Implementation and Optimization Studies of the Divergent Pointing Mode for CTAO

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On behalf of the CTAO Simulation team and the CTAO Consortium

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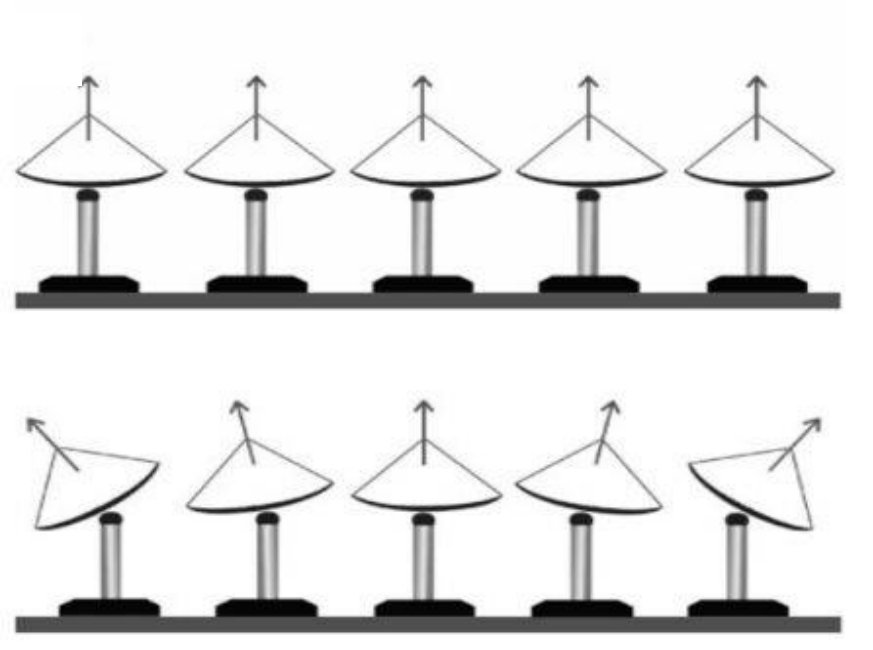
Implementation and Optimization Studies of the Divergent Pointing Mode for CTAO



1 Introduction to CTAO

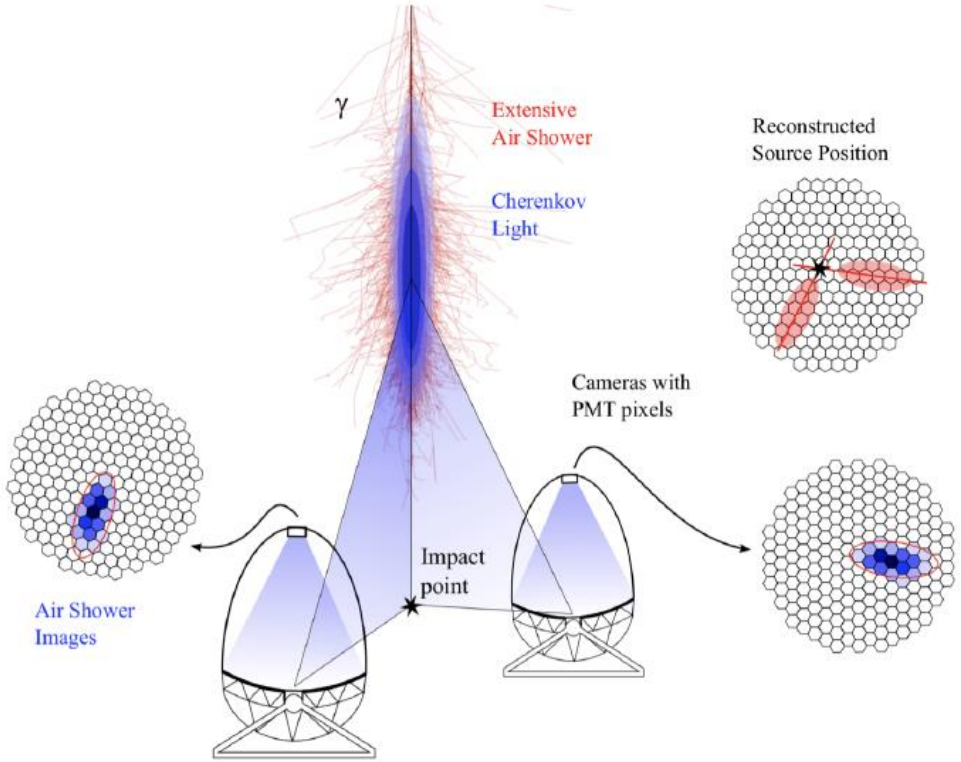
2 Simulation and Analysis

3 Divergent Pointing

4 Conclusions

Imaging Air Cherenkov Telescopes

Detecting Gamma-rays from Earth

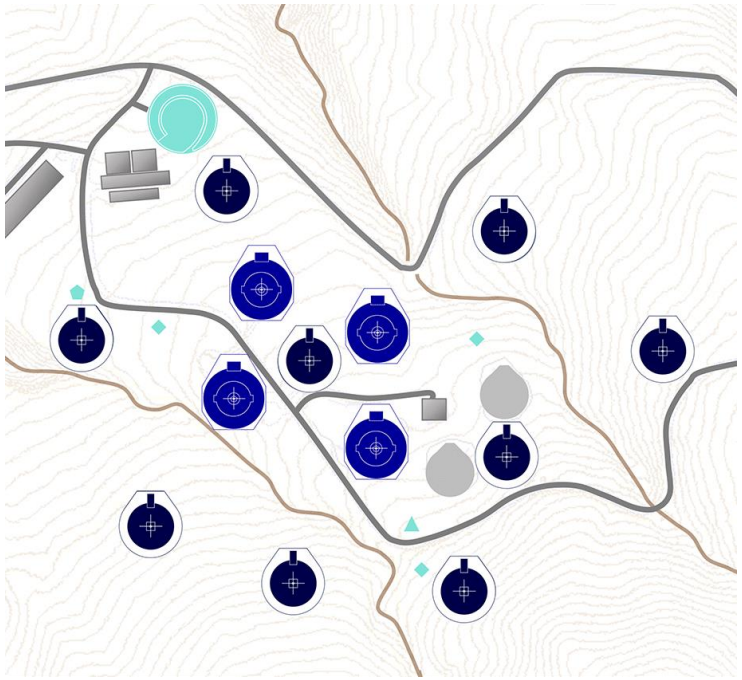


Stereoscopic Observation:

Multiple telescopes observe the same event or region from different angles, allowing for the **3D reconstruction**, improving spatial resolution and reducing background noise.

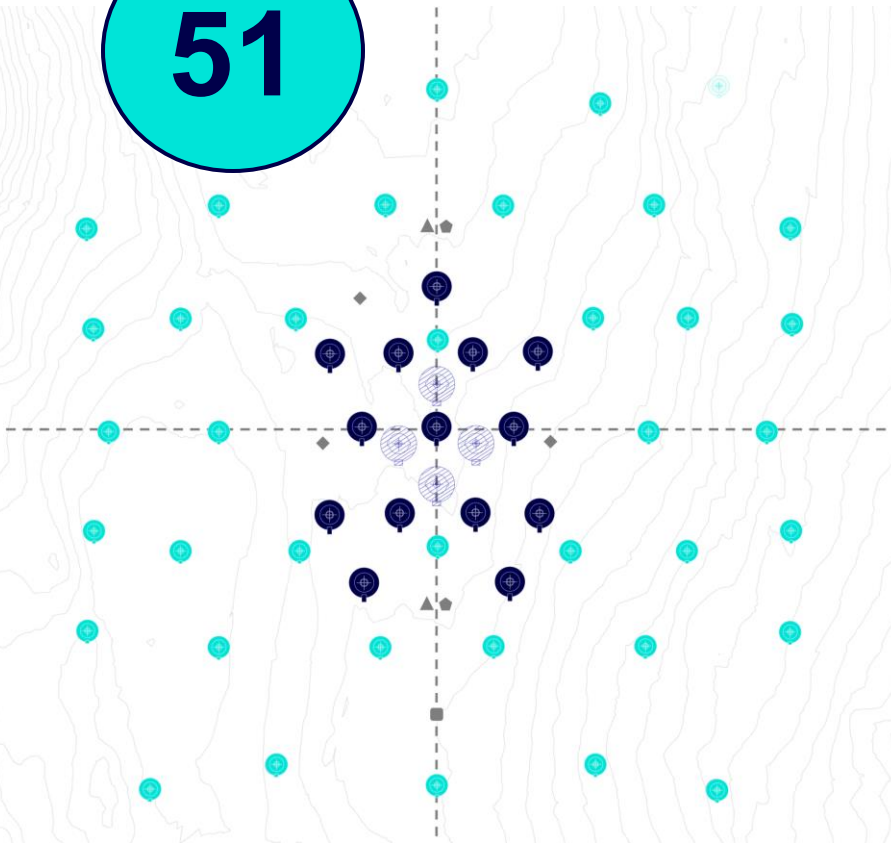
D. C. Fidalgo. Springer Theses. Springer, 2019

2 Sites

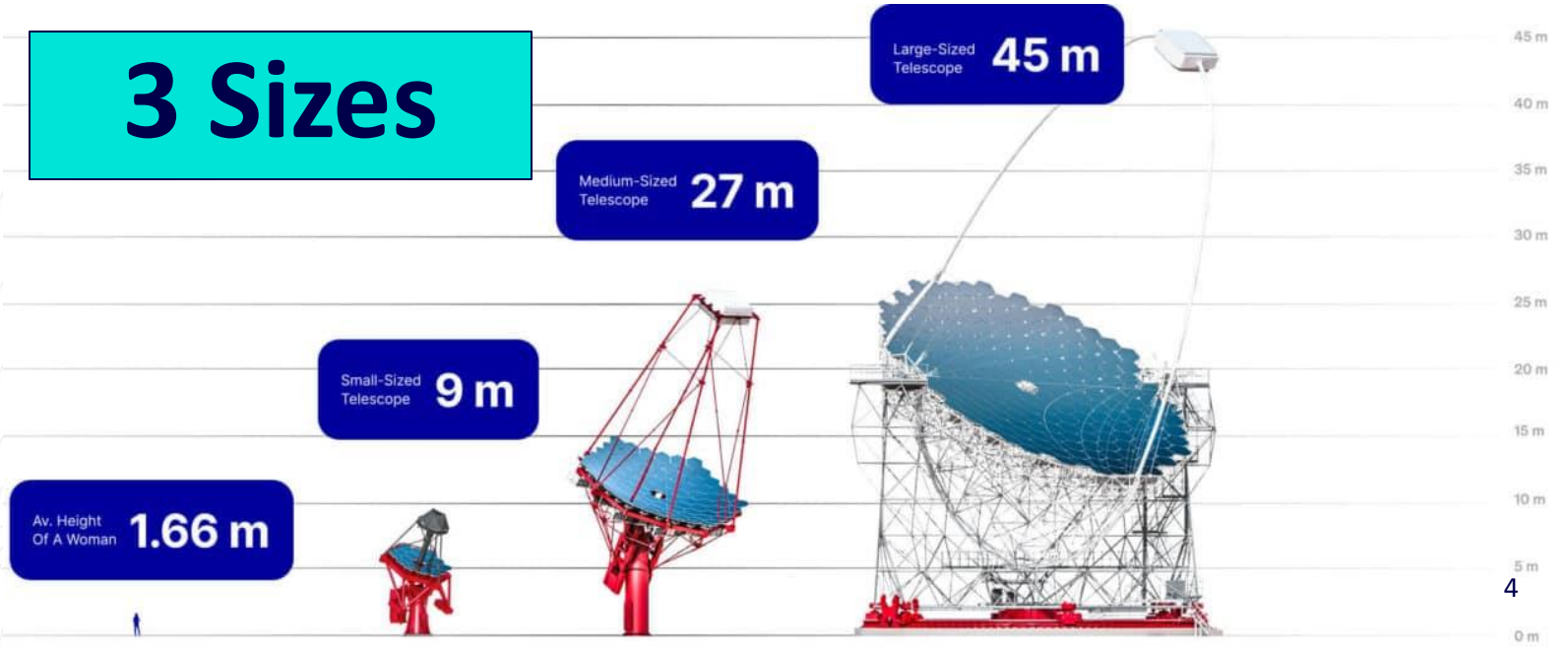


13

51

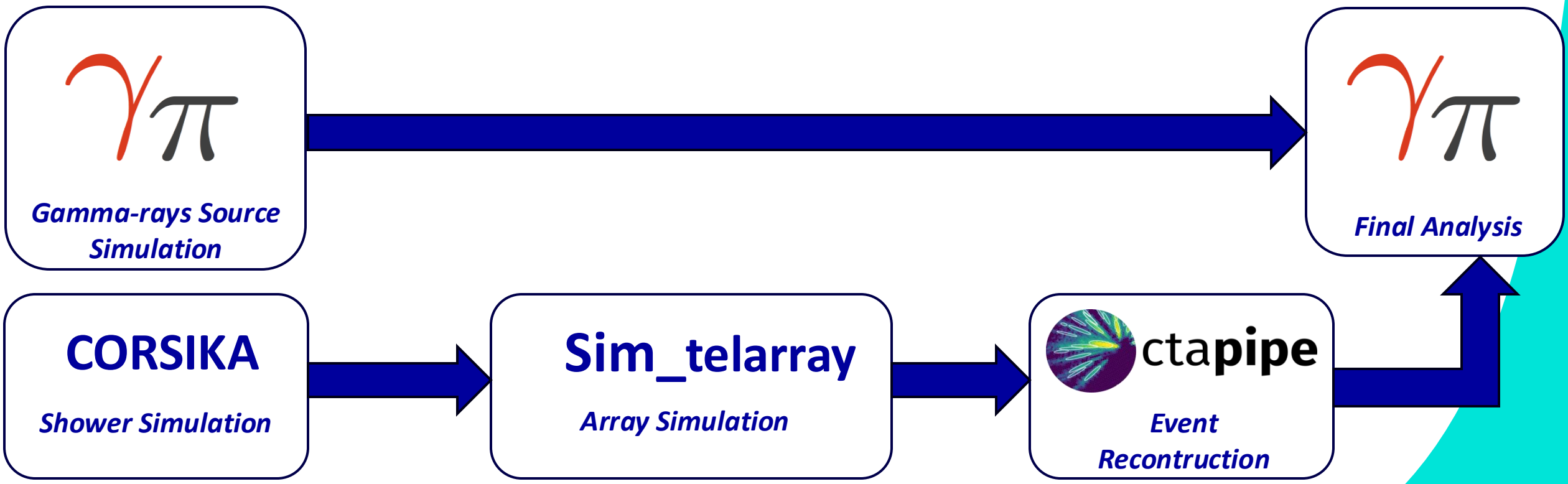


3 Sizes

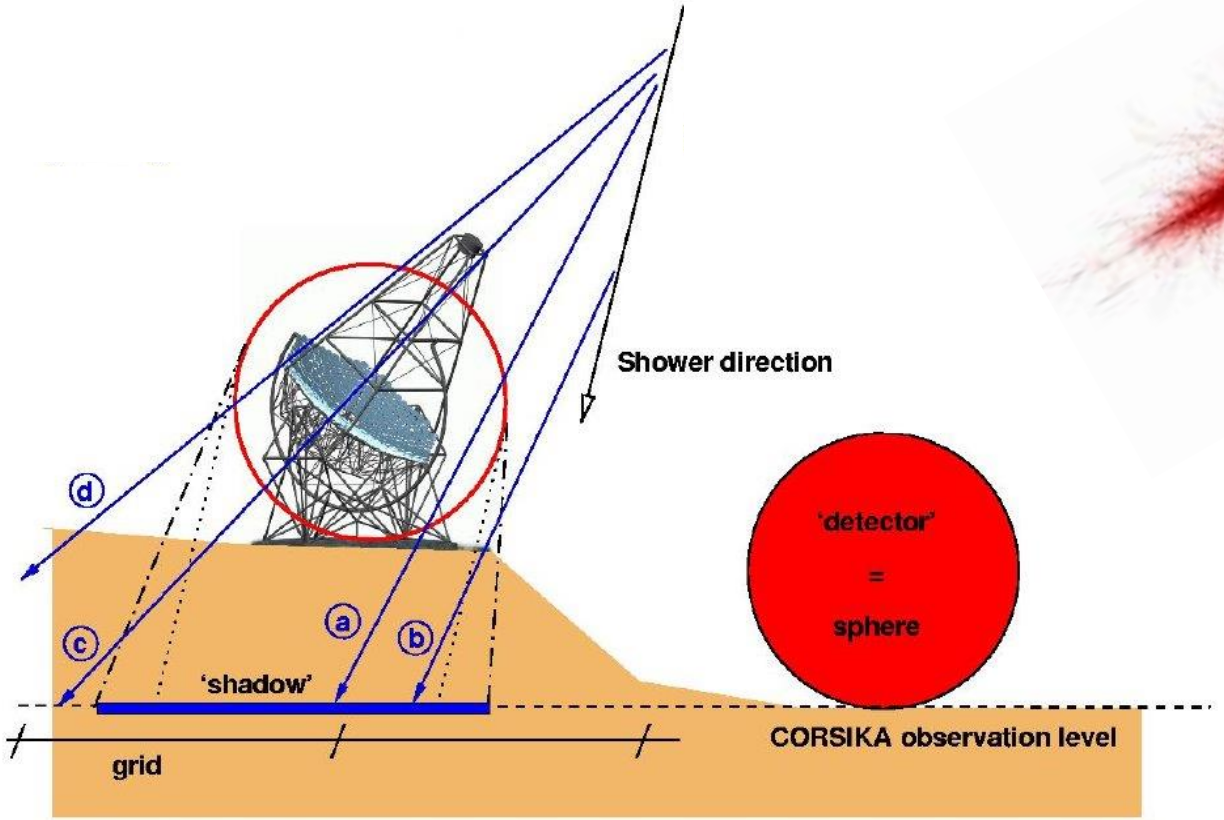


www.ctao.org

Simulation and Analysis Pipeline



Air Shower Simulation



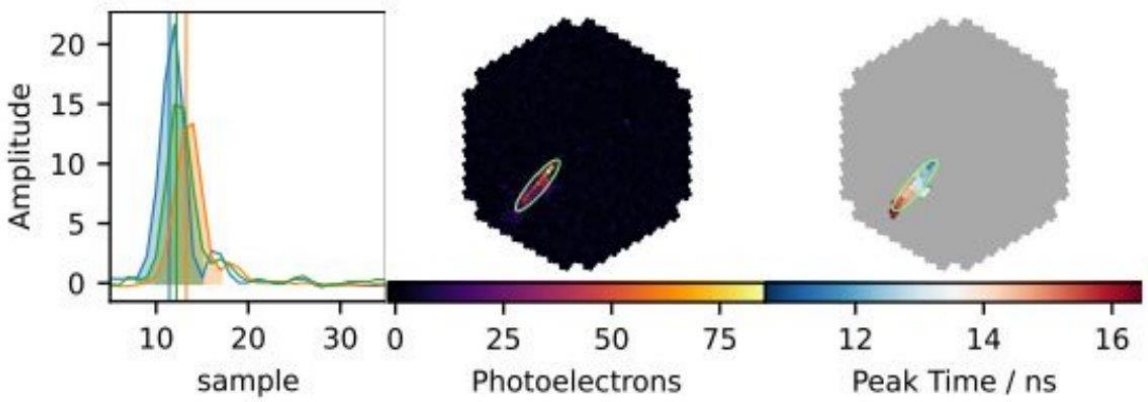
a: recorded photon bunch
b: not recorded because not intersecting sphere
c: recorded (not in 'shadow' but hitting a shadow grid cell)
d: not recorded because not hitting a shadow grid cell

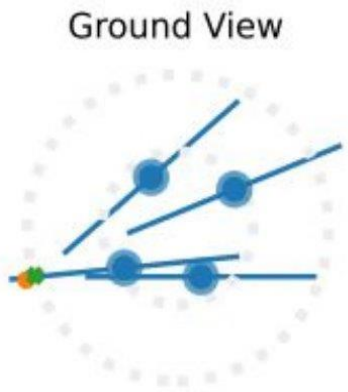
CORSIKA: Air shower simulation

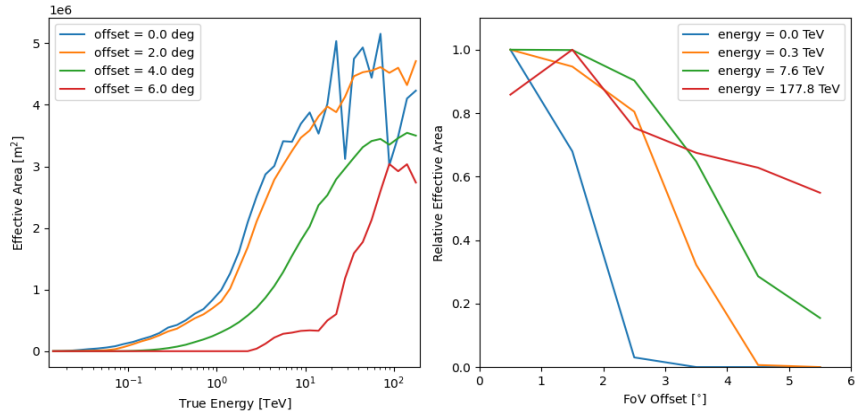
+

Sim_telarray: Telescope response simulation

Low-level Data Processing

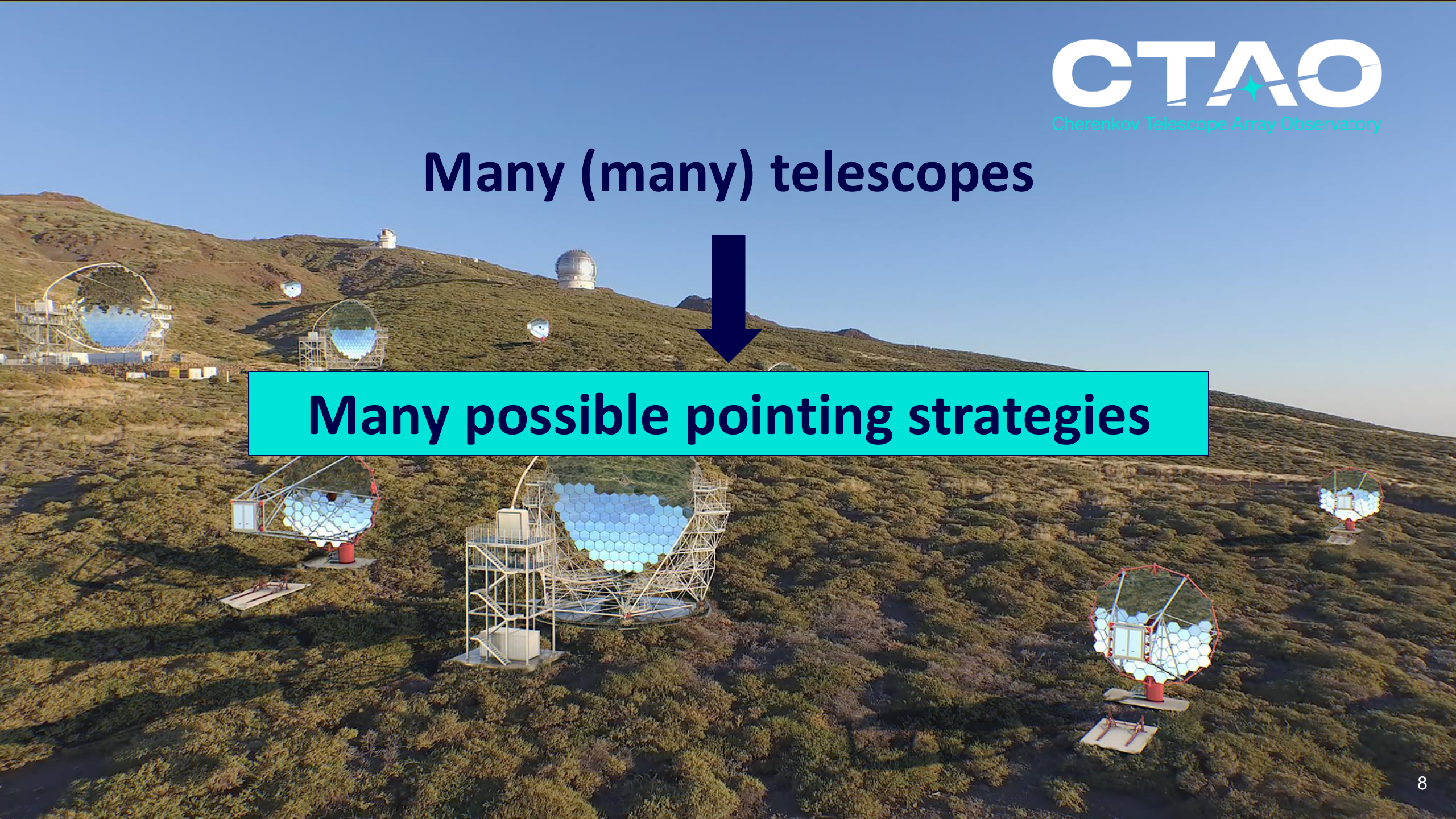




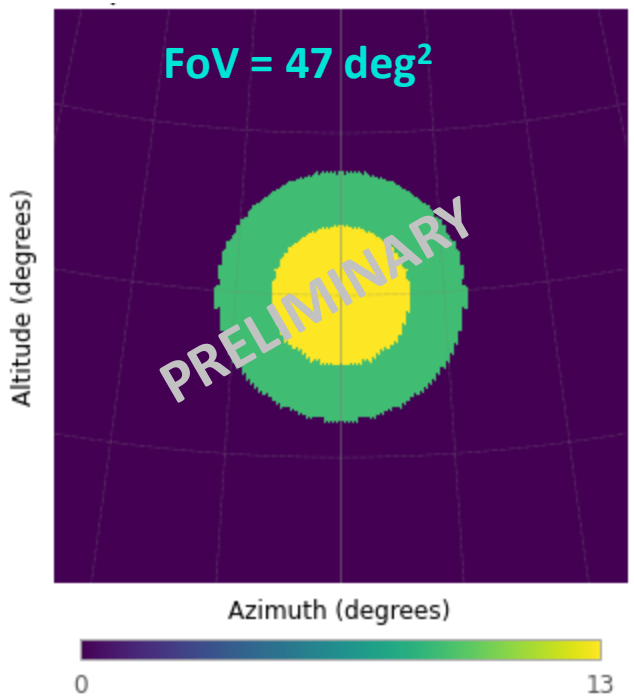


Raw single telescope	Processed single telescope	Reconstructed event	Gamma-like events, Instrument Response Functions

ctapipe

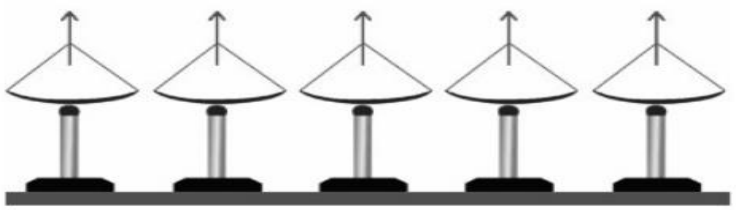

CTAO
Cherenkov Telescope Array Observatory
Many (many) telescopes
Many possible pointing strategies

Pointing Strategies



Parallel Pointing

All telescopes point together at the same direction

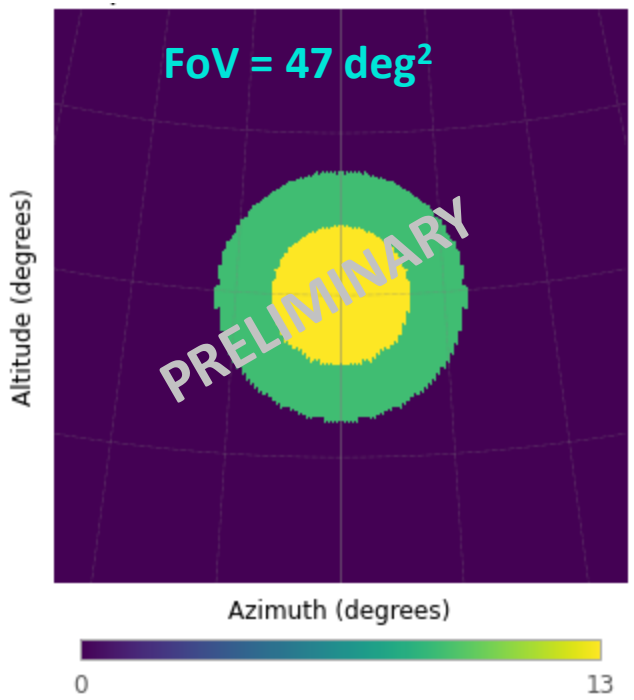


Szanecki M., et al. 2021

The usual **standard** observational mode for IACTS is the

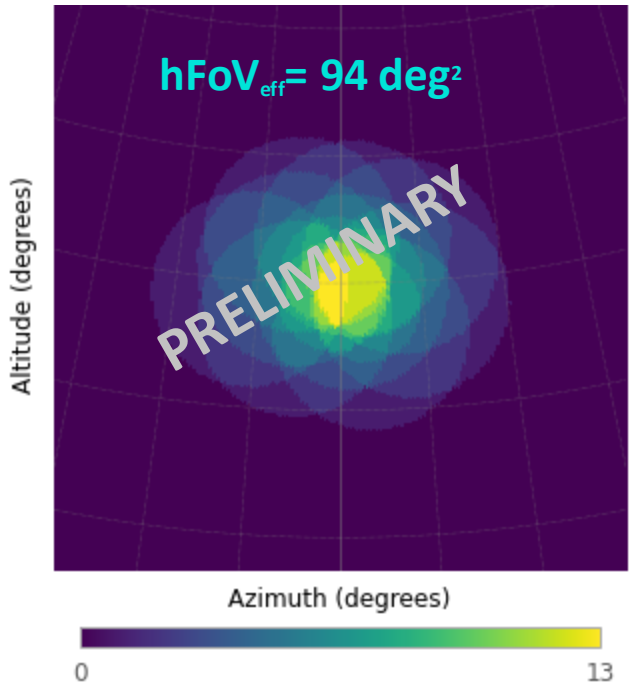
Parallel Pointing

Pointing Strategies



Pointing:
alt = 50°, az =360°

Divergent configuration:
div = 0.02
hFoV =123 deg²



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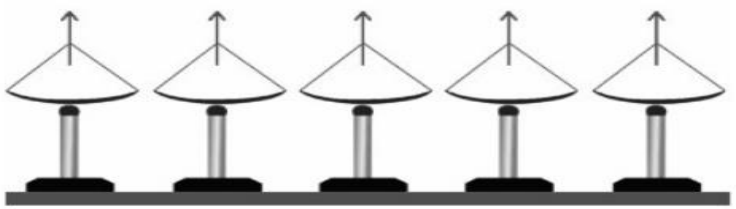
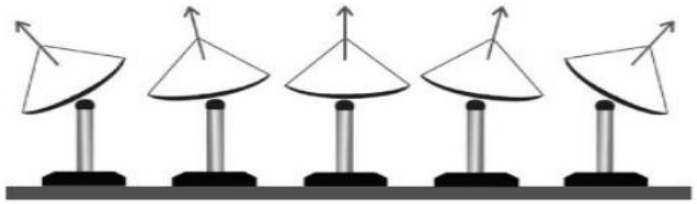


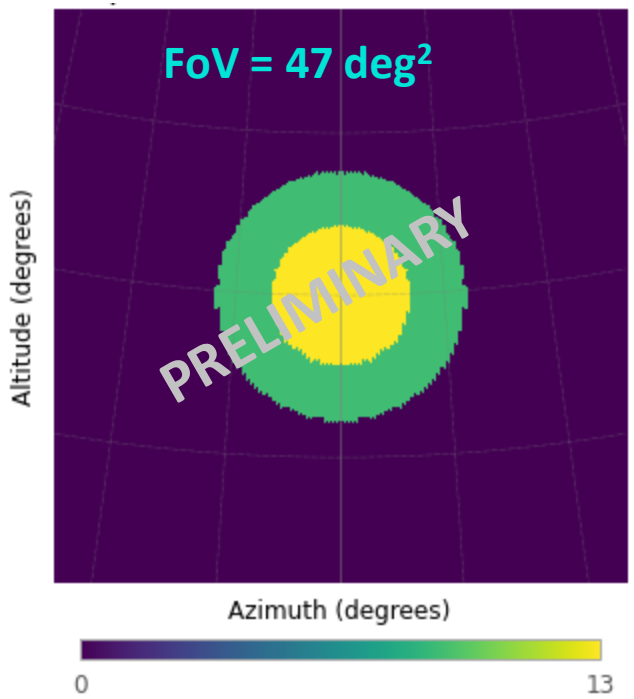
Divergent Pointing

Telescopes are tilted outward by an angle that grows with their distance from the array center



Szanecki M., et al. 2021

Pointing Strategies



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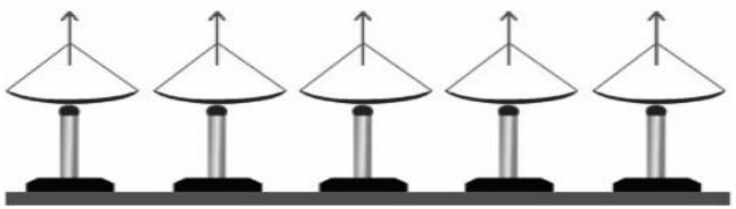

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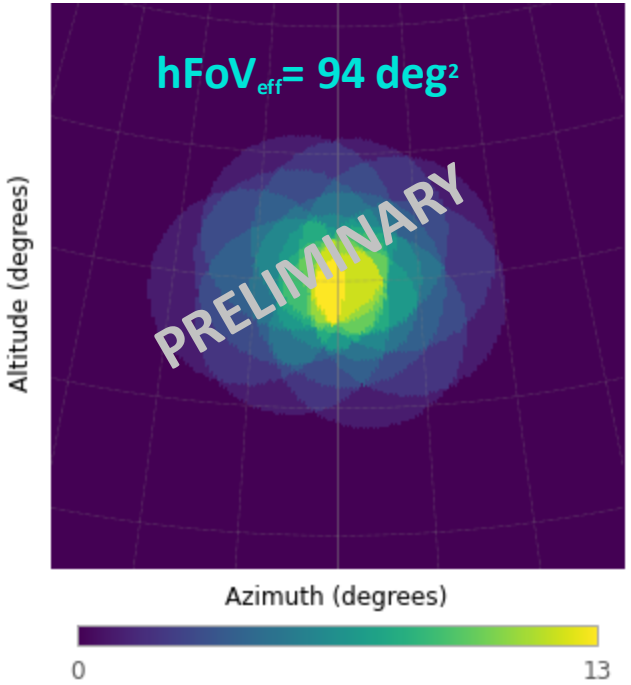
Hyper Stereoscopic Field of View



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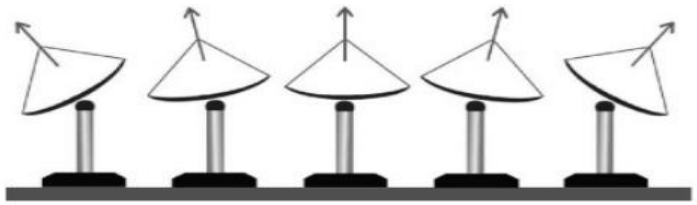
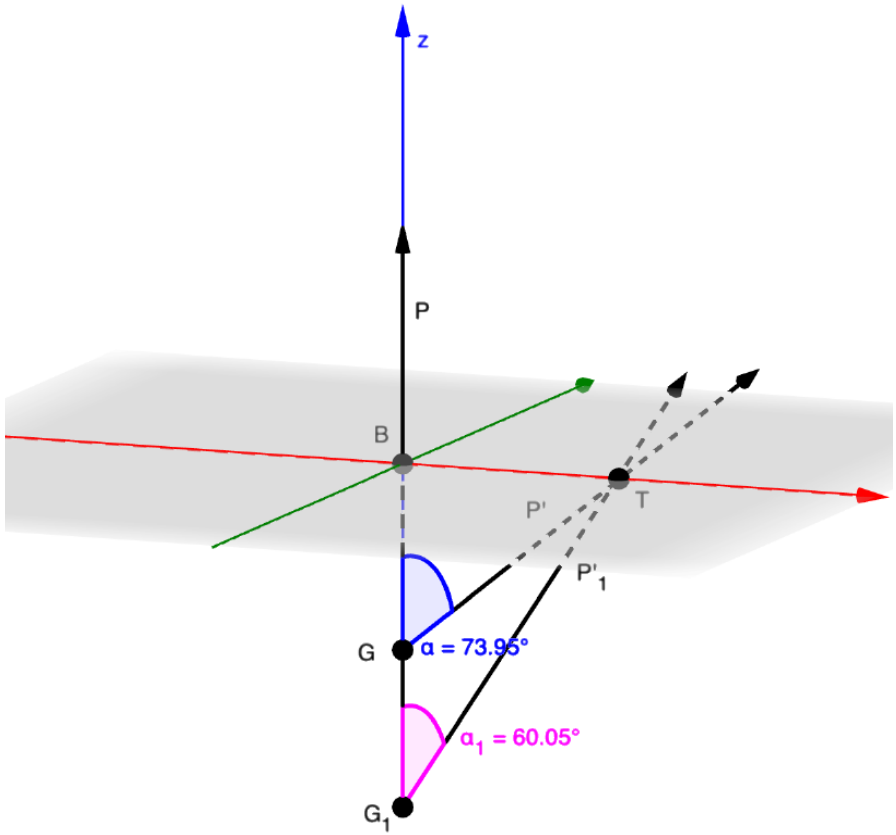


Szanecki M., et al. 2021

Umbrella Mode



Credit: Donini, A. PhD thesis (Univerità degli Studi di Udine, 2020)

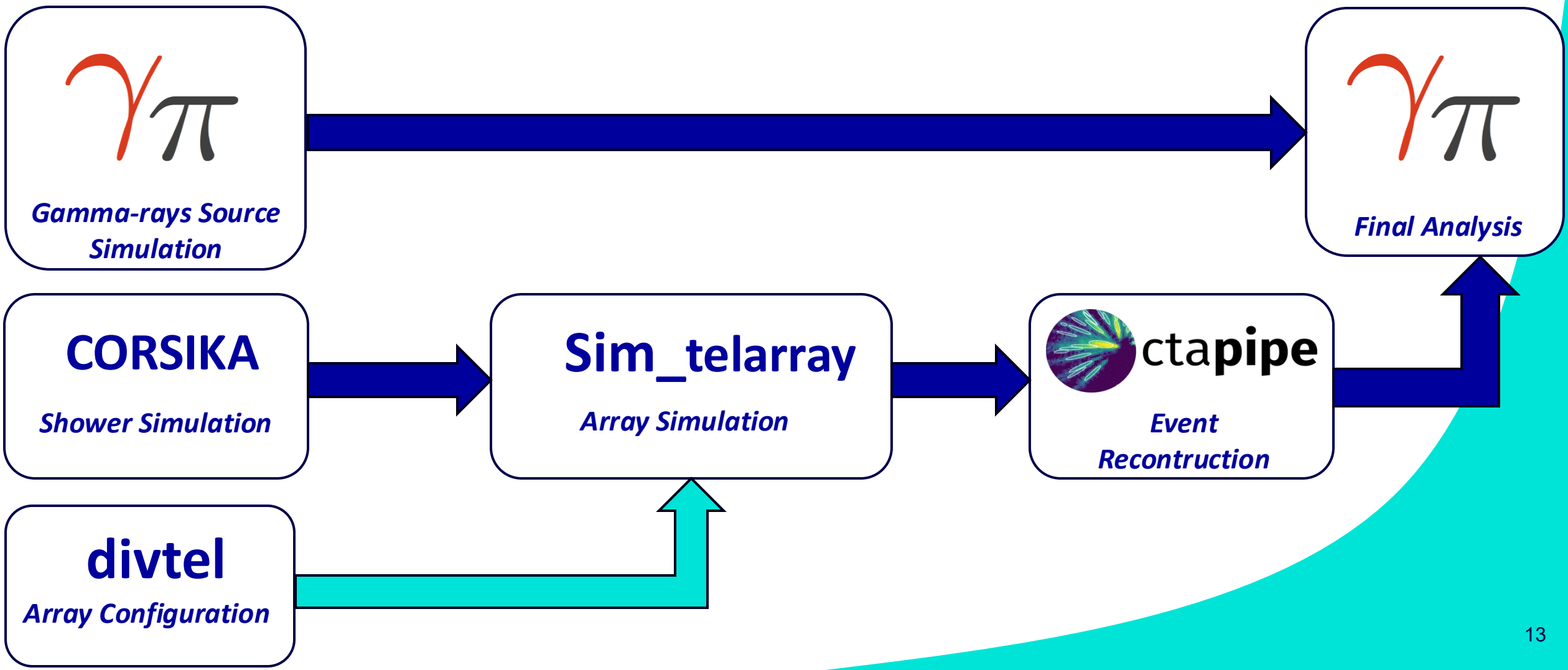
A **simple** strategy to define the pointing directions of **all** telescopes using a **single** parameter:

$$div = \sin(\alpha)$$

Input to divtel!

(A python code developed for divergent pointing simulations:
Vuillaume T., et al. 2022)

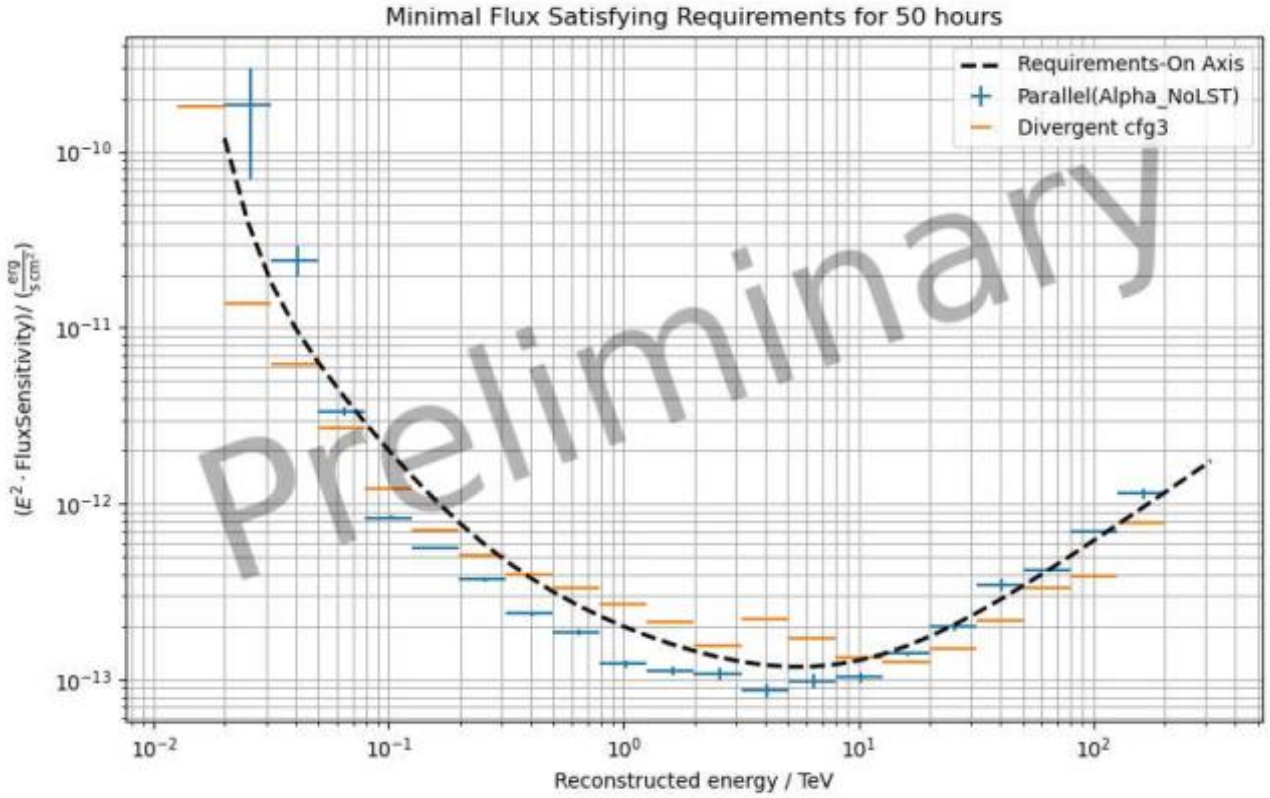
Simulation and Analysis Pipeline for Divergent mode



Preliminary Results

CTAO-South Analysis:
4 LSTs, 14 MSTs and 42 SSTs

div	hFoV (deg²)	$hFoV_{eff}$ (deg²)	m_{ave}
0.0	62.3	62.3	53.4
0.0022	99.0	89.6	33.5
0.0043	141.5	118.3	23.5
0.008	**232.1**	**174.7**	**14.3**
0.01135	331.2	230.1	10.0
0.01453	439.3	285.5	7.6



Burelli I. PhD thesis
(Univerità degli Studi di Udine, 2024)

hFoV: divergent array FoV
$hFoV_{eff}$: area seen by ≥3 telescopes
m_{ave}: avg. telescopes per sky region

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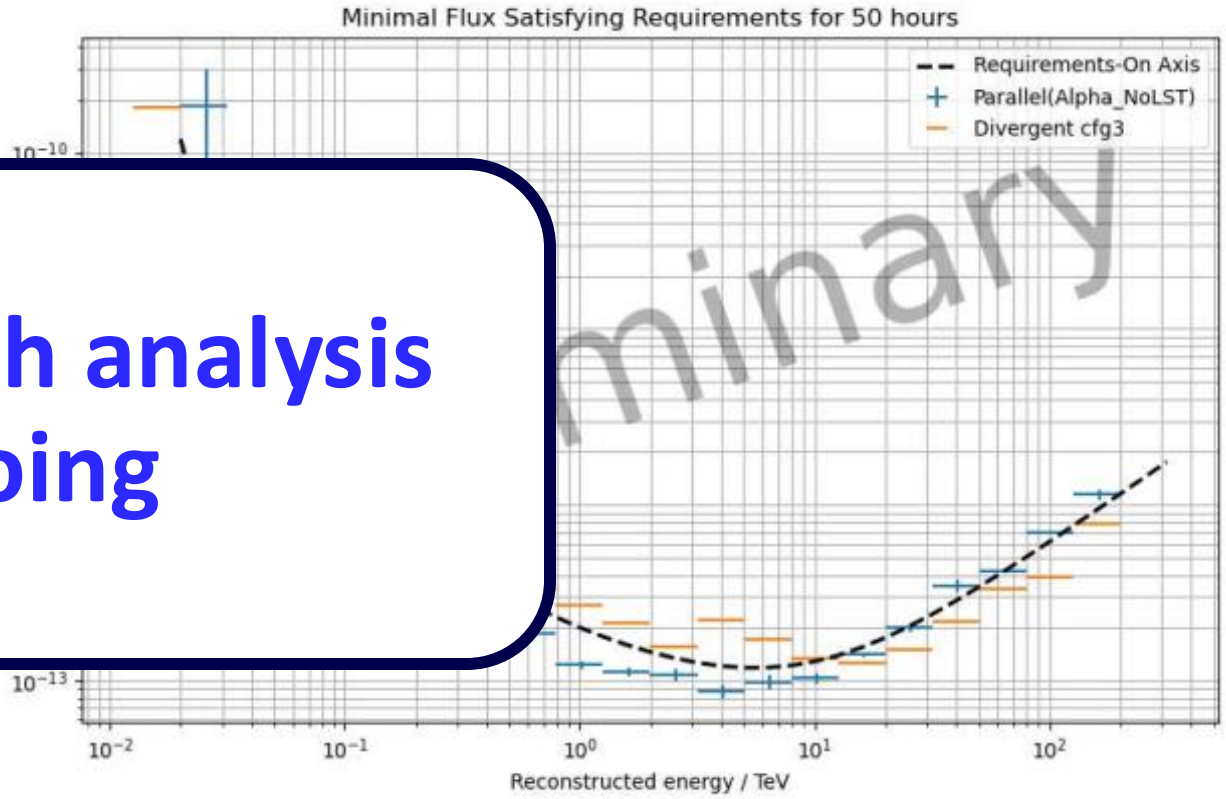
CTAO-North analysis ongoing



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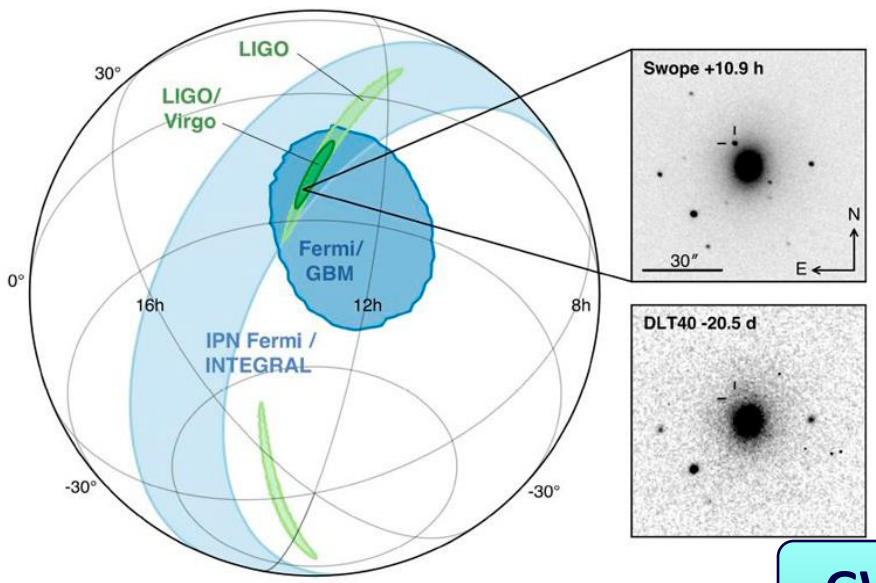
hFoV: divergent array FoV
$hFoV_{eff}$: area seen by ≥3 telescopes
m_{ave}: avg. telescopes per sky region

Science with Divergent pointing

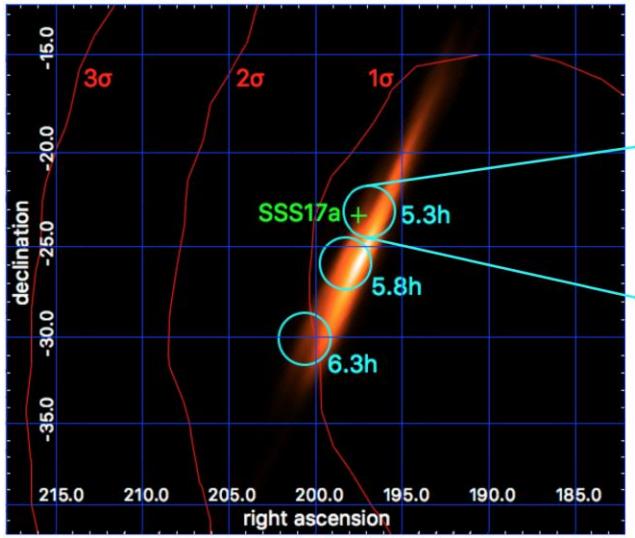
Scientific cases that could benefit from wider FoV include:

- **Sky surveys** – Efficiently mapping of large sky regions in a reducing observational time;
- **Transient searches** – Covering wide regions from gamma-ray burst localizations with large uncertainties;
- **Extended sources** – Investigating large sources exceeding the standard CTAO FoV;
- **Multimessenger follow-ups** – Surveying broad regions from neutrino or gravitational-wave alerts.

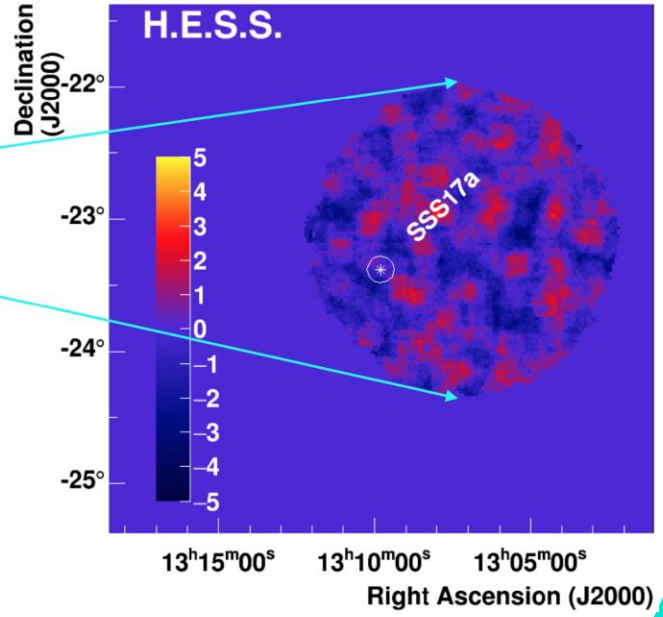
Gravitational Wave Follow-up



B. P. Abbott, et al, 2017



GW170817

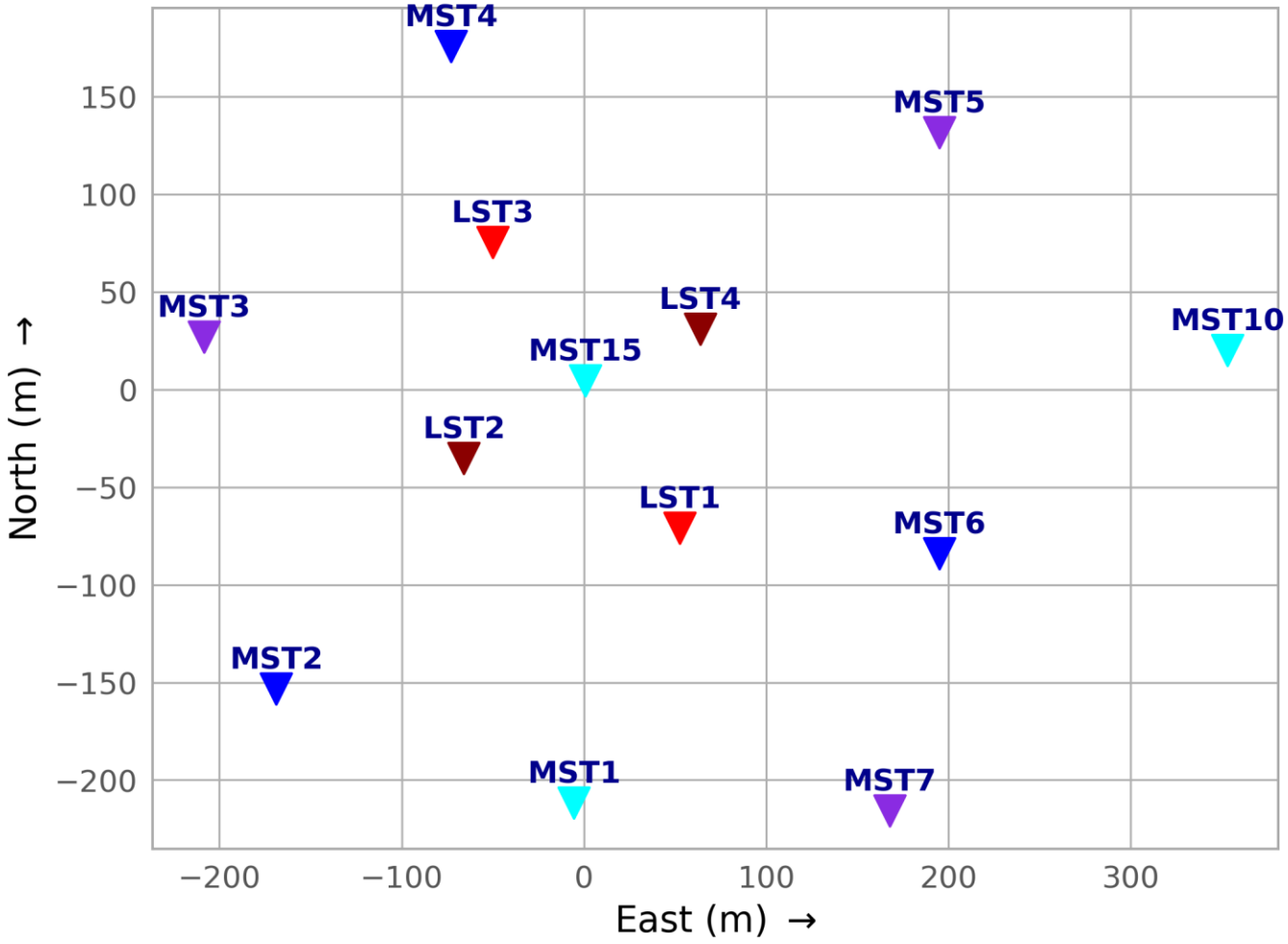


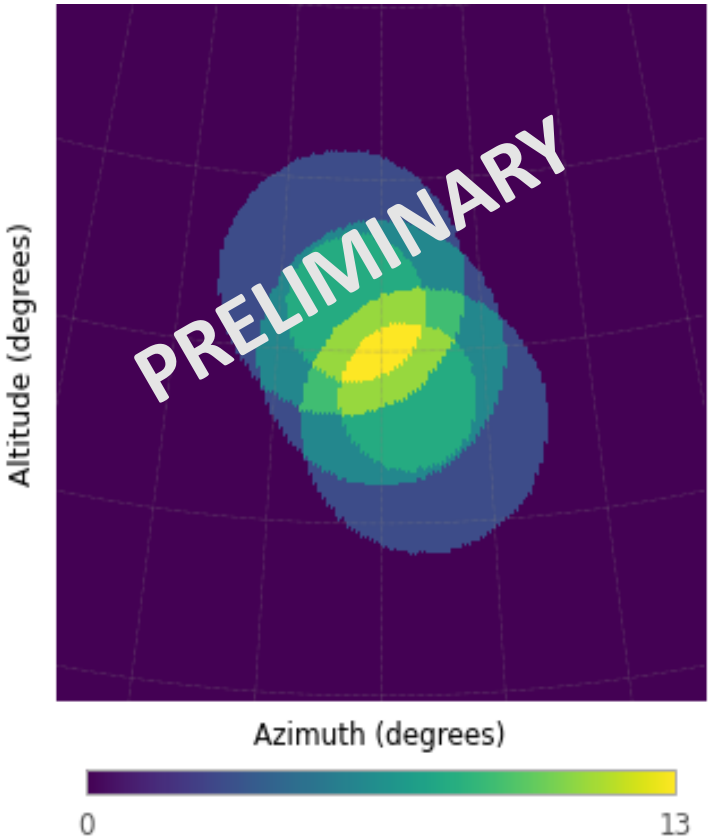
H. Abdalla, et al, 2017

- **Asymmetric** localization regions
- **Large** sky areas from tens to thousands of deg²
- **Rapid** EM follow-up crucial to identify the counterpart

Proposed Pointing Strategy

Testing **asymmetric FoVs** configurations with hypothetical mode of observation





Sub-arrays: 3 MST and 2 LST sub-arrays, with 2 MST sub-arrays and the two LST sub-arrays pointed with different offsets.

hFoV = 82 deg^2

Take Home Messages

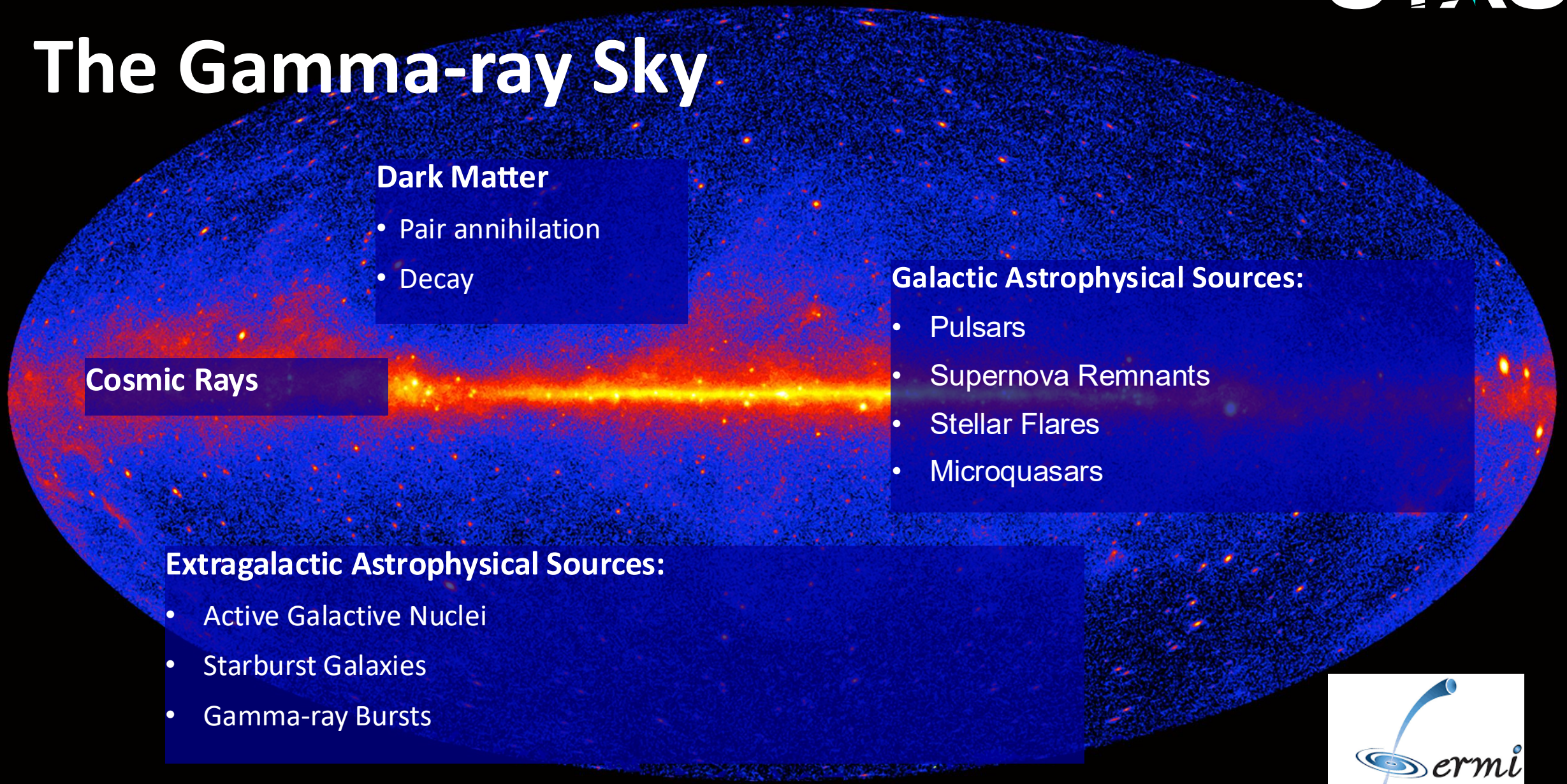
- Divergent pointing mode is promising for **wide-area surveys** and for the **follow-up of loosely localized transient events**.
- The **increased sky coverage**, however, results in a **reduction of angular and energy resolution**, requiring dedicated performance optimization strategy.
- The **Divergent Group is actively optimizing** the divergent mode configuration for different **CTAO science cases**.

Thank You!

And stay tuned for performance results at TeVPA 2026

Backup Slides

The Gamma-ray Sky



Dark Matter

- Pair annihilation
- Decay

Cosmic Rays

Galactic Astrophysical Sources:

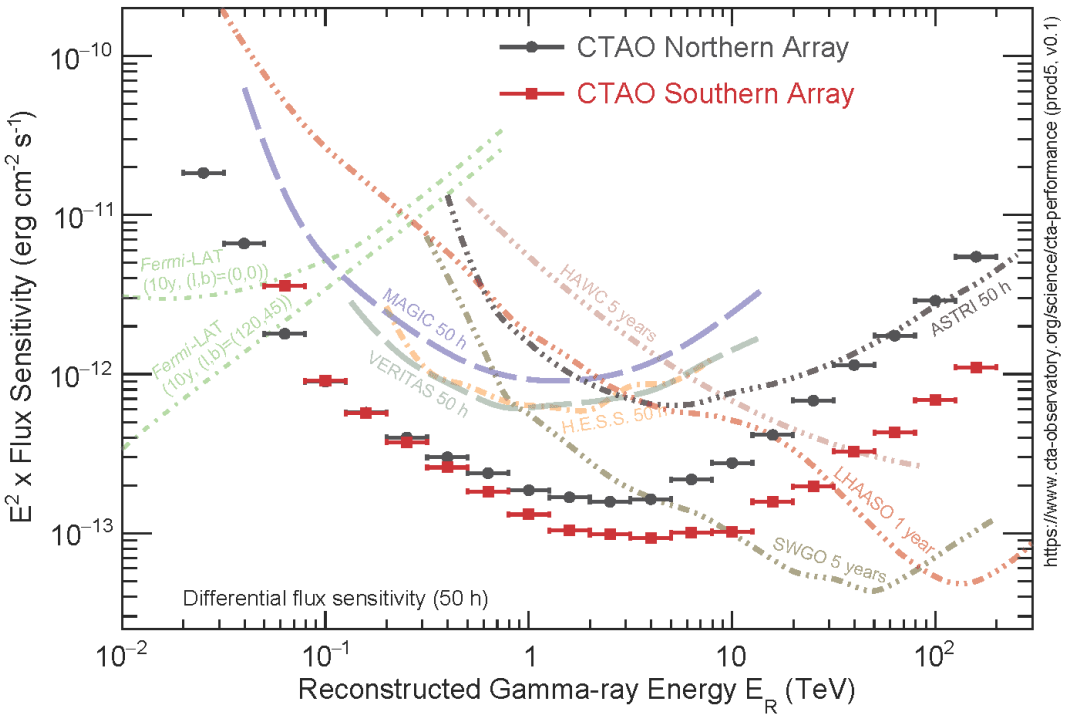
- Pulsars
- Supernova Remnants
- Stellar Flares
- Microquasars

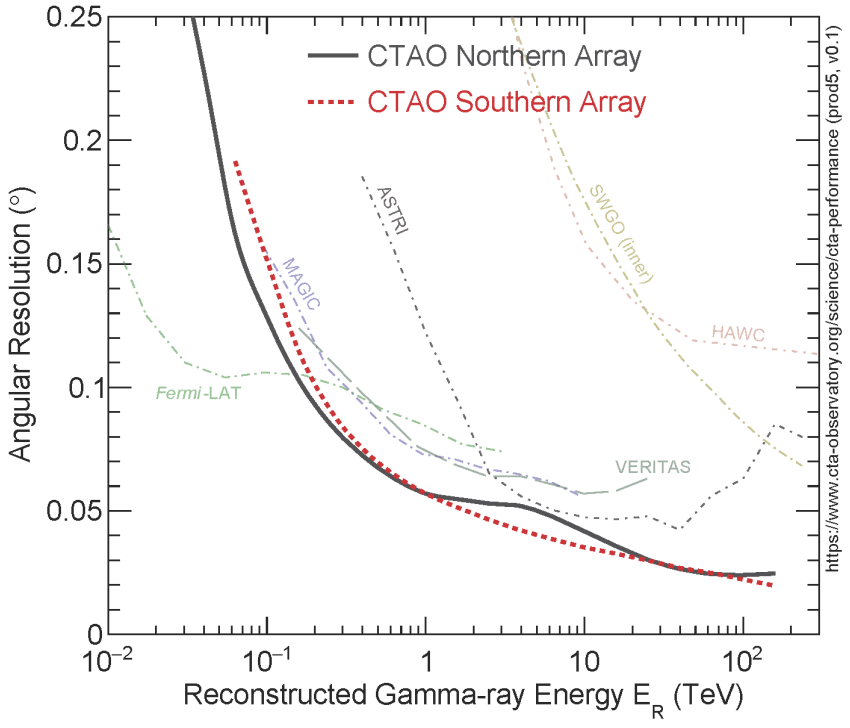
Extragalactic Astrophysical Sources:

- Active Galactive Nuclei
- Starburst Galaxies
- Gamma-ray Bursts

Fermi Gamma-ray Space Telescope

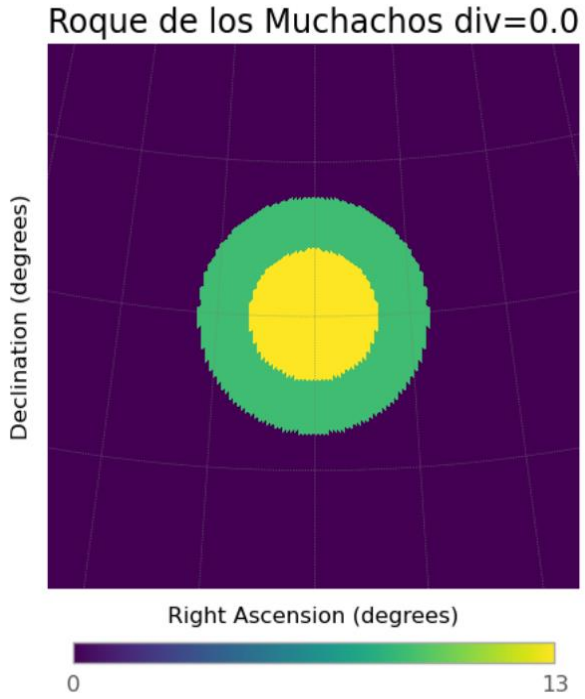
CTAO Performances

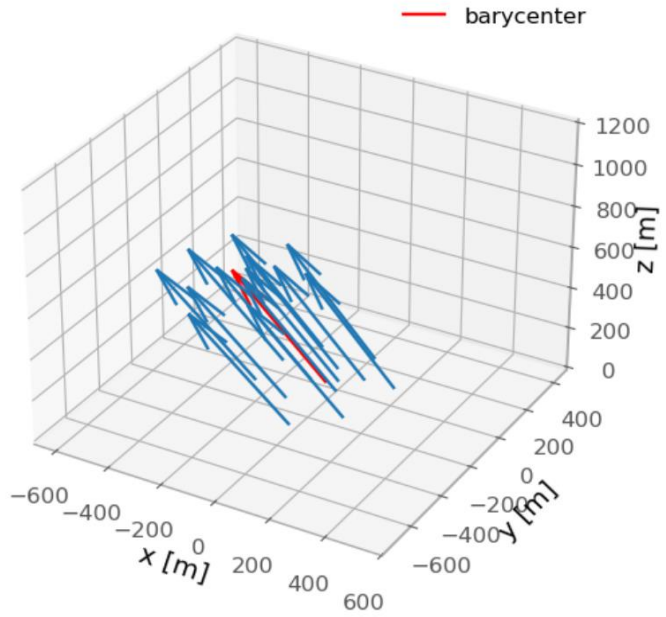


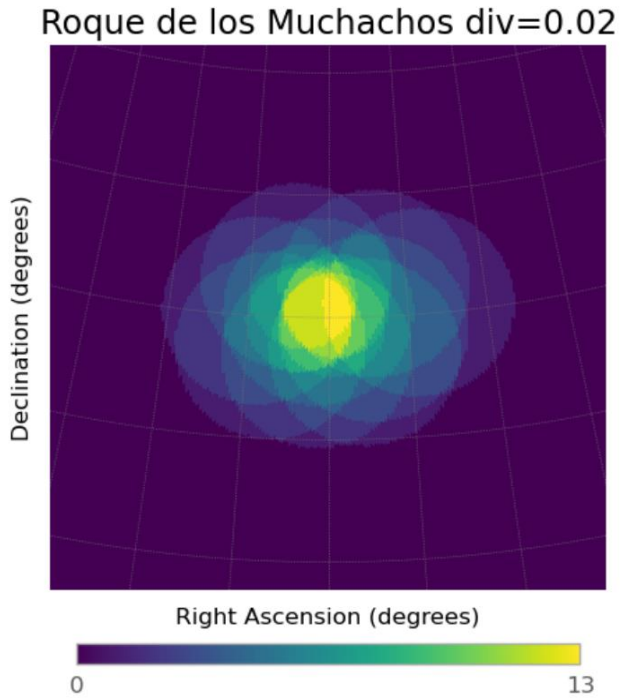


www.ctao.org

Array Configuration with *divtel*





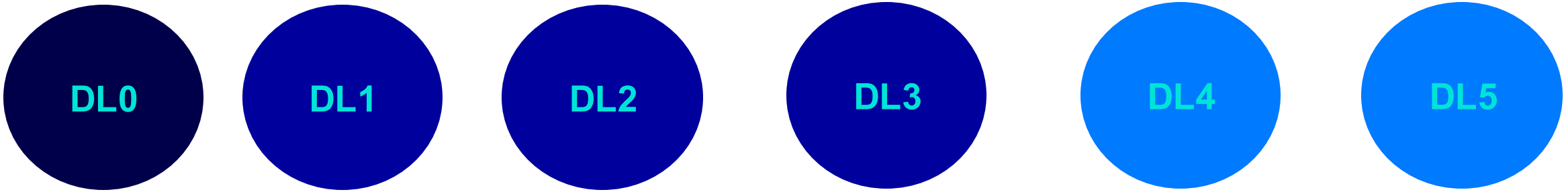


Cfg name	div	hFoV (deg^2)	$hFoV_{eff}$ (deg^2)	m_{ave}
parallel	0.0	62.3	62.3	53.4
cfg1.5	0.0022	99.0	89.6	33.5
cfg2	0.0043	141.5	118.3	23.5
cfg3	0.008	232.1	174.7	14.3
cfg4	0.01135	331.2	230.1	10.0
cfg5	0.01453	439.3	285.5	7.6

→ CTAO-South: 4 LSTs, 14 MSTs and 42 SSTs

Burelli, I. PhD thesis (Univerità degli Studi di Udine, 2024)

Data Levels in CTAO



DL0	DL1	DL2	DL3	DL4	DL5
Raw single telescope	Processed single telescope (e.g. Hillas)	Reconstructed event	Gamma-like events, IRFs	Binned data	Science products (Catalogs, flux maps, lightcurves)

Instrument Response Functions

A mathematical description *R* of the response of a telescope.

$$n(\boldsymbol{p}, E) = t_{obs} \int_{E_T} dE_T \int_{\boldsymbol{p}_T} d\boldsymbol{p}_T R(\boldsymbol{p}, E|\boldsymbol{p}_T, E_T) \times \Phi(\boldsymbol{p}_T, E_T)$$

The standard procedure for IACTs, including CTAO, is to factorize the function *R* into three independent functions:

$$R(\boldsymbol{p}, E|\boldsymbol{p}_T, E_T) = A_{eff}(\boldsymbol{p}_T, E_T) \times PSF(\boldsymbol{p}|p_T, E_T) \times E_{disp}(E|\boldsymbol{p}_T, E_T)$$

Effective Area

Energy Dispersion

Point Spread Function

Preliminary Results