

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

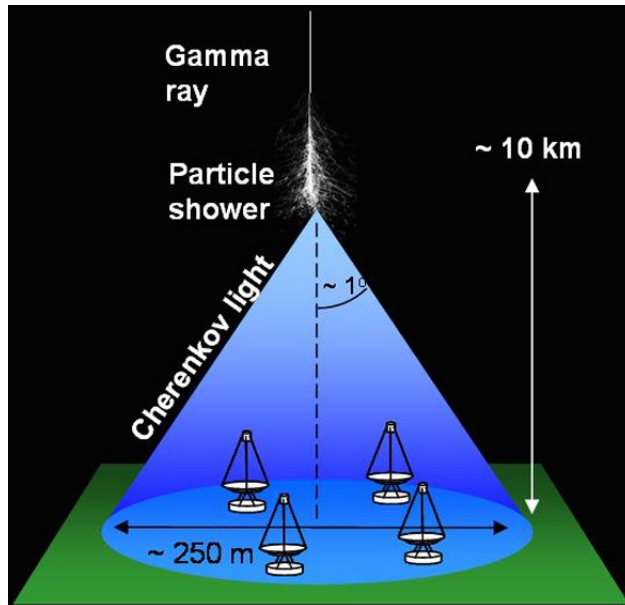


Lucia Ambrogi

Gran Sasso Science Institute, INFN L'Aquila

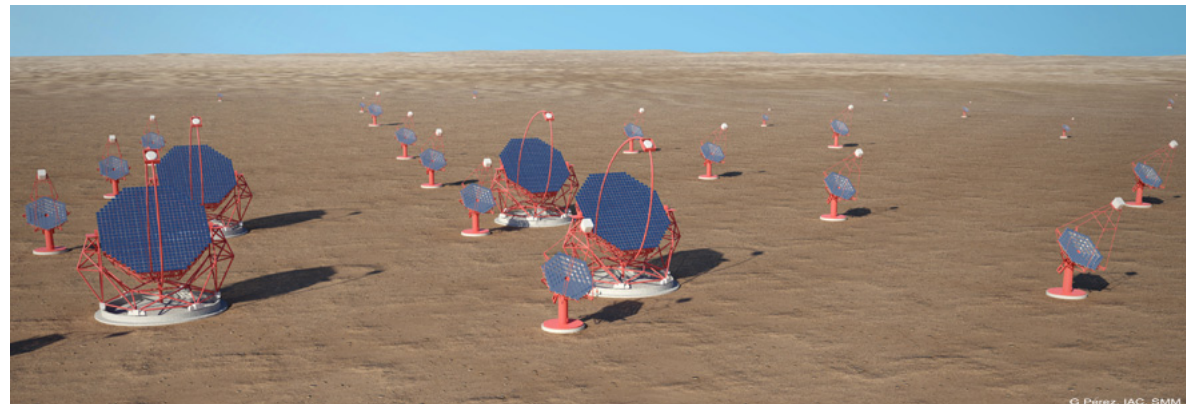
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Ground based Gamma-ray Astronomy



Next Generation IACT array: **CTA**

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



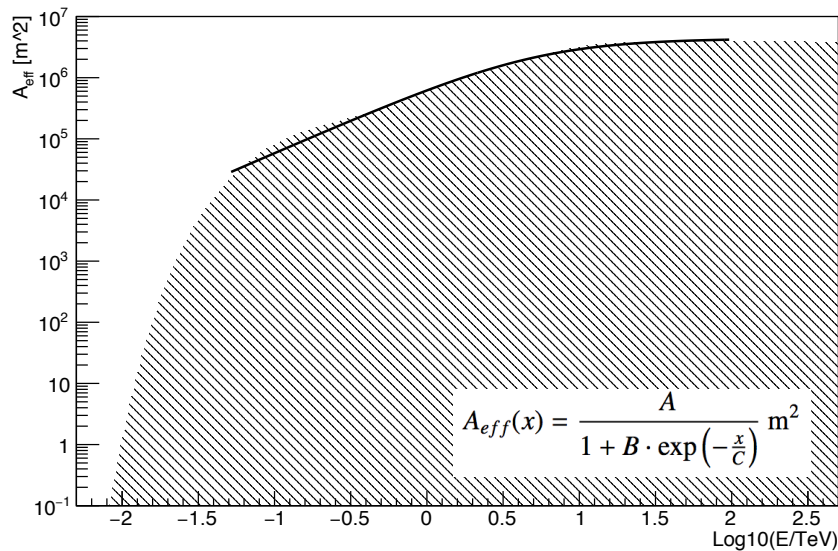
What is the potential of *CTA-like instrument* and its response to different observation modes and different source scenarios?

Detector response

CTA-like instrument recipe:

- ✓ Effective area
- ✓ Background rate

Effective Area



$$A = 4.36 \cdot 10^6 \text{ m}^2$$

$$B = 6$$

$$C = 0.4$$

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

$$A_1 = 0.4$$

$$\mu_1 = -1.23$$

$$\sigma_1 = 0.23$$

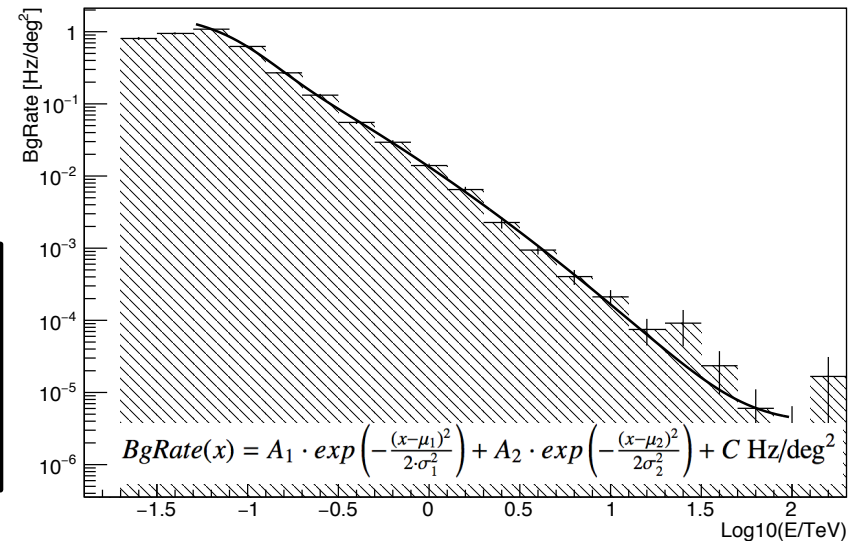
$$A_2 = 2.7$$

$$\mu_2 = -3.9$$

$$\sigma_2 = 1.0$$

$$C = 3.8 \cdot 10^{-6}$$

Background Rate per square degree



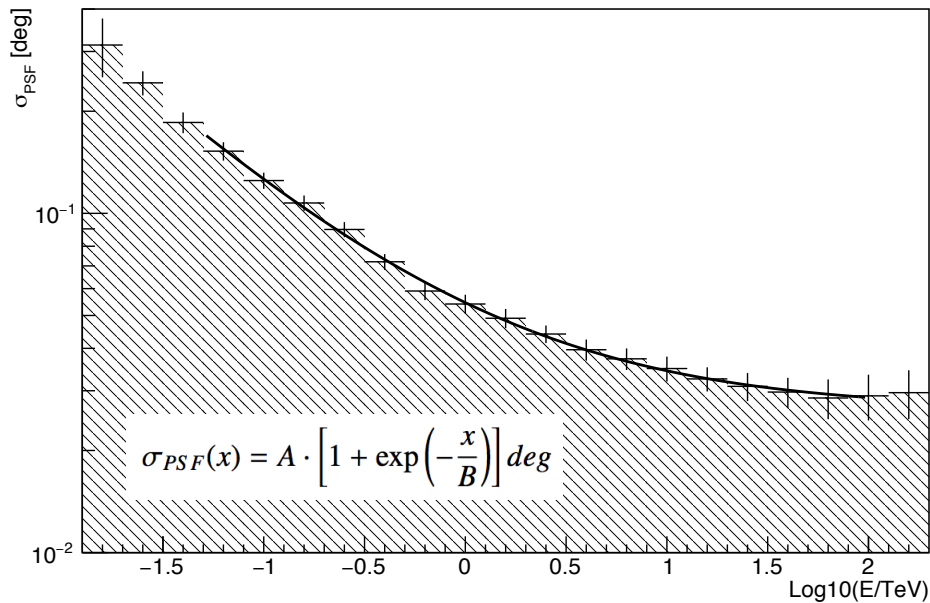
$$BgRate(x) = A_1 \cdot \exp\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right) + A_2 \cdot \exp\left(-\frac{(x-\mu_2)^2}{2\sigma_2^2}\right) + C \text{ Hz/deg}^2$$

Detector response

CTA-like instrument recipe:

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

Angular Resolution (68% containment)



$$A = 0.028 \text{ deg}$$
$$B = 0.8$$

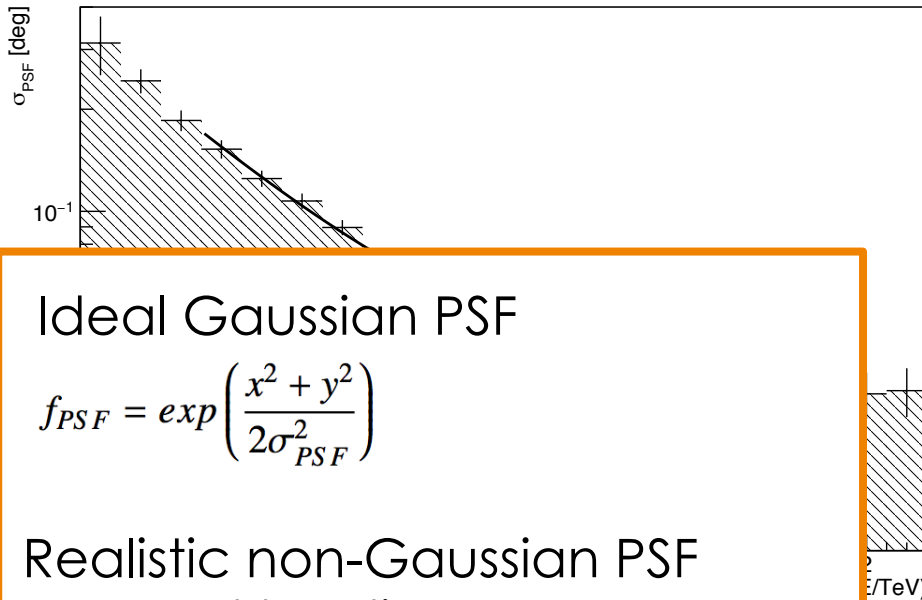
Ideal Gaussian PSF

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

Detector response

CTA-like instrument recipe:

Angular Resolution (68% containment)



Ideal Gaussian PSF

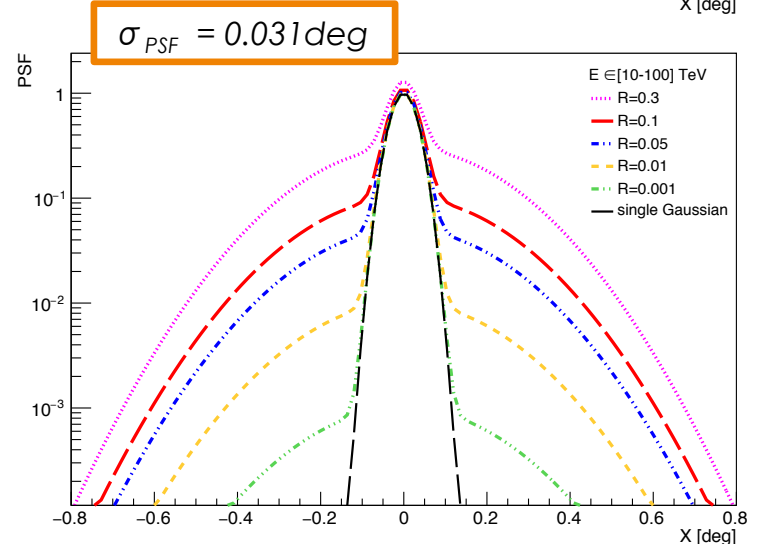
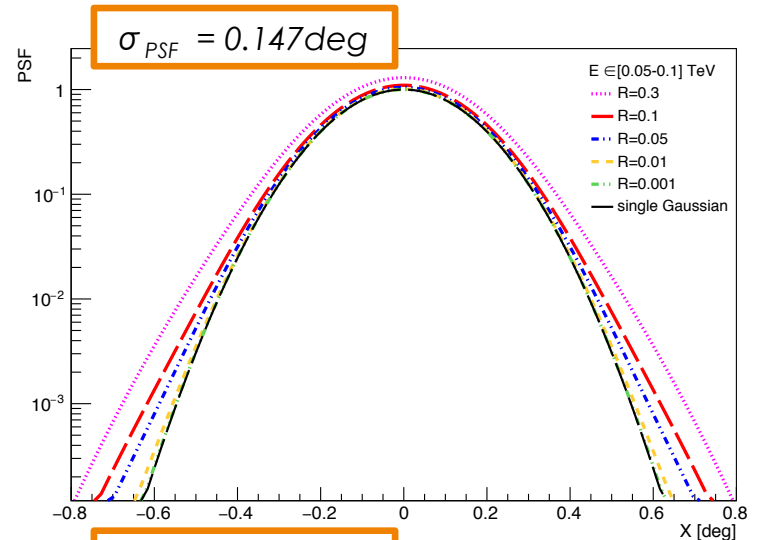
$$f_{PSF} = \exp\left(-\frac{x^2 + y^2}{2\sigma_{PSF}^2}\right)$$

Realistic non-Gaussian PSF
a reasonable option:

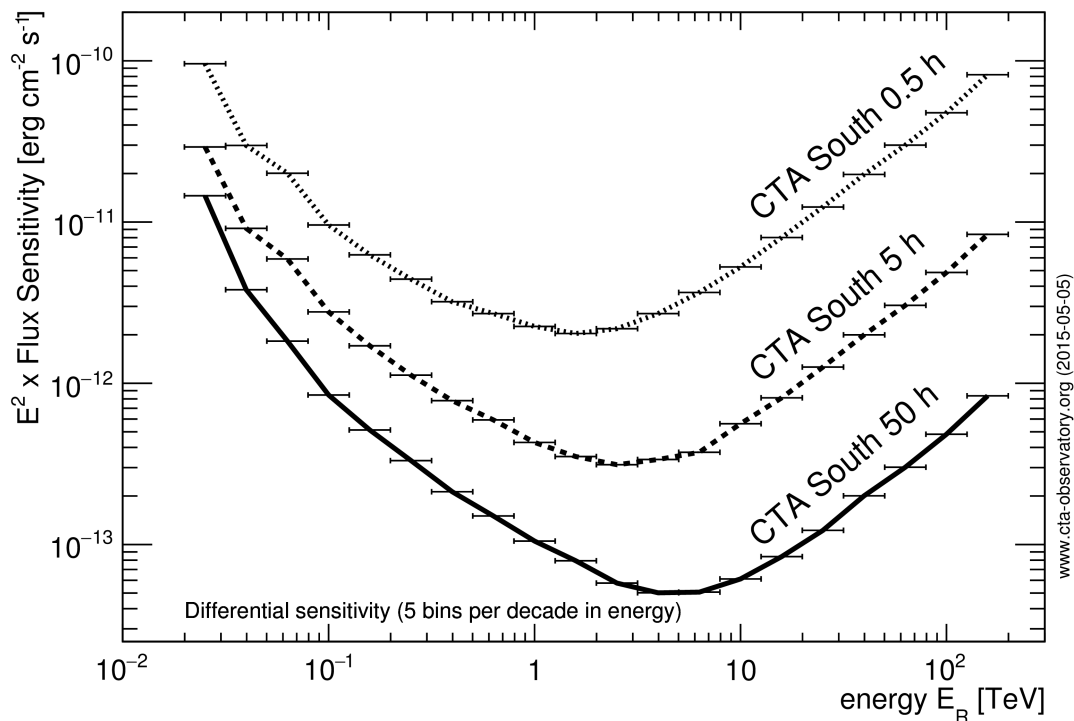
Astron.Astrophys. 457 (2006) 899-915

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

$$\sigma_{PSFtails} = 0.2 \text{ deg}$$



Expected CTA sensitivity



$$\sigma \geq 5$$

$$N_\gamma \geq 10$$

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

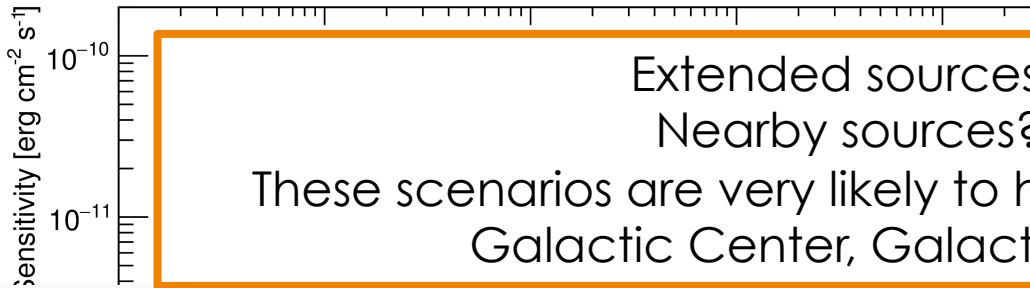
Hypothesis:

- Isolated point-like source
- Gaussian PSF

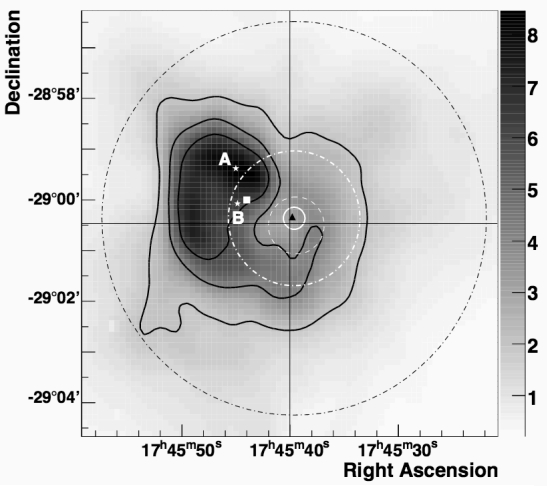
“ Improved sensitivity by at least an order of magnitude compared to existing VHE instruments ”

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

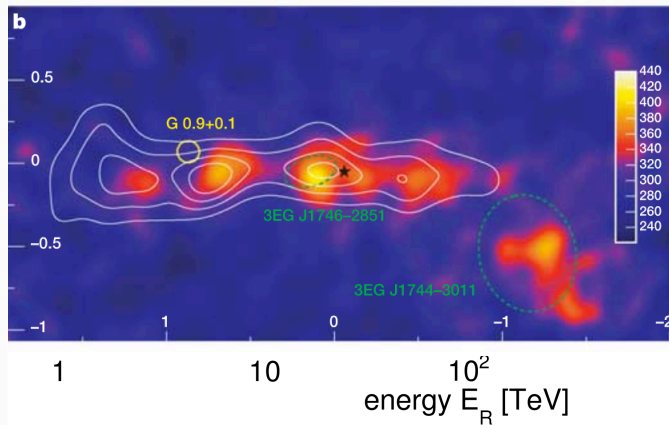
Expected CTA sensitivity



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



Mon.Not.Roy.Astron.Soc. 402 (2010) 1877-1882



Nature 439 (2006) 695-698

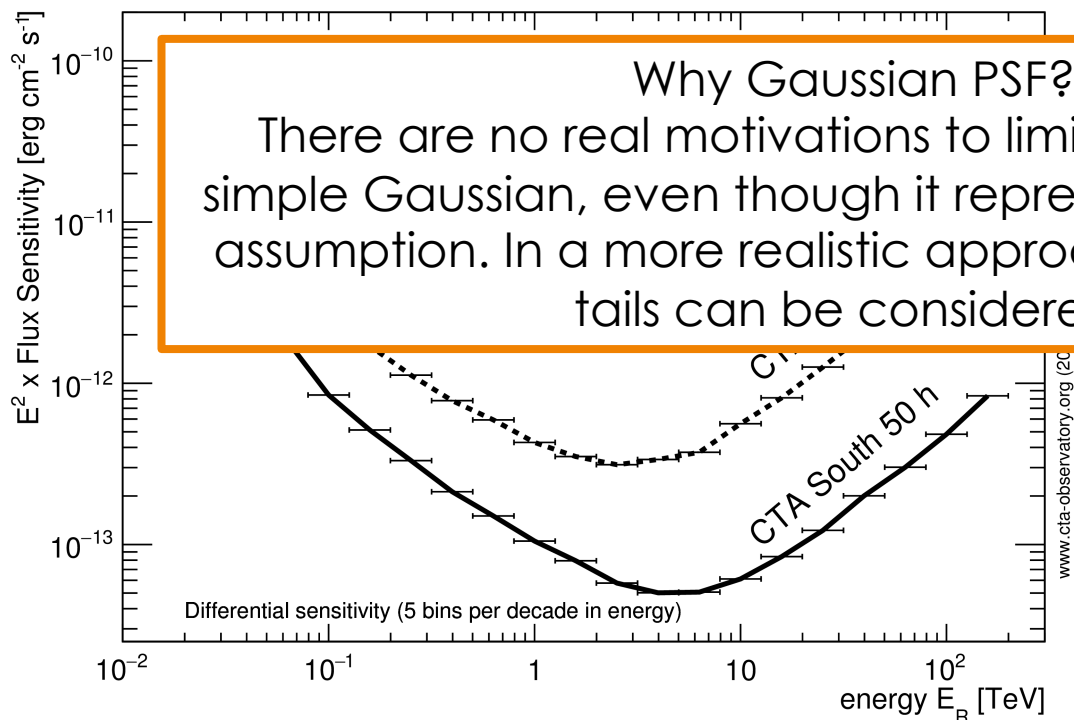
Hypothesis:

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“ 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



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.

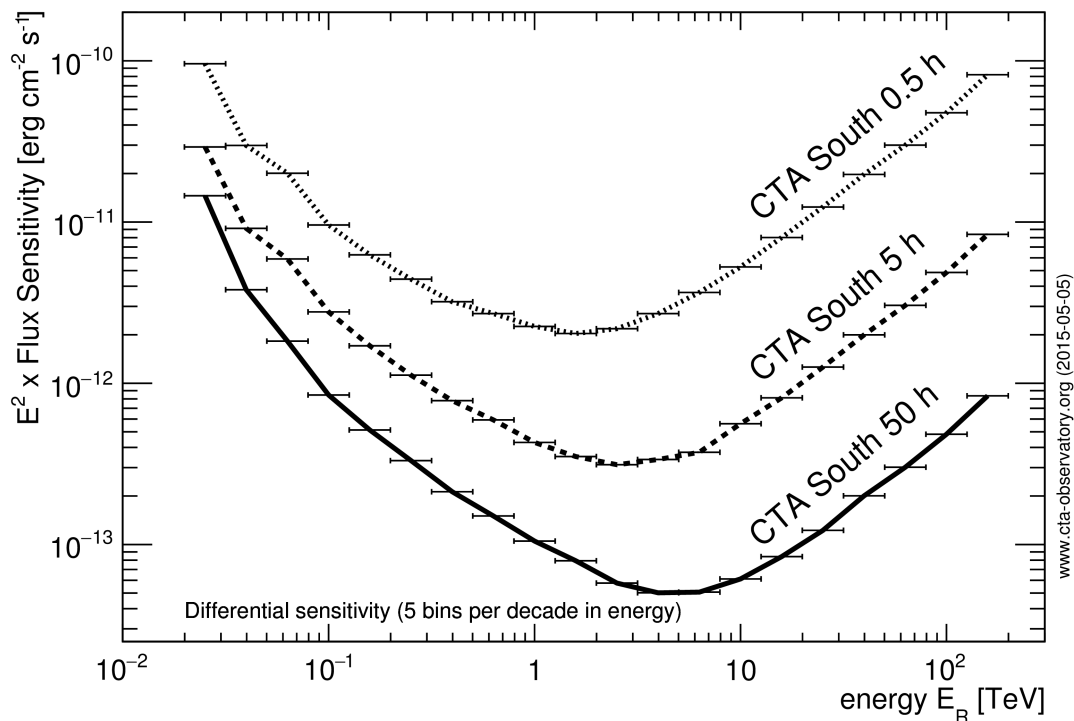
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Expected CTA sensitivity



$$\sigma \geq 5$$

$$N_\gamma \geq 10$$

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

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

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

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

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

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

$$\alpha = 2.62$$

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

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

Reconstruction of morphological parameters for non-Gaussian PSF response



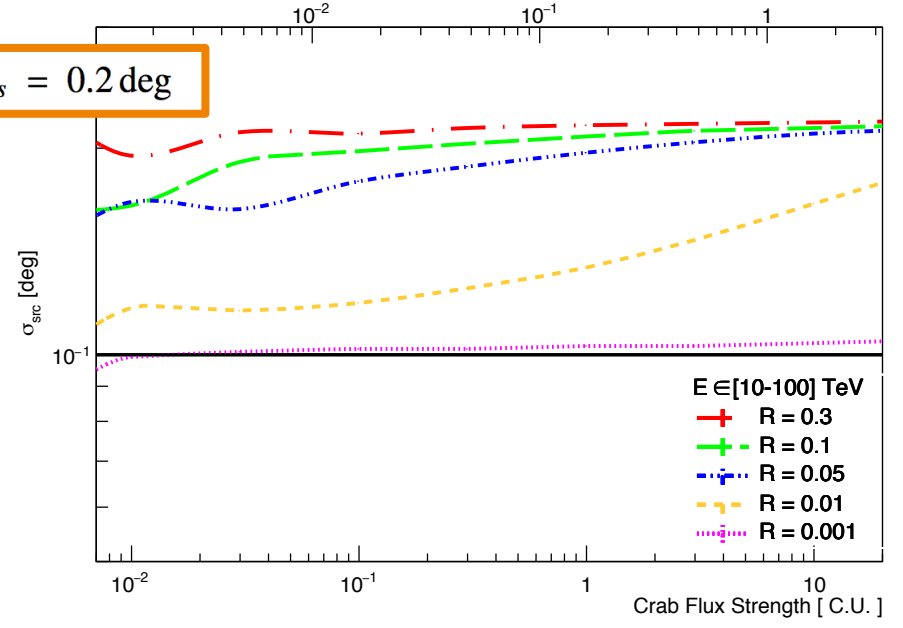
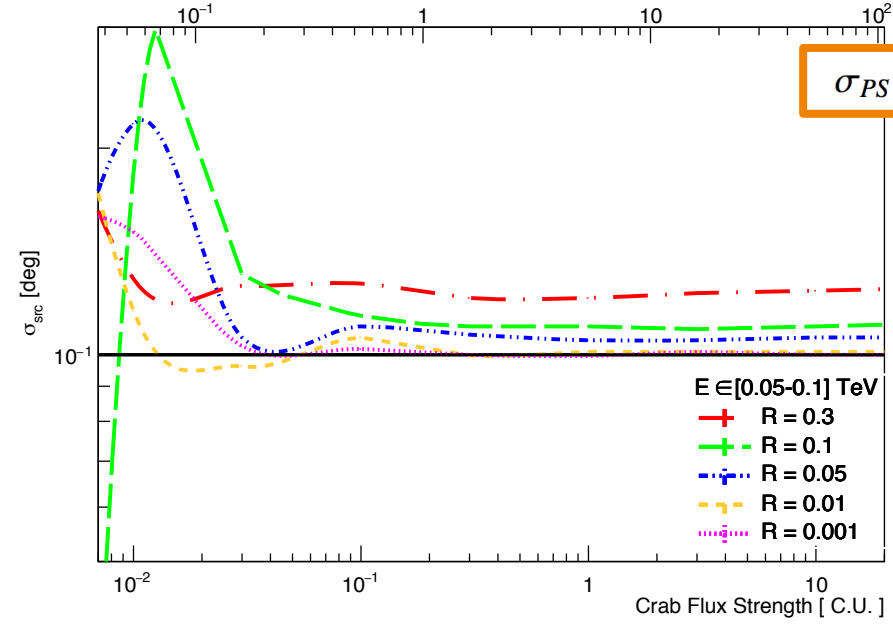
$\sigma_{PSF} = 0.147deg$

Equivalent E^{-2} Flux Strength [C.U.]

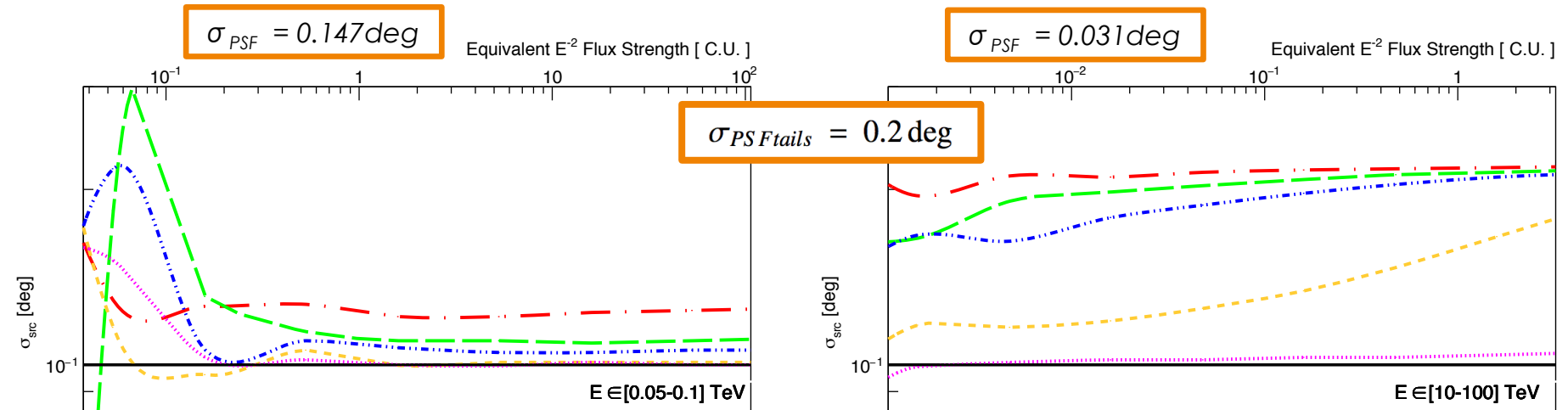
$\sigma_{PSF} = 0.031deg$

Equivalent E^{-2} Flux Strength [C.U.]

$\sigma_{PSFtails} = 0.2deg$



Reconstruction of morphological parameters for non-Gaussian PSF response



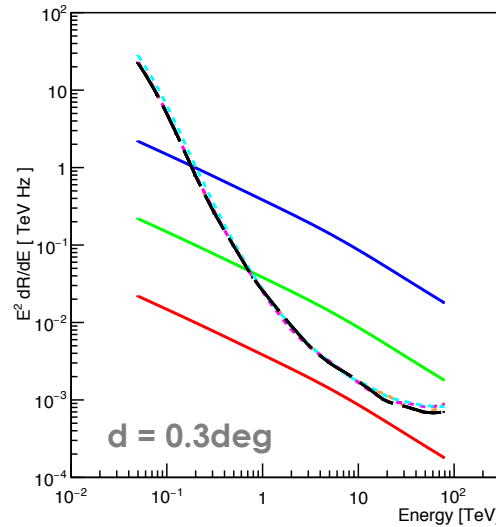
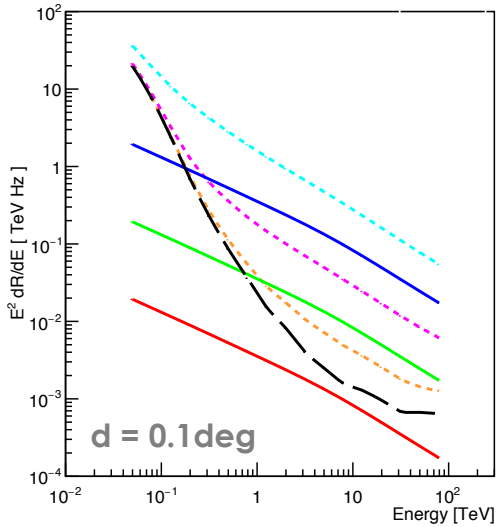
- at LE $\sigma_{PSF} \approx \sigma_{PSFtails} \rightarrow$ for small values of R the source size can be properly reconstructed. For larger values of R the estimation of the source size starts to be inaccurate.
- at HE $\sigma_{PSF} < \sigma_{PSFtails} \rightarrow$ the reconstruction of σ_{src} is hardly 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:
 - 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: $N_B = N_{CR} + N_Y$

Detection Rates for Gaussian PSF

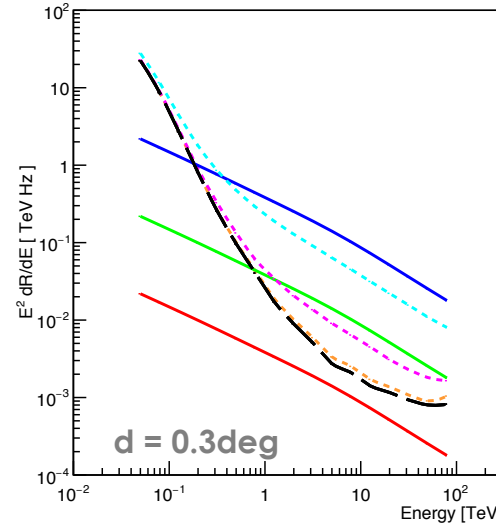
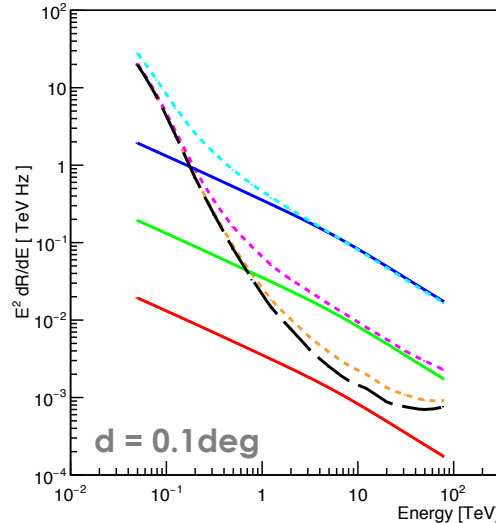
point-like 2nd source



- 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}

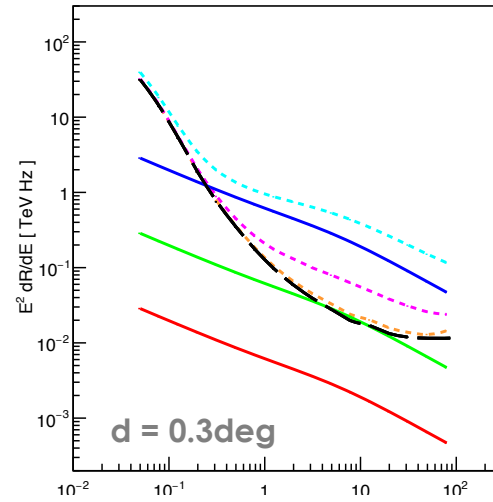
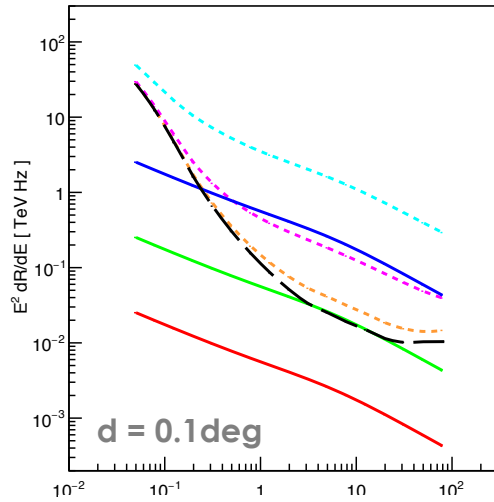
- the background regimes depend on the 1st source strength, on the 2nd source strength and on the distance.
- Point-like 2nd source at 0.3deg does not affect the target detection, only CR.
- in case of extended 2nd source a distance larger than 0.3deg is needed in order to deal with pure CR background.

extended 2nd source



Detection Rates for non-Gaussian PSF

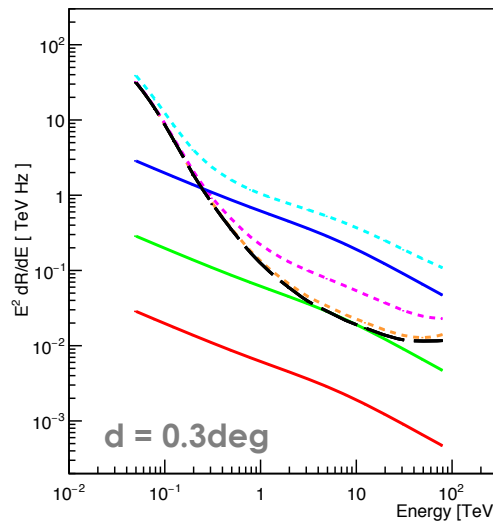
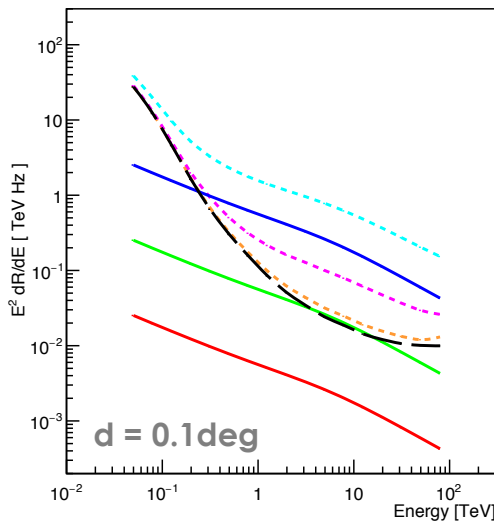
point-like 2nd source



- 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 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

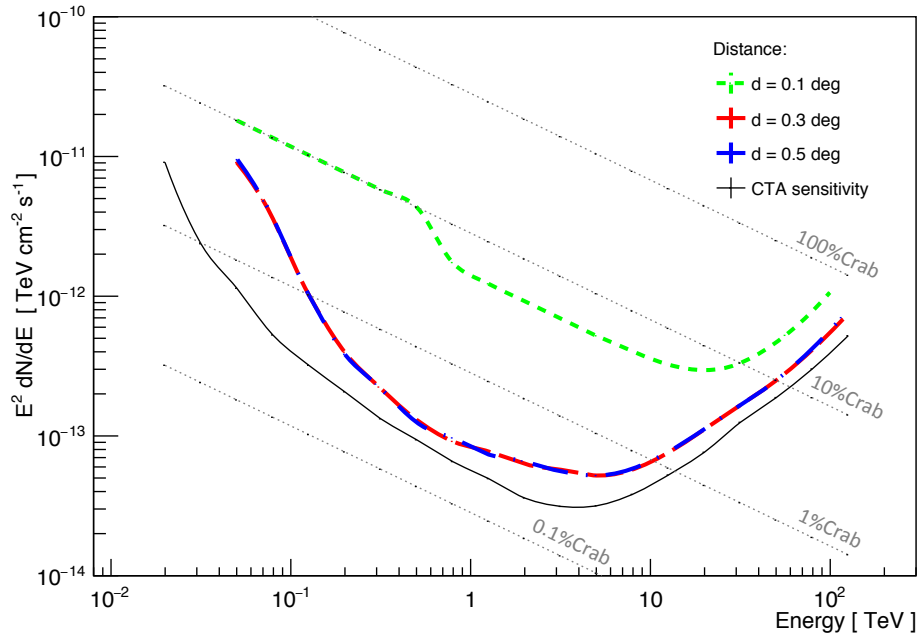
extended 2nd source



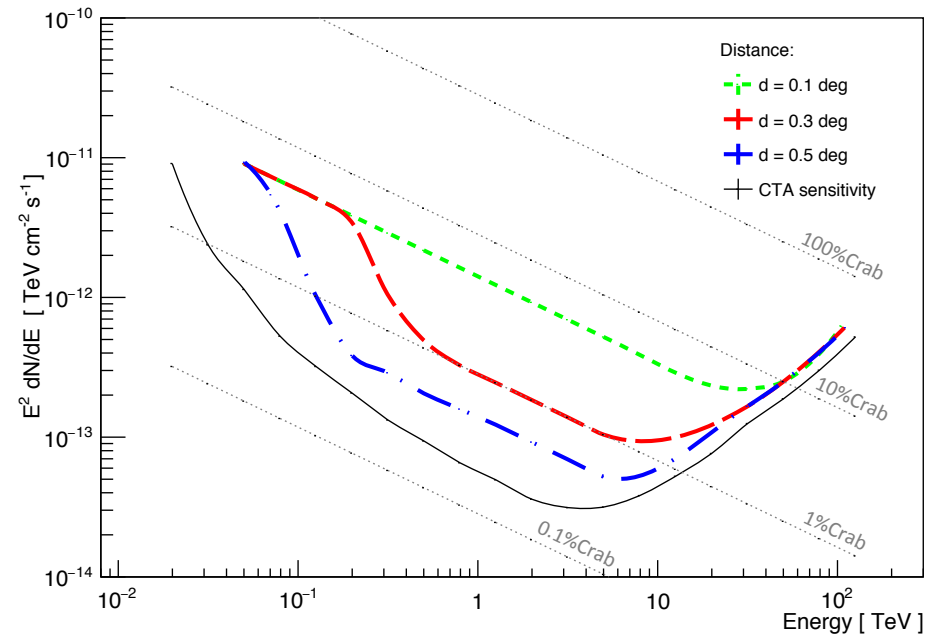
- the additional background from the tails makes the realization of the background free regime more challenging; a 1st source as bright as 10% Crab is needed to avoid background dominated regime
- the effect of the 2nd source on the total background is not really dependent on its actual size → close point-like gamma emitter behaves like a fake object having size $\sigma_{src2} = \sigma_{PSFtails} = 0.2$ deg.

Sensitivity curves for Gaussian PSF

point-like 2nd source



extended 2nd source



$$\sigma \geq 5$$

$$N_\gamma \geq 10$$

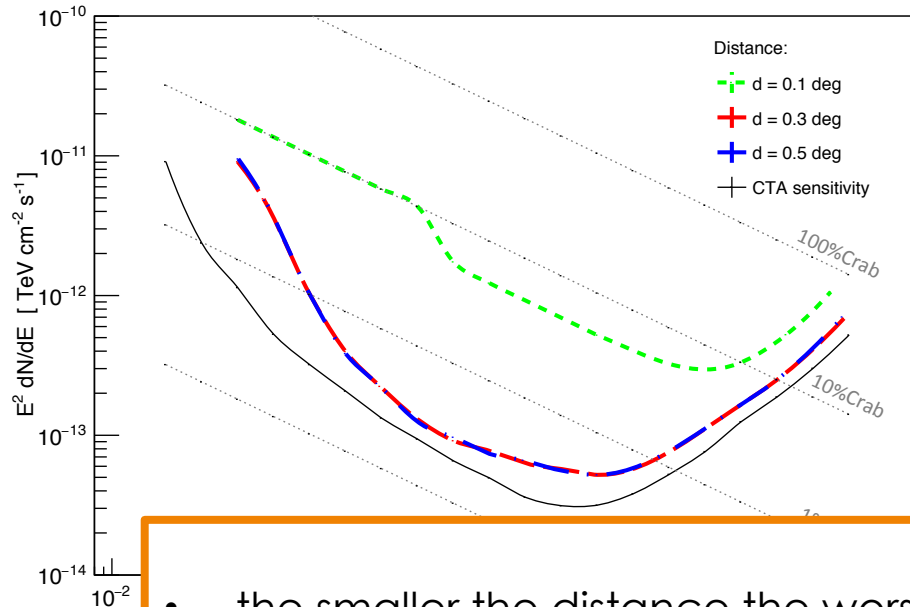
$$N_\gamma/N_{bkg} \geq 0.05$$

Hypothesis:

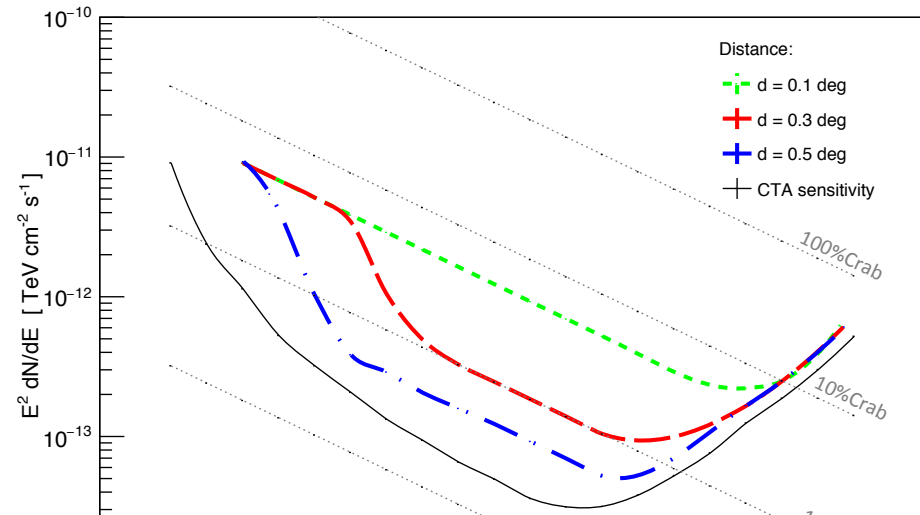
- obs. Time = 50 h
- 2nd source in the FoV of a point-like object @ 10%Crab
- Gaussian PSF

Sensitivity curves for Gaussian PSF

point-like 2nd source



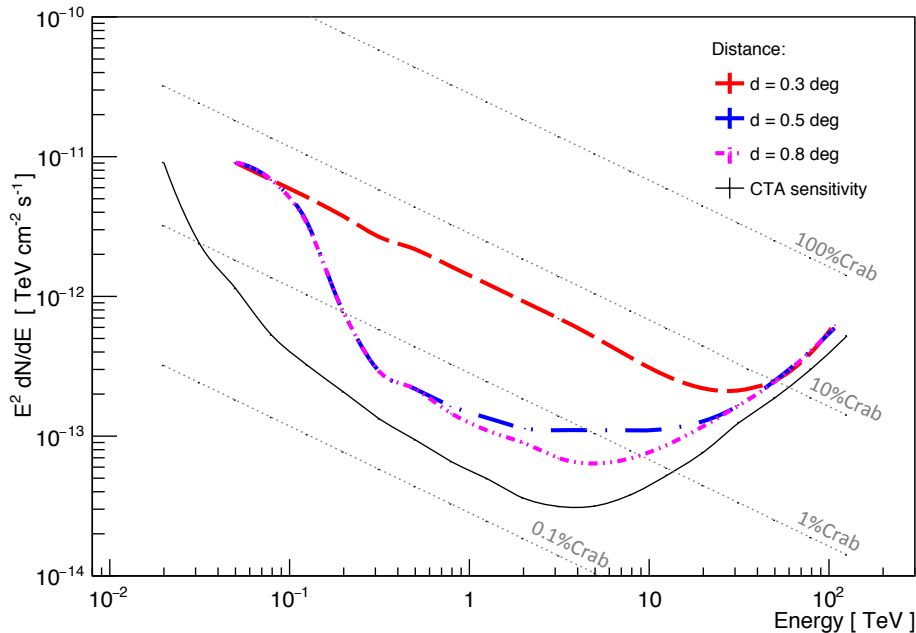
extended 2nd source



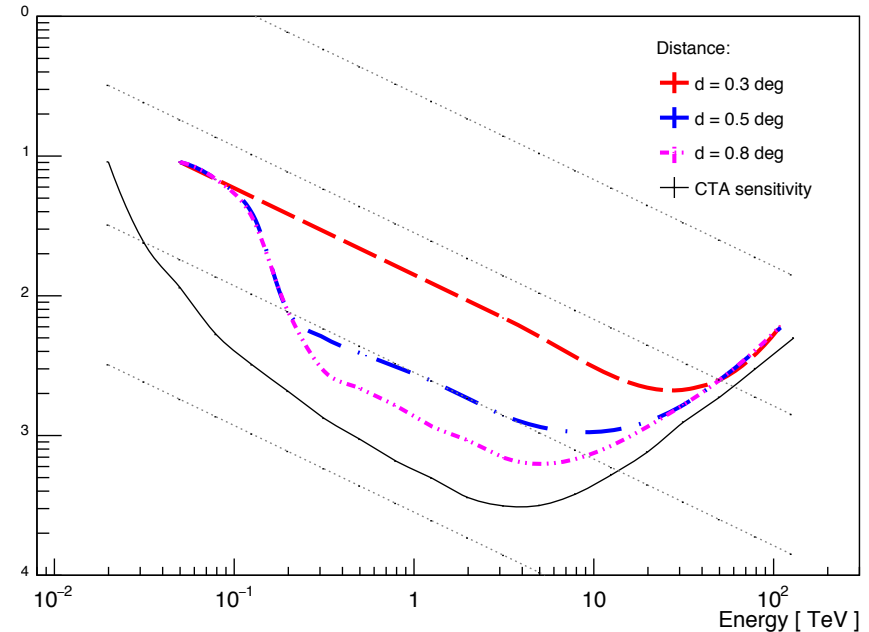
- the smaller the distance the worse the sensitivity of the telescope
- point-like 2nd source → @ 0.1deg sensitivity differs by a factor >10 from CTA expectations
@ ≥0.3deg pure CR background
- extended 2nd source → @0.5deg the nearby object still contributes as an additional background source resulting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

Sensitivity curves for non-Gaussian PSF

point-like 2nd source



extended 2nd source



$$\sigma \geq 5$$

$$N_\gamma \geq 10$$

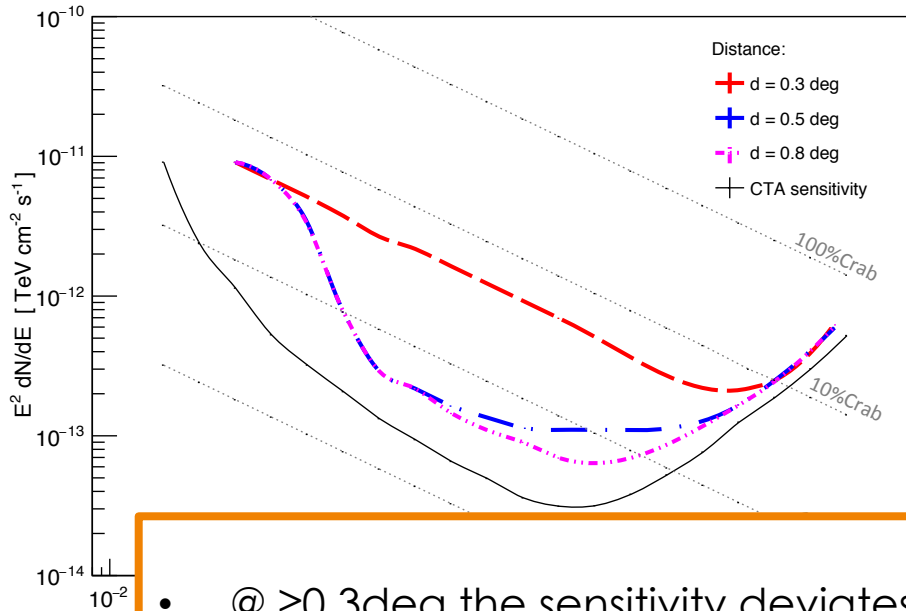
$$N_\gamma / N_{bkg} \geq 0.05$$

Hypothesis:

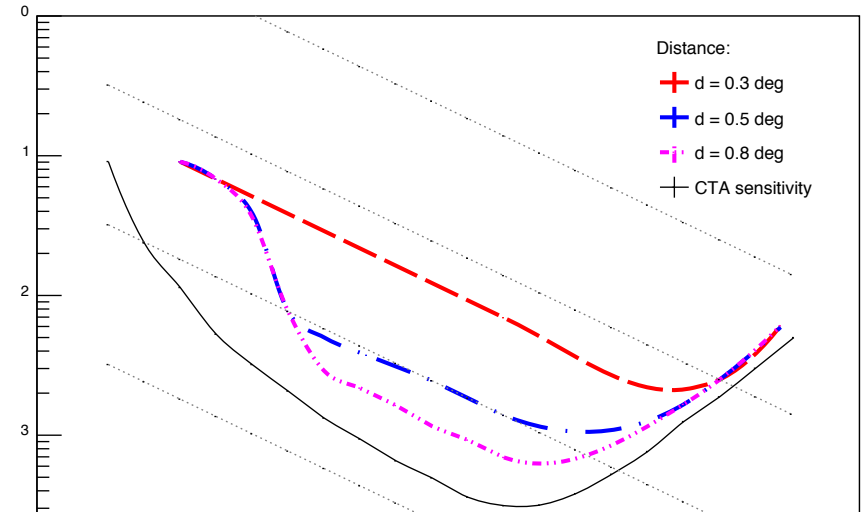
- obs. Time = 50 h
- 2nd source in the FoV of a point-like object @ 10%Crab
- non-Gaussian PSF with $\sigma_{\text{PSFtails}} = 0.2\text{deg}$ and $R = 0.3$

Sensitivity curves for non-Gaussian PSF

point-like 2nd source



extended 2nd source



- @ ≥ 0.3 deg 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 $\sigma_{\text{PSF tails}} = 0.2$ 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

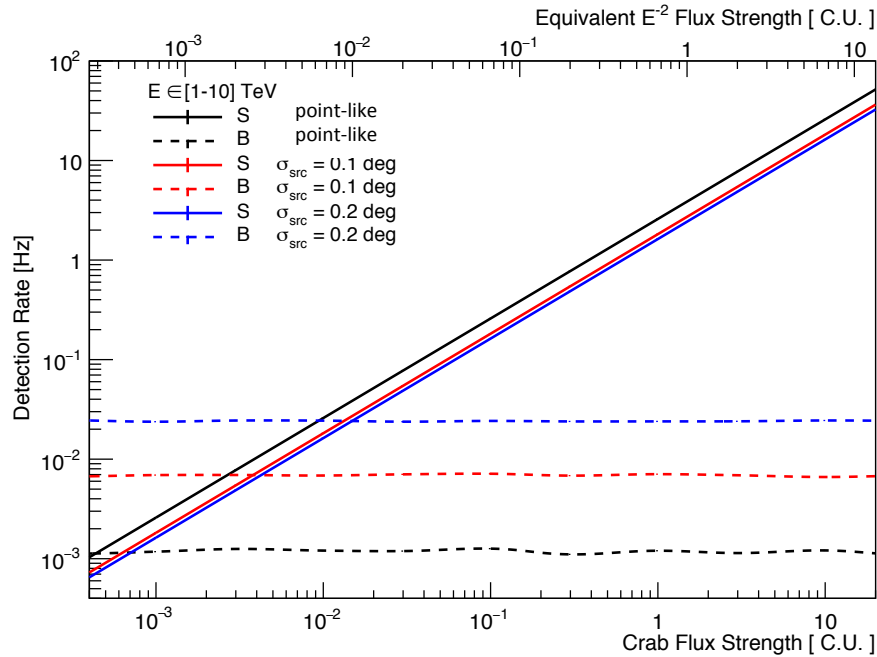
- In the framework of the Galactic Plane region, which is dense with HE sources, the detection of multiple sources in the same FoV is very likely to happen.
- The presence of a nearby source creates an additional and unavoidable background which might dominate over the CR noise.
- The sensitivity to 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
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Detection rates

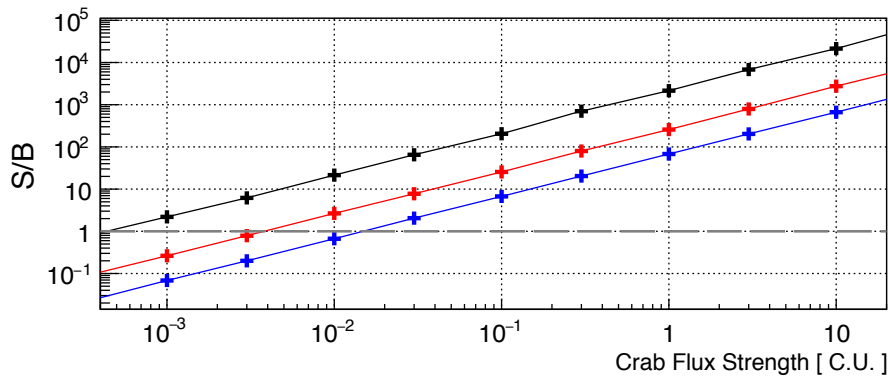


$$R_{ROI} = \sqrt{(2\sigma_{src})^2 + (2\sigma_{PSF})^2}$$

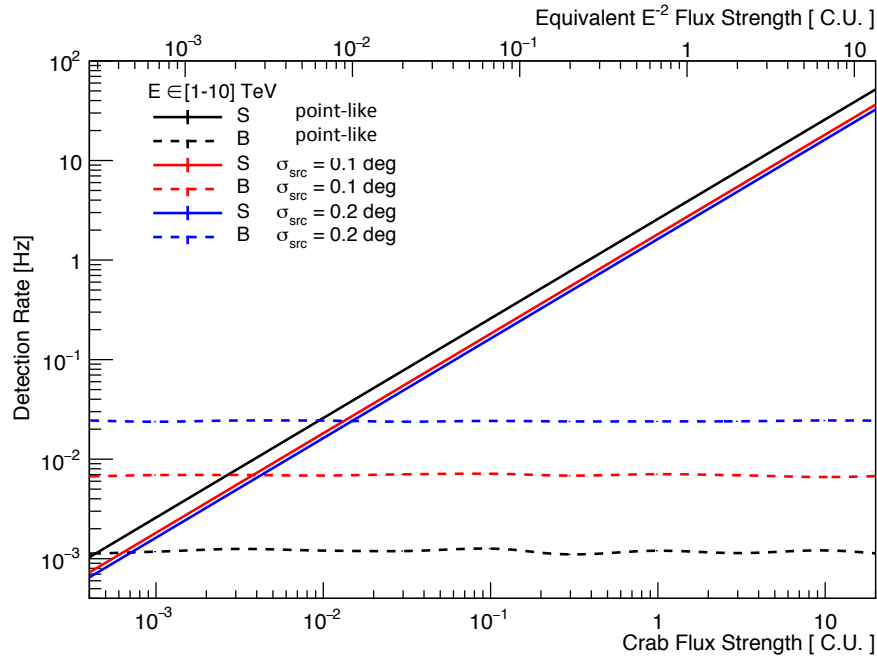
$$1 \text{ C.U.} = 2.83 \cdot 10^{-11} \times E^{-2.62} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$$

$S/B < 1$ Background dominated regime

$S/B > 1$ Background free regime



Detection rates

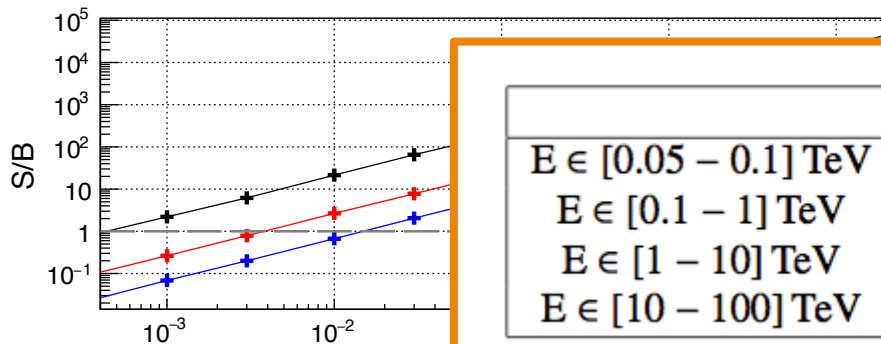


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$S/B < 1$ Background dominated regime

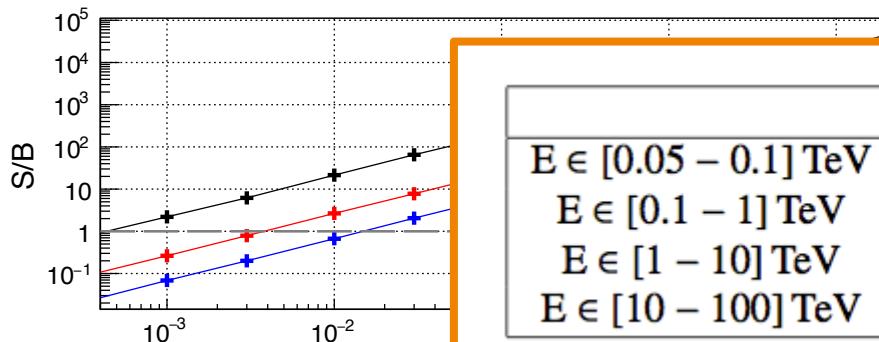
$S/B > 1$ Background free regime



	point-like	$\sigma_{src} = 0.1$ deg	$\sigma_{src} = 0.2$ deg
$E \in [0.05 - 0.1]$ TeV	30% Crab	50% Crab	100% Crab
$E \in [0.1 - 1]$ TeV	0.6% Crab	3% Crab	10% Crab
$E \in [1 - 10]$ TeV	< 0.1% Crab	0.4% Crab	1% Crab
$E \in [10 - 100]$ TeV	< 0.1% Crab	0.4% Crab	1% Crab

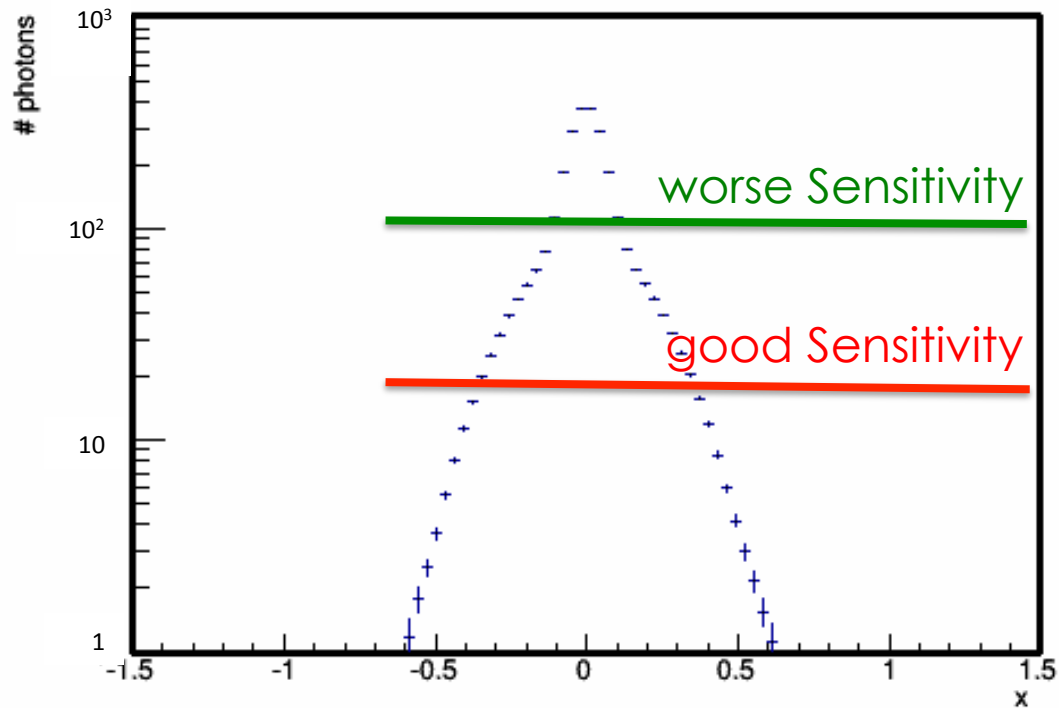
Detection rates

- point-like objects → the observation of very weak sources with a flux intensity smaller than 0.1% Crab proceeds under the background free regime for energies larger than few TeV. In the sub-TeV domain the CR noise does not allow a clean observation of such weak objects and the domination of the signal over the background takes place for flux intensity of the order of 1-10% Crab flux.
- extended objects → the transition from the background dominated to free regimes needs about one order of magnitude larger flux wrt point-like sources, mainly due to the larger integration region.



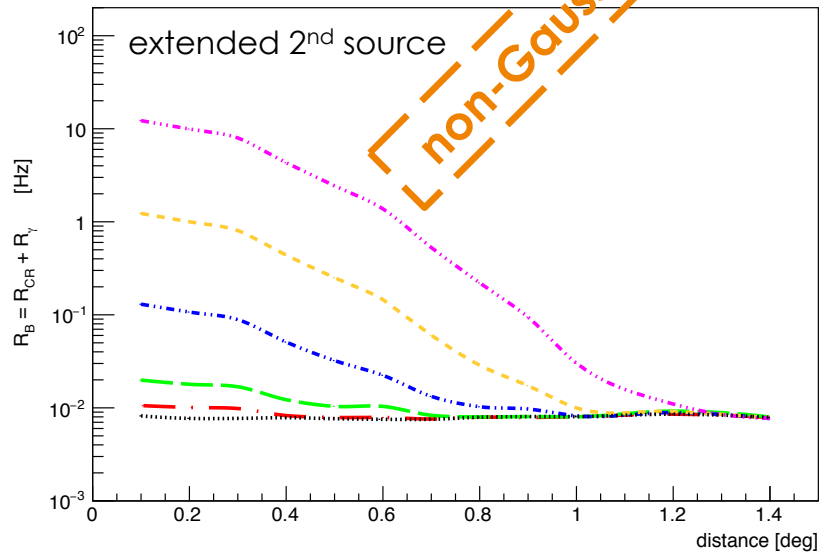
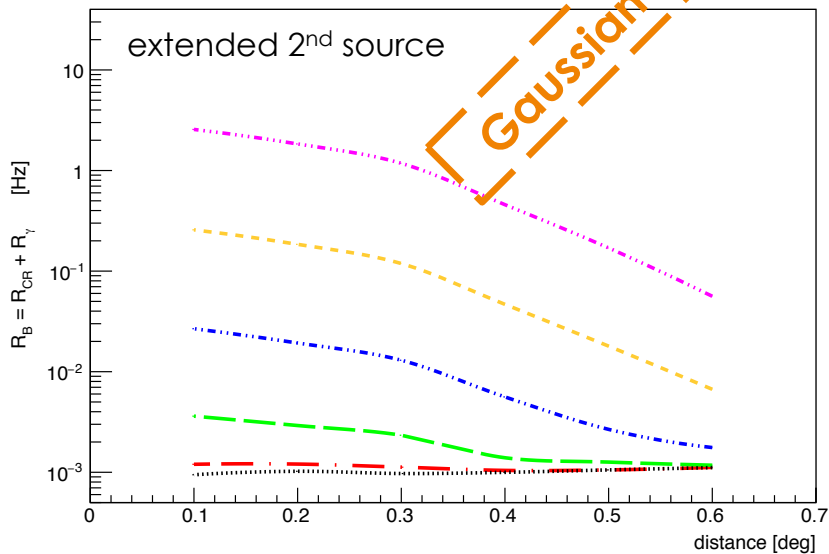
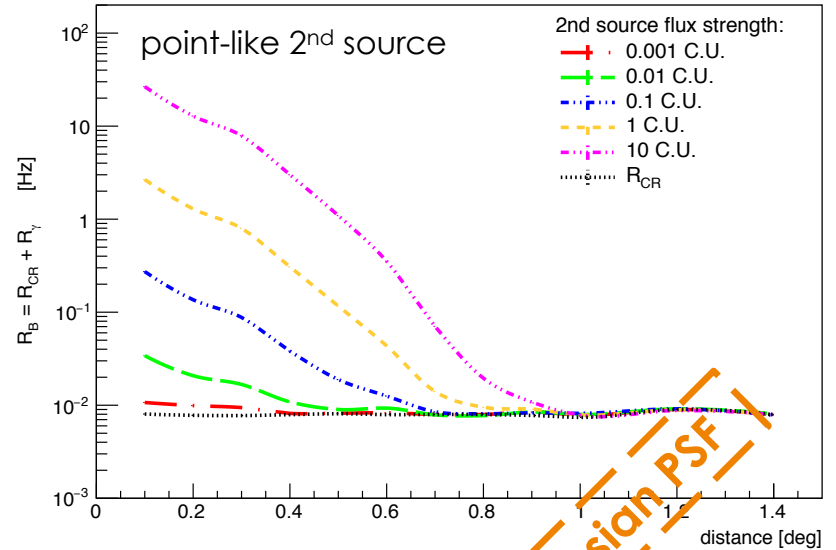
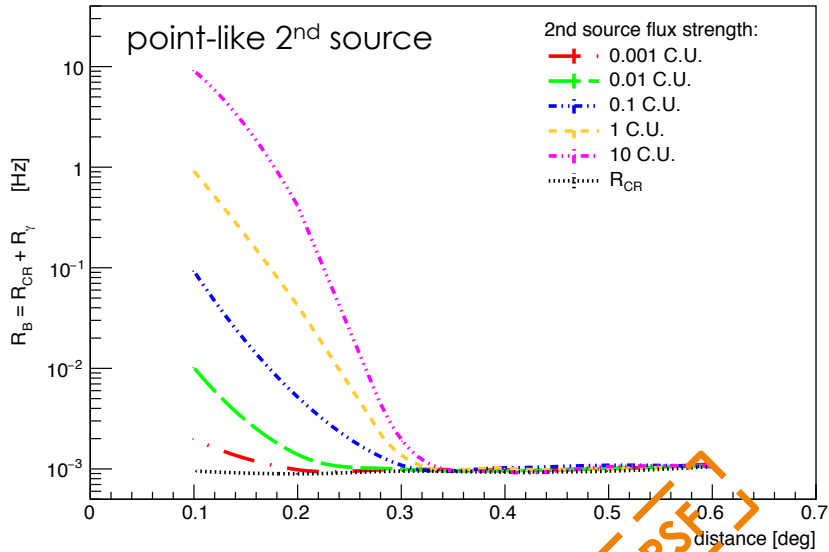
	point-like	$\sigma_{src} = 0.1 \text{ deg}$	$\sigma_{src} = 0.2 \text{ deg}$
$E \in [0.05 - 0.1] \text{ TeV}$	30% Crab	50% Crab	100% Crab
$E \in [0.1 - 1] \text{ TeV}$	0.6% Crab	3% Crab	10% Crab
$E \in [1 - 10] \text{ TeV}$	< 0.1% Crab	0.4% Crab	1% Crab
$E \in [10 - 100] \text{ TeV}$	< 0.1% Crab	0.4% Crab	1% Crab

Reconstruction of morphological parameters for non-Gaussian PSF response



- 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



Gaussian PSF

non-Gaussian PSF