Remote sensing of clouds and aerosols with cosmic rays

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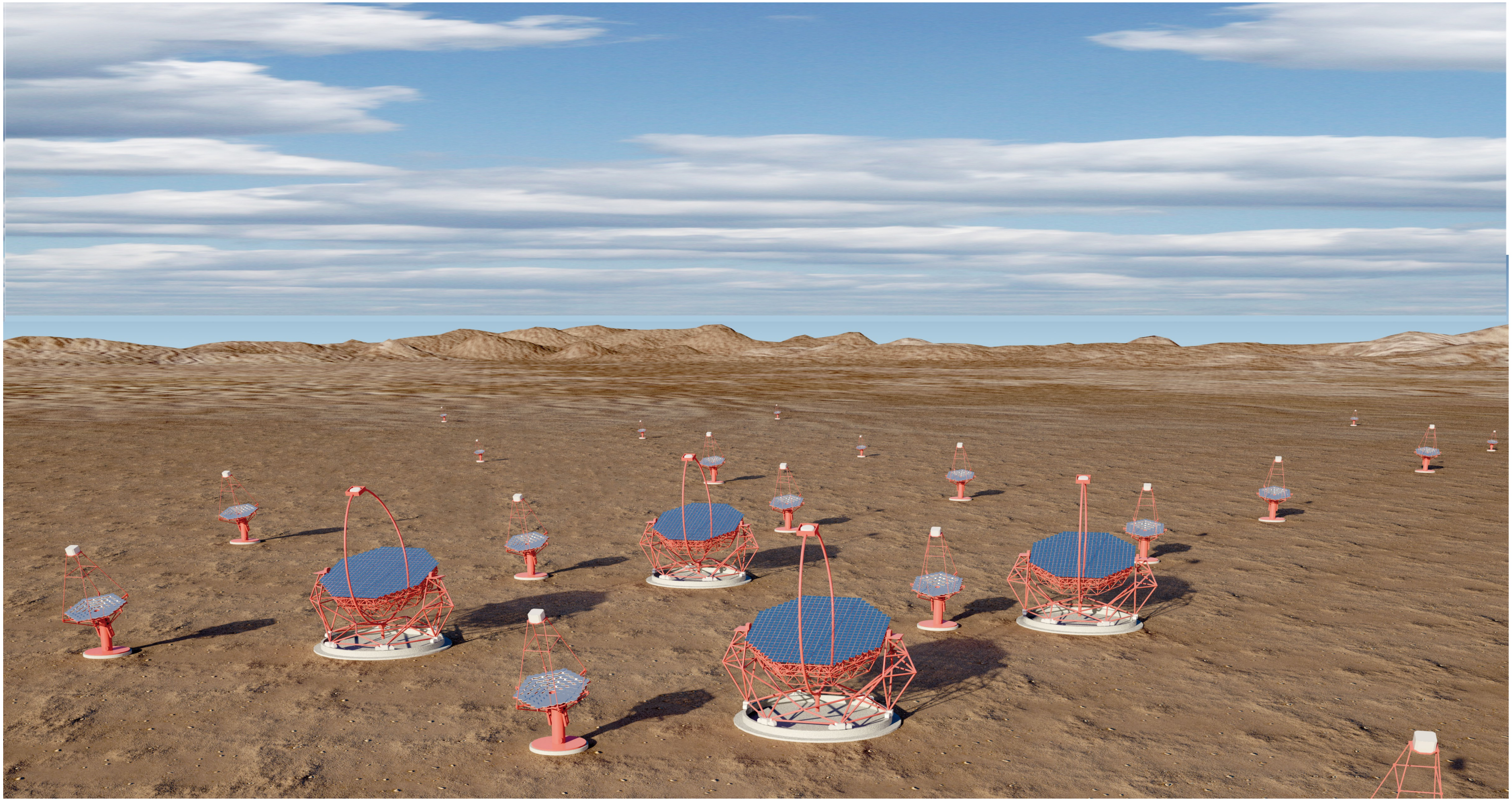


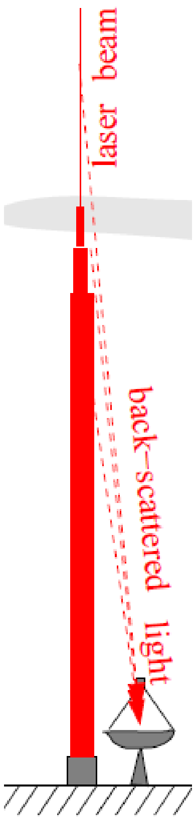
AtmoHead'14, 19-21 May, Padova

Clouds:

- Reflect and absorb radiation from the Sun – implications for climate and atmospheric science.
- Perturbs astronomical observations of VHE photons. Duty cycle of Cherenkov telescopes ~15%

Properties are obtained from

- imaging (space or ground)
- observations of transmitted light (Sun or Moon)
- LIDAR technique for vertical structure

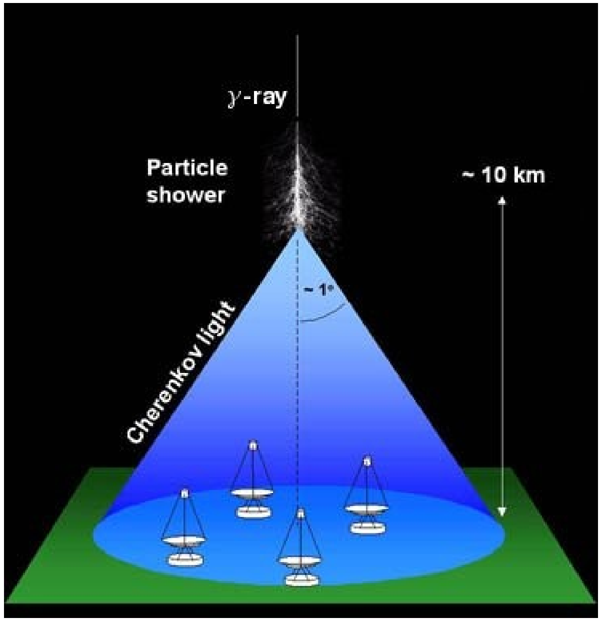


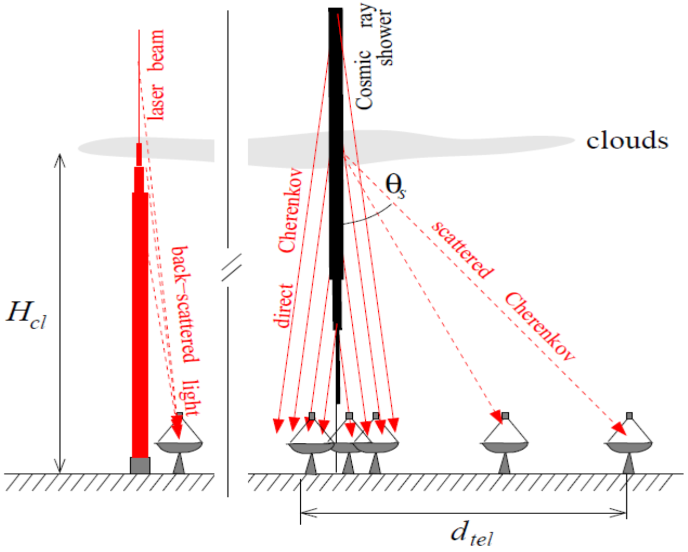
- We show that Cherenkov light produced by the CR shower could be used as a testing tool for 3d cloud/aerosol coverage

Cosmic rays hitting the atmosphere at a rate

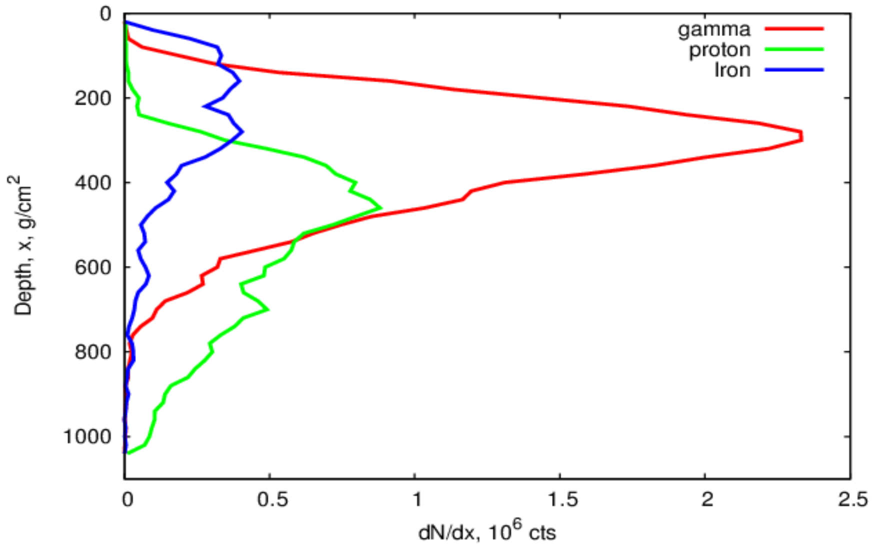
$$N_{cr}(E_{cr}) \sim 10\,[E_{cr}/100\ \mathrm{GeV}]^{-\gamma_{cr}+1}\ (\ \mathrm{m}^2\ \mathrm{s}\ \mathrm{sr})^{-1} \qquad \gamma_{cr} \simeq 2.7$$

- Each CR induced shower generates a short flash visible/UV light via Cherenkov and flourecence mechanisms.
- At energies >100GeV CR flux is invariable in time.





- Measurements of a large number of individual showers are combined into cumulative vertical profile $dN_{\gamma,cum}/dH(x, y, H)$
- Stereoscopic vision allows to reconstruct 3d profile.
- Scattering and absorbtion of the light by clouds leads to the distortion of cumulative vertical profile.



- Vertical profiles of individual showers are shaped by random process of collisions between HE particles and air. However stacking large number of showers removes these fluctuations.

- Rate of the showers detection is quite high,

$$\mathcal{R}_{cr} = N_{cr}(E_{thr})A_{eff} \sim 1\,[D_{tel}/10\text{ m}]^{2(\gamma_{cr}-1)}\text{ kHz}$$

- The shower is detected if more than 10-100photons reached the telescope, making photon statistic each second

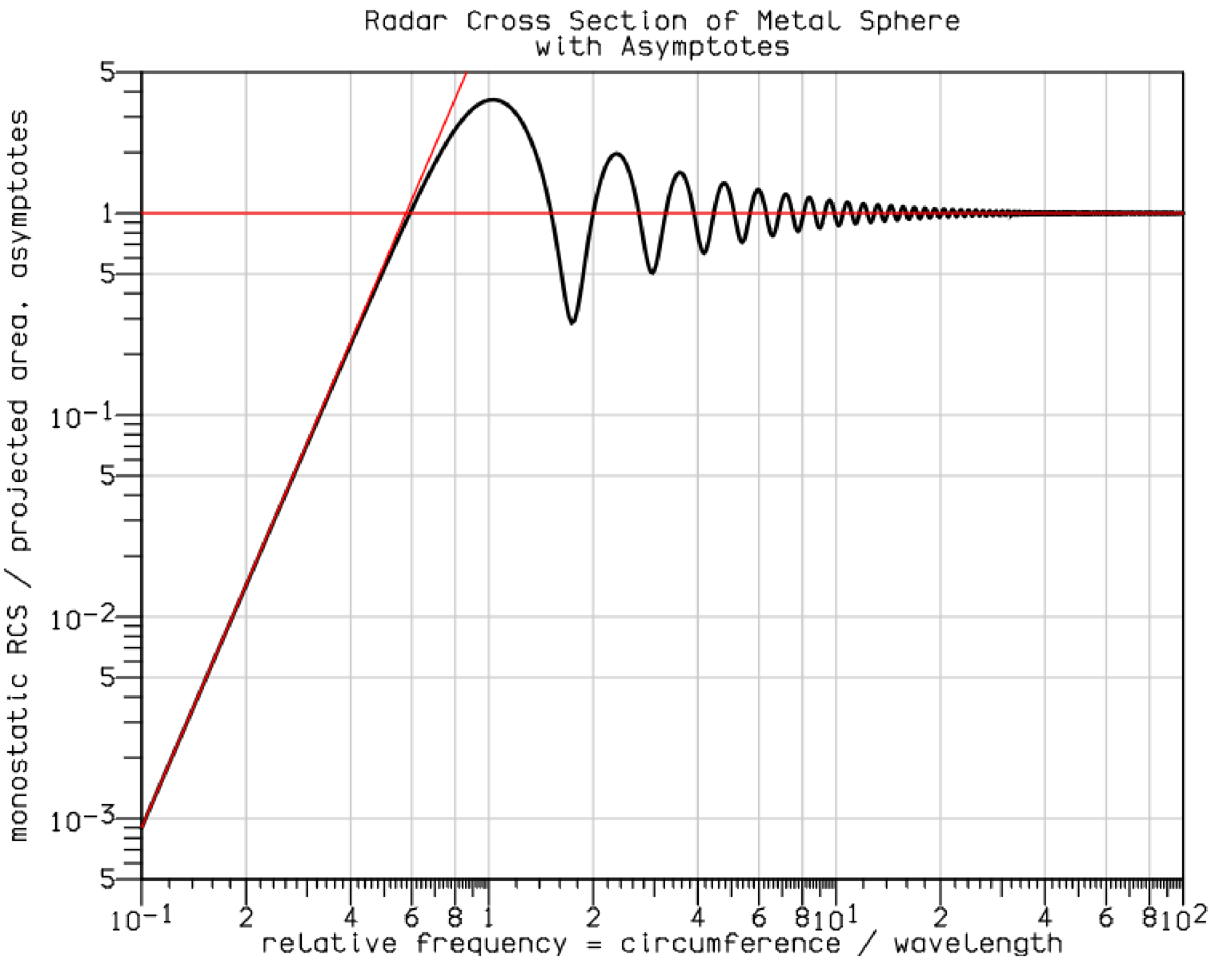
$$\sim 10^5\,[D_{tel}/10\text{ m}]^{2(\gamma_{cr}-1)}\text{ ph/s}$$

- Cherenkov photons are concenrated in a narrow beam

$$dN_{Ch}/dX(E_{cr}, X, \alpha, \lambda) = Y_{Ch}N_p(E_{cr}, X) \qquad dN_{Ch}/dX \sim \exp\left(-\alpha/\alpha_c\right),\text{ where }\alpha_c \sim 1^\circ$$

- As a function of altitude

- $$dN_{Ch}/dH = (\rho/\cos\theta_z)dN_{Ch}/dX$$



- Number of photons reaching the telescope

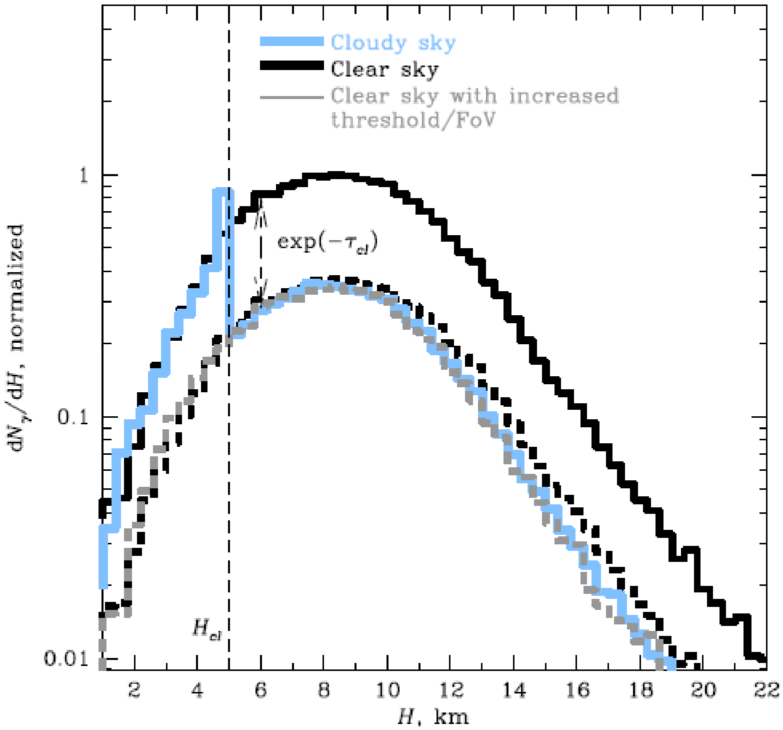
$$\frac{dN_\gamma}{dH} = \frac{dN_{Ch}(H,\alpha(H),\lambda)}{dH}\exp\left(-\tau(H,\lambda)\right)$$

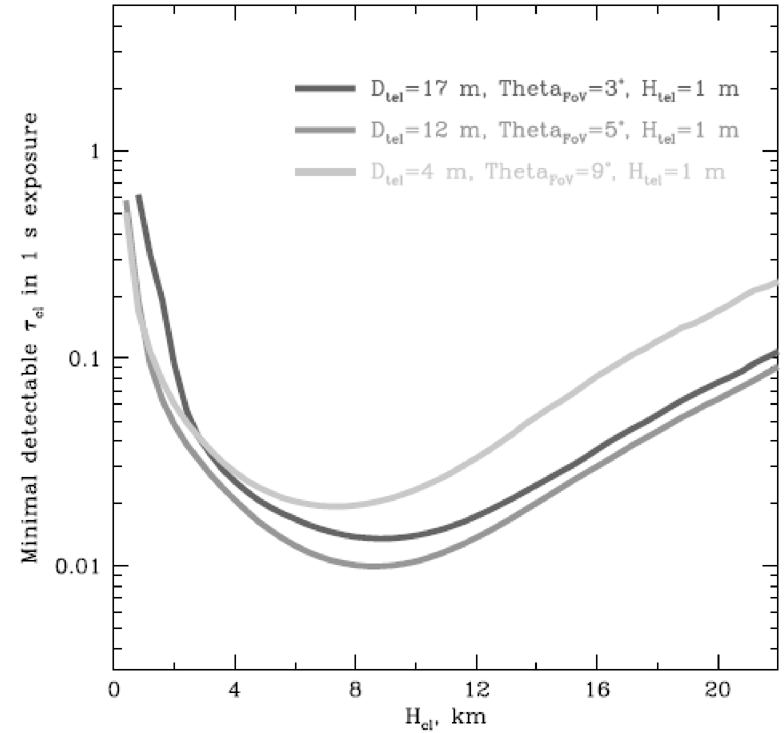
Optical depth measurements can allow to determined the density distribution and the extinction cross-section of scattering centres:

$$\tau = \int_{H_{tel}}^{H} \sigma_s(\lambda) n_s / \cos(\alpha) dh$$

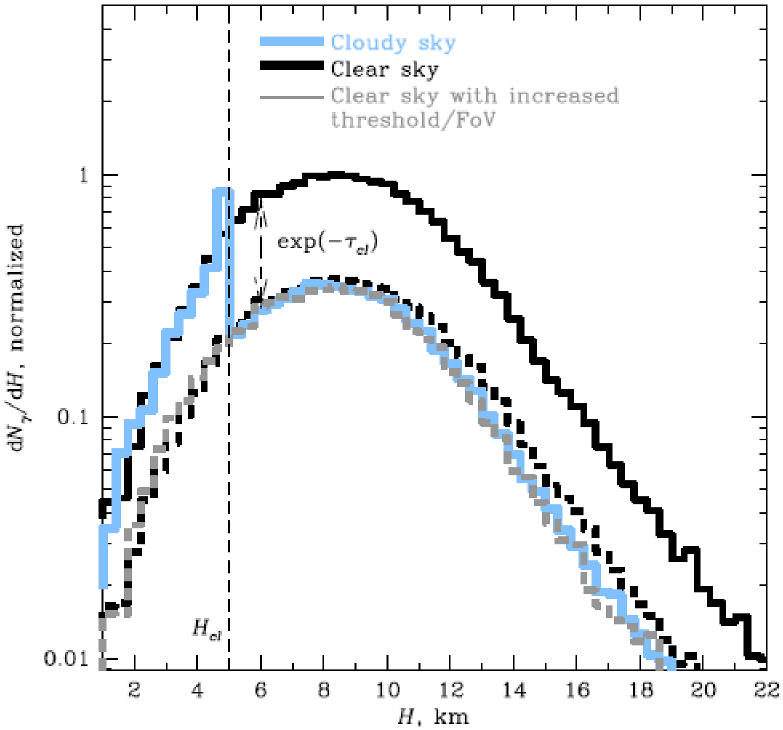
Presence of an atmospheric feature (cloud or aerosol) of non-zero optical depth distors the cumulative vertical profile in several ways:

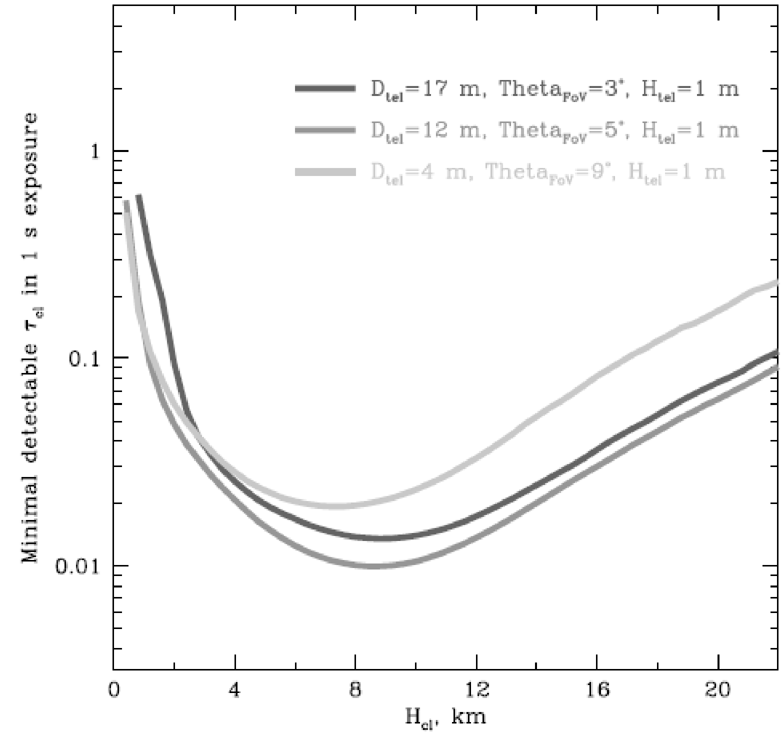
- Reduces the number of Cherenkov photons reaching the telescope from behind the feature by $\exp(-\tau_{cl})$
- Because of the reduction of photon number the minimal energy above which the shower can be detected can increase up to $\exp(\tau_{cl})$ times, depending on the altitude of the feature.
- Scattering of the Cherenkov light in the cloud increases the signal from the altitude of the cloud and facilitates detection of the signal at large off-axis angles, imitating an increase of the telescope's FoV.





- In order to verify previous qualitative arguments we performed Monte-Carlo simulations of vertical profiles of Cherenkov light in clear and cloudy sky using CORSIKA (v.7.40) software. We simulate 100 GeV – 10 TeV proton showers following powerlaw distribution with the slope p=-2.7. The shower assumed to be detected if the number of photons reaches the dish is >50.
- Cummulated vertical profile from 1s exposure of 17m telescope dish with thin cloud with optical depth=1 at 5km altitude is shown in left figure. The strength of the break is determined by the optical depth.



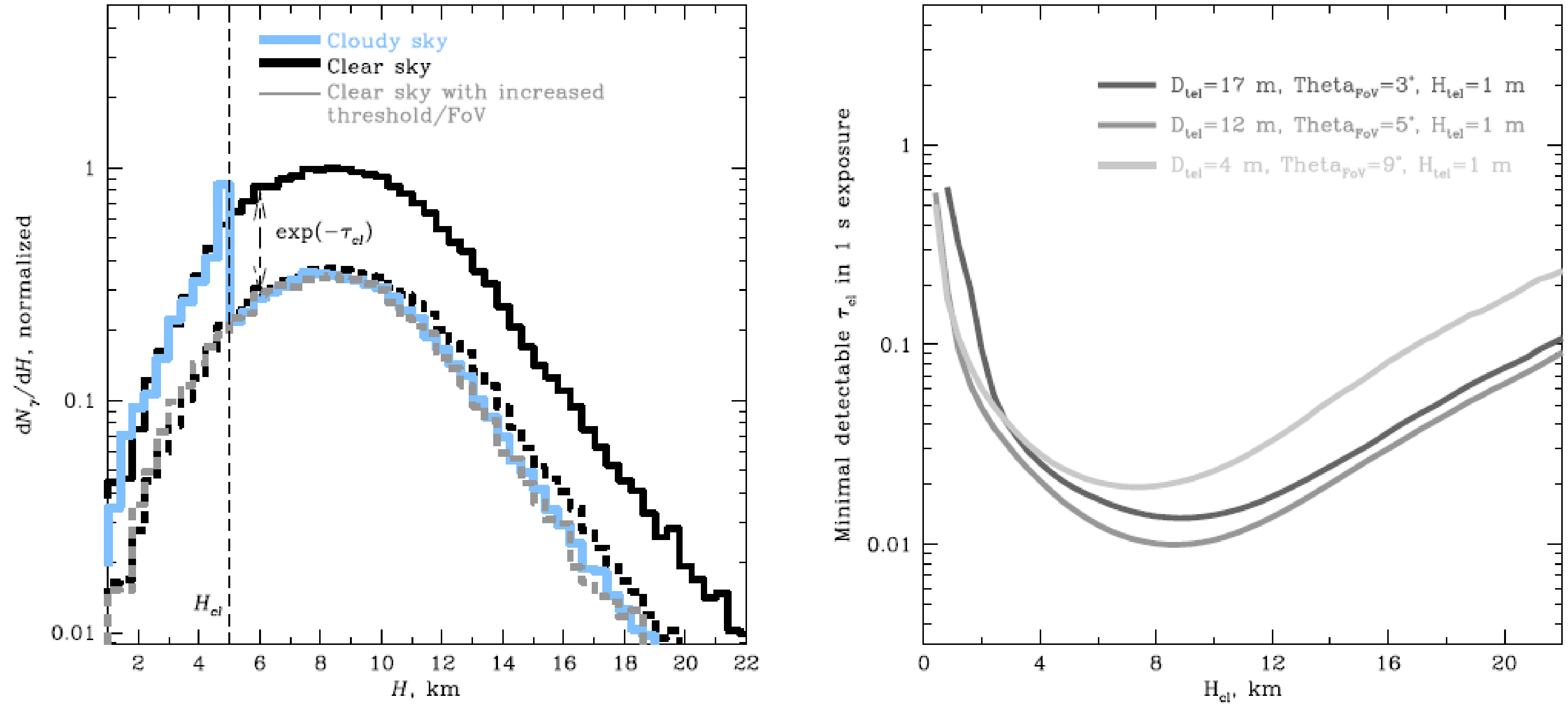


- The shape (but not normalization!) of cloudy sky profile follows clear sky profile below and above the cloud with properly adjusted minimal detected number of photons and telescope's FoV.

- This allows us to introduce a «scattering ratio»

$$SR(H) = \left[dN_\gamma/dH|_{cloudy}\right] / \left[dN_\gamma/dH|_{clear}\right]$$

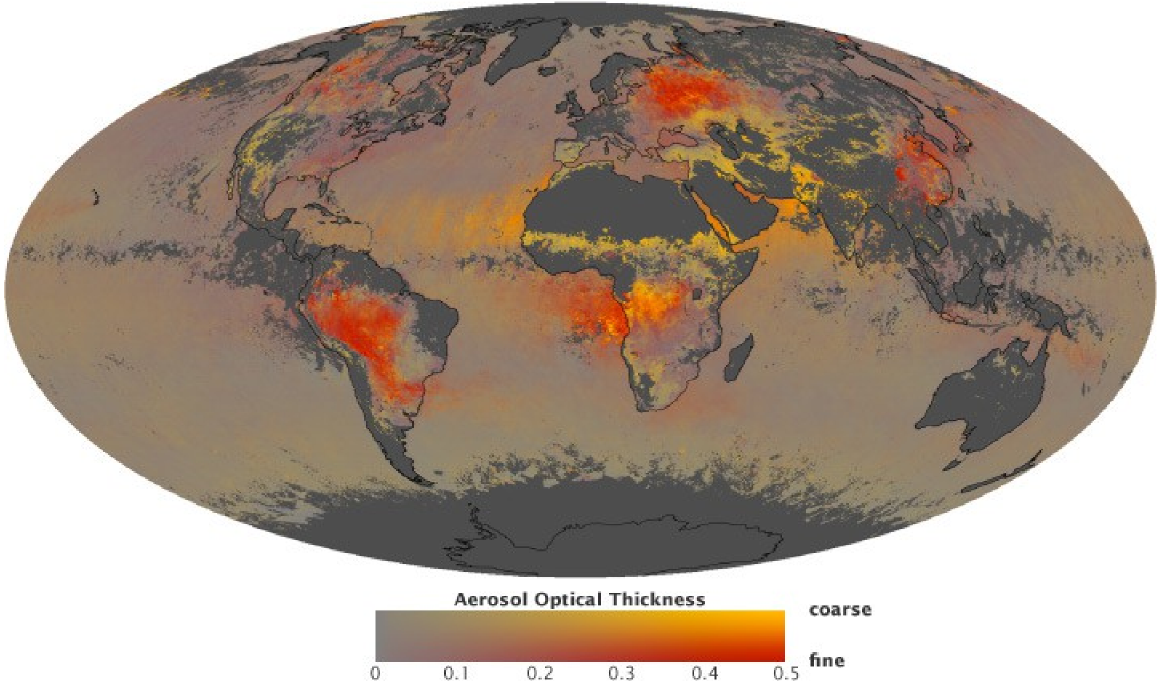
Which is roughly constant below and above cloud and has a break at H_{cloud}

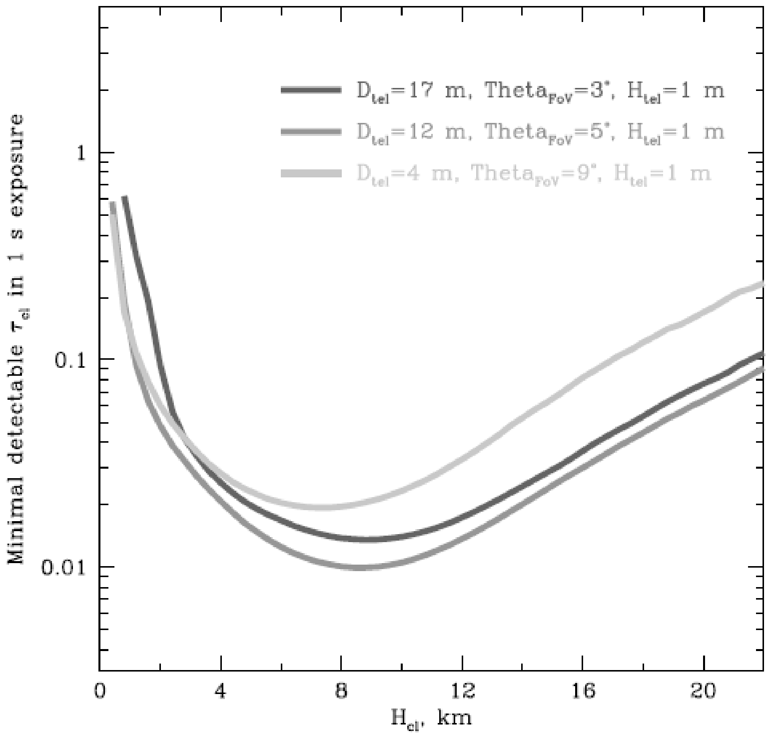


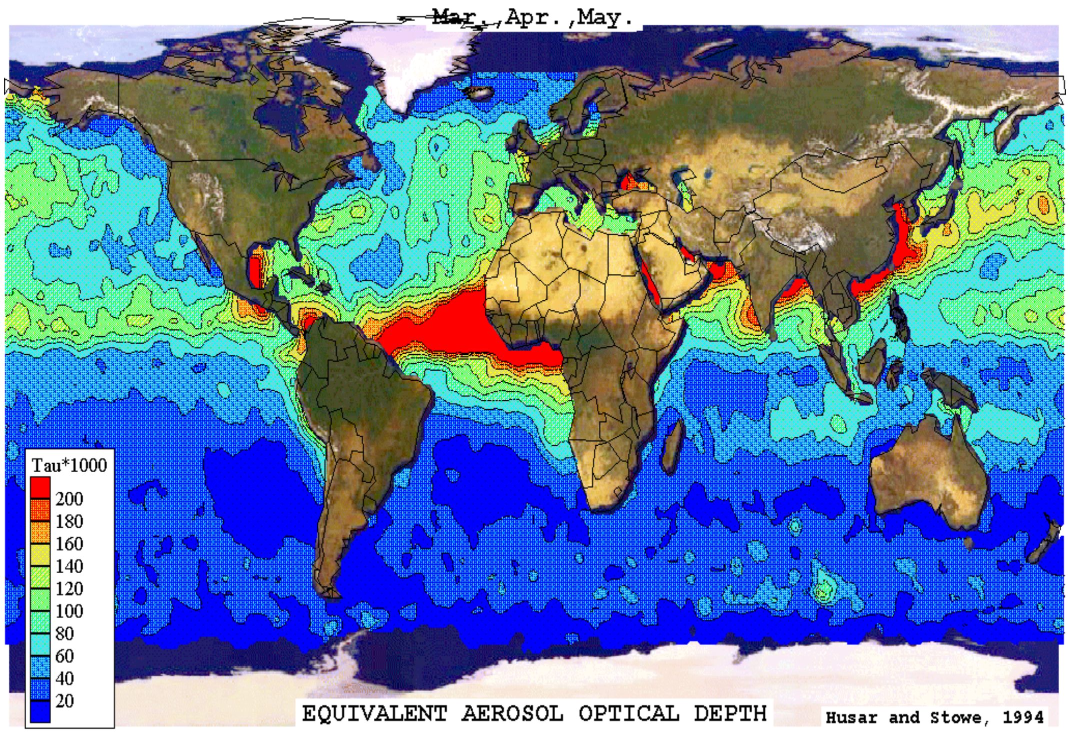
- Optical depth of the feature can be measured from SR below and above the feature:

$$\exp(-\tau_{cl}) = [SR(H > H_{cl})] \,/\, [SR(H < H_{cl})]$$

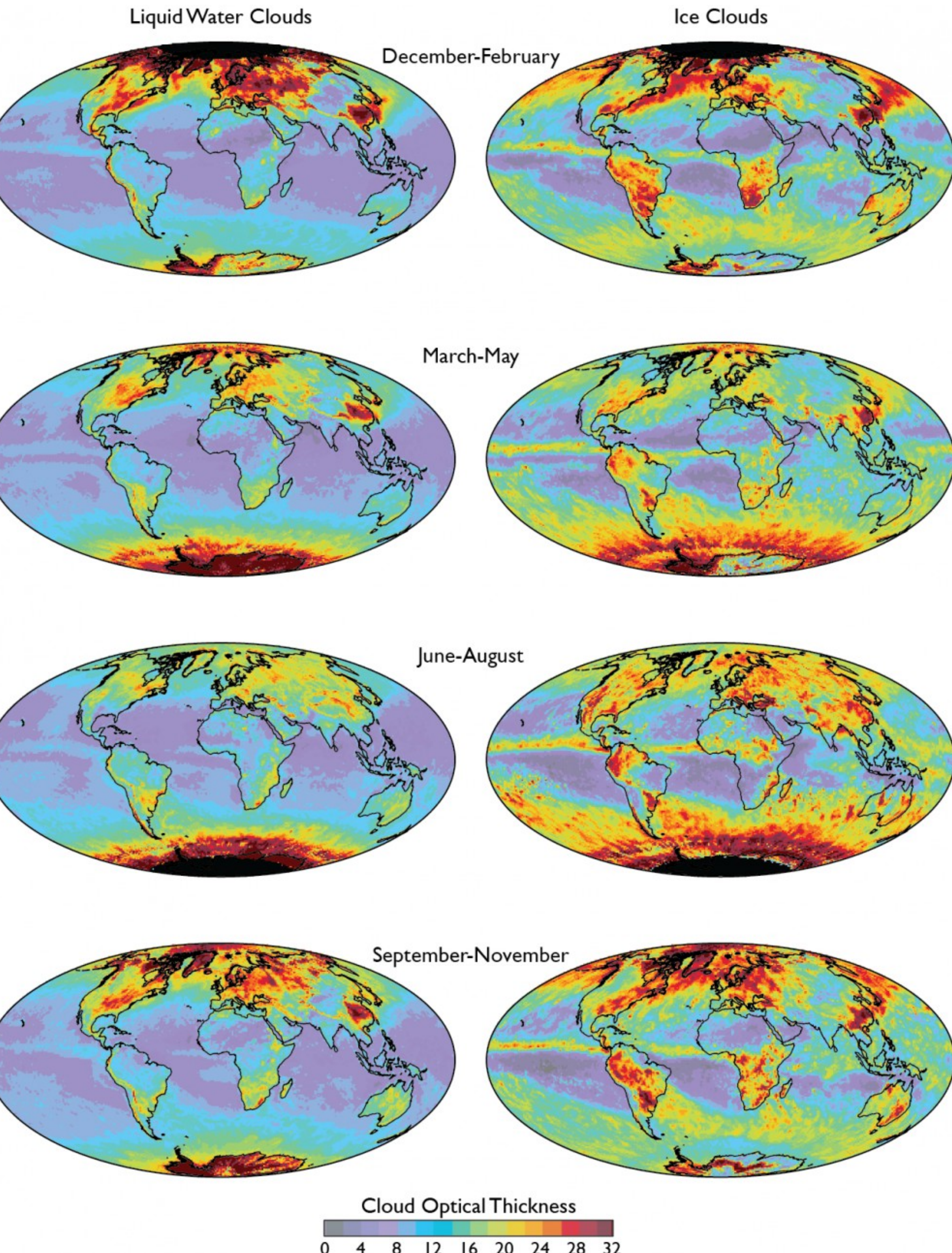
- The significance of the optical depth measurement is determined by numbers of photons detected from below and from above the cloud.
- Varying the dish/cloud parameters we estimated the cloud's minimal optical depth that can be (5sigma) detected in 1s (right figure)

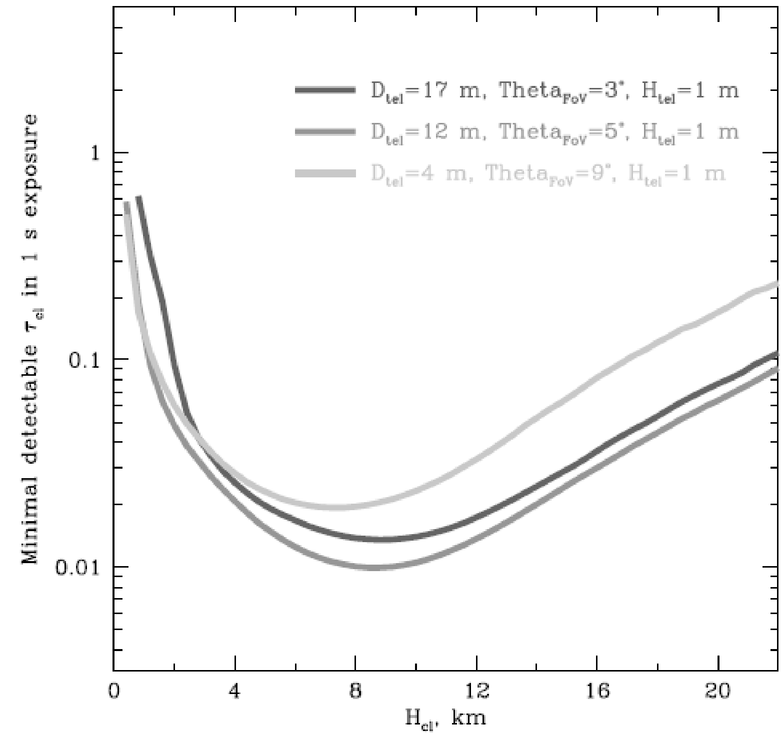






- We have taken the telescopes parameters close to those of existing and planned facilities, e.g. HESS (12m dishes and 5^o FoV), MAGIC (17m, 3^o), SST array of CTA (4m, 9^o).
- For all these telescopes clouds can be detected at 5sigma level just for 1second.





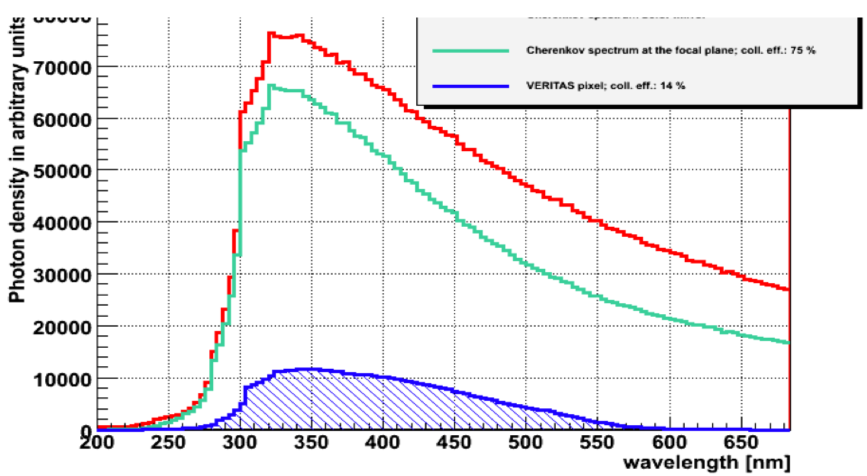
We have taken the telescopes parameters close to those of existing and planned facilities, e.g. HESS (12m dishes and 5° FoV), MAGIC (17m, 3°), SST array of CTA (4m, 9°).

For all these telescopes aerosols can be detected at 5sigma level just for 1second.

- The spectrum of Cherenkov emission

$$dN_{Ch}/d\lambda \sim \lambda^{-2} \left(1 - c^2/([n(\lambda)]^2 v^2)\right)$$

Continue through optical and UV bands. Cherenkov light provides a «white light» source in the atmosphere. Usage of such light has certain advantages prior to mono-wavelength LIDAR. Broad range of Cherenkov light allows for a measurement of the optical depth as a function of wavelength. This provides a tool for the measurement of sizes of aerosol particles, since the scattering/extinction cross-section depends on the size parameter.



Modifications of existing IACTs are however required for such study since current systems measure only the intensity of Cherenkov light integrated over a single spectral window of light sensors.

Conclusions

- We have proposed the approach for the remote sounding of the atmosphere using the UV Cherenkov light generated by cosmic ray induceed showers.
- This approach allows the detection of atmospheric features, such as clouds and aerosol layers and characterization of their geometrical and optical properties at a timescale ~1sec.
- The proposed method has certain advantages prior to LIDAR. Cherenkov light is continuously re-generated in the atmoshere and spans over visible and UV bands. This allows to use proposed method for the measurement of the physical charateristics of cloud/aerosol particles, e.g. size distribution and scattering phase function.

Conclusions

- The method can be implemented on already existed telescopes. The data collection does not require interruption of the planned astronomical observation schedule. Obtained atmospheric data could be collected in cloudy sky when astronomical observations are impossible

- Detailed simultaneous atmospheric data allow for a better control of the quality of the astronomical gamma-ray data taken by existing IACT, e.g. via a better definition of clear-sky conditions. Besides, this also should open a possibility for observations in a border-line situation of the presence of moderately optically thin clouds and aerosols.