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

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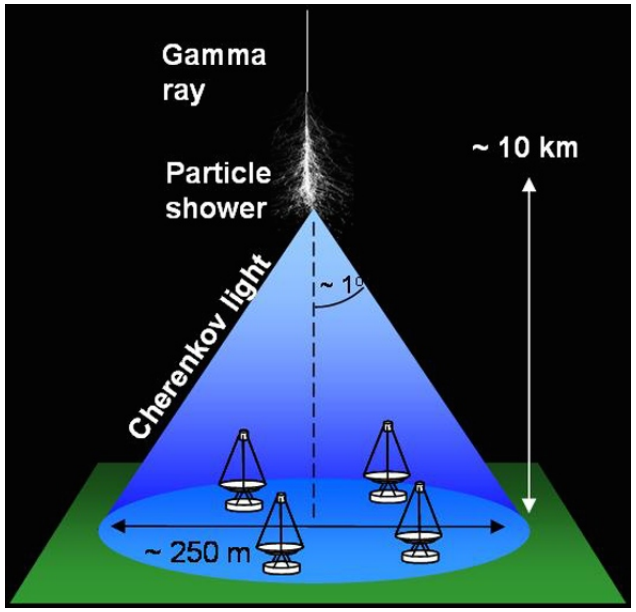
Outline:

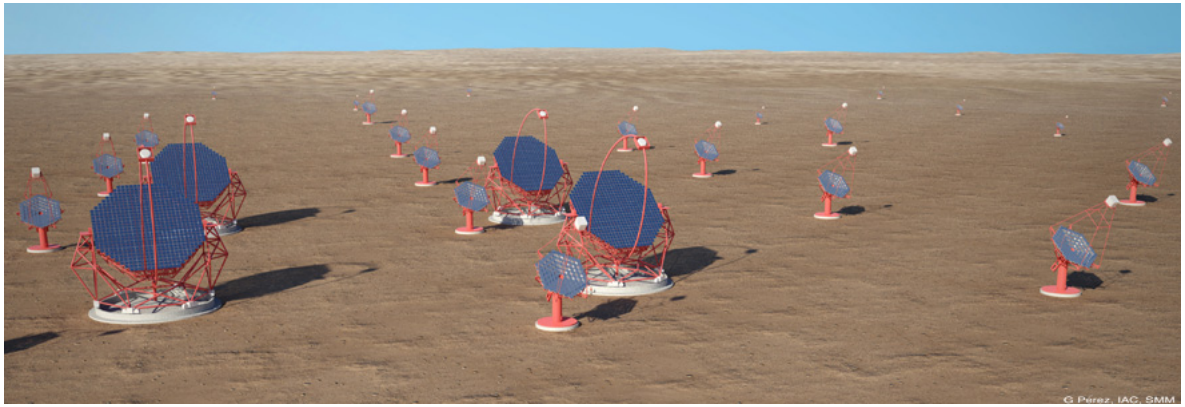
- Introduction
- Detector response for a CTA-like instrument
  - Effective Area
  - Background rate
  - Angular resolution: Gaussian and non-Gaussian PSF
- Morphological studies of isolated sources
- Sensitivity studies of multiple sources in the same FoV
- Summary

Ground based Gamma-ray Astronomy



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

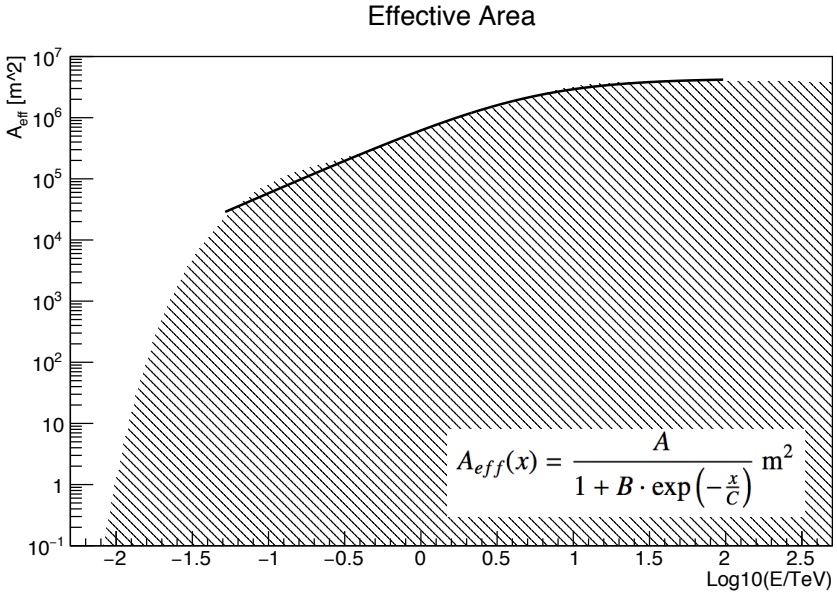
https://portal.cta-observatory.org/Pages/CTA-Performance.aspx

→ parameterization with analytical formula

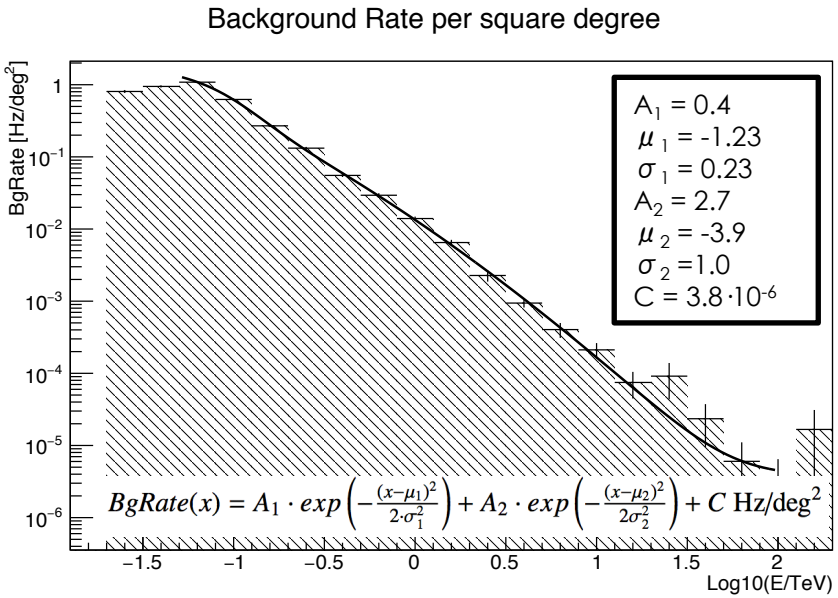
Detector response

CTA-like instrument recipe:

- ✓ Effective area
- ✓ Background rate



A = 4.36·10^6 m^2
B = 6
C = 0.4



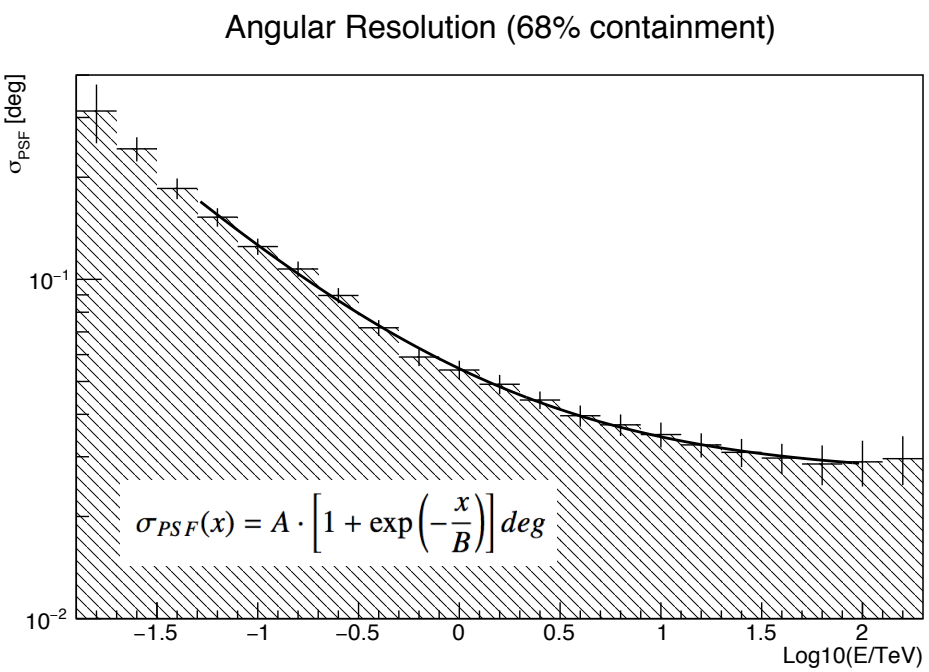
Random sampling from

$$f(N_B \mid \mu, \sigma) = \exp\left(-\frac{(N_B - N_{BgRate})^2}{2\sqrt{N_{BgRate}}^2}\right)$$

Detector response

CTA-like instrument recipe:

- ✓ Effective area
- ✓ Background rate
- ✓ Angular resolution



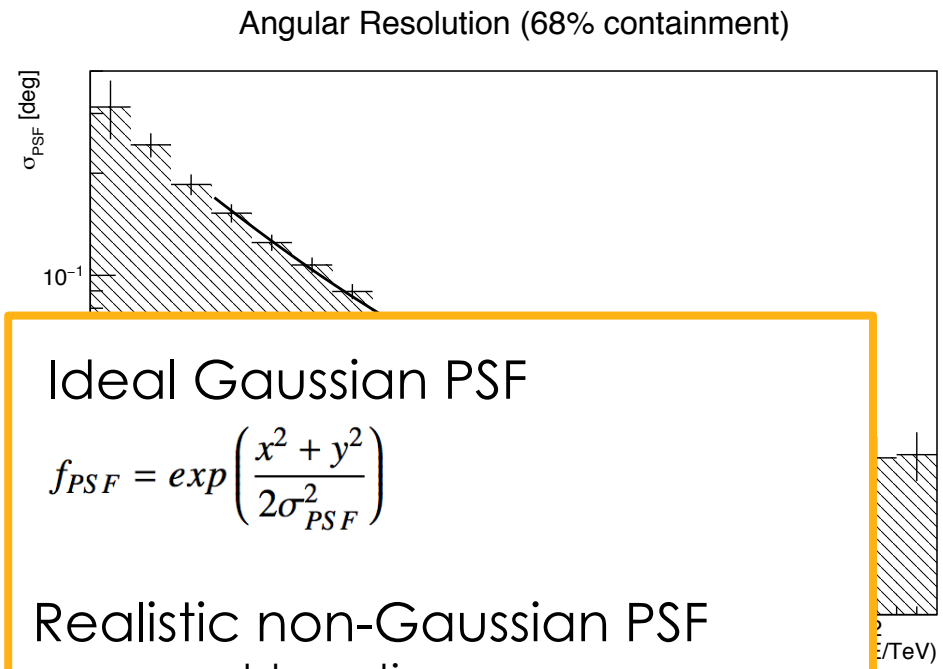
A= 0.028 deg
B= 0.8

Ideal Gaussian PSF

$$f_{PSF} = exp\left(\frac{x^2 + y^2}{2\sigma^2_{PSF}}\right)$$

Detector response

CTA-like instrument recipe:



Ideal Gaussian PSF

$$f_{PSF} = exp\left(\frac{x^2+y^2}{2\sigma^2_{PSF}}\right)$$

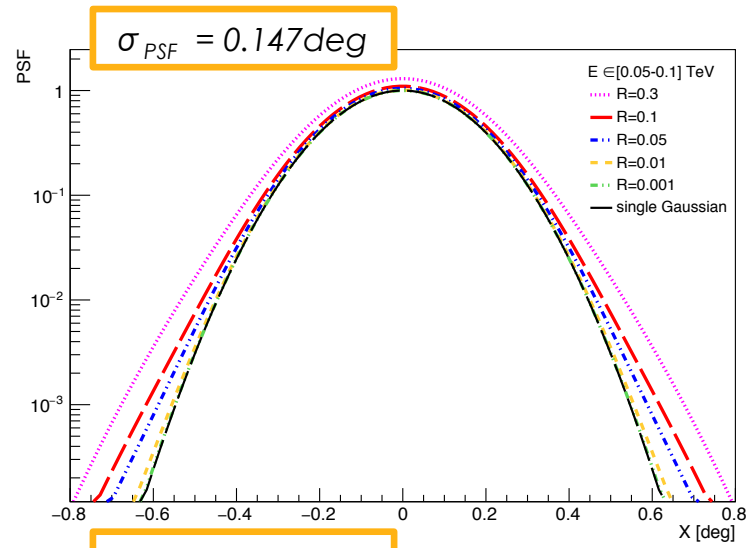
Realistic non-Gaussian PSF

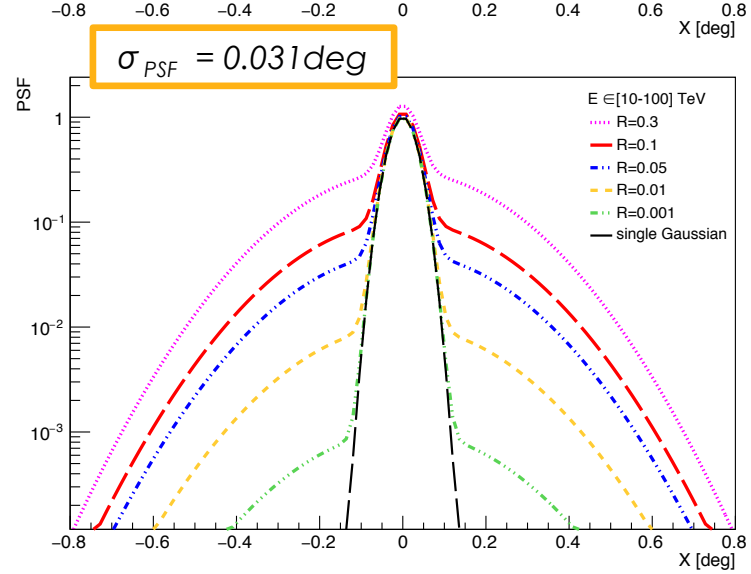
a reasonable option:

Astron.Astrophys. 457 (2006) 899-915

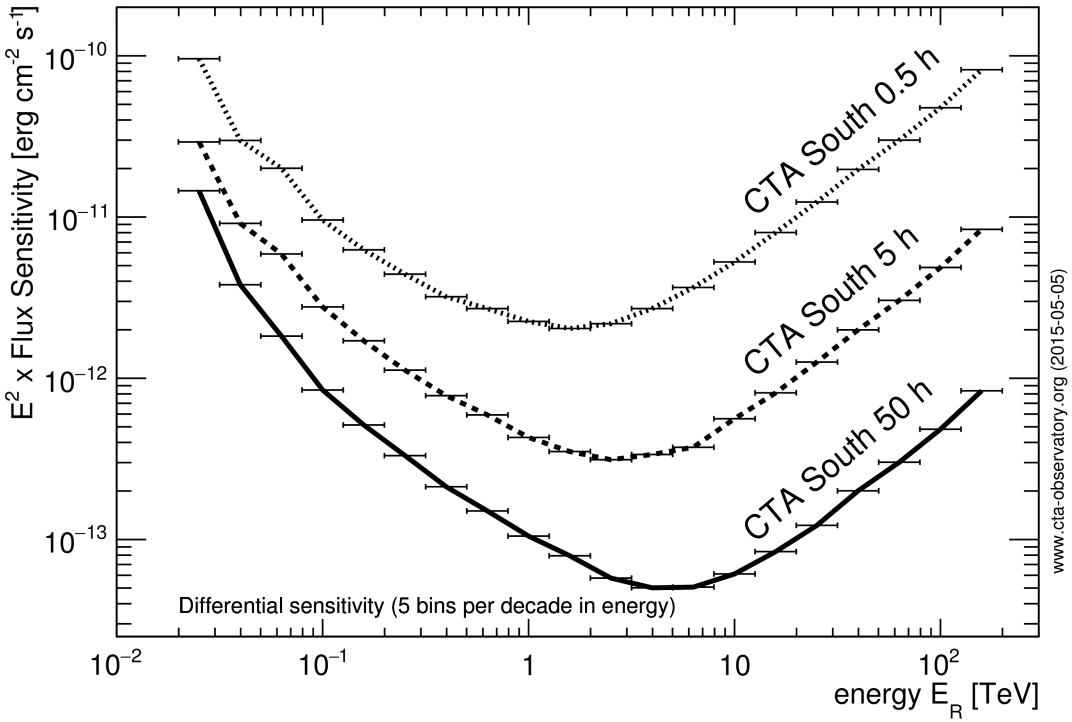
$$f_{PSFtails} = exp\left(\frac{x^2+y^2}{2\sigma^2_{PSF}}\right) + R \cdot exp\left(\frac{x^2+y^2}{2\sigma^2_{PSFtails}}\right)$$

$$\sigma_{PSFtails} = 0.2\,\mathrm{deg}$$





Expected CTA sensitivity



$\sigma \geq 5$

$N_\gamma \geq 10$

$N_\gamma / N_{bkg} \geq 0.05$

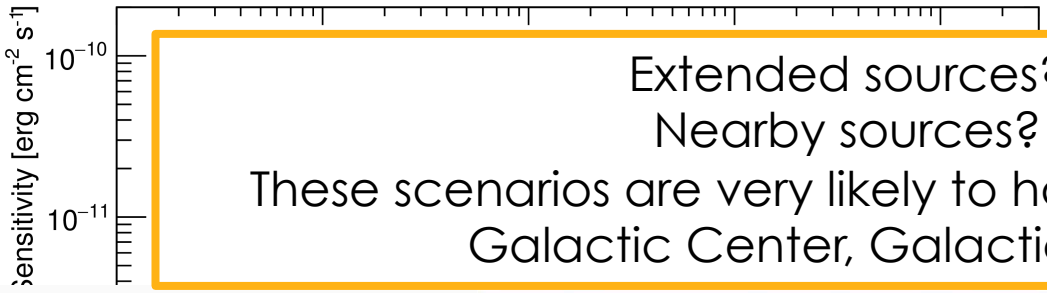
Hypothesis:

- Isolated point-like source
- Gaussian PSF

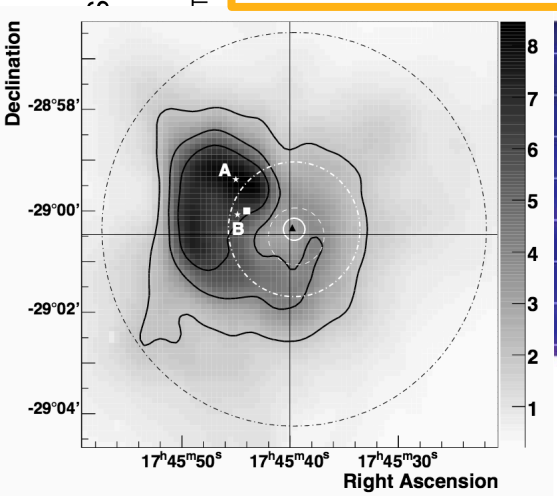
" Improved sensitivity by at least an order of magnitude compared to existing VHE instruments "

B.S. Acharya et al. Astroparticle Physics 43 (2013) 3–18

Expected CTA sensitivity



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



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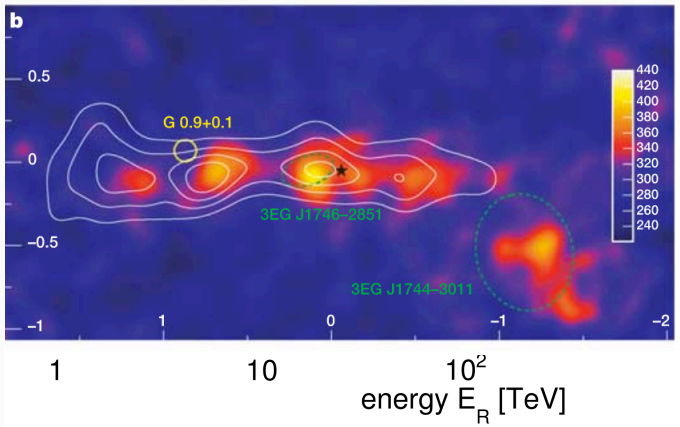

Nature 439 (2006) 695-698

Hypothesis:

- Isolated point-like source
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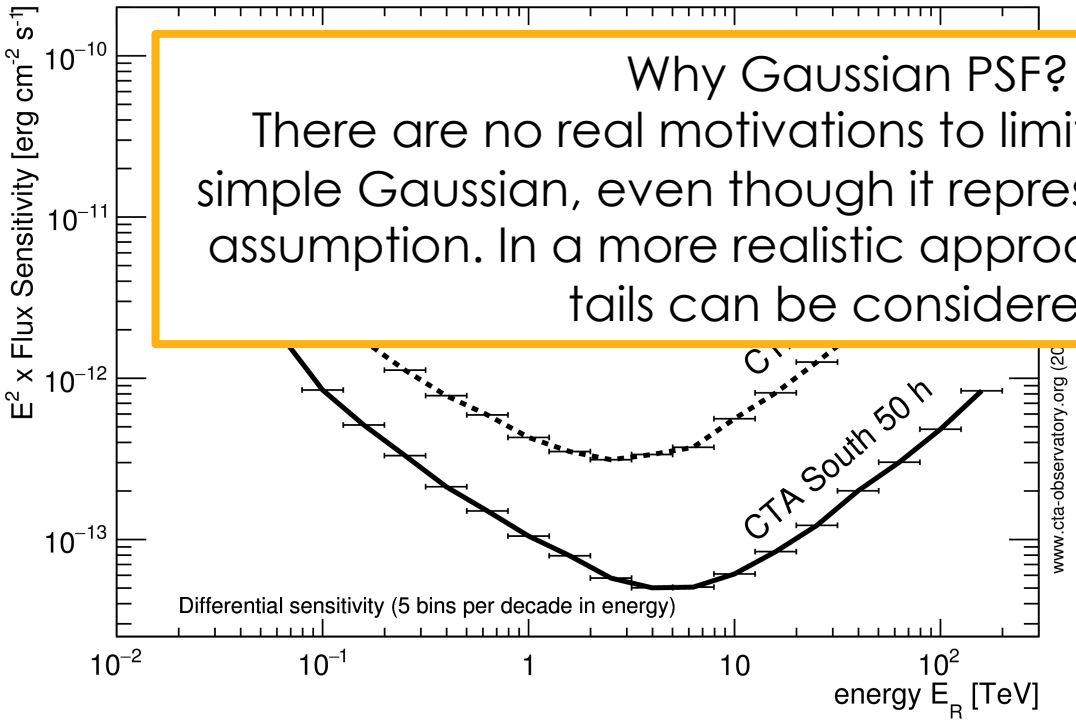
Expected CTA sensitivity



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

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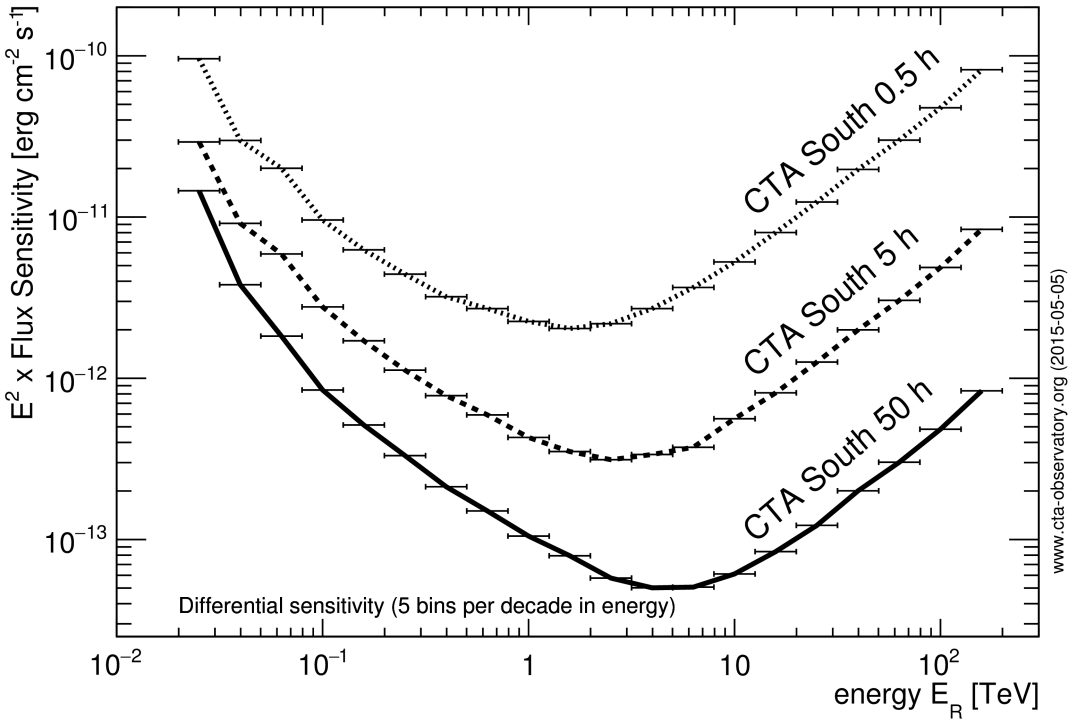
Expected CTA sensitivity



$\sigma \geq 5$

$N_\gamma \geq 10$

$N_\gamma / N_{bkg} \geq 0.05$

Hypothesis:

- Isolated point-like source
- Gaussian PSF

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

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

Isolated source simulation

- Gaussian shape

$$f(x,y) = A \cdot exp\left(-\left(\frac{(x-X_0)^2}{2\sigma_{src}^2}\right) + \left(\frac{(y-Y_0)^2}{2\sigma_{src}^2}\right)\right)$$

$$(X_0, Y_0) = (0,0)\,\mathrm{deg}$$

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

- Crab-like spectrum as measured by HEGRA Astrophys.J. 614 (2004) 897-913

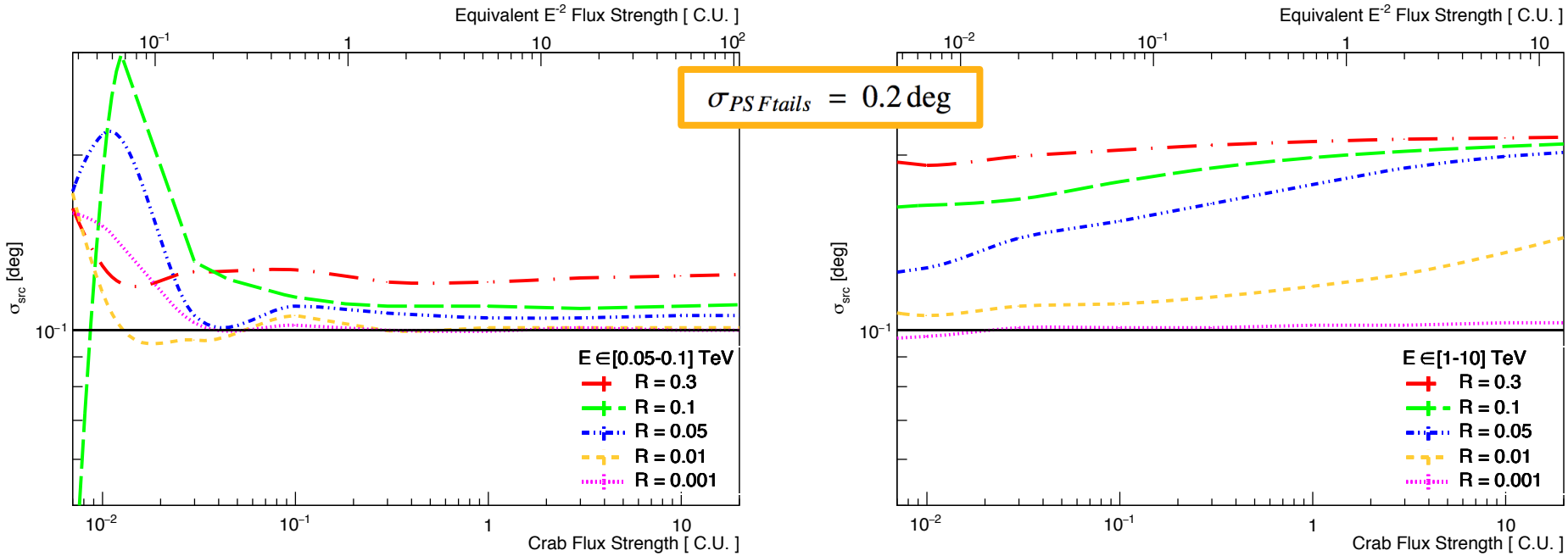
$$\frac{dN}{dE} = n \cdot N_0 \times \left(\frac{E}{1\,TeV}\right)^{-\alpha}$$

$$\alpha = 2.62$$

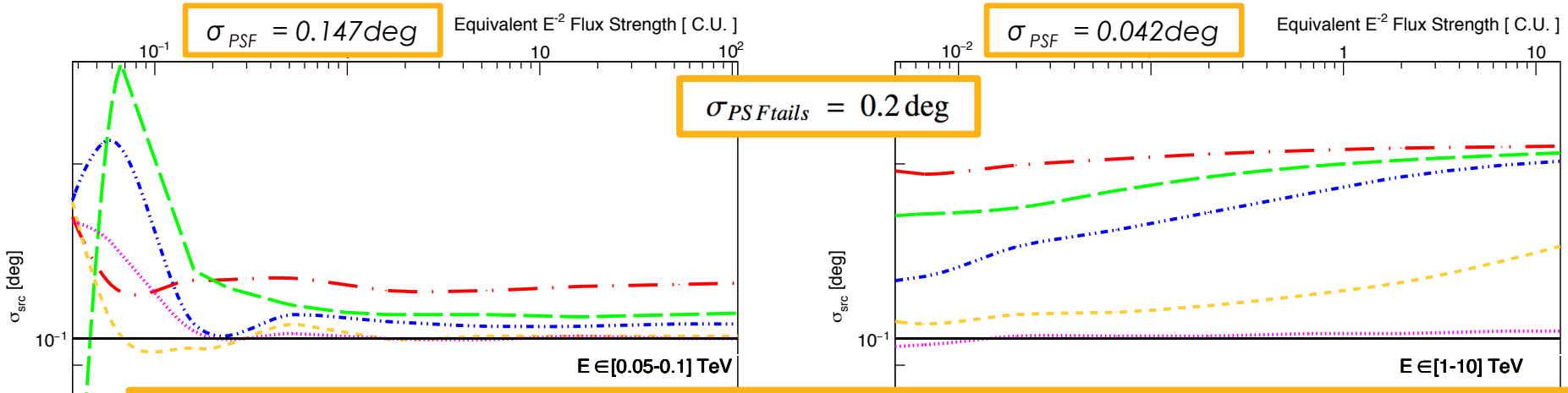
$$N_0 = 2.83 \cdot 10^{-11}\,\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$1\ \mathrm{C.U.} = 2.83 \cdot 10^{-11} \times E^{-2.62}\,\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Reconstruction of morphological parameters for non-Gaussian PSF response



Reconstruction of morphological parameters for non-Gaussian PSF response



- at LE $\sigma_{PSF} \approx \sigma_{PSFtails}$ → 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.

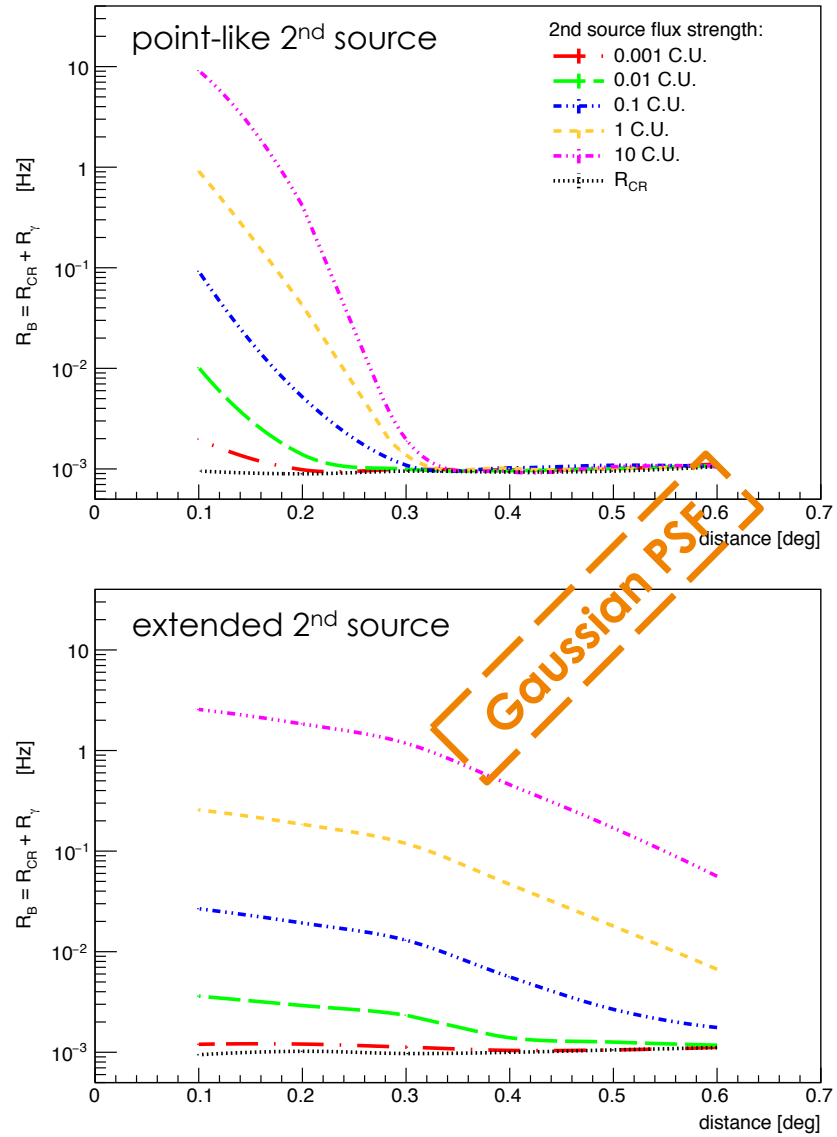
- at HE $\sigma_{PSF} < \sigma_{PSFtails}$ → the reconstruction of σ_{src} is hardly damaged by the tails and what is reconstructed is essentially $\sigma_{PSFtails}$ = 0.2deg.

- The tails effect depends on the value of *R*, on the actual source size and on the energy domain → on the sensitivity of the telescope.

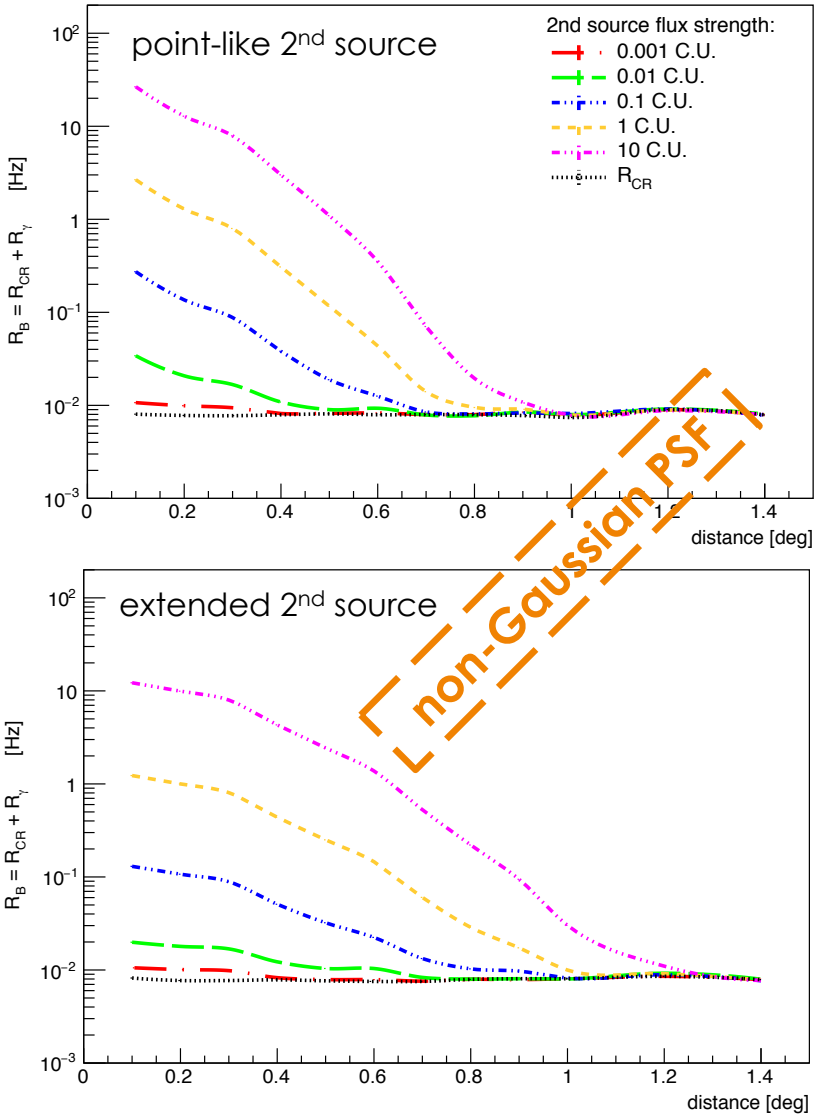
Two nearby sources

- 2 Gaussian shaped sources with a Crab-like spectrum placed in the same FoV:
  1st source → point-like
  2nd source → point-like, extended (0.2deg)

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



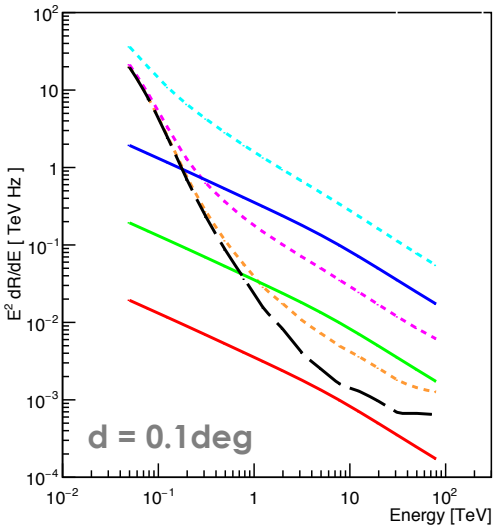
Two nearby sources

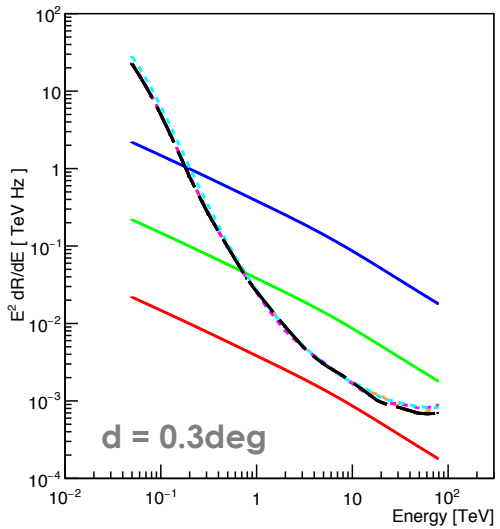


- the fake emission from the tails of the PSF works as an extra source of noise, in addition to the photons from the second source and to the CR background
- the minimum distance needed to limit the background to the pure CR component is larger than in case of Gaussian PSF and it depends on the second source size
- in case of tails the contamination from a close point-like gamma emitter behaves like a fake object having size $\sigma_{src2} = \sigma_{PSFtails} = 0.2$ deg.

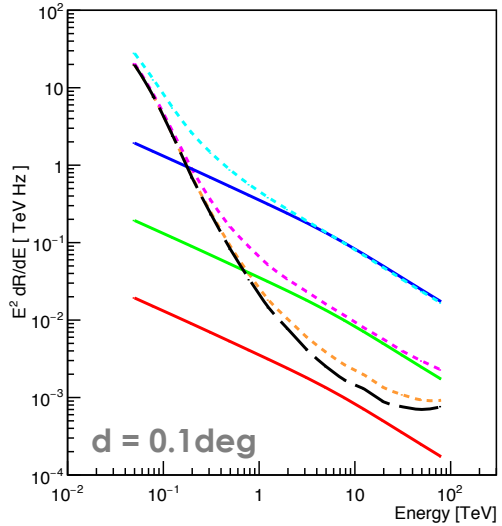
Detection Rates

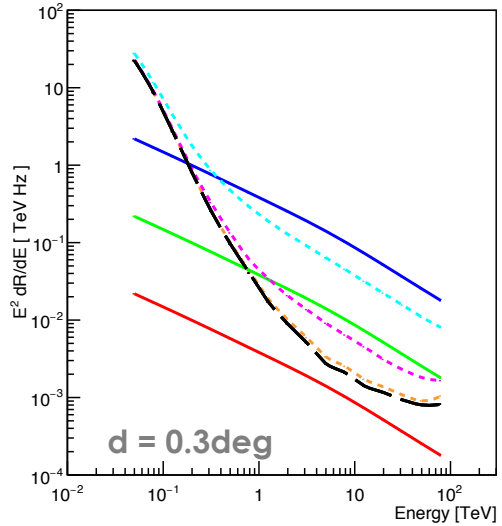
point-like 2nd source





extended 2nd source





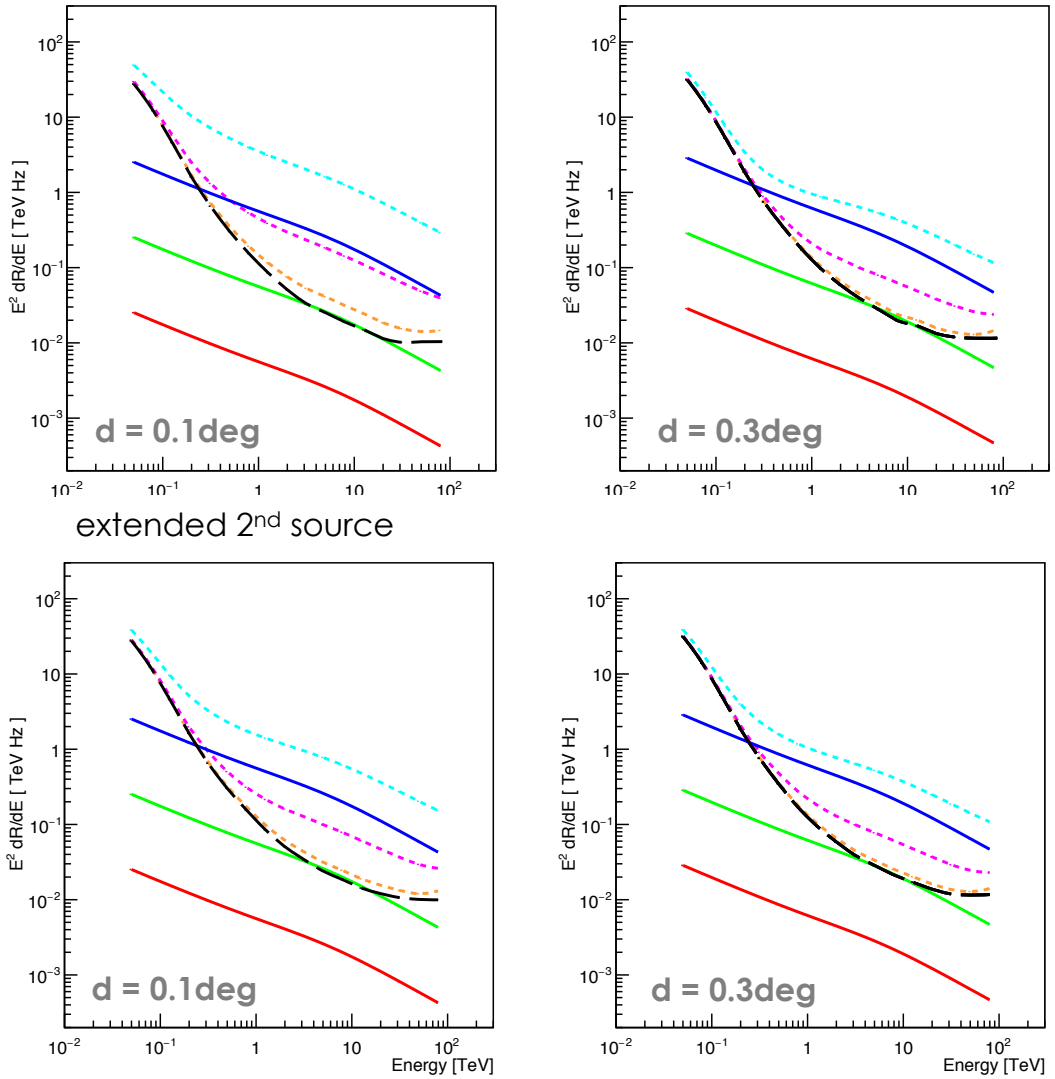
Gaussian PSF

- S — 1st src flux strength 0.001 C.U.
- B_{tot} — 2nd src flux strength 0.01 C.U.
- S — 1st src flux strength 0.01 C.U.
- B_{tot} — 2nd src flux strength 0.1 C.U.
- S — 1st src flux strength 0.1 C.U.
- B_{tot} — 2nd src flux strength 1 C.U.
- B_{CR}

- 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 2nd source



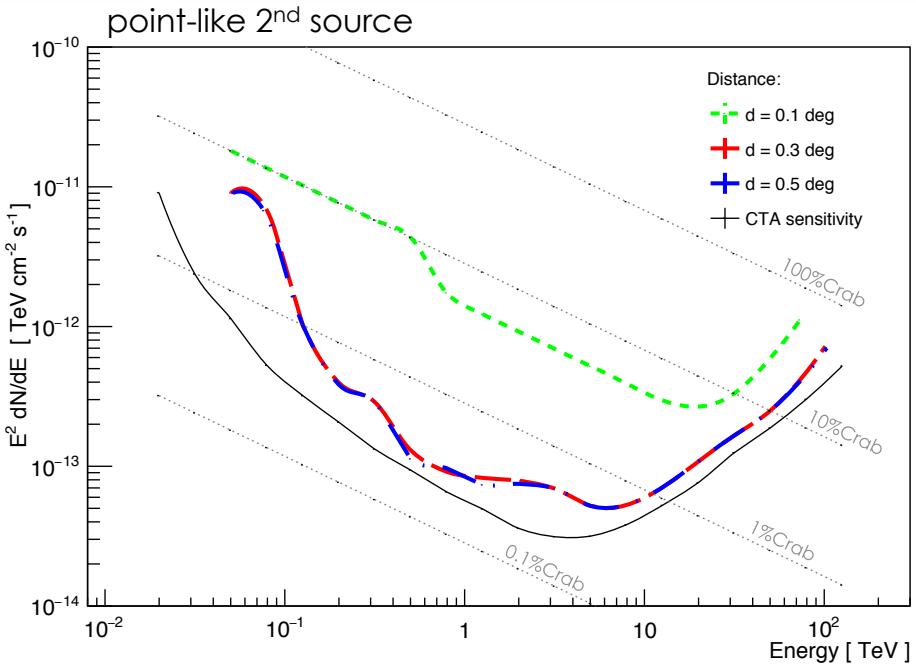
extended 2nd source

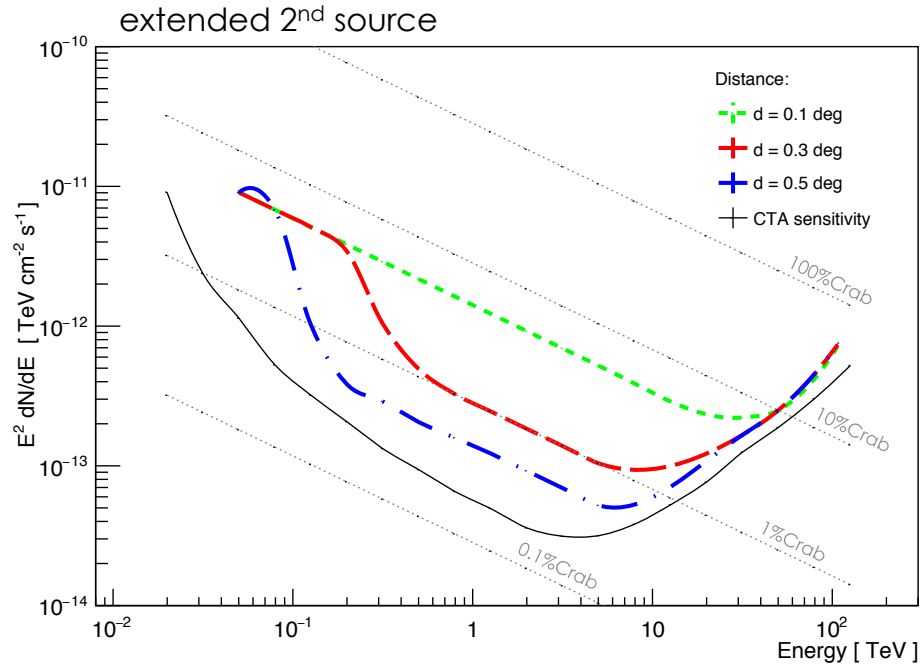
non-Gaussian PSF

S	1st src flux strength 0.001 C.U.
B_{tot}	2nd src flux strength 0.01 C.U.
S	1st src flux strength 0.01 C.U.
B_{tot}	2nd src flux strength 0.1 C.U.
S	1st src flux strength 0.1 C.U.
B_{tot}	2nd src flux strength 1 C.U.
B_{CR}	

- the additional background from the tails makes the realization of the background free regime more challenging; a 1st source as bright as 10%Crab is needed to avoid background dominated regime
- the effect of the 2nd source on the total background is not really dependent on its actual size (2nd point-like object at 0.3deg *does* affect the 1st source detection)

Sensitivity curves for Gaussian PSF





$\sigma \geq 5$

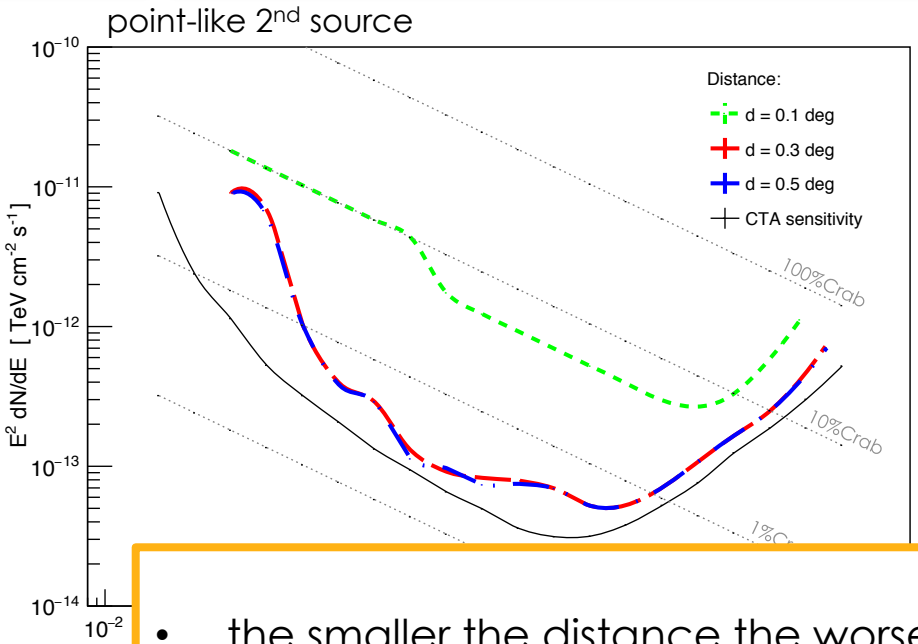
$N_\gamma \geq 10$

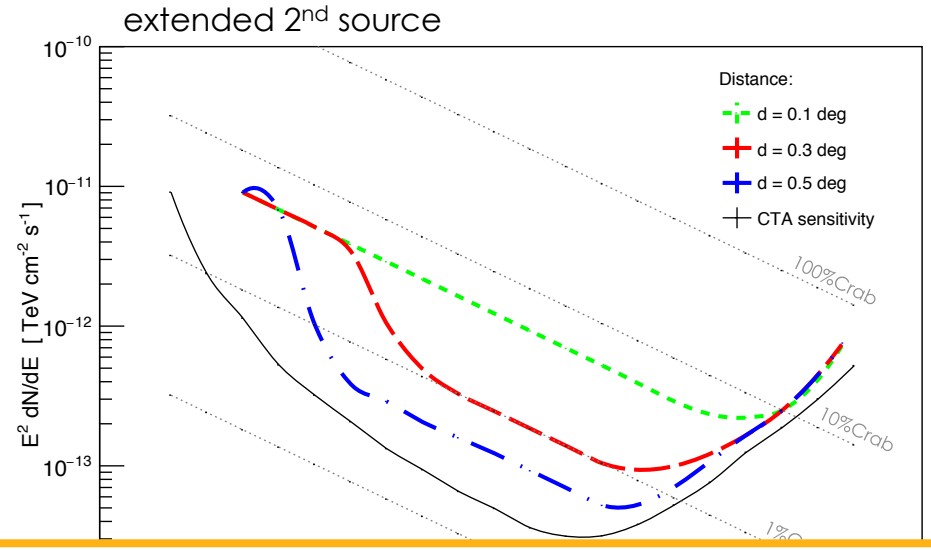
$N_\gamma / N_{bkg} \geq 0.05$

Hypothesis:

- obs. Time = 50 h
- 2nd source in the FoV of a point-like object @ 10%Crab
- Gaussian PSF

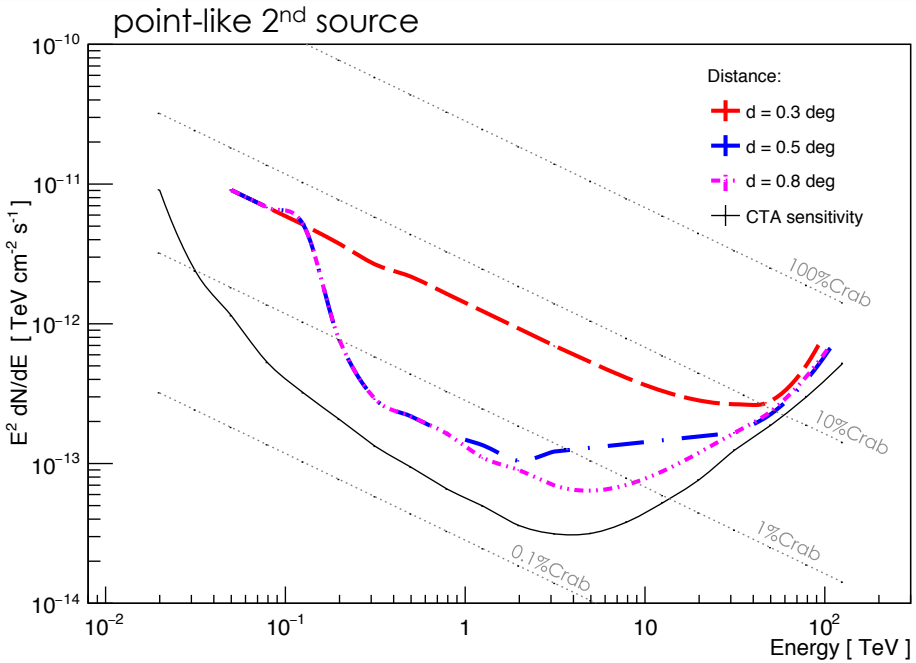
Sensitivity curves for Gaussian PSF

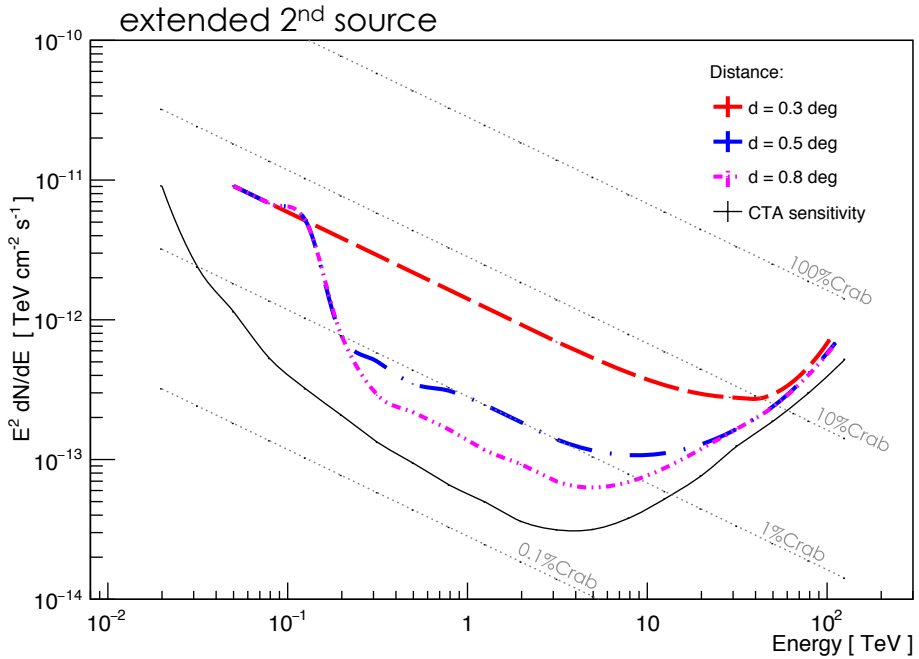




- the smaller the distance the worse the sensitivity of the telescope
- point-like 2nd source → @ ≥0.3deg pure CR background
  @ 0.1deg sensitivity differs by a factor >10 from CTA expectations
- extended 2nd source → @0.5deg the nearby object still contributes as an additional background source resulting in a worse sensitivity than foreseen by CTA

Sensitivity curves for non-Gaussian PSF





$\sigma \geq 5$

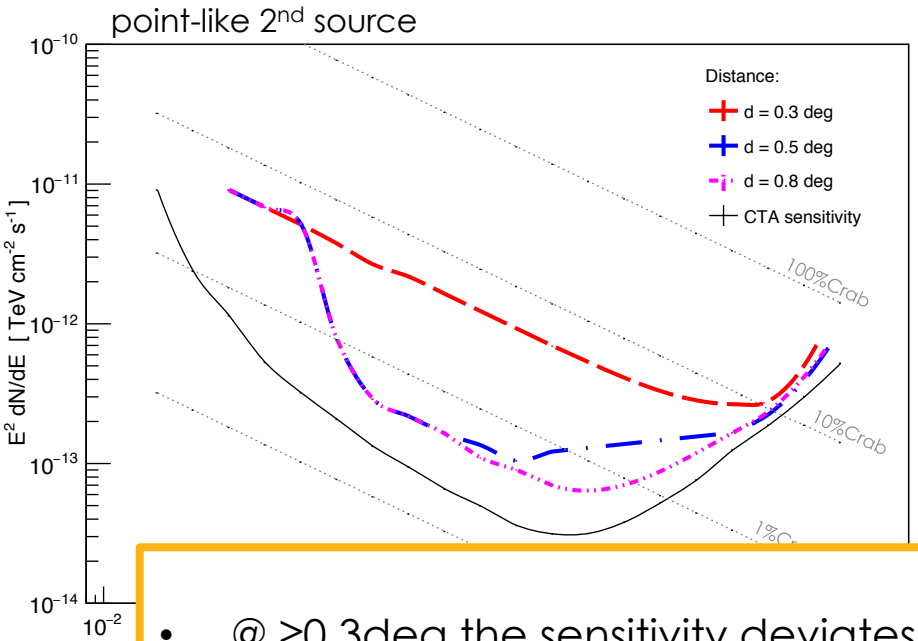
$N_\gamma \geq 10$

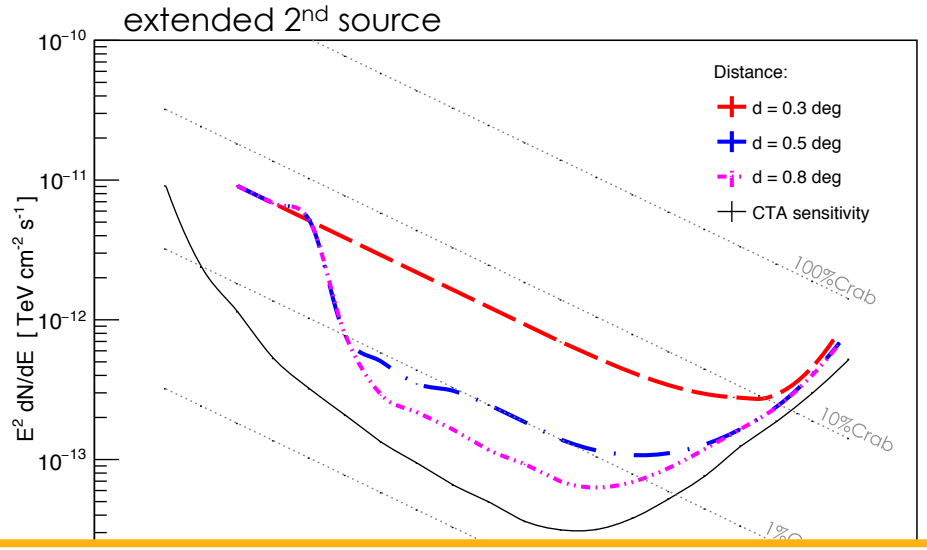
$N_\gamma / N_{bkg} \geq 0.05$

Hypothesis:

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

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 $\sigma_{PSFtails}$=0.2deg
- 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!

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Turin - TAUP15 - 10th September