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The AdvCam
Designing the future Imaging Atmospheric Cherenkov Telescope Cameras

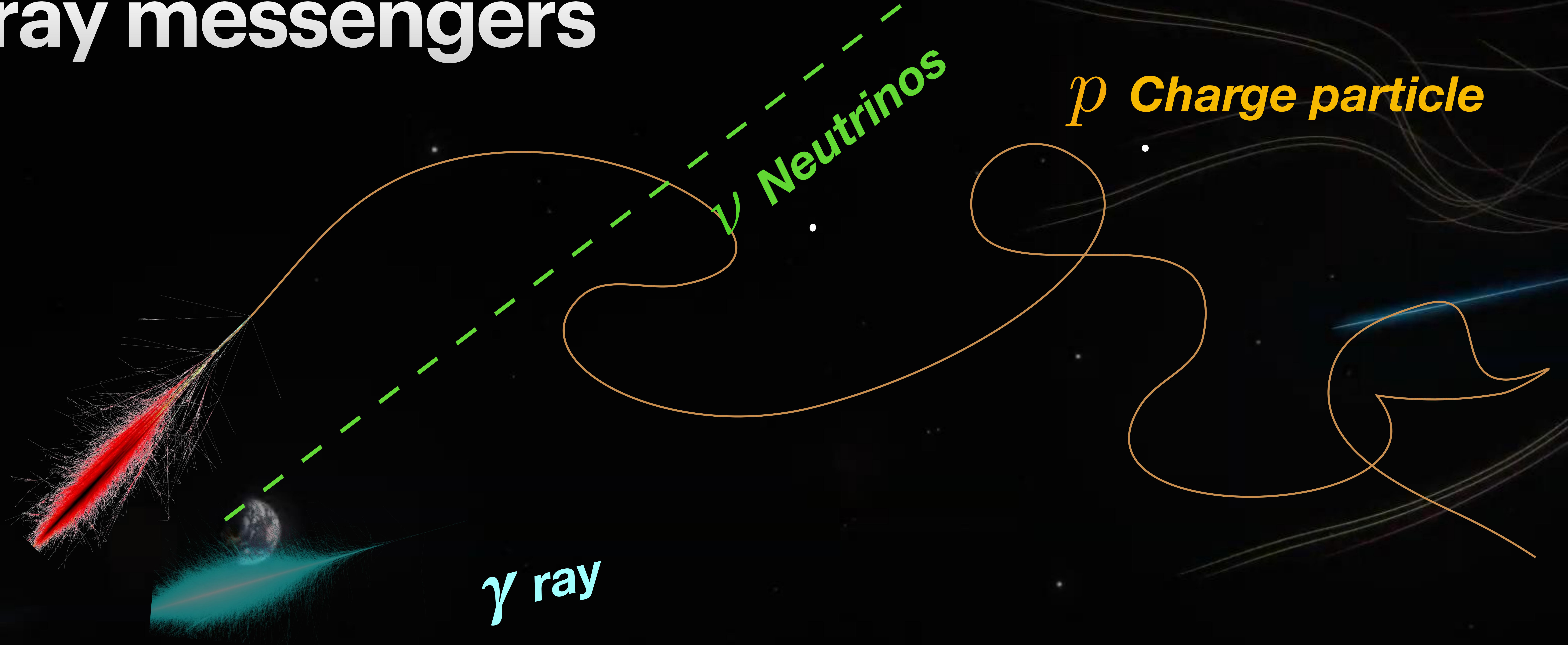
M. Heller, Université de Genève 19/02/2025
Séminaire DPNC, Semestre Printemps 2025

Credit: Otger Ballester (IFAE)

Cosmic ray messengers

Credit: CTAO/D. Della volpe

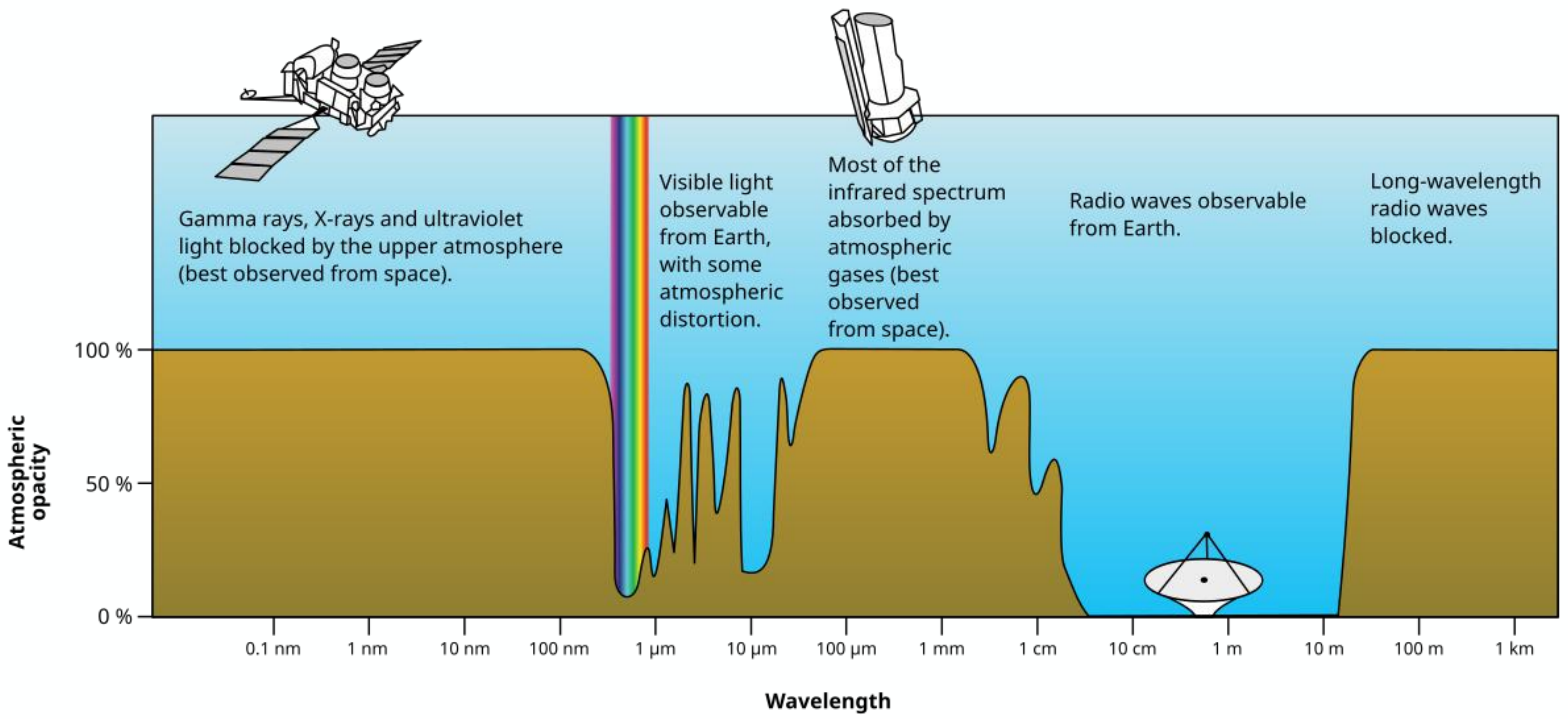
Cosmic ray messengers

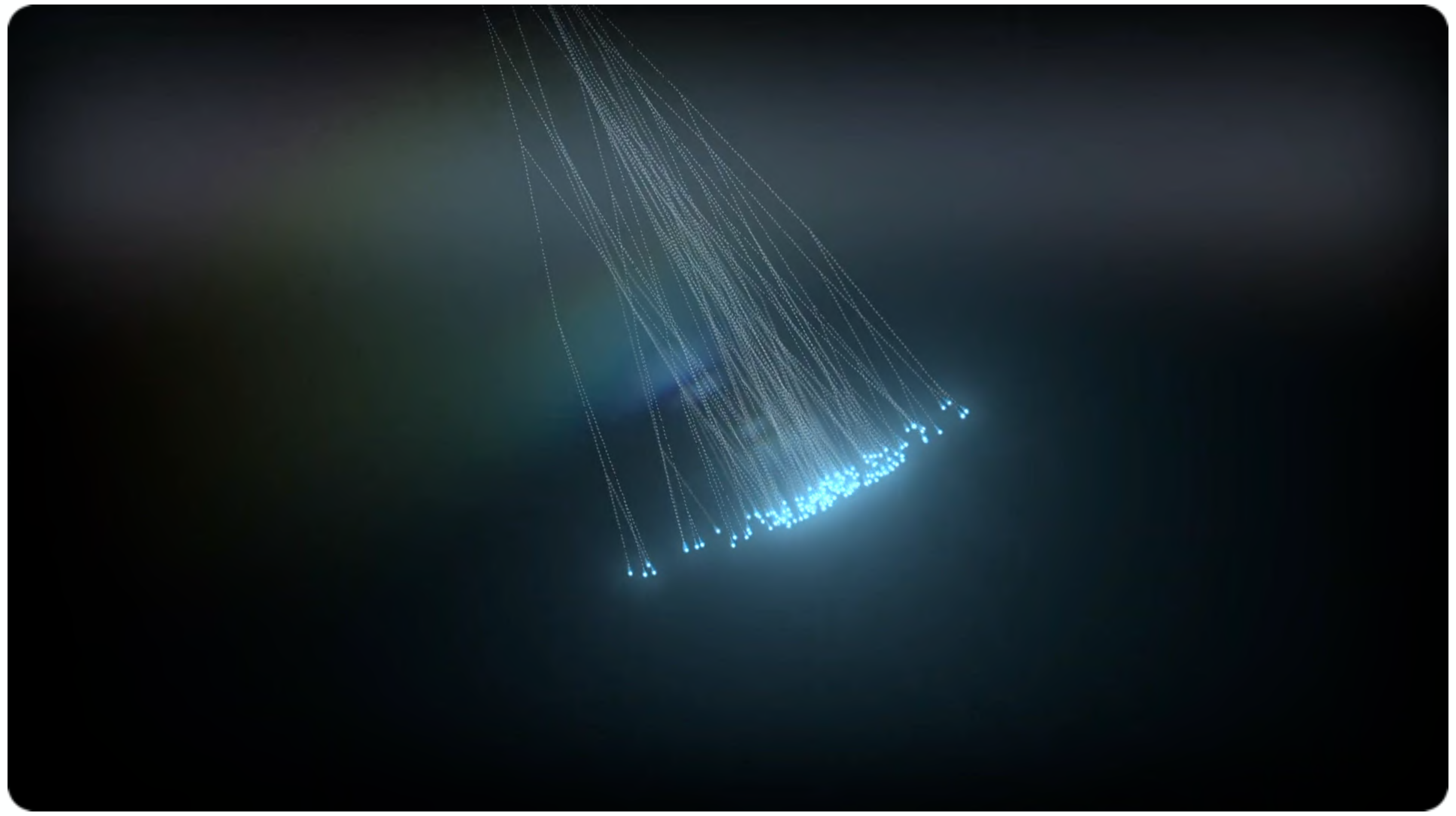


- Propagation is affected by
  - Intergalactic Magnetic Field
  - Intergalactic Matter/dust
  - Background Photons

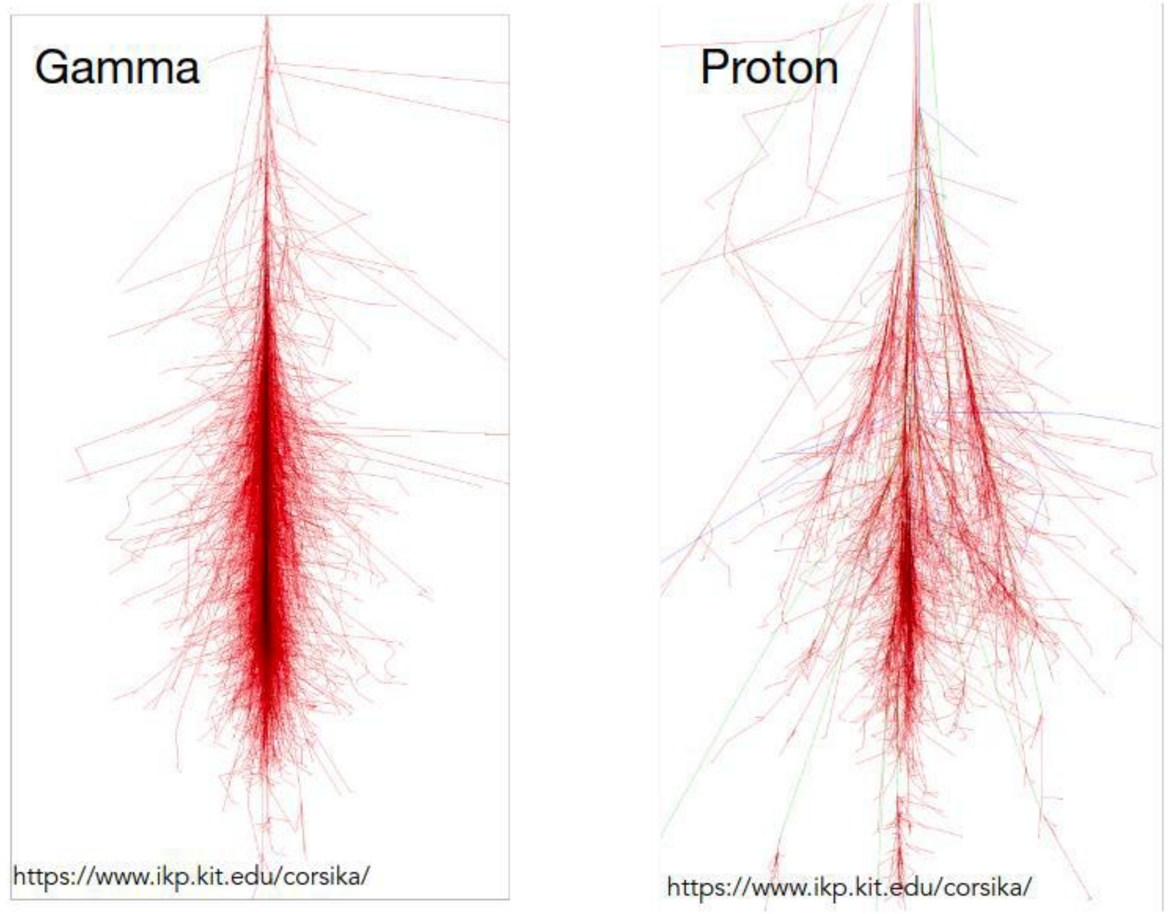
Credit: CTAO/D. Della volpe

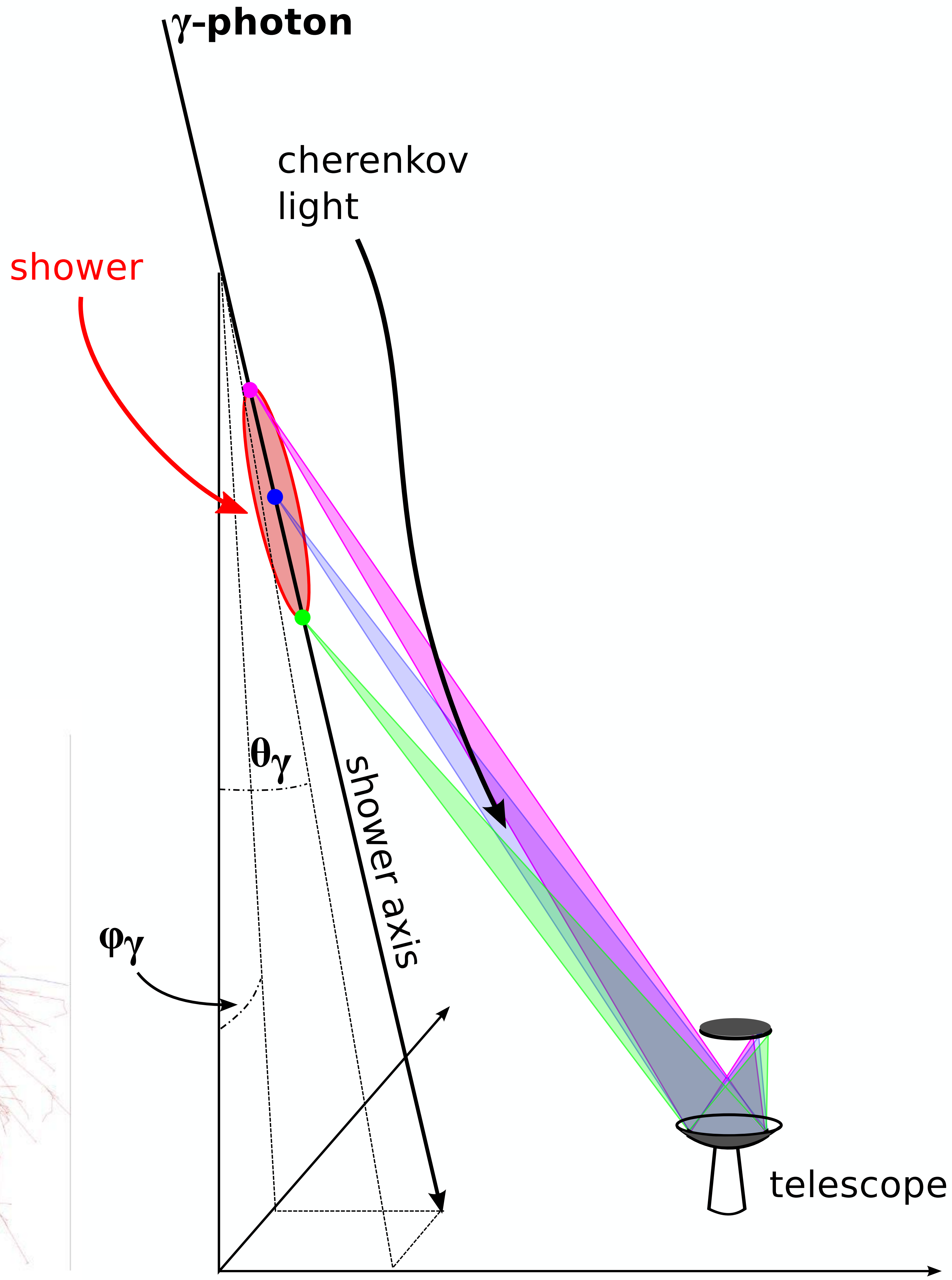
Imaging Atmospheric Cherenkov telescope



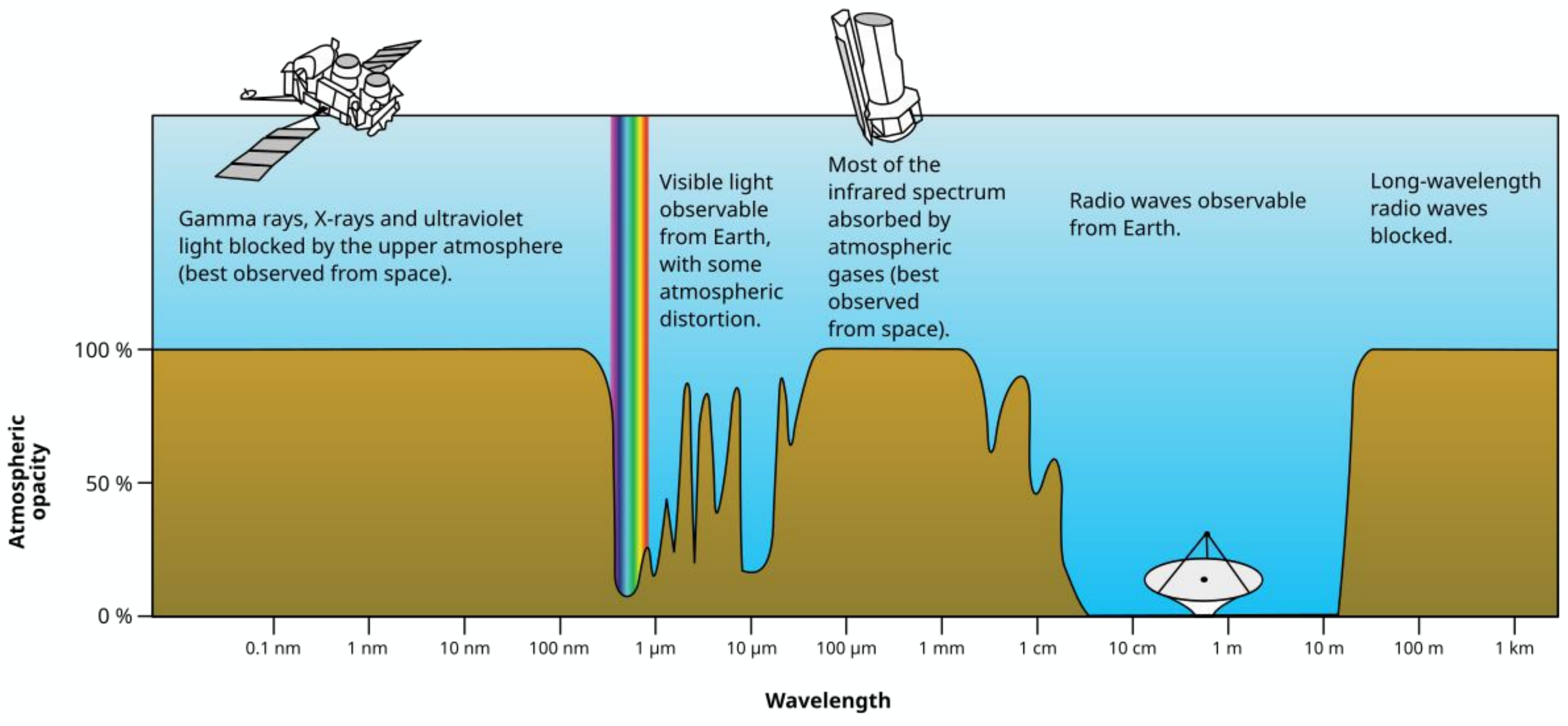


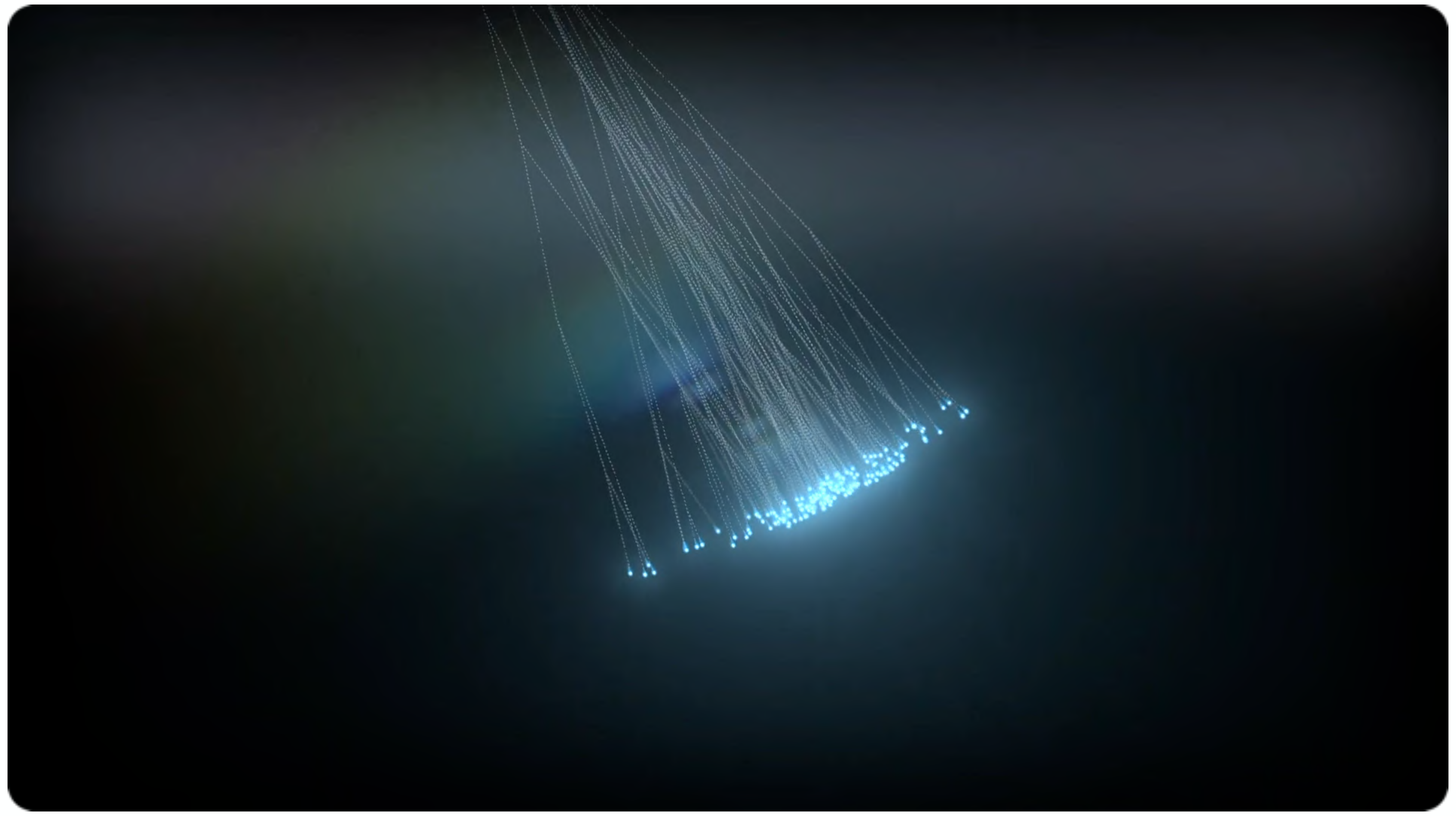
- Detection of Cherenkov flashes require:
  - ✦ *Single photon sensitivity*
  - ✦ *Nano-second time resolution*





Imaging Atmospheric Cherenkov telescope





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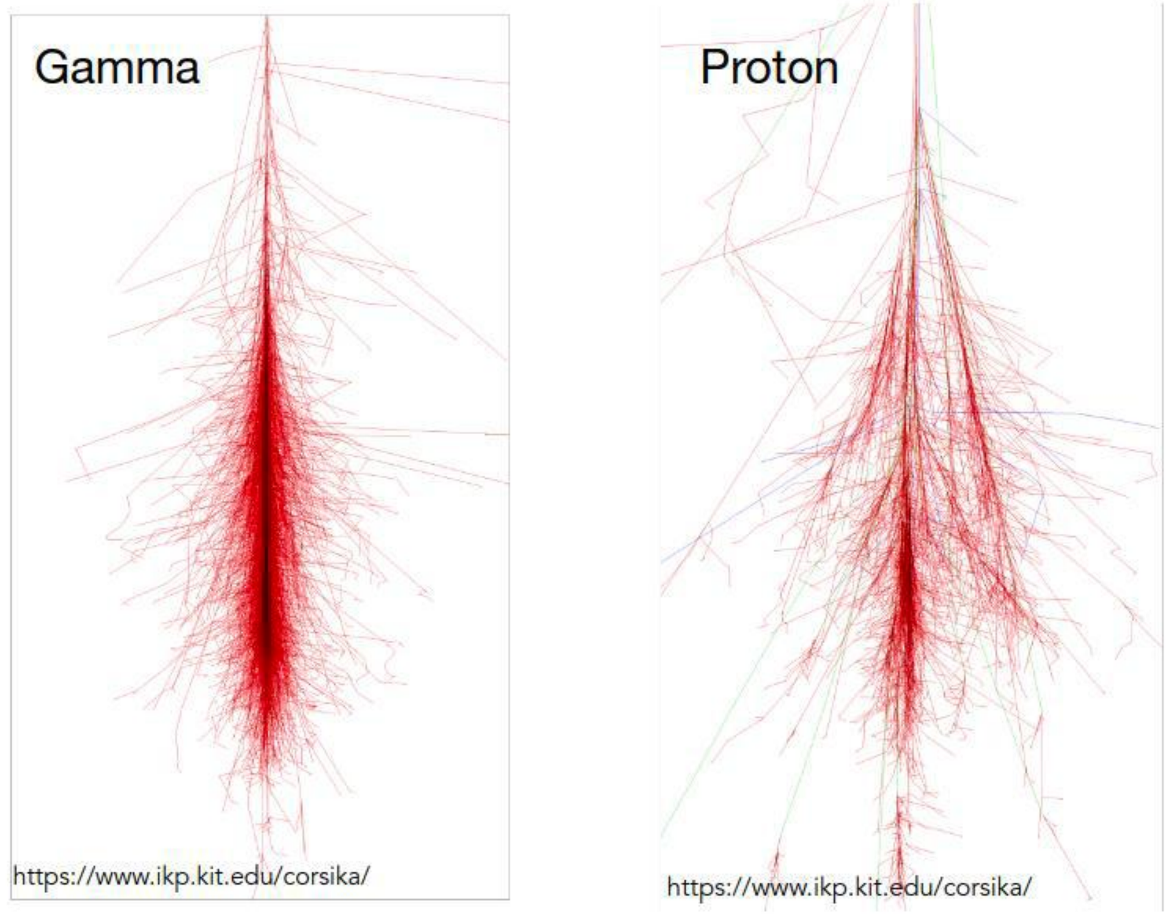

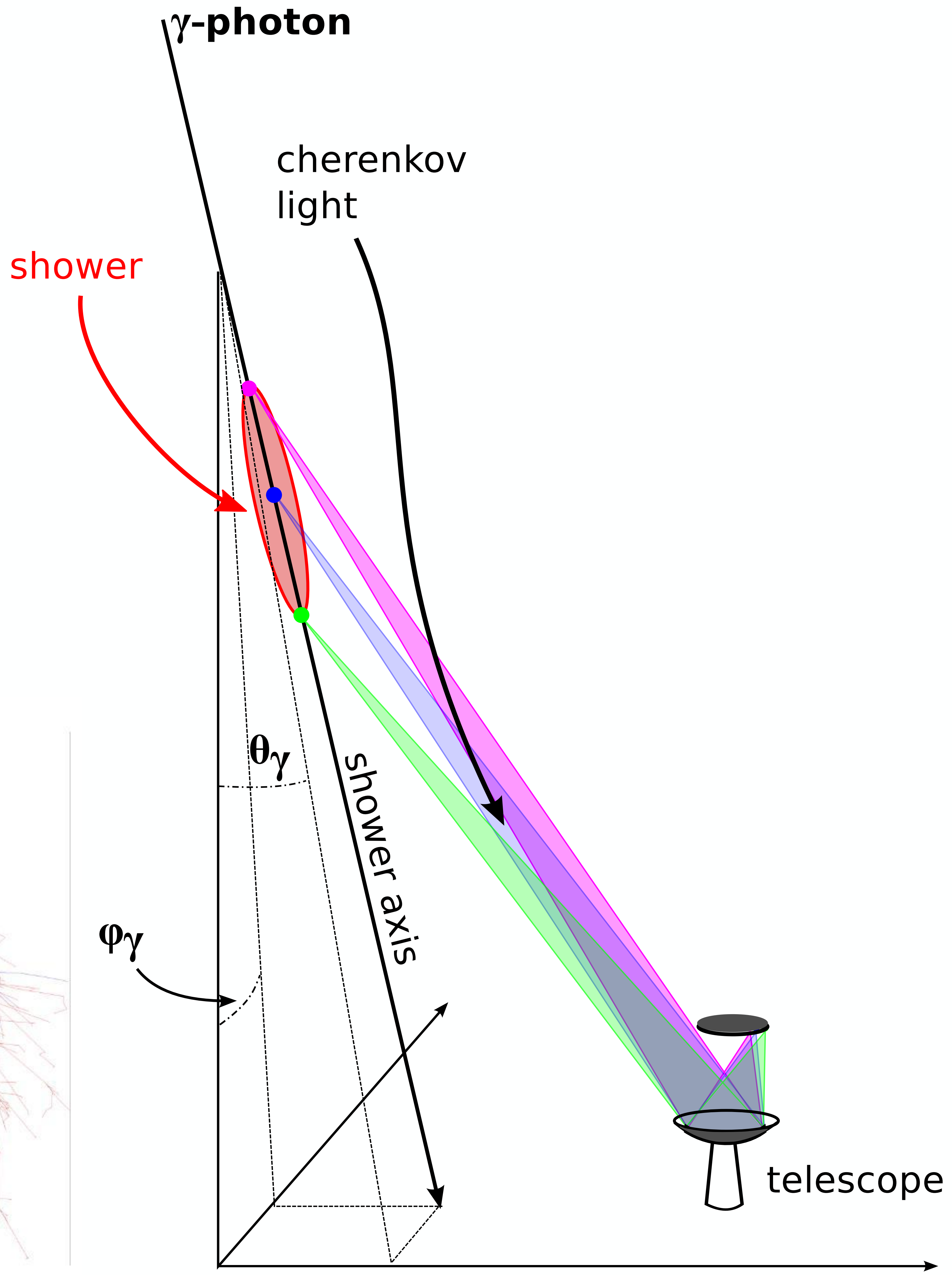

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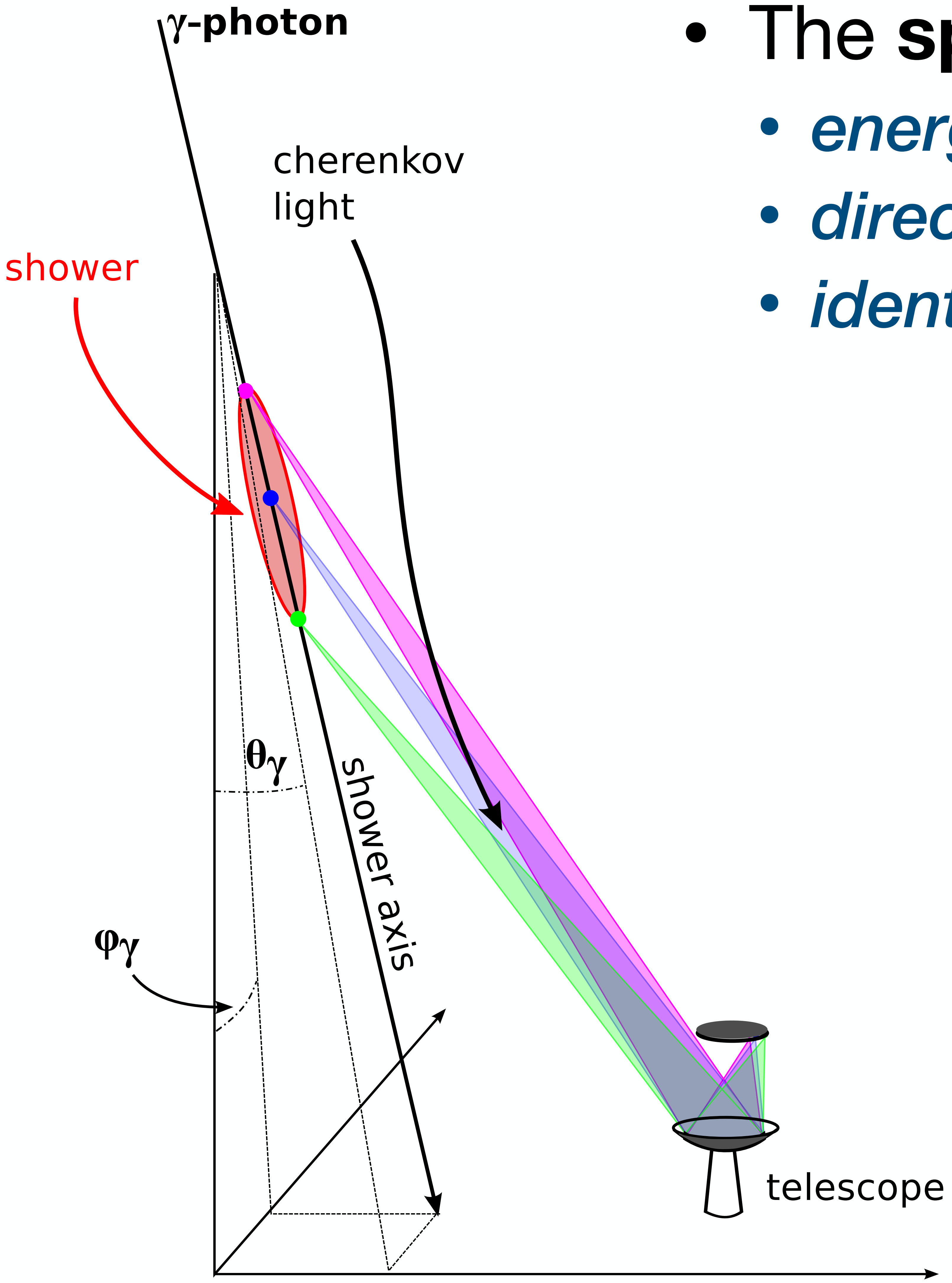
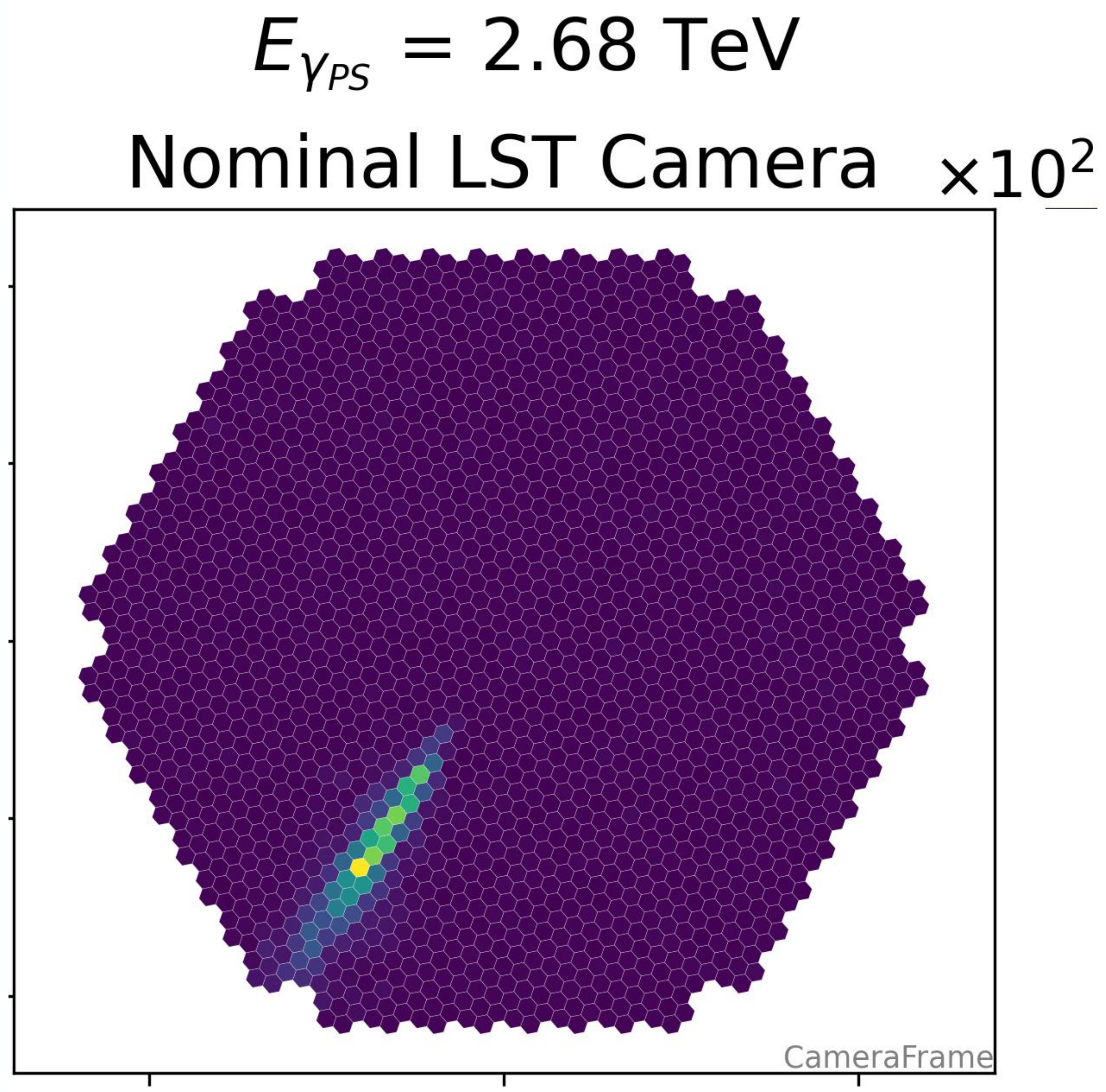
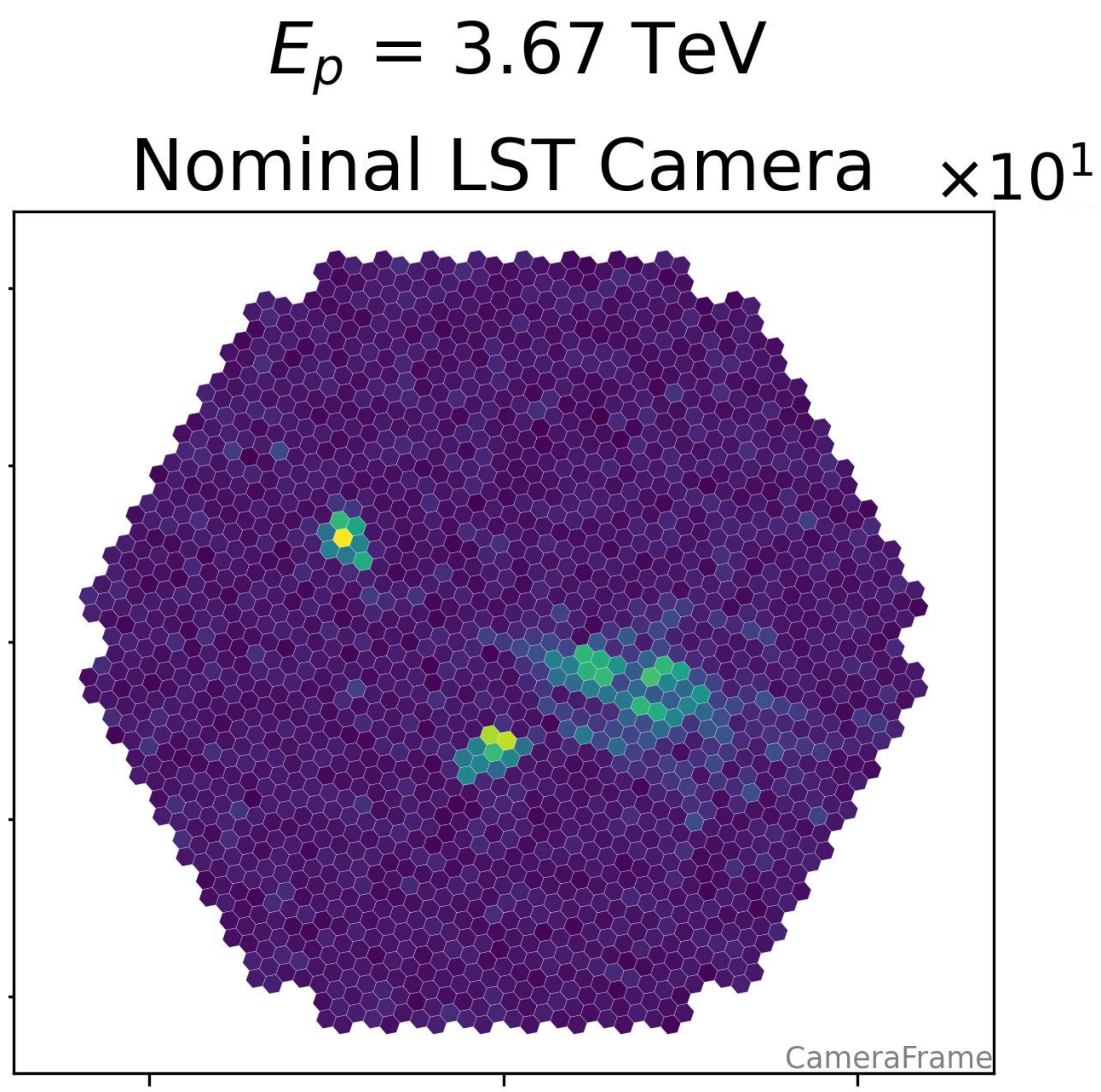


- The **spatio-temporal profile** of the shower image proxy to:
  - ***energy*** (image intensity, impact parameter)
  - ***direction*** (image orientation, timing)
  - ***identity of primary particle*** (image shape, timing)





What do we gain going for an IACT array ?

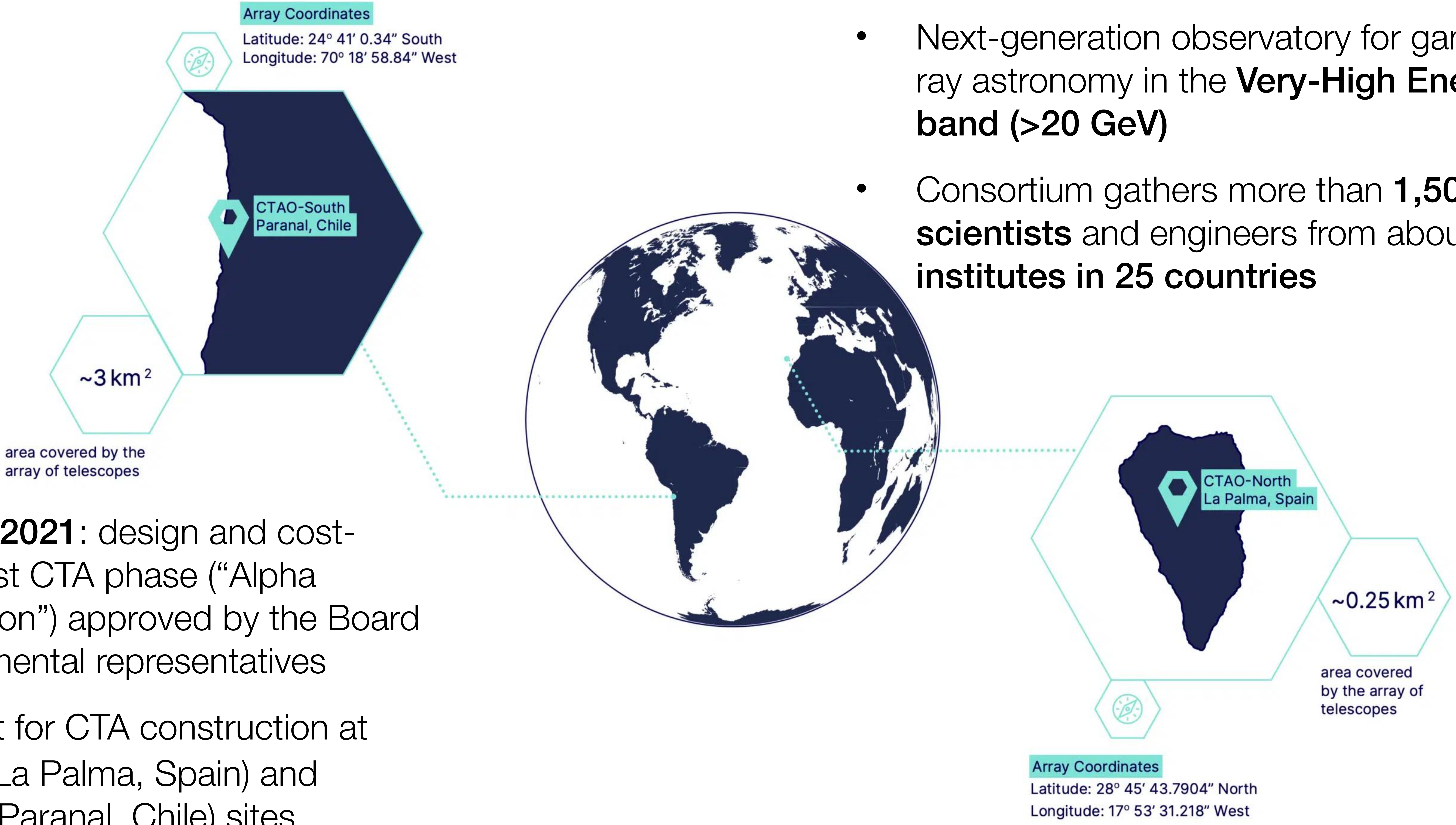
Credit: CTAO

What do we gain going for an IACT array ?

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

Credit: CTAO

The CTA Observatory



- Next-generation observatory for gamma-ray astronomy in the **Very-High Energy band (>20 GeV)**
- Consortium gathers more than **1,500 scientists** and engineers from about **150 institutes in 25 countries**

June 25th 2021: design and cost-book of first CTA phase (“Alpha configuration”) approved by the Board of governmental representatives

⟹ support for CTA construction at Northern (La Palma, Spain) and Southern (Paranal, Chile) sites

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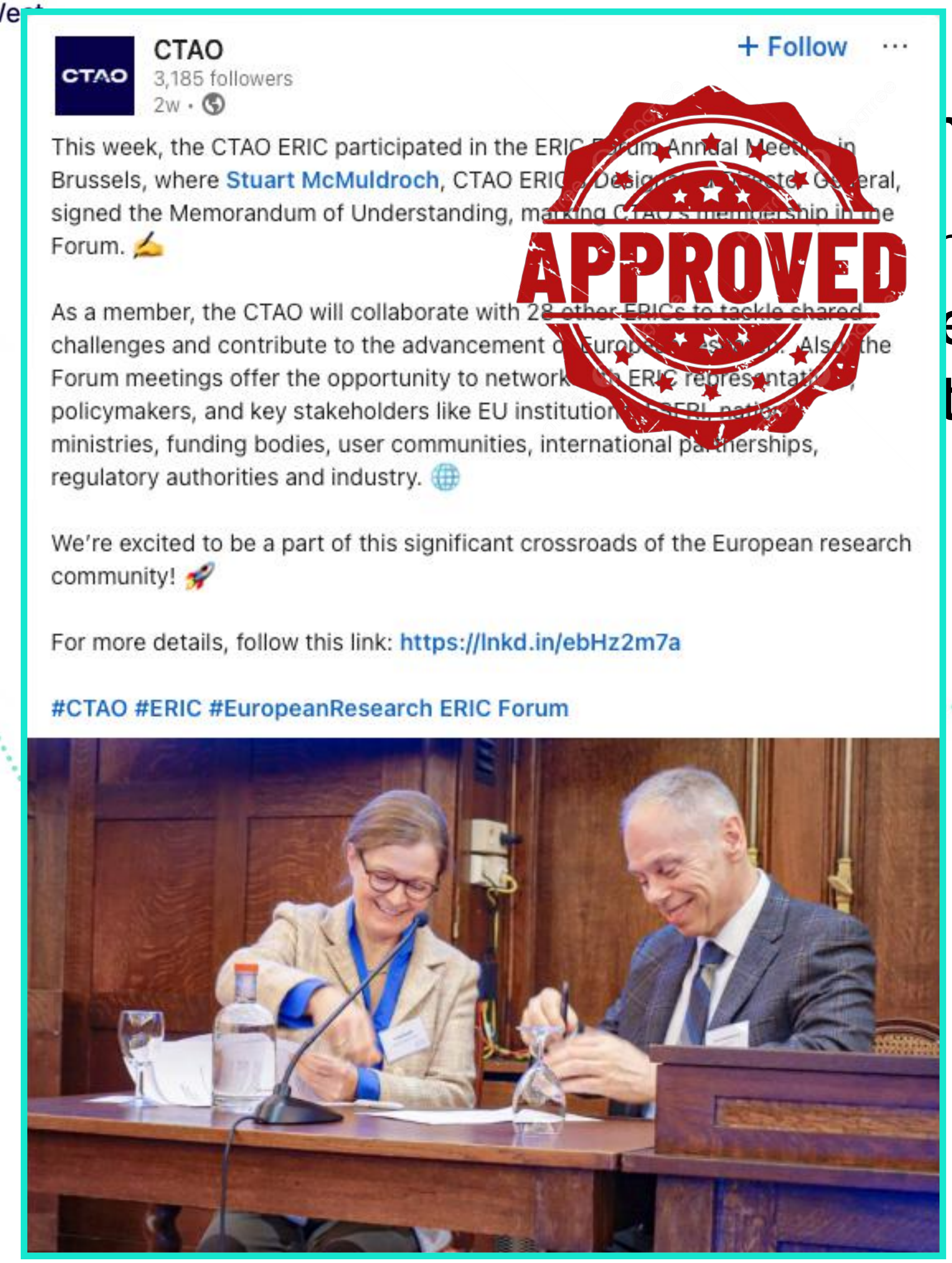

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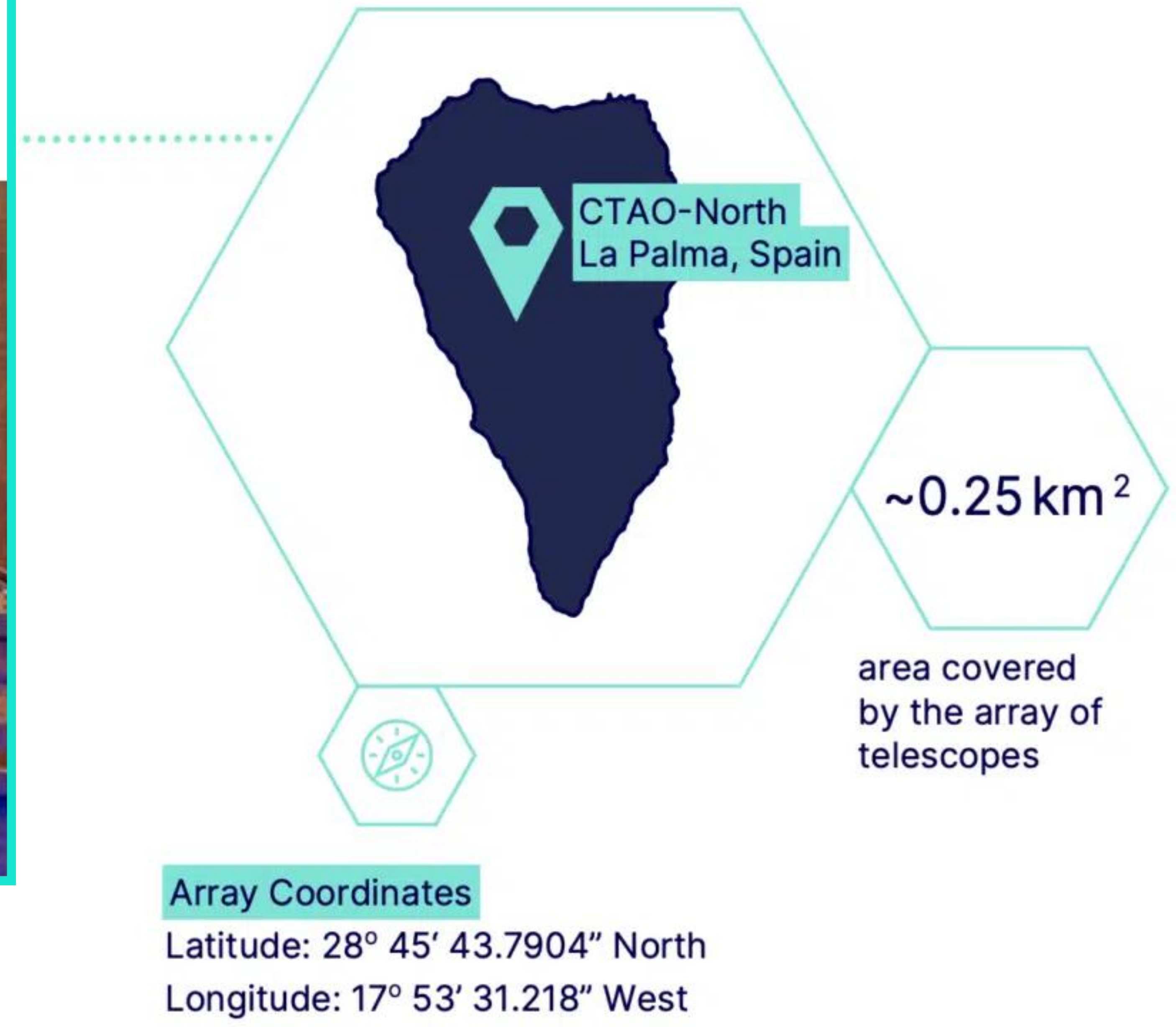
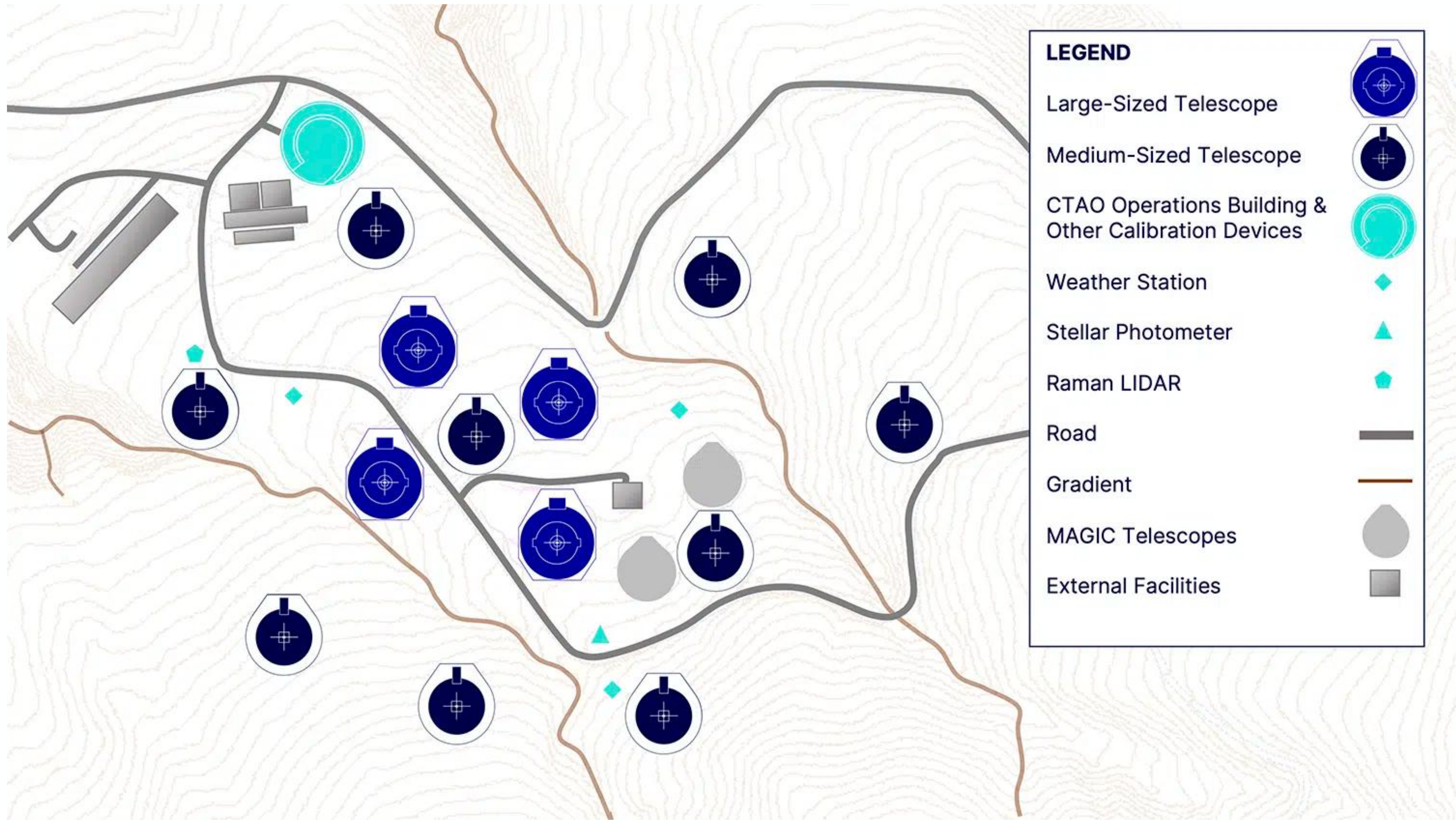
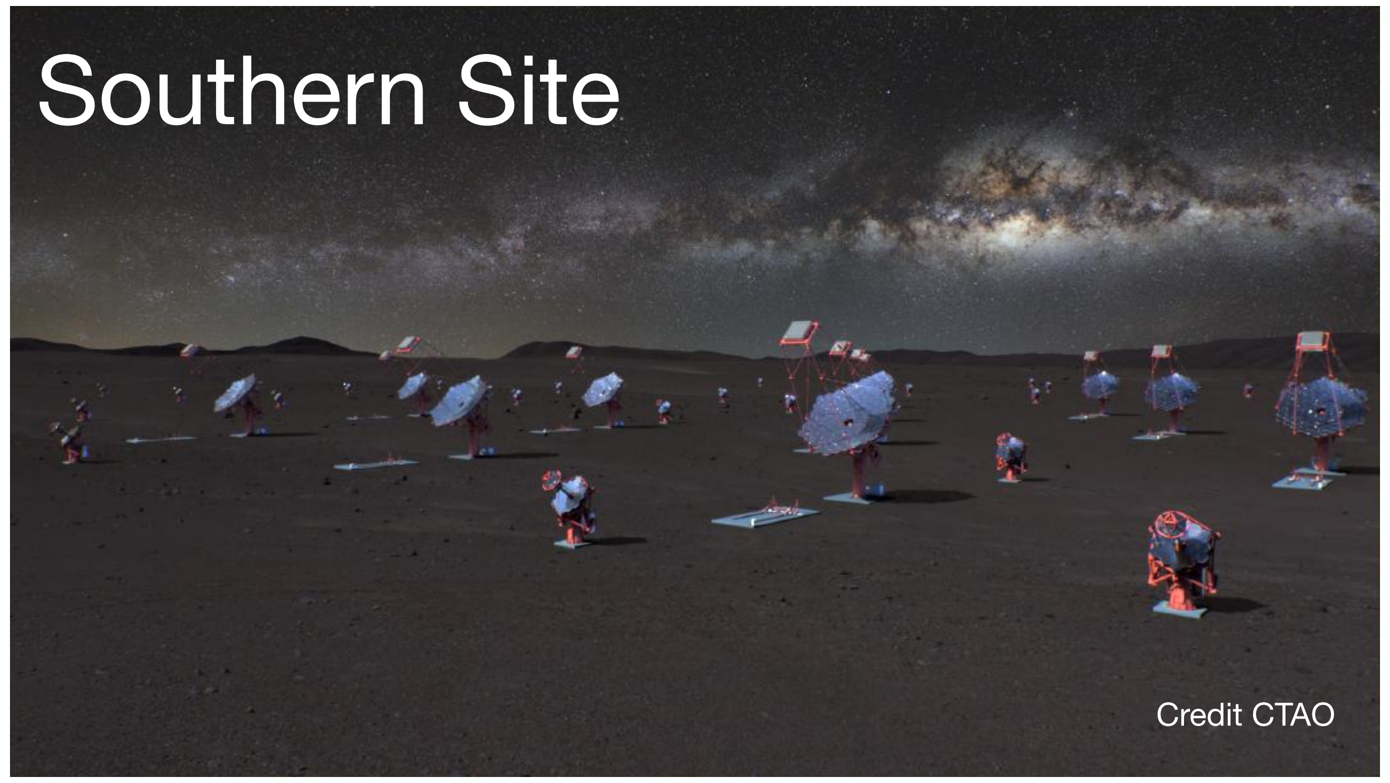
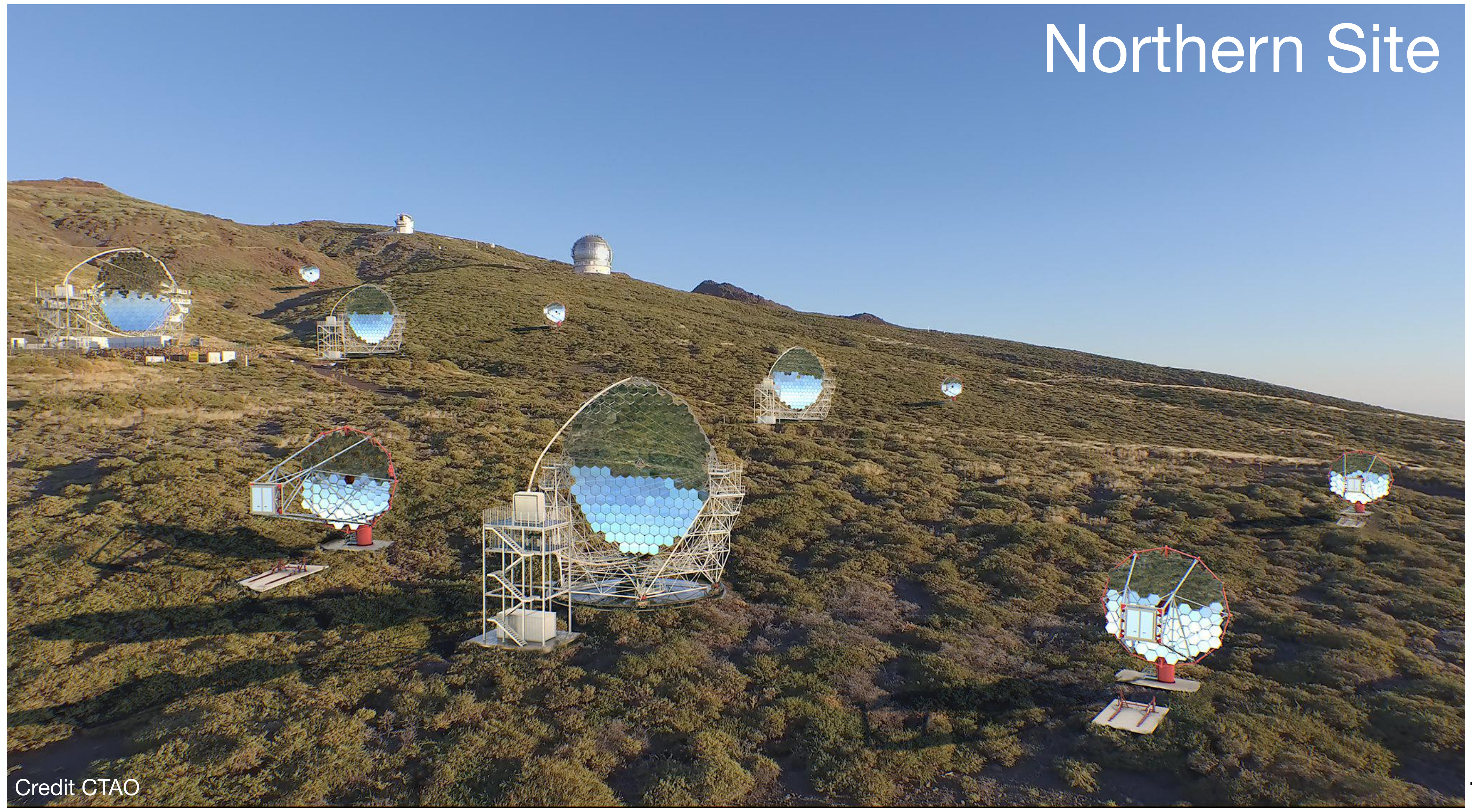
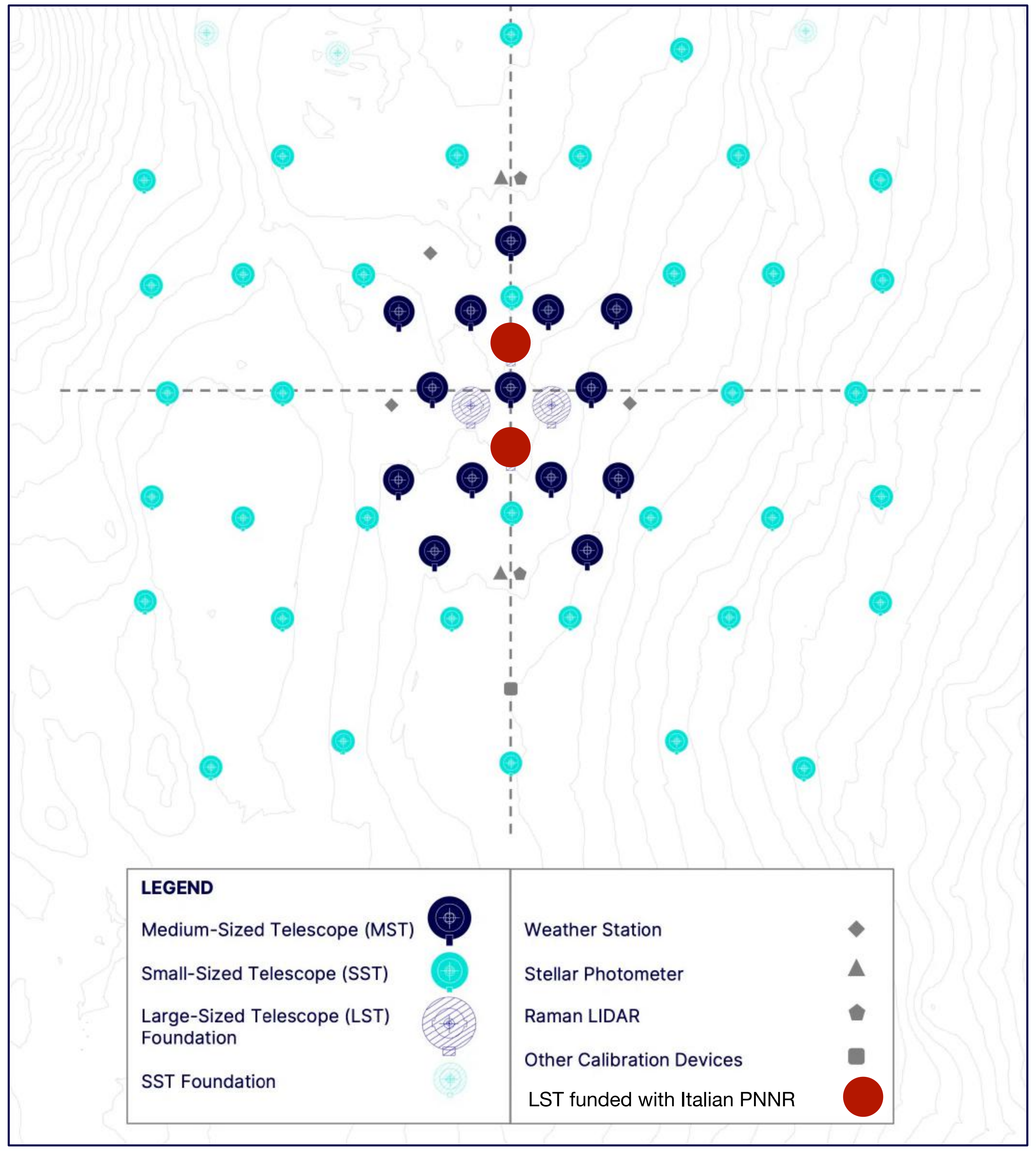


CTAO - Alpha configurations





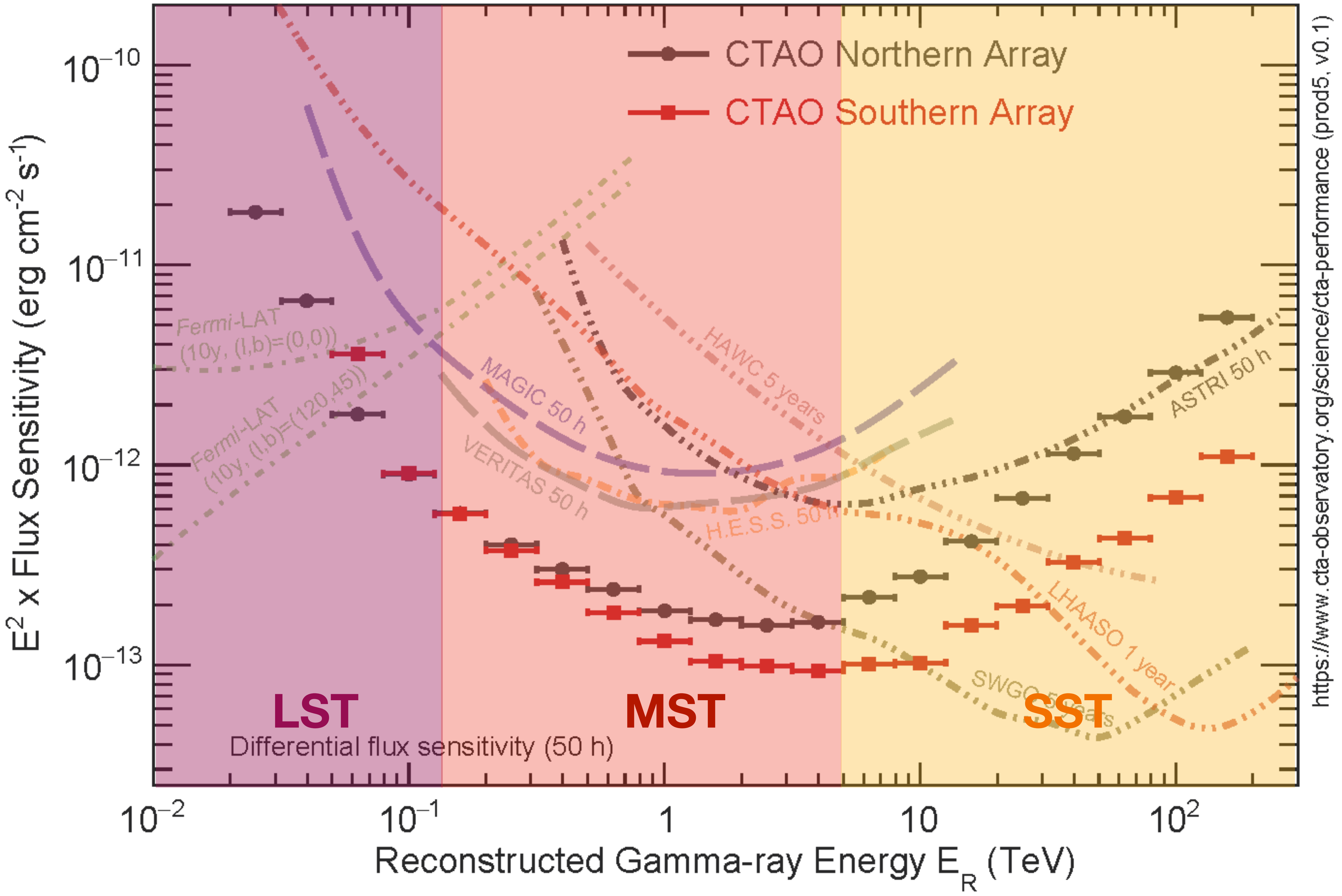




Cherenkov Telescope Array Observatory

The next generation of very high energy gamma ray observatory

	LST	MST	SST
Effective mirror area	*370 m²*	88 m²	*8m²*
#telescopes North	*4*	9	*0*
#Telescopes South	*0**	14	*37**

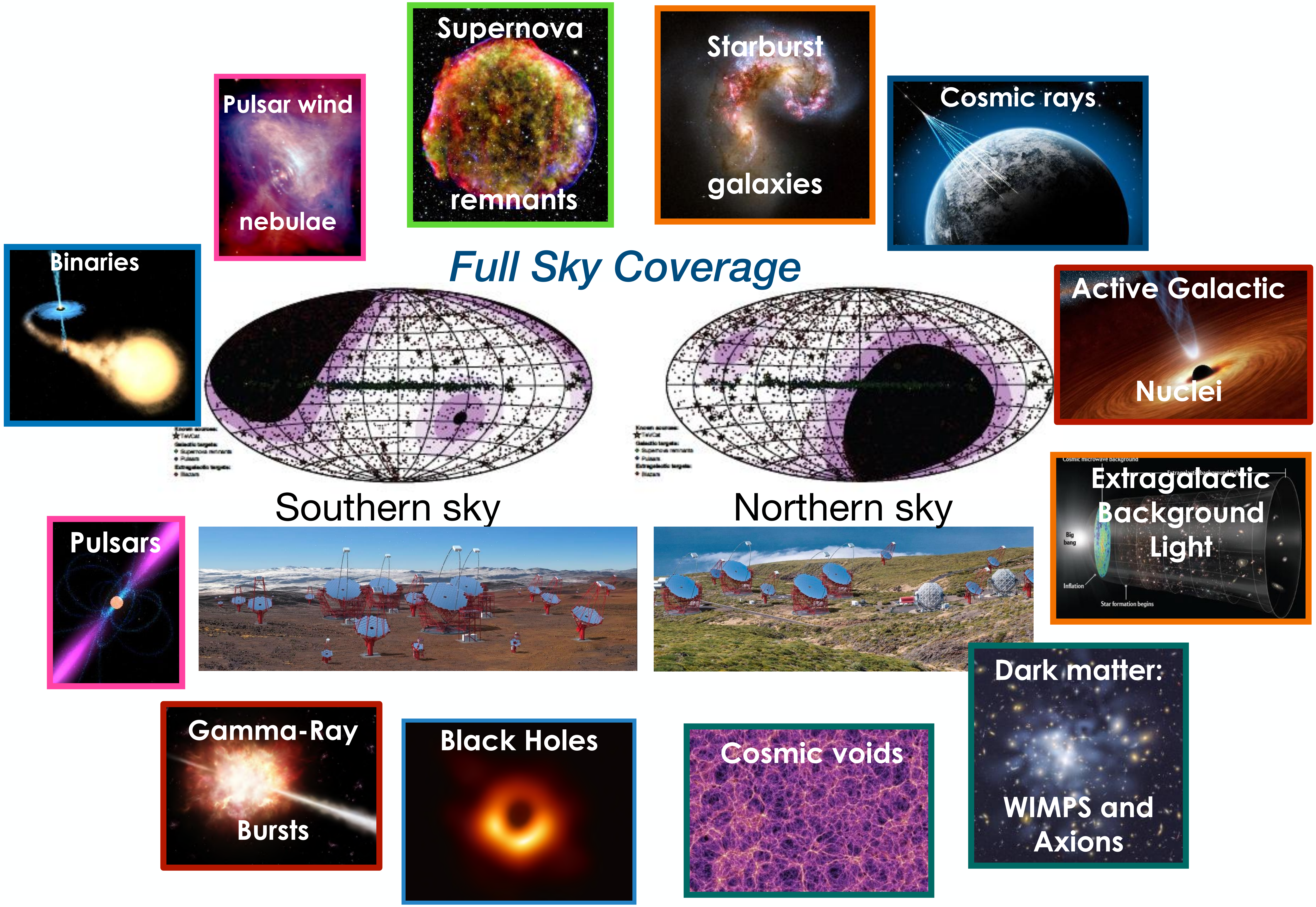


Differential sensitivity: the minimum flux that can be detected in 50h
*the lower the better

The CTA Observatory

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



The Large-Sized Telescope

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The instrument

	Large-Sized Telescope (LST)
Energy range (in which sensitivity is optimized)	20 GeV – 150 GeV
Number of LST telescopes	4 (North)
Optical design	Parabolic
Primary reflector diameter	23.0 m
Effective mirror area (including shadowing)	370 m^2
Focal length	28 m
Total weight	103 t
Field of view	4.3 deg
Number of pixels	1855
Pixel size (imaging)	0.1 deg
Photodetector type	PMT
Telescope readout event rate after array trigger	>7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s
Pointing precision	<14 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

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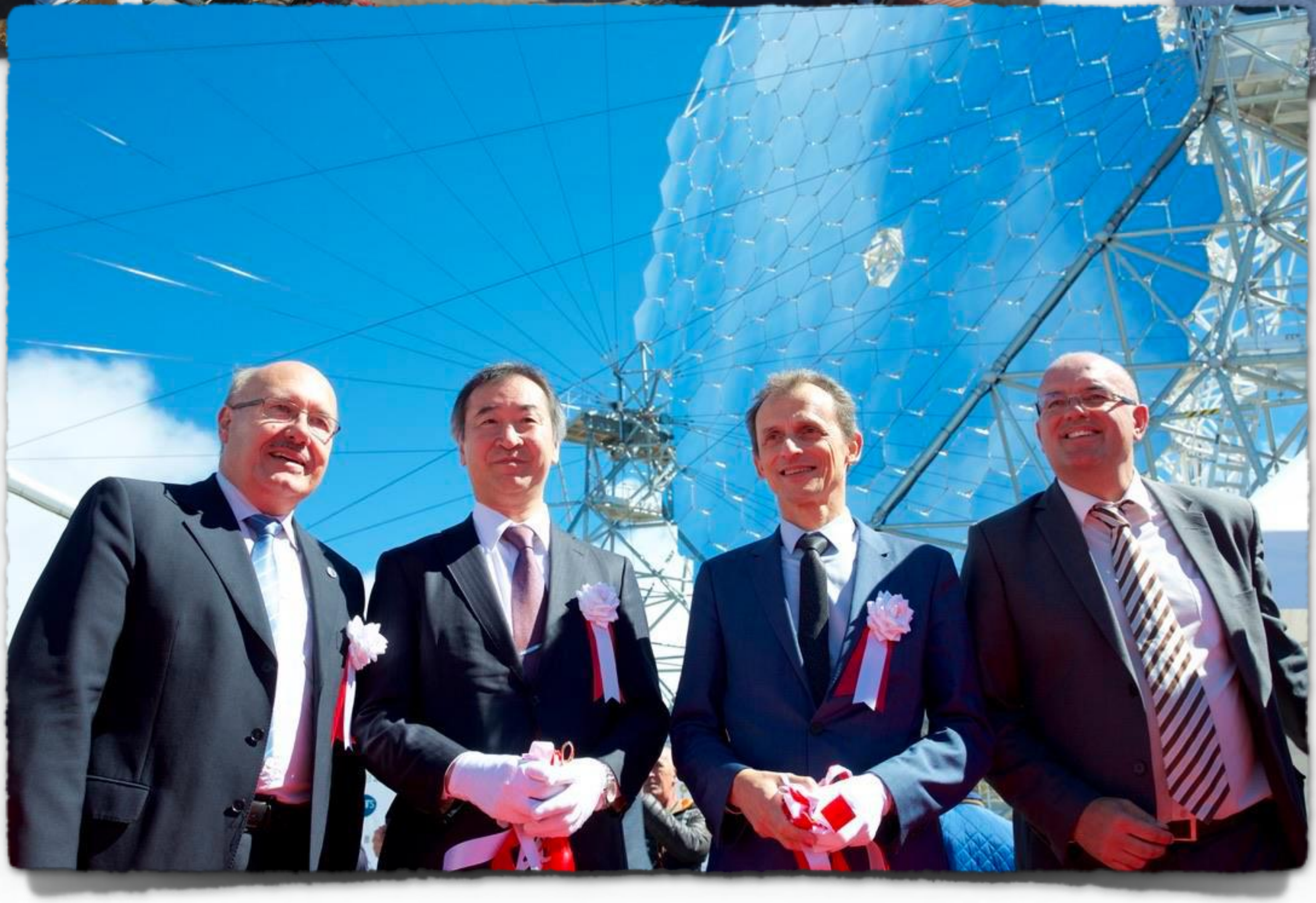
The Large-Sized Telescope

The inauguration - October 2018



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From mono to stereo observations

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LST-4 Dish installation

Unión Europea
Fondo Europeo
de desarrollo Regional
"Una manera de hacer Europa"

LST-4 Arch-CSS installation

Camera qualification at IAC

Science with LST-1

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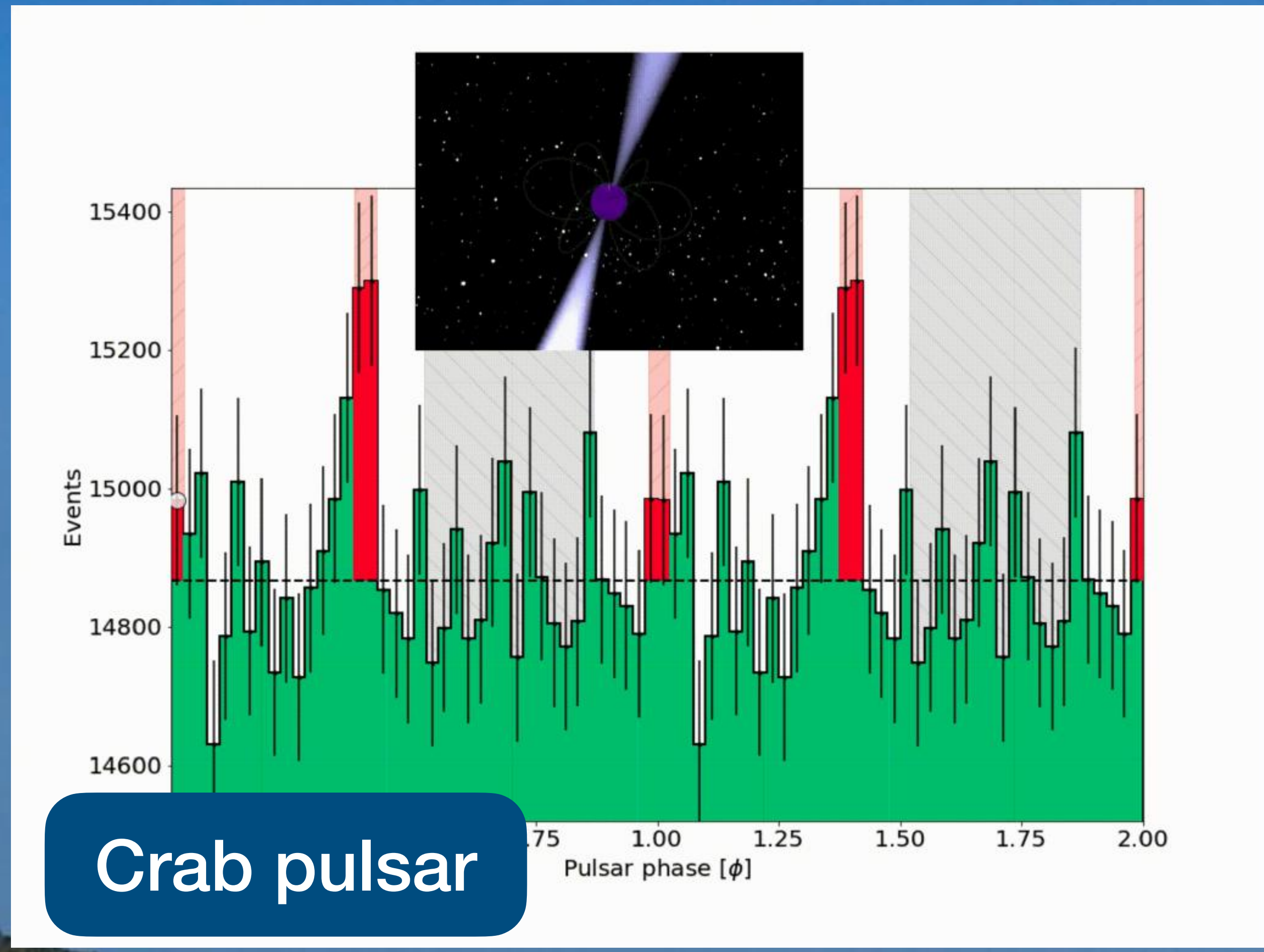
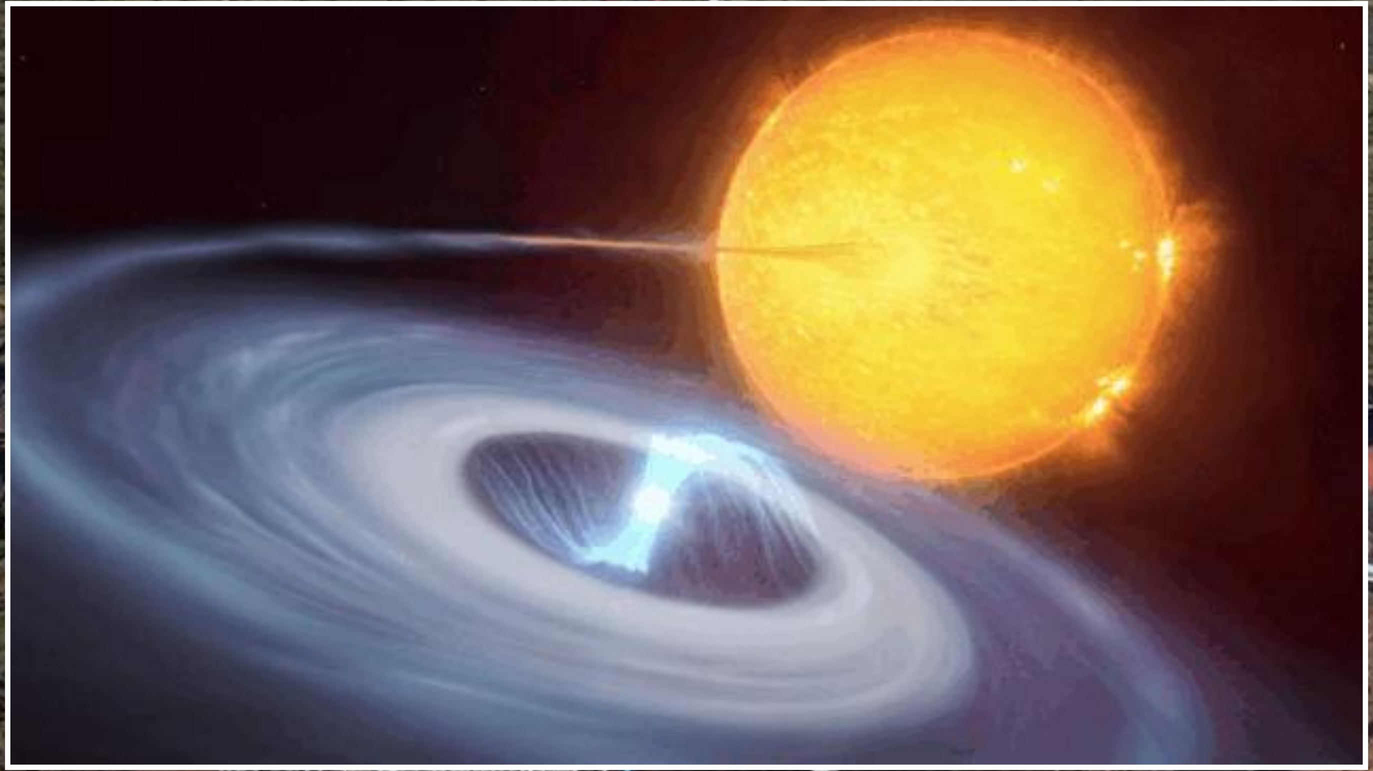
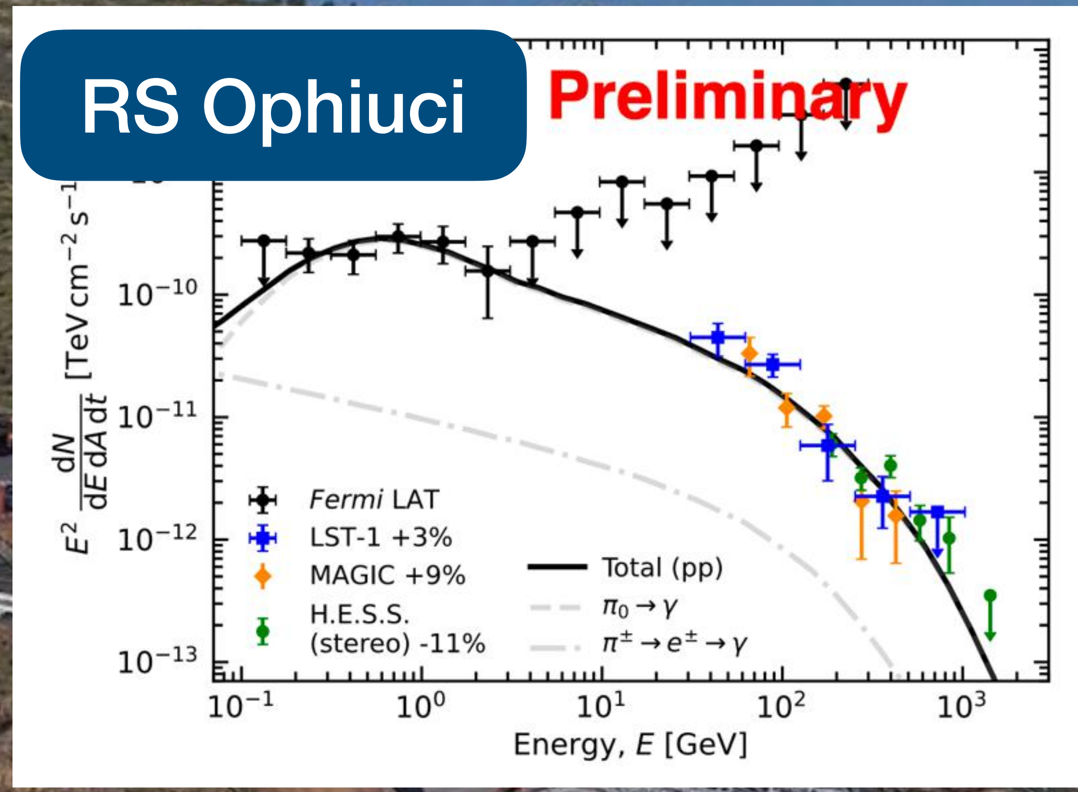
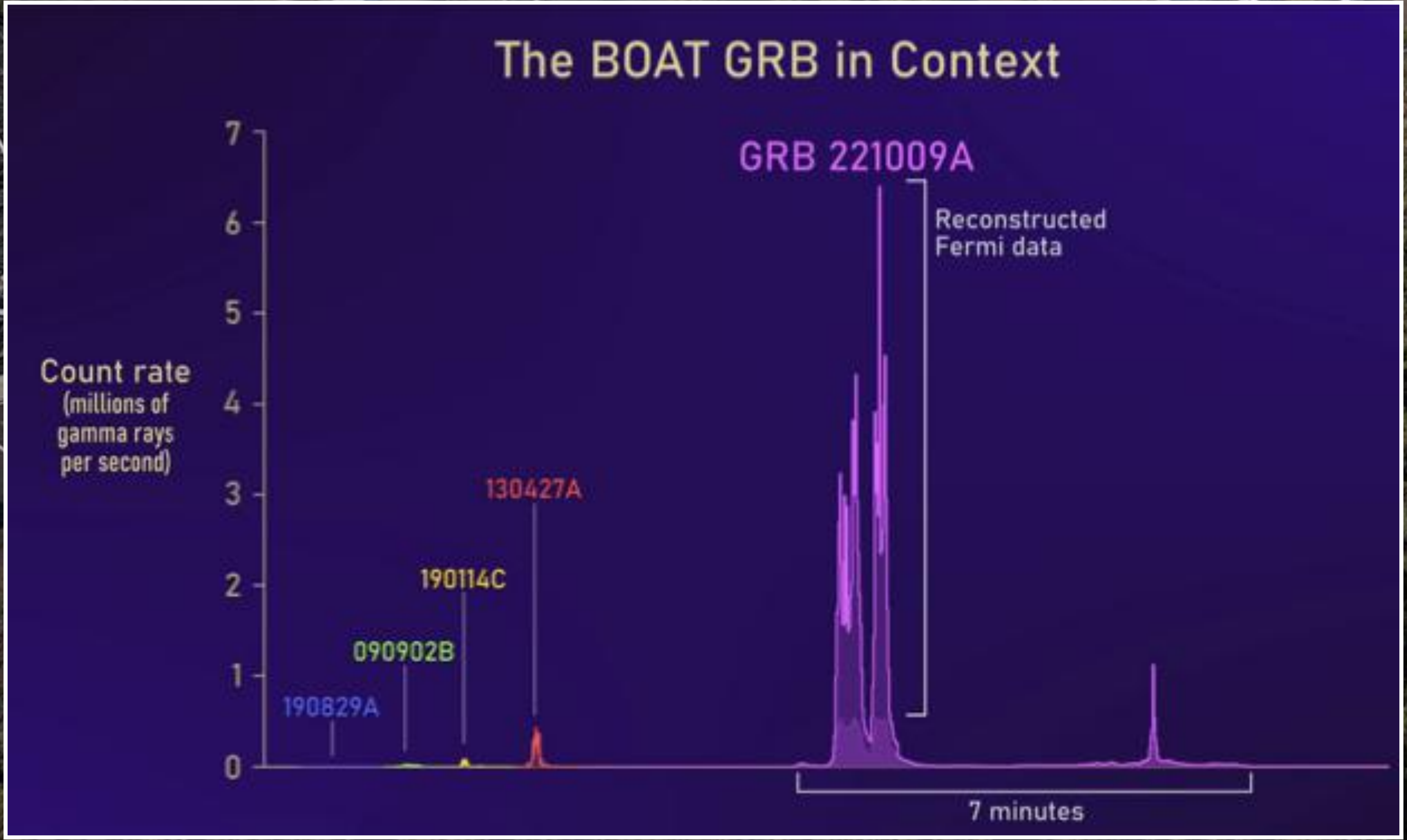
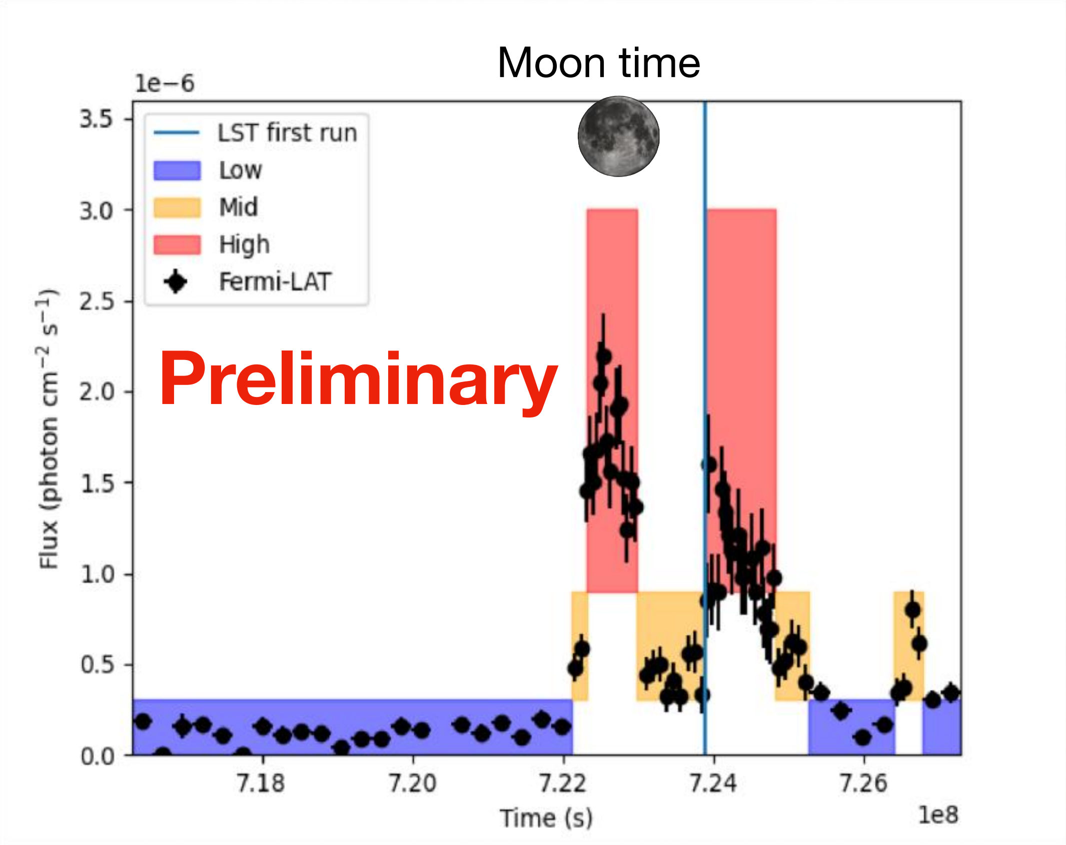
- In commissioning since 2019, however it delivers unique scientific results:
  - ✦ Pulsars (Crab, Geminga, Vela)
  - ✦ Recurent Symbiotic Nova (RS Oph, T CrB)
  - ✦ AGNs (OP313 furthest FSRQ ever observed)
  - ✦ Galactic Center
  - ✦ Transient (BOAT)

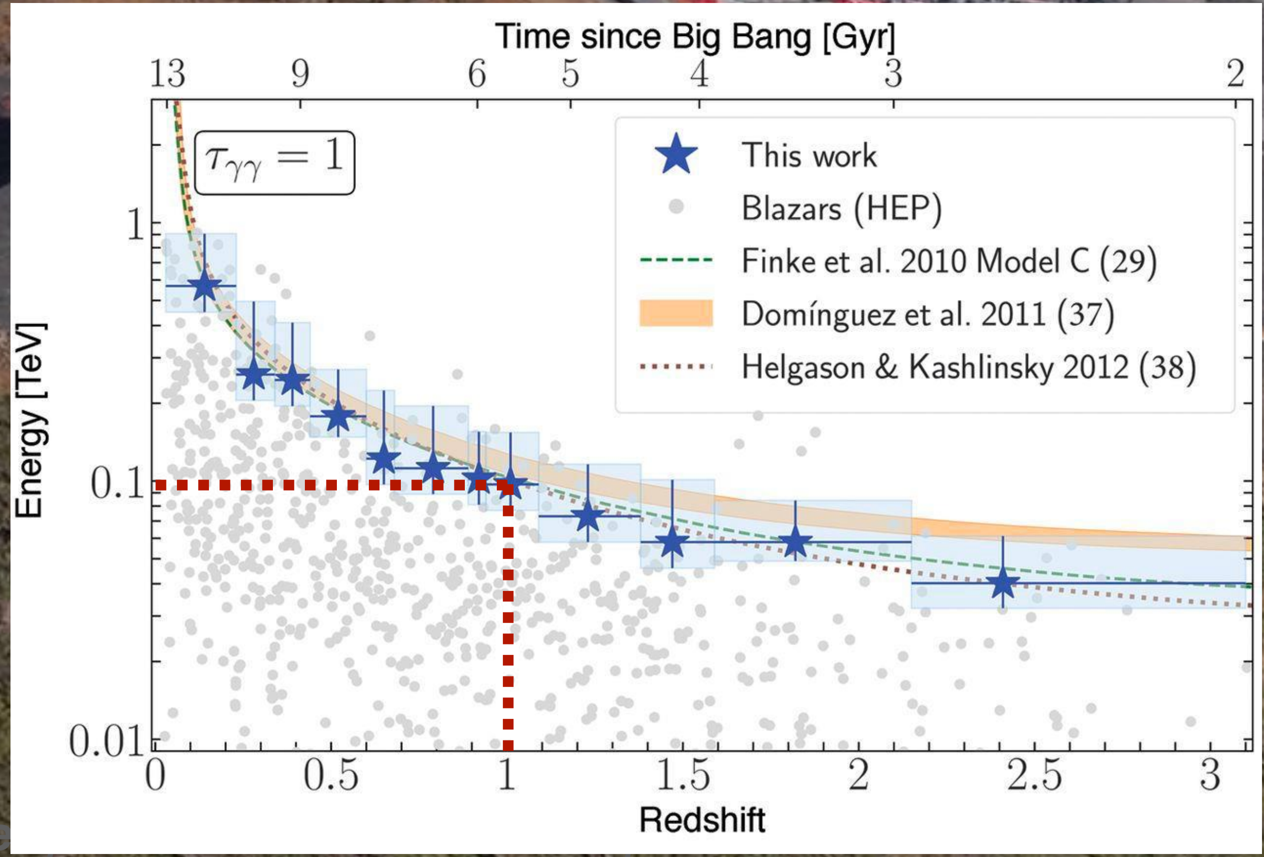












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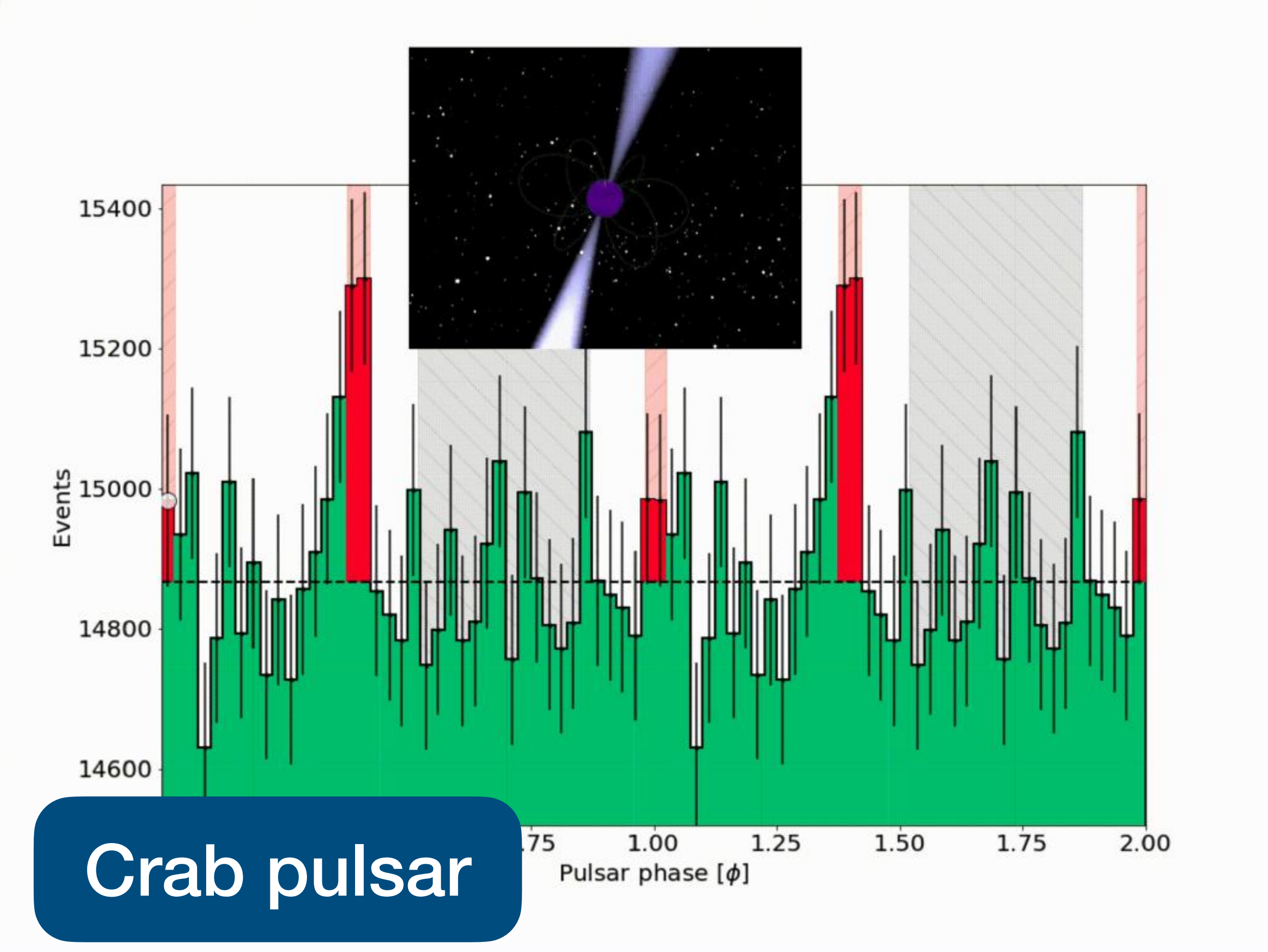
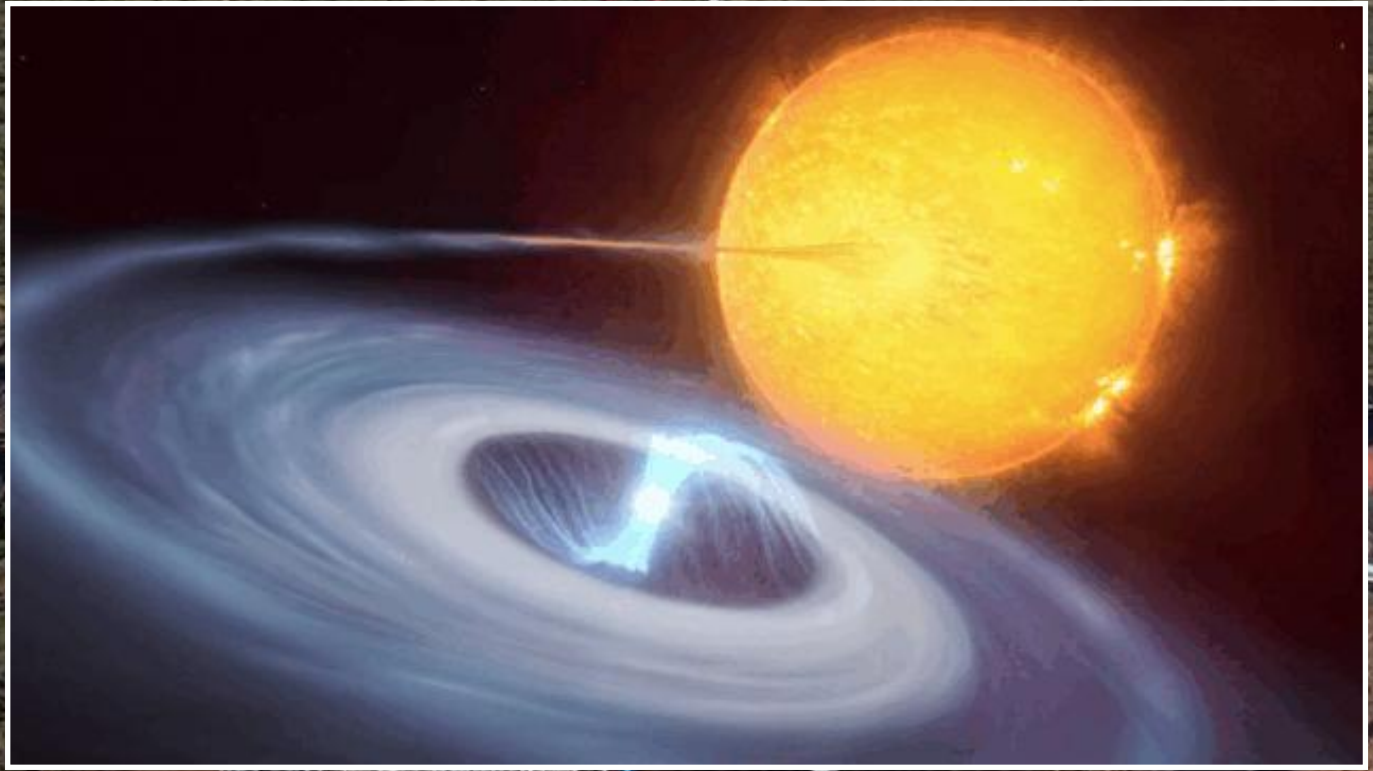
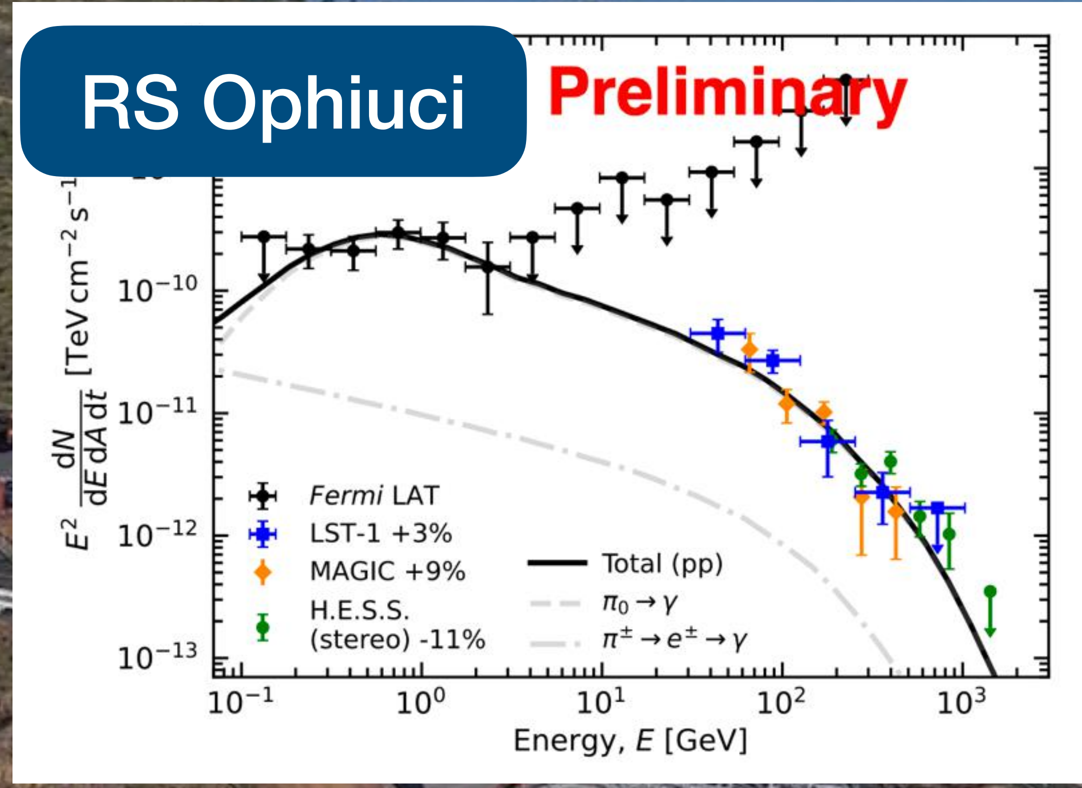
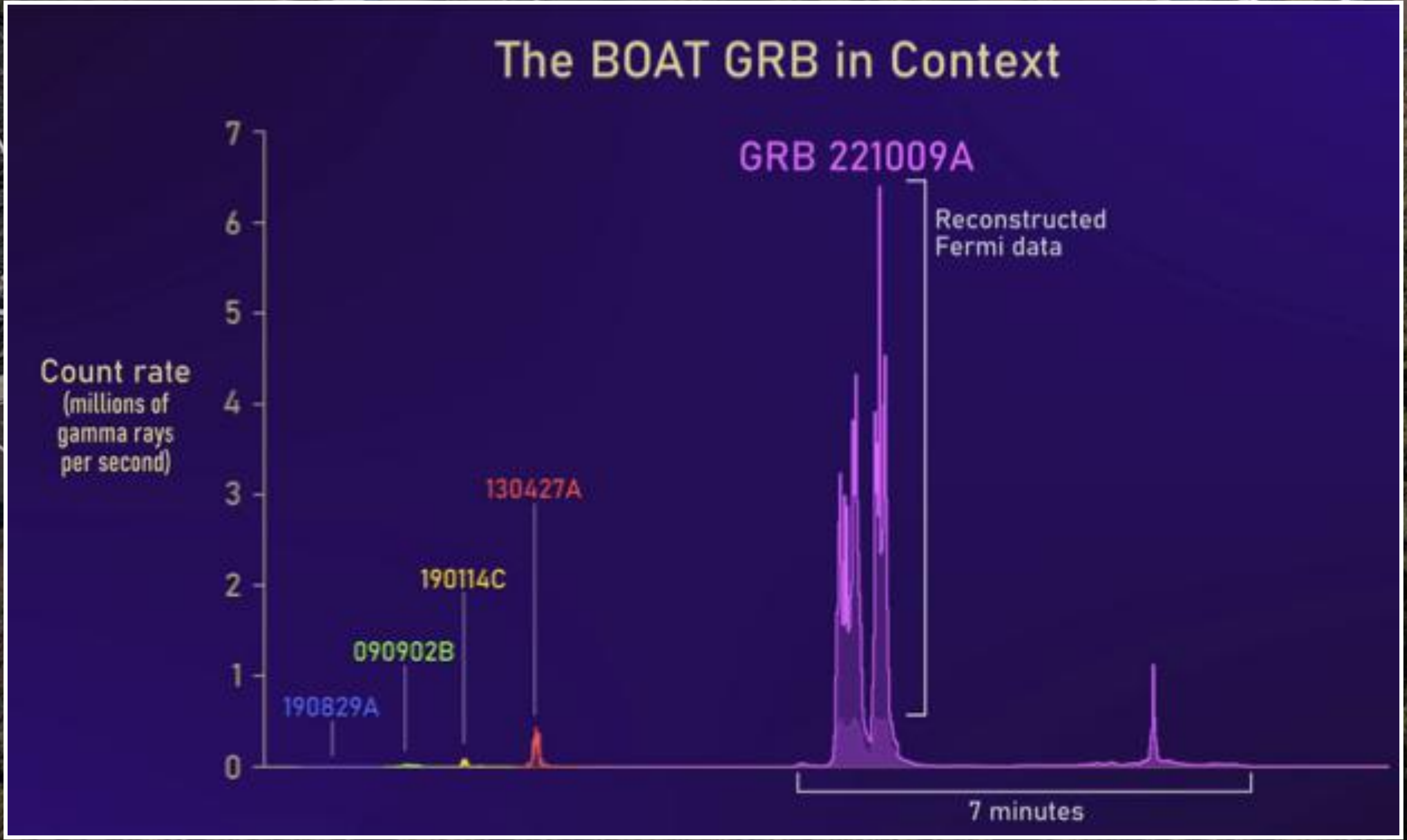
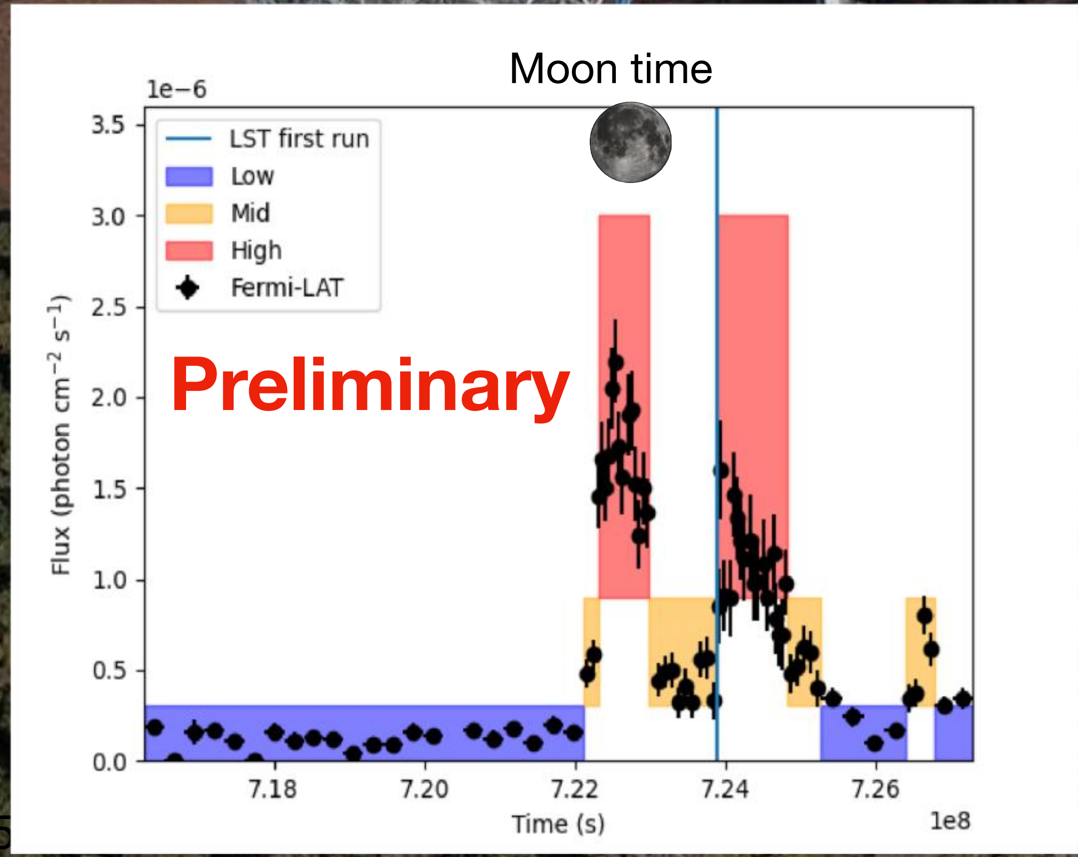
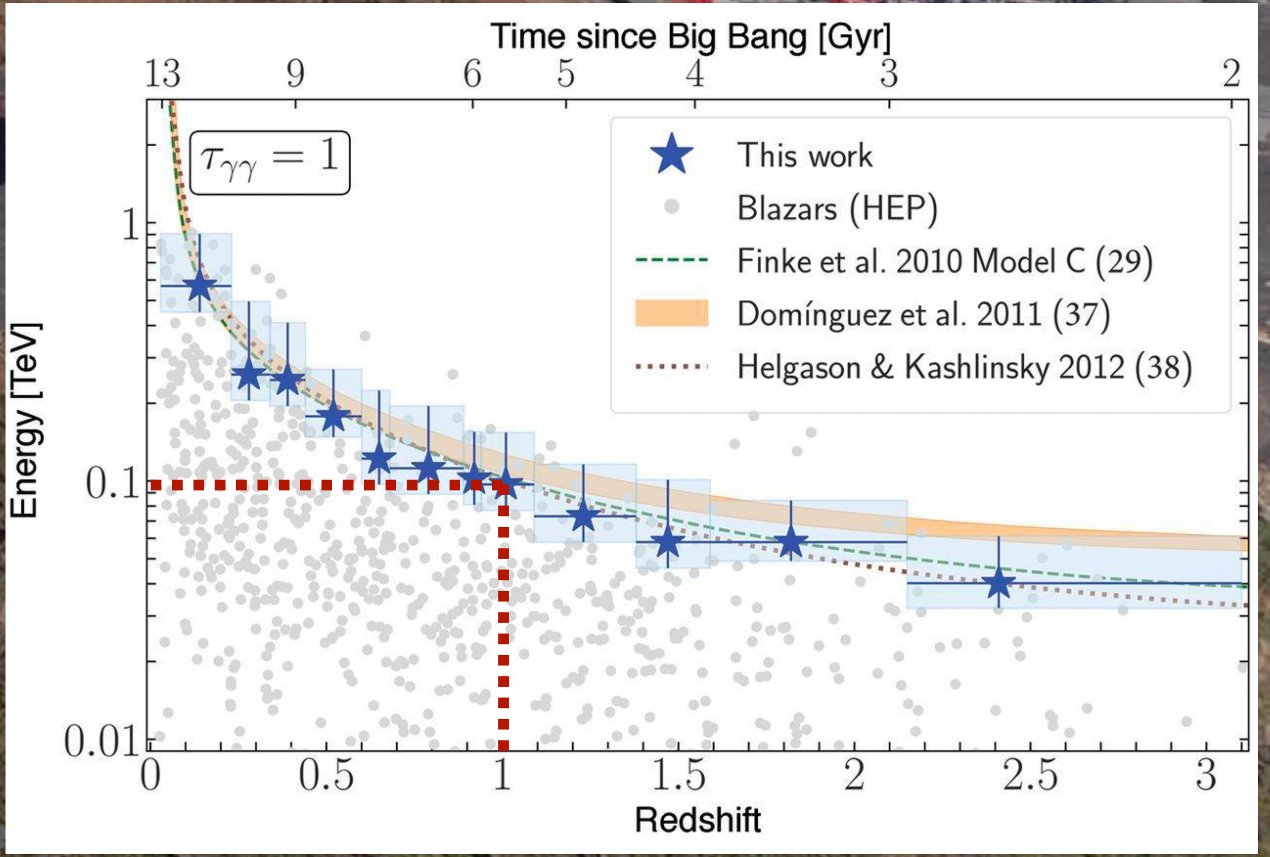




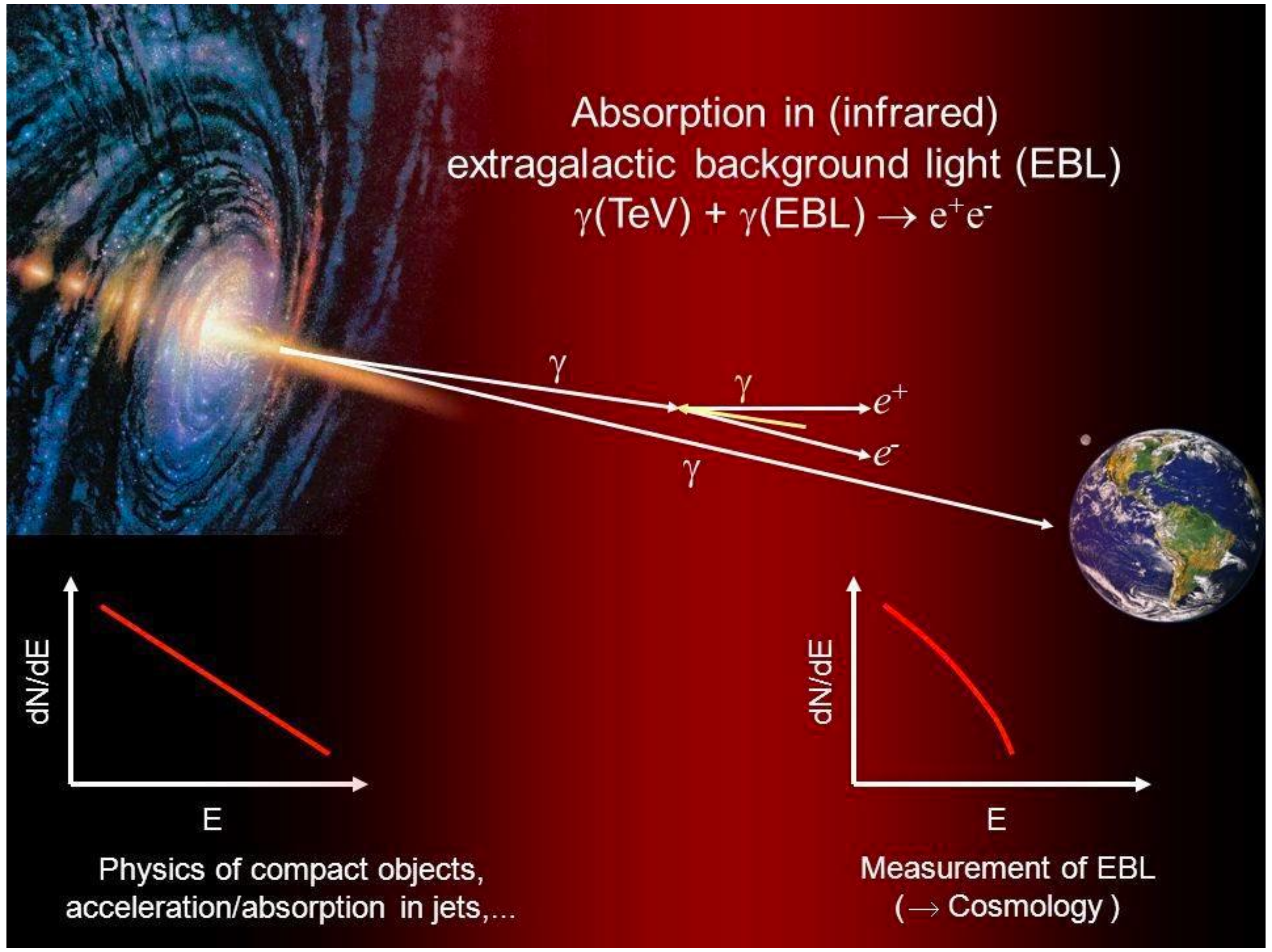


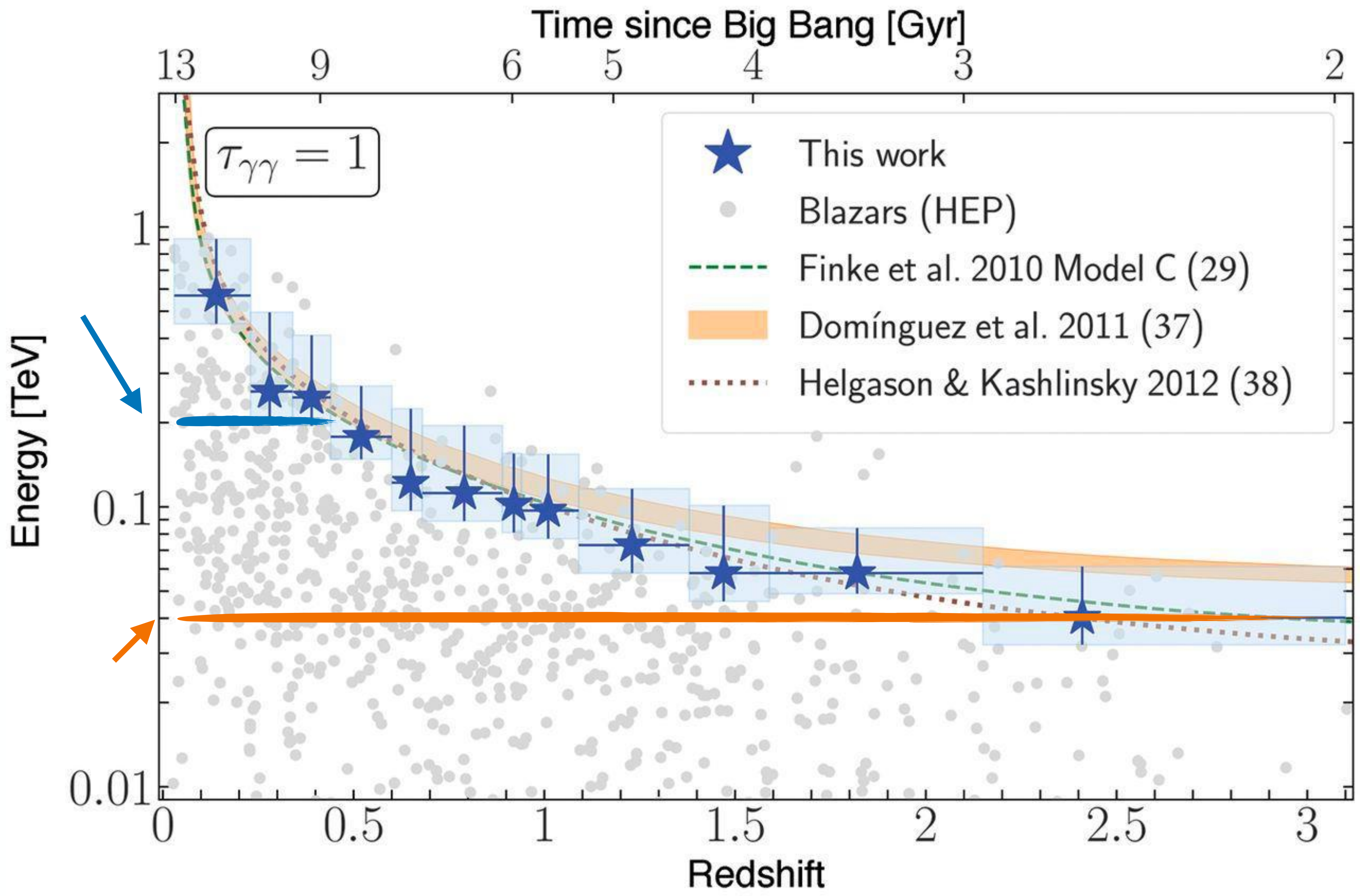






Why reaching the lowest energies?





- Pushing the limits of the lowest detectable energy on the ground means:
  - ✦ increasing the gamma-ray horizon
  - ✦ going back further in time

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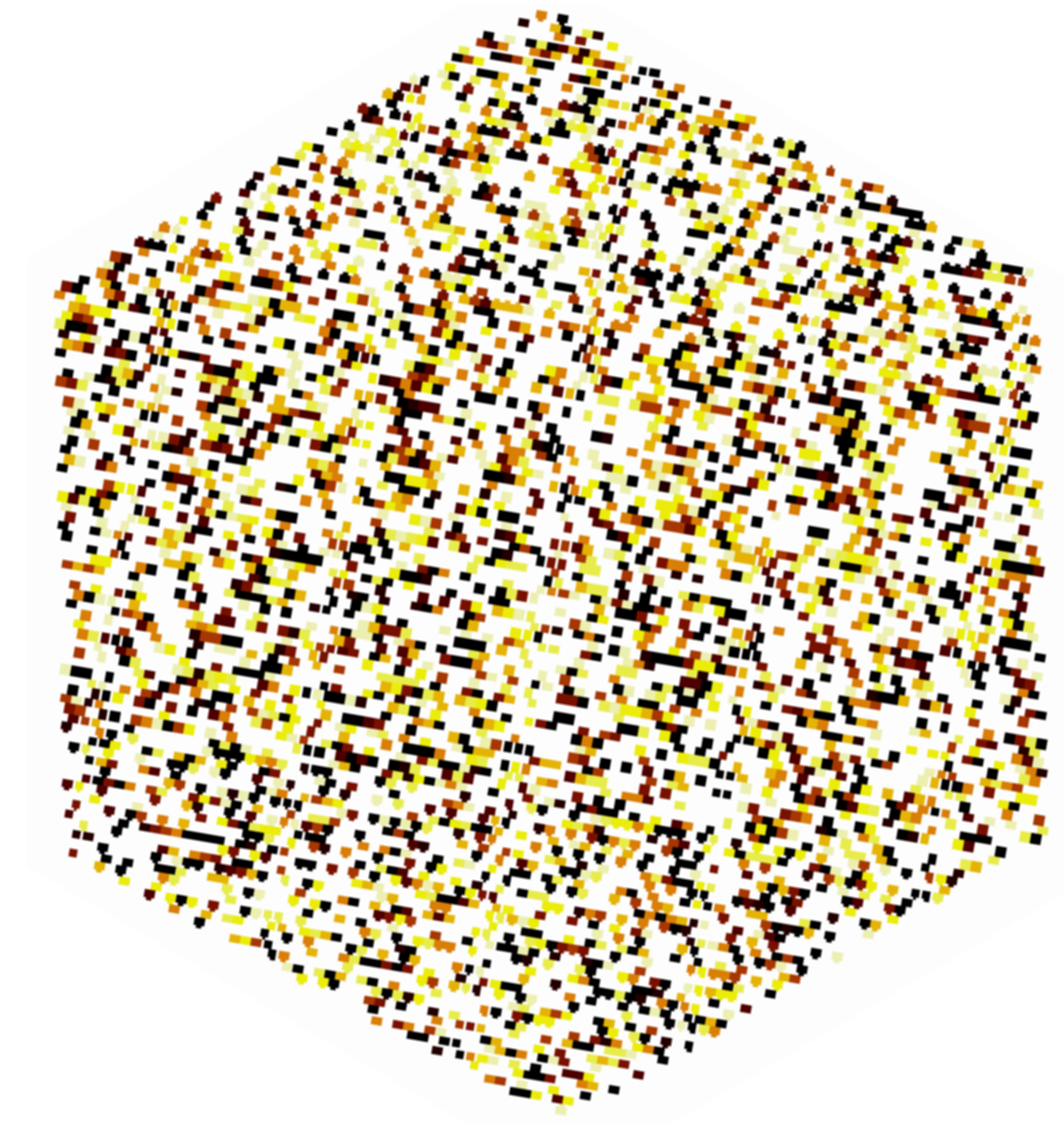
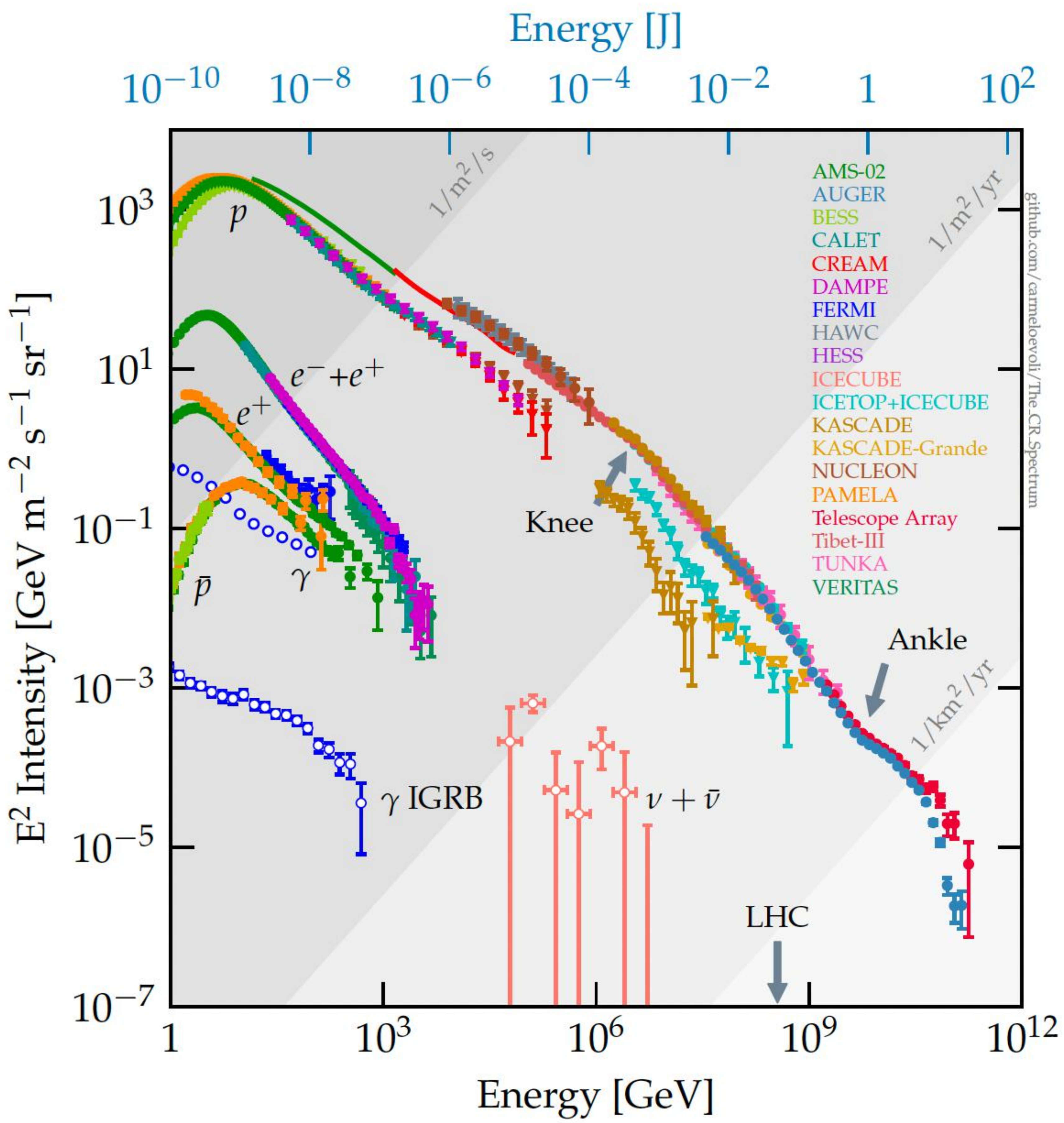
How we record events

- Physics events comes randomly:
  ➡ **Cameras needs to analyse images continuously to take a decision whether or not to acquire an event**

1 Gfps





What is an event?

A short clip of 50 frames (50 ns) with a 12 bit resolution also called **data cube**

- Physics events only represents about 0.1% of the observation time (20k events per seconds)

- With single photon sensitivity, dark is never really dark: Need to distinguish ***faint images*** from ***background light excesses***

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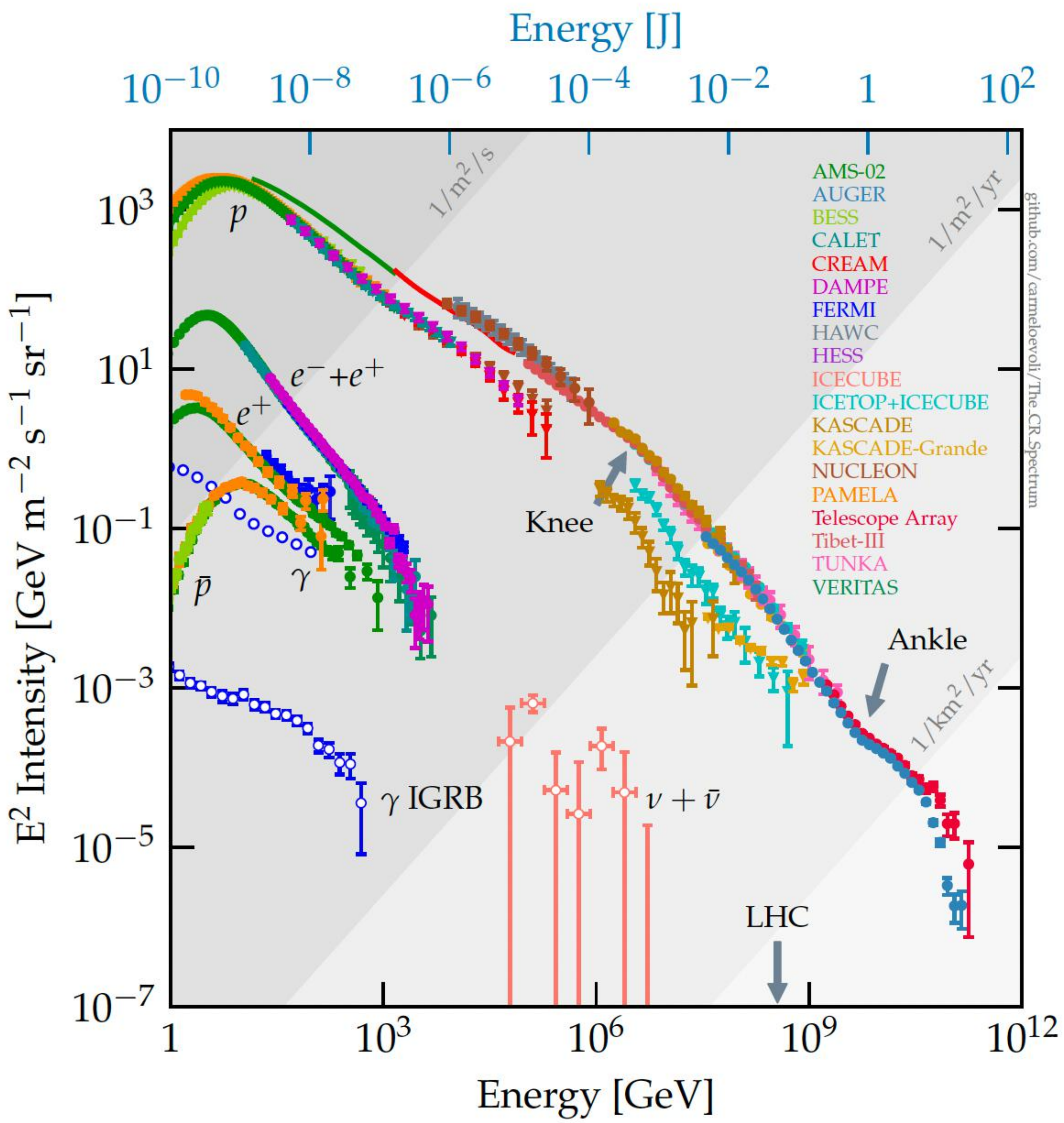

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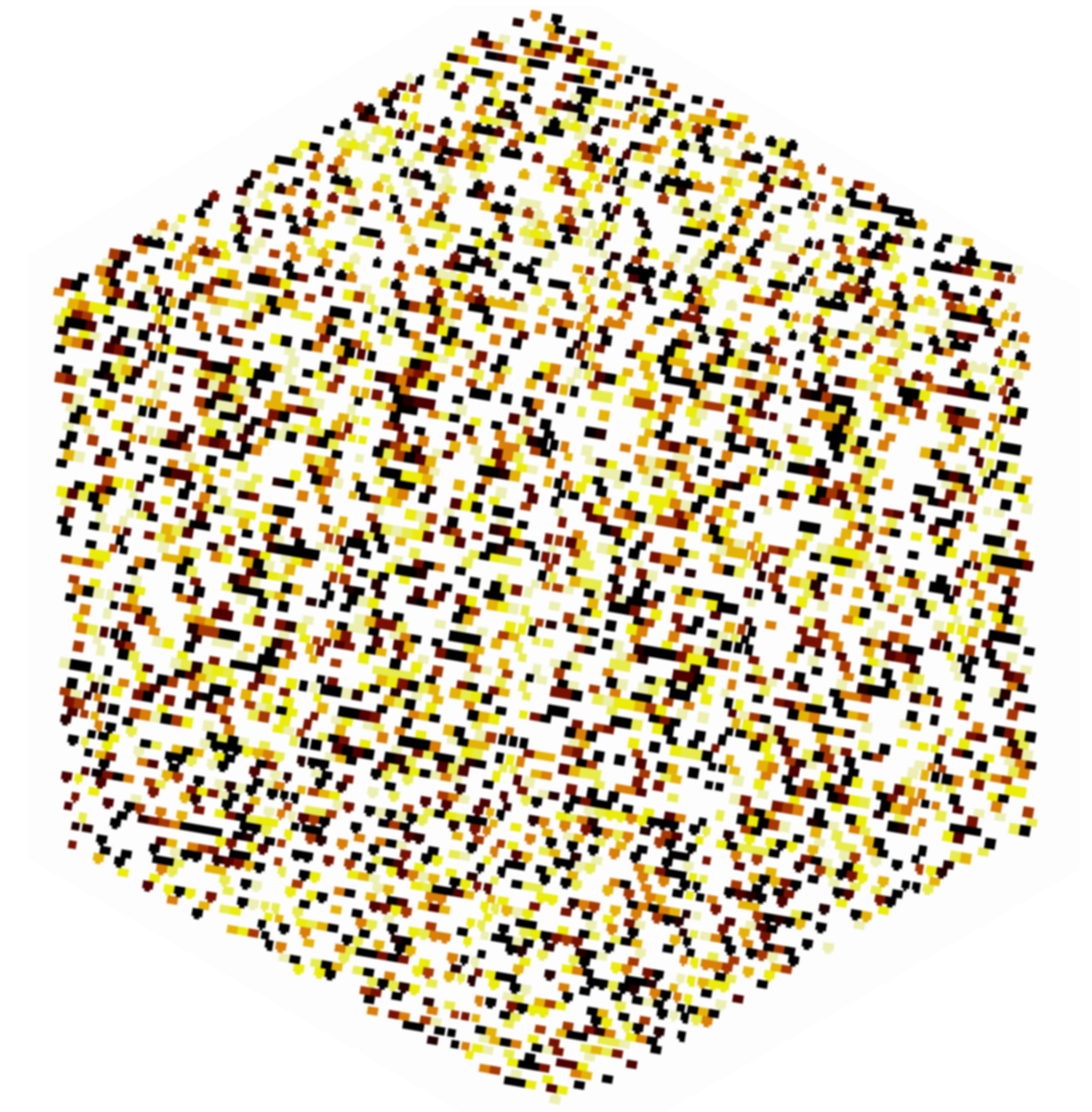

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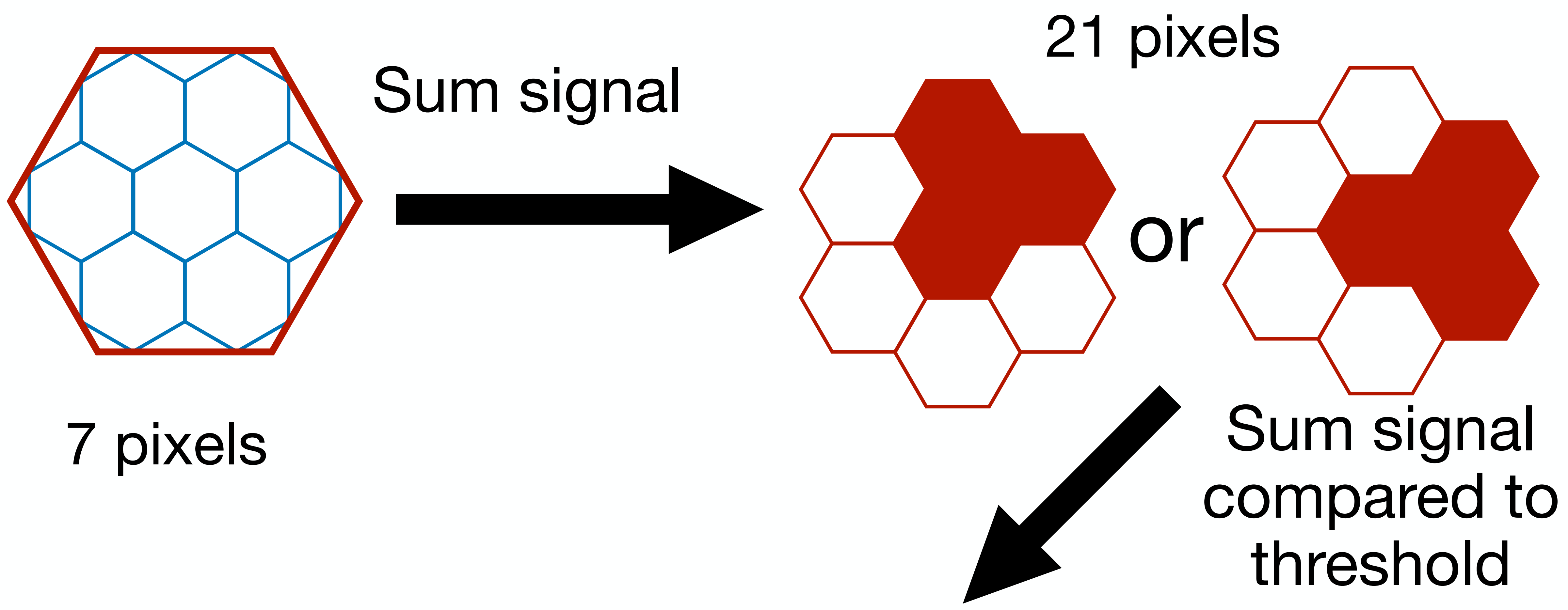
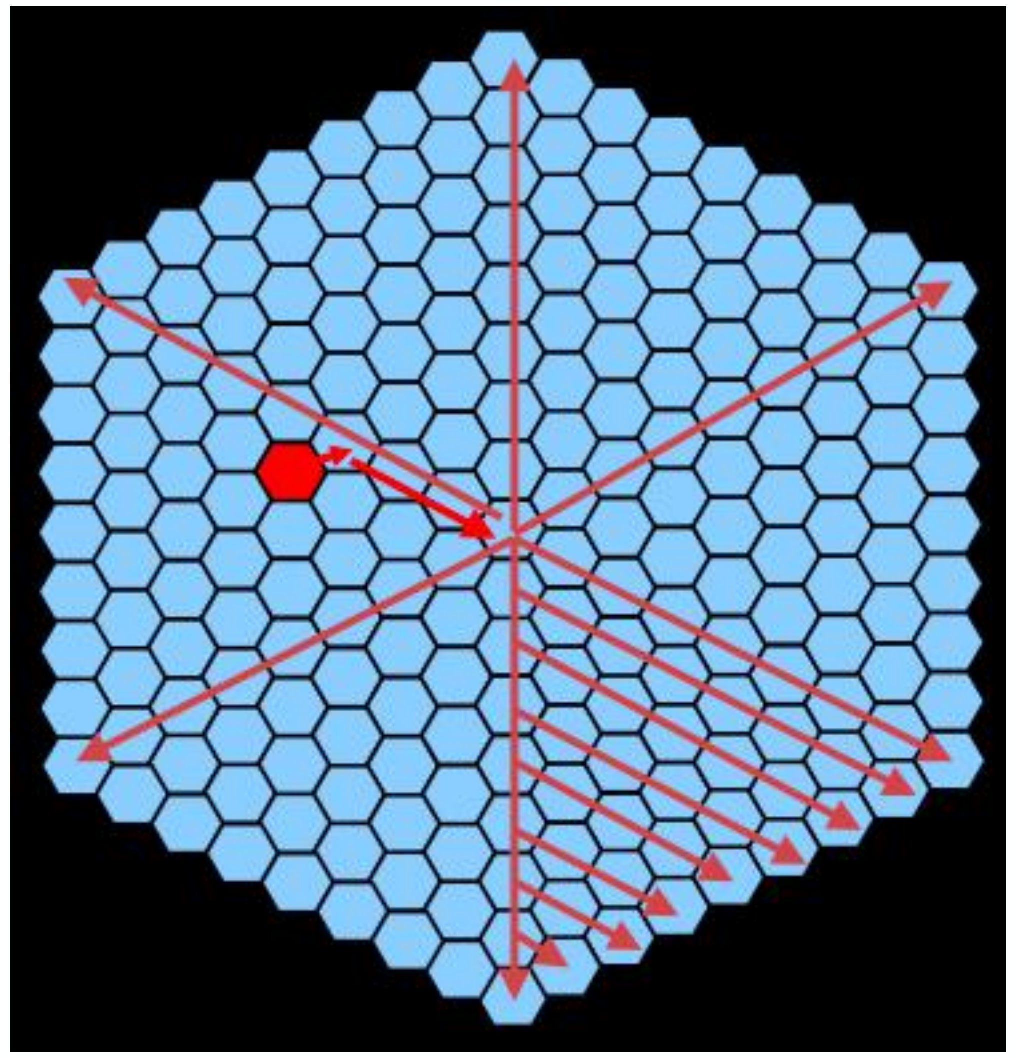
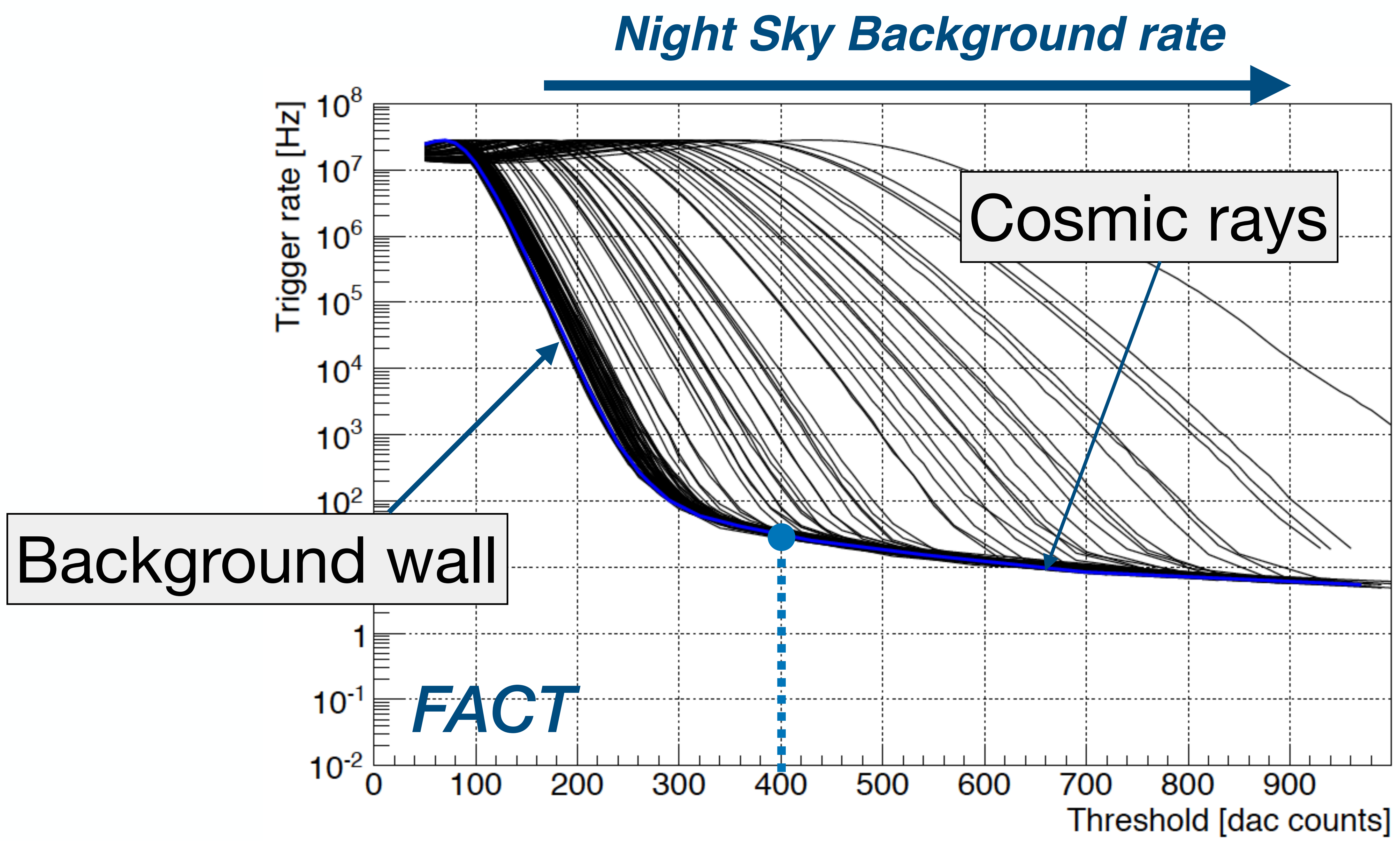
Triggering on showers with analogue trigger





Daisy chain propagation to all camera modules



- Operate telescopes far from "background wall"
- This hardware threshold imposes the lowest energy achievable later at analysis stage

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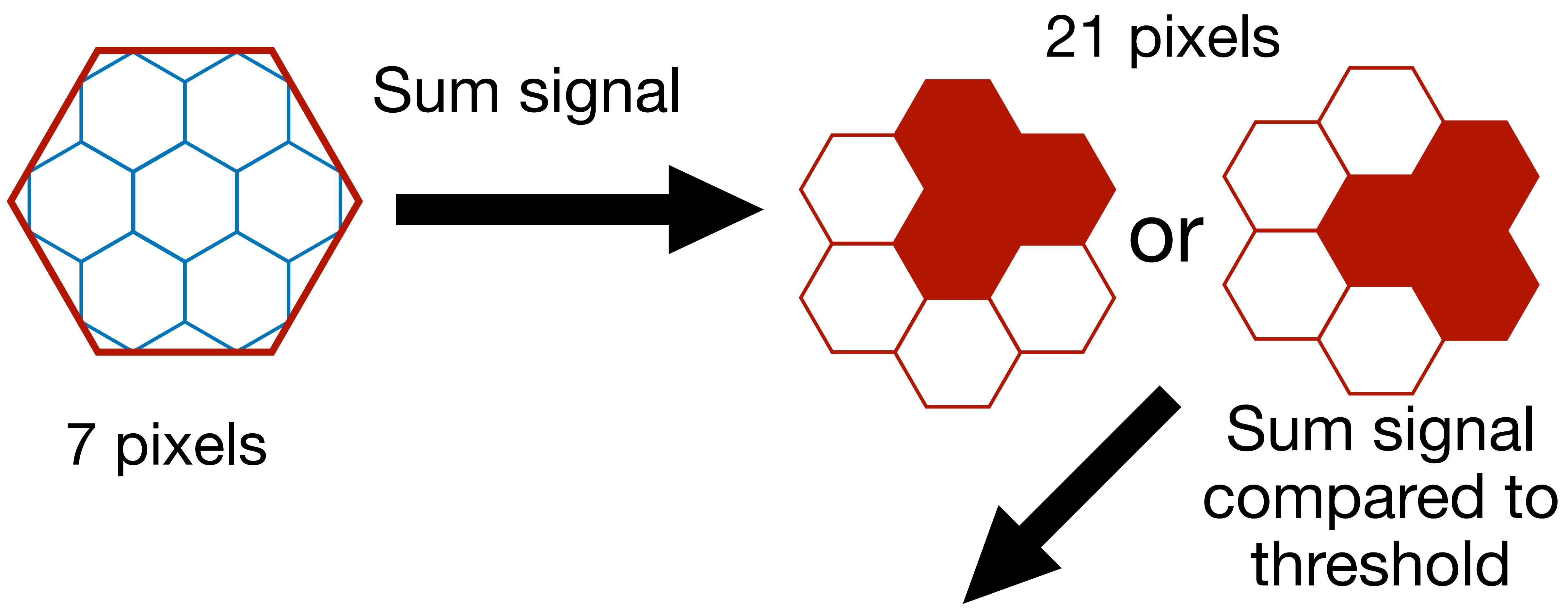

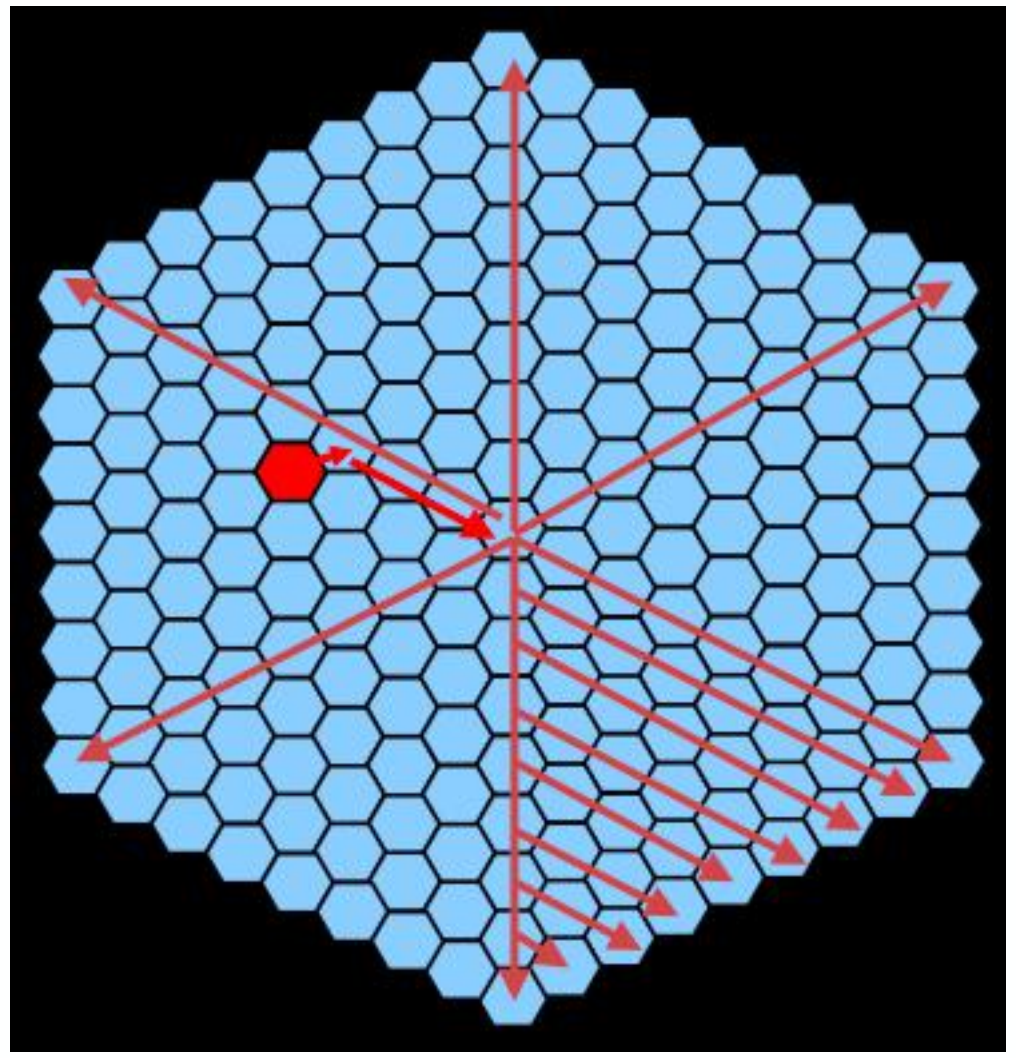

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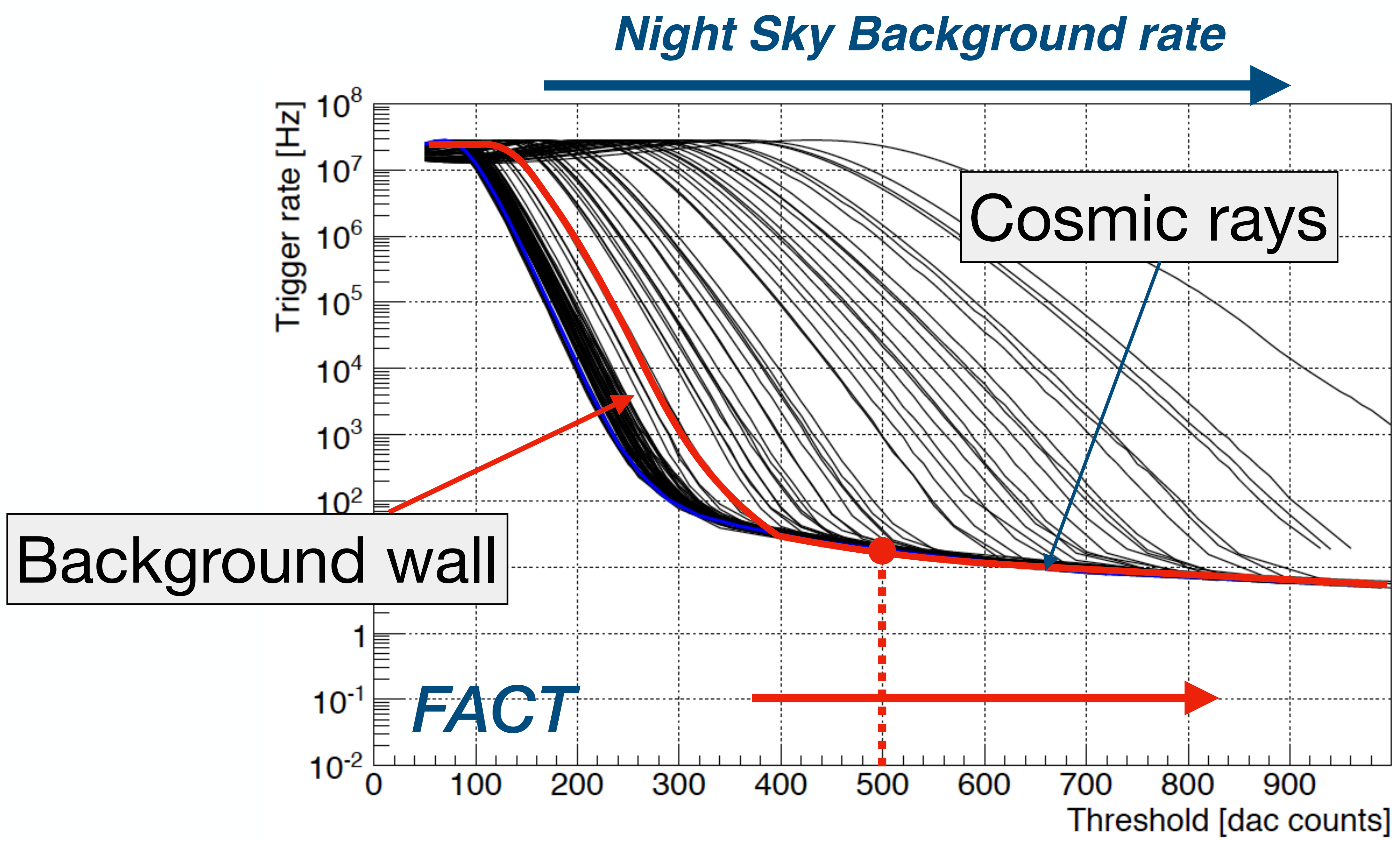

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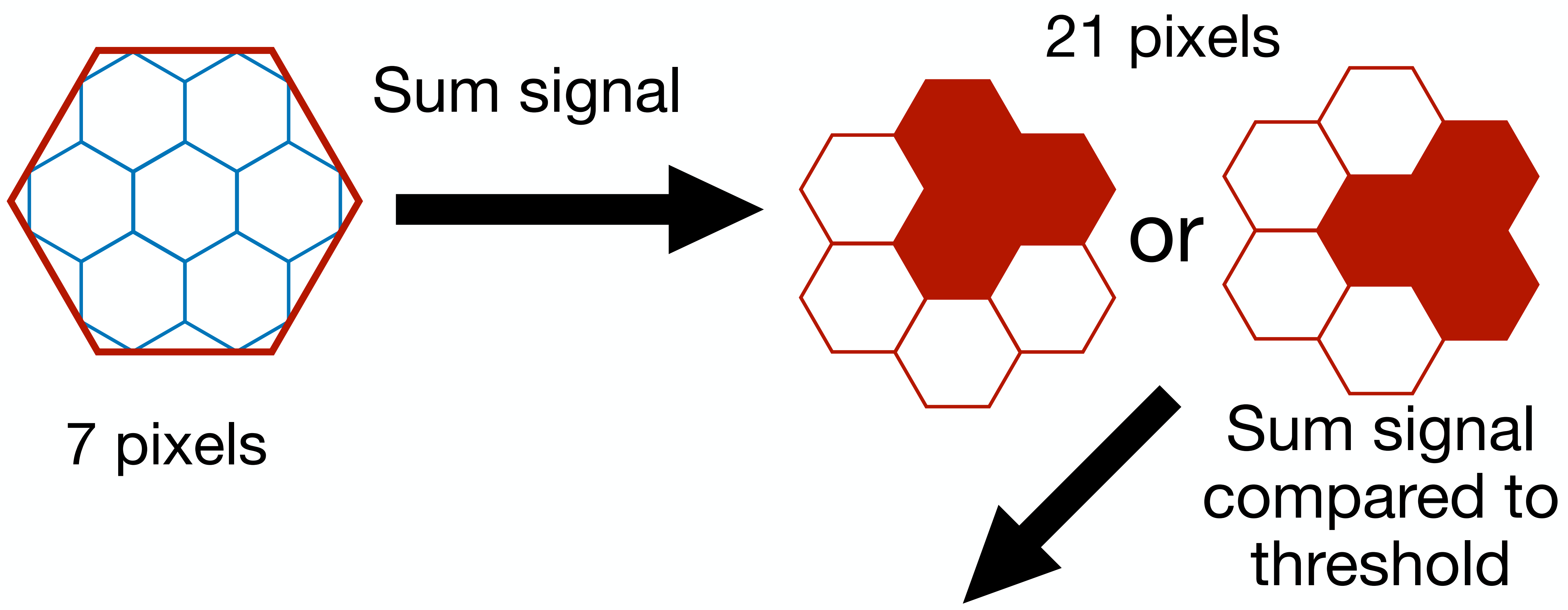

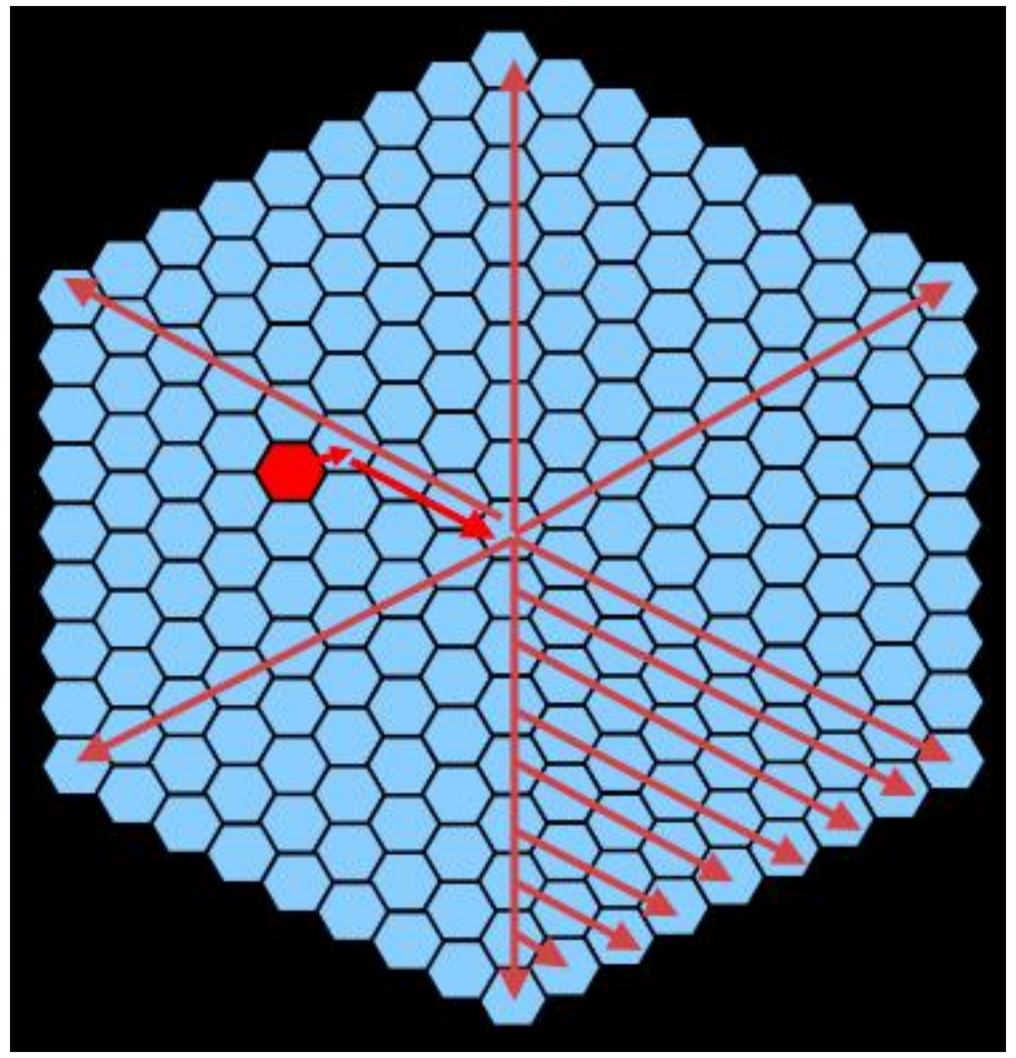

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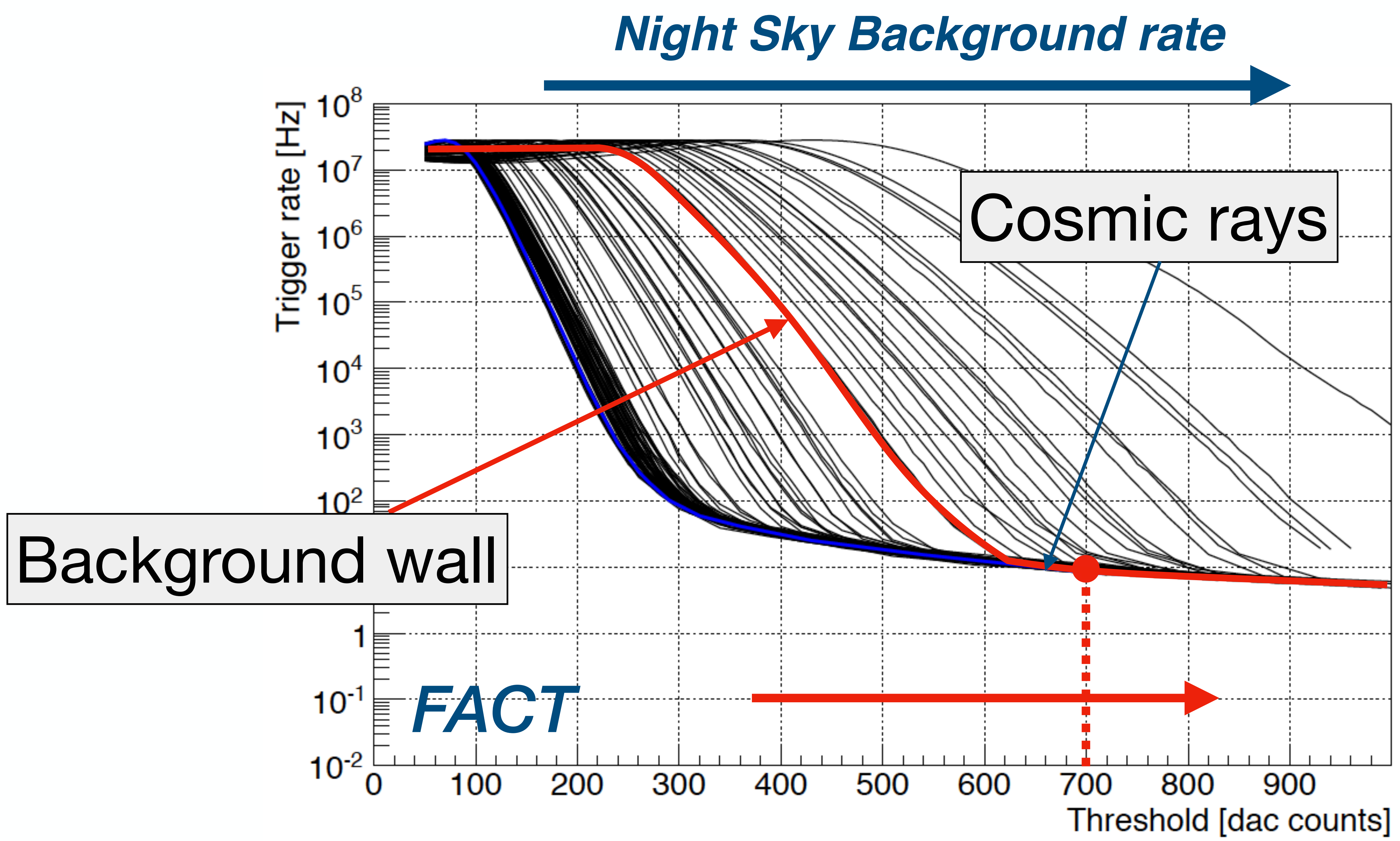
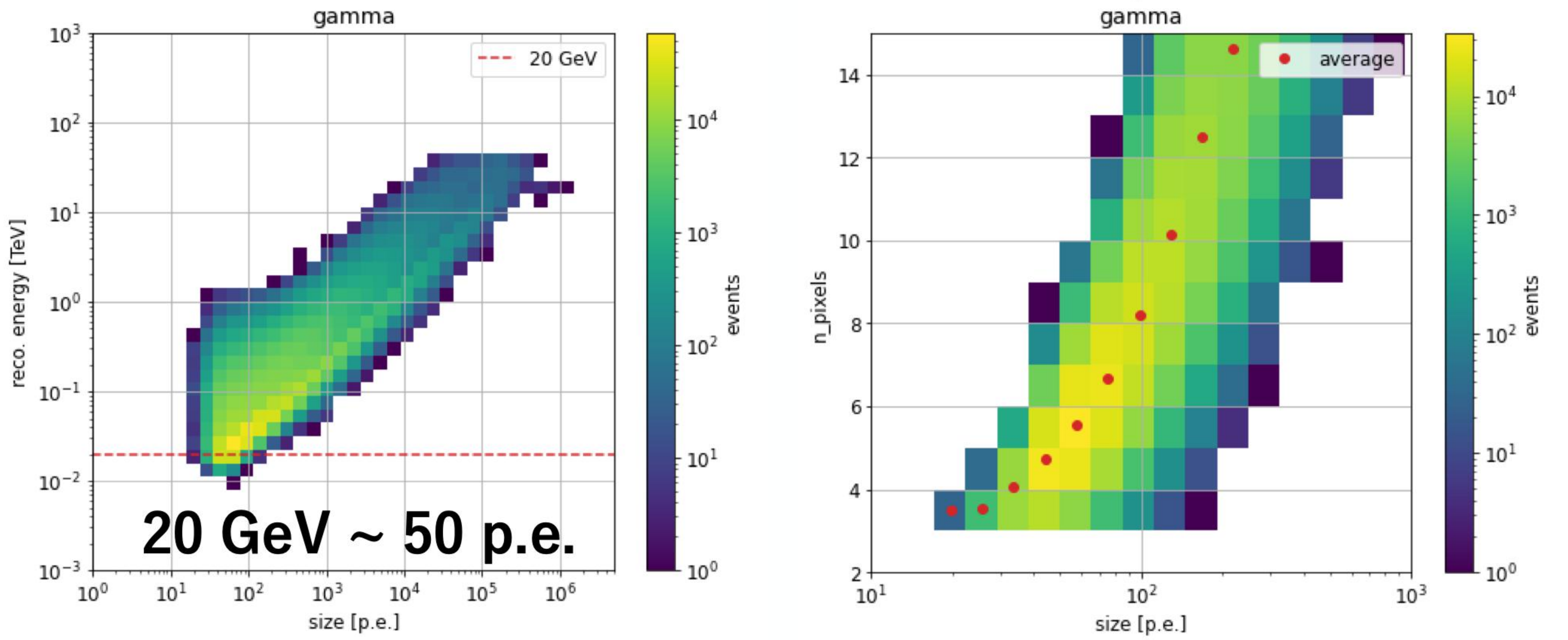


- Operate telescopes far from "background wall"
- This hardware threshold imposes the lowest energy achievable later at analysis stage

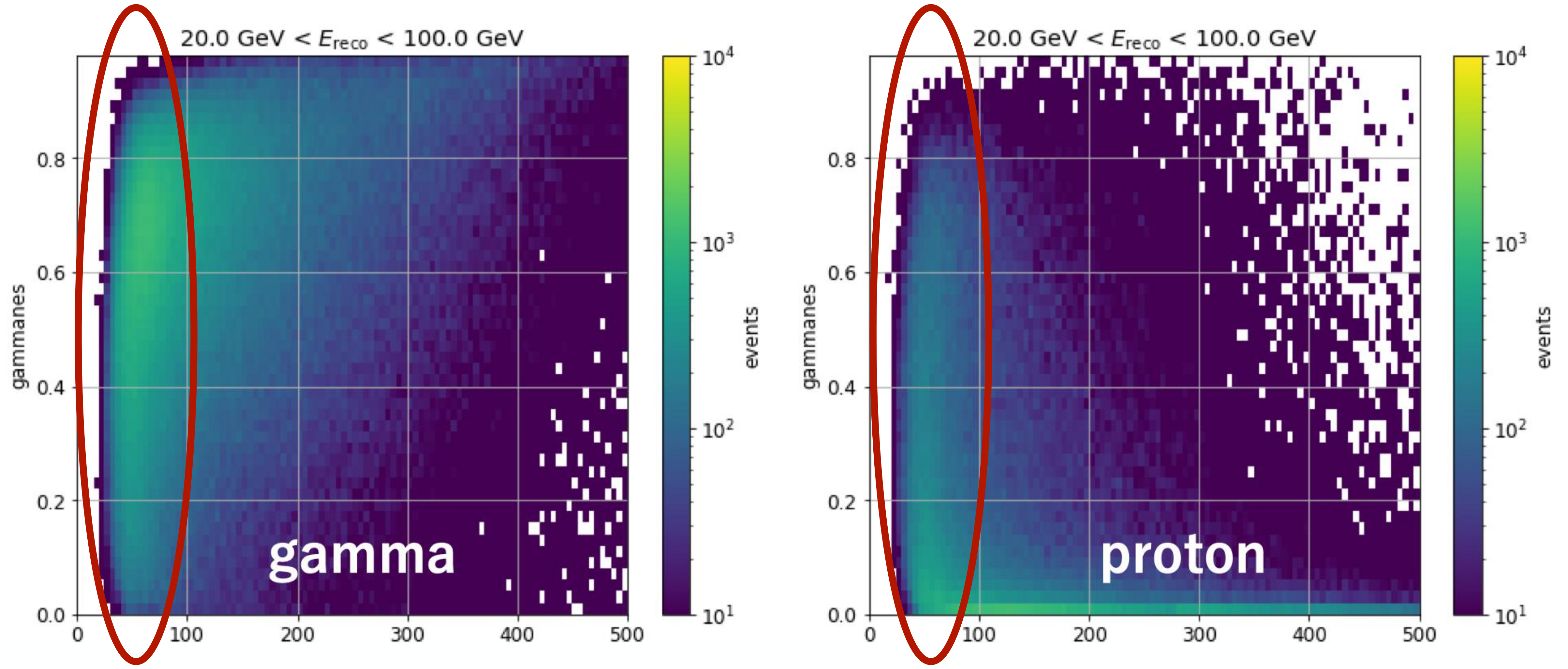
Data analysis methods will improve, hardware threshold must not be the limiting factor

Can we improve the performance?

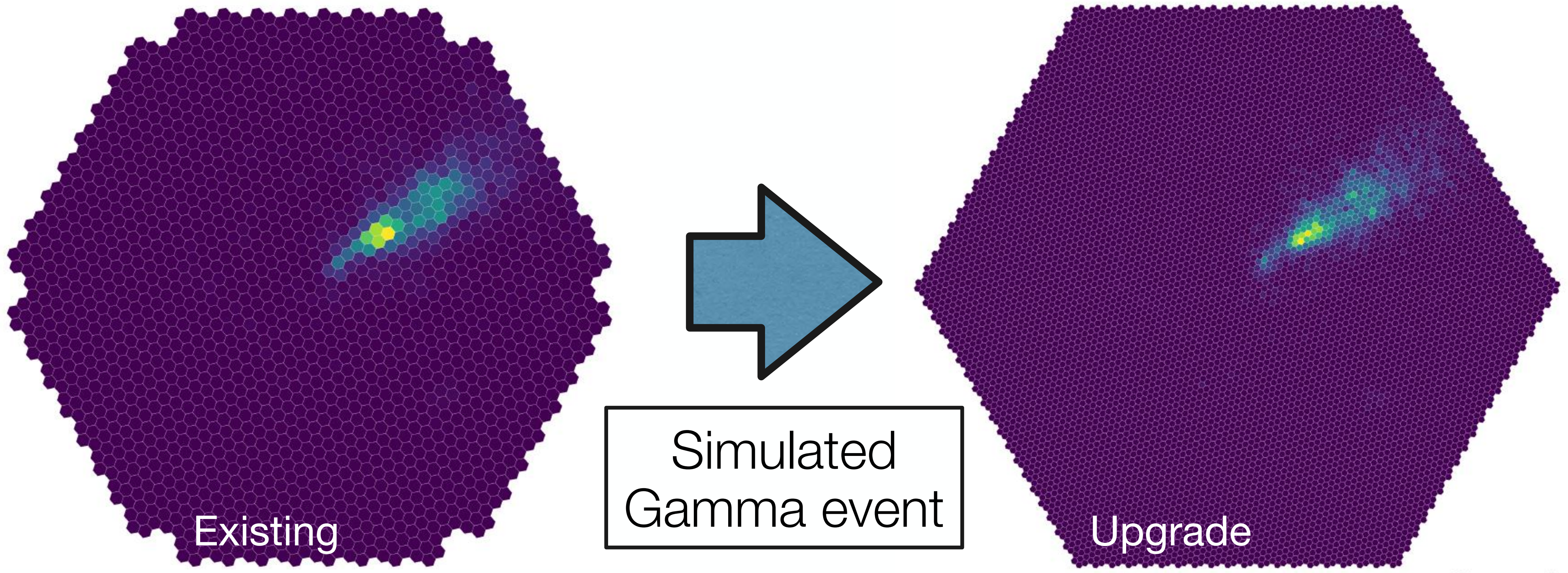
Performance from existing LST camera
@ low energy



Images are small and faints ➡ **Use sensors with higher sensitivity**



Gammas and Protons are very lookalike ➡ **Increase image granularity**



- Proposed detector upgrade for future imaging atmospheric telescopes
- Main upgrades:
  - ✦ Standard photomutiplier tubes
    ➡ **Solid state sensors (SiPM)**
    - Higher sensitivity
    - Smaller pixels (x 4)
  - ✦ Analog trigger and analogue memories
    ➡ **Fully digital readout**
    - Digital trigger
    - **Real-time processing capabilities**

The precursor

The Single Mirror Small-Size Telescope - SST-1M

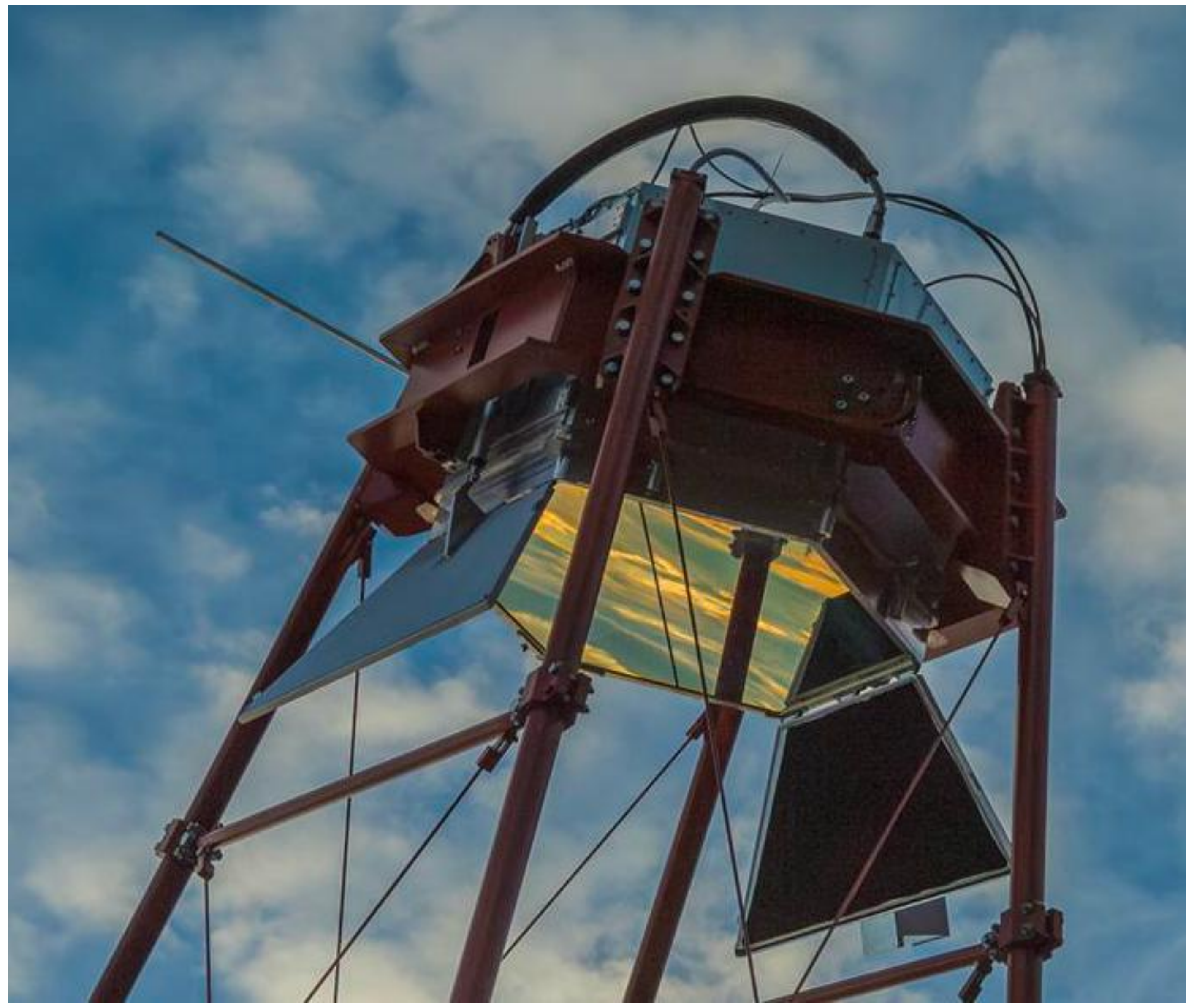
- Swiss, Czech and Polish project proposing a cost effective design for the small-sized telescope array of CTAO

- Not approved despite meeting all requirements

- One prototype and one pre-production telescope produced

- Both installed at the Ondrejov Observatory in Czech Republic, performing stereo observation since 2022

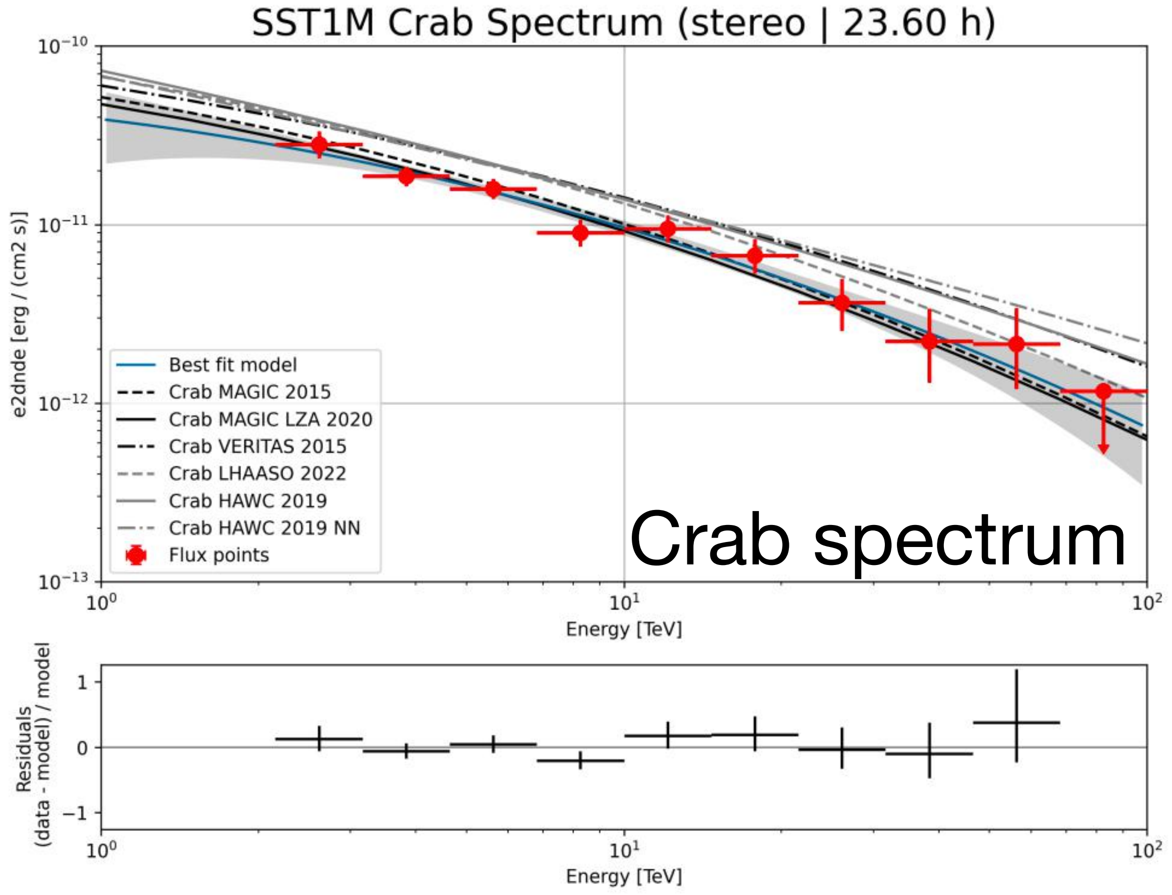
- SNF project started in February for relocation of the telescopes to a proper astronomical observatory (E.g. Hanle, India) and deployment of advanced trigger techniques

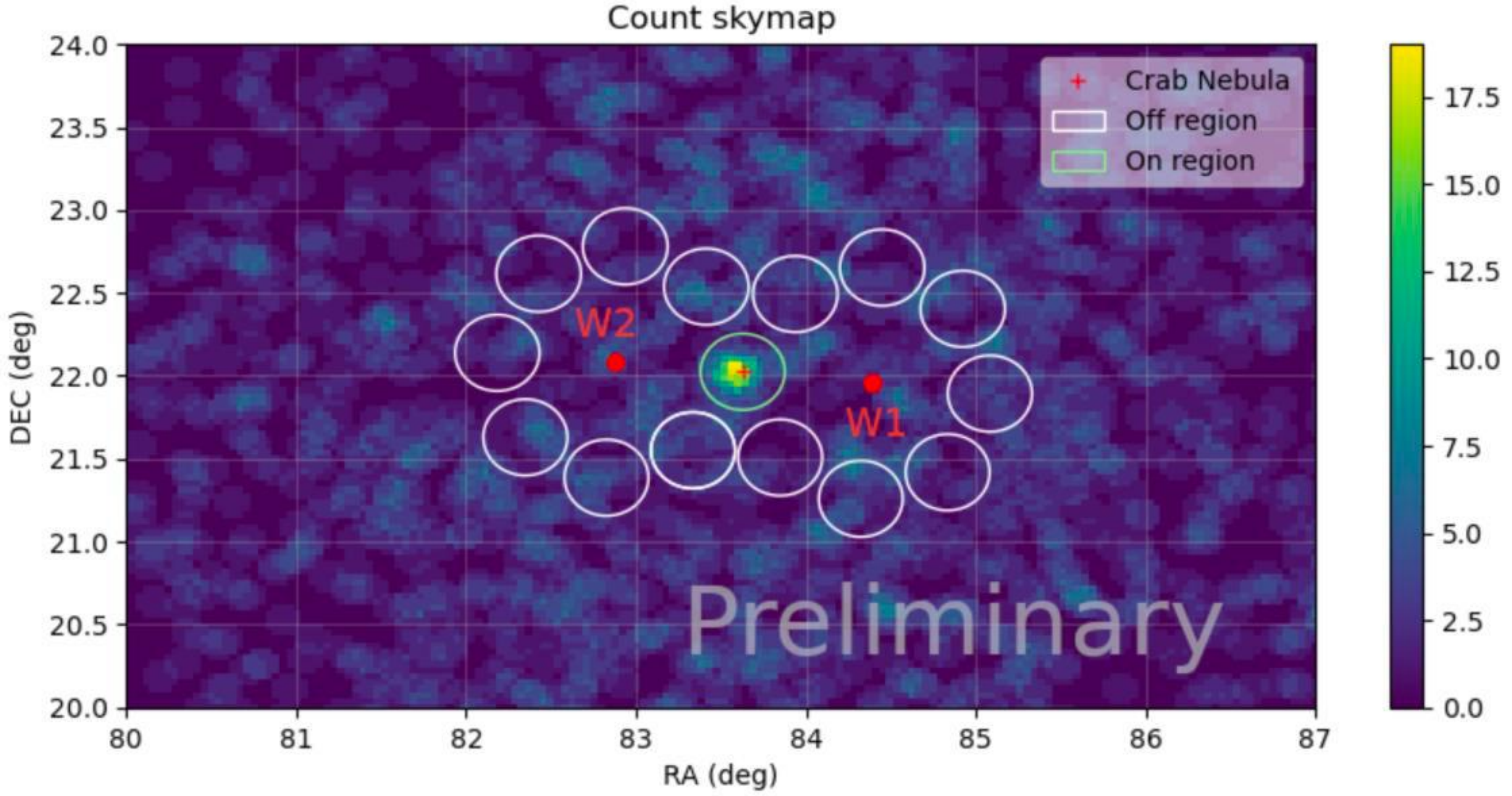


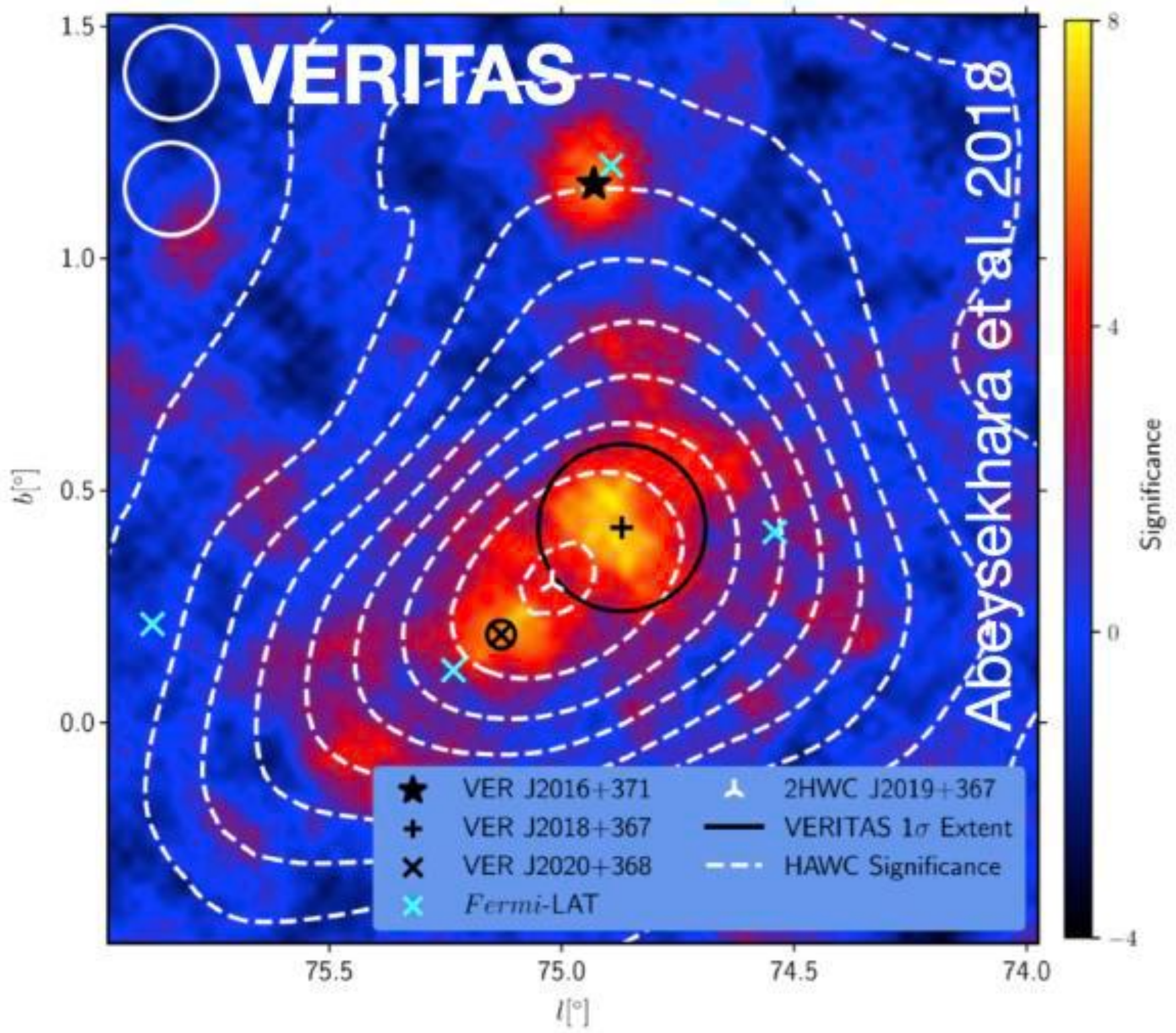
The precursor

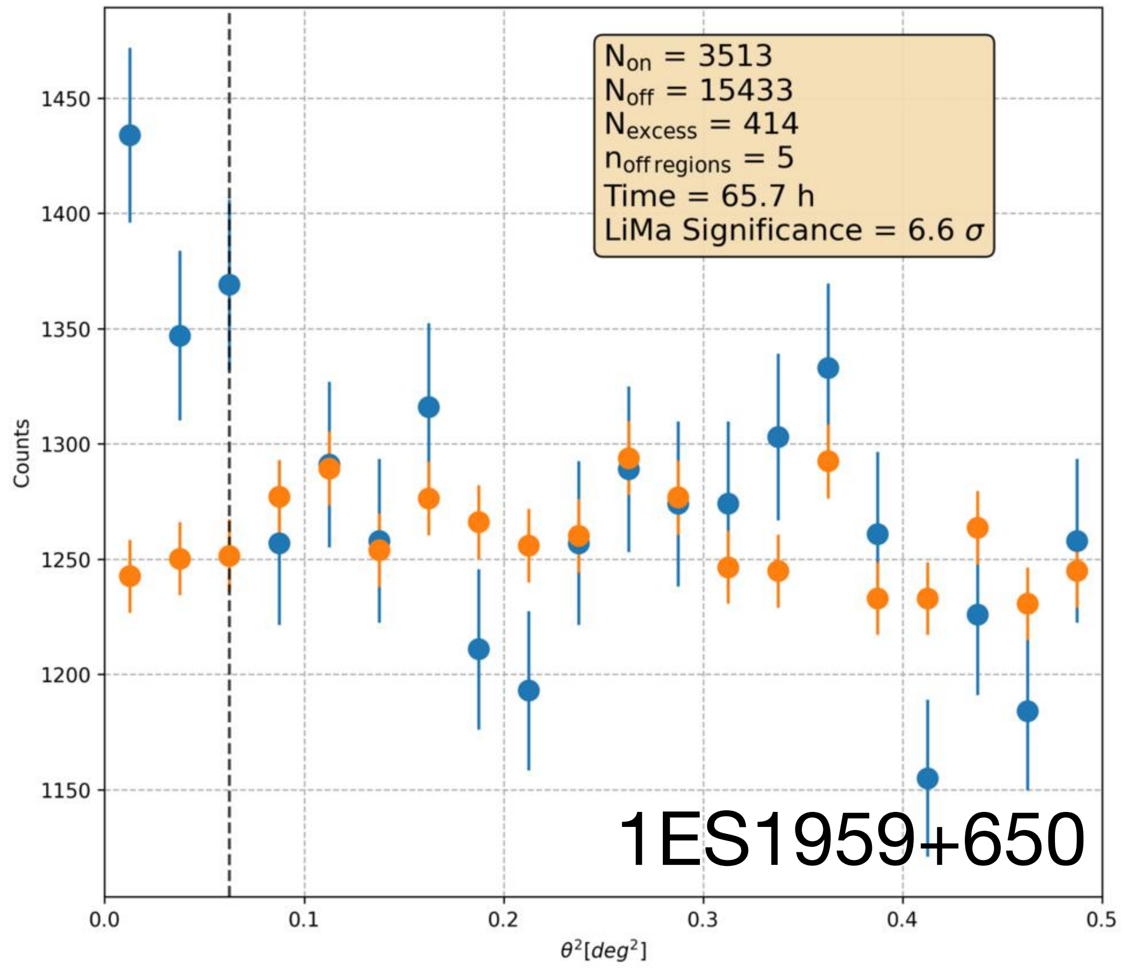
The Single Mirror Small-Size Telescope - SST-1M

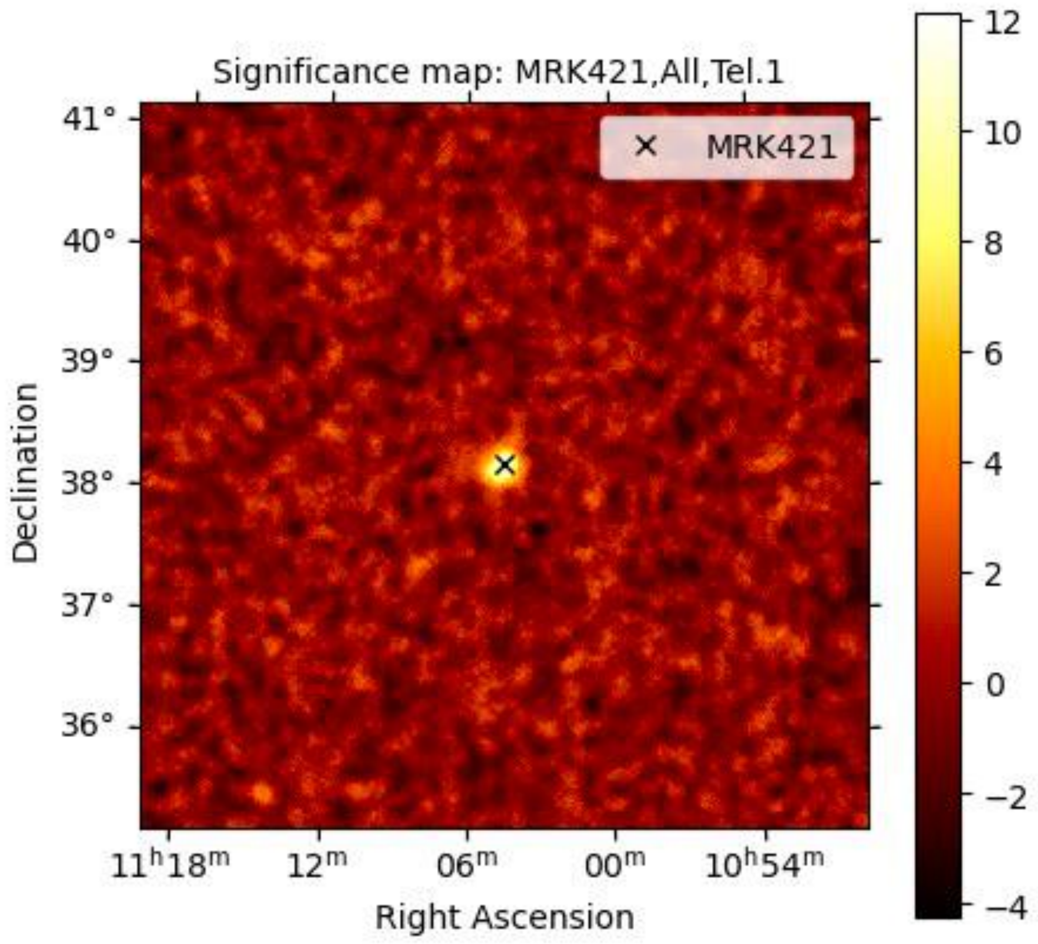
- Focusing on observations bright and nearby blazars
- Exploiting large FoV to observe extended sources

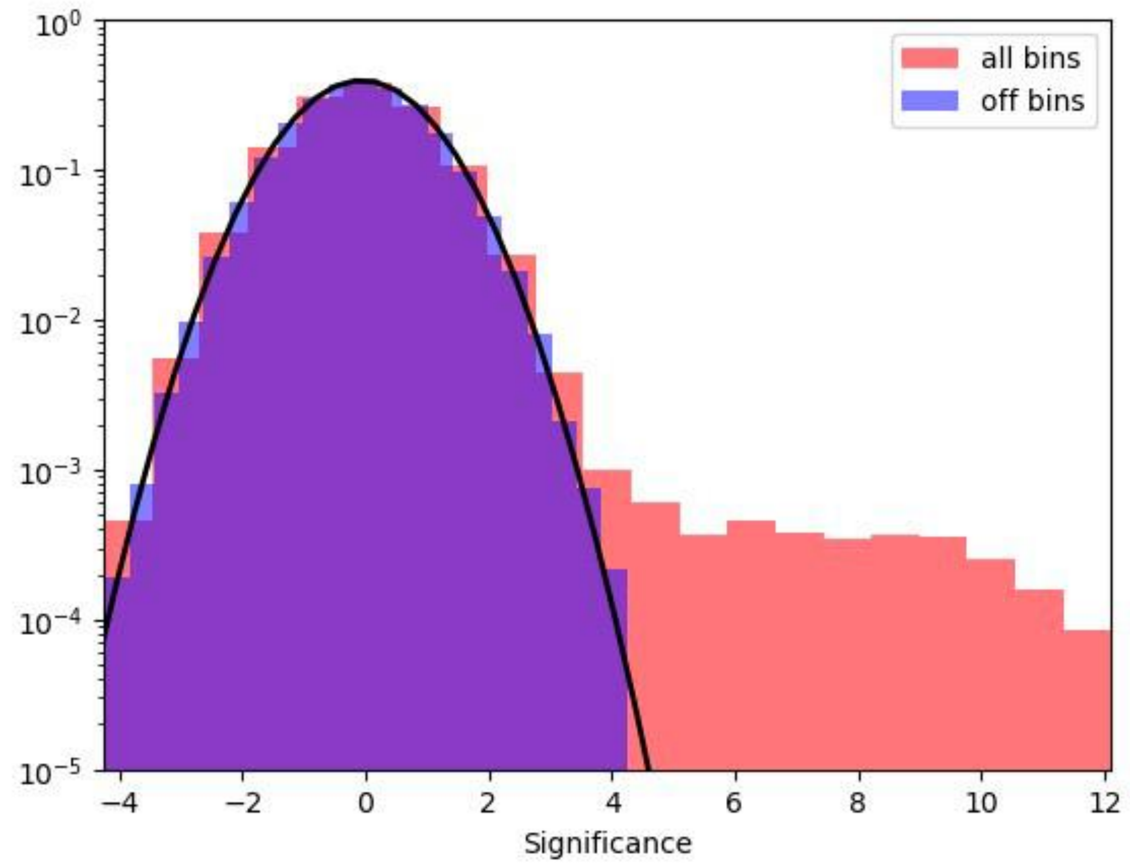


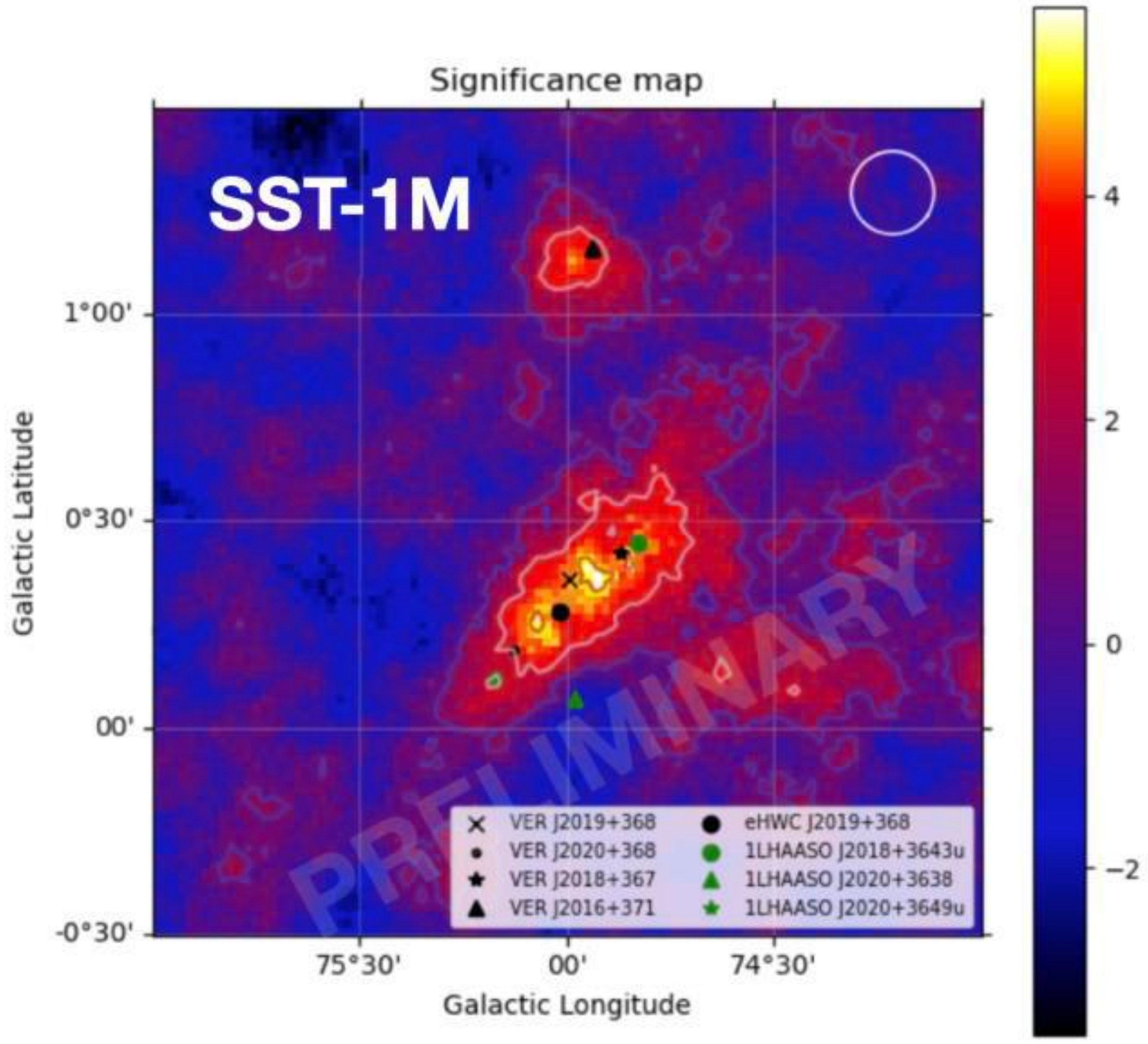








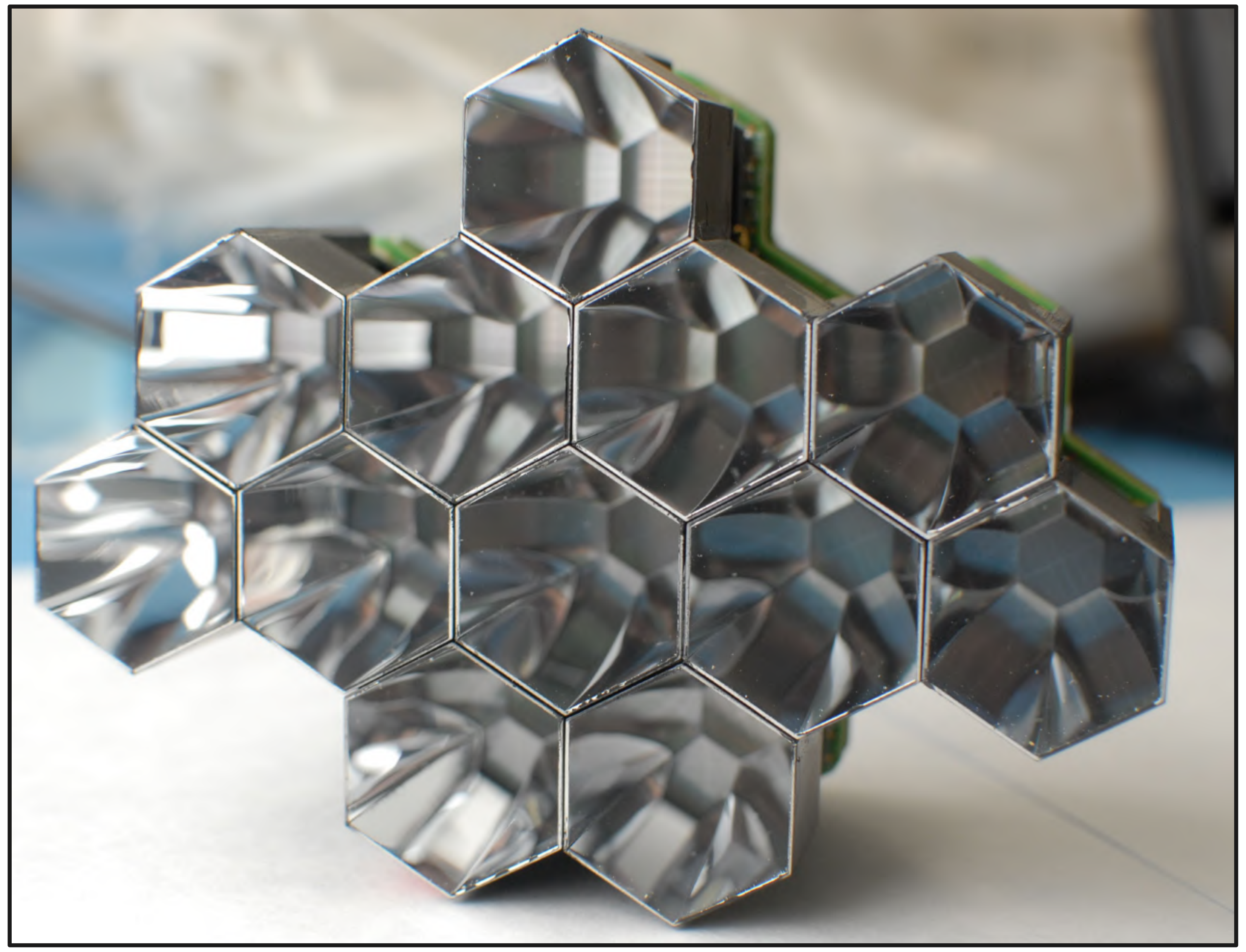




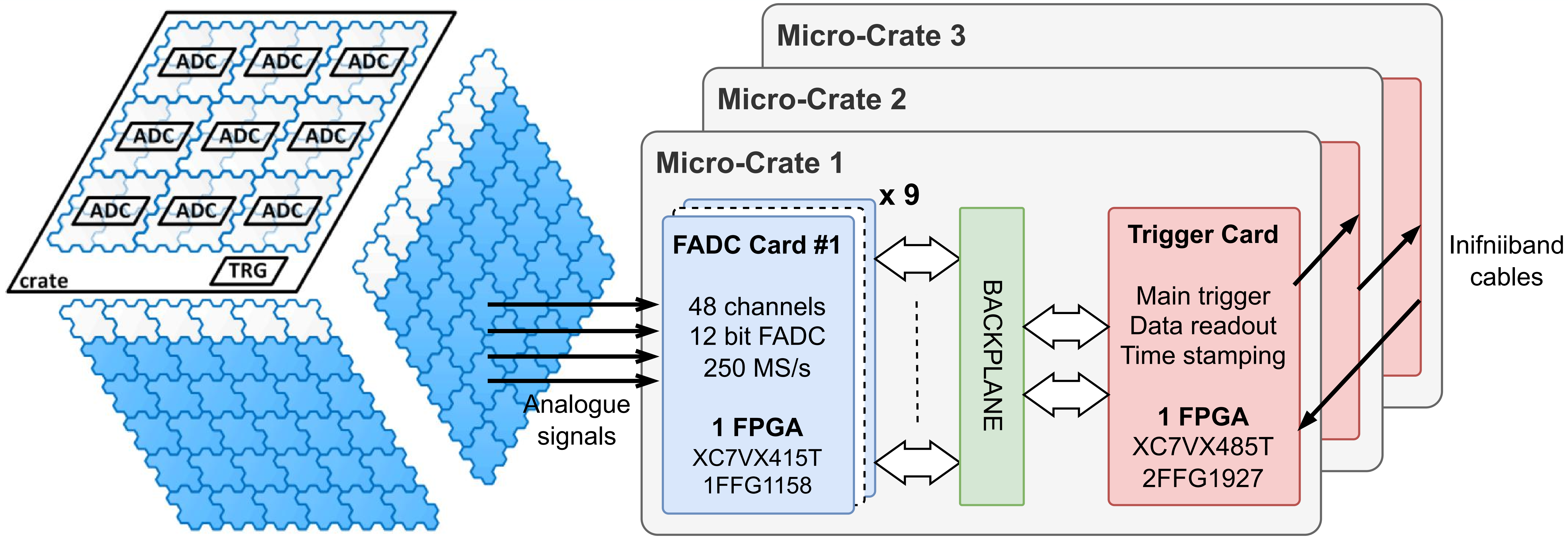
The precursor

The Single Mirror Small-Size Telescope - SST-1M

- All these excellent results confirmed the technological choices made
- Biggest advantages of the SST-1M telescope is its camera which feature **SiPMs** and **fully digital readout**



SST-1M Optical module



SST-1M readout architecture

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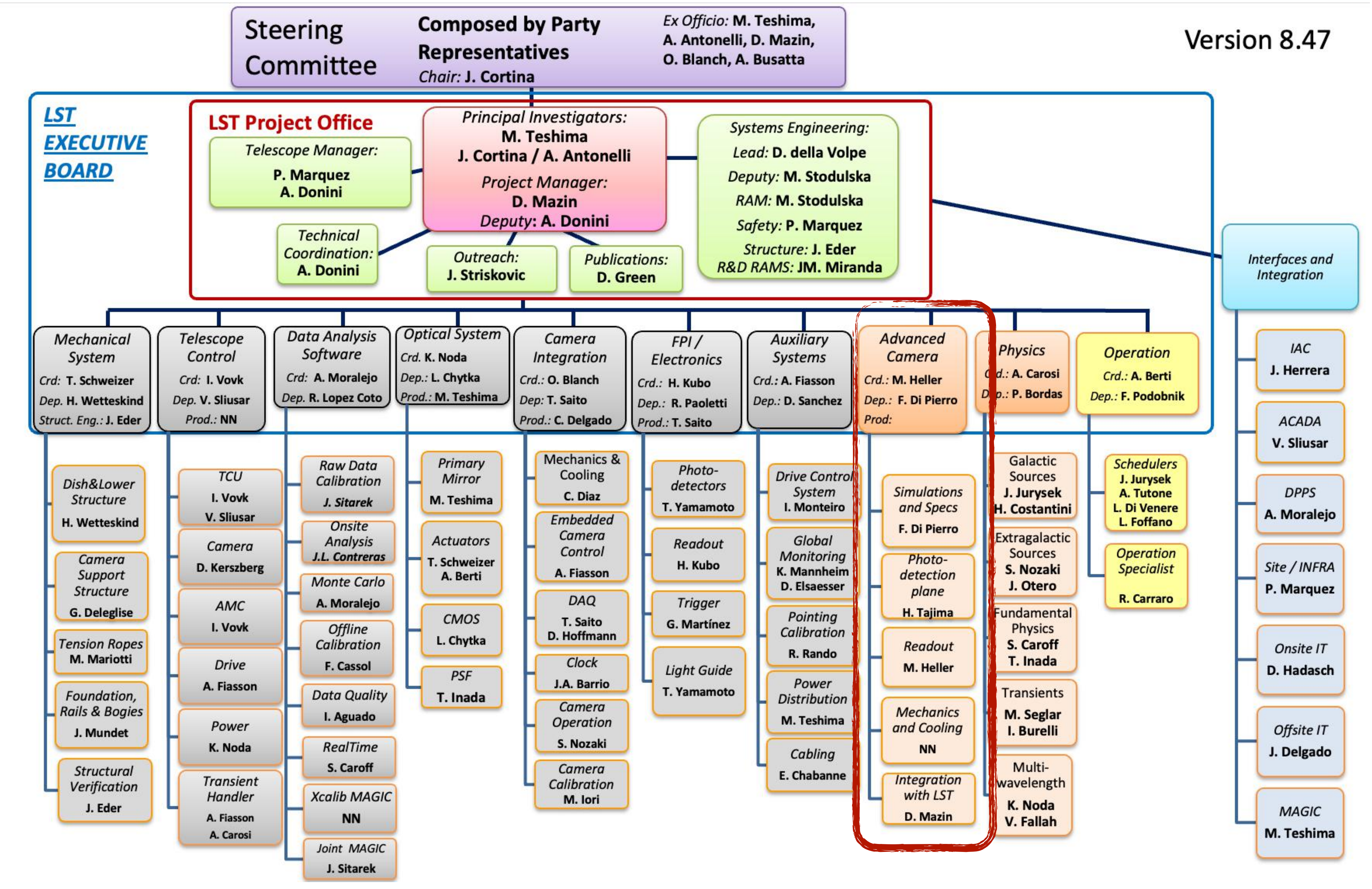
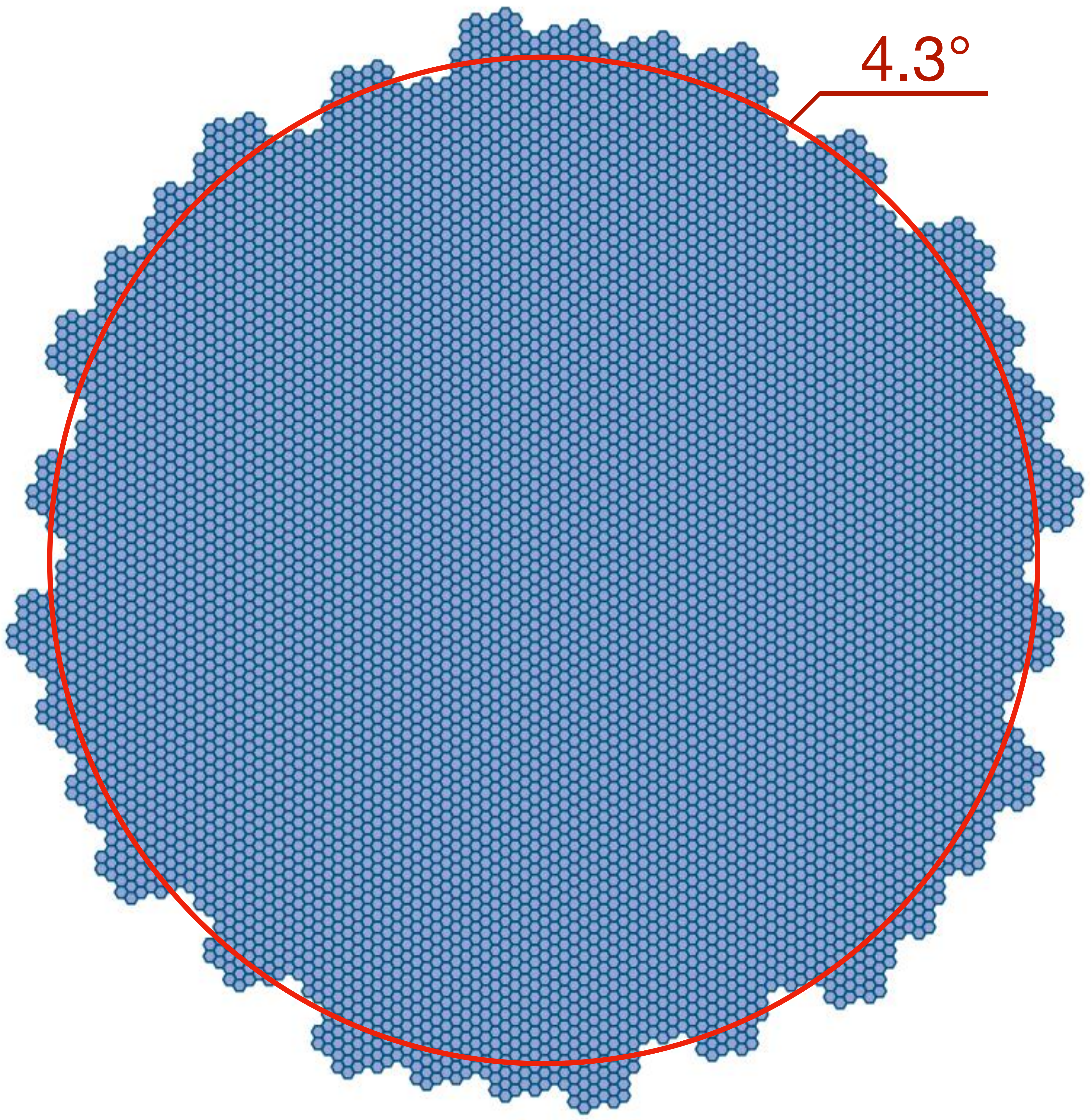
The AdvCamera

- International project within the Large-Sized Telescope of the Cherenkov Telescope Array Observatory
- Camera characteristics
  - ✦ 2.1 m diameter
  - ✦ 151 modules of 49 pixels ➡ 7399 pixel
  - ✦ Field of View of 4.3°
- Each pixel signal is amplified in a custom ASIC and digitized at 1 GSps with 12 bits resolution continuously
  - ✦ Digital waveform accessible as early as possible





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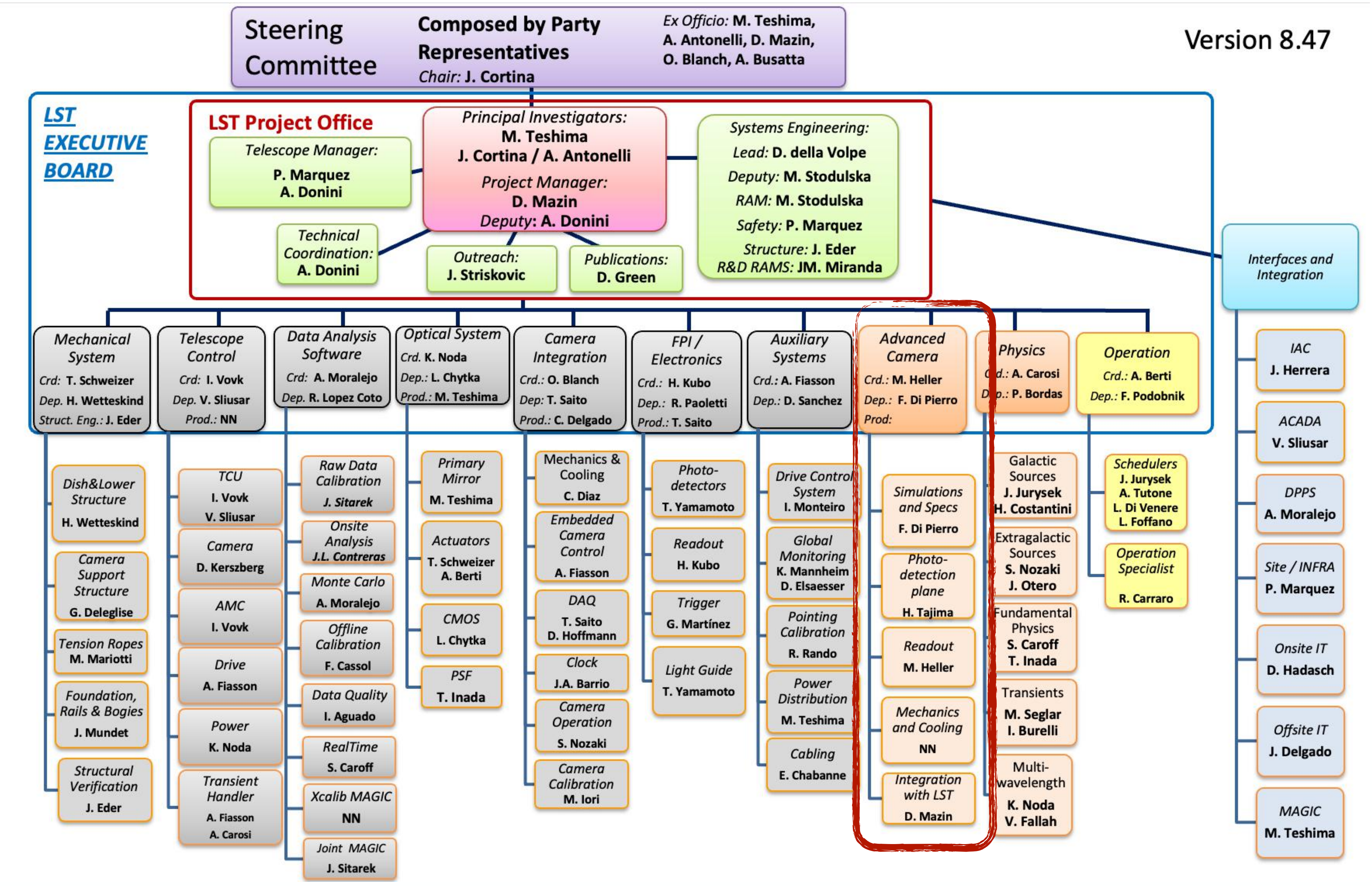
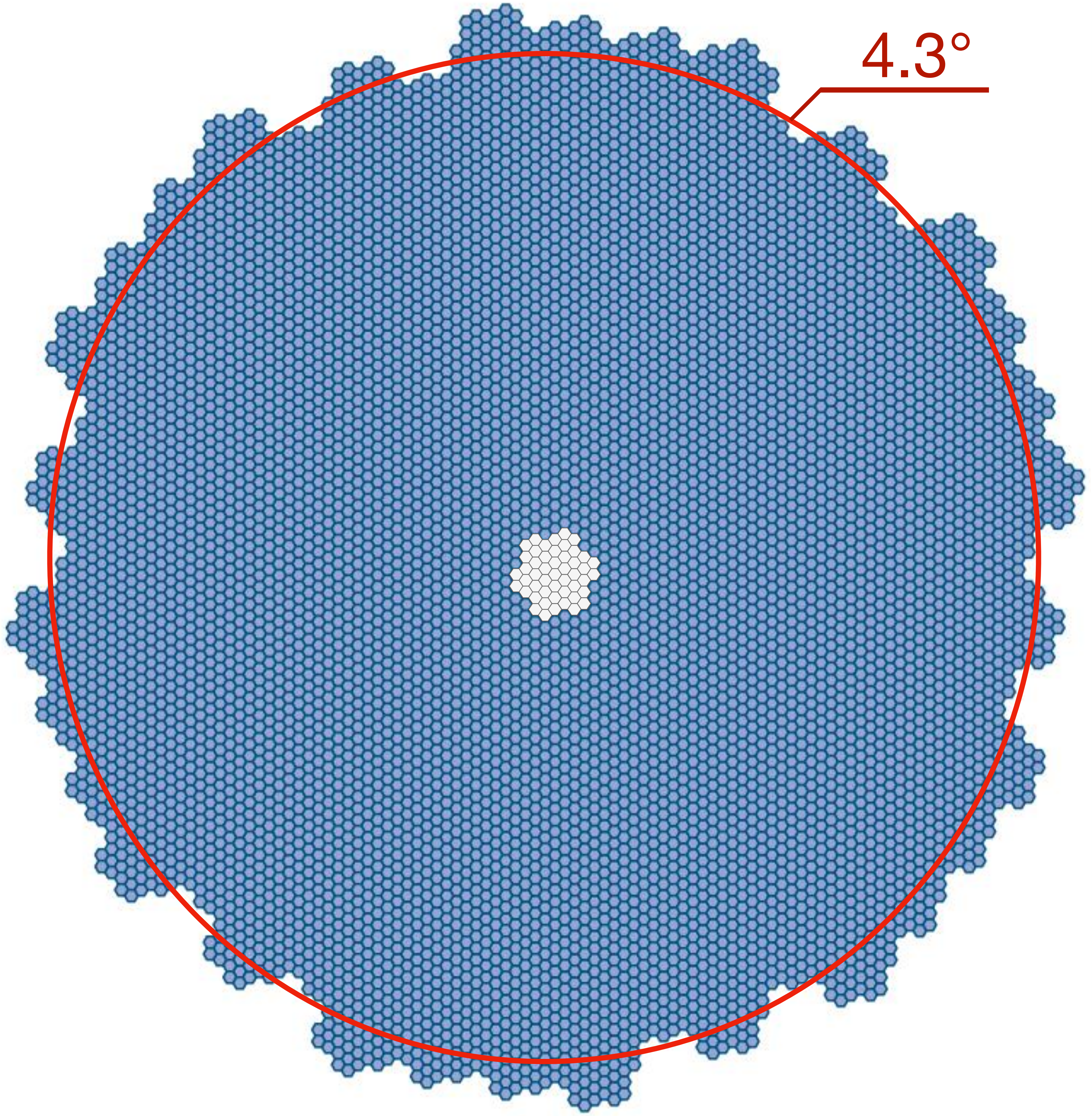
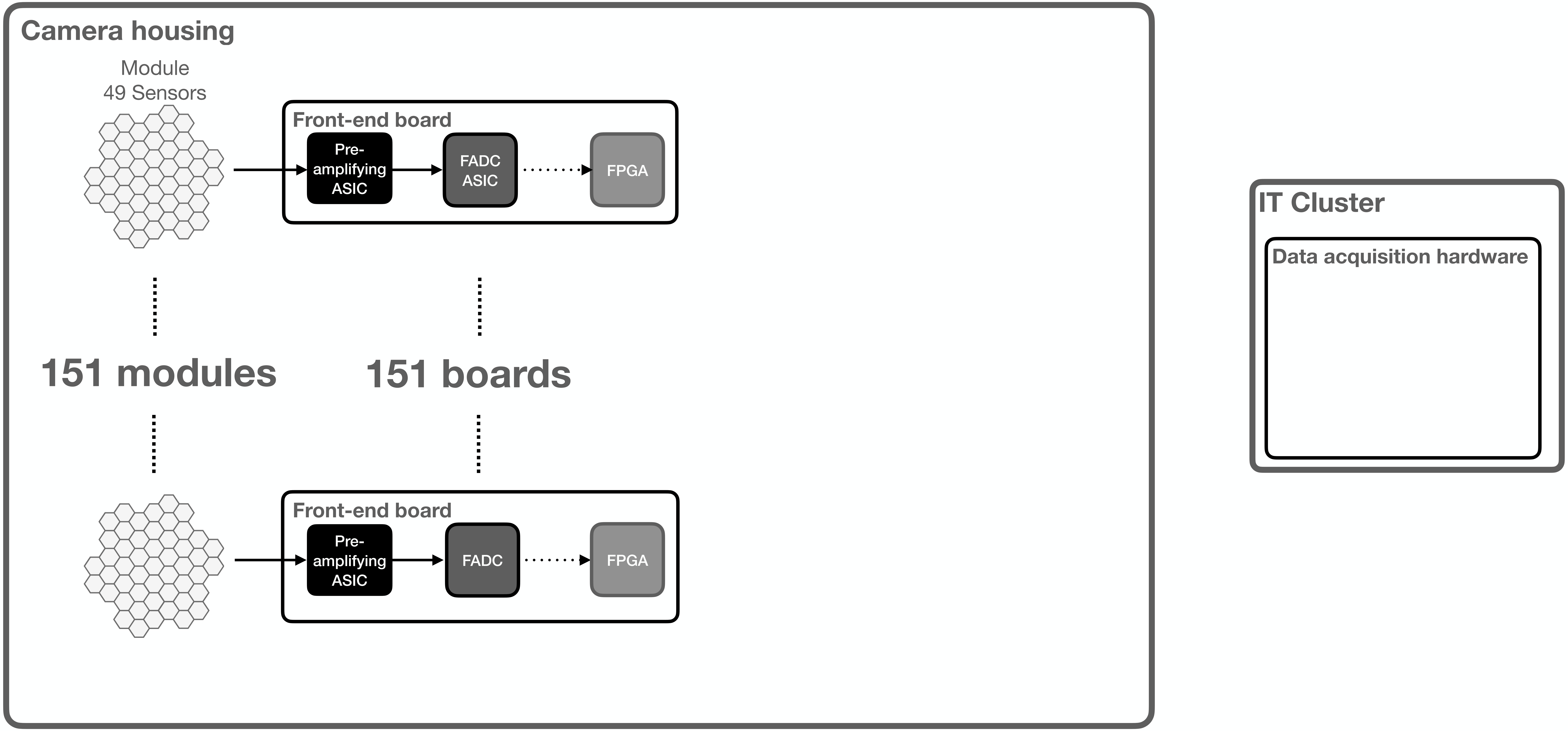
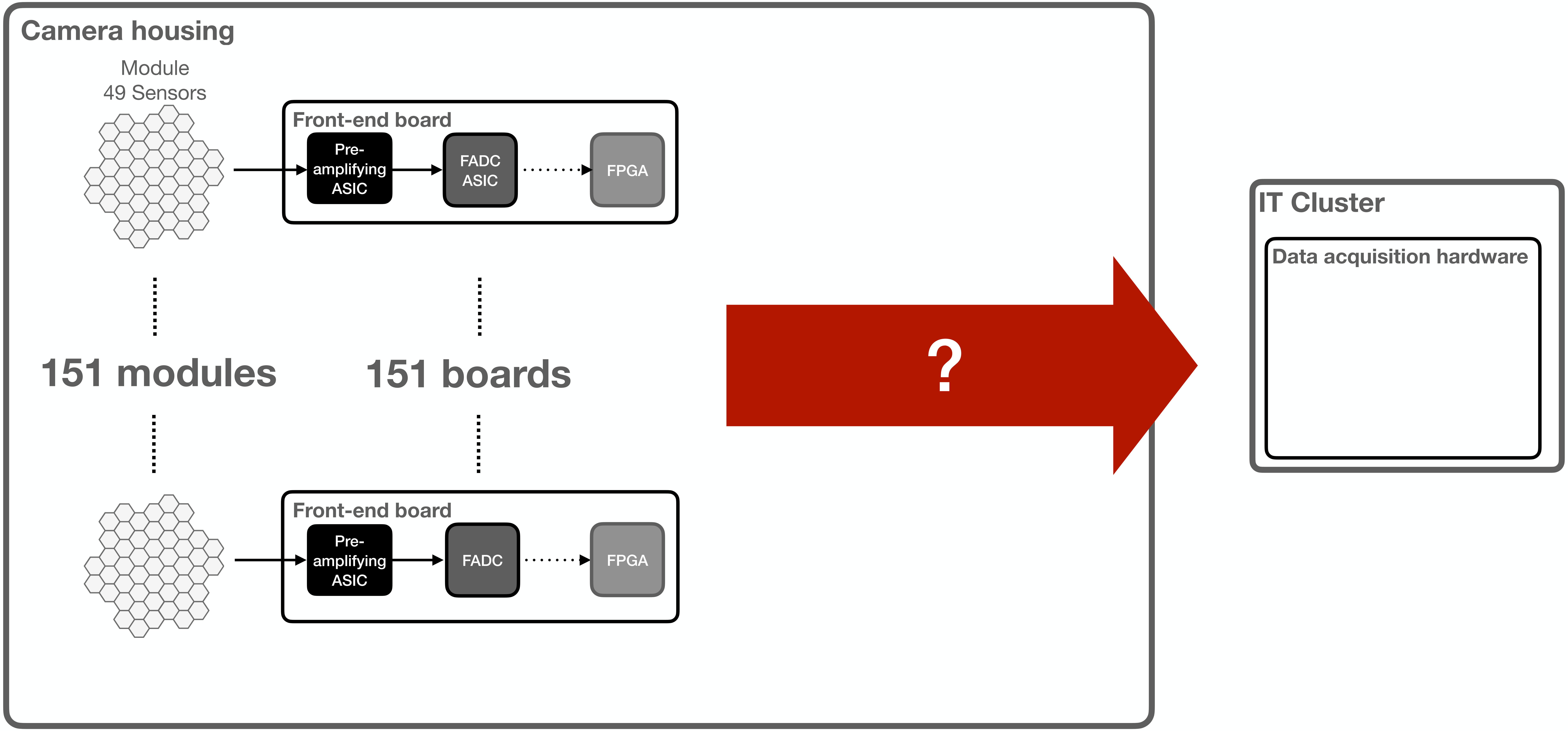




The AdvCam readout architecture



The AdvCam readout architecture



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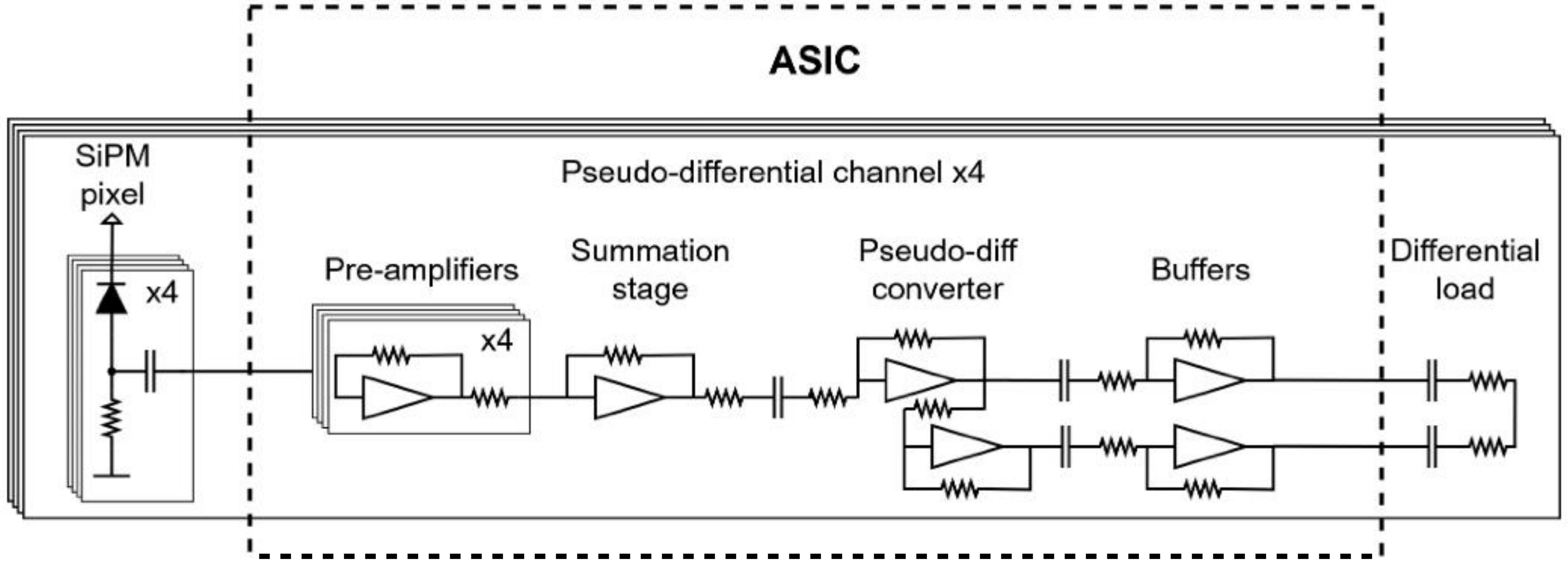
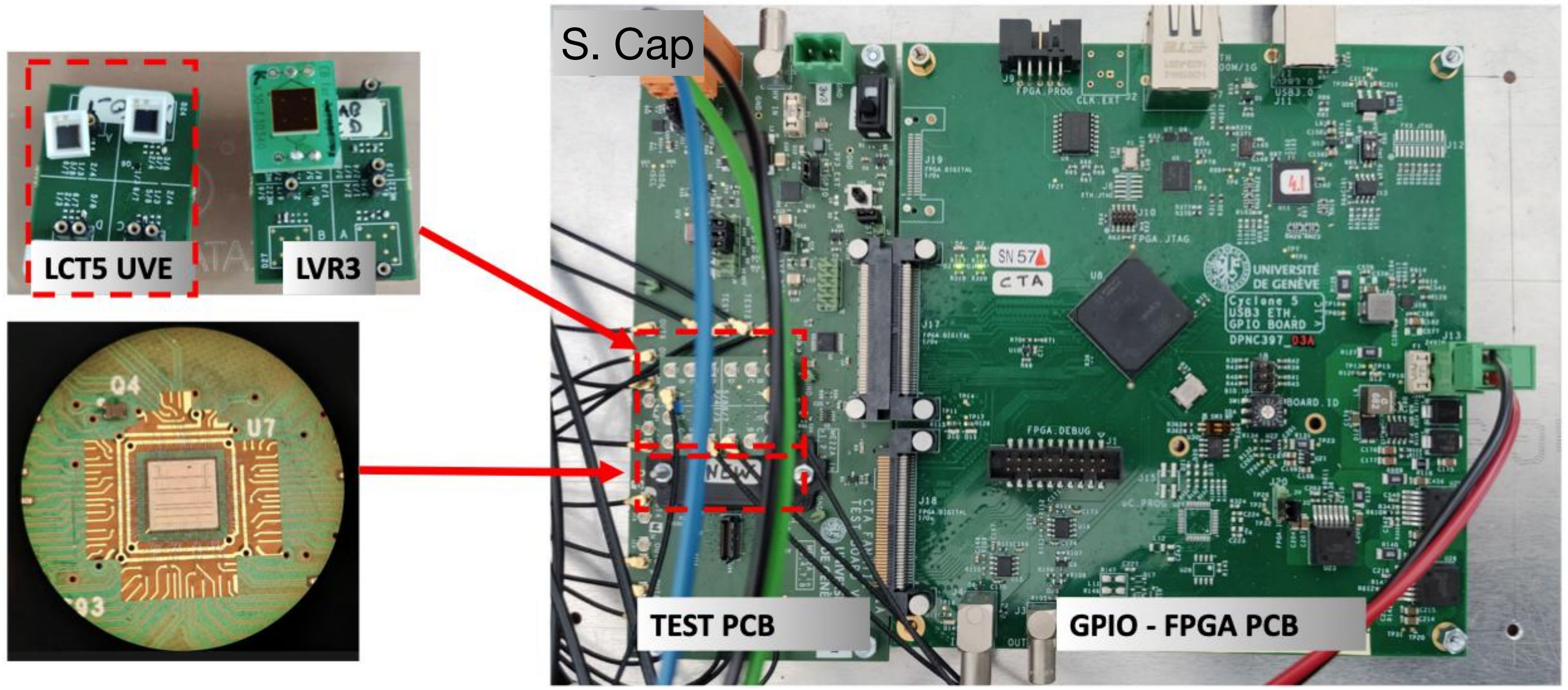
Pre-amplifying ASICs

FLARE project

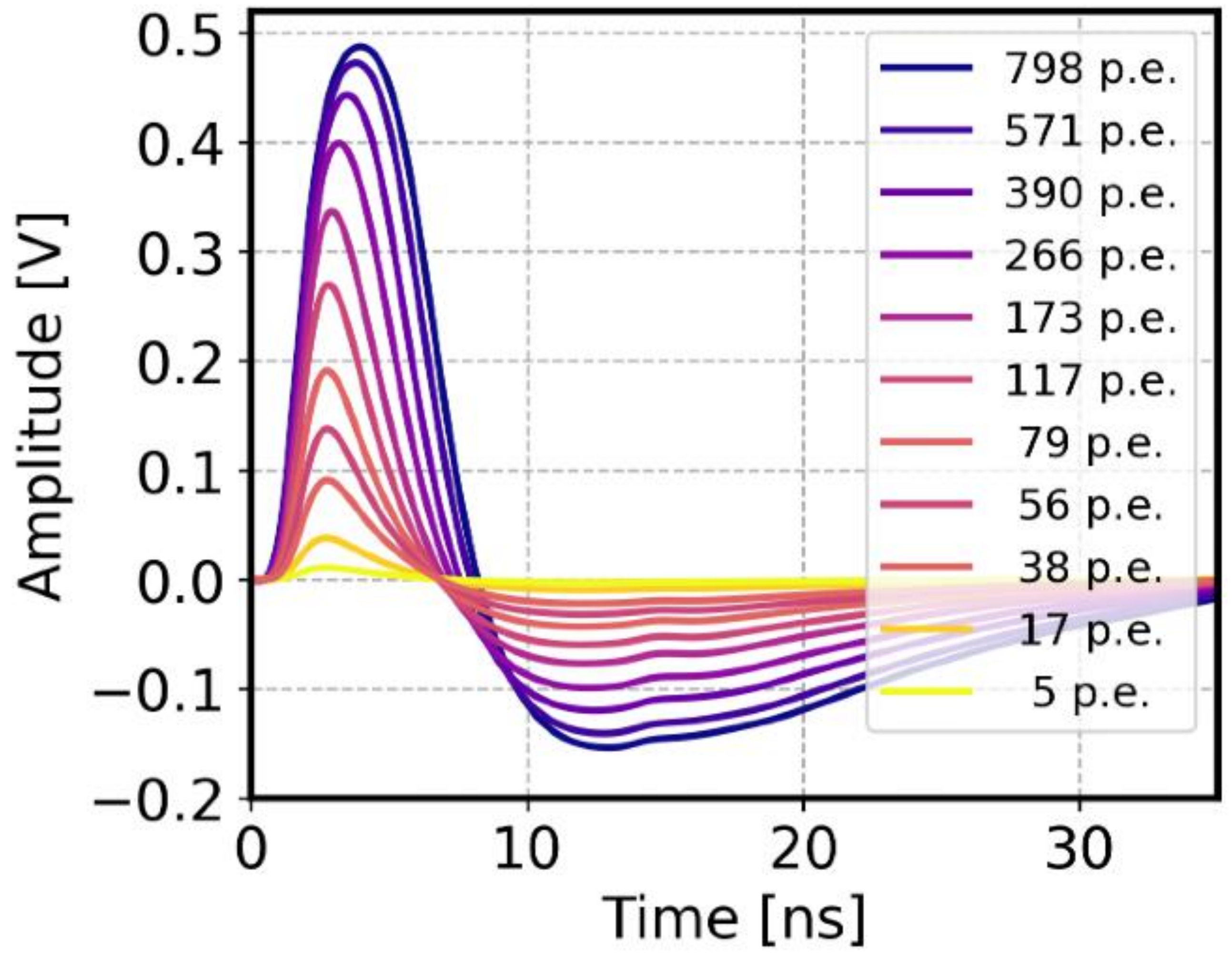
L. Giangrande (UniGe)

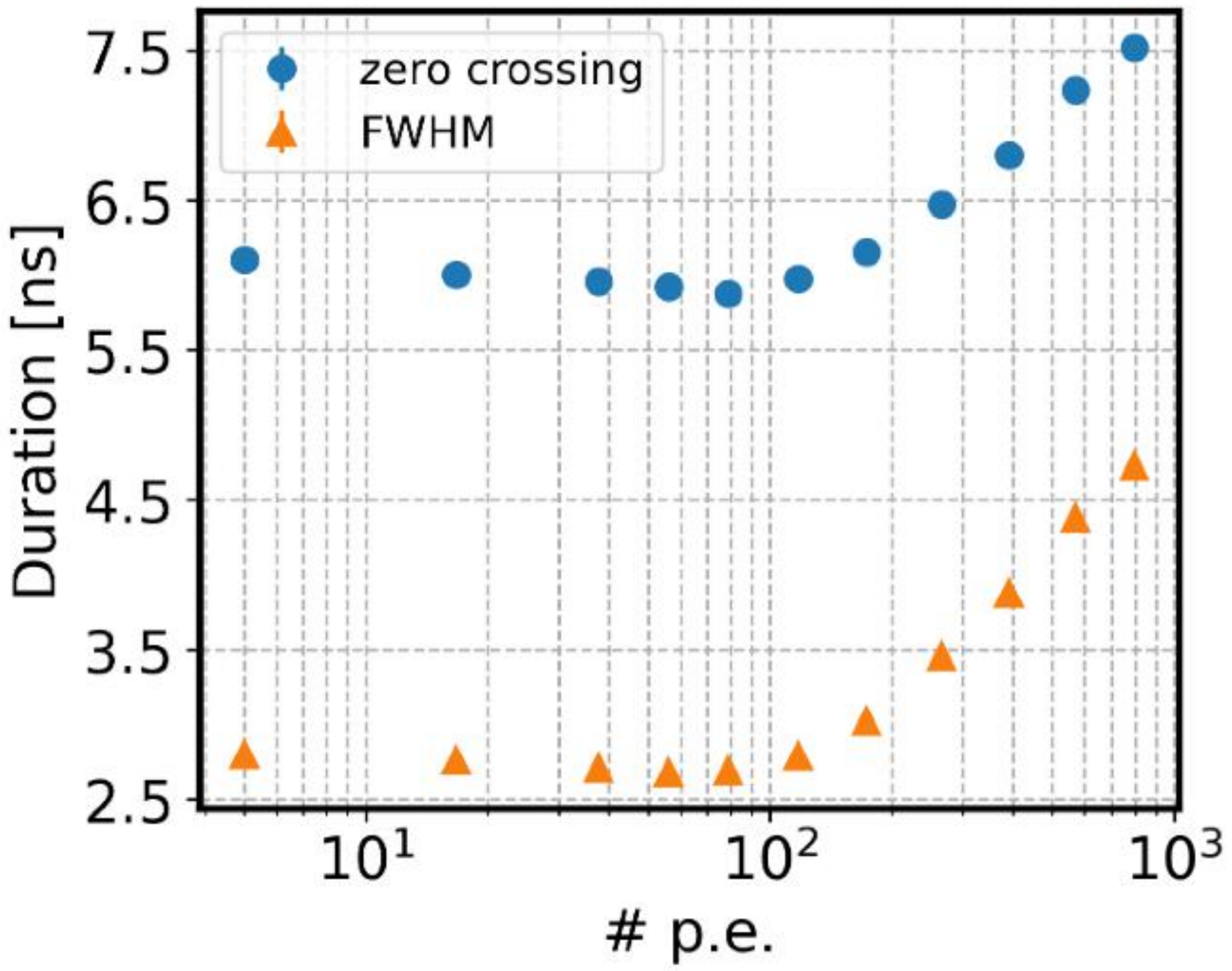




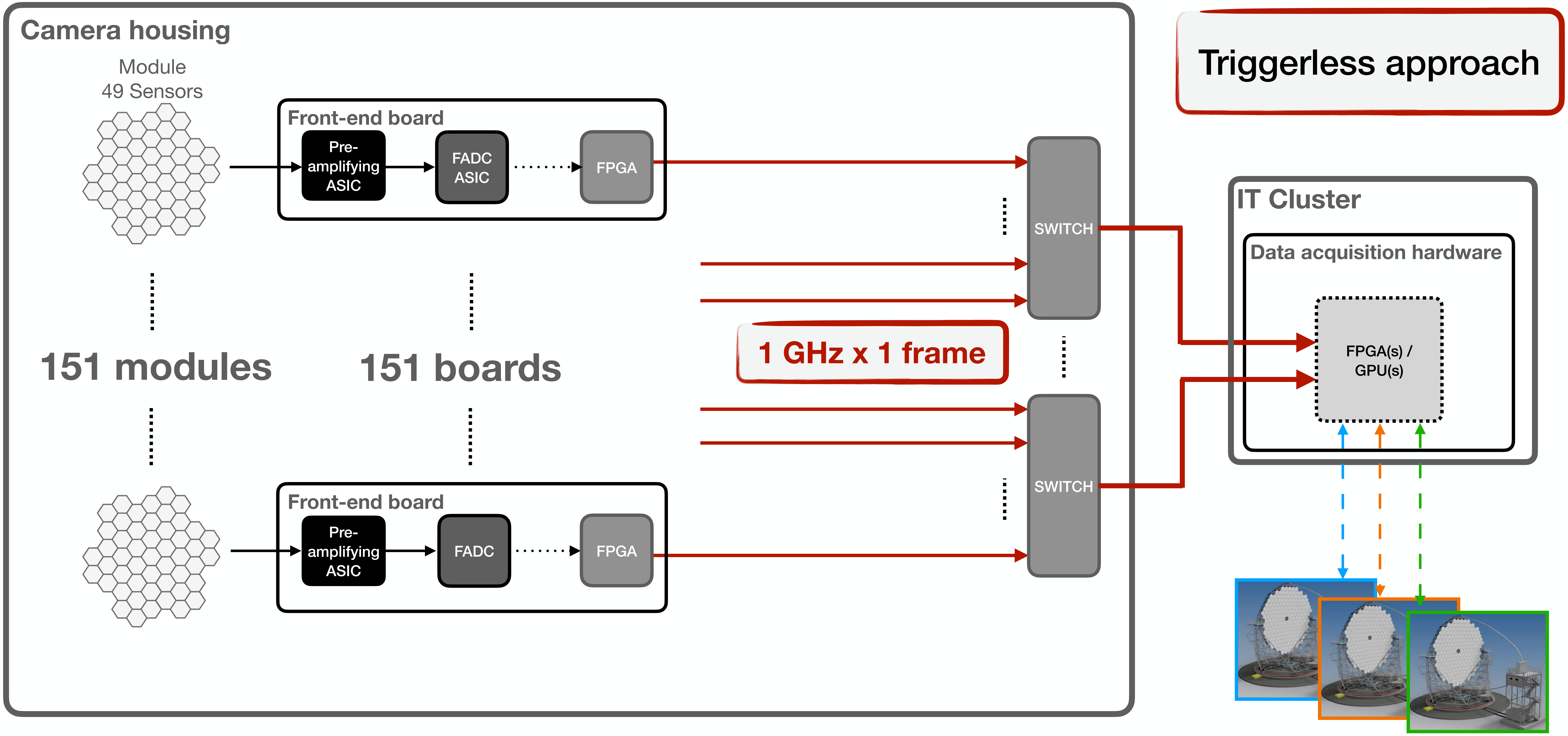
Performance summary	
FWHM [1-100] p.e.	> 3 ns
Power per pixel	23 mW
SNR	6.27
Linearity [1-100] p.e.	±6%
Recovery time	30.5 ns
Dynamic range	> 1000 p.e.

TSMC 65 nm

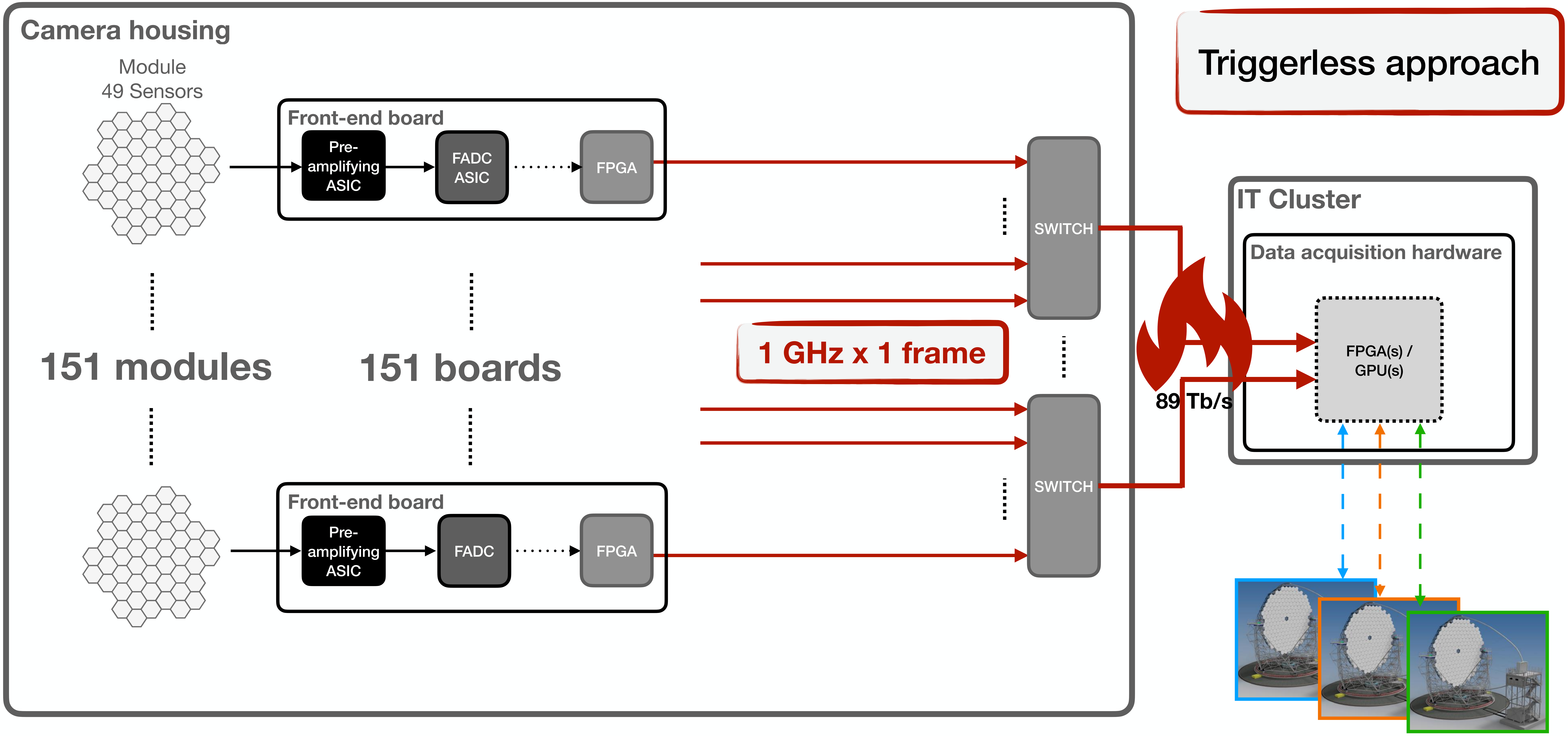




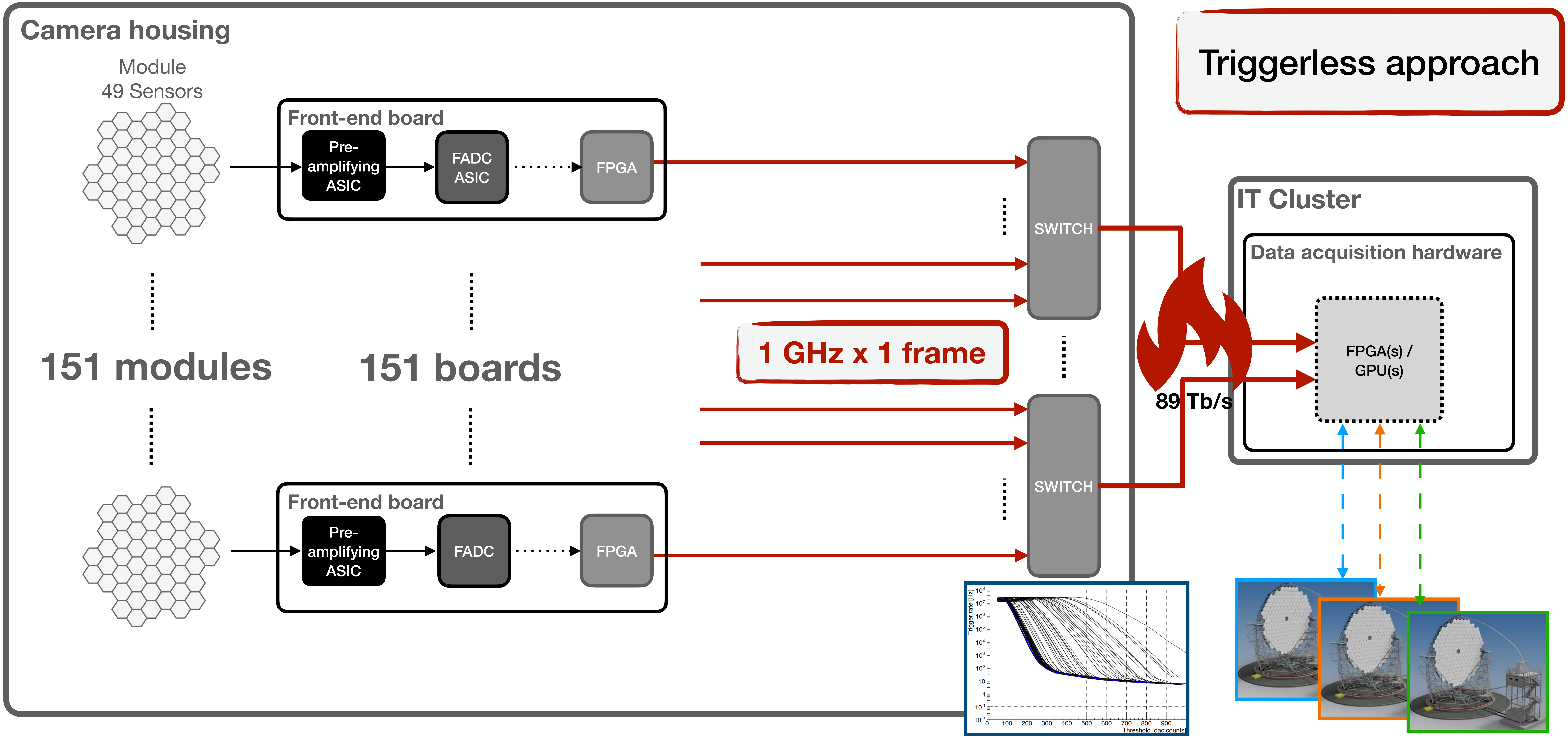
The AdvCam readout architecture



The AdvCam readout architecture



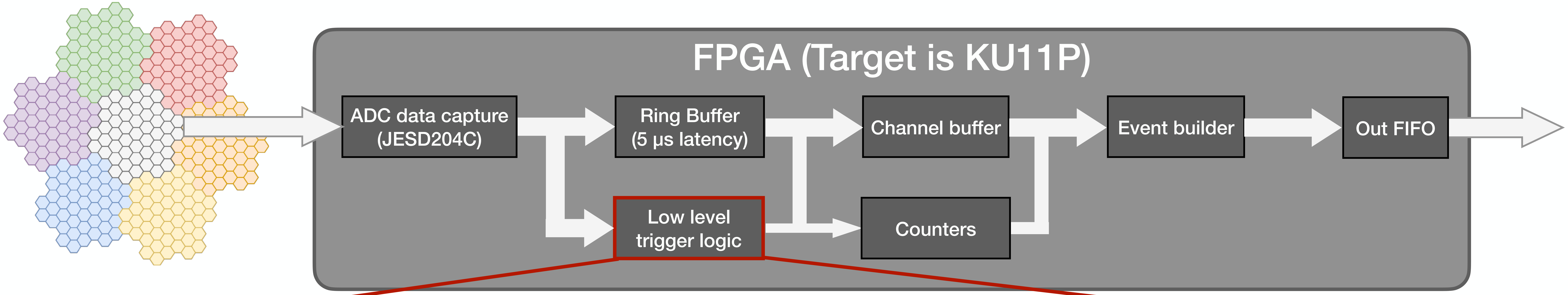
The AdvCam readout architecture



The AdvCam readout architecture

The low level hardware trigger

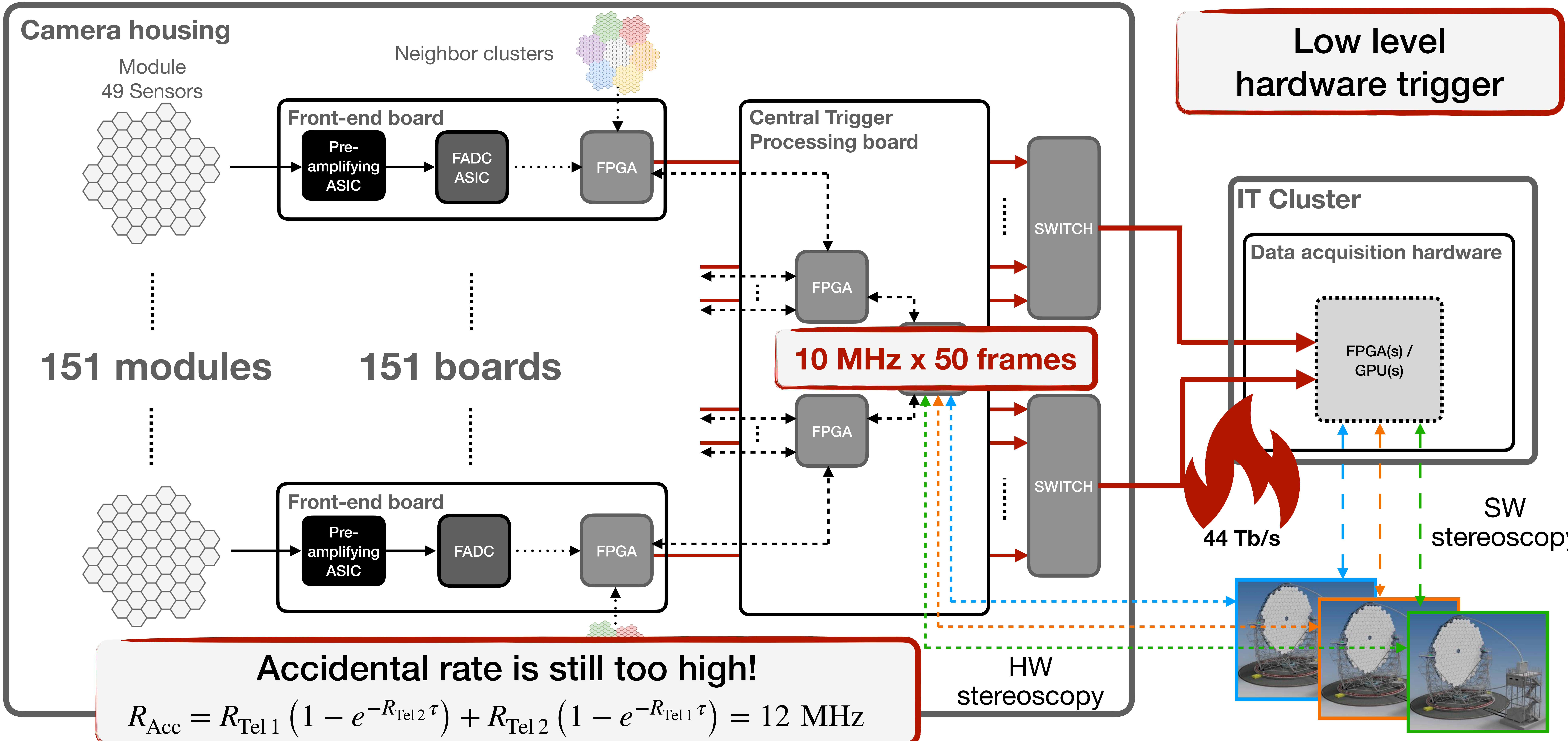
Implementation in FPGA



The AdvCam readout architecture

The AdvCam readout architecture

The AdvCam readout architecture



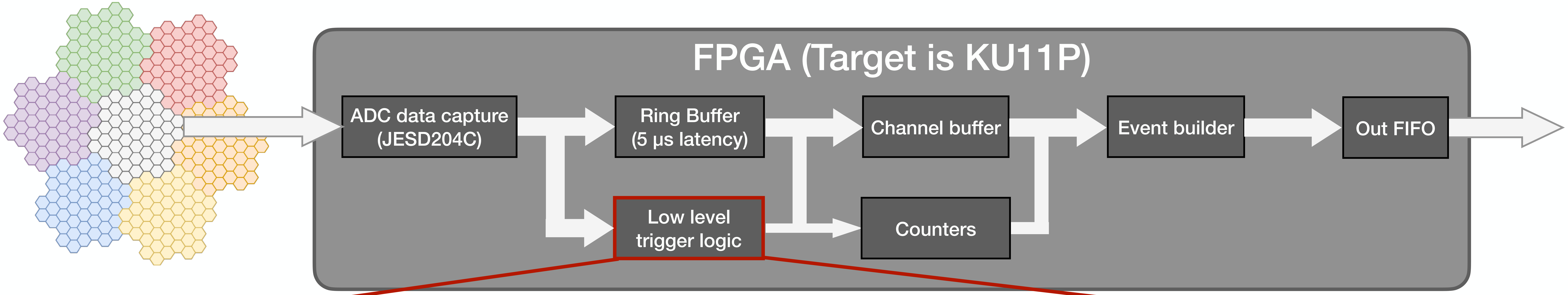
Low level hardware trigger

Accidental rate is still too high!

$$R_{\mathrm{Acc}} = R_{\mathrm{Tel\,1}}\left(1 - e^{-R_{\mathrm{Tel\,2}}\,\tau}\right) + R_{\mathrm{Tel\,2}}\left(1 - e^{-R_{\mathrm{Tel\,1}}\,\tau}\right) = 12\ \mathrm{MHz}$$

The low level hardware trigger

Implementation in FPGA



The low level hardware trigger

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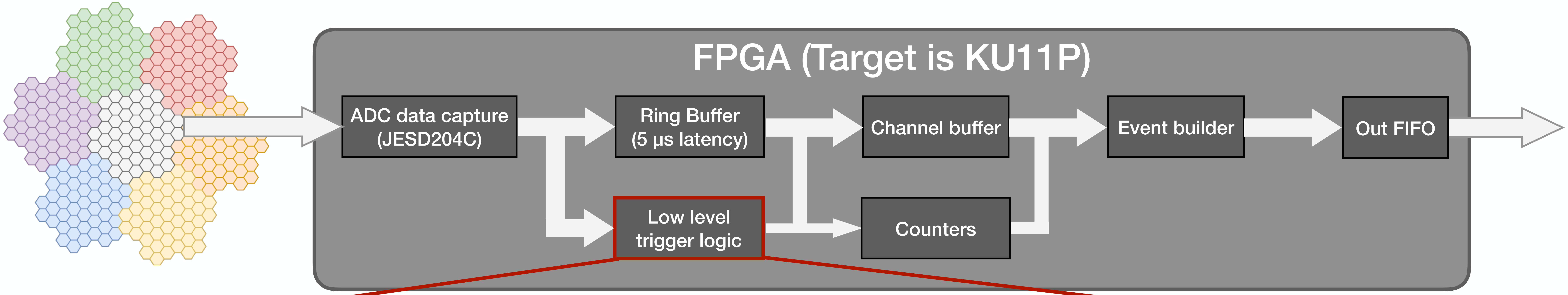
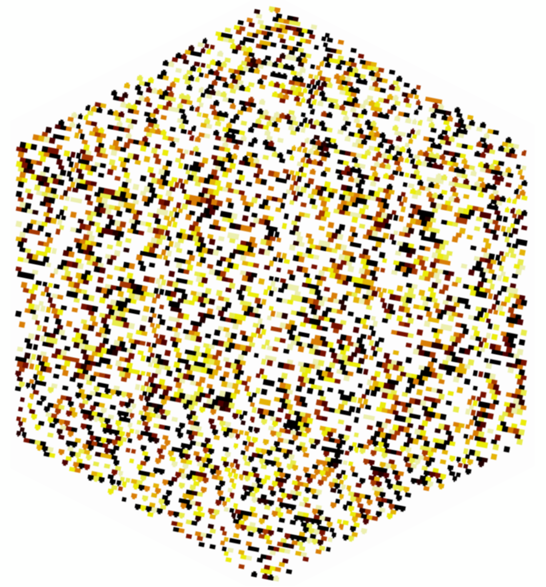


G. Martinez, I. J. Lopez CIEMAT

The high level hardware trigger

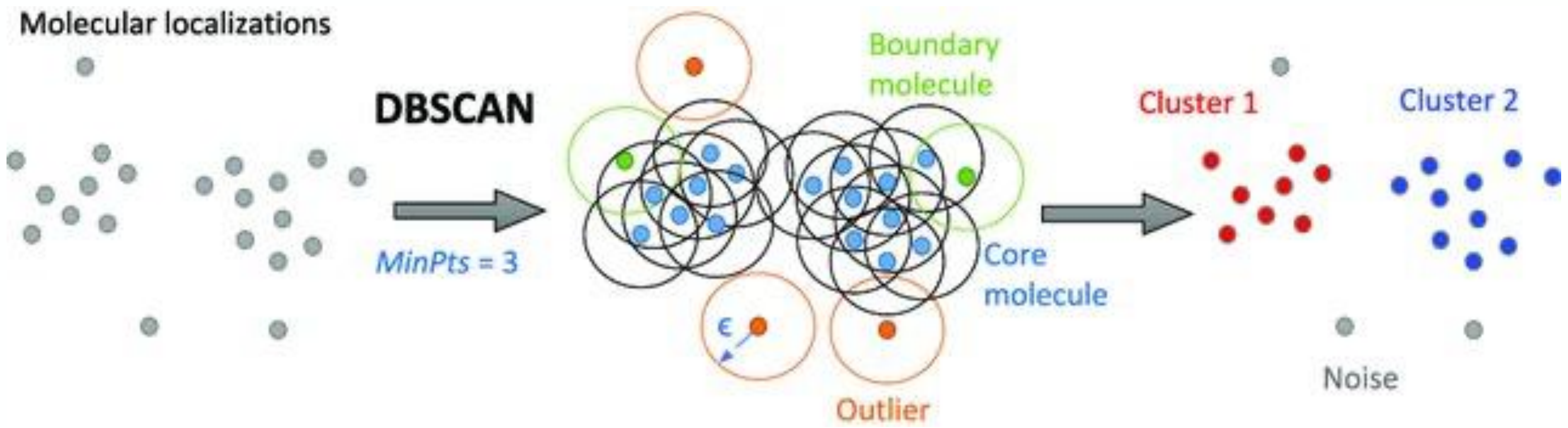
DBScan before HW stereoscopy

Trigger less

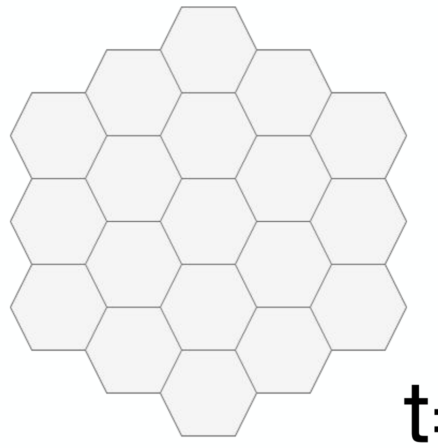


- Spatial clustering algorithm:
  - From: KDD-96 Proceedings. Copyright © 1996, AAAI (www.aaai.org). A Density-Based Algorithm for Discovering Clusters in Large Spatial Databases with Noise, Martin Ester, Hans-Peter Kriegel, Jiirg Sander, Xiaowei Xu

- One “point" = one cluster of 7 pixels which digital sum is above threshold



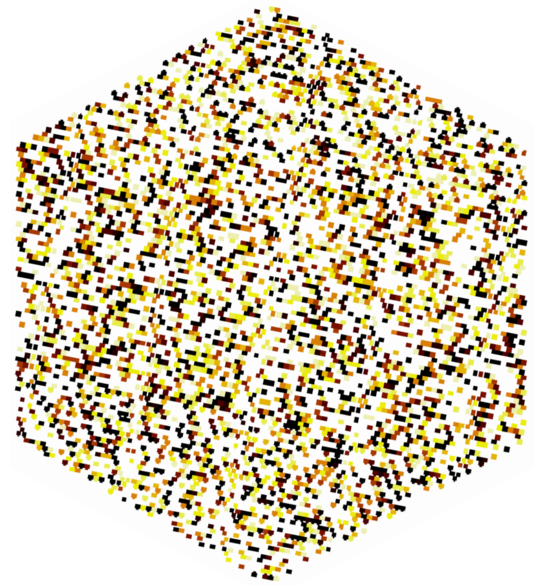
- Time introduced in the metric to account for shower development



The high level hardware trigger

DBScan before HW stereoscopy

Trigger less



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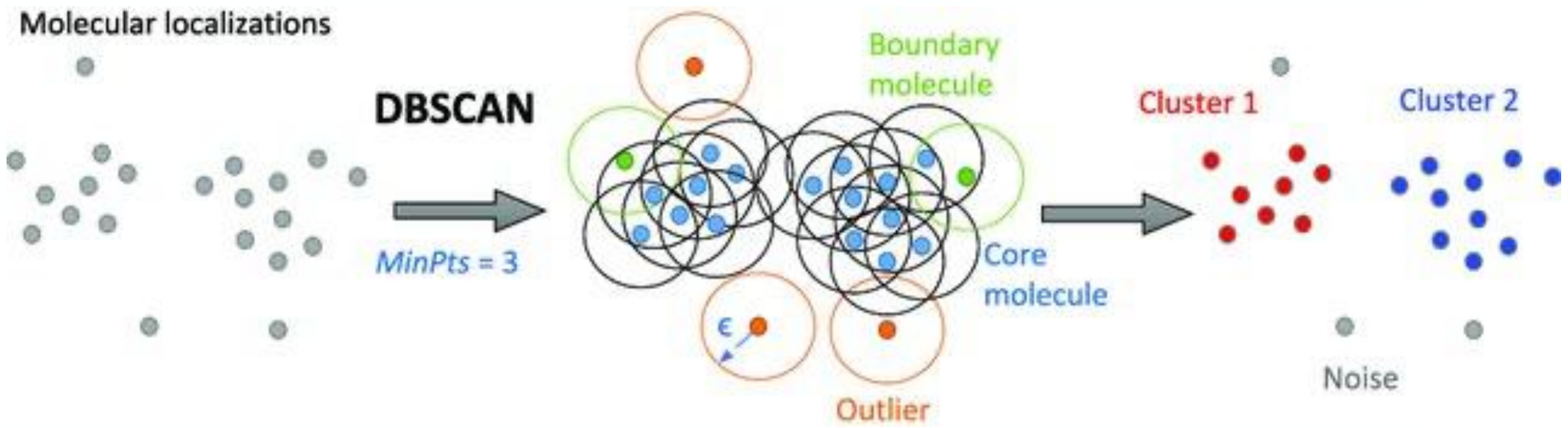

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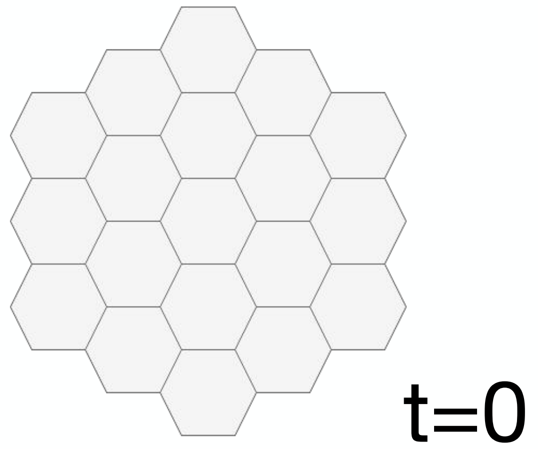

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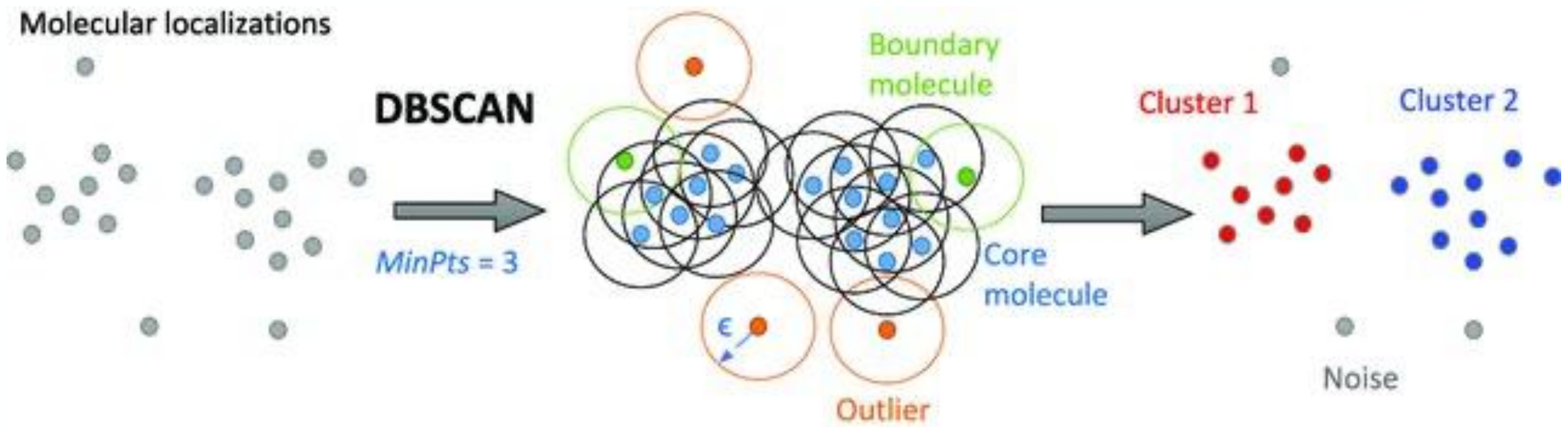

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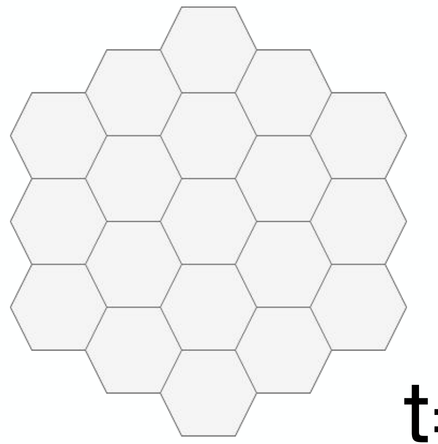

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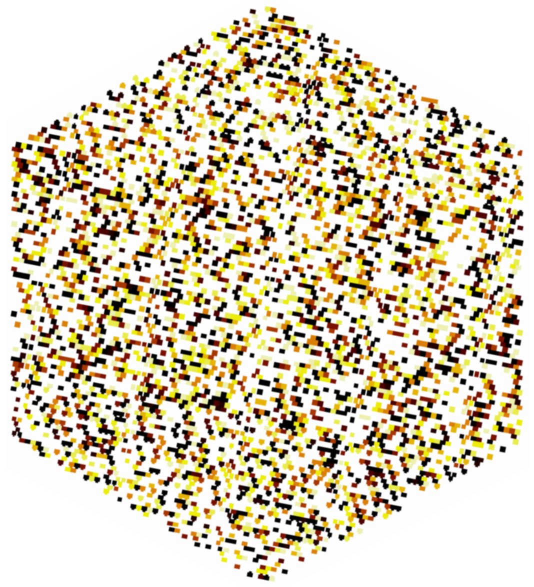
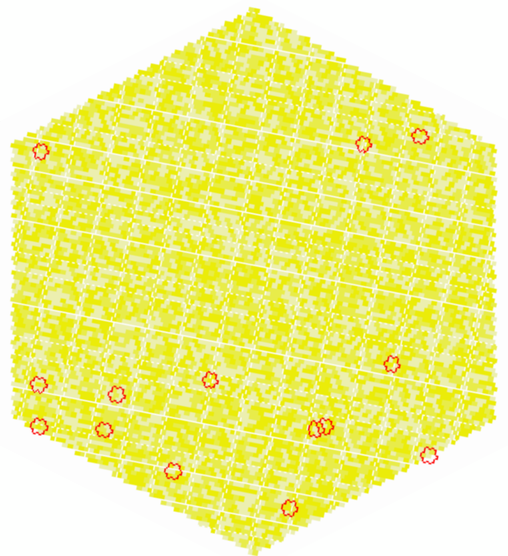


DBScan spatial only



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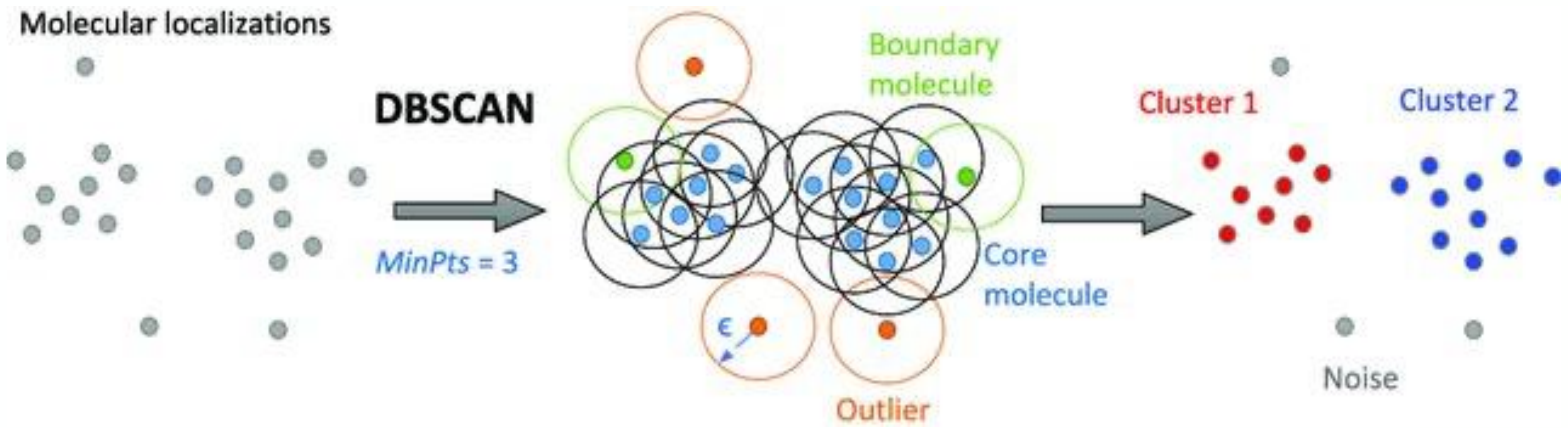

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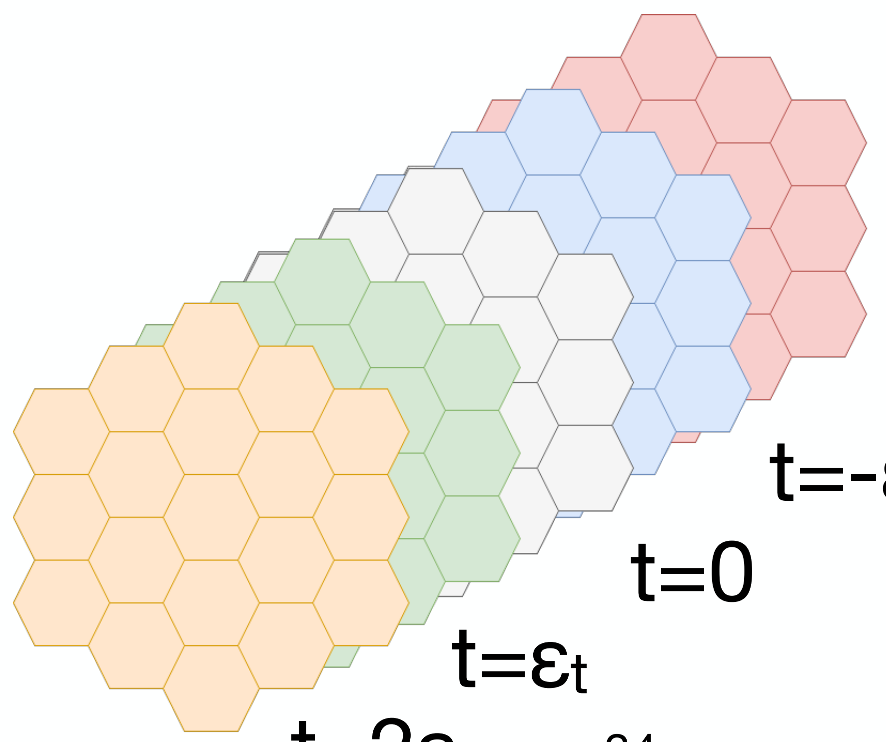
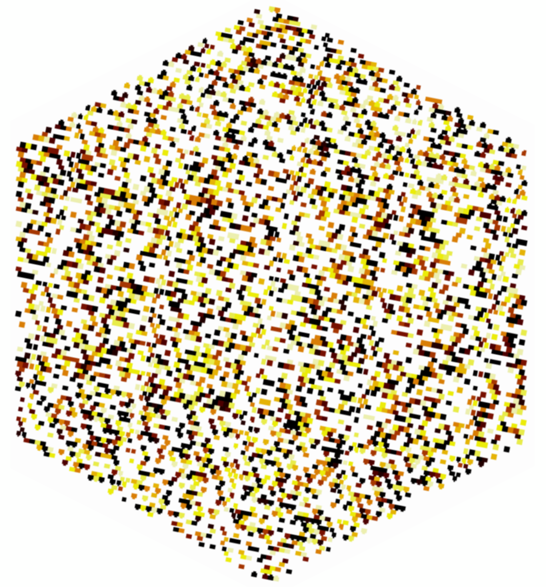


Trigger less



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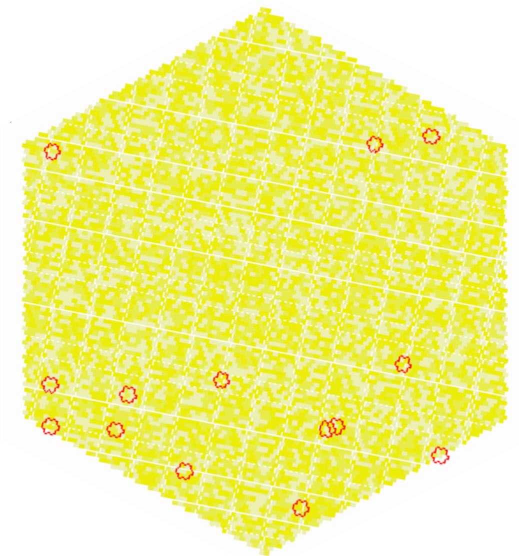

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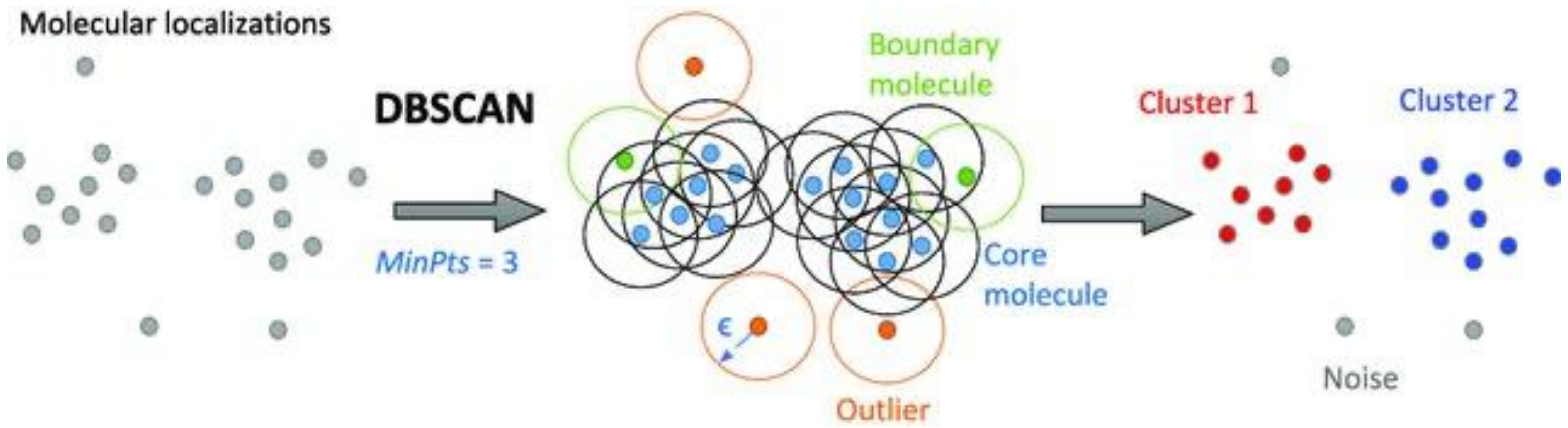

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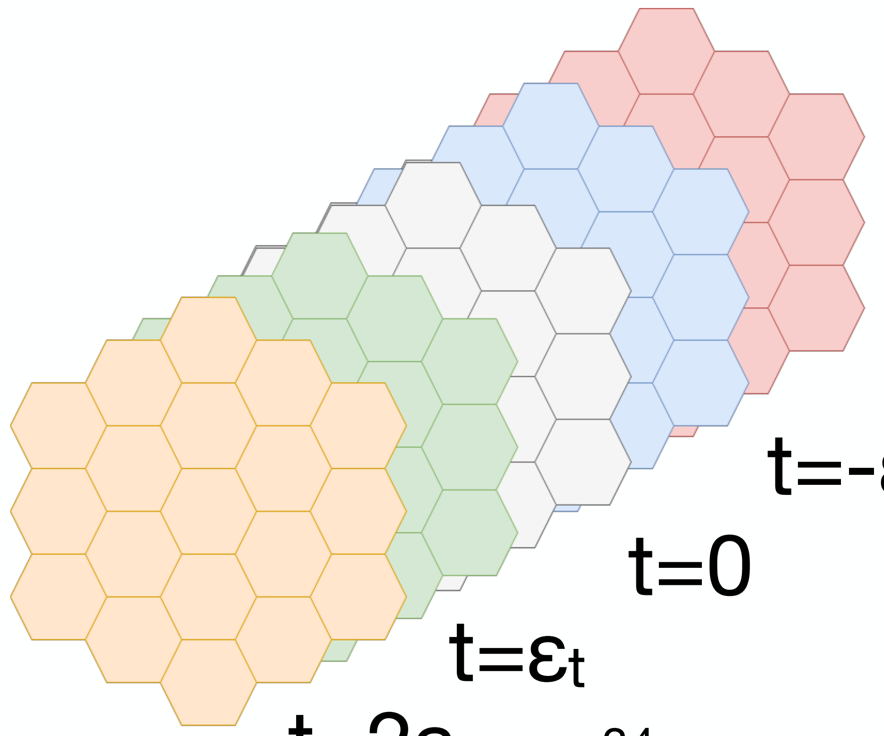

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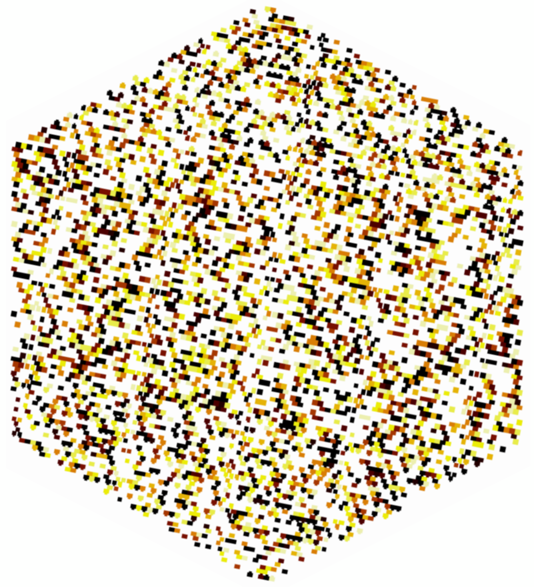

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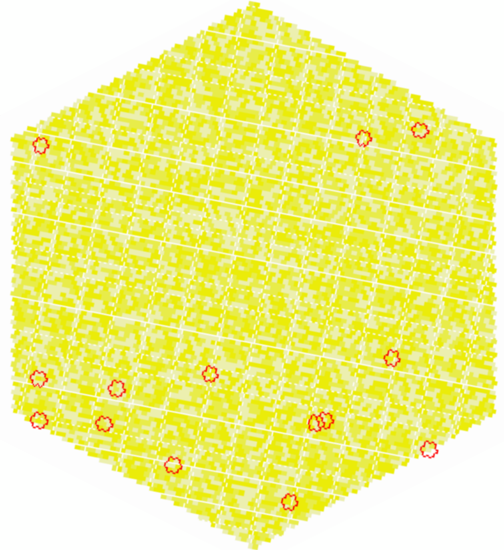
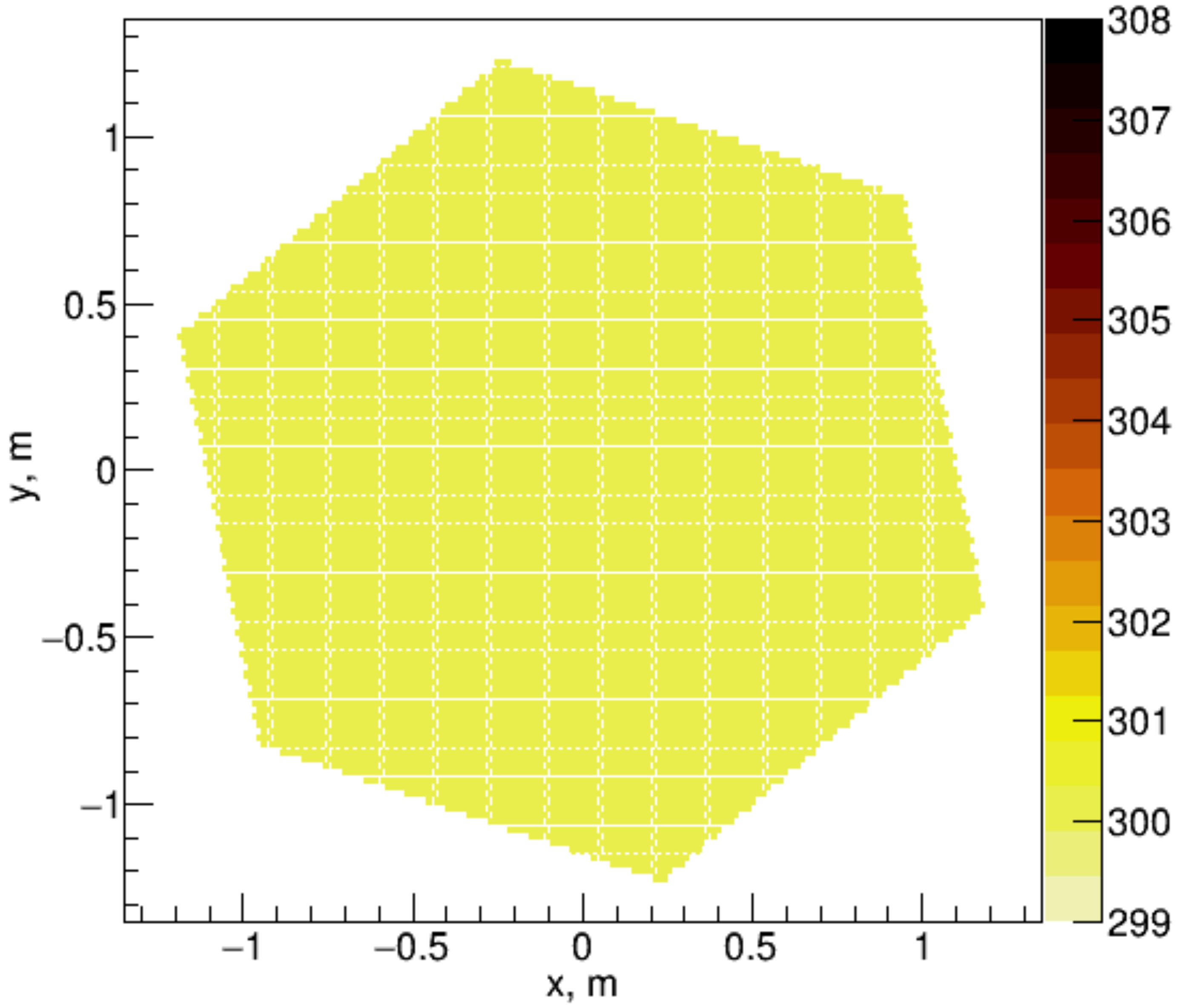


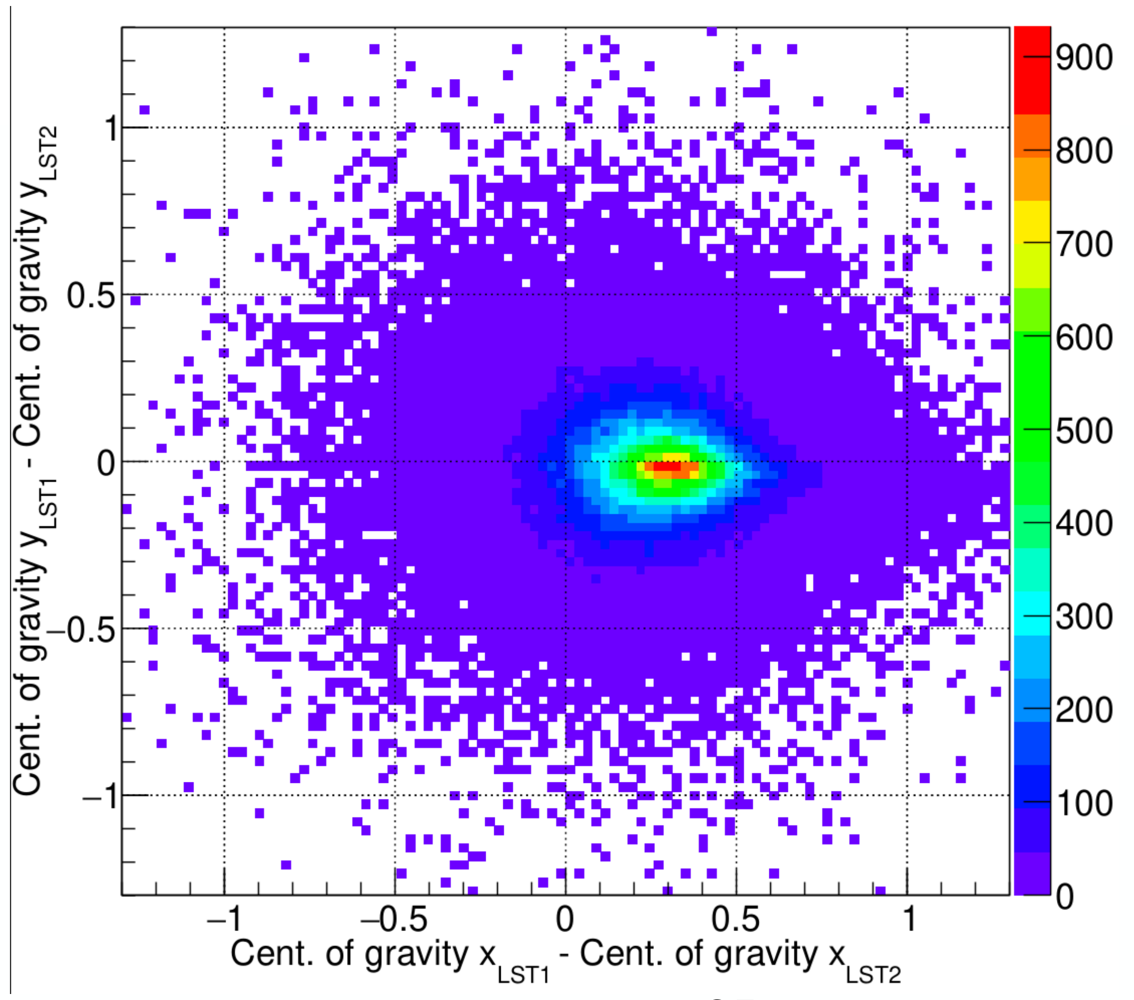
DBScan “full"

The high level hardware trigger

DBScan before HW stereoscopy and more

- In existing analysis, information about trigger is not used for image cleaning
- With DBScan, cluster found can be used as data cube cleaning mask
- Fast image analysis is possible:
    - Location in camera for topological trigger
    - Time of arrival of shower in camera for reduced coincidence window

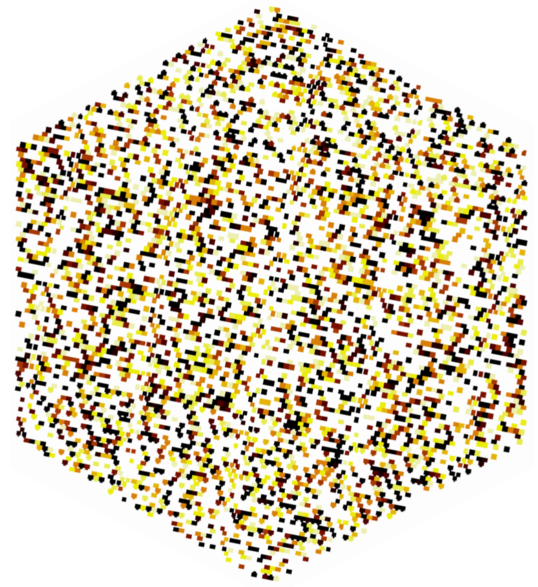




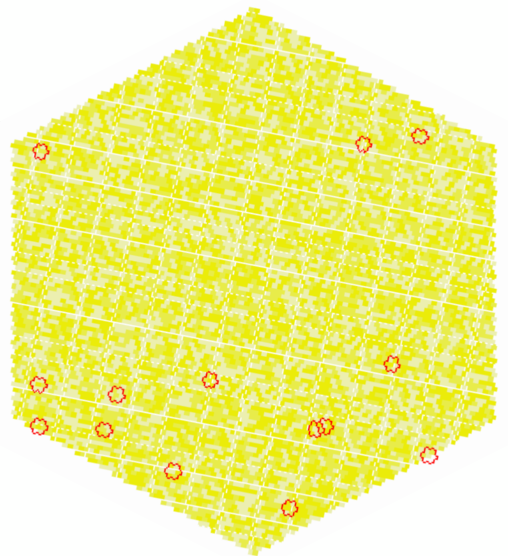
Topological trigger

Exploit correlation of shower position in camera for a given pointing direction

Trigger less



DBScan spatial only



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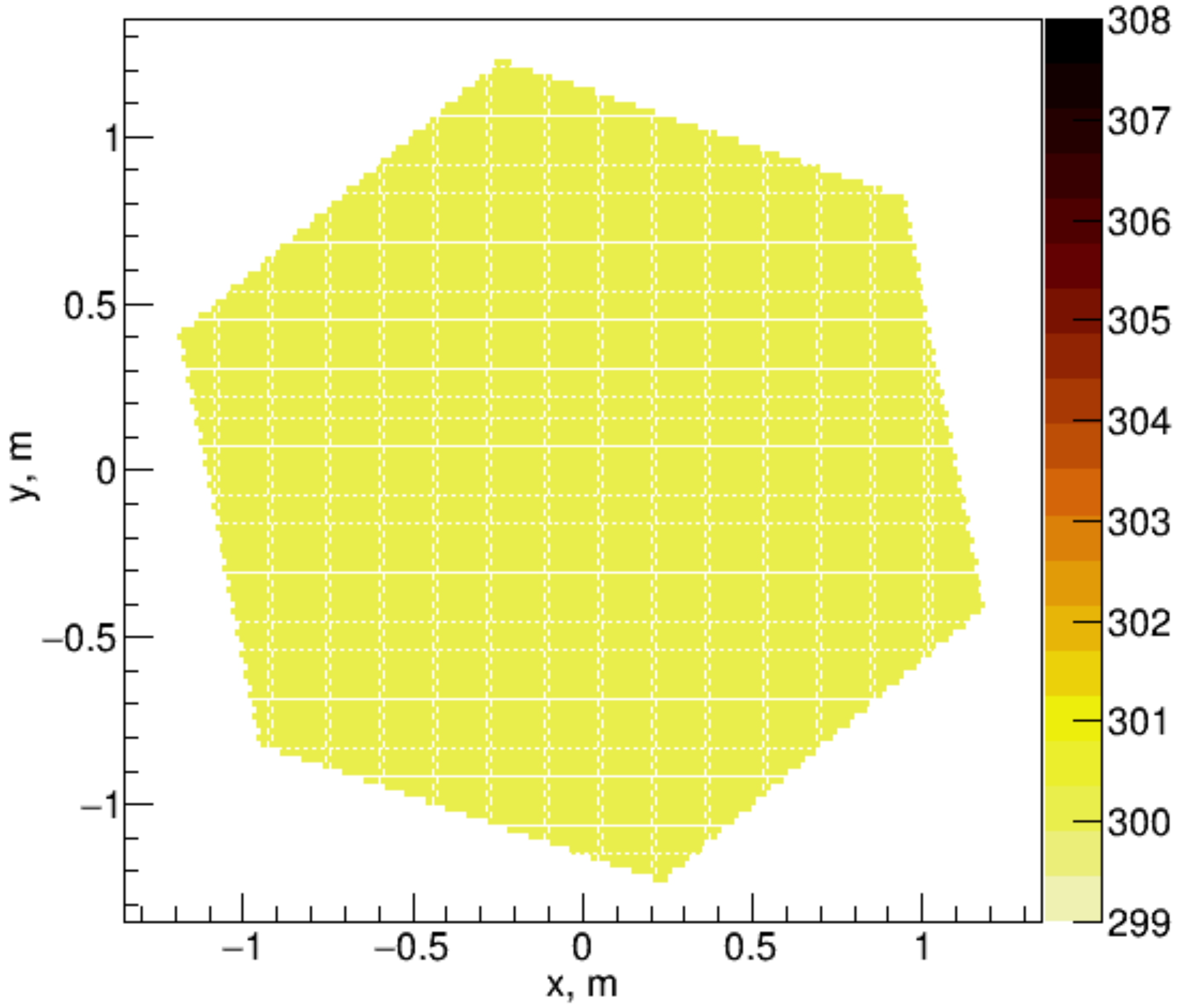

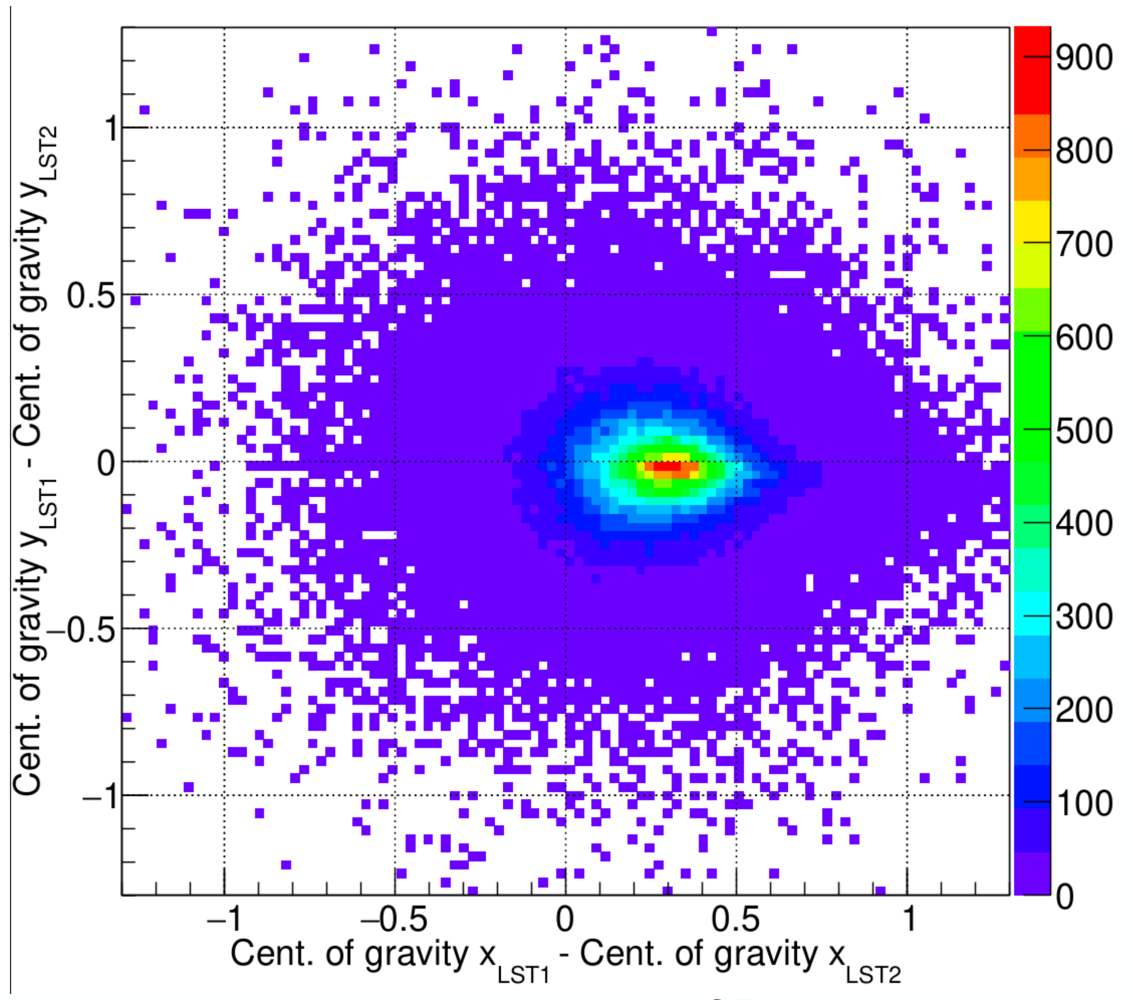

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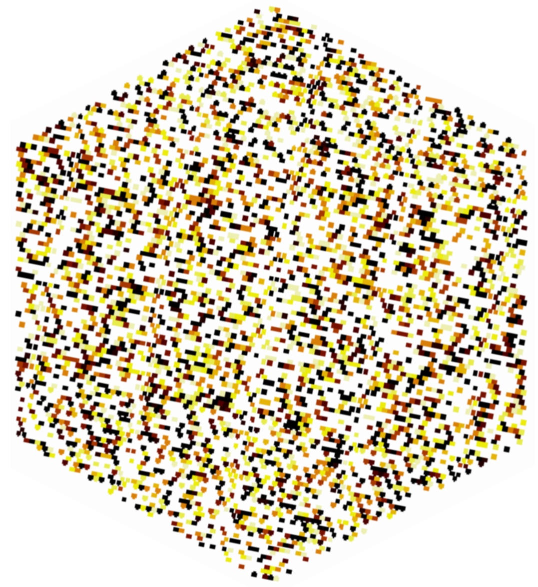
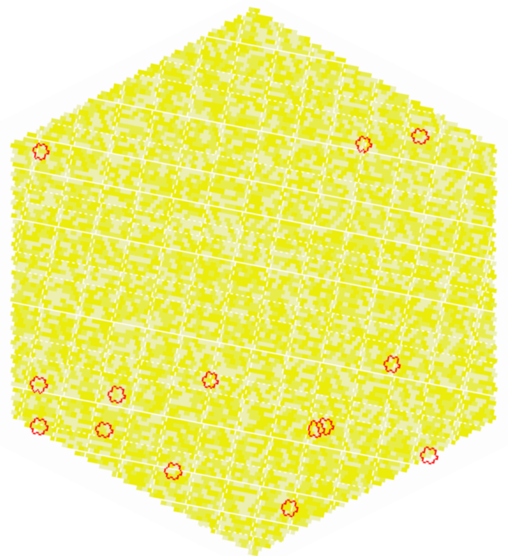


DBScan spatial only



DBScan “full"

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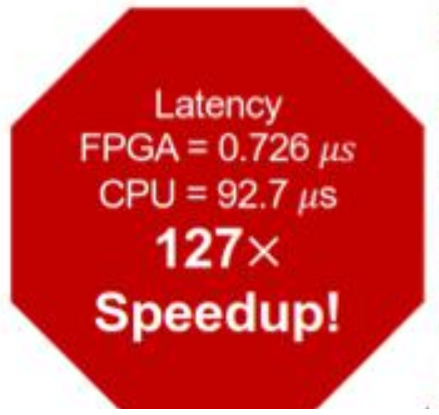
The high level hardware trigger

DBScan before HW stereoscopy and more

- Does it run well on a hardware accelerator?
  - ✦ Not straight forward, issues with varying latency (varying number of points)
  - ✦ Can be tackled by limiting the cluster growth

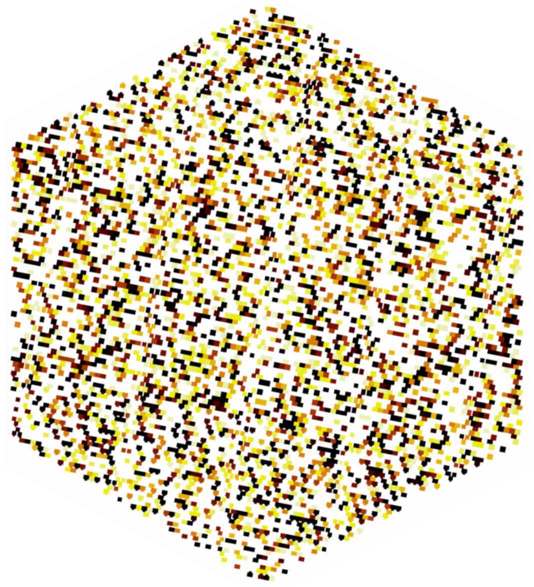
- <u>Accelerating the DBSCAN clustering algorithm for low-latency primary vertex reconstruction</u>
  - ✦ With 230 tracks (points) ➡ 0.726 μs latency. VU9P FPGA



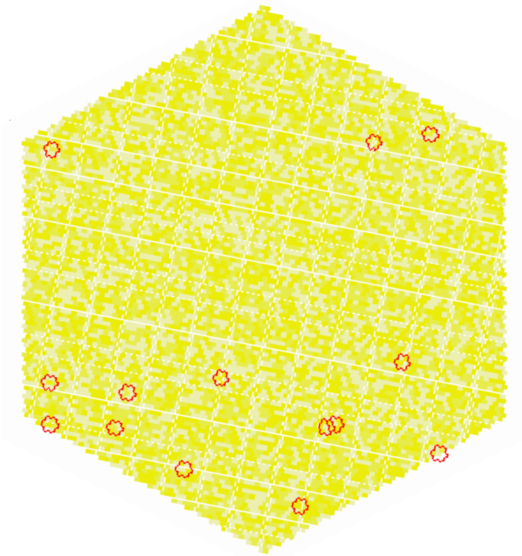
Alex Tapper (Imperial College London)
Andrew Rose
Lucas Santiago Borgna (Imperial College (GB))
Marco Barbone
Robert John Bainbridge (Imperial College (GB))
Wayne Luk

- Still not enough*, **we need latencies below 100 ns !**
  * Implementation not applicaiton specific

Trigger less



DBScan spatial only



DBScan “full"

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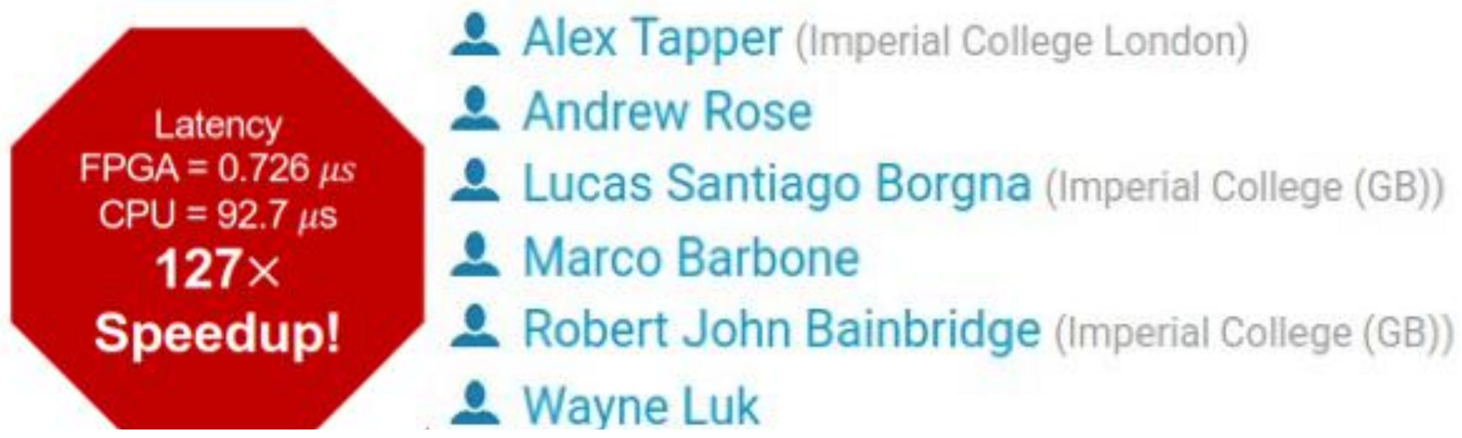

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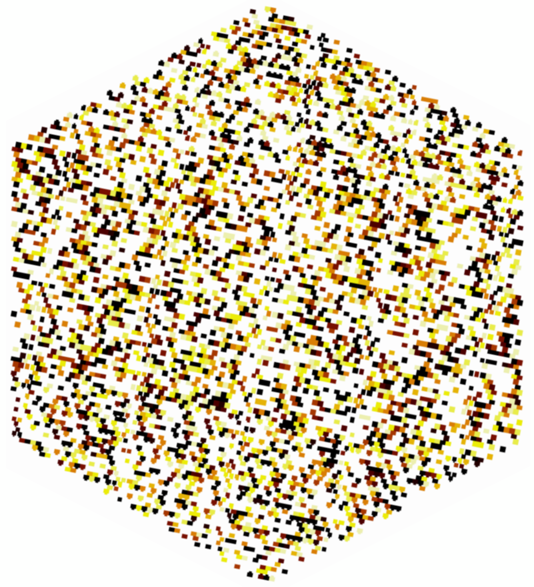
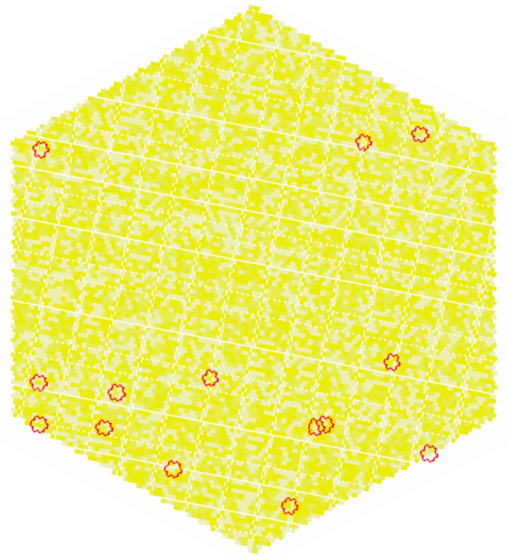


DBScan spatial only

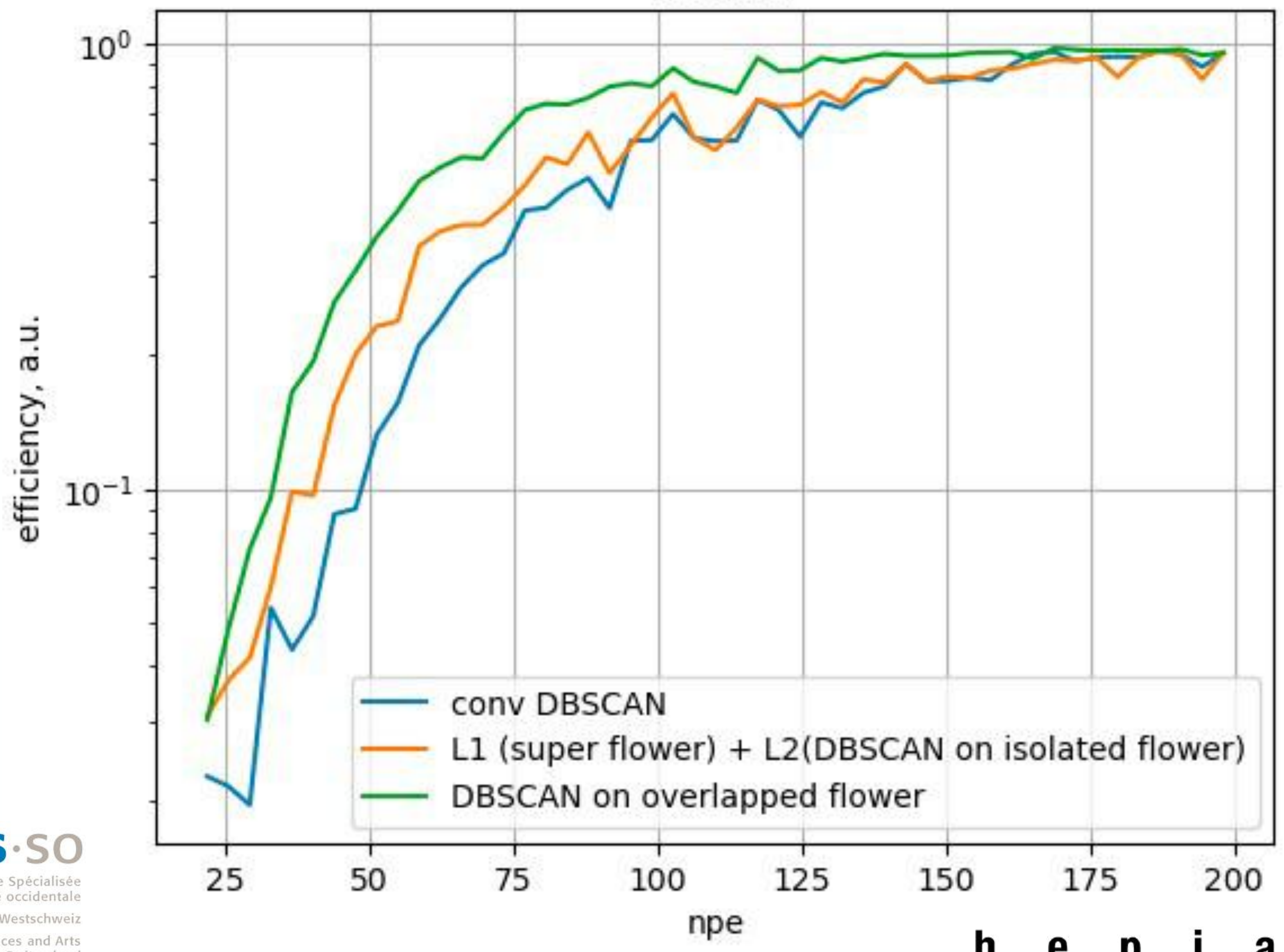


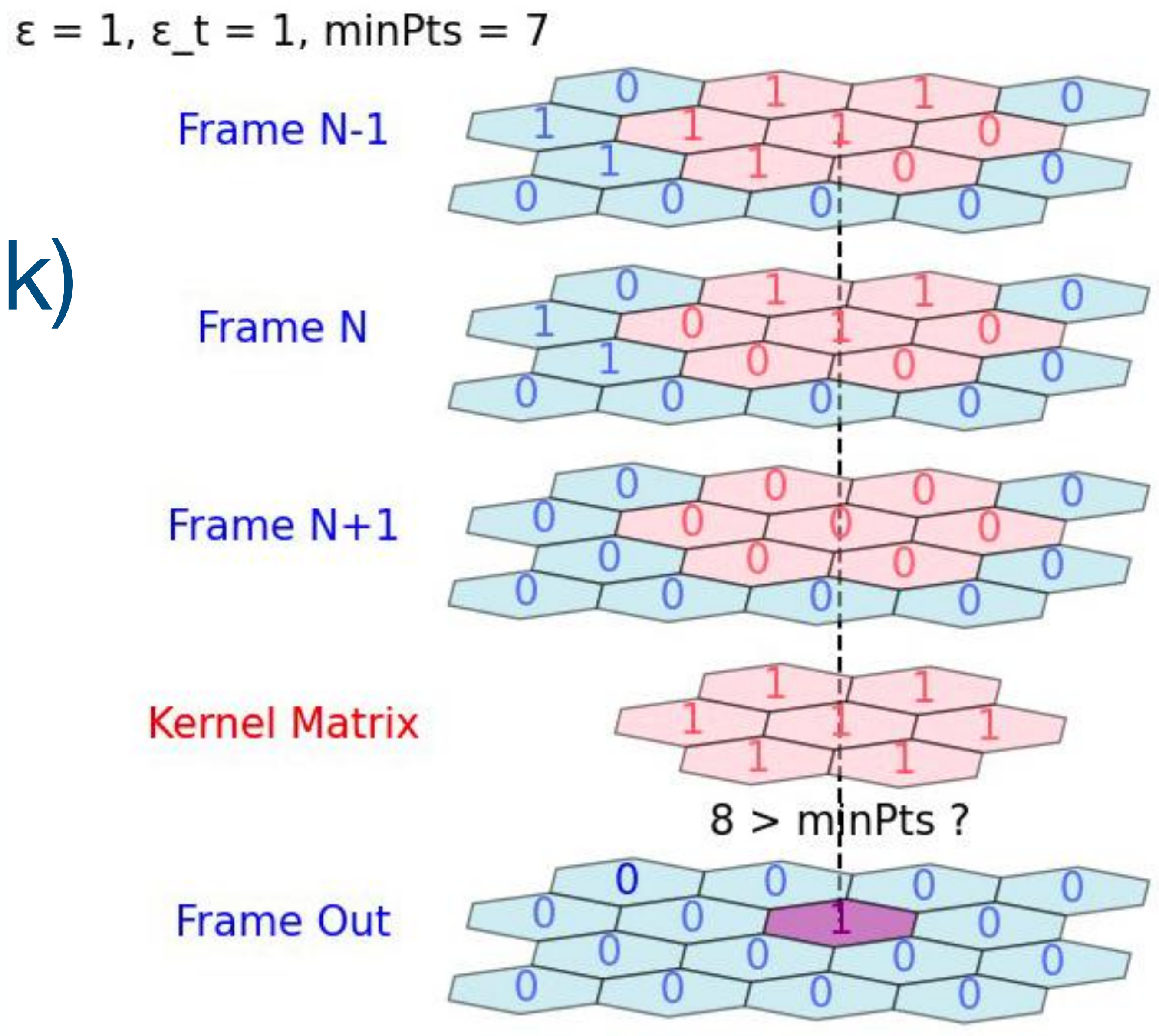
DBScan “full"

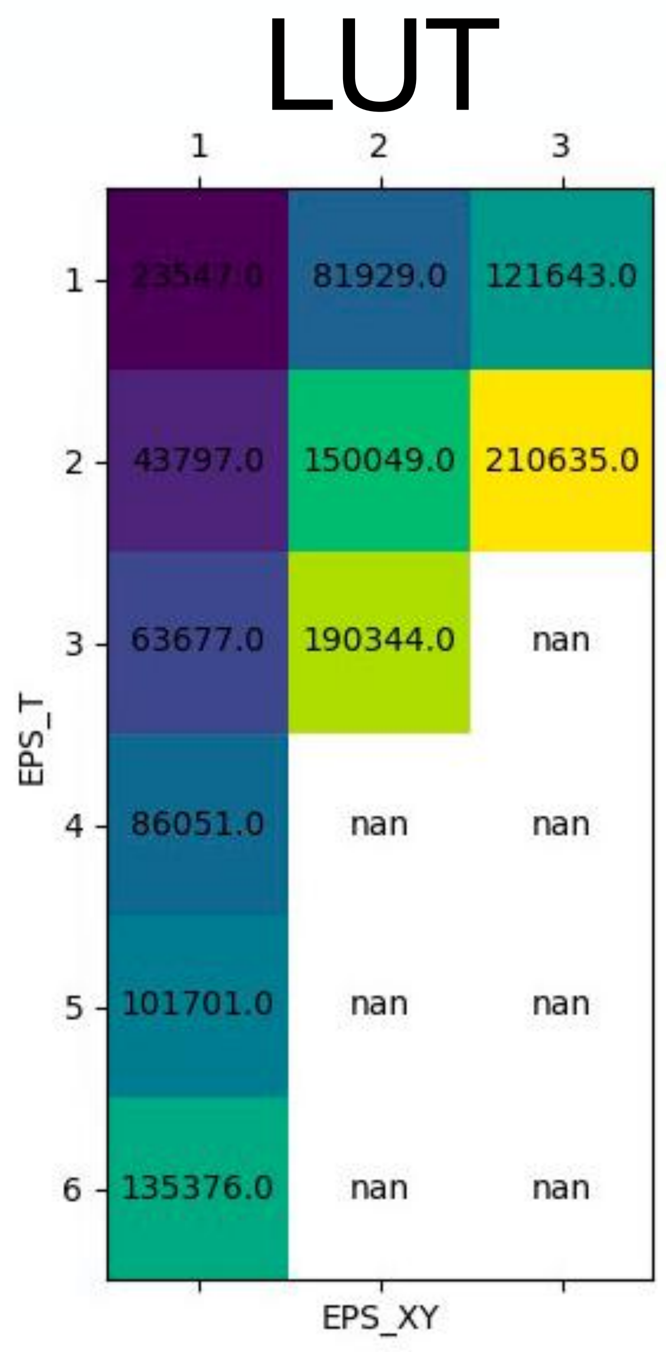
The high level hardware trigger

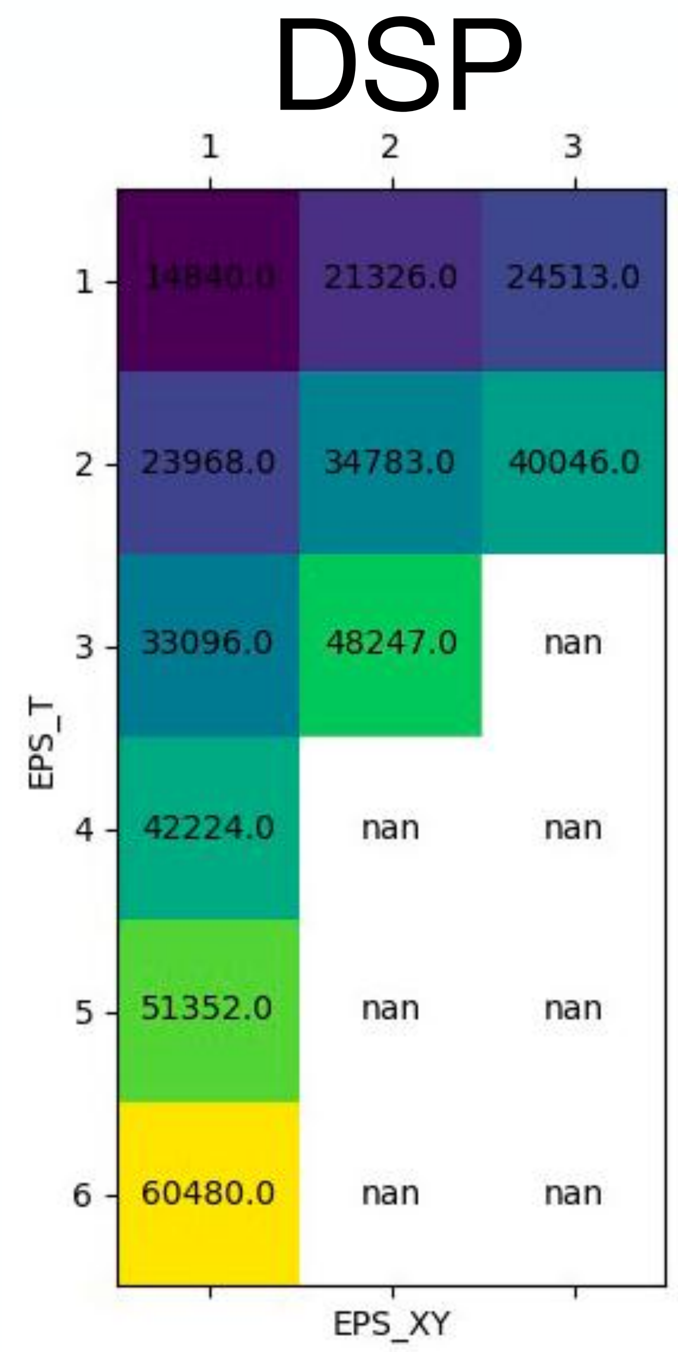
DBScan → 3DConvolution before HW stereoscopy

- Parameters :
  - ✦ ε_{XY} (kernel size)
  - ✦ ε_t (number of frame to look back)
  - ✦ MinPts (Threshold)
- Create a mask of the clusters







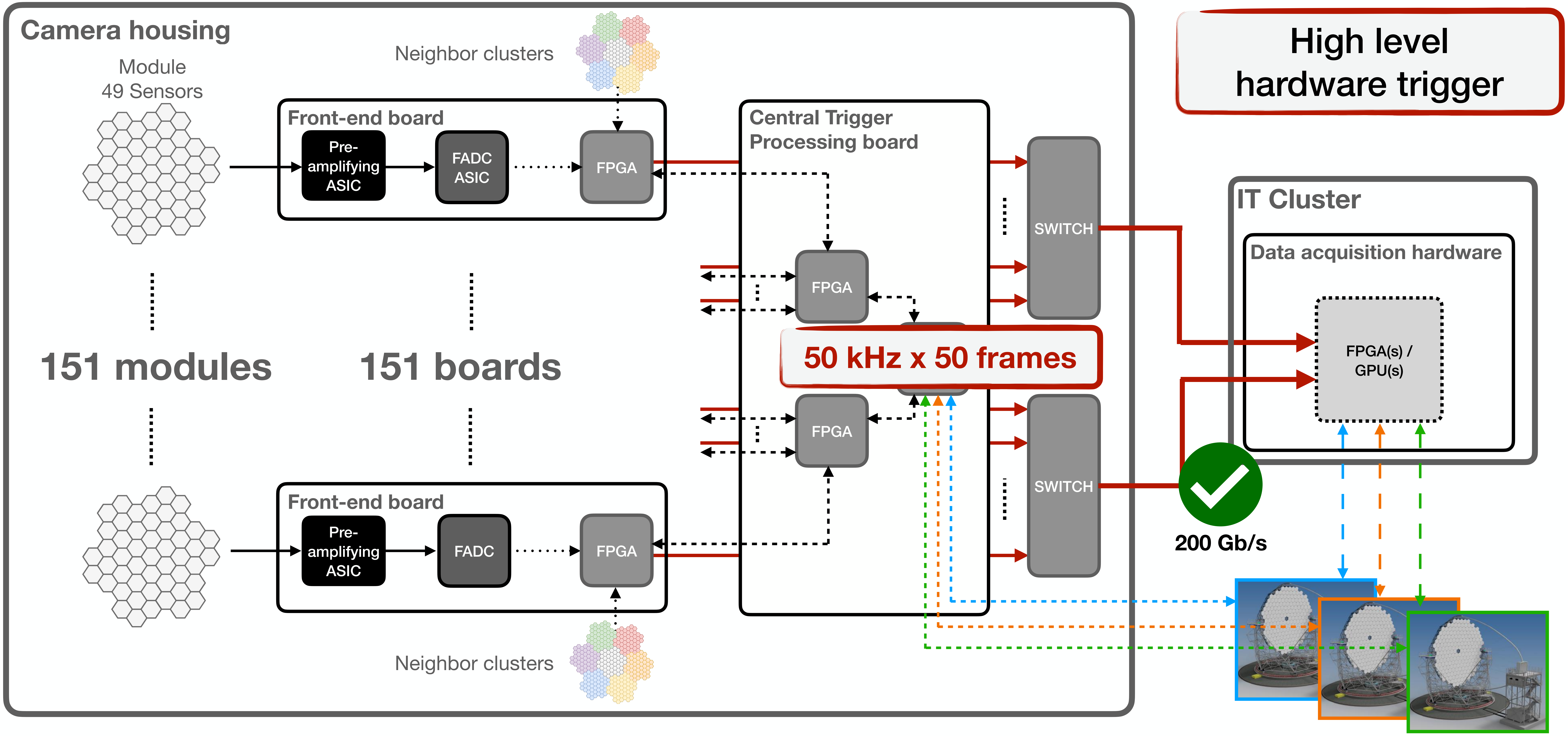


Main advantages of the 3DConvolution with respect to DBScan

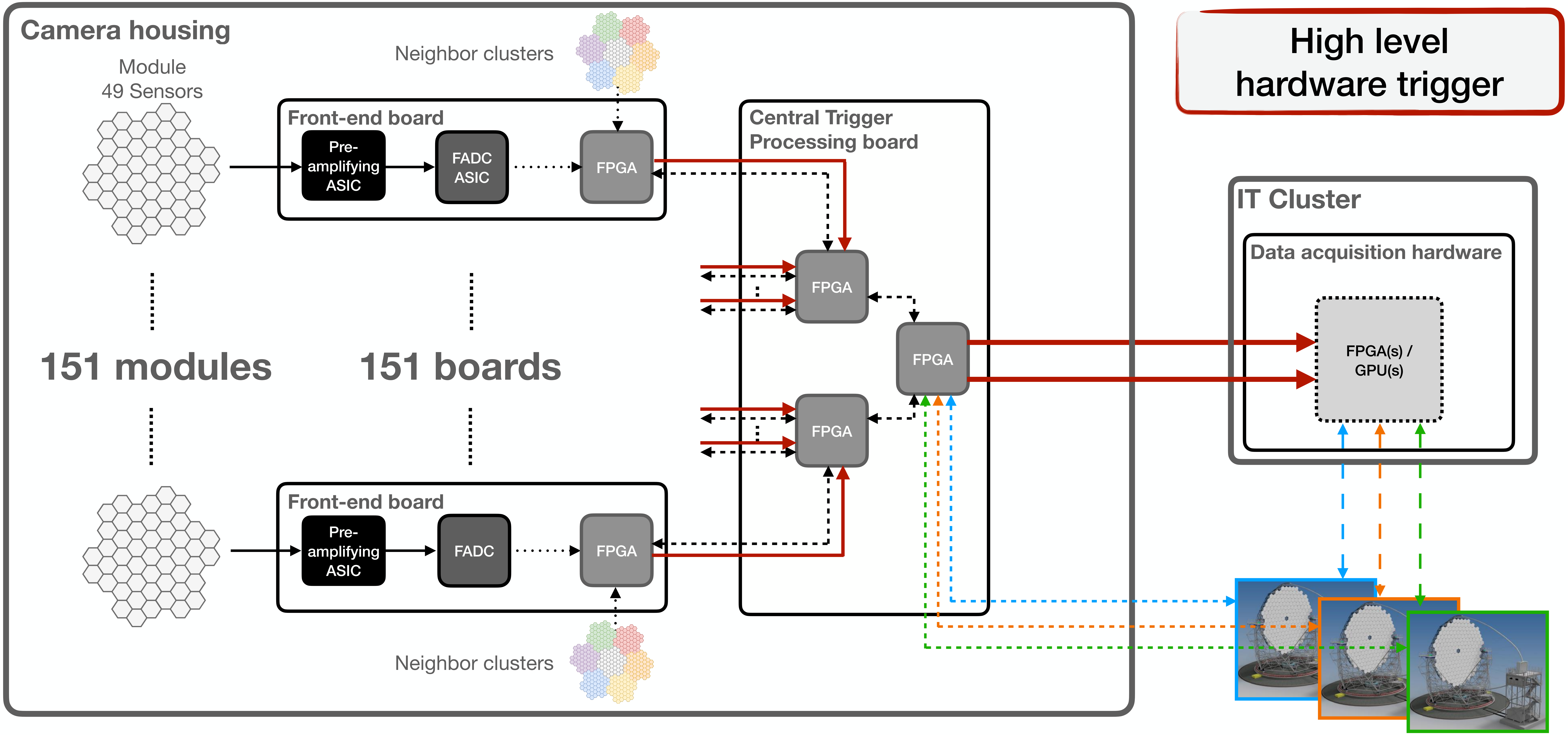
Run at 350MHz, Low and fixed Latency (~11.5ns)

T. Dietrich, A. Upegui, Q. Berthet (HEPIA)

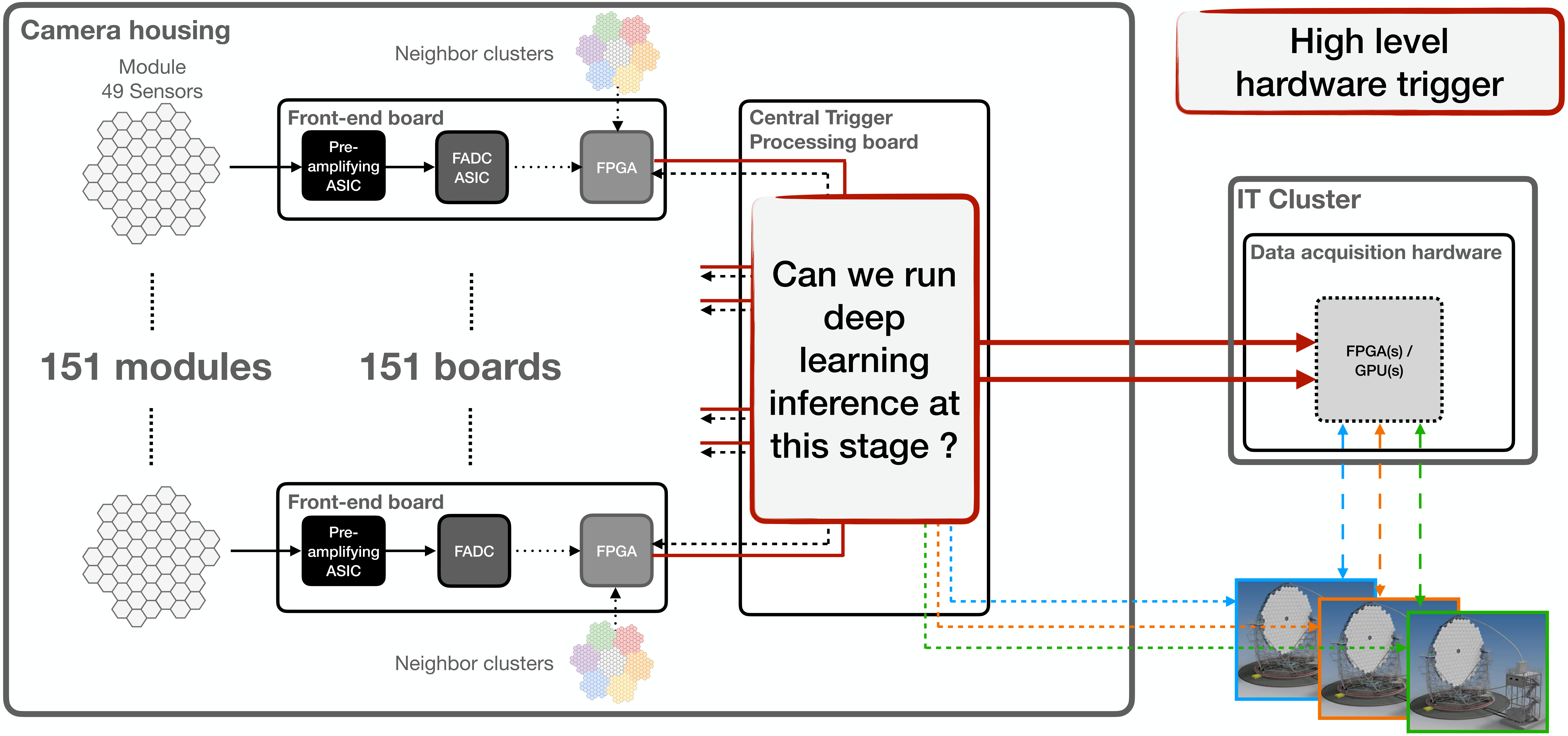
The AdvCam readout architecture



The AdvCam readout architecture



The AdvCam readout architecture



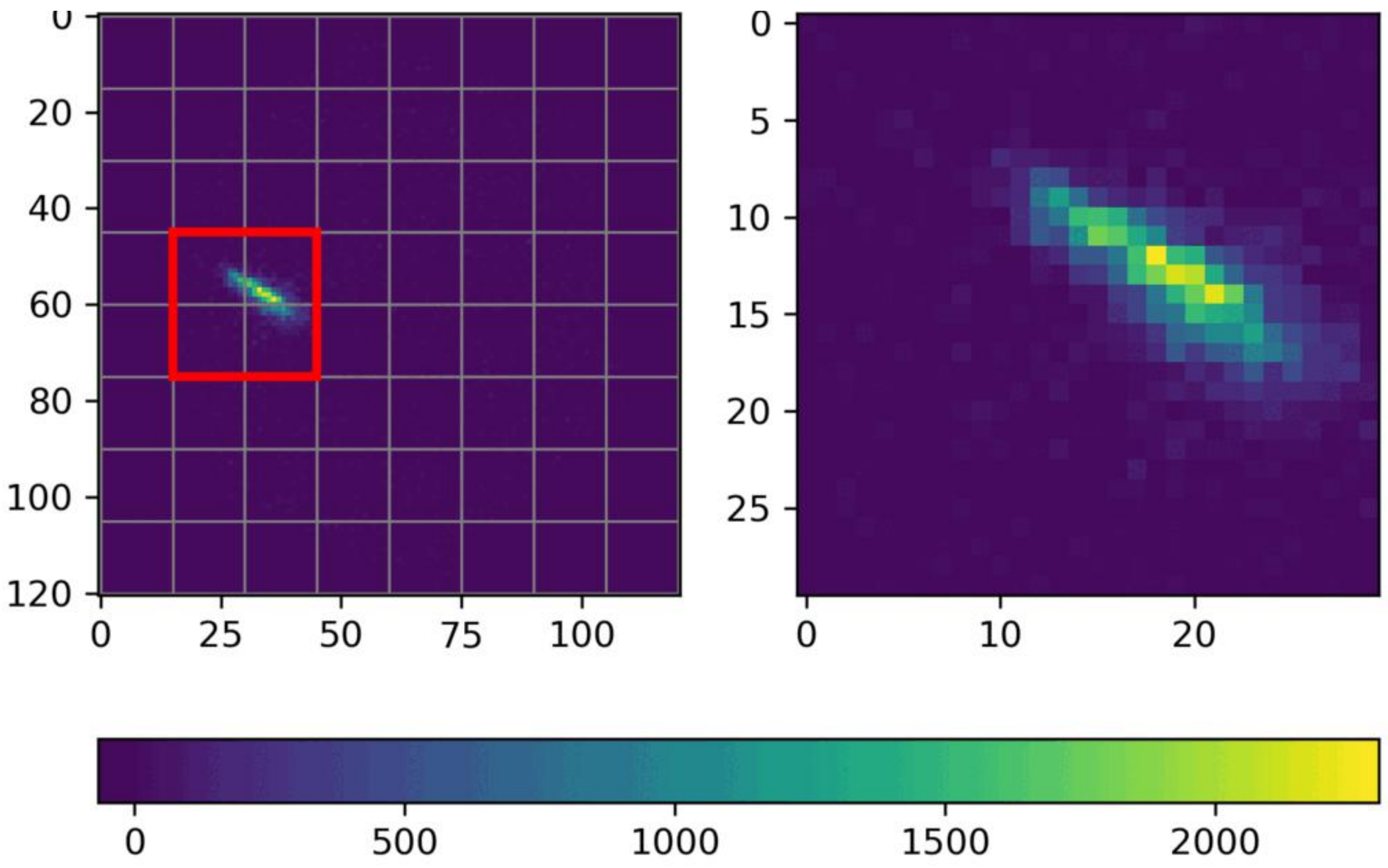
The high level hardware (and software) trigger

Can we use the full event data?

- We need the full data cube but we use a subset for the training
- **Two tasks:**
    1) shower/night sky background
    2) gamma/hadron

30x30 pixels x 5 frames
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)
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_________________________________________________________________
```

The high level hardware (and software) trigger

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

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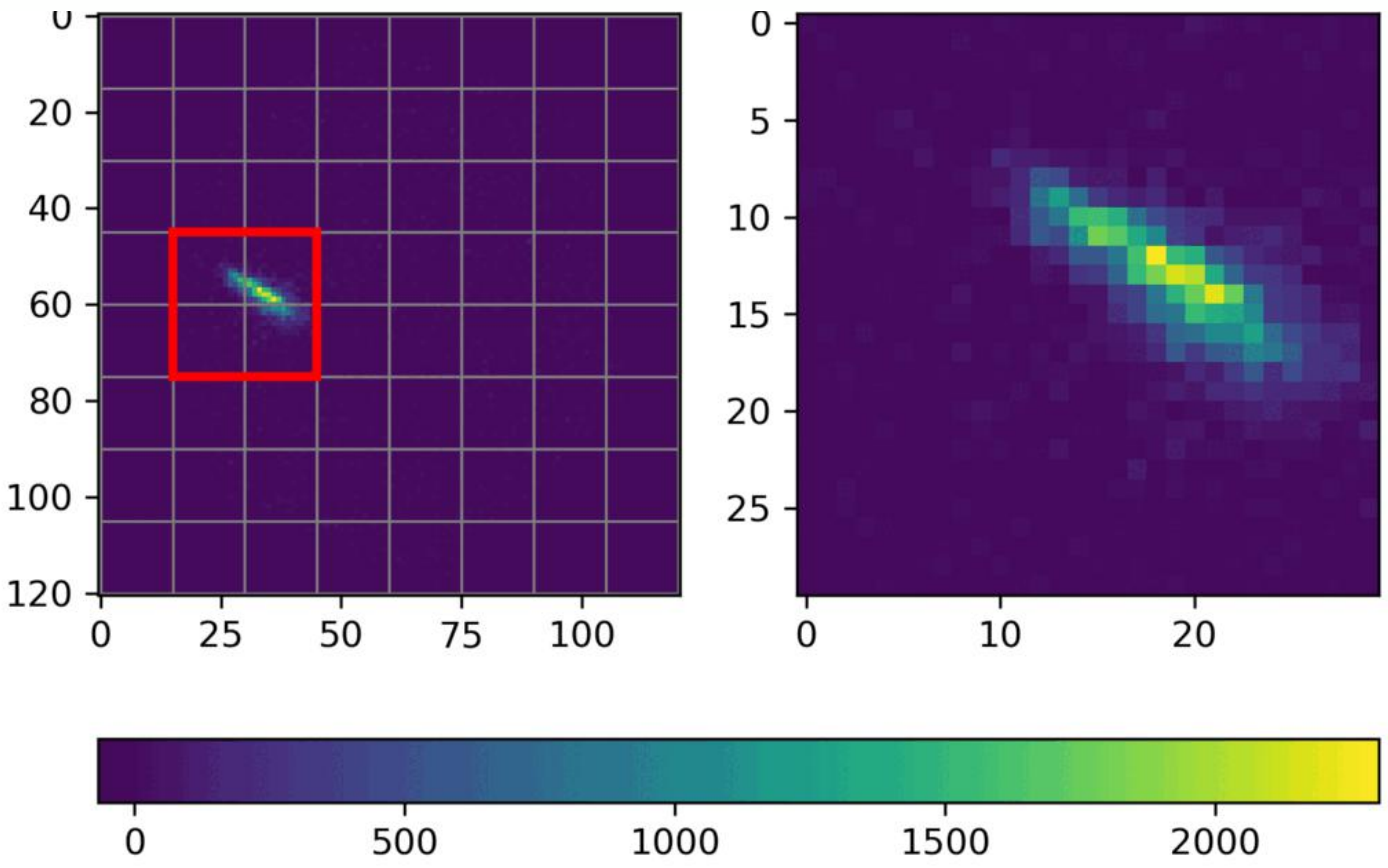

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Gamma, Hadron, NSB

CTLearn

```
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```
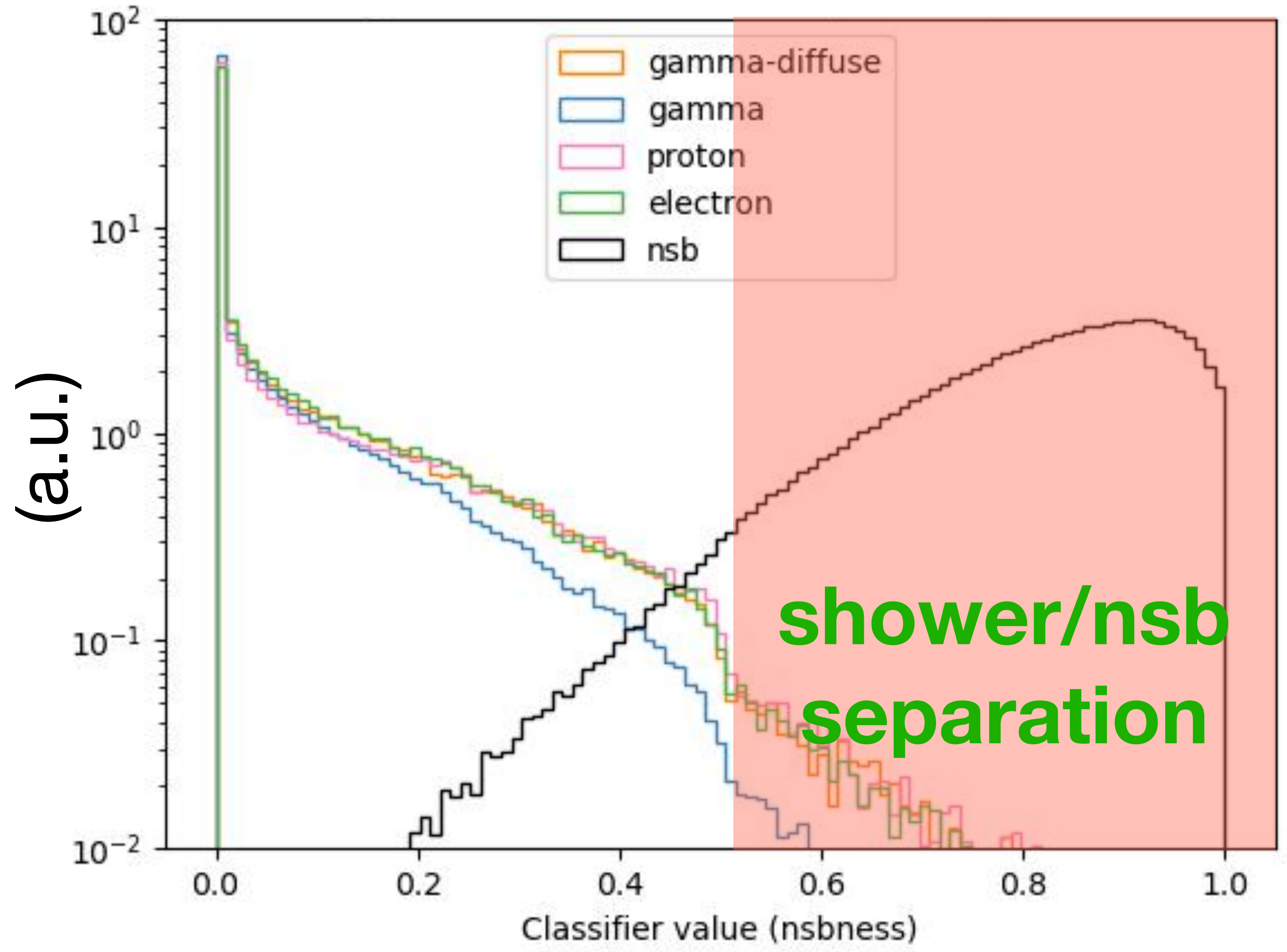
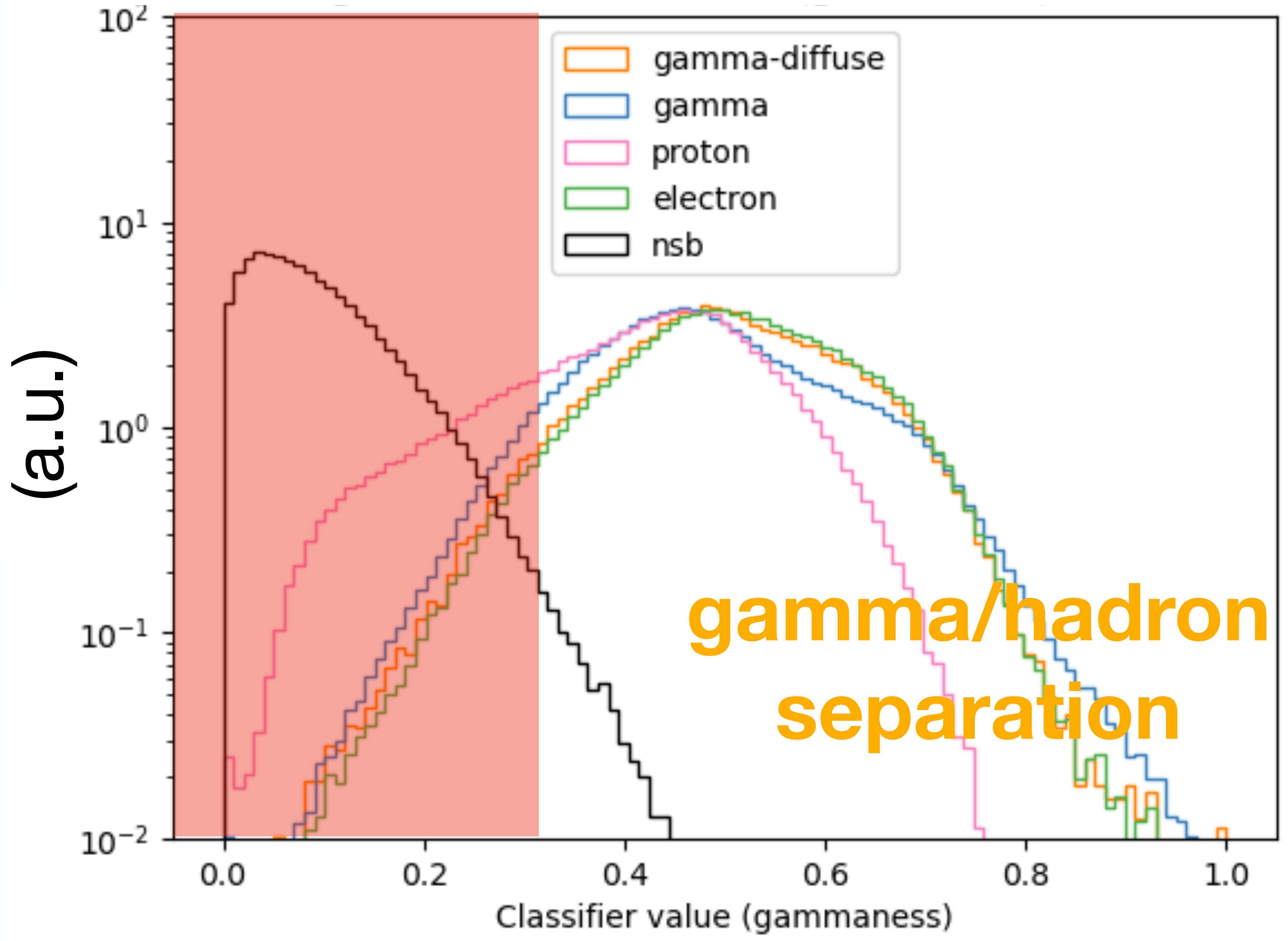

The high level hardware (and software) trigger

Can we use the full event data?





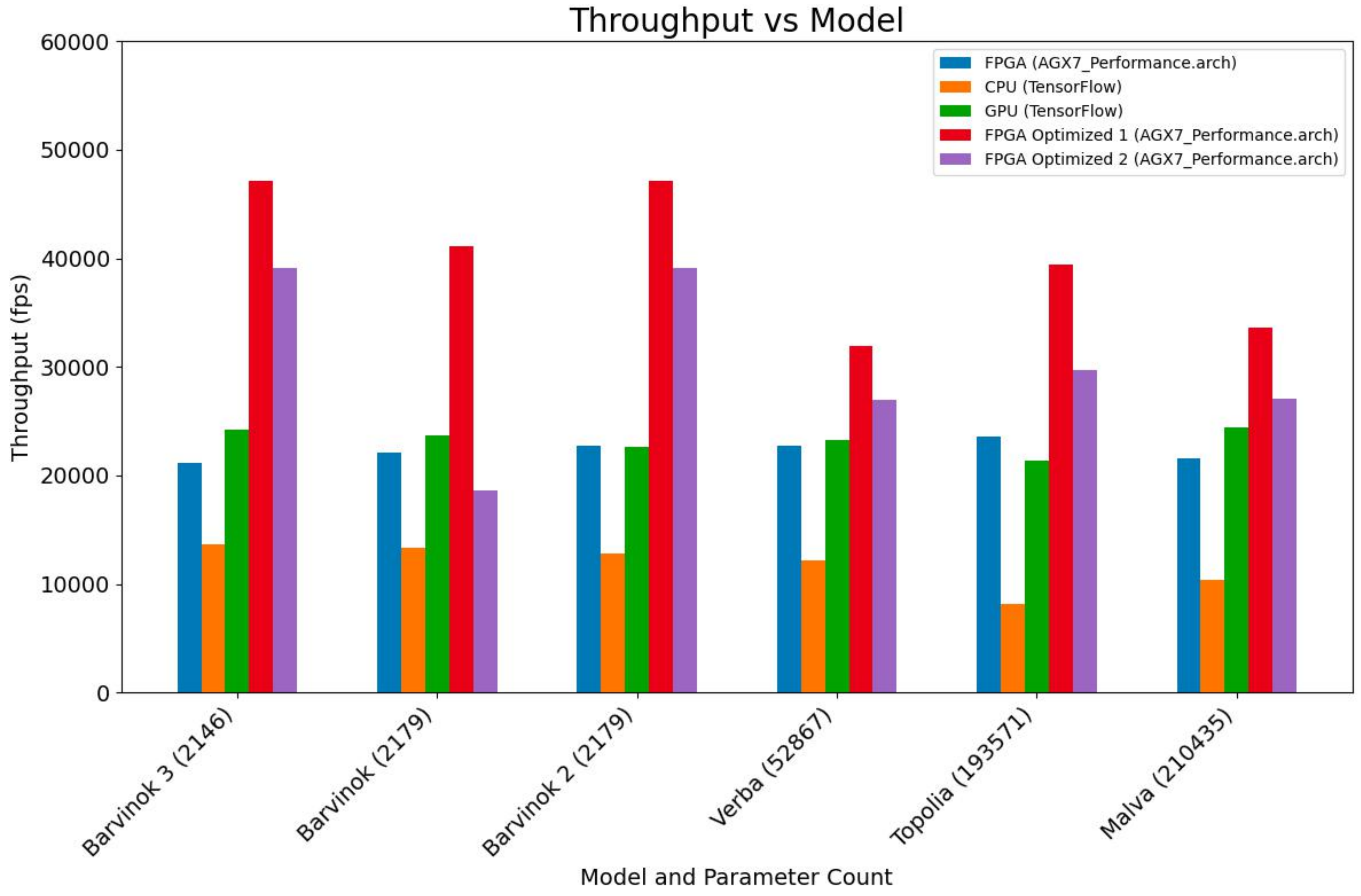
- Once optimized, algorithm can run on FPGA at throughput about twice larger when compared to GPU
- On Xilinx XCKU040 FPGA using HLS4ML reach ~5 μs latency
- If resources are available, network complexity does impact so much the throughput
- Performance on binary data cubes under test

* 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

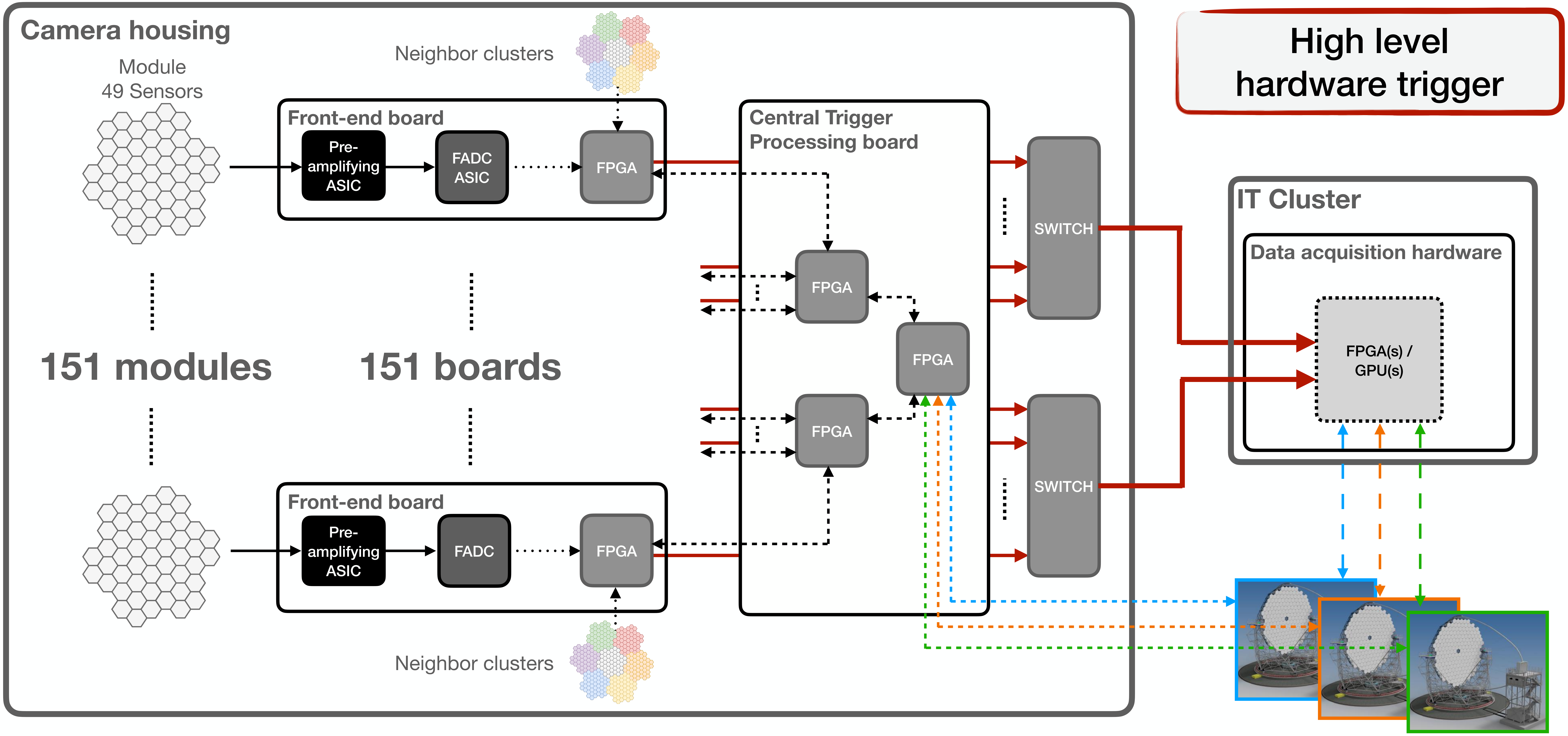
R. Factor	Latency (us)	DSP
1	5.2	122
8	12.9	66
16	15.3	52
32	15	29
64	20.4	17
128	33	9
256	41	6

*results for post-implementation simulation



T. Miener (UniGe), A. Perez, J. A. Barrio (UCM), C. Abellan Beteta, I. Bezshyiko (UZH)

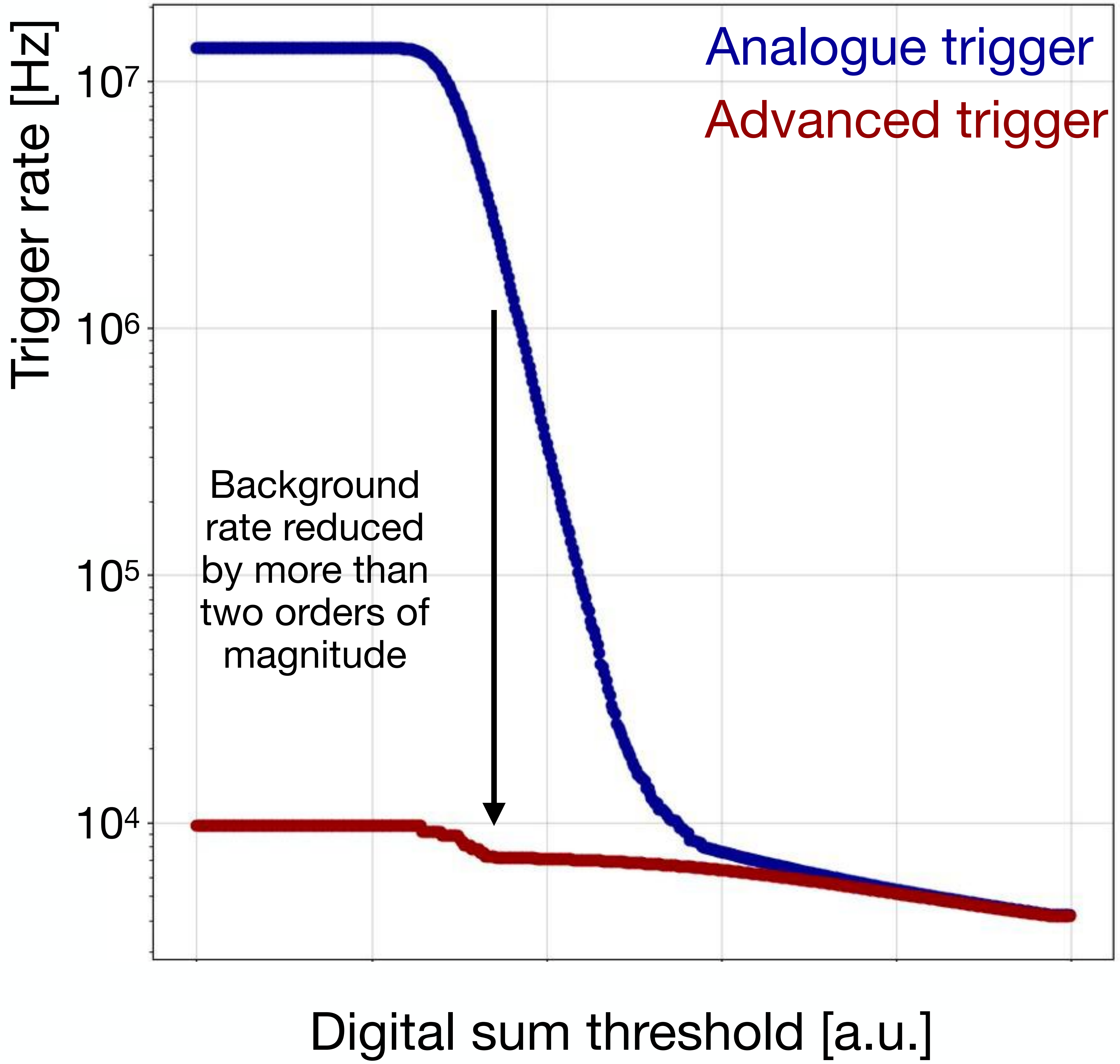
The AdvCam readout architecture

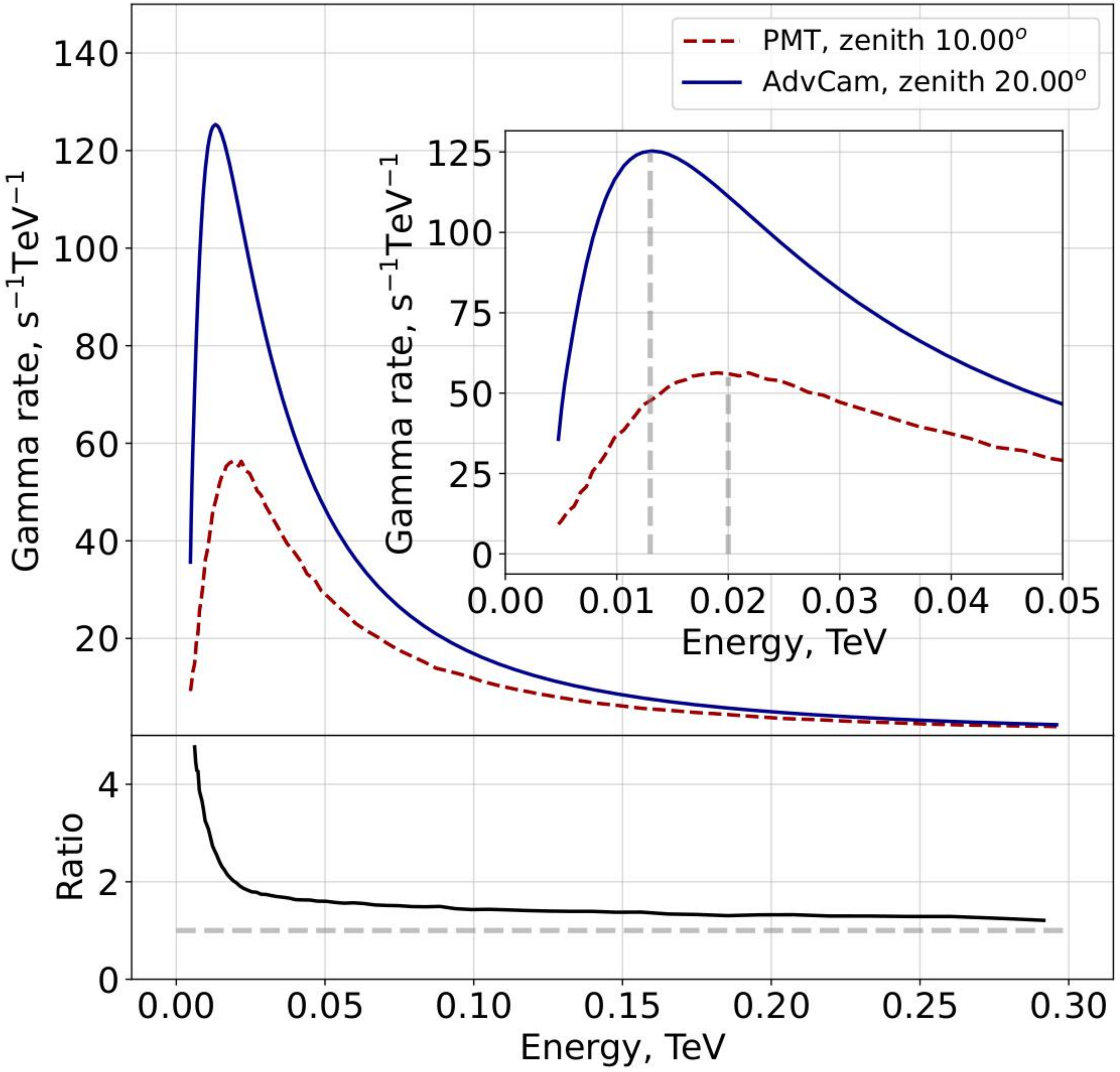


The AdvCam readout architecture

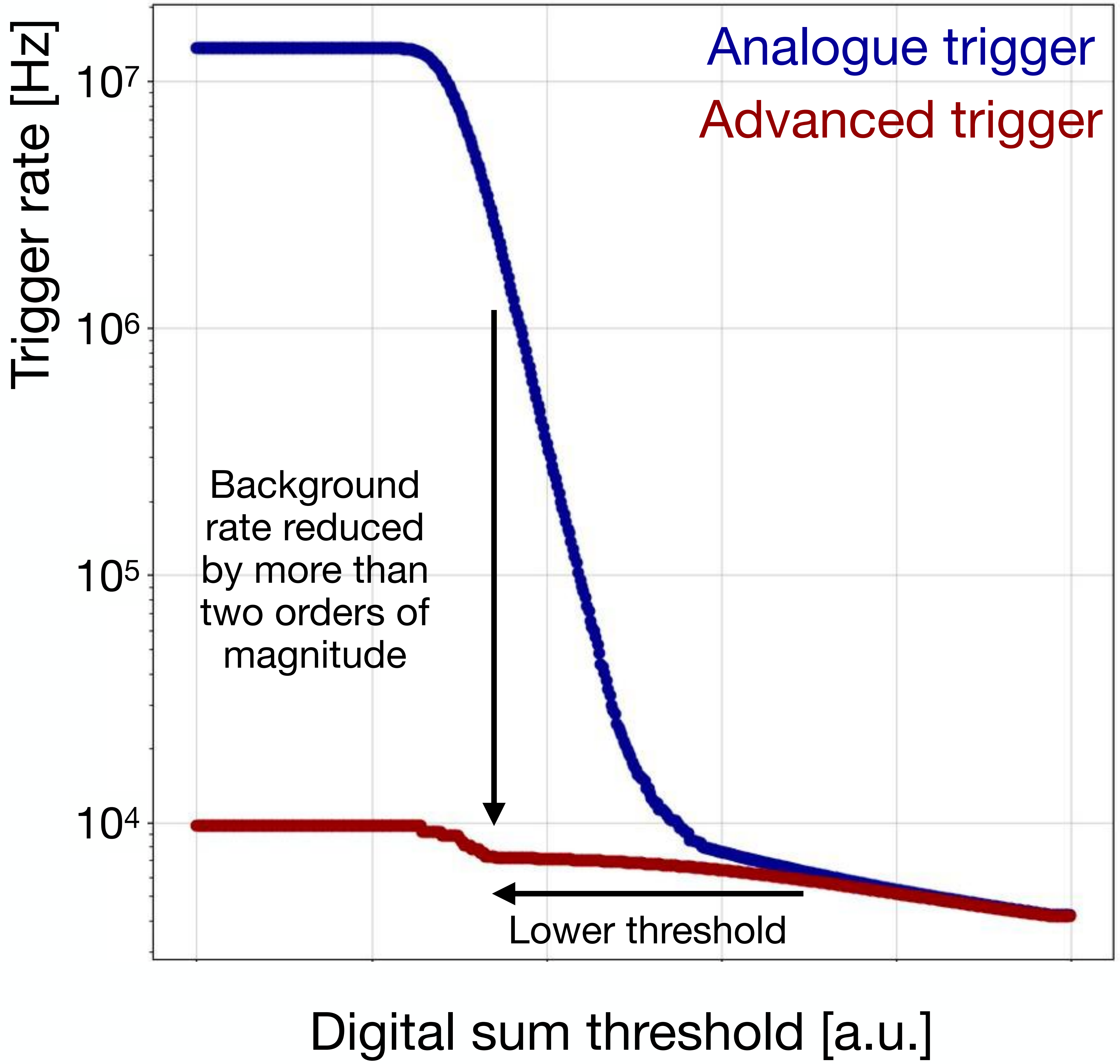
Going for RoCE compliant hardware (switch, network card and processing hardware)

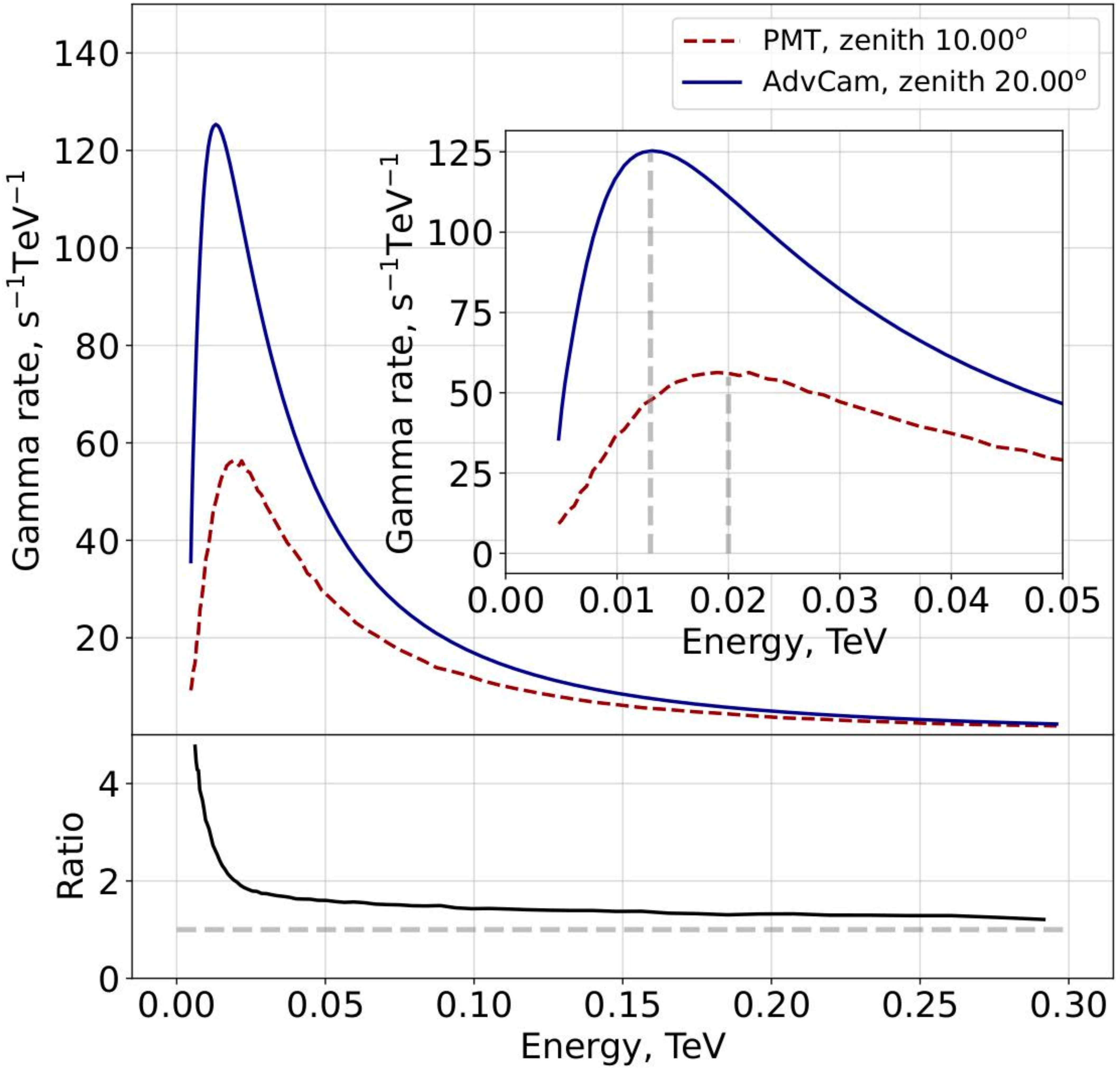
Reaching the lowest energies



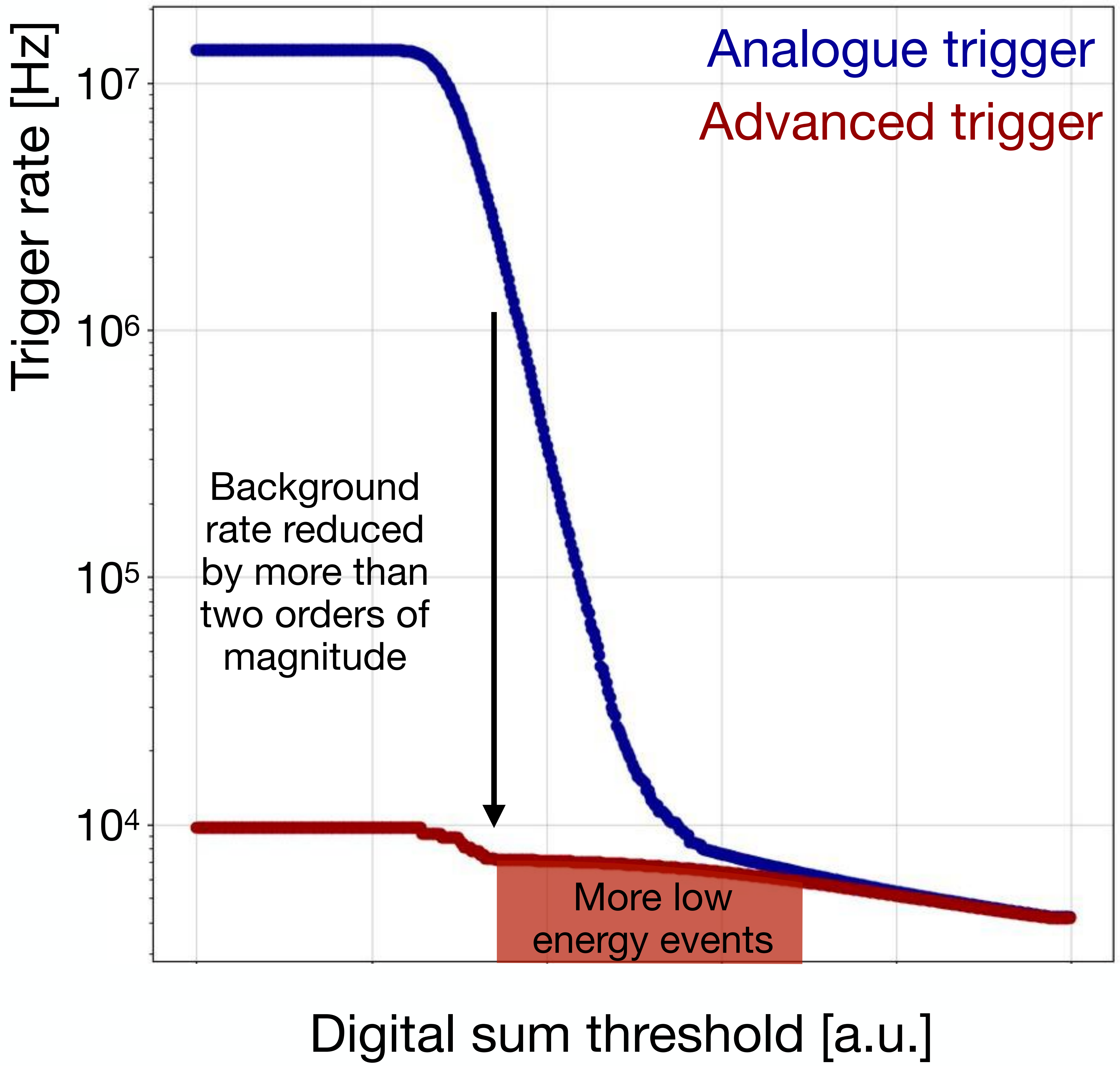


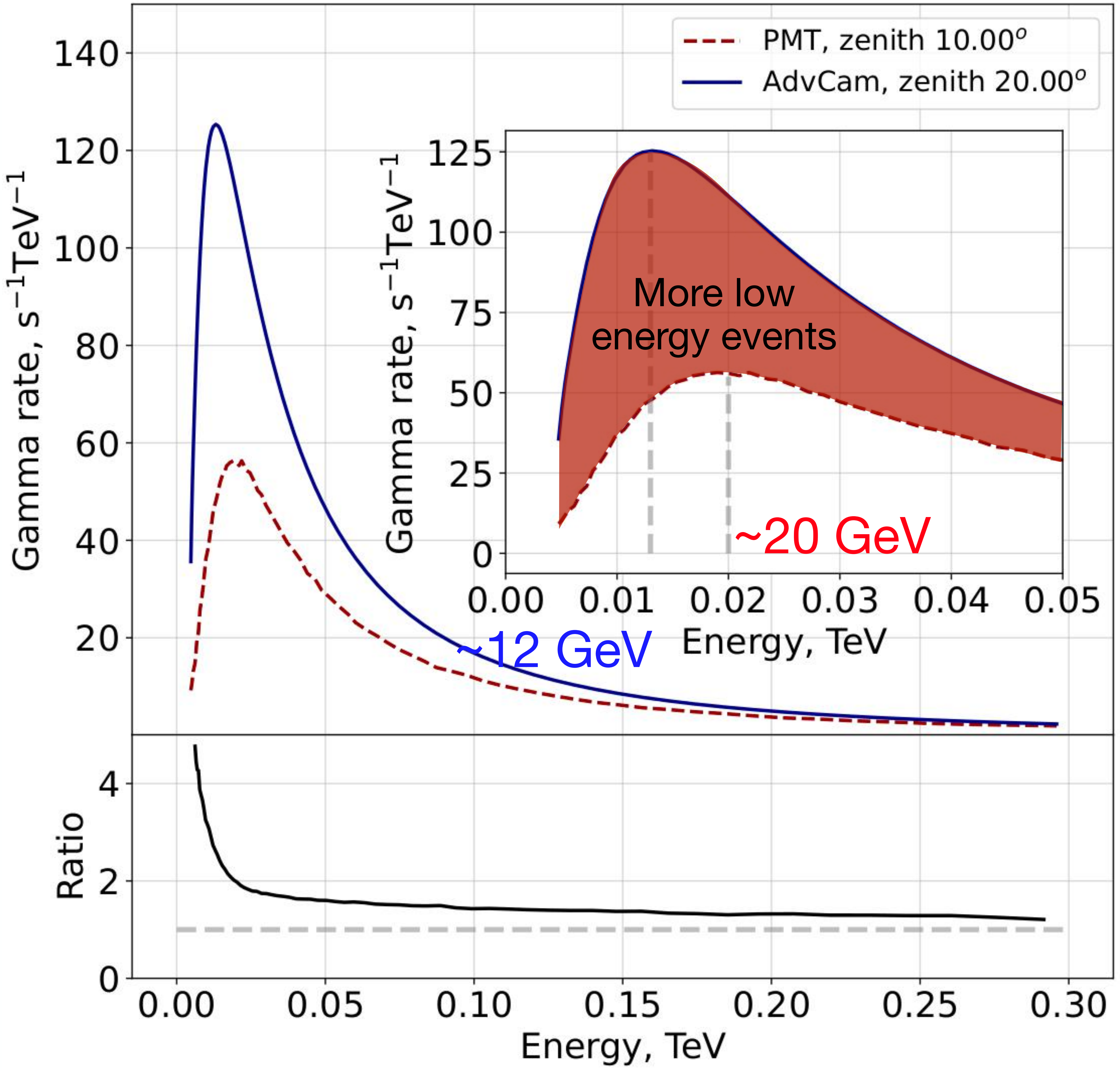
Reaching the lowest energies





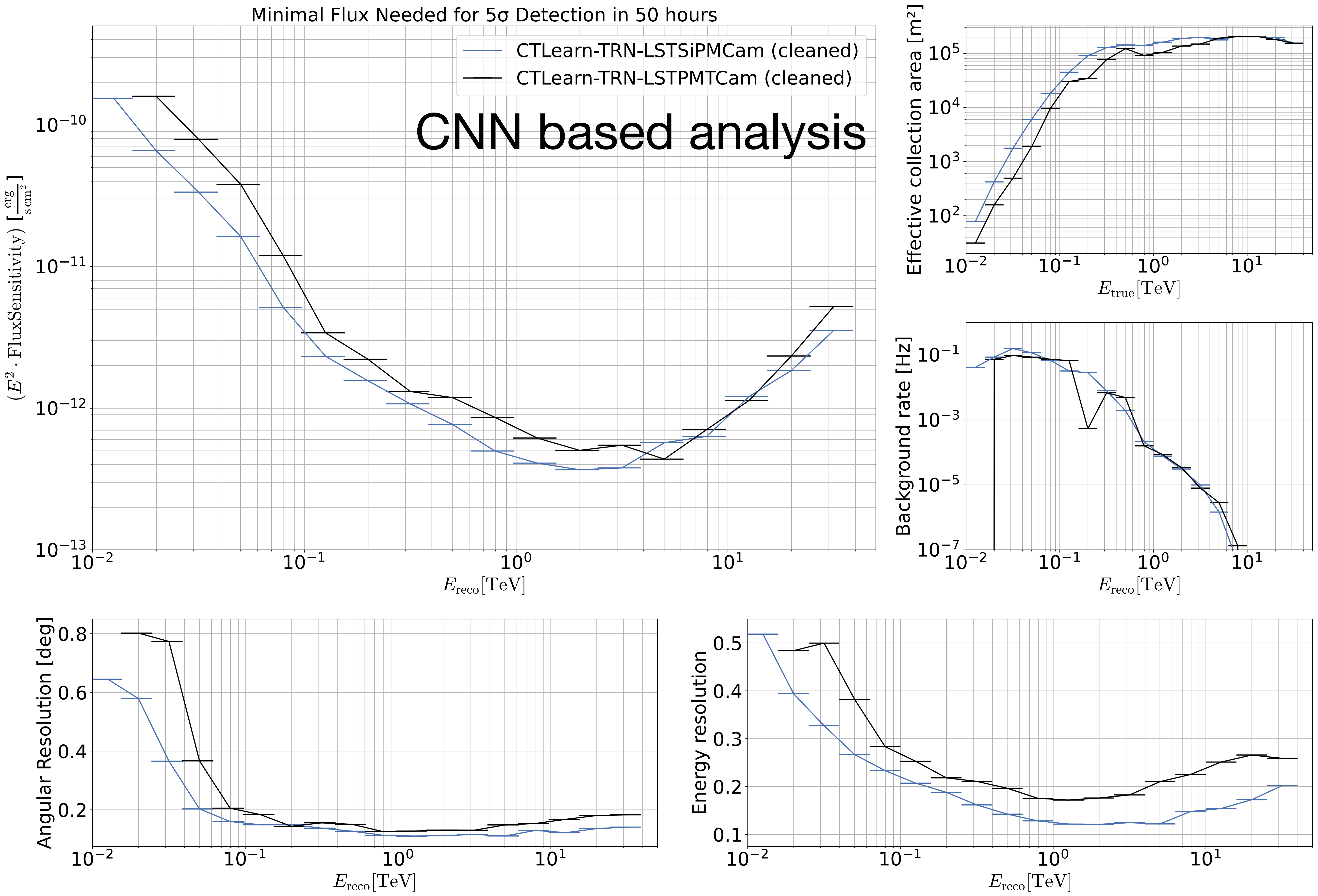
Reaching the lowest energies

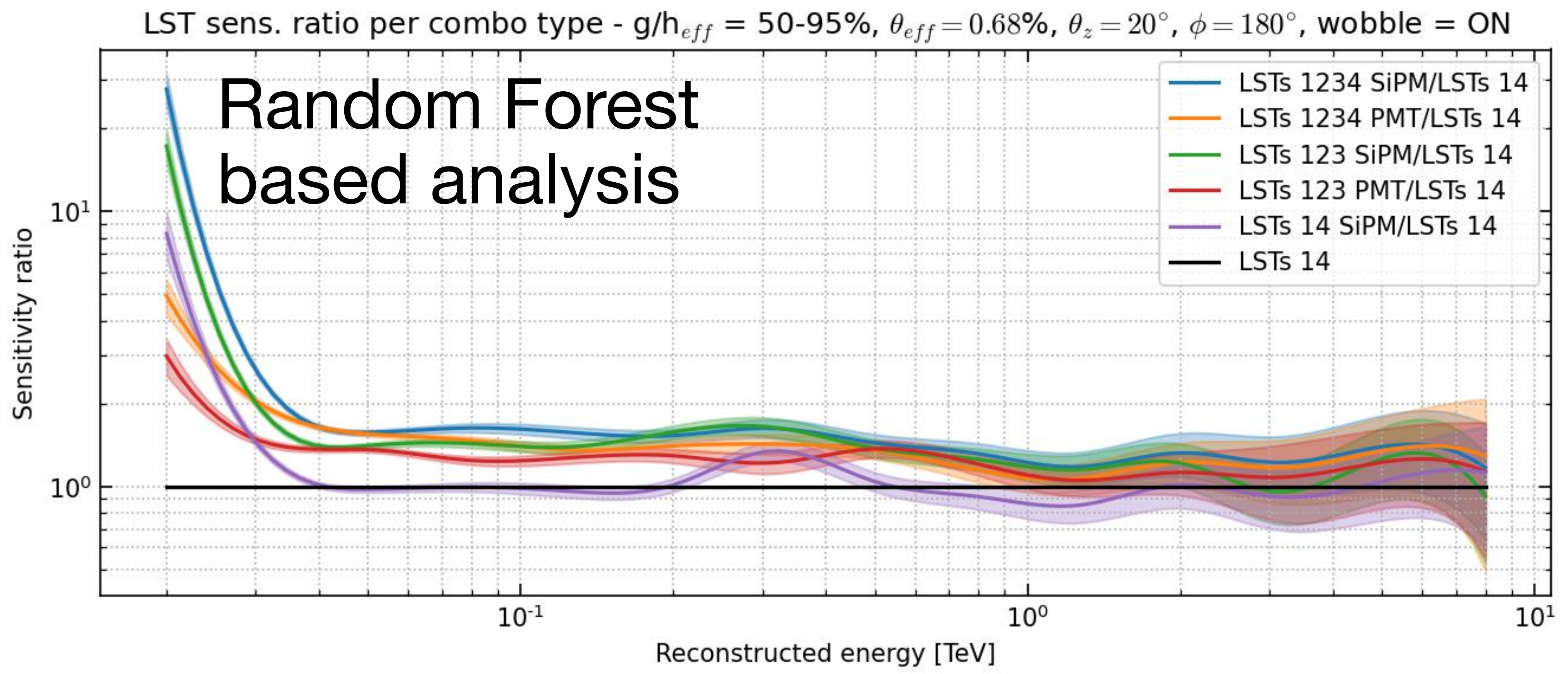




The AdvCam performance

Monoscopic performance only





- Preliminary results do not yet take advantage of new trigger scheme
- Still sensitivity improvement larger than factor 2 below 50 GeV and additionnal energy bin available!
- Analysis pipeline yet not ready to process such faint events, need to revise:
  - Training recipe
  - Network architecture
  - …

T. Miener, B. Lacave (UniGe)

Conclusions and Perspectives

- Gamma-ray astronomy enters a new era with the CTAO ERIC
  - Recognition of In Kind Contribution can start…
  - …acceptance of telescopes as well

- But this is a long journey, 30 years of observation is ahead of us, we need to plan for upgrades

- Sensitivity of instruments has been improving steadily since begining of the field, following mirrors and sensor technological improvement

- 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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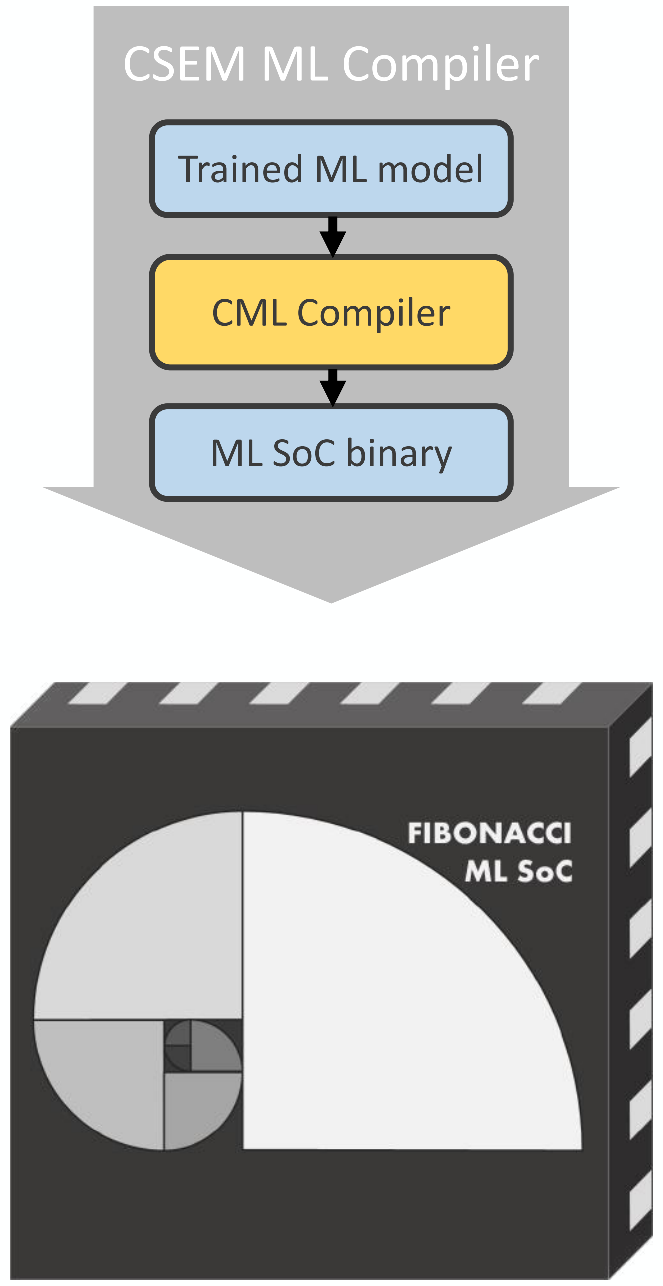
Thanks for your attention !

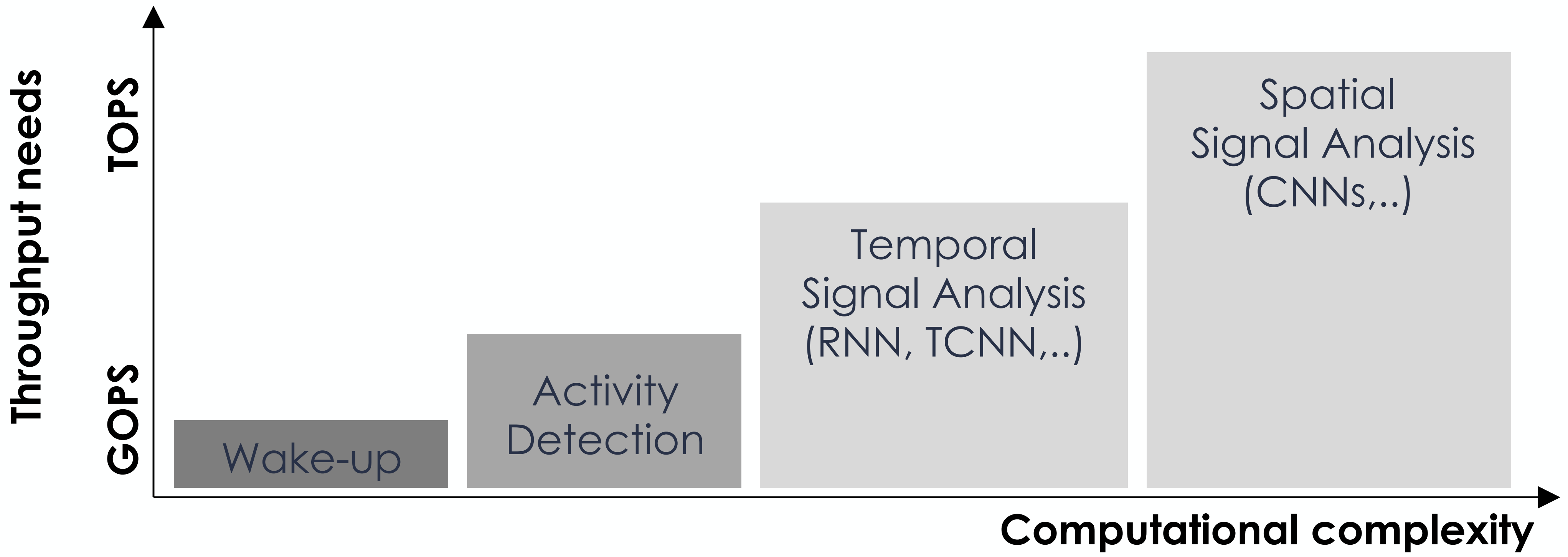
Credit: CTAO gGmbH

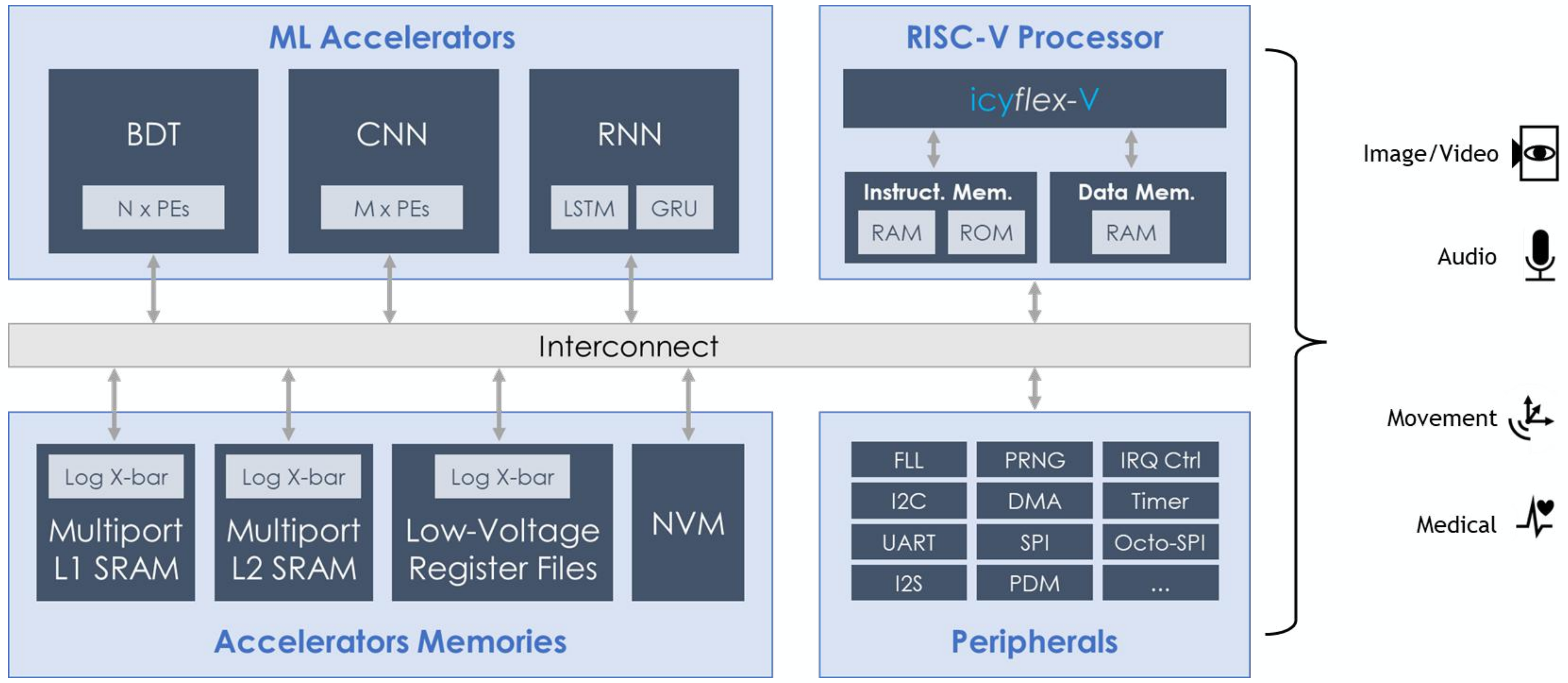
"Smart sensors"

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





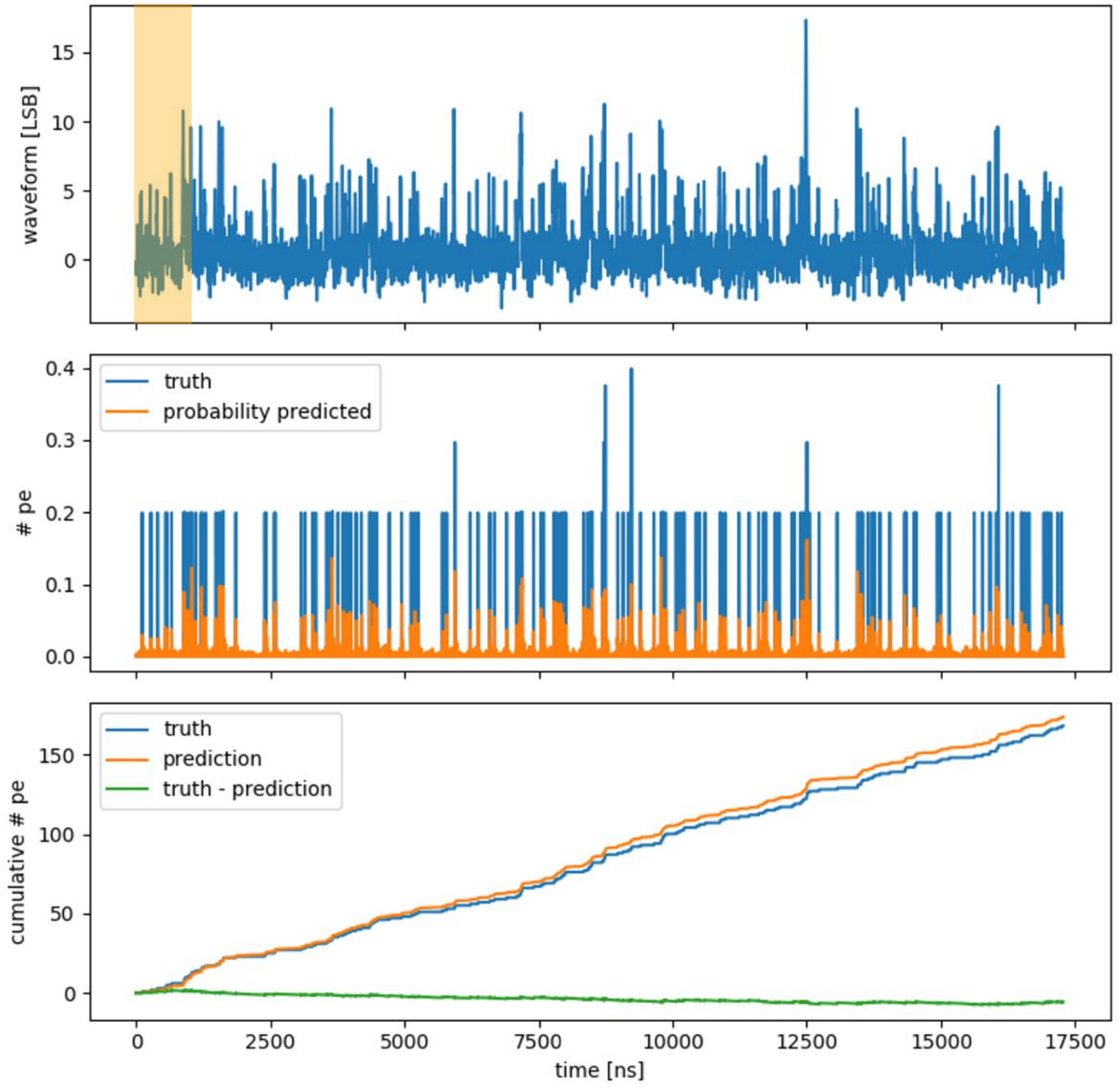


"Smart sensors"

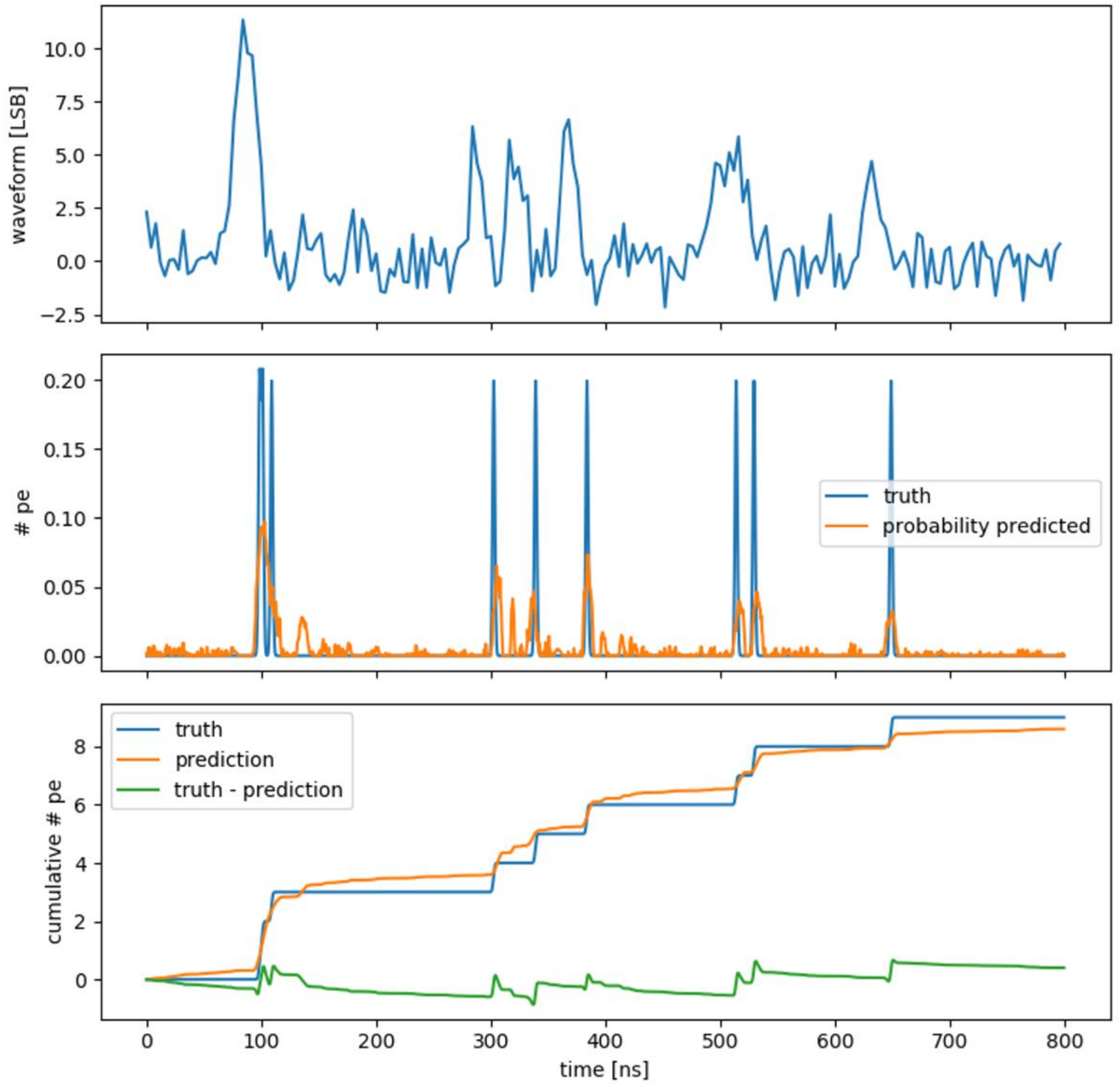
Developing single photo-electron extraction

- 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