Institute for theoretical physics IV
Chair for Plasma Astroparticle Physics

DATA VOLUME REDUCTION FOR THE LST PROTOTYPE

17.12.2021

Jonas Hackfeld

RUHR-UNIVERSITÄT BOCHUM

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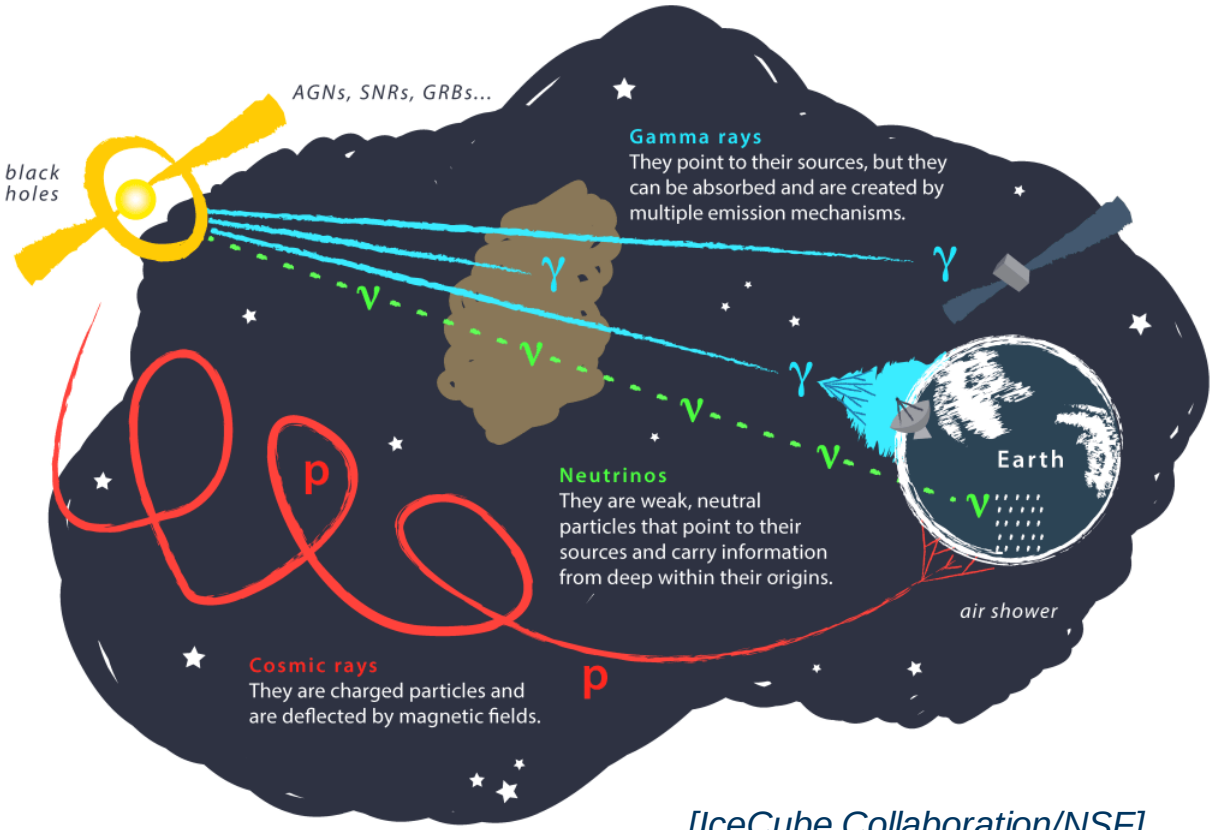
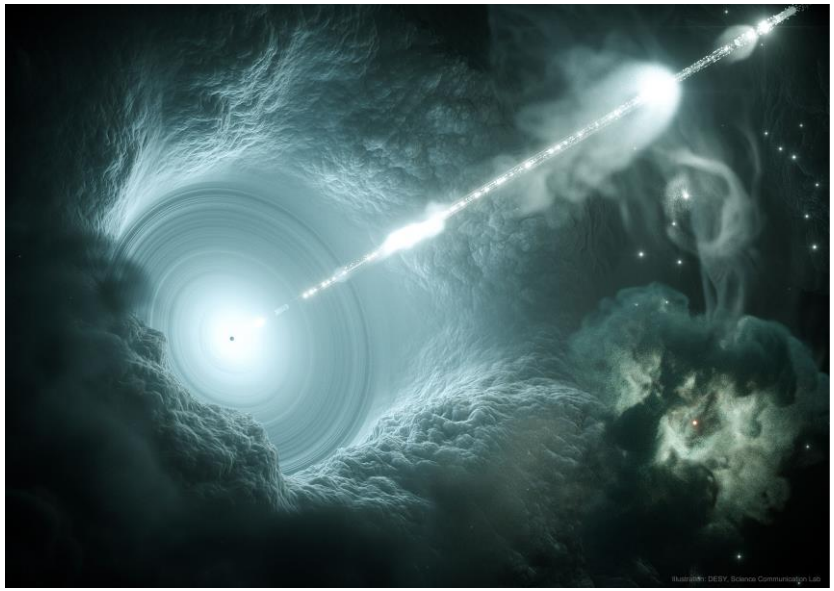
Multi-Messenger Astronomy



[IceCube Collaboration/NSF]

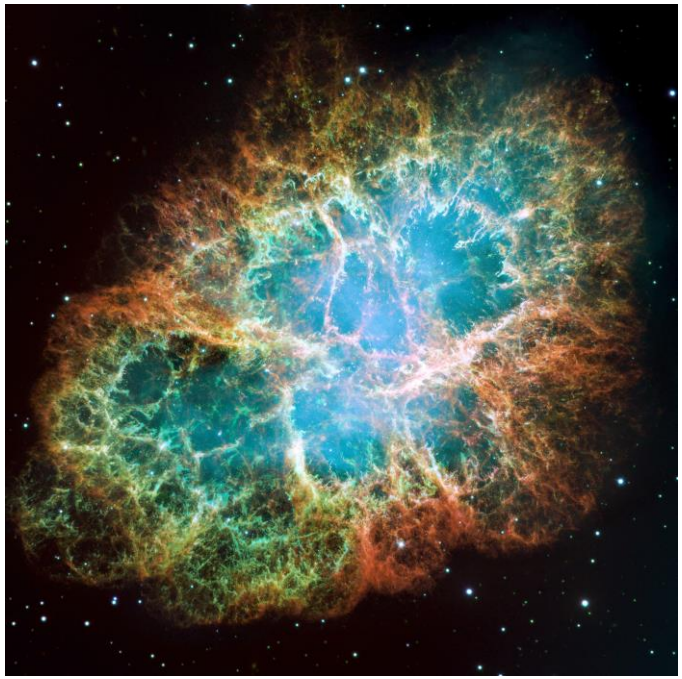
Sources in the Universe

Active Galactic Nuclei, AGNs



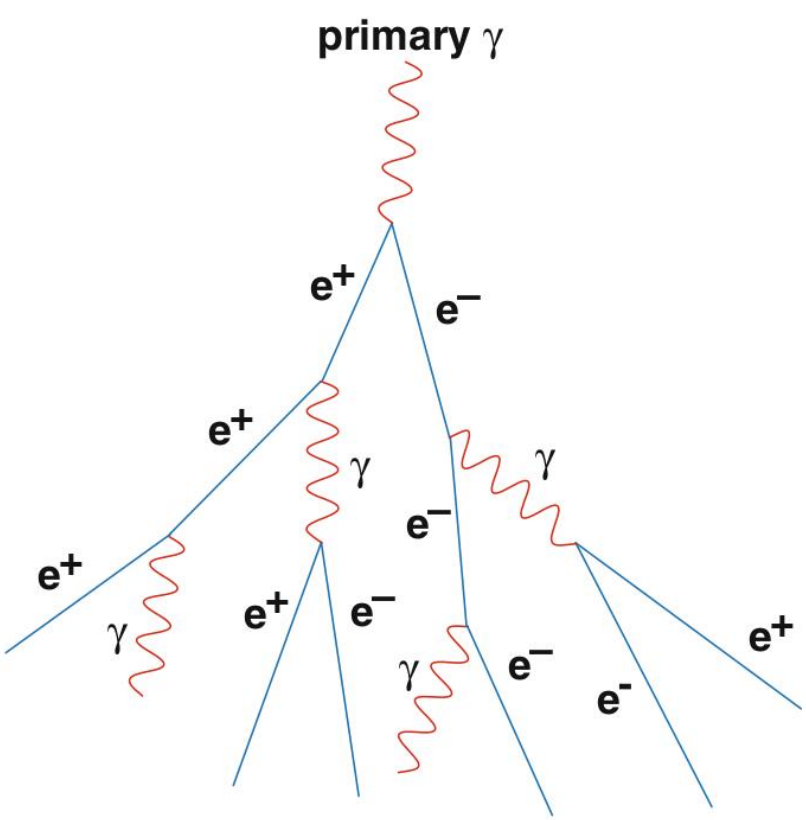
[Artistic impression of an AGN, APOD 2018-07-16]

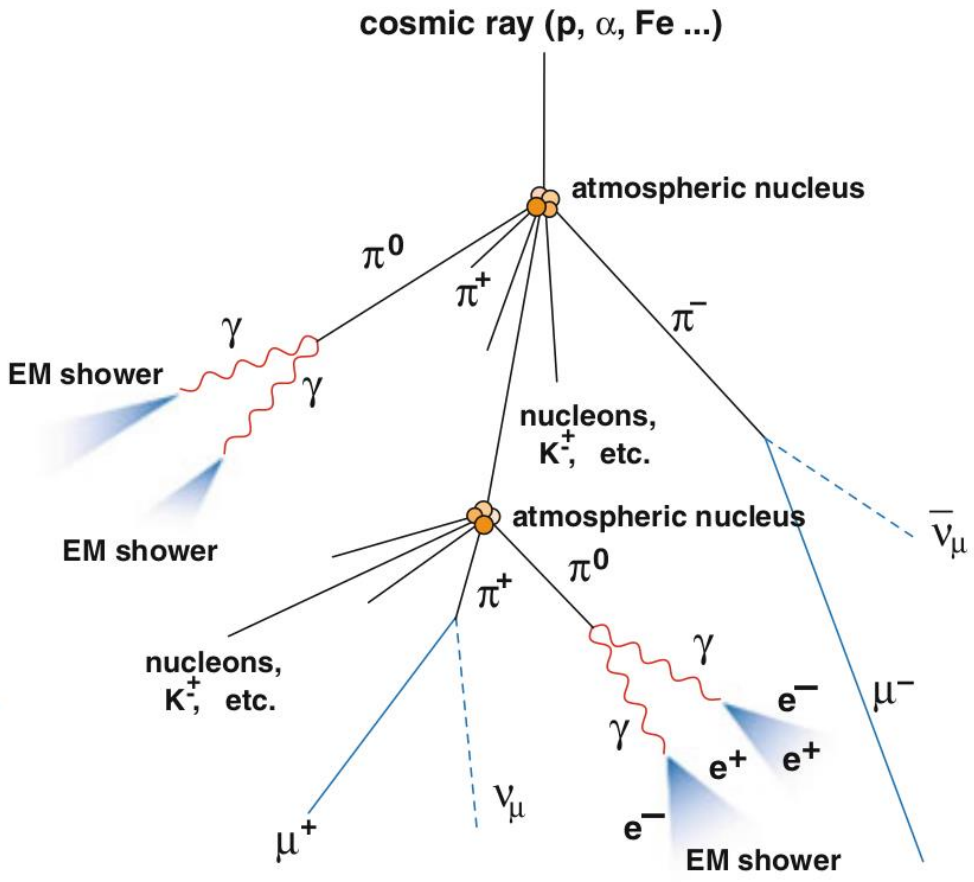
Supernova Remnants, SNRs



[HST image of the Crab Nebula]

Extensive Air Showers





[M.Nöthe]

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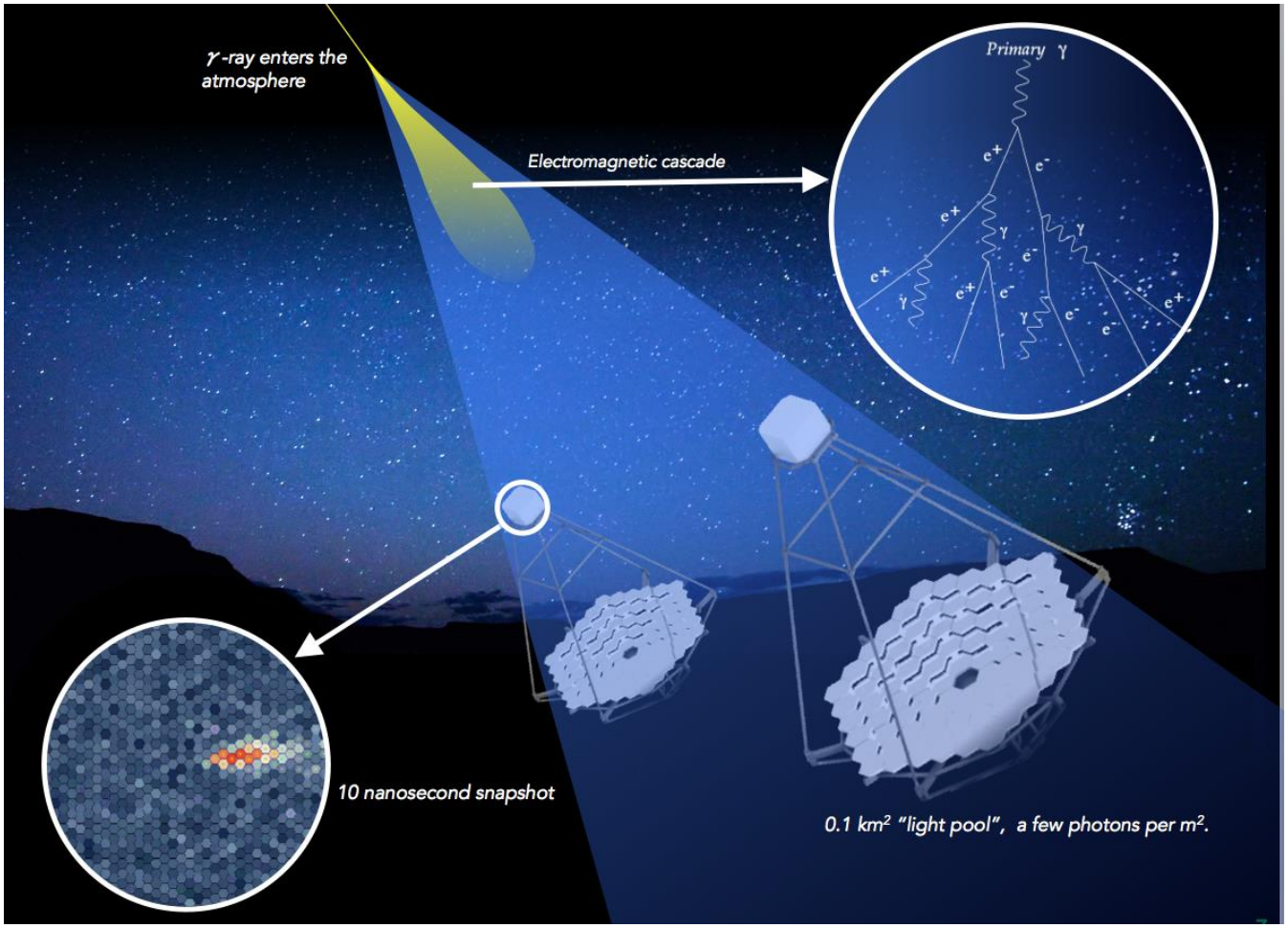
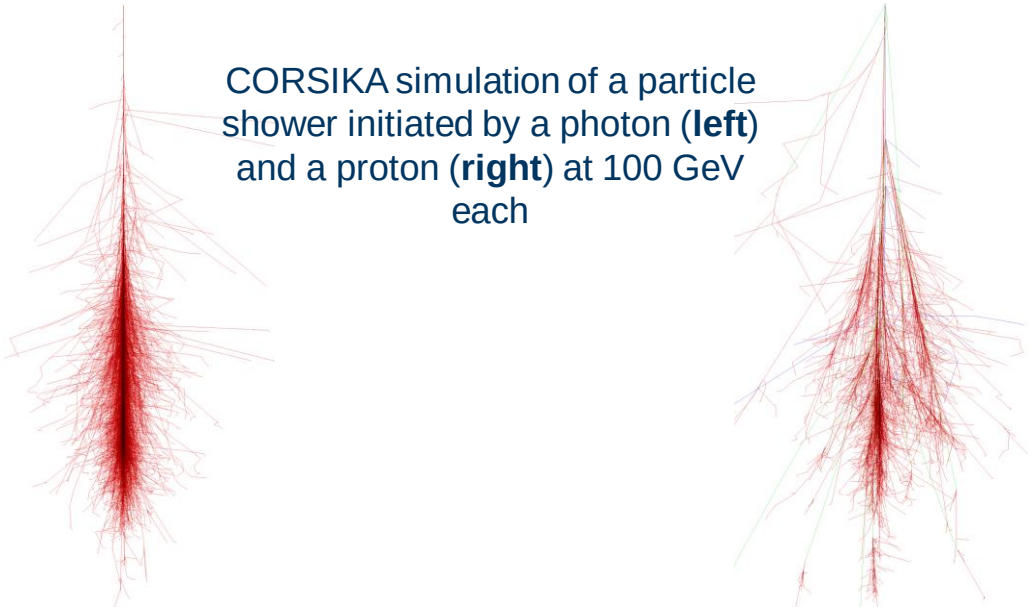
IACTs

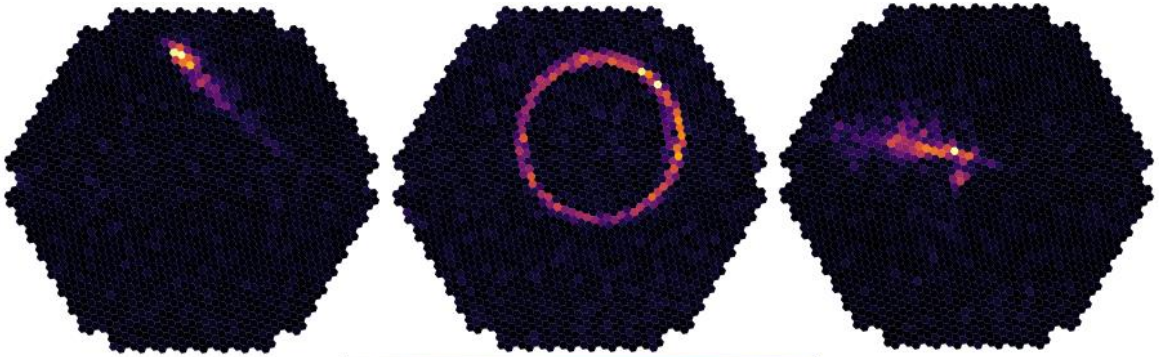


[CTA Observatory]

IACTs

CORSIKA simulation of a particle shower initiated by a photon (**left**) and a proton (**right**) at 100 GeV each





Photon

Muon

Proton

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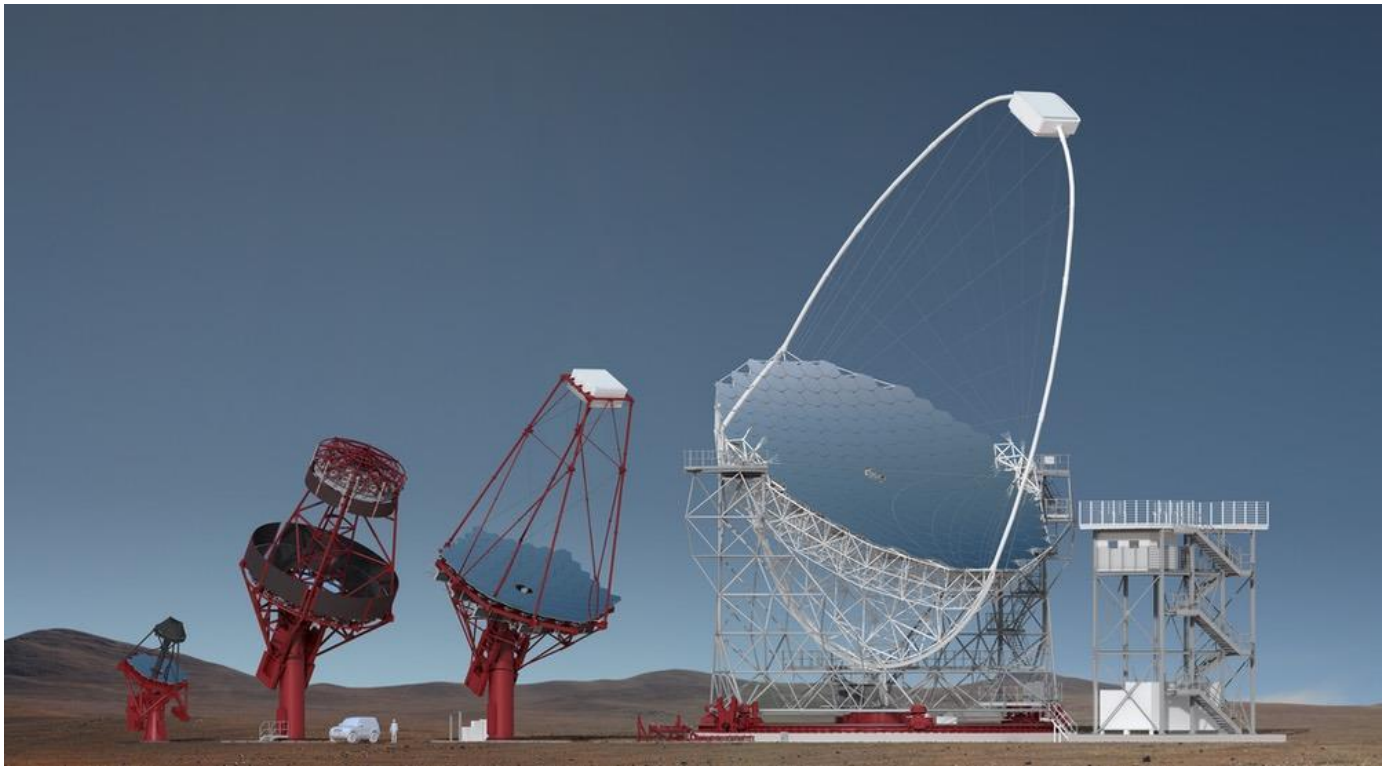
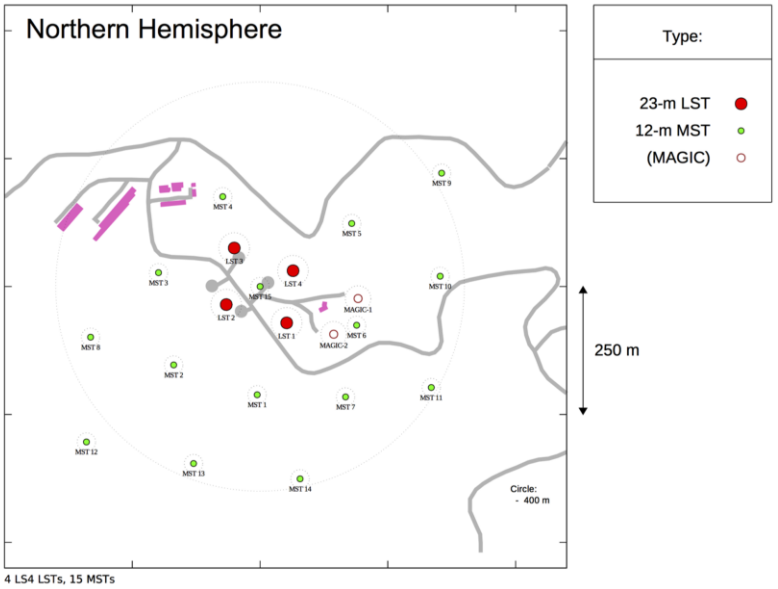
Cherenkov Telescope Array (CTA)



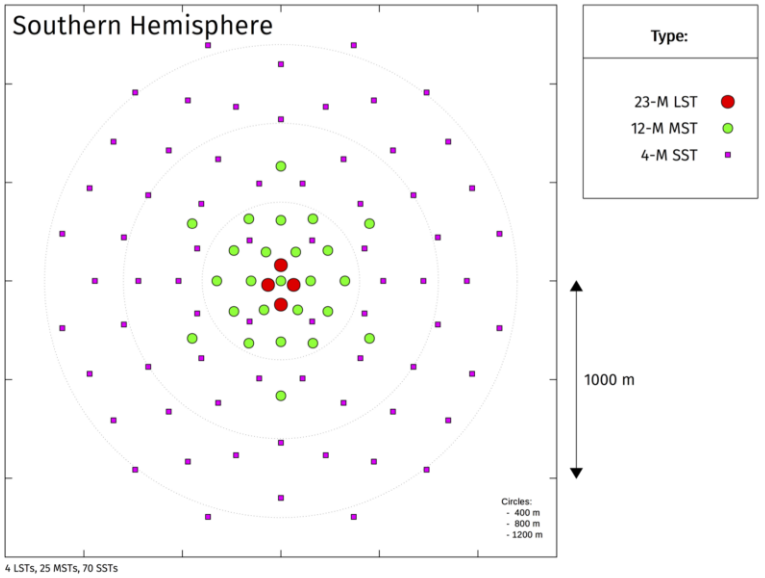
Telescope	SST	MST	LST
Energy range	5-300 TeV	150 GeV – 5 TeV	20-150 GeV
Field of view	10.5°	7.5° - 7.7°	4.3°
Reflector diameter	4.3 m	11.5 m	23 m

Cherenkov Telescope Array (CTA)

Omega configuration:



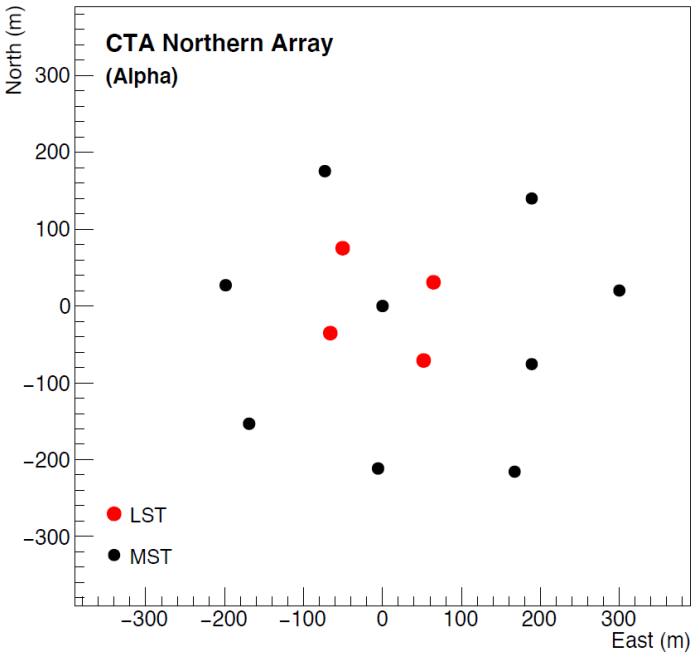
La Palma, Spain



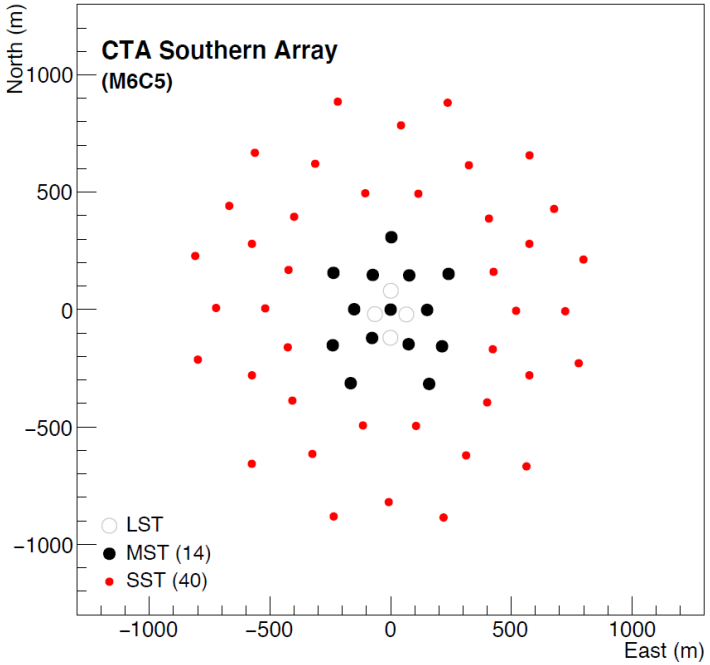
Atacama Desert, Chile

Cherenkov Telescope Array (CTA)

Alpha configuration:



La Palma, Spain



Atacama Desert, Chile

[Orel Gueta, ICRC21]

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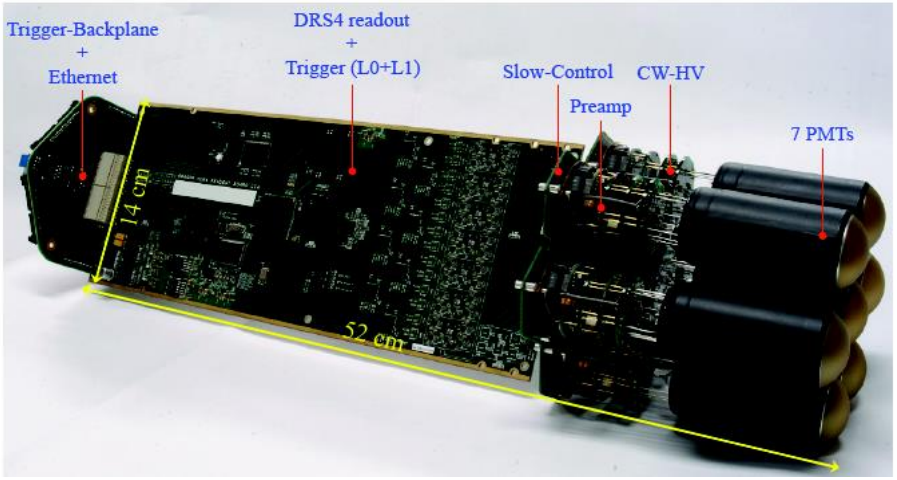
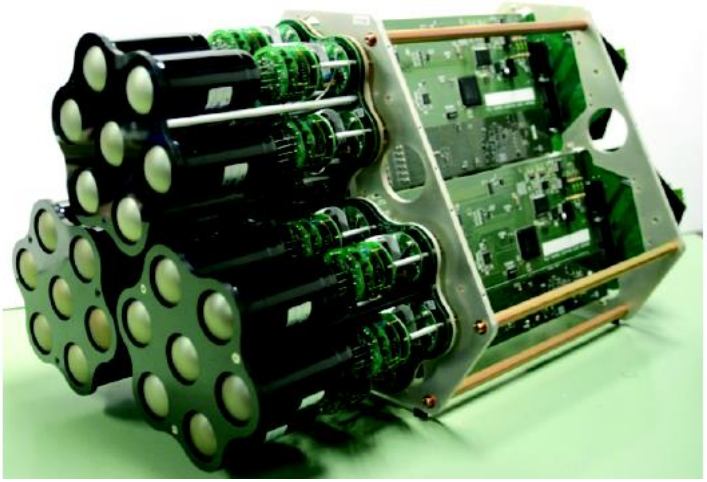
LST Prototype

[CTA Observatory flickr]

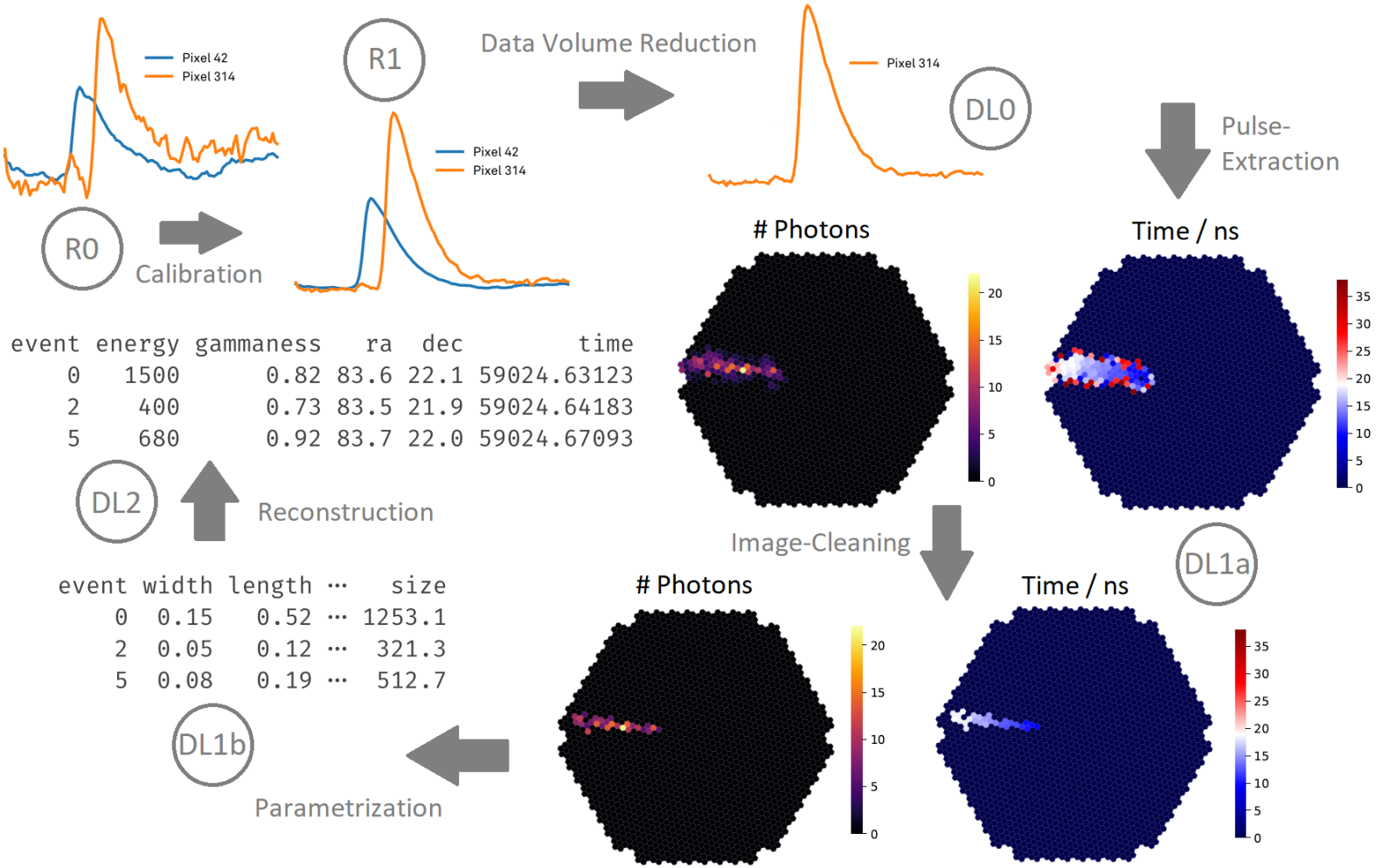
LST Prototype - Readout





Waveform

LST Prototype – Data Analysis Steps



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LST Prototype - Software

- **ctapipe**: Main processing pipeline for low level CTA data – Python based framework and hosted as an open-source project on GitHub
- **ctapipe-io-lst**: Plugin for ctapipe, which is able to read LST zfits files and calibrate them to R1-level as needed for the ctapipe tools
- **aict-tools**: Used to apply machine learning tasks for event reconstruction. It itself uses scikit-learn.
- **pyirf**: Main features include calculation of the Instrument Response Function (IRF) and sensitivity estimation of the array. Utilized in this thesis for cut optimization and event weighting

➢ **MC's**: South-pointing PROD5 simulations of the northern array with 20° zenith angle and 80% mirror reflectivity

Repository	Version
ctapipe	0.10.5 – 2021-03-04
ctapipe-io-lst	0.10.0 – 2021-05-05
aict-tools	0.27.1 – 2021-05-05
pyirf	0.5.0 – 2021-05-11

Data Volume Reduction

- Permanent storage of hundreds of PByte/year over a planned 30-year lifetime will be financially unsustainable.

Lossless:

- Data compression

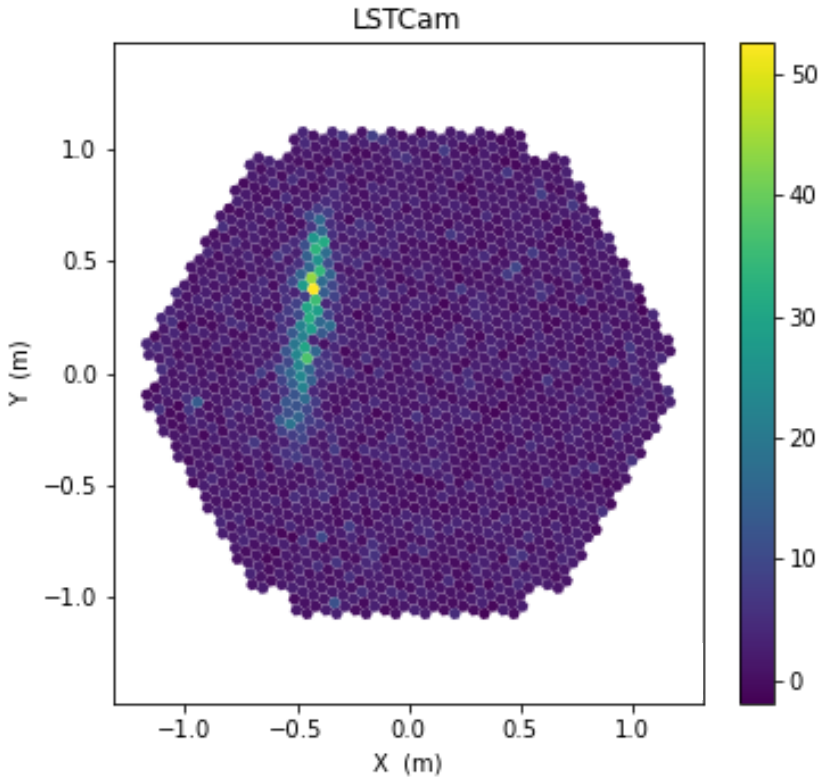
Lossy:

- Low/high gain selection
- Suppression of hadronic events
- Waveform parametrization
- Signal-pixel selection this thesis

Pixel selection

Approaches:

- Wavelets cleaning
- Deep-Learning
- Tailcuts cleaning



Pixel selection

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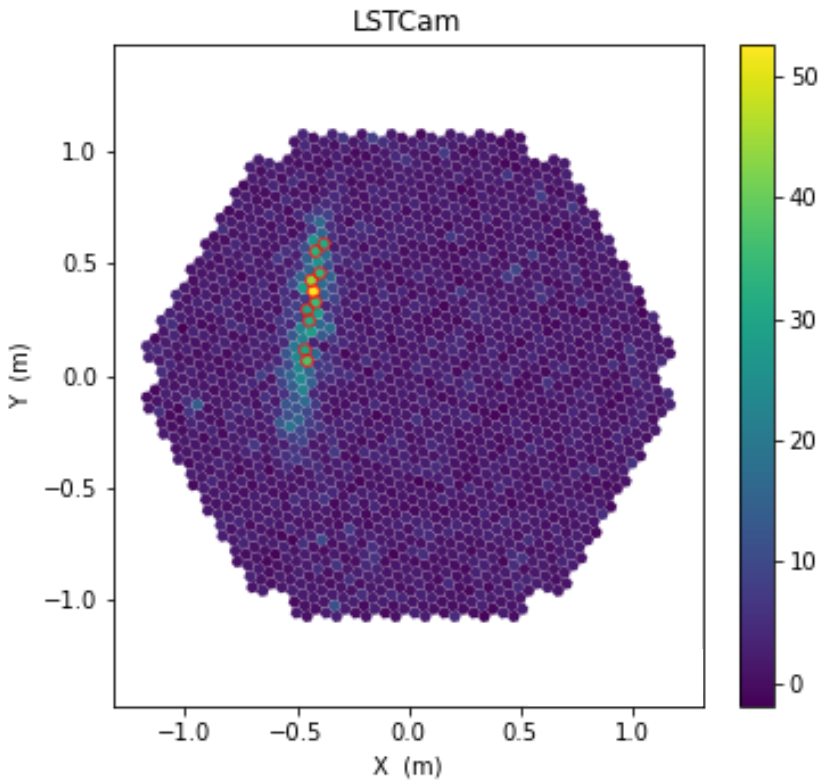

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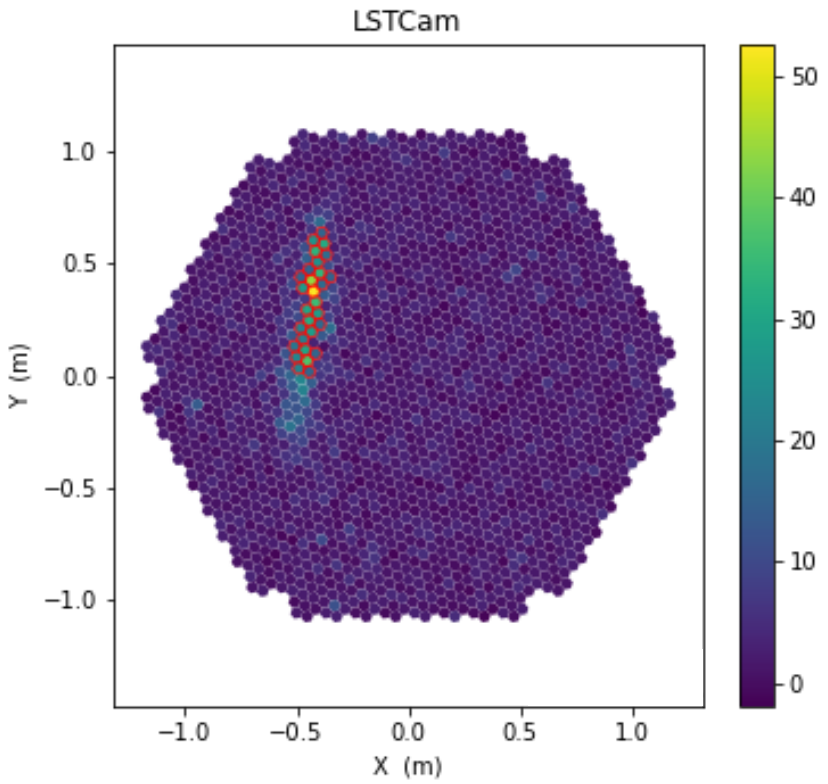
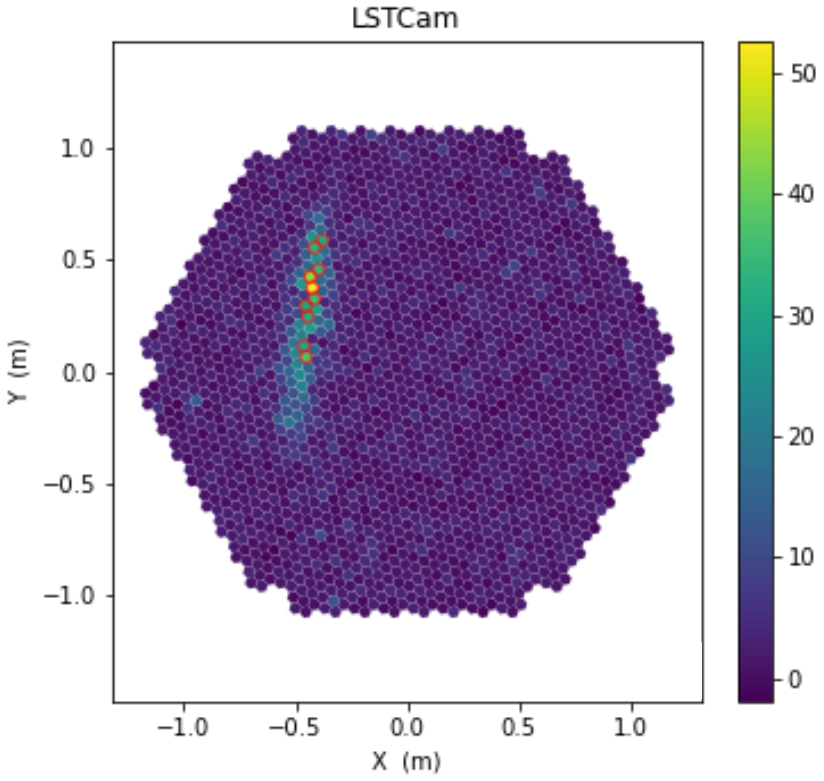


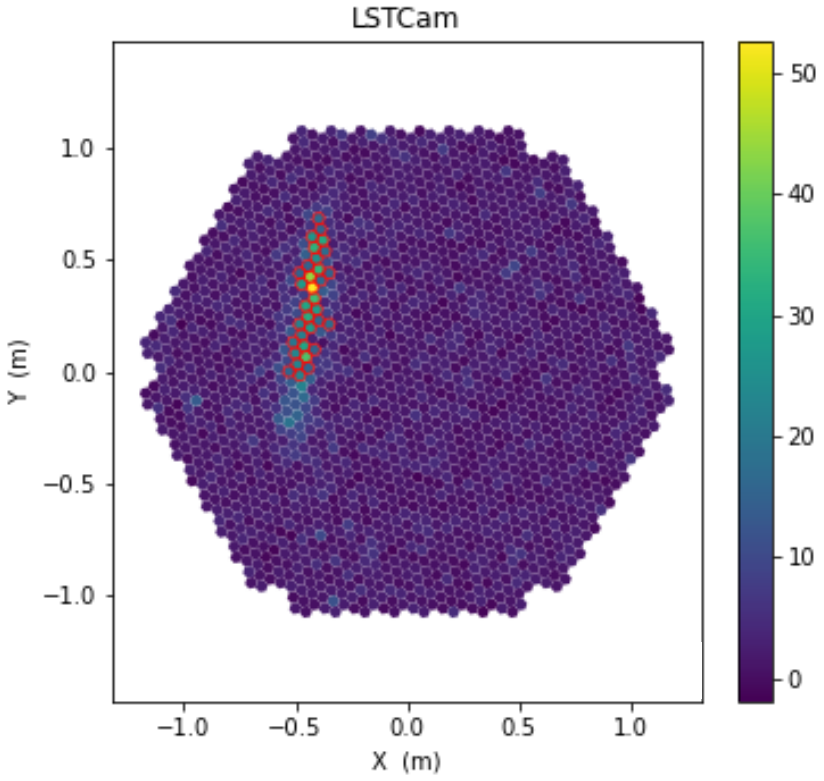
TailCutsDataVolumeReducer

1) Normal Tailcuts cleaning



TailCutsDataVolumeReducer

1) Normal Tailcuts cleaning
2) Iteratively adding neighbouring pixels above boundary threshold



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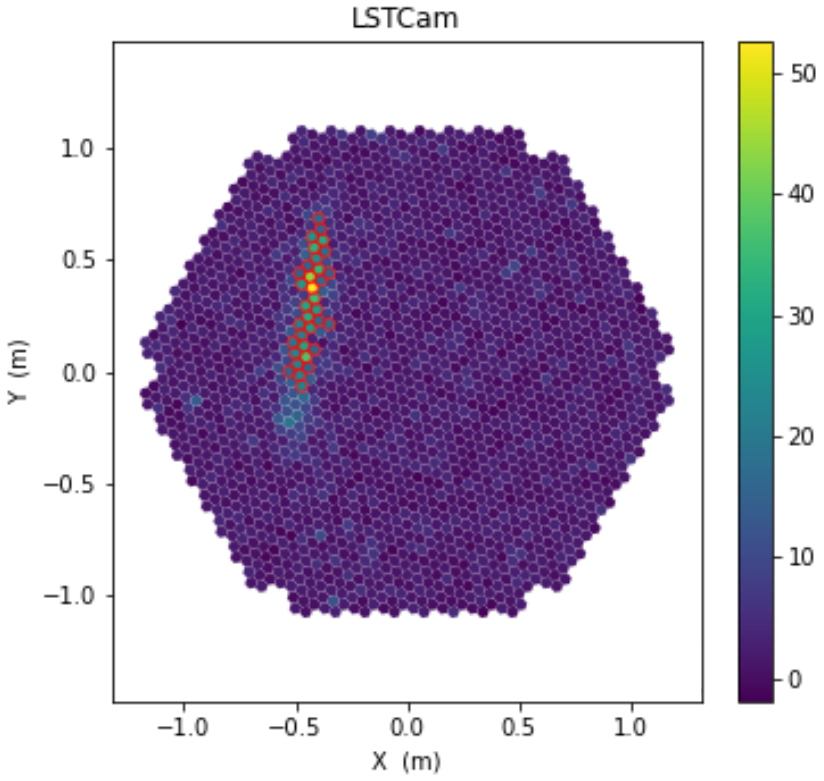

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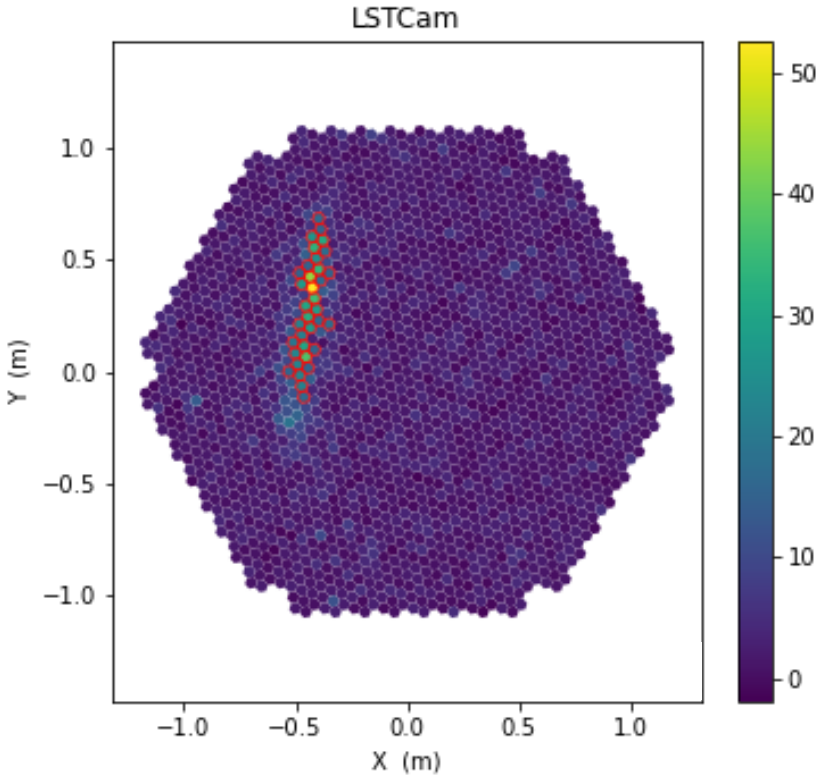
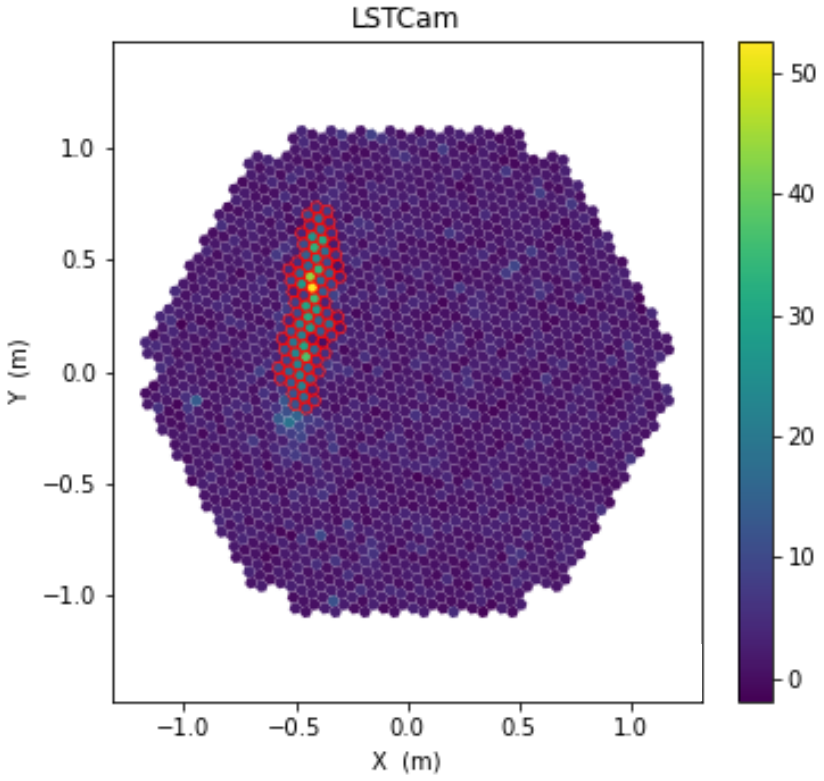


TailCutsDataVolumeReducer

1) Normal Tailcuts cleaning
2) Iteratively adding neighbouring pixels above boundary threshold
3) At the end: Adding all neighbouring pixels



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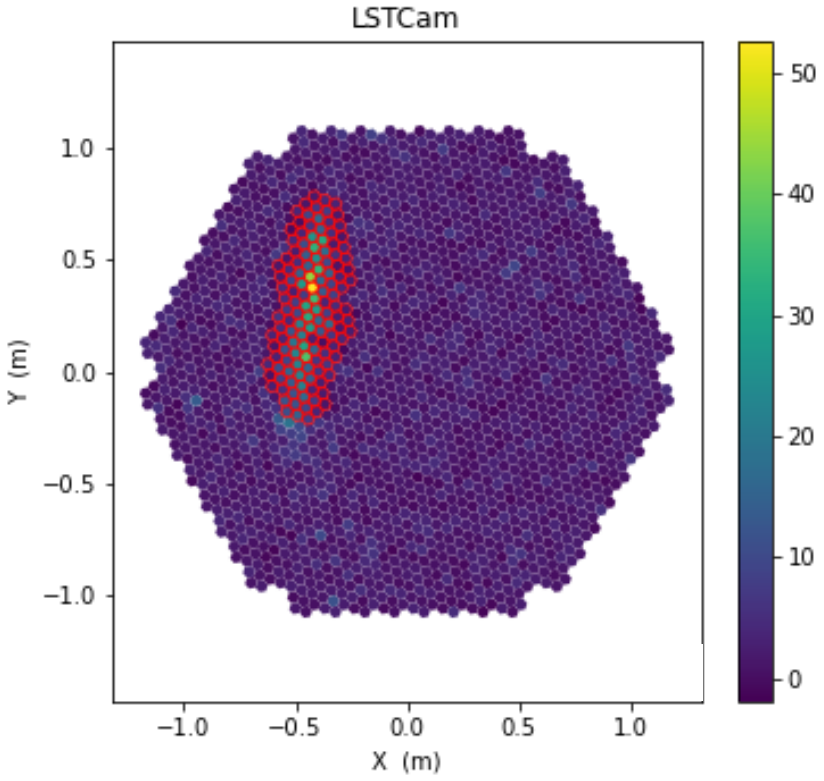
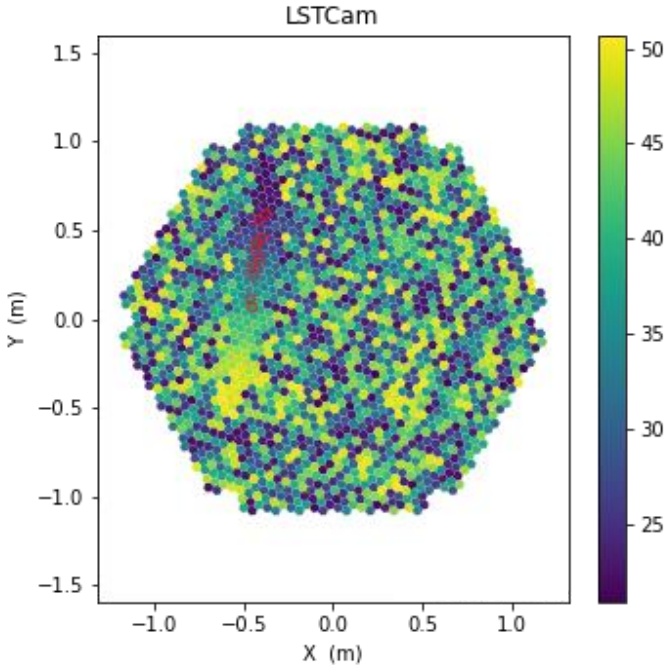
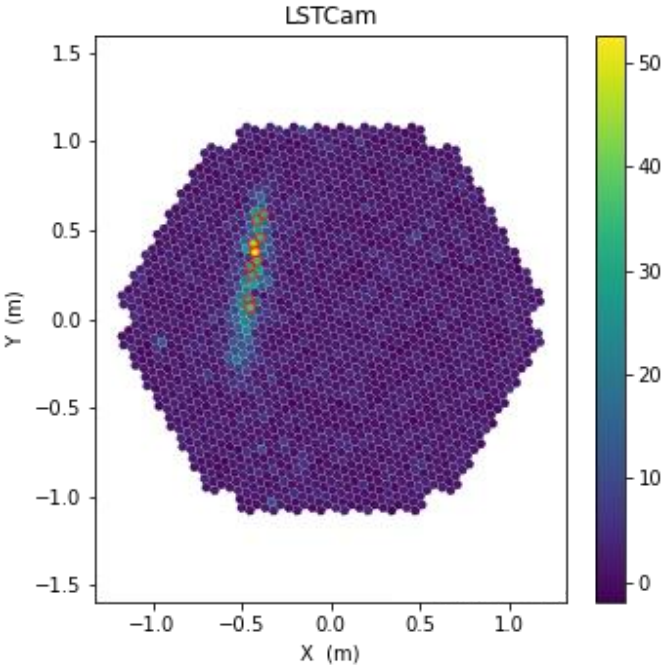


ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons



Time/ns



Photons

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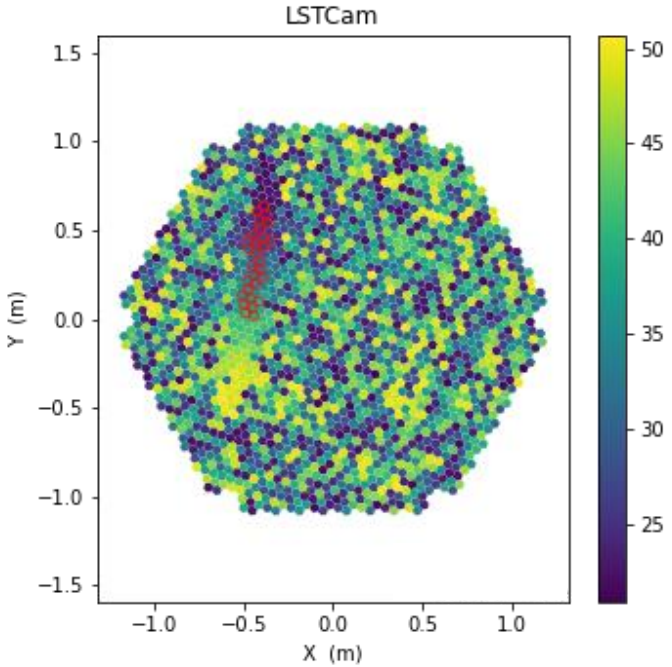

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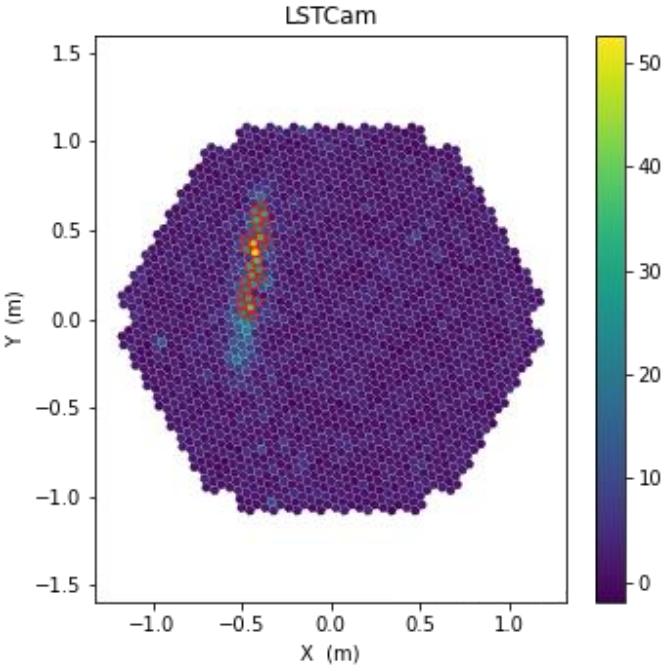
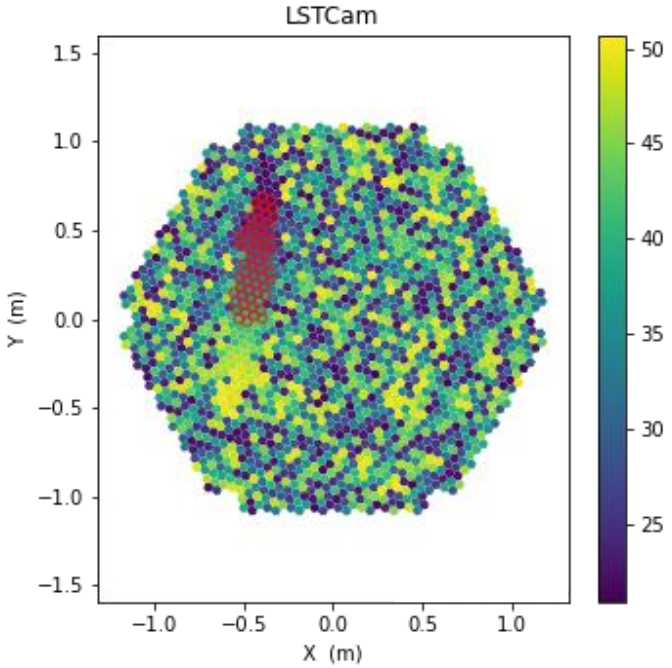


Photons

ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons
2) Iteratively adding all neighbouring pixels with a time difference lower than a threshold



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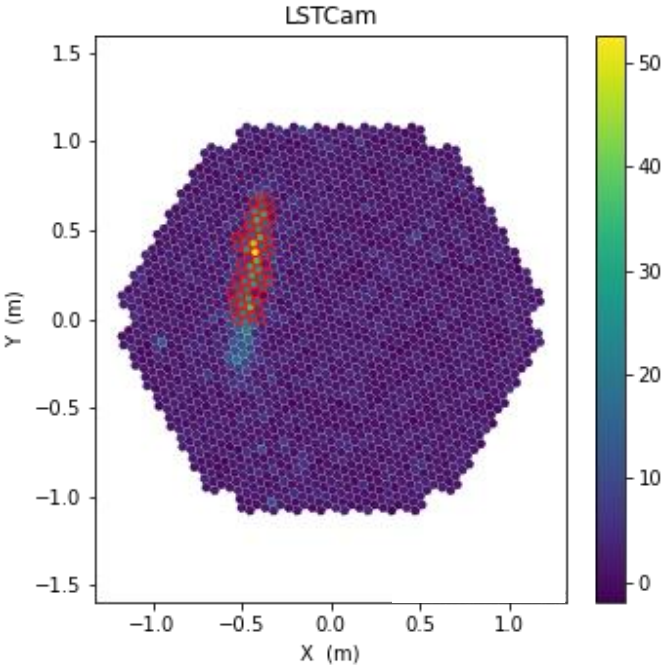

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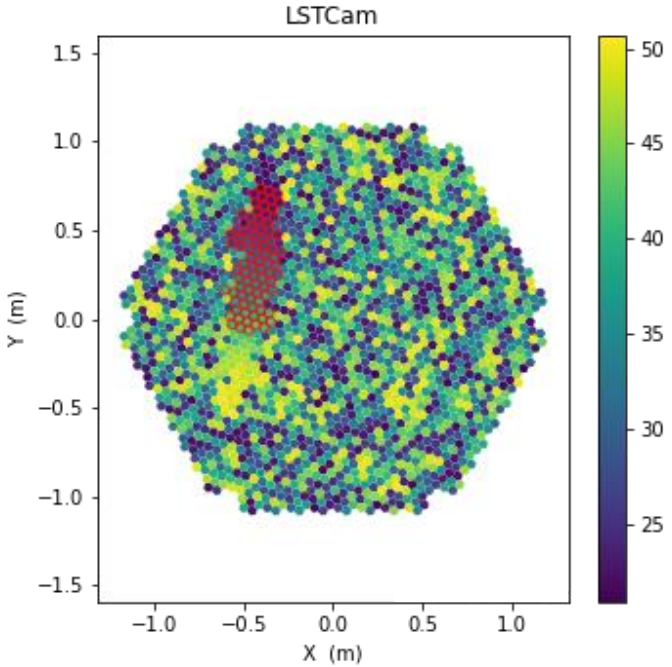

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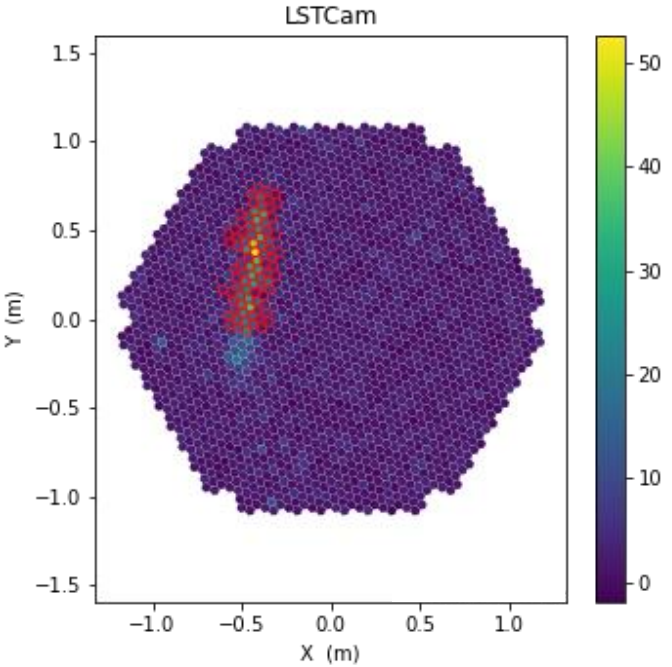

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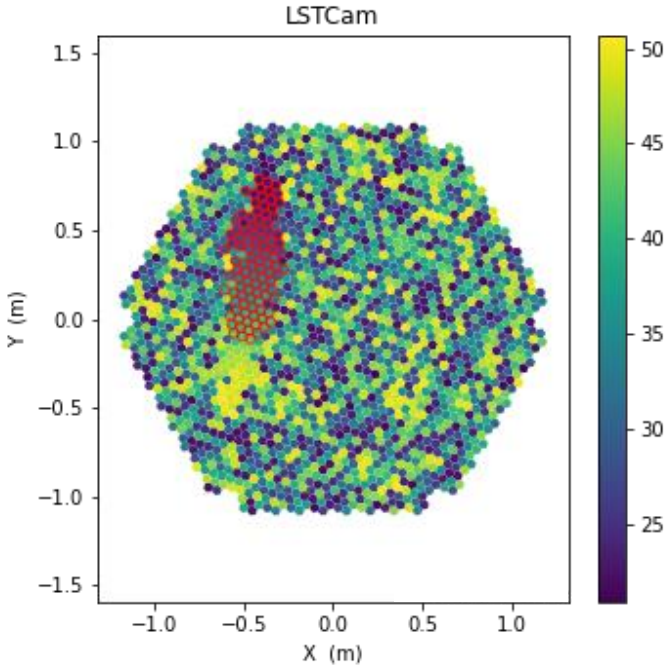

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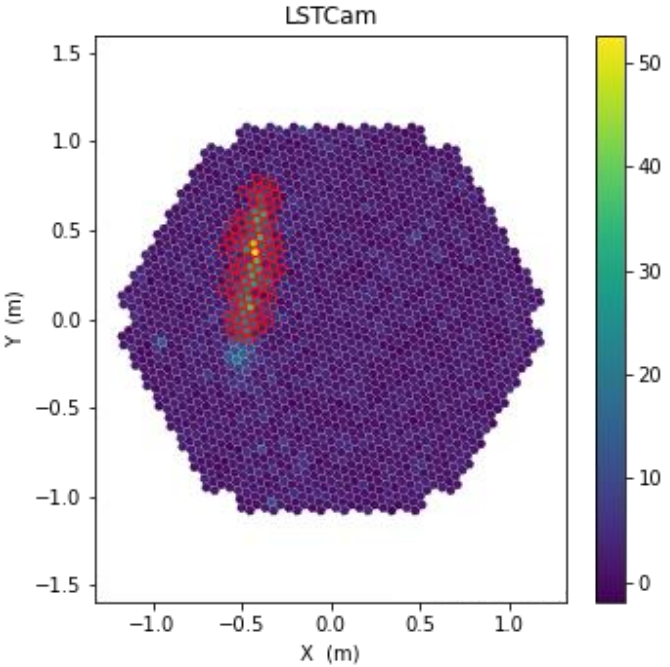

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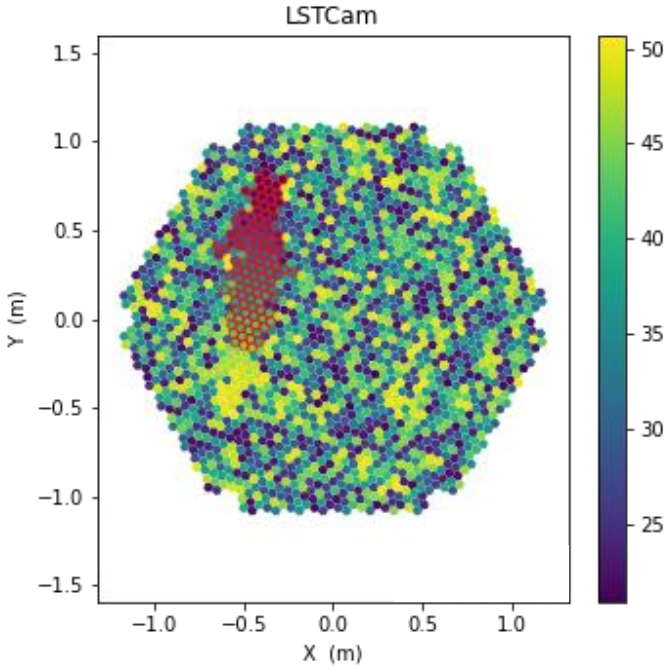

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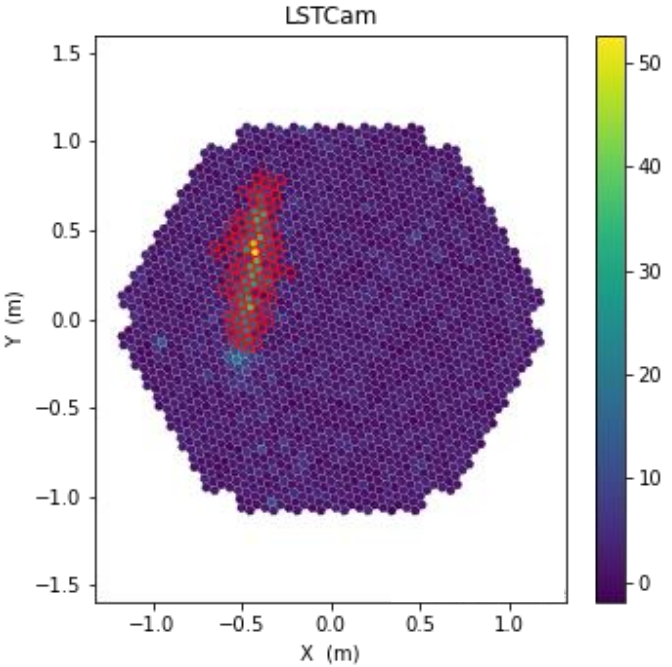

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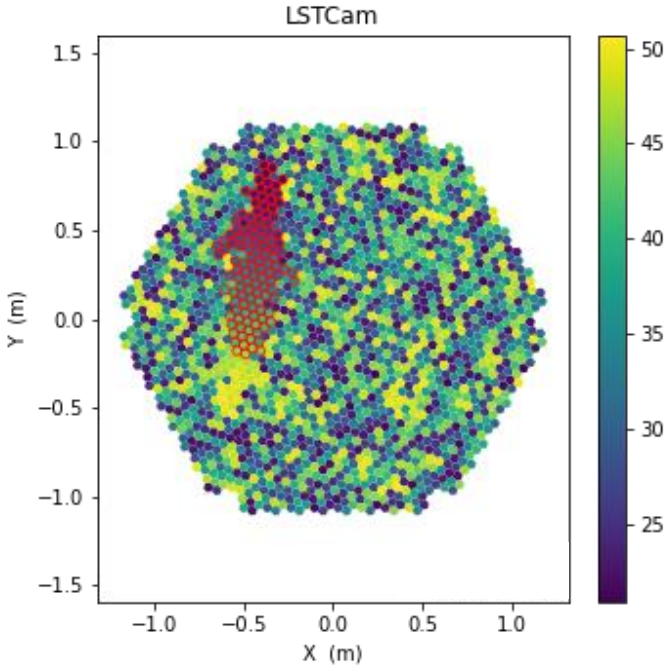

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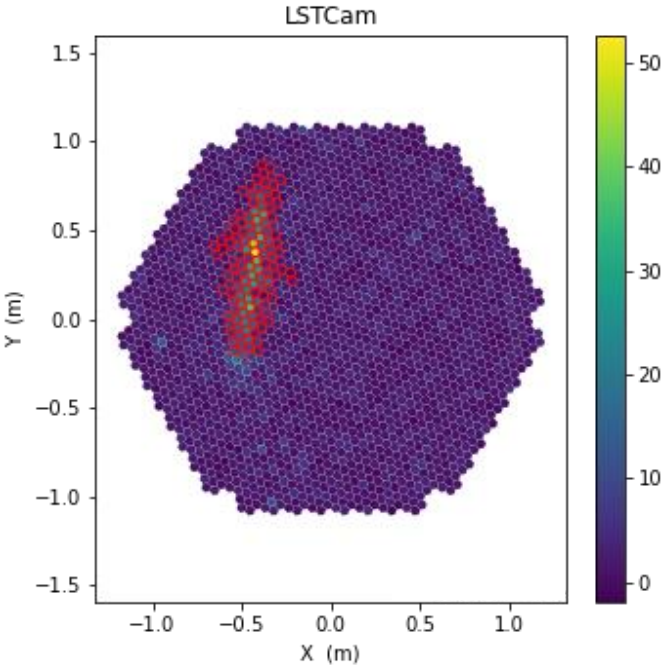

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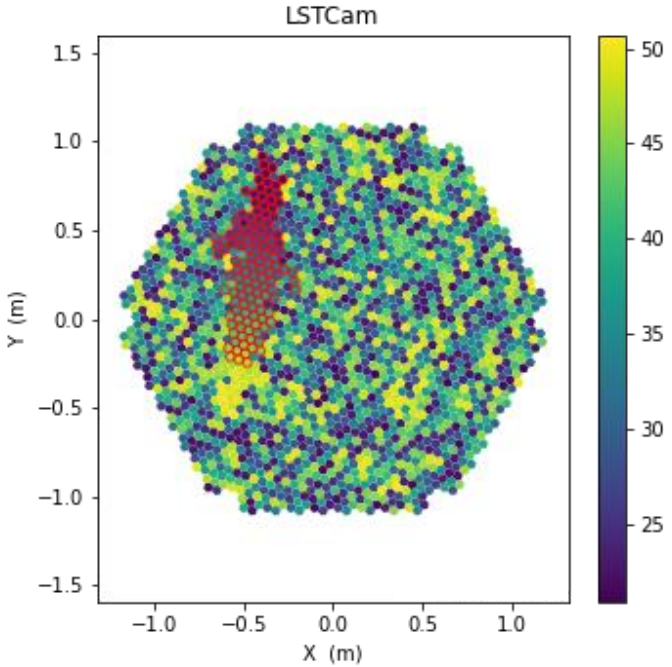

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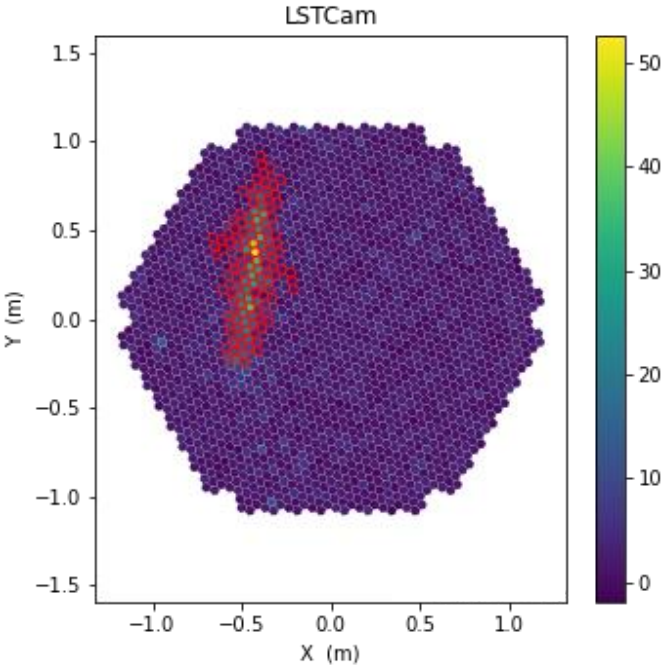

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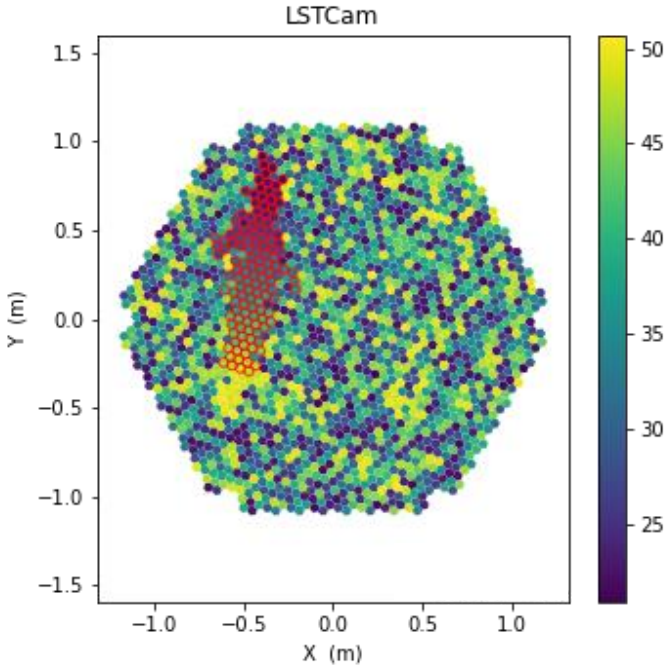

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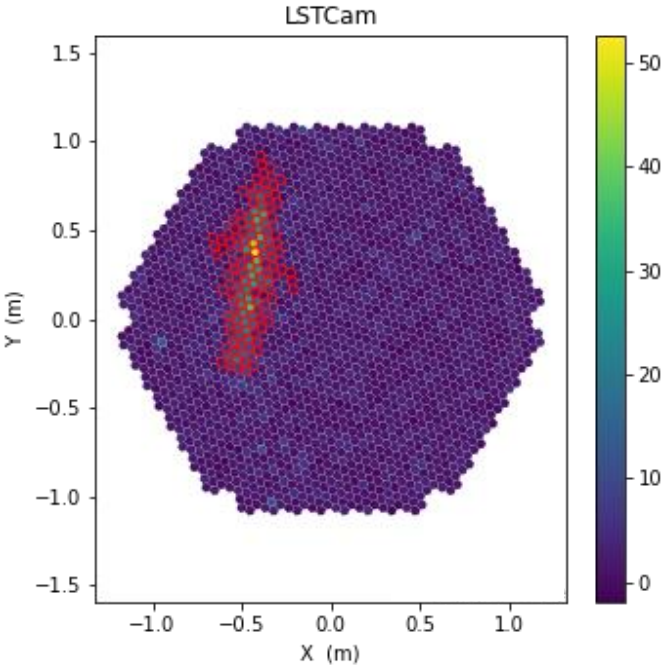

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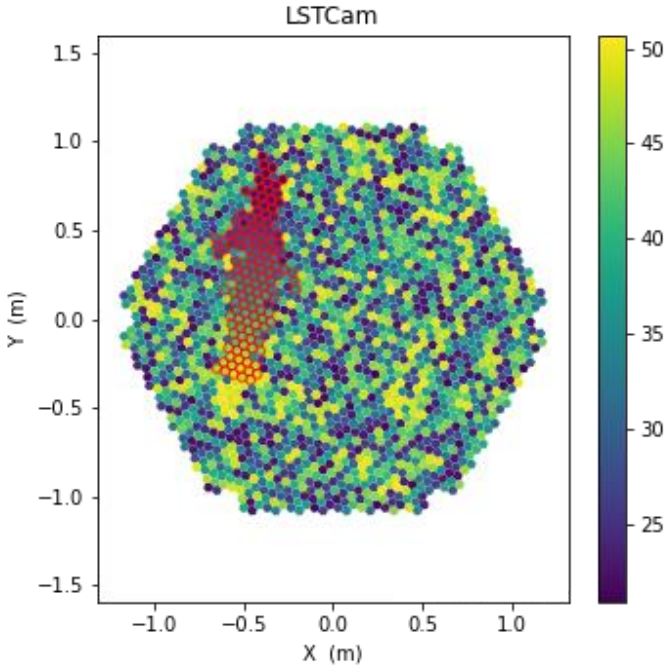

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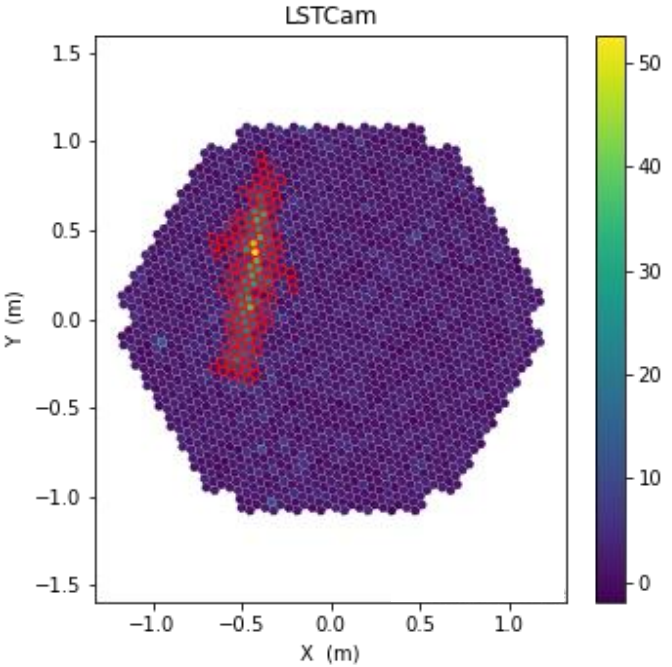

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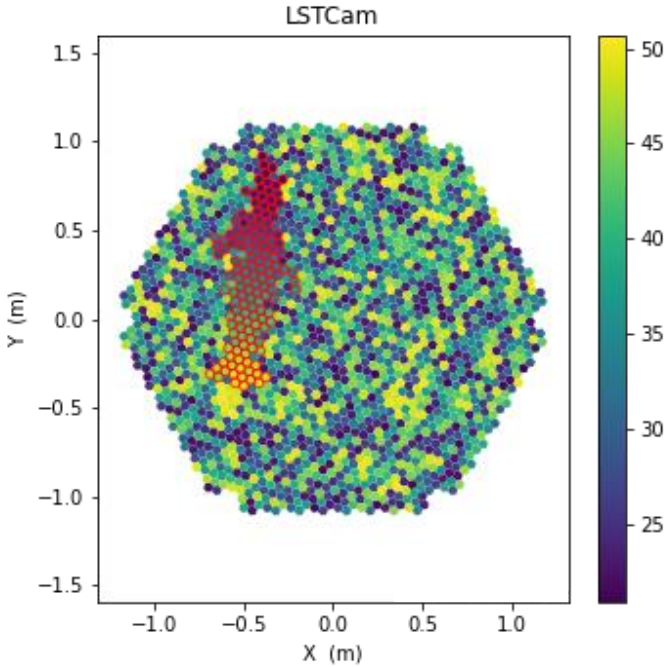

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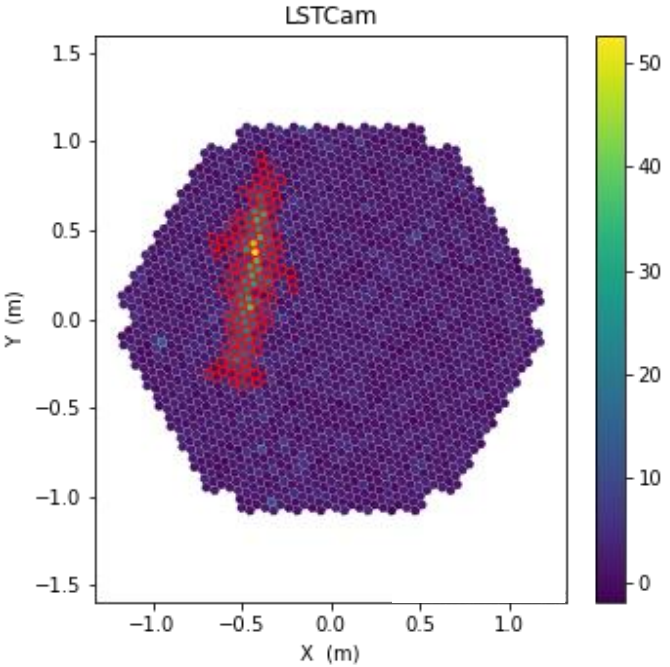

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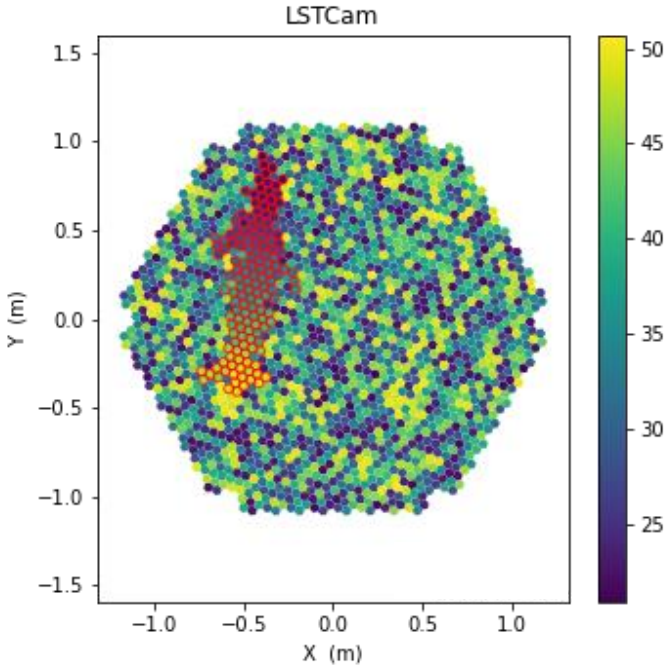

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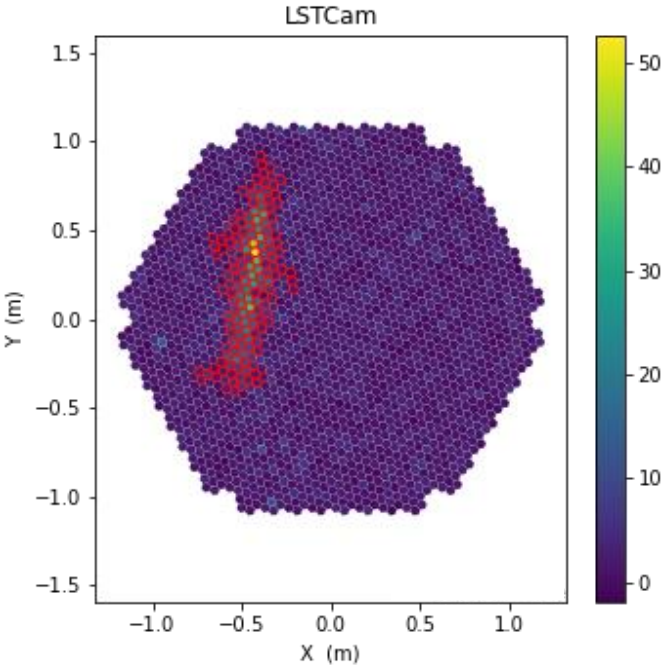

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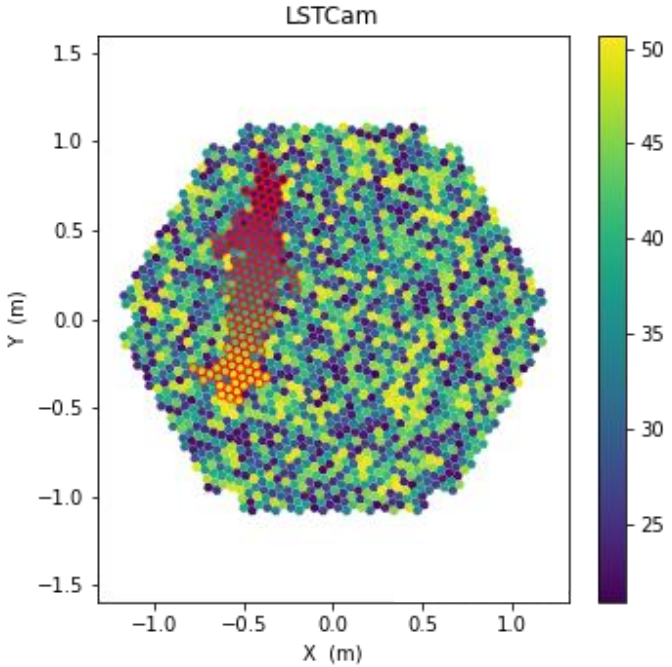
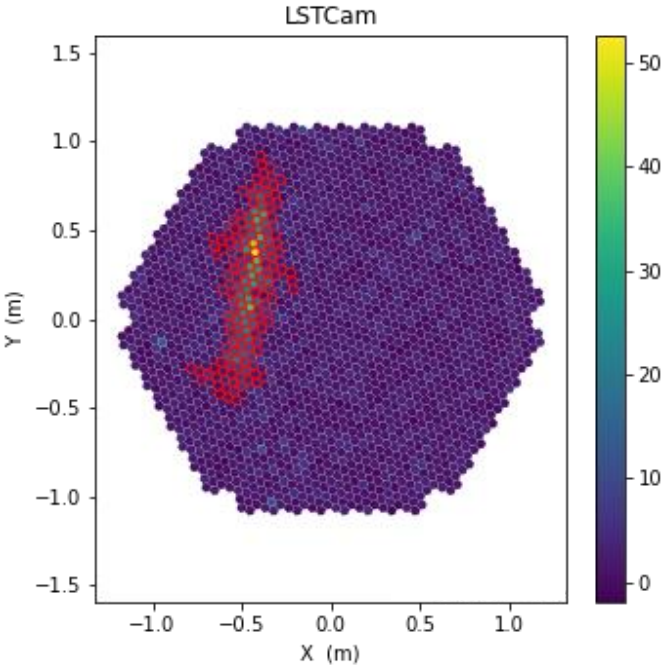


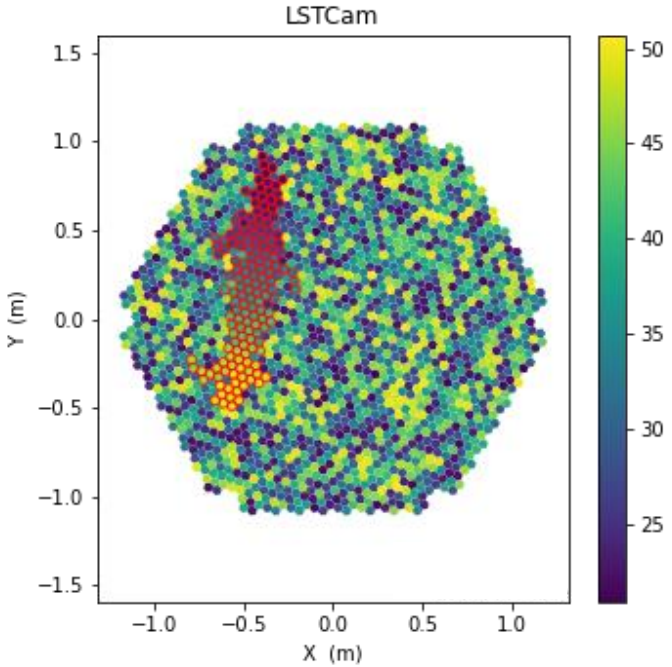
Time/ns



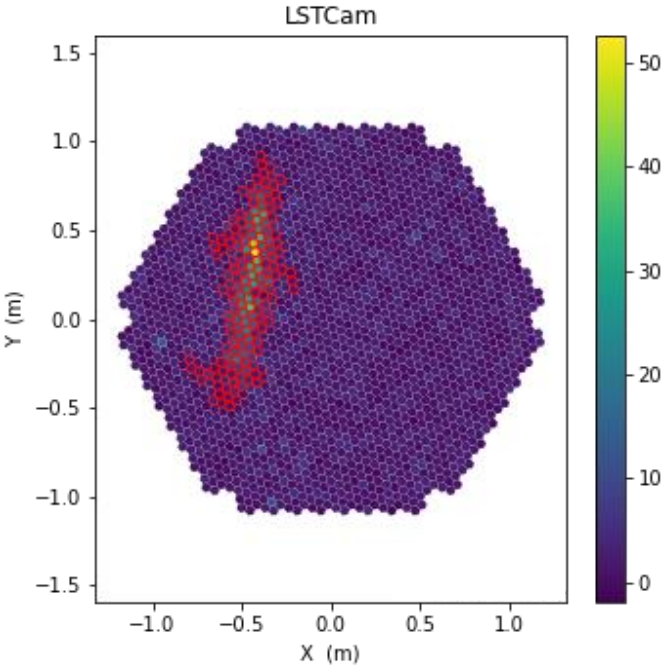
Photons

ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons
2) Iteratively adding all neighbouring pixels with a time difference lower than a threshold



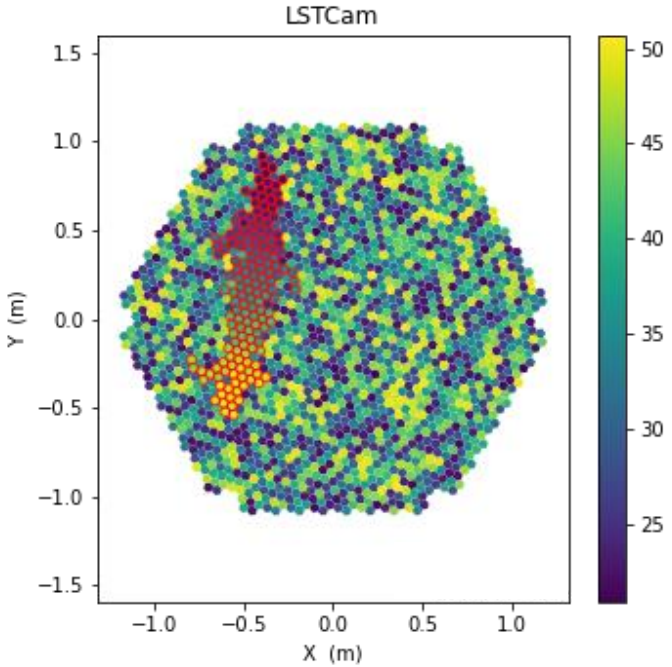
Time/ns



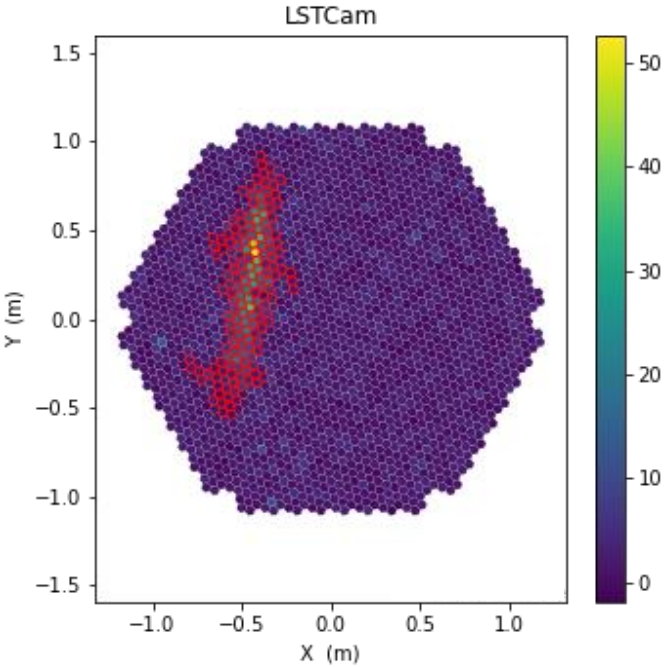
Photons

ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons
2) Iteratively adding all neighbouring pixels with a time difference lower than a threshold



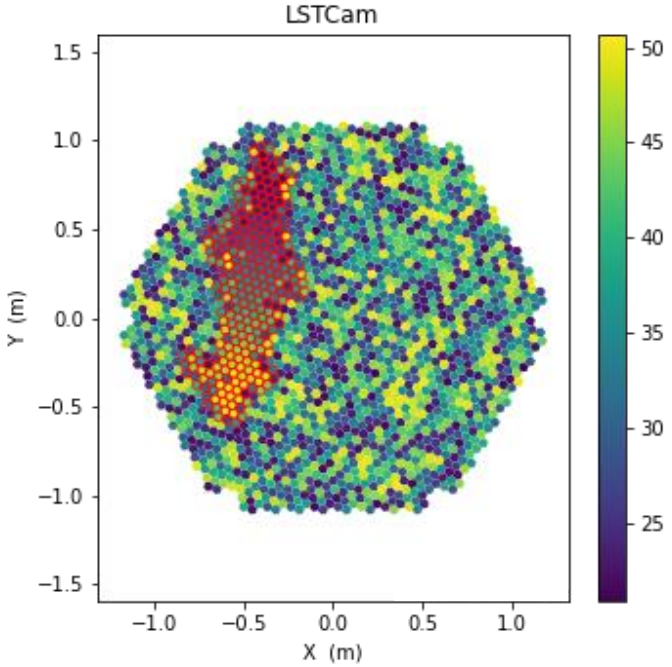
Time/ns



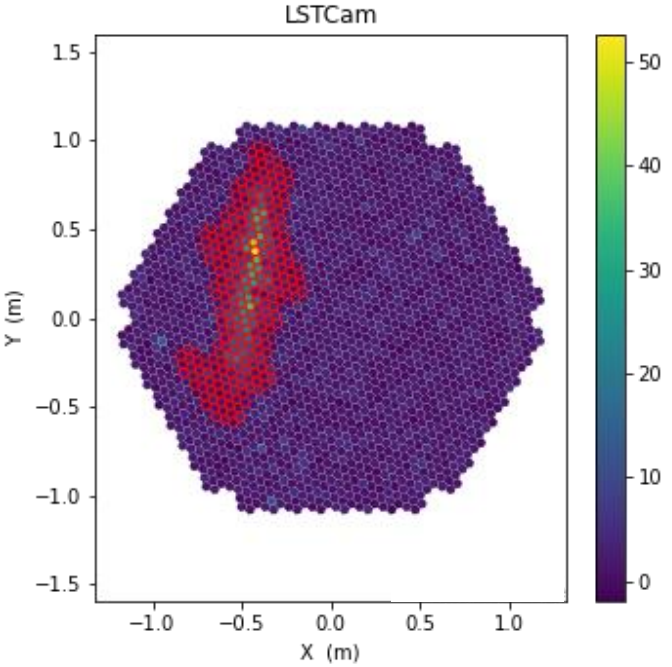
Photons

ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons
2) Iteratively adding all neighbouring pixels with a time difference lower than a threshold
3) At the end: Adding all neighbouring pixels



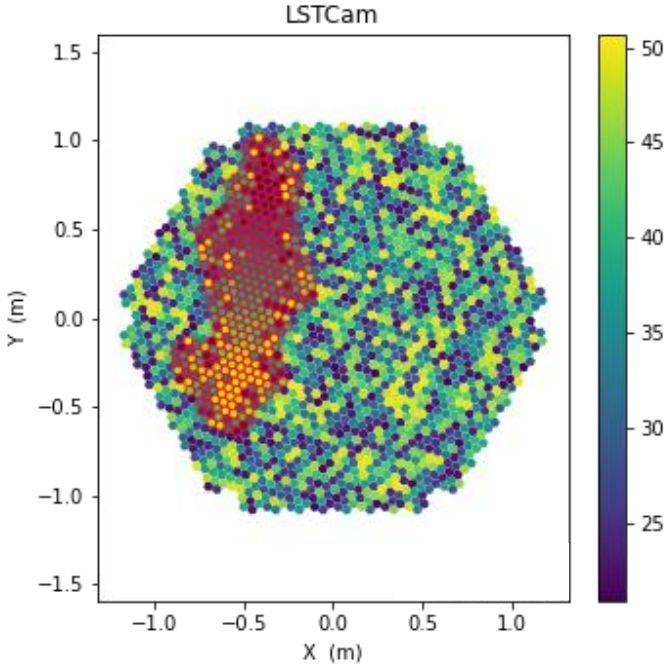
Time/ns



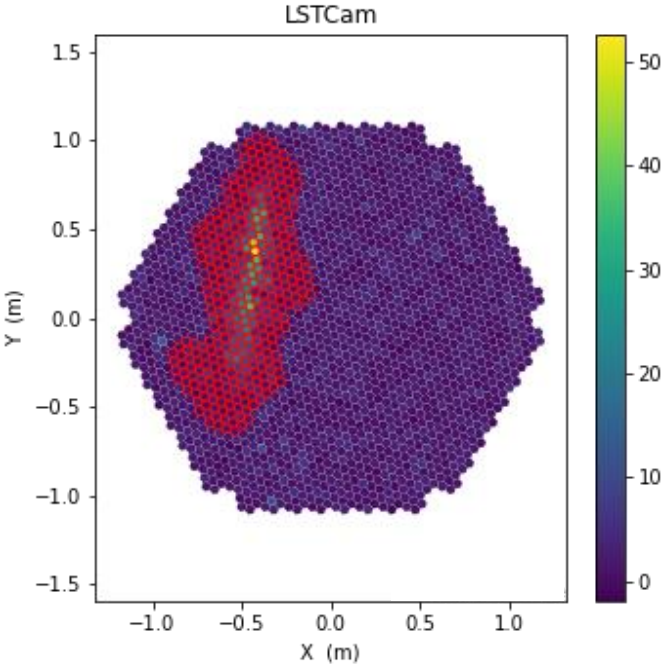
Photons

ArrivalTimesDataVolumeReducer

1) Normal Tailcuts cleaning on # Photons
2) Iteratively adding all neighbouring pixels with a time difference lower than a threshold
3) At the end: Adding all neighbouring pixels



Time/ns



Photons

TCDVR – ATDVR - Performance

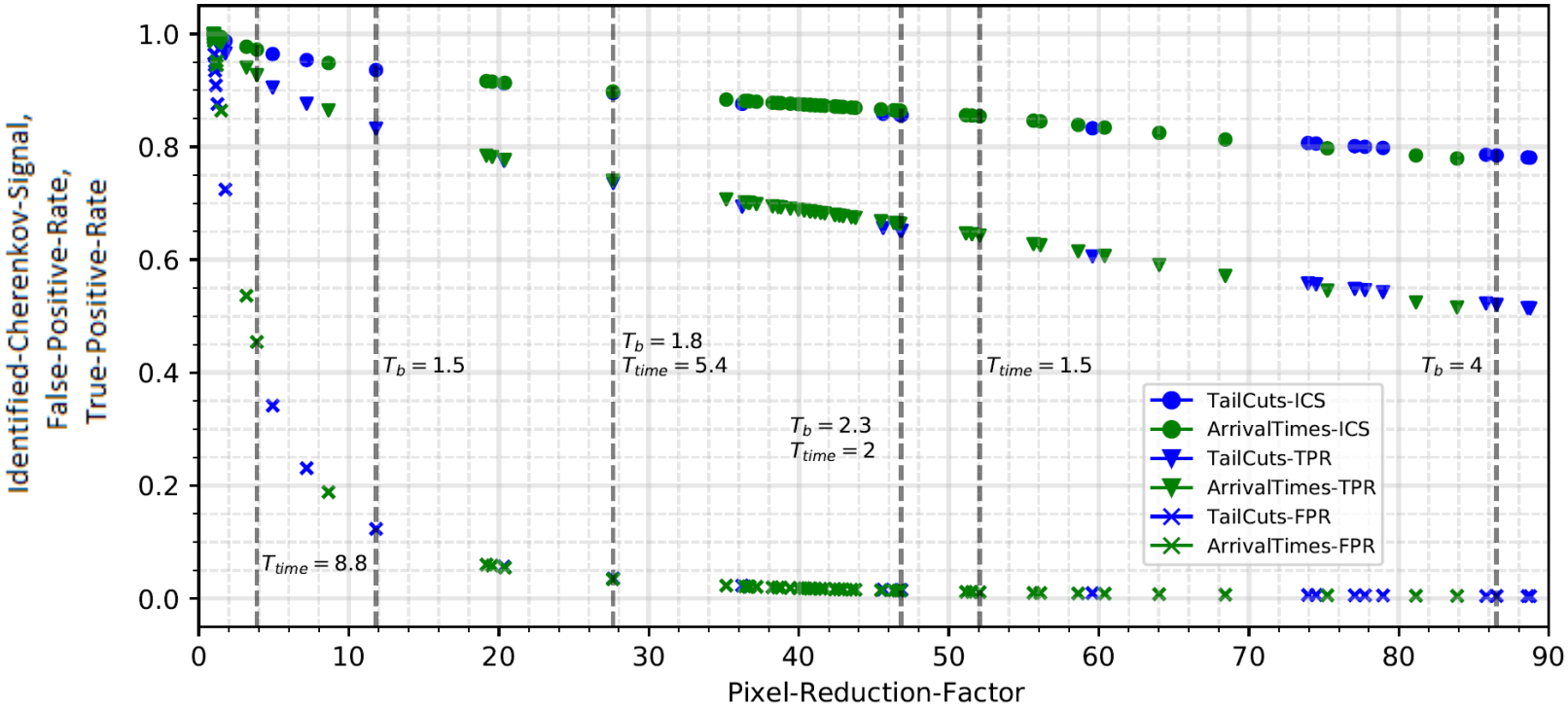
Quantitative Comparison on MC:

- First aim: Pixel-Reduction-Faktor of ~47 (~2.5 % of 1855 Pixels left)
- Some parameters were kept constant
- Set of values for T_b and T_{time} in a defined interval is drawn by means of a random selection

- Crab Nebula spectrum detected by HEGRA used for weights of gamma events
- Proton and Helium interpolated spectrum measured by DAMPE used for weights of proton events

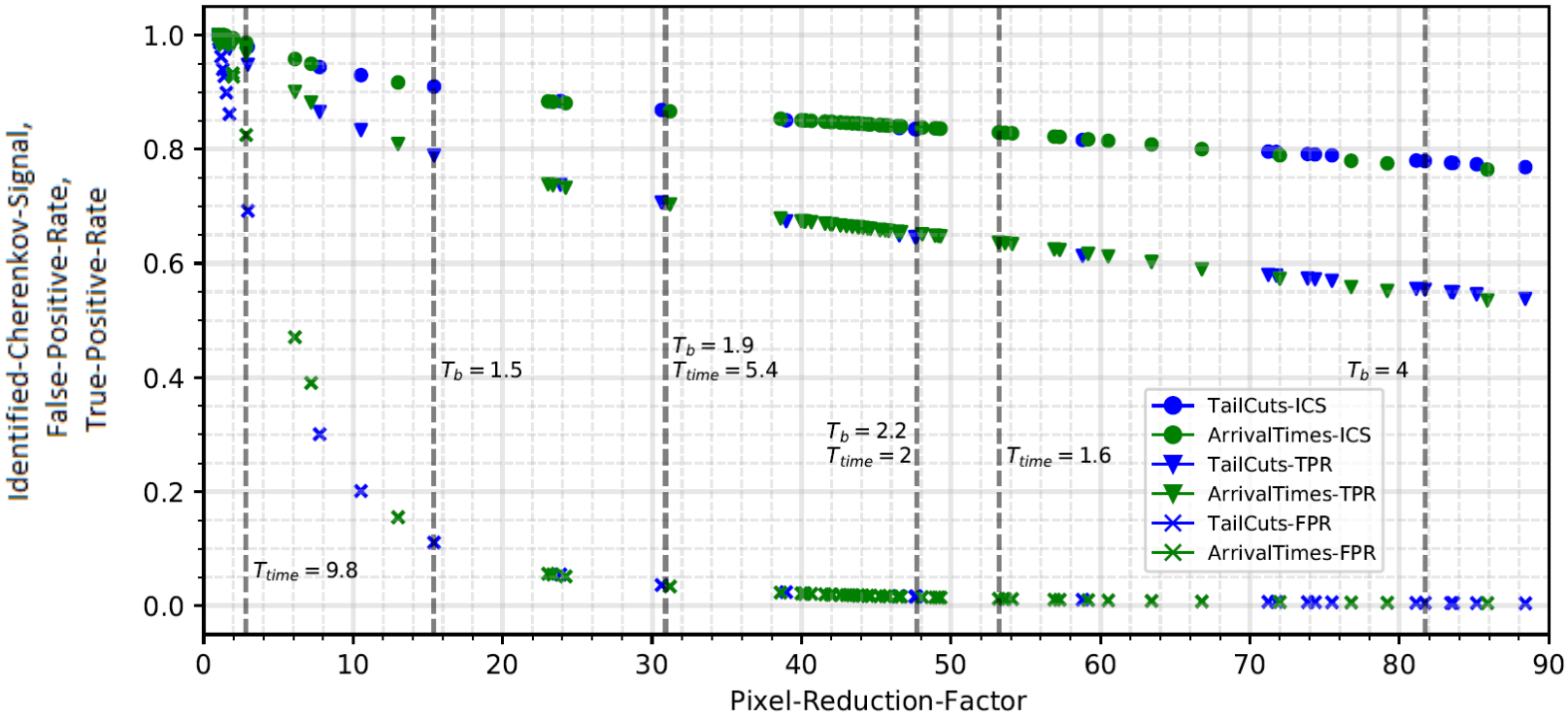
	TailCutsDVR	**ArrivalTimesDVR**
Core-Threshold T_c	8 p.e.	8 p.e.
Boundary-Threshold T_b	Variable	4 p.e.
Minimum core-neighbors	1	1
Keep isolated pixels	False	False
Dilate	1	1
Minimum time-neighbors	Not used	1
Time limit T_{time}	Not used	Variable

TCDVR – ATDVR - Performance



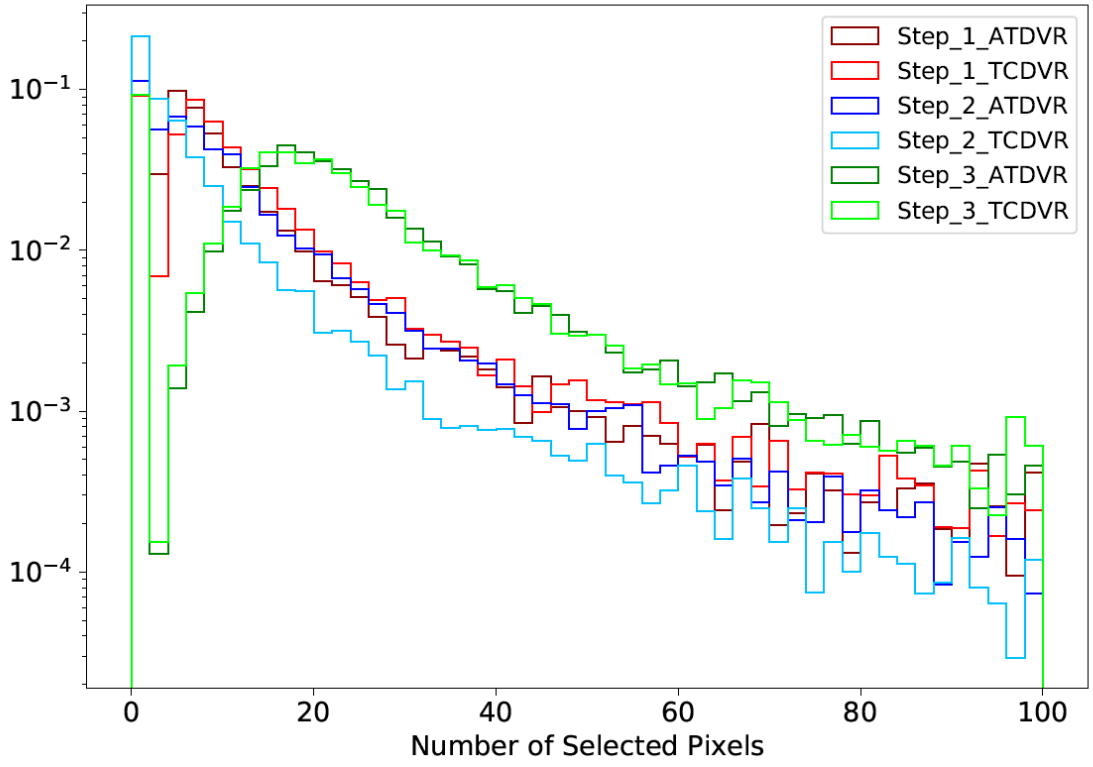
[20deg_Gamma_Prod5_MC]

TCDVR – ATDVR - Performance



[20deg_Proton_Prod5_MC]

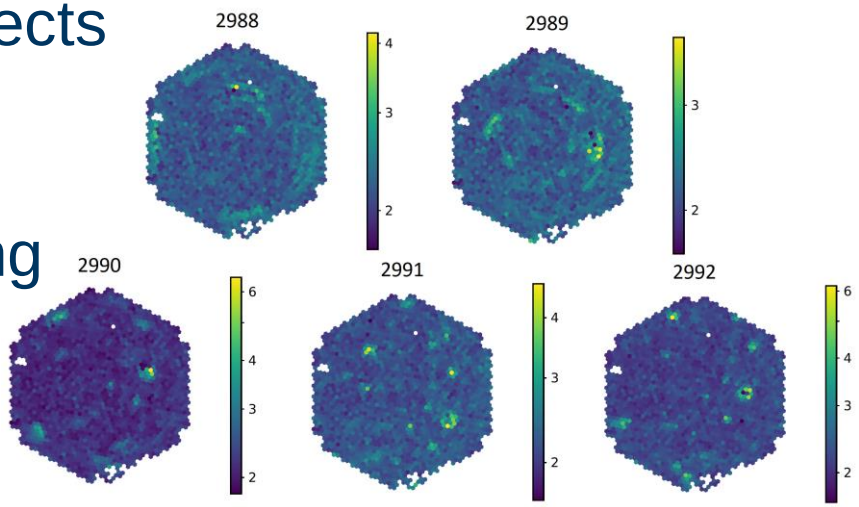
TCDVR – ATDVR - Performance



Crab Observation from 2020-11-21

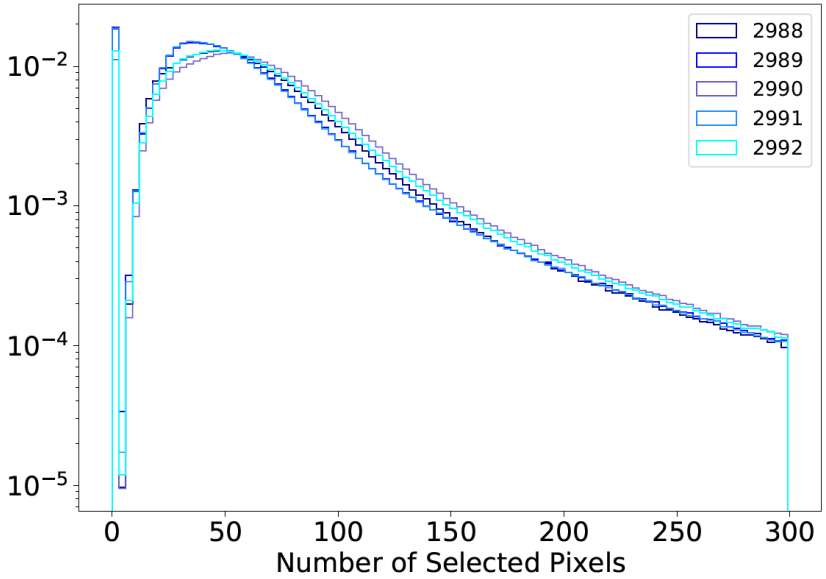
- Run 2988-2992 with ~1.6h Observation time
- 7-9 million events/file

- ➢ Flatfield Events: To reduce effects of image artifacts from the detector
- ➢ Interleaved Pedestals: Mapping the NSB



Crab Observation from 2020-11-21

Pixel selection with the ATDVR:

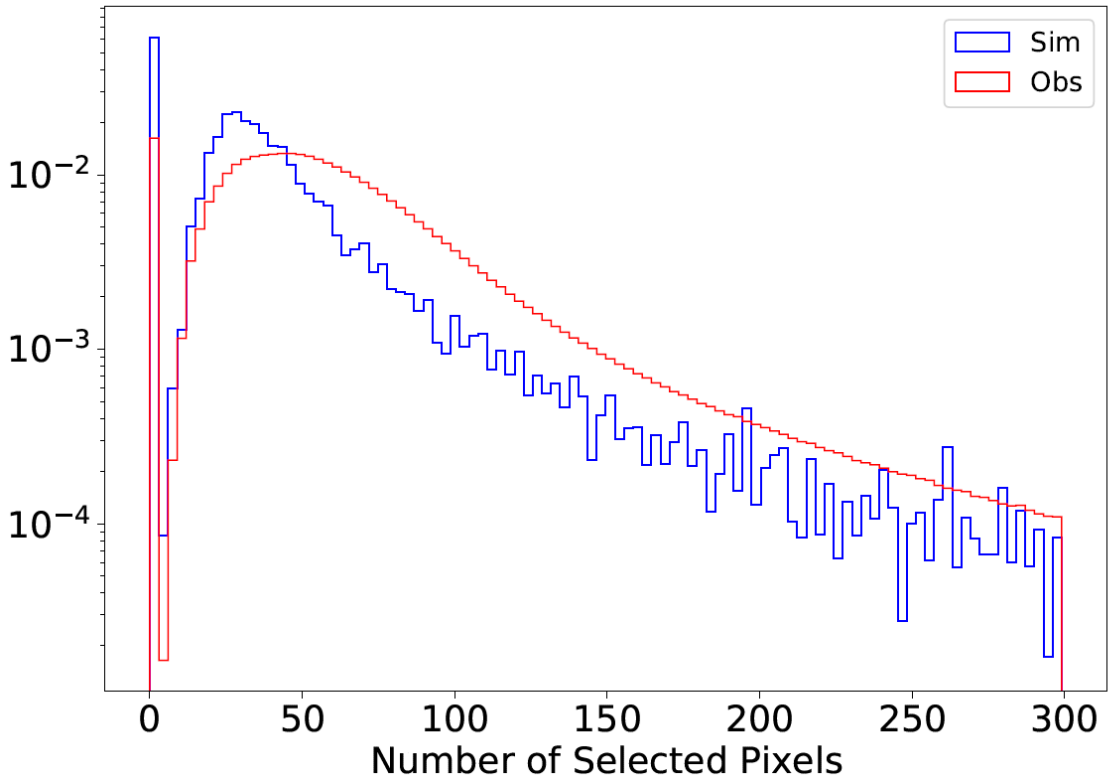


	ArrivalTimesDVR
Core-Threshold T_c	8 p.e.
Boundary-Threshold T_b	4 p.e.
Minimum core-neighbors	1
Keep isolated pixels	False
Dilate	1
Minimum time-neighbors	1
Time limit T_{time}	2.0

- Reduction per file from ~97.8 GByte to ~8.5 GByte
- PRF ~ 28

Crab Observation from 2020-11-21

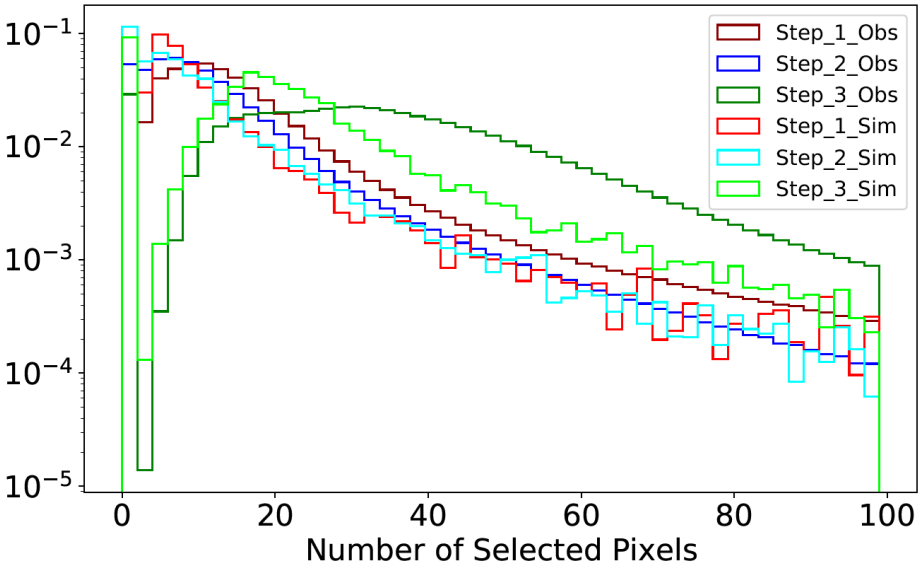
Pixel selection with the ATDVR:

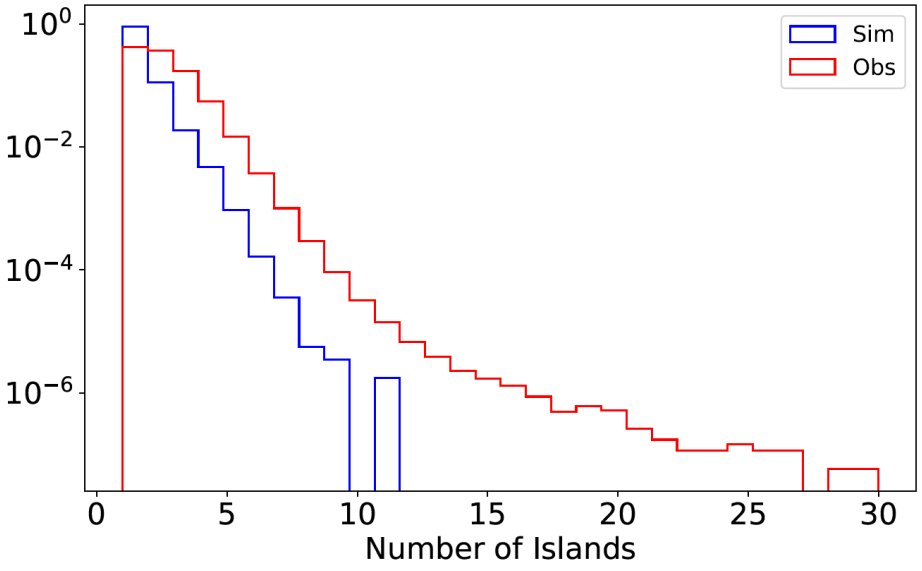


[weighted proton MC]

Crab Observation from 2020-11-21

Pixel selection with the ATDVR:





[weighted proton MC]

Crab Observation from 2020-11-21

Pixel selection with the ATDVR:

Approaching MC distribution of selected Pixels per image:

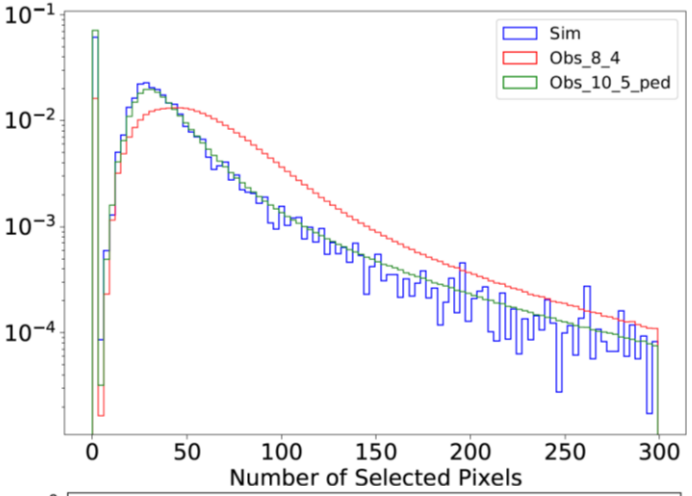
- Adapt $T_c = 10$ and $T_b = 5$
- Use interleaved pedestals for dynamic pixel thresholds

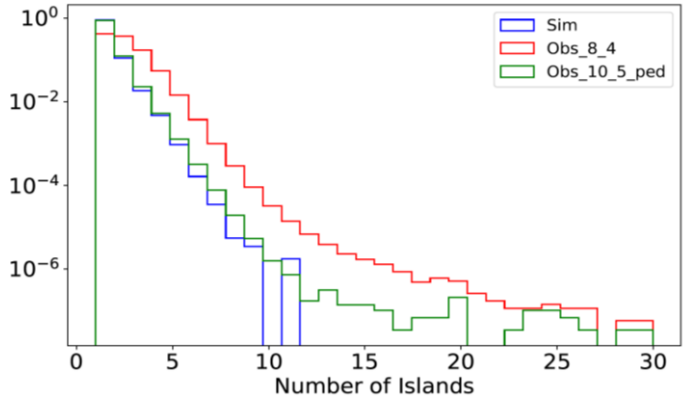
$$T_{ped} = \mu_{ped} + 2.5 * \sigma_{ped}$$

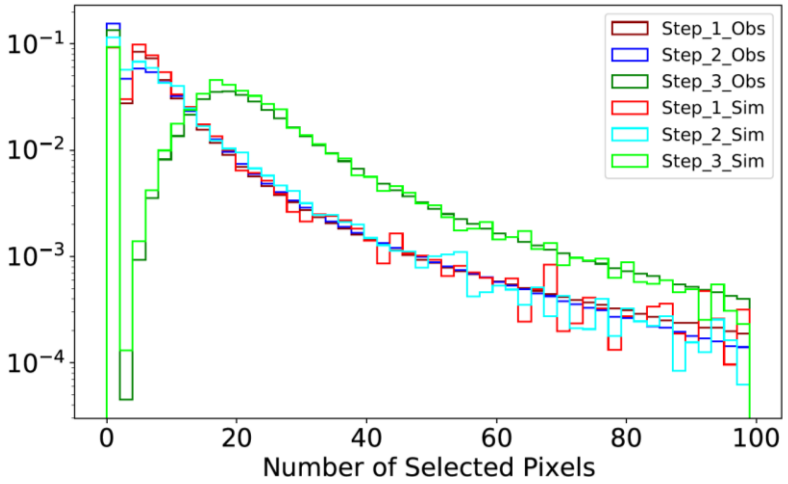
- Use T_{ped} if T_c is below T_{ped}

Crab Observation from 2020-11-21

Pixel selection with the ATDVR + adaptions:







- Reduction per file from ~8.5 GByte to ~6.8 GByte
- PRF ~ 42

[weighted proton MC]

Impact on Higher Level Analysis

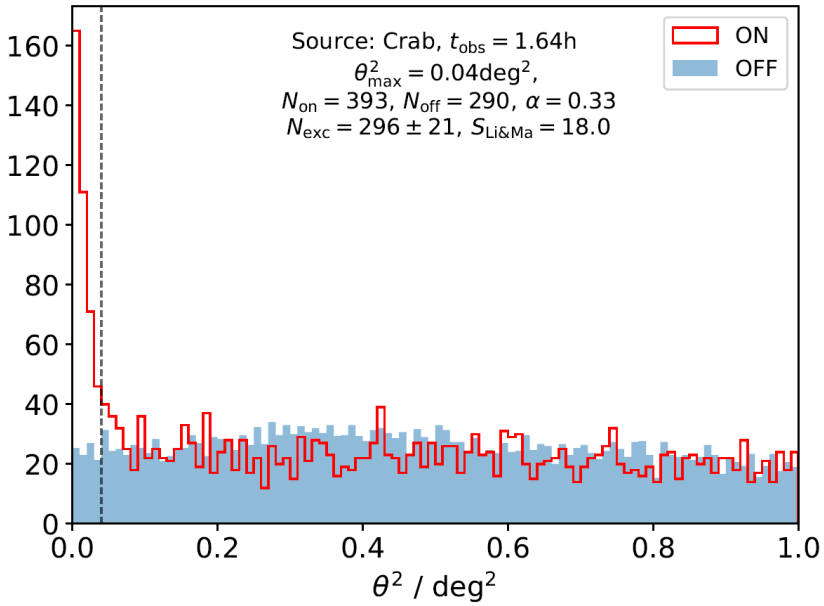
- Θ^2-Plot verification whether the analysis chain performs correctly
- Observations: Crab Nebula from 21.11.2020
- ArrivalTimesDVR
- Tailcuts Cleaning (8 | 4)
- DL2 processed with aict-tools (ctapipe processed MCs for RF training)
- Not optimized parameters

➢ Should have no difference by definition

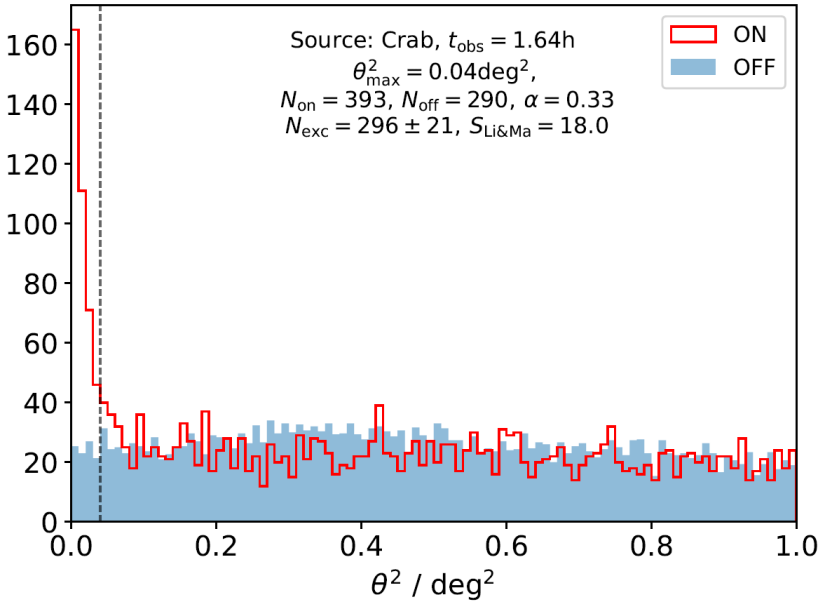
	ArrivalTimesDVR
Core-Threshold T_c	8 p.e.
Boundary-Threshold T_b	4 p.e.
Minimum core-neighbors	1
Keep isolated pixels	False
Dilate	1
Minimum time-neighbors	1
Time limit T_{time}	2.0

Impact on Higher Level Analysis

Without DVR



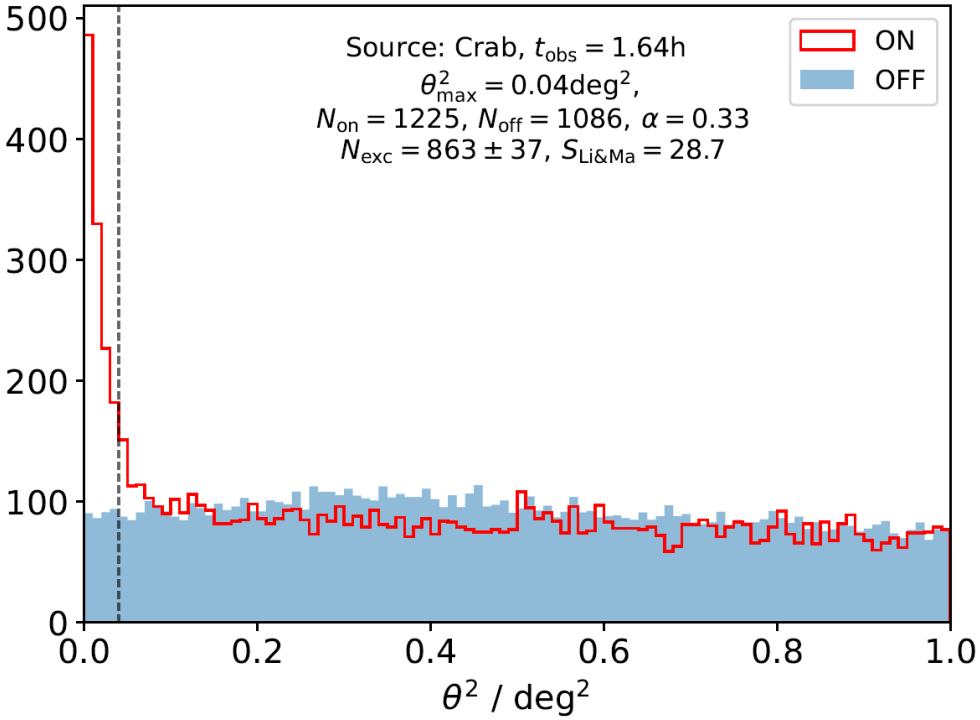
With DVR



[Crab Observation from 21.11.2020]

Impact on Higher Level Analysis

With Adaptions for DVR and cleaning:



[Crab Observation from 21.11.2020]

Summary

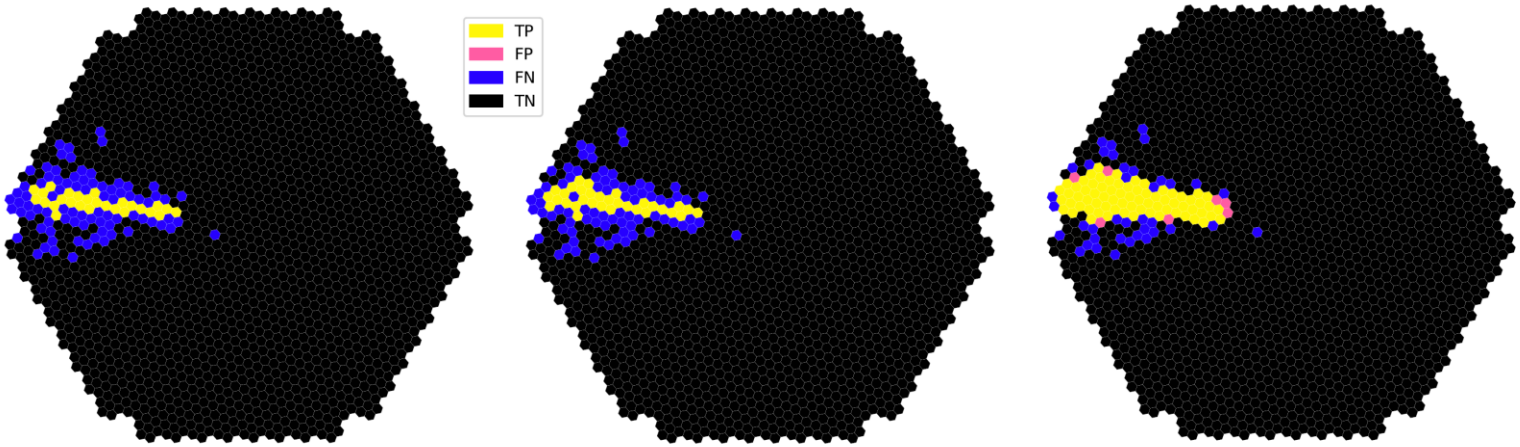
- TCDVR and ATDVR were tested and compared with MC data – perform equally well
- For PRF of 46: 0.83 ICS and 0.016 FPR on weighted simulated proton showers
- Employing ATDVR with same thresholds on Crab Nebula Observation: PRF of 28 and reduce data from 97.8 GByte to 8.5 GByte
- Increase PRF to 42 and decrease file size to 6.8 GByte with adapted thresholds
- Verifying used analysis chain by comparing Θ^2-Plots with and without DVR-step and detecting Crab Nebula with 18σ
- Detection increased to 28.7σ by using adapted cleaning thresholds

Outlook

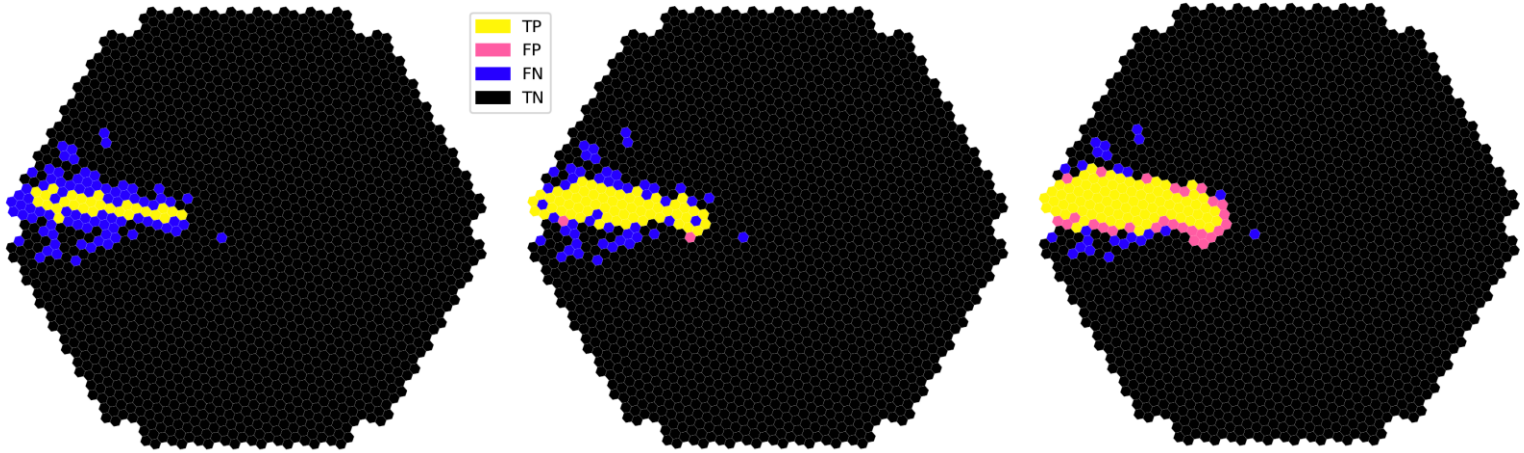
- Apply TCDVR to Crab Observations and compare it to the results obtained by the ATDVR
- Impact on higher data levels for different image cleaning algorithms
- Another way must be developed to include the interleaved pedestals events
- Vary other parameters
- Different benchmark criteria are needed (e.g. robustness, computation time, complexity etc.)
- General reference and training datasets for benchmarking must be defined

Backup TCDVR – ATDVR

TCDVR:



ATDVR:



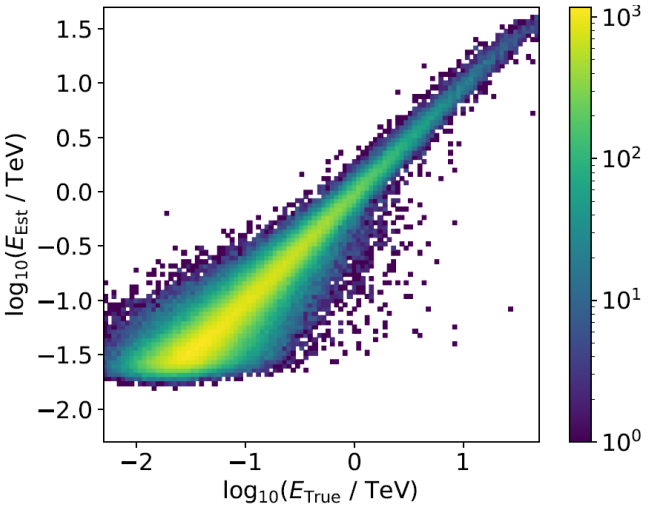
Backup – MC simulation properties

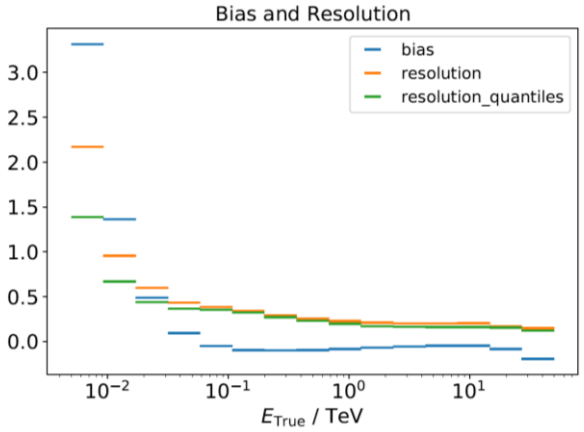
	Diffuse Gamma	Point-like Gamma	Proton	Elektron
Energy/TeV	0.005 - 50	0.005 - 50	0.001 - 100	0.005 - 5
Zenith angle/°	20	20	20	20
View cone/°	6	0	10	6
Spectral index	-2	-2	-2	-2

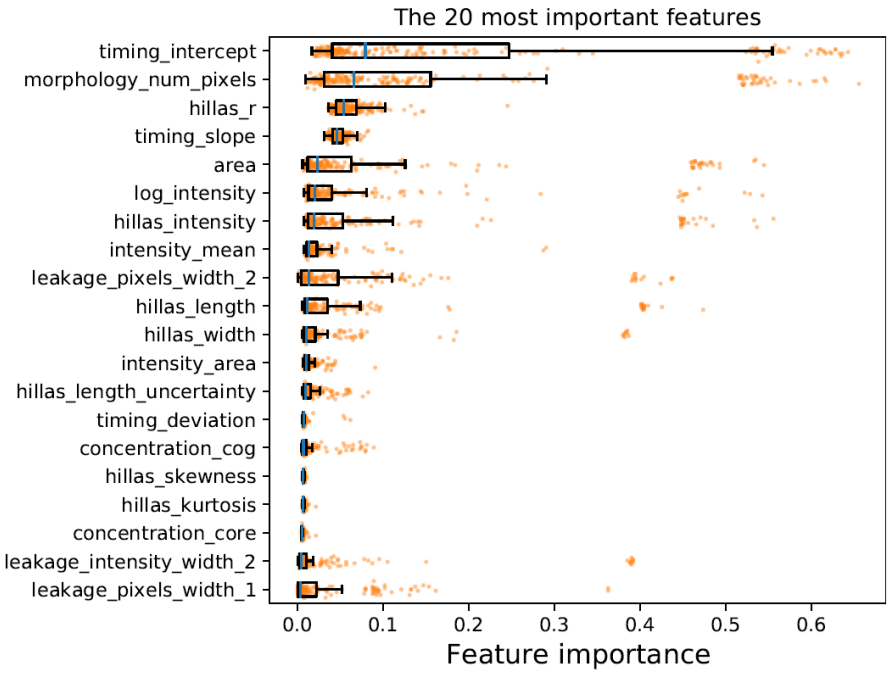
Backup – Quality Cuts

Parameter	Criteria
intensity	≥ 50
leakage_1_intensity	≤ 0.2
leakage_2_intensity	≤ 0.2

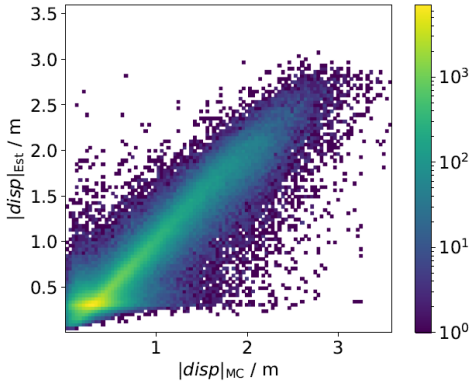
Backup – Energy Estimation

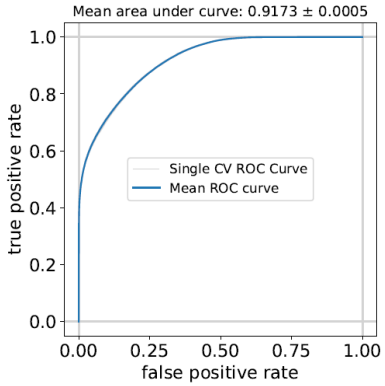


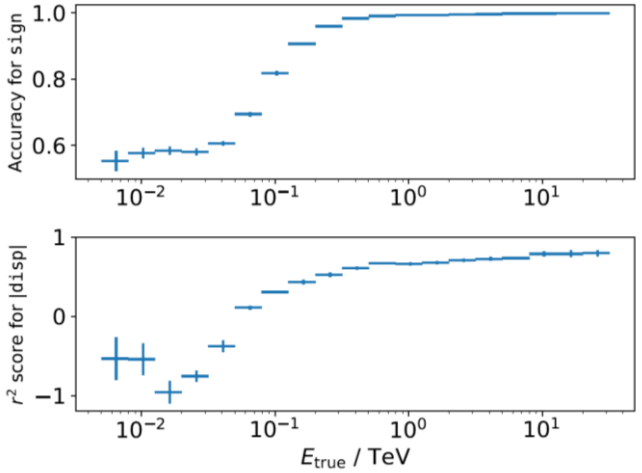


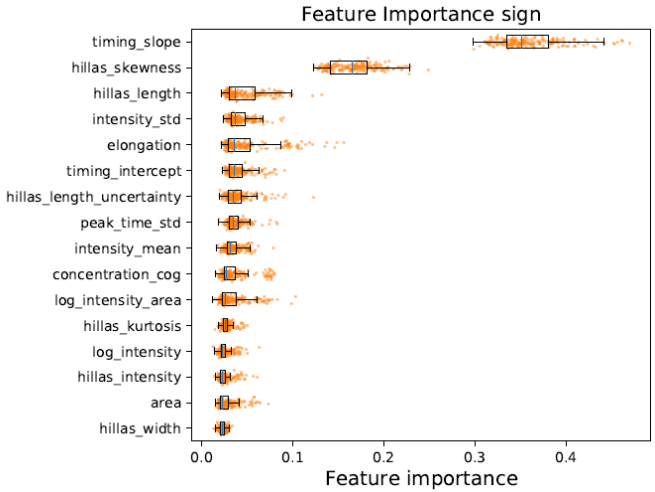


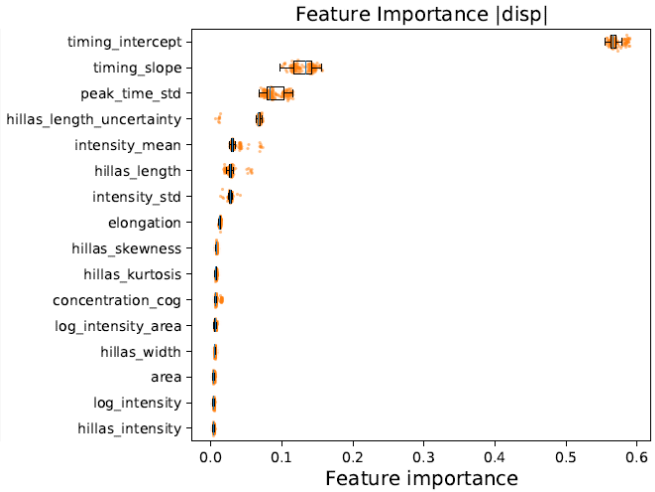
Backup – Origin Reconstruction











Backup – Background Separation