On the potential of atmospheric cherenkov telescope arrays for resolving TeV gamma-ray sources in the Galactic Plane

L. Ambrogi  F. Aharonian  E. de Oña Wilhelmi
Outline:

- Introduction
- Detector response for a CTA-like instrument
  - Effective Area
  - Background rate
  - Angular resolution: Gaussian and non-Gaussian PSF
- Morphological studies of isolated sources
- Sensitivity studies of multiple sources in the same FoV
- Summary
Next Generation IACT array: CTA

expected to qualitatively extend our knowledge in HE astrophysics thanks to its capabilities well beyond those of existing instruments

What is the potential of CTA-like instrument and its response to different observation modes and different source scenarios?
Detector response

CTA-like instrument recipe:

- Effective area
- Background rate
- Angular resolution

Publicly available results of calculations of the performance for the southern site of CTA from 50 GeV to 100 TeV


→ Parameterization with analytical formula
Detector response

CTA-like instrument recipe: ✓ Effective area ✓ Background rate

Effective Area

\[ A_{\text{eff}}(x) = \frac{A}{1 + B \cdot \exp\left(\frac{-x}{\sigma}\right)} \text{m}^2 \]

Log10(E/TeV)

Random sampling from

\[ f(N_B | \mu, \sigma) = \exp\left( -\frac{(N_B - N_{\text{BgRate}})^2}{2 \sqrt{N_{\text{BgRate}}}} \right) \]

Background Rate per square degree

\[ \text{BgRate}(x) = A_1 \cdot \exp\left( -\frac{(x-\mu_1)^2}{2 \sigma_1^2} \right) + A_2 \cdot \exp\left( -\frac{(x-\mu_2)^2}{2 \sigma_2^2} \right) + C \text{ Hz/deg}^2 \]

- \[ A_1 = 0.4 \]
- \[ \mu_1 = -1.23 \]
- \[ \sigma_1 = 0.23 \]
- \[ A_2 = 2.7 \]
- \[ \mu_2 = -3.9 \]
- \[ \sigma_2 = 1.0 \]
- \[ C = 3.8 \cdot 10^{-6} \]
Detector response

CTA-like instrument recipe:

- Effective area
- Background rate
- Angular resolution

Angular Resolution (68% containment)

\[ \sigma_{PSF}(x) = A \cdot \left[ 1 + \exp\left(-\frac{x}{B}\right) \right] \text{deg} \]

Ideal Gaussian PSF

\[ f_{PSF} = \exp\left(\frac{x^2 + y^2}{2\sigma_{PSF}^2}\right) \]

\[ A = 0.028 \text{ deg} \]

\[ B = 0.8 \]
Detector response

CTA-like instrument recipe:

**Angular Resolution (68% containment)**

- Ideal Gaussian PSF
  \[ f_{PSF} = \exp \left( \frac{x^2 + y^2}{2\sigma_{PSF}^2} \right) \]

- Realistic non-Gaussian PSF
  \[ f_{PSF_{tails}} = \exp \left( \frac{x^2 + y^2}{2\sigma_{PSF}^2} \right) + R \cdot \exp \left( \frac{x^2 + y^2}{2\sigma_{PSF_{tails}}^2} \right) \]
  \[ \sigma_{PSF_{tails}} = 0.2 \text{ deg} \]

**Figure:**
- \[ \sigma_{PSF} = 0.147 \text{ deg} \]
- \[ \sigma_{PSF} = 0.031 \text{ deg} \]
"Improved sensitivity by at least an order of magnitude compared to existing VHE instruments"

Expected CTA sensitivity

**Hypothesis:**
- Isolated point-like source
- Gaussian PSF

Extended sources?
Nearby sources?
These scenarios are very likely to happen in real life!
Galactic Center, Galactic Plane.

“Improved sensitivity by at least an order of magnitude compared to existing VHE instruments”

Expected CTA sensitivity

Why Gaussian PSF?
There are no real motivations to limit PSF shape to a simple Gaussian, even though it represents the standard assumption. In a more realistic approach non-Gaussian tails can be considered.

Hypothesis:
- Isolated point-like source
- Gaussian PSF

“Improved sensitivity by at least an order of magnitude compared to existing VHE instruments”

Expected CTA sensitivity

What is the response of a CTA-like instrument to multiple sources in the same FoV?

How do the non-Gaussian tails of the PSF change the potential of the instrument?

Hypothesis:
- Isolated point-like source
- Gaussian PSF

$\sigma \geq 5$

$N_\gamma \geq 10$

$N_\gamma / N_{bkg} \geq 0.05$
Isolated source simulation

- Gaussian shape
  \[ f(x, y) = A \cdot \exp\left( -\left( \frac{(x-X_0)^2}{2\sigma_{src}^2} \right) + \left( \frac{(y-Y_0)^2}{2\sigma_{src}^2} \right) \right) \]
  \( (X_0, Y_0) = (0, 0) \text{ deg} \)

  point-like and extended sources, i.e. 0.1 deg and 0.2 deg.


  \[ \frac{dN}{dE} = n \cdot N_0 \times \left( \frac{E}{1 \text{ TeV}} \right)^{-\alpha} \]
  \[ \alpha = 2.62 \]
  \[ N_0 = 2.83 \cdot 10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \]
  \[ 1 \text{ C.U.} = 2.83 \cdot 10^{-11} \times E^{-2.62} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}. \]
Reconstruction of morphological parameters for non-Gaussian PSF response

\[ \sigma_{PS\, tails} = 0.2 \, \text{deg} \]
Reconstruction of morphological parameters for non-Gaussian PSF response

- at LE $\sigma_{PSF} \approx \sigma_{PSFtails}$ $\rightarrow$ for small values of $R$ the final PSF shape does not differ much from Gaussian PSF and the source size can be properly reconstructed. For larger values of $R$ the estimation of the source size starts to be inaccurate.

- at HE $\sigma_{PSF} < \sigma_{PSFtails}$ $\rightarrow$ the reconstruction of $\sigma_{src}$ is hardly damaged by the tails and what is reconstructed is essentially $\sigma_{PSFtails} = 0.2\text{deg}$.

- The tails effect depends on the value of $R$, on the actual source size and on the energy domain $\rightarrow$ on the sensitivity of the telescope.
Two nearby sources

- 2 Gaussian shaped sources with a Crab-like spectrum placed in the same FoV:
  1\textsuperscript{st} source $\rightarrow$ point-like
  2\textsuperscript{nd} source $\rightarrow$ point-like, extended (0.2\,deg)

- The gamma photons emitted by the 2\textsuperscript{nd} object represent an extra source of background in addition to the CR noise: $N_B = N_{CR} + N_\gamma$
Two nearby sources

- the fake emission from the tails of the PSF works as an extra source of noise, in addition to the photons from the second source and to the CR background.

- the minimum distance needed to limit the background to the pure CR component is larger than in case of Gaussian PSF and it depends on the second source size.

- in case of tails the contamination from a close point-like gamma emitter behaves like a fake object having size $\sigma_{\text{src2}} = \sigma_{\text{PSF tails}} = 0.2$ deg.
Detection Rates

- the background regimes depend on the 1st source strength, on the 2nd source strength and on the distance.

- Point-like 2nd source at 0.3deg does not affect the target detection, only CR.

- in case of extended 2nd source a distance larger than 0.3deg is needed in order to deal with pure CR background.
Detection Rates

Point-like 2\textsuperscript{nd} source

\begin{itemize}
  \item the additional background from the tails makes the realization of the background free regime more challenging; a 1\textsuperscript{st} source as bright as 10\% Crab is needed to avoid background dominated regime
  \item the effect of the 2\textsuperscript{nd} source on the total background is not really dependent on its actual size (2\textsuperscript{nd} point-like object at 0.3\textdegree\ does affect the 1\textsuperscript{st} source detection)
\end{itemize}
Sensitivity curves for Gaussian PSF

**Hypothesis:**
- \( \sigma \geq 5 \)
- \( N_\gamma \geq 10 \)
- \( N_\gamma / N_{bkg} \geq 0.05 \)
- obs. Time = 50 h
- 2\(^{nd}\) source in the FoV of a point-like object @ 10\% Crab
- Gaussian PSF
Sensitivity curves for Gaussian PSF

- the smaller the distance the worse the sensitivity of the telescope
- point-like 2\textsuperscript{nd} source $\Rightarrow$ @ $\geq 0.3$\,deg pure CR background
  @ 0.1\,deg sensitivity differs by a factor $> 10$ from CTA expectations
- extended 2\textsuperscript{nd} source $\Rightarrow$ @ 0.5\,deg the nearby object still contributes as an additional background source resulting in a worse sensitivity than foreseen by CTA
Sensitivity curves for non-Gaussian PSF

Hypothesis:

- obs. Time = 50 h
- 2nd source in the FoV of a point-like object @ 10% Crab
- non-Gaussian PSF with $\sigma_{PSFtails} = 0.2\text{deg}$ and $R=0.3$

$\sigma \geq 5$

$N_\gamma \geq 10$

$N_\gamma / N_{bkg} \geq 0.05$
Sensitivity curves for non-Gaussian PSF

- @ ≥0.3deg the sensitivity deviates from CTA expectations regardless the size of the 2nd source
- the non-Gaussian shape of the PSF makes the distributions for different sizes of the 2nd source to be similar due to the fake emission from the tails which behave like an artificial object having size $\sigma_{PSF\text{tails}}=0.2\text{deg}$
- the sensitivity might get worse by a factor >10 due to the combination of fake emission from the tails and real emission from the 2nd source
Summary

- In the framework of the Galactic Plane region, which is dense with HE sources, the detection of multiple sources in the same FoV is very likely to happen.

- The presence of a nearby source creates an additional and unavoidable background which might dominate over the CR noise.

- The sensitivity to observe sources as weak as those foreseen by CTA might get worse and the expected factor 10 improvement might not be fulfilled in such scenarios.

- The fake emission from the tails of a non-Gaussian PSF (for which we gave one possible representation) might add extra noise which might compromise proper morphological studies and make the observation of weak sources even more challenging.
Thank you!

Lucia Ambrogi
Gran Sasso Science Institute, INFN L’Aquila
Turin - TAUP15 - 10th September