Fluorescence light emission in CORSIKA 8

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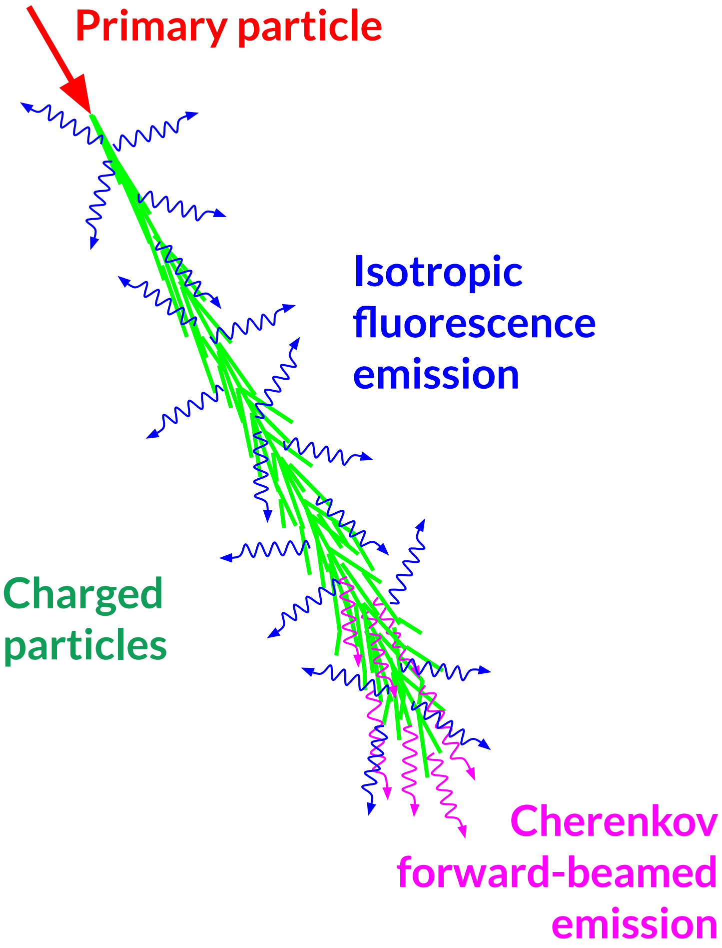
CORSIKA 8 Workshop 2023

Outline

- Motivation
    - Cherenkov vs fluorescence
    - Relevance of fluorescence in the Cherenkov technique
    - Cherenkov telescopes in “fluorescence mode”
- Implementation in CORSIKA 7
- Towards fluorescence implementation in CORSIKA 8

Light emission in EAS



Primary particle

Isotropic fluorescence emission

Charged particles

Cherenkov forward-beamed emission

Cherenkov

- Concentrated along the shower axis ~1°
- Emission $\propto 1/\lambda^2$ peaking at 300-450 nm
- Pulse width ~ nanoseconds

Fluorescence

- Isotropic
- De-excitation of N_2 states

Both **arrive simultaneously** (Cherenkov observations) and within **similar spectral range**

Different light yield. 1-GeV electron in 1 m of atmosphere near the ground produces:

- 30 Cherenkov photons
- 4 fluorescence photons

Motivation: Relevance of fluorescence in the Cherenkov technique

Fluorescence light **indistinguishable from Cherenkov** signal:

- Similar spectral range and pulse width

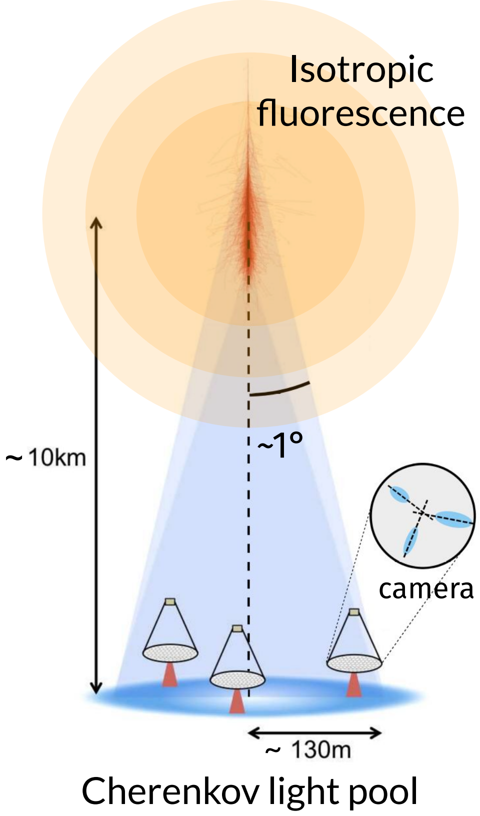
Fluorescence is a small contribution compared with Cherenkov light and **normally neglected**:

- Isotropic emission
- Lower light yield than Cherenkov

Is the fluorescence radiation ***always negligible*** in Cherenkov telescopes?

Method: systematic MC study with CORSIKA to quantify its effect

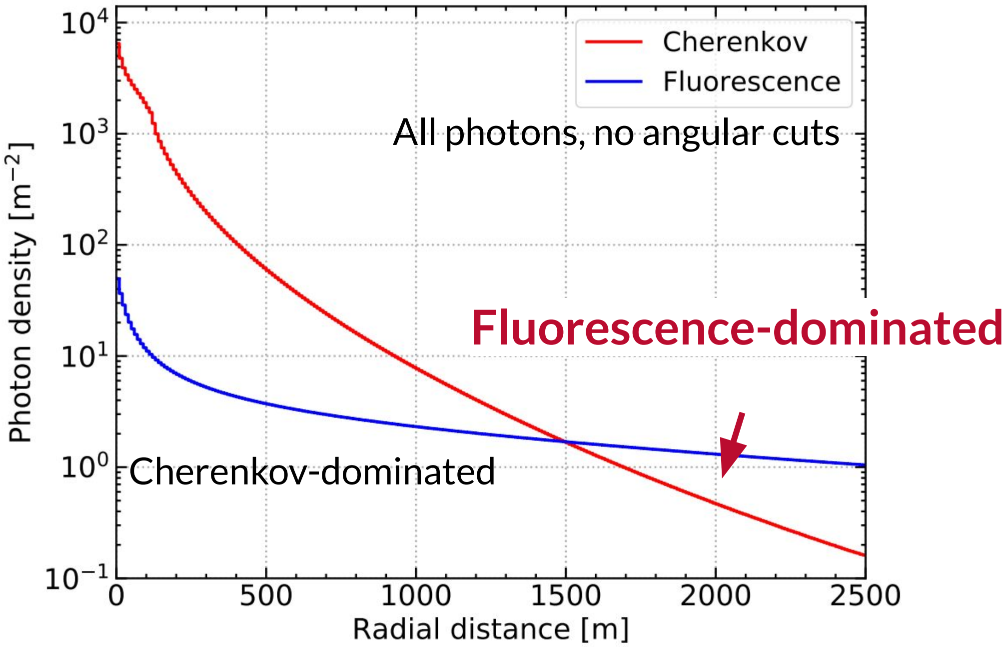
D. Morcuende et al. Astropart. Phys. 107 (2019) 26-34



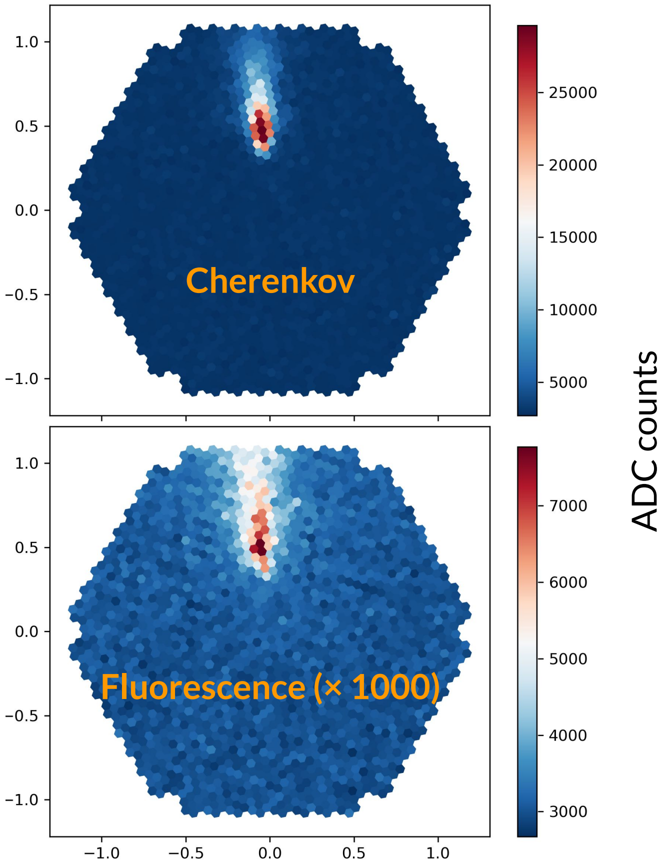
Motivation: Relevance of fluorescence in the Cherenkov technique

Fluorescence comparable at *O*(km) core distances and dominates at greater distances (could be non-negligible for km-scale arrays like CTA)

Similar charge and temporal distributions of across the camera of a Cherenkov telescope (CORSIKA 7 + sim_telarray)



Distribution of both light components on the ground:
10 TeV vertical gamma showers



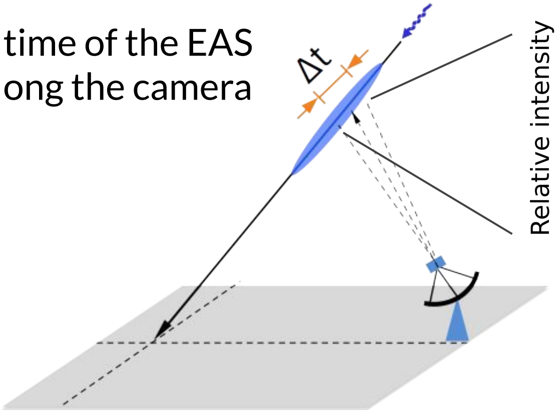
Motivation: Cherenkov telescopes in “fluorescence mode”

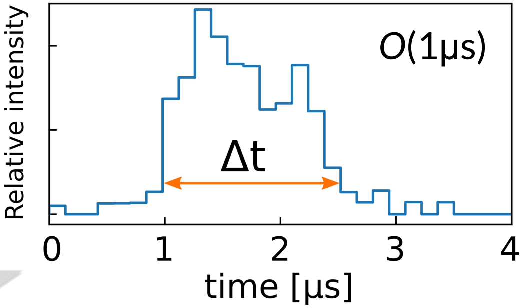
Inspired in the fluorescence telescopes, large arrays of Cherenkov telescopes (CTA) **simultaneously running as a fluorescence observatory** by also observing showers sideways. First proposed in PoS(ICRC2015)993

Aim: **larger effective area -> higher energies not extensively explored yet -> PeVatrons**

Method: **MC simulations** including the telescopes (sim_telarray) + **modelling** (ShowerModel)
-> Adapt the Trigger & Readout system of the cameras

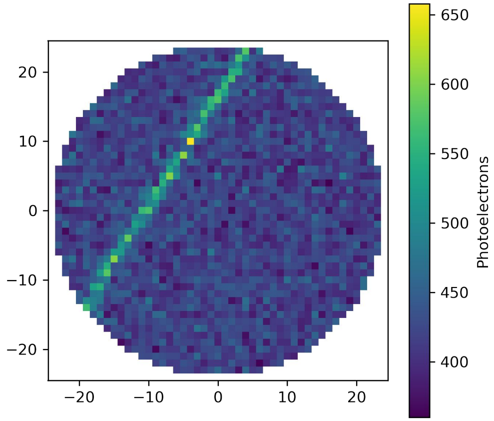
Transit time of the EAS trace along the camera



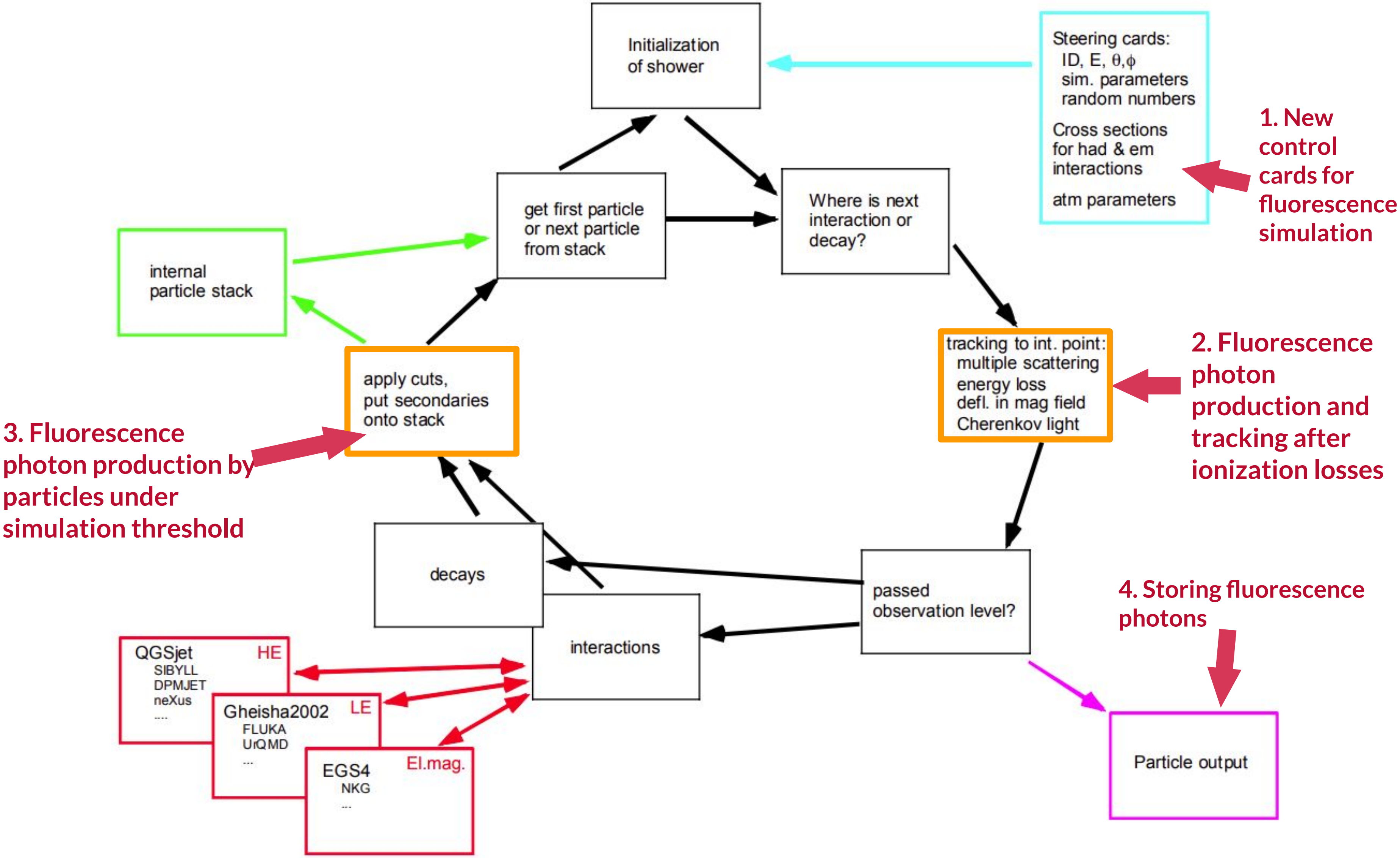


vs Cherenkov mode O(10-100 ns)

Trace in the camera



Implementation of fluorescence in CORSIKA 7



1. New control cards for fluorescence simulation

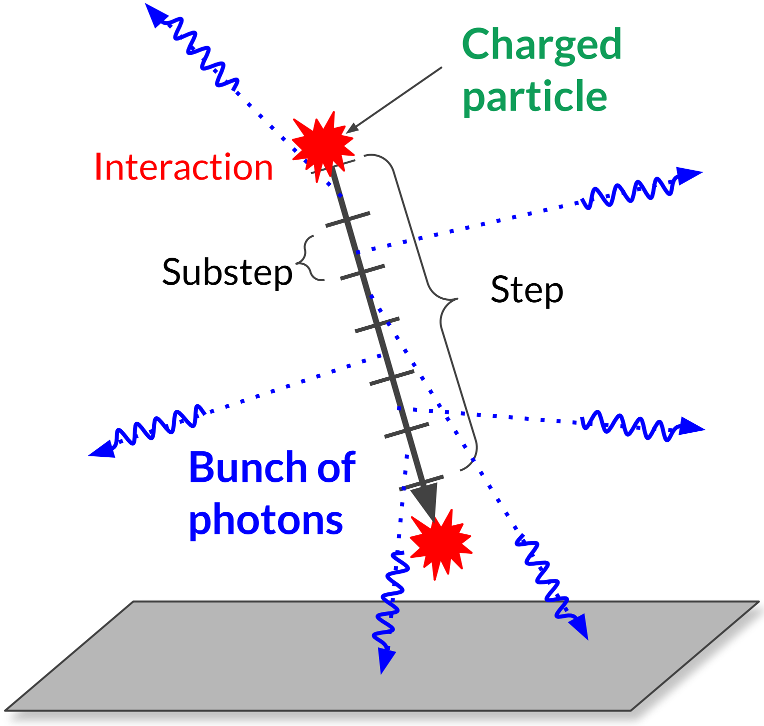
2. Fluorescence photon production and tracking after ionization losses

3. Fluorescence photon production by particles under simulation threshold

4. Storing fluorescence photons

Modifications in the workflow of CORSIKA to include fluorescence emission.

Implementation of fluorescence in CORSIKA 7



Implemented FORTRAN routines available in github.com/morcuended/test-fluorescence

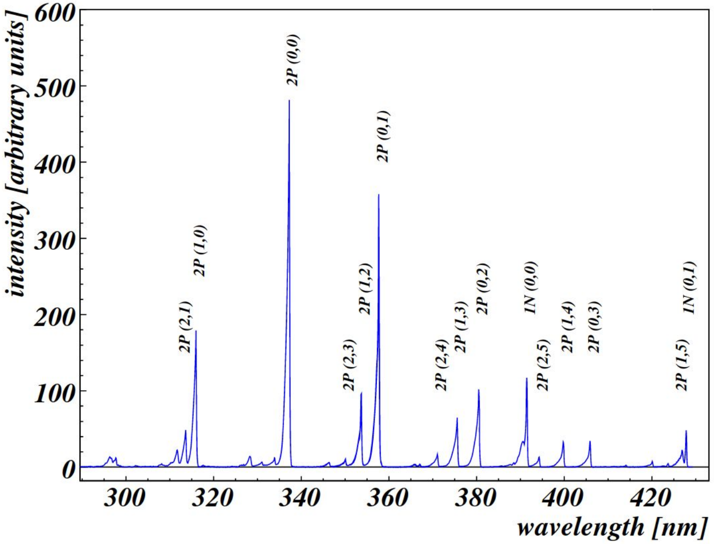
- **New routines** adapted from the Cherenkov one
- Particle steps between two interactions: E_{dep}
- Subdivide in smaller steps when deposited energy is larger than 200 MeV or step length is larger than 20 m to keep granularity of simulations. Constant energy deposit per substep is assumed
- **Bunches of fluorescence photons** from each substep produced **isotropically** according to fluorescence parameterization:

$$dN/dX = Y_\lambda(P, T, h)\, dE/dX$$

- **Wavelength** assigned to each bunch from a known **fluorescence spectrum**
- We keep either all photons on ground or in volumes around telescopes (IACT option)

Production of fluorescence photons in CORSIKA 7

Fluorescence spectrum (AIRFLY Coll.)



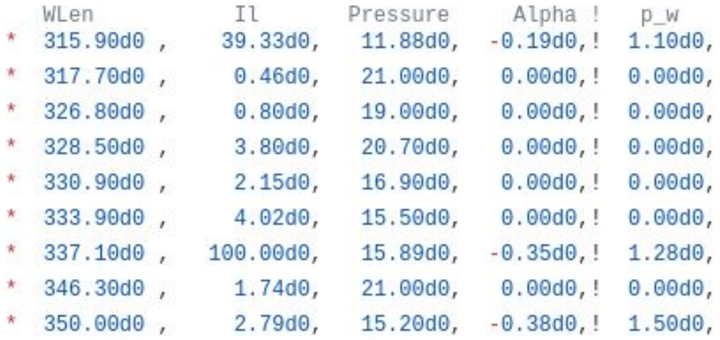
Fluorescence parameterization:

$$dN/dX = Y_\lambda(P, T, h)\, dE/dX,$$

with **fluorescence yield $Y_\lambda(P, T, h)$** for any molecular band given as a function of the 337 nm band:

$$Y_\lambda(P, T, h) = Y_{337}(P_0, T_0)\, I_\lambda(P_0, T_0)\, \frac{1 + P_0/P'_{337}(T_0)}{1 + P/P'_\lambda(T, h)}$$

where $Y_{337}(P_0, T_0) = 7.04 \pm 0.24\ \mathrm{MeV}^{-1}$. Relative intensities and all other needed parameters are provided:



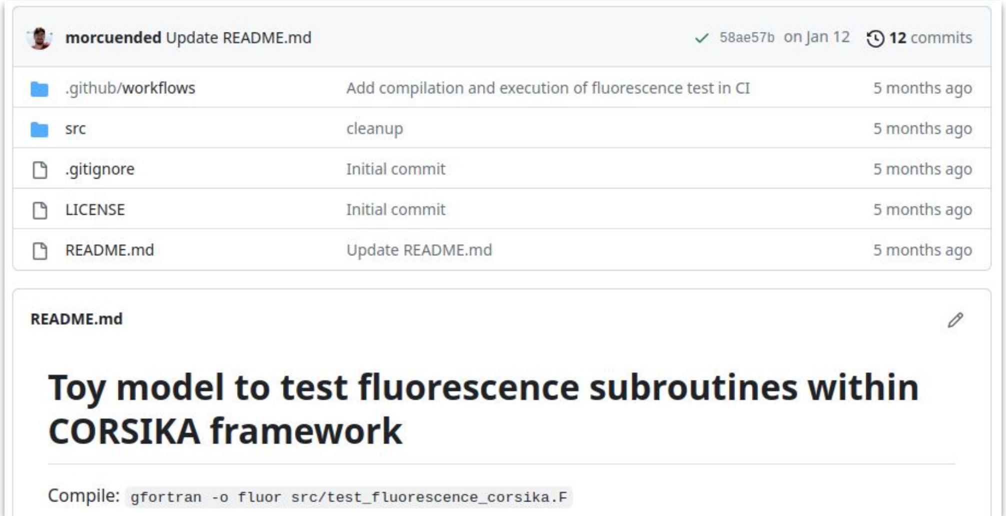
```
      WLen           Il       Pressure    Alpha !   p_w
*  315.90d0 ,    39.33d0,    11.88d0,  -0.19d0,!  1.10d0,
*  317.70d0 ,     0.46d0,    21.00d0,   0.00d0,!  0.00d0,
*  326.80d0 ,     0.80d0,    19.00d0,   0.00d0,!  0.00d0,
*  328.50d0 ,     3.80d0,    20.70d0,   0.00d0,!  0.00d0,
*  330.90d0 ,     2.15d0,    16.90d0,   0.00d0,!  0.00d0,
*  333.90d0 ,     4.02d0,    15.50d0,   0.00d0,!  0.00d0,
*  337.10d0 ,   100.00d0,    15.89d0,  -0.35d0,!  1.28d0,
*  346.30d0 ,     1.74d0,    21.00d0,   0.00d0,!  0.00d0,
*  350.00d0 ,     2.79d0,    15.20d0,  -0.38d0,!  1.50d0,
```

Independent of *E* and type of ionizing particle

Implemented FORTRAN routines available in github.com/morcuended/test-fluorescence

Production of fluorescence photons in CORSIKA 7

Fluorescence yield parameterization available in github.com/morcuended/test-fluorescence as a toy-model example of its usage



morcuended Update README.md ✓ 58ae57b on Jan 12 **12** commits

.github/workflows	Add compilation and execution of fluorescence test in CI	5 months ago
src	cleanup	5 months ago
.gitignore	Initial commit	5 months ago
LICENSE	Initial commit	5 months ago
README.md	Update README.md	5 months ago

README.md

Toy model to test fluorescence subroutines within CORSIKA framework

Compile: `gfortran -o fluor src/test_fluorescence_corsika.F`

FYIELD subroutine to calculate the number of produced fluorescence photons given an energy deposit and height of emission based on parameterized fluorescence spectrum. It also determines the wavelength.

- Depends on pressure and temperature

Some **functions** to calculate **atmospheric parameters**

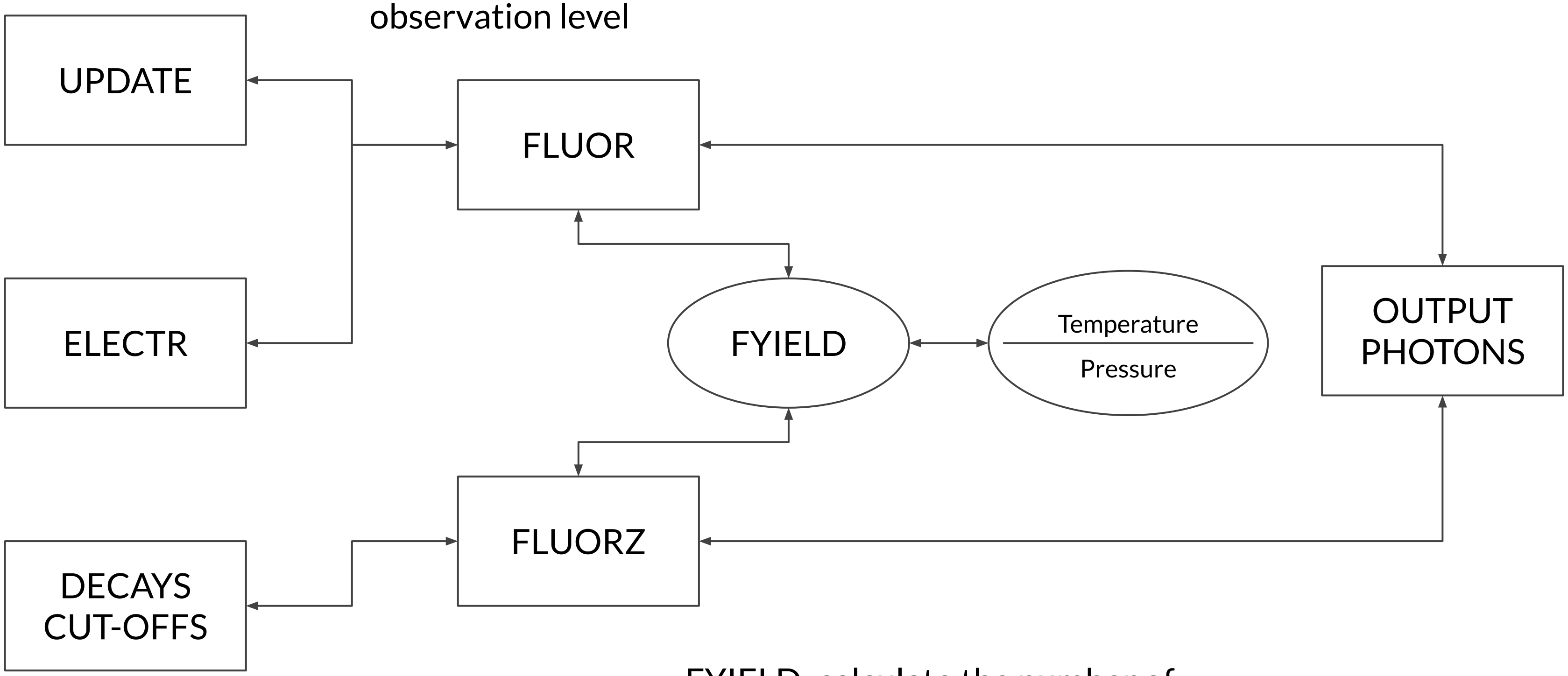
Some other general CORSIKA subroutines:

- Simple example atmosphere
- Random number generator

Another routine (not in this repository), analog to the Cherenkov one propagates isotropically the emitted photons to the observation level/telescopes

Production of fluorescence photons in CORSIKA 7

FLUOR: analog to Cherenkov routine. Propagate photons to observation level

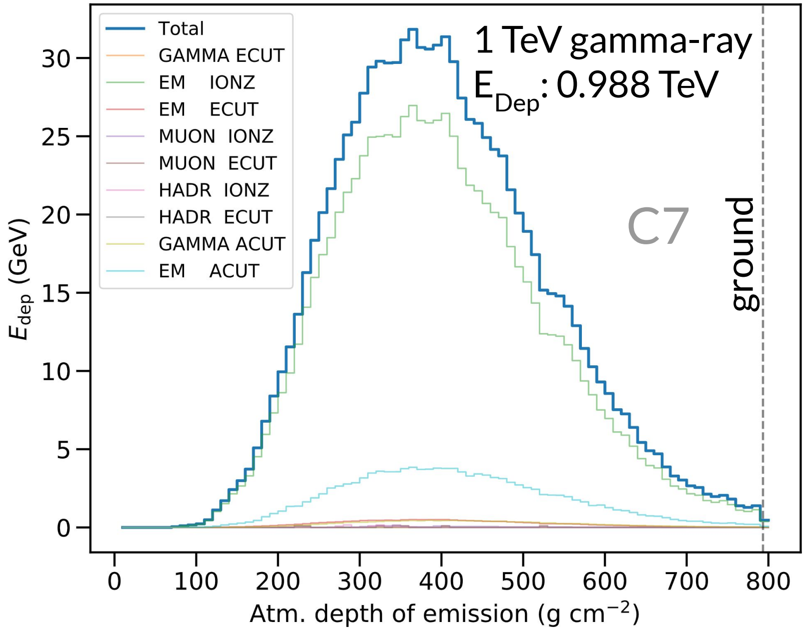


FYIELD: calculate the number of fluorescence photons to be emitted along with their wavelength (based on a known air-fluorescence spectrum)

CORSIKA core routines:
- Particle tracking
- Decays
- Simulation cut-offs

Required aspects for implementation in CORSIKA 8

- **Input interface**: size of simulated bunches of photons, seeds for random number generation, range of wavelengths.
- **Tracking of charged particles** (hadronic and EM component)
- **Deposition of energy**:
  - Ionization
  - Sub-threshold particles
- Tabulated **atmosphere**: fluorescence yield depends on atmospheric conditions (temperature, pressure and humidity)
- **Output interface** for Cherenkov and fluorescence photons



Longitudinal profile of deposited energy

With these ingredients in place fluorescence emission could be added (translating the FORTRAN code to C++)

Summary

- Implemented fluorescence light emission in CORSIKA 7

  (Astroparticle Physics 107 (2019) 26–34)

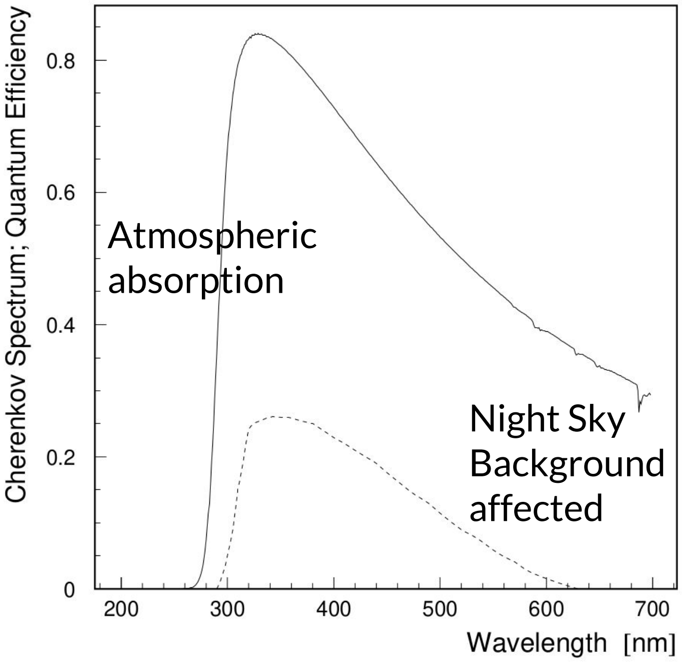
- Source code of the implementation available at

  https://github.com/morcuended/test-fluorescence

- Starting point for implementing fluorescence light emission in CORSIKA 8

Backup

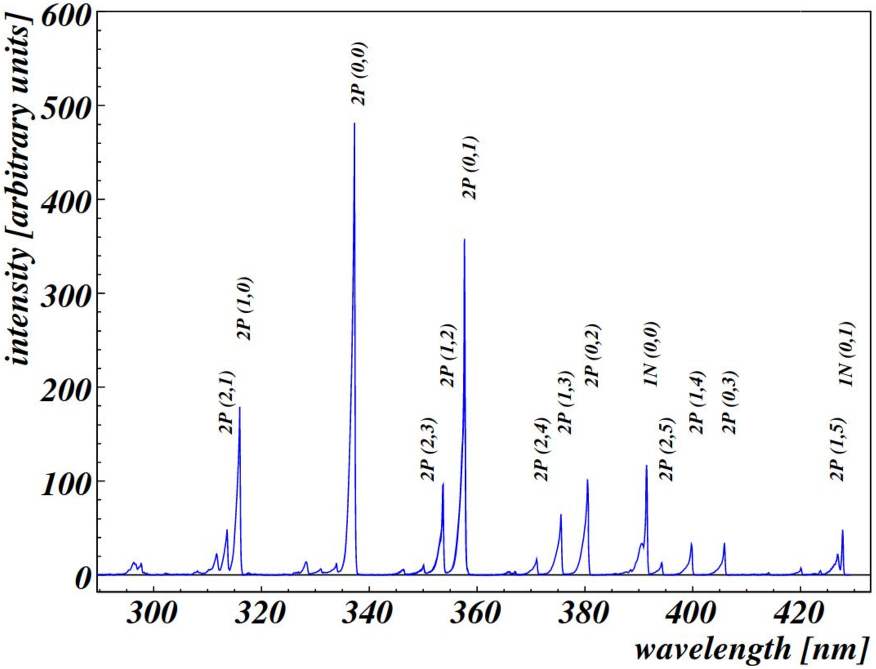
Cherenkov and fluorescence light spectrum



Atmospheric absorption

Night Sky Background affected

Cherenkov spectrum 2200 masl. Dashed line is the QE of HEGRA's PMTs. From Doering et al. (2001).



Air fluorescence spectrum by AIRFLY Collaboration produced by 3 MeV electrons at 800 hPa

Fluorescence light spectrum

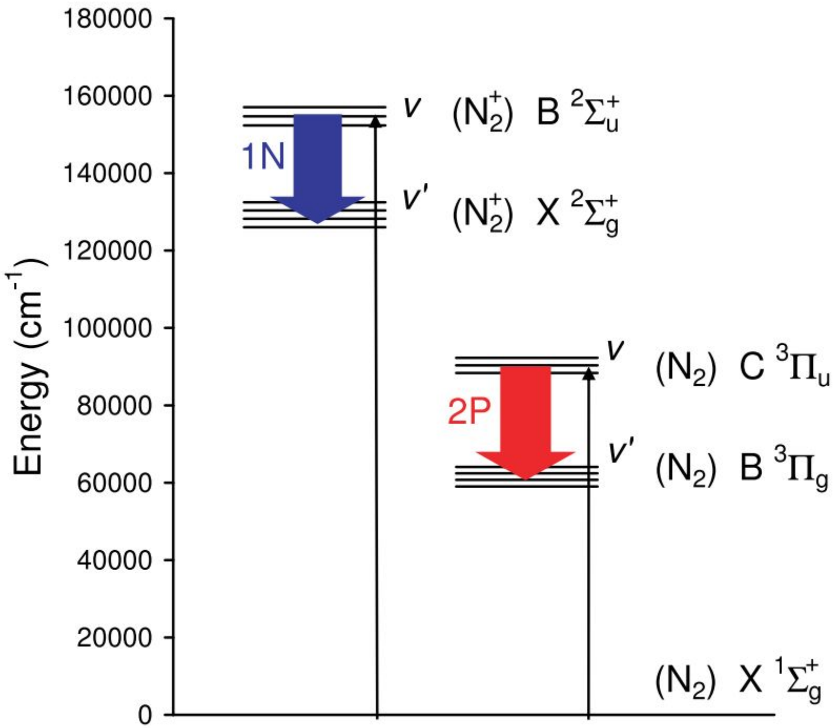
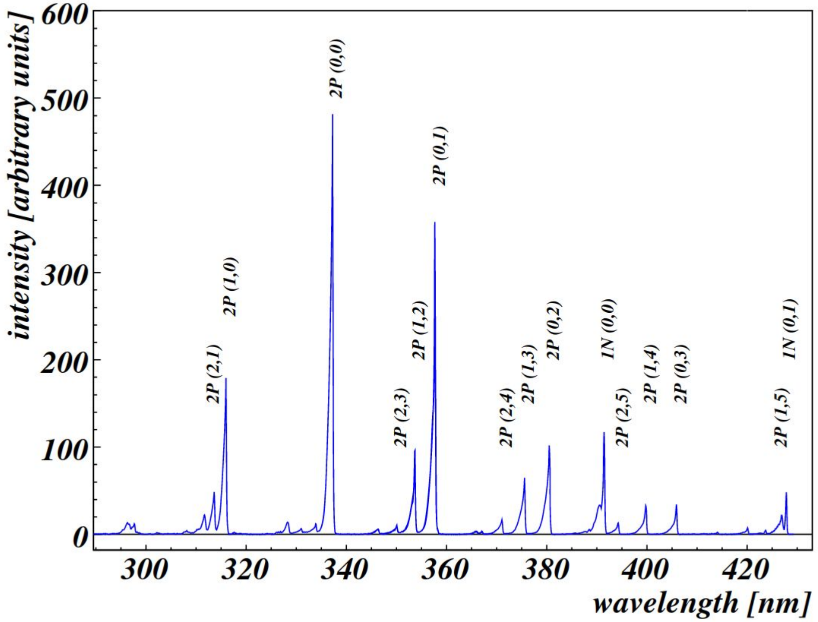


Figure 1. Schematic diagram of the main nitrogen molecular levels involved in the air-fluorescence emission (red and blue arrows) following electron excitation (thin black arrows).

Air fluorescence spectrum by AIRFLY
produced by 3 MeV electrons at 800 hPa



Modifications in CORSIKA

1. Include new cards to steer fluorescence simulation.
2. Add parametrization of fluorescence emission by particles after an energy deposit.
3. Add calls to fluorescence emission associated to ionization losses while tracking.
4. Add calls to fluorescence emission for particles under simulation thresholds due to energy limits (particles with energy below cutoff) and angular limits (CORSIKA cuts upward going particles). Lots of different processes involved, up to now 96% of deposited energy included.
5. Track fluorescence photons to ground.
6. Store Fluorescence photons in output.

Output of fluorescence photons in CORSIKA 7

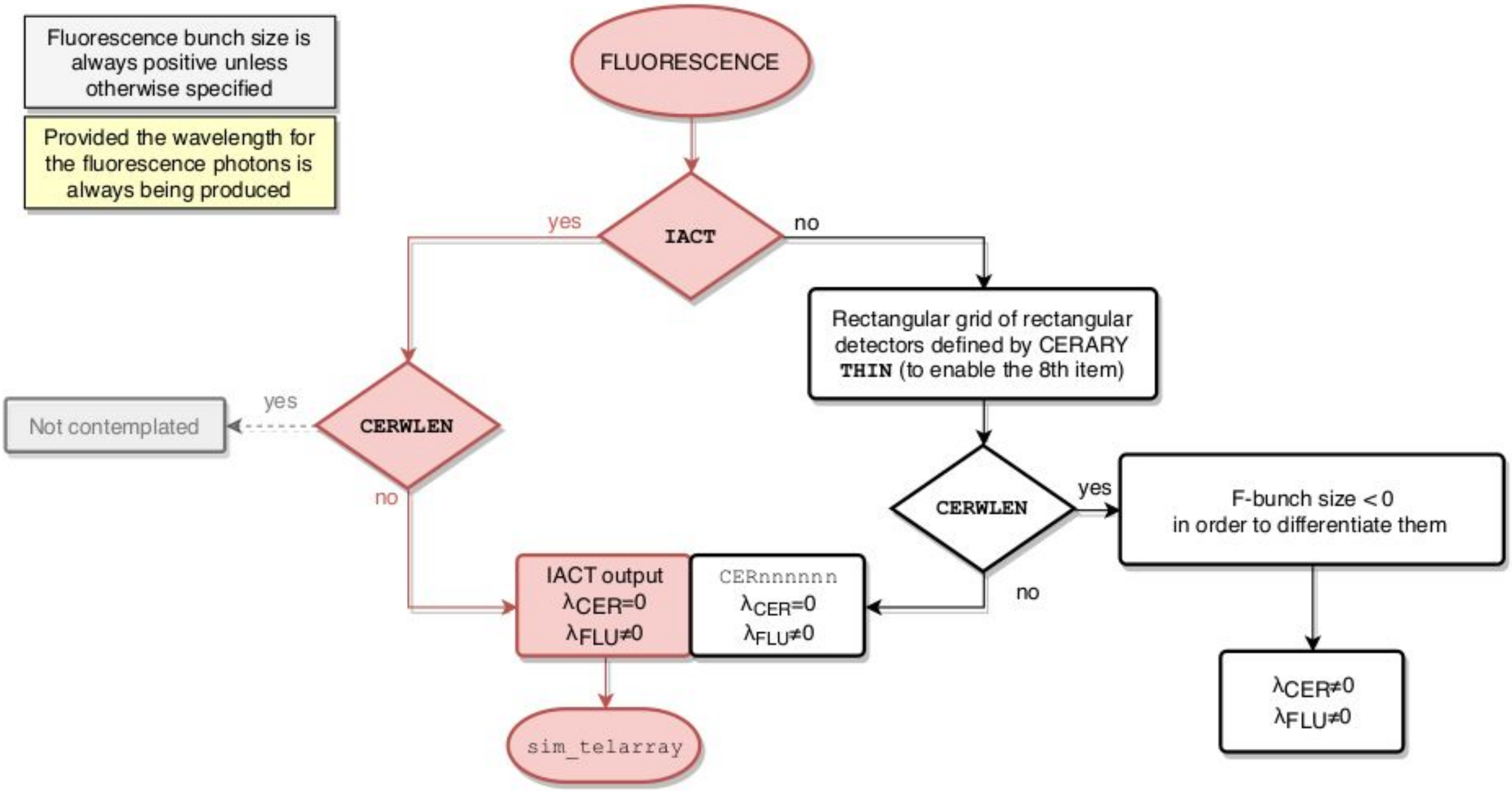
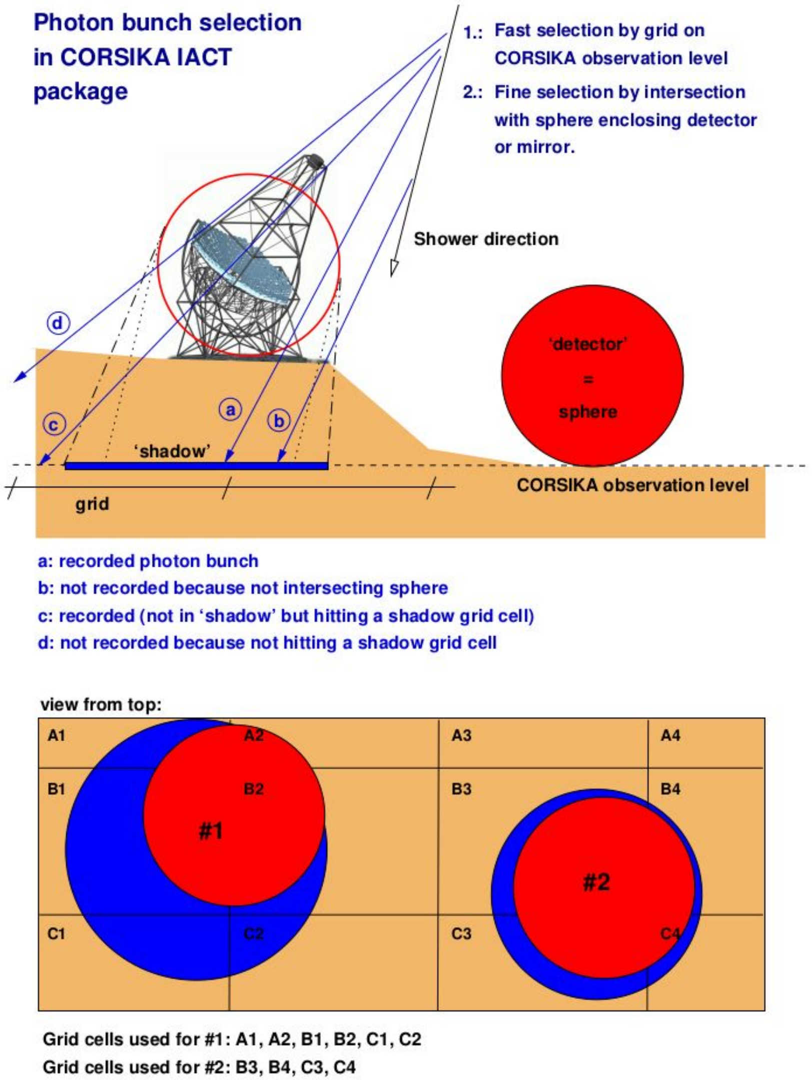


Figure 2.5: Output format according to the selected compiling options.

IACT geometry - Cherenkov emission in CORSIKA



1.: Fast selection by grid on CORSIKA observation level

2.: Fine selection by intersection with sphere enclosing detector or mirror.

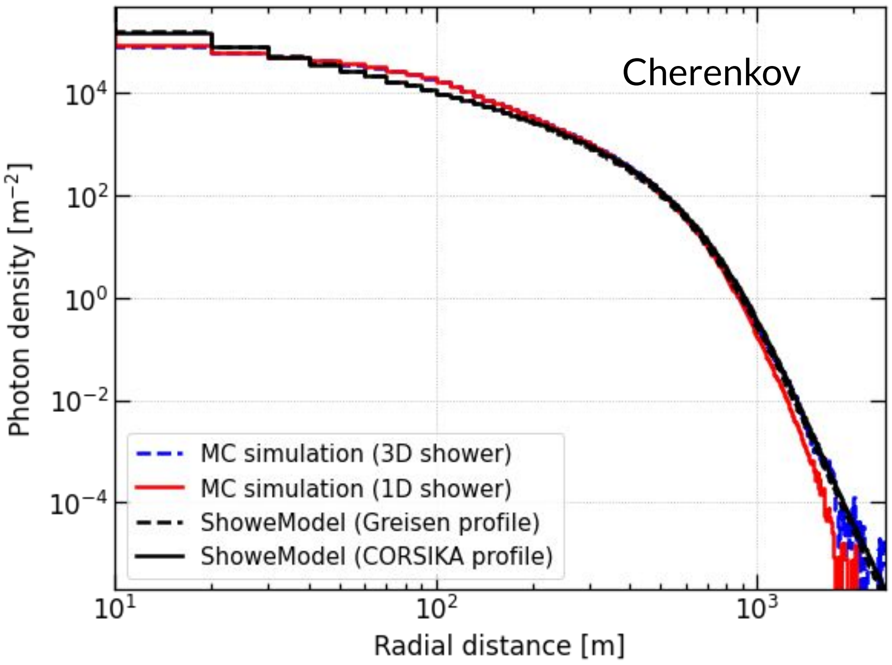
a: recorded photon bunch
b: not recorded because not intersecting sphere
c: recorded (not in 'shadow' but hitting a shadow grid cell)
d: not recorded because not hitting a shadow grid cell

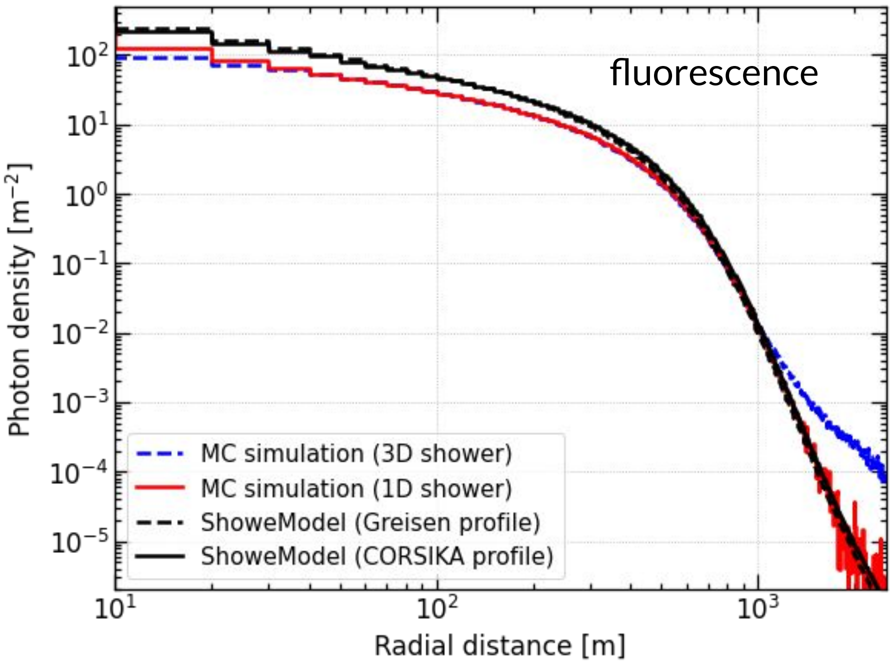
Grid cells used for #1: A1, A2, B1, B2, C1, C2
Grid cells used for #2: B3, B4, C3, C4

Credit: Konrad Bernlöhr

ShowerModel (MC validation)

Validation of fluorescence and Cherenkov simulations





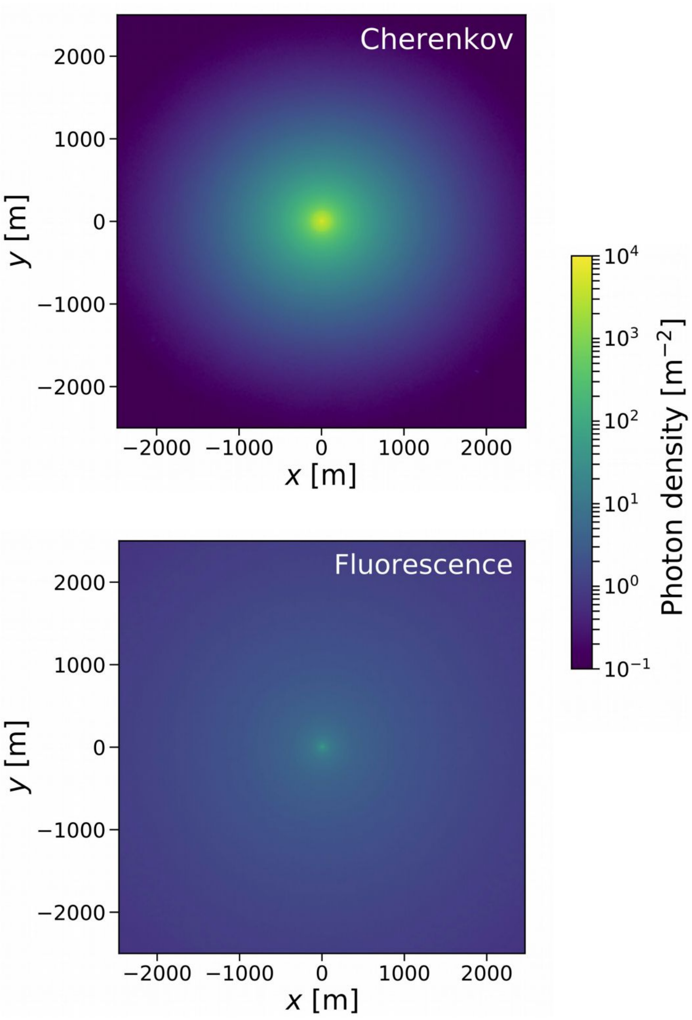
Fluorescence relevance in the Cherenkov technique

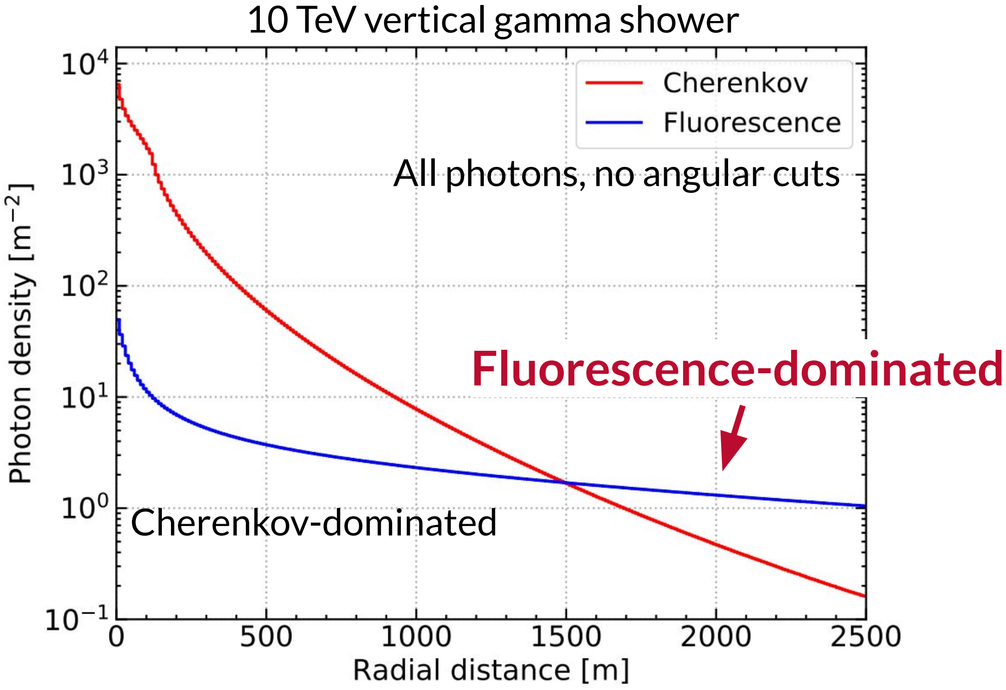
D. Morcuende, J. Rosado, J. L. Contreras, F. Arqueros, Astrop. Phys., 107, 2019, 26-34
https://doi.org/10.1016/j.astropartphys.2018.11.003

F. Arqueros et al 2019 J. Phys.: Conf. Ser. 1181 012047 10.1088/1742-6596/1181/1/012047

- Description of the fluorescence implementation in CORSIKA 7
- Systematic study of the fluorescence contamination in two Cherenkov detection techniques:
    - Imaging Air Cherenkov Telescopes (IACTs)
    - Wide Angle Cherenkov Timing Detectors (WACDs)
- Validation against semi-analytical model

Relevance of fluorescence in the Cherenkov technique





2-D distributions (left) and lateral profile (right) of light on the ground for both light components.

Fluorescence comparable at ~ km distances and dominates at greater distances

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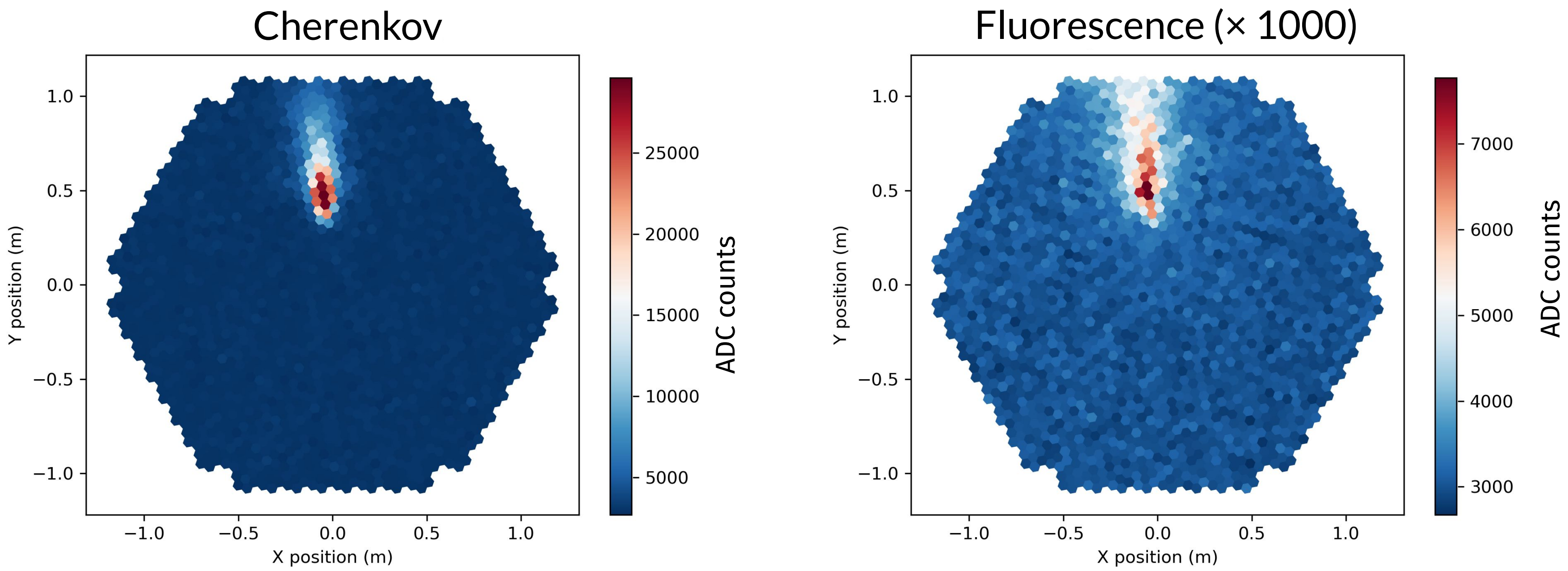
Distribution of light in the camera of an IACT

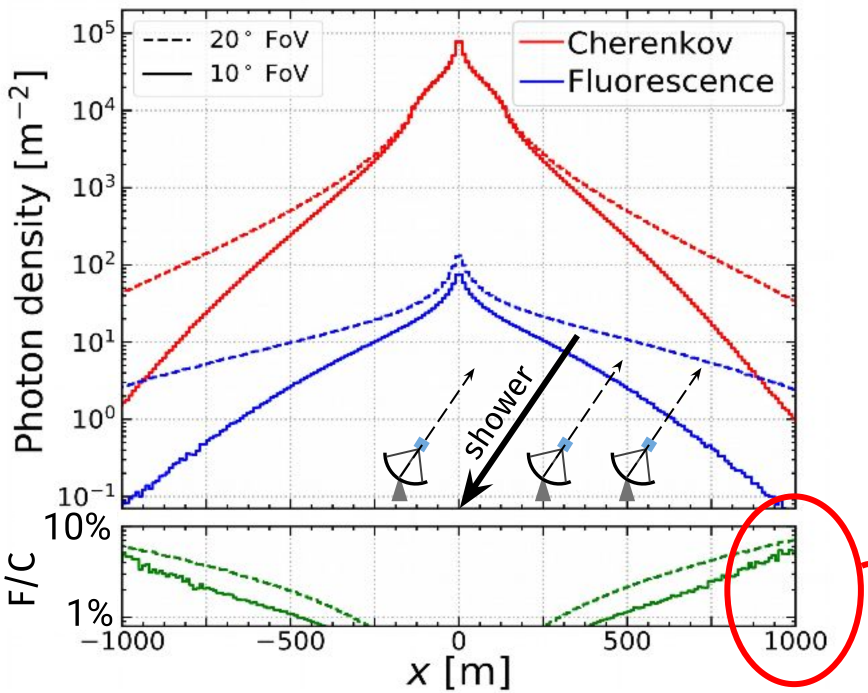
Similar charge and temporal distributions of both light components across the camera of a **Cherenkov telescope** (end-to-end simulation CORSIKA + sim_telarray)



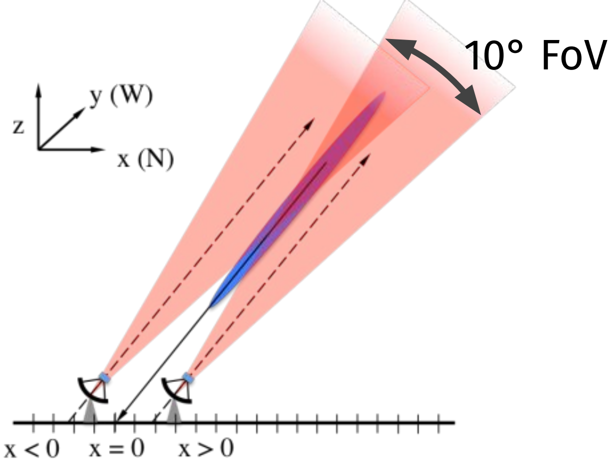
Simulated CTA Large-Sized Telescope camera images from Cherenkov and fluorescence light with CORSIKA 7 and sim_telarray. Impact parameter < 100 m.

Example: fluorescence contamination in IACTs (e.g. CTA)

Lateral light profiles



e.g. 100 TeV gamma-showers, θ = 20 deg



Small effect but sizable at large distances

Fluorescence ~ 5% of the recorded signal

Effect of field of view in the fluorescence contamination: smaller FoV -> more limited for isotropic fluorescence light whereas beamed Cherenkov is not that affected near the impact point.

ShowerModel

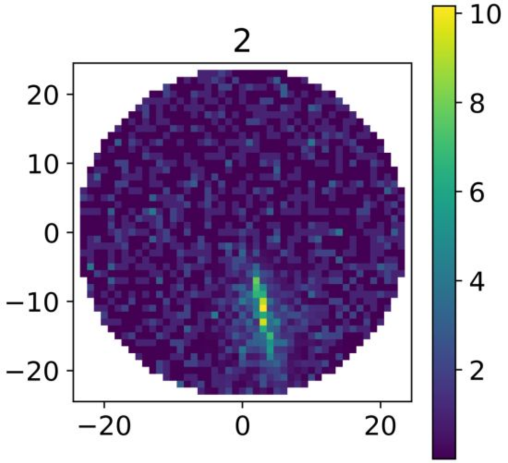
Python package for **fast end-to-end modelling of EAS**, their light production and their detection

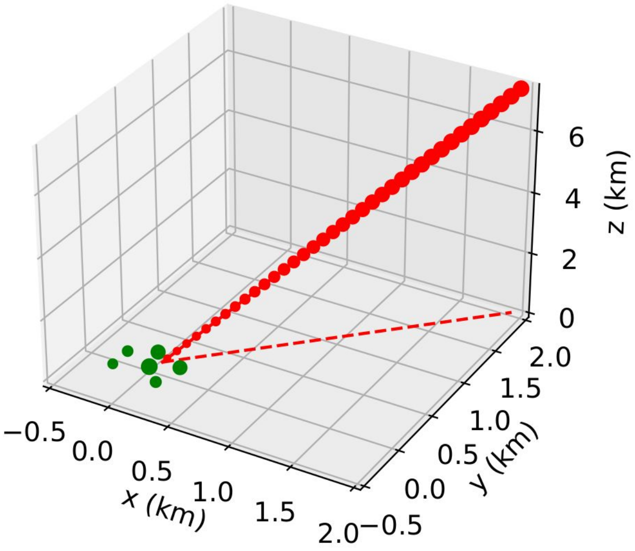
Code available at
github.com/JaimeRosado/ShowerModel

ADASS XXX (ASP Conference Series, Vol. 532)

Features:

- Design array of telescopes/detectors
- Shower track projections
- Longitudinal profiles
- Cherenkov and fluorescence production
- Camera image

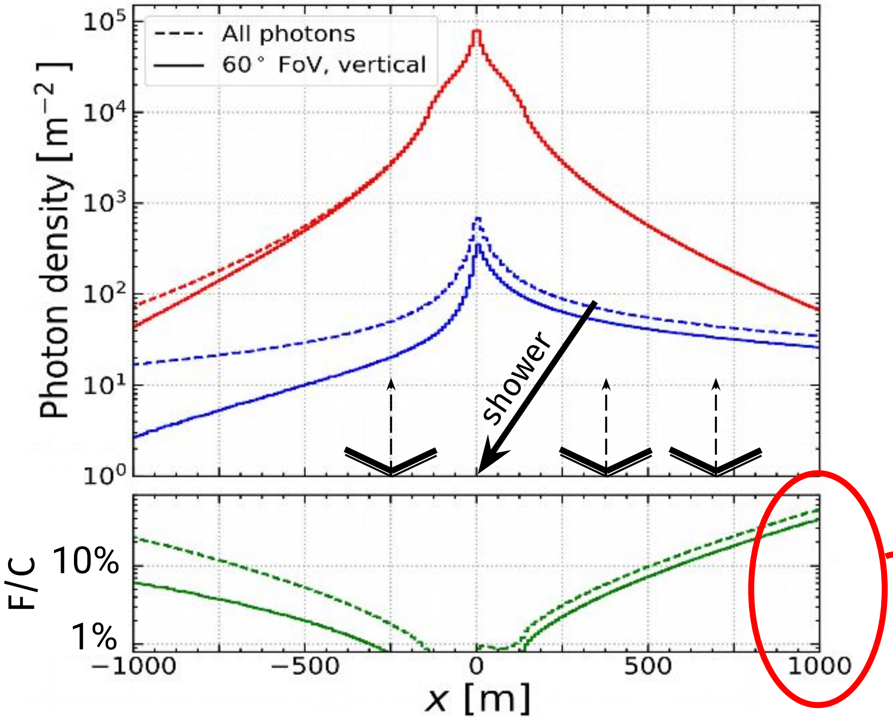




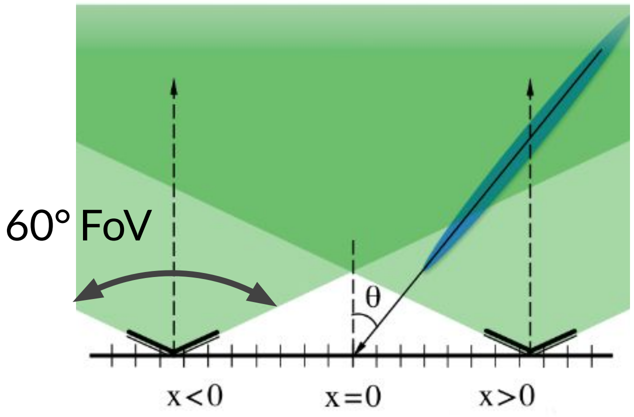
Example of IACT camera image (left) and shower track projection and layout of six telescopes (right) modeled with ShowerModel.

Fluorescence contamination in WACDs

Lateral light profiles



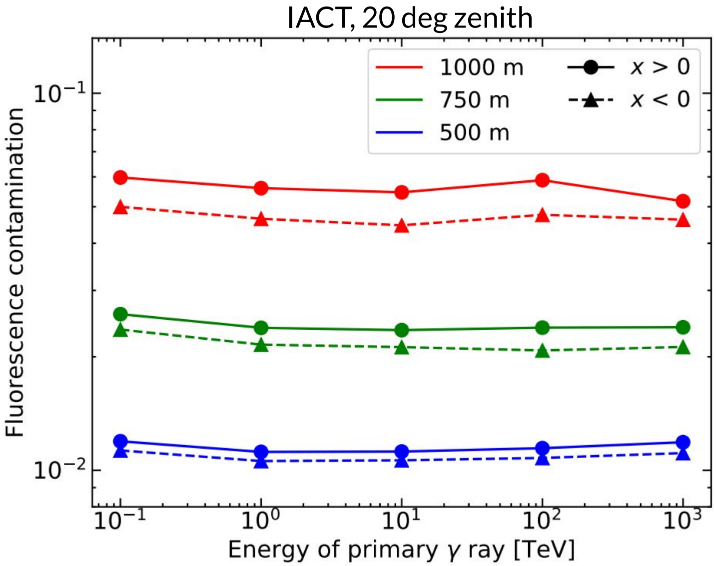
e.g. 100 TeV gamma-showers, θ = 20 deg

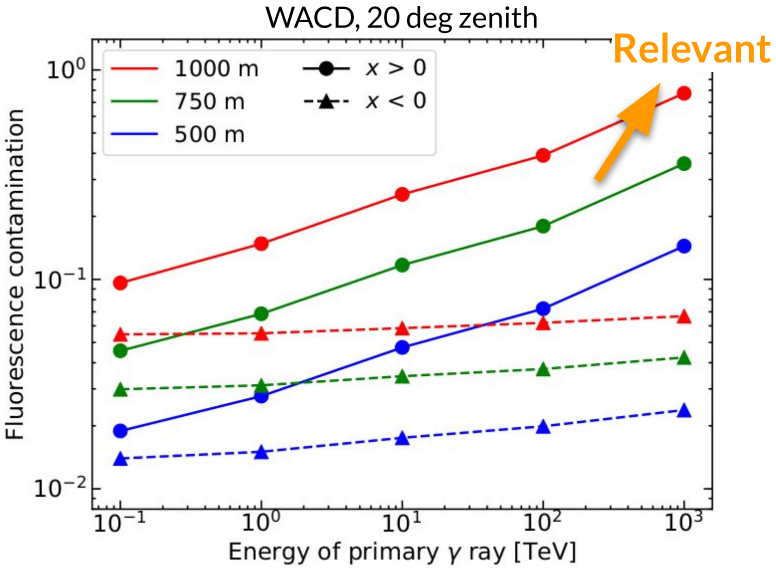


Significant at large distances

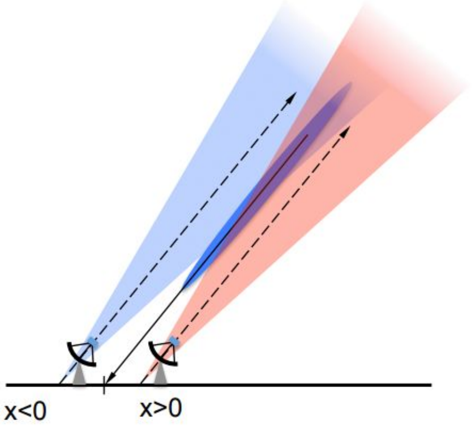
Fluorescence ~ 45% of the recorded signal

Dependence on distance, energy (+ zenith angle, off-axis angle)

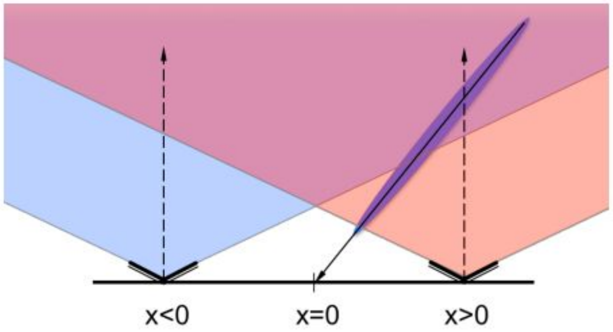

IACT, 20 deg zenith


WACD, 20 deg zenith

Relevant



IACT, 20 deg zenith



WACD, 20 deg zenith

Systematic study of fluorescence contamination (zenith)

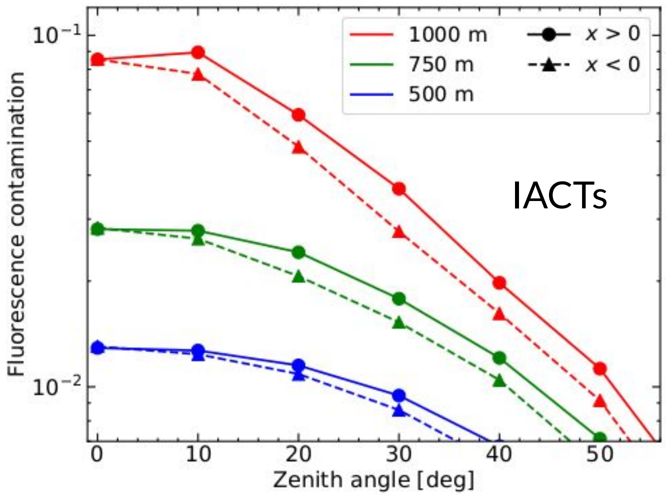


Figure 2.15: The same as Fig. 2.14, but for IACTs with a FoV of 10° centered at the arrival shower direction.

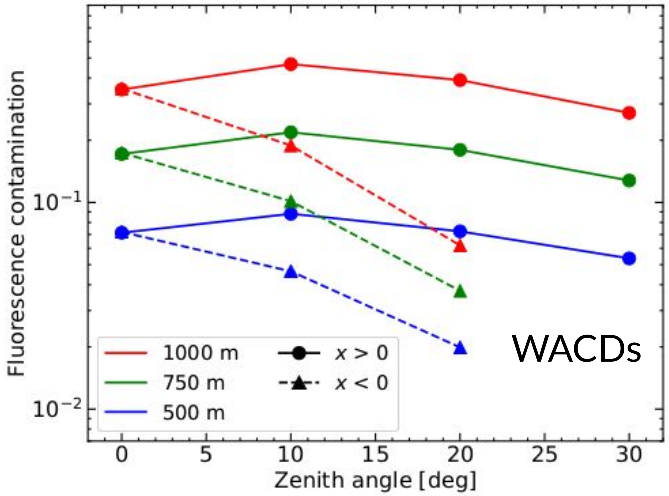
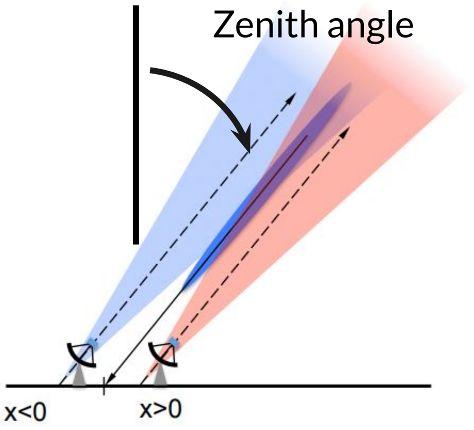
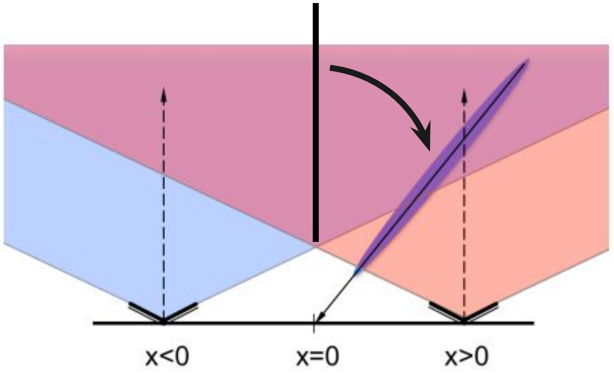


Figure 2.14: Fluorescence contamination as a function of zenith angle and x distance for WACDS with FoV of 60° in the vertical direction. Results were obtained for 100 TeV γ-ray showers.





Systematic study of fluorescence contamination vs. off-axis observations angle

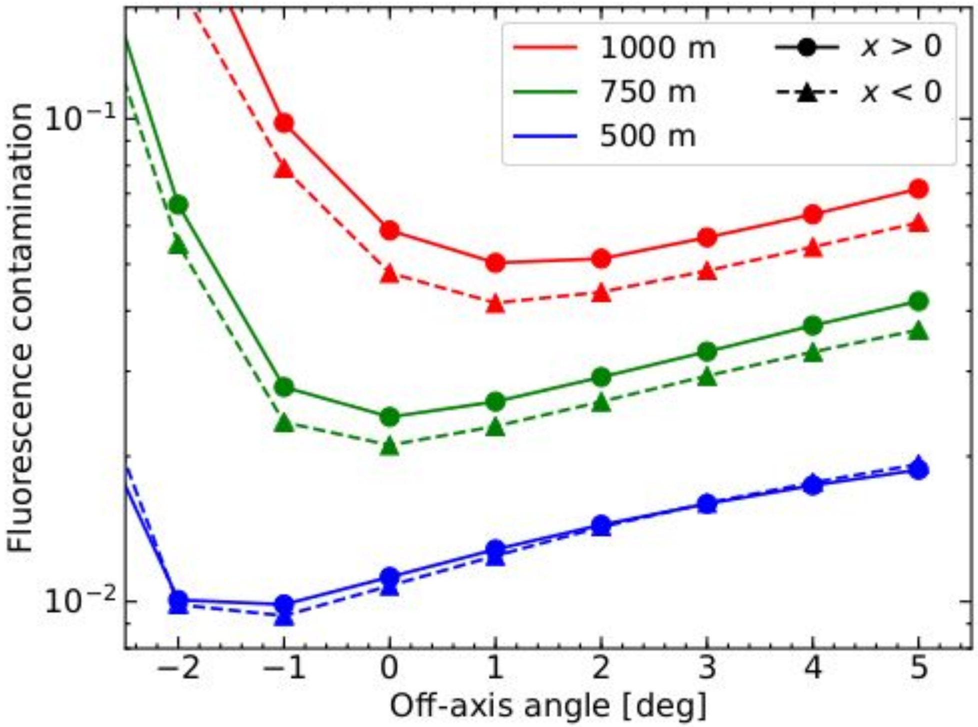


Figure 2.16: Fluorescence contamination as a function of telescope off-axis angle and x distance for IACTs with a FoV of 10°. Results were obtained for 100 TeV showers with 20° zenith angle.

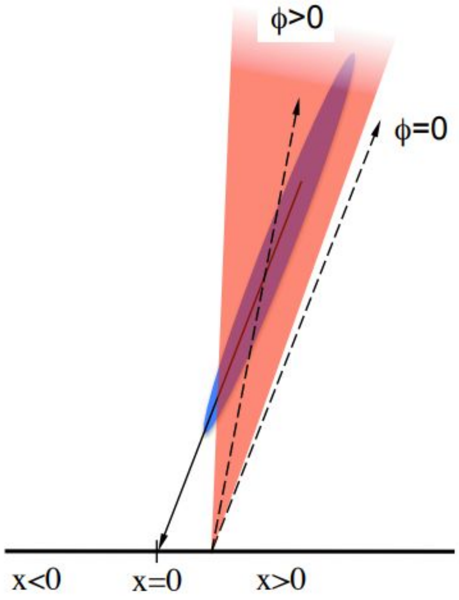


Figure 10: Schematic view of an off-axis observation.