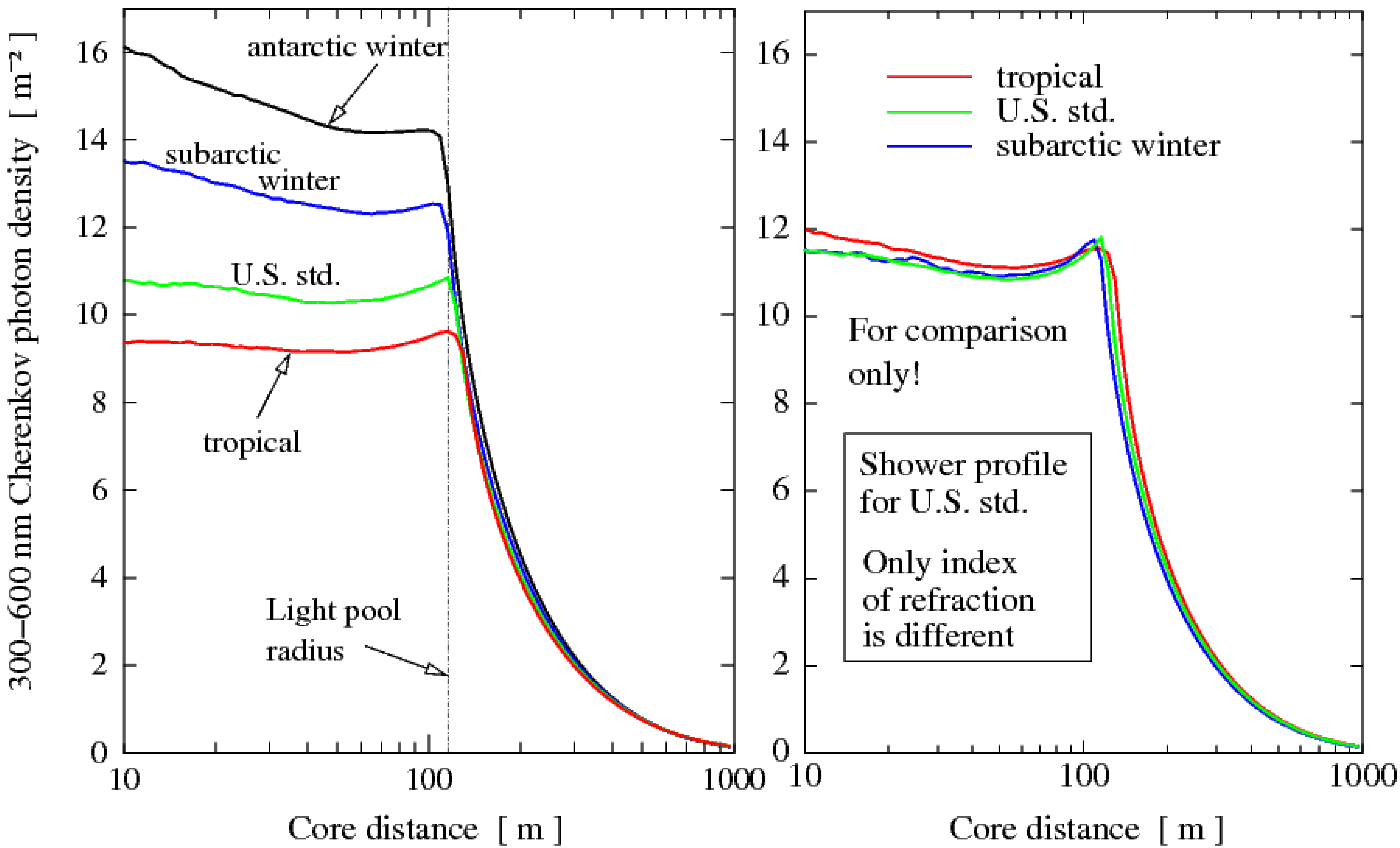
Atmospheric profiles



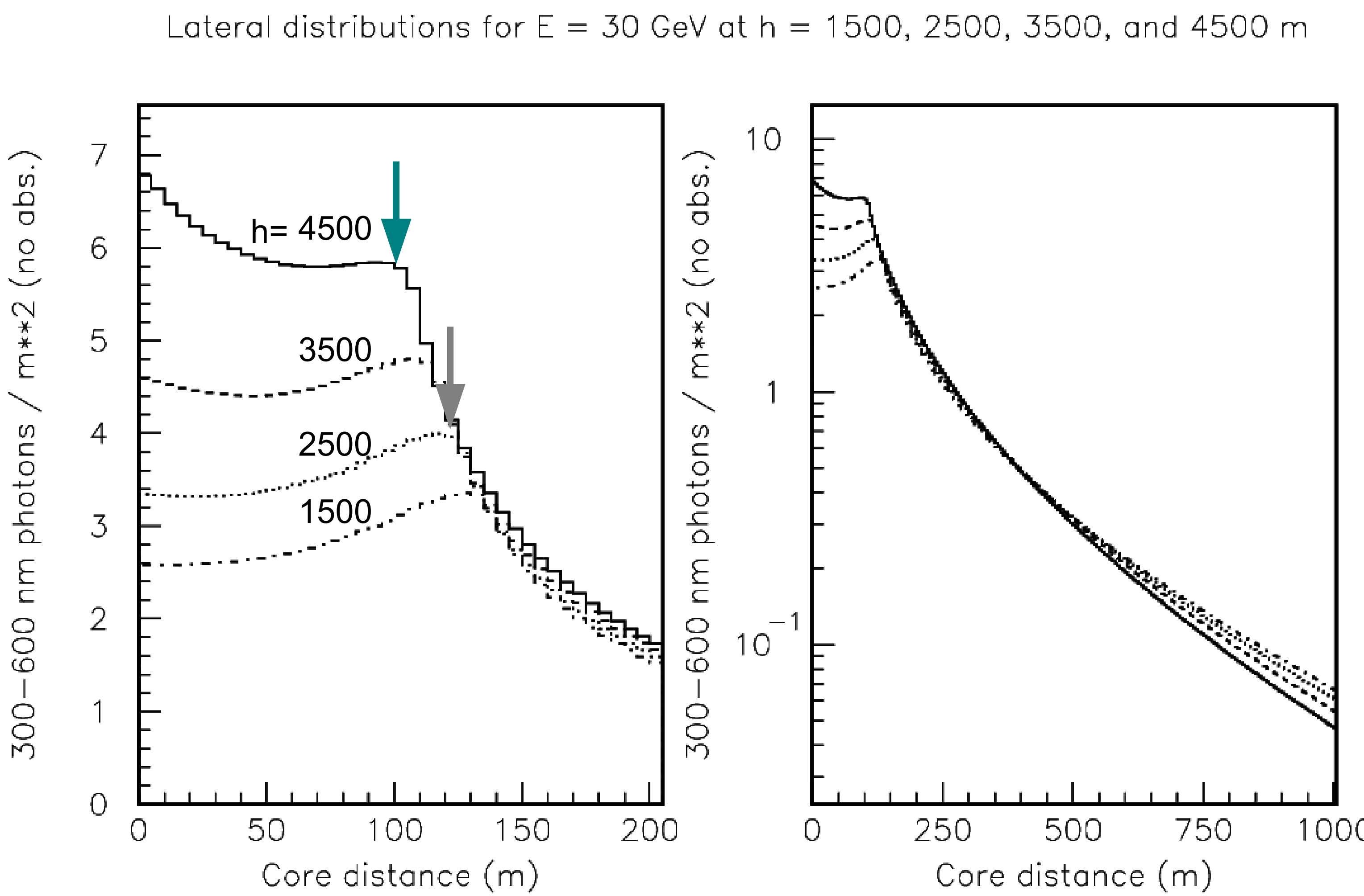
Atmospheric profiles example: Namibia



Impact of atmospheric profiles: lateral distribution of Cherenkov light



Different profiles similar to different site altitude



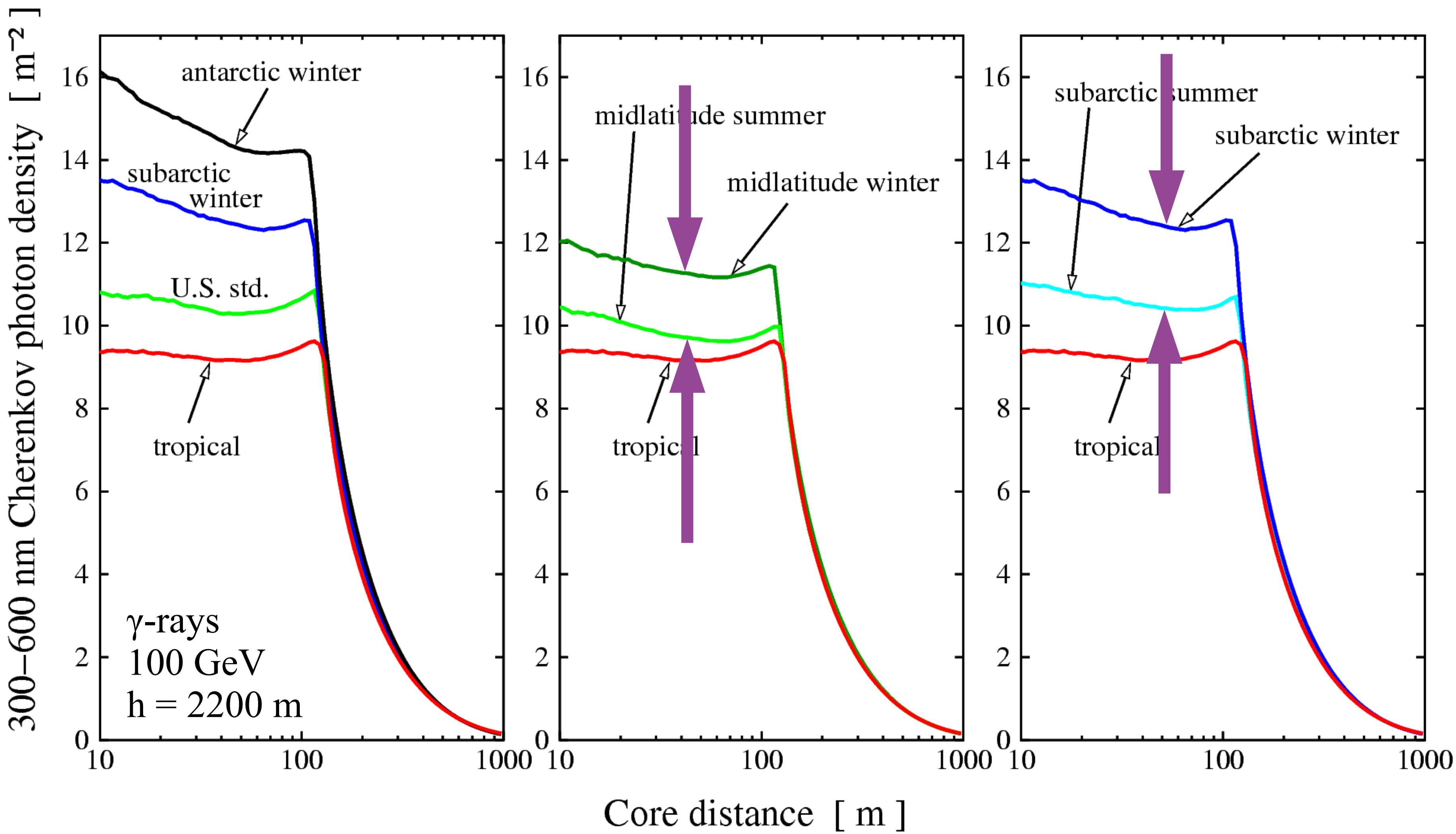
Average of 30 GeV gamma showers:
300 – 600 nm,
no extinction,
at any angle,
at any time.

Higher intensity at high altitude - but within a smaller area.

Distance from shower max. to obs. level is what counts mainly.

Impact of atmospheric profiles: lateral distribution of Cherenkov light

Seasonal variations !



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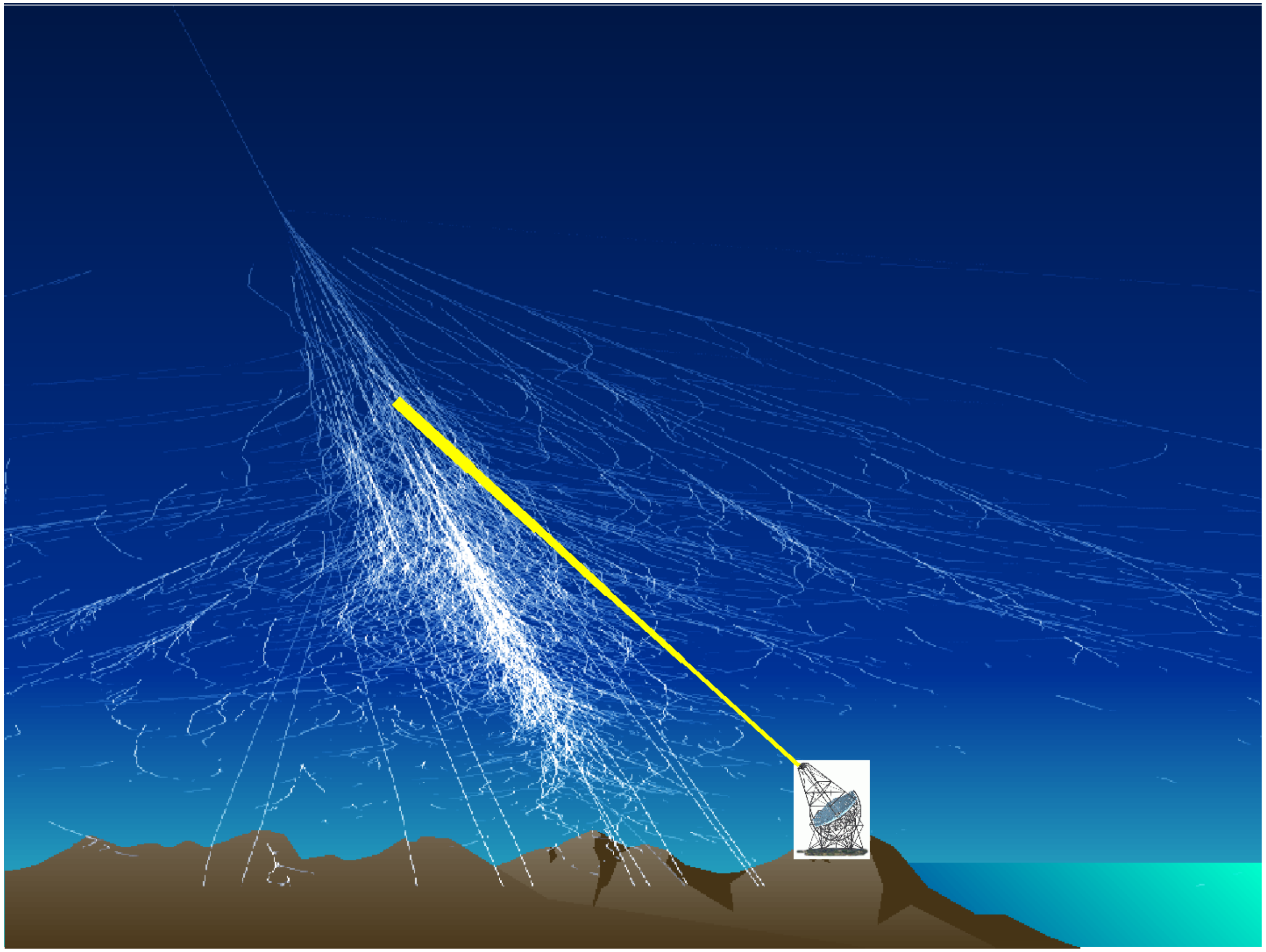
Extinction of Cherenkov light



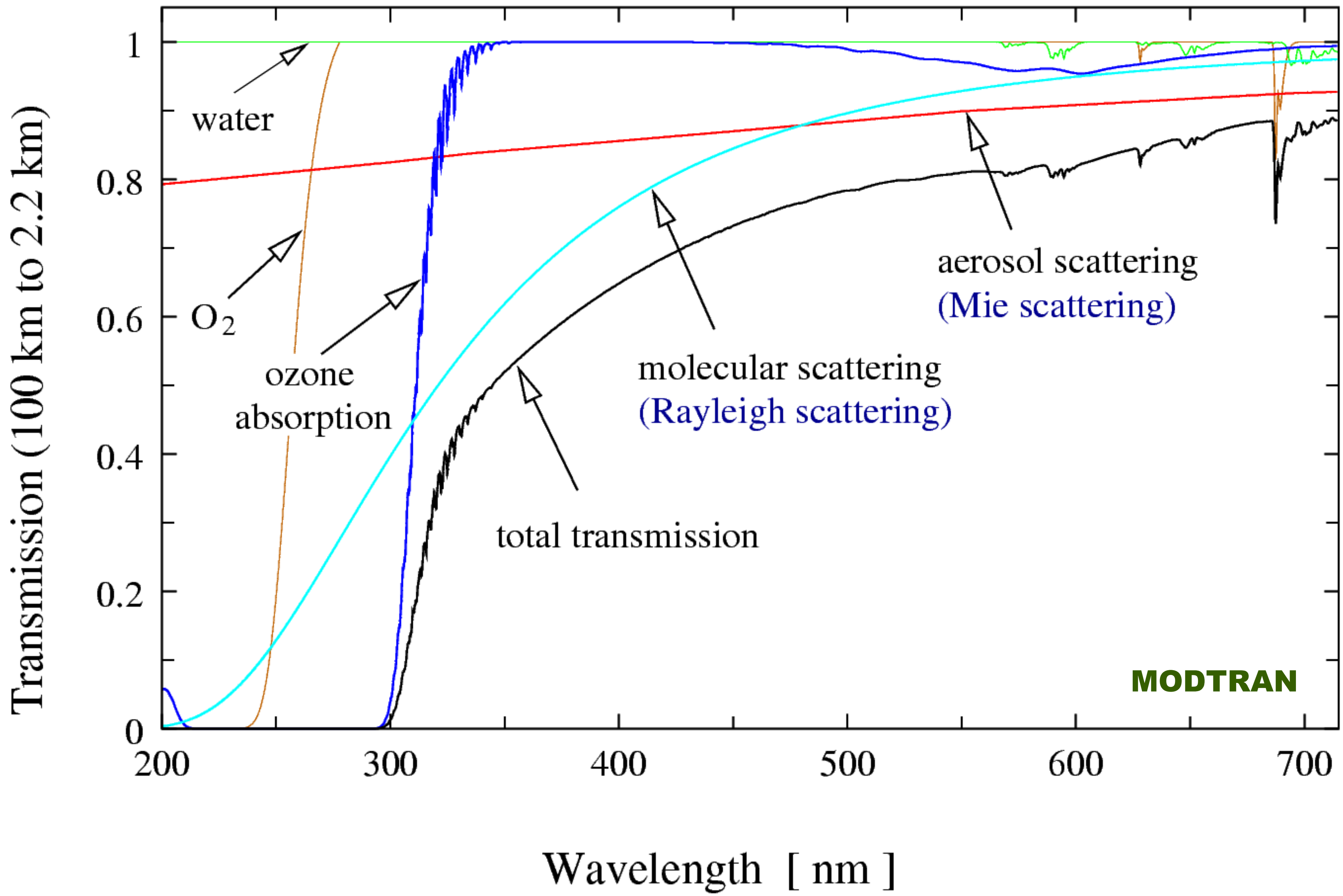
Due to different processes, Cherenkov light gets lost along the line of sight to the observer.

Extinction of Cherenkov or fluorescence light

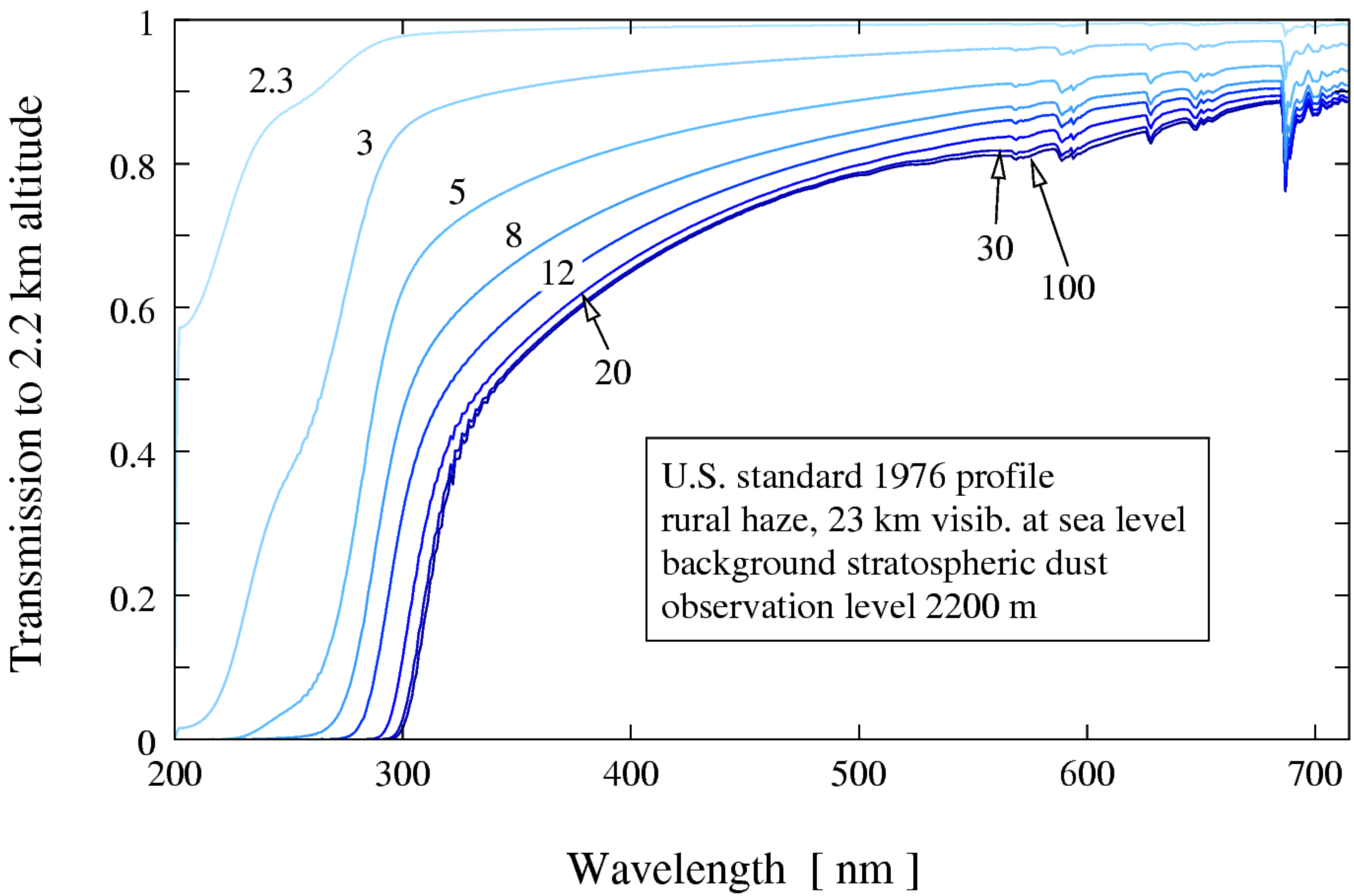
Extinction of Cherenkov or fluorescence light due to:

- 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)

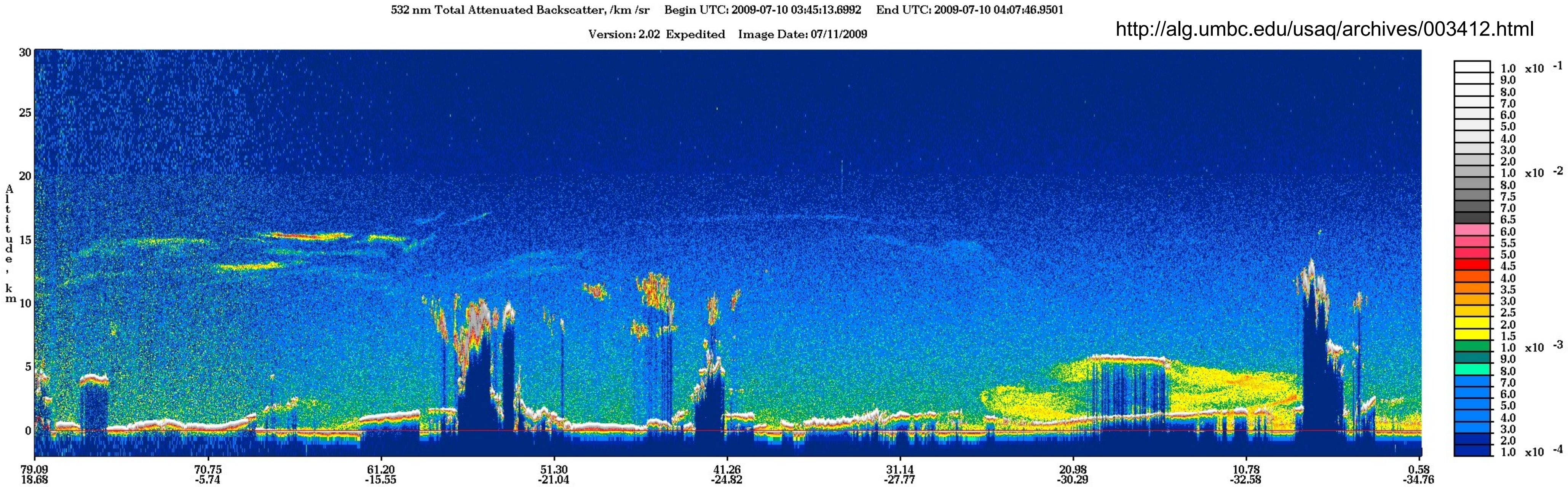
Extinction processes



Transmission from different altitudes to the experiment



The impact of high clouds / cirrus / ashes

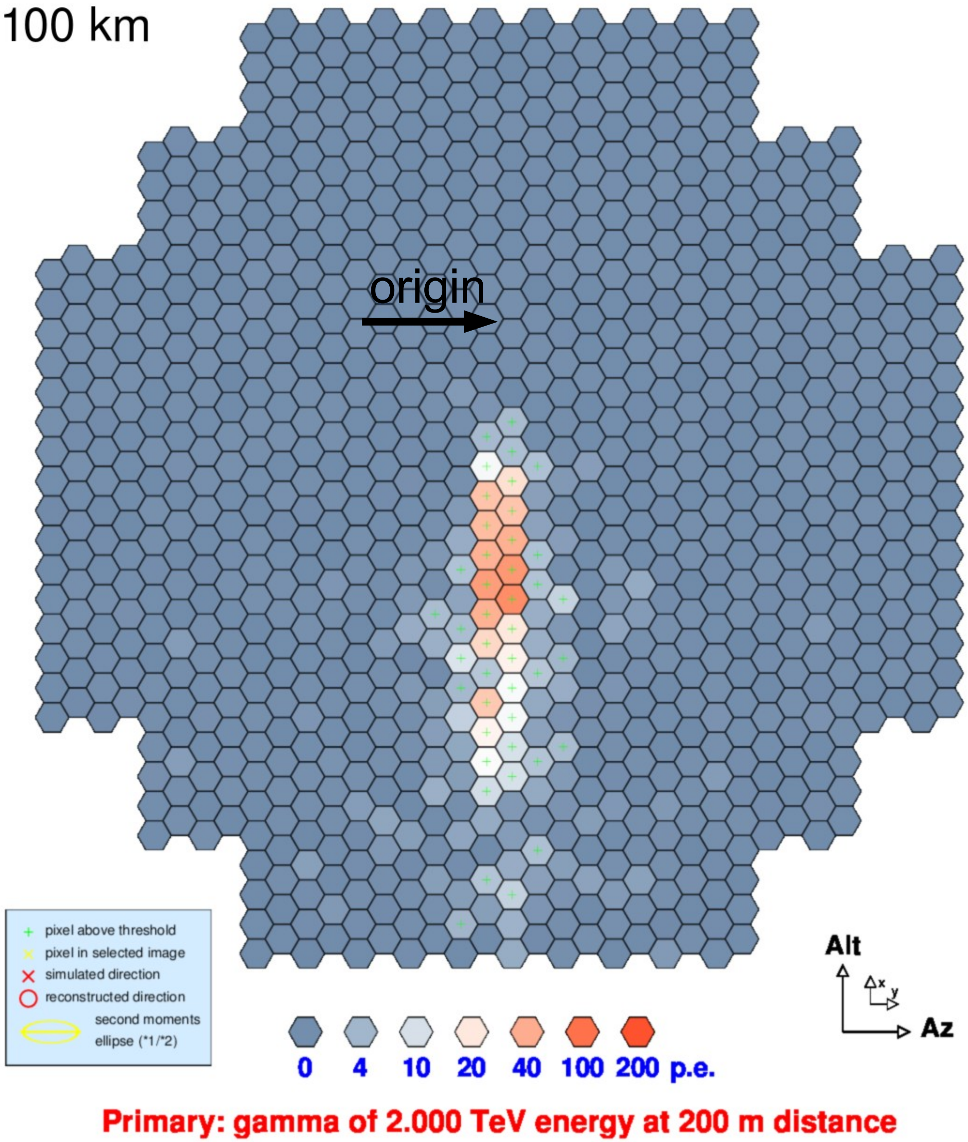


http://alg.umbc.edu/usaq/archives/003412.html

Clouds at high altitude, in particular thin cirrus clouds or ashes (from biomass burning or volcanic events) might go unnoticed in normal Cherenkov (fluorescence) observations but could have an impact on image shape (or long. profile for fluorescence obs.).

Impact of a cloud on Cherenkov images

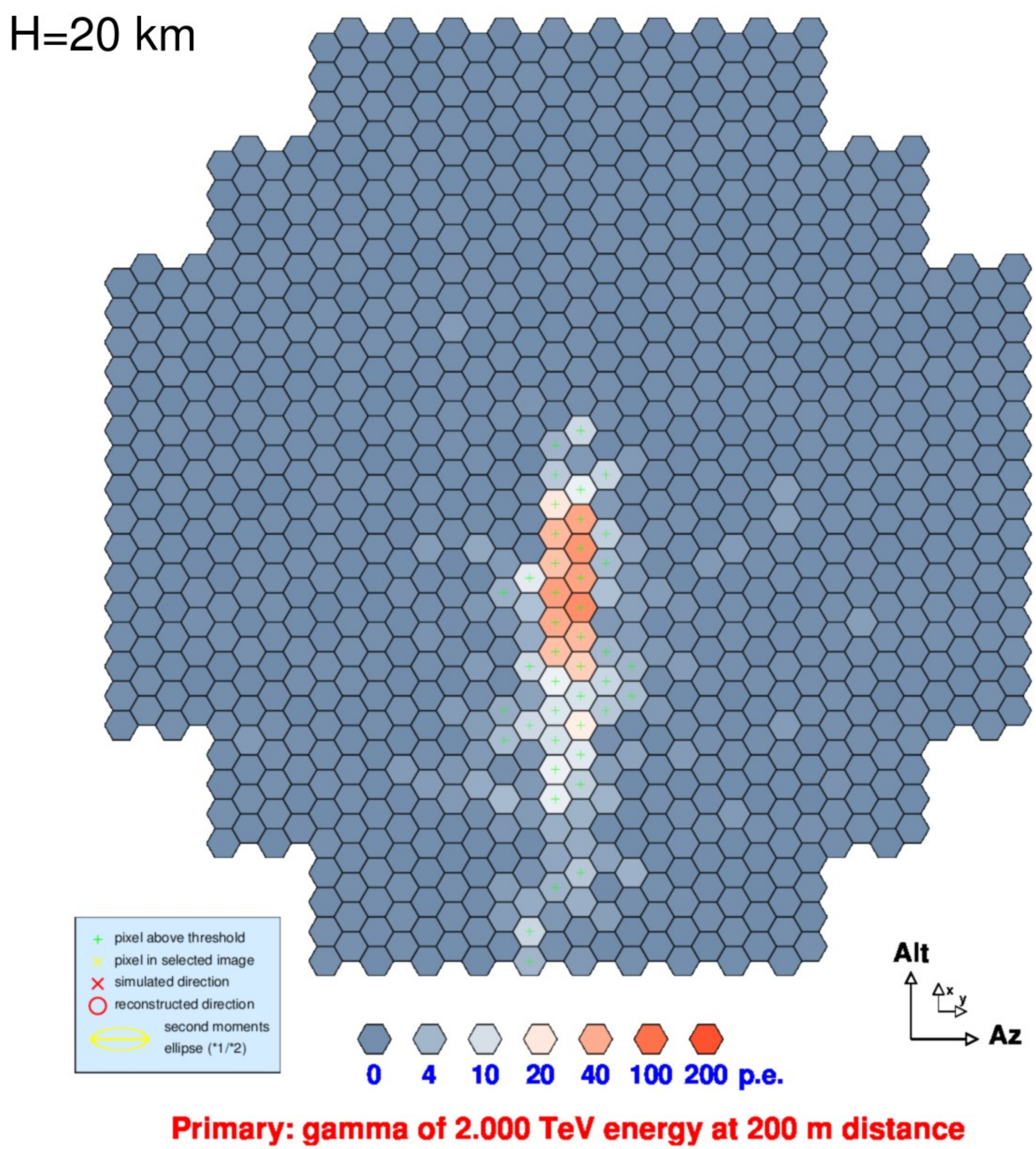
Cloud: H=100 km



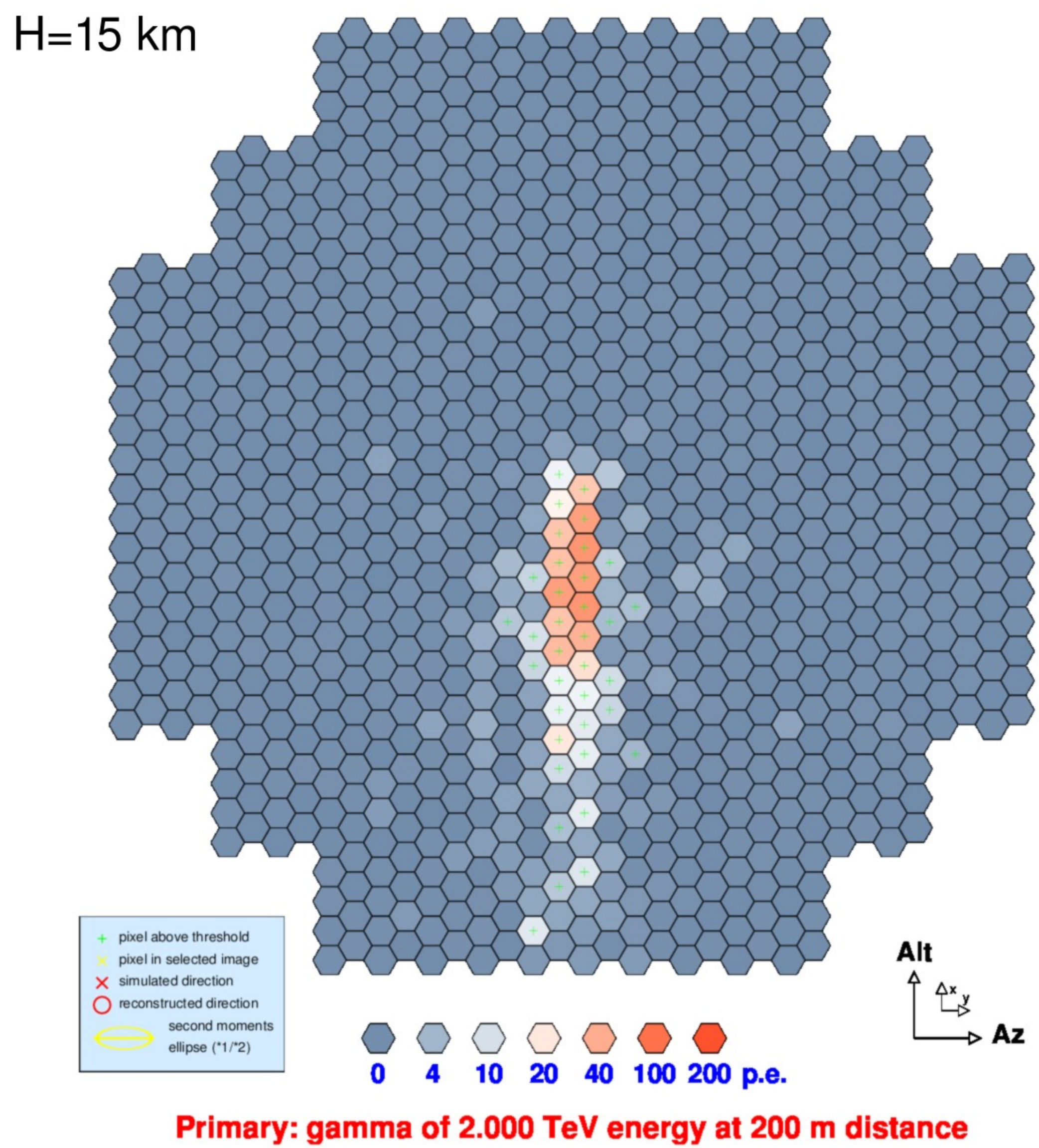
Assuming a H.E.S.S.-1-like telescope, no night-sky light, and full absorption by a cloud layer at the given height.

Shower develops in this direction.

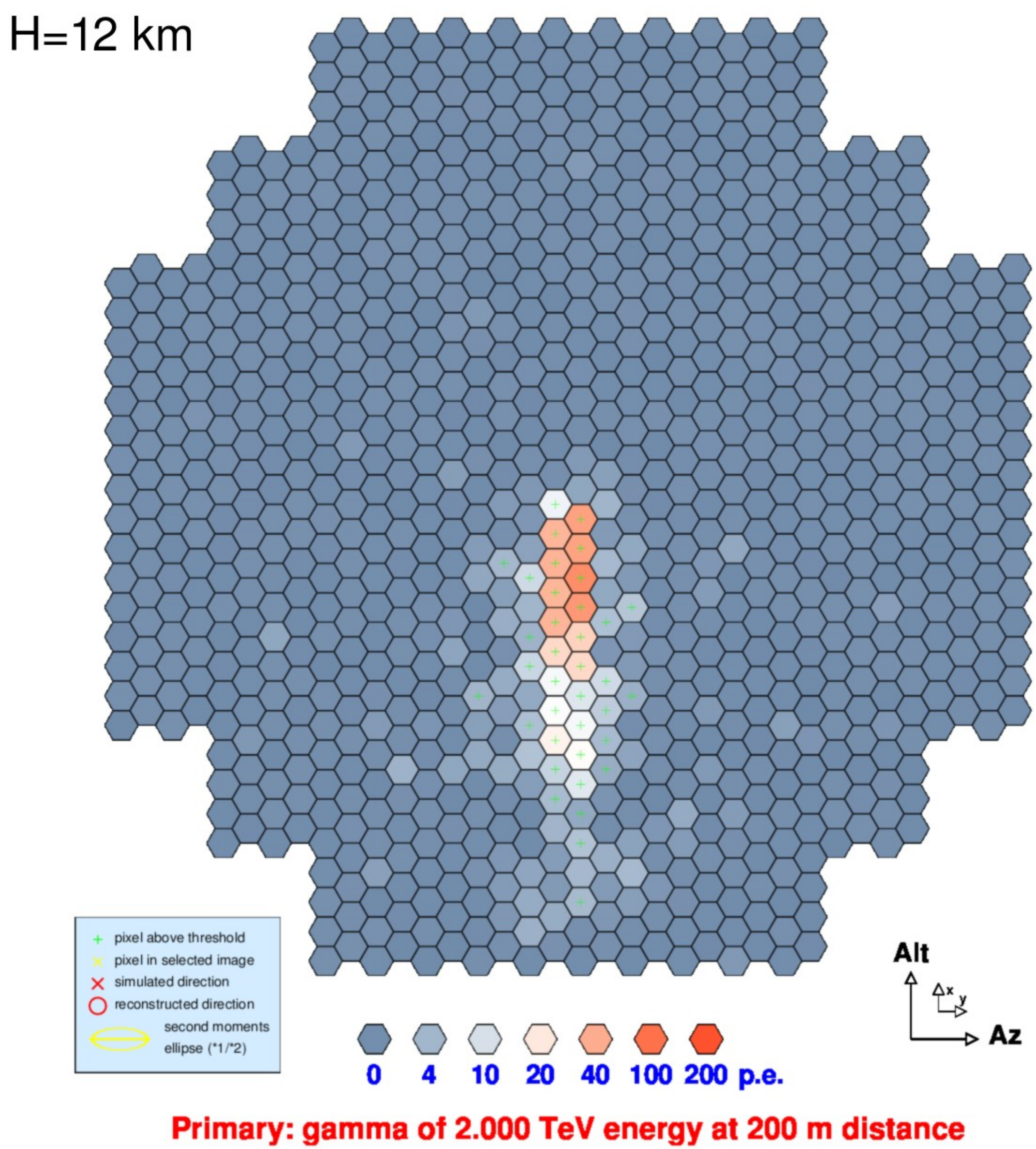
Impact of a cloud on Cherenkov images



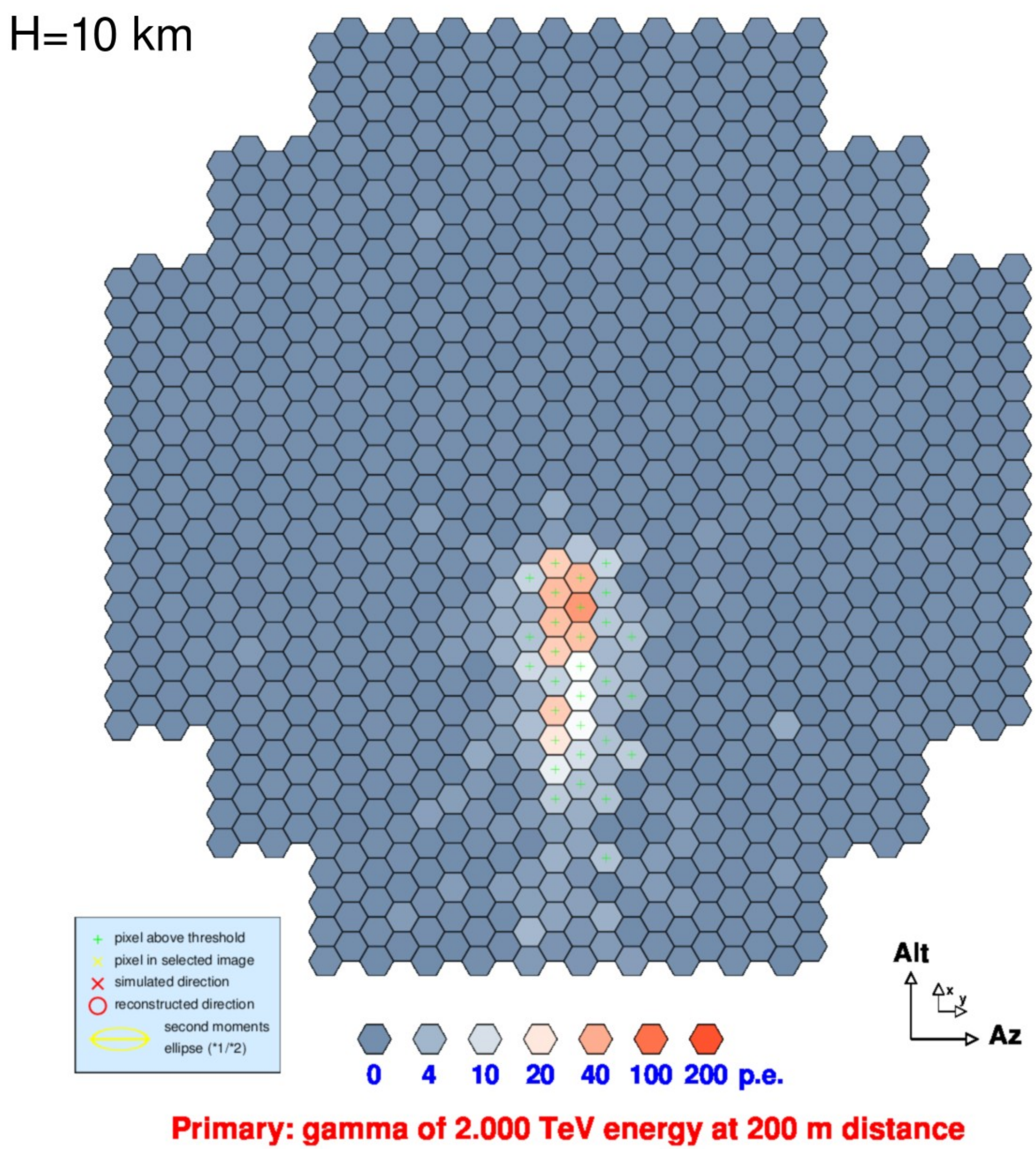
Impact of a cloud on Cherenkov images



Impact of a cloud on Cherenkov images

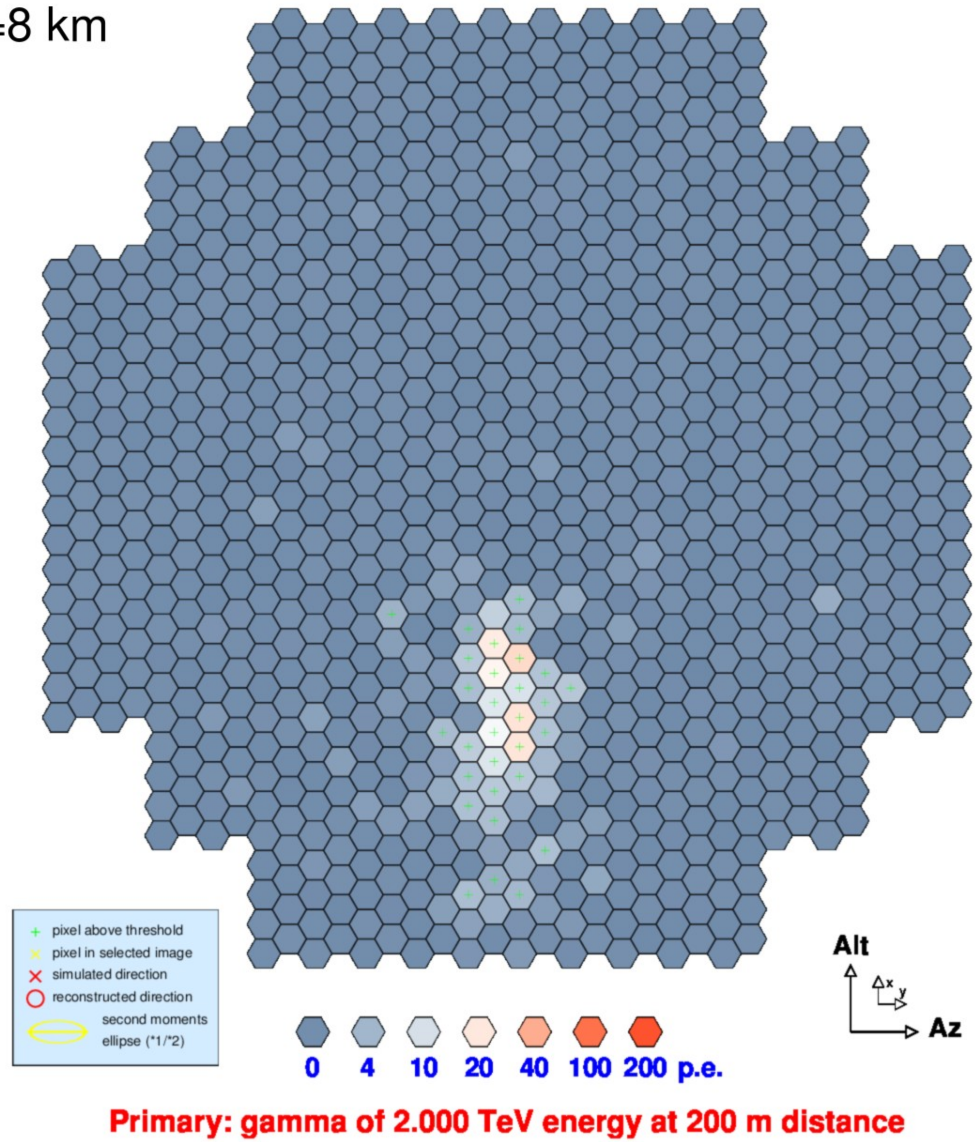


Impact of a cloud on Cherenkov images



Impact of a cloud on Cherenkov images

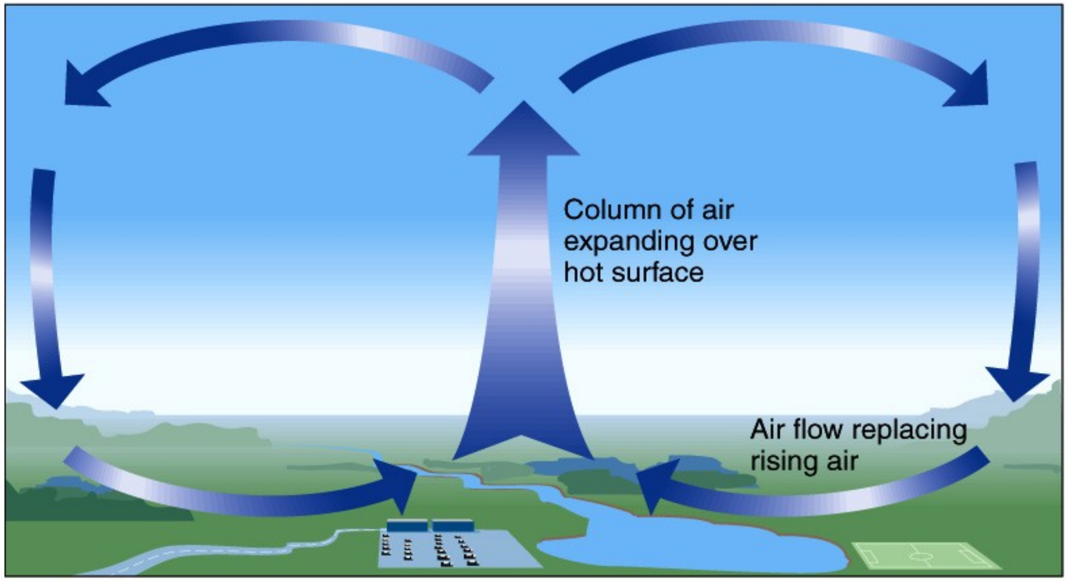
H=8 km

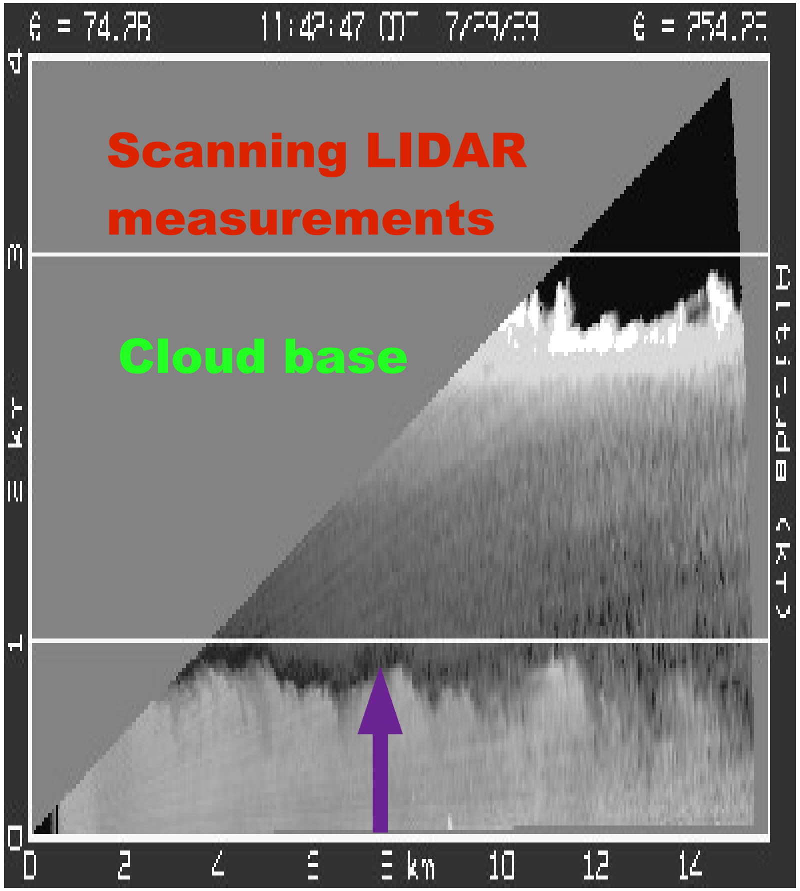


Clouds and aerosol layers between ~5 km and ~20 km result in distortion of images (longitudinal shower profiles).

The boundary layer

Diurnal convection and turbulence raises aerosols from ground.



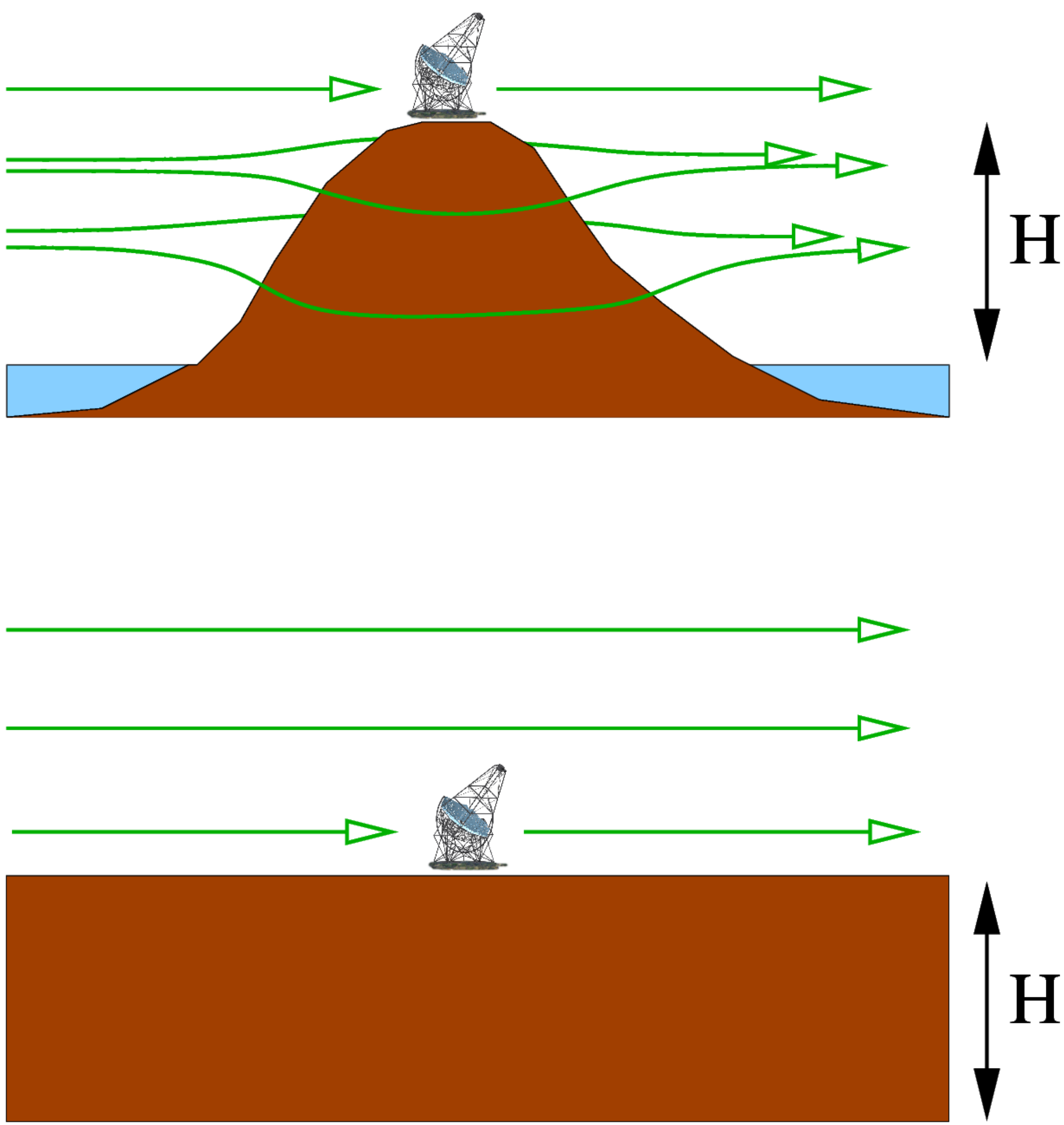


A **boundary layer** of 1 to 2 km thickness has a higher aerosol content than the air above.

Aerosols in the boundary layer

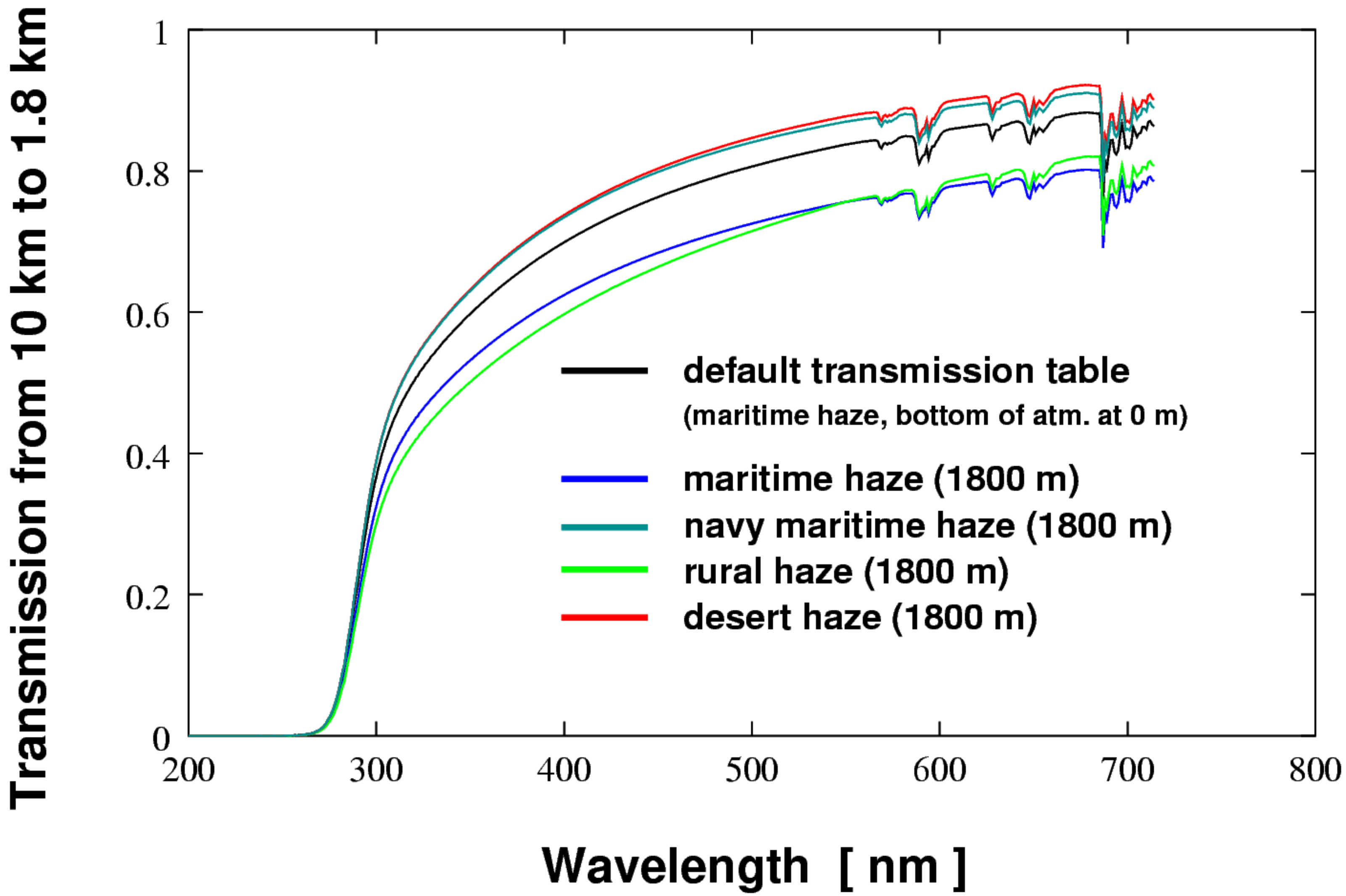
- Aerosol content and composition in the boundary layer depends on the history of the air during the last several days: over which surface, wind speed, turbulence, precipation ...
- Aerosols (including hydrosols) can change with temperature/humidity.
- Models can be adapted to reality with
  - Observations 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.

Importance of air flow



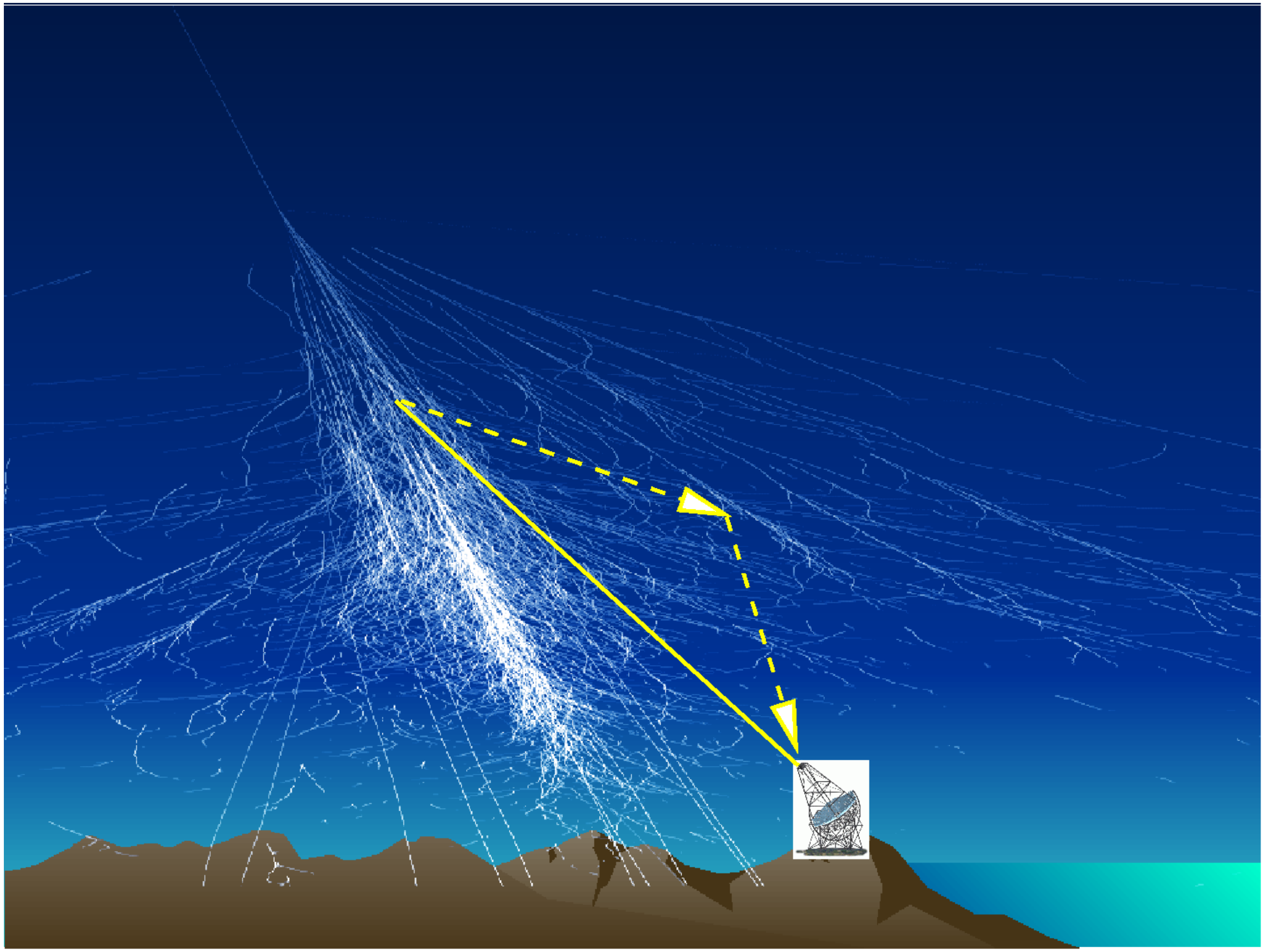
Aerosol content above observer not just a function of altitude *H* but also of the air flow, where it came from etc.

Individual extinction sources: the real trouble: aerosols



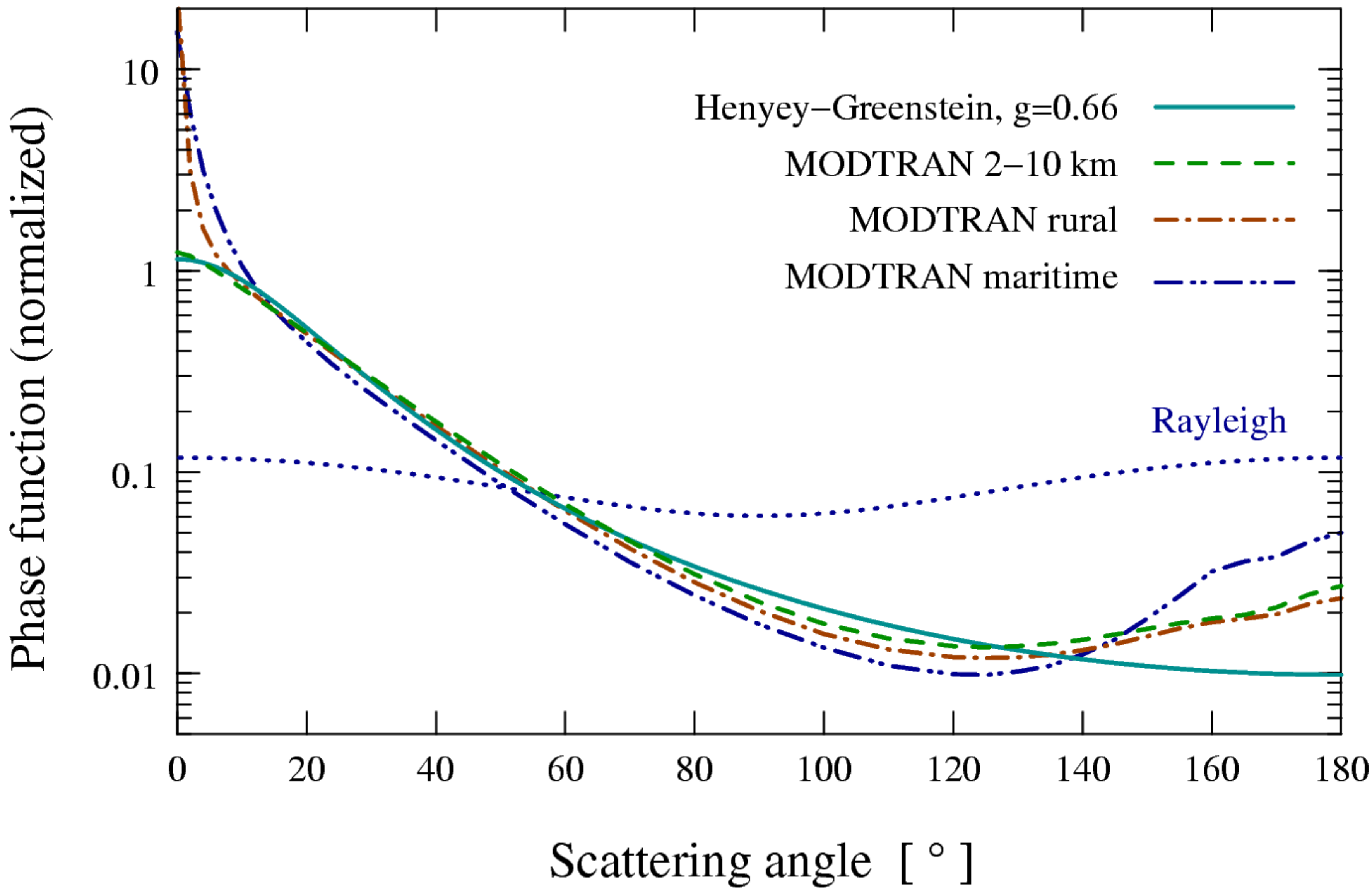
You need measurements to decide which model is most appropriate!

Scattered Cherenkov light

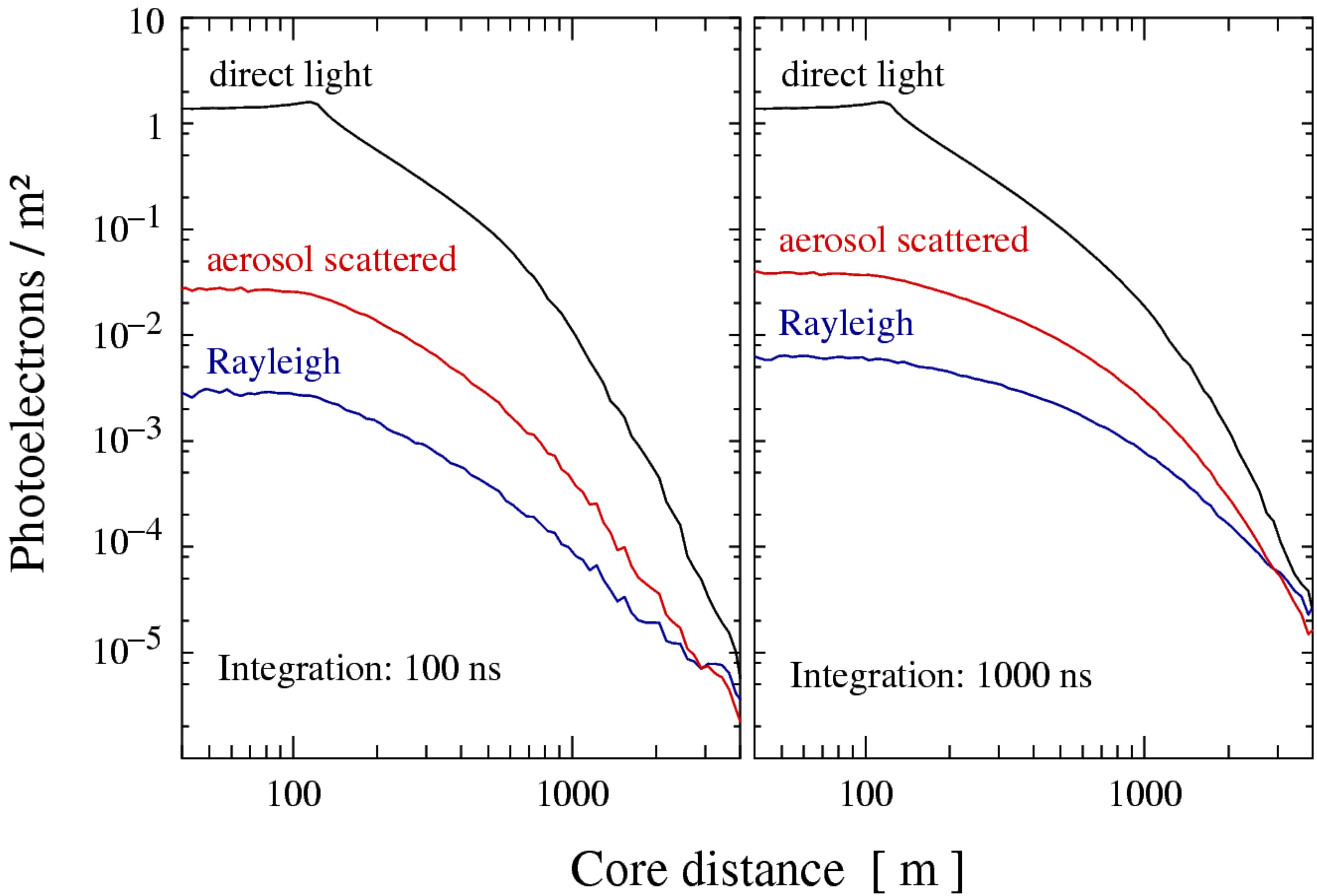


Scattered light may fall into the field of view – but typically later than direct light from the shower. Integration time matters.

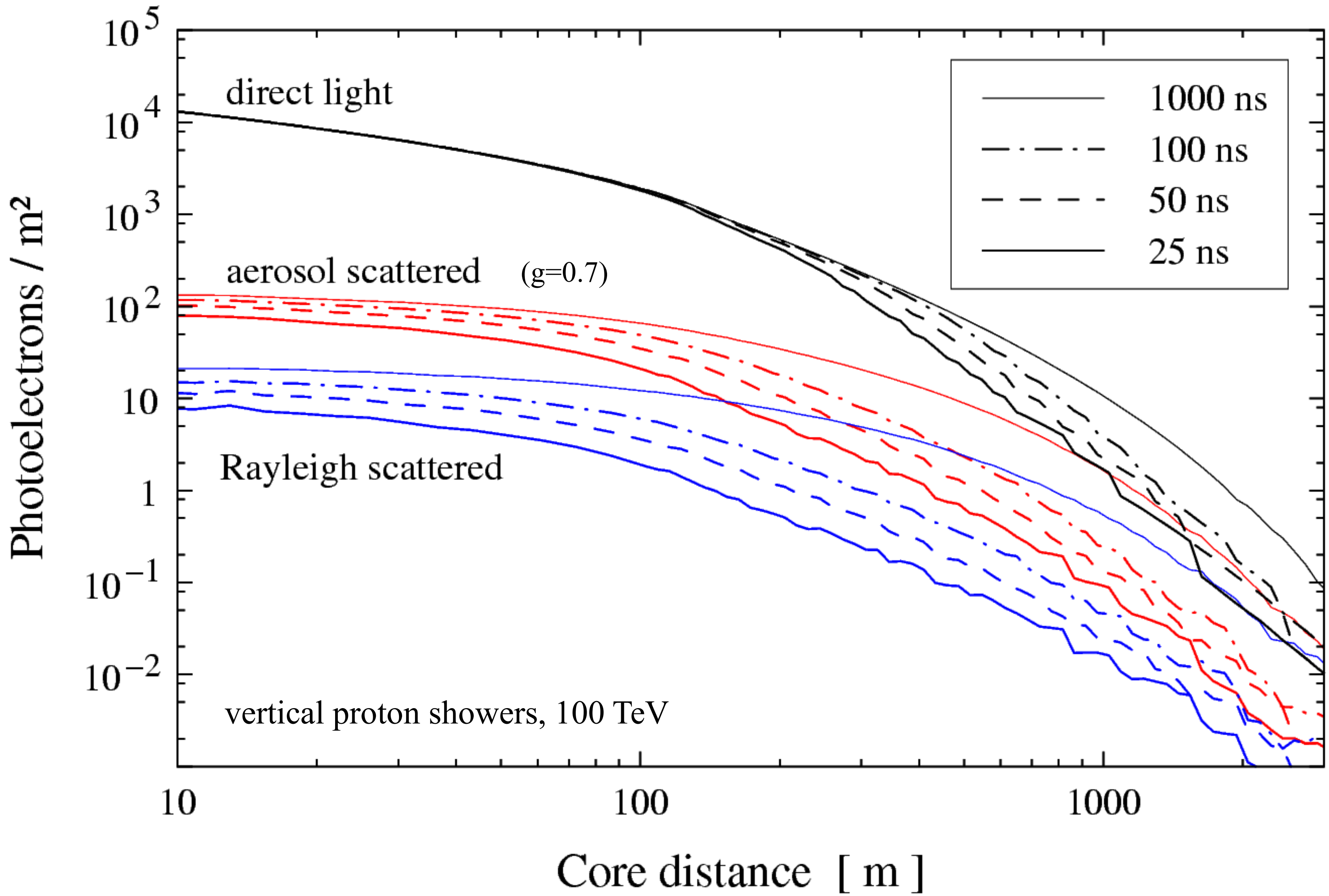
Scattering phase functions



Relevance of scattered Cherenkov light



Relevance of scattered Cherenkov light



Relevance of scattered Cherenkov light

For Cherenkov experiments, scattered Cherenkov light is insignificant since

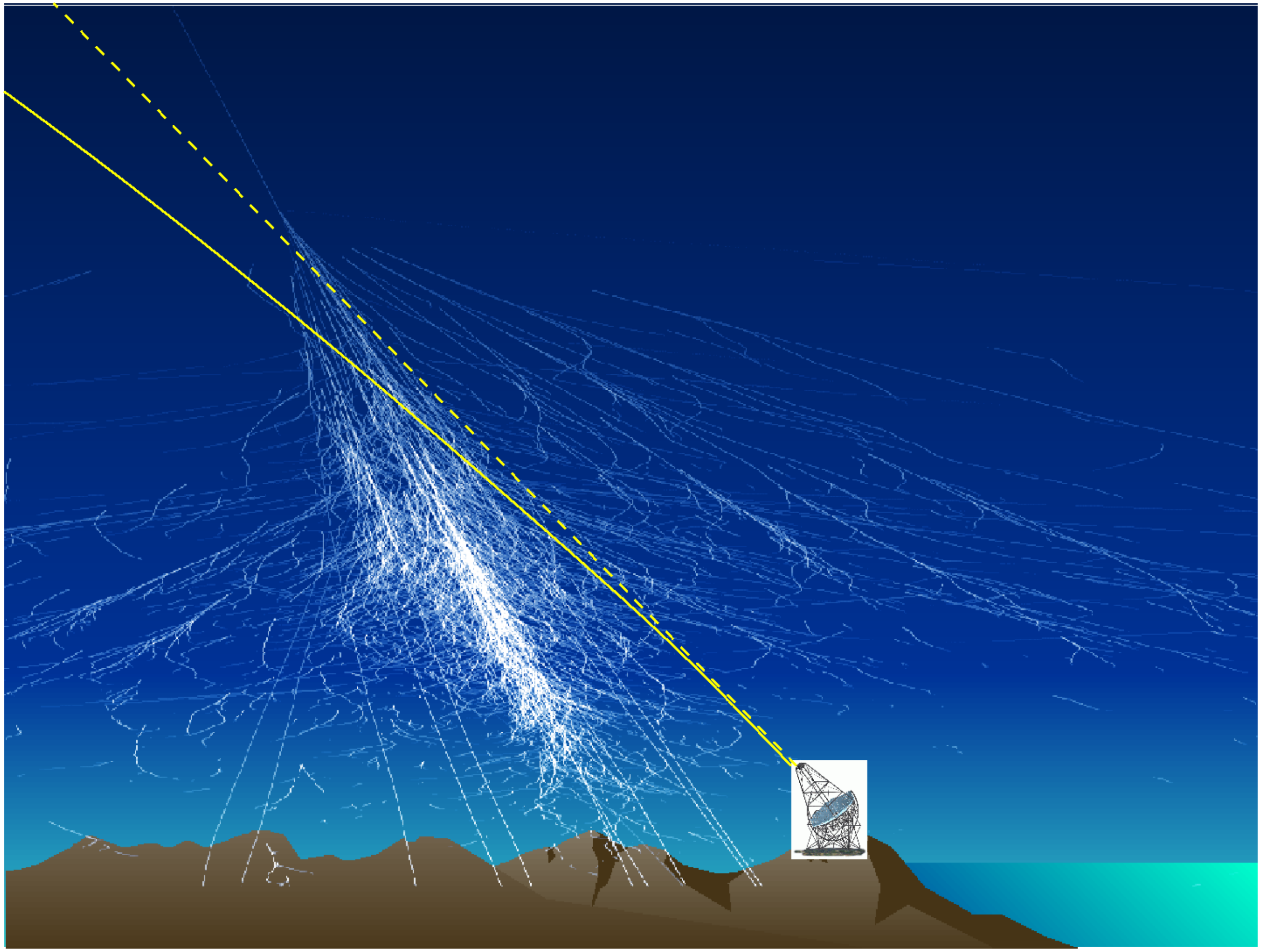
a) Integration times are short ($\ll$ 100 ns)

b) Gamma-showers only observed at distances below 1000 m due to small field of view.

Even for CTA just a small contribution.

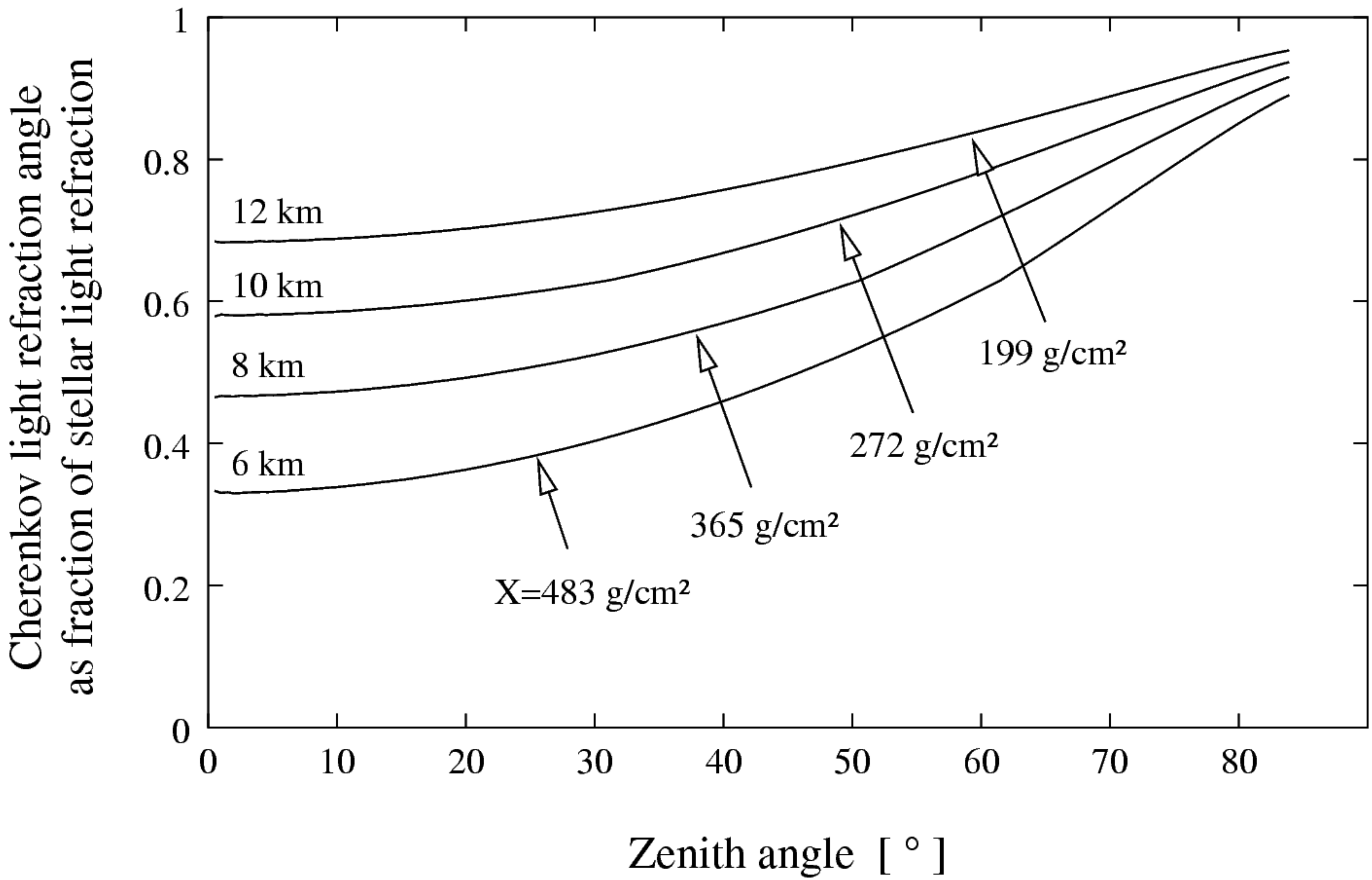
For fluorescence experiments (observing at large core distances, large integration times), the scattered light can exceed the direct light and Rayleigh scattering can exceed Mie scattering (mainly Cherenkov light – at small core distances Cherenkov light always dominates; scattered fluorescence light only relevant at very large core distance).

Atmospheric refraction



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

Atmospheric refraction



Conclusions

- Knowledge of the atmospheric profiles is needed for proper simulation of any air shower instrument.
- Instruments observing Cherenkov or fluorescence light depend on many additional parameters.
- Extinction of light depends on aerosols and trace gases (in particular ozone, also near ground: UV only).
- The most important cross-check for any aerosol model is star-light extinction in the B and V (blue and green).
- High clouds or aerosol layers can be tricky for data analysis and need to be monitored.
- Scattered light is only for the fluorescence folks.
- Refraction corrections needed for accurate positions.