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CTAO

Real-time processing at the Large-Sized Telescopes of the Cherenkov Telescope Array Observatory

M. Heller on behalf of the CTAO LST Collaboration - 26/09/2024

SMARTHEP
REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY
NexTGen
EDGE ML SCHOOL

Courtesy of D. Kerszberg

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Outline

CTAO LST COLLABORATION

- The Imaging Atmospheric Cherenkov Telescope principle
- The Cherenkov Telescope Array Observatory
- The Large-Sized Telescope of CTAO
- Real-time processing in the Advanced SiPM Camera of LST
  - The project
  - Data volume reduction at all stages
- Real-time Analysis for CTAO: Scientific Alert Generation

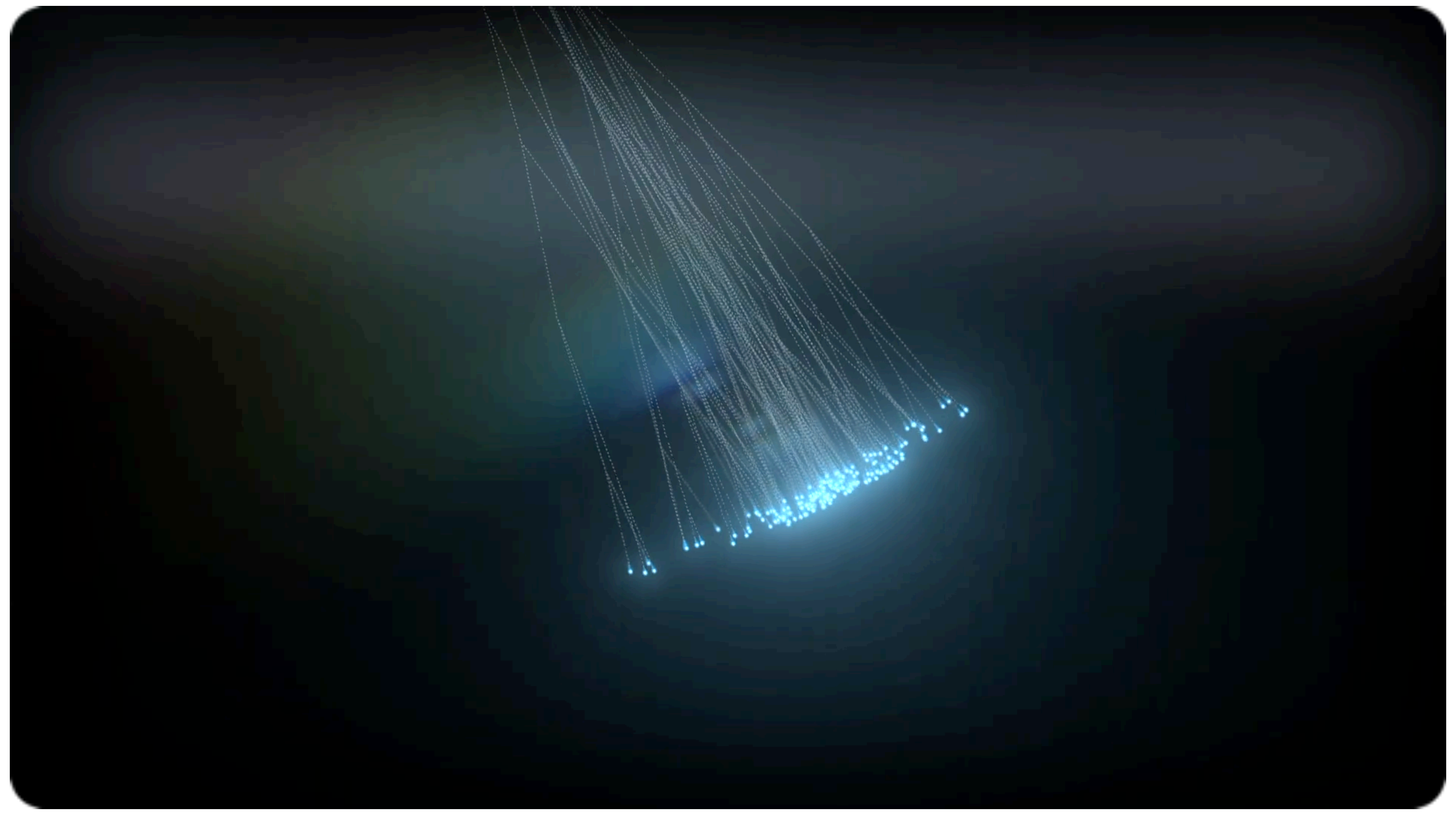
Credit: CTAO gGmbH

Cosmic ray messengers

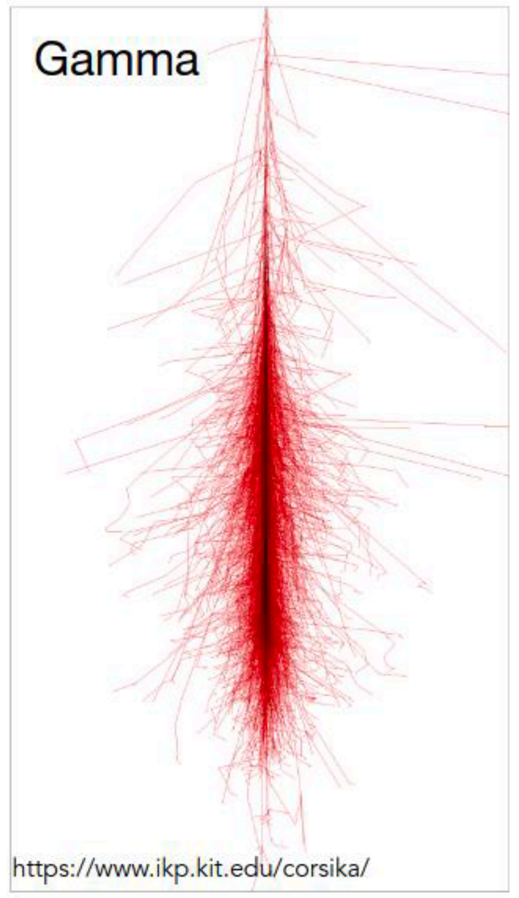
- Propagation is affected by
  - Intergalactic Magnetic Field
  - Intergalactic Matter/dust
  - Background Photons

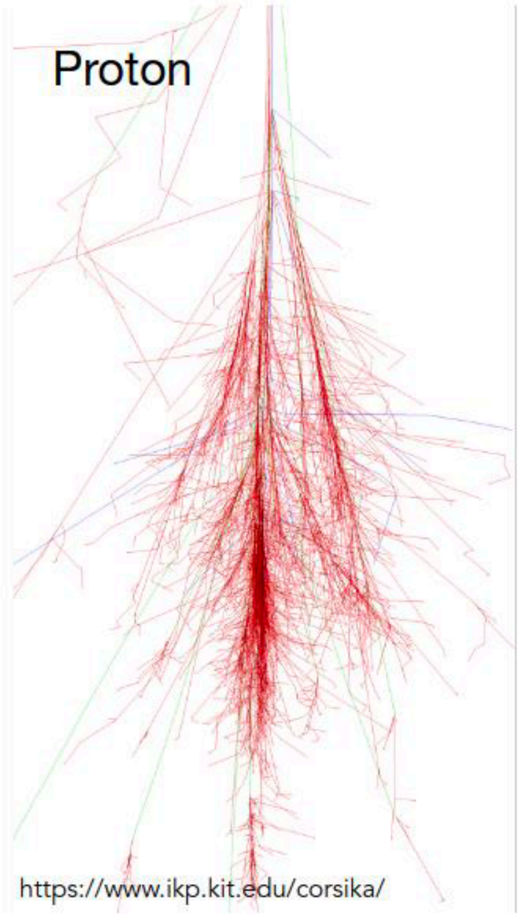
Credit: CTAO/D. Della volpe

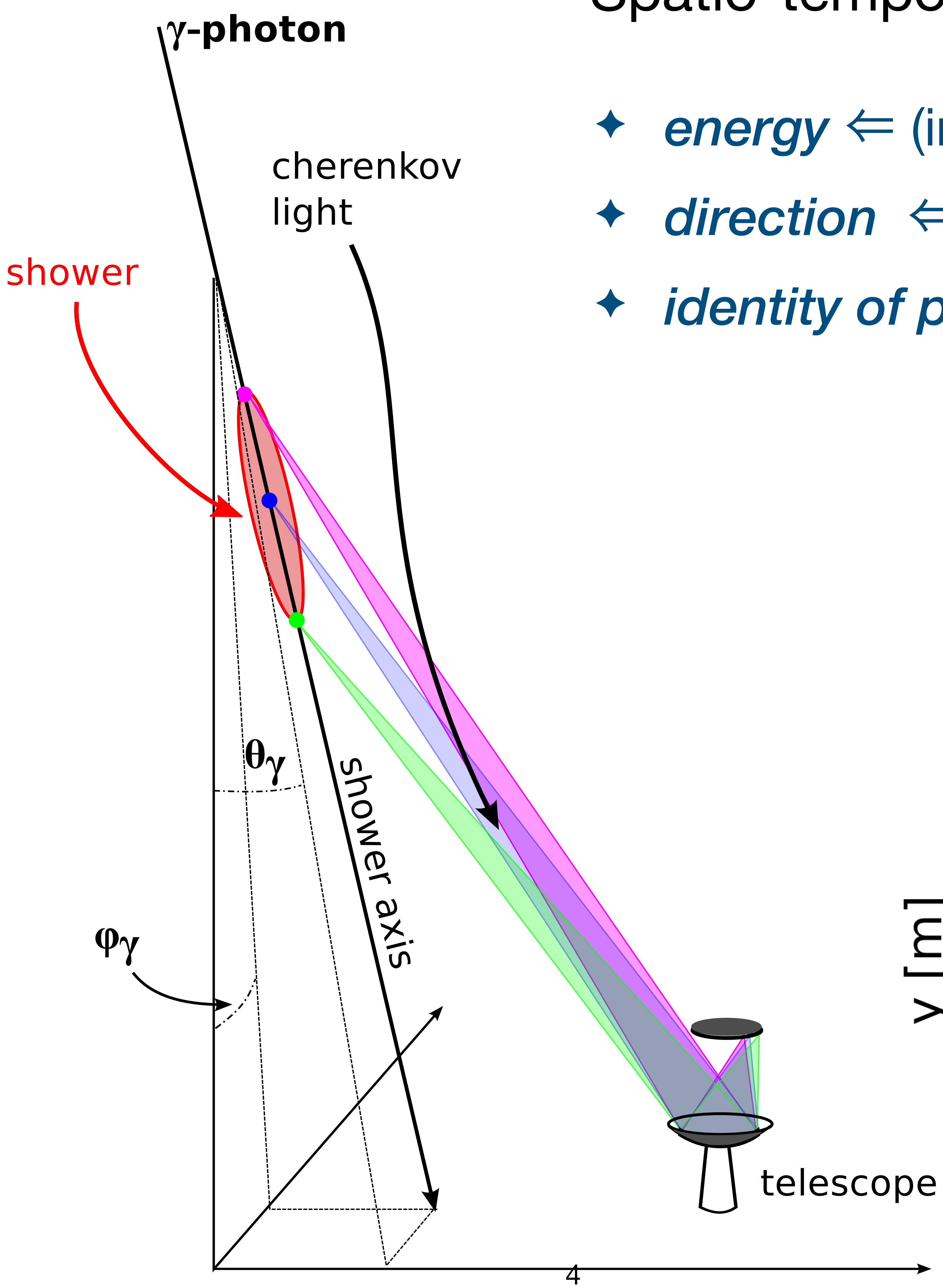
Imaging Atmospheric Cherenkov telescope



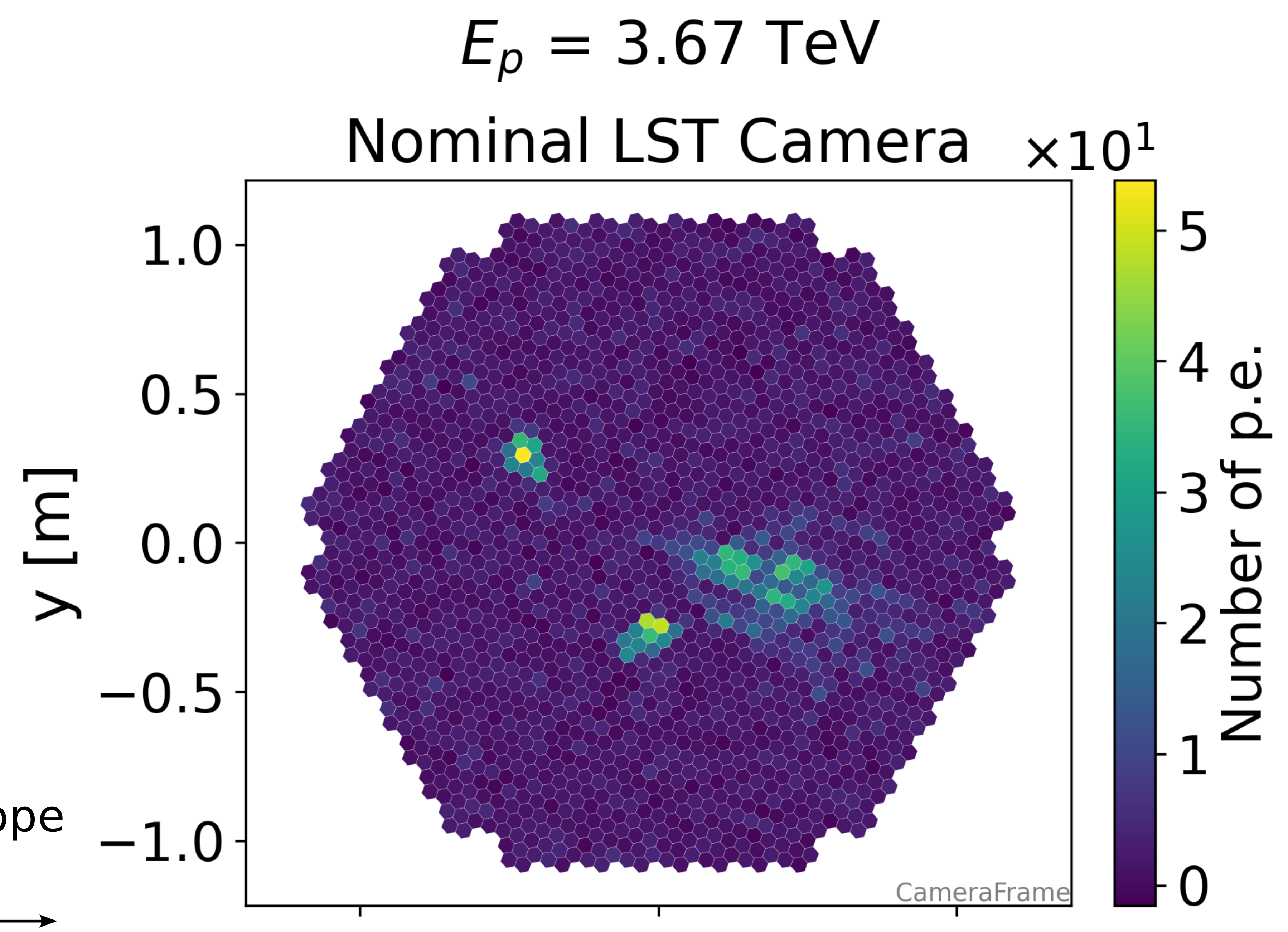
- Detection of Cherenkov flashes require:
  - ✦ ***Single photon sensitivity***
  - ✦ ***Nano-second time resolution***







- Spatio-temporal profile of the shower image proxy to:
  - ✦ ***energy*** ⇐ (image intensity, impact parameter)
  - ✦ ***direction*** ⇐ (image orientation, timing)
  - ✦ ***identity of primary particle*** ⇐ (image shape, timing)



What do we gain going for an IACT array ?

- Better parameter reconstruction:
  - ✦ Improved angular resolution
  - ✦ Improved energy resolution
  - ✦ Improved background rejection

Credit: CTAO

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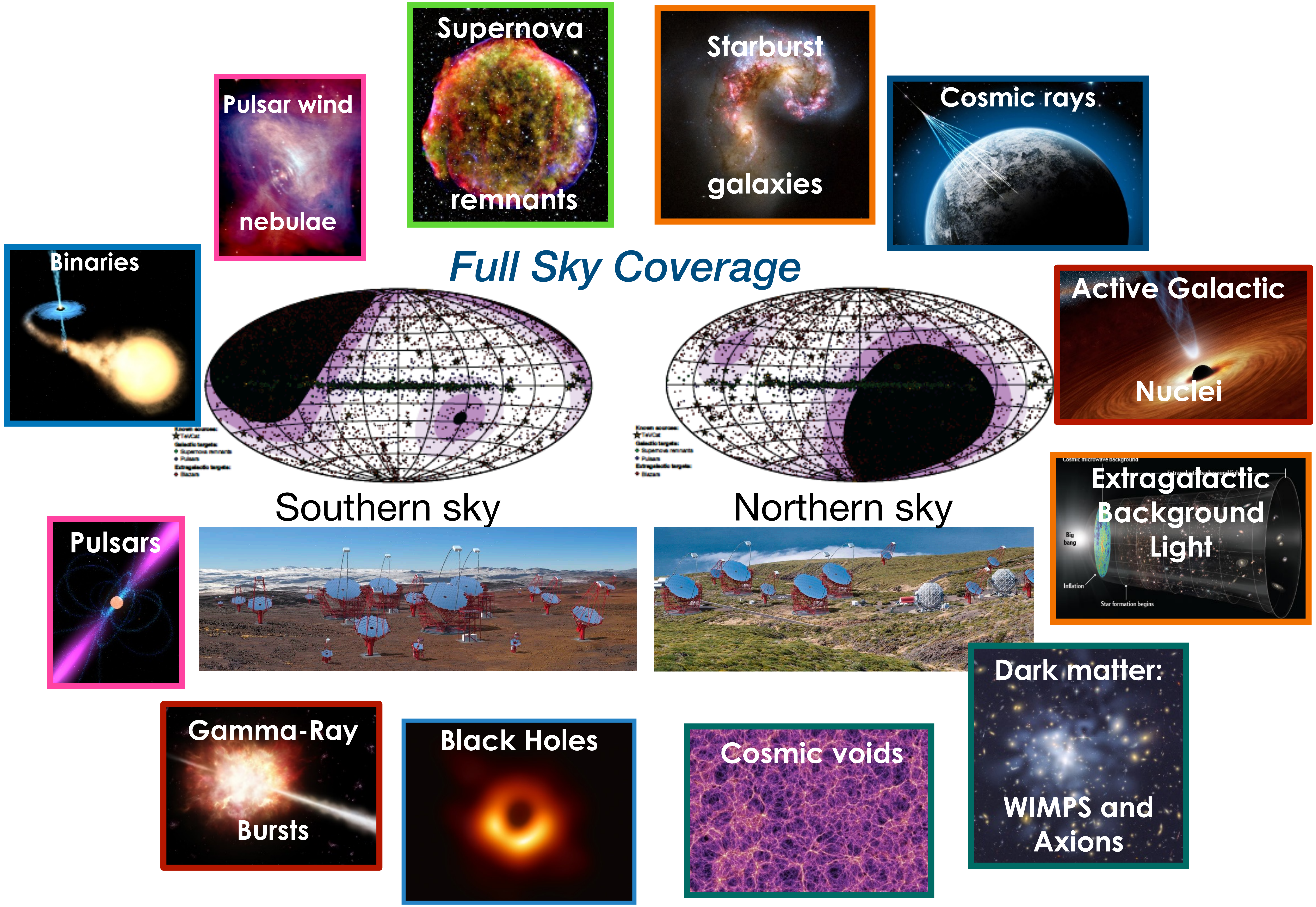
Gamma ray astronomy

CTAO LST COLLABORATION

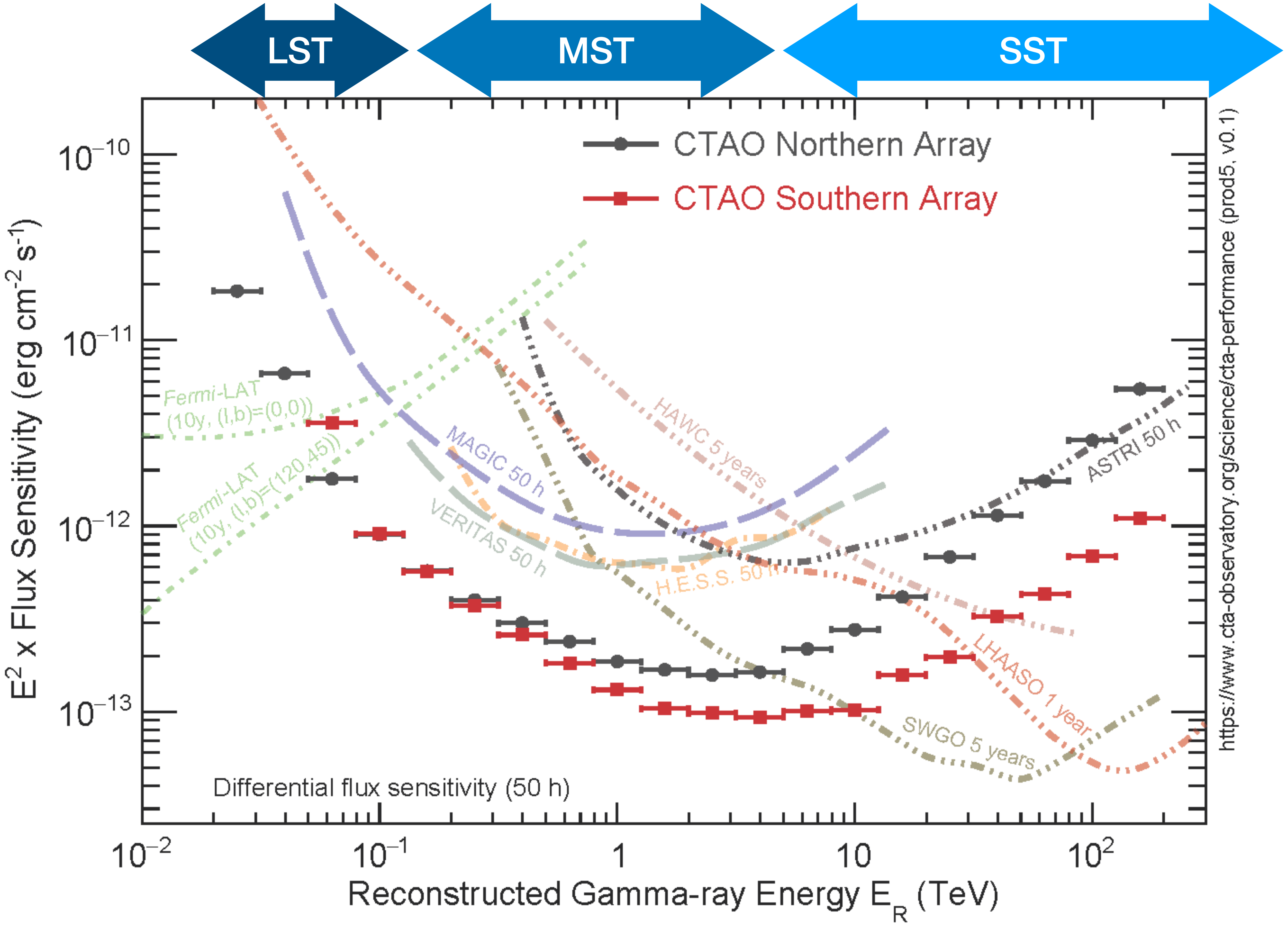
CTA Science cases

- Understanding the origin and role of relativistic cosmic particles
    - ✦ Cosmic accelerators
    - ✦ Propagation and influence of Accelerated particles
- Probing Extreme environments
    - ✦ Black hole and jets
    - ✦ Neutron stars and relativistic outflows
    - ✦ Cosmic voids
- Exploring frontiers in physics
    - ✦ Dark matter
    - ✦ Quantum gravity and Axion-like particle



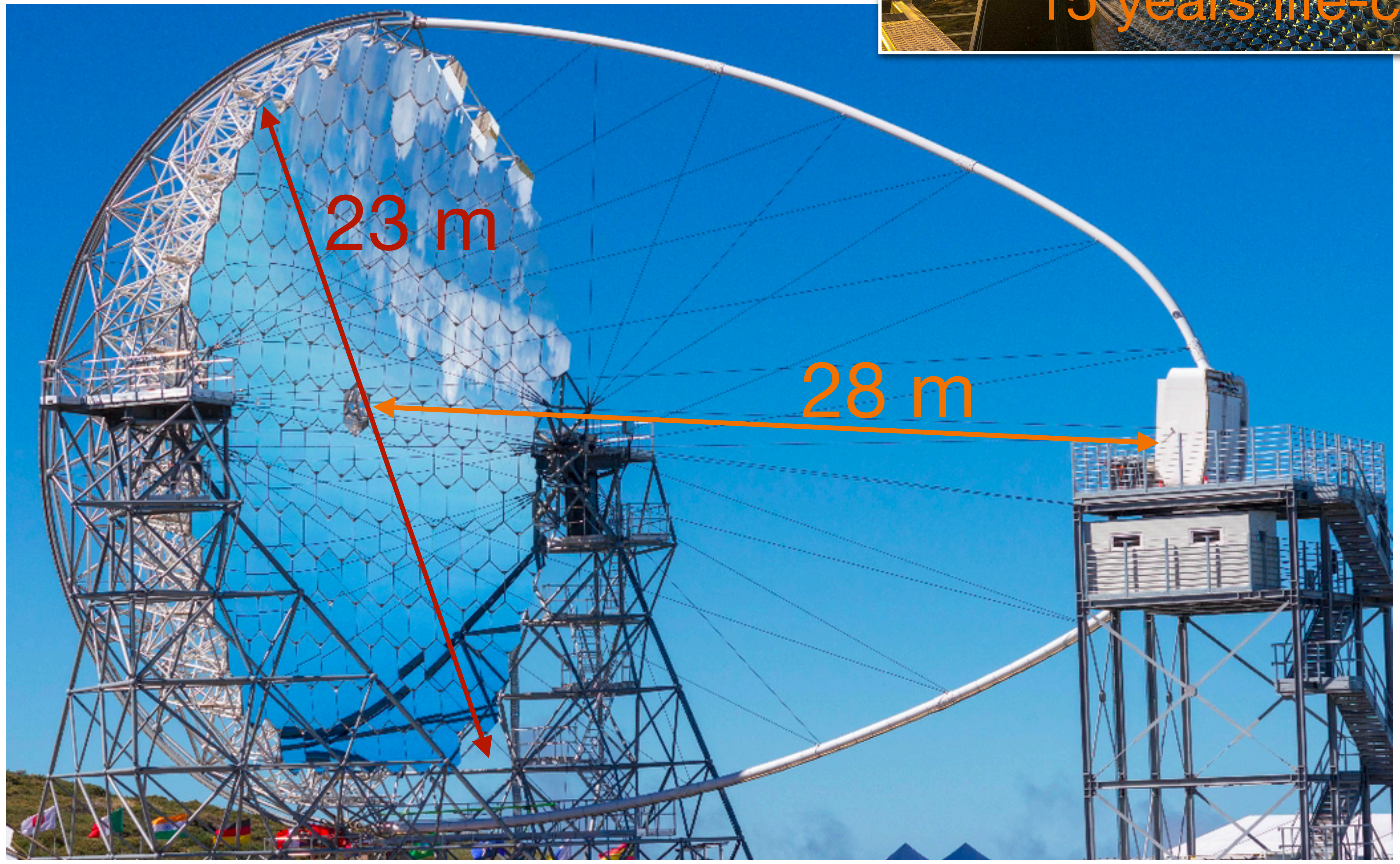
Cherenkov Telescope Array

	LST	MST	SST
Effective mirror area	***370 m²***	88 m²	***8m²***
Energy range	***20GeV - 3 TeV***	80 GeV - 50 TeV	***1 TeV - 300 TeV***
Exclusive energy range	***20GeV - 150 GeV***	150 GeV - 5 TeV	***5 TeV - 300 TeV***
#telescopes North	***4***	9	***0***
#Telescopes South	***0****	14	***37****
Photo-sensors	***PMT***	PMT	***SiPM***



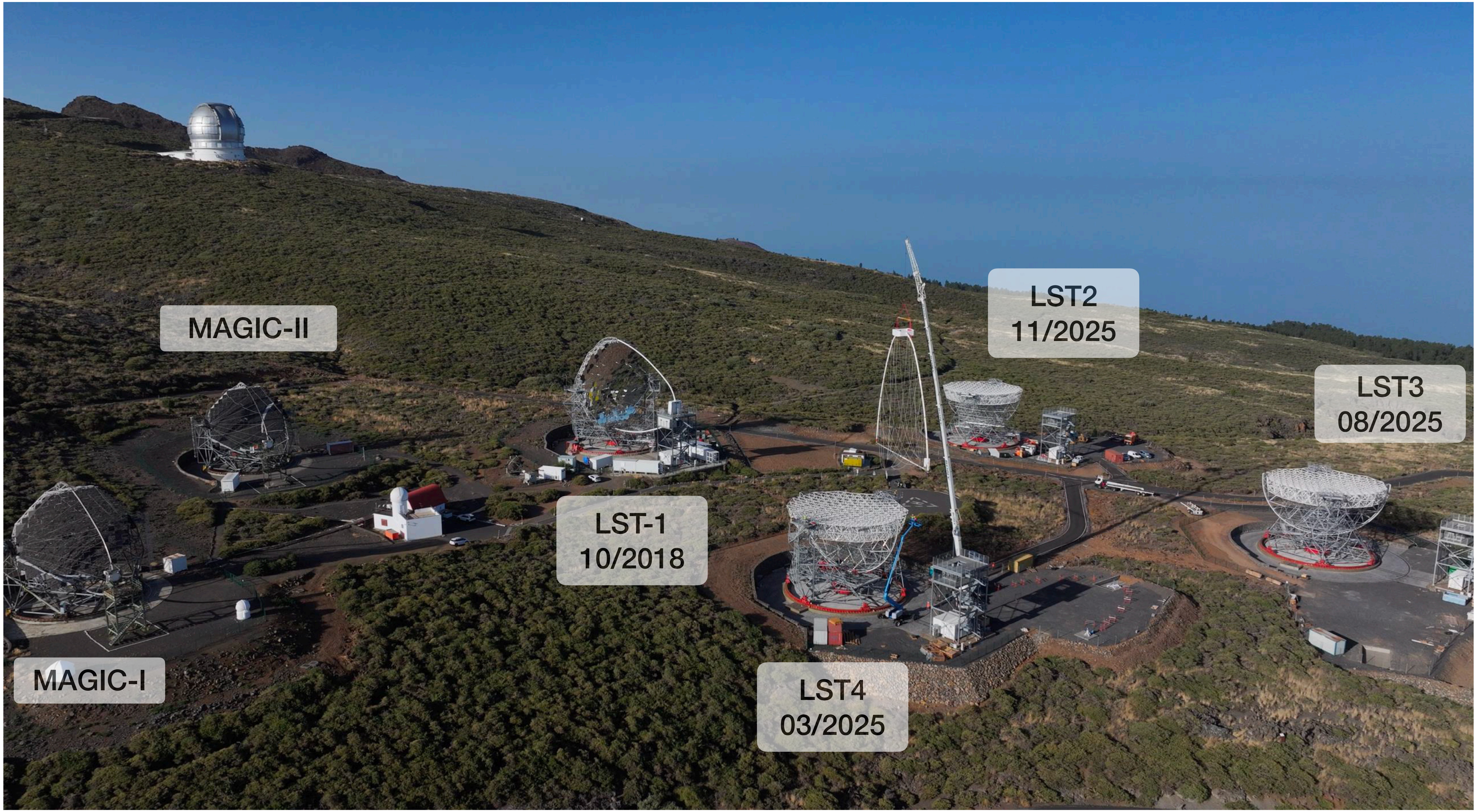
The Large-Sized Telescope of CTAO

Stucture	
Alt-Azimuth Mount on a circular rail	
Tubular Structure in CFRP & Steel	
Full Telescope Weight	103 tons
Maximum time for repositioning	30 s
Optics - Parabolic Mirror	
Primary Mirror Diameter	23 m
Focal Length	28 m
Effective area including	370 m²
Camera	
Field of View	4.3°
Number of Pixels	1855
Pixel size	0.1°
Photo Sensor	PMT
Signal sampling rate	1 GHz



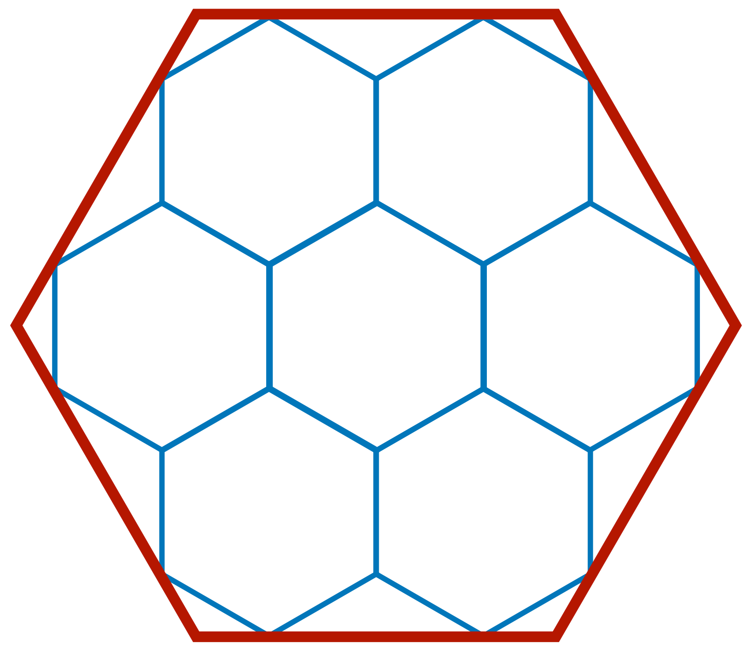
- First prototype LST-1 inaugurated in October 2018 at La Palma, Canary Island

The Large-Sized Telescope of CTAO



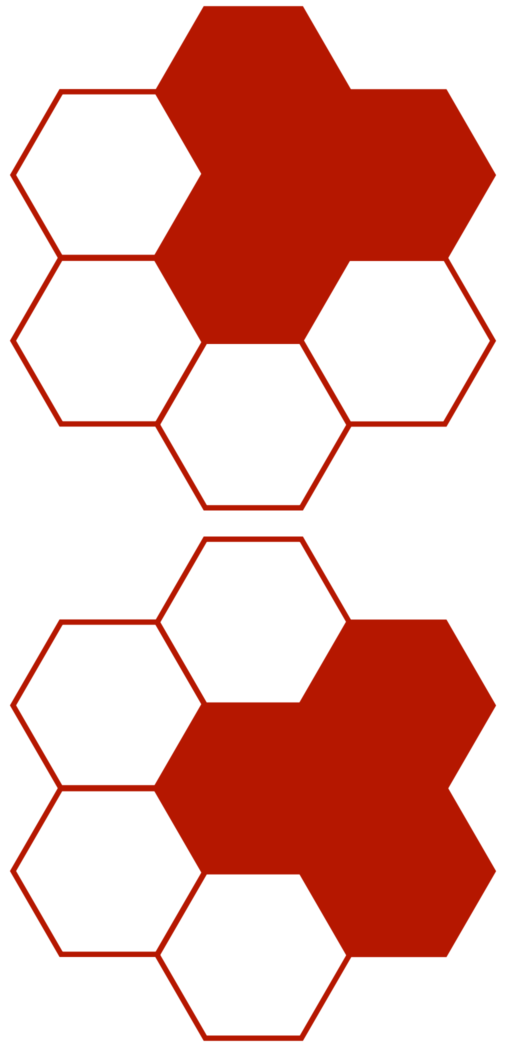
Triggering on showers with LST

Analog trigger - LST



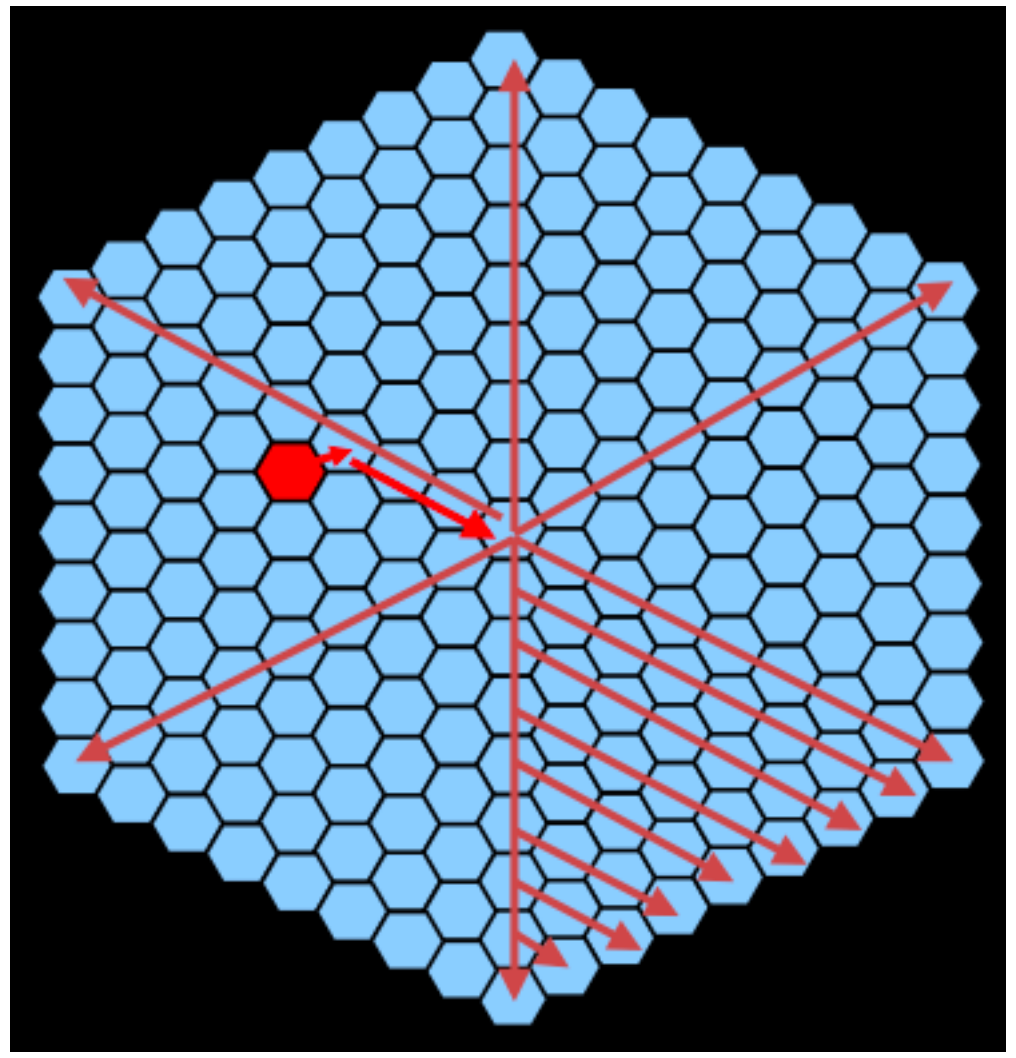
7 pixels

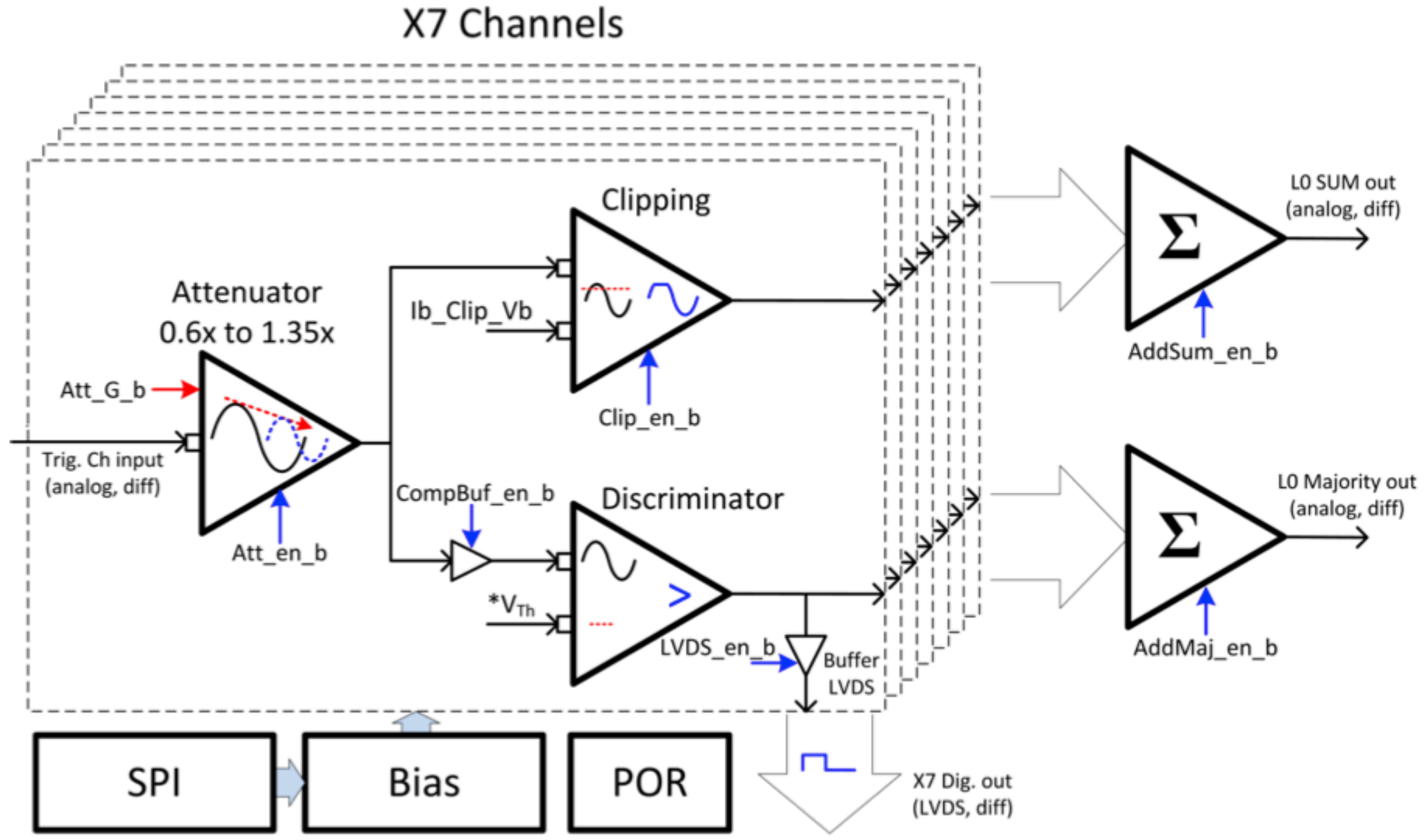
Sum signal (L0)

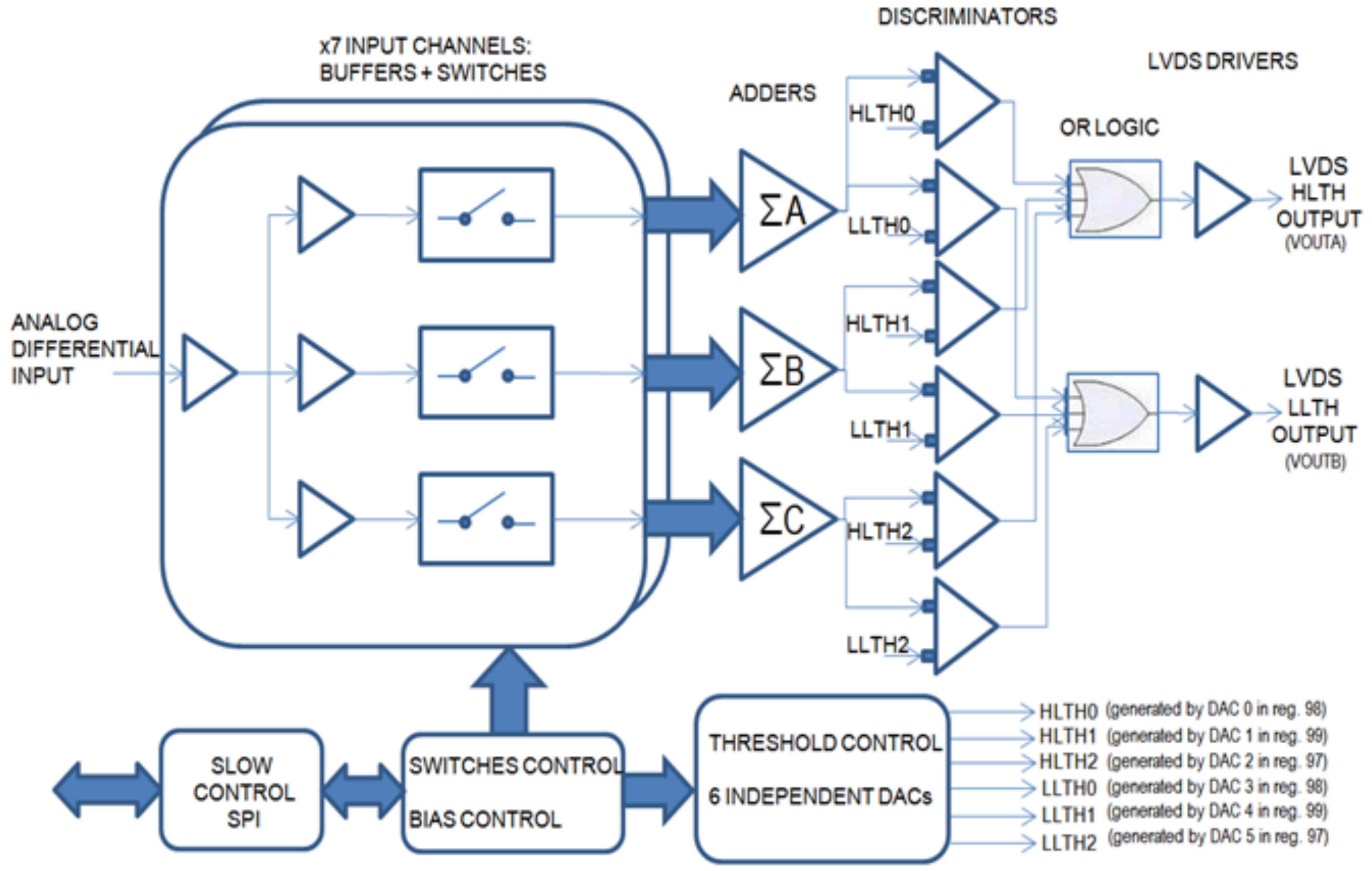


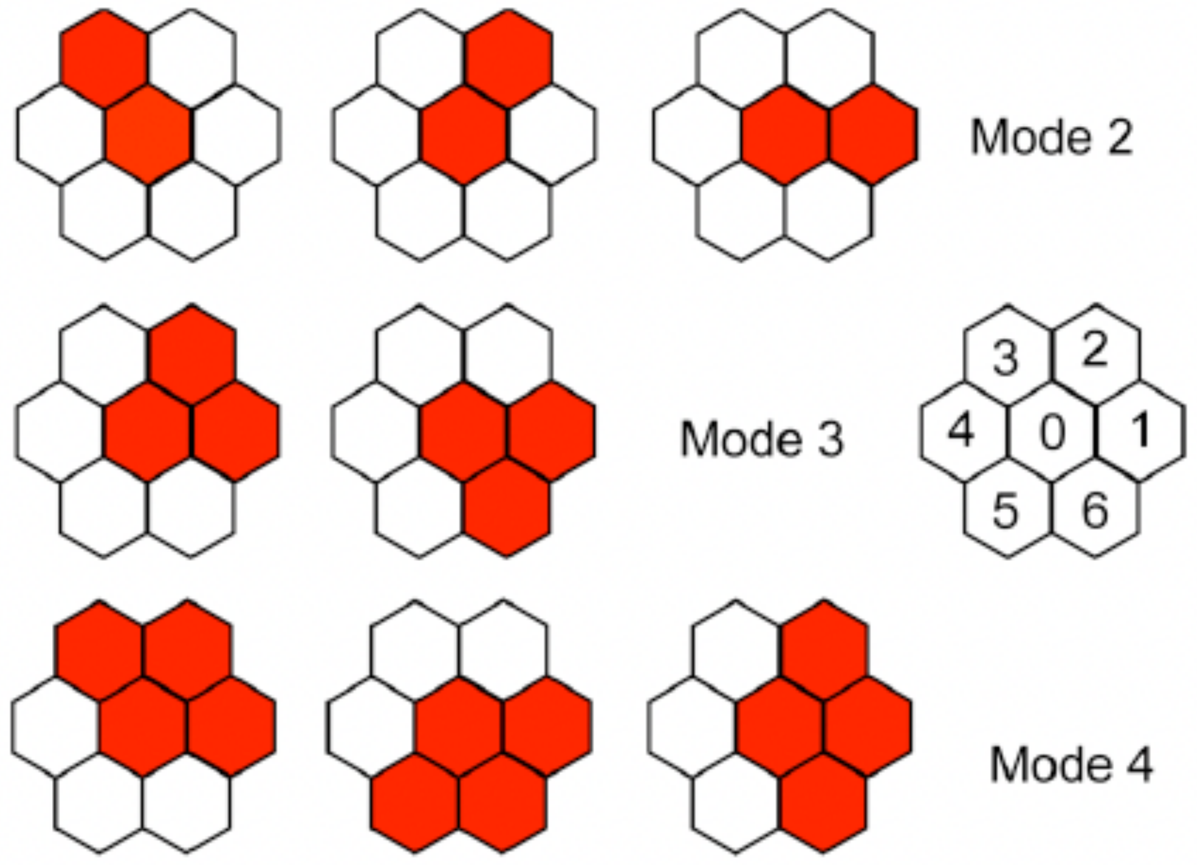
49 pixels = 1 cluster

Sum signal (L1)





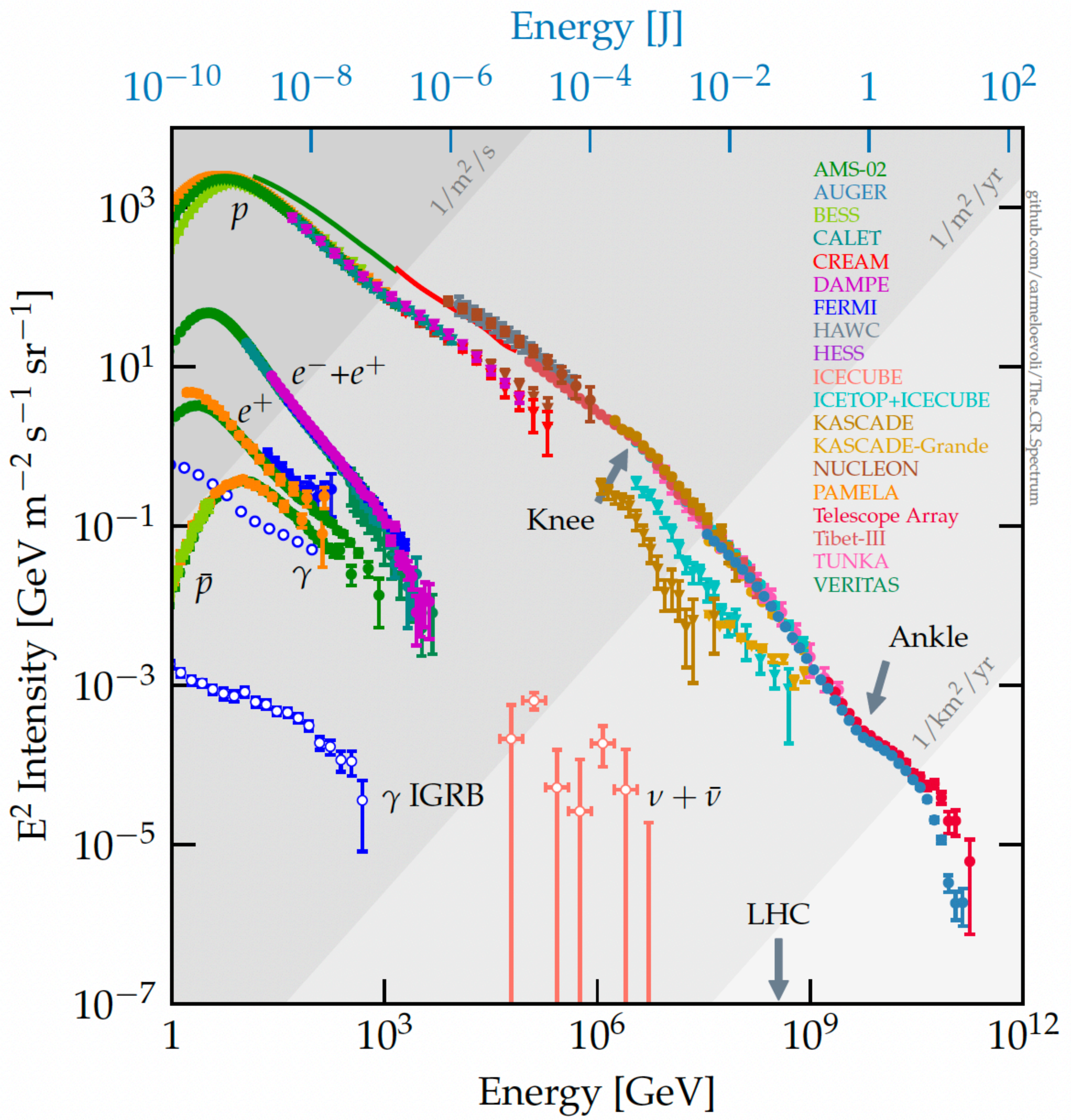




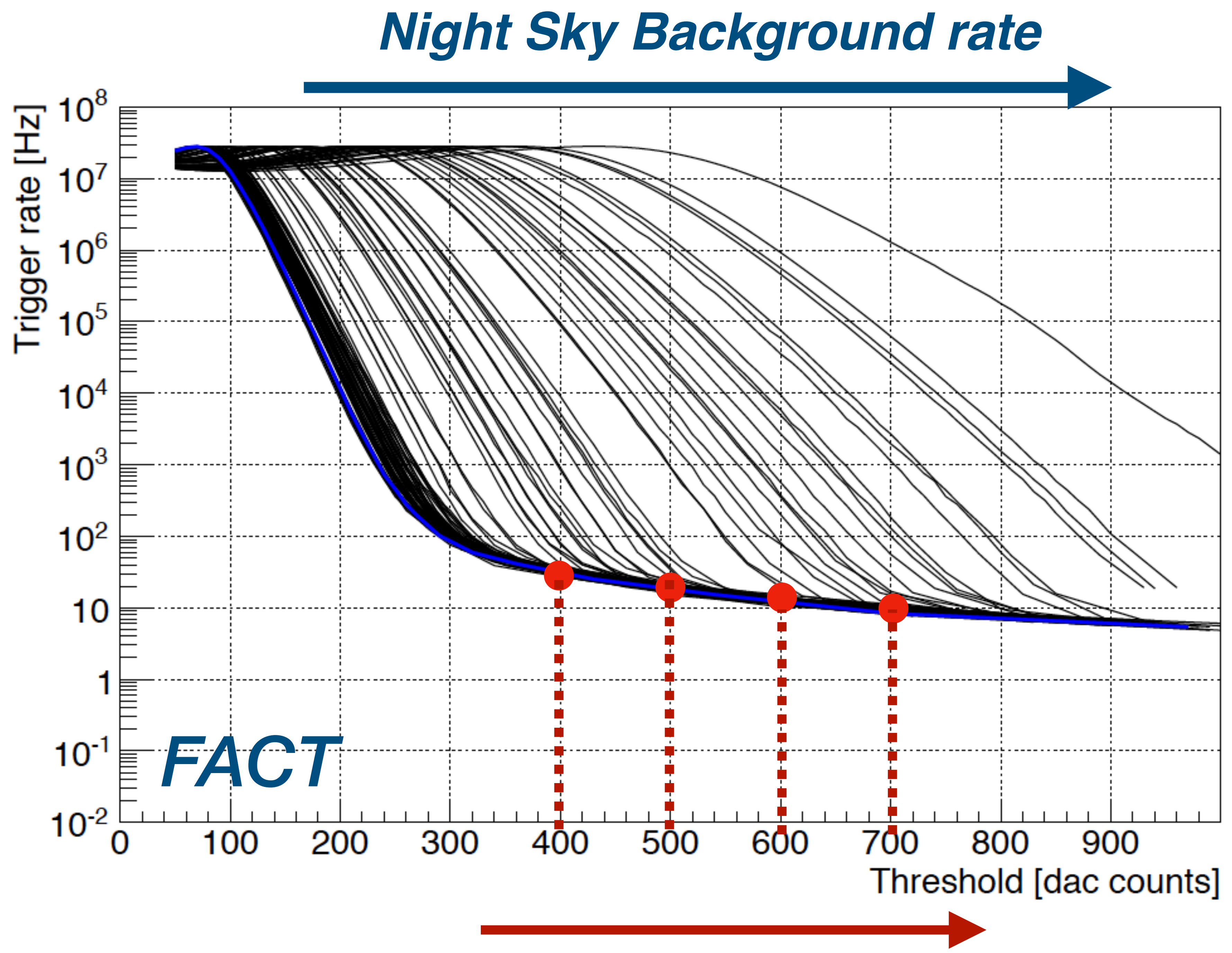
Possible topologies

Triggering on Shower with LST

How does it looks like?

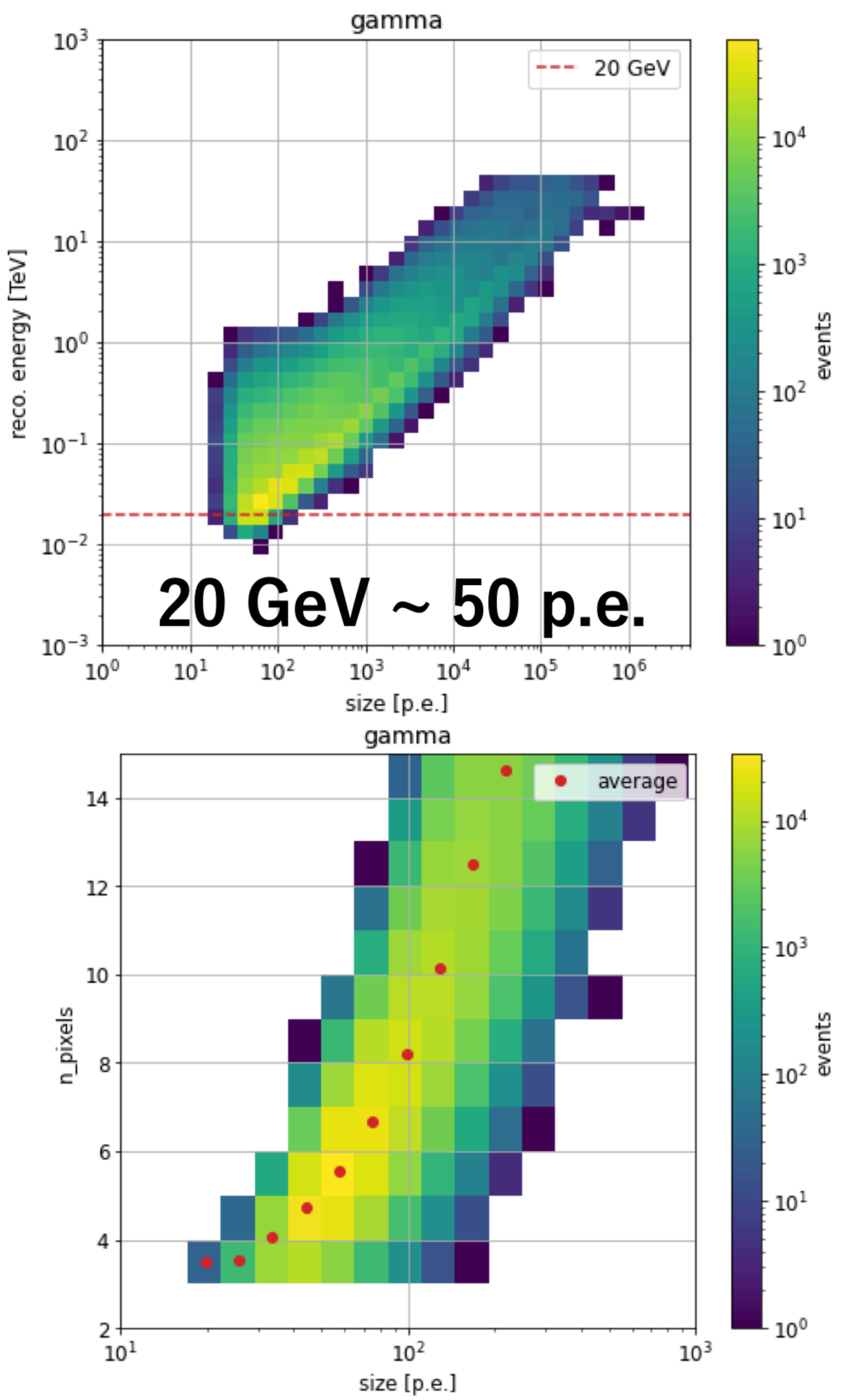


- Physics rate completely dominated by cosmic rays
- Operate telescopes at so-called safe threshold:
  - ✦ Intersection between:
    - trigger rate resulting from 2 x NSB level
    - trigger rate from 1.5 x protons
- This hardware threshold imposes the lowest energy achievable later at analysis stage
- Data analysis methods will improve, hardware threshold must not be the limiting factor

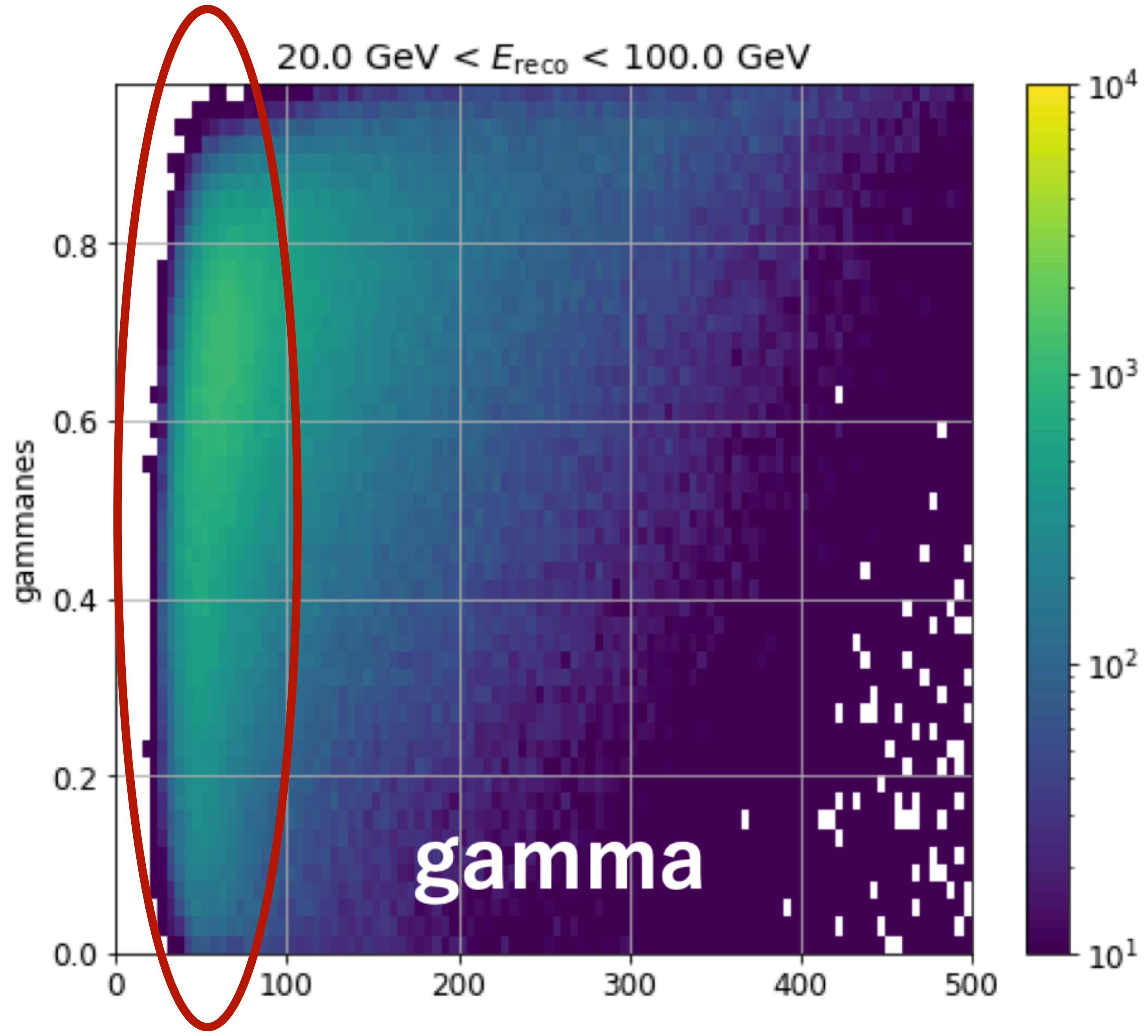


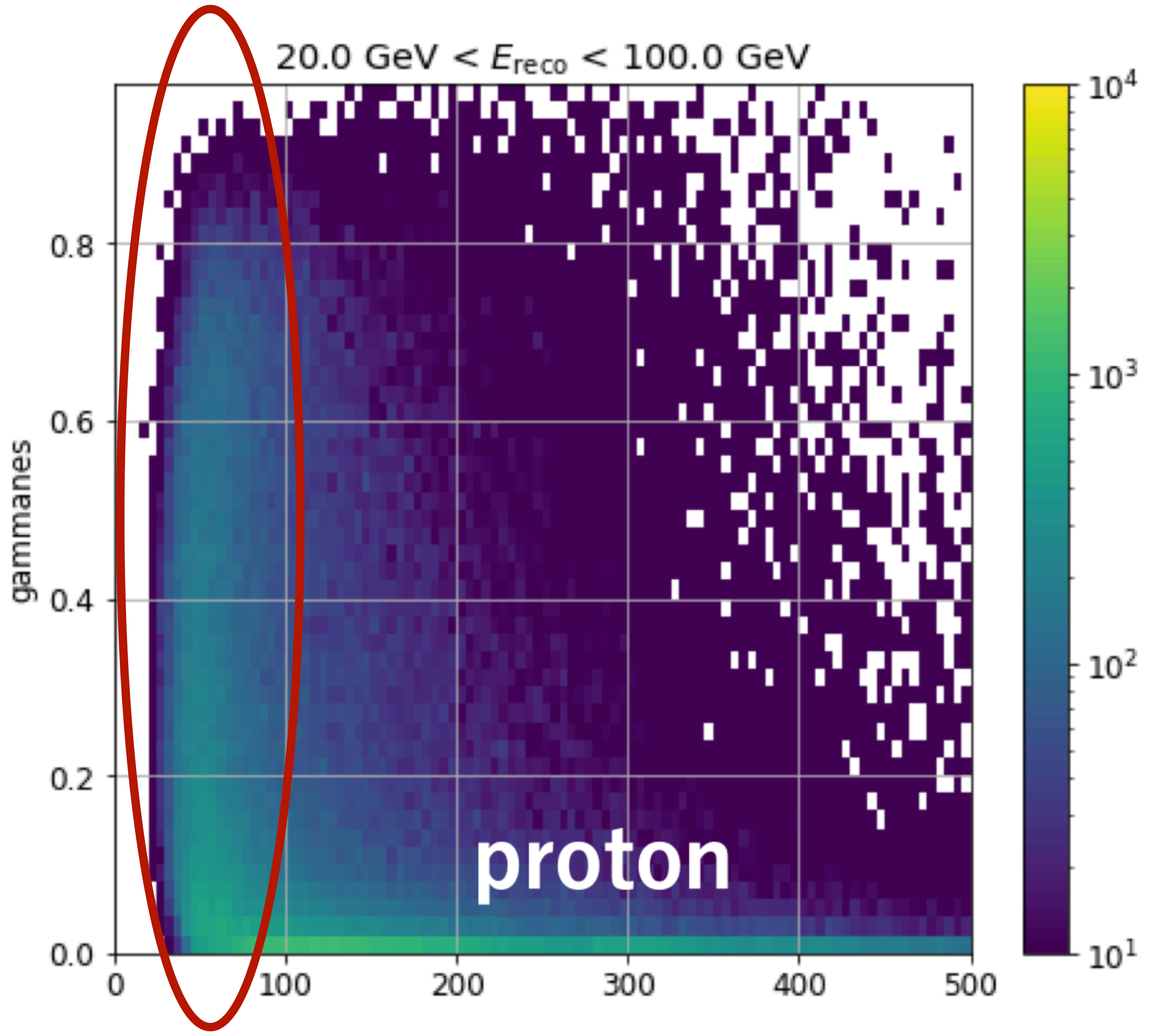
Designing the next generation of cameras for LST

How to improve performance ?



20 GeV ~ 50 p.e. ~ 5 pixels





- ***At low energies***:
  - ✦ Images are small and faints:
    - ➡ **Use sensors with higher sensitivity** ➧ **Silicon Photo Multipliers**
  - ✦ Gammas and Protons are very lookalike
    - ➡ **Increase image granularity** ➧ **Smaller pixels**

Plots from Y. Kobayashi

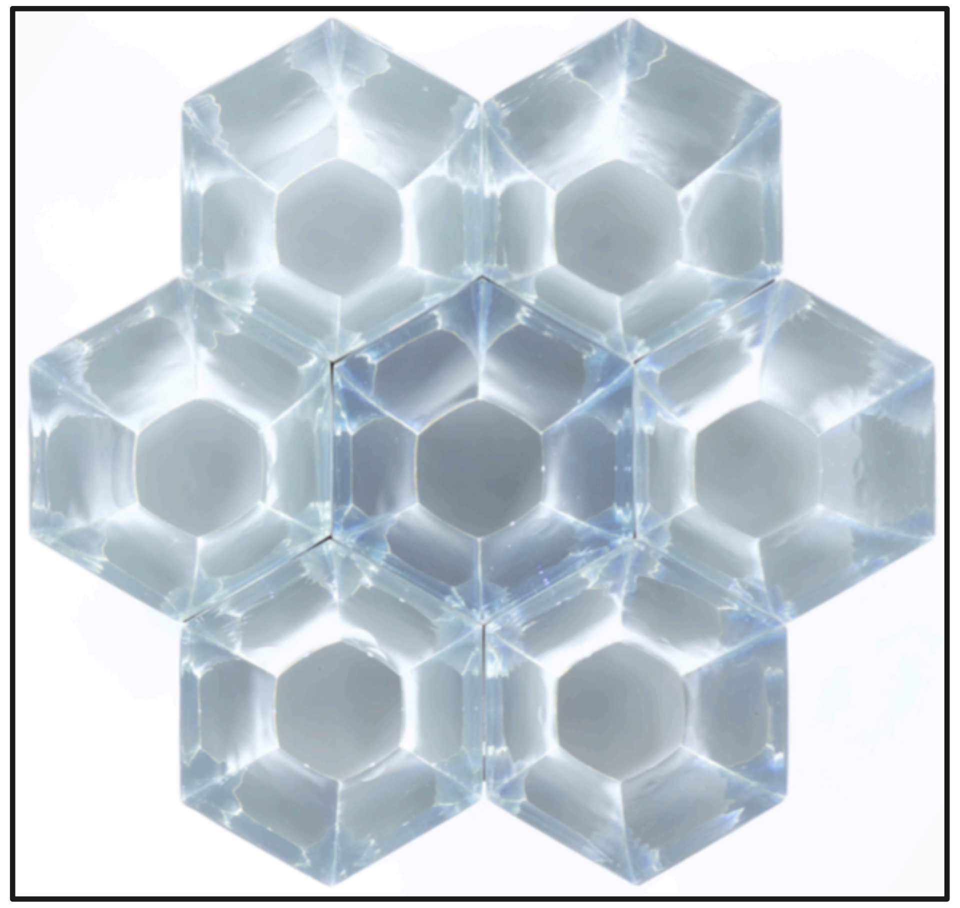
The Advanced SiPM Camera

- The proposed design should take full advantage of the SiPM characteristics
  - Gain in duty-cycle, robustness, stability, self-calibration, etc…
  - Utilise Swiss experience in using SiPM for IACT (FACT, SST-1M)

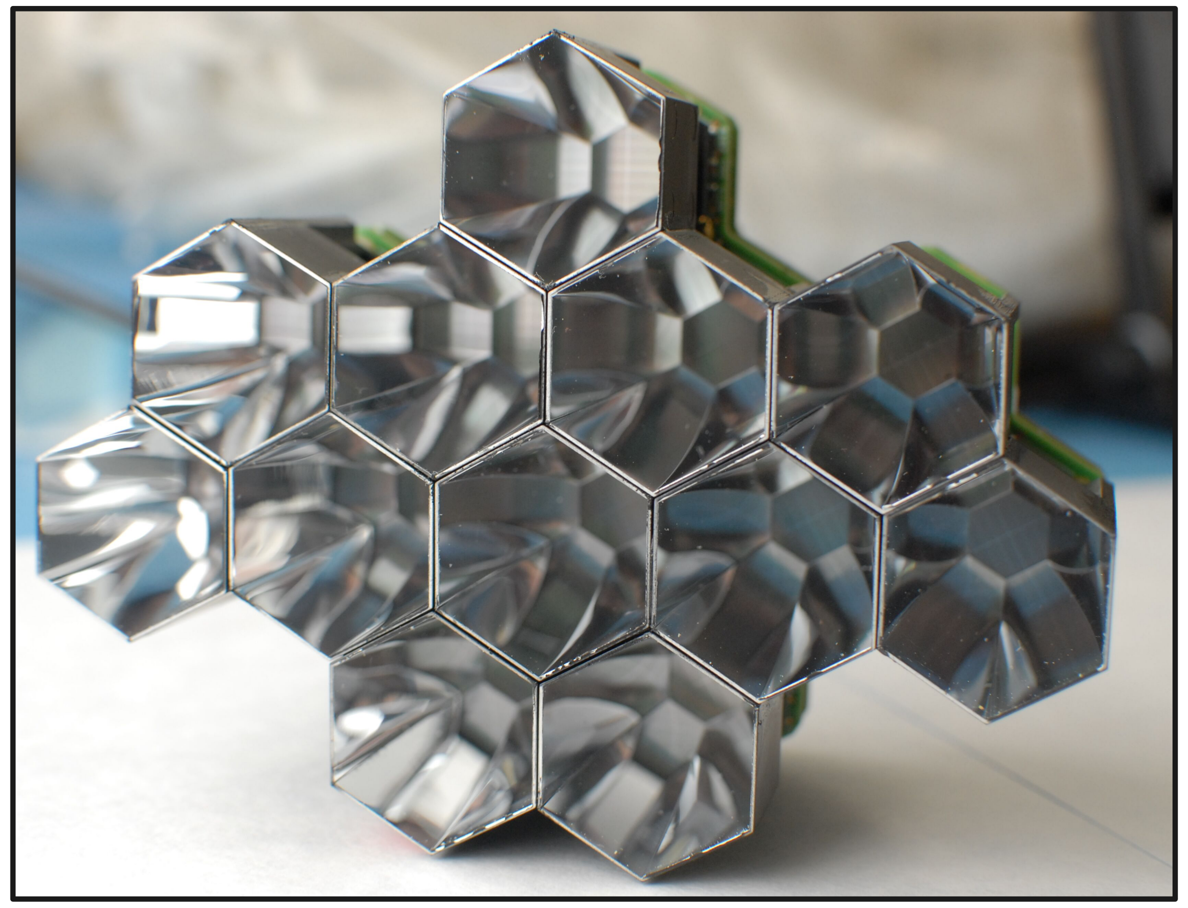
- The Advanced SiPM Camera must:
  - outperform the existing camera over the entire energy range
  - be upgradable/reprogrammable

- Baseline design:
  - Decreasing pixel size **from 0.1° to 0.05°**
    - **4 times more pixels !**
  - Going for **fully digital readout**
    - **Opens a lot of opertunity for real-time processing**

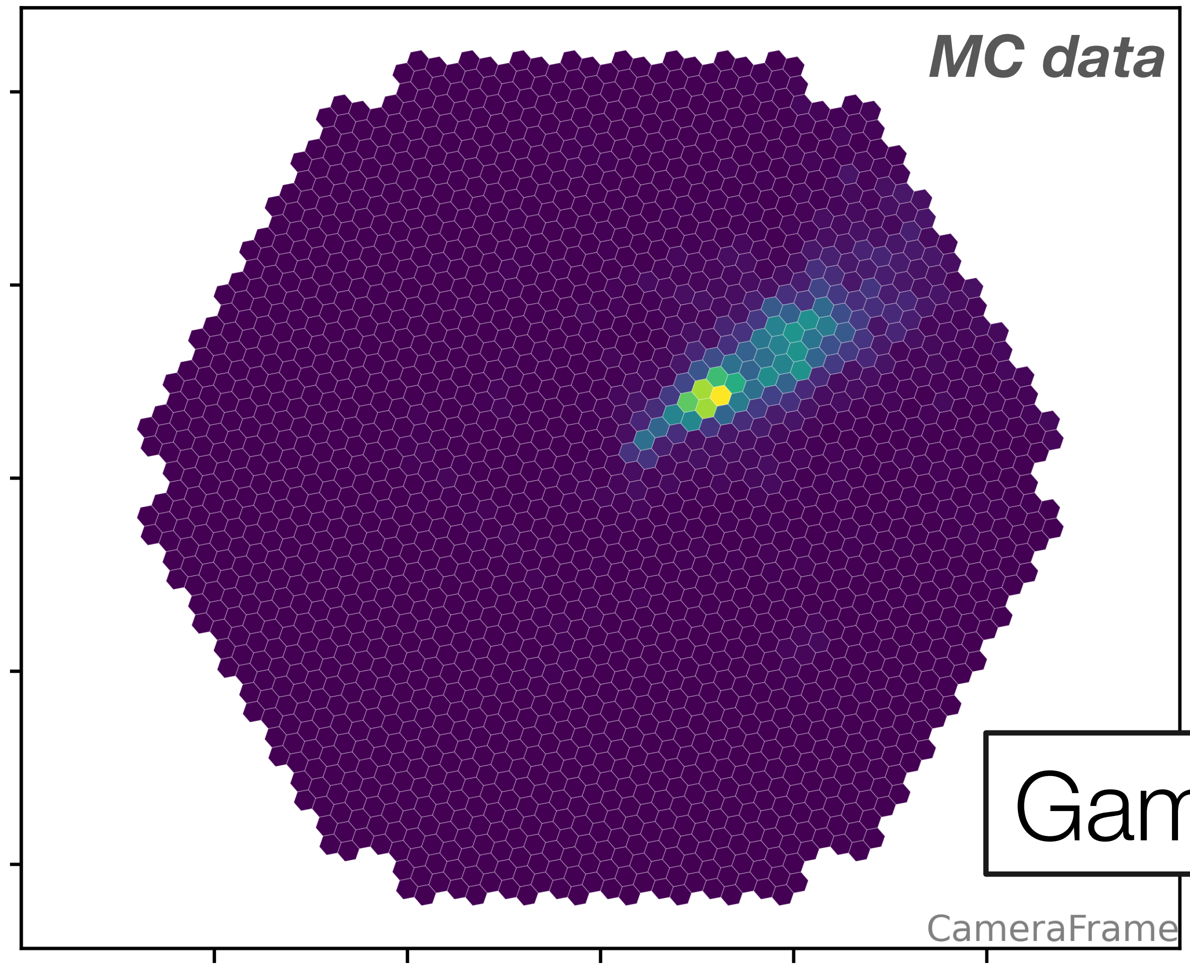
- Many challenges to tackle:
  - High power consumption
  - High data throughput
  - High cost

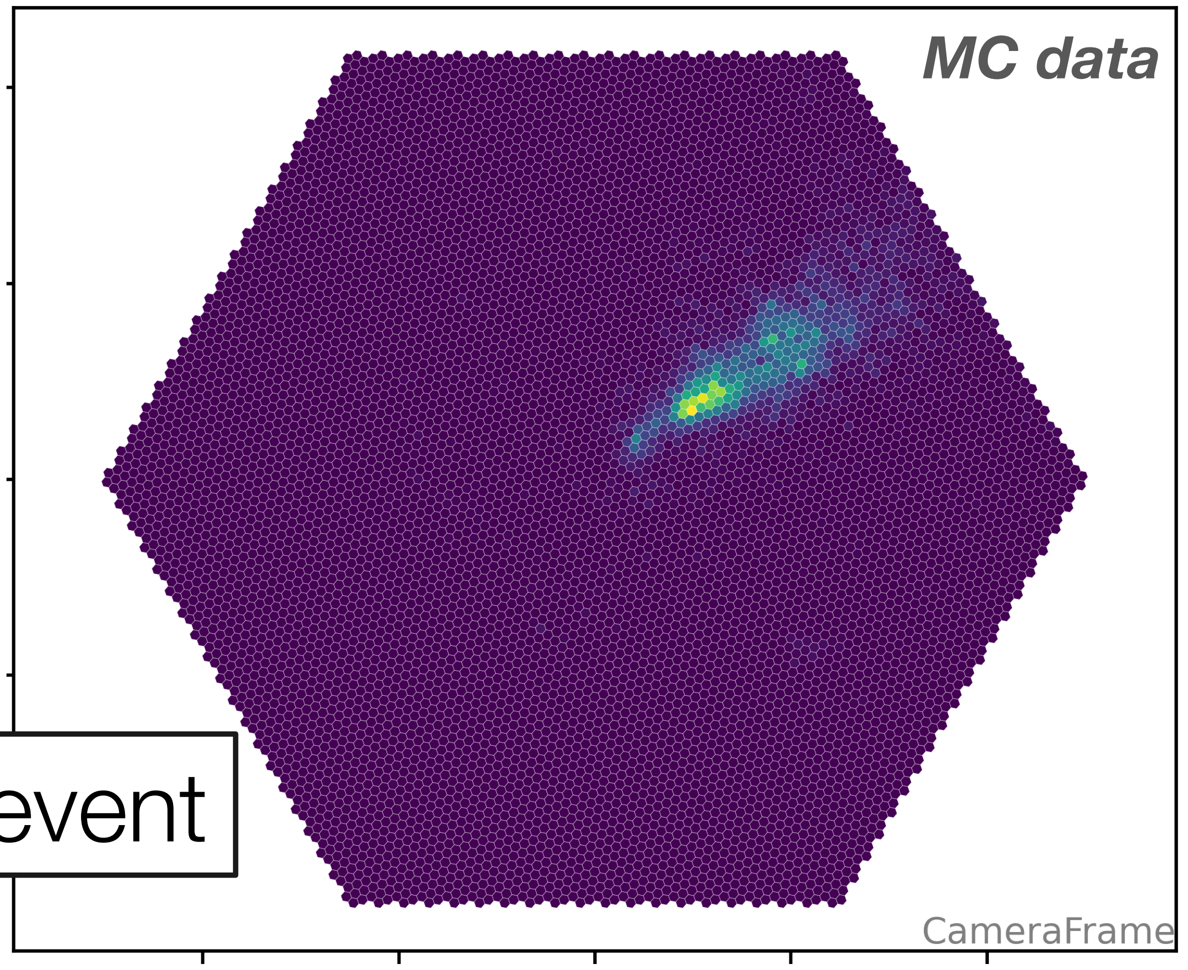


LST PMT camera **(0.1°)**



LST SiPM camera (**0.05°**)

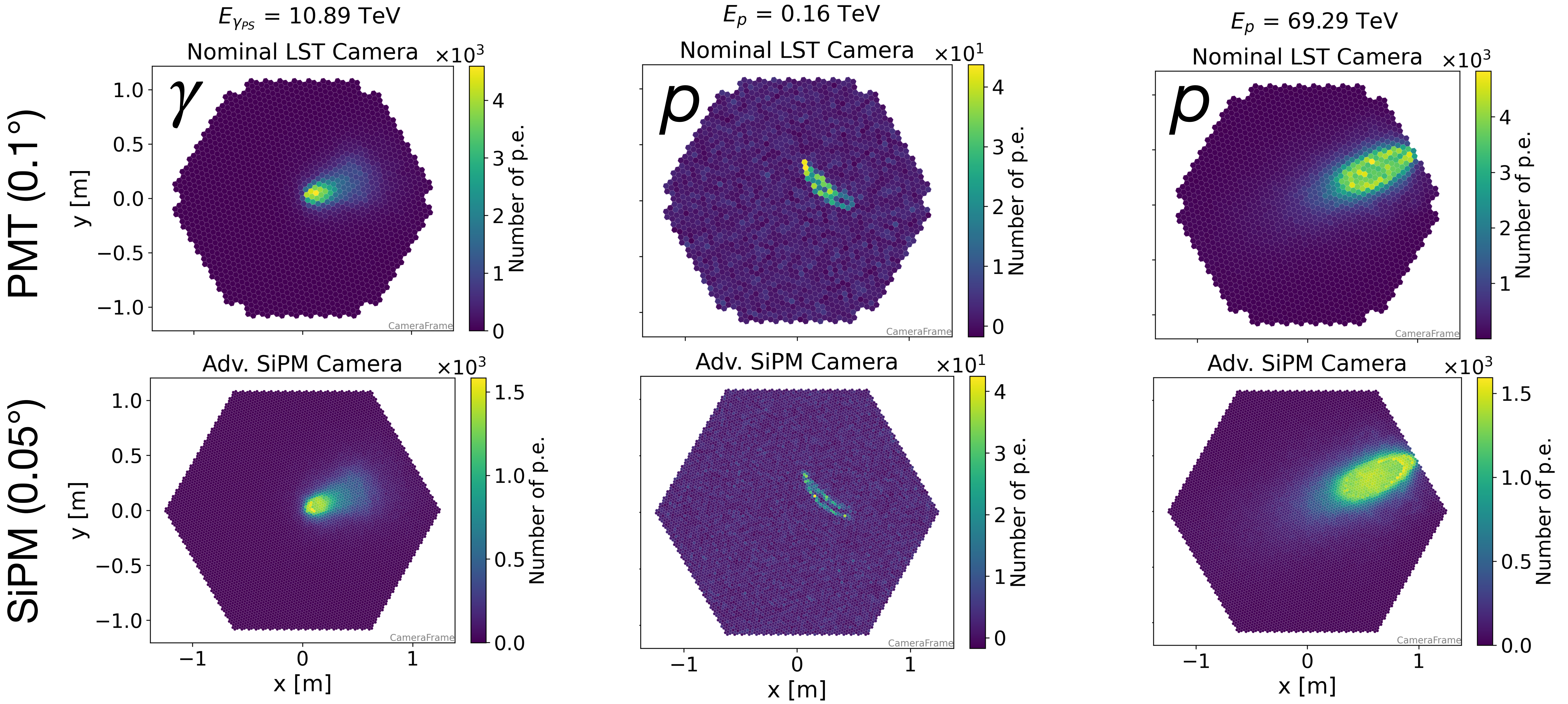




Gamma event

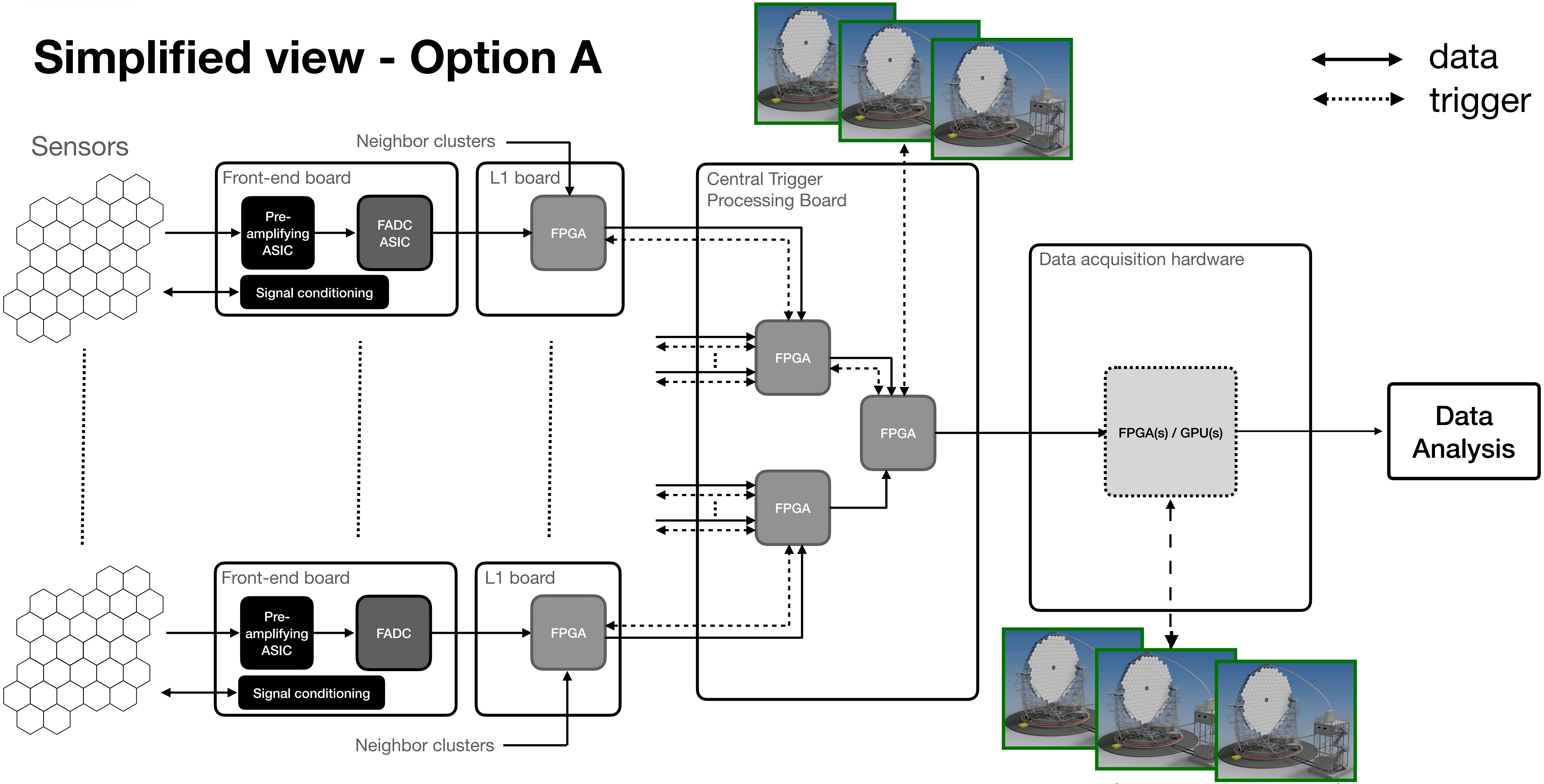
Higher granularity images

… for more feature extraction



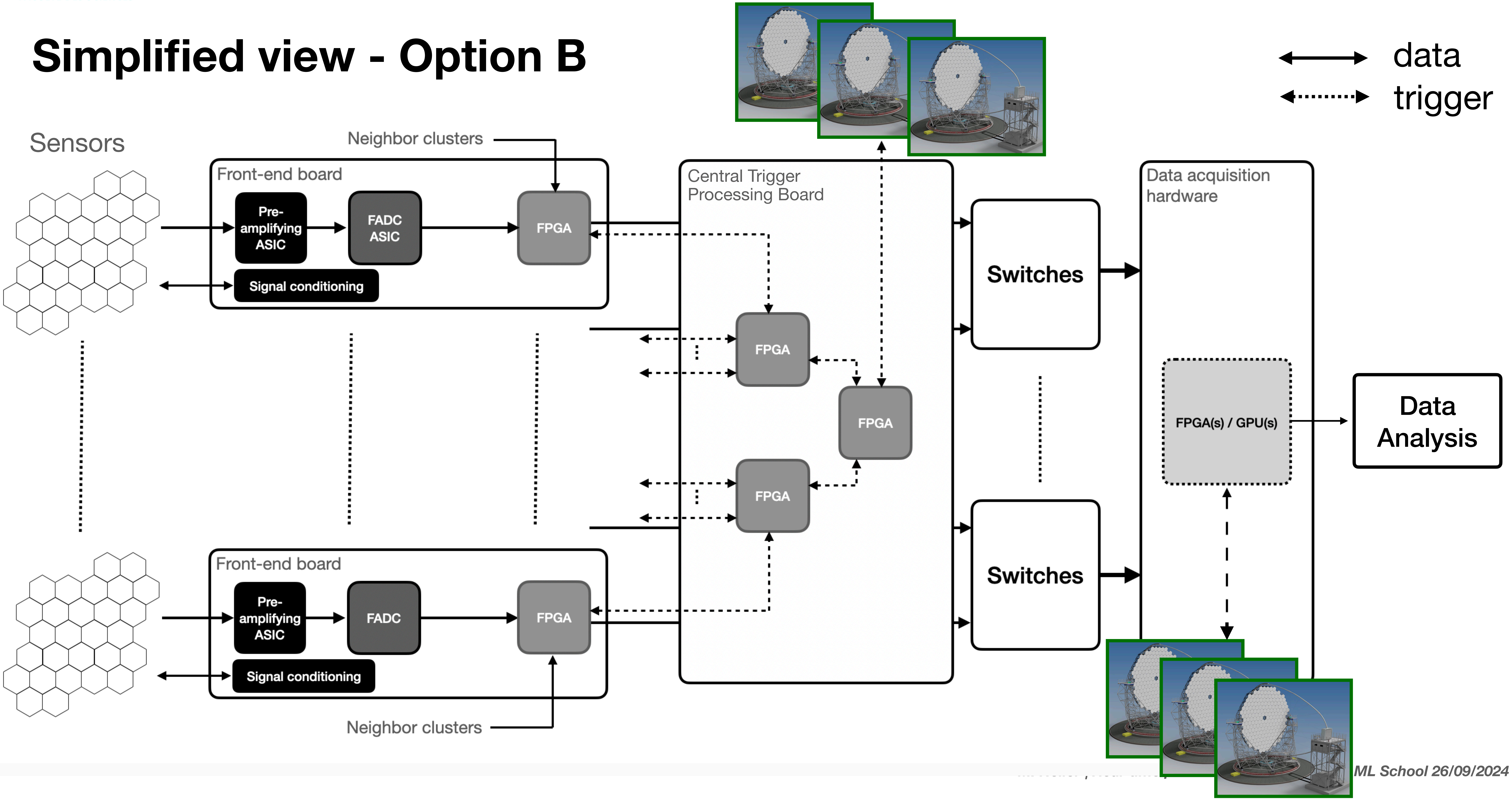
Camera readout architecture

Simplified view - Option A



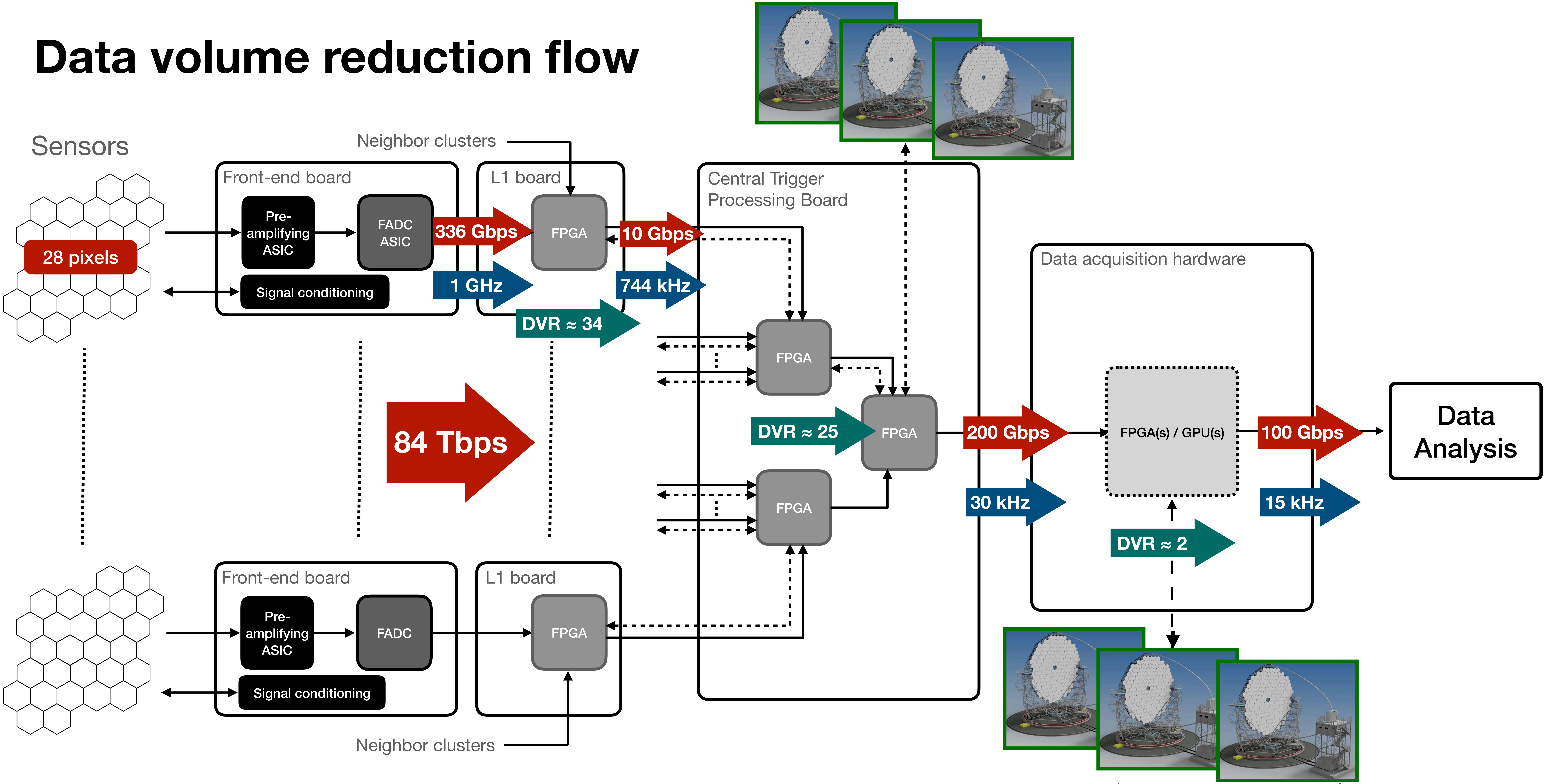
Camera readout architecture

Simplified view - Option B



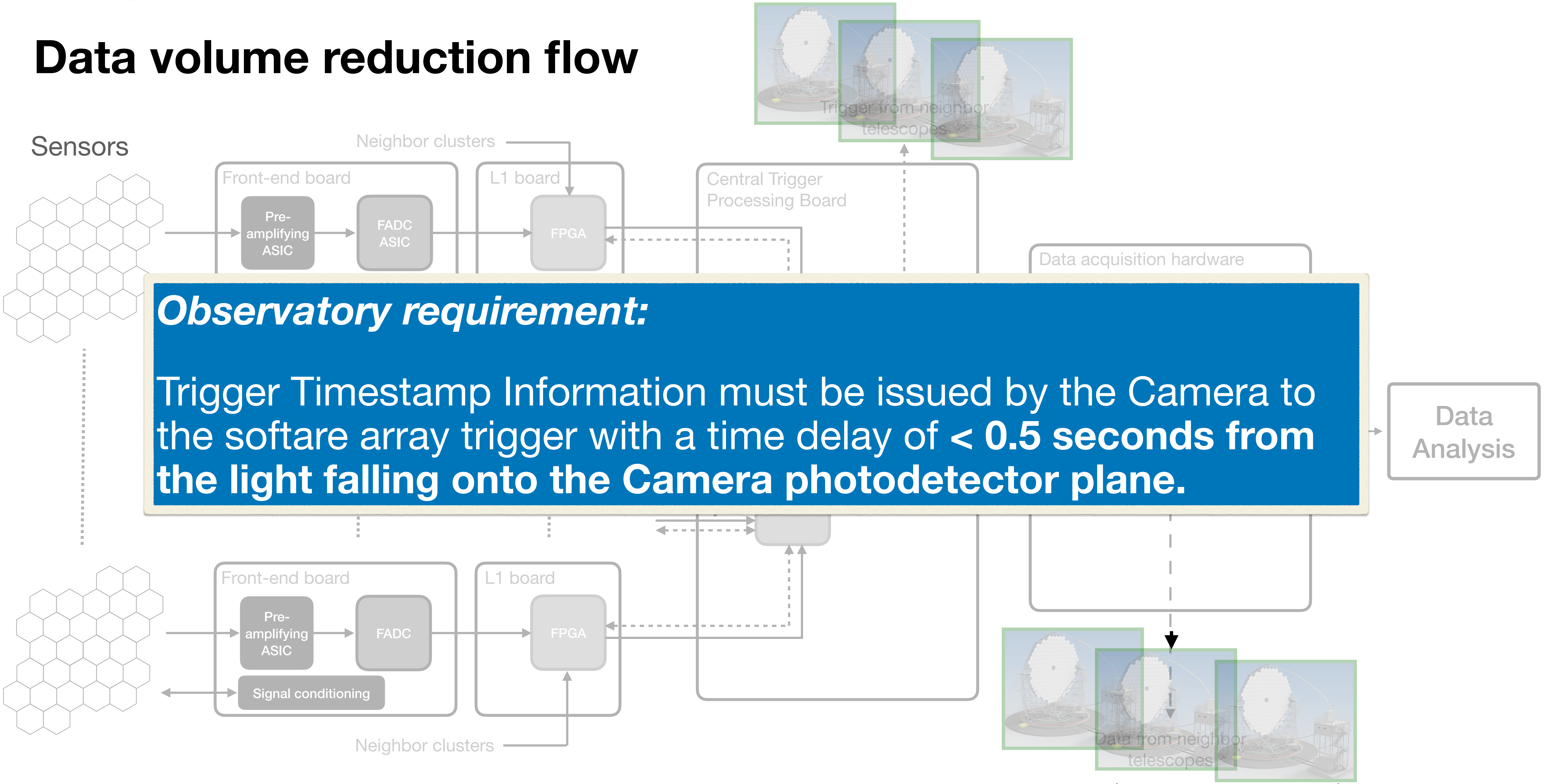
Camera readout architecture

Data volume reduction flow



Data Volume Reduction

Data volume reduction flow

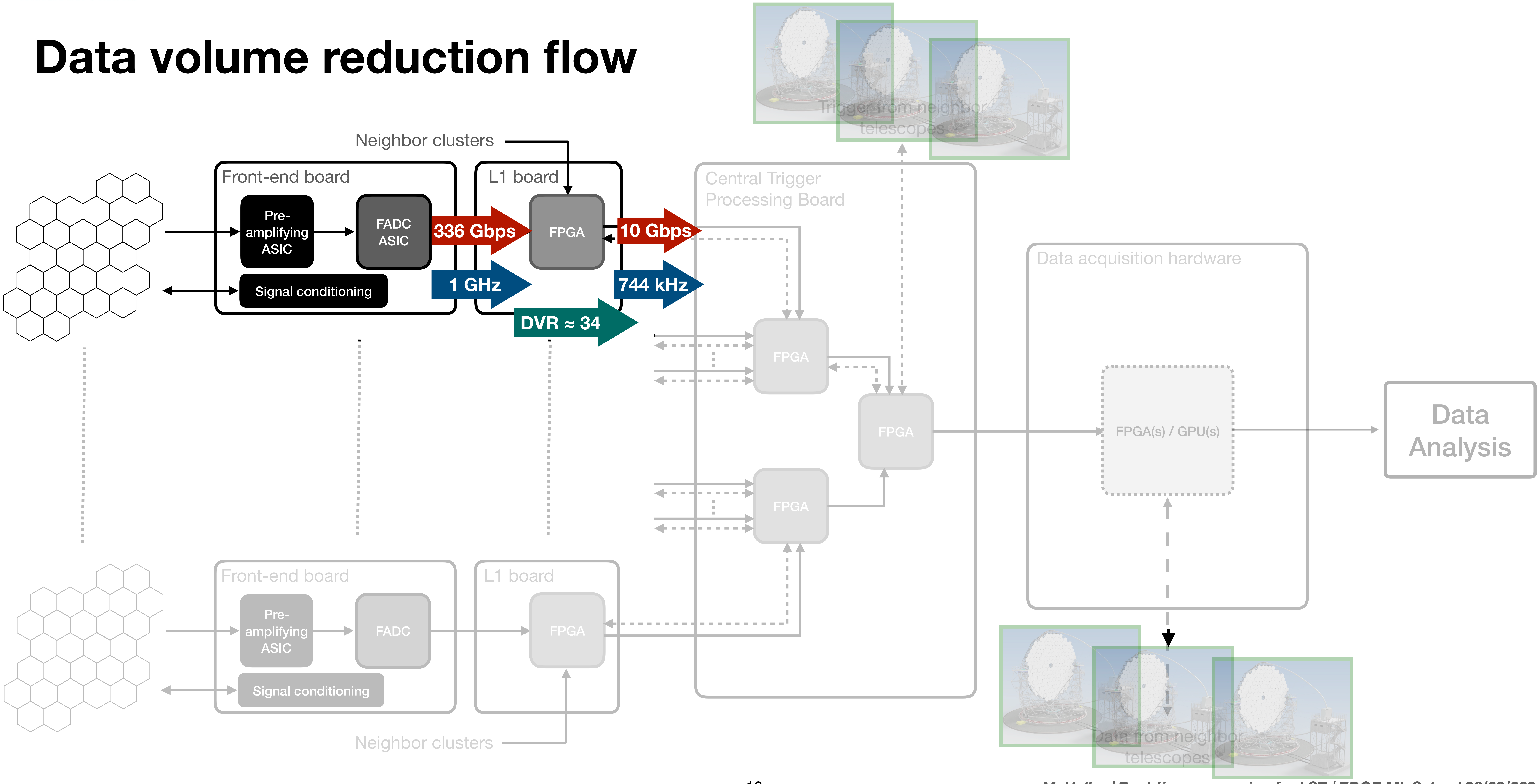


Observatory requirement:

Trigger Timestamp Information must be issued by the Camera to the softare array trigger with a time delay of **< 0.5 seconds from the light falling onto the Camera photodetector plane.**

Data Volume Reduction

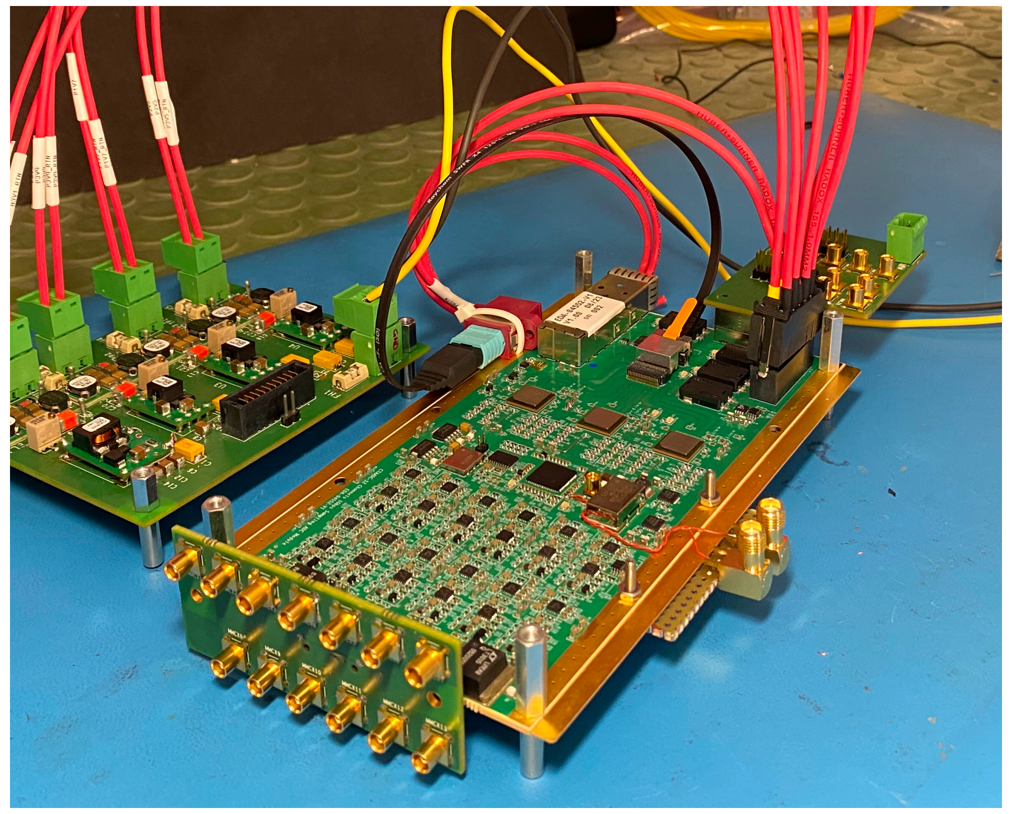
Data volume reduction flow



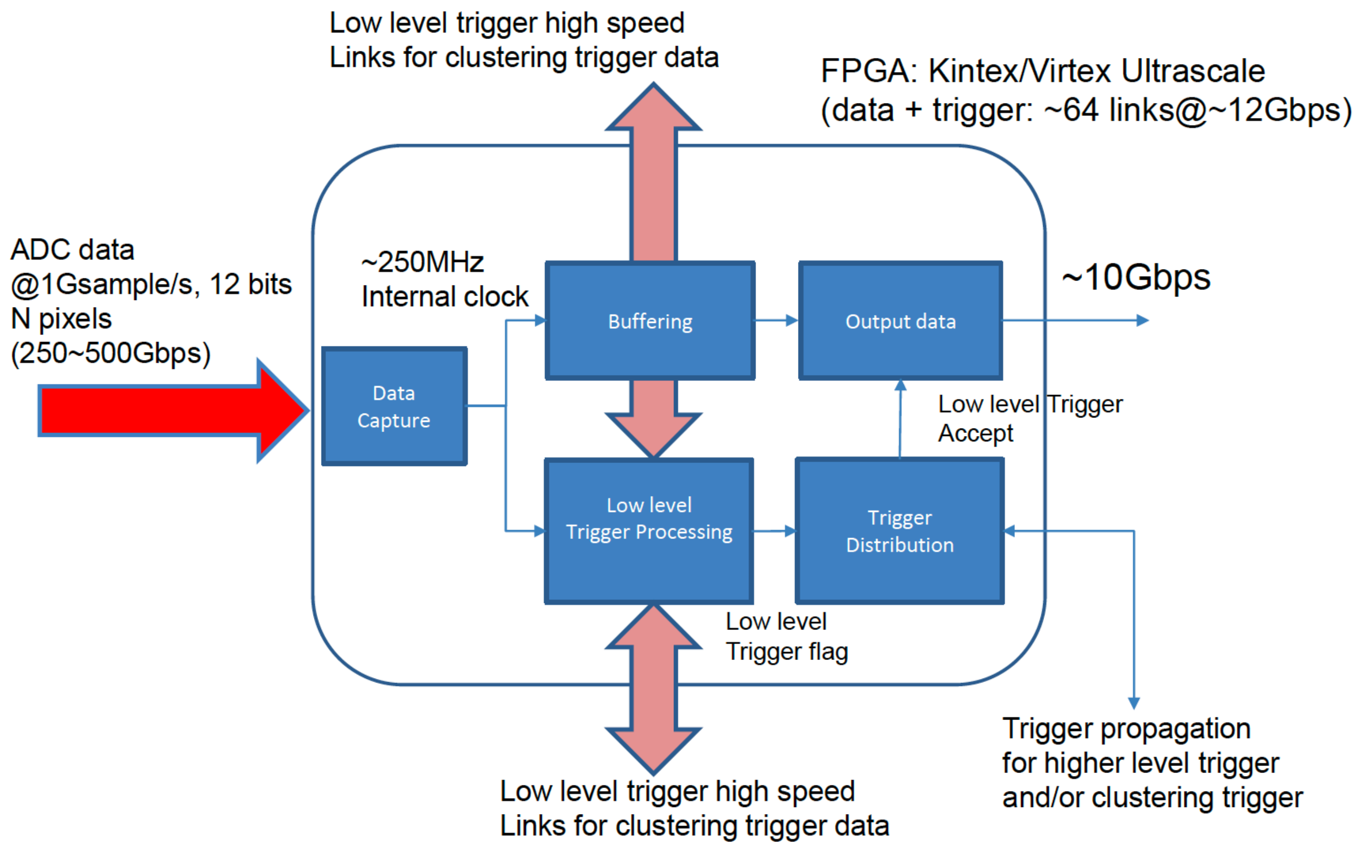
FADC and L1 board

- Functionalities:
  - **Digitize analog signals from SiPMs**
  - **Capture and buffer (~ 4 μs) FADC stream**
  - Perform **low level trigger (digital sum)**
    - **1 GHz throughput**
    - **~10 ns latency**
  - Send to Central Trigger Processor:
    - Option A: trigger bits and data from triggered events only
    - Option B: trigger bits and high level trigger information (sum of seven pixels)
  - FADC and L1 boards to be merged

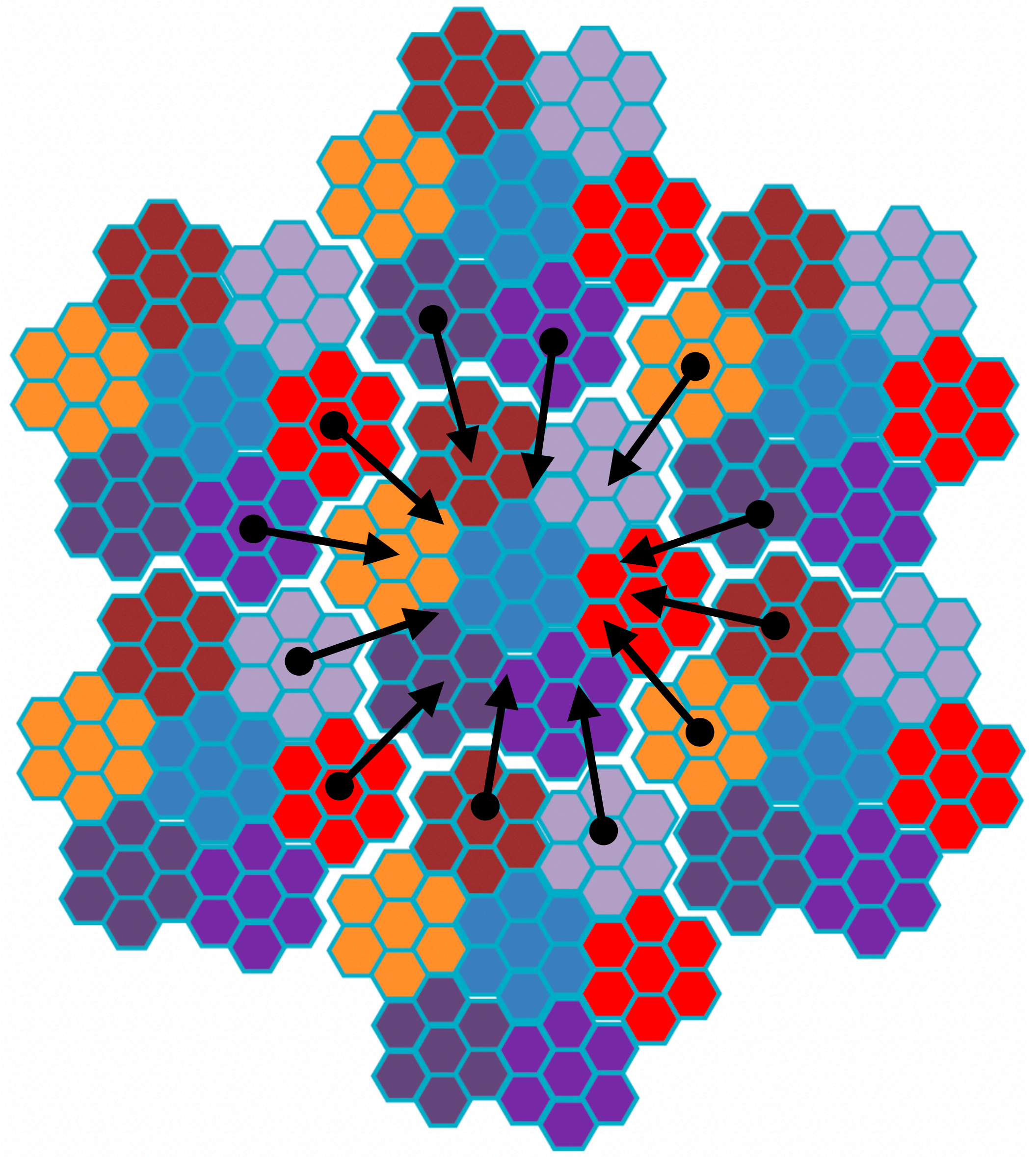
- Proof-of-concept test bench setup:
  - Implementation and test for both options almost over:
    - JESD204C
    - RoCE for Option B
  - Implementation of low level trigger



FADC Board



L1 Board

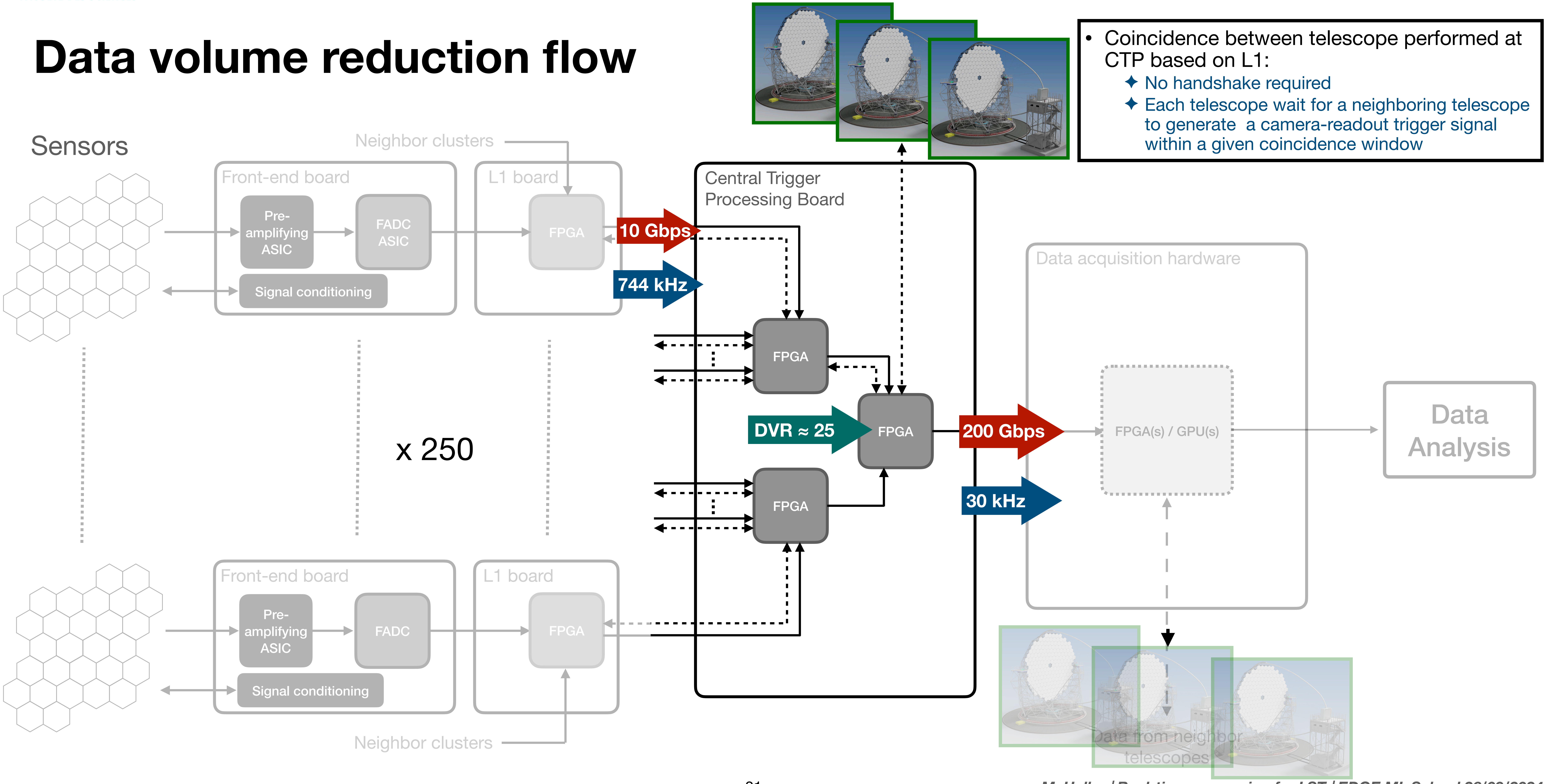


- L1 trigger, digital sum:
  - Compute sum, clipped to 8 bits, for each group of 7 pixels (flower)
  - Collect sum values from neighboring flowers
  - Compute sum of 7 flowers, i.e. 48 pixels and compare to threshold
    - Option A: trigger bits and high level trigger information (sum of seven pixels)
    - Option B: trigger bits and data from triggered events only

Camera readout architecture

Data volume reduction flow

- Coincidence between telescope performed at CTP based on L1:
  - ✦ No handshake required
  - ✦ Each telescope wait for a neighboring telescope to generate a camera-readout trigger signal within a given coincidence window



Central Trigger Processor board

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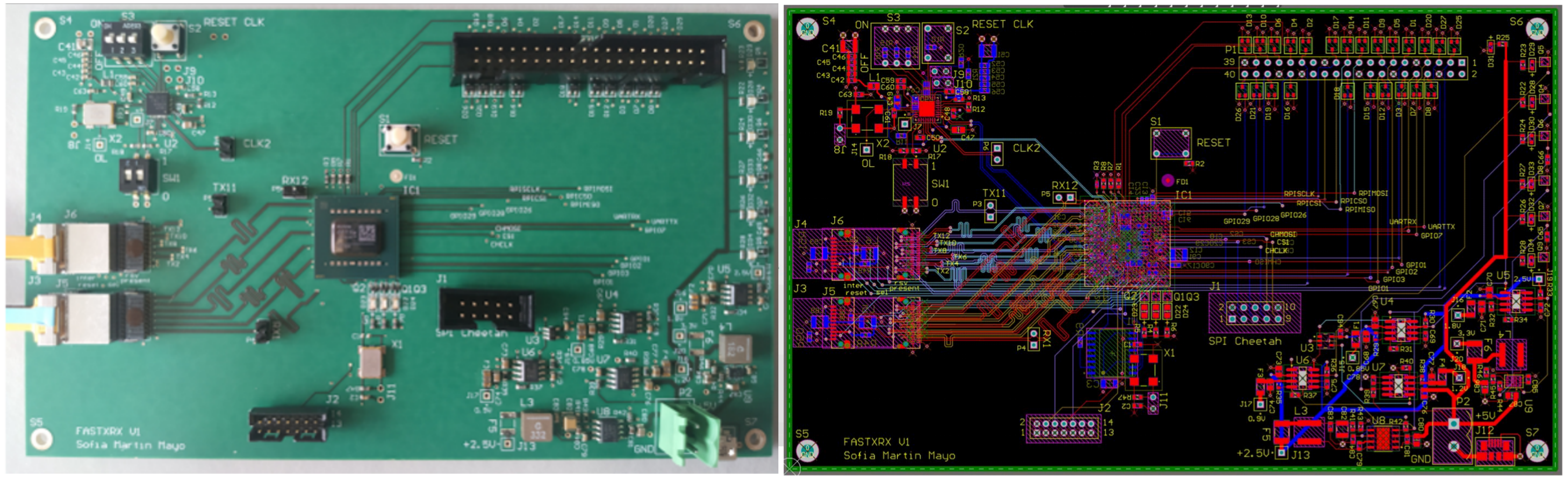
See contribution from A. Pérez

- Functionalities:
  - ✦ Collect and propagate trigger bits to build coincidences
  - ✦ **Option A:**
    - ◉ Collect data from events passing L1 trigger condition
    - ◉ Perform **partial event building**
    - ◉ **Level 2 HW trigger based on full data**
  - ✦ **Option B:**
    - ◉ **Level 2 HW trigger based on trigger output**
  - ✦ Manage trigger hardware triggers (optical link with neighbour telescopes)
- Proof-of-concept test bench setup:
  - ✦ Manufacture test PCB for optical transceivers with a FPGA tests
  - ✦ Test for porting deep learning models or DBScan to CTP FPGA

Tentative FPGA models: Kintex UltraScale KU085, KU095 or KU115



CTLearn model

Model: "CTLearn_model"

Layer (type)	Output Shape	Param #
waveforms (InputLayer)	[(None, 30, 30, 5)]	0
SingleCNN_block (Functional)	(None, 16)	1536
fc_particletype_1 (Dense)	(None, 32)	544
particletype (Dense)	(None, 3)	99
type (Softmax)	(None, 3)	0

Total params: 2179 (8.51 KB)
Trainable params: 2179 (8.51 KB)
Non-trainable params: 0 (0.00 Byte)

→

Model synthesis

Utilization Estimates

* Summary:

Name	BRAM_18K	DSP48E	FF	LUT	URAM
DSP	-	-	-	-	-
Expression	-	-	0	2	-
FIFO	69	-	5814	7931	-
Instance	3	122	17599	90345	-
Memory	-	-	-	-	-
Multiplexer	-	-	-	-	-
Register	-	-	-	-	-
Total	72	122	23413	98278	0
Available	1080	1700	406256	203128	0
Utilization (%)	6	7	5	48	0

DBScan for Level 2 HW trigger

- Spatial clustering algorithm:
  - From: KDD-96 Proceedings. Copyright © 1996, AAAI (www.aaai.org). A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise, Martin Ester, Hans-Peter Kriegel, Jiirg Sander, Xiaowei Xu
- One “point" = one flower which digital sum is above threshold
- Determine optimal settings from k-dist plot

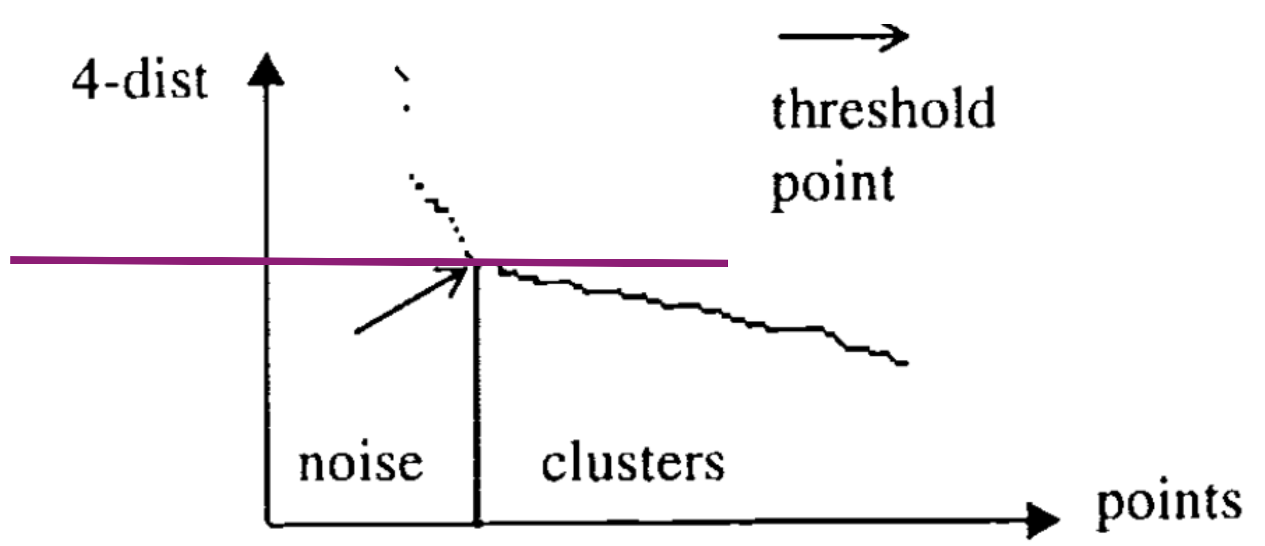


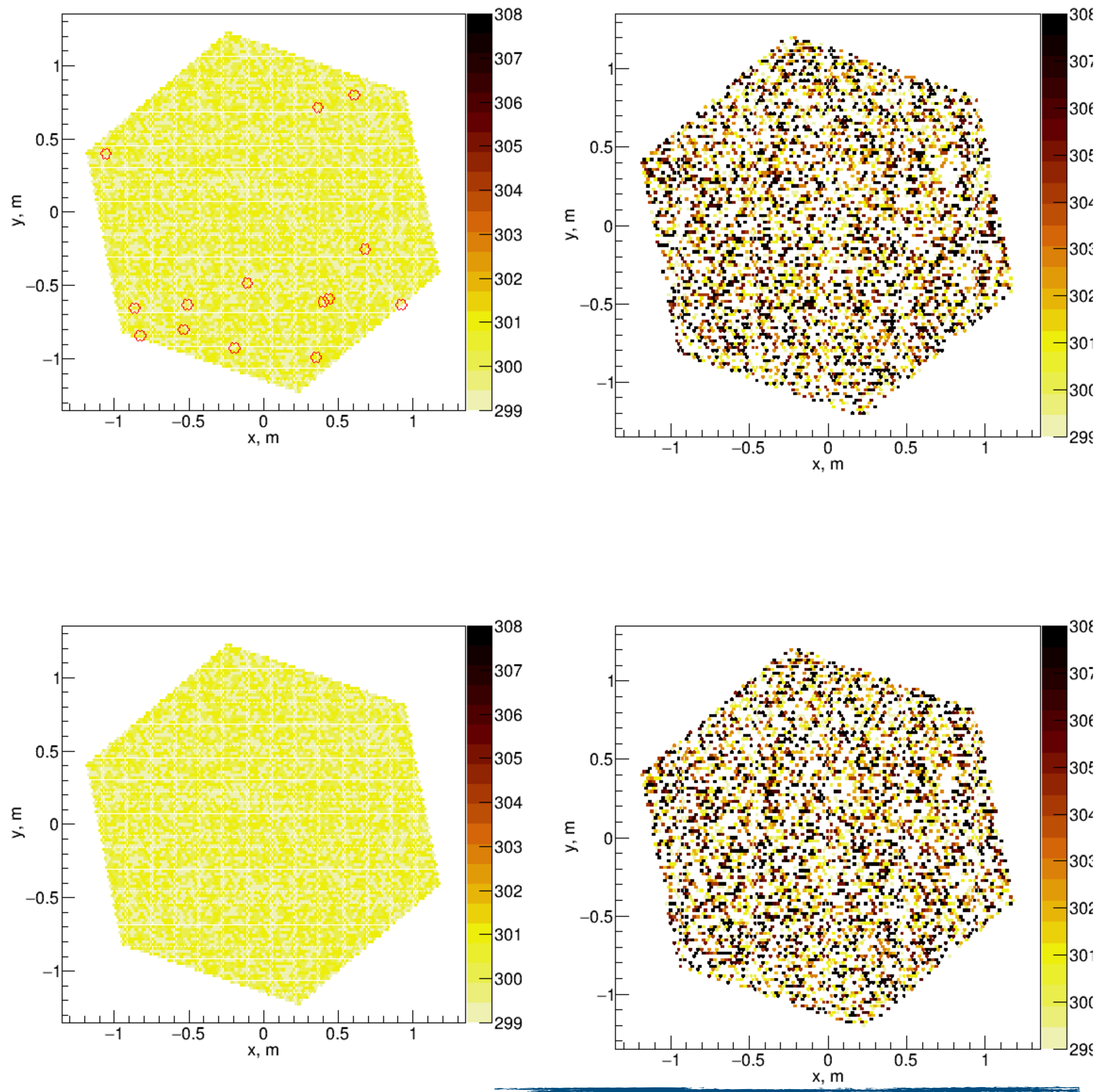
figure 4: sorted 4-dist graph for sample database 3

- Time introduced in the metric to account for shower development

Initial hyper parameters of the model

→ Type of the digital sum **(3n flower)**
→ Threshold on the digital sum to form micro cluster **(307)**
→ How do we include timing component into the metric **(z = 0.05*t)**
→ The maximum distance between two micro clusters to form to form neighborhood **(eps = 0.1)**
→ The number of samples in a neighborhood for a point to be considered as a core point **(minPts = 15)**.
→ Metric : **euclidean distance.**

Two tasks: 1) Shower/NSB separation 2) RoI identification



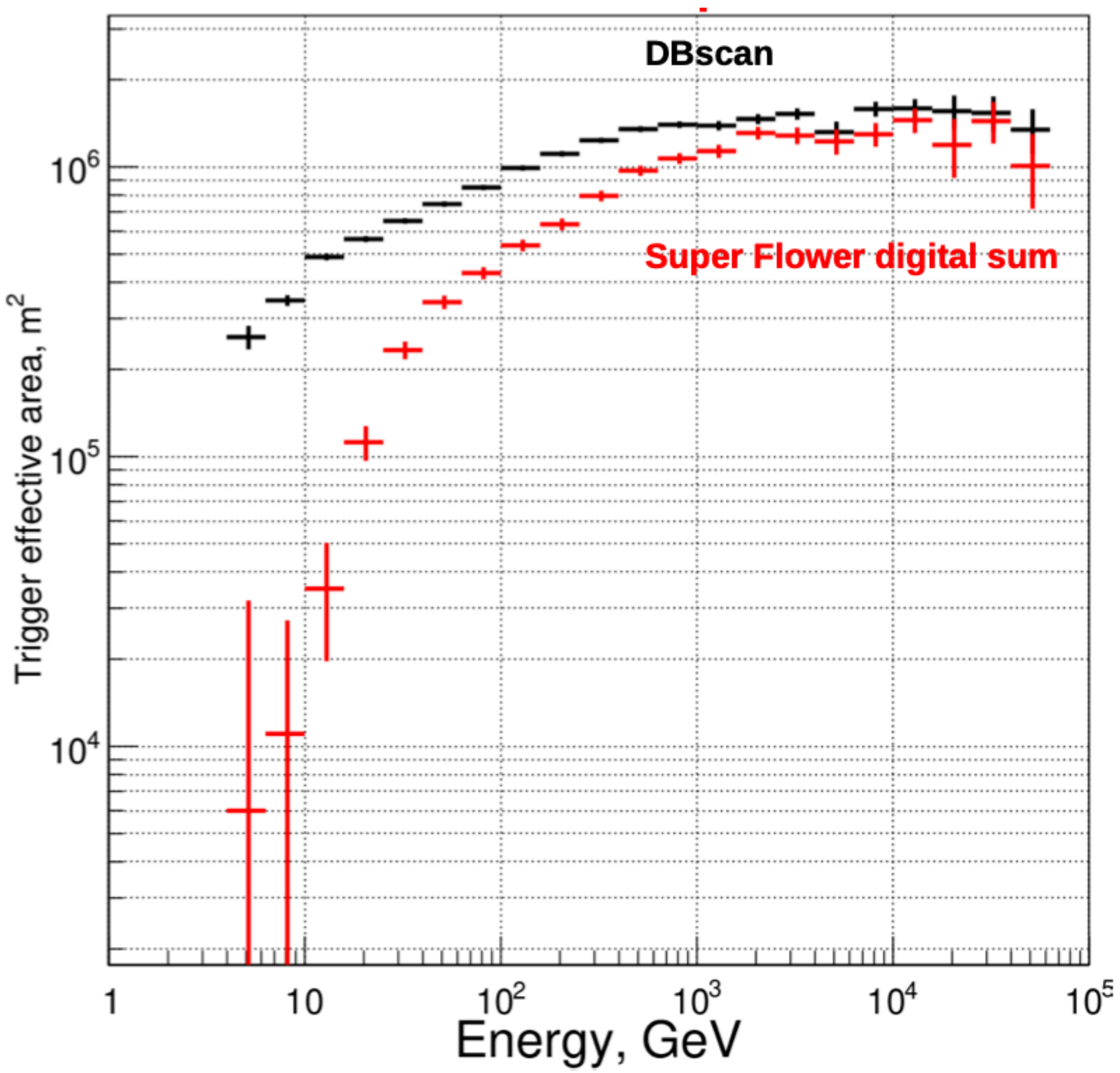
wf_time : 0 ns
gamma
event_id : 23801
energy : 15 GeV
xcore : -51 m
ycore : -203 m
ev_time : -71 ns
nphotons : 146
n_pe : 42
n_pixels : 25
azimuth : 1800/10 deg
altitude : 699/10 deg
h_first_int : 23186 km
hmax : 11727 km

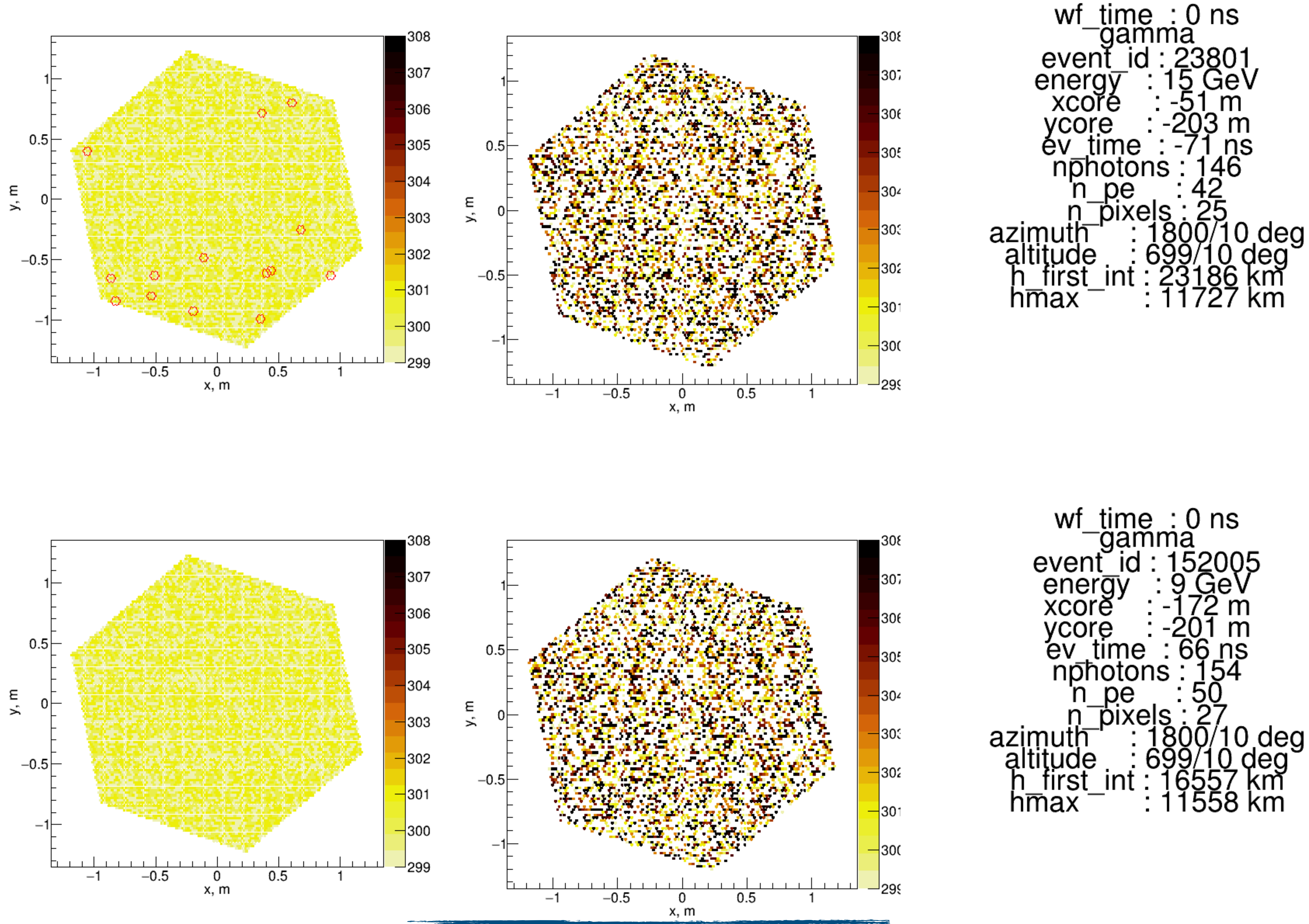
wf_time : 0 ns
gamma
event_id : 152005
energy : 9 GeV
xcore : -172 m
ycore : -201 m
ev_time : 66 ns
nphotons : 154
n_pe : 50
n_pixels : 27
azimuth : 1800/10 deg
altitude : 699/10 deg
h_first_int : 16557 km
hmax : 11558 km

Simulation and tests ran at CSCS

DBScan for Level 2 HW trigger

- Challenges ahead are to run DBScan algorithm with **high throughput (max. 750 kHz) and low latency (2 µs)**
- Implementation study started as collaboration between University of Geneva and HEPIA (Prof. A. Upegui. Prof. Q. Berthet, T. Classen)





Simulation and tests ran at CSCS

L. Burmistrov (UniGe)

DBScan for Level 2 HW trigger

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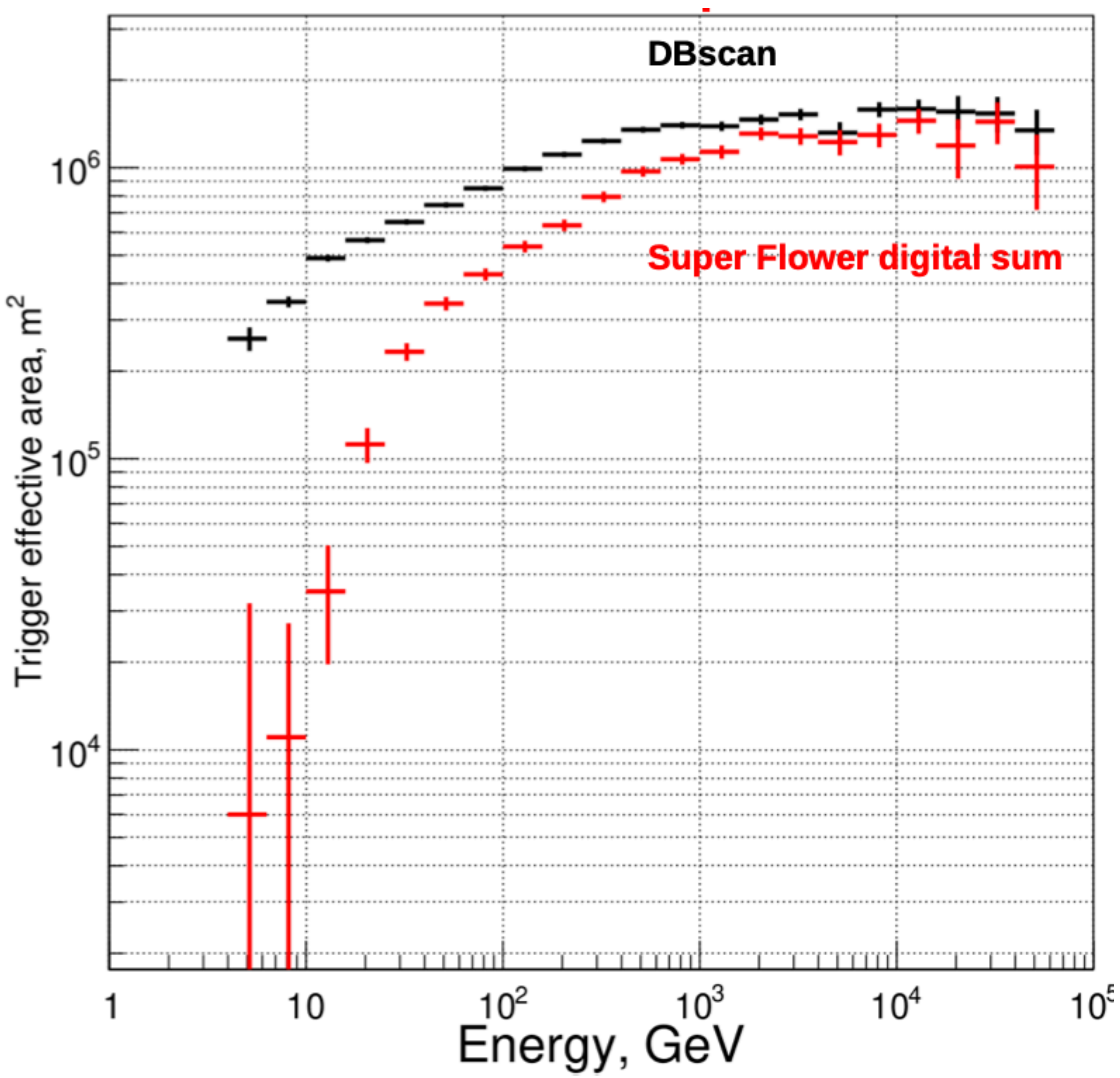

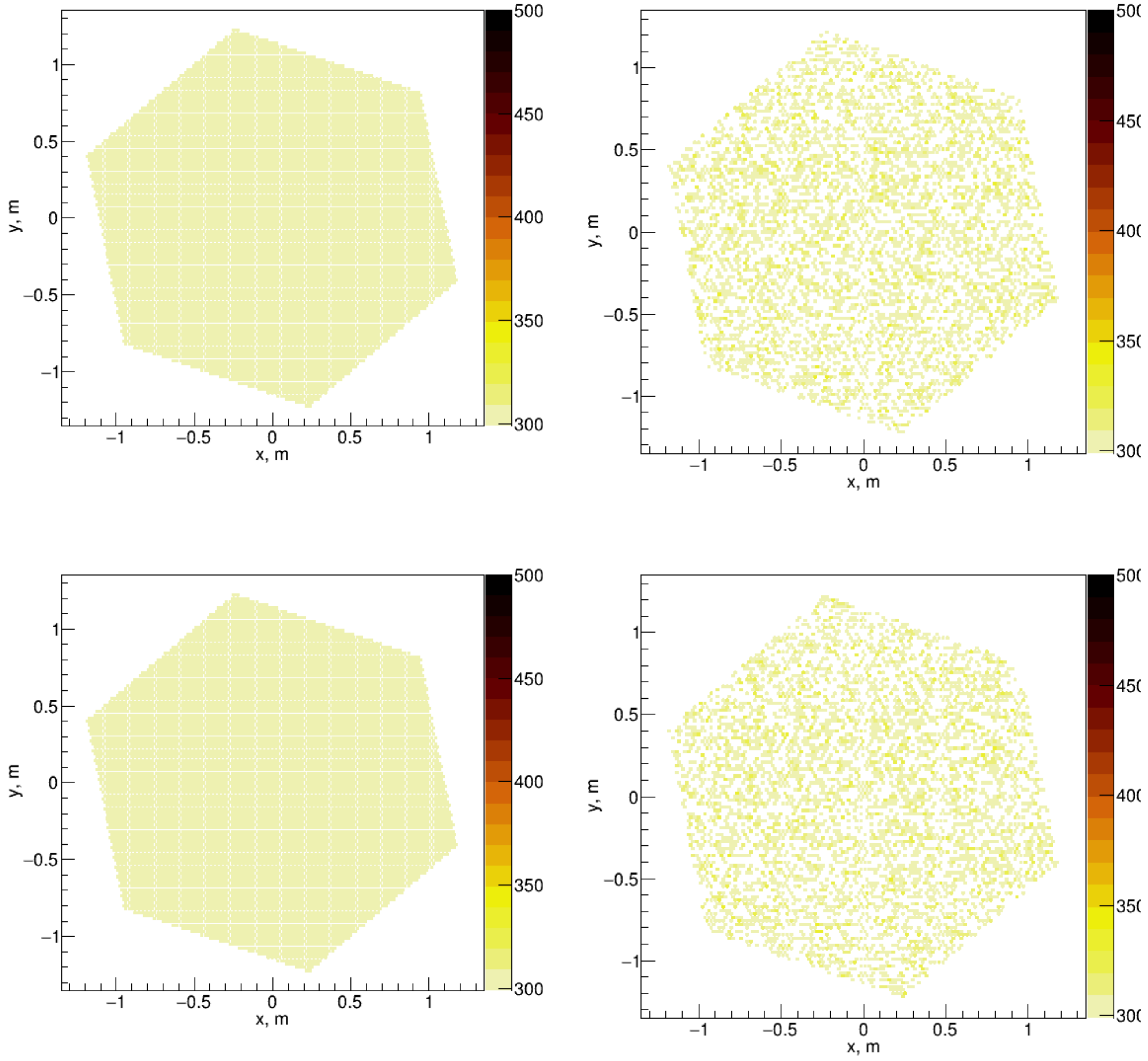

wf_time : 27 ns
gamma_diff
event_id : 2280406
energy : 1422 GeV
xcore : -37 m
ycore : 34 m
ev_time : -95 ns
nphotons : 39522
n_pe : 15250
n_pixels : 1256
azimuth : 1769/10 deg
altitude : 698/10 deg
h_first_int : 22417 km
hmax : 10449 km

wf_time : 27 ns
proton
event_id : 6945503
energy : 4119 GeV
xcore : -34 m
ycore : -117 m
ev_time : -93 ns
nphotons : 50403
n_pe : 18990
n_pixels : 2279
azimuth : 1800/10 deg
altitude : 690/10 deg
h_first_int : 17954 km
hmax : 10501 km

Simulation and tests ran at CSCS

L. Burmistrov (UniGe)

CNN for Level 2 HW level trigger

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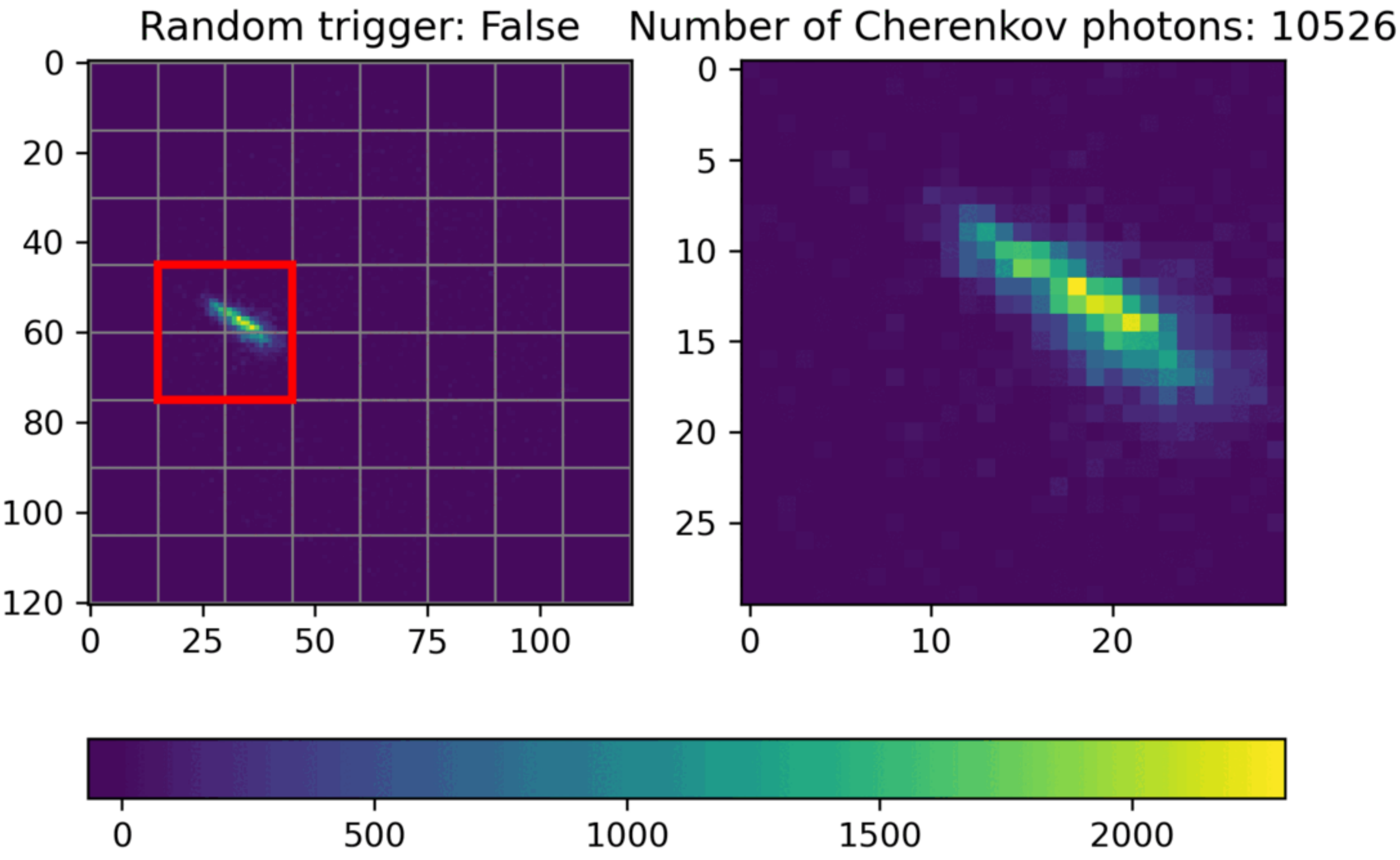
CTLearn

Latency ~ 5 us

Two tasks: 1) shower/night sky background 2) gamma/hadron



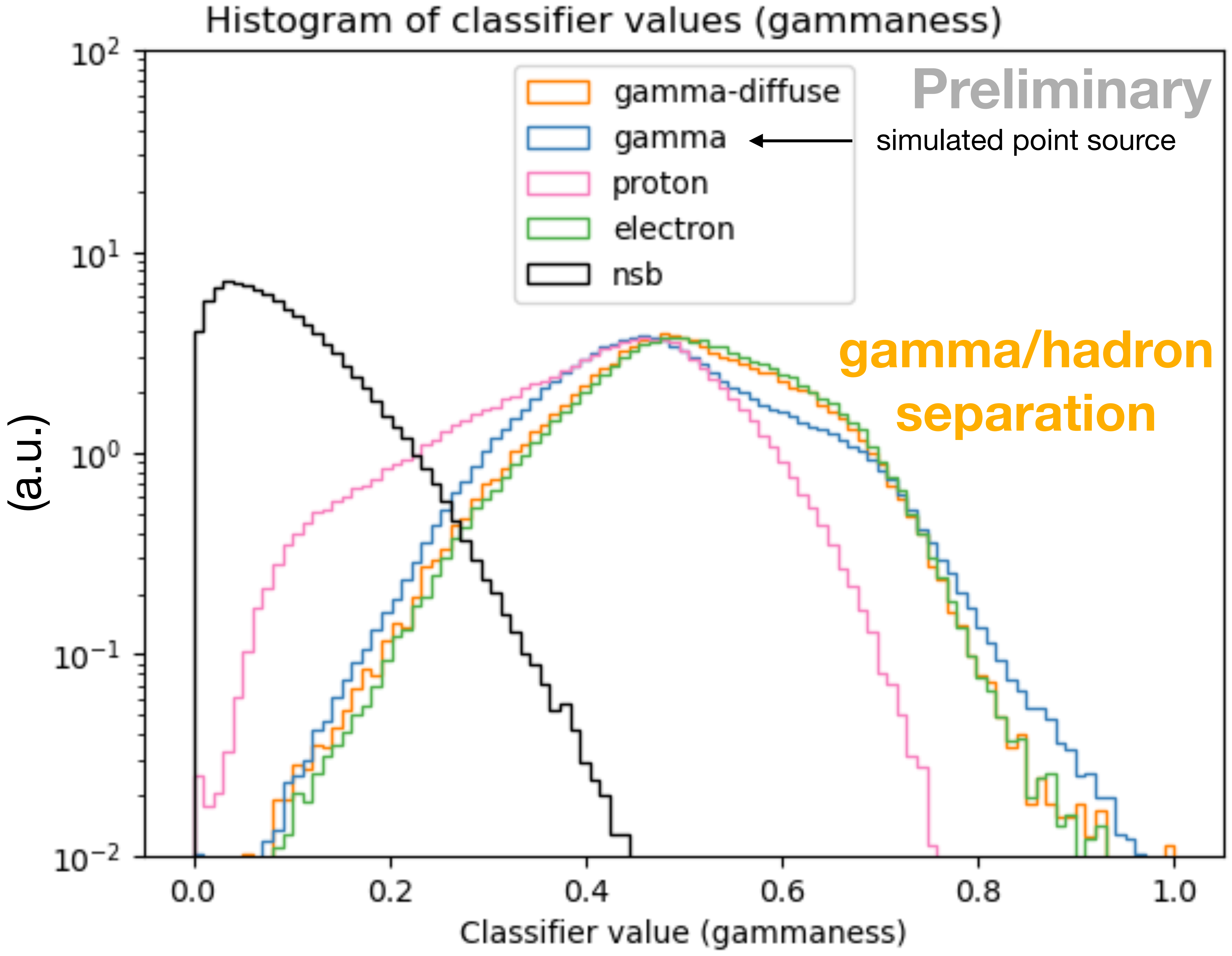
30x30 pixels x 5ns
2 CNN layers (8, 16)
GlobalMaxPooling
2 dense layers (32, 2) or (32, 3)

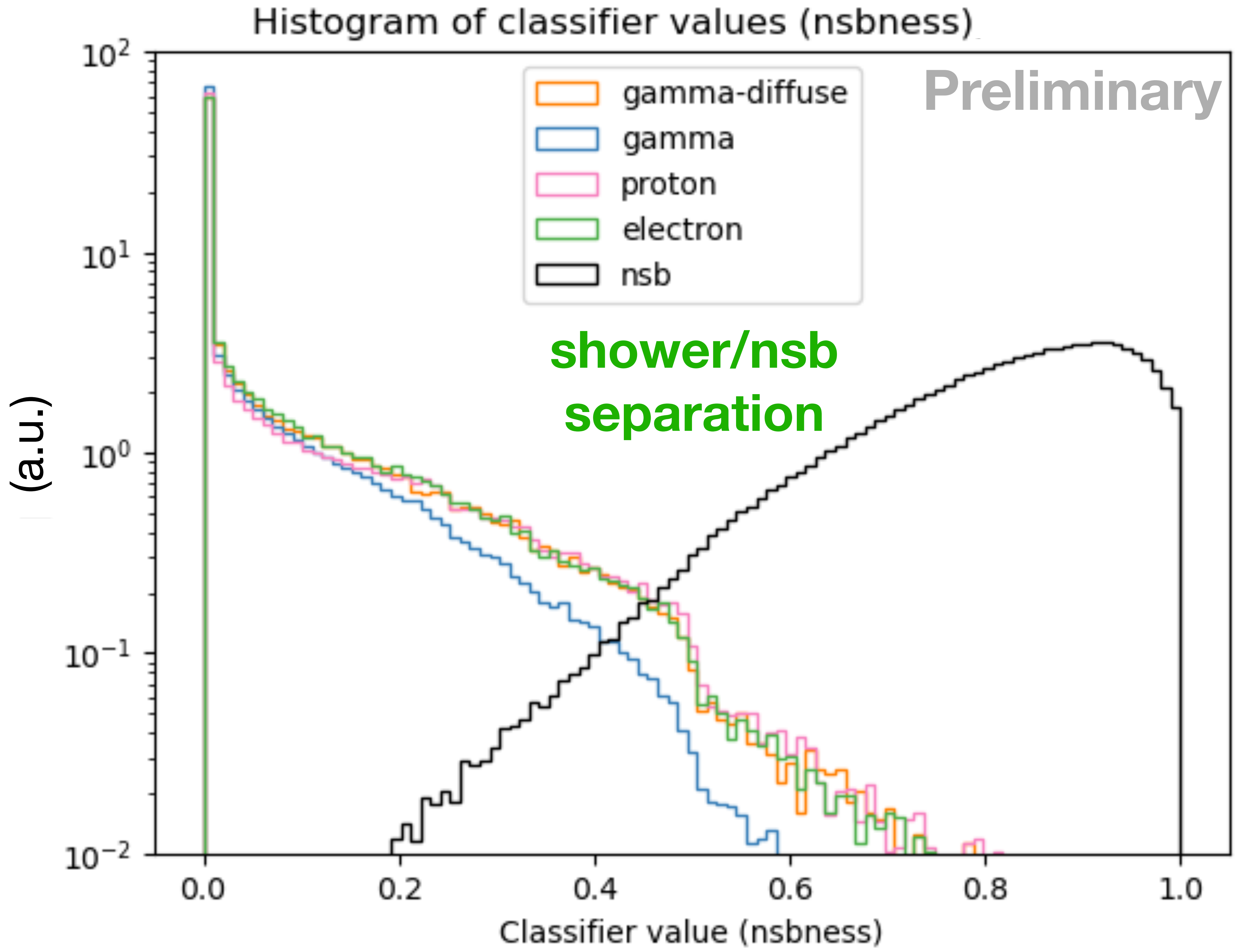
Gamma, Hadron, NSB

```
Model: "SingleCNN_block"
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 waveforms (InputLayer)      [(None, 30, 30, 5)]       0

 SingleCNN_block_wvf_conv_1  (None, 30, 30, 8)         368
 _1 (Conv2D)

 SingleCNN_block_wvf_pool_1  (None, 15, 15, 8)         0
  (MaxPooling2D)

 SingleCNN_block_wvf_conv_2  (None, 15, 15, 16)        1168
 _1 (Conv2D)

 SingleCNN_block_wvf_pool_2  (None, 7, 7, 16)          0
  (MaxPooling2D)

 SingleCNN_block_wvf_global  (None, 16)                0
 _maxpool (GlobalMaxPooling
 2D)

=================================================================
Total params: 1536 (6.00 KB)
Trainable params: 1536 (6.00 KB)
Non-trainable params: 0 (0.00 Byte)
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 waveforms (InputLayer)      [(None, 30, 30, 5)]       0

 SingleCNN_block (Functiona  (None, 16)                1536
 l)

 fc_particletype_1 (Dense)   (None, 32)                544

 particletype (Dense)        (None, 2)                 66

 type (Softmax)              (None, 2)                 0

=================================================================
Total params: 2146 (8.38 KB)
Trainable params: 2146 (8.38 KB)
Non-trainable params: 0 (0.00 Byte)
_________________________________________________________________
```

Signal efficiency & NSB contamination - 3 classes model

- **Categorial classification task** is performed including **gamma/hadron separation** and atmospheric **shower/night sky background (NSB)** with Cherenkov-free **NSB patches**.
- Histogram below shows **mean classifier value of all triggered telescopes**





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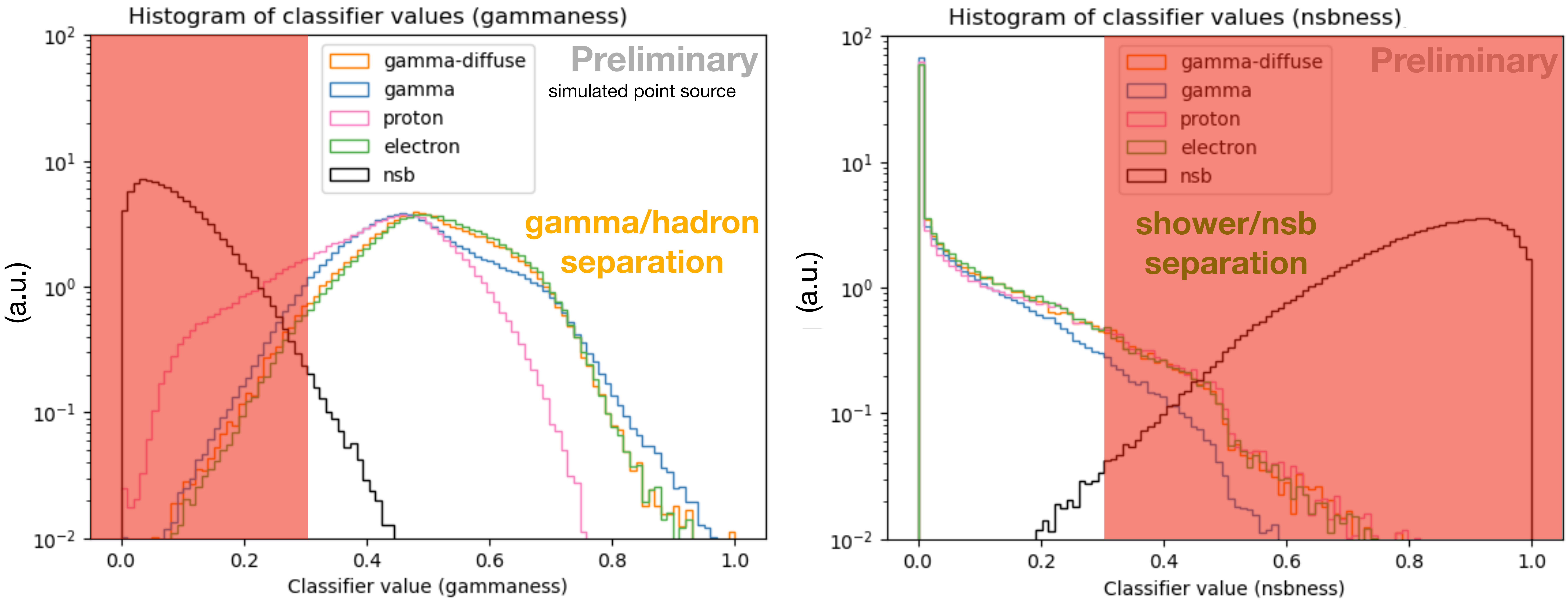

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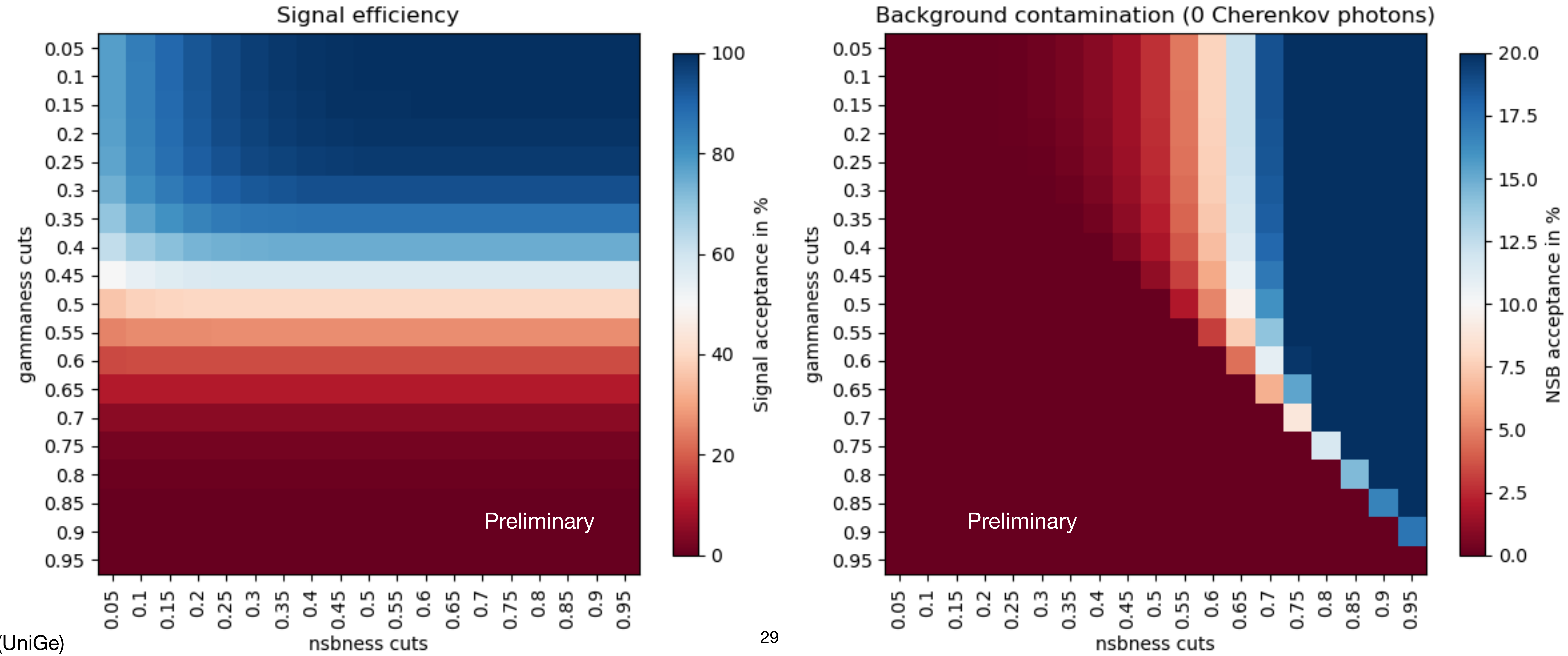
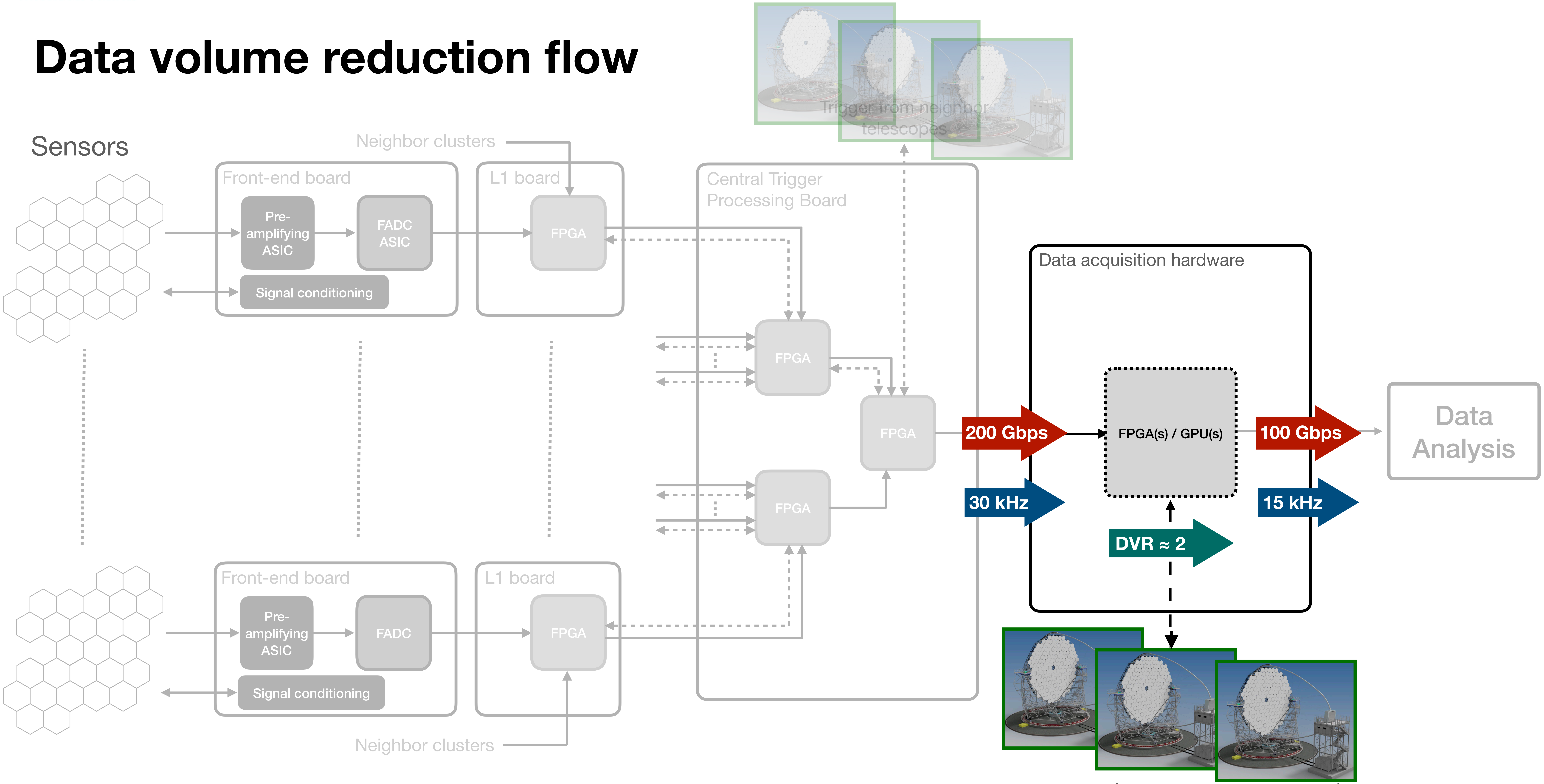


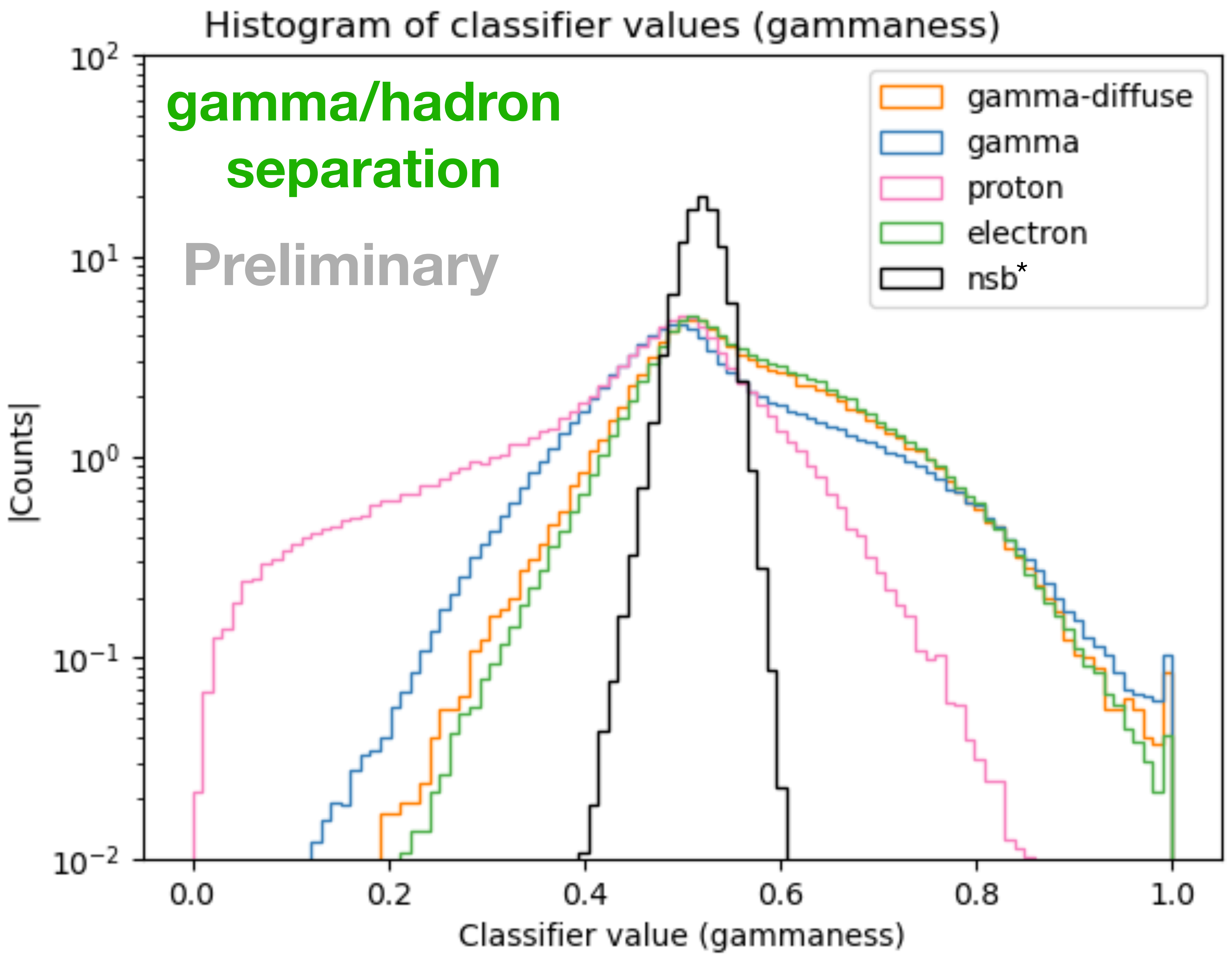
Camera readout architecture

Data volume reduction flow

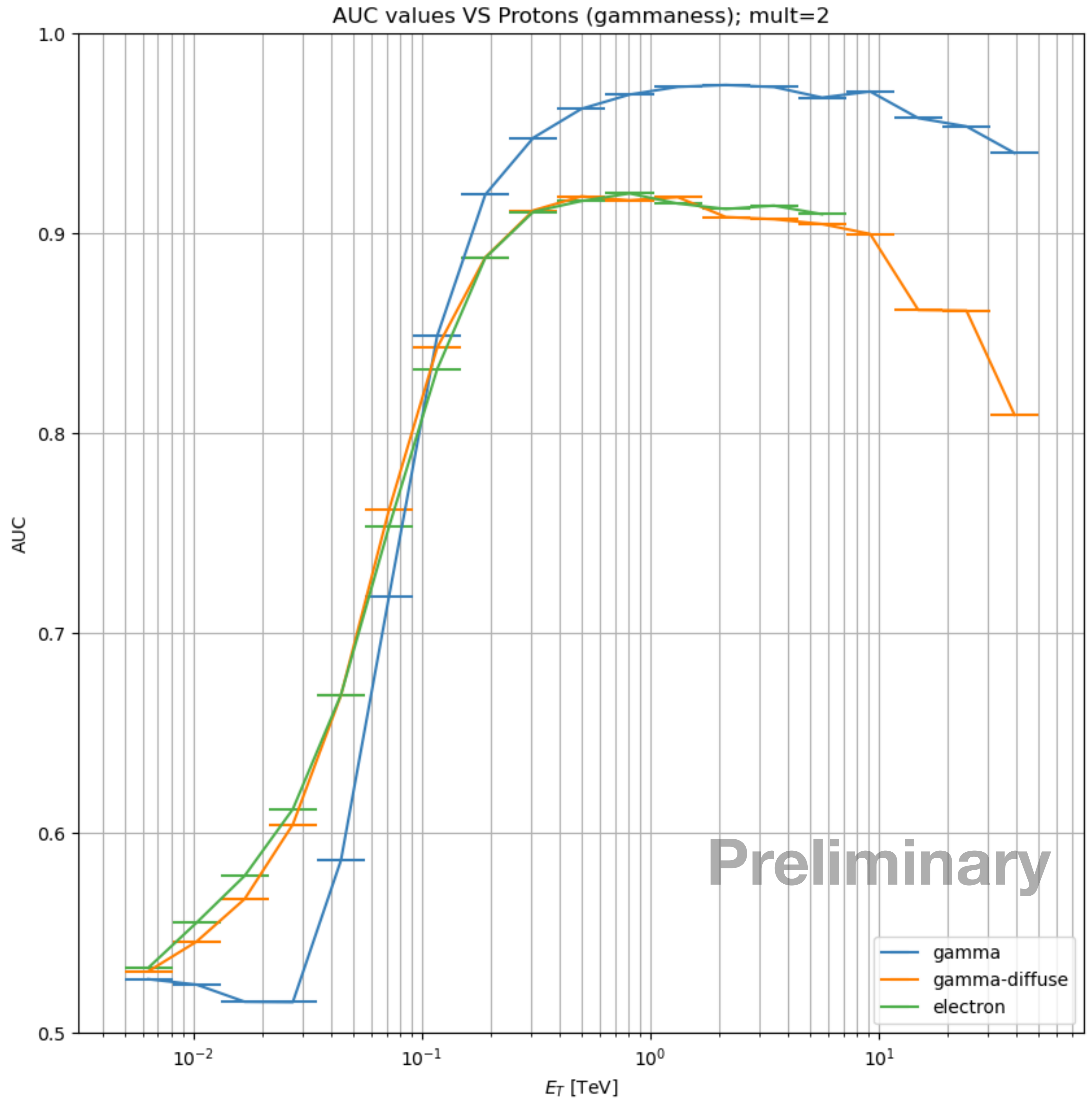


Gamma/hadron high-level software trigger system - 2 classes model

- Assuming that the **shower/NSB separation** is achieved at a low-level trigger stage, e.g. using cluster algorithm such as the DB-Scan algorithm or CNN-based algorithm as shown previously, the high-level trigger can **only** focus on the **gamma/hadron separation**.



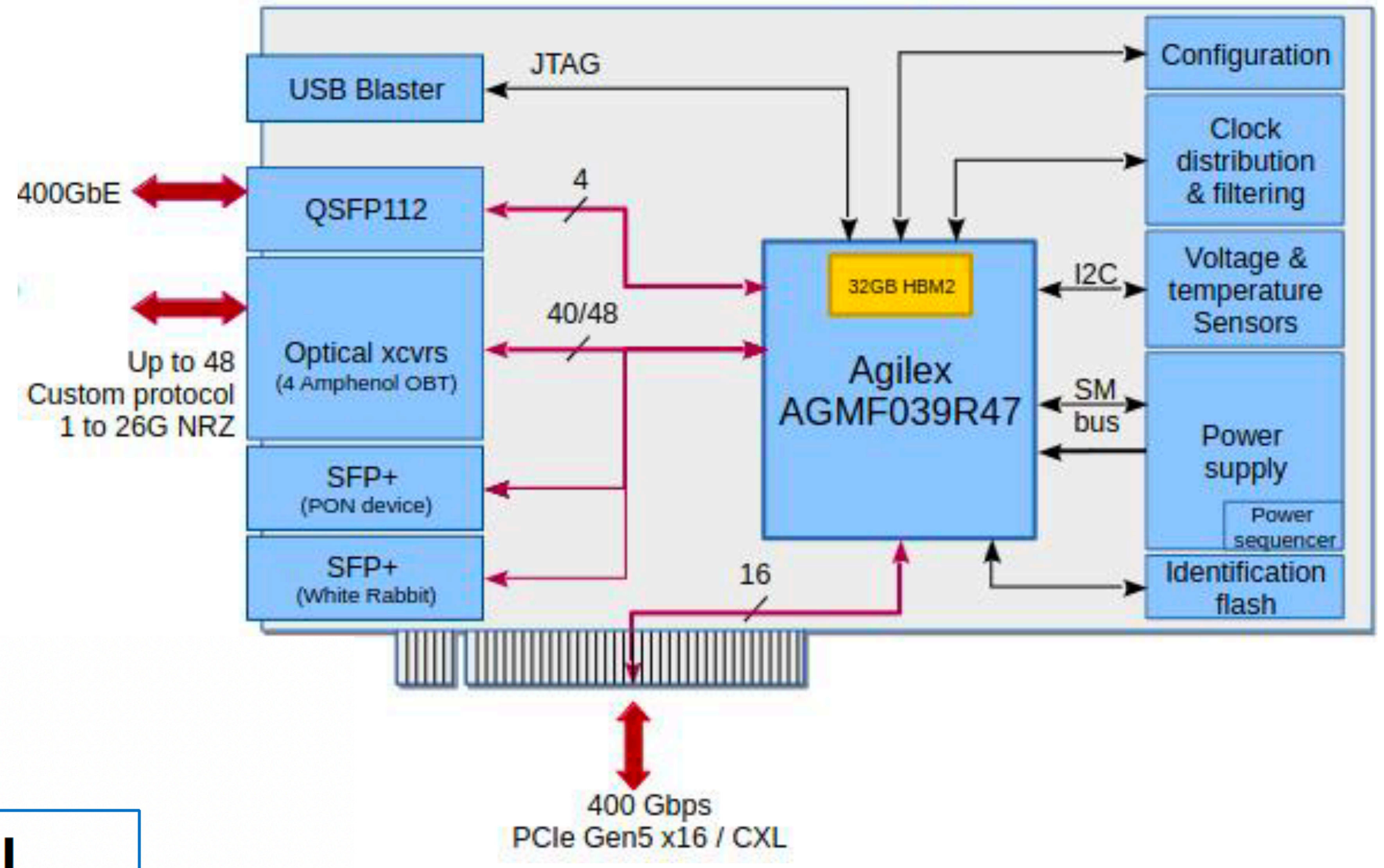
*No Cherenkov-free **NSB patches** are included at training phase.



Porting AI algorithms to hardware accelerators

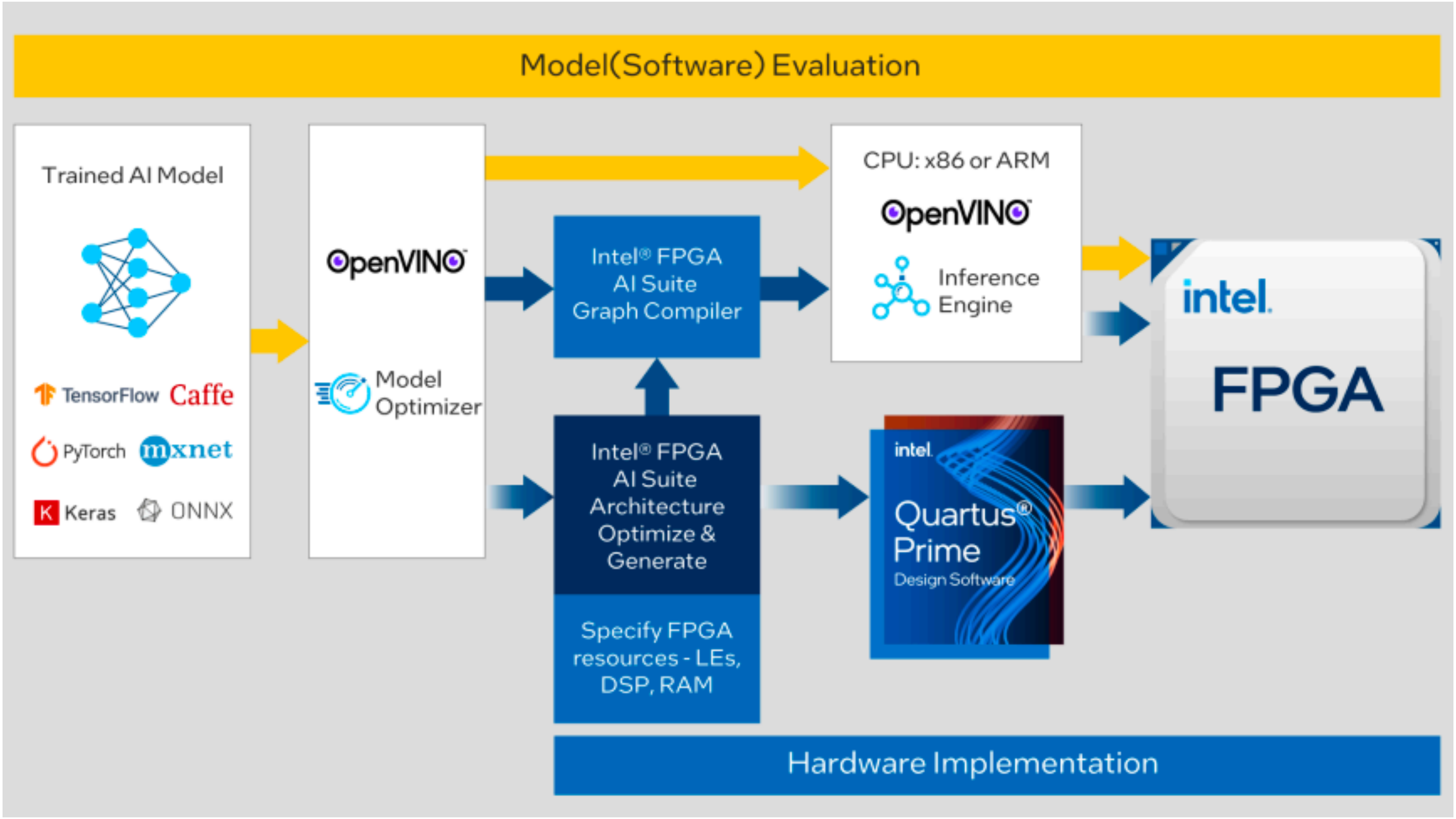
- In this particular case, we focus on Intel Altera FPGAs (Agilex 7) as collaboration with CPPM in LST that develops the PCIe400 board for LHCb
- As it is not the first choice for HLC experiments, porting AI algorithm on those FPGAs is not a “walk in the park"

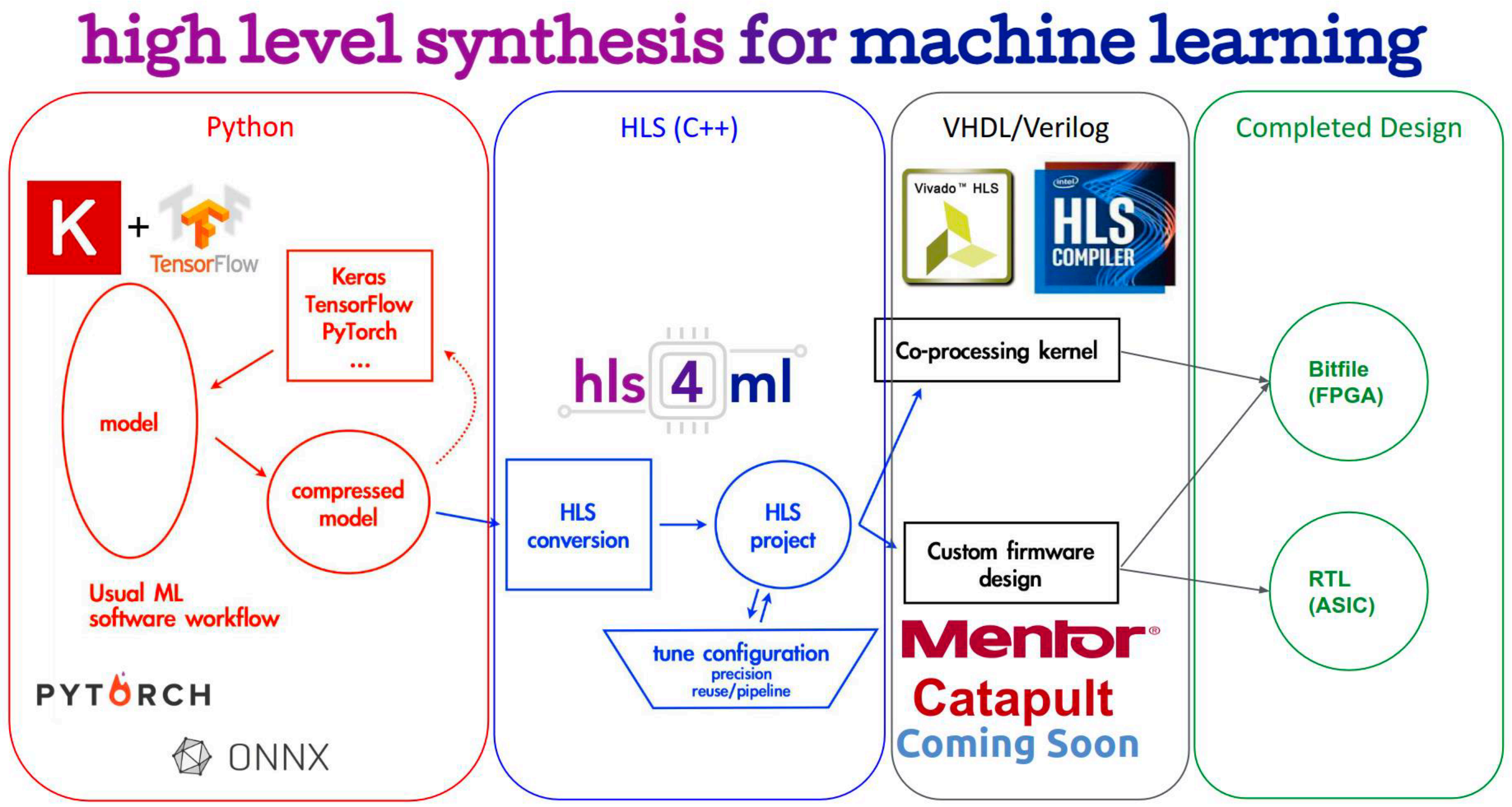
PCIe400 synoptic



Altera® FPGAs

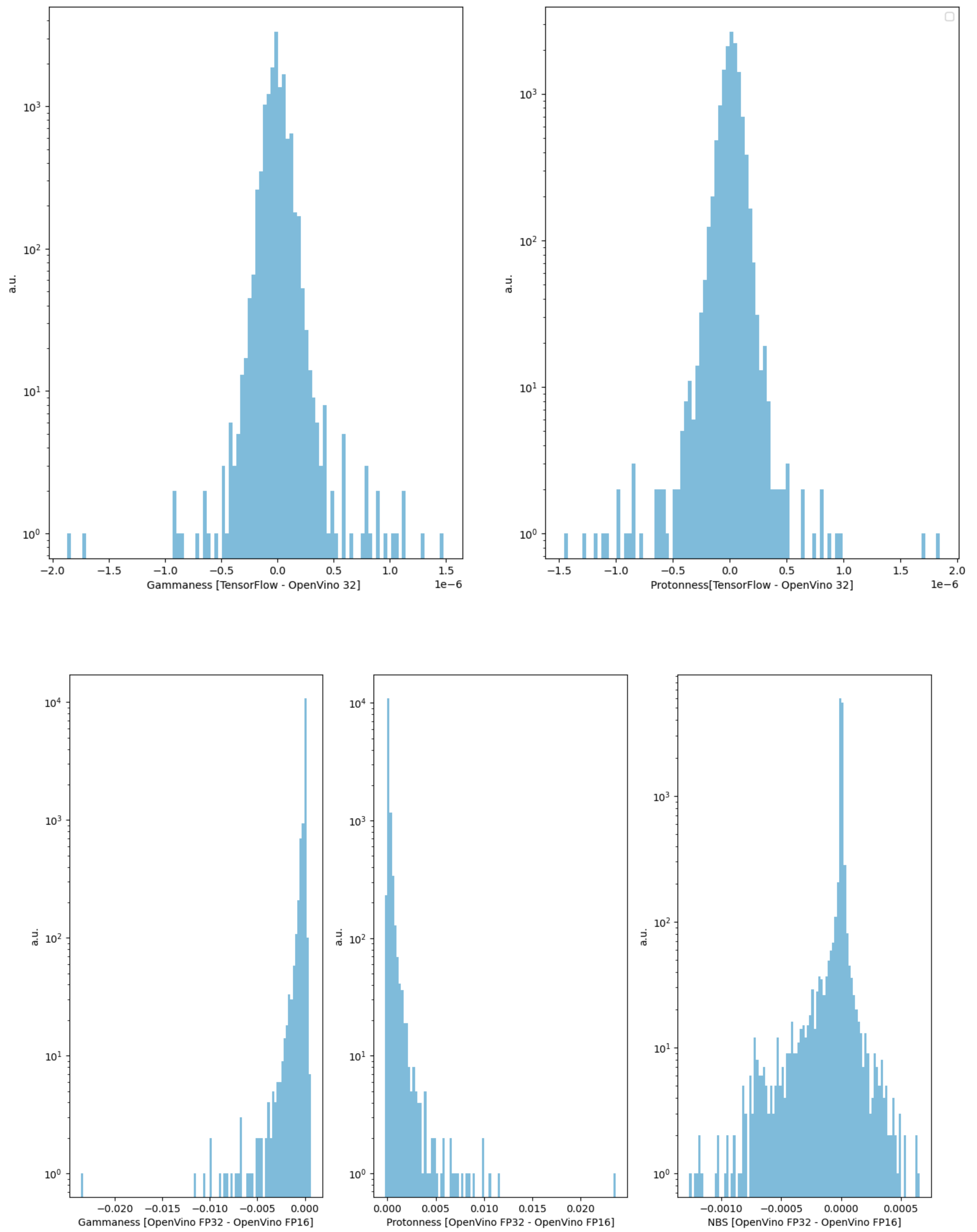
Intel® FPGA AI Suite	**hls4ml**
- various model sizes to fit - provided directly by Altera® experts - lower throughput depending on the model size	- potentially higher possible throughput - smaller model sizes to fit





Porting AI algorithms to hardware accelerators

- Our finding's:
  - ✦ Hls4ml provides better results in terms of maximum achievable throughput in perspective, but currently is very limited support for Altera® boards due to deprecation of the Intel® HLS compiler. Good potential with the release of the new Intel® oneAPI backend support.
  - ✦ Initially, only 200 inferences/s were achieved on the Intel® Arria®10 PAC card for the original model for high-level triggers (6M parameters). Can we do better?
    - Increasing the clock rate to 600 MHz (standard 400 MHz) to determine the maximum achievable performance
      - ➡ 732 inferences/s.
    - Assuming an implementation with 4 instances of the inference IP in Agilex® 7
      - ➡ 2928 inferences/s.
  - ✦ The model sizes were reduced to almost two orders of magnitude:
    - By optimising the architecture based on the graph of the network, ~ 40k fps could be achieved with one instance.



Porting AI algorithms to hardware accelerators

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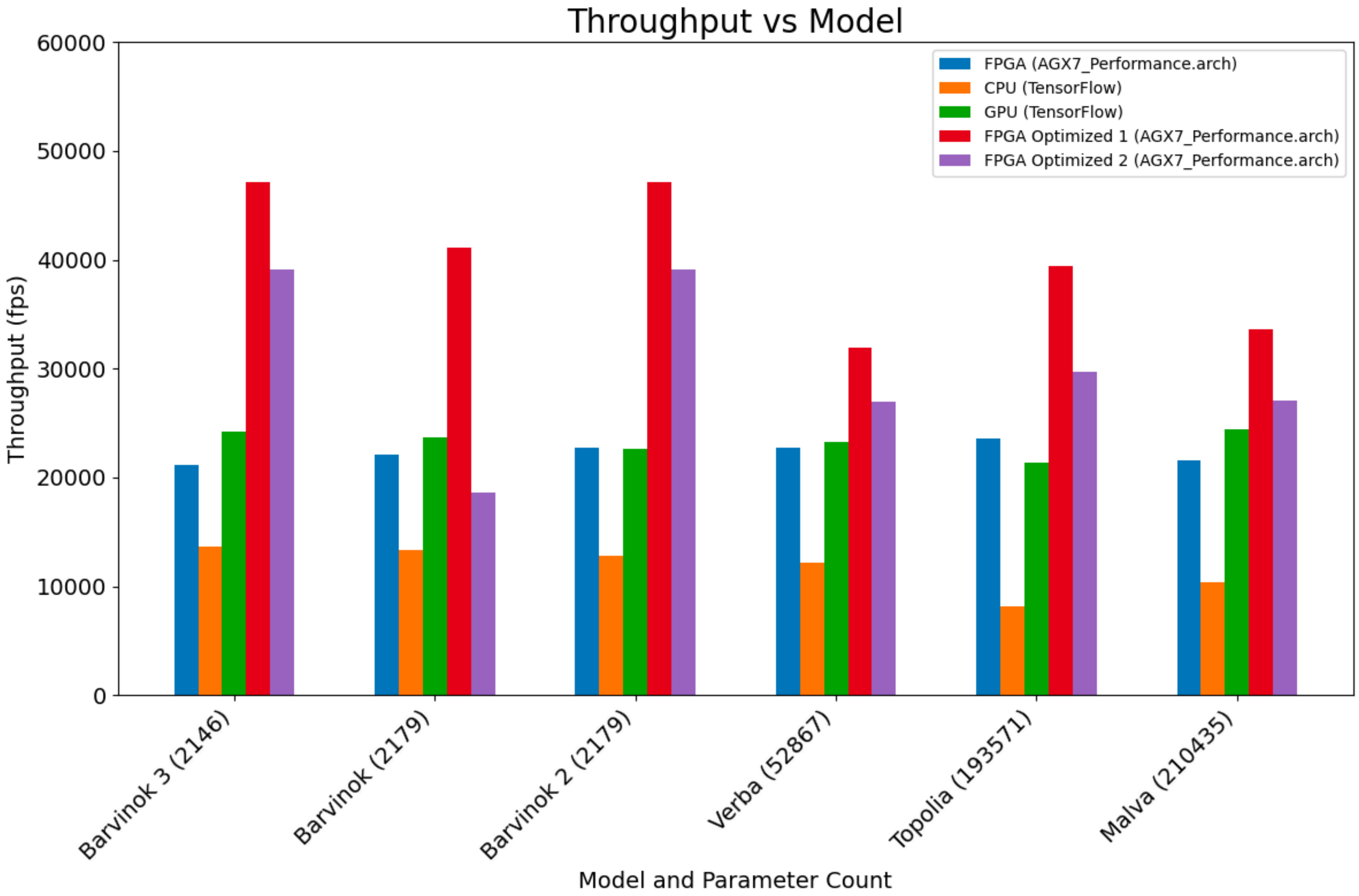
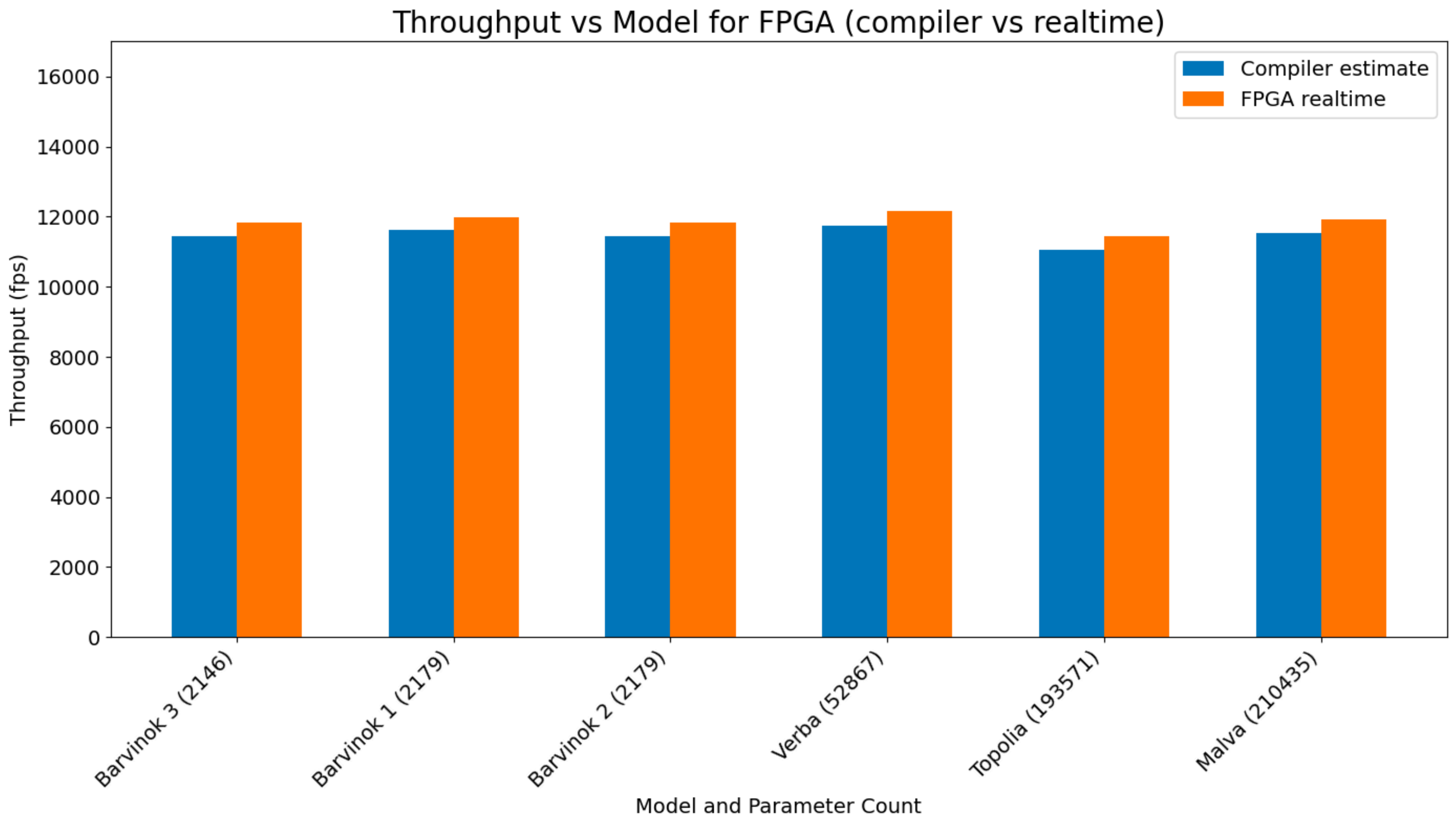
CTAO LST COLLABORATION

- FPGA:
  - ✦ Prediction of throughput with AI Suite on Agilex7 performance architecture + 2 optimised architectures
- GPU:
  - ✦ Results of throughput on Nvidia L40S GPU with Tensorflow (48 GB VRAM, 18 176 CUDA cores)
- CPU:
  - ✦ Results of throughtput on Intel CPU with Tensorflow(Intel(R) Xeon(R) Silver 4215R @ 3.20GHz)

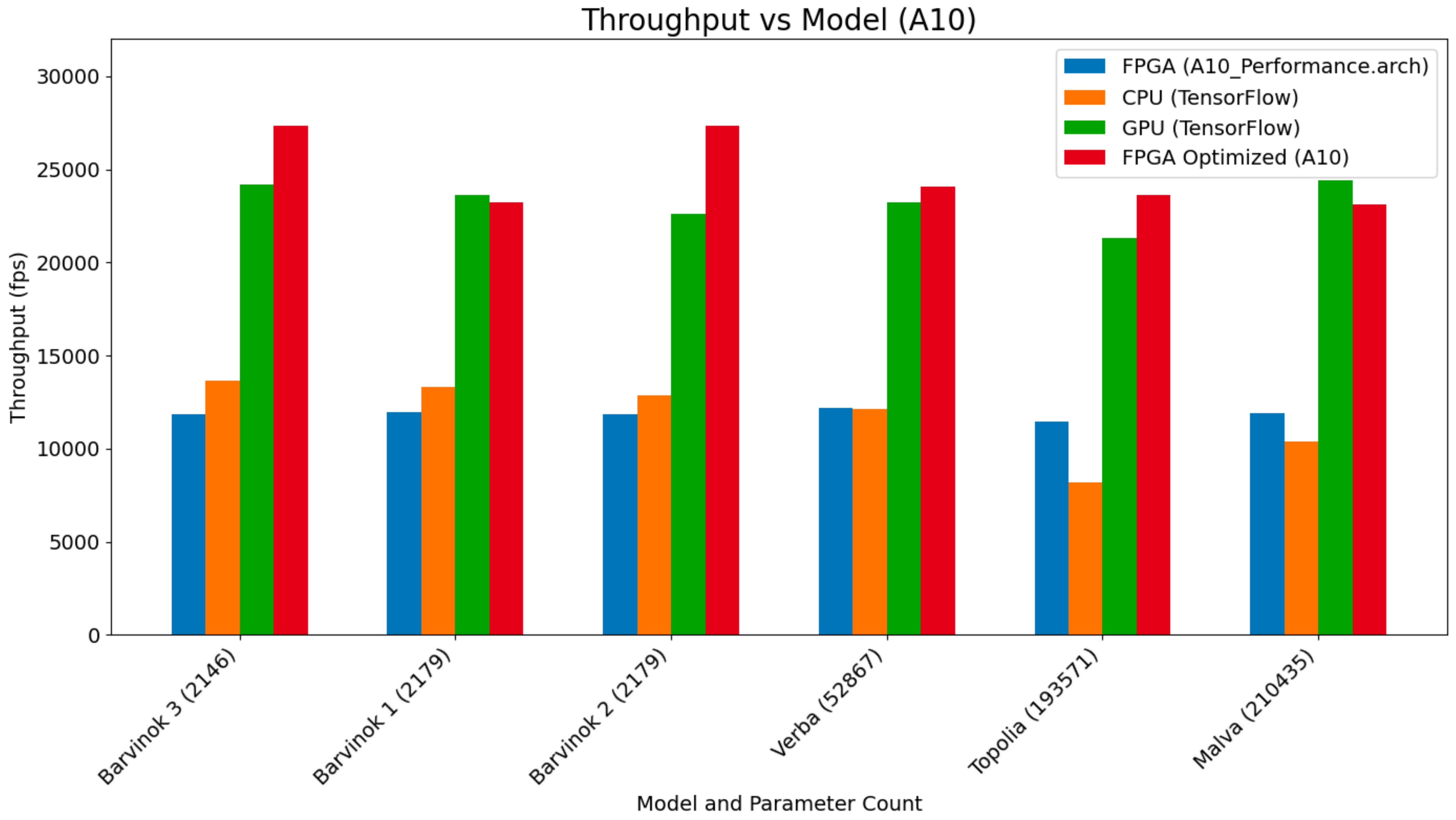


Porting AI algorithms to hardware accelerators



- FPGA:
  - ✦ Comparison of the prediction of throughput with the AI Suite on the Arria10 performance architecture and the result in real operation

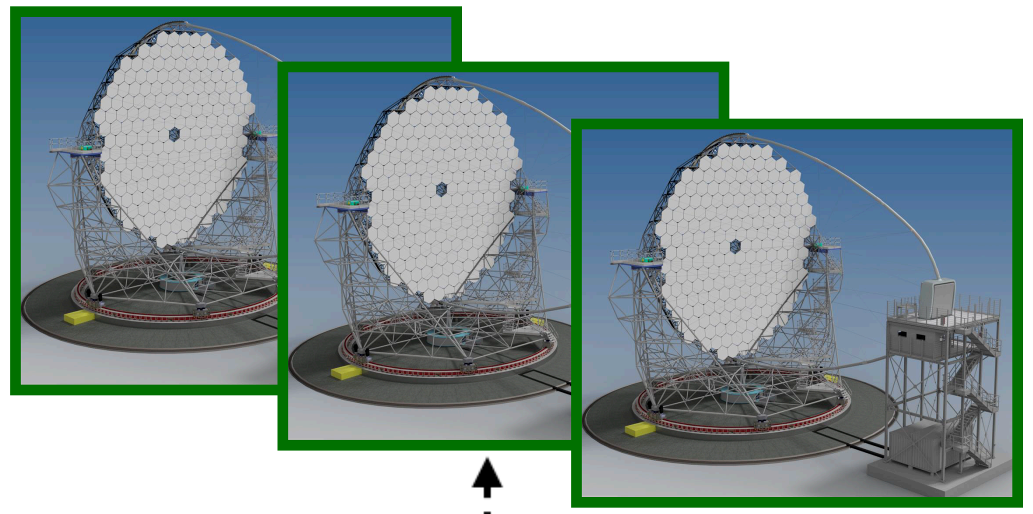
- FPGA:
  - ✦ Prediction of throughput with AI Suite on Arria10 performance architecture + optimised architecture

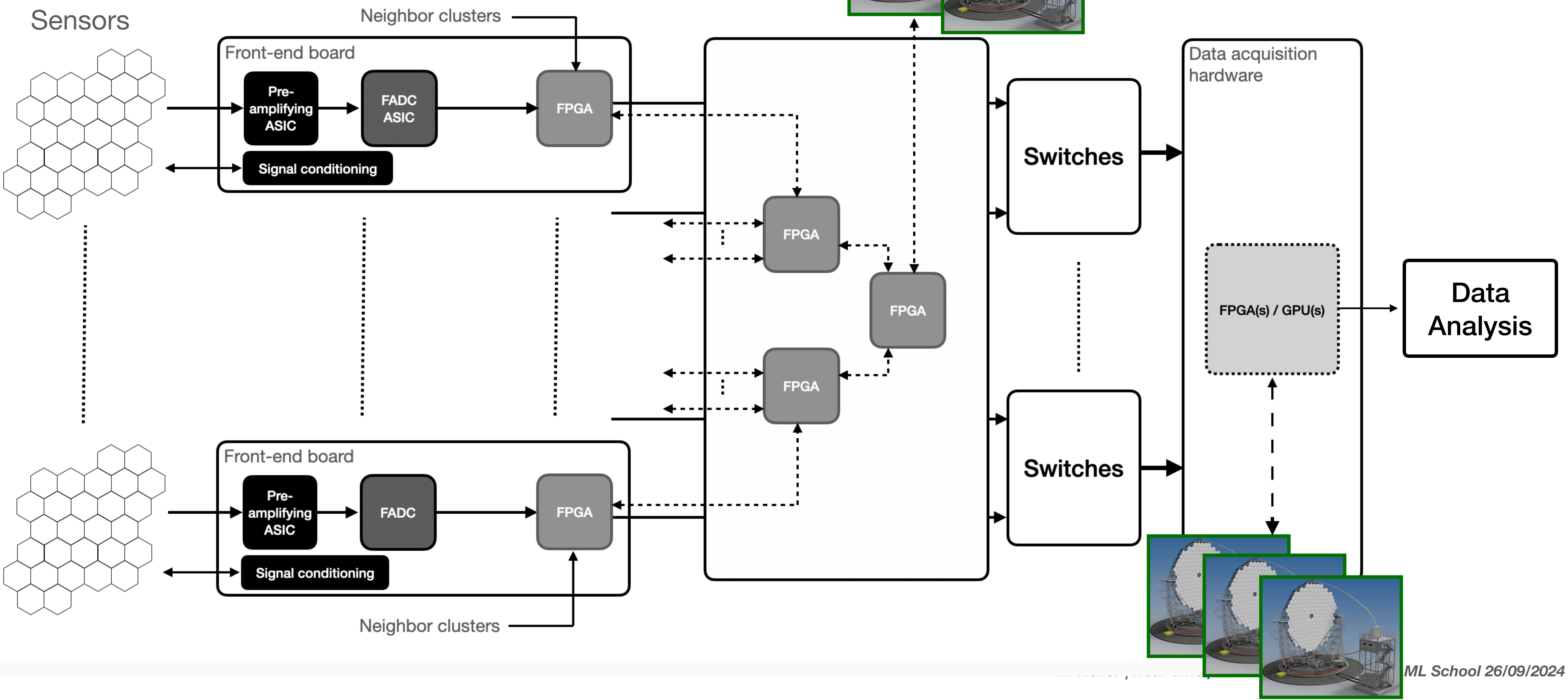


C. Abellan Beteta, I. Bezshyiko (UZH)

Camera readout architecture

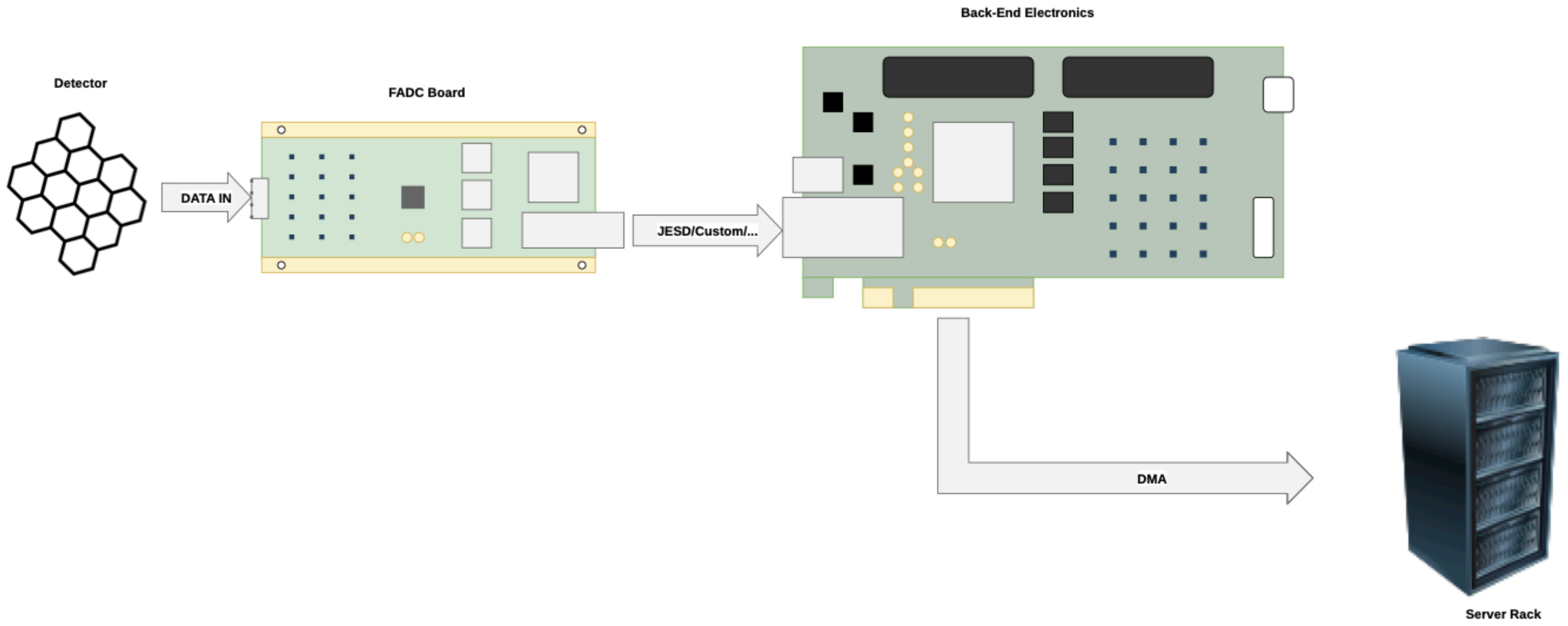
Simplified view - Option B





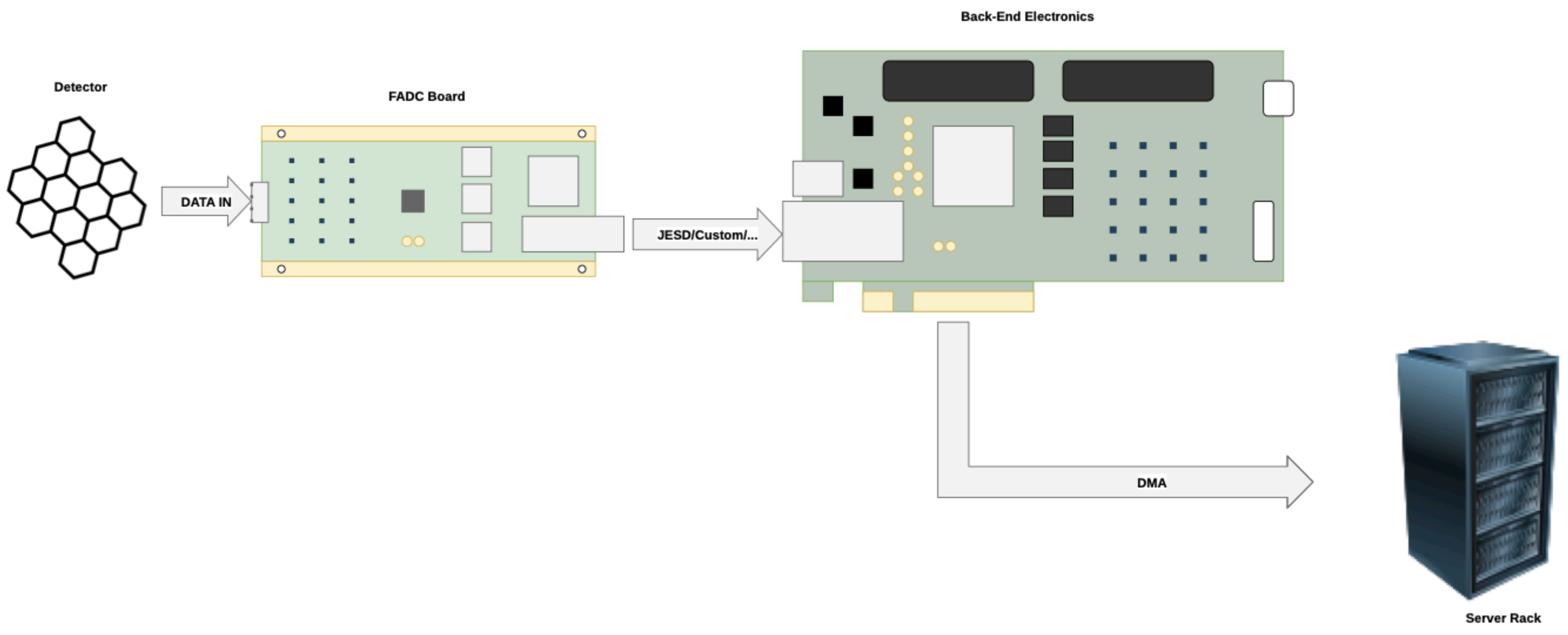
Camera readout architecture

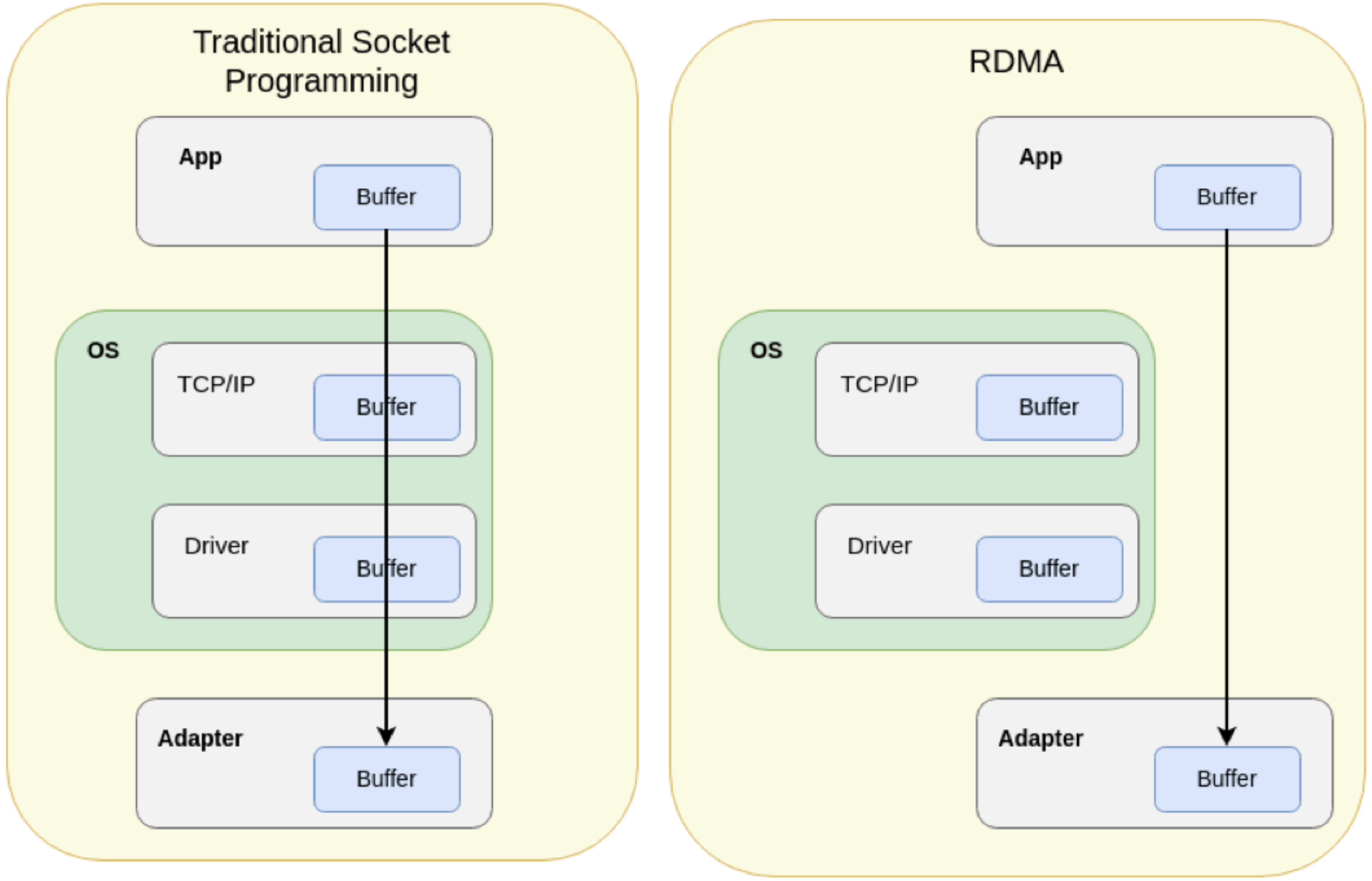
RoCE protocol



Camera readout architecture

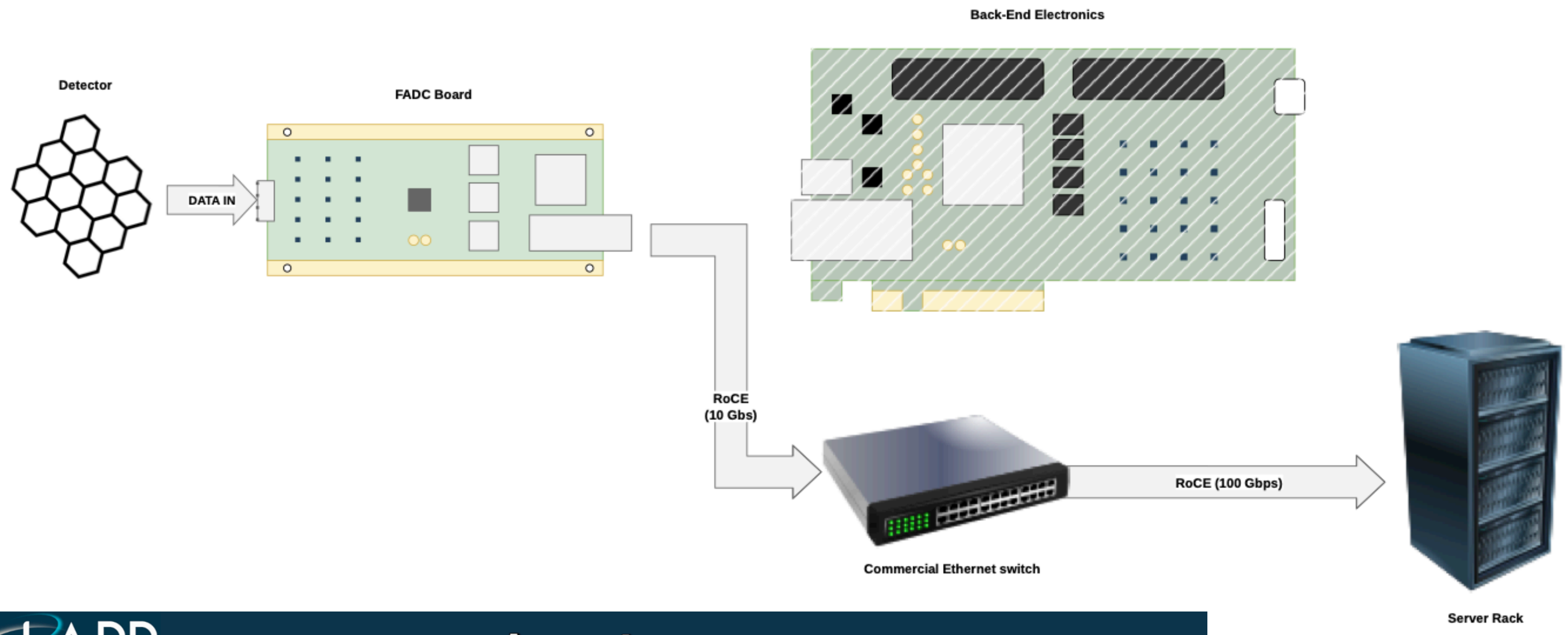
RoCE protocol



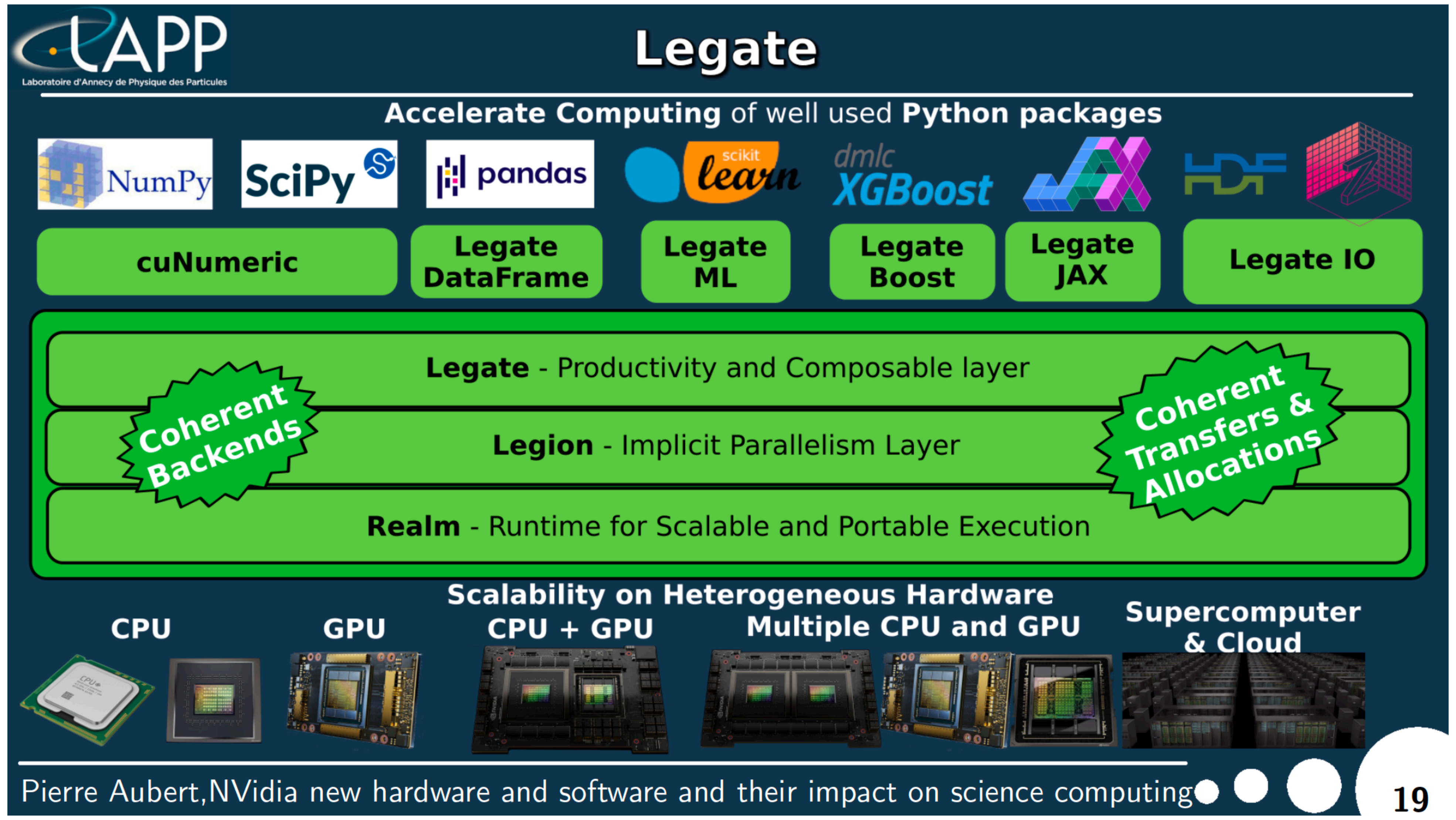


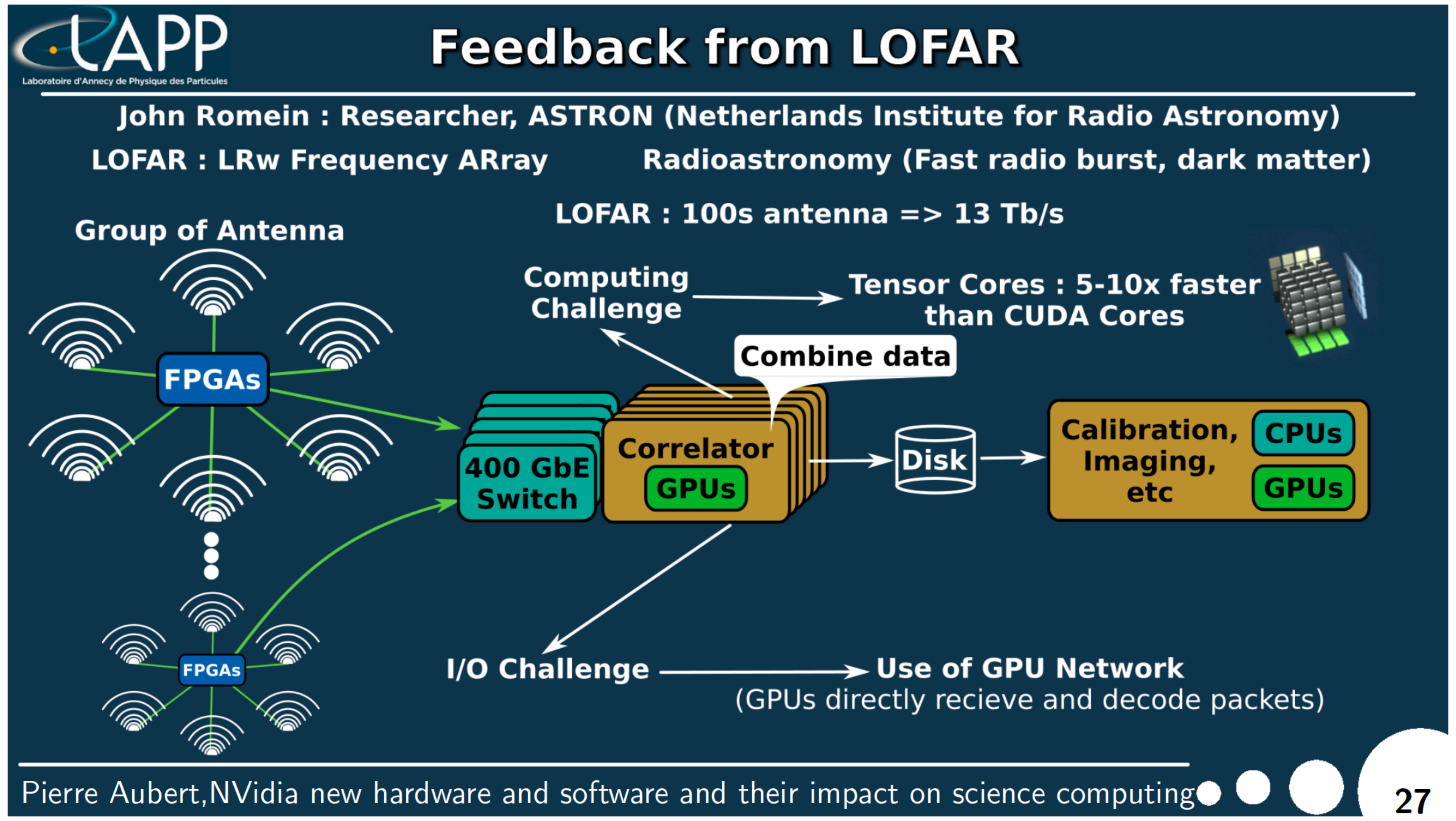
Camera readout architecture

RoCE protocol - Entering the NVidia realm



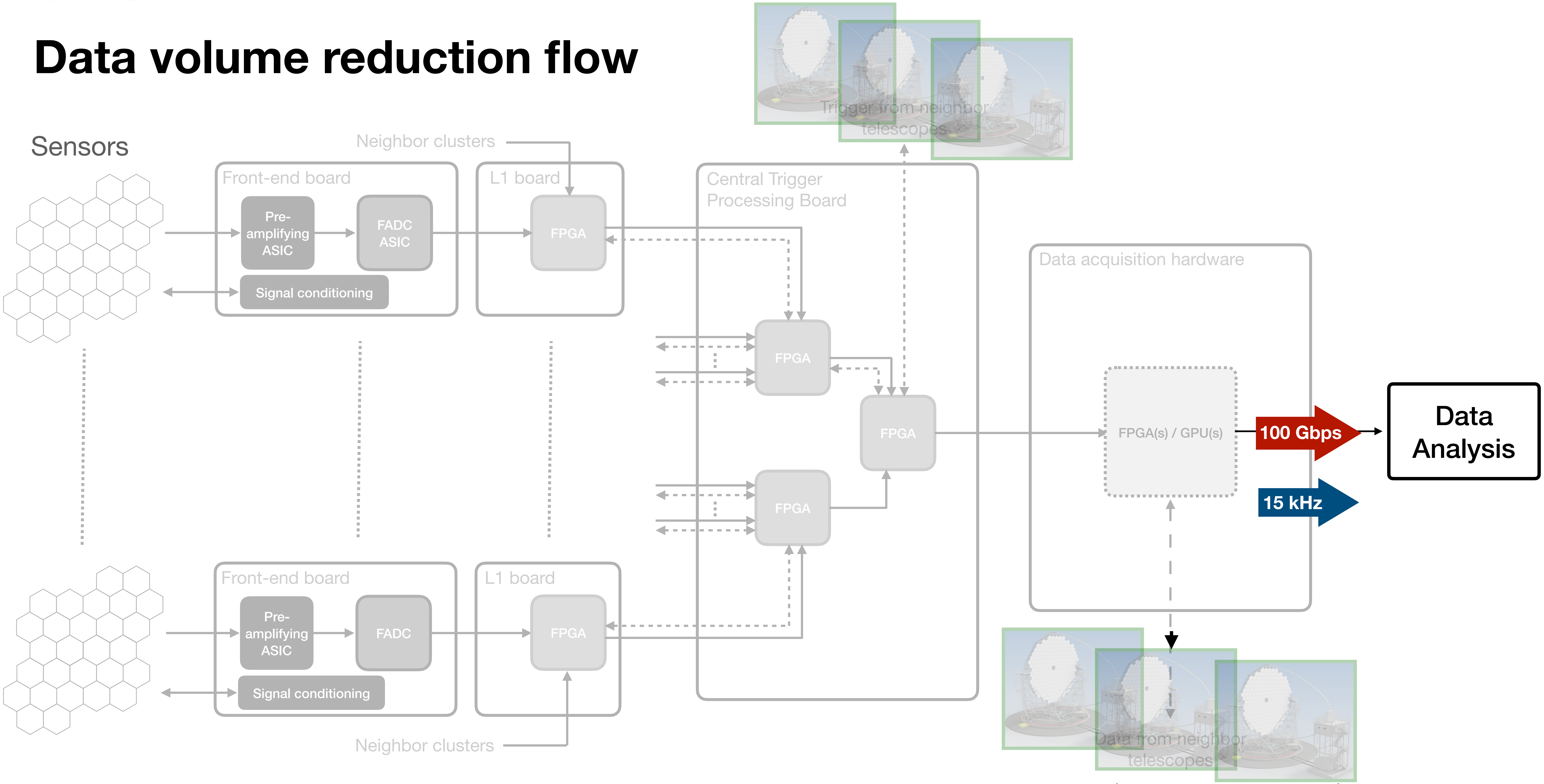
- Most of the processing power is moved to GPU, simpler for porting complex algorithms at the cost of potential performance loss wrt. FPGA





Camera readout architecture

Data volume reduction flow



Real-time analysis

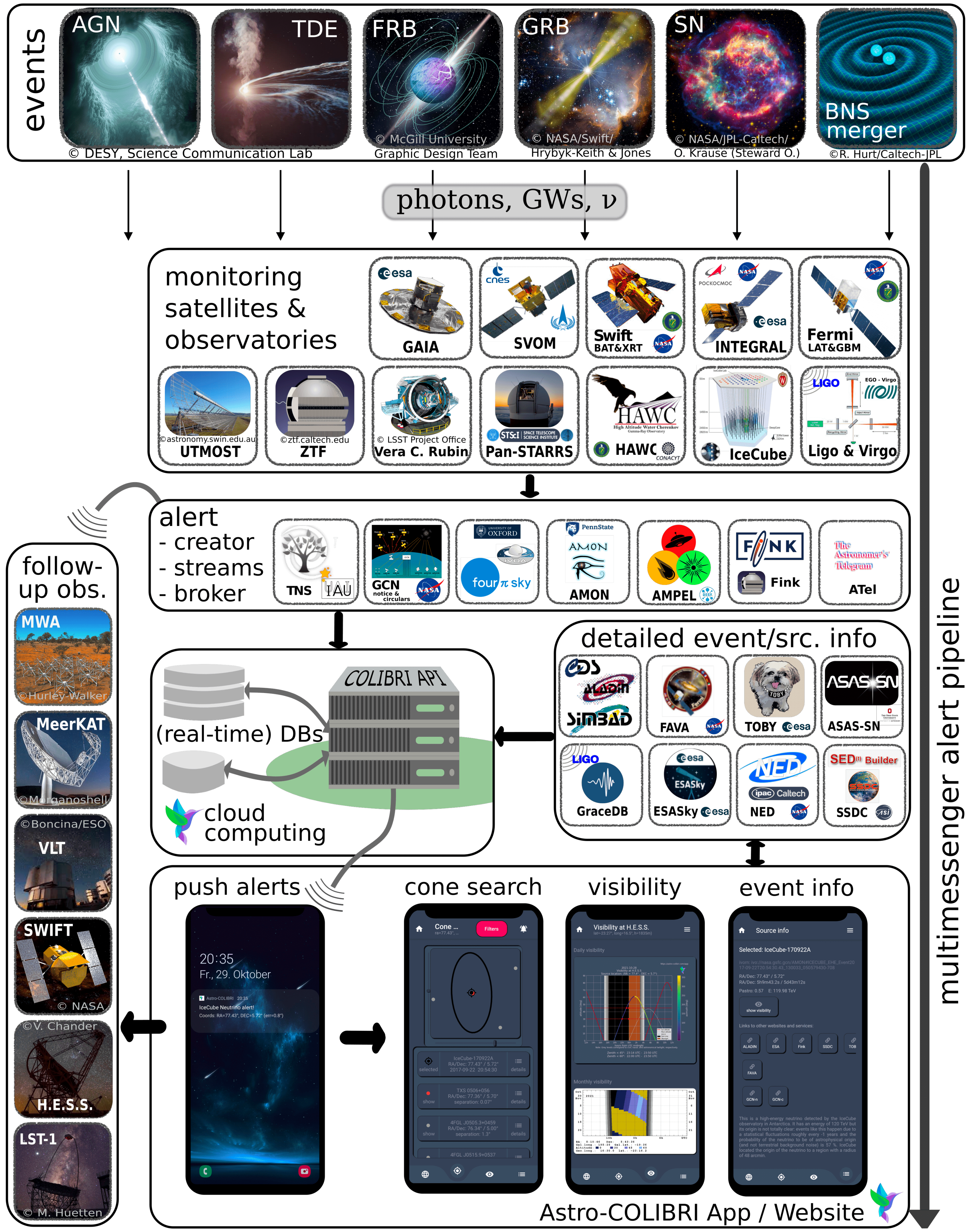
CTAO: one eye among a multisensorial environment

- All-relevant observatories in the world are interconnected via alert systems
  - ✦ LST and to further extent, CTAO must be able to receive and emit alerts
    - ◉ Extremely important for transient phenomenon, e.g. Gamma Ray Burst
  - ✦ Upon reception of a high-priority alert (criteria depends on observatory and moment), observation schedule is altered
    - ◉ Some alerts do not provide precise direction, CTAO might improve there
  - ✦ During survey's or observation, some transient acitivity might be reported by CTAO itself
  - ✦ Some sources may flare while being observed, need to inform other observatory about the increase in activity.

➡ Need of a real-time analysis pipeline

AstroColibri

https://doi.org/10.3390/galaxies11010022



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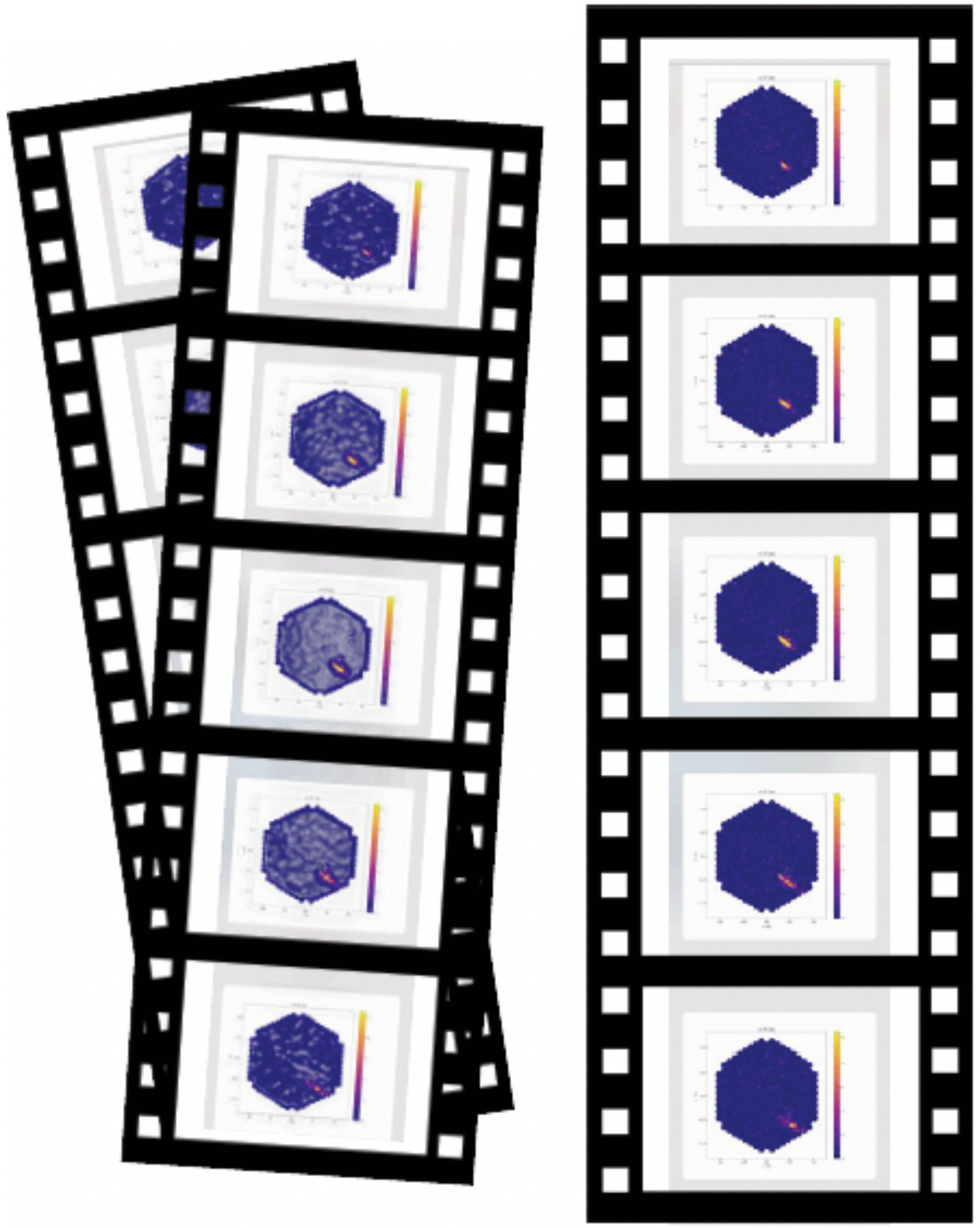
LST Analysis pipeline

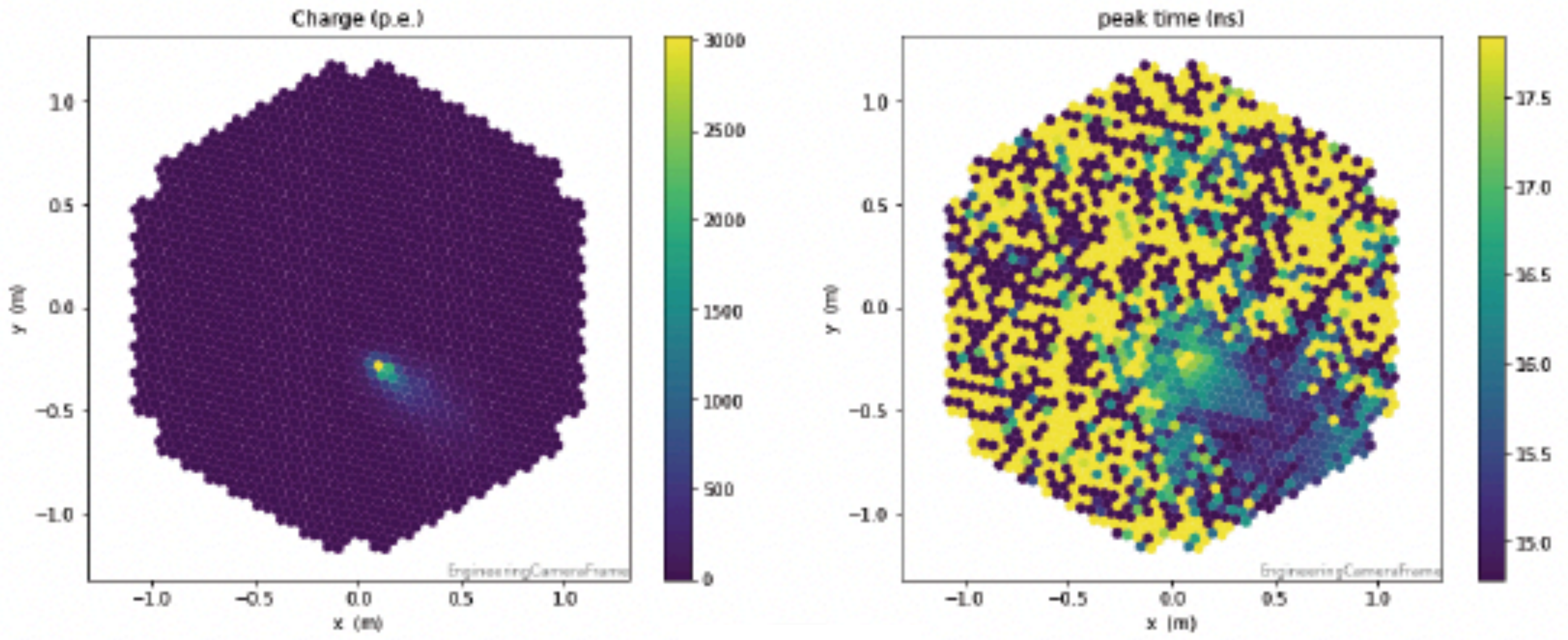
CTAO LST COLLABORATION

Classical approach

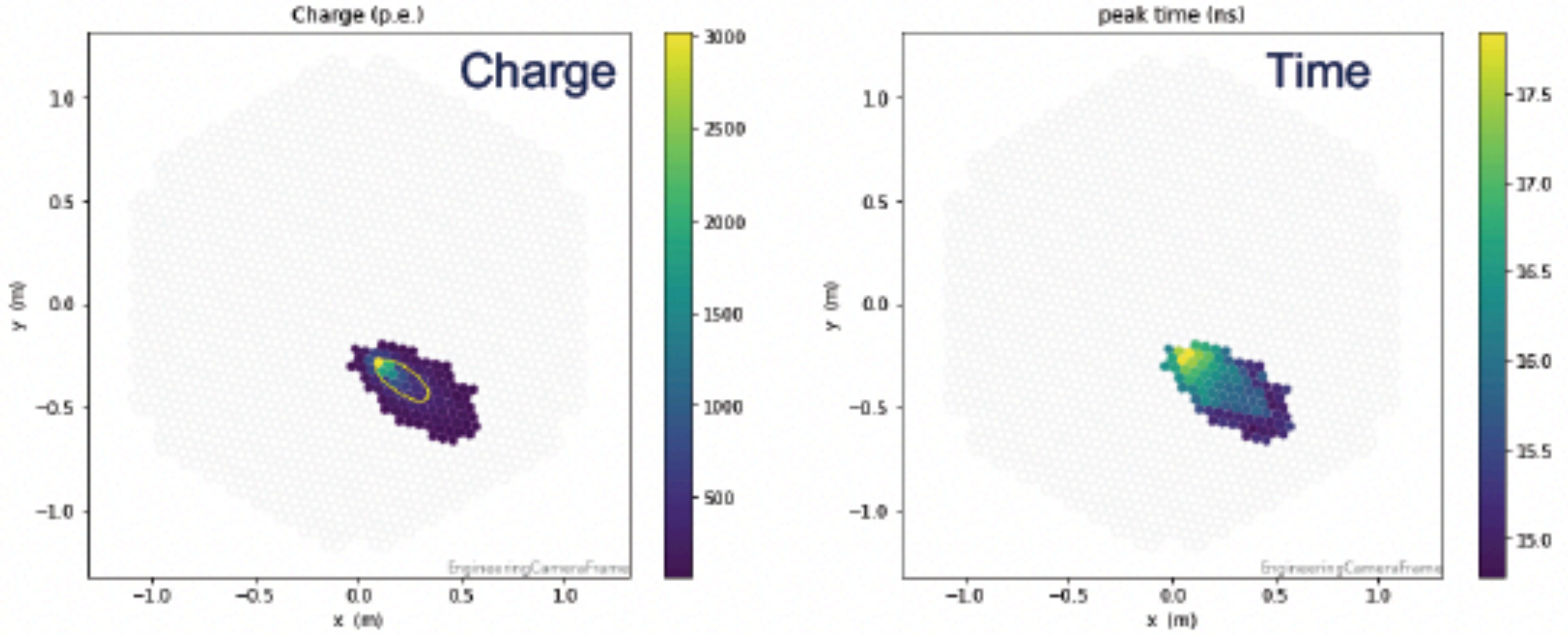
Raw event → Calibrated event →



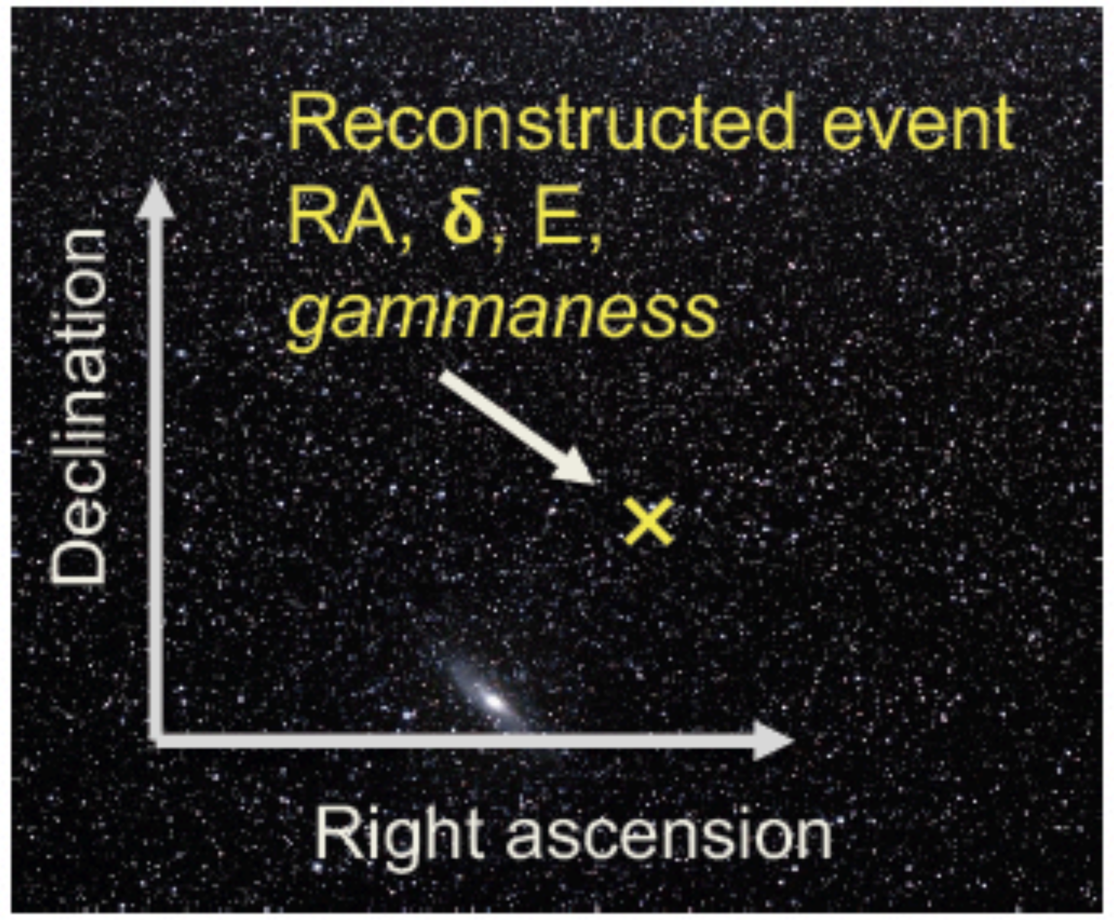
Integrated charge (p.e.)
+
Peak time (ns)



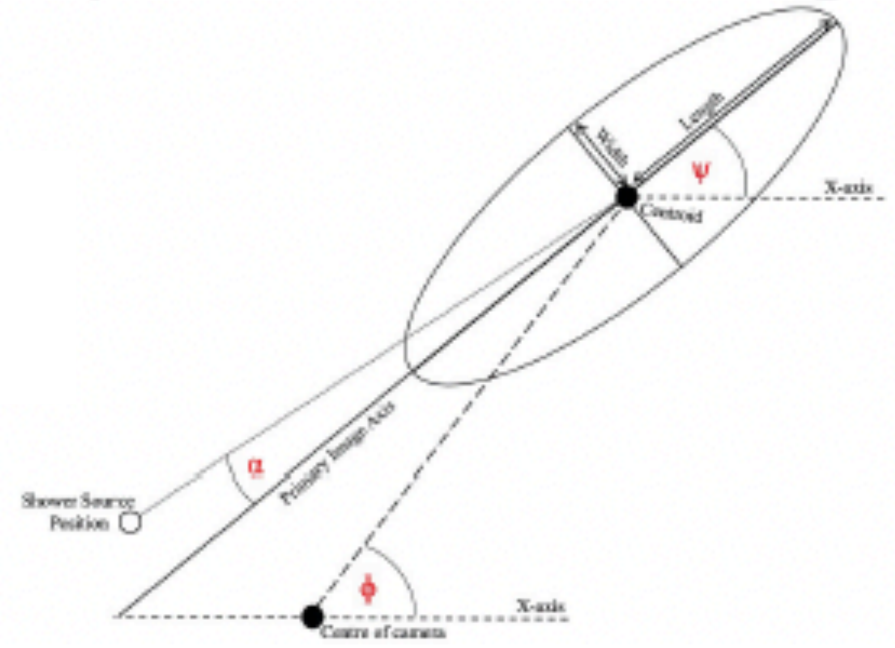
Cleaned image



Regression for direction and energy reconstruction, and γ/h classification performed with dedicated random forests



Parameterised image

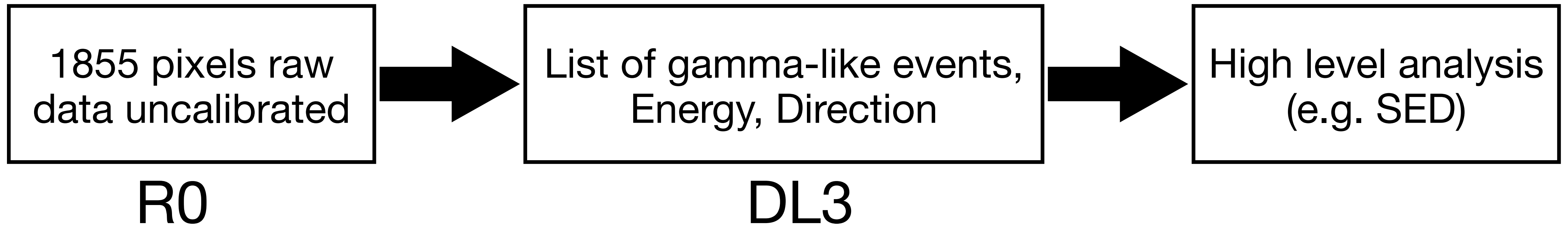


Credit: A. Moralejo, LST Analysis school

Real-time analysis

The Science Alerte Generation system

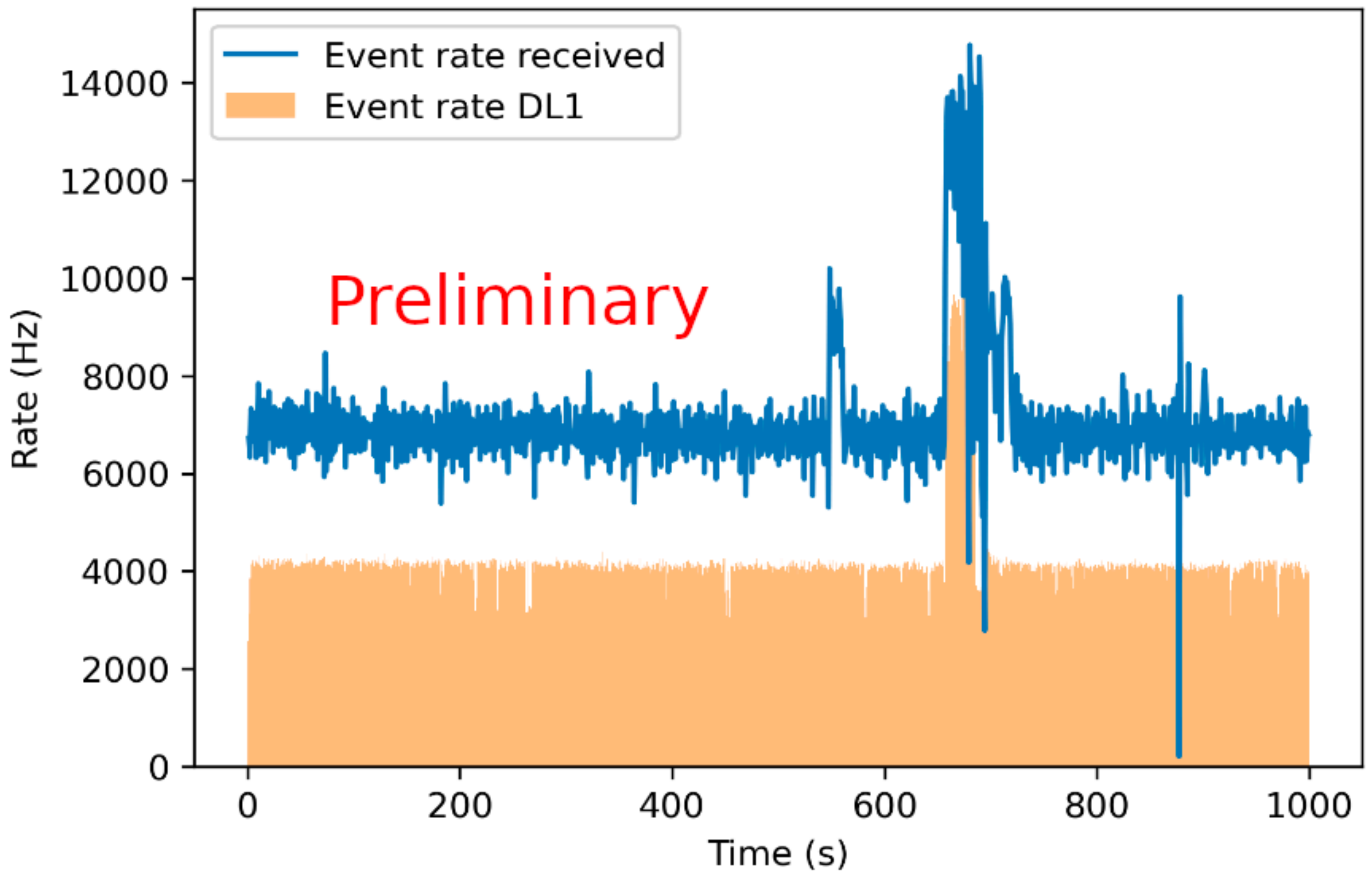
- Aim is to provide real time feedback on the telescope observation (for transient and variable source observations)



- Run optimized version of the off-line analysis software, coded in C++

- In total, 66 seconds are needed to produce a DL3 from 20k R0 events (scales linearly with number of events)
  - ✦ offline analysis 30 ms/event
  - ✦ RTA ~0.5 ms/event

- Configuration:
  - ✦ one new file every 20k events
  - ✦ 4 streams x 1 cores used
  - ✦ rate per core ~ 2000Hz



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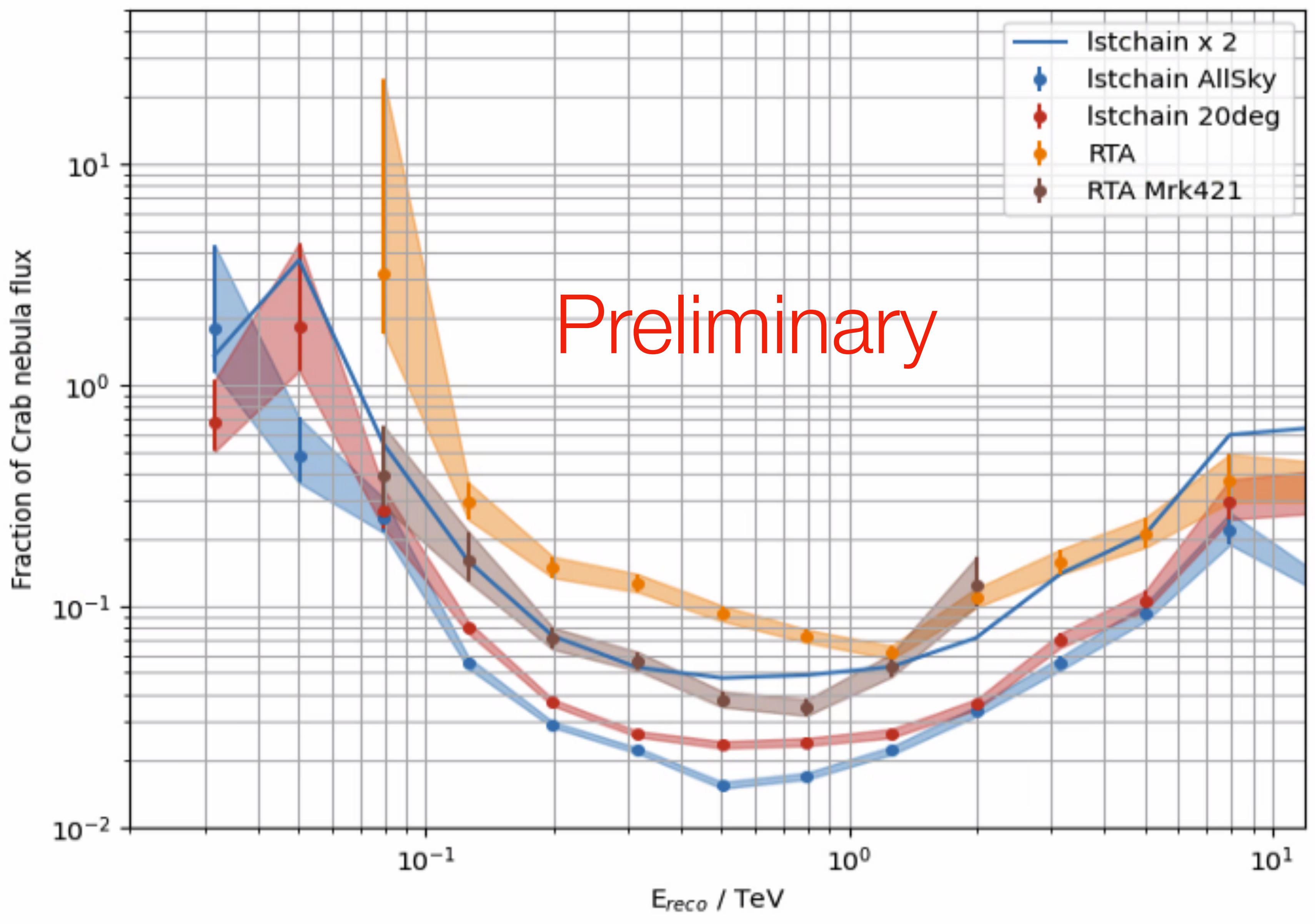
Real-time analysis

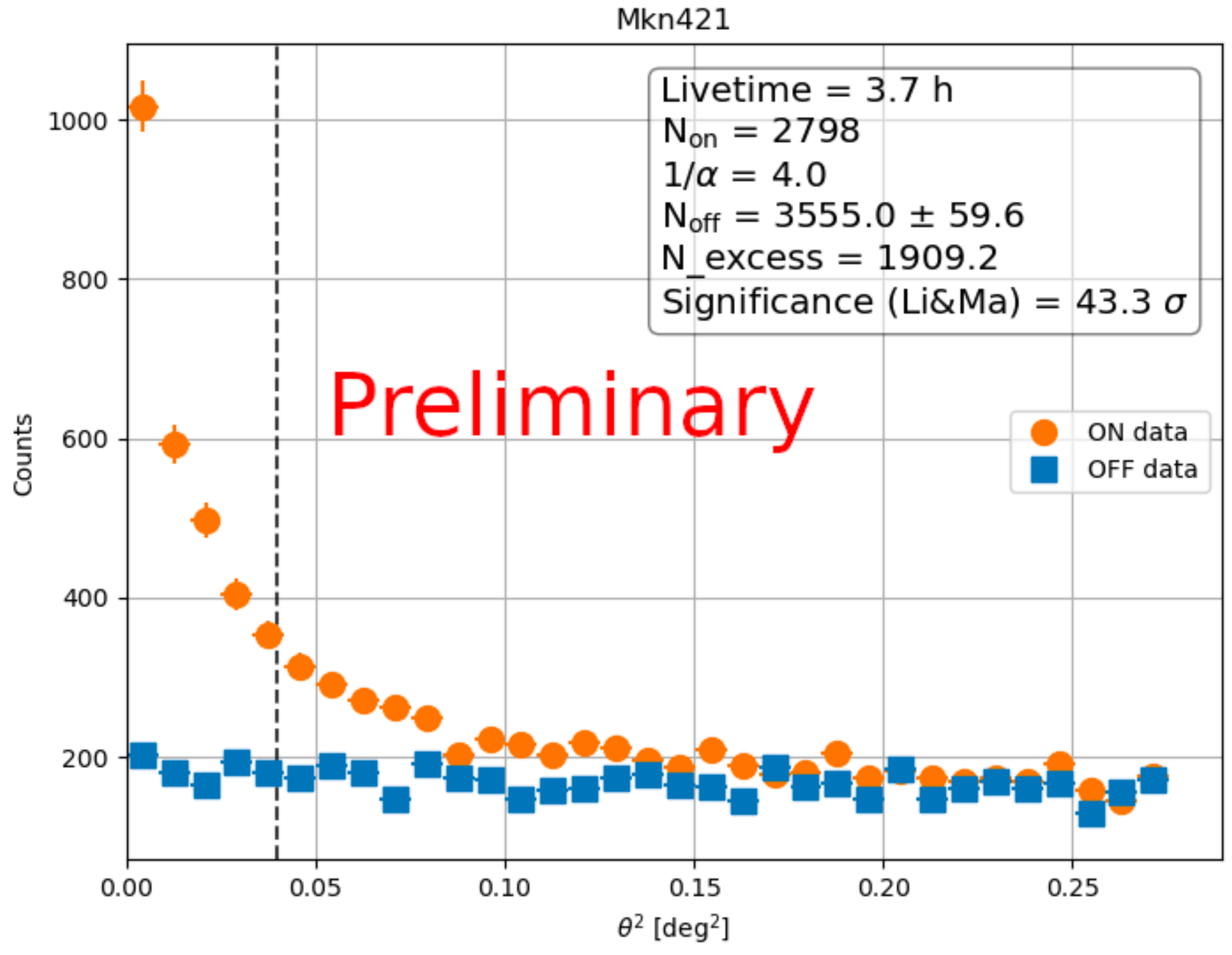
CTAO LST COLLABORATION

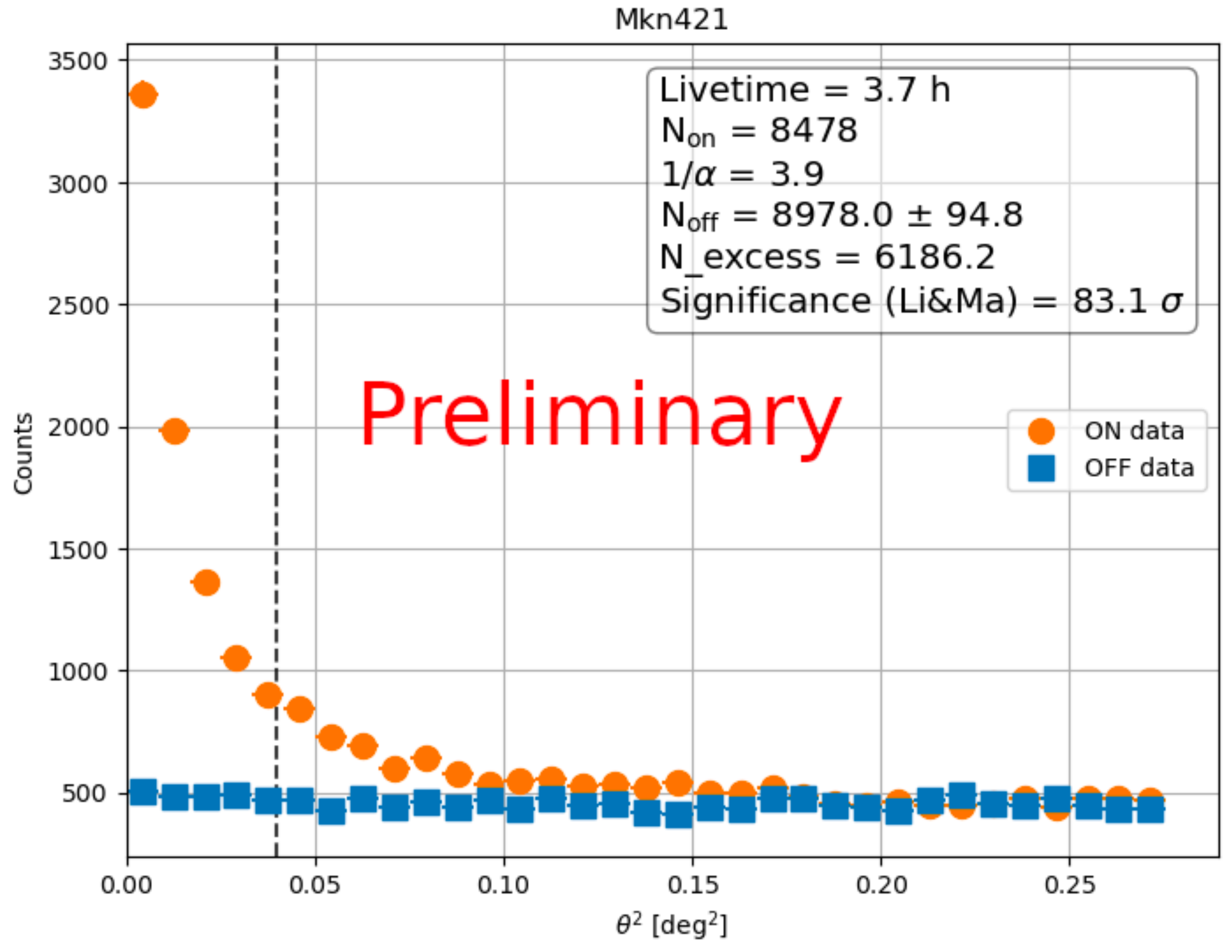
Performance

- Crab field sensitivity ~ lstchain x 4
- Mkn 421 sensitivity ~ lstchain x 2
- RTA results seems highly affected by NSB

- Performance mostly affected by non-optimized image cleaning with respect to classical analysis



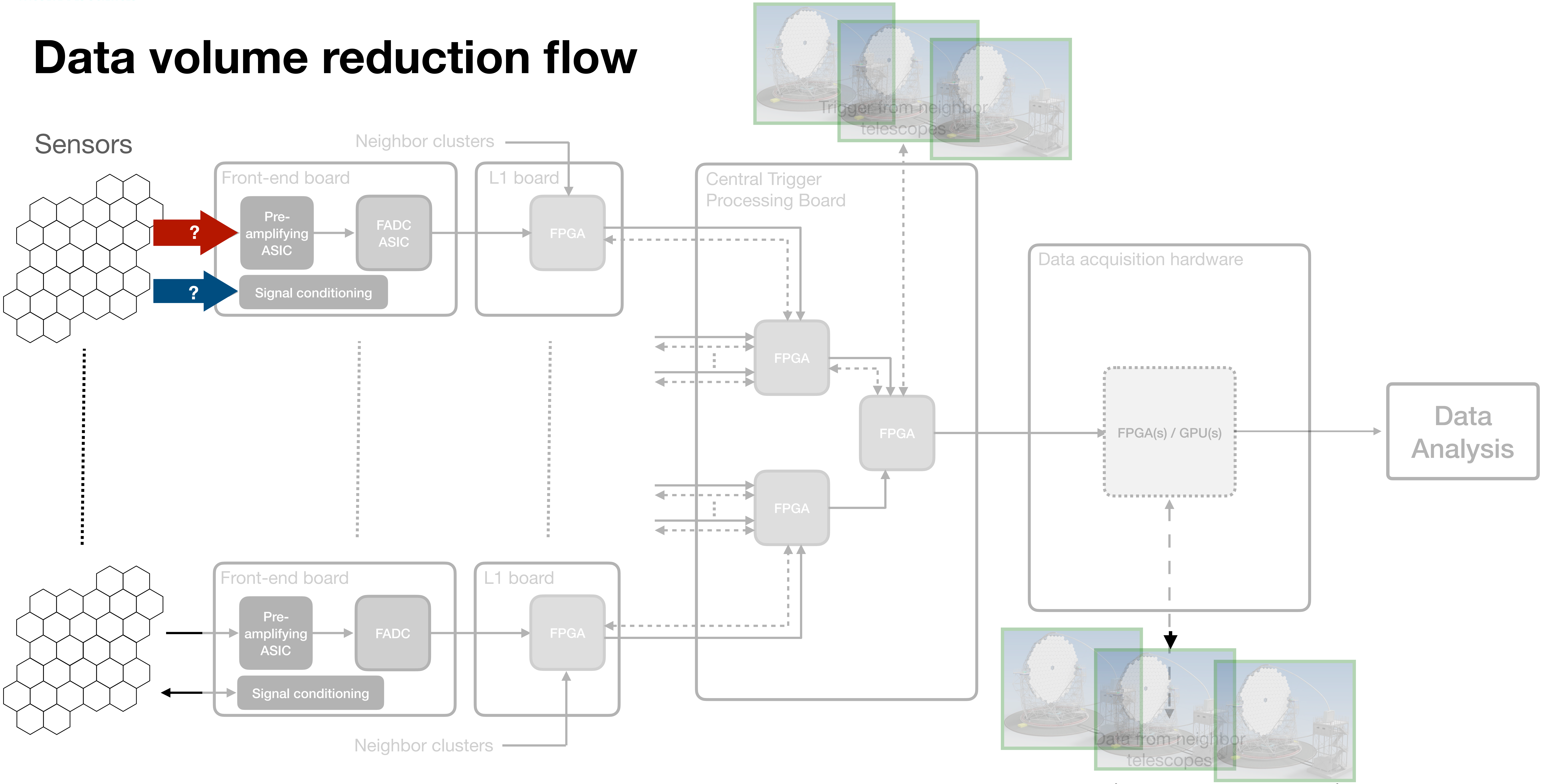




S. Caroff, P. Aubert, V. Pollet, T. Vuillaume (LAPP)

Camera readout architecture

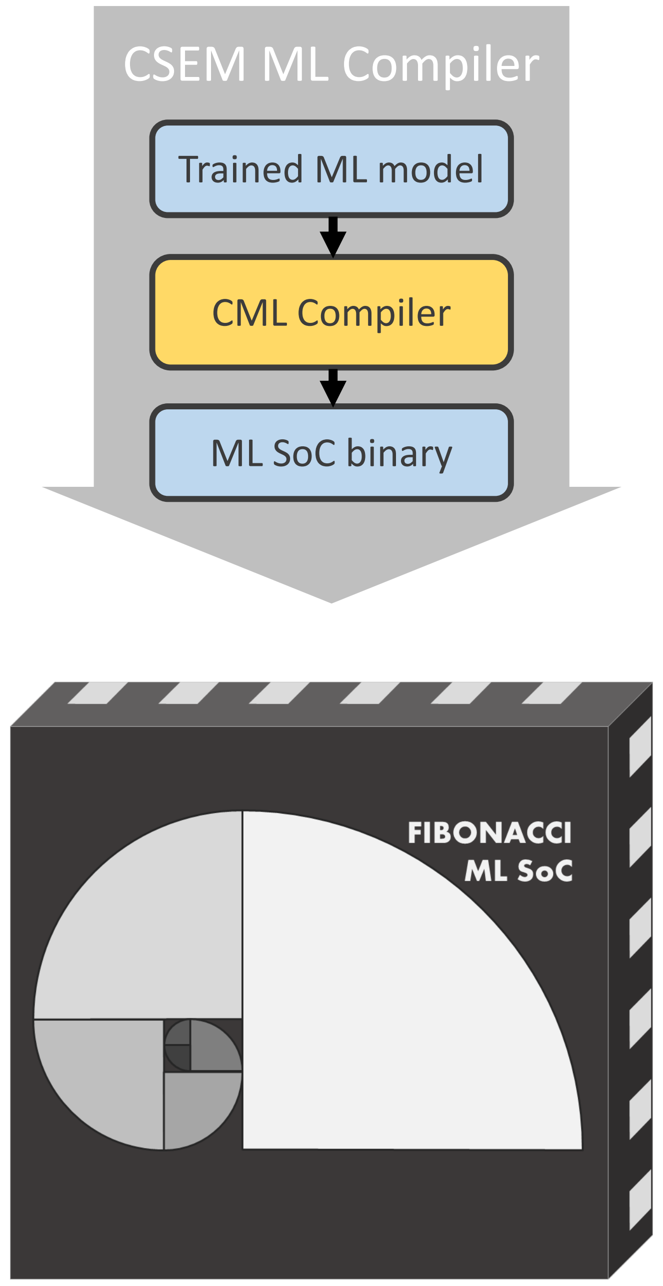
Data volume reduction flow

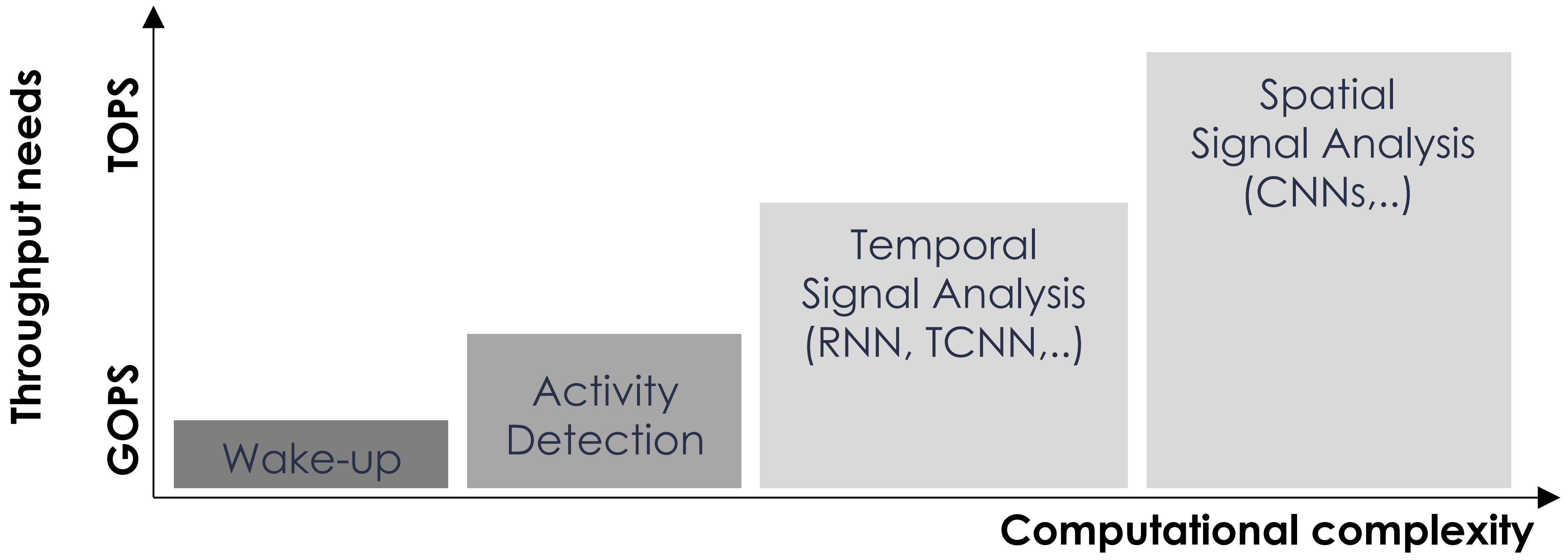


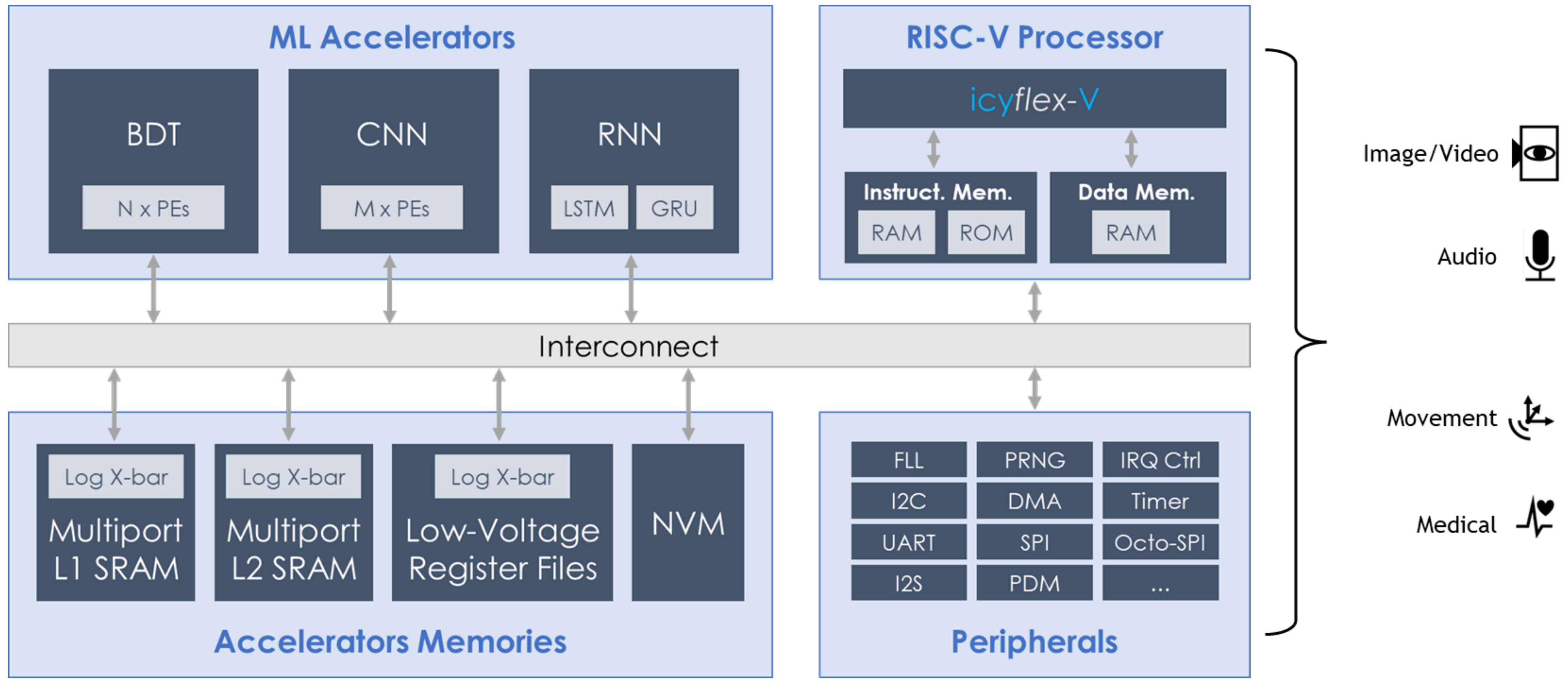
"Smart sensors"

Use of AI ASICs for sensor real-time processing

- Goal: EdgeML accelerator ASIC for targeting real-time waveform analysis
  - Temporal signal analysis (1D CNN, …)
  - (Data reduction, e.g. auto-encoder for denoising)
- CSEM edgeML technology:
  - CSEM Portfolio of different IP blocks to build system-on-chip





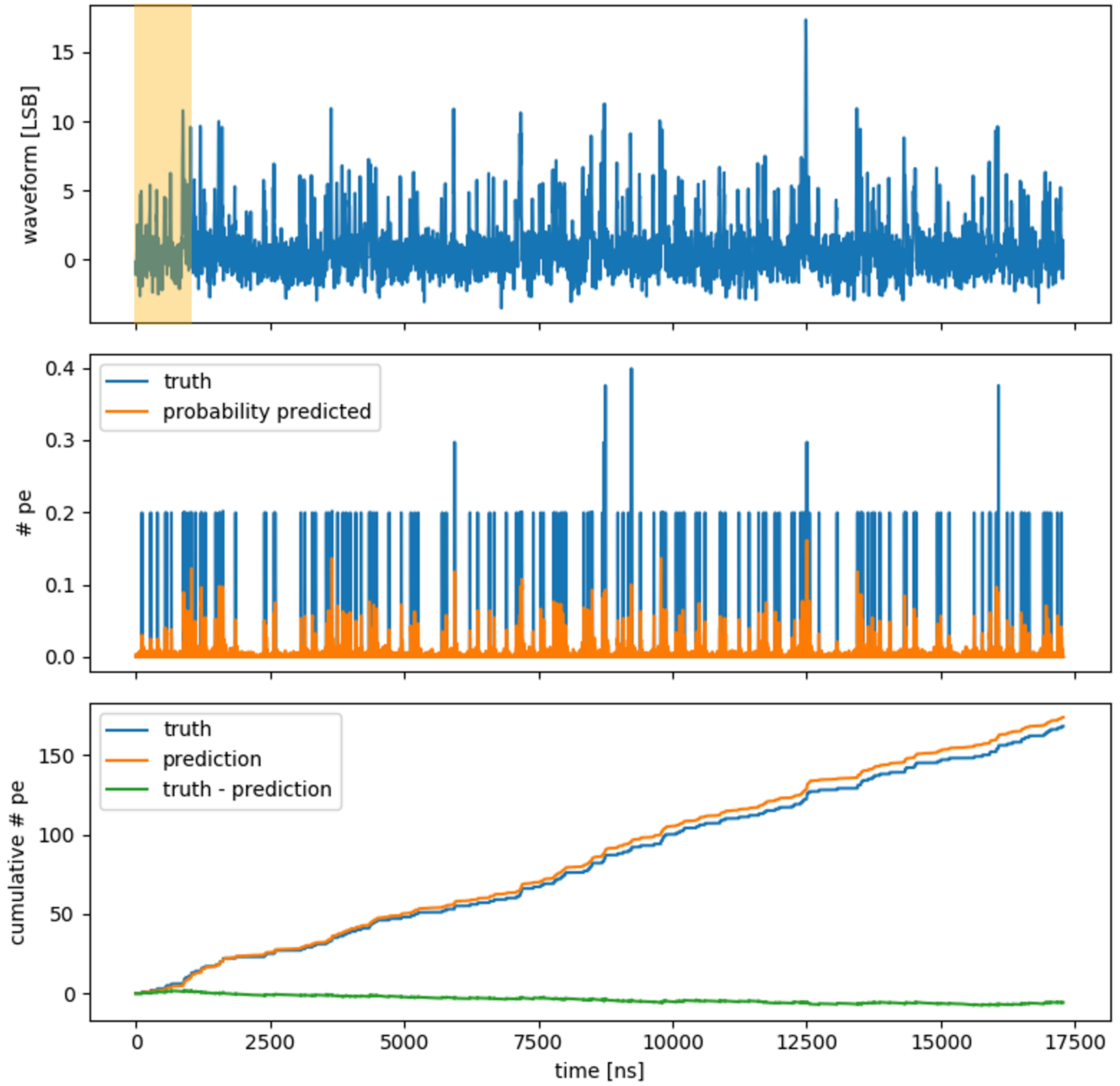


"Smart sensors"

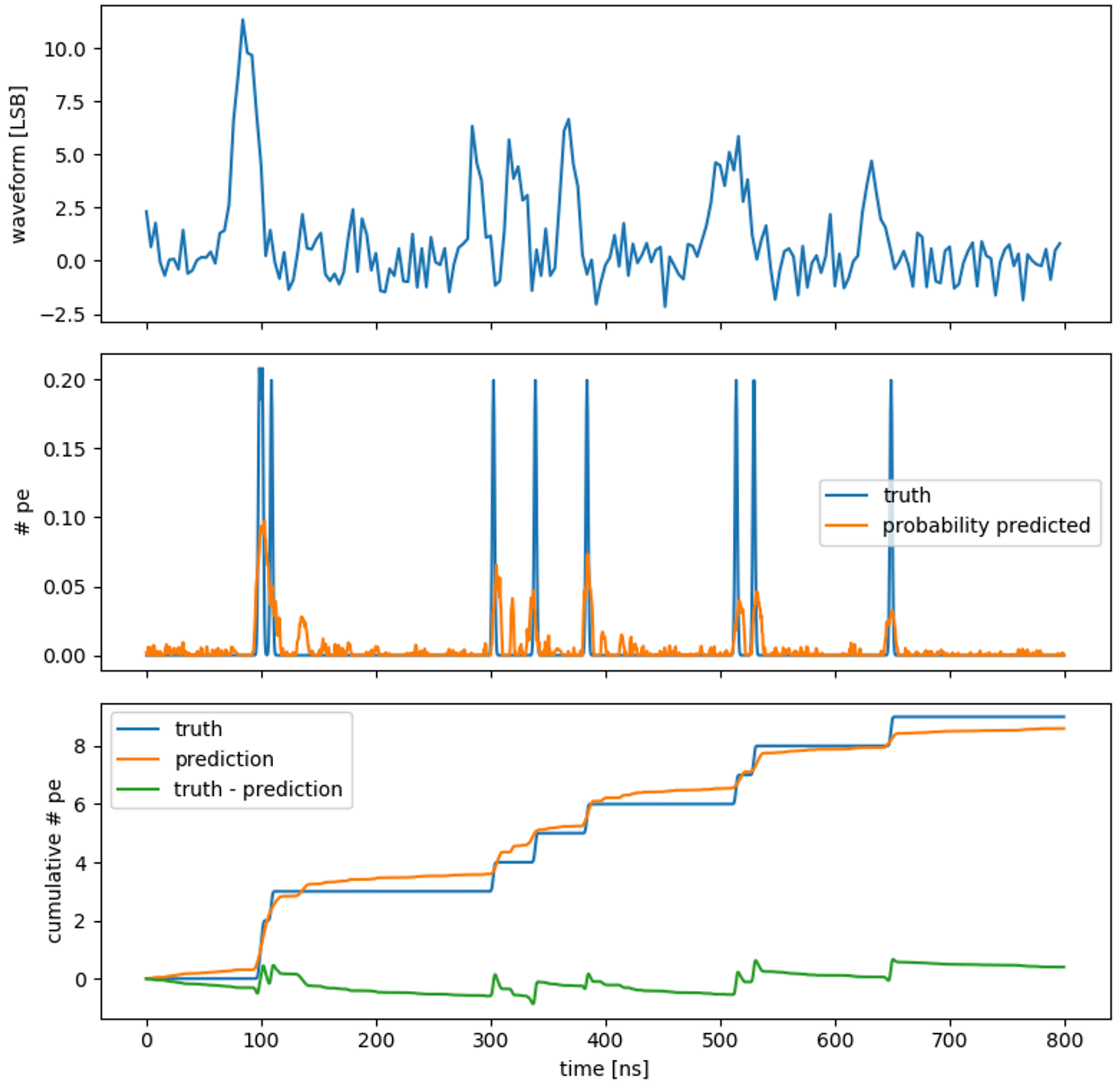
Developing single photo-electron extraction

- Identify single photons out of uncalibrated waveforms
- Output is a quantity of photons per unit of time
- Baseline algorithm already developed for CTA based on 1D CNN ("only" 28k parameters)

10 MHz of random p.e.



Zoomed window

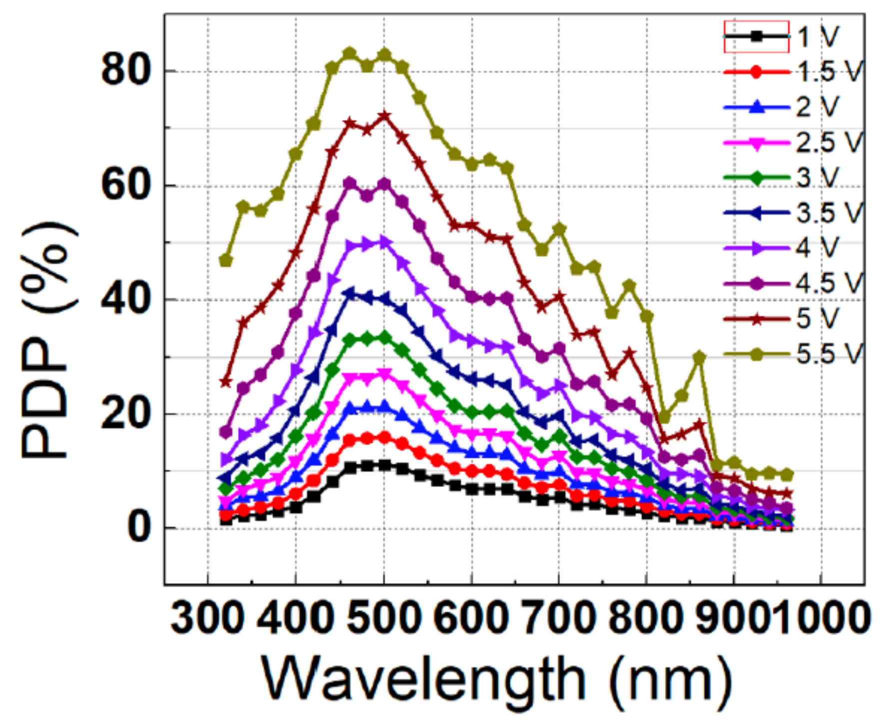


- Study feasibility to run real-time inference
- Risk mitigation scenario
  - ✦ The algorithms runs on pre-selected waveform (after low level trigger implement in FPGA)
- Project updated in collaboration with HEPIA Prof. A. Upegui, Y. Perin

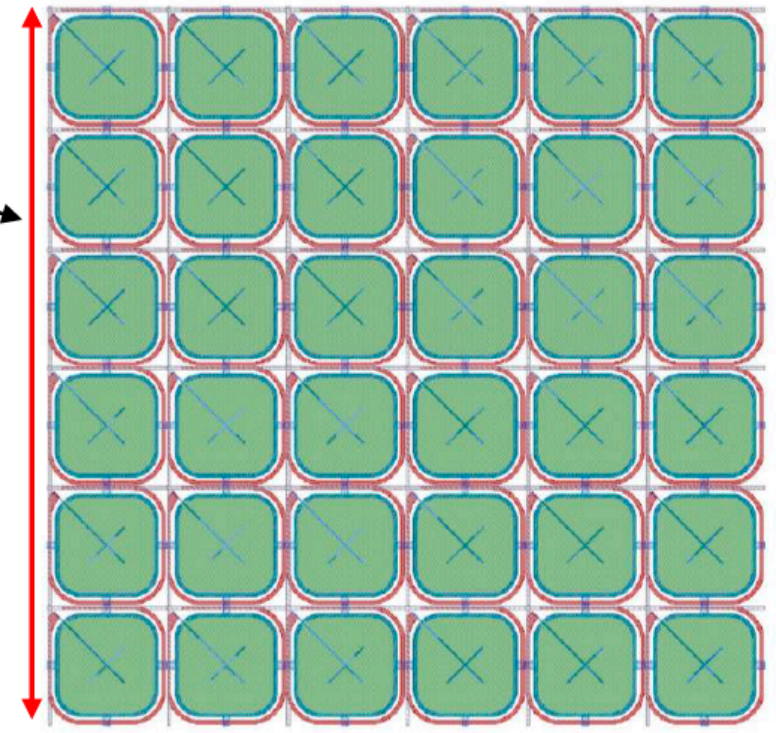
"Smart sensors"

Digital Photon Conter (DiPC)

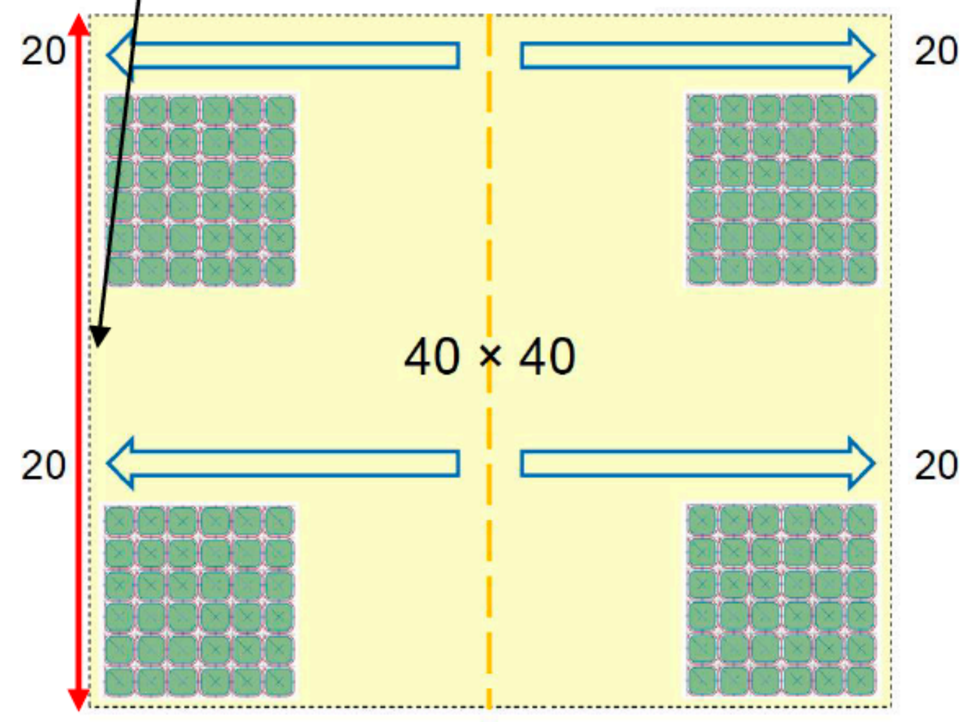
SPAD
- aqua SPAD #31
- PDP = [10, 35]% @ [320, 500]nm @ 3.3V excess bias



CHANNEL
- 6 × 6 Quad SPAD
- Side = 216 μm
- Fill factor **FF** = 47 %
- **PDE**
  = FF × PDP
  = 5 ÷ 16 %

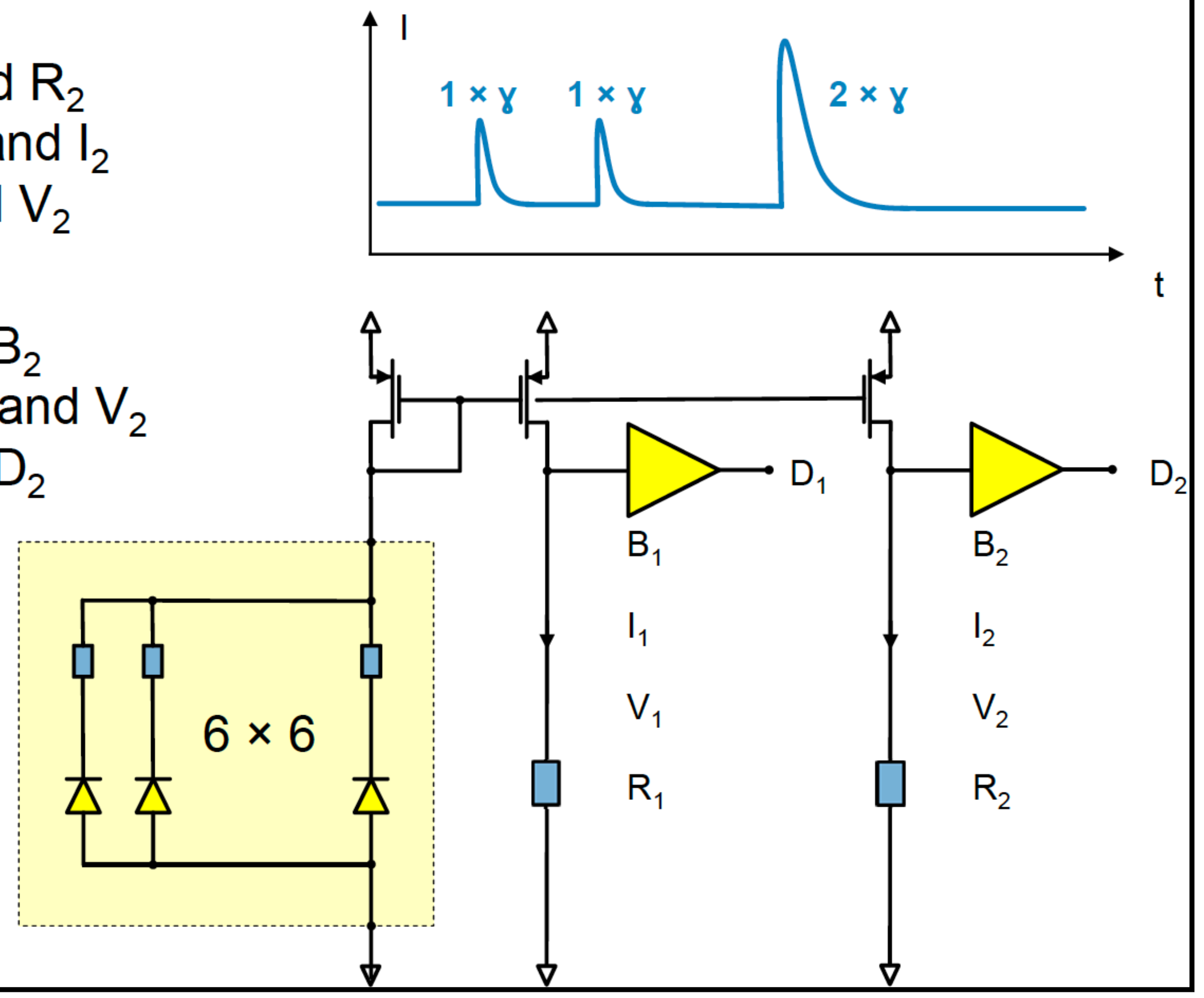


PIXEL
- 40 × 40 = 1'600 channels
- Side = 8,64 mm
- Total area = 74,65 mm²



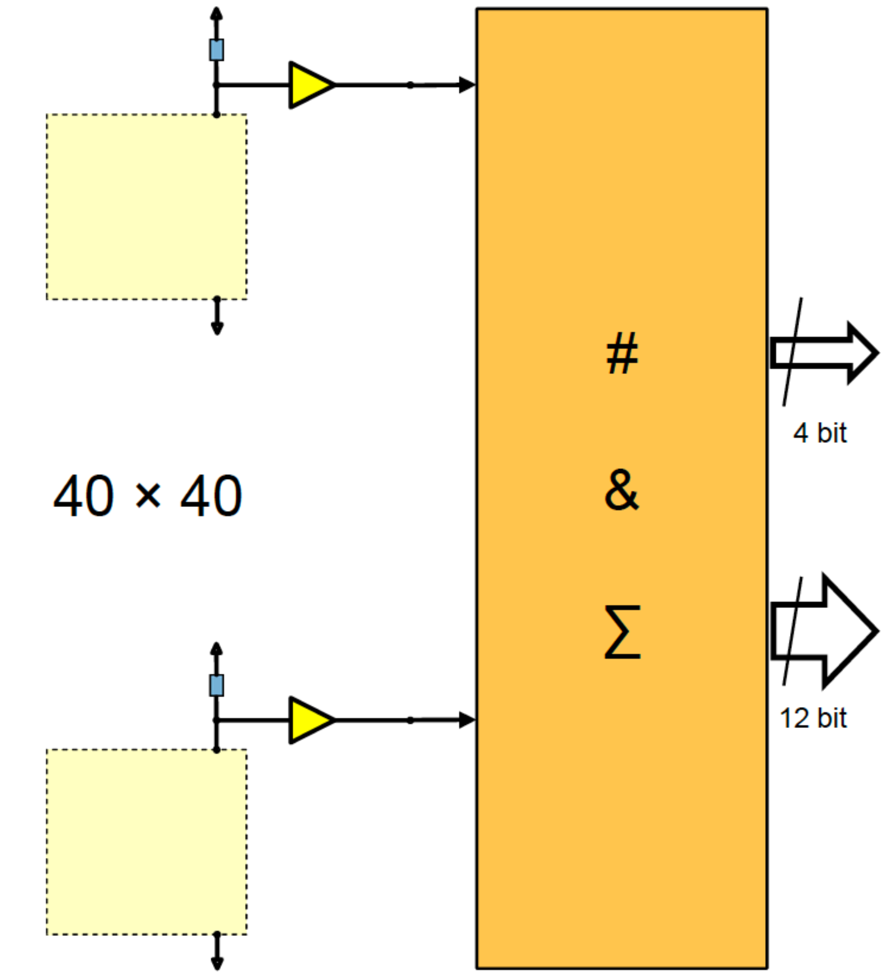
Comparator

- The resistors R_1 and R_2 convert currents I_1 and I_2 into voltages V_1 and V_2
- The buffers B_1 and B_2 digitize voltages V_1 and V_2 into signals D_1 and D_2



Architecture

- The comparator outputs are counted (#) and summed (∑)
- A binary tree adder implements the summing
- A 4 bit bus outputs the result every 4 ns (L0 trigger)
- A 12 bit bus outputs the result on demand (L1 trigger)



E.Bernasconi, E. Charbon (EPFL), A. Biland (ETHZ)

Conclusions and Perspectives

- Gamma-ray astronomy already relies on real-time processing due the to nature of observations
  - ✦ Constantly looking at the sky, awaiting for (non-bunched) Cherenkov flashes
  - ✦ Variable observing conditions

- Sensitivity of instruments are improving, but major steps in gamma-ray astronomy in the future will also heavily rely on real-time processing:
  - ✦ FADC cost and power consumption going down, cameras will unevitably move to fully digital readout opening new opportunities:
    - Sensor signal treatment
    - More sofisticated low level trigger algorithm to fight against the NSB wall
    - Robust and efficient high level trigger to to particle classification
    - Fast and performing real-time analysis pipelines for better reaction to alert or emission

- Stay tuned, more telescopes are coming and CTAO will soon deliver science as an array!

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Thanks for your attention !

CTAO | LST COLLABORATION