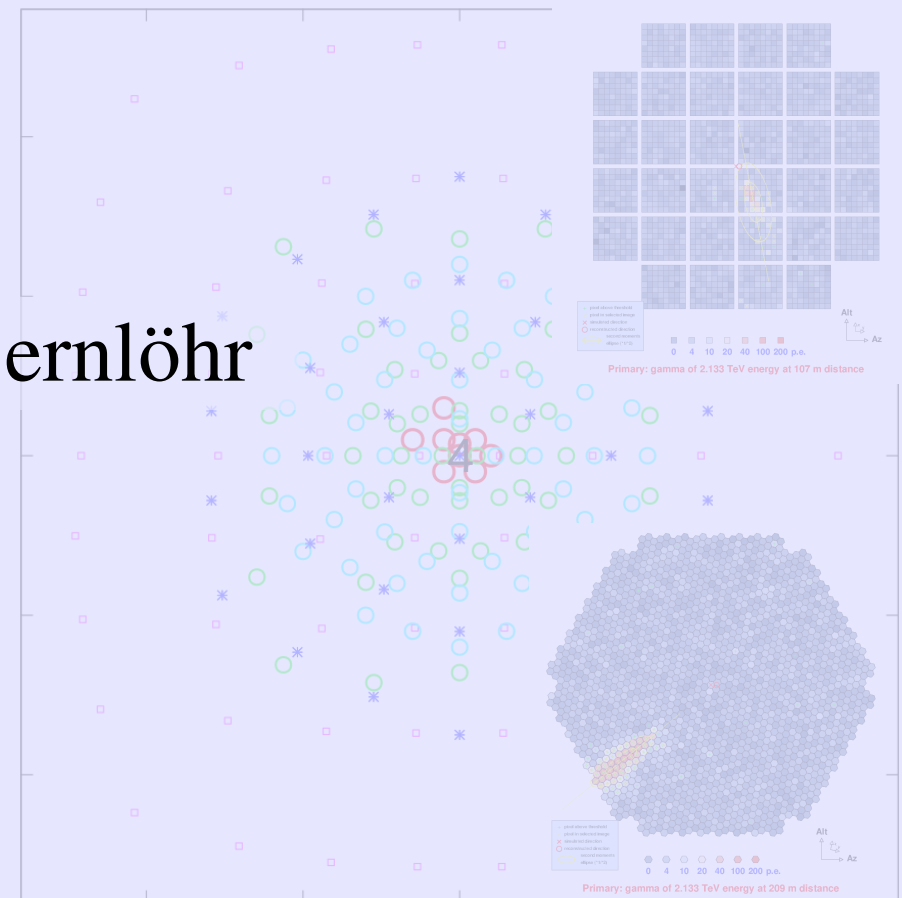


Cherenkov light production and the simulation of Imaging Atmospheric Cherenkov Telescopes

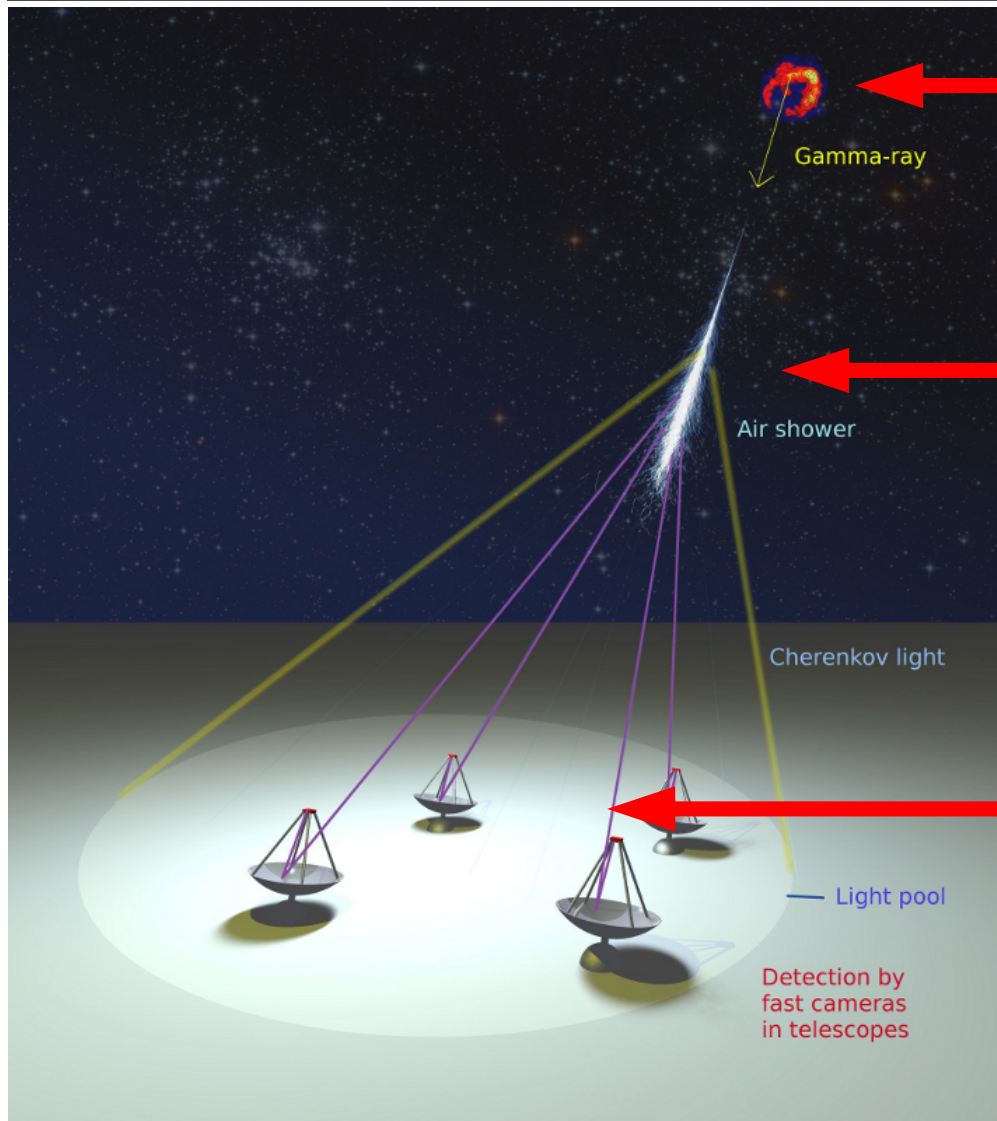


by

Konrad Bernlöhr



Simulation steps



Emission and propagation to Earth:
Astrophysics (not dealt with here).

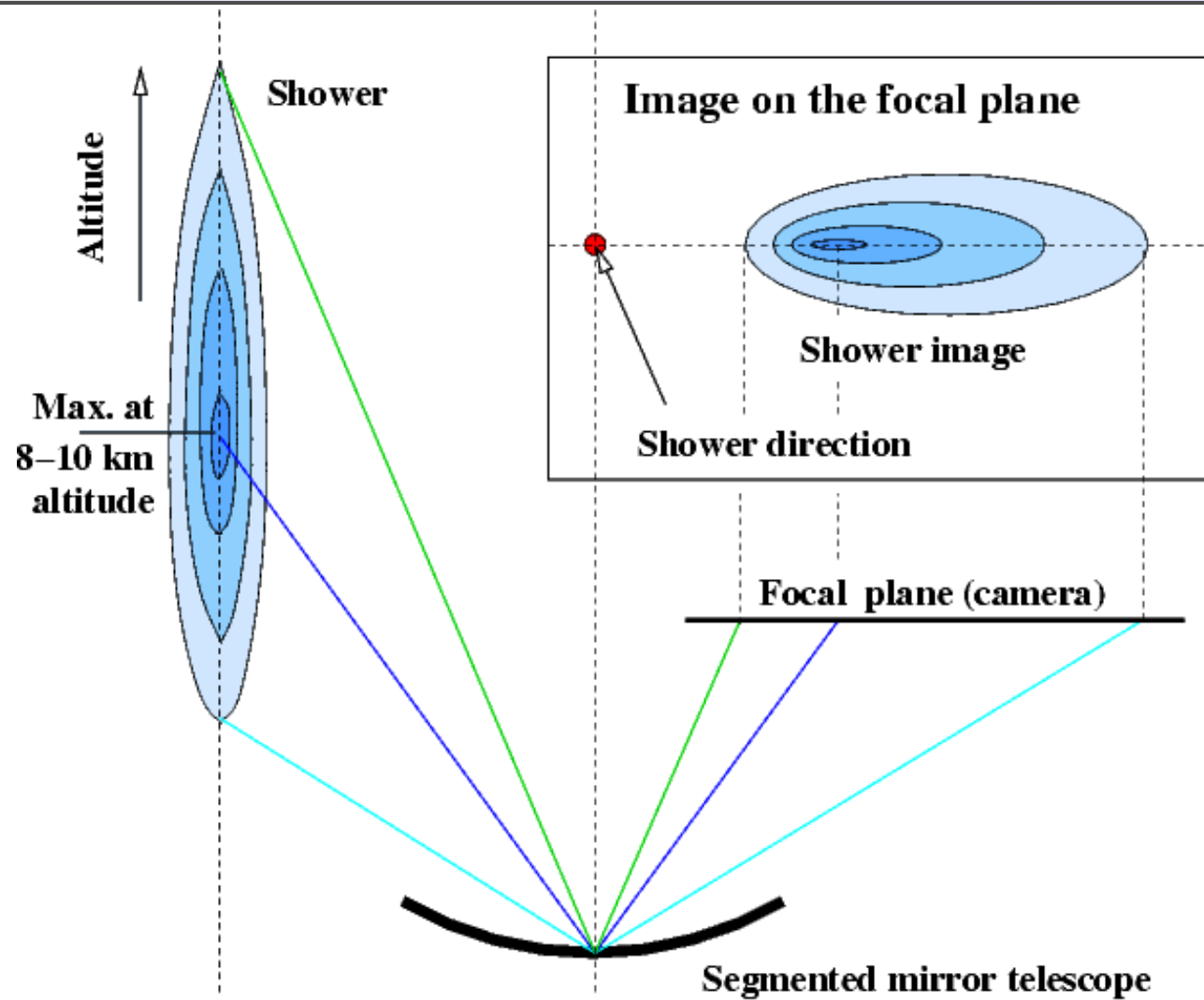
Particle cascade (“air shower”) is
normally simulated with CORSIKA,
up to light propagation to positions
of individual telescopes.

Shower simulation

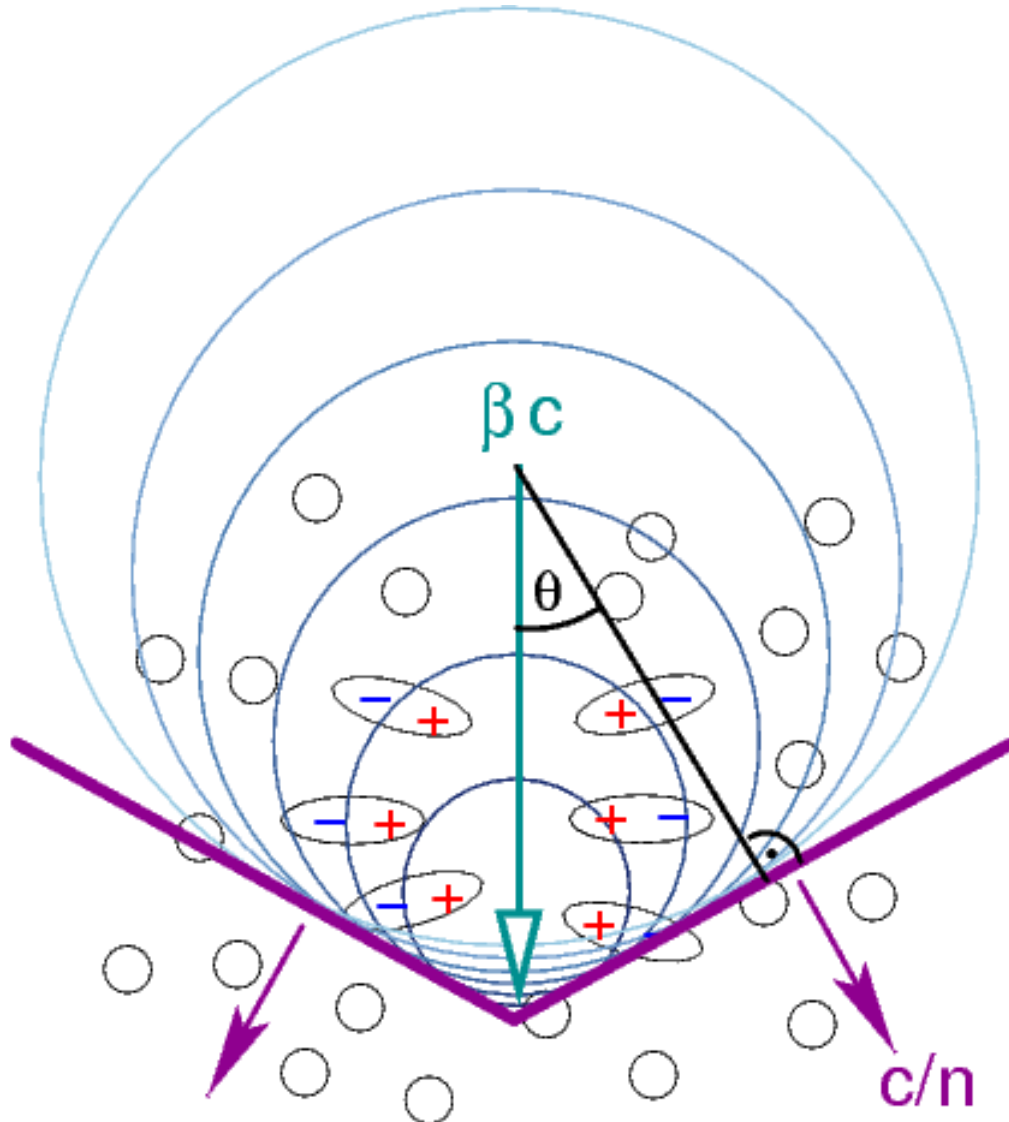
Cherenkov light atm. transmission,
optical properties of telescopes,
photon detection, nightsky background,
electronic signals, trigger decisions,
digitization of signals, ...

Telescope simulation

Imaging of showers by telescopes



Cherenkov light emission



- Dielectric medium is polarized by charged particle.
- Constructive interference only when particle of speed βc is faster the emitted radiation (c/n).
- Emission is all on a cone of half opening angle θ w.r.t. the particle direction.

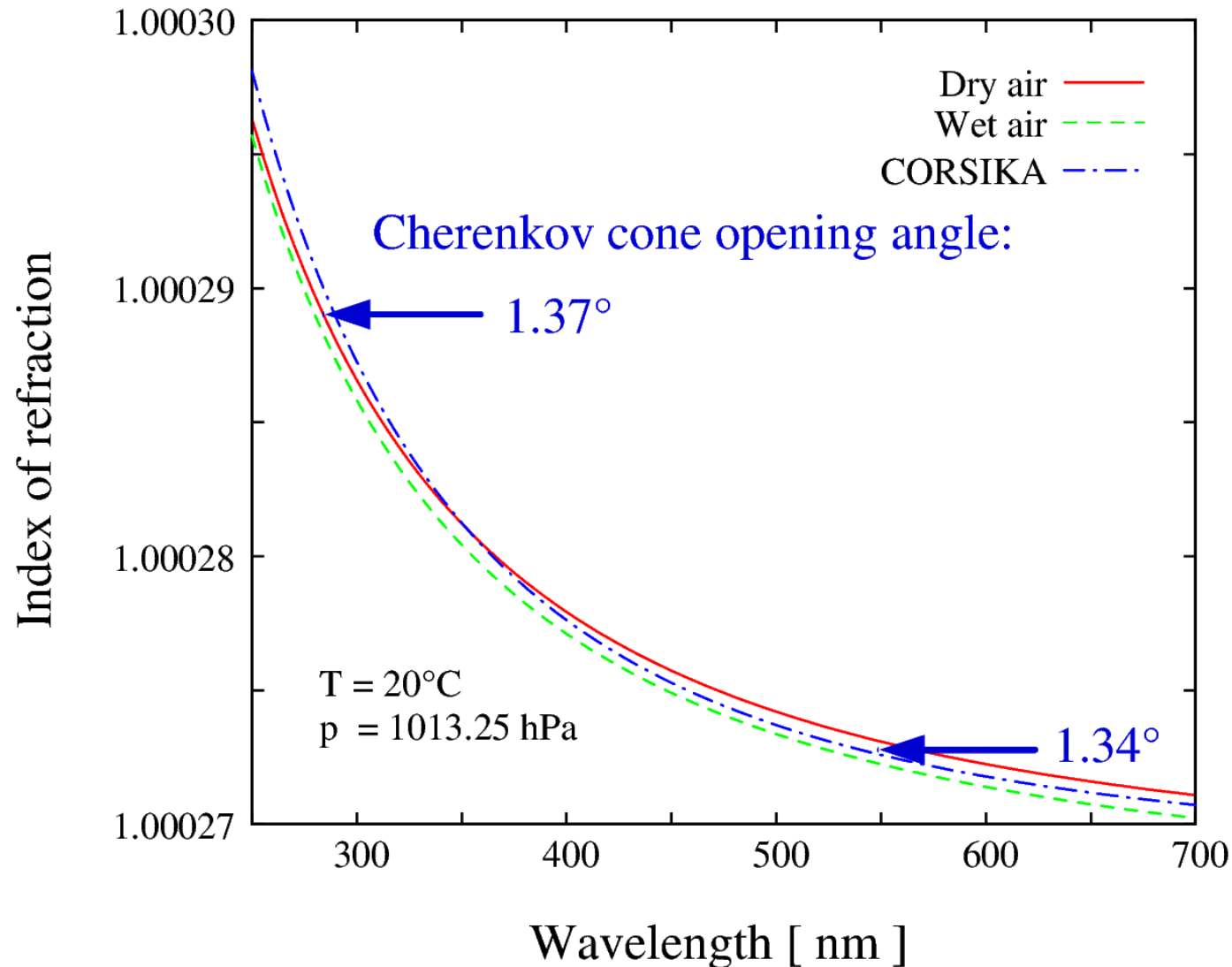
Basic formulae for Cherenkov light emission

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

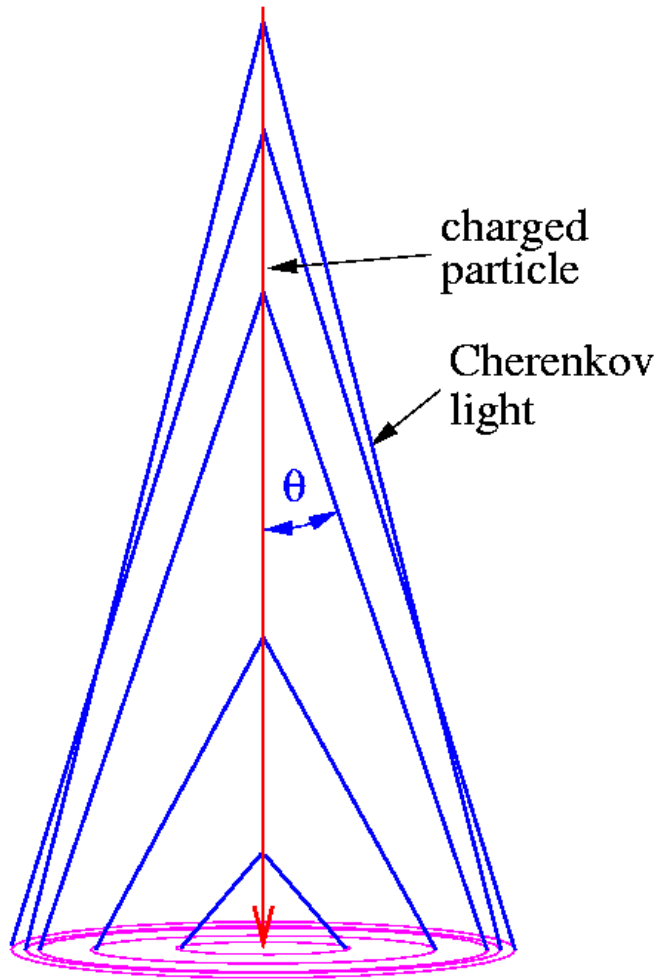
$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \sin^2 \theta \frac{d\lambda}{\lambda^2}$$

with z : charge number of particle, λ : wavelength of emitted light, n : index of refraction, βc : particle velocity (with $\beta > 1/n$), θ : emission angle, α : fine structure constant ($\approx 1/137$), dN/dx : photons emitted per unit path length.

Index of refraction not constant



Emission by a single particle



$n - 1$ is proportional to air density.

The Cherenkov opening angle θ 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.

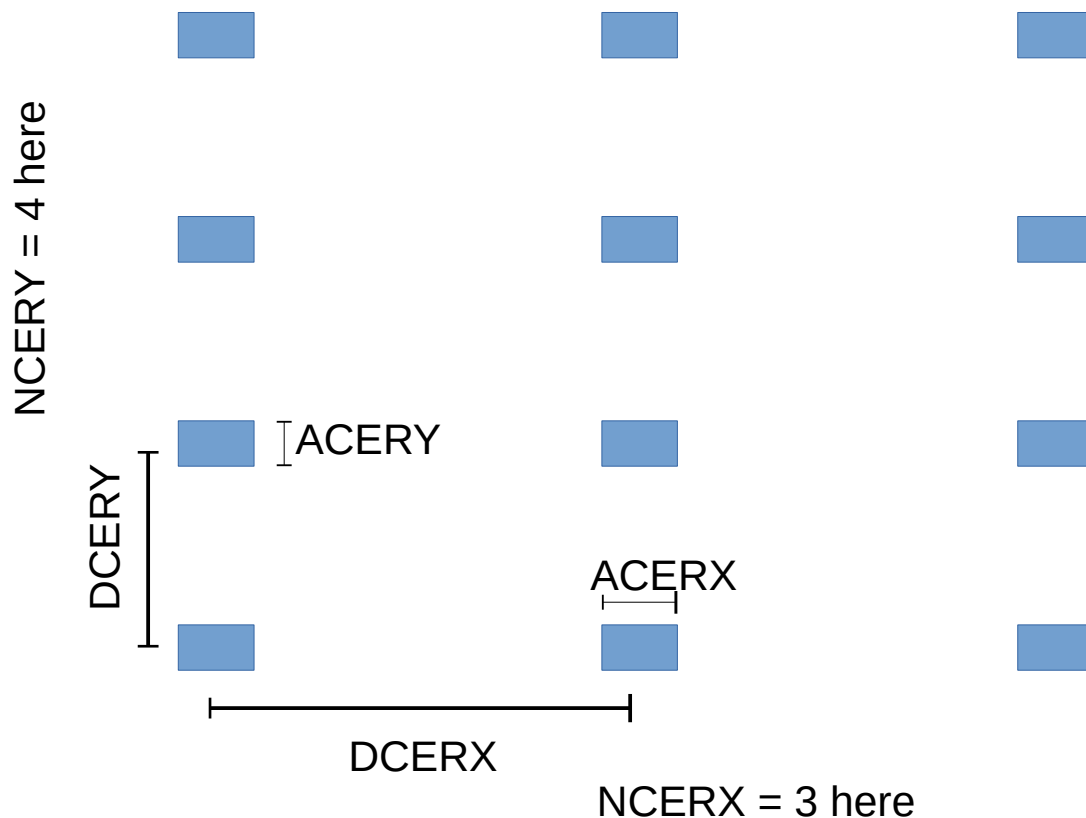
Just a few details of simulations

- Particle losing energy on each track segment:
 - Could start above threshold for Cherenkov emission and then fall below.
- Particle moving down into denser air (larger n):
 - Could start below threshold and then go above threshold.
- With wavelength dependence (CERWLEN option):
 - a particle could be above threshold for blue light but below threshold for red light.
- Trying to handle this efficiently ...

Speaking of efficiency ...

- A single singly-charged vertical particle could emit up to half a million photons.
A gamma shower of 100 TeV may result in more than 100 billion photons.
- You do not want to store them all, one by one, and you cannot handle them all in memory.
- Tracking photons down to detector level and storing only those hitting the detector.
- Not storing them one by one but in ‘bunches’.

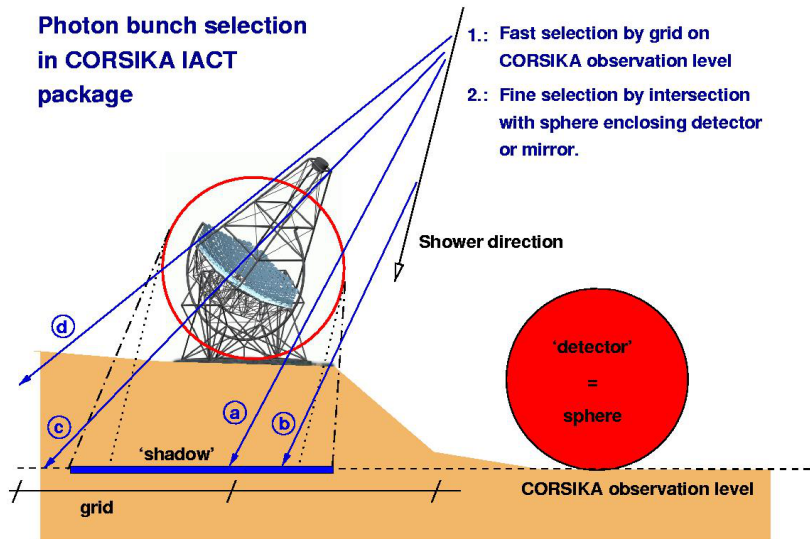
At detector level (without IACT)



- Rectangular flat grid of rectangular detectors.
- Defined by inputs CERARY parameters for number, spacing, and size of detectors in x and y directions.
- Output data for Cherenkov photons is (like for particles) in a machine- and compiler-dependent format.

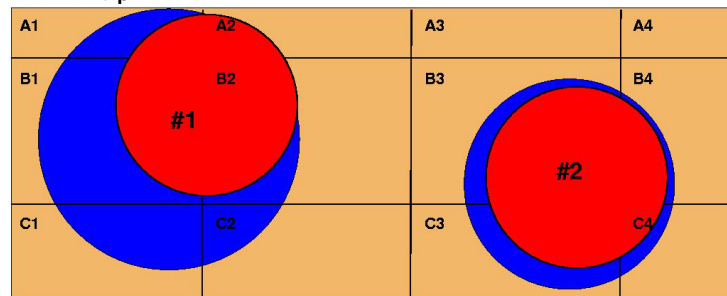
Originally developed for HEGRA AIROBIC array on La Palma

At detector level (with IACT option)



- 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

- A detector is defined by its fiducial sphere – e.g. for a telescope the reflector should fit into the sphere.
- Defined by x, y, z w.r.t. observation level and radius r .
- Up to 999 detectors. Showers used multiple times with random offsets.
- Observation level plane sub-divided into grid cells. Intersection with only those spheres registered for the grid cell hit by a photon bunch.
- Photon bunch can be used multiple times with overlapping spheres.
- Output format is machine- and compiler independent ('eventio').

Photon bunches

- Not every photon will be detected due to reflection losses, quantum efficiency, ...
- For this reason, photons can be packed in ‘bunches’ (of typically non-integer size).
- Saves CPU time for sub-dividing particle track segments and emission of photons.
- Bunch size should be adjusted such that bunches of photons of identical direction, emission time (and wavelength in case of CERWLEN / CEFFIC options) do not enhance image fluctuations (aim: $N_B \varepsilon \lesssim 0.5$).

What if bunch size is too large?

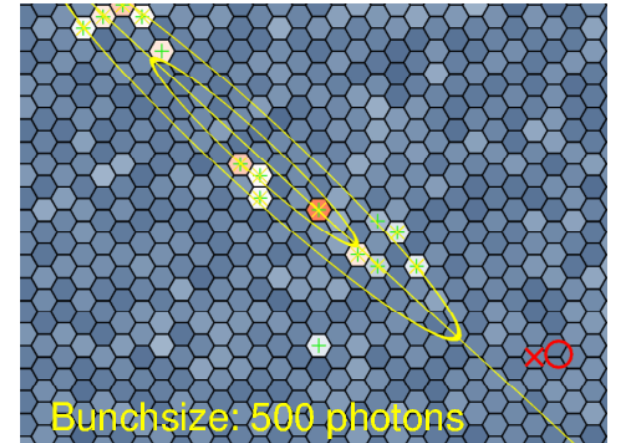
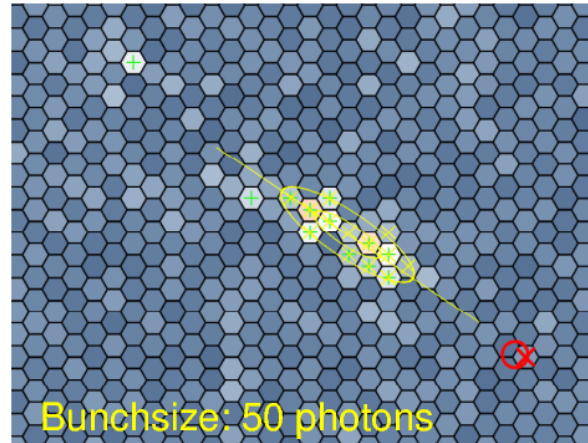
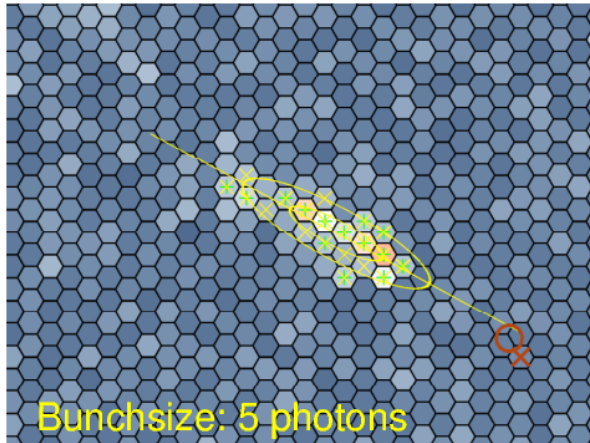
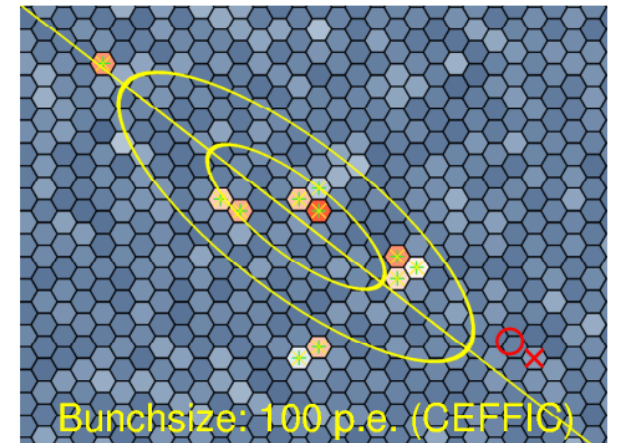
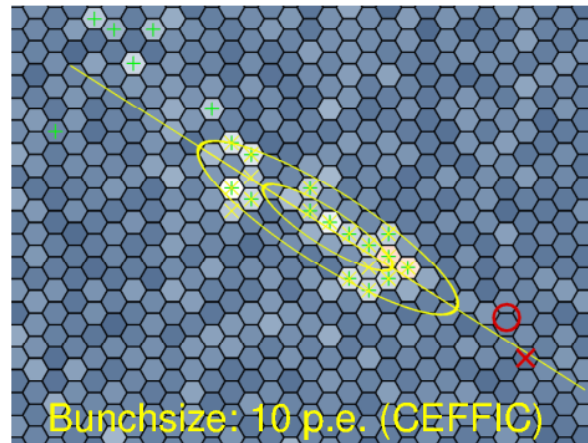
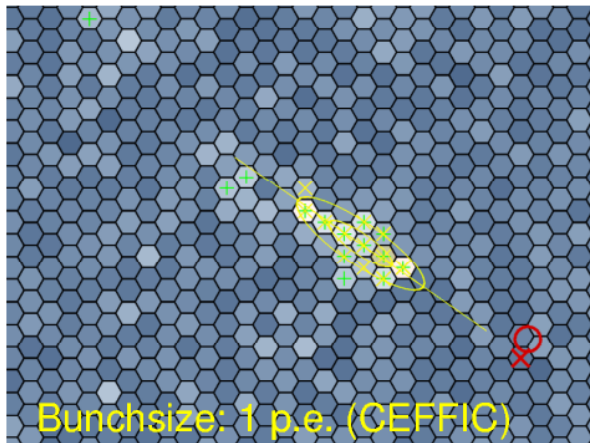


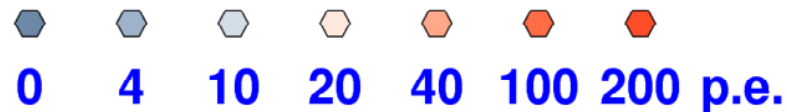
Image quality: good

poor

unusable



Part of the focal plane of
an IACT for the same event.



Bunch size recommendations

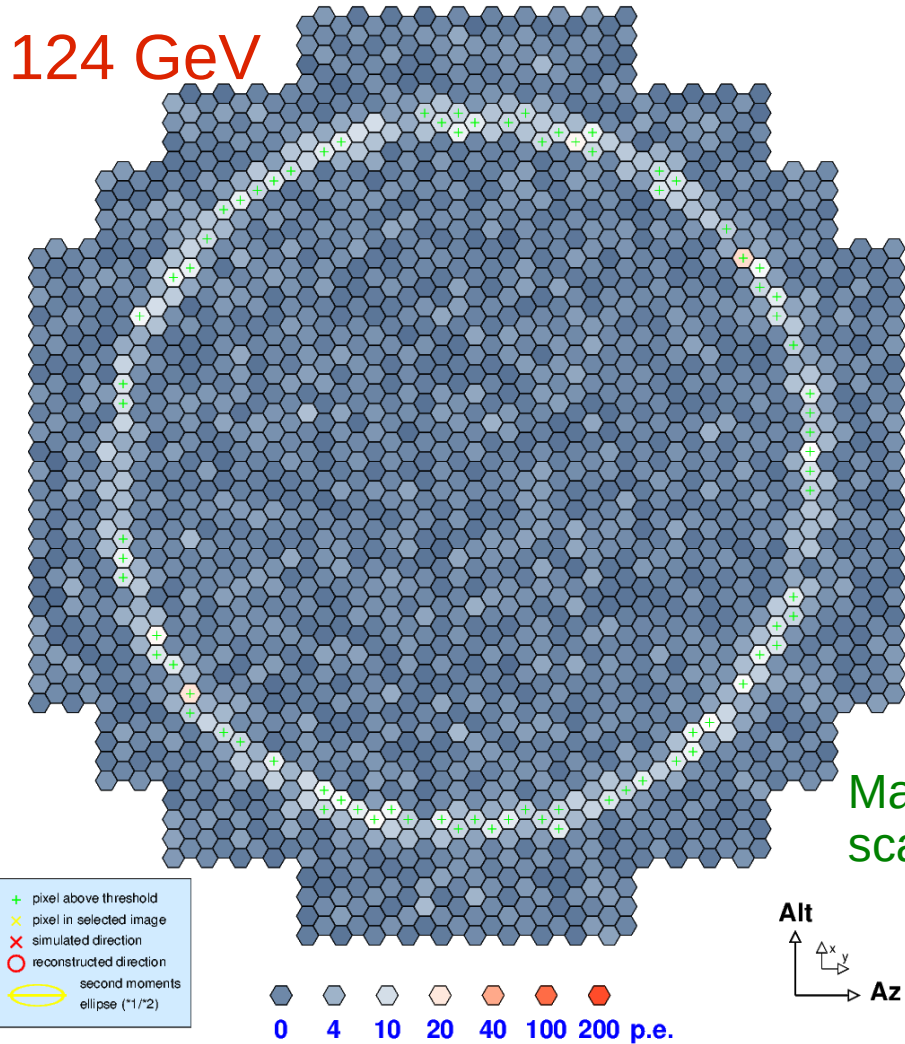
- Since Imaging Atmospheric Cherenkov Telescopes (IACTs) are sensitive to image features at the level of a few photo-electrons (p.e.), the chances of a single bunch resulting in multiple p.e. should be small.
- With CEFFIC option (storing photo-electron bunches, thus $\varepsilon=1$): $N_B \lesssim 1$ (with binom. distrib.)
- Without CEFFIC but with CERWLEN (storing photon bunches of given λ): $N_B \varepsilon_{\max} \lesssim 0.5$
- Without CEFFIC and CERWLEN: $N_B \langle \varepsilon \rangle \lesssim 0.5$

Particle step sizes

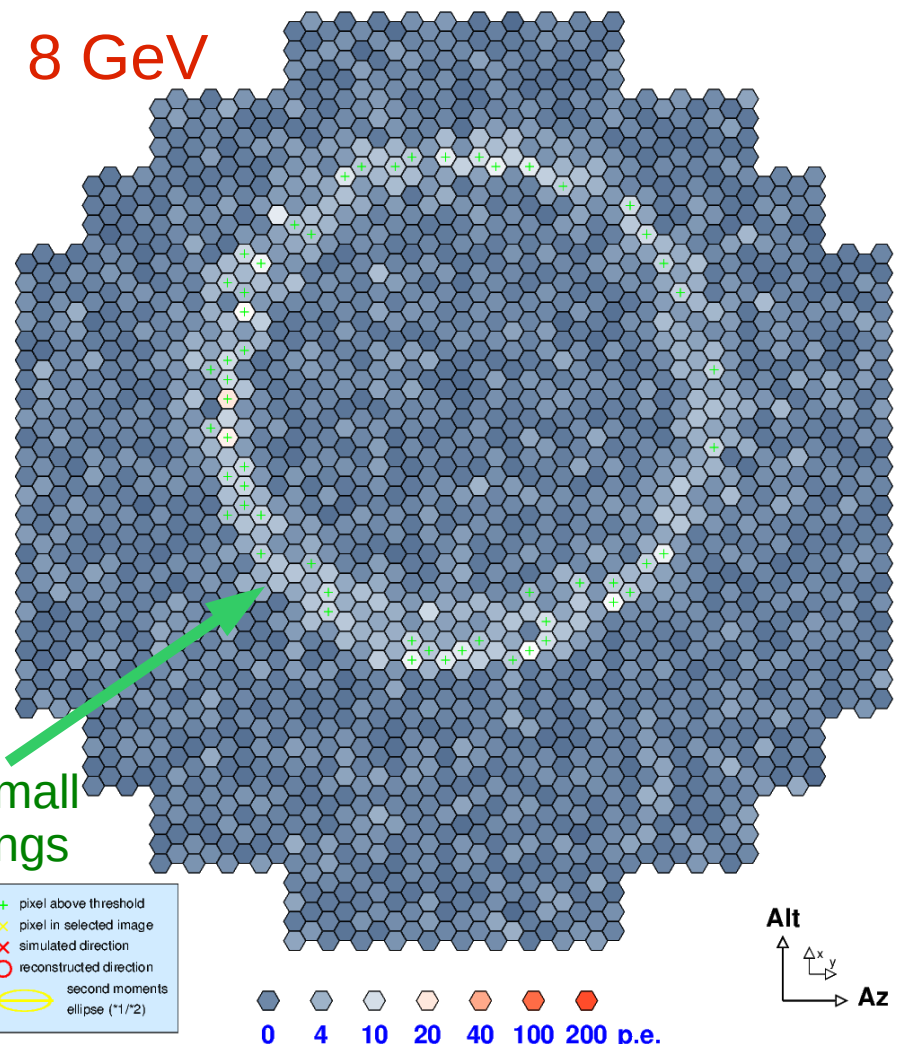
- The maximum step sizes in CORSIKA with the IACT option are smaller than without IACT because of the high angular resolution (smallest pixels: 0.06°).
- Maximum bending in geomagnetic field between two track segments must be below pixel size.
- Multiple scattering angle between track segments must be well below pixel size.
- Limits are hard-coded and thus need to be re-considered for the next telescope generation.

Multiple scattering of muons

H.E.S.S. CT5 simulation



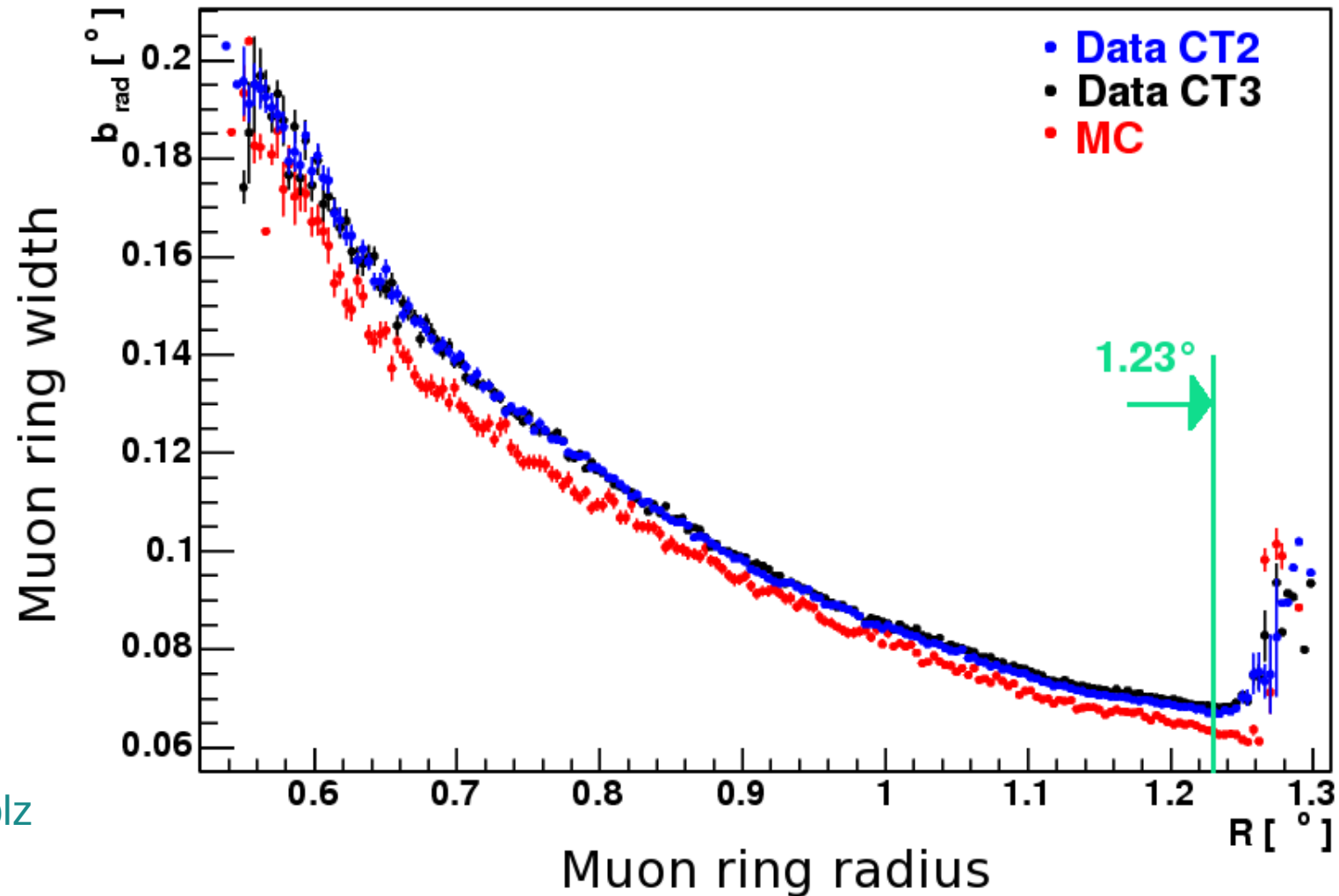
Primary: muon of 0.124 TeV energy at 2 m distance



Many small scatterings

Primary: muon of 0.008 TeV energy at 7 m distance

Muon ring width (H.E.S.S.)

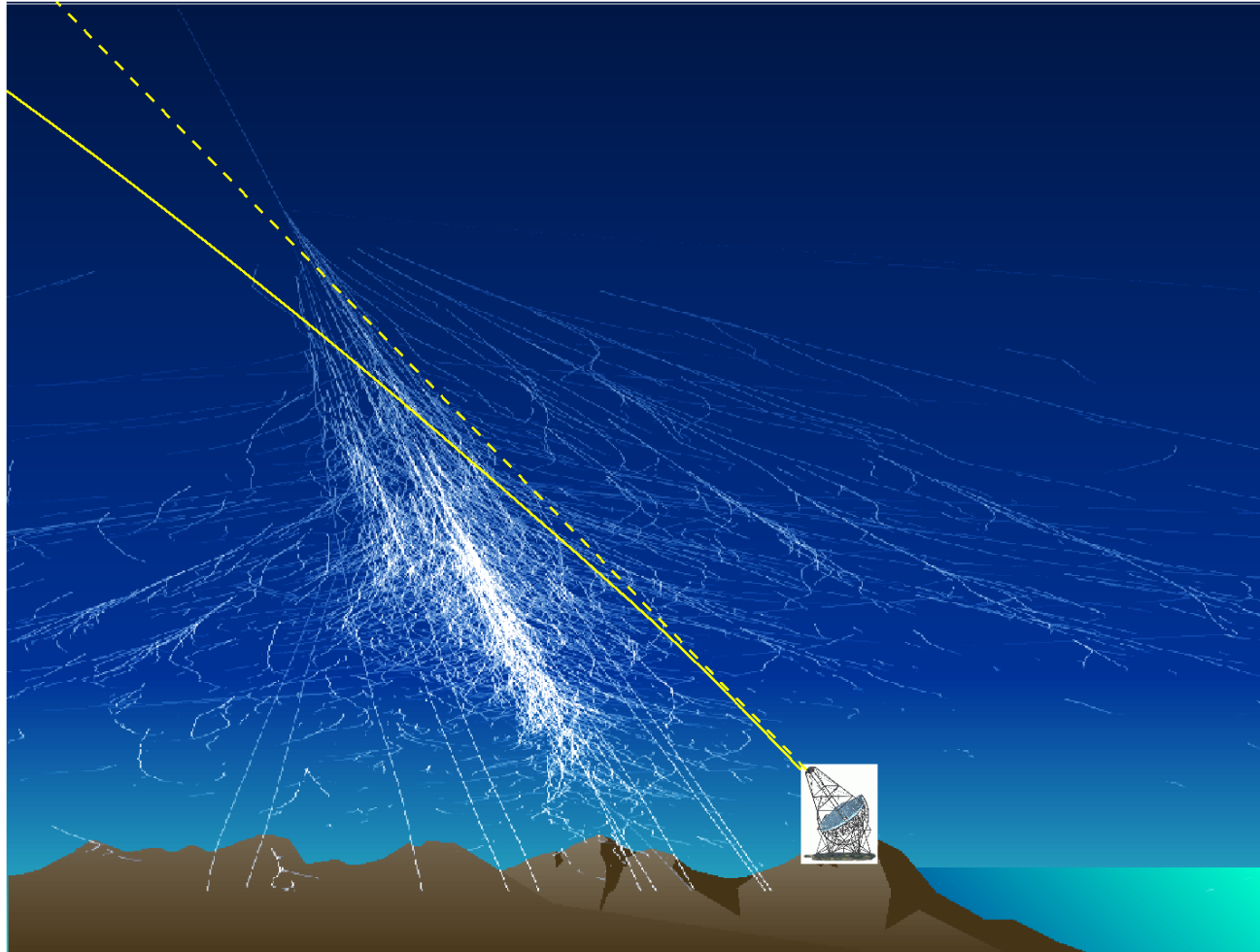


O. Bolz

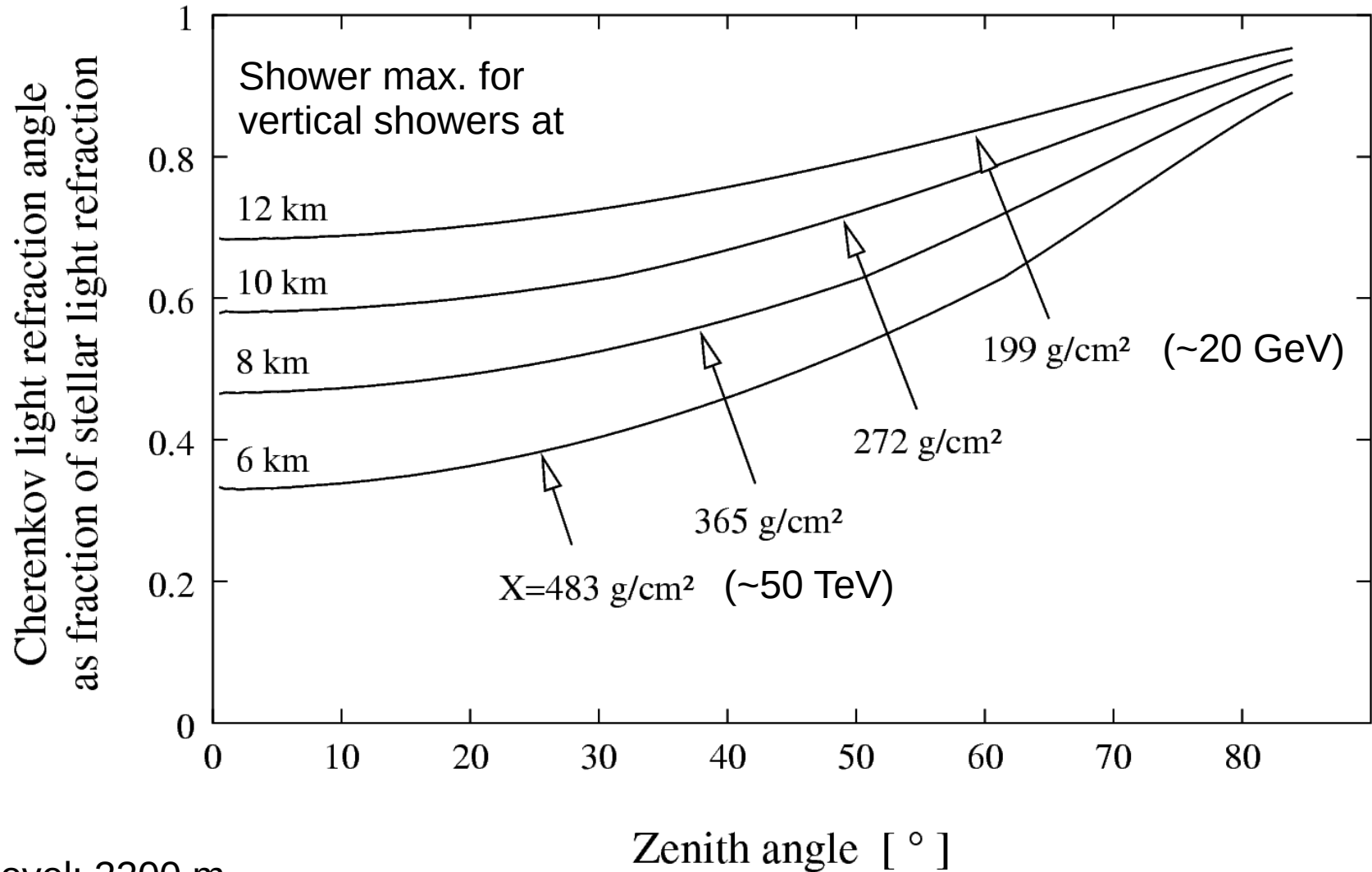
Other details for IACTs

- Due to the high angular and energy resolution of IACTs, there are also other details in CORSIKA which get relevant, for example
 - Refraction of Cherenkov light:
 - Total refraction at 45° zenith angle: up to one arc minute.
 - Source position accuracy with IACTs: a few arc seconds.
 - Details of atmospheric profiles:
 - Actual profiles are not exponential but CORSIKA still approximates the atmosphere with only four exponentials (+lin.) for electrons & gammas (all particles with CURVED).
 - Artifacts even seen with 40 steps tabulated atmospheres.

Atmospheric refraction

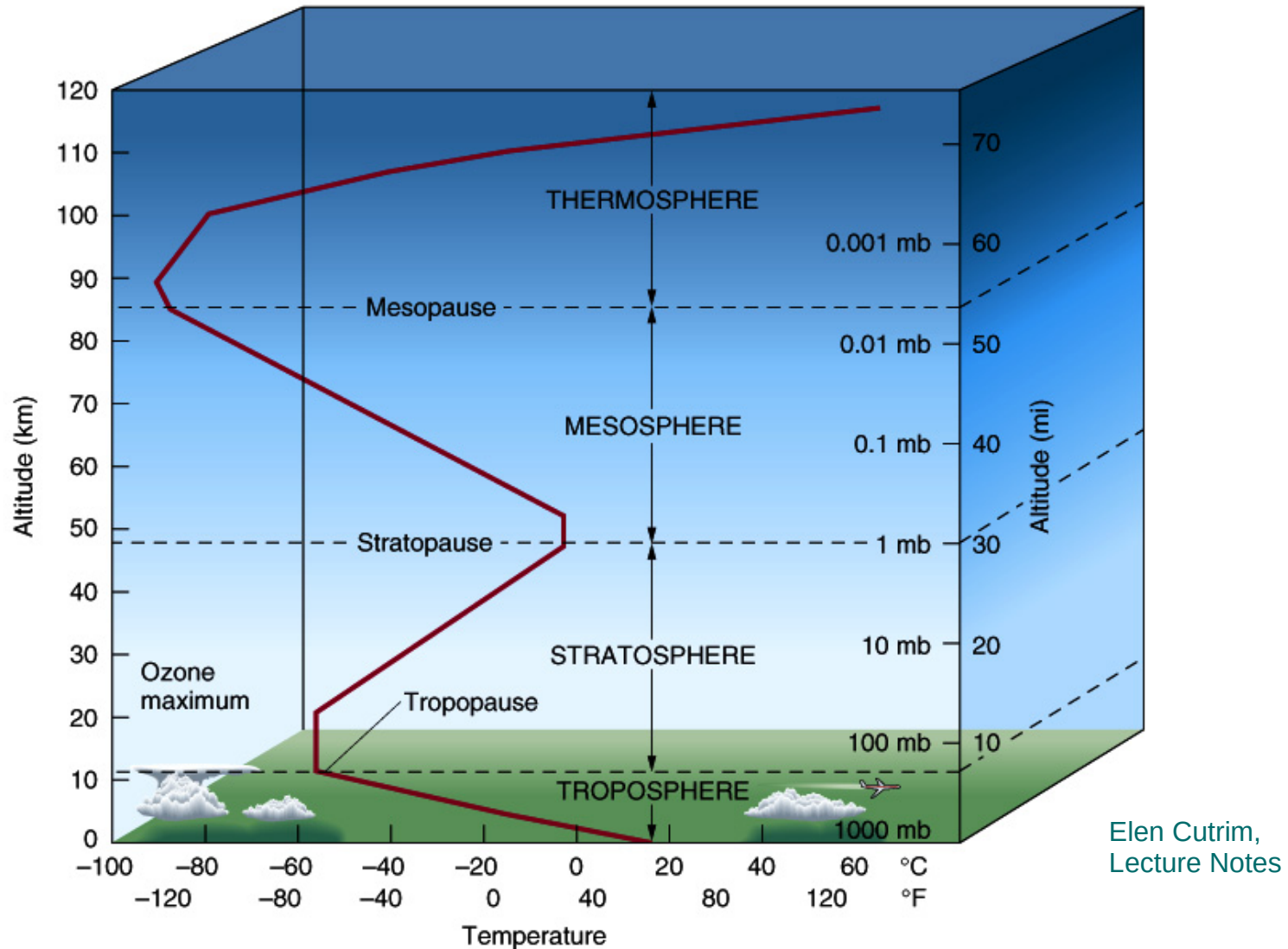


Atmospheric refraction

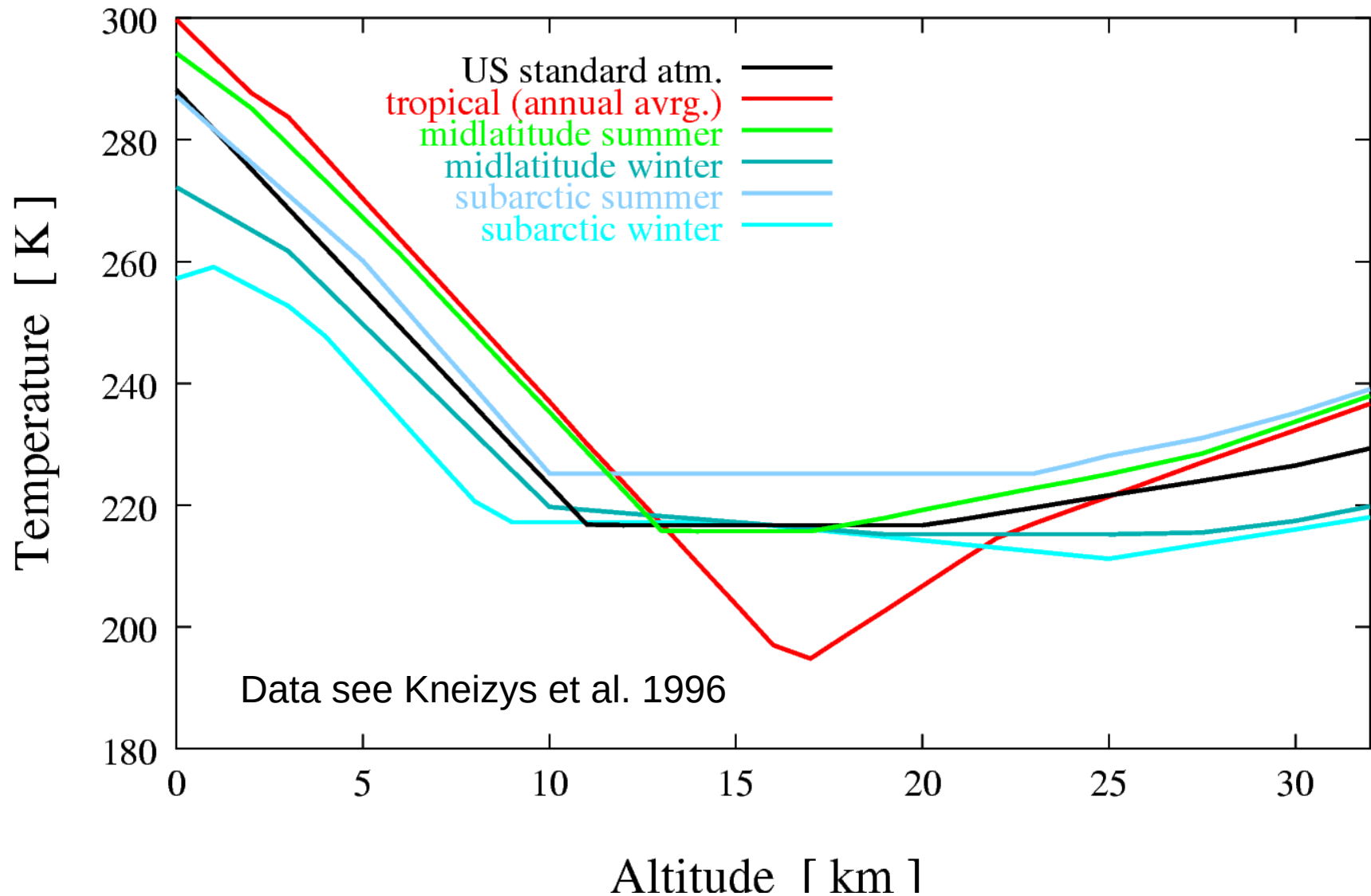


Obs. level: 2200 m

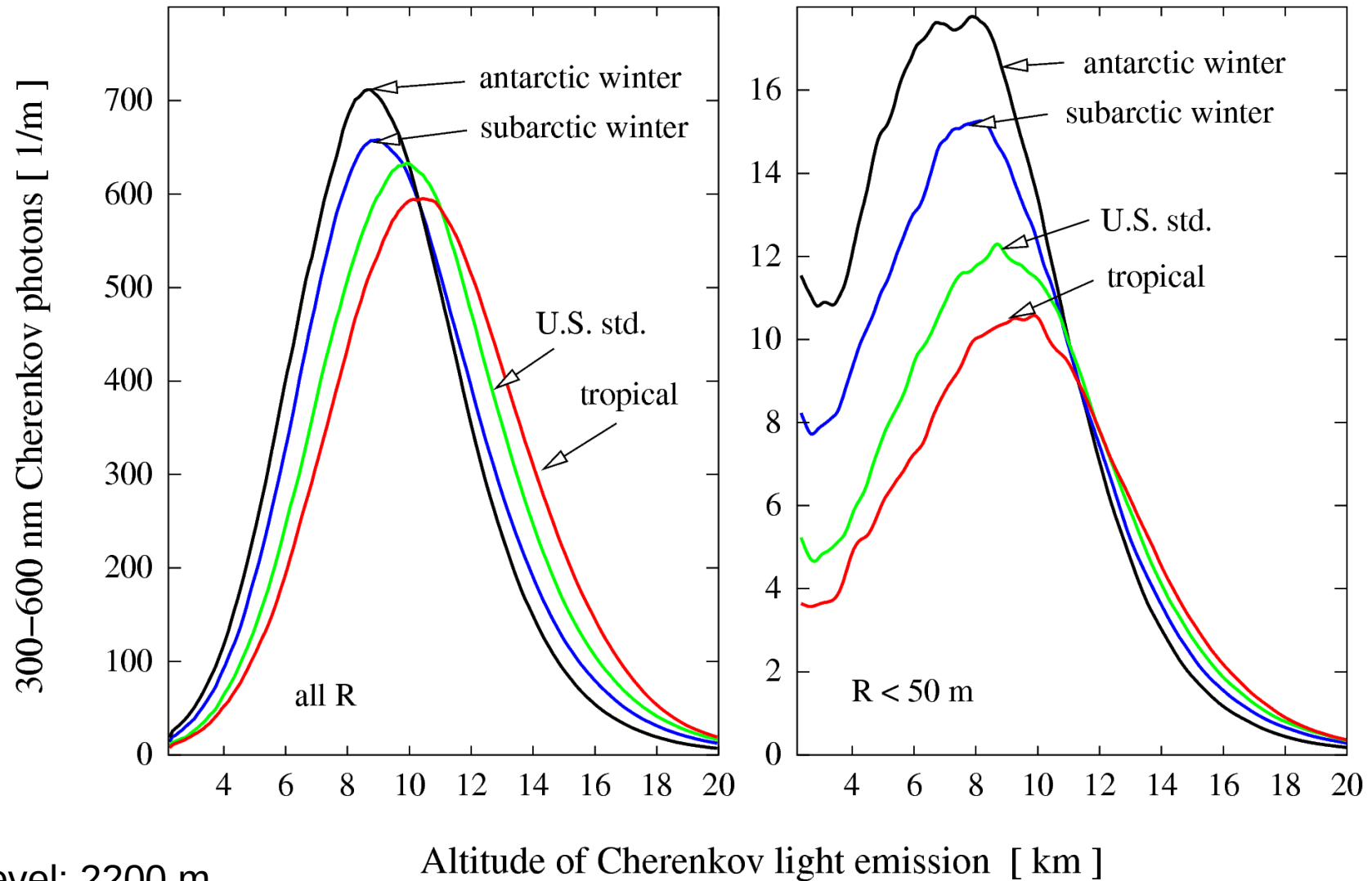
Atmospheric profiles



Atmospheric profiles



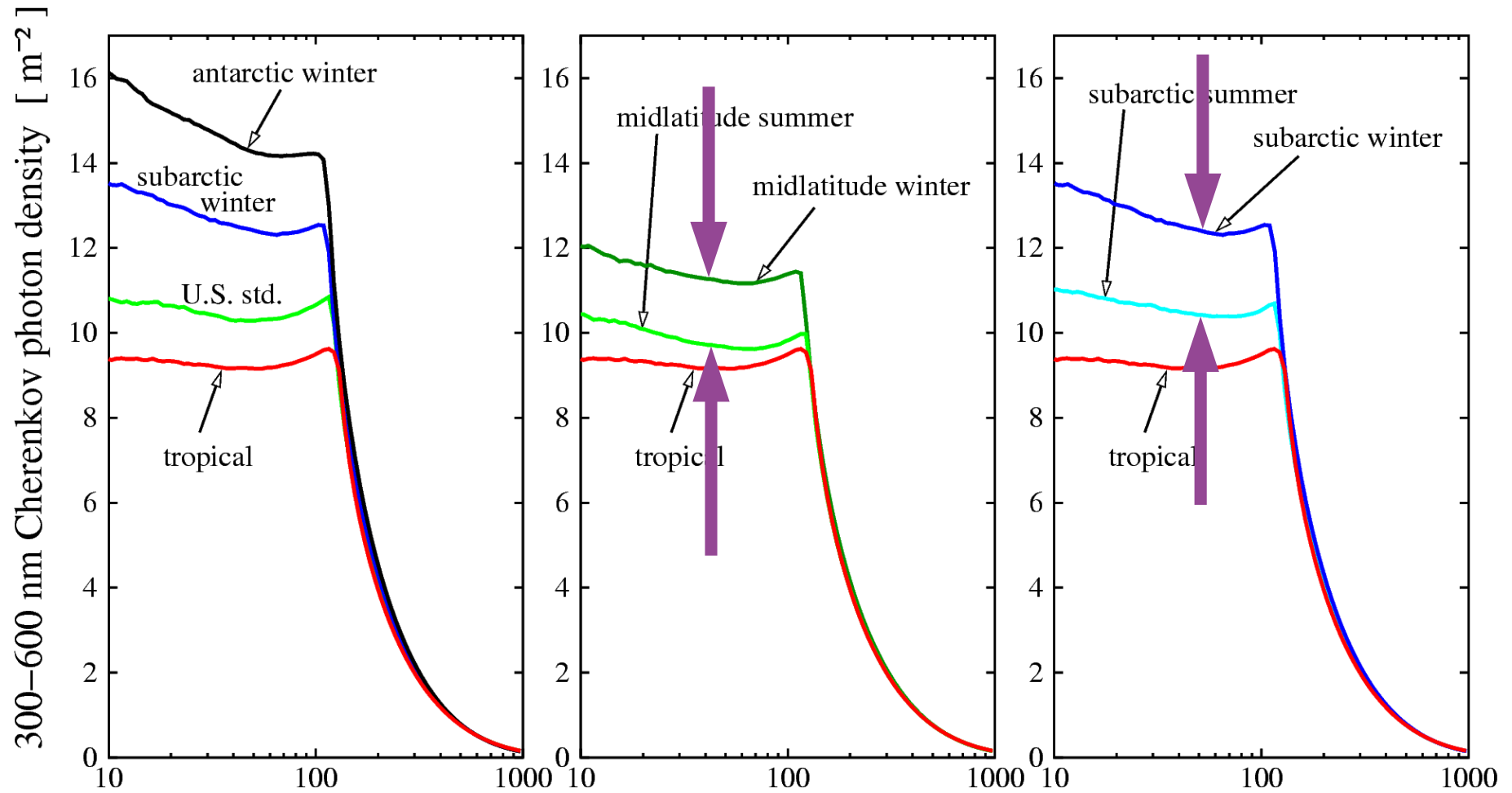
Impact of atmospheric profiles



Obs. level: 2200 m

Impact of atmospheric profiles

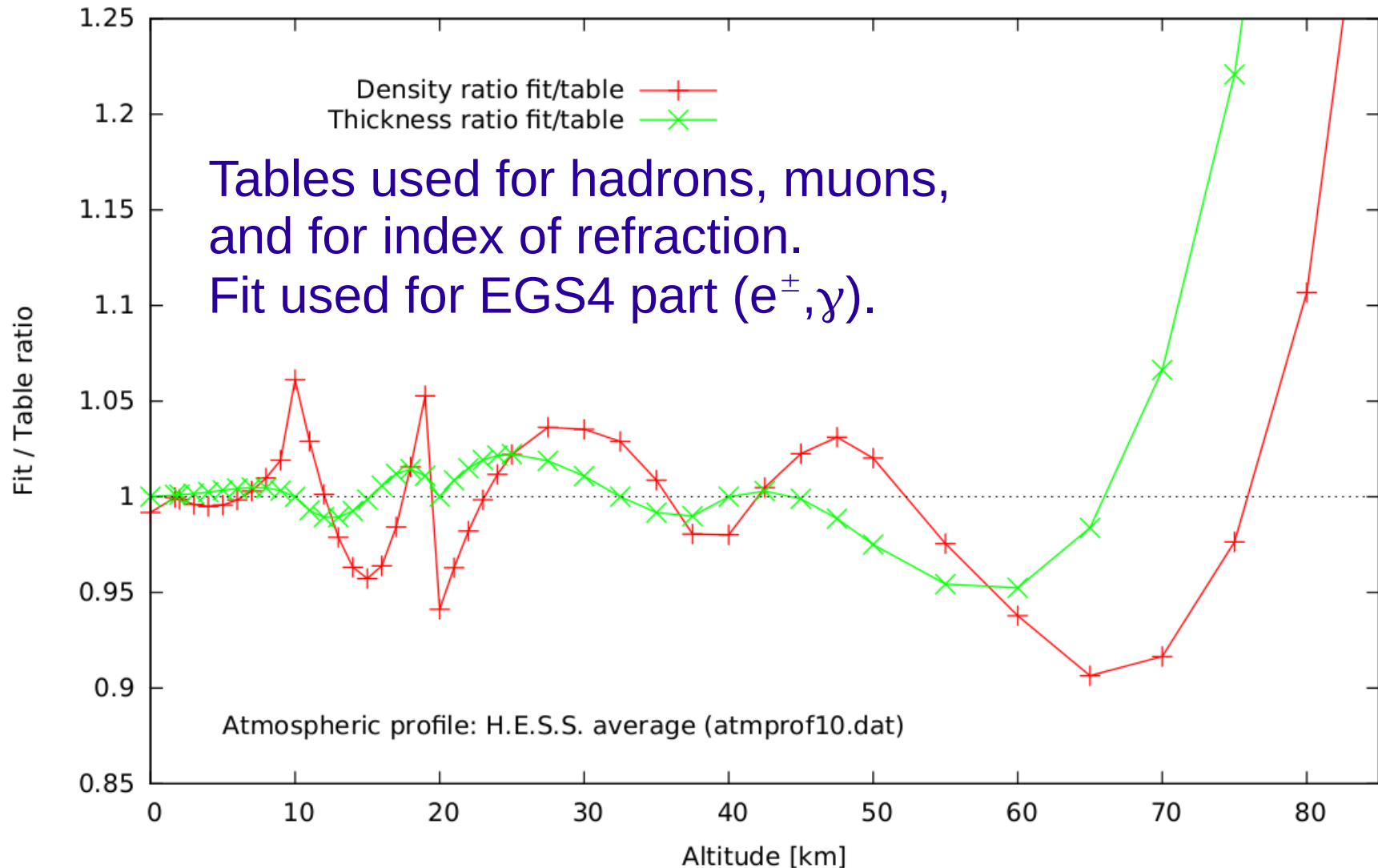
Seasonal variations !



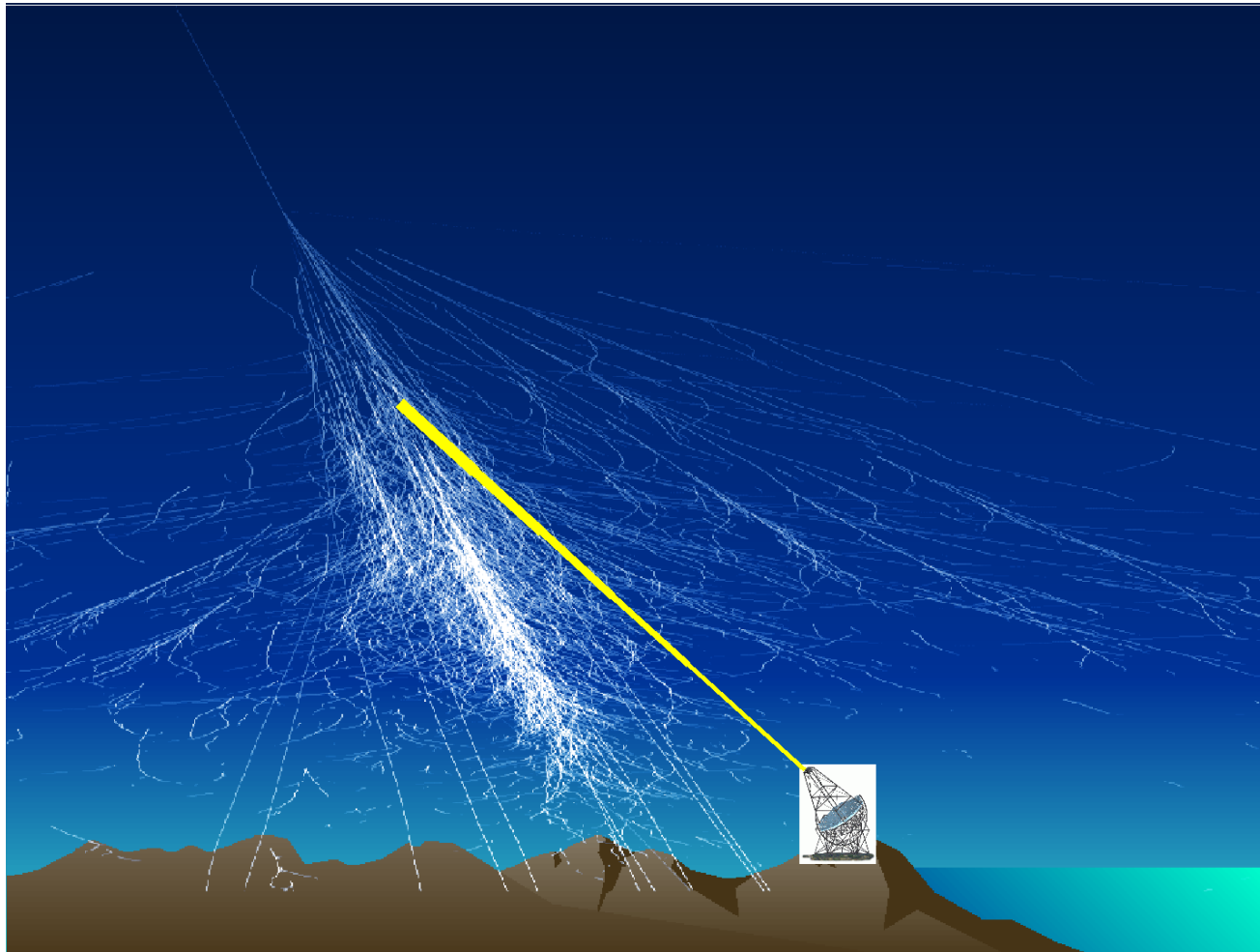
Obs. level: 2200 m

Core distance [m]

Fit to tabulated atmospheric profiles



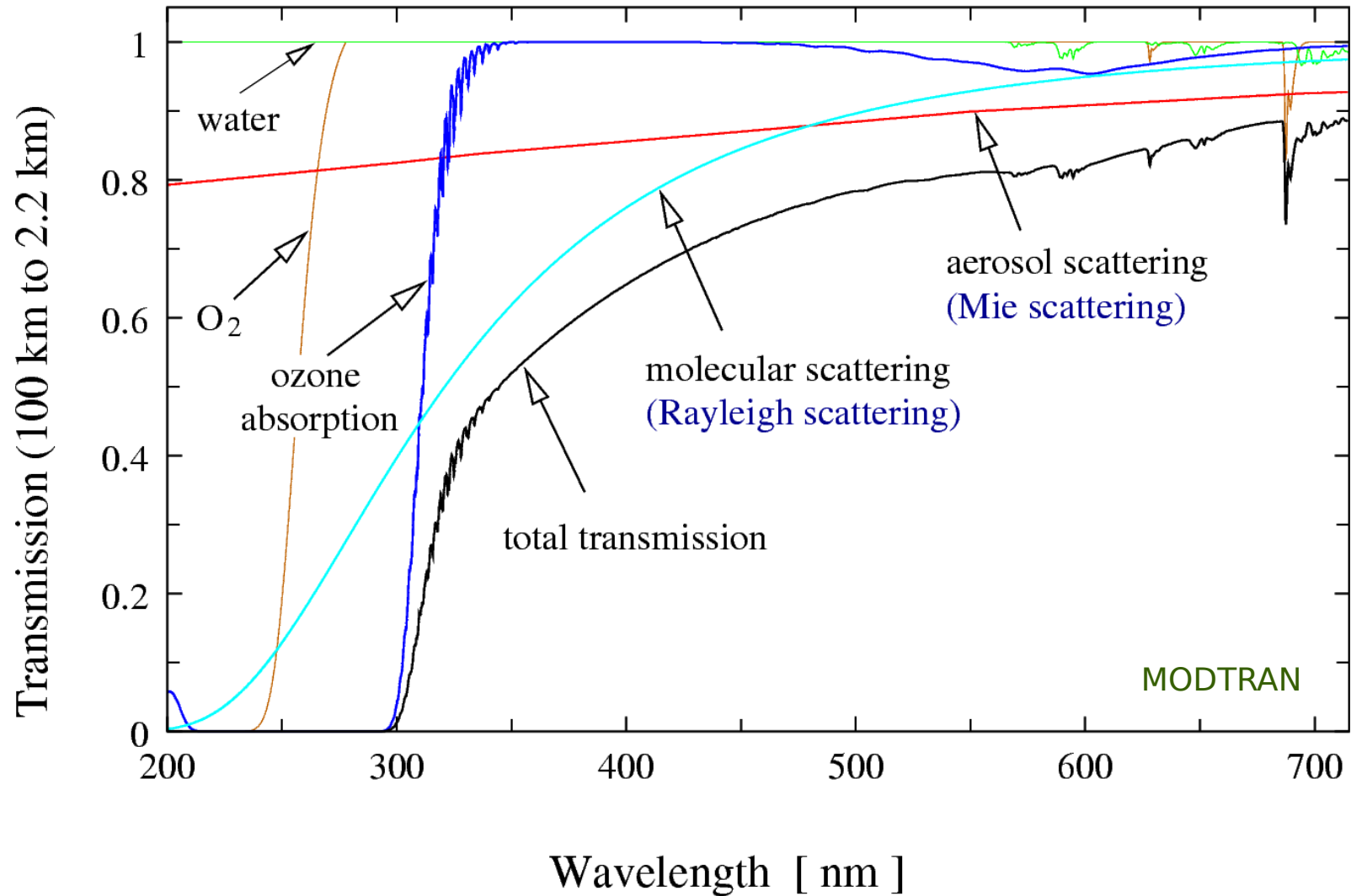
Extinction of Cherenkov light



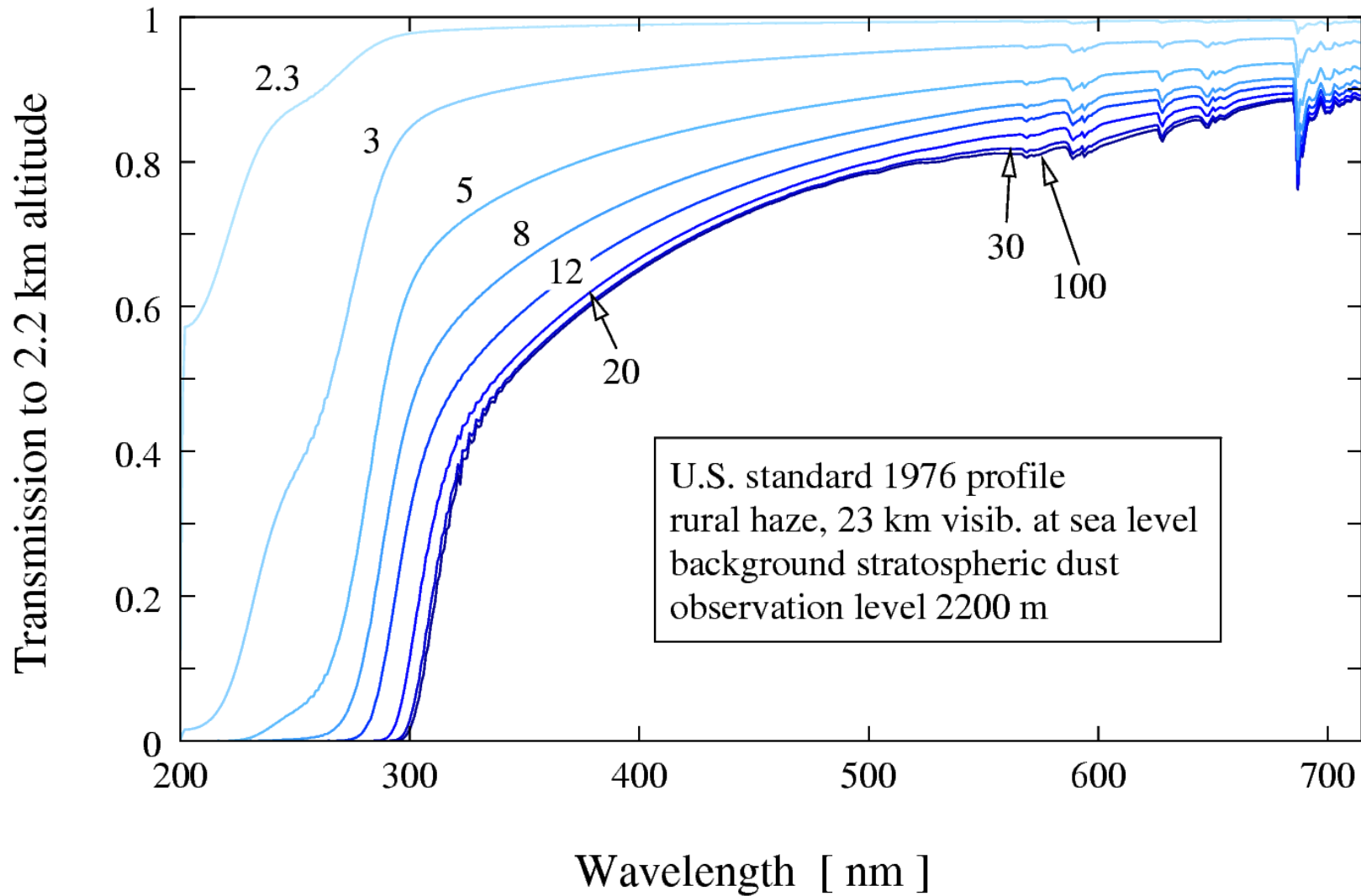
Extinction processes

- Scattering:
 - Rayleigh (molecular) scattering
 - Mie (aerosol) scattering and absorption
- Absorption by molecules:
 - Ozone
 - Oxygen
 - Water vapour

Extinction processes



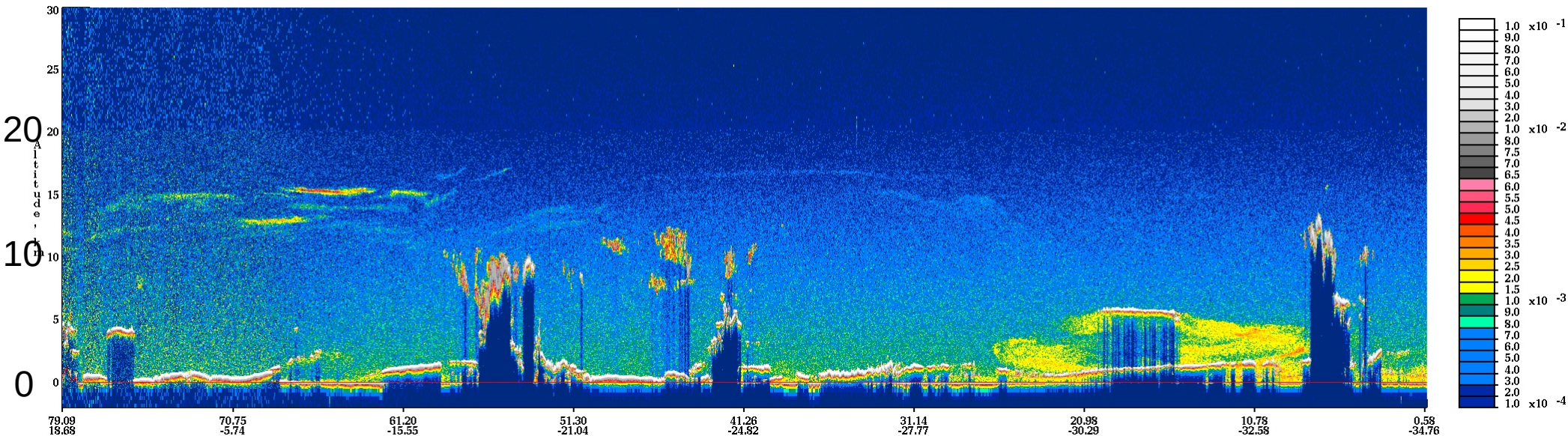
Transmission from different altitudes



High-altitude clouds

532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2009-07-10 03:45:13.6992 End UTC: 2009-07-10 04:07:46.9501

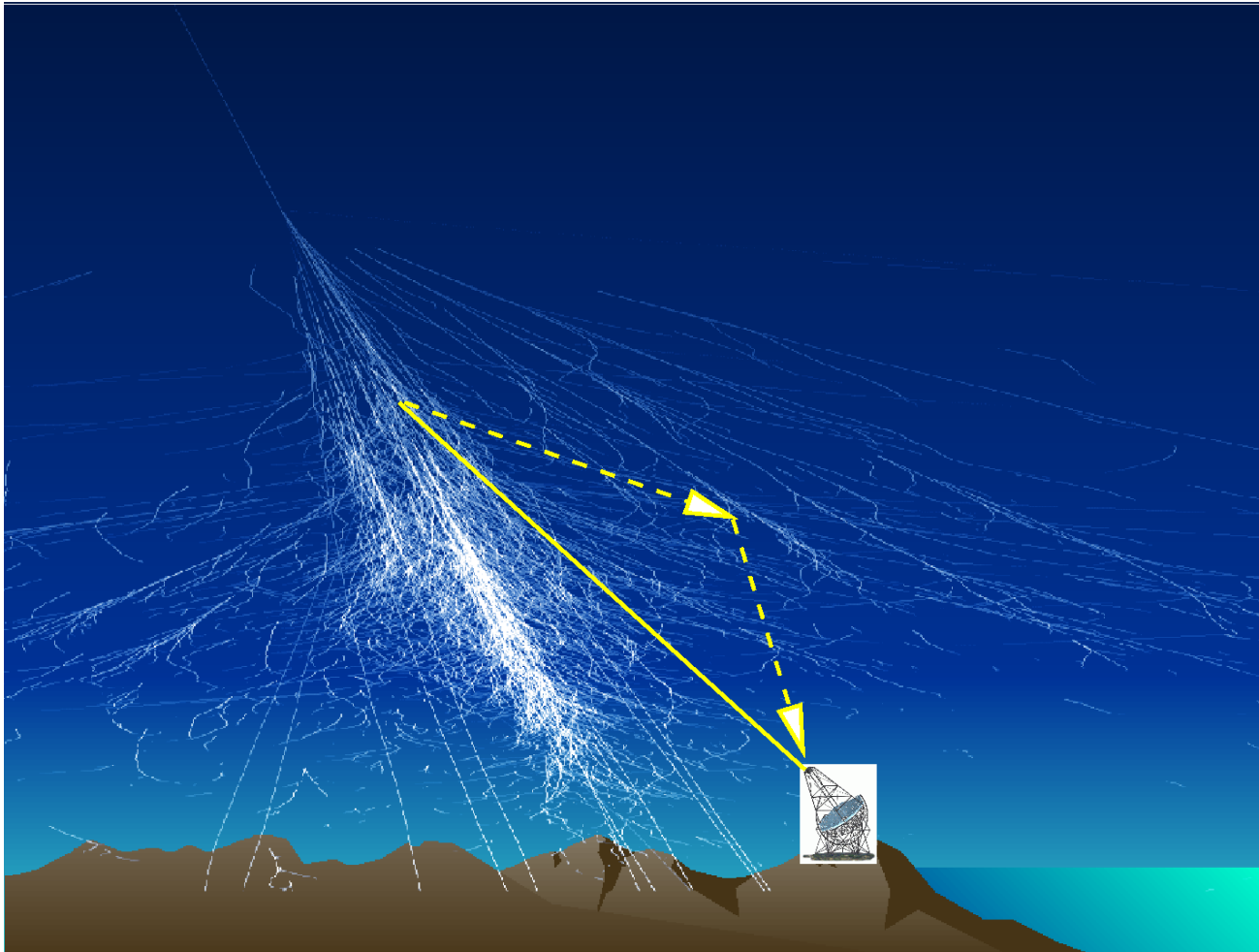
Version: 2.02 Expedited Image Date: 07/11/2009



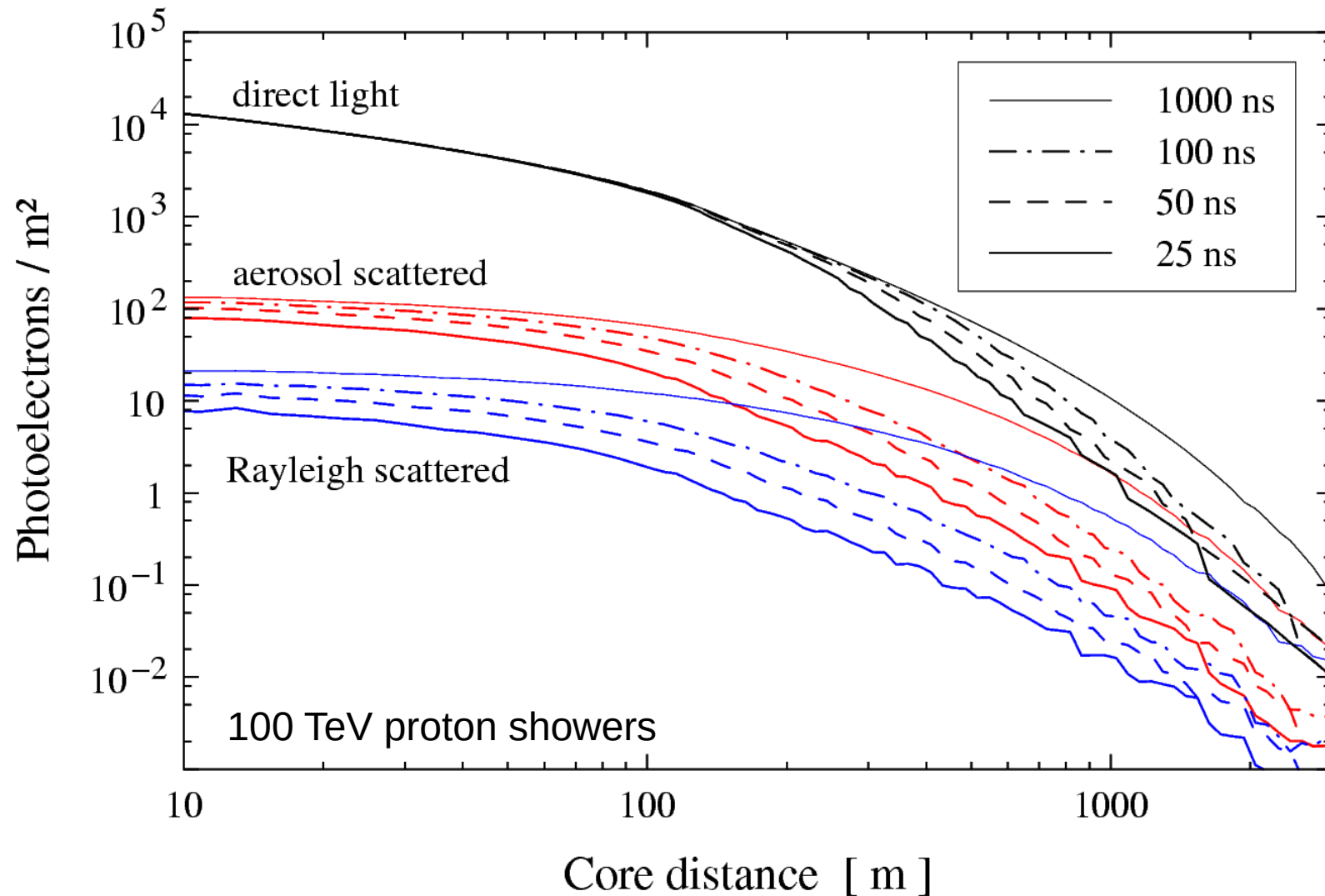
Clouds are more difficult to model:

- Some are above the showers (no effect).
- Some are below the showers (“gray” filter).
- The difficult ones are those intersecting the showers.

Scattered Cherenkov light ?



Scattered Cherenkov light



Scattered Cherenkov light

- Scattered Cherenkov light is 100 to 1000 times weaker than direct Cherenkov light, for integration times and core offsets typical with IACTs.
- Only in conditions with much enhanced small-angle scattering (large aerosols) there could be a significant contribution of scattered light.
- For reasonable observing conditions, it can generally be ignored.

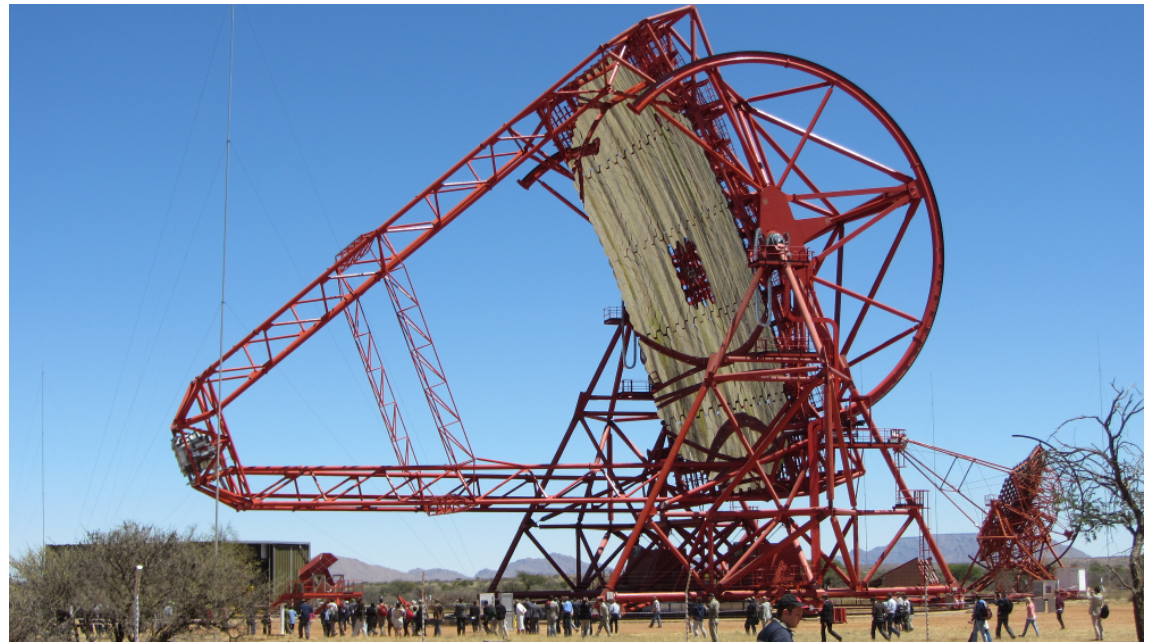
Cherenkov telescopes

- Coming in diameters from ~ 3 m to 28 m.
- Single or dual reflectors.



ASTRI (CTA):
4 m diameter,
dual reflector.

H.E.S.S. CT5: 28 m diameter, single reflector



Cameras of IACTs

- Traditionally built from photo-multiplier tubes (PMTs) as camera pixels:
 - First camera of the Whipple telescope: 37 pixels.
 - HEGRA stereoscopic system: 271 pixels.
 - Camera of H.E.S.S. CT5: 2048 pixels of 42 mm \varnothing .
- Newer developments:
 - “Silicon PMs” (SiPM / GAPDs)
 - CTA SC-MST: 11328 pixels of 6.4 mm \varnothing
 - Multi-anode PMTs (MaPMTs)

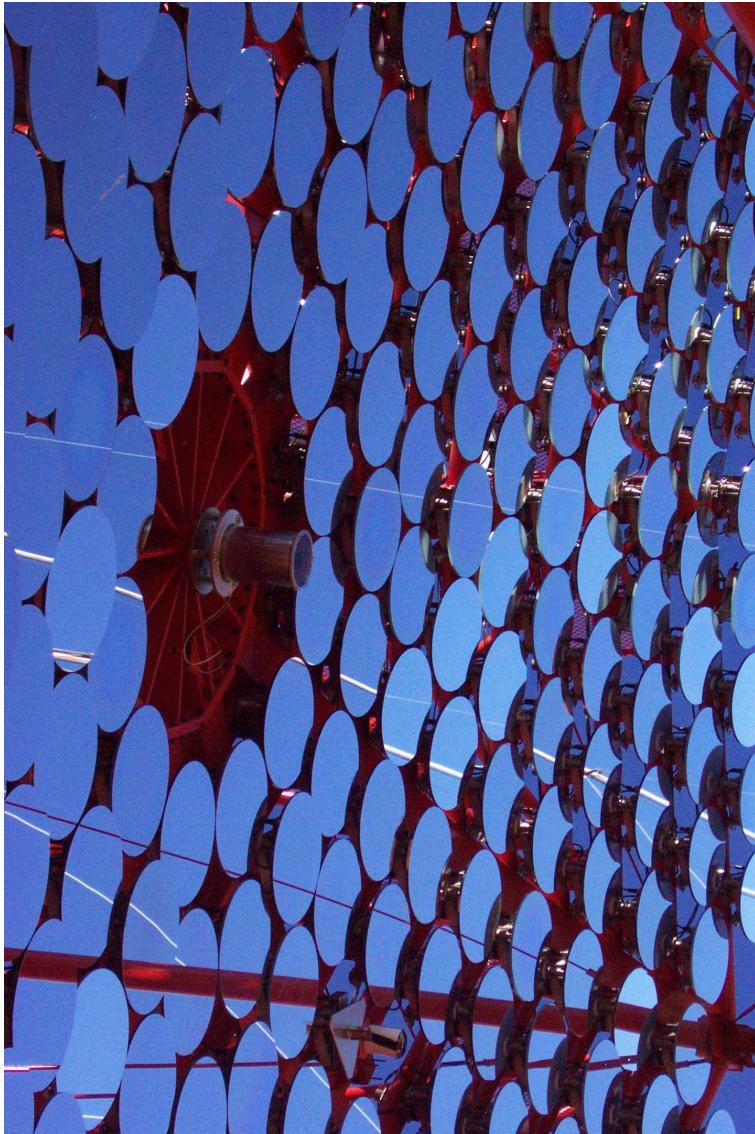
Simulation of IACTs

- Every experiment used to have its own simulation codes.
- Codes freely available and configurable for different telescope types (and in use for CTA, ...):
 - **sim_telarray** (http://www.mpi-hd.mpg.de/hfm/~bernlohr/sim_telarray/)
 - See also <http://www.mpi-hd.mpg.de/hfm/~bernlohr/iact-atmo/> for latest version of CORSIKA-IACT/ATMO package.
 - ROBAST (<http://sourceforge.net/projects/robast/>)
 - CARE/GrOptics

Sim_telarray

- Originally developed for HEGRA telescopes.
- Adapted then to H.E.S.S.
- Tested extensively against H.E.S.S. data.
- Telescopes and cameras are fully configurable.
- Each telescope can be configured separately on the command line and via configuration files.
- Main production tool for CTA simulations (together with CORSIKA).

Optics simulation

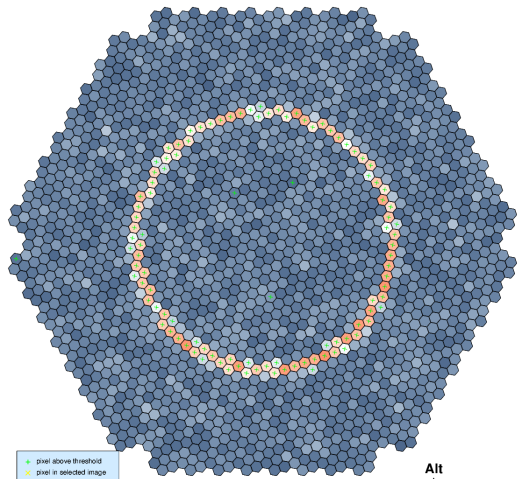


- Photons are fully ray-traced on non-perfect mirror facets with random misalignment.
- Alignment accuracy depending on zenith angle.
- Acceptance in camera depending on angle of incidence.

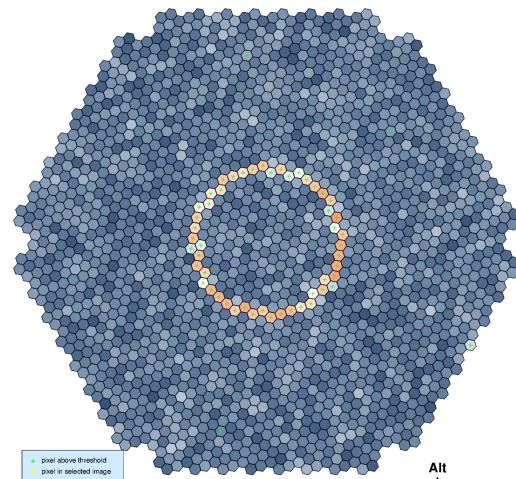
Camera simulation

- Pixel geometry and efficiency fully configurable.
- Analog channel for trigger
- One or two gains for digitized signal
- Different types of telescope trigger supported:
 - Majority
 - Analog sum
 - Digital sum
- Output with configuration, calibration & raw data.
- Efficient and machine-independent data format.

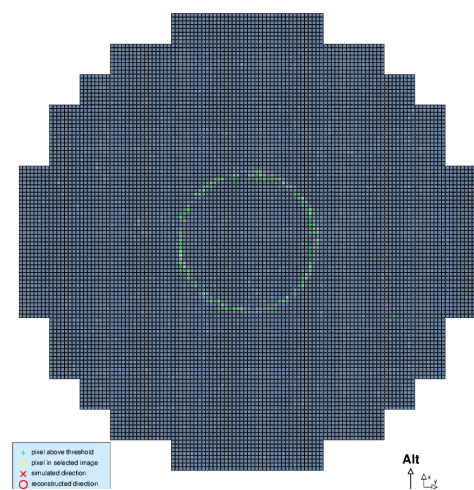
A selection of CTA cameras



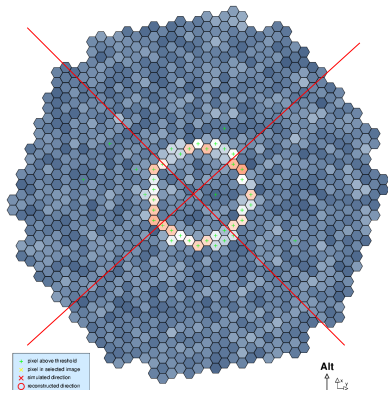
LST



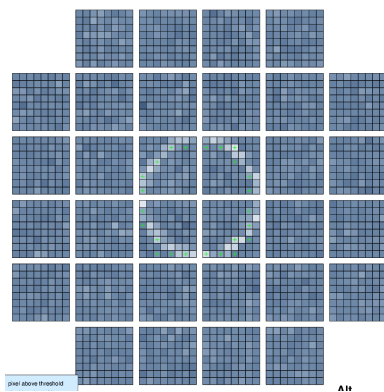
MST



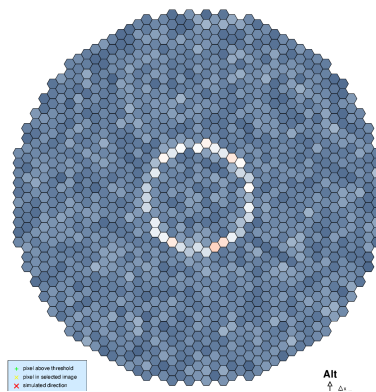
SC-MST



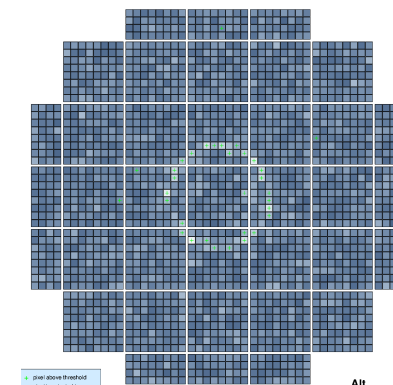
7-m DC



SC-SST (CHEC)

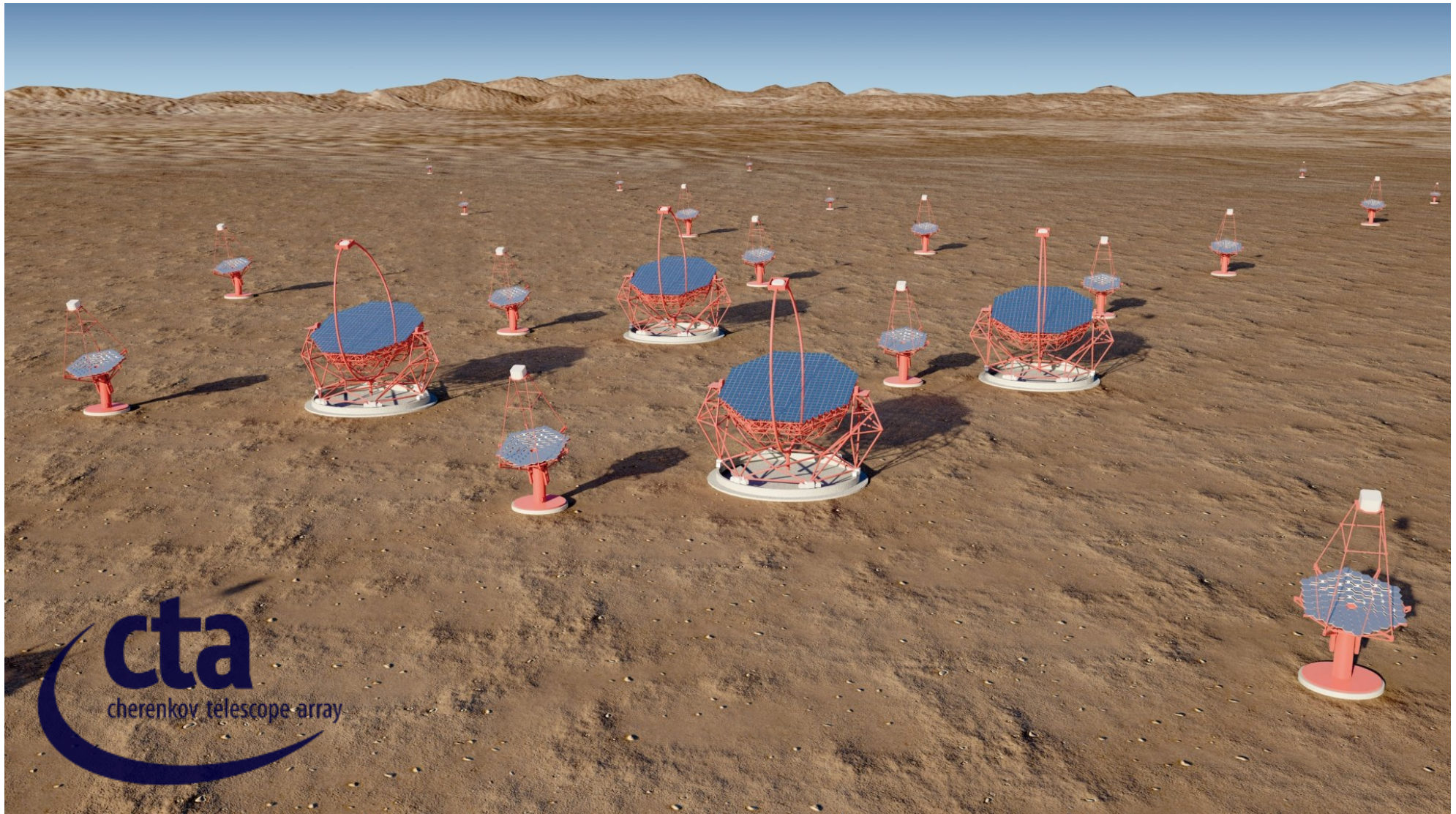


4-m DC

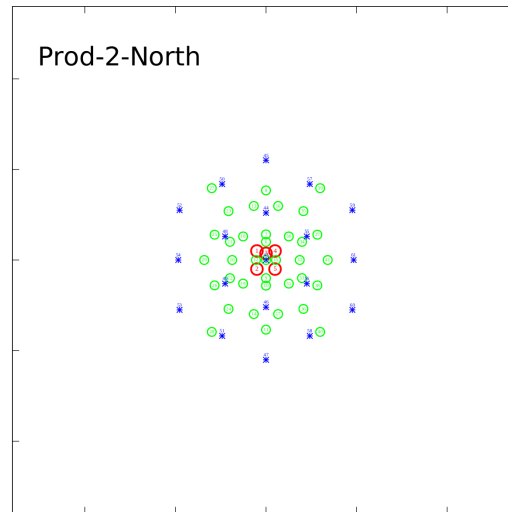
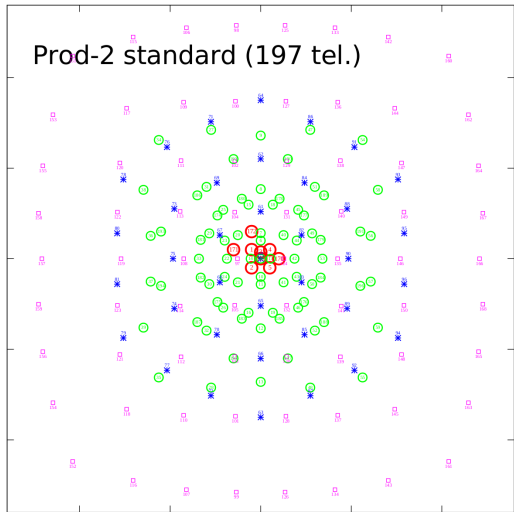


ASTRI

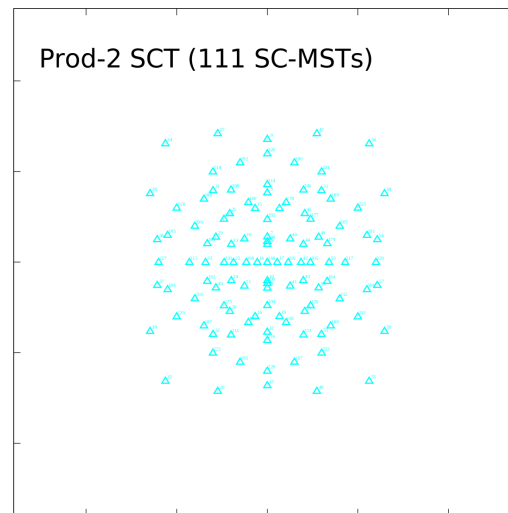
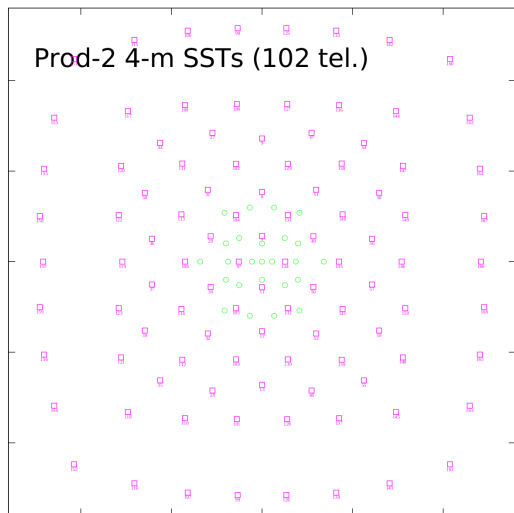
The Cherenkov Telescope Array



CTA: many tel. types, many layouts



Type:	
23-m LST	○
12-m MST	○
7-m SST	*
4-m SST	□
SCT	△



2000 m

The Cherenkov Telescope Array (CTA) will use several types of telescopes. Site and layout studies based on up to 410 simulated telescopes at 229 positions, for later selecting arrays from it.

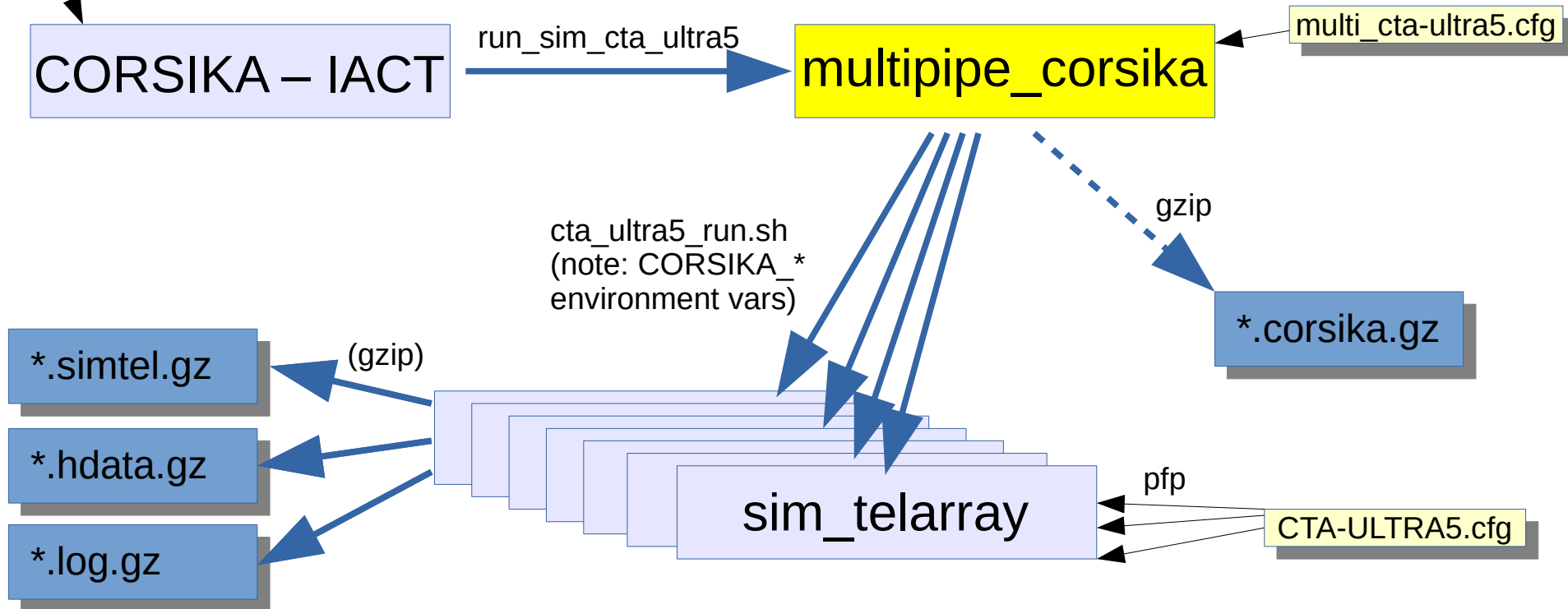
Simulation data pipeline for CORSIKA-IACT with sim_telarray

- CORSIKA writes a single sequential data file per run:
 - Can be stored on disk, typically compressed.
 - Can be piped into a single telescope simulation, or
 - can be piped into several telescope simulations in parallel (with a little utility program).
- Sim_telarray
 - reads (typically) a single CORSIKA data file per run,
 - writes a single sequential data file per invocation,
 - can also write histogram and other optional files not strictly needed for analysis.

INPUTS_CTA_PROD2_...

Running all at once

corsika_autoinputs



Failure of individual pipes are tolerated, as long as one pipe remains.

Programs are finished when no pipe is left.

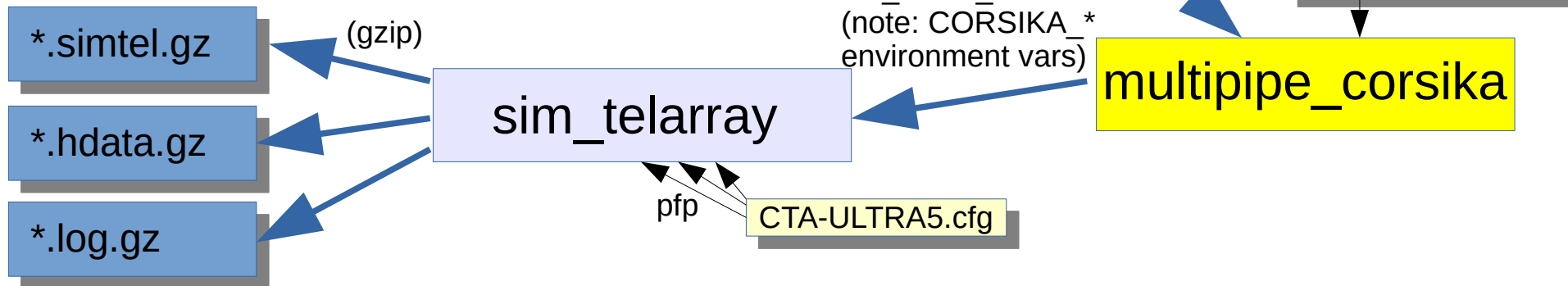
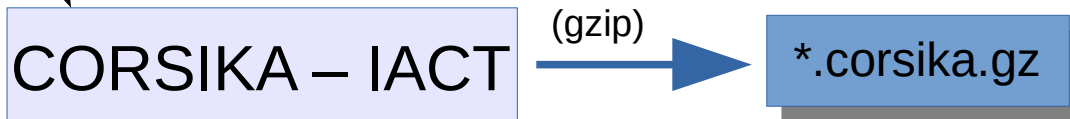
To have processing in more sequential order, set

`CORSIKA_MULTAPIPE_SEQUENTIAL` environment variable.

INPUTS_CTA_PROD2_...

Running things separately

corsika_autoinputs

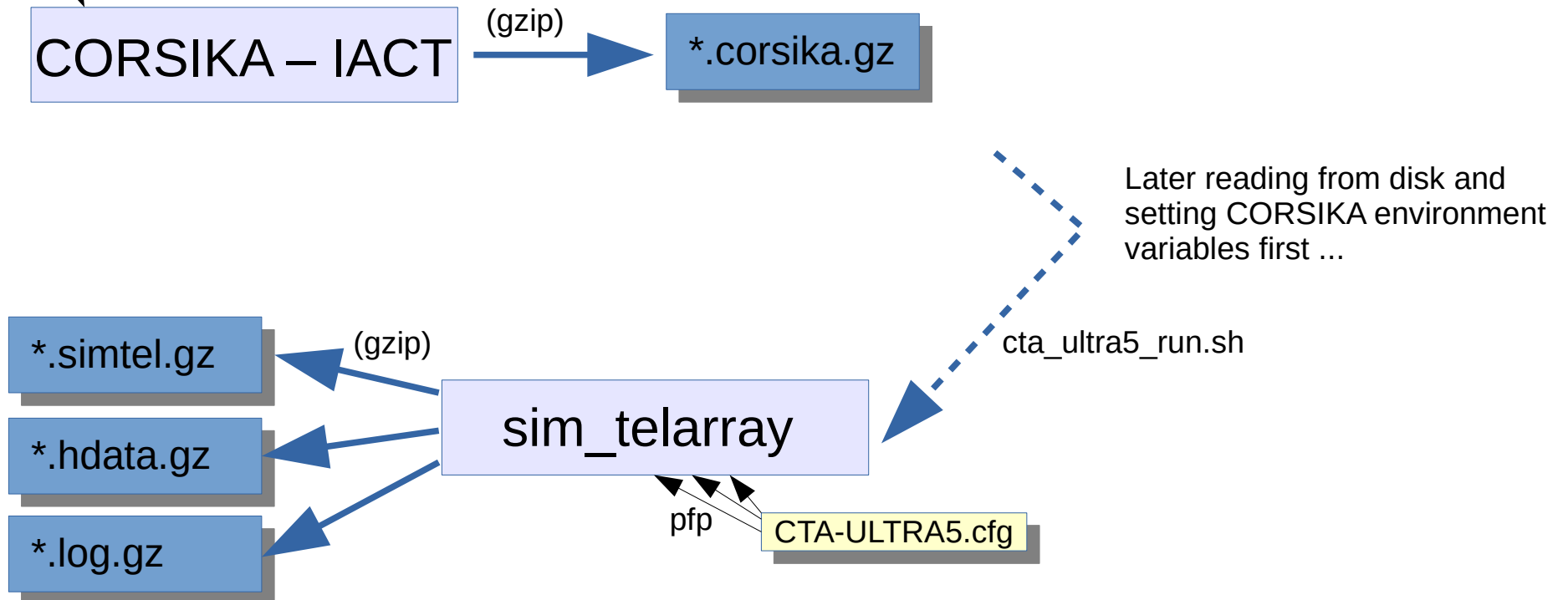


Failure of individual pipes are tolerated, as long as one pipe remains.
Programs are finished when no pipe is left.

INPUTS_CTA_PROD2_...

Running things separately

corsika_autoinputs



Later reading from disk and setting CORSIKA environment variables first ...

Failure of individual pipes are tolerated, as long as one pipe remains.
Programs are finished when no pipe is left.

Running things separately

INPUTS_CTA_PROD2_...

corsika_autoinputs

CORSIKA – IACT

(gzip)

*.corsika.gz

Later reading from disk and
setting up sim_telarray
command line directly ...

*.simtel.gz

(gzip)

*.hdata.gz

sim_telarray

*.log.gz

pfp

CTA-ULTRA5.cfg

Failure of individual pipes are tolerated, as long as one pipe remains.
Programs are finished when no pipe is left.

The underlying eventio format

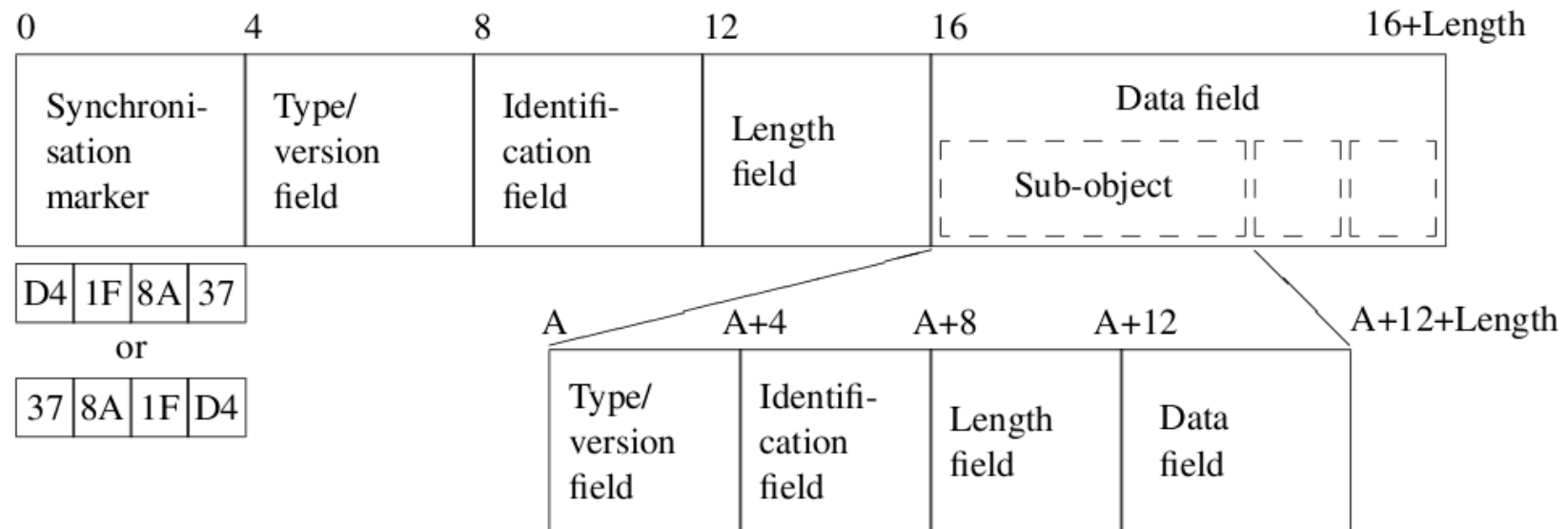


Figure 1: Schematic structure of a top-level object and a sub-object

Data format is machine-independent and hierarchical. For each object/data type, a pair of read/write functions is needed (a bit like ROOT custom streamers). Access is sequential. File I/O with automatic (de)compression.

Convertors and analysis

- Native sim_telarray output format can be processed and analyzed with read_cta (aka read_hess) or
- converted into data formats suitable for
 - MARS (MAGIC analysis; convertor: chimp),
 - SASH (HESS analysis; convertor: eventio),
 - Evndisp (VERITAS analysis; convertor:)
 - ...
 - (and histograms into ROOT or PAW)
- or, if the file contains photo-electron information, used for re-simulating the event (e.g. trigsim).

Conclusions

- CORSIKA has a Cherenkov light option for many years now which is well tested, both with imaging telescopes and with non-imaging detector arrays.
- For CTA a better representation of atmospheric profiles may become desirable.
- The IACT option allows for flexible definition of detector/telescope arrays.
- The eventio format IACT output can be piped into `sim_telarray` or other detector simulation codes (e.g. one based on the `sim_skeleton` template code).