Introduction to Cherenkov experiments

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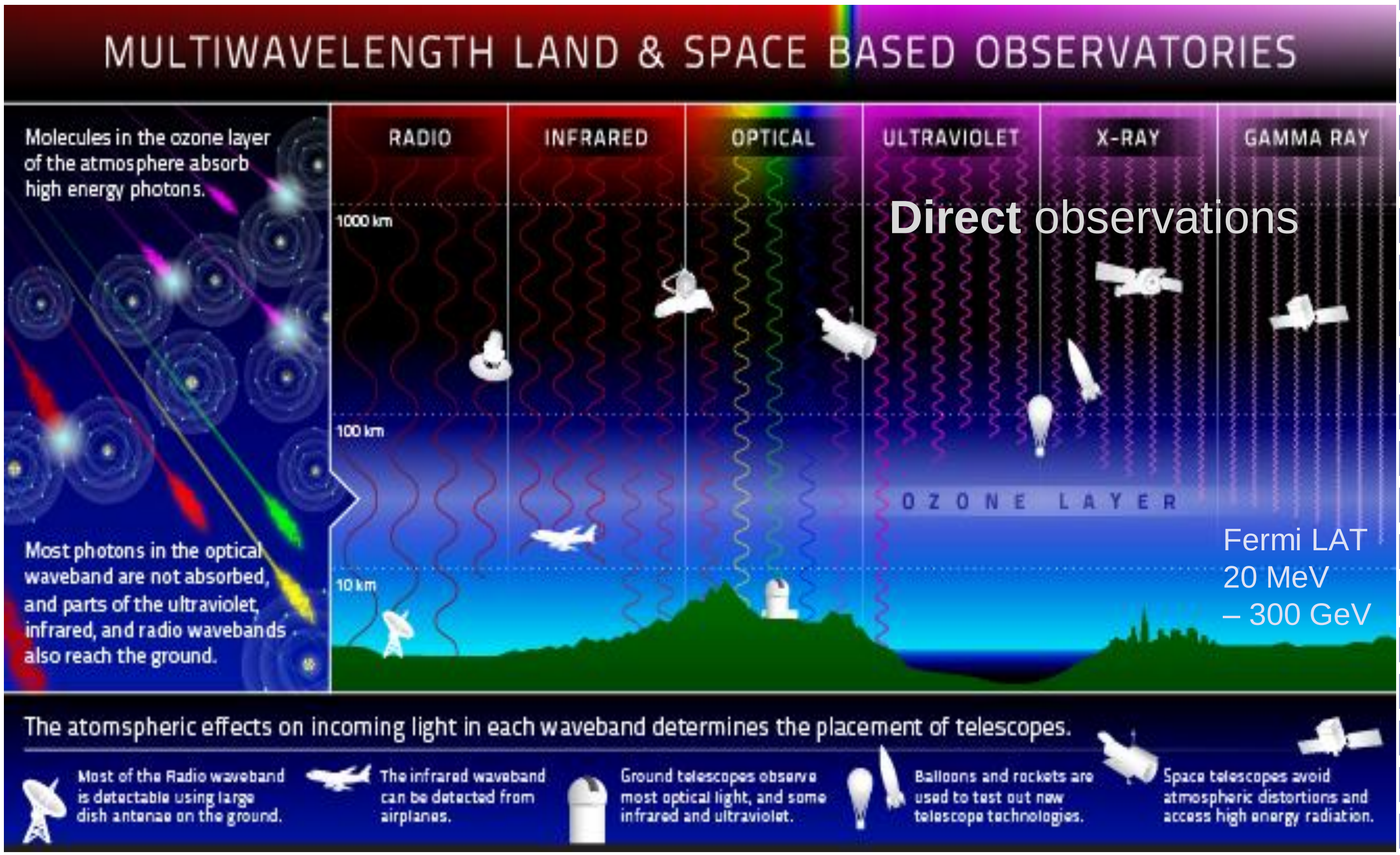
2022/03/24
Workshop "Synergies at new frontiers at gamma-rays, neutrinos and gravitational waves" @ICRR

Ground-based γ-ray observation: high energy end of the photon observation



https://ecuip.lib.uchicago.edu/multiwavelength-astronomy/astrophysics/07.html

GAMMA RAY

Indirect observations

Detectors on the ground (the air is not transparent)

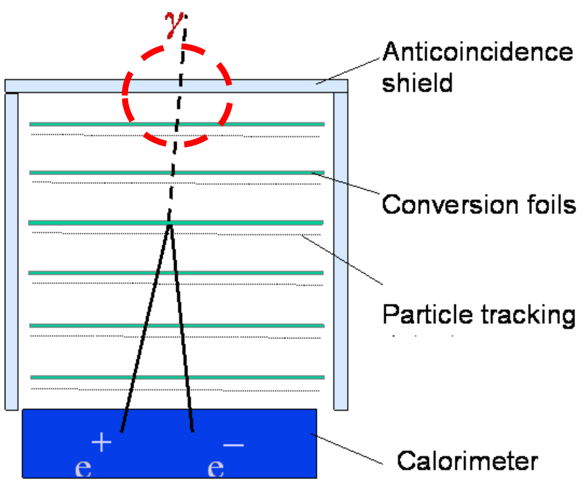
IACT
20 GeV – 50 TeV (currently)

Imaging
Atmospheric
Cherenkov
Telescope

Imaging Atmospheric Chererenkov Telescopes: low energy end of the air shower detectors

Direct

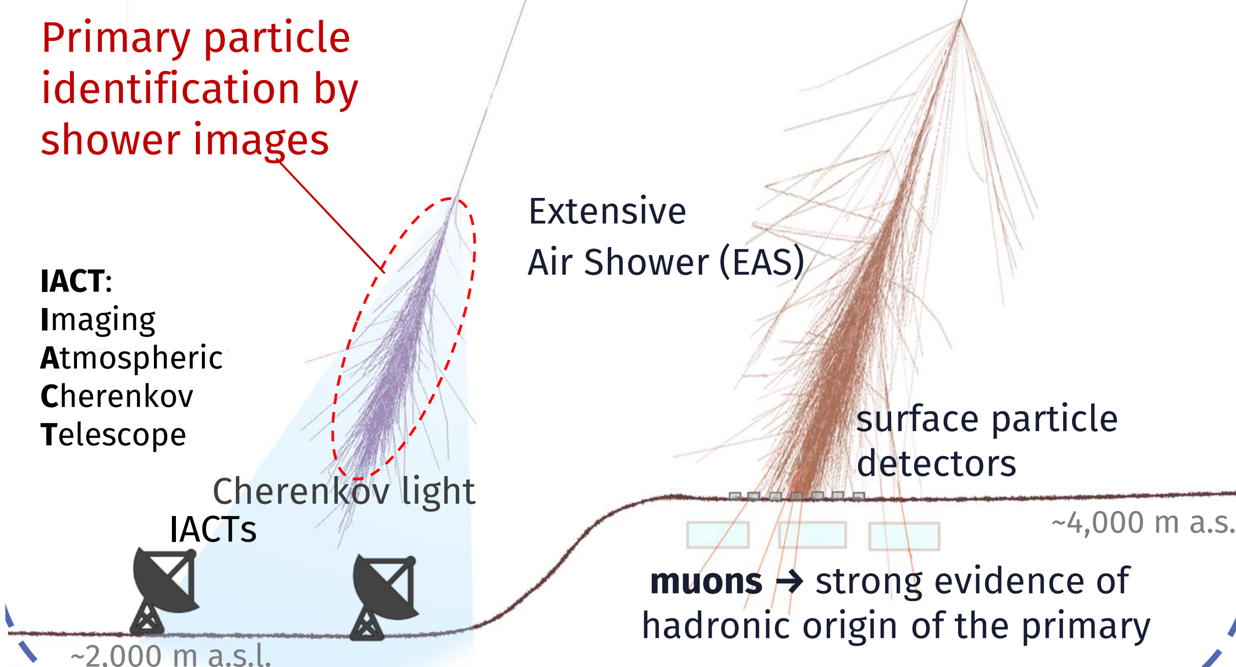
primary charge
→ most important info for the screening of charged cosmic rays



(figure from NASA GSFC website)

Indirect (Air shower experiments)

primary charge → cannot be measured*



* Except for IACT observations of heavy nuclei in limited situations

✓ Particle identification (γ or not) is more difficult in indirect observations
→ higher background level due to charged cosmic rays

Evolution of γ-ray observations with ground-based detectors including IACTs: Kifune-plot

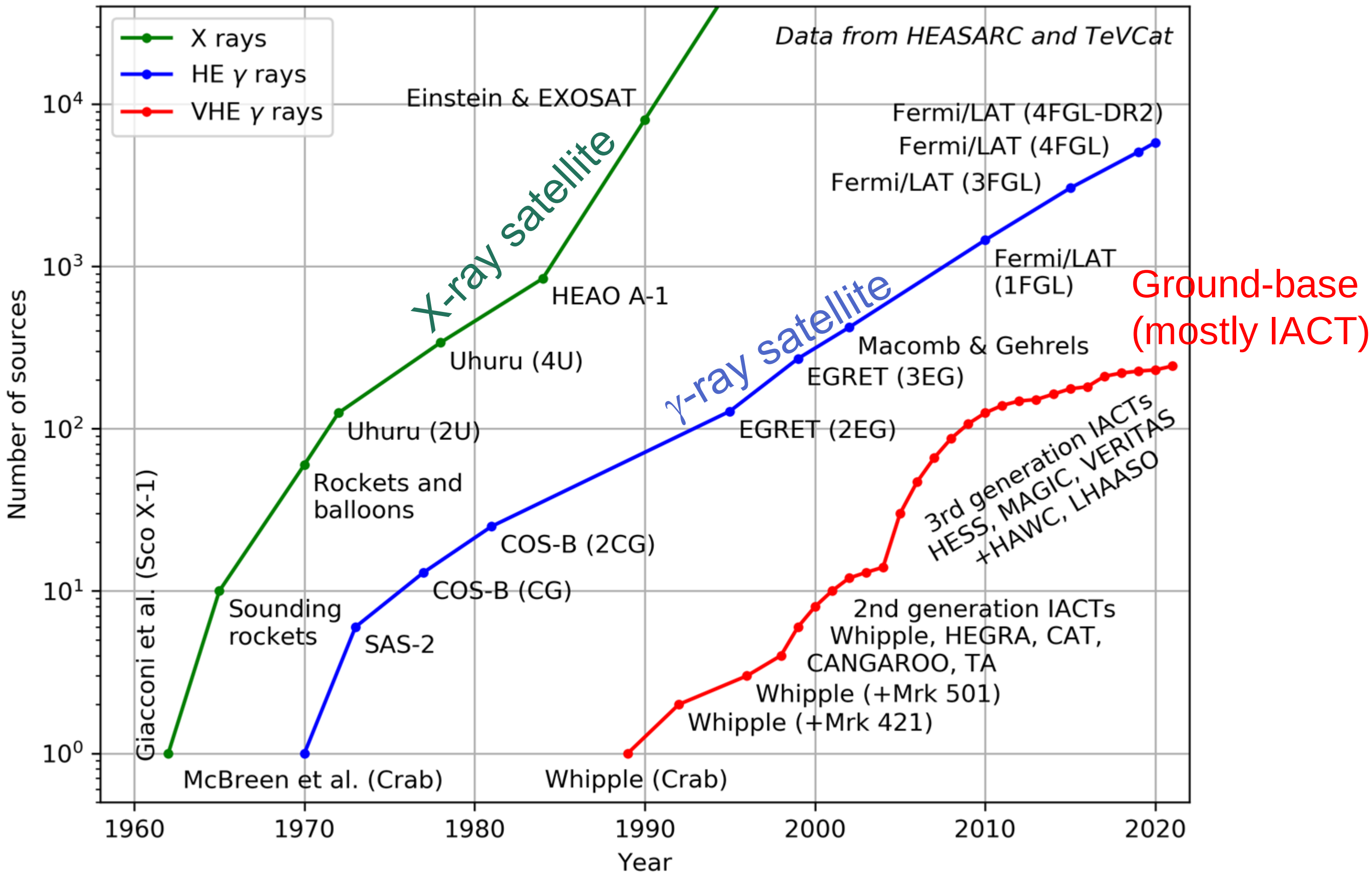


Figure from https://github.com/sfegan/kifune-plot by Stephen Fegan

Evolution of γ-ray observations with ground-based detectors including IACTs: Kifune-plot

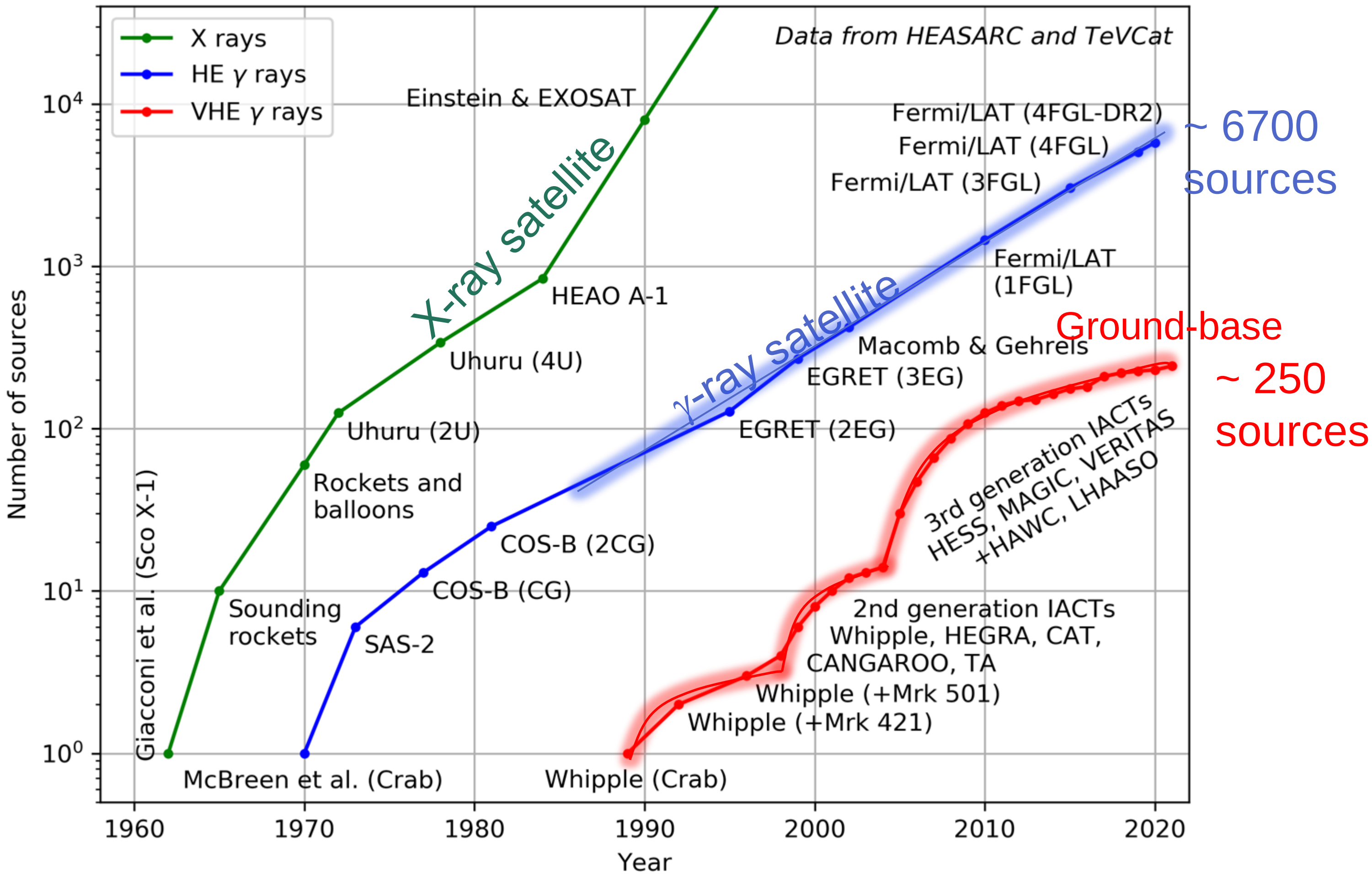
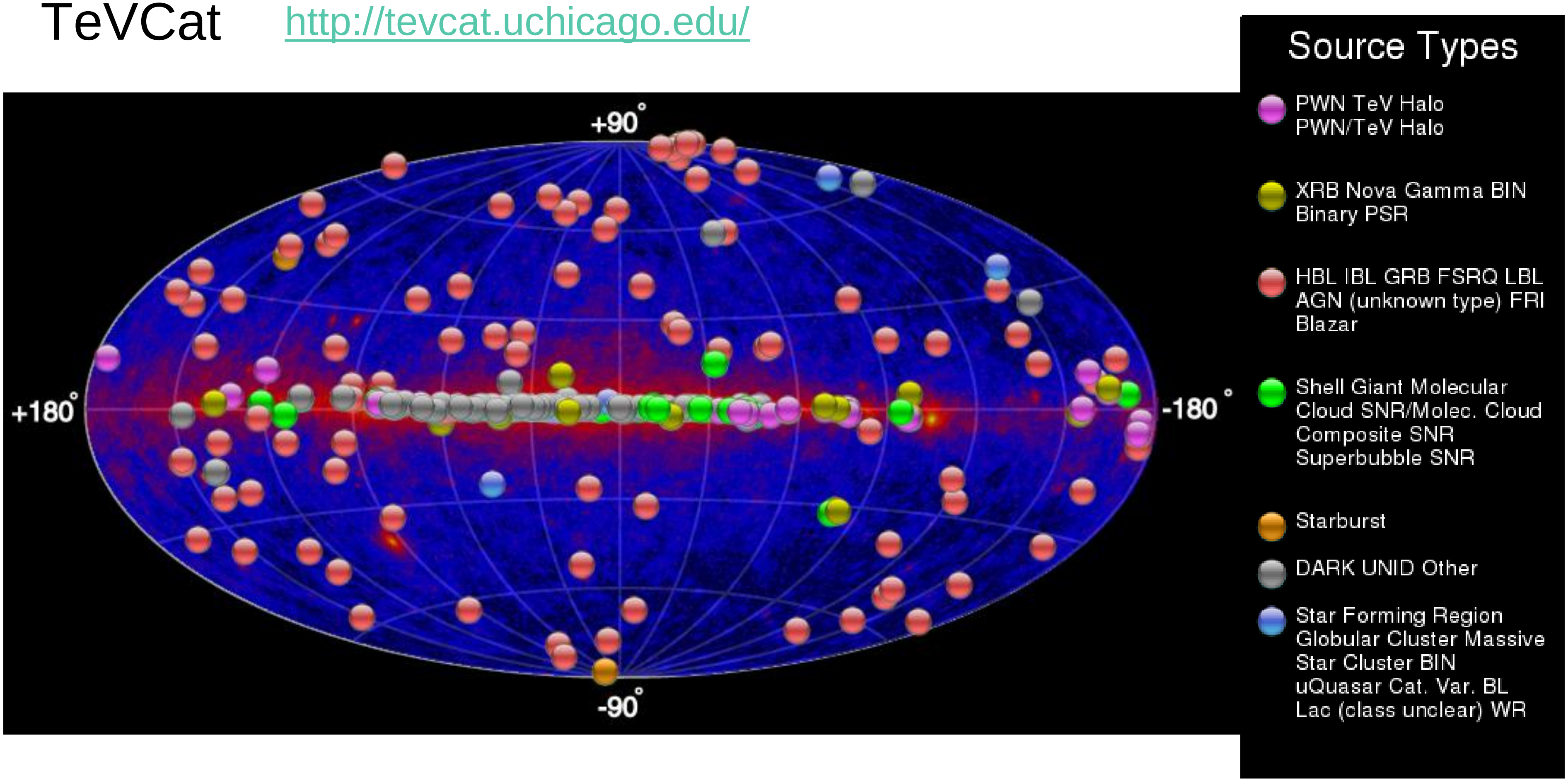


Figure from https://github.com/sfegan/kifune-plot by Stephen Fegan

TeV γ-ray source catalog

TeVCat   http://tevcat.uchicago.edu/



The flux level of the faintest source detected : ~ 0.003 Crab (0.3% Crab)

TeV γ-ray source catalog

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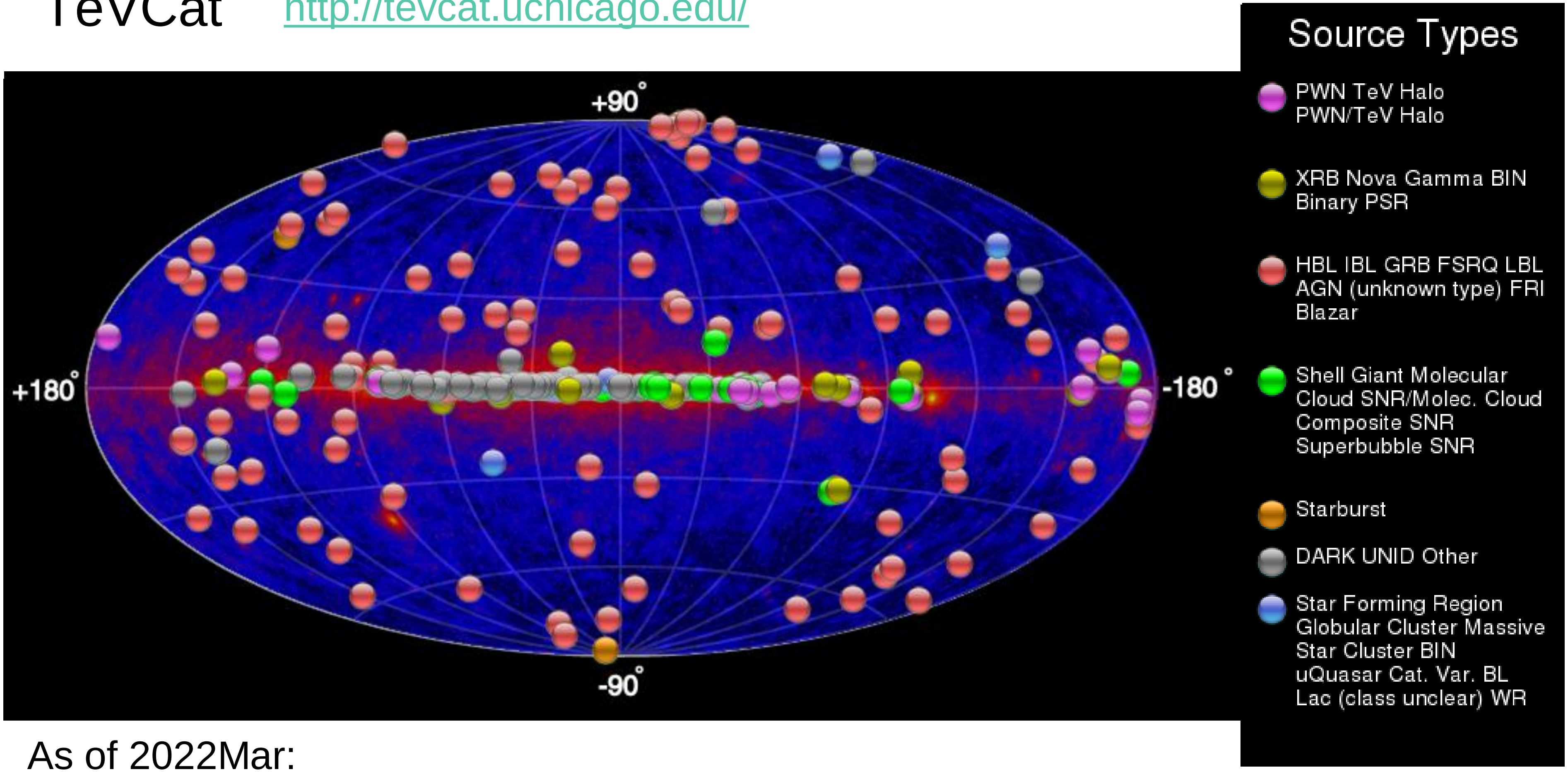

As of 2022Mar:
55 HBL(High-frequency peaked BL Lac)s, 34 PWNe (6 discovered by Milagro/HAWC),
76 unidentified sources (37 discovered by Milagro/HAWC/LHASSO)
6 GRBs…

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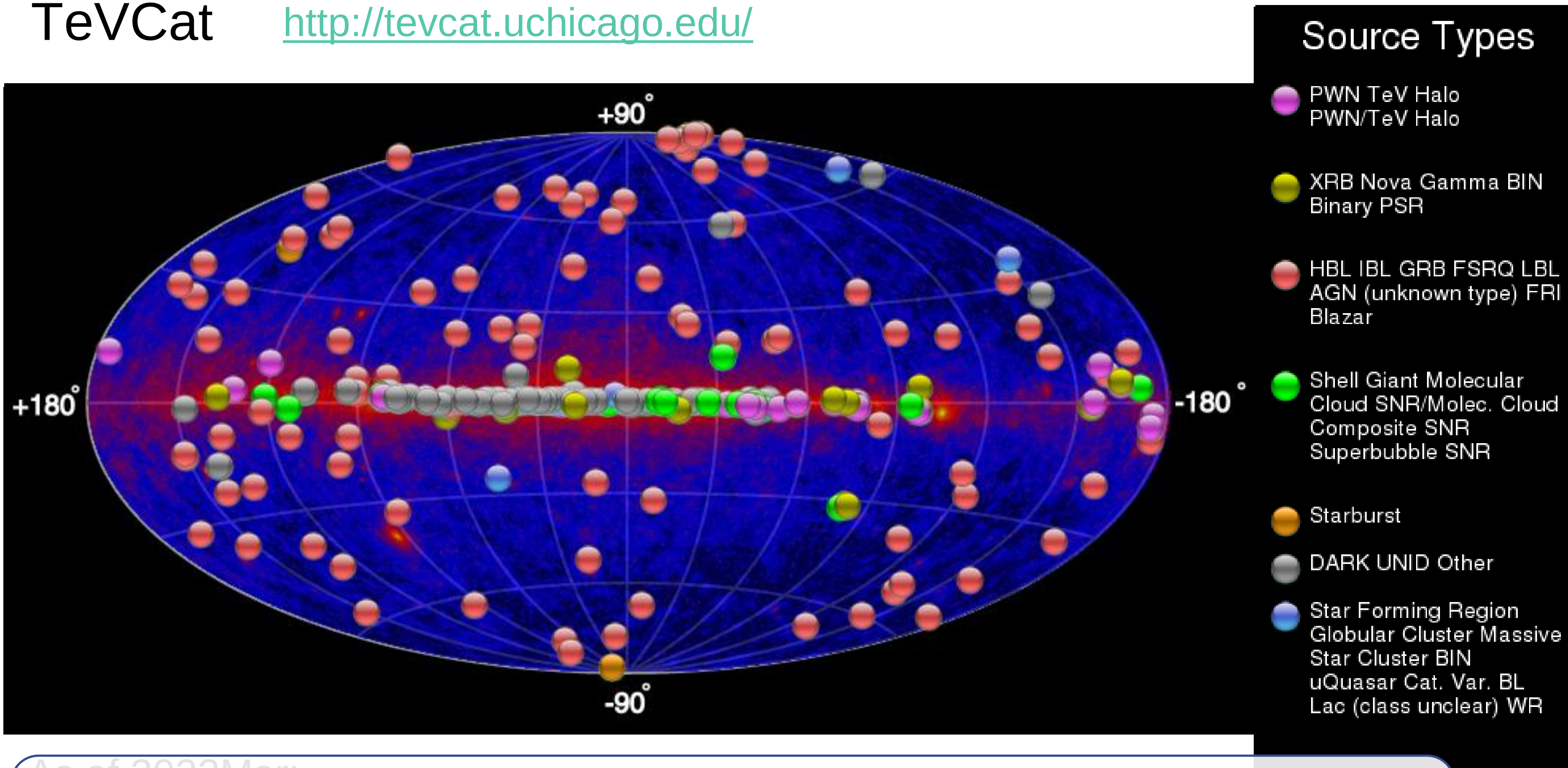

As of 2022Mar:
55 HBL(High-frequency peaked BL Lac)s, 34 PWNS (6 discovered by Milagro/HAWC),
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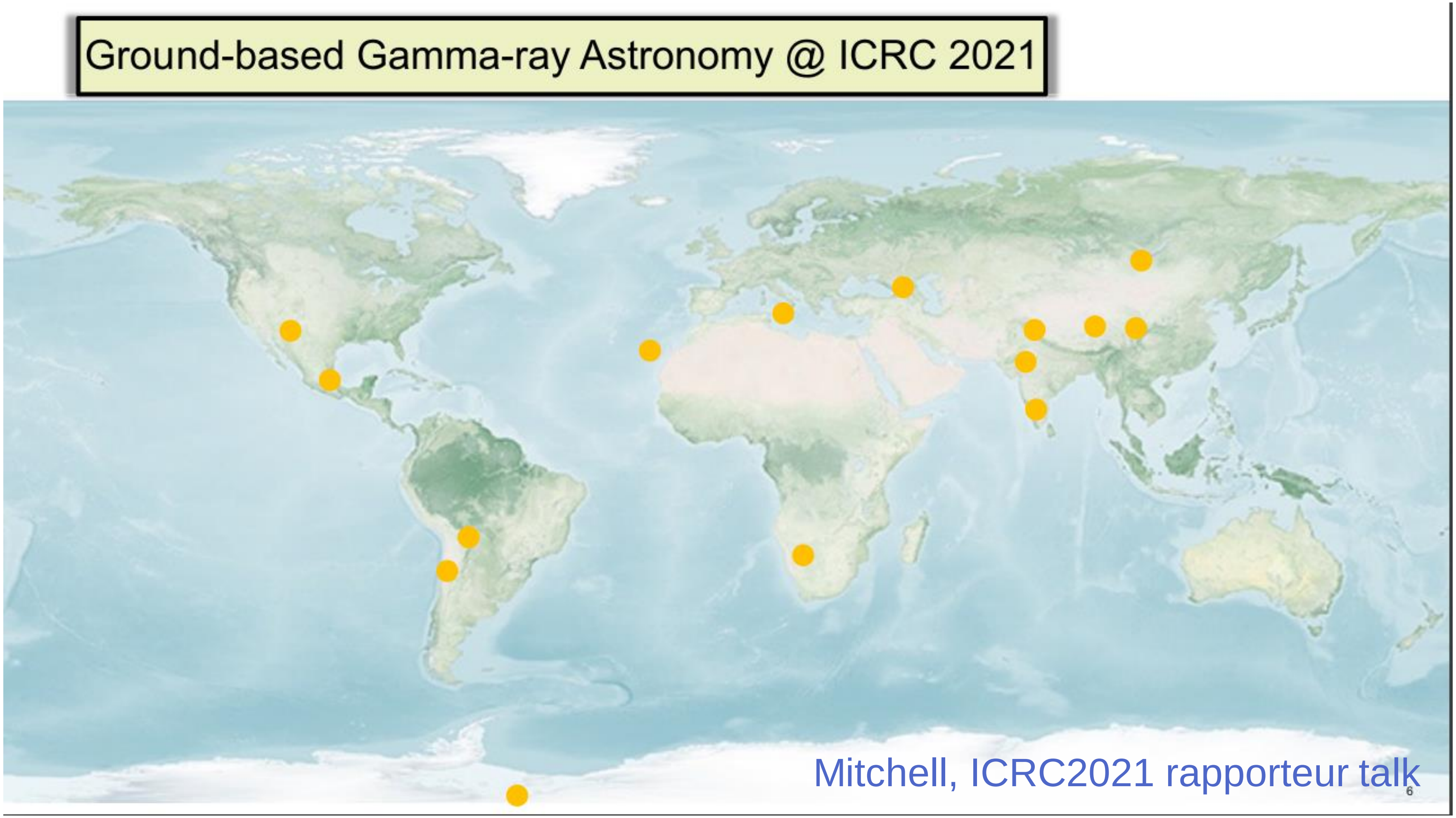
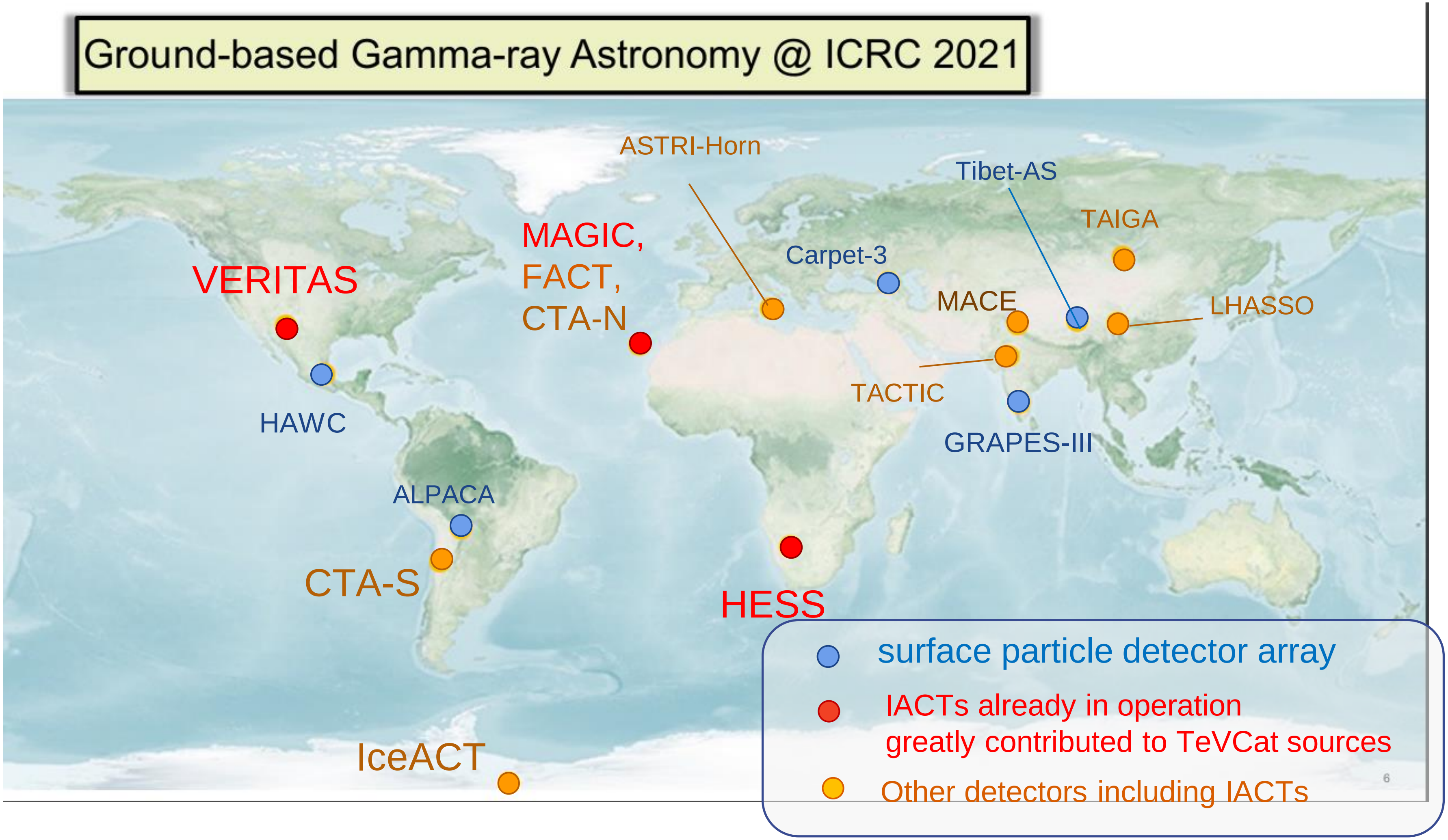
6 GRBs…

Introduction of those sources is out of scope of this talk.

Ground-based γ-ray detectors



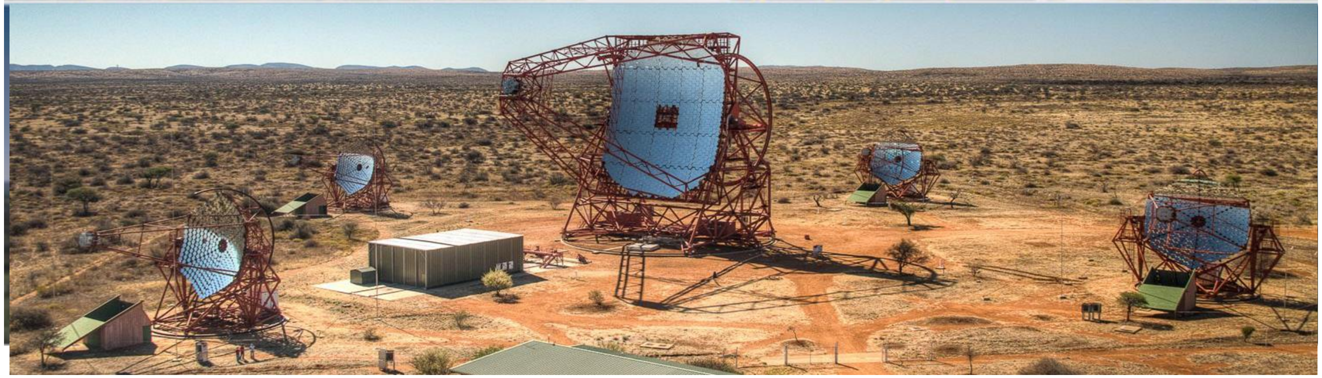
Ground-based γ-ray detectors (2)



MAGIC/VERITAS/H.E.S.S.

MAGIC
Dia. 17 m × 2 tels
2,200 m a. s. l.

VERITAS
Dia.12 m x 4 tels
1,260 m a. s. l.



H. E. S. S.(-II)
Dia. 12 m x 4 tels
+
Dia. 28 m*1 tel
1,800 m a. s. l.

*1 32.6 m x 24.3 m, equivalent to ϕ 28 m

Ground-based γ-ray detector: role-sharing North and South

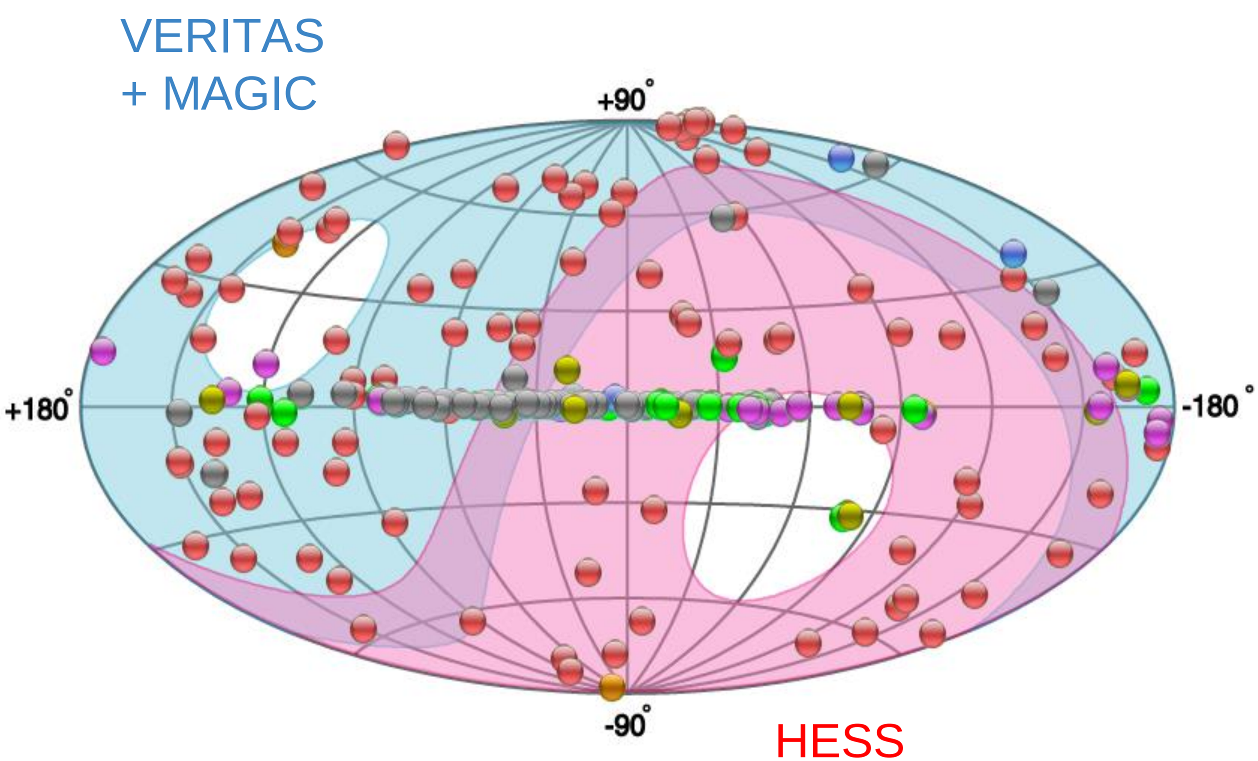


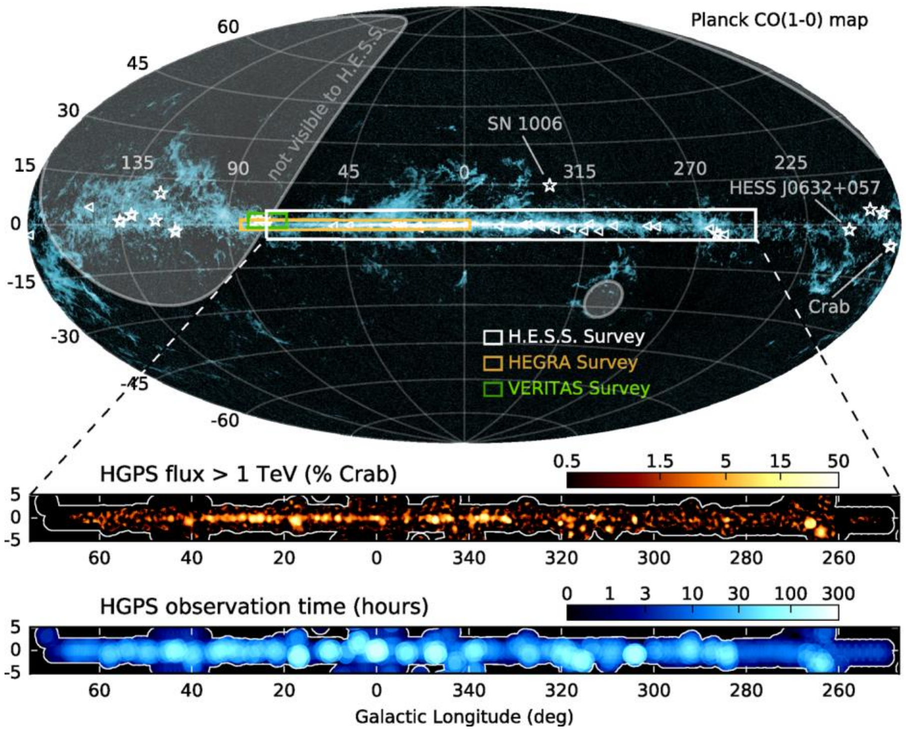
Figure from http://tevcat.uchicago.edu/

VERITAS site
N 31° 40′30″
W 110°57′07

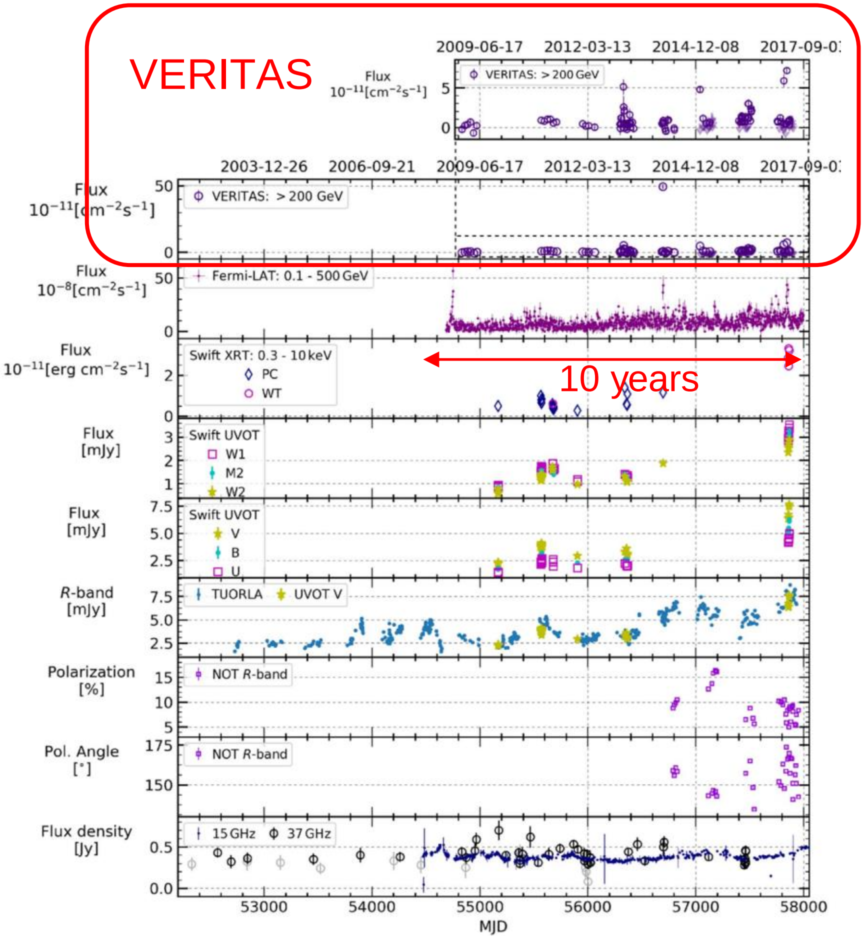
MAGIC site
N 28° 45′43″
W 17°53′24″

H.E.S.S. site
S 23° 16′18″
E 16°30′00″

Ground-based γ-ray detector: role-sharing North and South

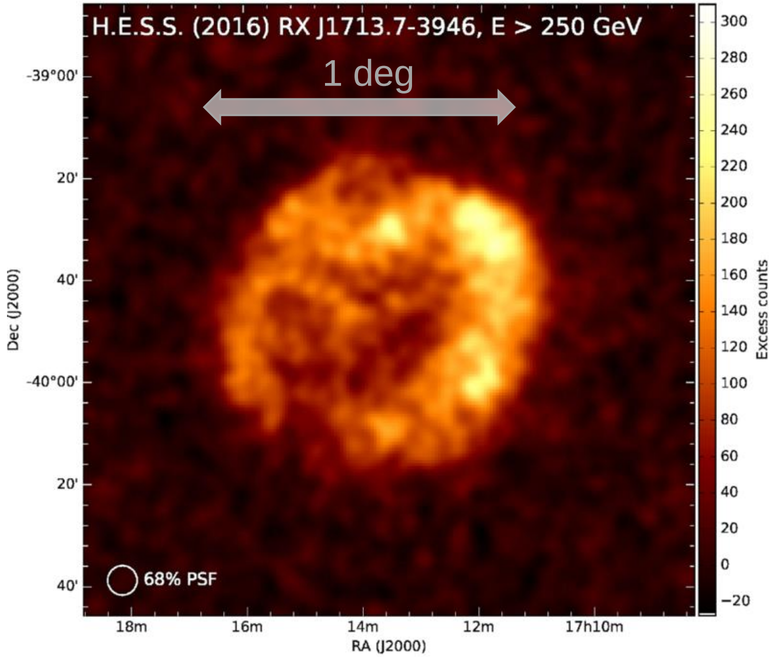


H. E. S. S. galactic plane survey (2018)



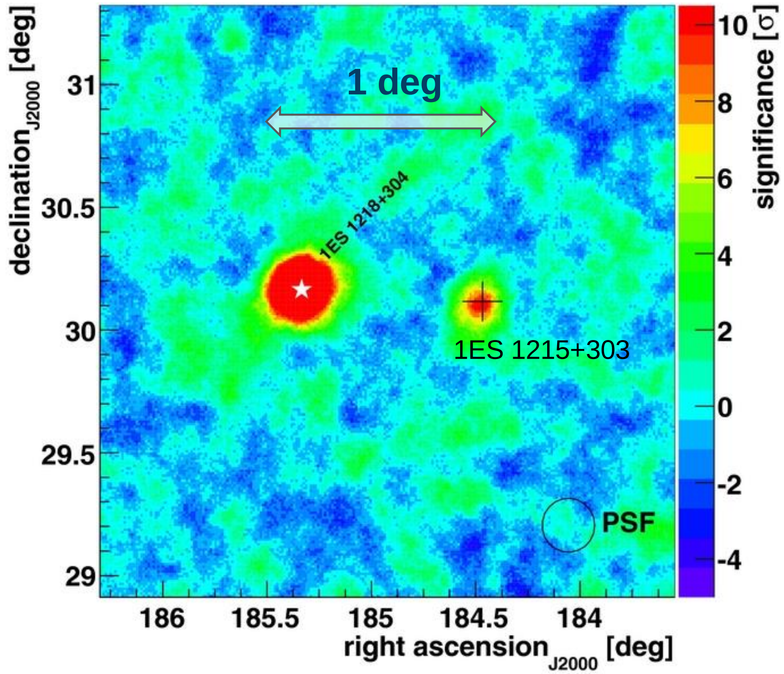
A decade observations of TeV Blazar 1ES 1215+303 (Valverde+ 2020)

Small difference in design concept



(Abdalla+ 2018)

VERITAS



(Aliu+ 2013)

galactic sources → extended → **wide FOV** camera
extragalactic sources → compact, soft spectra
→ narrower FOV camera (with a large reflector)

FOV size: (South) HESS **5.0** deg, (North) VERITAS **3.5** deg, MAGIC **3.5** deg

Indirect/direct, IACT/surface particle detector comparison

	Fermi	(3rd gen.) IACTs	Surface particle detectors
Energy Range	20 MeV – 200 GeV	100 GeV - 50 TeV	400 GeV - 100 TeV
Field of View	$4\pi/5$ (2.5) sr	5° x 5 ° 6×10^{-3} (sr)	$4\pi/6$ (2.1) sr
Duty factor	80%	~ 15%	> 90%
Angular resolution	< 0°.15 (> 10 GeV)	0°.07	0°.5
Energy resolution	5-10 %	15-20%	~50 %
Effective Area	0.8 m^2 (on-axis)	~ 1×10^5 m^2 *1	6×10^4 m^2 *2

Figures in dark blue taken from “Introduction to Particle and Astroparticle Physics” De Angelis & Pimenta

*1 @1 TeV, 10m x 4 system *2 Tibet-AS array case

Indirect/direct, IACT/surface particle detector comparison

Observations of time transients

	Fermi	IACTs	Surface particle detector
Field of View	$4\pi/5$ (2.5) sr	5° x 5 ° 6×10^{-3} (sr)	$4\pi/6$ (2.1) sr
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Observations of **transient** objects by IACTs
→
follow-up observations with information given by other wide FoV detectors
(if conditions are met)

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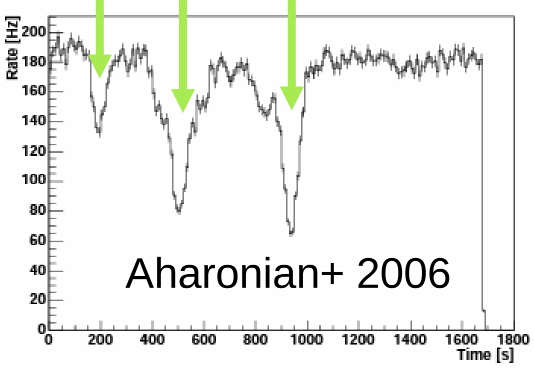
Trigger rate drop by passing clouds



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Observations of **transient** objects by IACTs
→
follow-up observations with information given by other wide FoV detectors
(if conditions are met)

Night time

Good weather

Moon is low

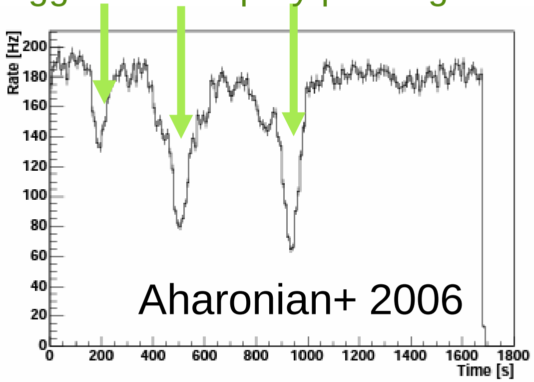
Proper Az/El range

Indirect/direct, IACT/surface particle detector comparison

	Fermi	IACTs	Surface particle detector
Field of View	$4\pi/5$ (2.5) sr	5° x 5 ° 6×10^{-3} (sr)	$4\pi/6$ (2.1) sr
Duty factor	80%	~ 15%	> 90%
Effective Area	0.8 m^2 (on-axis)	~ 1×10^5 m^2 @1 TeV	6×10^4 m^2 (Tibet AS case)

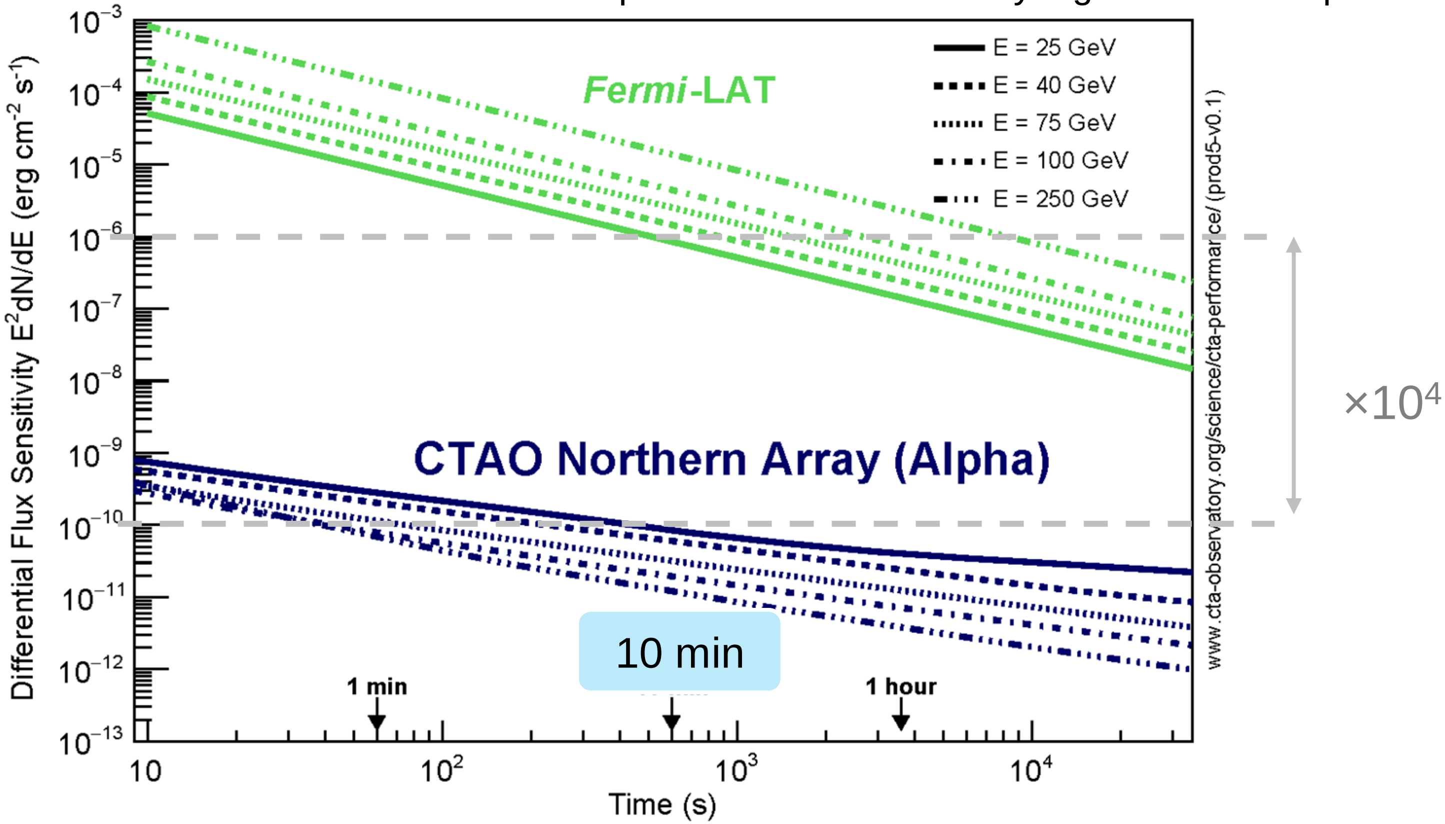
Exposure　S・Ω・T (or duty factor)
As for IACTs:
S → large enough
Ω → significantly small
T → relatively small

Trigger rate drop by passing clouds



Difference in effective area : direct and indirect 10 – 100 GeV region

Figure from
https://www.cta-observatory.org/science/ctao-performance/

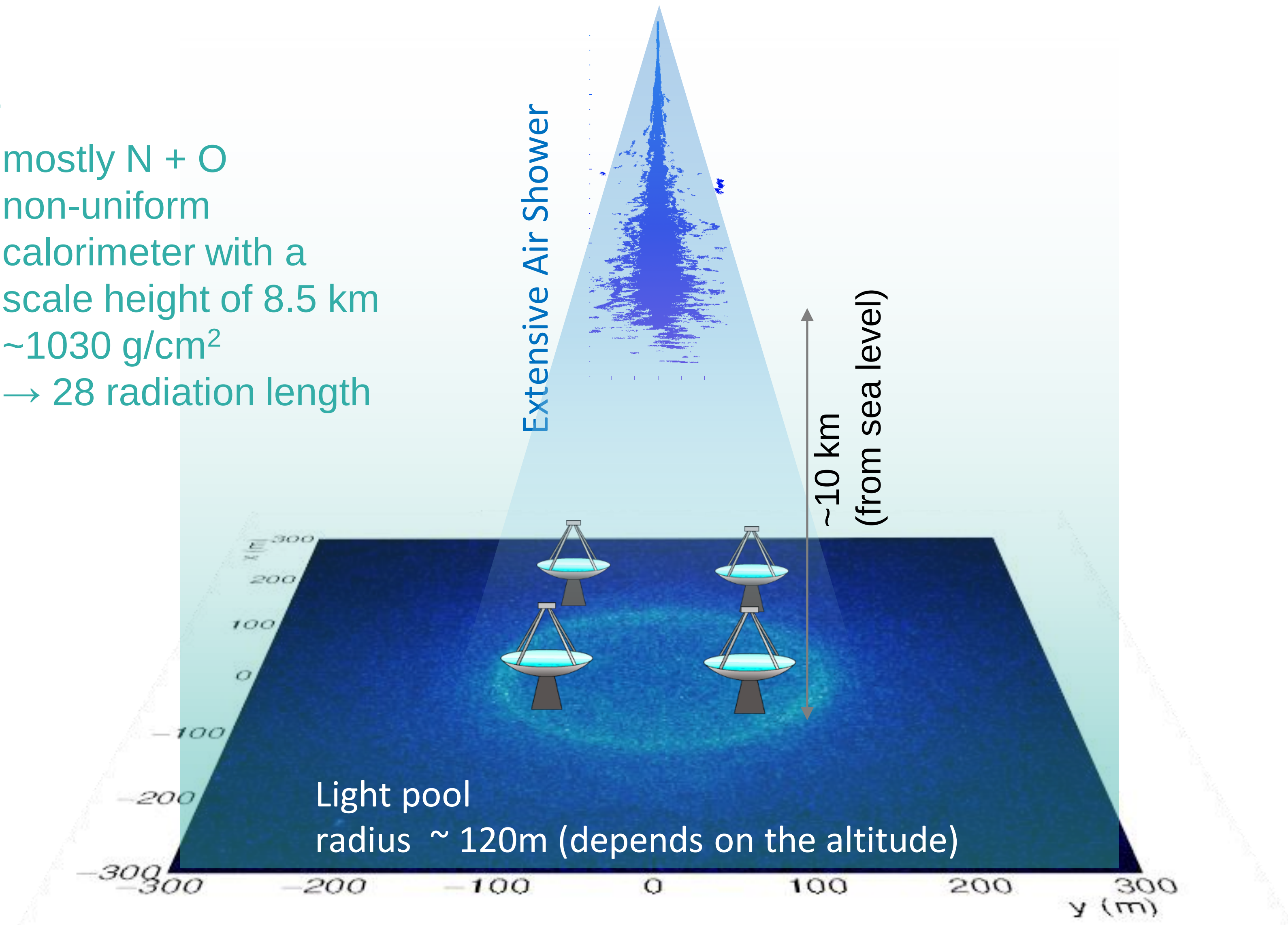


- IACT's large collection area effectively works for a strong γ-ray emission in a short duration (which you expect for very eneegetic phenomena)

IACT γ-ray detection principle

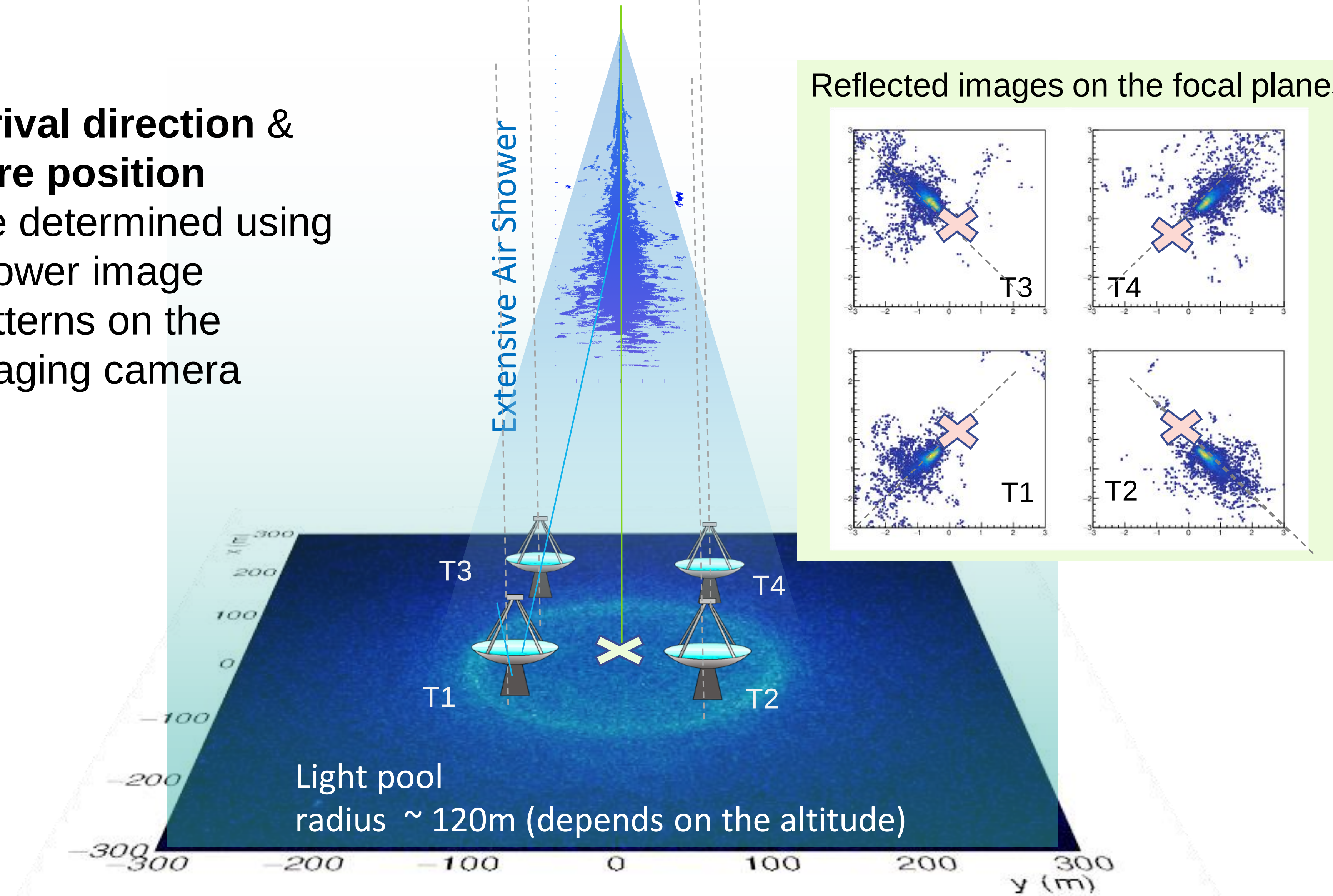
Air

- mostly N + O
- non-uniform calorimeter with a scale height of 8.5 km
- ~1030 g/cm^2 → 28 radiation length



IACT γ-ray detection principle:reconstruction

arrival direction &
core position
are determined using shower image patterns on the imaging camera



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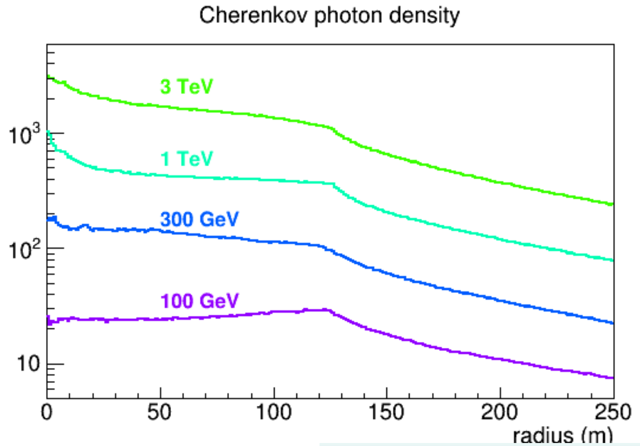
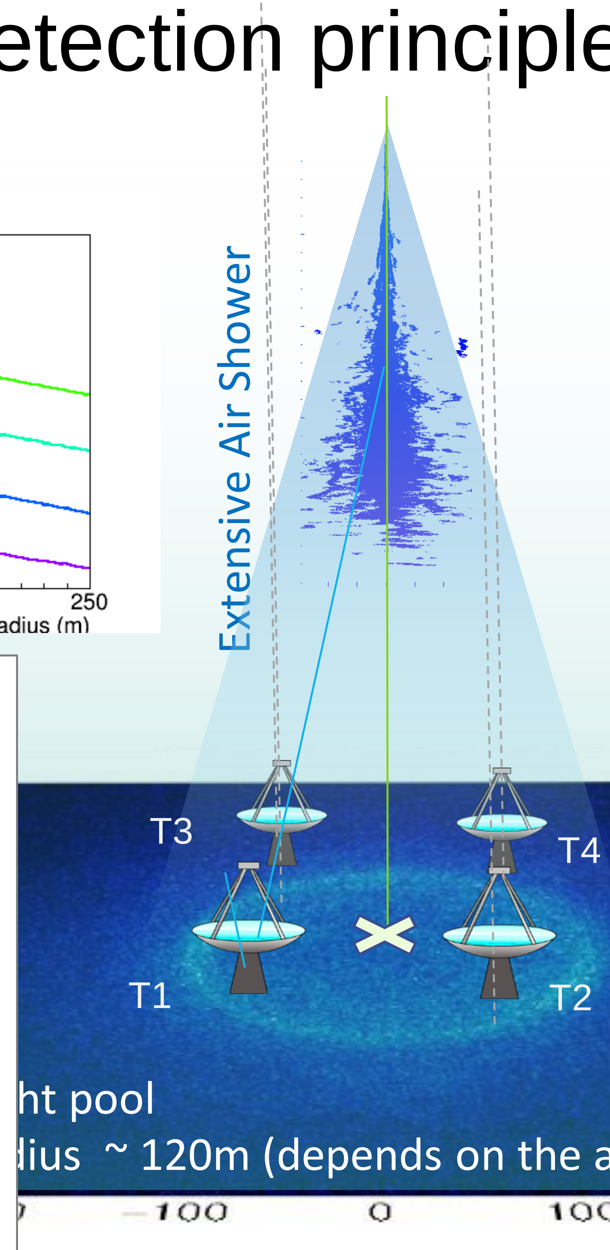
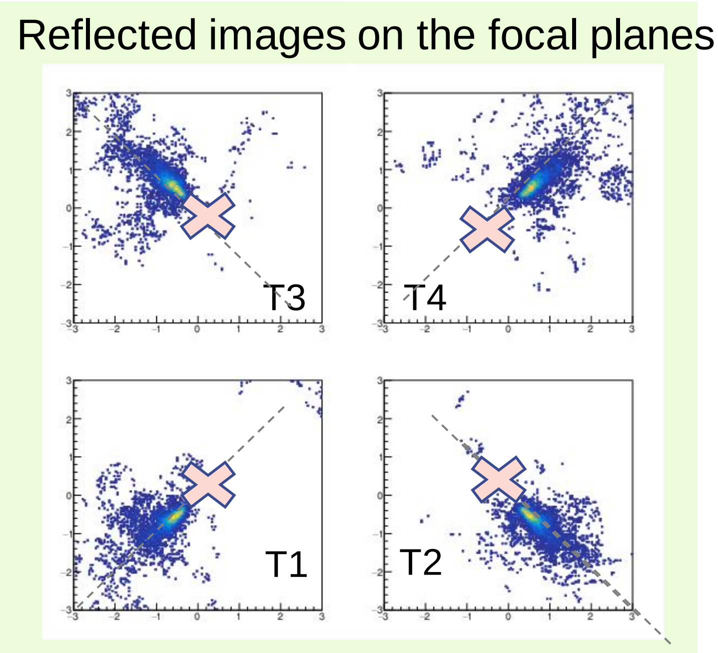






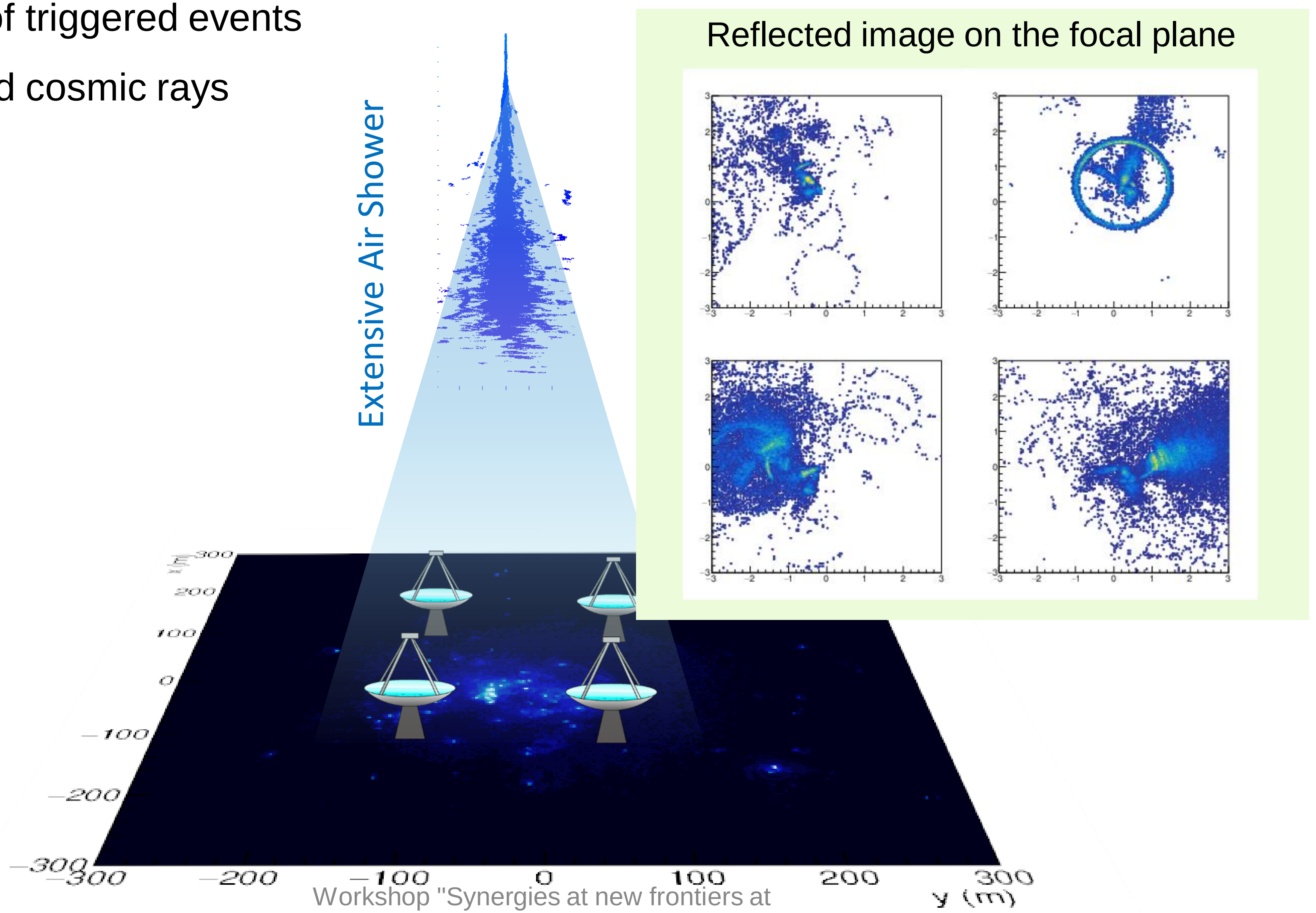
- Energy is estimated using conversion table which describes relation between observed p.e.s & energies, which depends on the impact parameter
- The table is created with Monte Carlo simulated events

* Note that the description about energy reconstruction here is simplified. Implementations are different for each group.

IACT γ-ray detection principle: γ/hadron separation

Majority of triggered events

→charged cosmic rays



IACT γ-ray detection principle : γ/hadron separation

Majority of triggered events

→charged cosmic rays

<u>γ-ray flux from **Crab nebula**</u>

~ 2.8×10^{-11} $(E/TeV)^{\beta}$ $/cm^2/s/TeV$

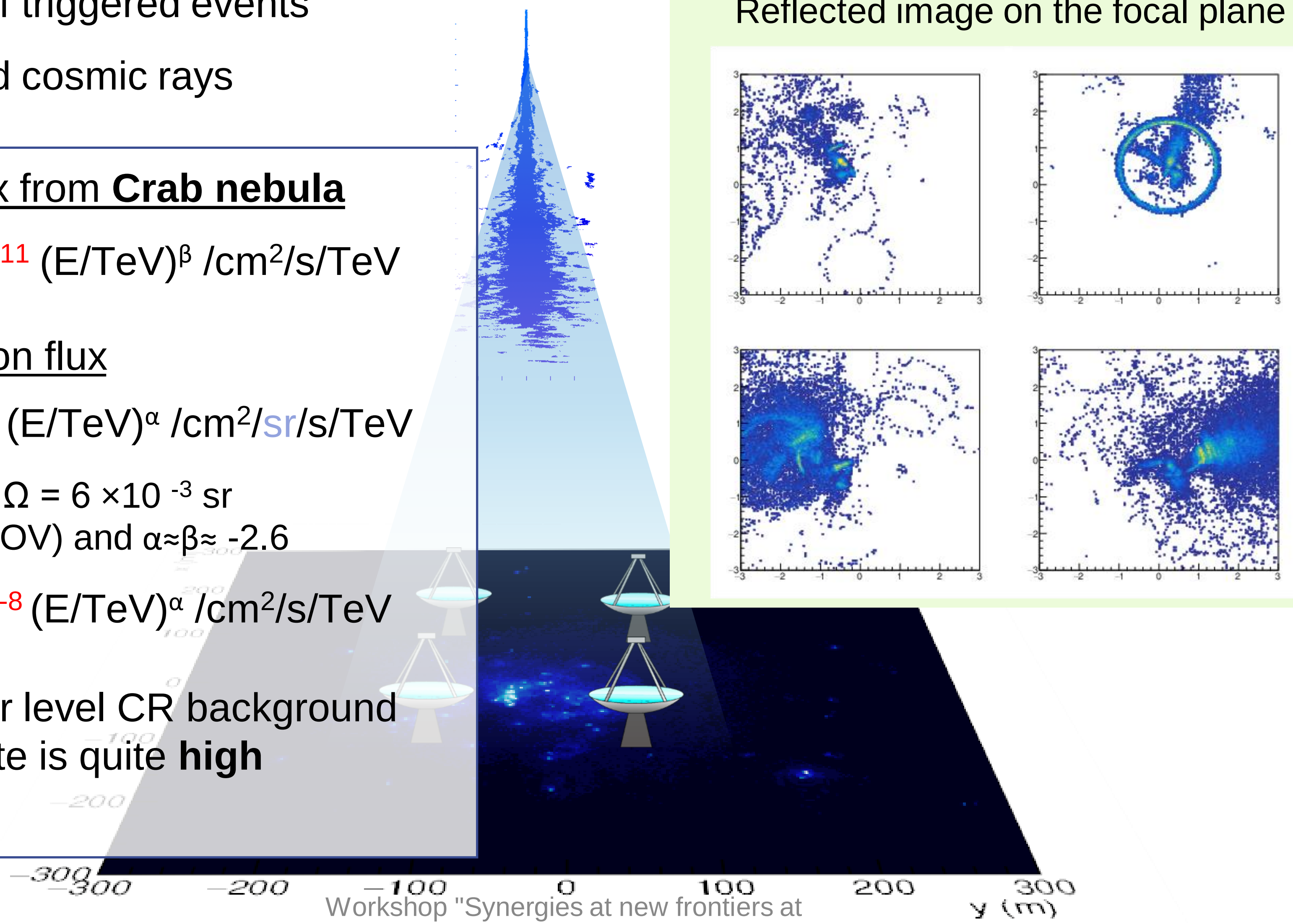
<u>CR proton flux</u>

~1.0×10^{-5} $(E/TeV)^{\alpha}$ $/cm^2/sr/s/TeV$

Assuming $\Omega = 6 \times 10^{-3}$ sr
(camera FOV) and $\alpha \approx \beta \approx -2.6$

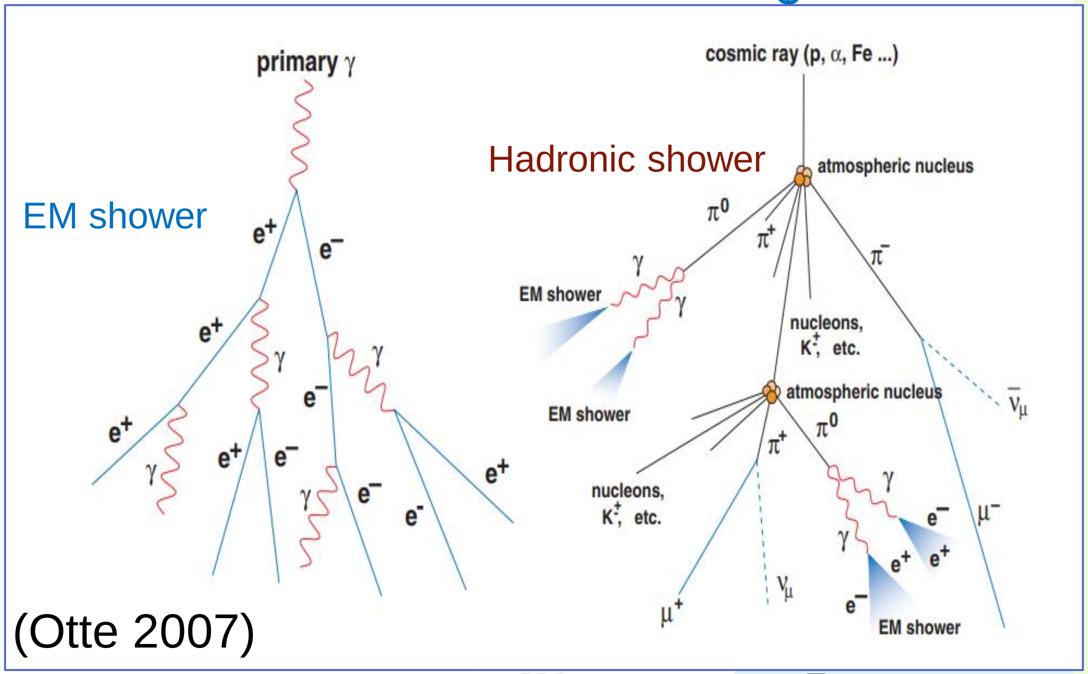
→ 6×10^{-8} $(E/TeV)^{\alpha}$ $/cm^2/s/TeV$

At trigger level CR background event rate is quite **high**



Reflected image on the focal plane

IACT γ-ray detection principle γ/hadron separation



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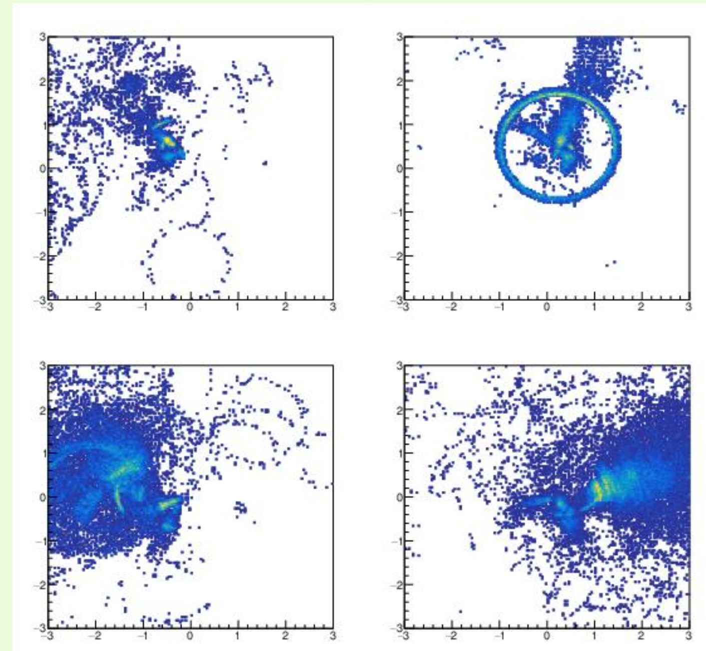
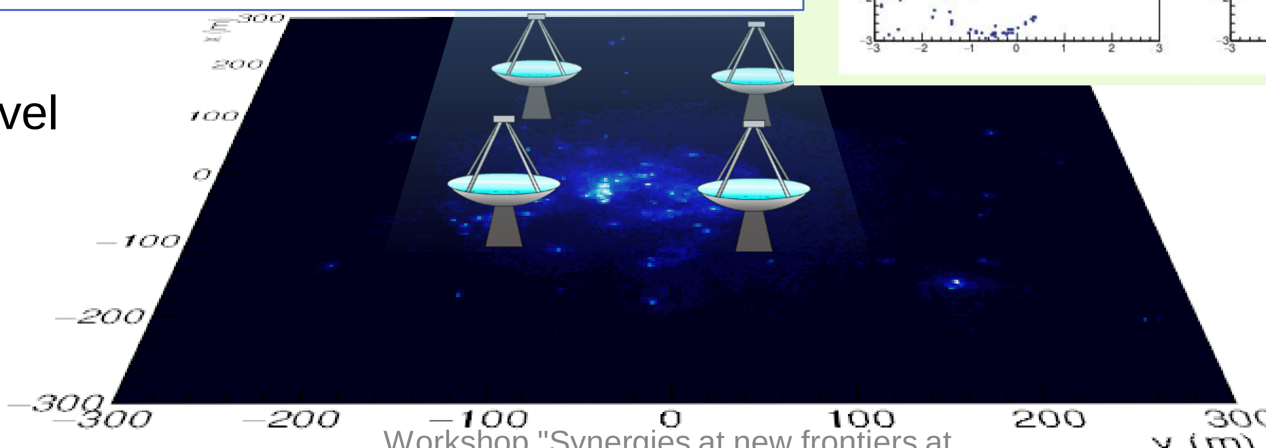


At trigger level

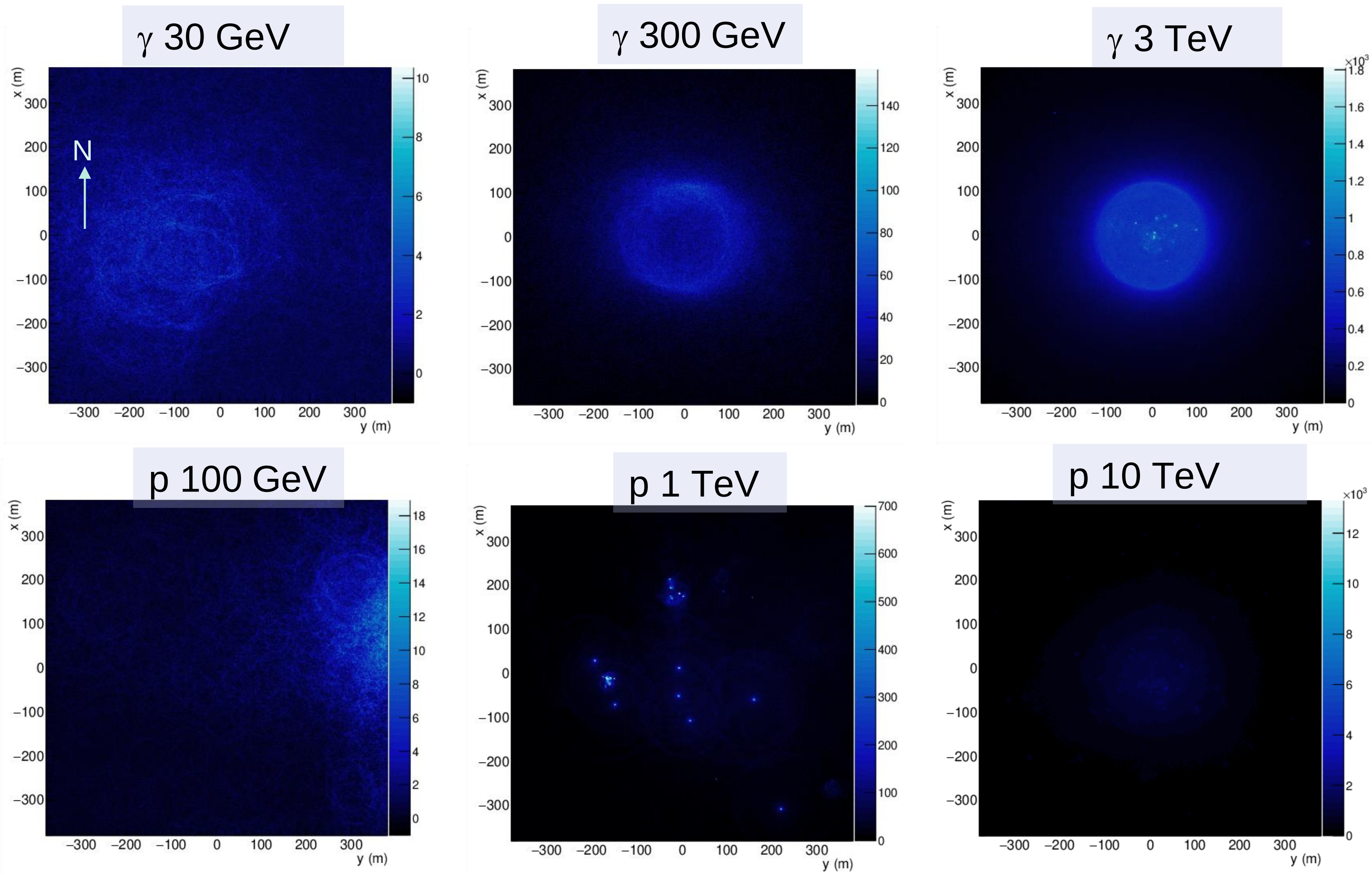
CR γ

$>10^3$: 1



Light pool patterns on the ground

CORSIKA 7.74,
2,000m a. s. l.

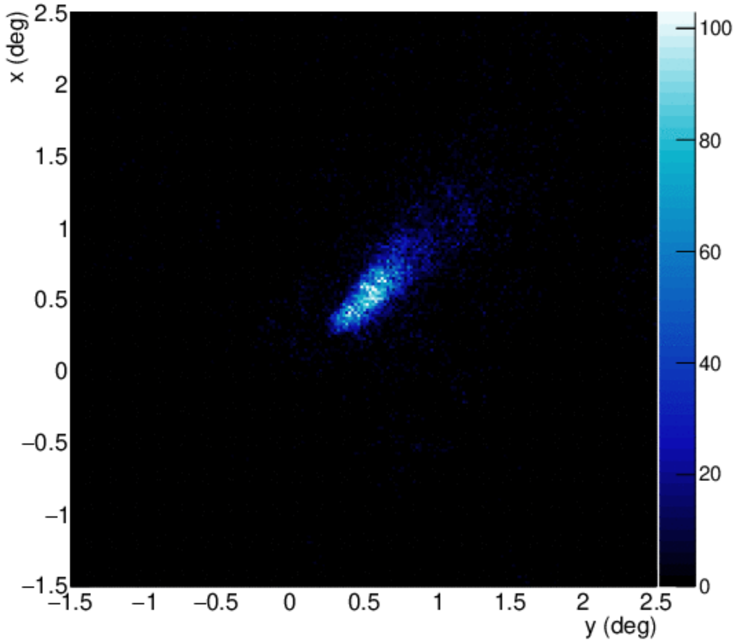


Light-pool photon density fluctuates event to event, caused by the variation in the first interaction height (limiting energy resolution)

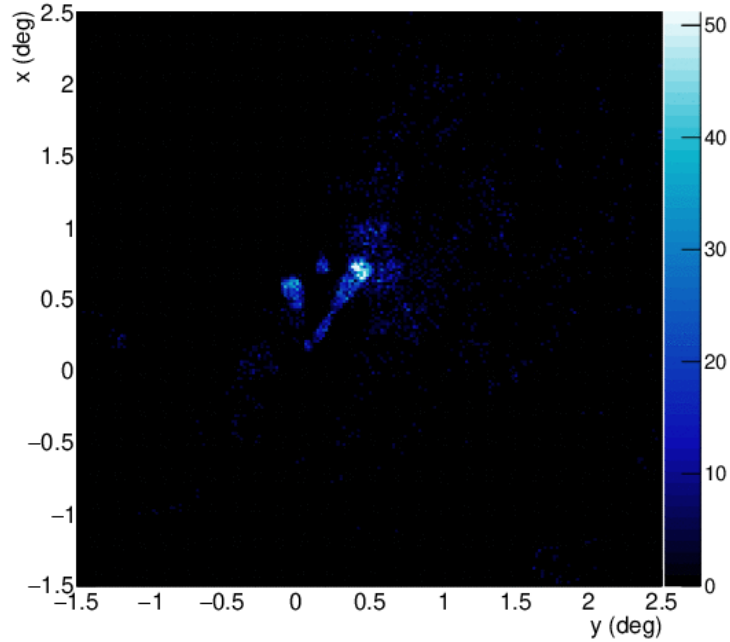
Cherenkov photon angle distribution

Impact parameter *d* = 70 m, photon collection area radius = 10 m

γ 300 GeV



p 1 TeV

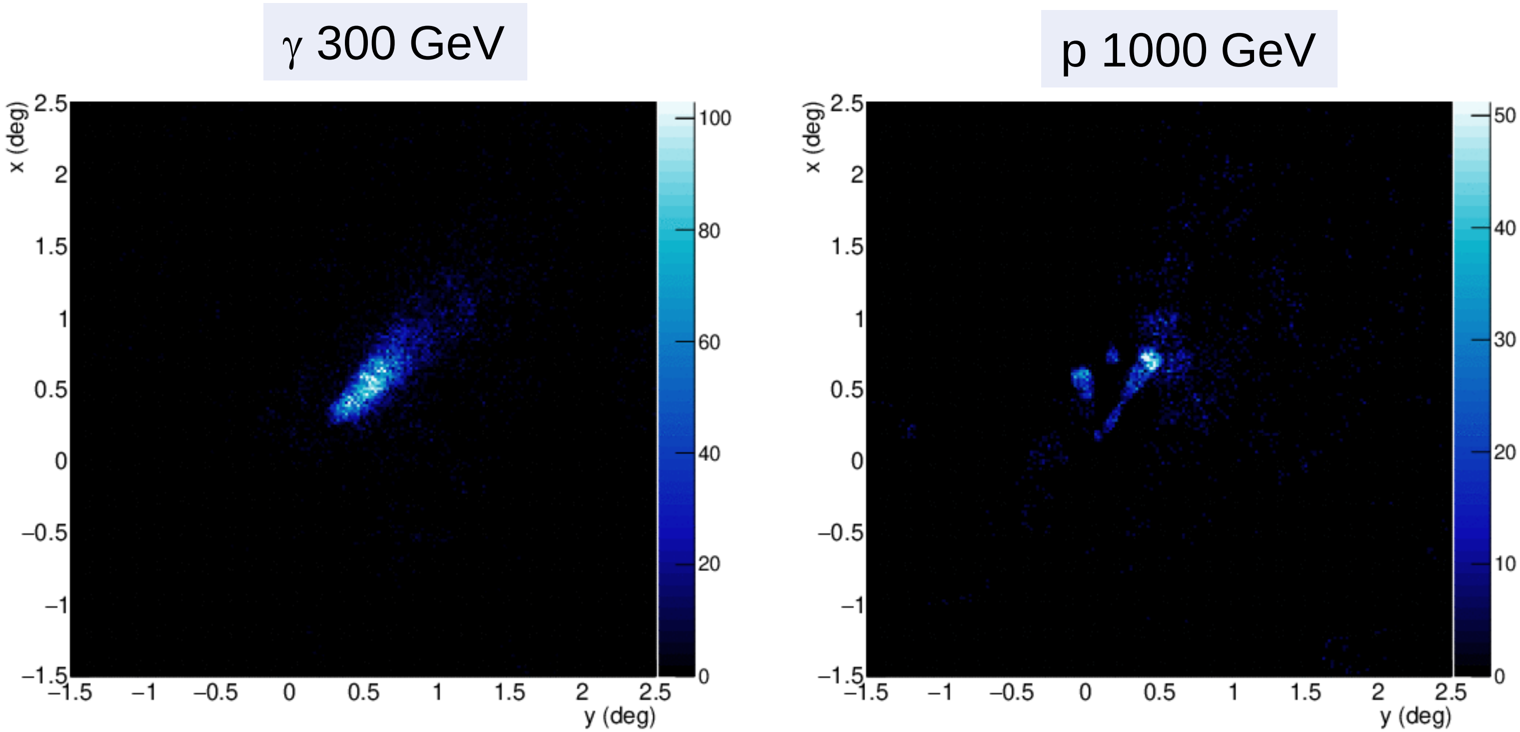


Single electromagnetic shower
→ One elongated ellipse

Superposition of sub-structures:
- μ-ring
- μ-arc
- sub-EM showers

Cherenkov photon angle distribution

Impact parameter *d* = 70 m, photon collection area radius = 10 m



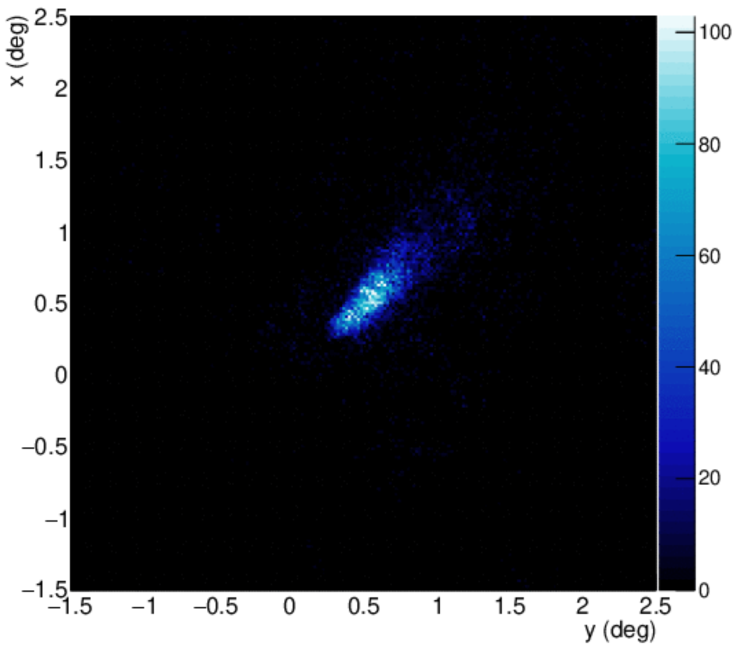
In the observation data:

- \+ finite point spread function (PSF) of the reflector
- \+ finite pixel-size of the imaging camera at the focal plane
- \+ noise: night sky background (starlight, moonlight etc.)
- \+ noise: electric noises

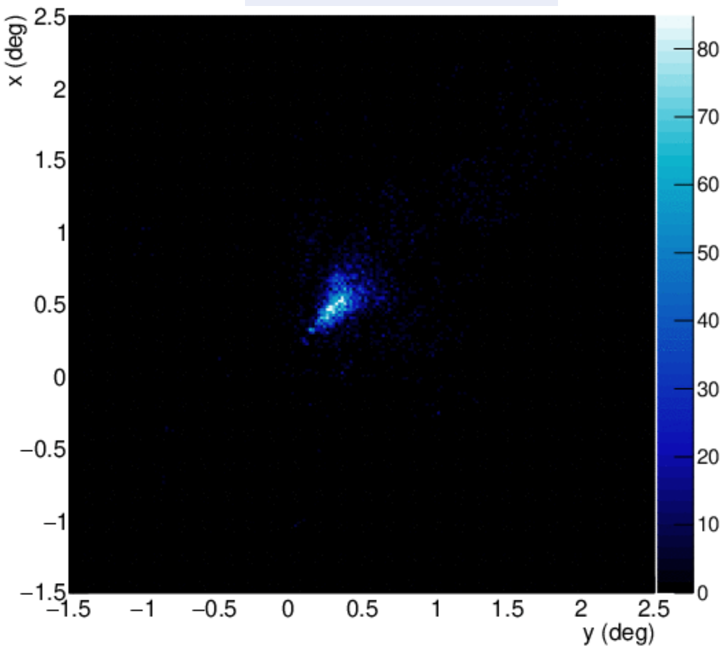
Cherenkov photon incident angle distribution

Impact parameter d = 70 m, photon collection area radius = 10 m

γ 300 GeV



e^- 300 GeV



- Both γ and e^-(e^+) form electromagnetic shower (difference in the first interaction, but the rest is same)
  $\rightarrow$ basically indistinguishable on event-by-event basis
  $\rightarrow$ **Irreducible CR background**

Conditions which determine γ-ray sensitivity of an IACT system

- Minimum number of signal events ($N\gamma \geq 10$)

Simulation setting

$$N_\gamma = F_\gamma A_{0\gamma}\epsilon_\gamma t \geq 10 \quad \Rightarrow \quad F_\gamma = \boxed{\frac{1}{A_{0\gamma}}}\boxed{\frac{1}{\epsilon_\gamma}} N_\gamma t^{-1}$$

efficiency in the analysis

- Significance to the background events ($N\sigma \geq 5$)

$$N_\sigma = \frac{1}{\sqrt{1+\alpha}}\frac{N_\gamma}{\sqrt{N_B}} = \frac{1}{\sqrt{1+\alpha}}\frac{F_\gamma A_{0\gamma}\epsilon_\gamma t}{\sqrt{F_B A_{0B}\epsilon_B \Omega t}} \geq 5$$

Literature value

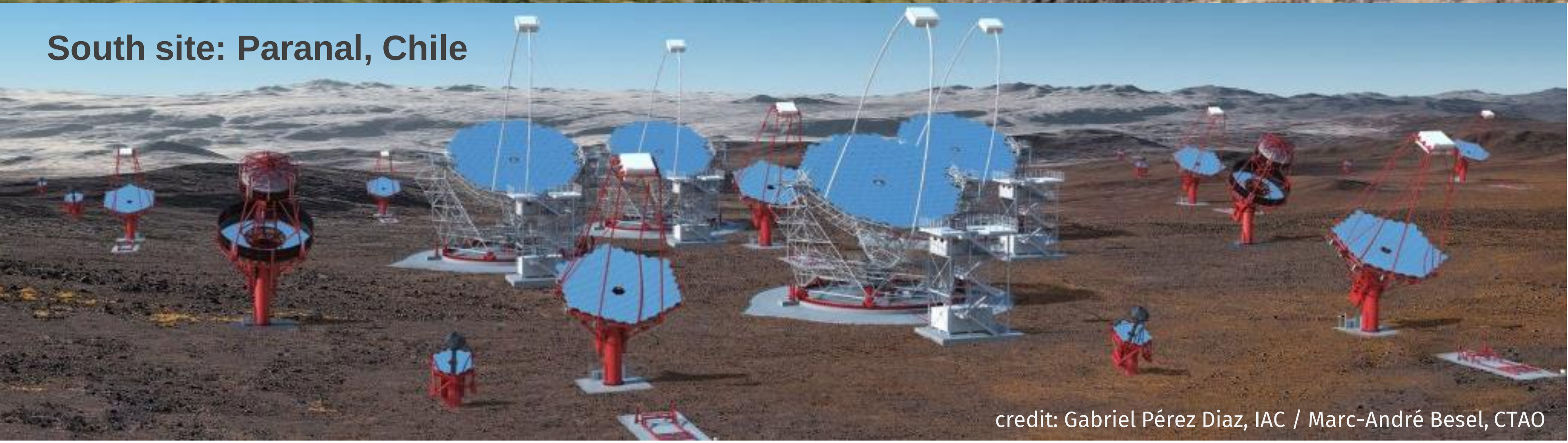
$$\Rightarrow \quad F_\gamma = \boxed{\sqrt{F_B}}\boxed{\frac{\sqrt{A_{0B}\Omega}}{A_{0\gamma}}}\boxed{\frac{\sqrt{\epsilon_B}}{\epsilon_\gamma}}\sqrt{1+\alpha}N_\sigma t^{-1/2}$$

- Signal to background ratio ($N_\gamma/N_B \geq 0.05$)

$$R_{\gamma B} = \frac{N_\gamma}{N_B} = \frac{F_\gamma A_{0\gamma}\epsilon_\gamma}{F_B A_{0B}\epsilon_B\Omega} > 0.05 \qquad F_\gamma = \boxed{F_B}\boxed{\frac{A_{0B}\Omega}{A_{0\gamma}}}\boxed{\frac{\epsilon_B}{\epsilon_\gamma}}R_{\gamma B}$$

Cherenkov Telescope Array (CTA)

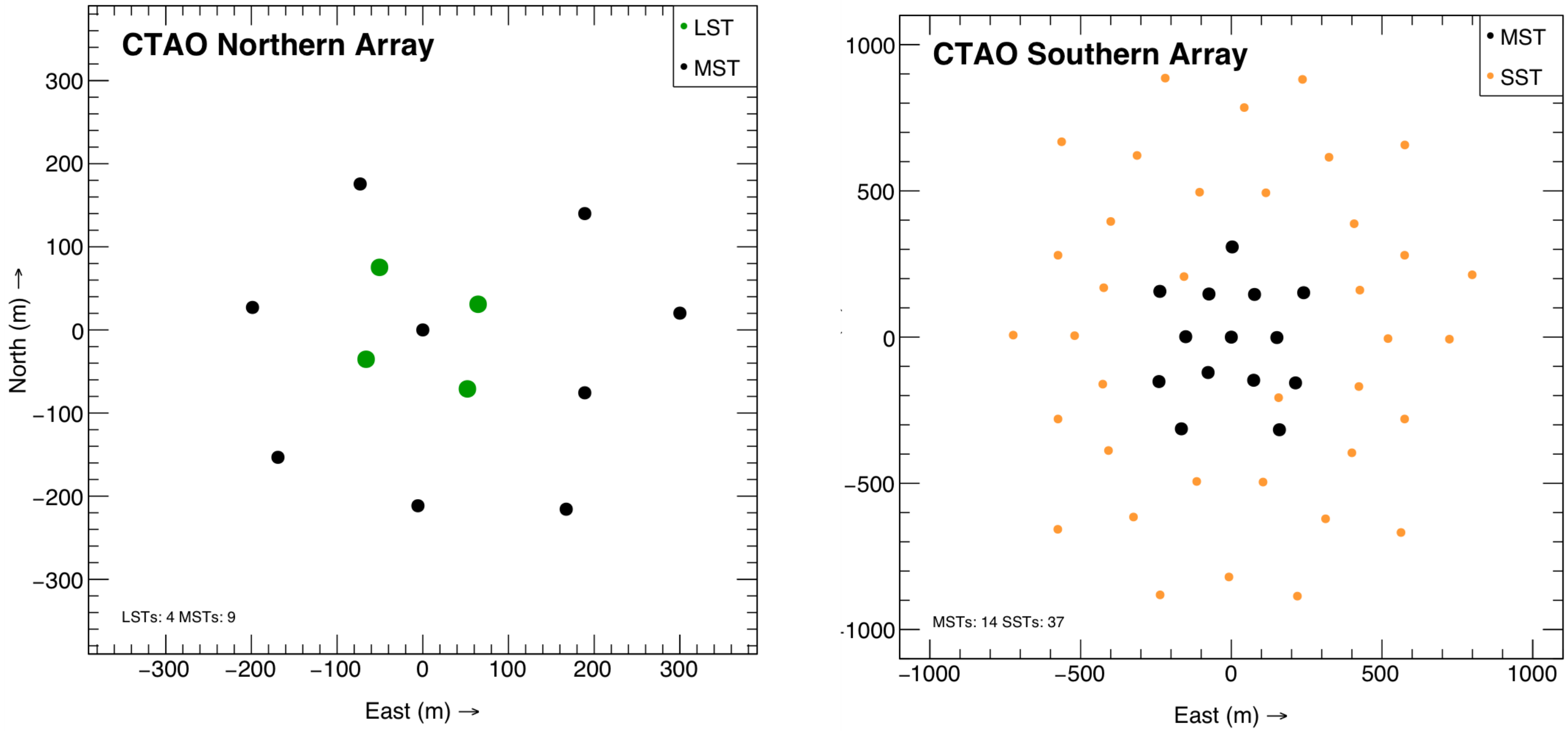
https://www.cta-observatory.org/



- CTA array consists of 3 types of telescopes (LST, MST, SST) to cover 20 GeV to 300 TeV energy range
- LST (ϕ 23m, 20 GeV – 3 TeV), MST (ϕ 12m, 80GeV - 50 TeV), SST (ϕ 4.3m, 1 TeV - 300 TeV)

Array configuration for the current public IRFs

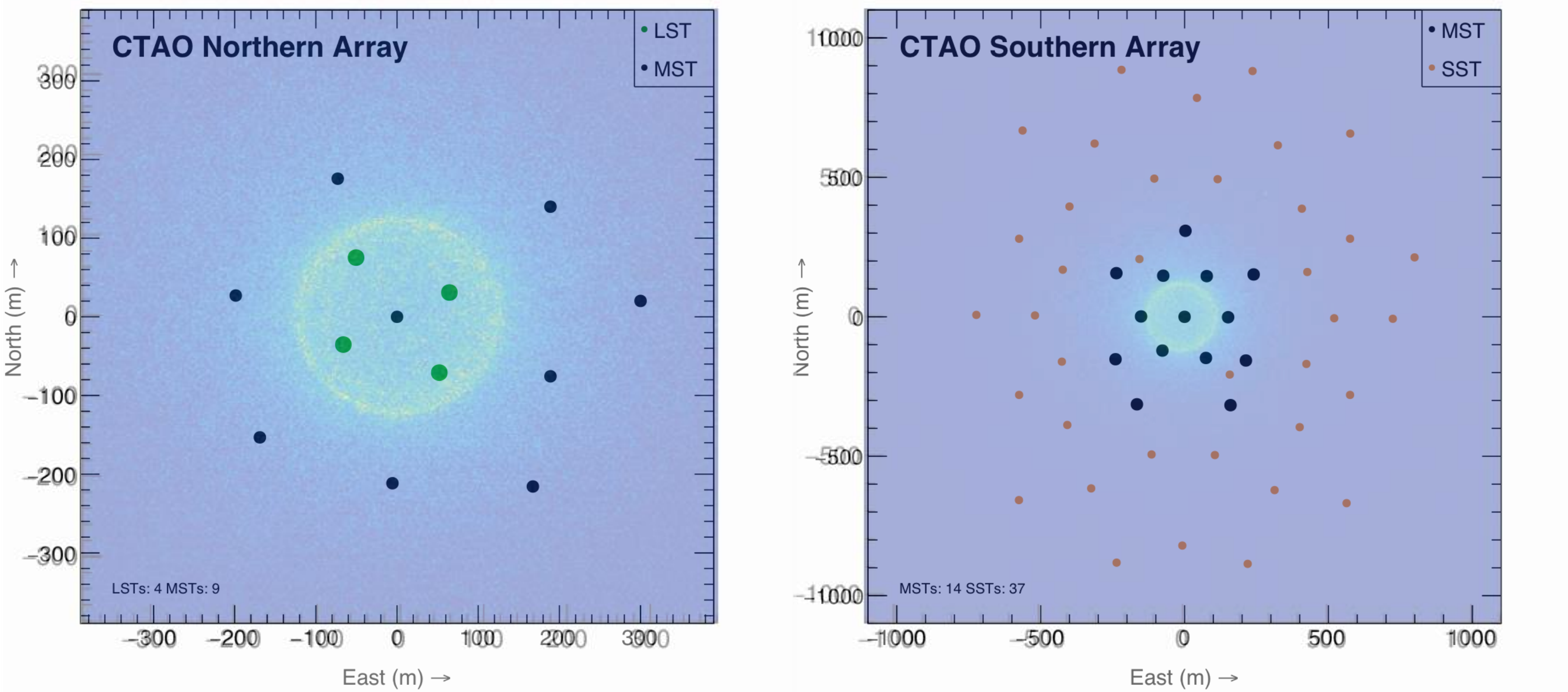
"Alpha configuration" : first construction phase



These figures and instrument response functions (IRFs) are public on Zenodo: https://zenodo.org/record/5499840#.YihE73_P1hF

Array configuration for the current public IRFs

“Alpha configuration” : first construction phase



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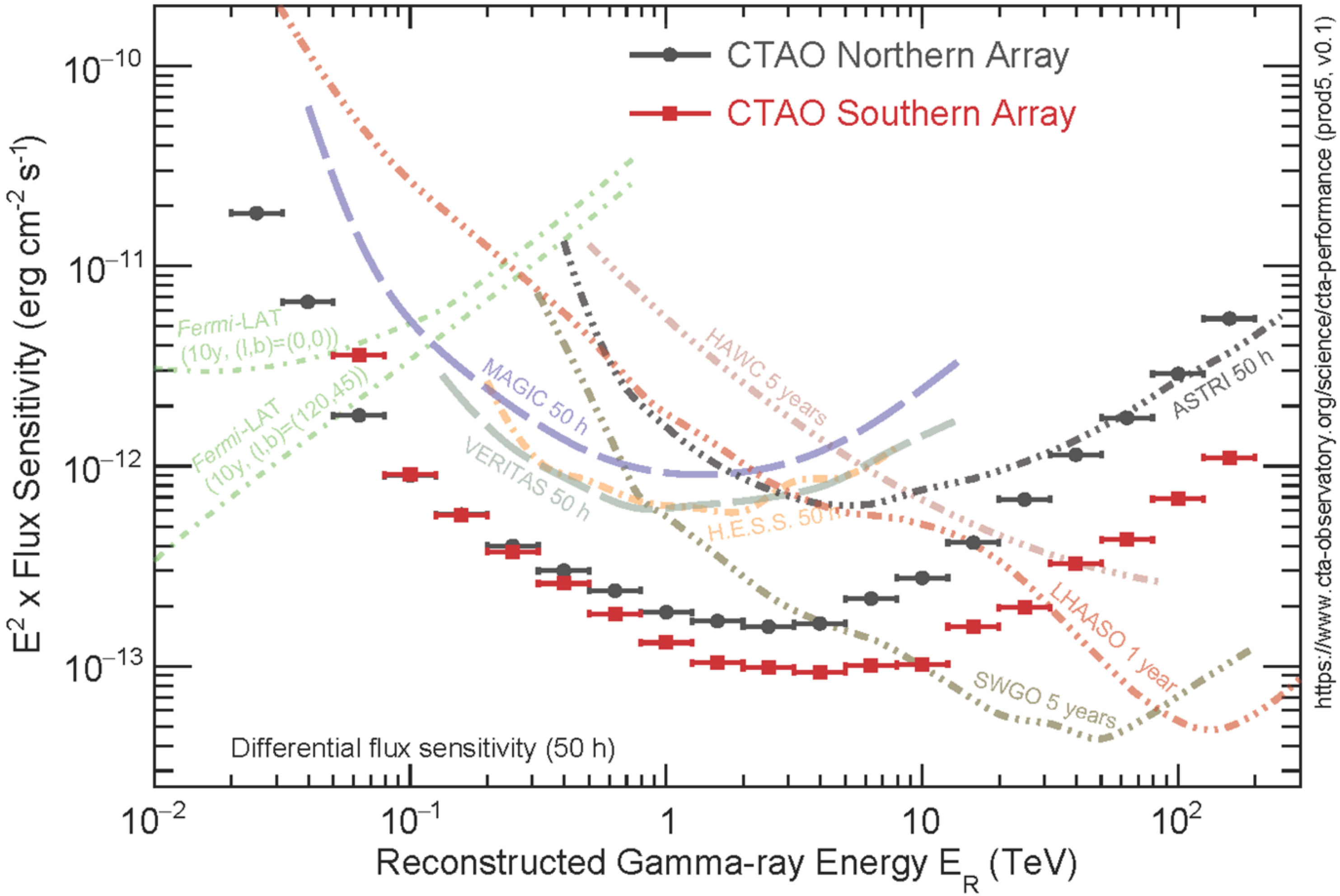
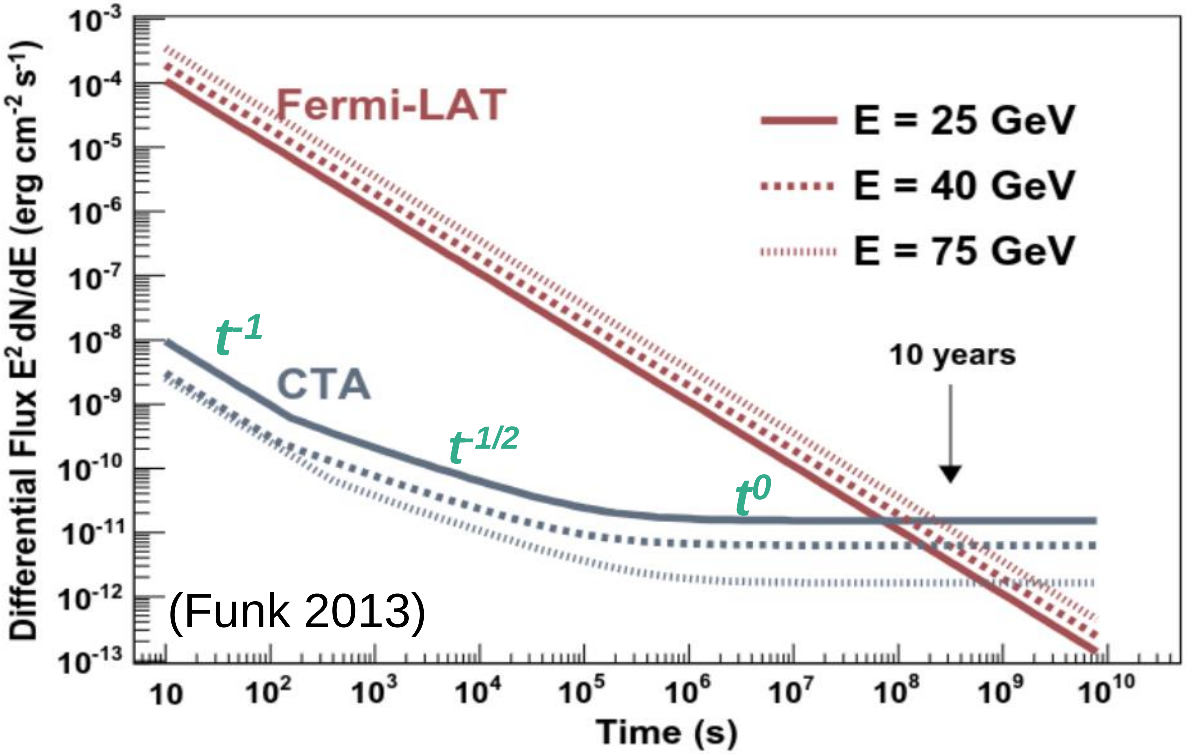
Sensitivity curve for various IACTs and ground-based γ-ray observatories



Sensitivity and observation time relation: (10-year scale)

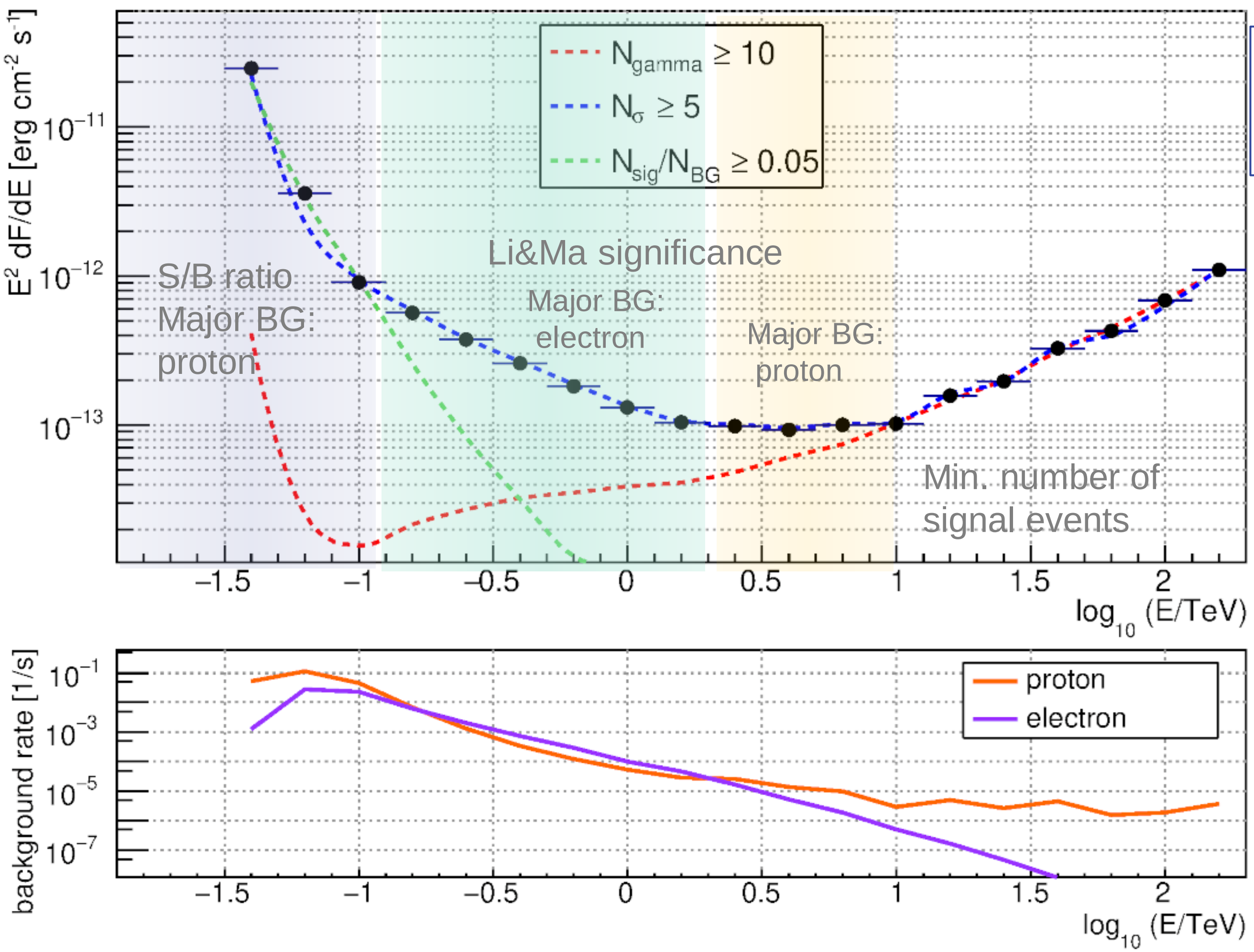
*Array configuration for this plot is different from the current, but relation between observation time and sensitivity shows same feature



* Detector configuration (as of 2013) is different from the one in the previous page

Sensitivity curve and dominant conditions

CTA Instrument Response Functions public at Zenodo (Prod5 ver v0.1) :
https://zenodo.org/record/5499840#.YjiDQ-rP1D9



Alpha configuration
South site array
50h differential sensitivity

Dominant condition depends on the energy range
(4 regions in this case)

Summary

- γ-ray observations with IACT have been continuously developed over the past 30 years, more than 200 objects have been discovered by IACTs.
- It can achieve lower energy thresholds (currently 20 GeV) than surface particle detectors, but its small field of view makes it essential to cooperate with a wFoV detector for observations of transient objects.
- IACT observations can only be performed in clear and moon-less nights, forming a network consists of multiple observatories with different longitude/latitude is meaningful.
- The most important factor to determine the IACT sensitivity curve is background rejection capability. To improve sensitivity, development of new hardware/software and building accurate Monte Carlo simulation are ongoing.

Backup

Common requirements for the IACT detectors: Optics and imaging camera pixel size

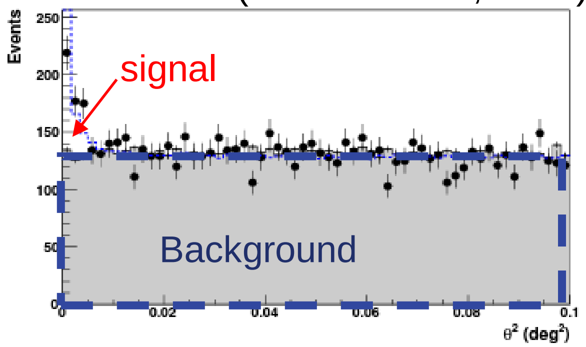
- Cherenkov photon density of 100 GeV γ at 2,000m
  $\rightarrow$ 10 photons/m^2

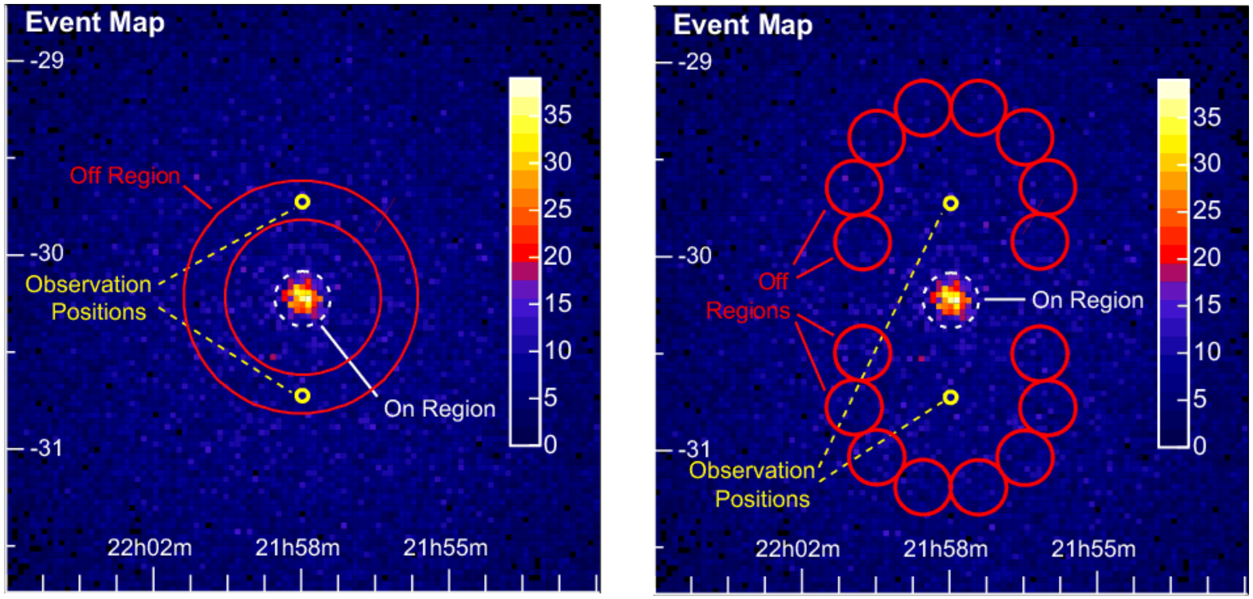
- ~ 100 photo-electrons (multiplied mirror reflectivity and Q. E. of the photo-detector) is required for a reasonable image analysis
- Optical PSF and camera pixel-size $\leftarrow$ need to distinguish EM shower and hadronic shower
- EM shower itself has a finite extension (σ=0°. 05)
  $\rightarrow$ Optical PSF smaller than σ = 0°.05 and pixel size of $\phi \sim$ 0°.1
- Practical solution of the reflector design $\rightarrow$ tessellated reflector with spherical segmented mirrors

Background estimation : ON - OFF

- “γ-like event list” ≠ “photon list
  It includes a significant number of irreducible, misidentified charged cosmic-ray events
- Estimation of background level is essential
- In many cases OFF region data is used to estimate BG level

θ^2plot sample
(Abramowski+, 2012)

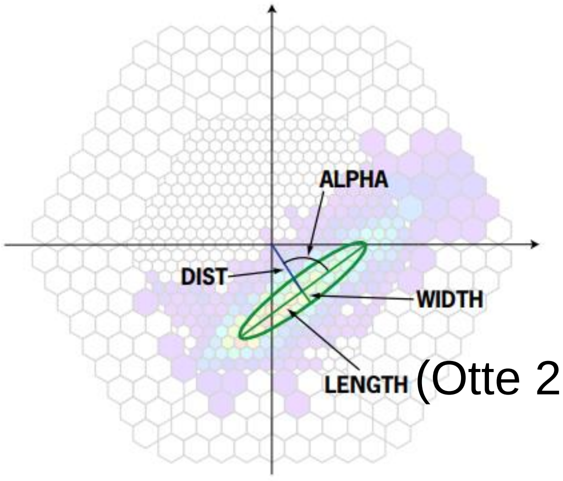




(Berge+, 2007)

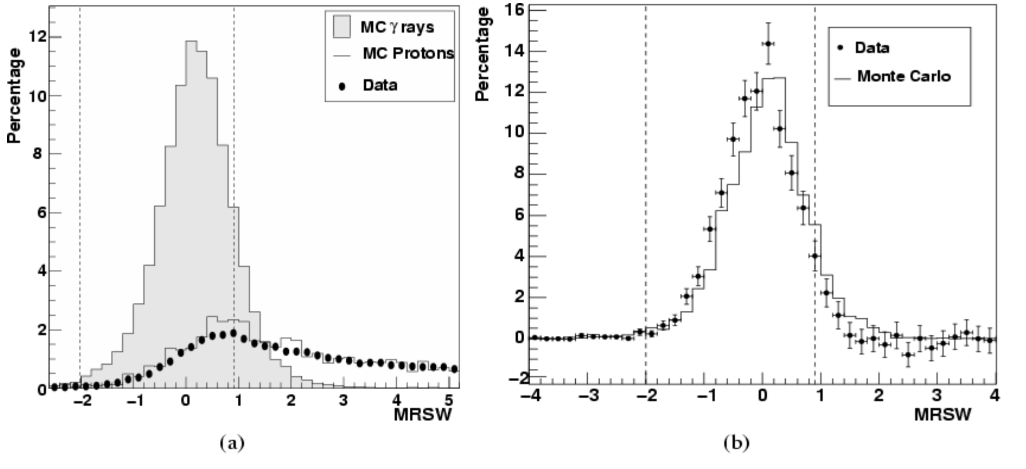
γ/hadron separation in the analysis
- Hillas parameter-based analysis -

- Characteristics extraction of air shower images using 2nd/3rd moment
- *WIDTH* : lateral size of an EAS,
  LENGTH : longitudinal size of an EAS
- Simple but robust and worked well in the IACT experiments in early stage
- Hillas parameters show dependence on core distance (impact parameter) and Size (total p. e. in the image)
  $\rightarrow$ corrected Hillas parameters (Mean Reduce Scaled Width etc.) describes characteristics of an EAS better



(Otte 2017)

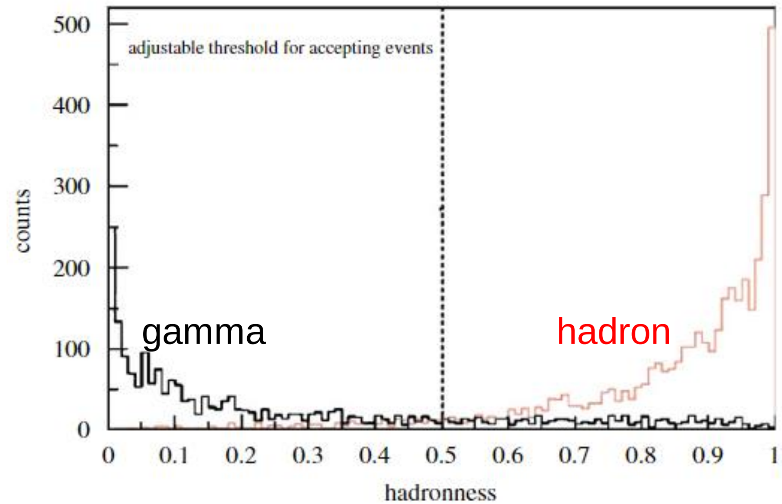
(Aharonian+ 2006, H.E.S.S. Crab)

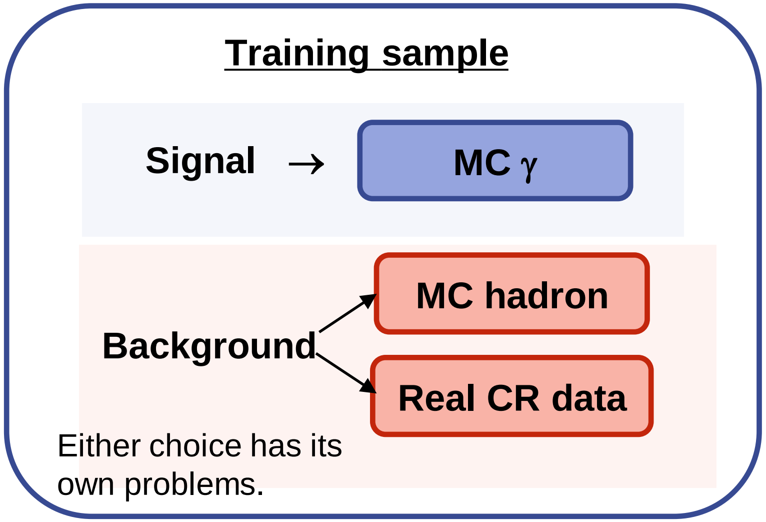


γ/hadron separation in the analysis
- machine learning classification -

- Current popular analysis approach
  implementation is different for each group:
  MAGIC → Random Forest (RF)
  VERITAS → Boosted Decision Tree (BDT)
- With signal and background data samples, the machine learning scheme is trained to separate two data samples best (classification)
- Multiple input parameters, single output parameter (*hadroness*, or *gammaness*)
- Choice of input parameters is also different for each group (Hillas parameters, corrected Hillas parameters, pixel charge, etc.)
- There are two choices for BG training sample:
  - MC hardon → suffers from uncertainties in hadronic interaction
  - Real CR data → discrepancy between MC setting and real (atmosphere and hardware condition)

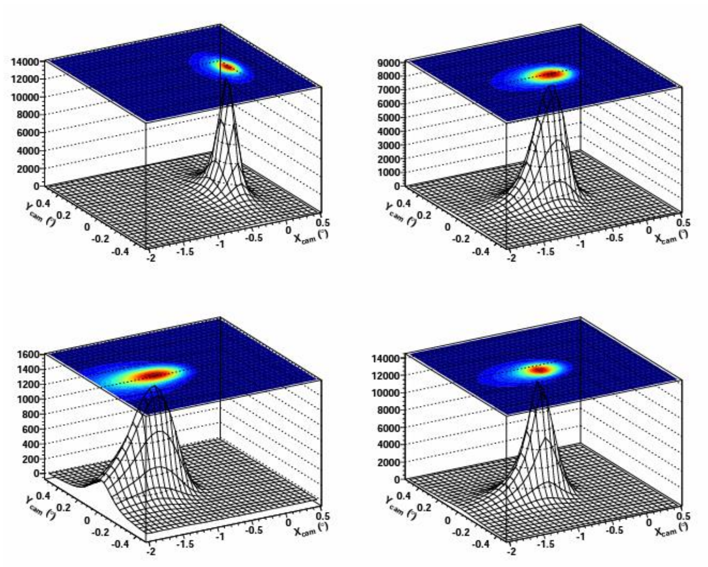
Albert+ 2008



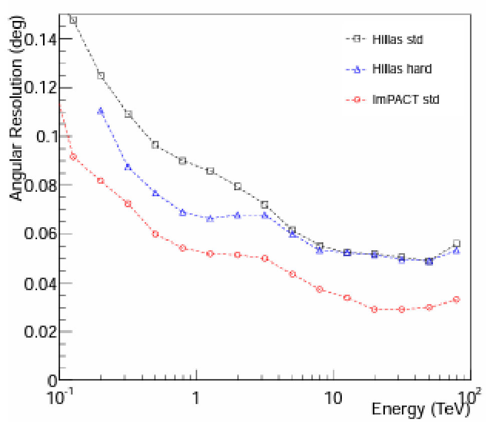


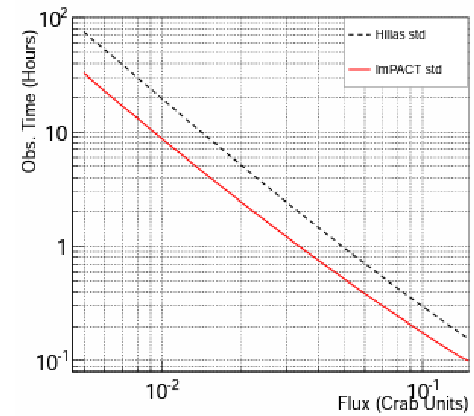
γ/hadron separation in the analysis
- template likelihood -

- Search for a **best-fit** image from a **database** of γ-ray shower images for various conditions (impact parameter, energy, incident angle, etc.)
- Shower reconstruction and evaluation of gammaness (goodness-of-fit) is performed simultaneously
- Only γ-ray is needed for MC
- Used in H.E.S.S. and showed better results than Hillas-parameter based analysis
- Computing resource consumption for creating database and best-fit image search is relatively high

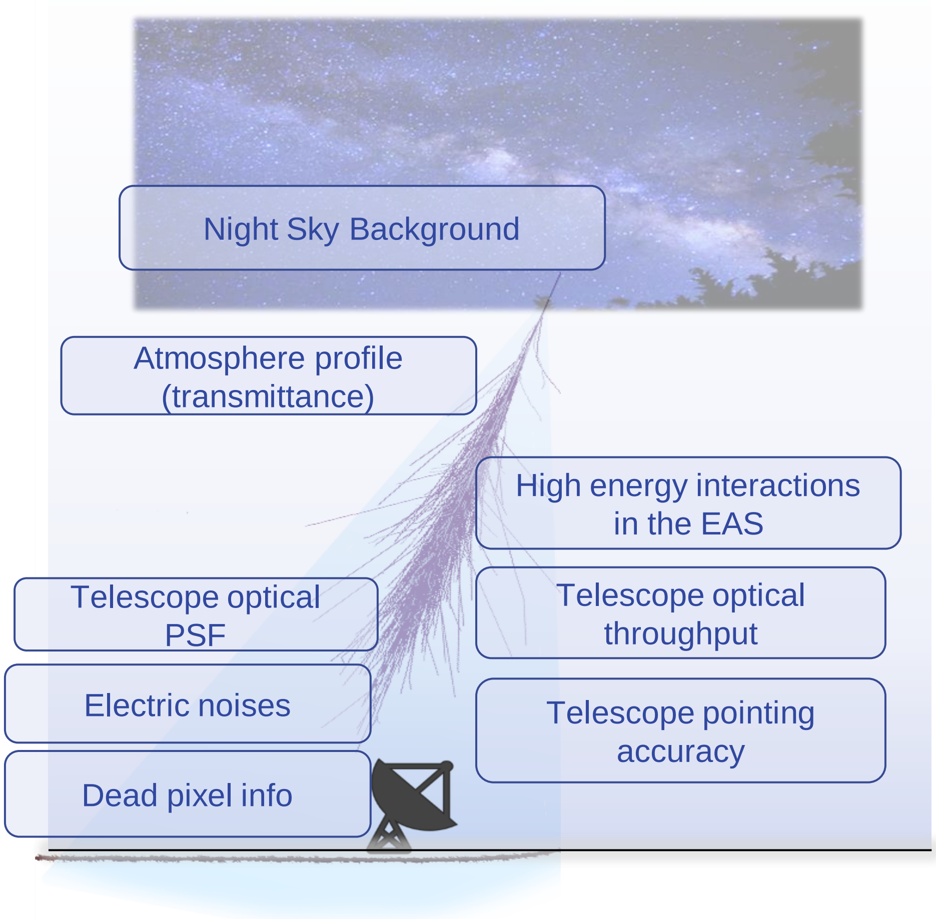


(Parsons&Hinton 2014)



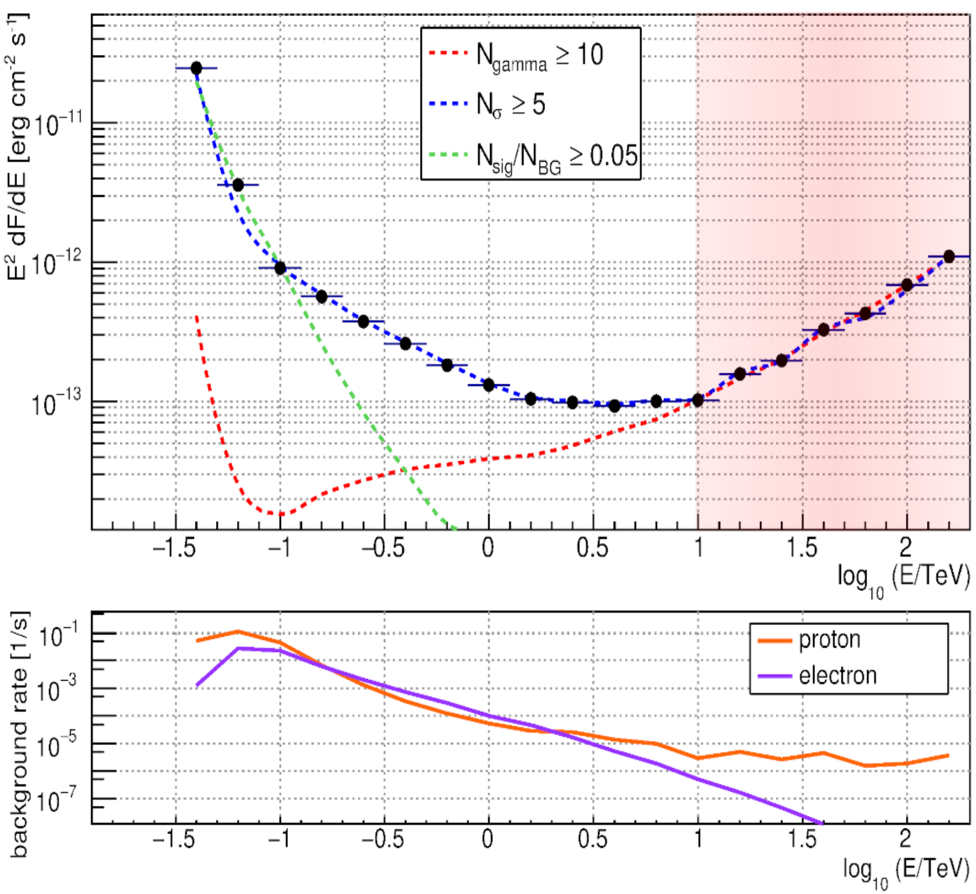


Importance of Monte Carlo simulation accuracy



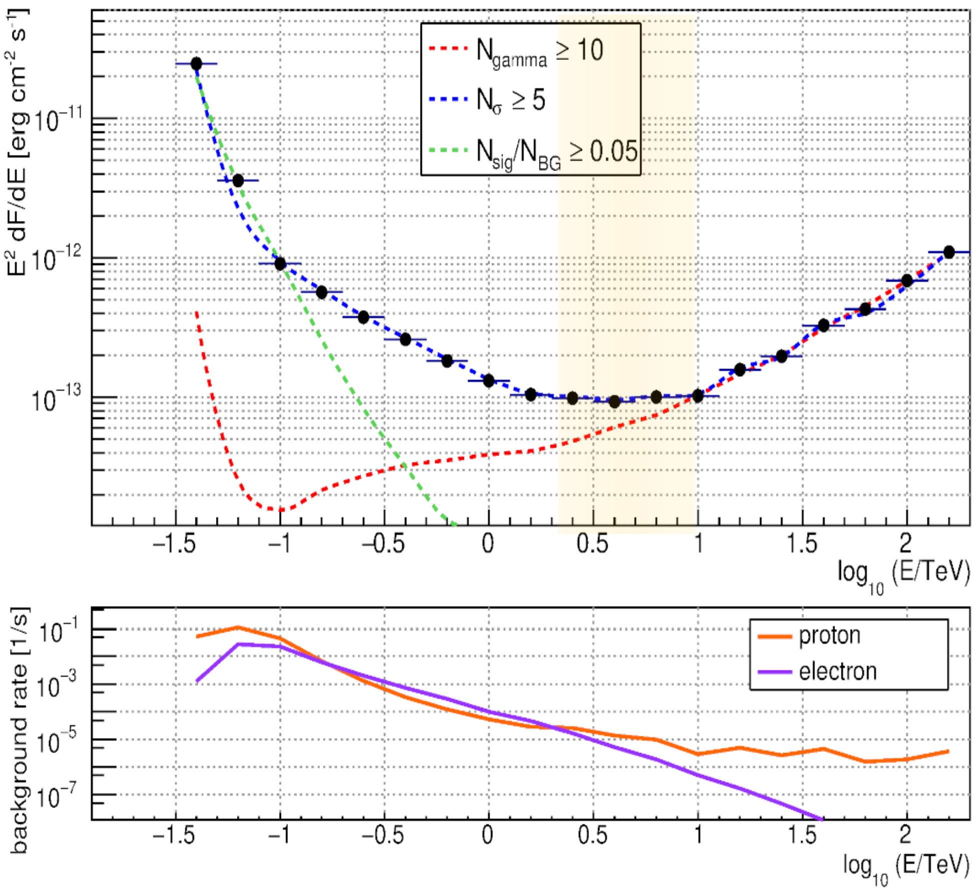
- Precise matching between Monte Carlo simulation data and real data is essential for IACT experiments
- There are numerous parameters to be tuned in MC
- Some of them are variable on run by run (day by day) basis:
    - Atmosphere condition
    - Night sky background
    - Telescope optical throughput
    - Telescope pointing accuracy
- Using various monitor data and info from supplemental devices (LIDAR, skymonitor camera, etc.), there parameters are supposed to be properly tuned for each data run

Conditions which determines γ-ray sensitivity of an IACT (CTA) case : E> 10 TeV



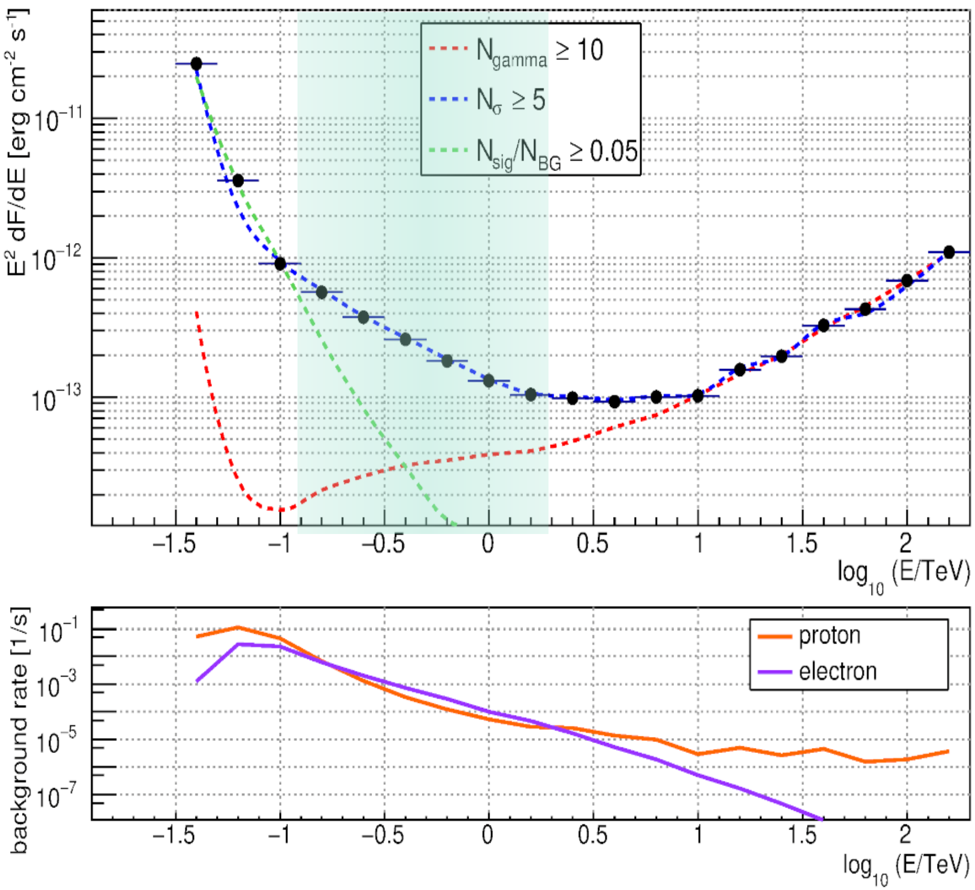
- Gamma/hadron separation in this energy band by IACT is excellent
  → Number of signal event (Nγ≥ 10) limits the sensitivity
- Large exposure is needed
- Overlapping energy range with surface particle detectors (their detectors have high duty factor)

Conditions which determines γ-ray sensitivity of an IACT (CTA) case : A few TeV to 10 TeV



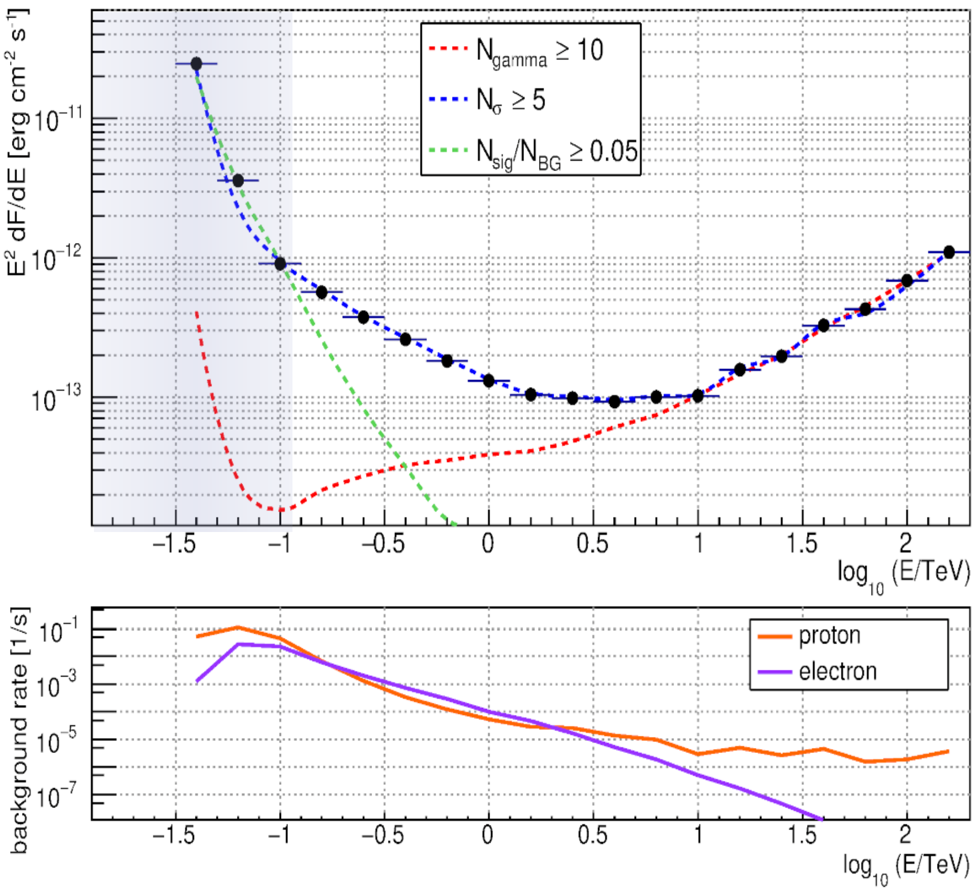
- Li&Ma significance is the dominant condition and major background is CR proton
- More reduction of hadron component may improve the sensitivity, but Nγ limit is also close

Conditions which determines γ-ray sensitivity of an IACT (CTA) case : 100 GeV to a few TeV



- Li&Ma significance is the dominant condition and major background is CR electron
- Basically CR electrons are irreducible background for IACT gamma observation
- New-type detector will be needed in the future improvement of the sensitivity

Conditions which determines gamma-ray sensitivity of an IACT (CTA) case : E< 100 GeV



- S/B ratio determines the sensitivity, thus extension of observation time does not improve the sensitivity
- Major background is CR proton again
- Effort to improve γ/hadron separation efficiency is essential (in software or hardware) in this energy band

Energy resolution and angular resolution from detection principle

Statistical fluctuation in the image

Threshold effects

Fluctuation in the shower development

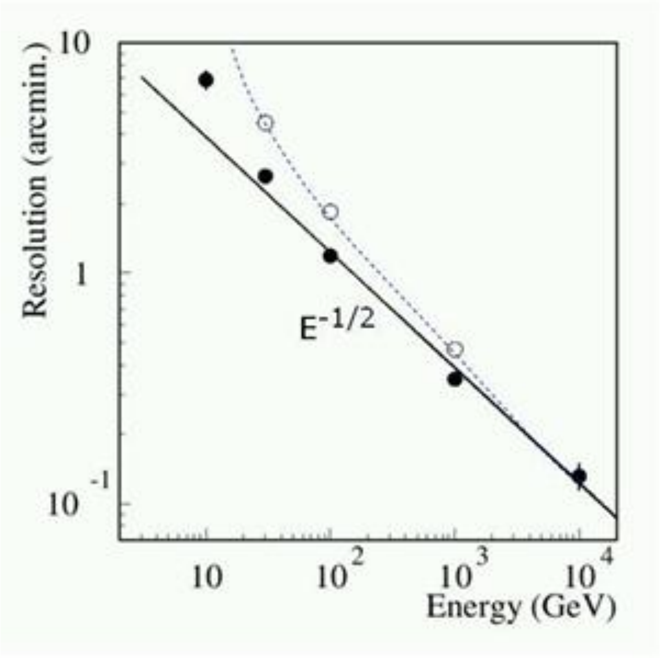
Image truncation

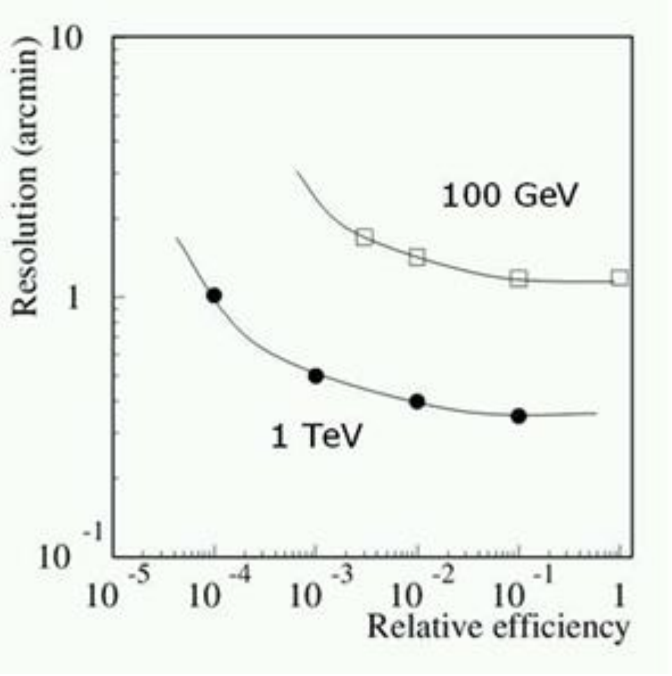
Errors in the core position reconstruction

Systematic errors (between Real and MC)

Hoffman 2000

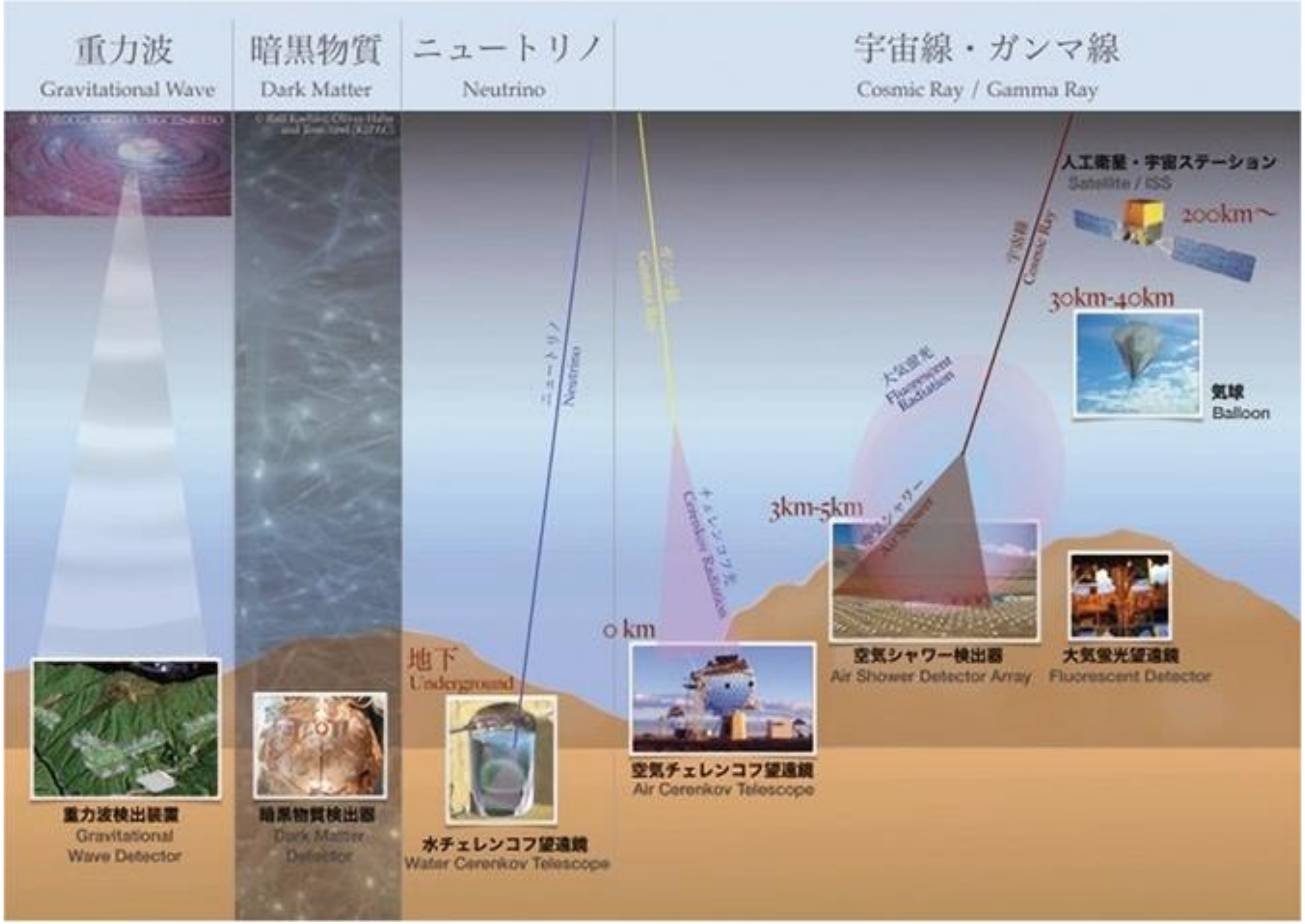
Angular resolution limiting factors





(Hofmann 2006)

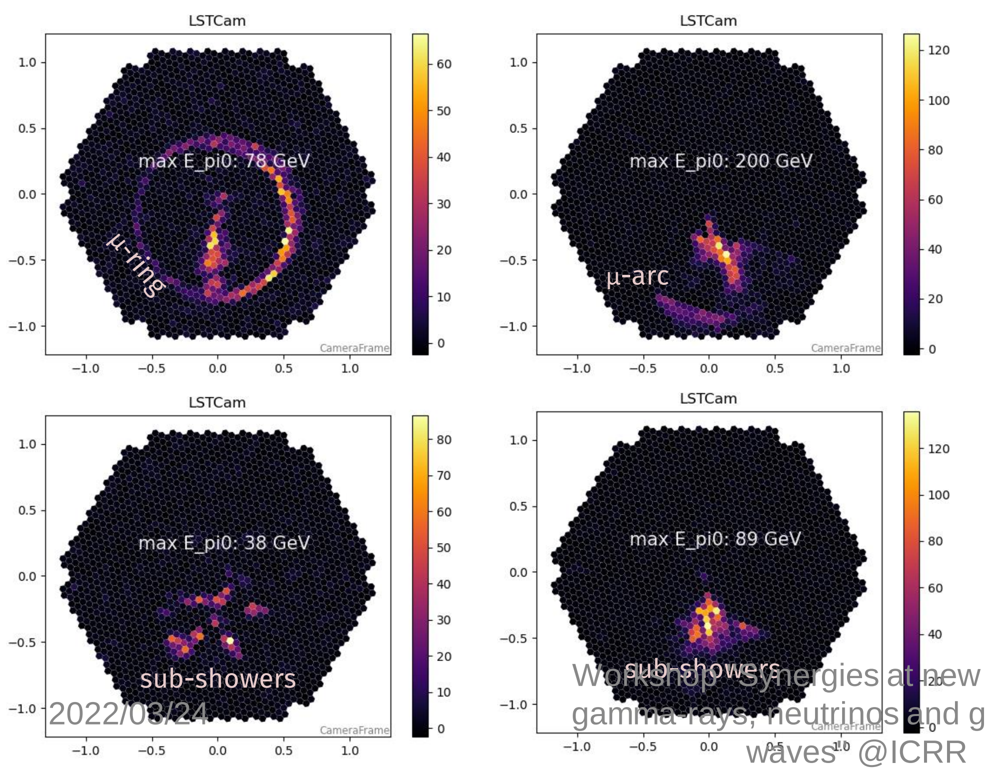
Indirect CR experiments



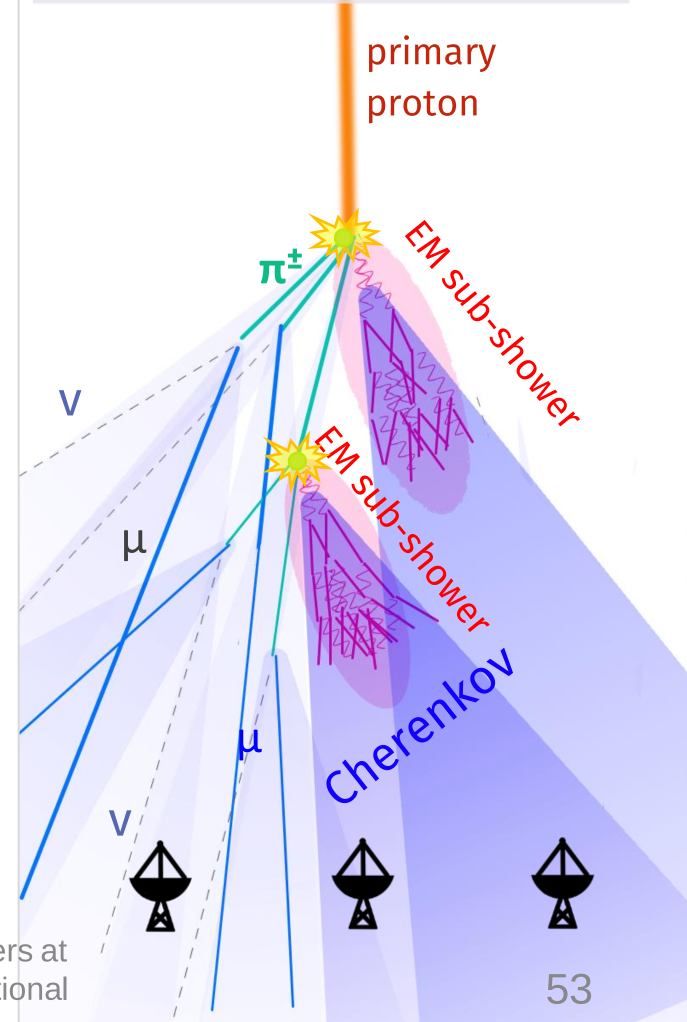
Proton-induced shower images in IACTs

- EASs from cosmic-ray protons : sub-structures
  - **EM sub-showers** from π^0
  - **Muons** from $\pi^\pm$
- Wide variation in observed images

Cherenkov Image samples for 1 TeV proton
z : 0 deg, Impact Parameter : 120 m,
first interaction height : 20km, target nucleus: Nitrogen (all fixed)



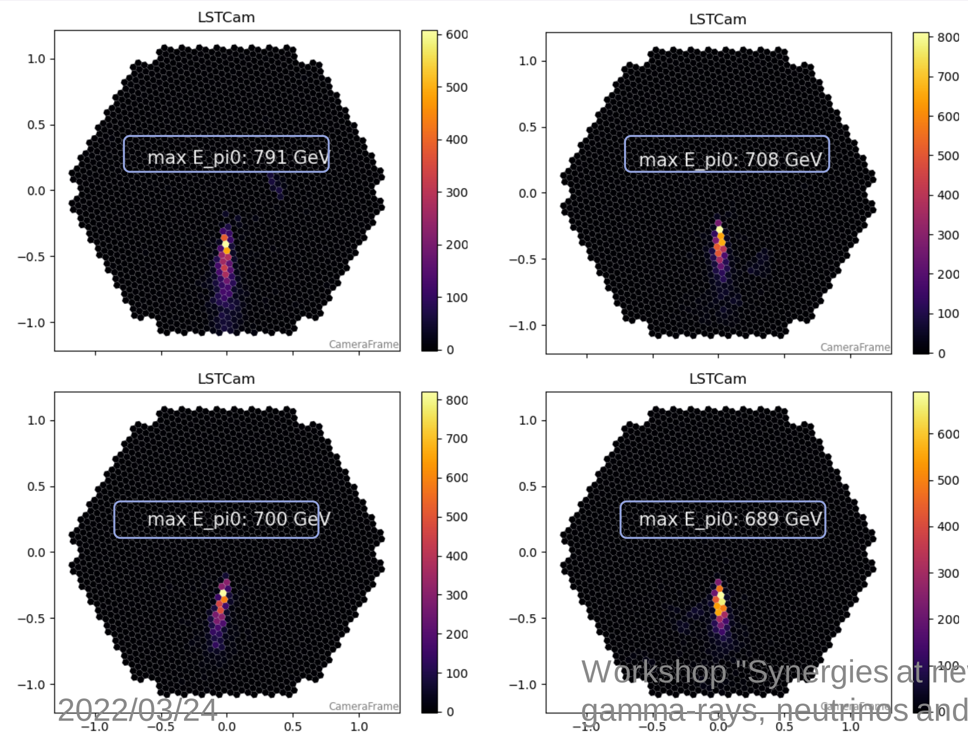
Schematic diagram of a proton-induced EAS



Proton-induced shower images in IACTs

- Previous studies on nature of γ-like proton events:
  Maier+ (2007), Sitarek+ (2018), Sobczyńska (2008, 2015) etc.
- Emission of **energetic π^0** → **γ** -like shower
- Rate of γ-like events depends on π^0 spectrum

High max $E_{\pi0}$ image samples for 1 TeV proton
z : 0 deg, Impact Parameter : 120 m,
first interaction height : 20km, target nucleus: Nitrogen (all fixed)



Schematic diagram of a γ-like EAS