

# Cherenkov Light in CORSIKA

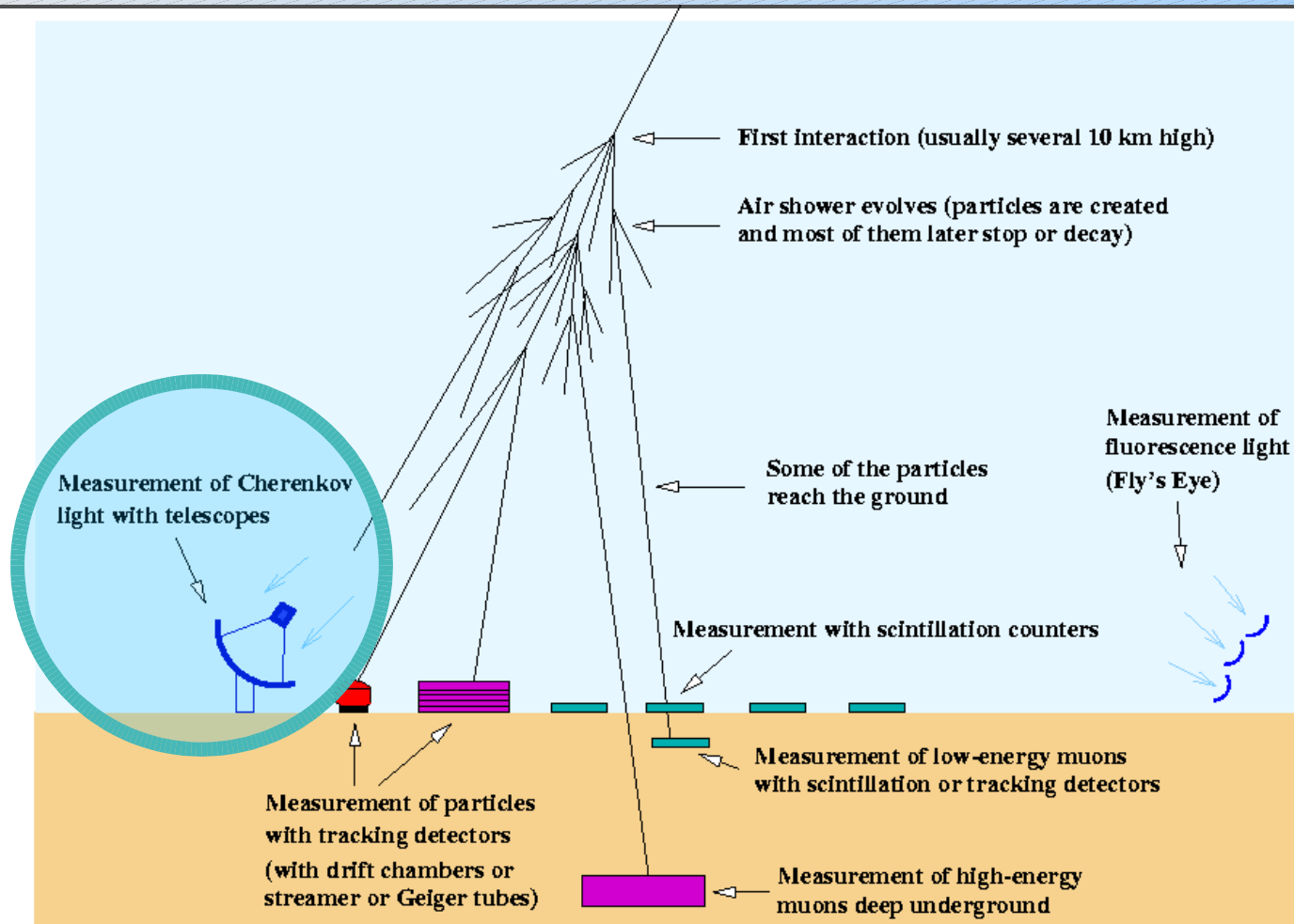
by

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# Air shower measurement methods



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# Atmospheric Cherenkov experiments

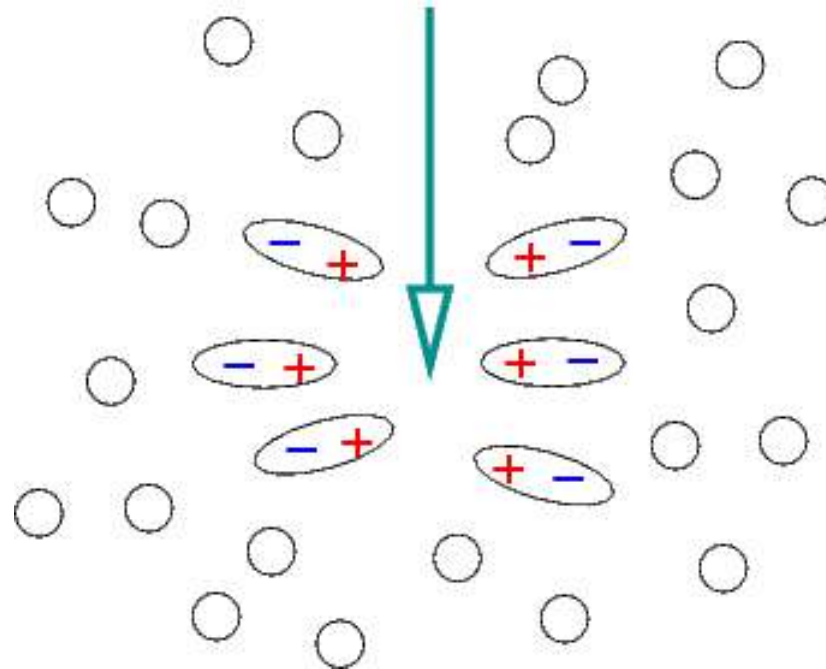
- Shower-front sampling by wide-angle detectors: AIROBICC, BLANCA, TUNKA. ( $E_\gamma > 10$  TeV)
- Shower-front sampling by heliostat arrays with or without secondary optics: CELESTE, STACEE, ... ( $E_\gamma > 50$  GeV)
- Imaging atmospheric Cherenkov telescopes (IACT): Whipple, HEGRA, CANGAROO, ...
- Fluorescence detectors: need to subtract C signal.

# Energy ranges of primaries

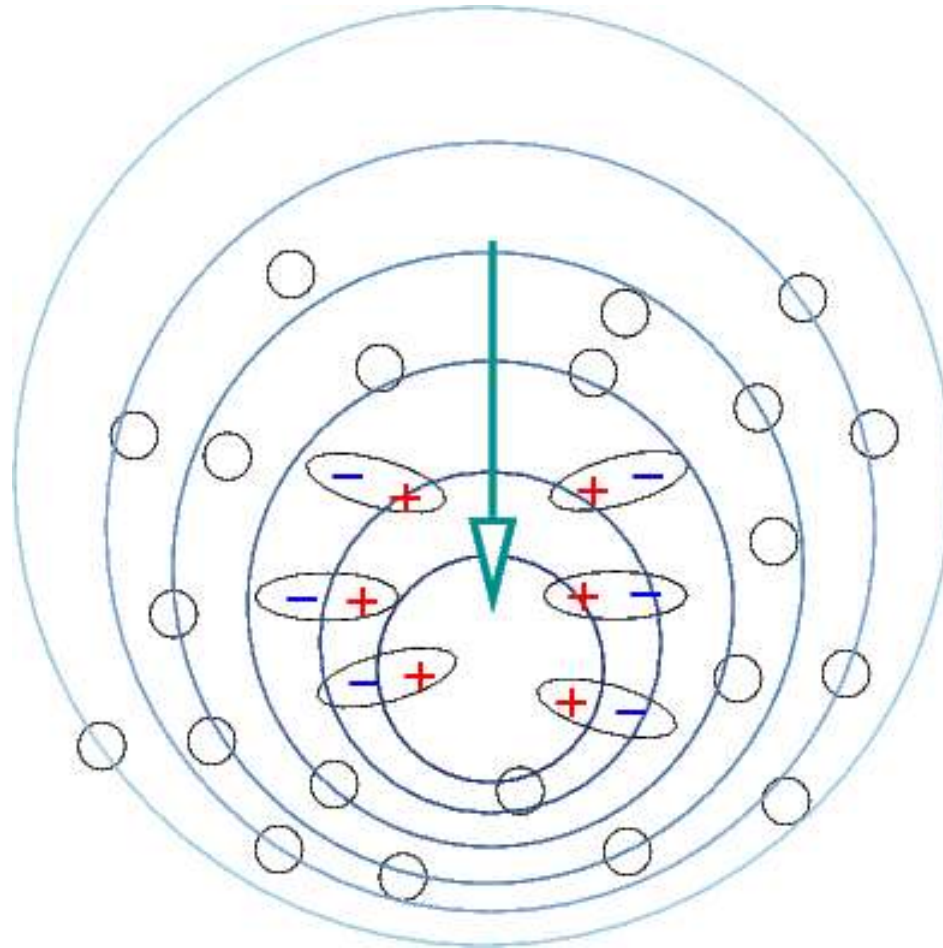
- For the current typical (IACT or solar tower) Cherenkov instrument the range of  $\gamma$ -ray energies of interest is from about 50 GeV to 100 TeV. This may be extended down to 5 GeV.
- The extension of interaction models to higher energies is of no interest to us. We need accurate models below 1 PeV.

# Cherenkov light basics

Charged particle polarizing  
a dielectric medium with index  
of refraction  $n$ .

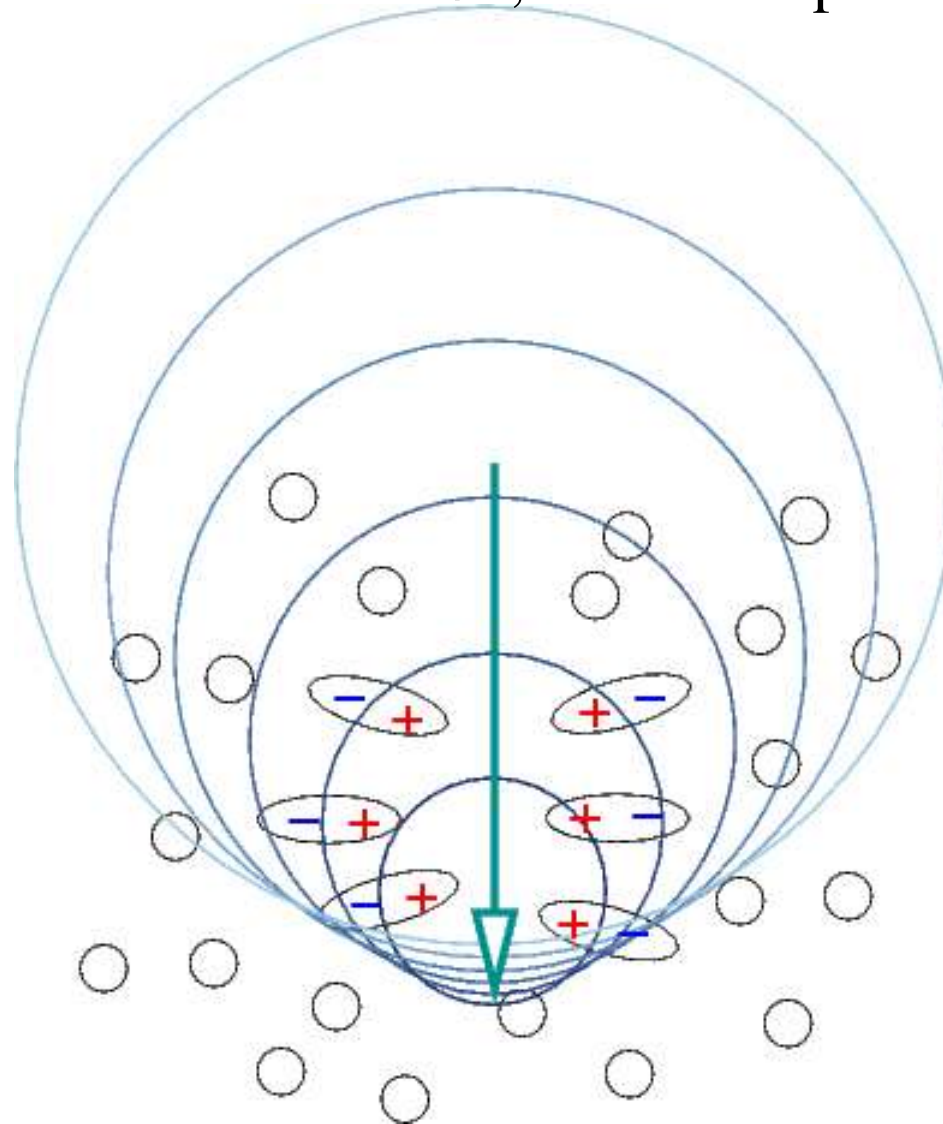


For a particle slower than light ( $v_l = c/n$ ), there is no positive interference of any potential radiation by the polarized medium.





When the particle is faster than  $c/n$ , we have a positive interference.

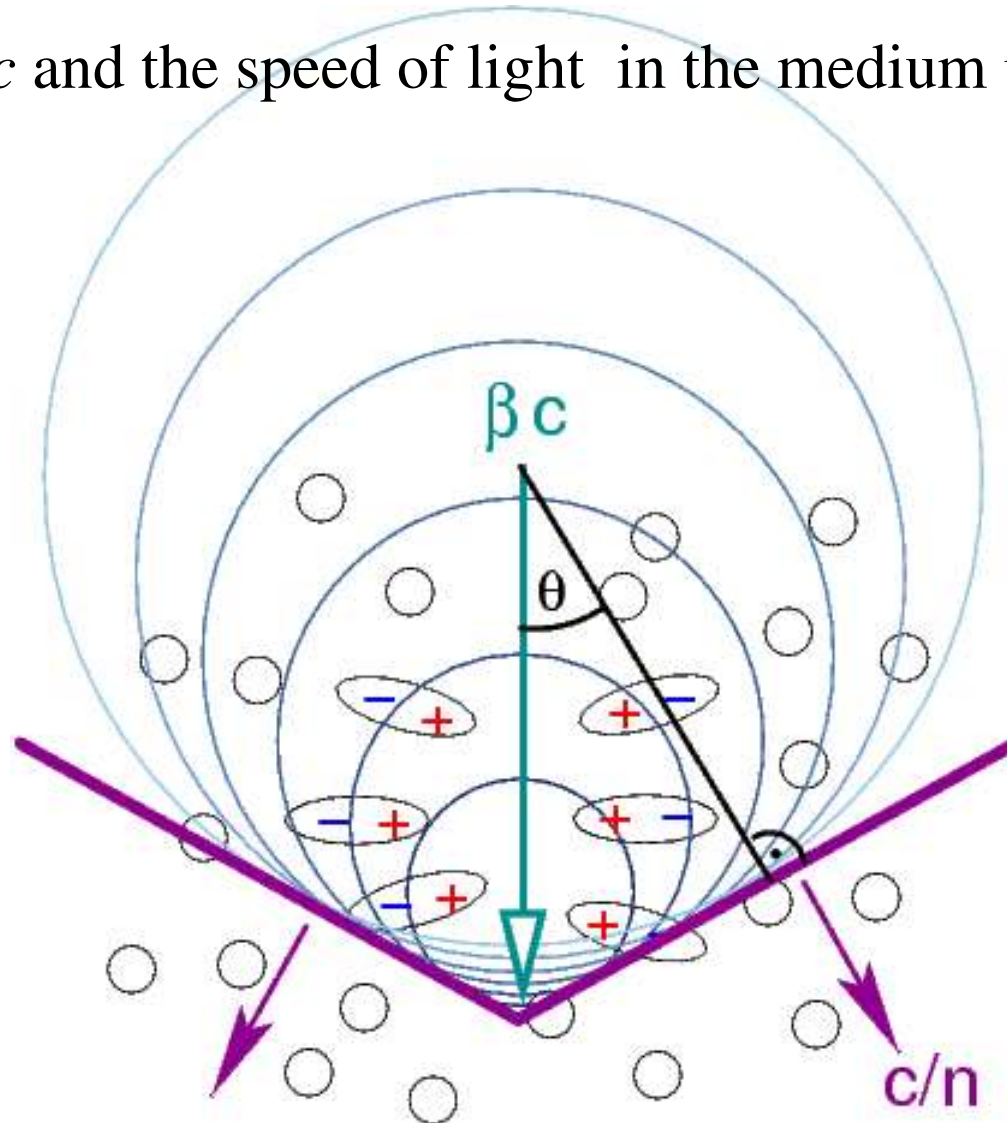








The geometry of the Cherenkov wave front is defined by the particle velocity  $v_p = \beta c$  and the speed of light in the medium  $v_l = c/n$ .



# Cherenkov light basics

- Basic formulae:

$$\cos \theta = \frac{1}{n \beta}$$

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

- Only particles faster than light ( $\beta > 1/n$ ) emit light.
- That is for electrons above 20 MeV or muons above 4 GeV near sea level.

# Cherenkov light basics

- Basic formulae:

$$\cos \theta = \frac{1}{n \beta}$$

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

- Light is emitted along a cone of half opening angle  $\theta$ .

# Cherenkov light basics

- Basic formulae (with small dispersion):

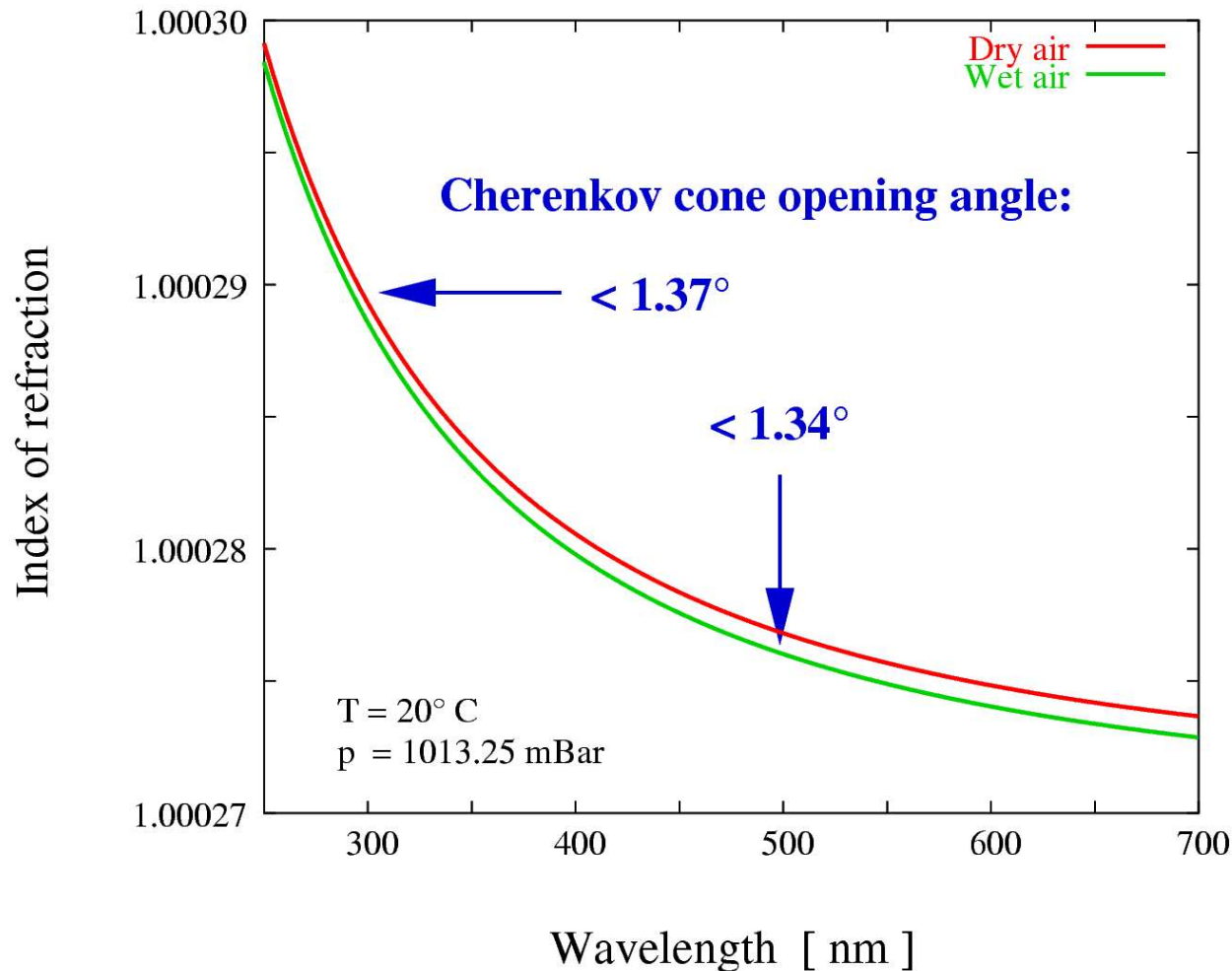
$$\cos \theta = \frac{1}{n(\lambda)\beta}$$

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

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



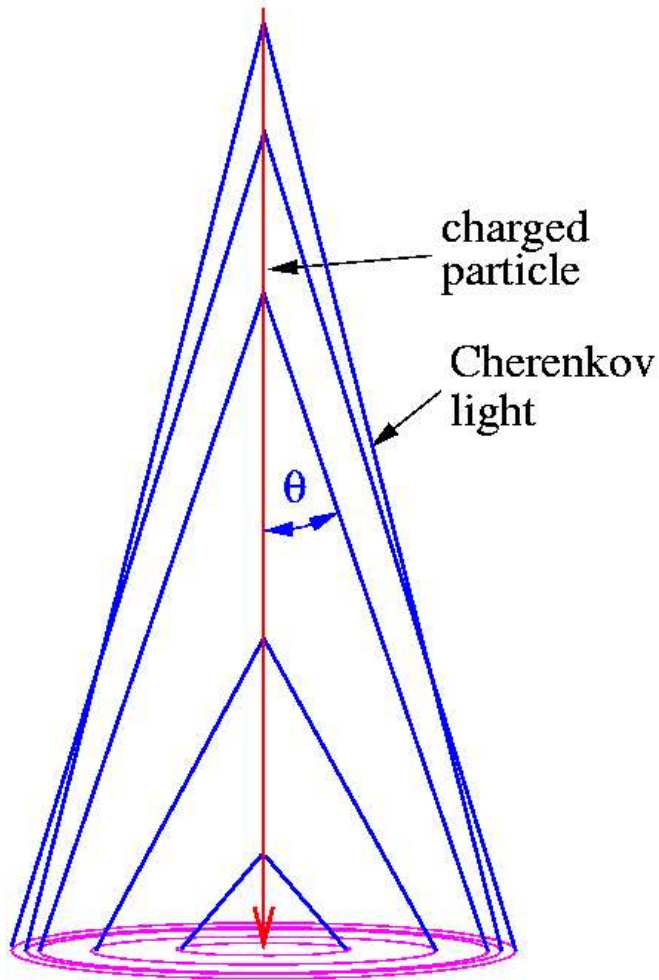
# Wavelength dependence of $n$



Between 300 and 700 nm rather small change of  $n$ .  
Ideally, we should take account of that.  
**For efficiency reasons, it is ignored.**  
Also note a small effect of humidity.



# Emission by a single particle

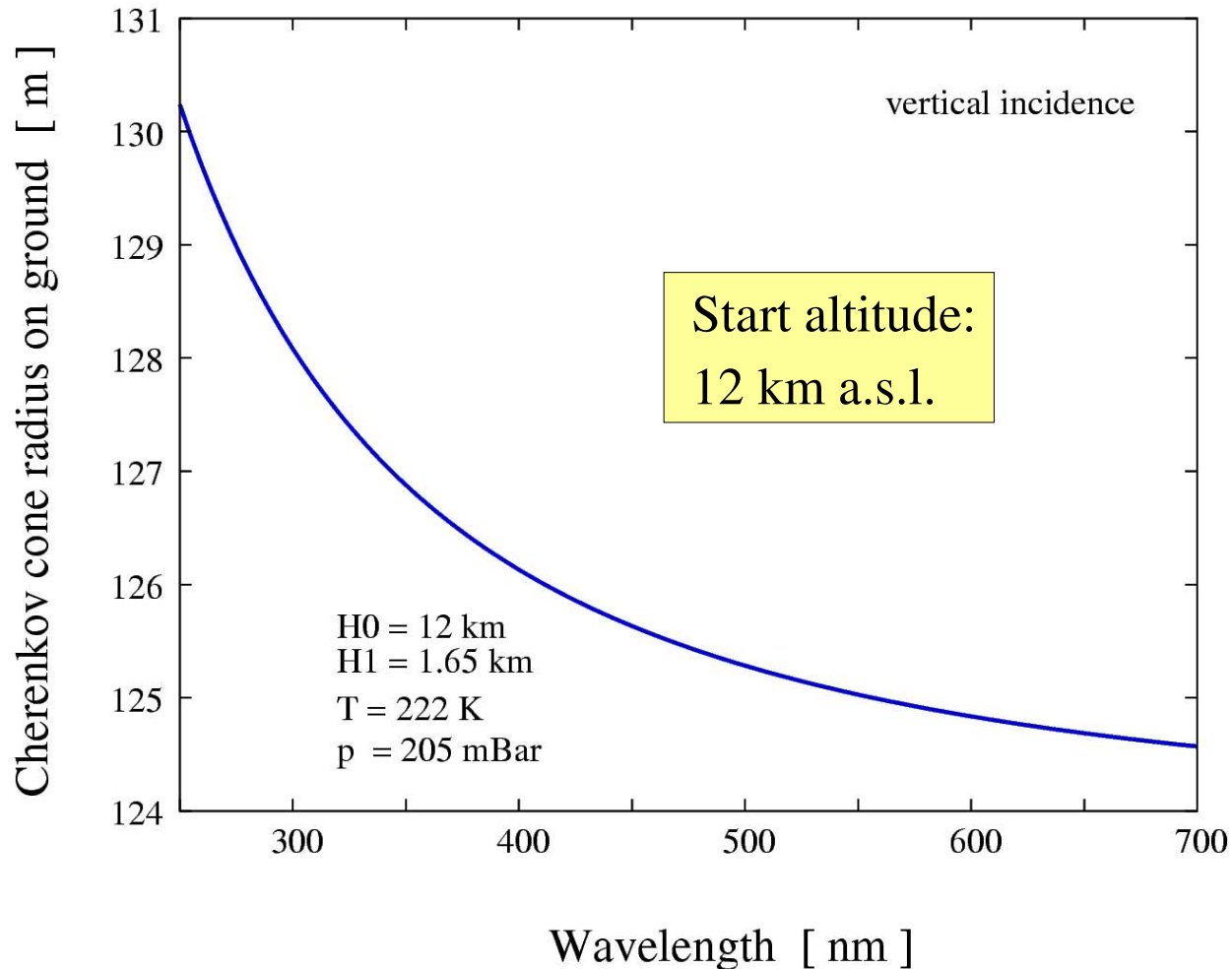


$n - 1$  is proportional to air density.

The Cherenkov opening angle  $\theta$  is increasing downwards.

For a particle moving vertically downwards, the largest ring on the ground near sea level is from 12 to 15 km height.

# Cherenkov ring on the ground



Between 300 and 600 nm the ring radius changes by up to 3 m.

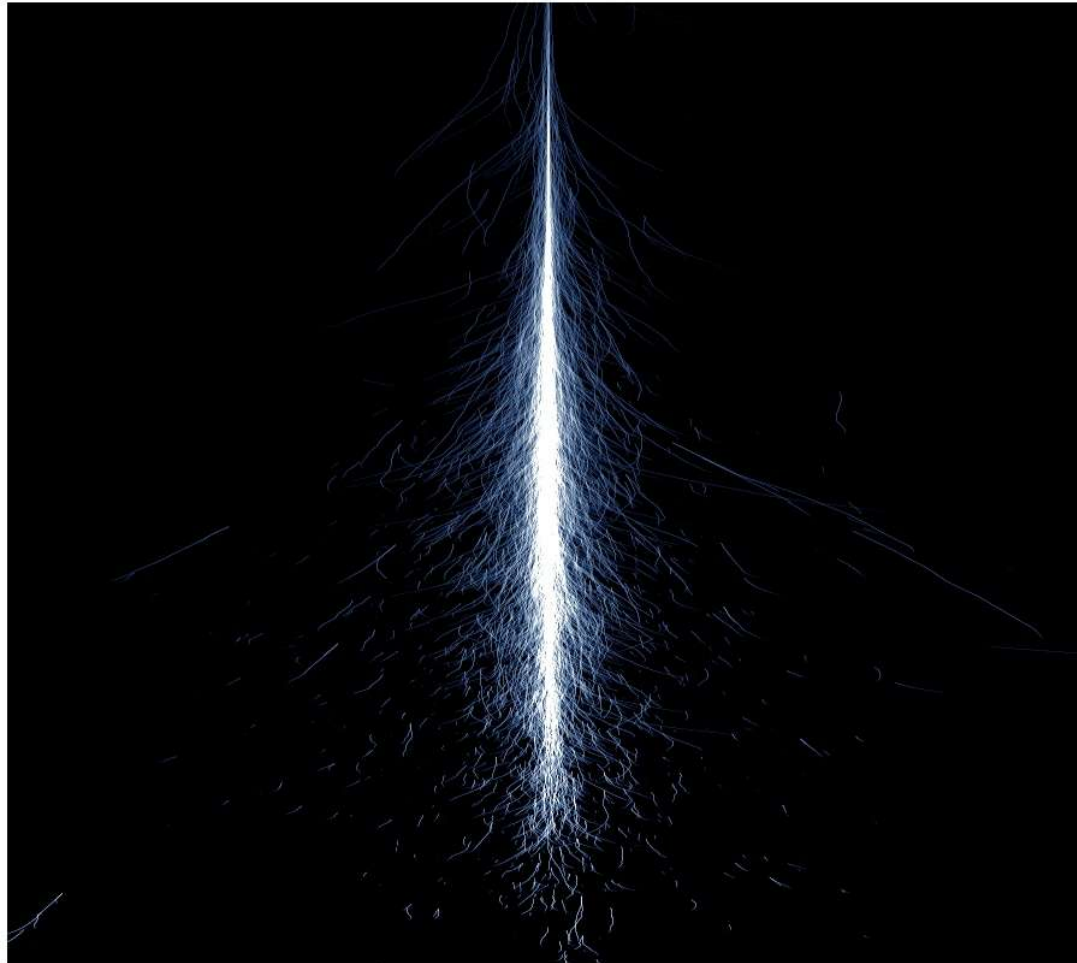
This is small compared to the lateral extension of the Cherenkov light from an air shower (~250 m).

# A gamma-ray shower example

Note that this is only 1.8 km wide but 16.0 km high

Gamma-ray  
of 1 TeV:

Tracks of all  
particles  
emitting  
Cherenkov  
light.

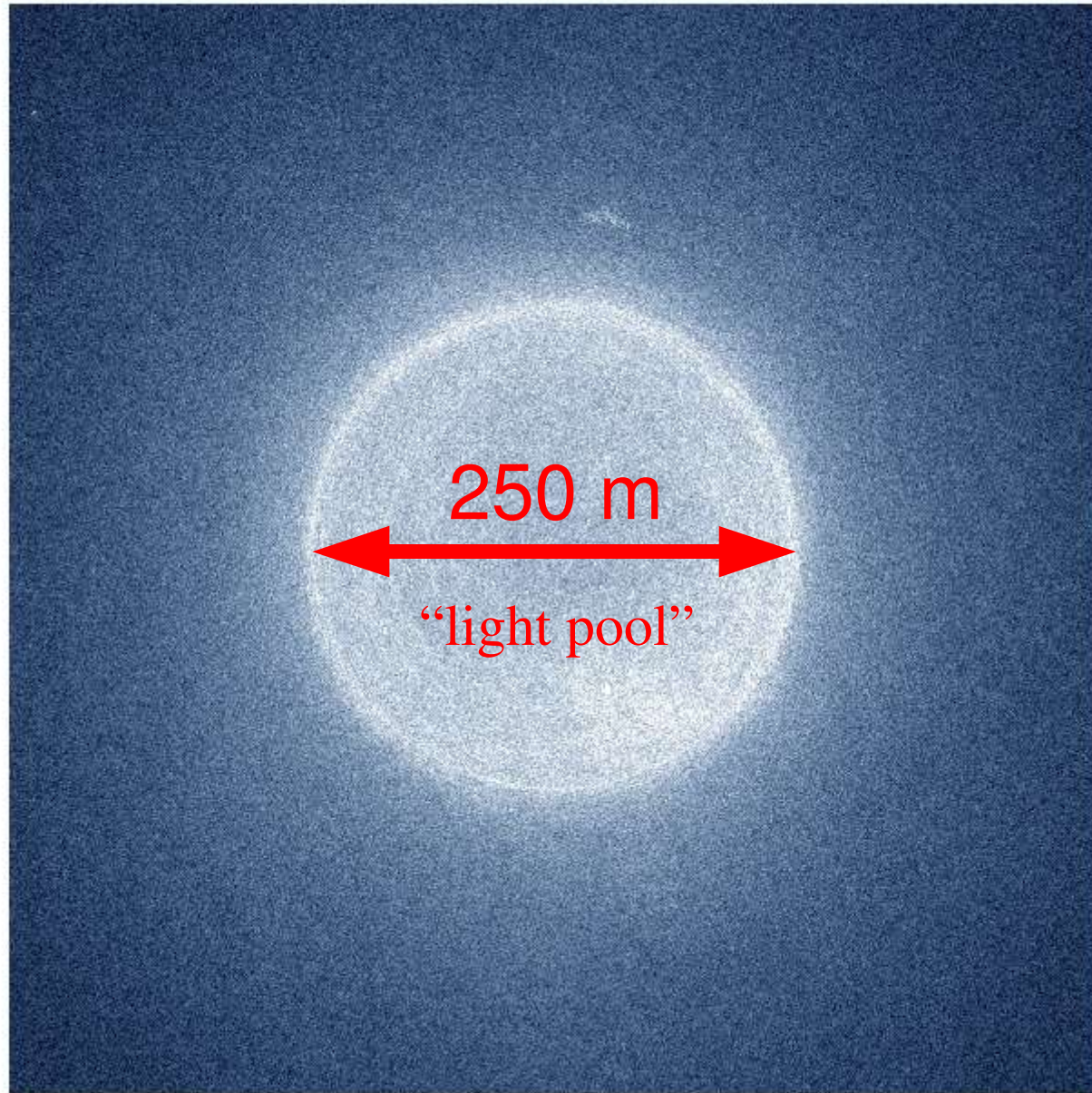


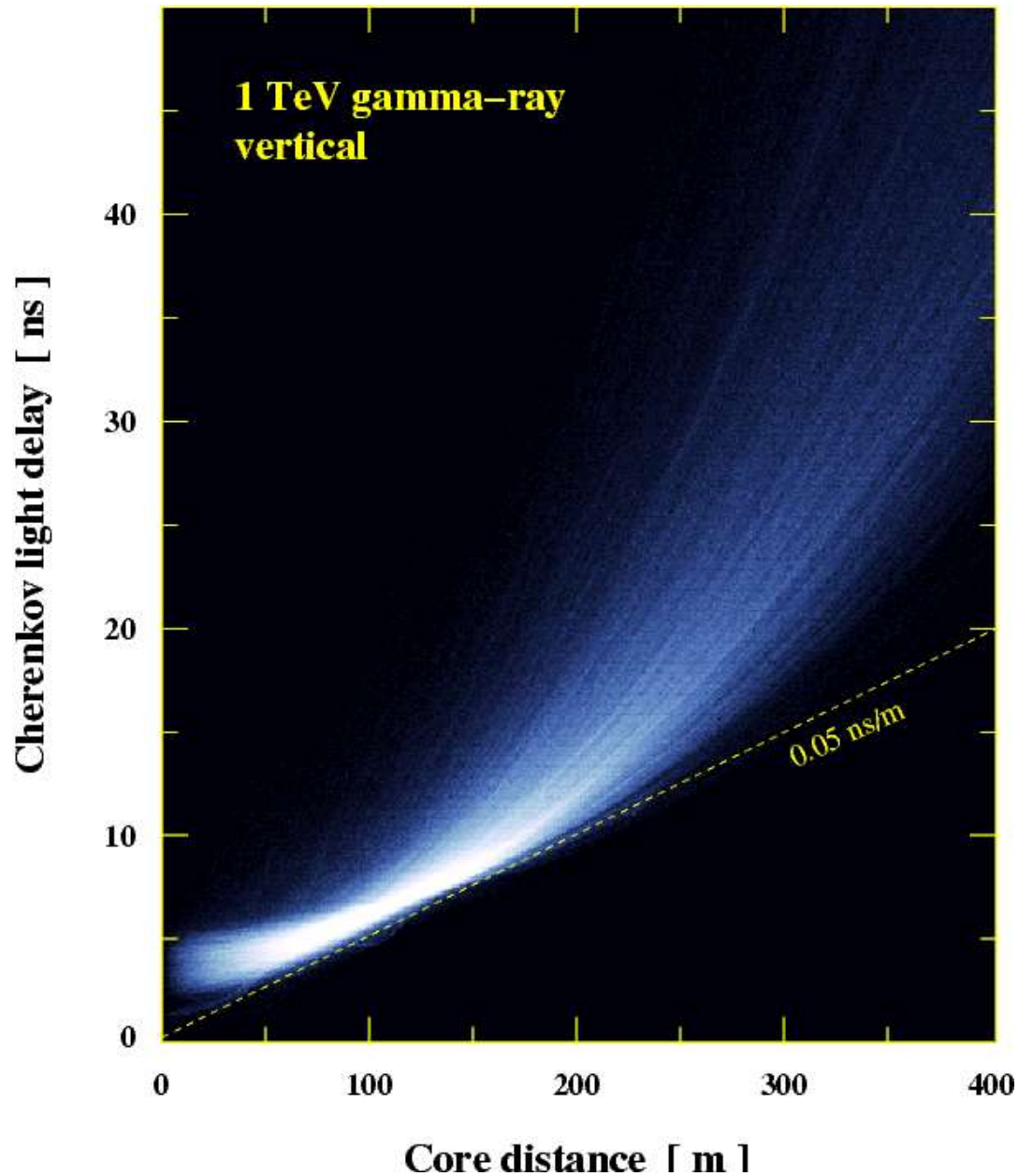


Size of area as shown: 600 m \* 600 m

Cherenkov  
light as  
arriving on  
the ground.

Observation  
level here at  
1800 m a.s.l.

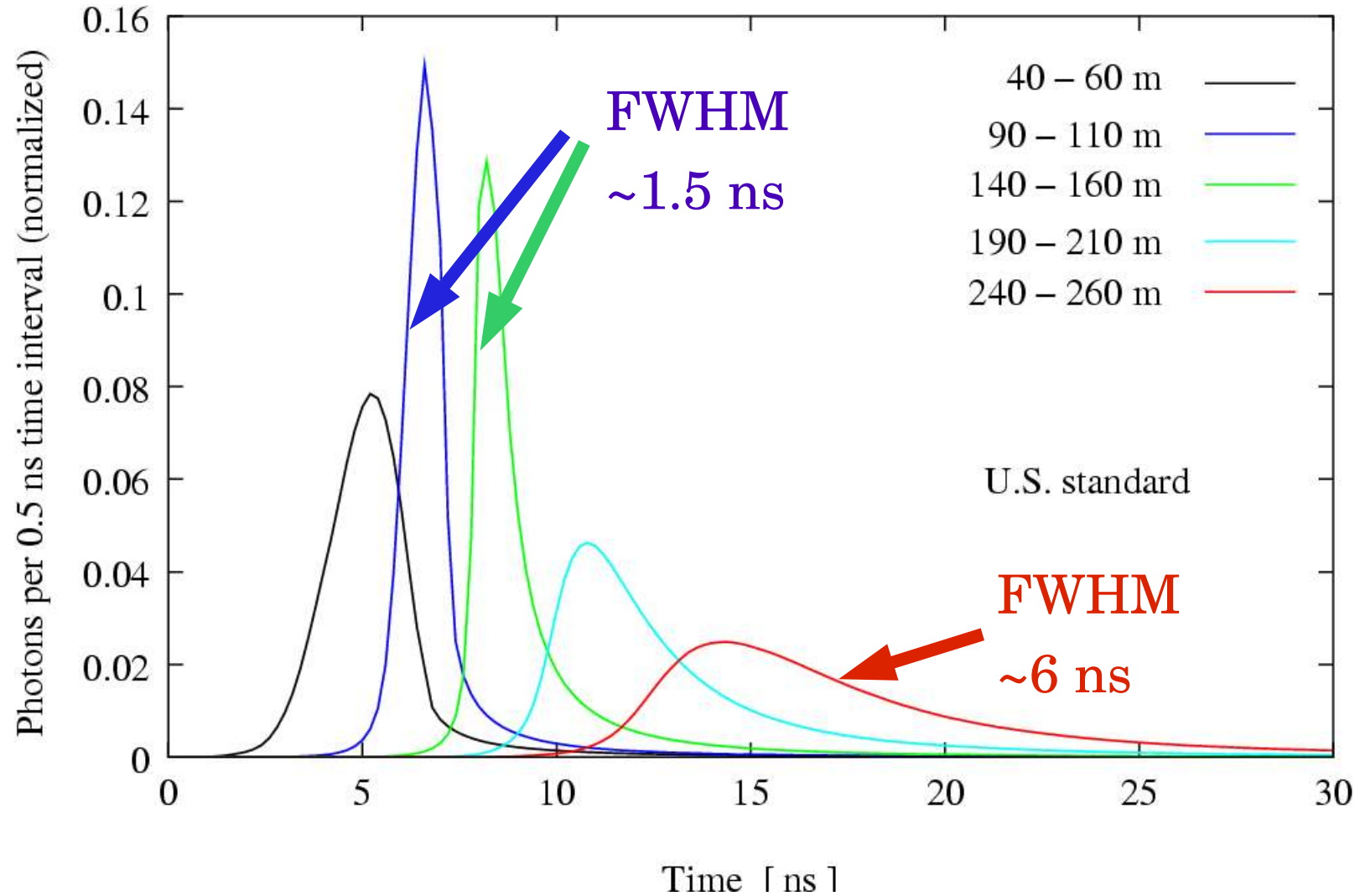




Since the index of refraction is so close to 1, the Cherenkov light almost keeps pace with the particles.

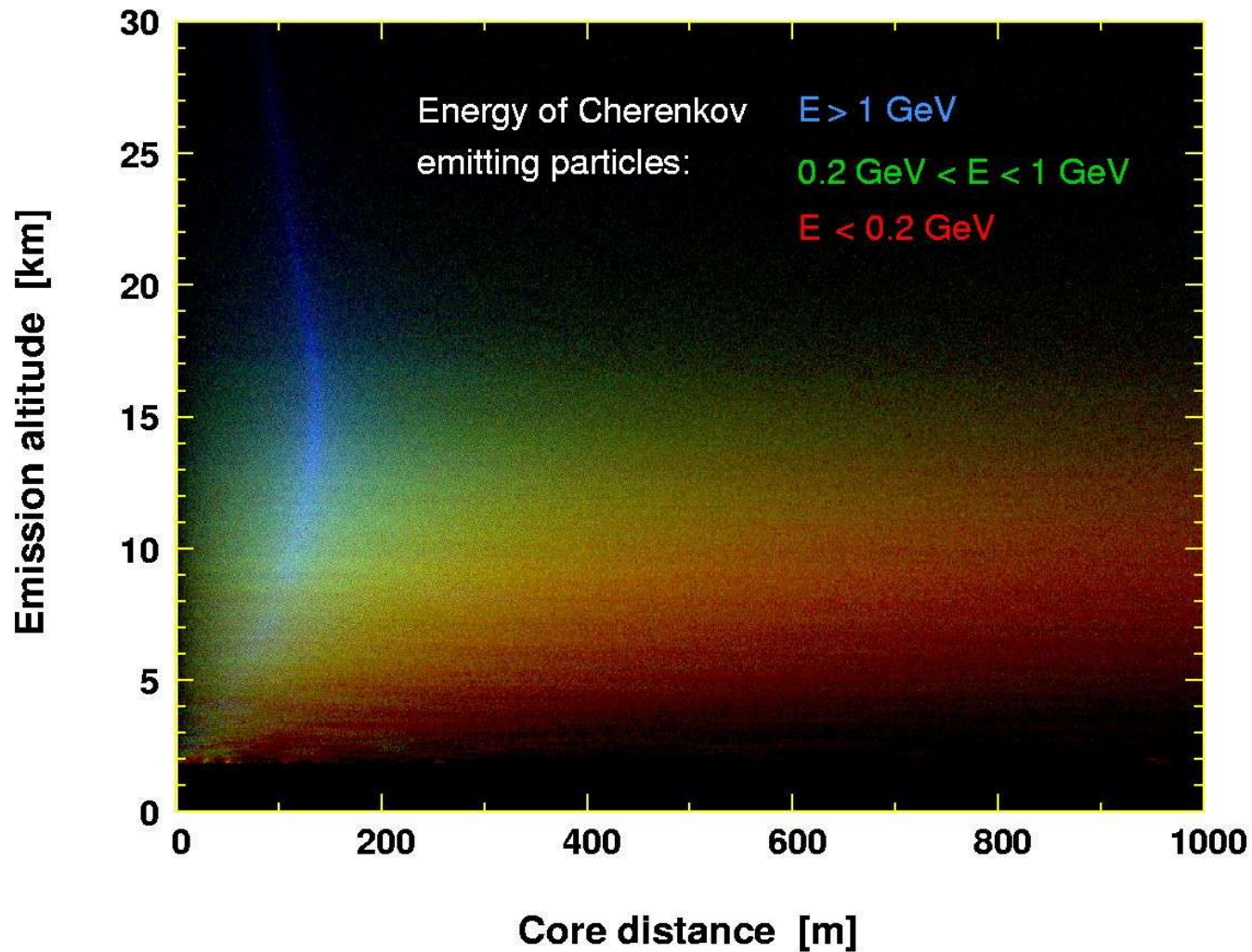
Near the edge of the `light pool` most light from a gamma-ray shower arrives within 2 ns.

# Cherenkov arrival time distribution



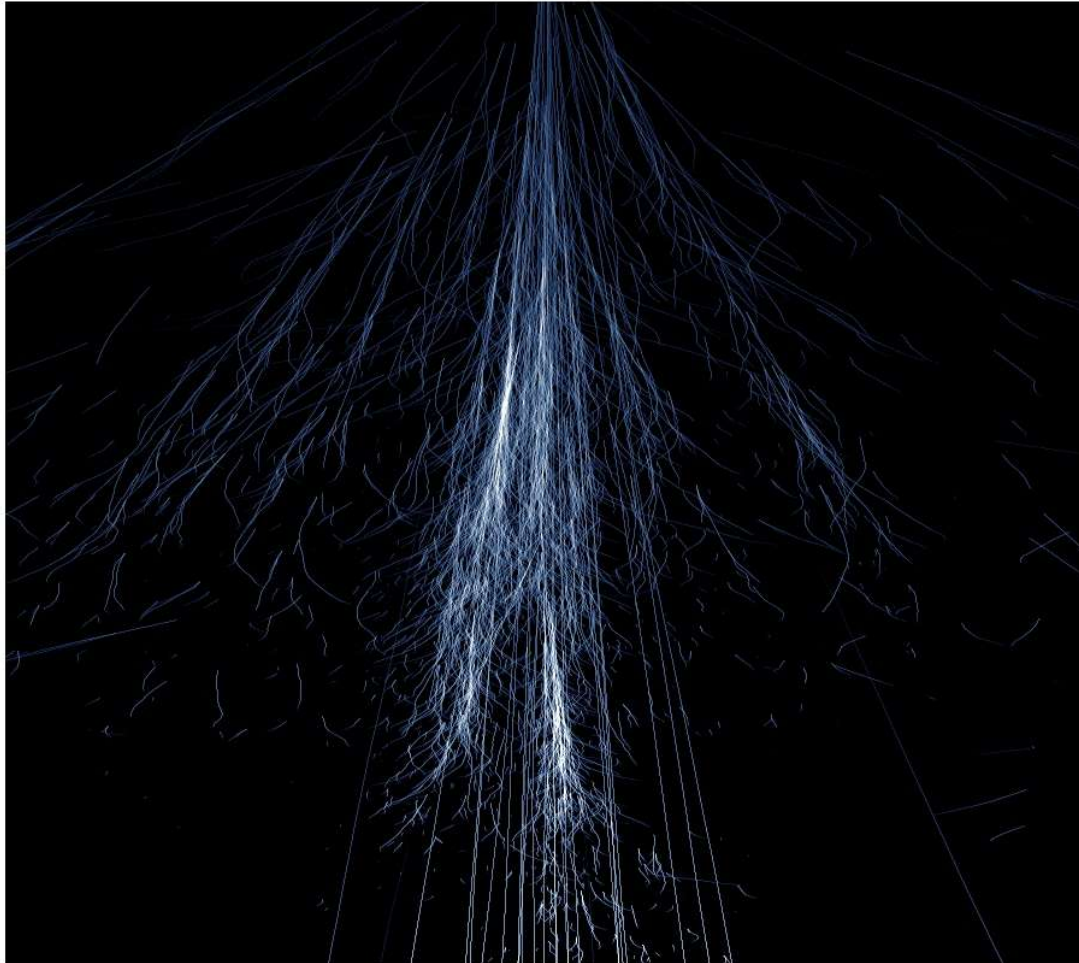


# Energies of emitting particles



# A proton shower example

Note that this is only 1.8 km wide but 16.0 km high

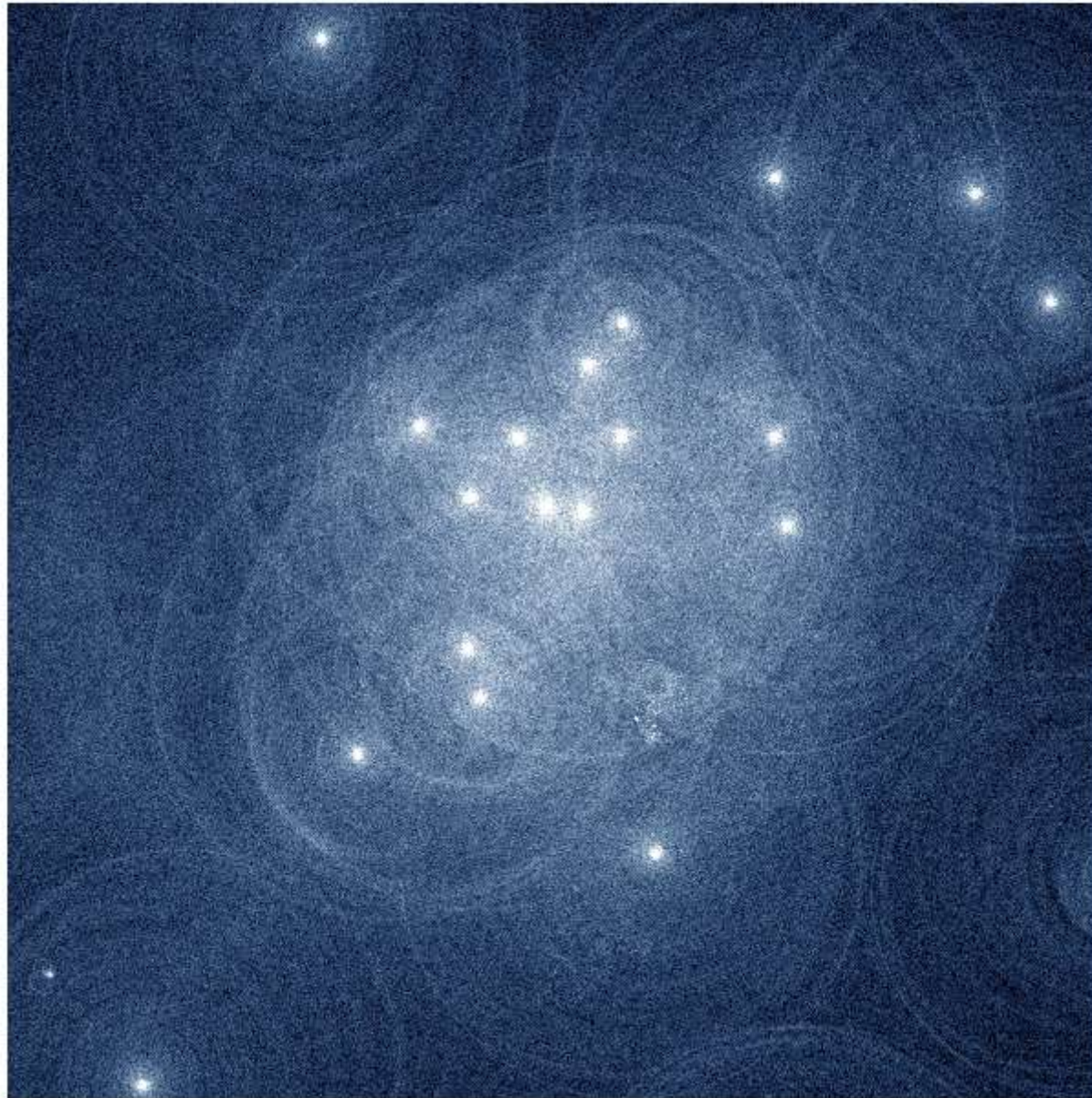




Size of area as shown: 600 m \* 600 m

Proton of  
2 TeV:

Distribution  
of light on  
the detection  
level.



# Cherenkov light in CORSIKA

- Particle path steps are shorter than normally in CORSIKA such that multiple scattering and deflection in geomagnetic field are less than the pixel size in Cherenkov telescopes.
- EGS step length factor STEPF=1 by default.
- In Cherenkov subroutine, the steps are further subdivided such that a maximum of CERSIZ photons are emitted per sub-step.

# Cherenkov light in CORSIKA

- From sub-step to sub-step, continuous energy loss and increase of the index of refraction is taken into account. We could have tracks
  - emitting over the full path length step, or
  - starting with emission, then losing energy and not emitting at the end, or
  - not emitting at the start, then entering denser atmosphere and starting to emit Cherenkov light, ...



# Cherenkov light in CORSIKA

For optimization reasons,

- the index of refraction is assumed to be wavelength-independent. Built-in:  $n(400 \text{ nm})$ . Use the `ATMEXT` option to set different  $n$ .
- Cherenkov light is emitted in photon bunches (one bunch per sub-step). For a maximum bunch size (`CERSIZ`) of 5.0 you may get 4.96 photons in a bunch.



# Cherenkov light options

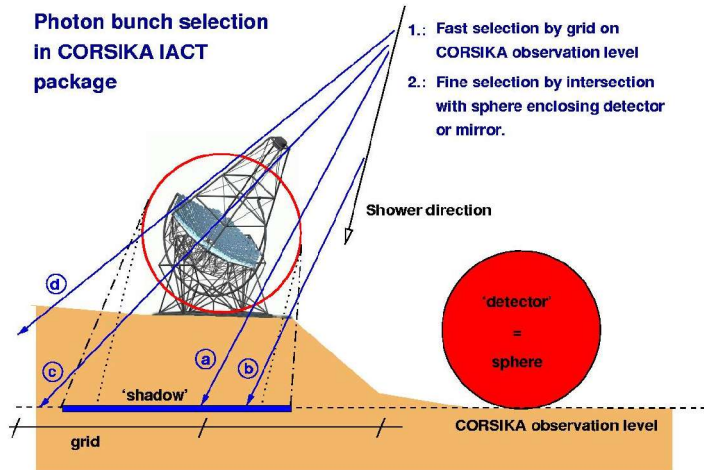
- Plain CERENKOV version:
  - rectangular, regular, flat detector grid,
  - output in particle output file or separate file.
- A number of options (at the CMZ-extraction stage), either Cherenkov-specific or more general, are available: IACT, ATMEXT, CURVED, CEFFIC, VOLUMEDET, ...

# The IACT option

- Detectors (telescopes) are individually defined by  $x, y, z, R$  of fiducial sphere around detectors.
- Only photon bunches hitting a sphere are recorded.
- Multiple instances of a telescope system (detector array) with random offsets of the whole system.
- Output in extended, machine-independent format.

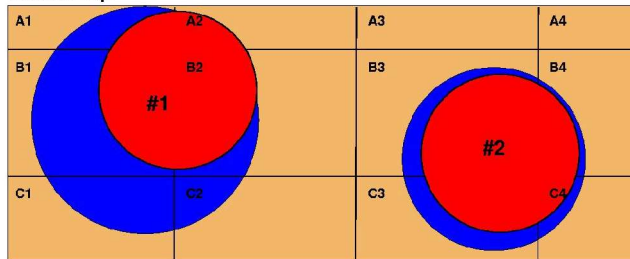
# Detector hits in IACT package

Photon bunch selection  
in CORSIKA IACT  
package



- a: recorded photon bunch
- b: not recorded because not intersecting sphere
- c: recorded (not in 'shadow' but hitting a shadow grid cell)
- d: not recorded because not hitting a shadow grid cell

view from top:



Grid cells used for #1: A1, A2, B1, B2, C1, C2

Grid cells used for #2: B3, B4, C3, C4

Rectangular area at CORSIKA observation level sub-divided into a grid.

Each telescope of each array is related to one or more grid cells.

Intersection of photon with detector sphere is only attempted for telescopes related to the grid cell where the photon arrives.

# The **VOLUMEDET** option

Without **VOLUMEDET**:

- Angular distribution corresponds to flat detector.
- Random array offsets in IACT are horizontal.

With **VOLUMEDET**:

- Angular distribution for spherical detector.
- Random array offsets in IACT in shower plane (and then projected into horizontal plane).

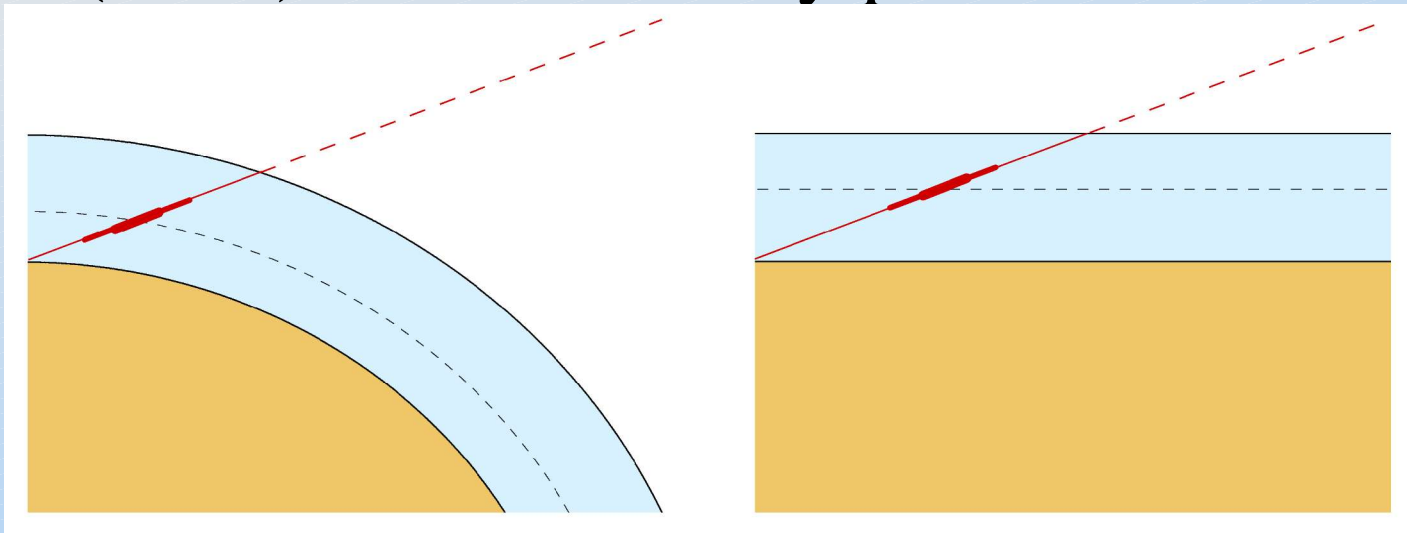
# The ATMEXT option

- Use built-in or external atmospheric profiles in tabulated form (with index of refraction).
- External tables are fitted by the piece-wise exponentials as used in EGS part of CORSIKA.
- Hadrons and muons use table interpolation (except with CURVED option).
- **Atmospheric refraction** is taken into account.



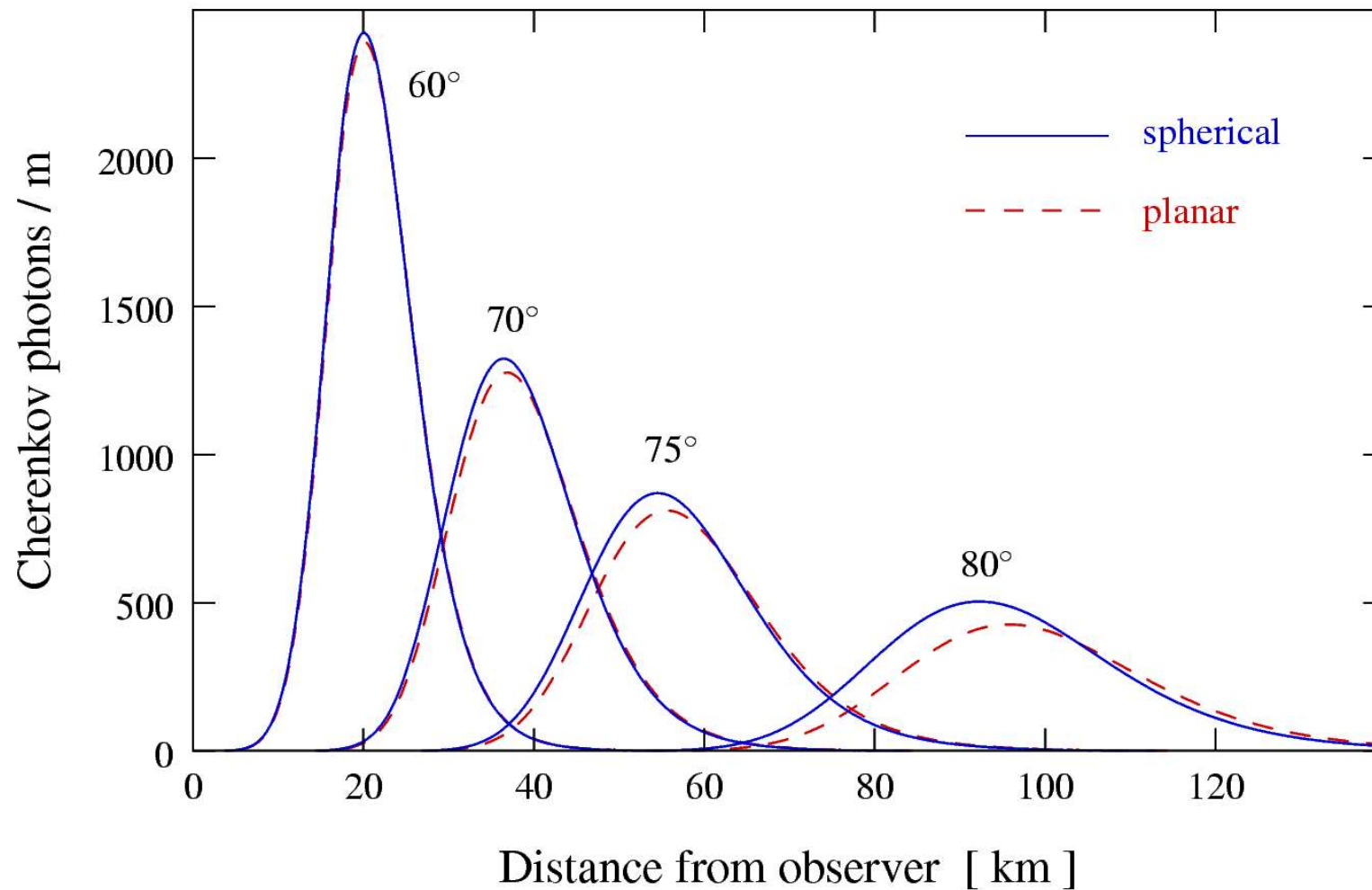
# The CURVED option

- Atmosphere no longer plane-parallel but curvature approximately taken into account. Use it for  $\theta > 60^\circ$ !
- Had (Has?) lots of stability problems.





# Spherical vs. planar atmosphere



# The CEFFIC option

- Normally both atmospheric transmission and detector response is expected to be treated in a subsequent program reading the CORSIKA output.
- A simplified detector simulation, taking into account atmospheric transmission, mirror reflectivity, and quantum efficiency is provided by the CEFFIC option. Data files from Whipple.

# CEFFIC: pros and cons

## Pro:

- Only photoelectron (bunches) recorded: some potential for saving disk space.
- May save you some time in development of your detector simulation program.

# CEFFIC: pros and cons

## Contra:

- CERSIZ has to be reduced to  $\sim 1.0$  because photon **bunches** are detected.
- Treatment of detector response is very simplistic.
- Data files that come with it seem to date back to the old days of Whipple. You should replace them by your own tables!



# CEFFIC / IACT co-operation

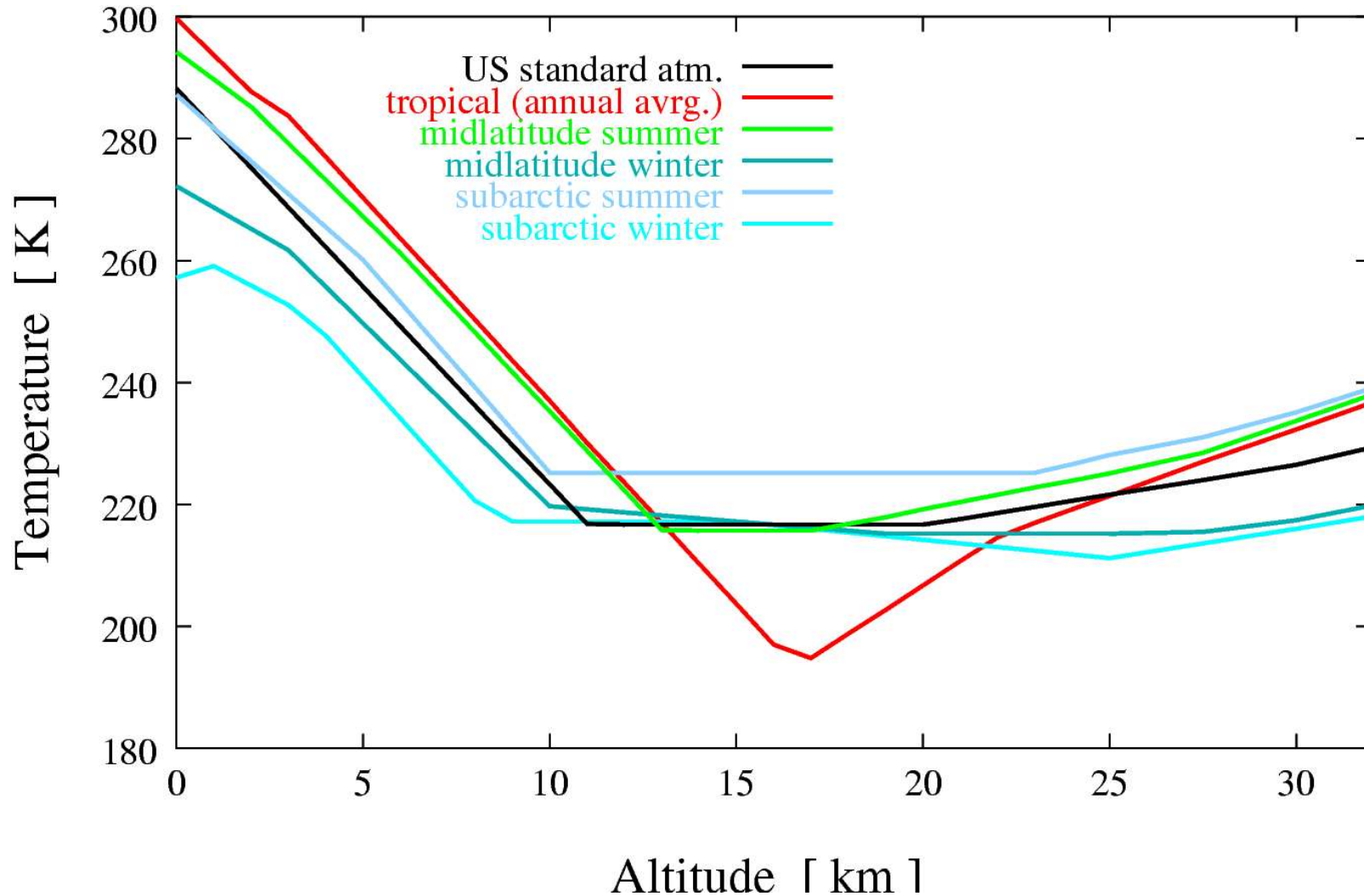
- IACT data format can distinguish data with or without CEFFIC option by wavelength:
  - $\lambda > 100$ : for future implementation with wavelength-dependent index of refraction ( $\lambda$  is in nanometers).
  - $\lambda = 0$ : without CEFFIC. Detector simulation program should throw random  $\lambda$ s within CWAVLG range.
  - $\lambda = -1$ : current CEFFIC indicator: photo-electrons.
  - $\lambda < -100$ : CEFFIC with  $-\lambda$  as thrown (requested!)

# Important ingredients

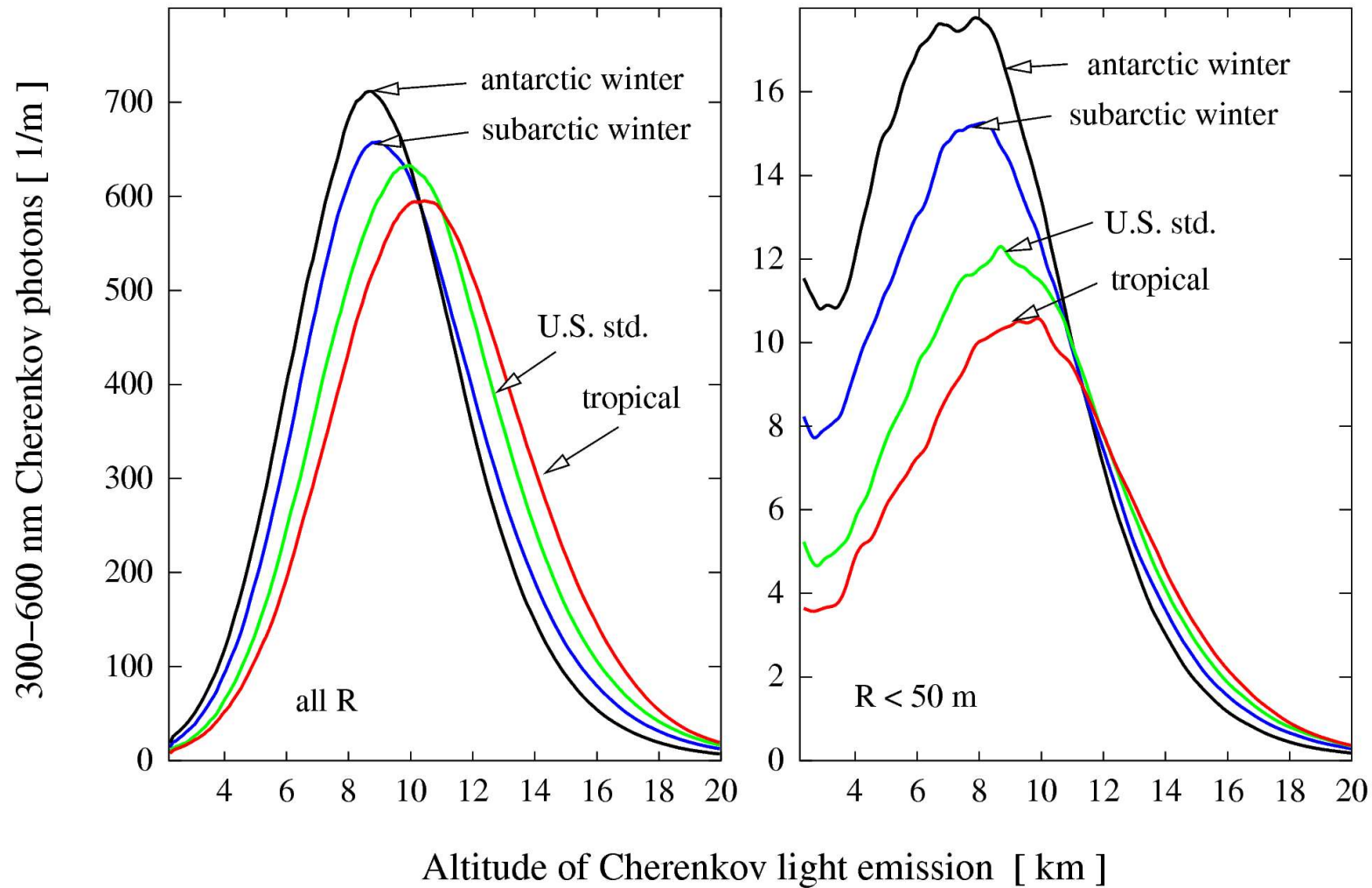
- Atmospheric density profile and its seasonal variations.
- Geomagnetic field.
- Extinction of Cherenkov light (treated in detector simulation program or by CEFFIC option).
- Scattered light (*but only for fluorescence detectors*).



# Atmospheric profiles

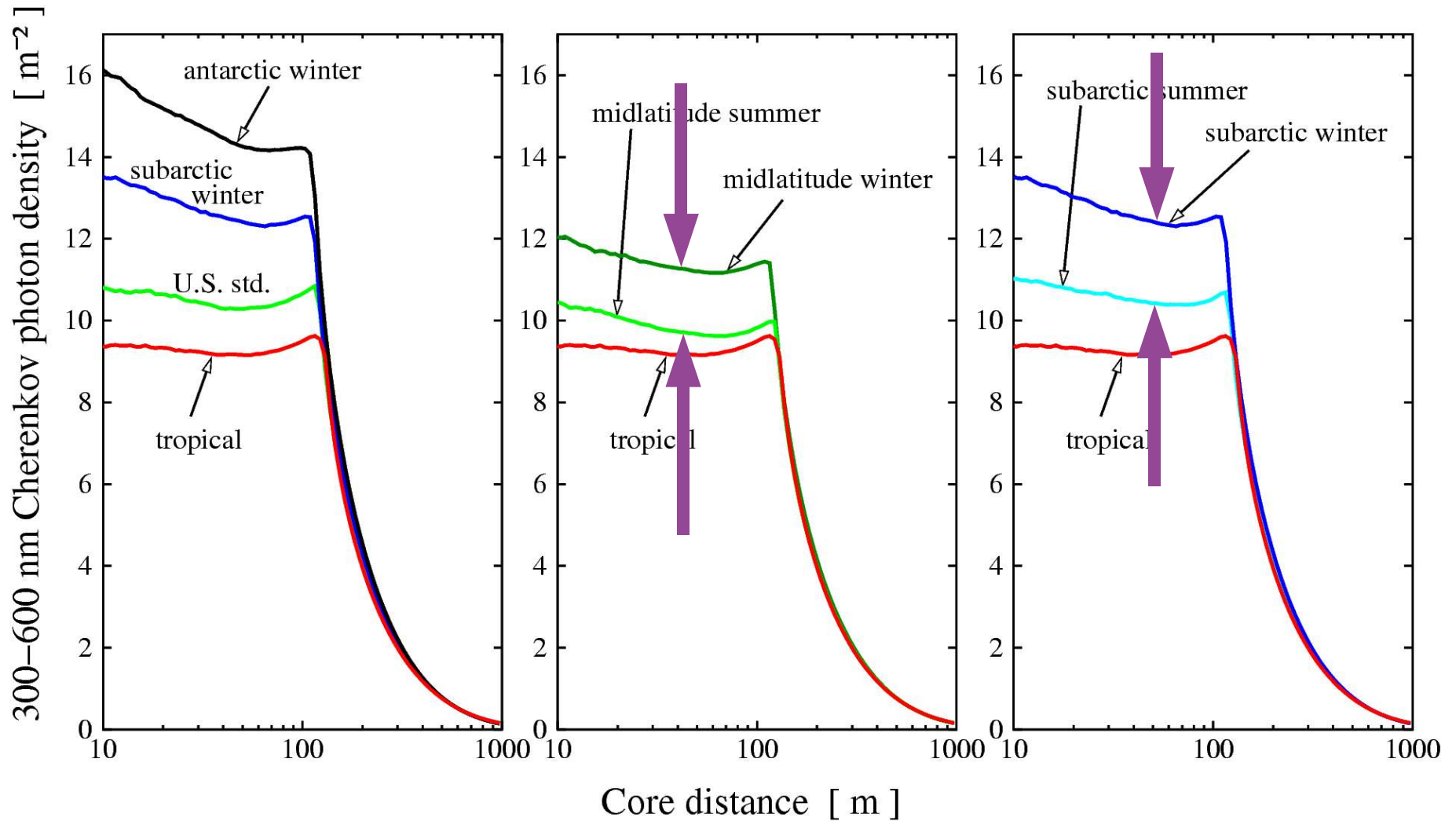


# Impact of atmospheric profiles



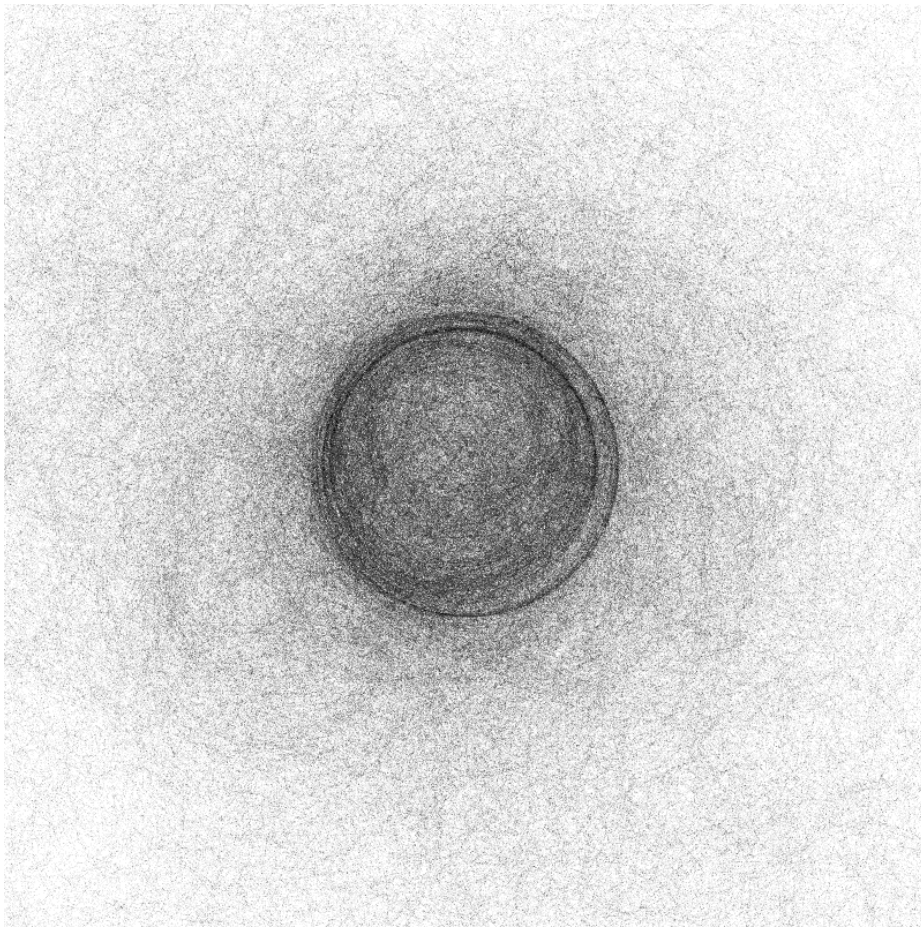


# Impact of atmospheric profiles



**Seasonal variations !**

# The geomagnetic field

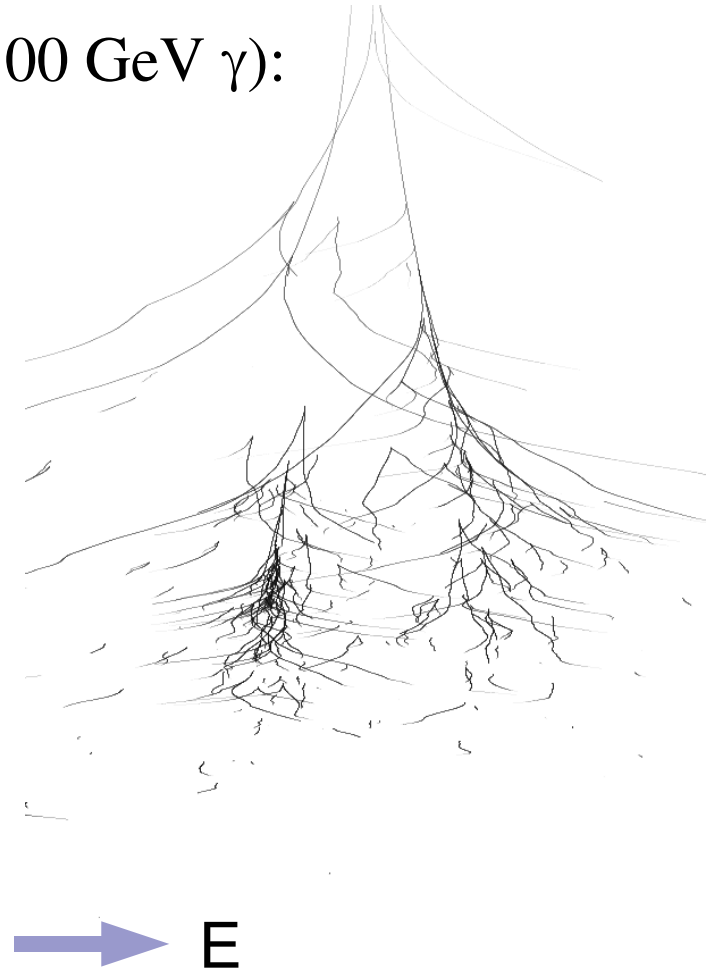
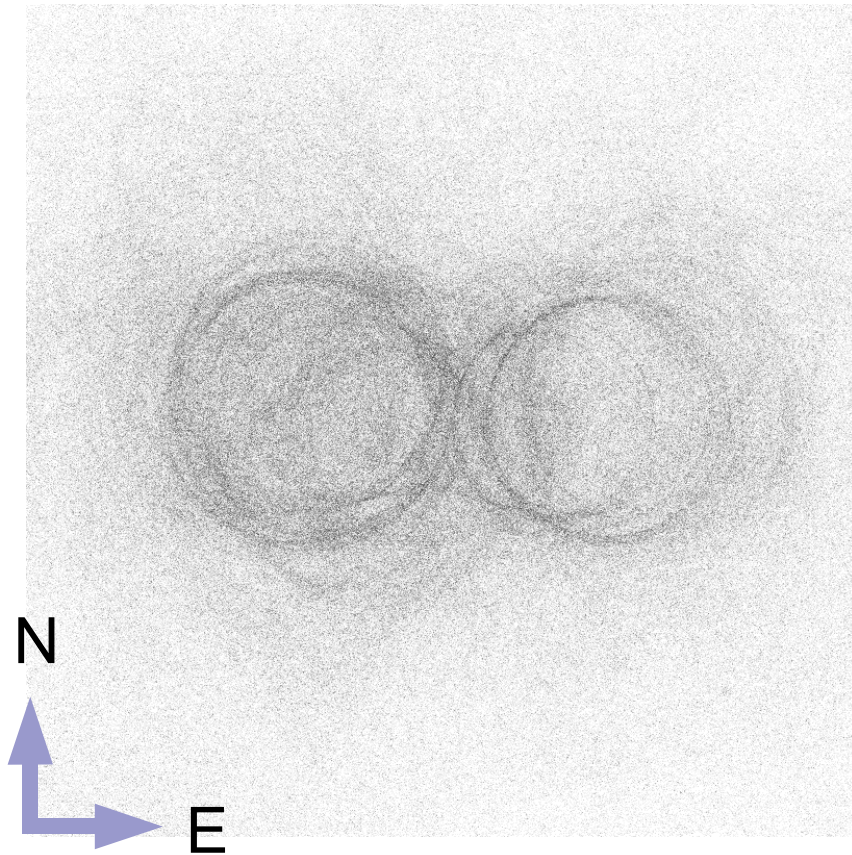


- Without geomagnetic field the  $\gamma$ -ray showers look quite symmetric (see image to the left).
- With B field there can be a large separation in East-West direction ...

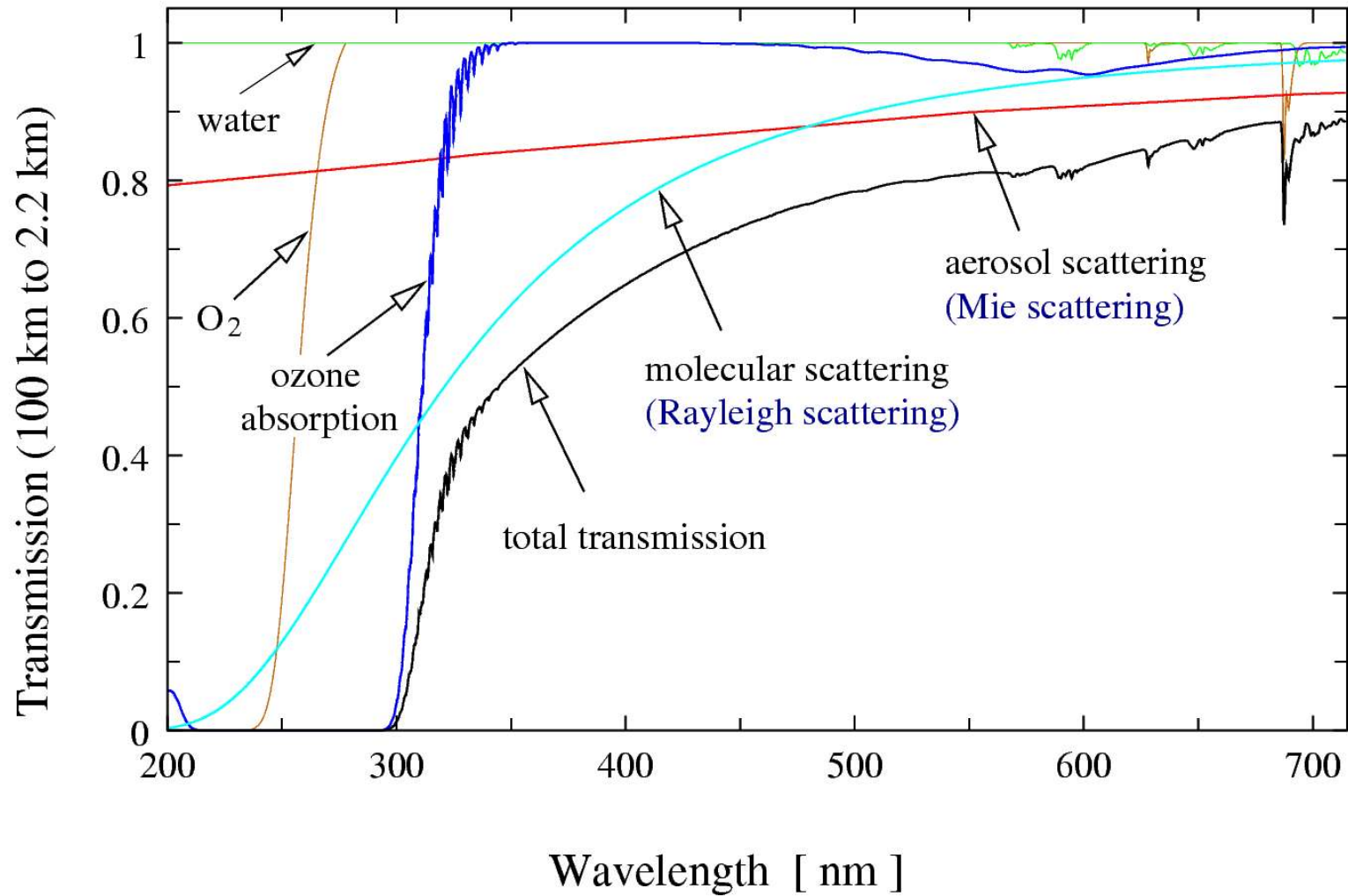


# The geomagnetic field

An untypical but not extreme example (100 GeV  $\gamma$ ):



# Atmospheric extinction

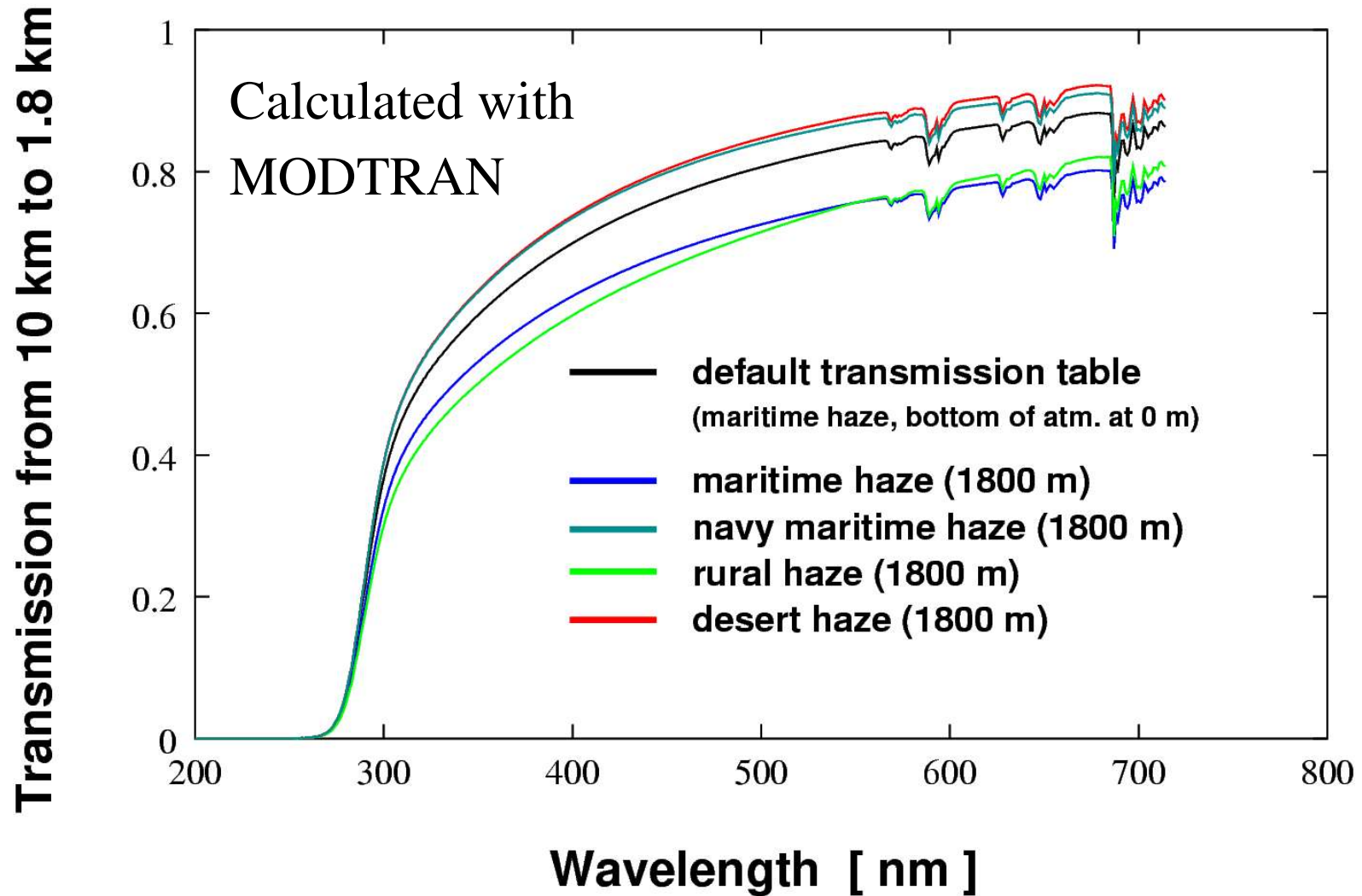




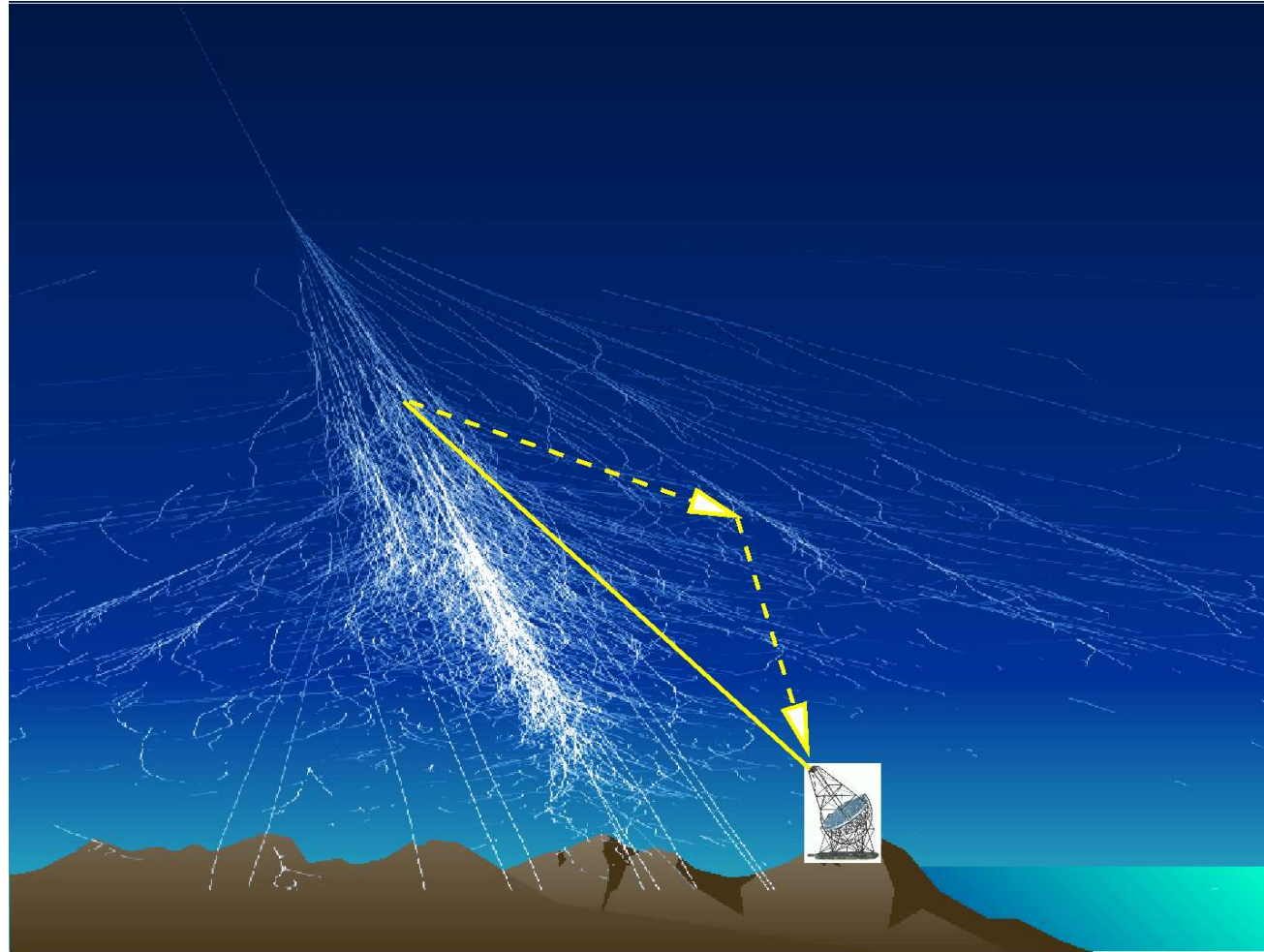
# Atmospheric extinction

- Only Rayleigh scattering and absorption on  $O_2$  are fixed by the density profile.
- All other source of extinction, in particular Mie scattering on aerosols, are site-specific and variable.
- You need to adapt this to your site.
- Best treated as part of the detector simulation.

# Aerosols: variable and site-specific

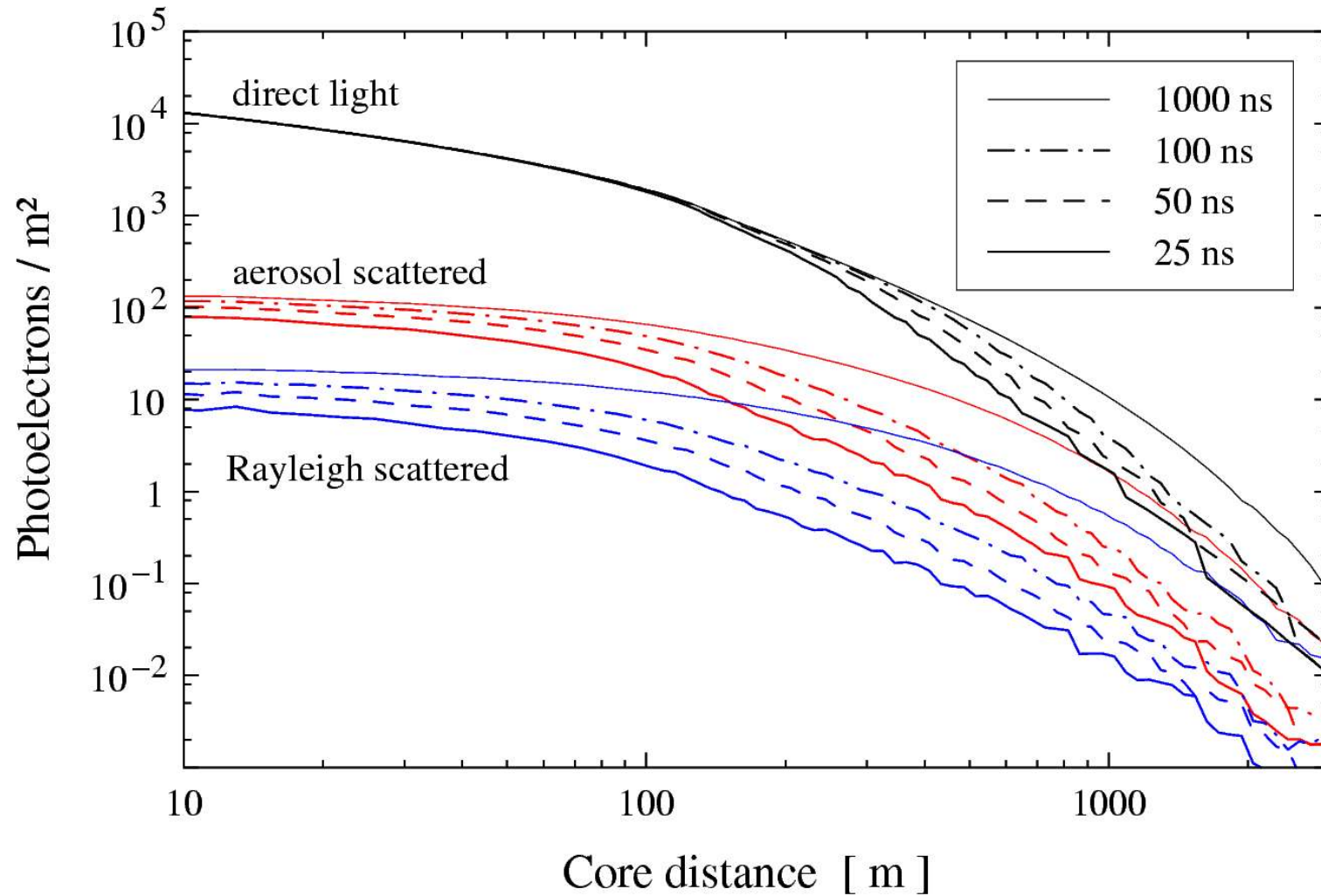


# Scattered Cherenkov light ?



Do we have to  
care about  
including  
scattered  
Cherenkov  
light in our  
simulations?

# Scattered Cherenkov light ?





# Scattered Cherenkov light ?

- With the short integration times in use in the atmospheric Cherenkov technique, the scattered light is of very little relevance.
- With the long integration time in the fluorescence technique, scattered Cherenkov light exceeds direct Cherenkov light above a few kilometers core distance.



# Summary

- Cherenkov emission in CORSIKA for efficiency reasons with
  - wavelength independent index of refraction
  - photons come in bunches (of non-integer size)
- Several options available to adapt to your needs.
- Site-specific input needed for CORSIKA and/or subsequent detector simulation (atm. profile, index of refraction, extinction).