Atmospheric monitoring using the Cherenkov Transparency Coefficient for the Cherenkov Telescope Array

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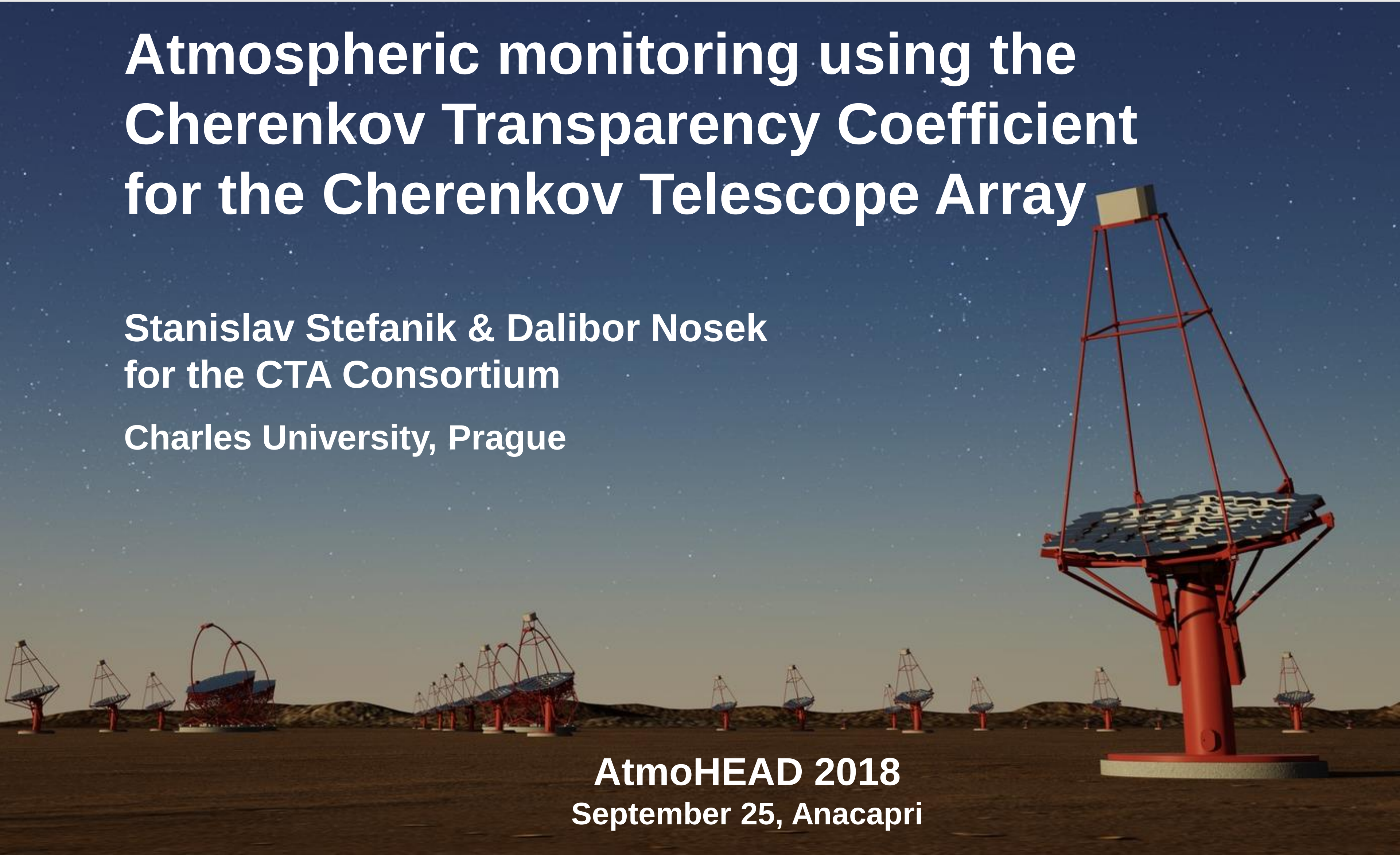

AtmoHEAD 2018
September 25, Anacapri

Outline

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   - Challenges in the application to larger arrays
2. **Extension of the CTC for CTA**
   - Geometrical & instrumental considerations
3. **Atmospheric monitoring with the CTC**
   - Aerosols & molecular profiles
4. **Summary**

Introduction

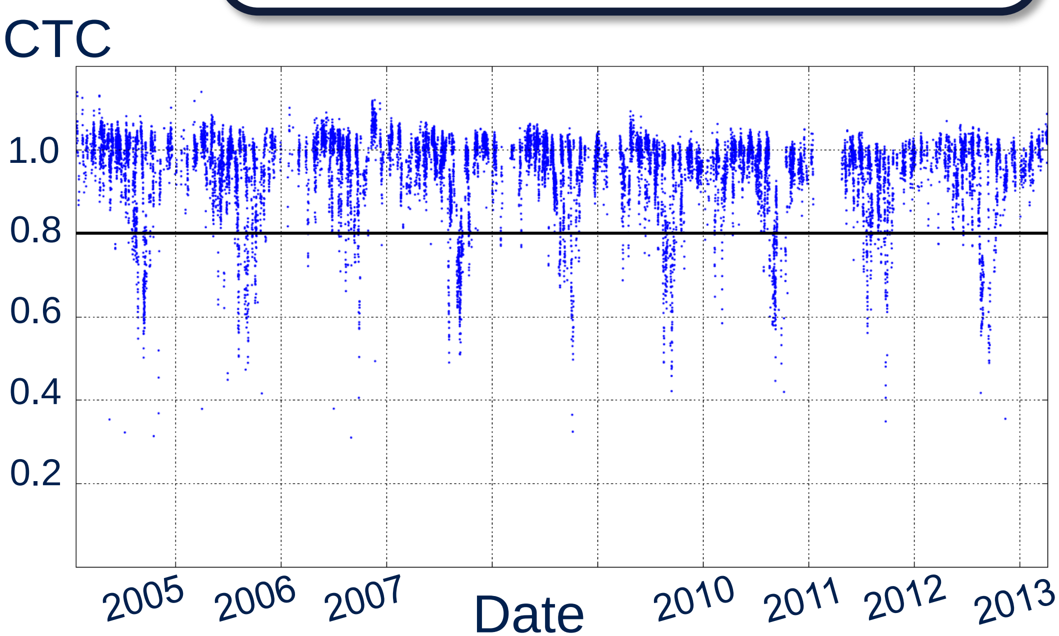
Cherenkov Transparency Coefficient (H.E.S.S.)

Motivation:

- Estimate the atmospheric transparency (T) to Cherenkov light from air showers seen by imaging atmospheric Cherenkov telescopes (IACTs)
- Telescope data only

CTC :

$$T = \frac{1}{N \cdot k_N} \sum_{i=1}^{N} \frac{[R_i(\theta = 0^\circ)]^{\frac{1}{1.7}}}{\mu_i \cdot g_i}$$



Telescope-wise:

- R_i … stereo trigger rate
- μ_i … muon efficiency
- g_i … average pixel gain

Array-wise:

- N … no. of active telescopes
- k_N … multiplicity correction
- θ … zenith angle of observation

Hahn et al., Astropart. Phys. 54, 25, 2014

CTC: Challenges

H.E.S.S. - I:

- 4 IACTs, 1 design
- Square layout
- 2 multiplicity corrections k_N (k_3 / k_4)
- No geometrical layout correction
- Small influence of Earth's *B*-field
- CTC precision 9%

Next generation arrays:

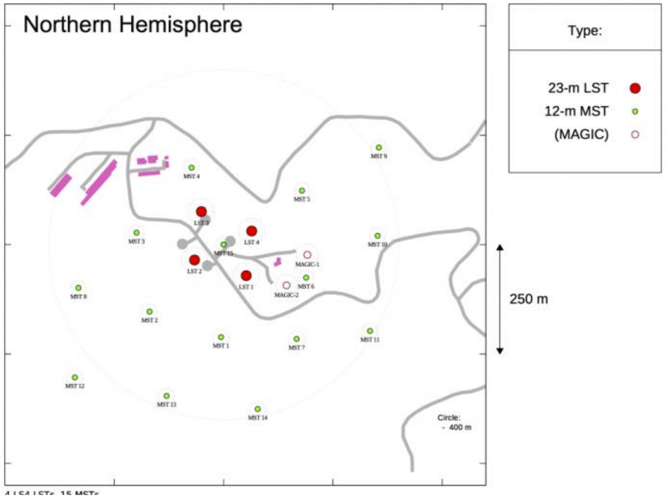
- Tens of IACTs, multiple designs
- Possibly non-symmetric layouts
- Many possible sub-arrays
- Many layout-dependent factors
- Non-negligible effects of the *B*-field in some locations
- Need for better precision

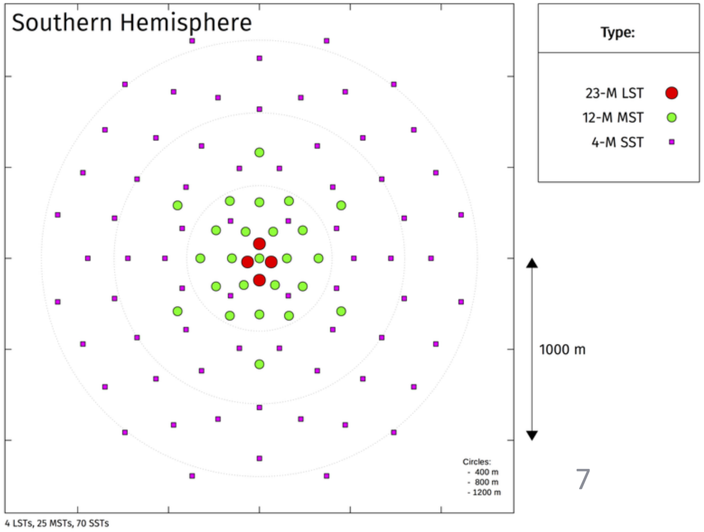
Extension of the CTC for CTA

Cherenkov Telescope Array

A ground-based γ-ray observatory in preparation

- Detection of very high energetic
  (~ 20 GeV to > 300 TeV) cosmic photons
- Multiple designs of IACTs:
  - large (ø 23 m), medium (ø 12 m)
    & small-size (ø 4 m)
  - variety of structures and hardware
- One array in each hemisphere
- Need for robust atmospheric monitoring
  - see also talks by J.Ebr, M.Gaug, P. Janecek, S. Micanovic, P. Munar-Adrover, V. Rizi





Trigger rates of telescopes

- Trigger rates of IACTs given mainly by the flux of cosmic rays:

$$R \propto \int_{E_{\mathrm{th}}}^{\infty} J(E) \cdot A_{\mathrm{eff}}(E)\mathrm{d}E \qquad J(E) \propto E^{-2.7}$$

(A_{eff}: effective area)

- Other dependencies:
  - atmospheric transparency to Cherenkov light (aerosol optical depth)
  - random fluctuations
  - telescope array layout
  - geometrical configuration
  - geomagnetic field
  - telescope optical throughput

- **Eliminate instrumental & geometrical dependencies of trigger rates to estimate the atmospheric transparency**

Extended CTC for CTA

Cherenkov Transparency Coefficient:

$$\hat{T}(\mathrm{AOD}) = \frac{1}{P}\sum_{\substack{i=1\\i<j}}^{N} \hat{T}_{ij} = \frac{1}{P\cdot\mathcal{K}}\sum_{\substack{i=1\\i<j}}^{N}\left(\frac{R_{ij}(\mathrm{AOD},\mathcal{O},\varepsilon_i,\varepsilon_j)}{\varepsilon_i\cdot\varepsilon_j\cdot\hat{R}^0_{ij}(\mathcal{O})}\right)^{\frac{1}{1.7}}$$

Pair-wise

(telescopes *i & j* of a same type):

- R_{ij} … trigger rate (experiment)
- $\hat{R}^0_{ij}$ … rate approximation (Monte Carlo simulations)

Telescope-wise:

- ε_i … optical efficiency ($0 \leq \varepsilon \leq 1$)

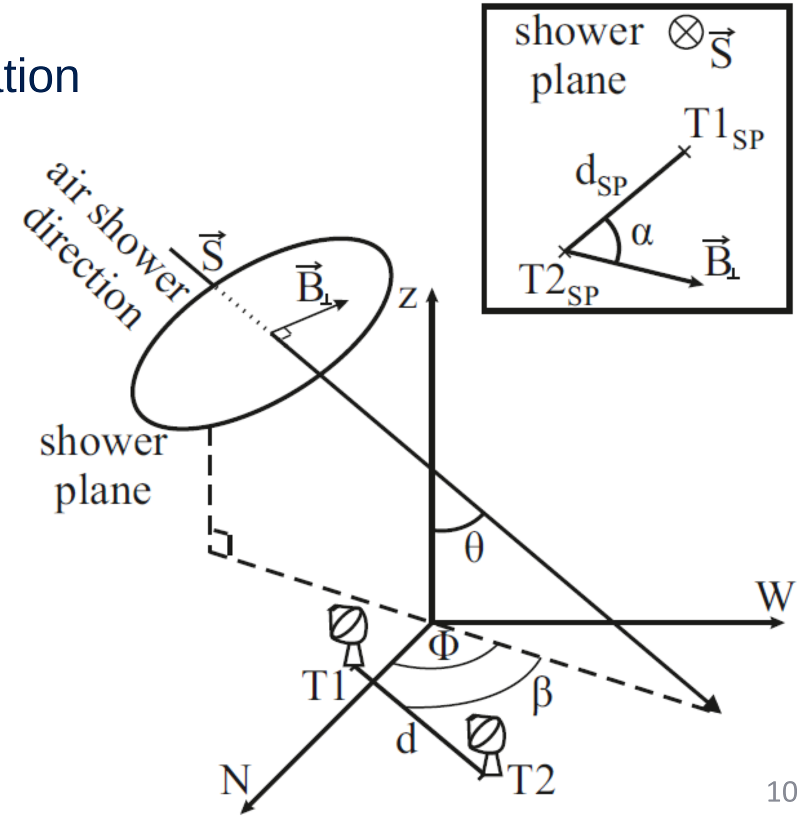
Array-wise:

- N … no. of active telescopes
- P … no. of chosen pairs
- $\mathcal{K}$ … normalization
- $\mathcal{O}$ … observation conditions (θ, β, d, B)

Monte Carlo study

- Study of the **pairwise** trigger rates

- MC simulations of air showers observed by CTA-N
  - primary particles = protons
  - 5 x 10^8 air showers per configuration
  - 0.004 – 100 TeV



Random fluctuations

Individual telescopes:

- Significant number of non-air-shower triggers
  - night sky background (NSB)
  - accidental triggers
  - muons

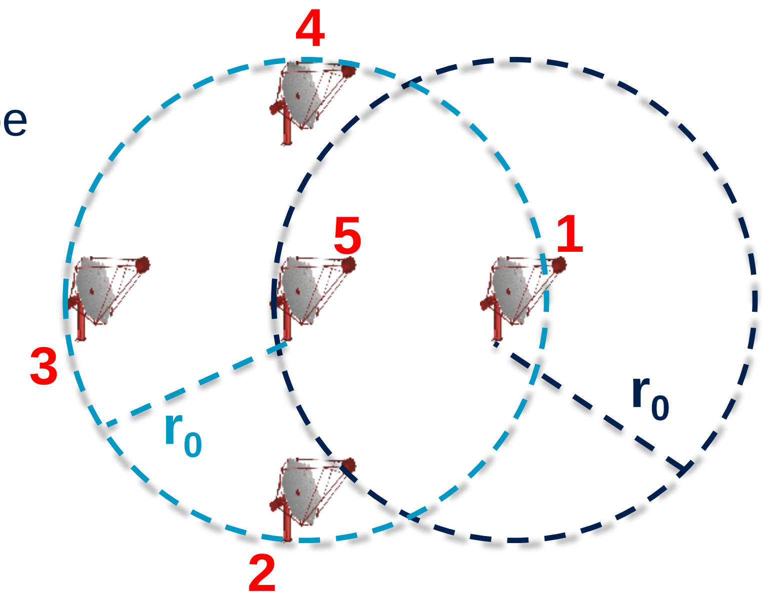
☞ **Use only stereo trigger rate**
(at least 2 telescopes in coincidence)

$$\hat{T} = \frac{1}{P \cdot \mathcal{K}} \sum_{\substack{i=1 \\ i<j}}^{N} \left(\frac{R_{ij}}{\varepsilon_i \cdot \varepsilon_j \cdot \hat{R}_{ij}{}^{0}} \right)^{\frac{1}{1.7}}$$

Telescope array layout

Stereo trigger rate:

- Counting all events triggering a single telescope together with any other telescope:
  - trigger rates of individual telescopes depend on the array layout
  - higher rates for telescopes with more neighbours in the vicinity
- Observations by different sub-arrays:
  - many layout-dependent factors
  - not feasible for large arrays



# of neighbours: N_1 $(r < r_0) = 1$ — Trigger rate: $R_1 < R_5$

N_5 $(r < r_0) = 4$

Use only pairwise trigger rate: air showers detected by a selected pair of telescopes

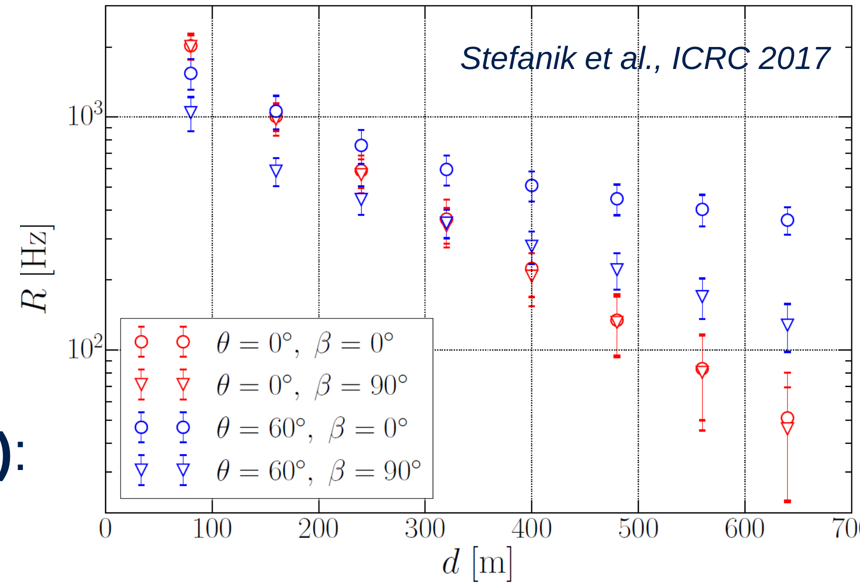
$$\hat{T} = \frac{1}{P \cdot \mathcal{K}} \sum_{\substack{i=1 \\ i<j}}^{N} \left(\frac{R_{ij}}{\varepsilon_i \cdot \varepsilon_j \cdot \hat{R}_{ij}{}^{0}} \right)^{\frac{1}{1.7}}$$

Geometrical configuration

Pairwise trigger rate:

- Increasing **zenith angle (*θ*)**:
  - larger area illuminated by Cher. light
    - trigger rate increase for distant tels.
  - smaller ground density of Cher. photons
    - trigger rate decrease
  - depends also on the inter-tel. distance

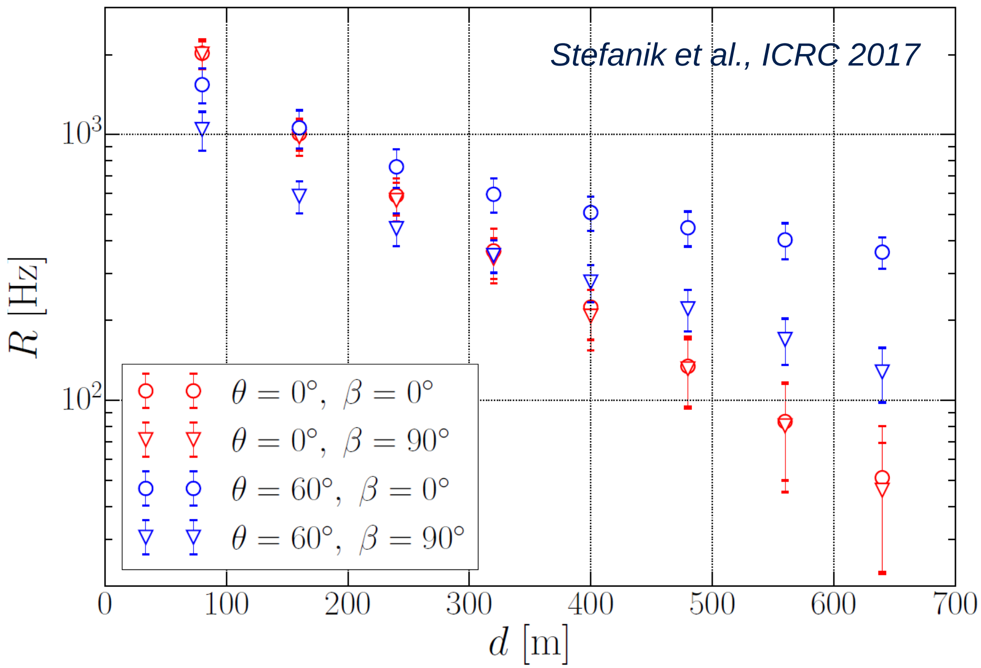
- Increasing **inter-telescope distance (*d*)**:
  - trigger rate decrease (for given *θ*)

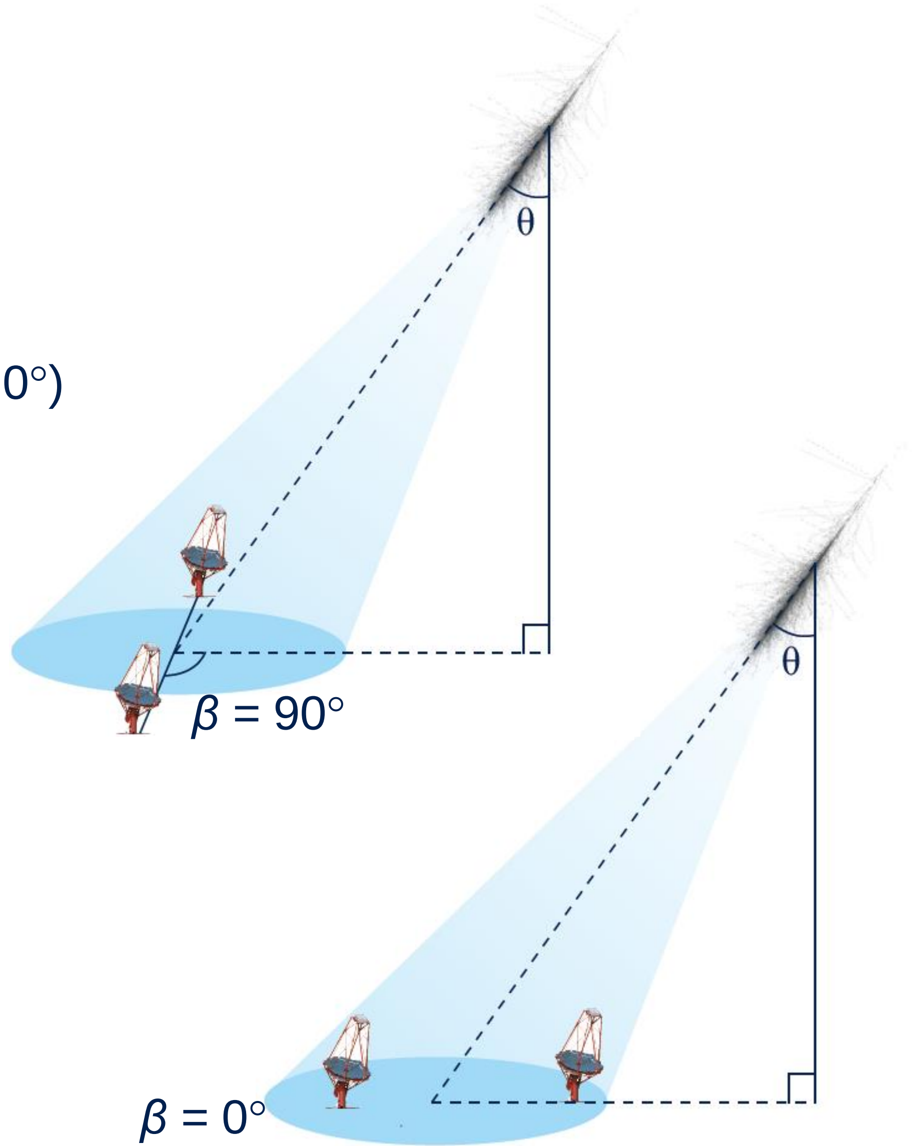


Geometrical configuration

Pairwise trigger rate:

- **Telescope alignment (*β*)**:
  - Cher. pool roughly elliptical for $\theta > 0°$
  - higher rate when line between tels. aligned with the shower direction ($\beta = 0°$)





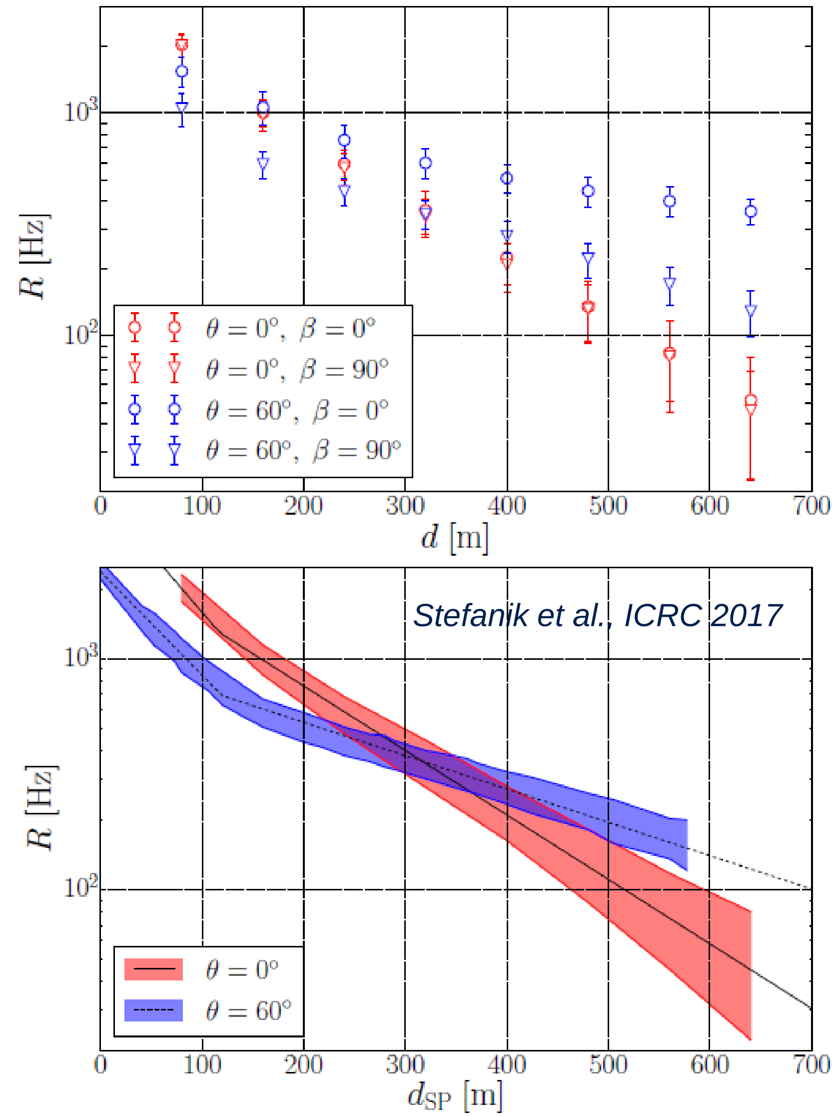
Geometrical configuration

Pairwise trigger rate:

- **Transform inter-telescope distance in the shower plane**
- **Estimate geometrical effects by a function $\hat{R}^0(\theta, d_{SP})$**

(valid for $\varepsilon = 1$ & $B = 0$)

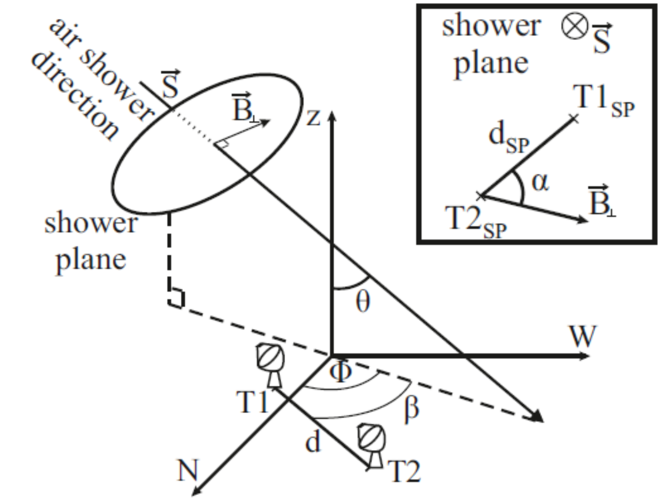
$$\hat{T} = \frac{1}{P \cdot \mathcal{K}} \sum_{\substack{i=1 \\ i<j}}^{N} \left(\frac{R_{ij}}{\varepsilon_i \cdot \varepsilon_j \cdot \hat{R}^0_{ij}} \right)^{\frac{1}{1.7}}$$

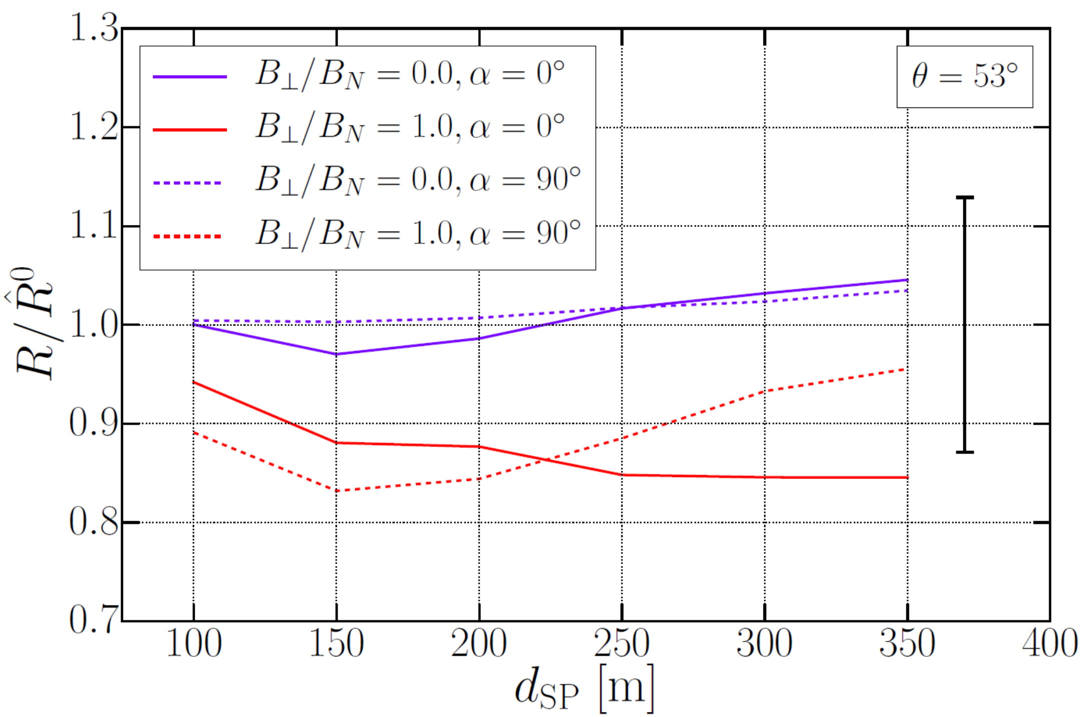


Geomagnetic field

- Pairwise trigger rates in the *B*-field:
  - deflection of charged particles in the air shower
  - governed by $B_\perp$ (Φ,θ) and the angle α

Systematic uncertainty estimate on $\hat{R}^0(\theta, d_{SP})$





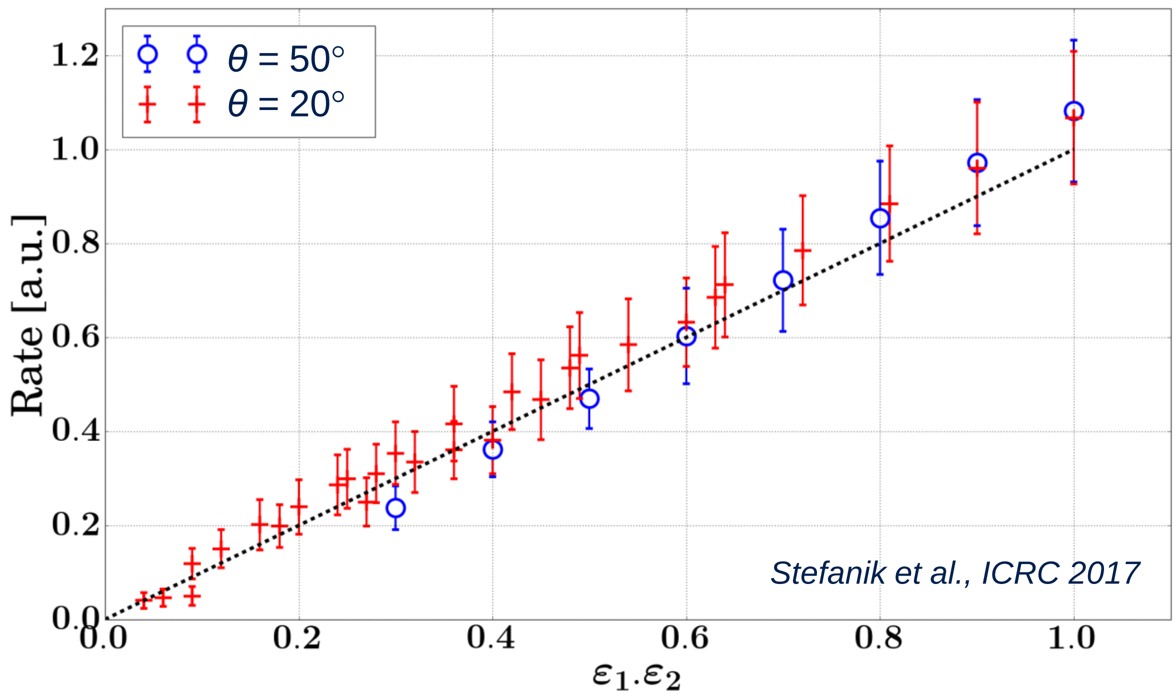
Telescope hardware

Optical elements & PMTs / SiPMs:

- Hardware degradation similar effect as long-term atmo. phenomena (less Cherenkov photons detected)
- Pairwise trigger rate affected by the optical efficiencies of **both** telescopes

Account for the optical throughput of both telescopes

$$\hat{T} = \frac{1}{P \cdot \mathcal{K}} \sum_{\substack{i=1 \\ i<j}}^{N} \left(\frac{R_{ij}}{\varepsilon_i \cdot \varepsilon_j \cdot \hat{R}^0_{ij}} \right)^{\frac{1}{1.7}}$$

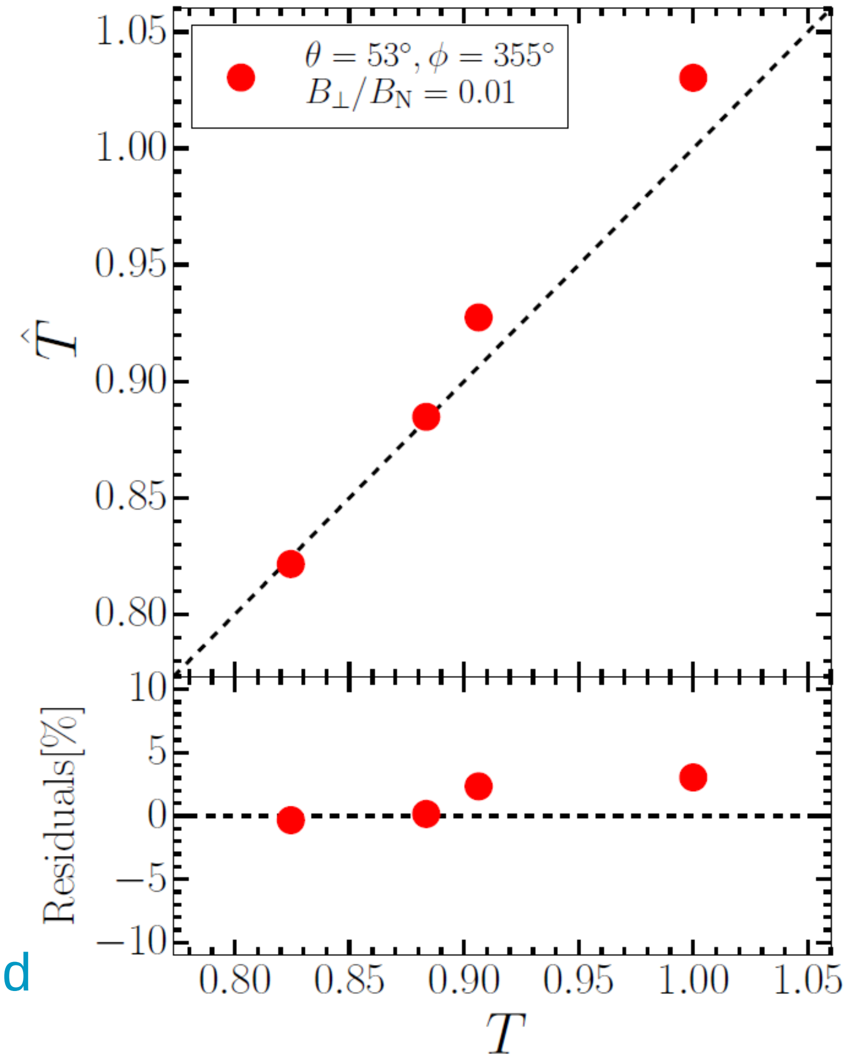


Atmospheric monitoring with the CTC

Aerosol optical depth

Test of the extended CTC method (MC):

- CTA-N layout (4 LSTs, 15 MSTs)
- Random degraded optical efficiencies
- **4 AOD profiles** (MODTRAN):
  - no aerosols
  - navy maritime
  - desert
  - tropospheric
- Same molecular density profile
- Atmospheric transparency reconstructed with a **resolution of 3%**



Molecular density profile

Test of the extended CTC method (MC):

- CTA-N layout (4 LSTs, 15 MSTs)
- Random degraded optical efficiencies
- $\theta = 53°$, $\Phi = 355°$, $B_{\perp} / B_{N} = 0.01$
- **7 molecular density profiles**
  (see talk by P. Munar-Adrover)
- No aerosols
- **CTC consistent for all profiles**

Profile	$\hat{T}$
CTA-N template	1.03
Average summer	0.99
Average winter	1.01
Density minimum at 14 km	0.99
Density maximum at 16 km	1.00
Density minimum at 7 km	1.00
Density maximum at 5 km	1.02

Caveats and technique uncertainties

- Statistical uncertainty ~ 14%
  - low trigger efficiency for proton-initiated air showers
  - uncertainty will be negligible for the CTA observations
- Systematic uncertainty ~ 5%
  - for small influence of the geomagnetic field
- Optical throughput has to be estimated by another procedure
  - contribution to the uncertainty on the CTC (e.g. ~ 4% for muons)
- CTC is an integral measure of the AOD:
  - below the production height of air showers
  - in the wavelength range covered by Cherenkov radiation (no information about wavelength dependency of the AOD)
- CTC applicable in systems with stable trigger energy thresholds
  - further treatment necessary to adapt for individual camera pixel control

Summary

Summary

- Cherenkov Transparency Coefficient:
  - stable measure of the atmospheric transparency to Cherenkov light
  - non-invasive method (calculated from telescope data)
  - same field of view & time range as observations
  - no interference with the observatories on site

- CTC adapted for CTA

- Atmospheric monitoring with the CTC:
  - resolution ~ 3% for different aerosol concentrations (MC simulations)
  - not sensitive to variations of molecular density profile

- Future steps:
  - cross-check with real data & other instruments
  - CTC under dynamic trigger energy thresholds
  - CTC under different NSB levels

cta cherenkov telescope array

Thank you!

Questions? ☺