Fluorescence emission and IACTs

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Outline

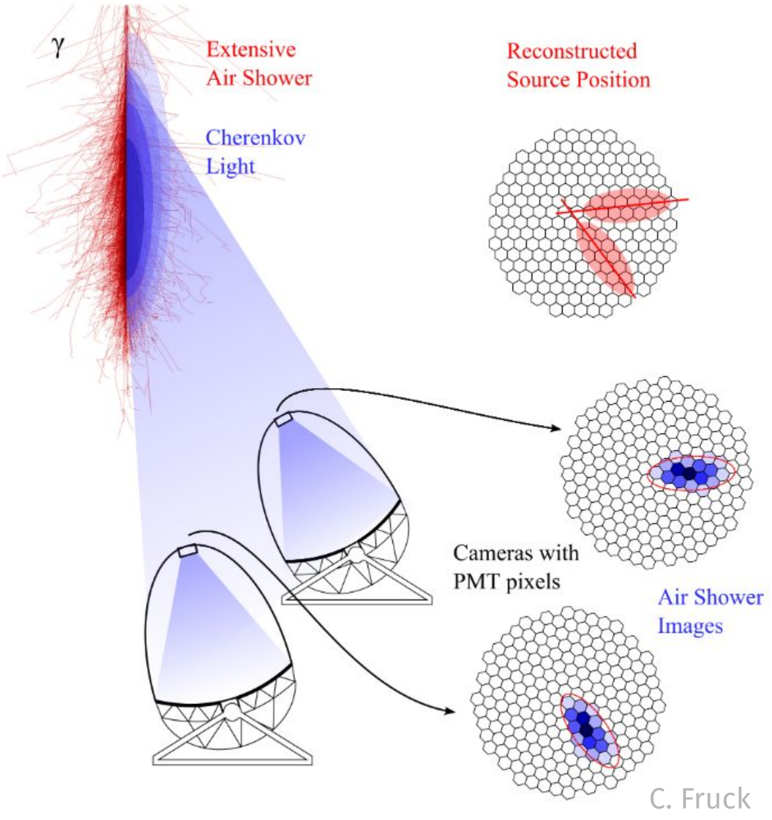
- Motivation: **Study of Cherenkov and fluorescence light from air showers**
- Method: **Implementation in CORSIKA**
- Results: **Fluorescence contamination** in the Cherenkov technique
- Ongoing work:
  - **Effect on the reconstructed shower parameters**
  - **Cherenkov telescopes in “fluorescence mode”**
  - **Comparison with numerical Toy Model**
- Conclusions and outlook

Cherenkov and fluorescence light from EAS

- Indirect detection of very-energetic particles using the atmosphere as a calorimeter through
    - **Cherenkov light flashes**
        - Pulse width ~ 10 ns
        - Spectral range: 300 - 500 nm

- Detection techniques:
    - Imaging Air Cherenkov Telescopes (IACTs):
      CTA, MAGIC, VERITAS, H.E.S.S.
    - Wide-angle Cherenkov detectors (WACDs):
      TAIGA-HiSCORE, LHAASO-WFCTA

- Simulations needed in:
    - Instrument calibration
    - Signal reconstruction

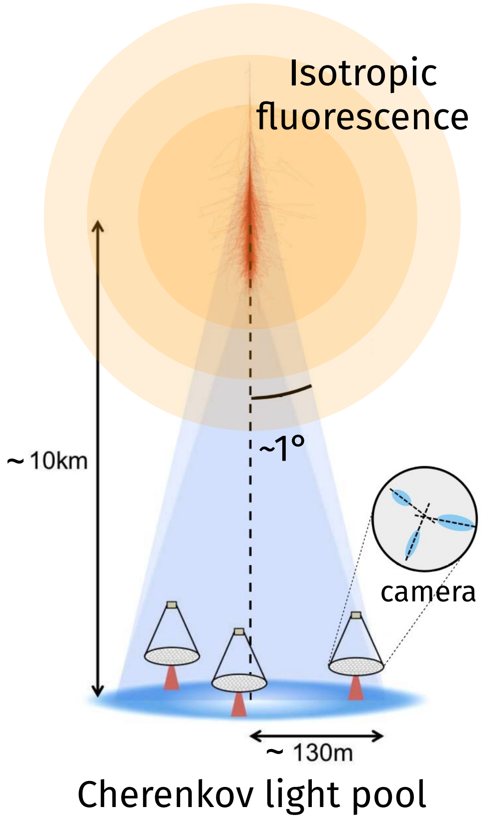


Cherenkov and fluorescence light from EAS

- **Fluorescence** light (de-excitation of N_2 states) also produced in air showers and **indistinguishable from Cherenkov** signal:
    - Same spectral range and pulse width

- Expected to be a **small contribution** compared to Cherenkov light and normally neglected:
    - Isotropic emission
    - Less efficient than Cherenkov

Is the fluorescence radiation always negligible in Cherenkov telescopes?



Implementation in CORSIKA

- **Implementation of fluorescence light emission in CORSIKA** (as detailed as Cherenkov light)
  Up to now in version 7.6XXX

- **`sim_telarray`** adapted by K. Bernlöhr to handle these photons

- Plan:
  - Include fluorescence subroutine in the official upcoming CORSIKA v7 releases?
  - Implement it in the new CORSIKA8?

Computational cost:

computation time $\times$ 5-6

Our modifications in CORSIKA

1. Include **new cards to steer fluorescence simulation.**

2. Add **parametrization of fluorescence emission after an energy deposit**.

3. Add **calls to fluorescence emission associated to ionization losses while tracking**.

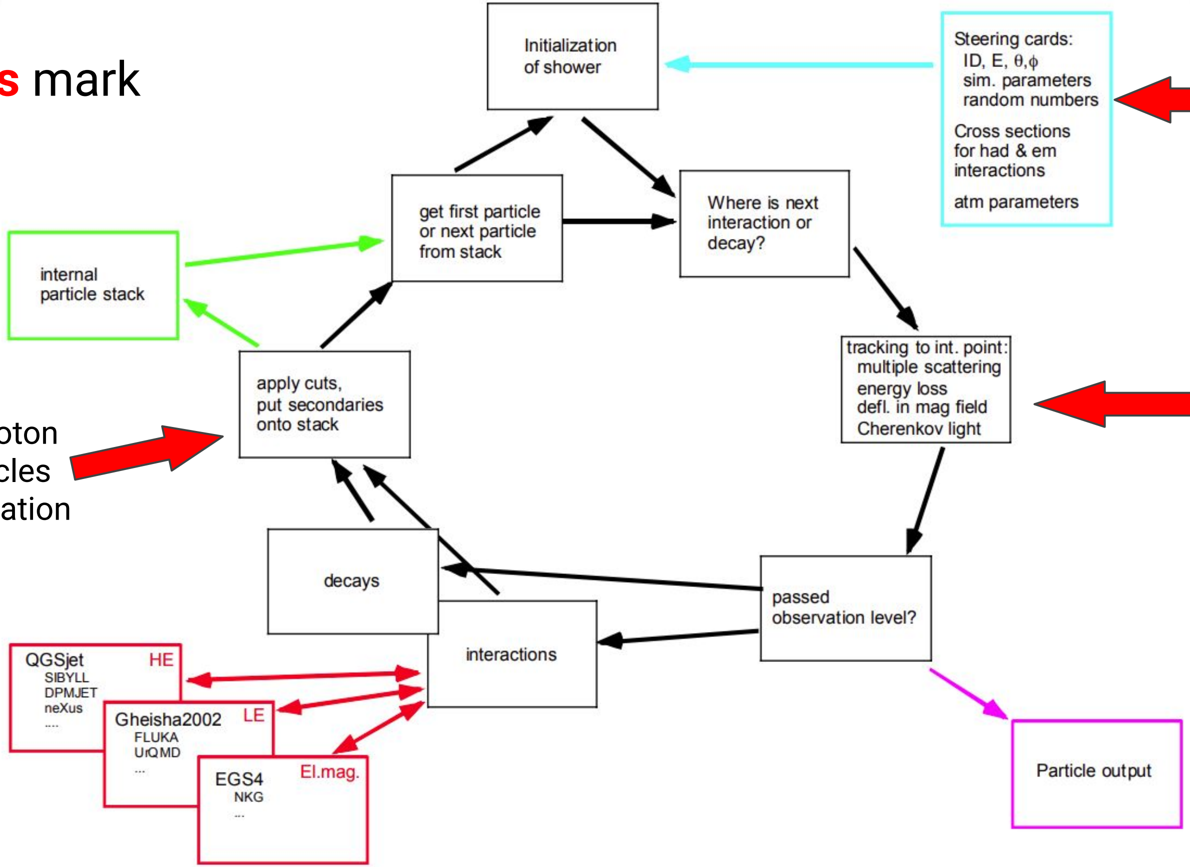
4. Add **calls to fluorescence emission for particles under simulation thresholds** due to energy limits (particles with energy below cutoff) and angular limits (CORSIKA cuts upward going particles). Lots of different processes involved, up to now 96% of deposited energy included.

5. **Track fluorescence photons to ground**.

6. **Store Fluorescence photons in output** (CERnnnnnn/IACT eventio format).

General workflow and our modifications

Red arrows mark our mods



1. New control cards for fluorescence simulation

2. Fluorescence photon production and tracking after ionization losses

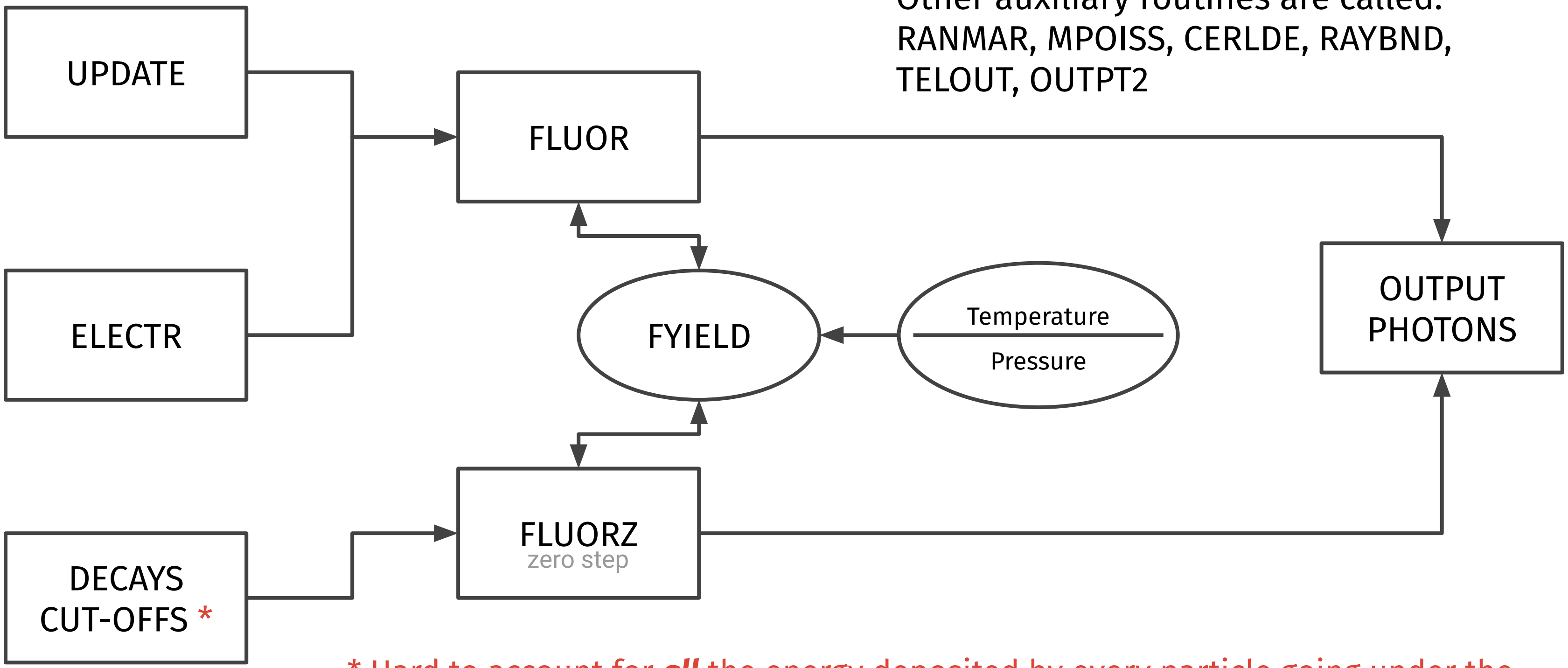
3. Fluorescence photon production by particles falling below simulation threshold

4. Storing fluorescence photons

Credit: J. Knapp

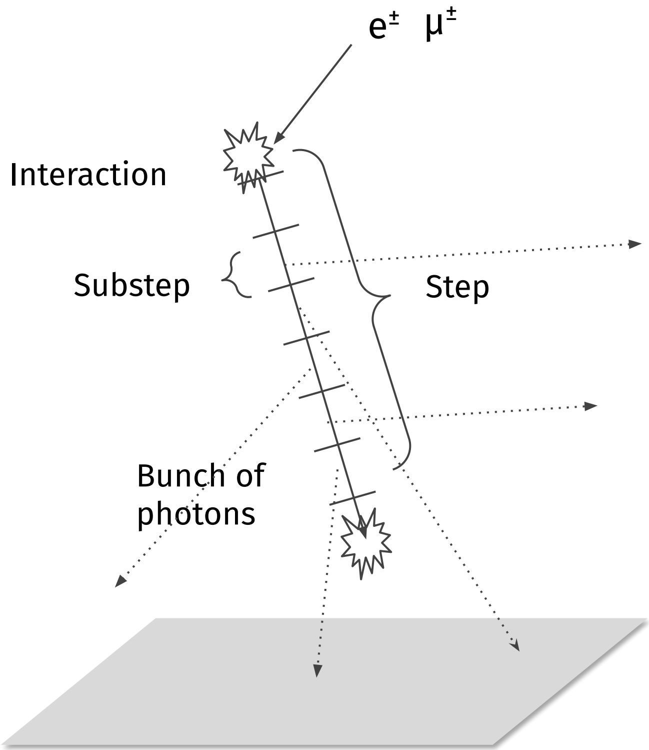
Production of Fluorescence photons

Other auxiliary routines are called:
RANMAR, MPOISS, CERLDE, RAYBND, TELOUT, OUTPT2



* Hard to account for ***all*** the energy deposited by every particle going under the simulation thresholds. Too many small deposits spread all over the code

FLUOR subroutine



Our subroutine was adapted from the Cherenkov one.

Particle steps between two interactions.

We 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.

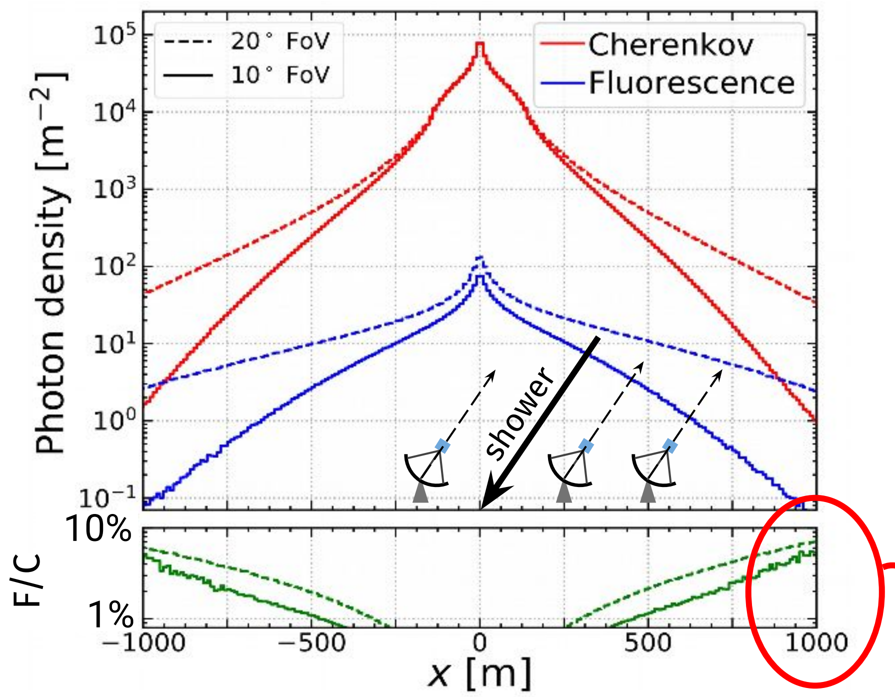
Bunches of fluorescence photons from each substep are produced according to fluorescence parameterization.

A wavelength is assigned to each bunch according to known fluorescence spectrum.

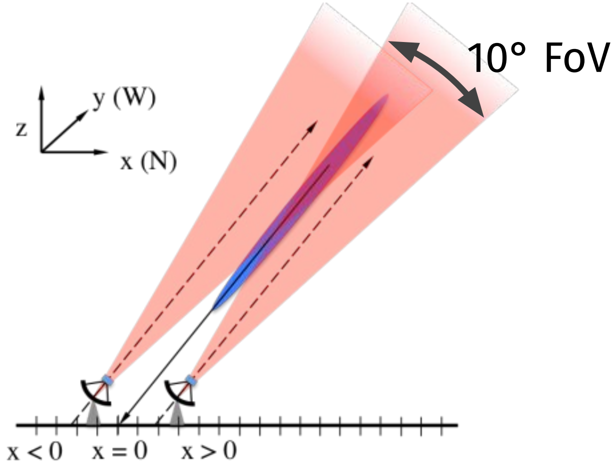
We keep either all photons on ground or in volumes around telescopes (IACT options).

Results: fluorescence contamination in IACTs

Lateral light profiles



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



Small effect but sizable at large distance

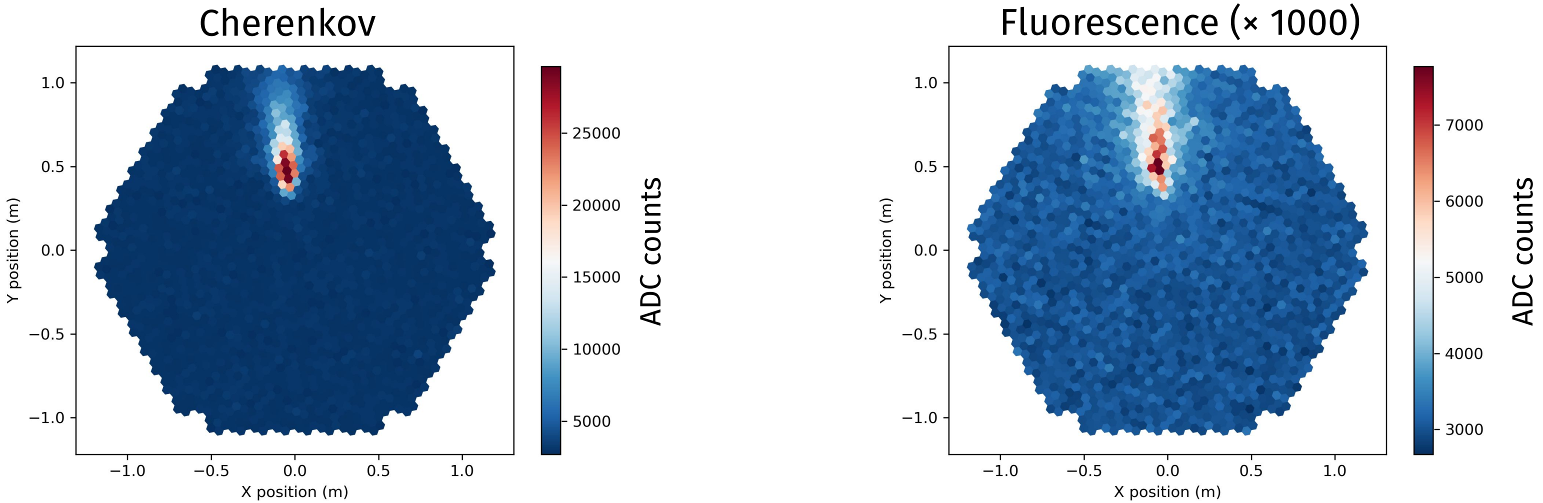
Fluorescence ~ 5% of the recorded signal

More details ([+ WACDs]): **Astropart. Phys. 107 (2019) 26-34** & **26th E+CRS, J. Phys.: Conf. Ser. 1181 012047**

WIP: reconstruction of air shower parameters

ctapipe-based analysis:

- Effect on the reconstructed shower parameters (energy and direction) when including fluorescence light.



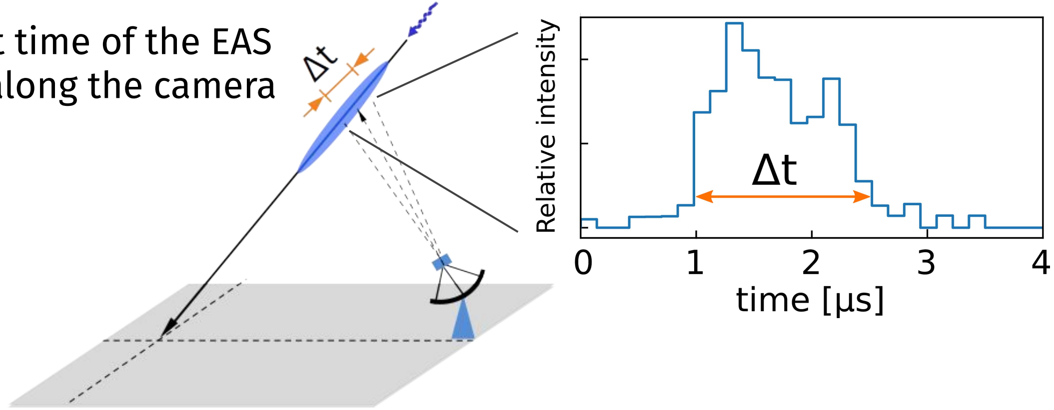
Simulated LST camera images from Cherenkov and fluorescence light. Impact parameter < 100 m

WIP: Cherenkov telescope in “fluorescence mode”

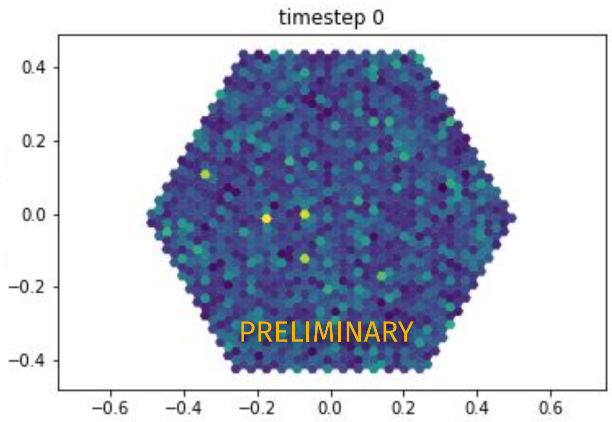
Simultaneously observing air showers transversely. PoS(ICRC2015)993

- MC simulations including the telescopes (`sim_telarray`)
  → Adapt the Trigger & Readout system of the cameras

Transit time of the EAS trace along the camera



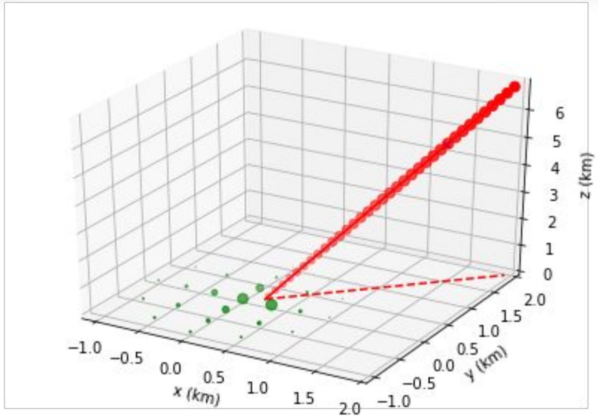
Trace in the camera (?)

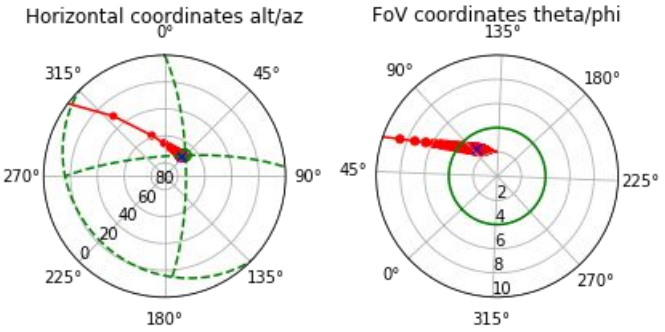


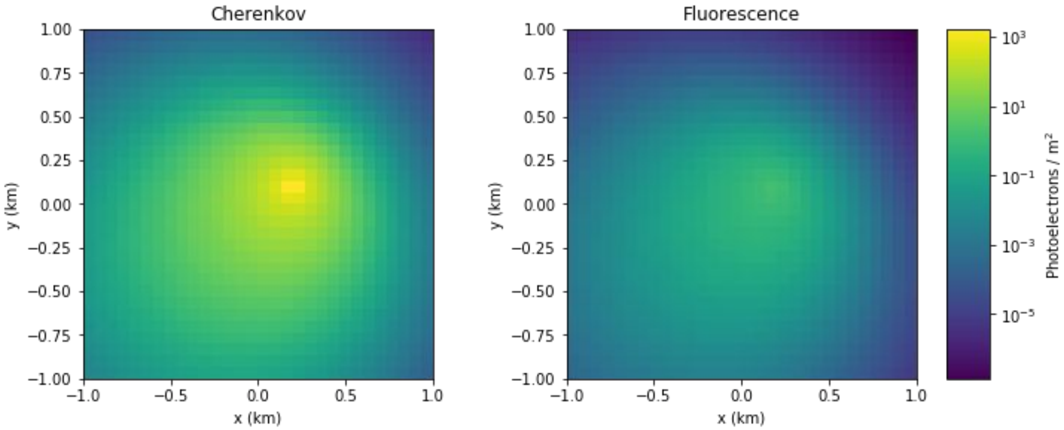
- **Goal: larger detection effective area → reach higher energies not explored yet**

WIP: Toy model

- Numerical calculations of both Cherenkov and fluorescence signals based on shower parameterization (no simulation).
- Motivation: Interactive tool to obtain fast results and validation of simulations.
- Open-code python module being developed.







Conclusions & Outlook

- **Inclusion of fluorescence light emission in CORSIKA + `sim_telarray`** ✓ **Ready to be used!**

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

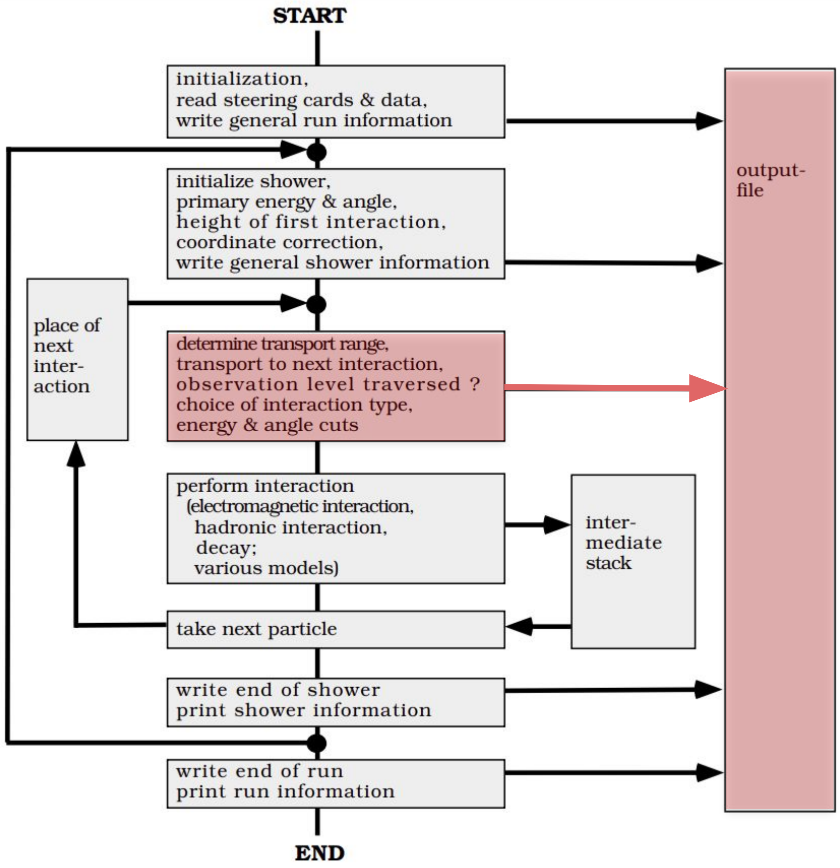
- **Fluorescence light contribution should not be always neglected in IACTs:**
  - Non-negligible (~ 5%) at large distances (~ 1000 m)

- **Potentially useful in other situations**:
  - Very significant contribution (~ 45%) at large distances in the PeV region for Wide Angle Cherenkov Detectors (WACDs)

- Work in progress:
  - Detailed **MC study including telescope simulations** → more accurate fluorescence evaluation
  - Explore the possibility of using **Cherenkov telescopes as fluorescence detectors**
  - **Including thinning option** (thanks to S. Sailer and K. Bernlöhr)

backup

Overview: fluorescence emission in CORSIKA Flow



Our code only interacts with the rest of CORSIKA flow whenever a charged particle is transported or no longer simulated due to cutoffs and therefore energy is deposited in both cases.

List of modifications

1. Add a new control card that governs whether fluorescence photons are written or not and the size of the bunches. → The code has to be added inside subroutine DATAC (reads control cards) And the variable is kept together with those controlling Cherenkov emission Cherenkov in COMMON /CRCEREN1/

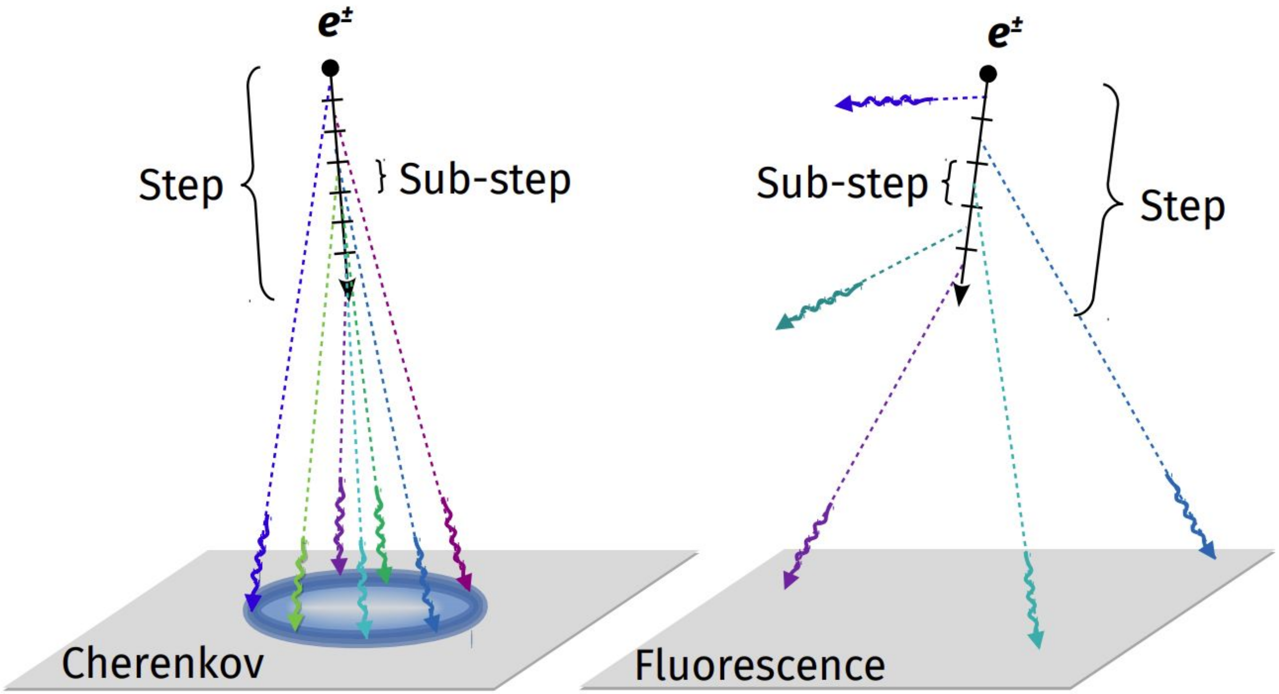
2. Main modification: Add calls to the subroutine FLUOR which produces the fluorescence photons for ionization losses and track them to the ground (more details later). They are added in two places:
   a. SUBROUTINE ELECTR for electromagnetic particles
   b. SUBROUTINE UPDATE for other long lived particles (charged pions, muons).

3. Include calls to routine FLUORZ, which generates fluorescence photons whenever there is a deposit of energy not related to ionization (<u>unfortunately energy deposits are distributed into many places in CORSIKA</u>).

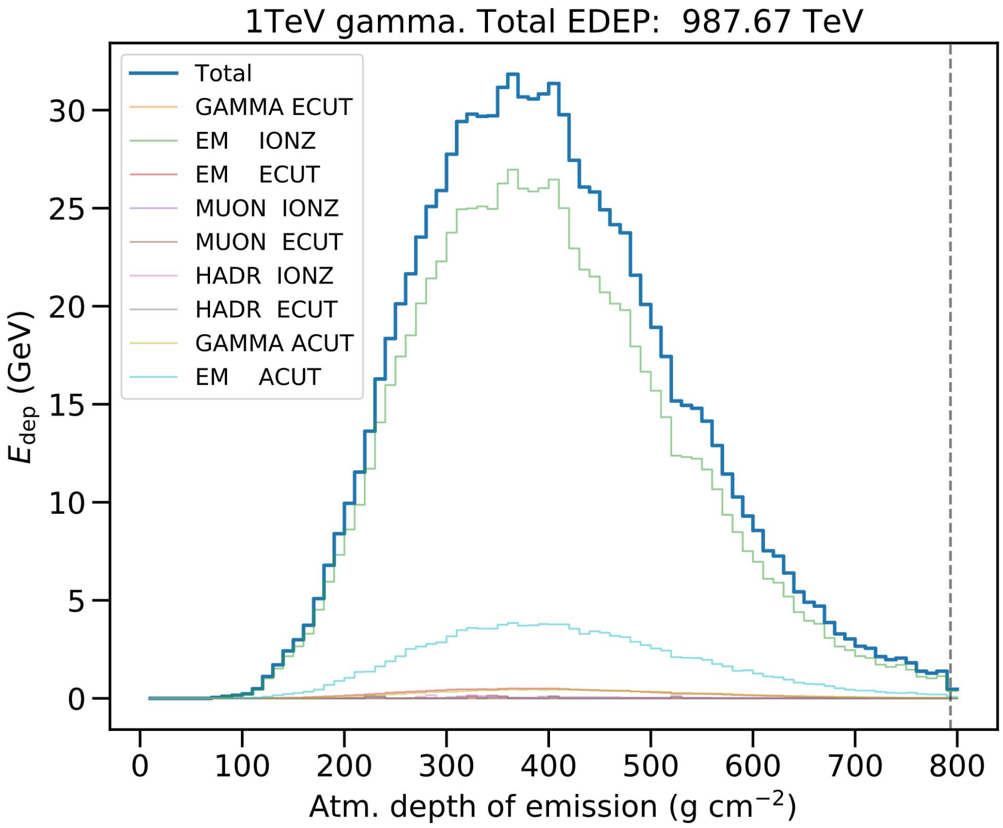
4. Add calls to record the photons in the output files, and develop code to read them and produce plots. Output is done in points 2 and 3. In addition to geometric formulae we call routines to bend photon trajectories (“raybnd”), check they impact on telescopes (“telout”), and save then (“outpt2”) using . We use:

   a. Binary data files for Cherenkov photons (*CERnnnnnn* files)
   b. IACT files (from K. Bernlöhr package for IACTs)

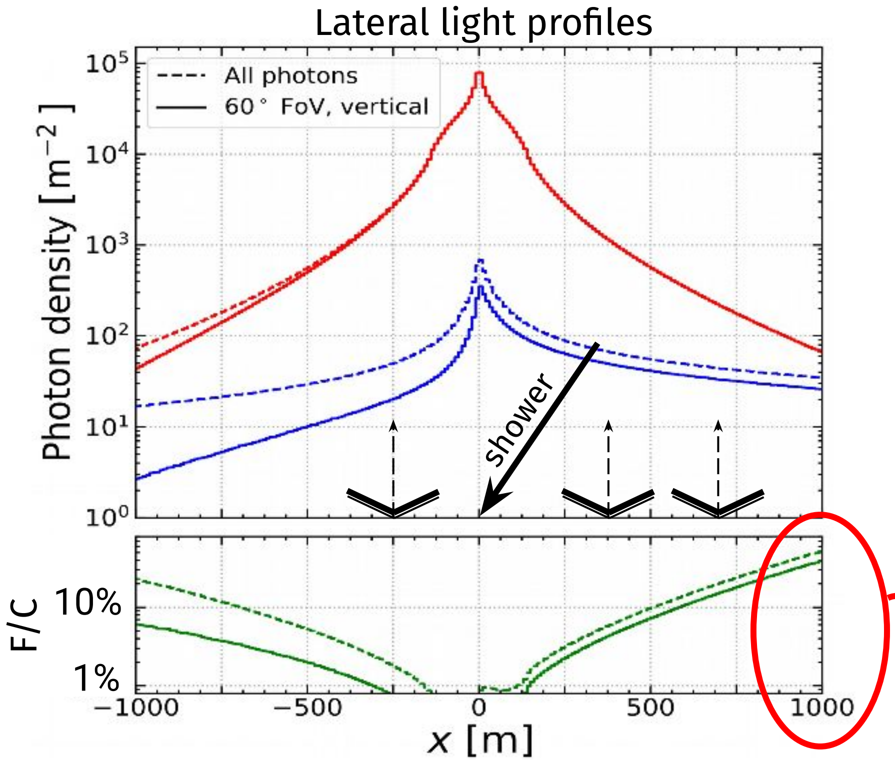
FLUOR subroutine vs CERENK subroutine



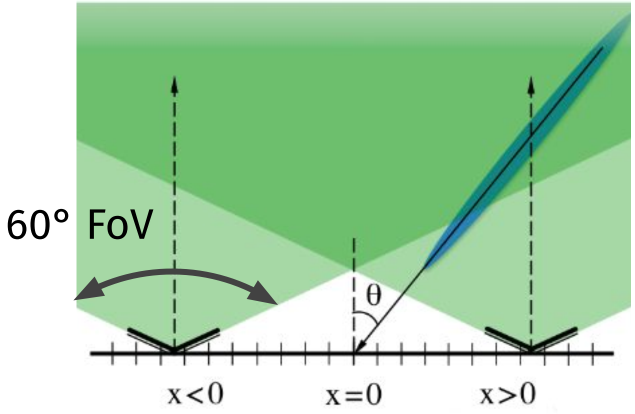
Deposited energy



Results: fluorescence contamination in WACDs



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



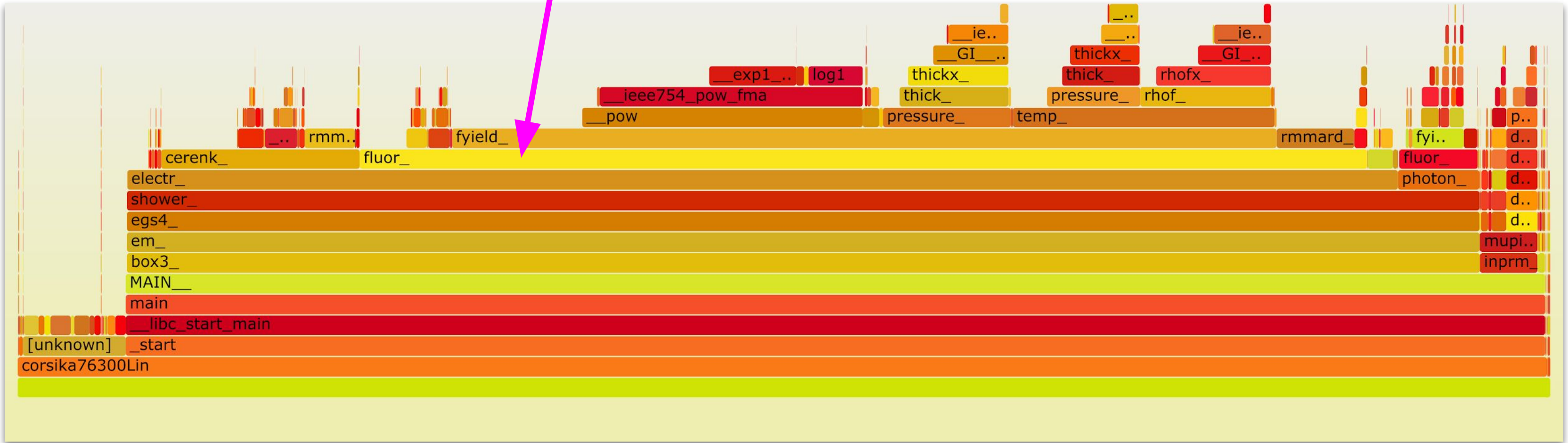
Significant at large distance

Fluorescence ~ 45% of the recorded signal

More details: **Astropart. Phys. 107 (2019) 26-34** & **26th E+CRS, J. Phys.: Conf. Ser. 1181 012047**

Increase in computation time

- Much larger number of particles producing fluorescence than Cherenkov photons. Hence the larger number of calls to fluorescence subroutine



- Need for optimization. A possible solution is the usage of voxels

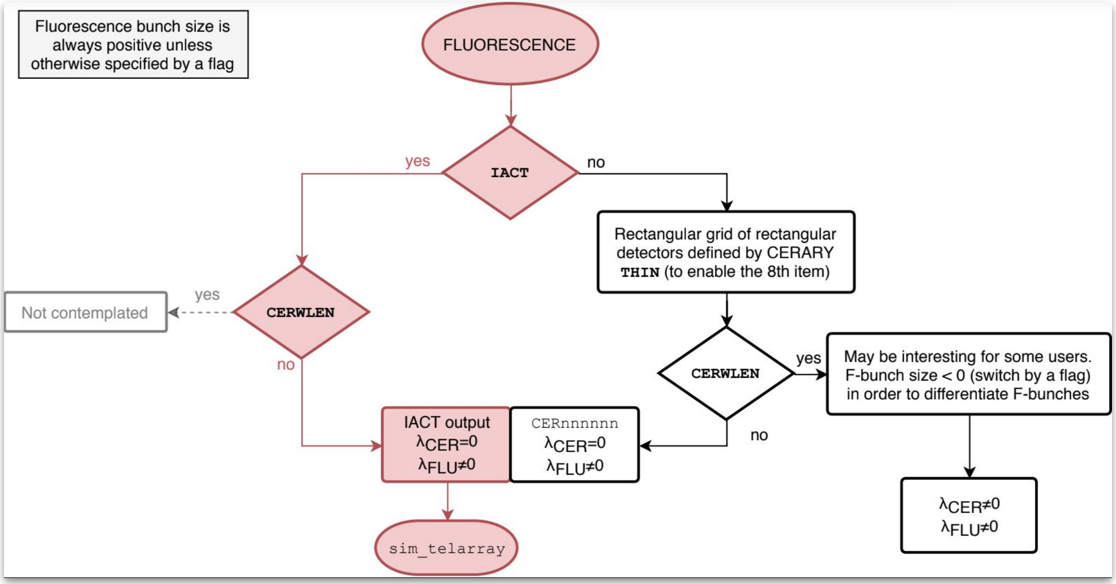
IACT output + `sim_telarray` (K. Bernlöhr)

CORSIKA → IACT output → `sim_telarray` → ctapipe

EAS | Telescopes / detectors | Analysis

`sim_telarray` adapted to handle F-photons with a new variable:

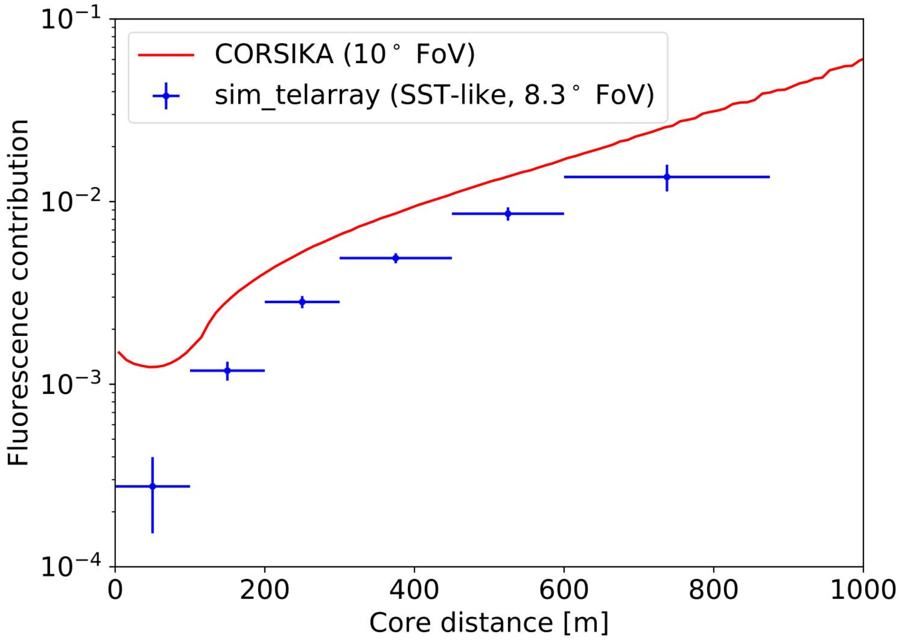
`select_light_component`



Fluorescence contamination using `sim_telarray`

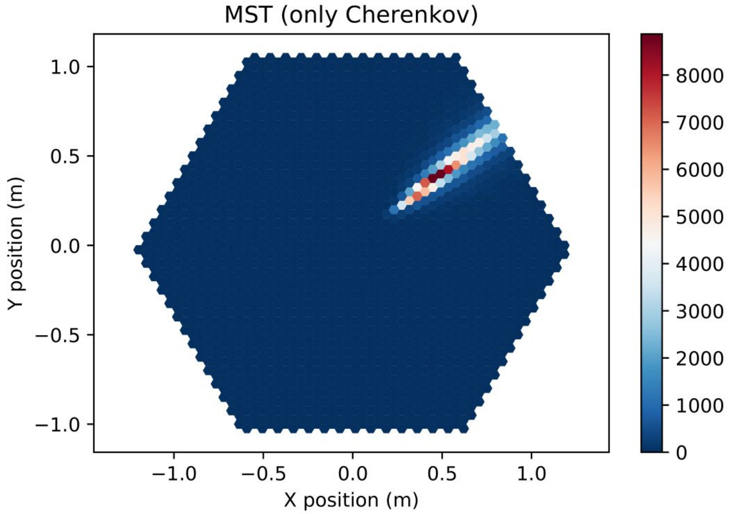
Simulated (CORSIKA + `sim_telarray`) contribution of fluorescence light to the total signal registered by SST-like CTA telescopes as a function of their distance to the shower impact point (in blue). The values were averaged over 6000 vertical showers initiated by 100-TeV gamma rays.

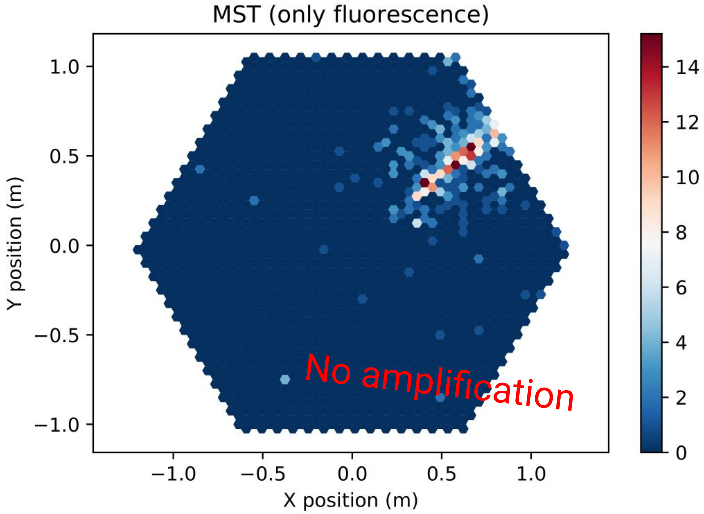
For comparison, the fluorescence contamination previously estimated only from CORSIKA simulations (considering 10 deg FoV telescopes) is plotted in red.



Cherenkov and fluorescence camera images

Simulated photo-electrons in the camera of a MST-like IACT from Cherenkov (left) and fluorescence (right) light produced in a 300-TeV gamma-ray induced vertical shower using the simulation tool sim_telarray. Telescope located ~ 200m away from the shower impact point. These images do not contain night-sky background nor electronic noise.





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