SST Camera:
Muon Rate Calculations for the SST and QCAMi Camera (Tenerife Campaign)
(Preliminary Results)

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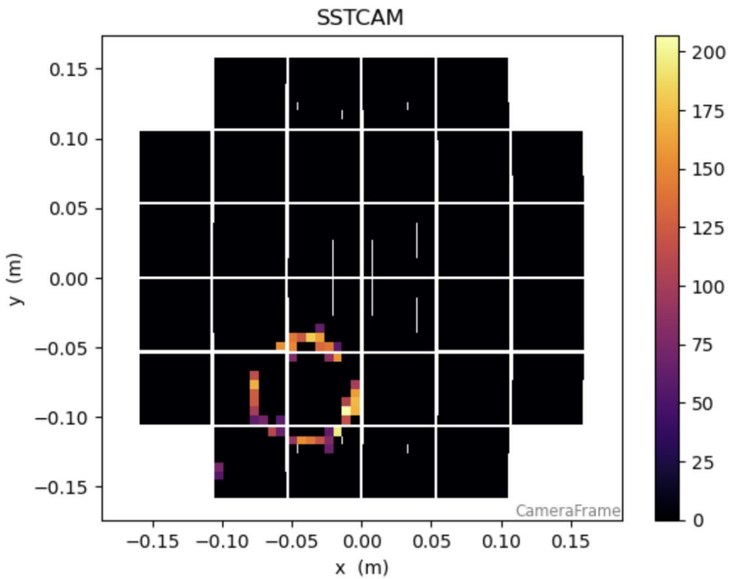
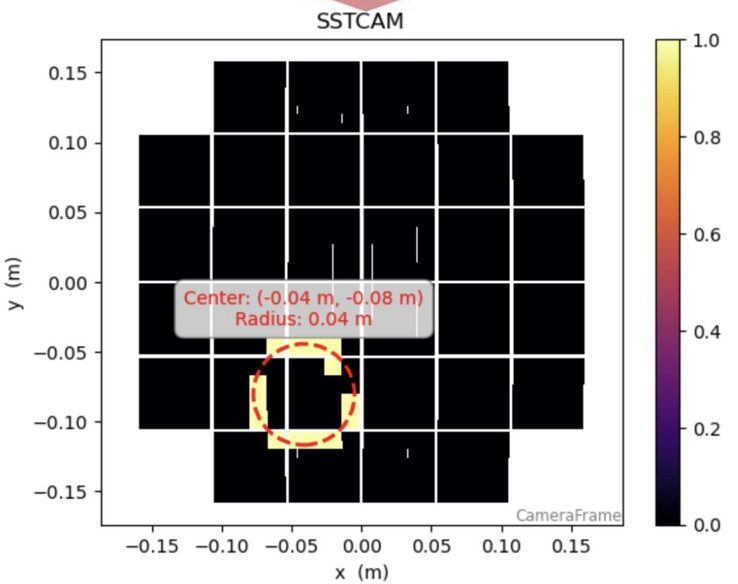
Campaign on Tenerife

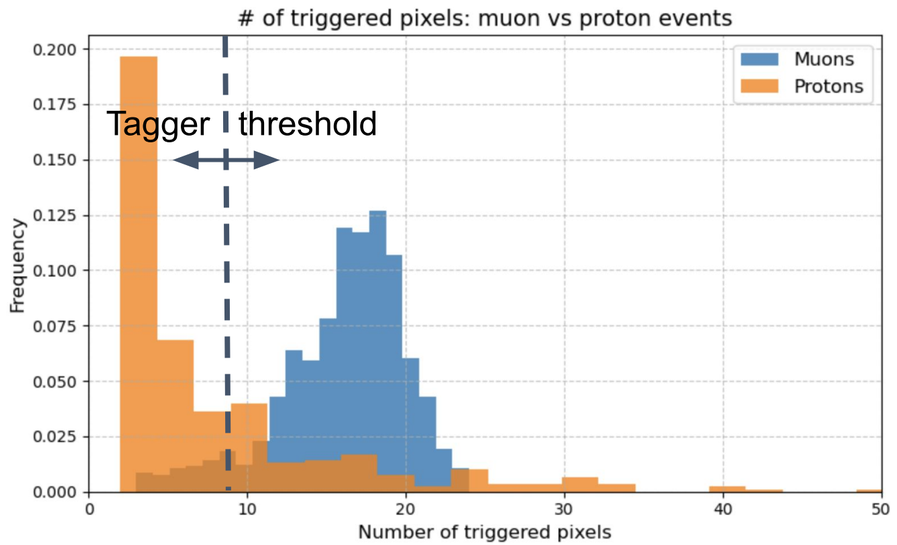
- 22-29 July 2025: test campaign on the Small-Sized Telescope (SST) camera prototype
- The camera prototype was integrated into the ASTRI-2 telescope, on Tenerife, Spain
- The prototype (QCAMi) consisted only of one quadrant of the whole camera

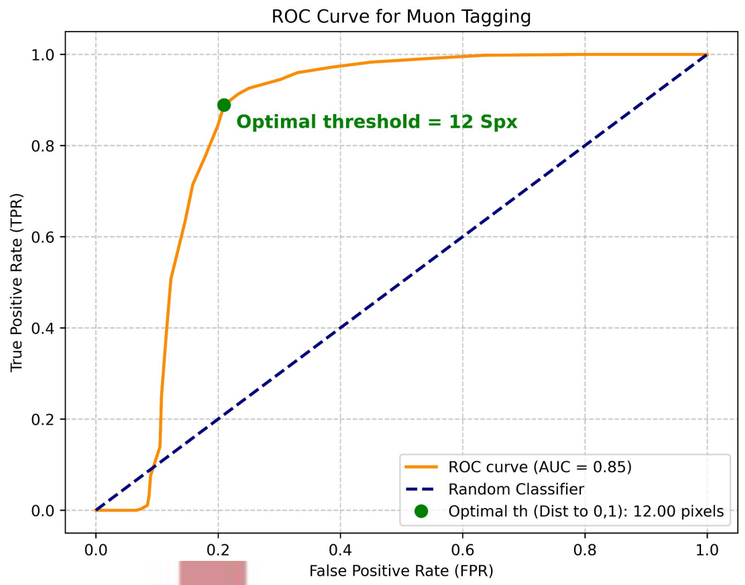
Photo by Connor Duffy

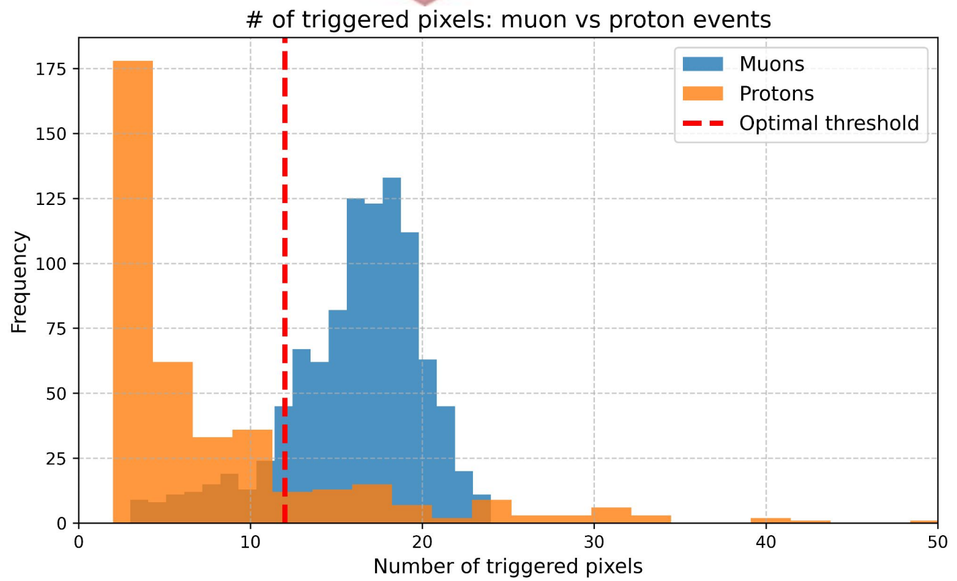
Muon Tagging: Number of Triggered Pixels + Ring Completeness



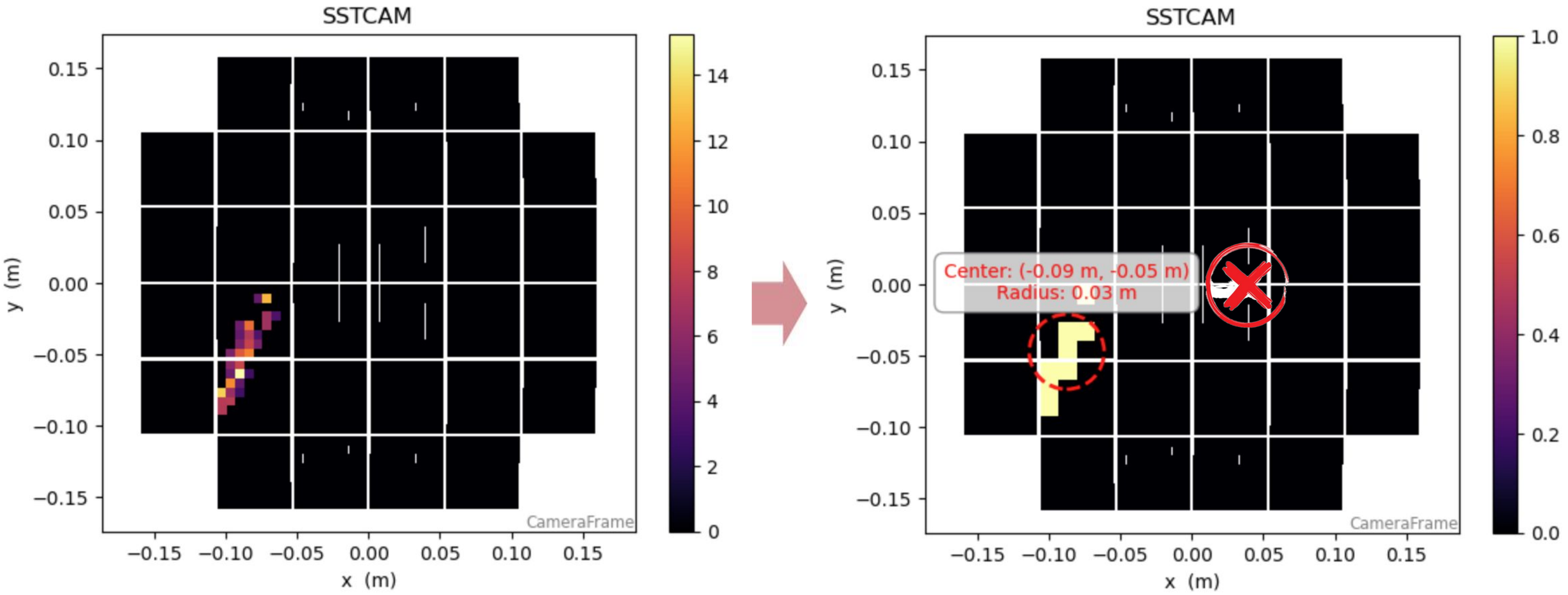








Muon Tagging: Circle Fit Issue



Muon Tagging: Ring-Center Cleanness Check

Circle fit method:

```
x = cam_geometry[image_mask].pix_x
y = cam_geometry[image_mask].pix_y
weights = cleaned_image[image_mask]

fit_radius, fit_x, fit_y, *_= kundu_chaudhuri_circle_fit(
    x,
    y,
    weights
)

ring_frac = .65
d = np.sqrt((x- fit_x)**2 + (y - fit_y)**2)
is_pixels_at_center = (d < (ring_frac * fit_radius)) & q1[image_mask]
is_pixels_at_center = any(is_pixels_at_center)
```

ctapipe built-in

Centroid depletion check method:

```
# Centroid
xc, yc = np.mean(x), np.mean(y)

# Euclidean distance from each pixel to the centroid
d = np.sqrt((x - xc) ** 2 + (y - yc) ** 2)

# Central exclusion zone
exclusion_zone = 0.4 * np.max(d)

is_pixels_at_center_c = np.any(d < exclusion_zone)
```

Muon Tagging: Ring-Center Cleanness Check

Circle fit method:

```
x = cam_geometry[image_mask].pix_x
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weights = cleaned_image[image_mask]

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is_pixels_at_center = (d < (ring_frac * fit_radius)) & q1[image_mask]
is_pixels_at_center = any(is_pixels_at_center)
```
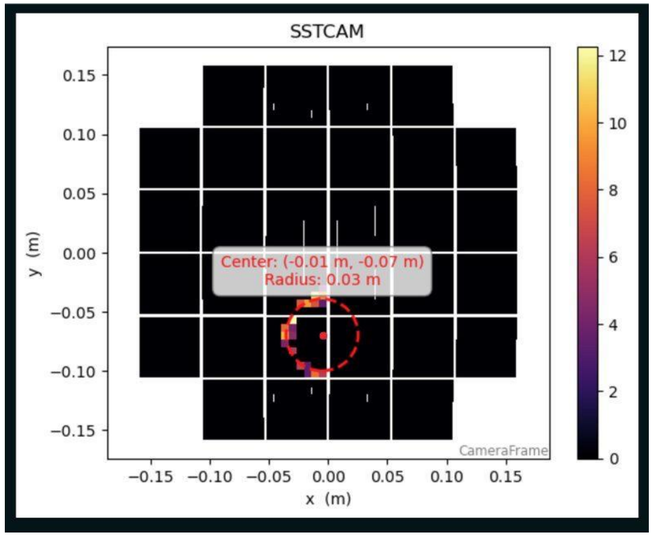

ctapipe built-in



Check distance from Circle's geometric center

Centroid depletion check method:

```
# Centroid
xc, yc = np.mean(x), np.mean(y)

# Euclidean distance from each pixel to the centroid
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# Central exclusion zone
exclusion_zone = 0.4 * np.max(d)

is_pixels_at_center_c = np.any(d < exclusion_zone)
```
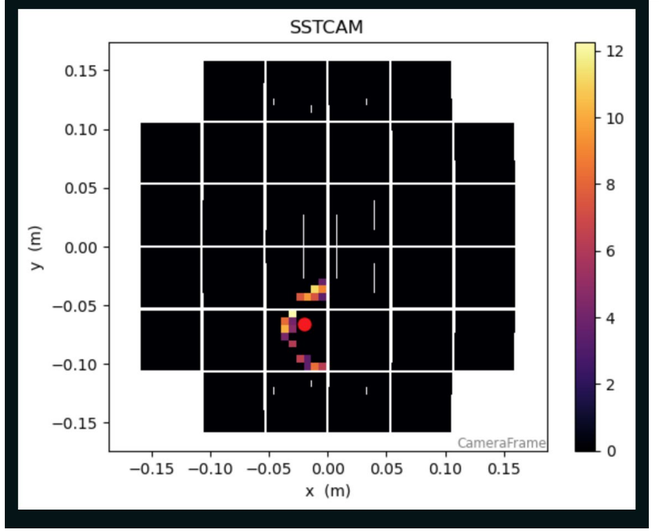

computationally simpler

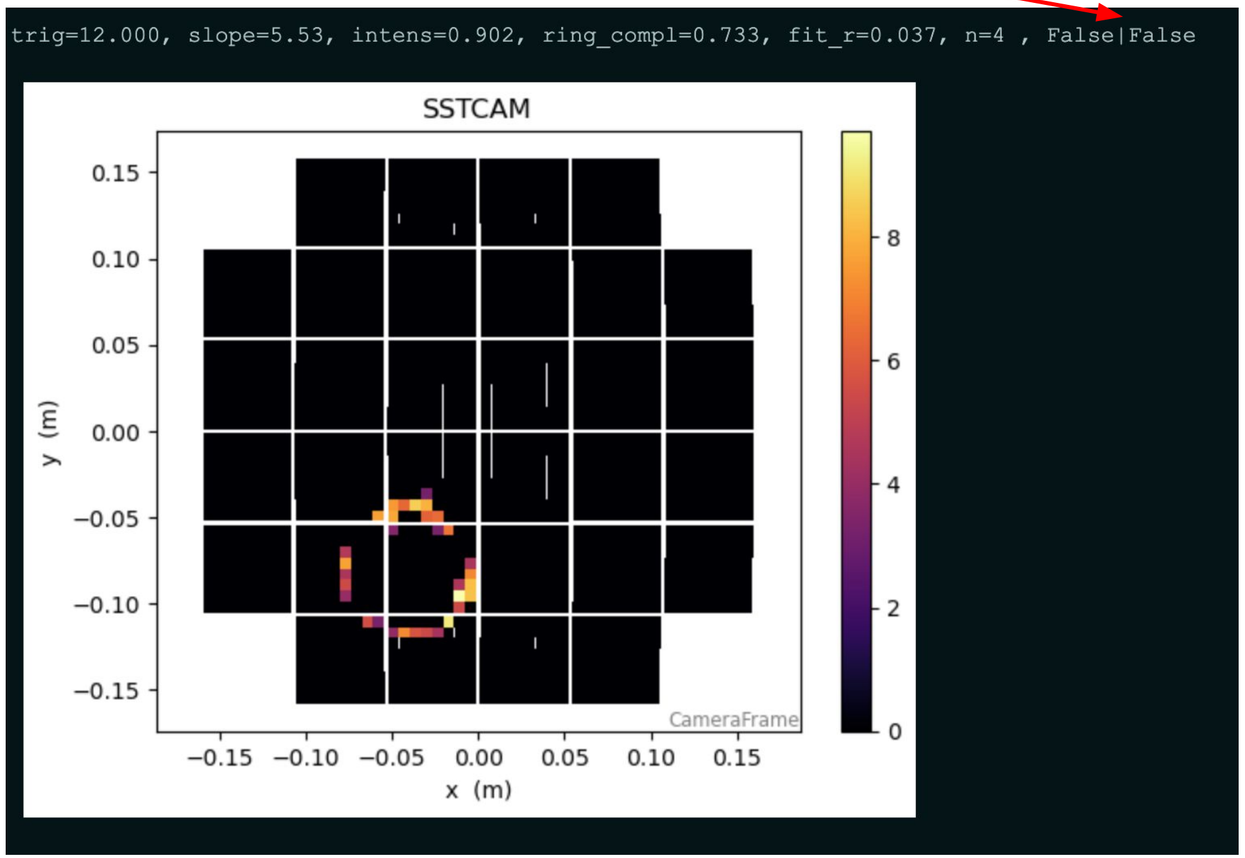
```
if (6 < len(trig_sp) < 20)  and (not is_pixels_at_center_c):
```

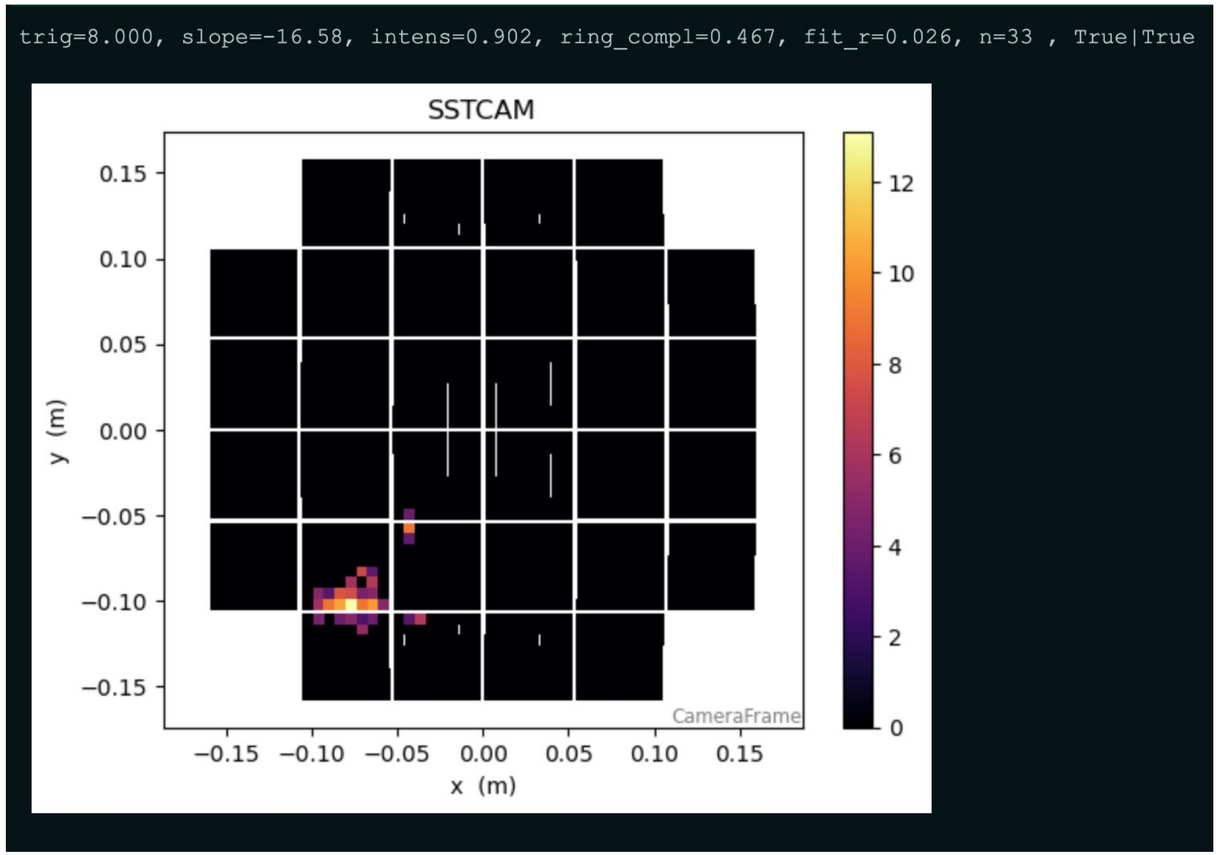


Check distance from Pixels' center of mass

Muon Tagging: Circle Fit vs Centroid Depletion

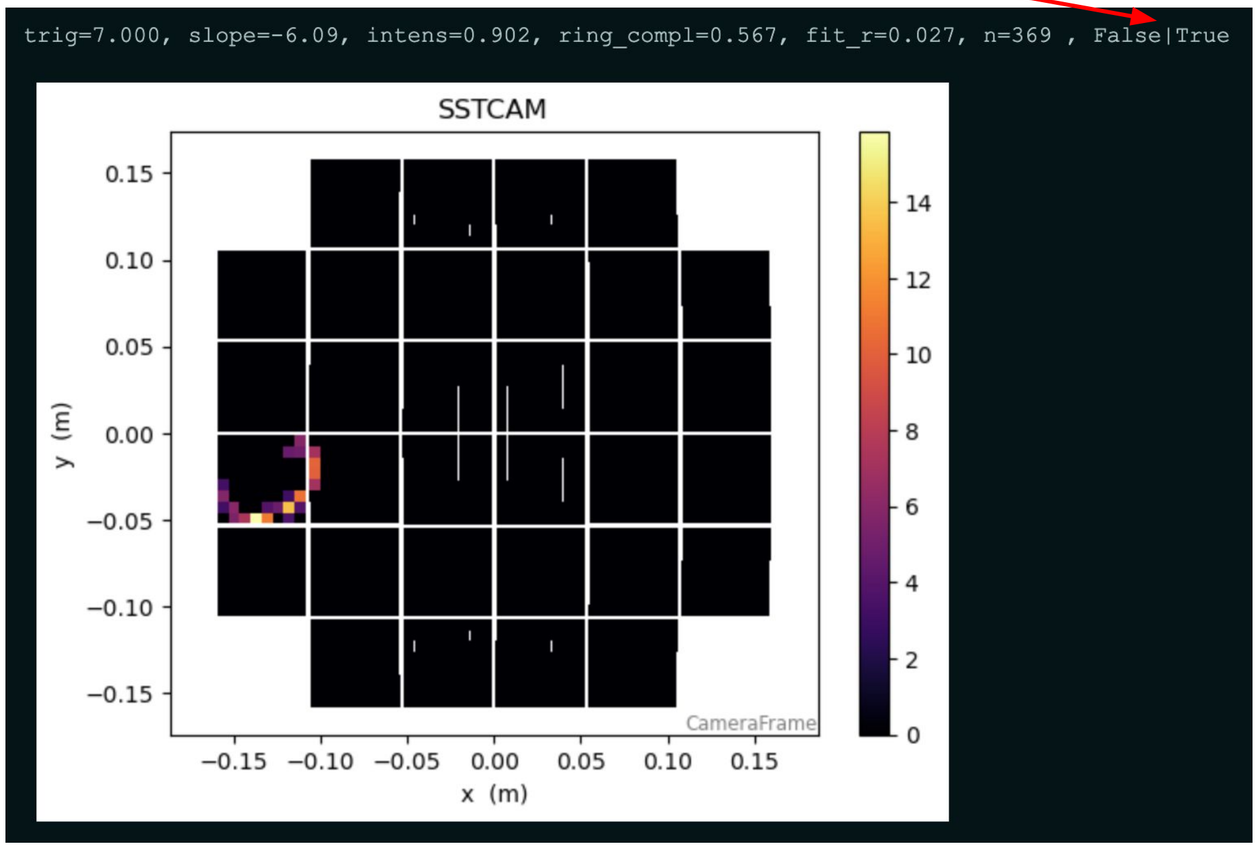
is_pixels_at_center: Circle fit | Centroid depletion

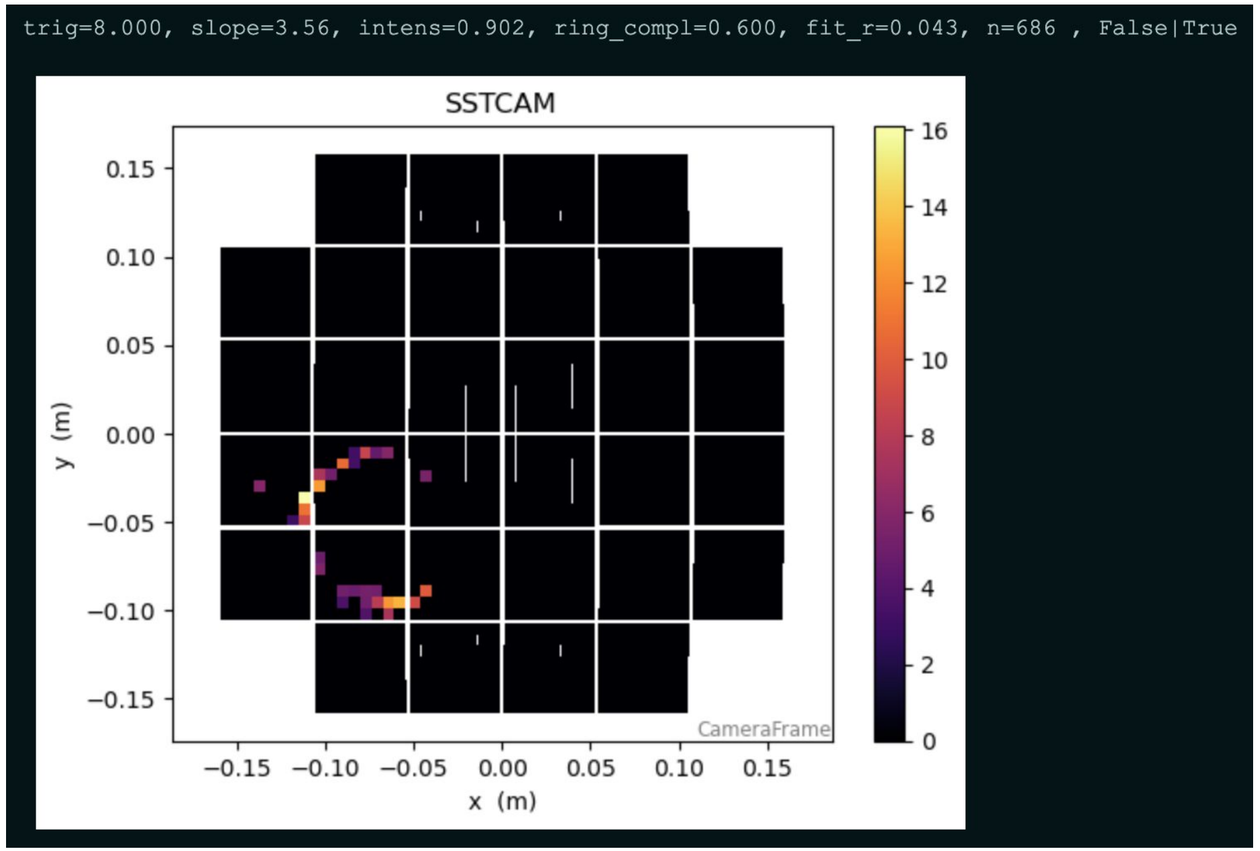




Muon Tagging: Circle Fit vs Centroid Depletion

is_pixels_at_center: Circle fit | Centroid depletion





MC rate calculation: Generation Phase Space & Normalization

1. MC Generation Phase Space & Normalization

- **Generation Area (A_{MC}):**

$$A_{\mathrm{MC}} = \pi R_{\mathrm{max}}^2$$

- **Generation Solid Angle (Ω_{MC}):**

$$\Omega_{\mathrm{MC}} = 2\pi(1 - \cos\theta_{\mathrm{max}})$$

- **Spectral Integration Constant (I_{MC}):**

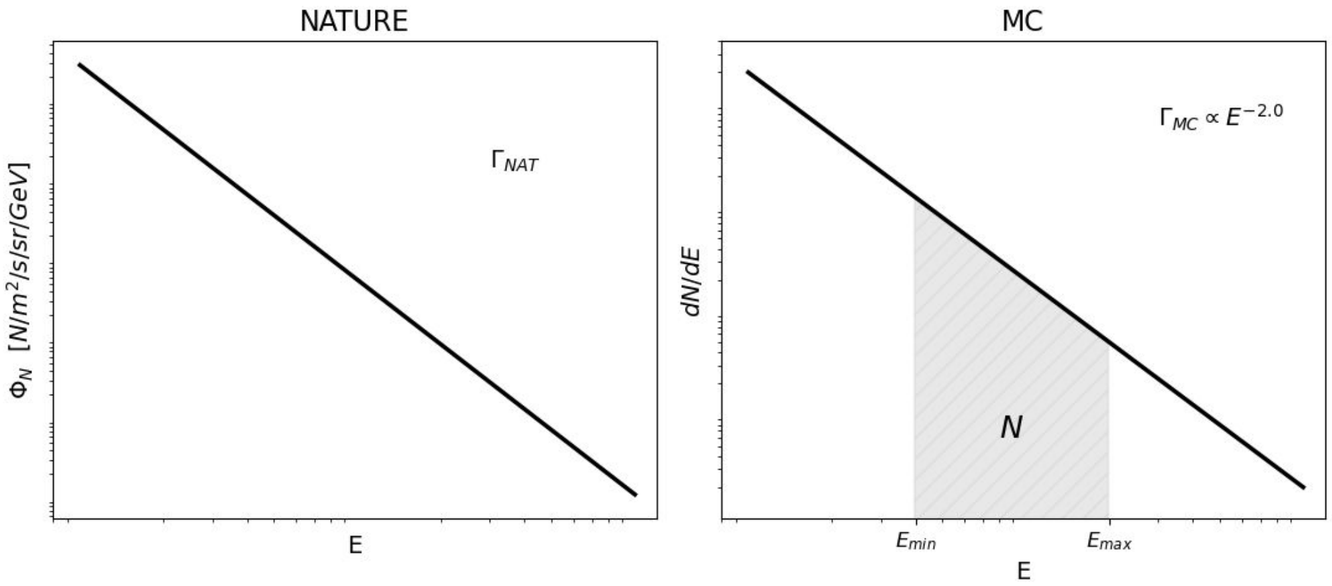
$$I_{\mathrm{MC}} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} E^{-\gamma_{\mathrm{MC}}} dE = \frac{E_{\mathrm{max}}^{1-\gamma_{\mathrm{MC}}} - E_{\mathrm{min}}^{1-\gamma_{\mathrm{MC}}}}{1 - \gamma_{\mathrm{MC}}}$$

- **Global Normalization Factor:**

$$\mathrm{normalization\_factor} = \frac{A_{\mathrm{MC}} \cdot \Omega_{\mathrm{MC}} \cdot I_{\mathrm{MC}}}{N_{\mathrm{showers}}}$$

2. Natural Differential Muon Flux

- **Low Energy Regime ($E \leq 100$ GeV):** $\Phi_{\mathrm{low}}(E, \theta)$ — Hebbeker-Timmermans analytical model with local altitude (h) and zenith angle (θ) corrections.
- **High Energy Regime ($E > 100$ GeV):** $\Phi_{\mathrm{high}}(E, \theta)$ — Modified Gaisser analytical parameterization.
- **Reference:** M. Gaug et al., *The Astrophysical Journal Supplement Series*, 243:11 (2019). DOI: 10.3847/1538-4365/ab2123



MC rate calculation: Generation Phase Space & Normalization

3. Event Reweighting & Detected Rate (R_{det})

- **MC Generation Density:**

$$\text{mc\_density}_i = E_i^{-\gamma_{\text{MC}}}$$

- **Event Weight:**

$$w_i = \text{normalization\_factor} \times \frac{\Phi_{\text{NAT}}(E_i, \theta_i)}{\text{mc\_density}_i}$$

- **Detected Rate:**

$$R_{\text{det}} = \sum_i w_i$$

4. Telescope Efficiency

- **Injected Background Rate (R_{inj}):**

$$R_{\text{inj}} = \left(\int_{E_{\text{min}}}^{100} \Phi_{\text{low}}(E) dE + \int_{100}^{E_{\text{max}}} \Phi_{\text{high}}(E) dE \right) \cdot \text{geom\_factor}$$

- **Telescope Efficiency:**

$$\epsilon = \frac{R_{\text{det}}}{R_{\text{inj}}}$$

Muon rate for the SST: Calculations

Gaug's paper:

	SST	
	$\vartheta = 0°$	$\vartheta = 60°$
Maximum impact distance ρ_{max} (m)	2.0	
Maximum muon angle υ_{max} (deg)	3.1	
Determination of optical bandwidth B_μ		
R_{max} (Hz)	0.8	0.2
$T_{monitor}$ for 1% resolution	28 min	18 min

Absolute maximum rate at strictly 0 deg zenith angle

?

Under these assumptions, the estimated maximally available rate of useful muons ranges from ~0.4 Hz (for the SSTs) to $\lesssim$10 Hz (for the LSTs) (see Table 6). These values are sufficiently high to yield acceptable statistics for nightly calibration.

Representative average rate across observing zenith angles (?)

MC Rate: Ring Completeness

Doesn't take into account:
- *Precise telescope geometry*
- *Shadowing by telescope structure & components*

+ ring completeness def

Gaug's paper: max μ-Rate ~ 0.4 – 0.8 Hz

ring_completeness

ctapipe built-in

```
ctapipe.image.muon.ring_completeness(pixel_fov_lon: Quantity,
pixel_fov_lat: Quantity, weights: Quantity | ndarray | Sequence[float],
ring: MuonRingContainer, threshold: float = 30, bins: int = 30) → float
```

Full cam:

- ring_completeness = 0.9

```
Detected muons : 628
Injected Muon Rate (R_inj) : 1.7373 Hz
Detected Muon Rate (R_det) : 0.1954 Hz
Telescope Efficiency (epsilon) : 11.2470 %
```

- ring_completeness = 0.8

```
Detected muons : 1614
Injected Muon Rate (R_inj) : 1.7376 Hz
Detected Muon Rate (R_det) : 0.5331 Hz
Telescope Efficiency (epsilon) : 30.6808 %
```

- ring_completeness = 0.7

```
Detected muons : 1861
Injected Muon Rate (R_inj) : 1.7373 Hz
Detected Muon Rate (R_det) : 0.6219 Hz
Telescope Efficiency (epsilon) : 35.7968 %
```

- ring_completeness = 0.6

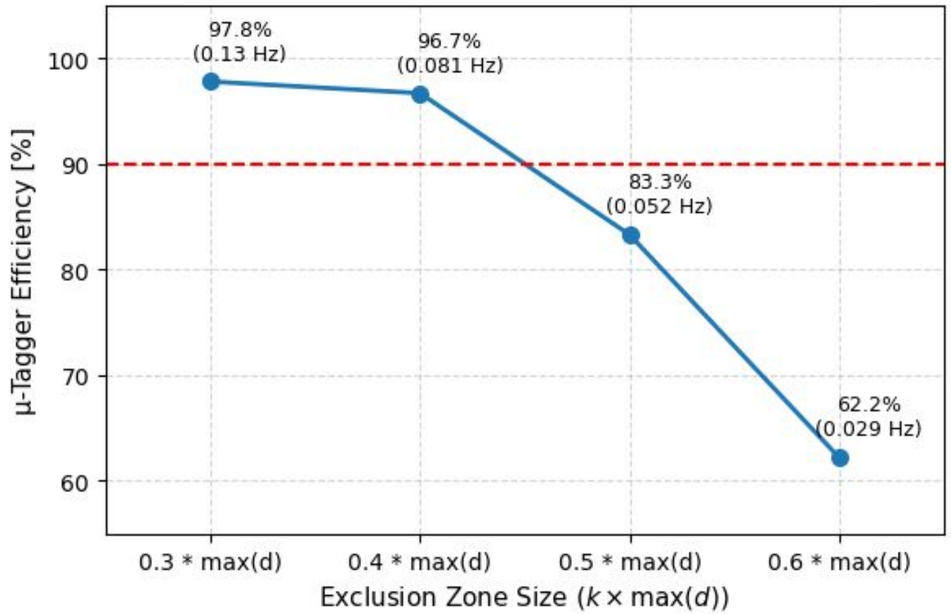
```
Detected muons : 2363
Injected Muon Rate (R_inj) : 1.7373 Hz
Detected Muon Rate (R_det) : 0.7998 Hz
Telescope Efficiency (epsilon) : 46.0390 %
```

Muon Tagging: Centroid Depletion Check Optimization

Full cam:
ring_completeness = 0.8

```
Detected muons : 1614
Injected Muon Rate (R_inj) : 1.7376 Hz
Detected Muon Rate (R_det) : 0.5331 Hz
Telescope Efficiency (epsilon) : 30.6808 %
```

$$\text{Tagger\_eff} = \frac{N_{[\text{centr\_depl \& complet}>0.8]}}{N_{[\text{complet}>0.8]}}$$



Full cam:
Centroid depletion check (0.4 * max_d)

```
Detected muons : 1861
Injected Muon Rate (R_inj) : 1.7373 Hz
Detected Muon Rate (R_det) : 0.6312 Hz
Telescope Efficiency (epsilon) : 36.3330 %
```

Muon Tagging: Centroid Depletion Check Optimization

Full cam:
ring_completeness = 0.8

```
Detected muons : 1614
Injected Muon Rate (R_inj) : 1.7376 Hz
Detected Muon Rate (R_det) : 0.5331 Hz
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Full cam:
Centroid depletion check (0.4 * max_d)

```
Detected muons : 1861
Injected Muon Rate (R_inj) : 1.7373 Hz
Detected Muon Rate (R_det) : 0.6312 Hz
Telescope Efficiency (epsilon) : 36.3330 %
```

Muon Tagging: QCAMi

n_showers | 5000

Detected muons : 207
Injected Muon Rate (R_inj) : 1.7370 Hz (0.4344 Hz)
Detected Muon Rate (R_det) : 0.0751 Hz
Telescope Efficiency (epsilon) : 4.3256 % (17.3024 %)

Muon Tagging: Centroid Depletion Check Optimization

Full cam:
ring_completeness = 0.8

```
Detected muons : 1614
Injected Muon Rate (R_inj) : 1.7376 Hz
Detected Muon Rate (R_det) : 0.5331 Hz
Telescope Efficiency (epsilon) : 30.6808 %
```

Full cam:
Centroid depletion check (0.4 * max_d)

```
Detected muons : 1861
Injected Muon Rate (R_inj) : 1.7373 Hz
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Muon Tagging: QCAMi

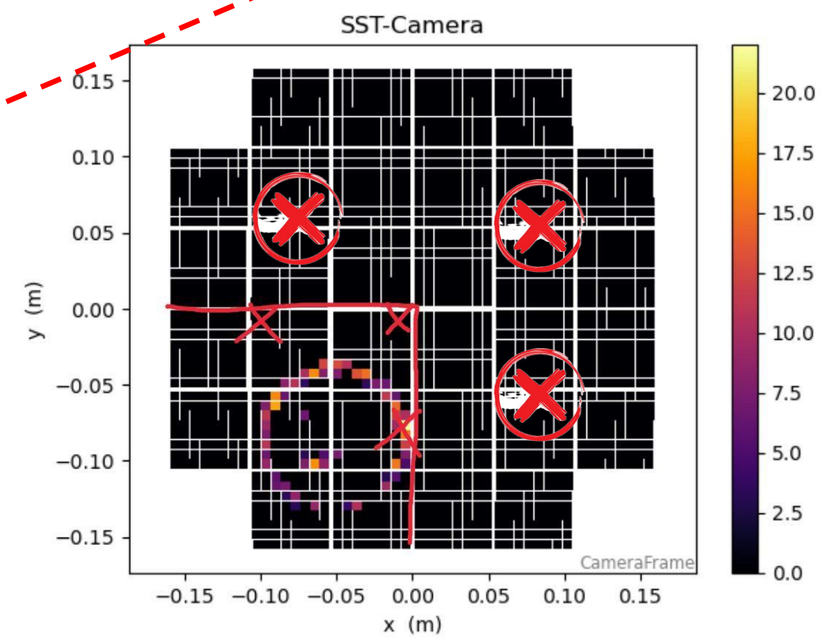
n_showers | 5000

Detected muons : 207
Injected Muon Rate (R_inj) : 1.7370 Hz (0.4344 Hz)
Detected Muon Rate (R_det) : 0.0751 Hz
Telescope Efficiency (epsilon) : 4.3256 % (17.3024 %)

36.3 * 0.25 * 0.7~ 6%

quadrant

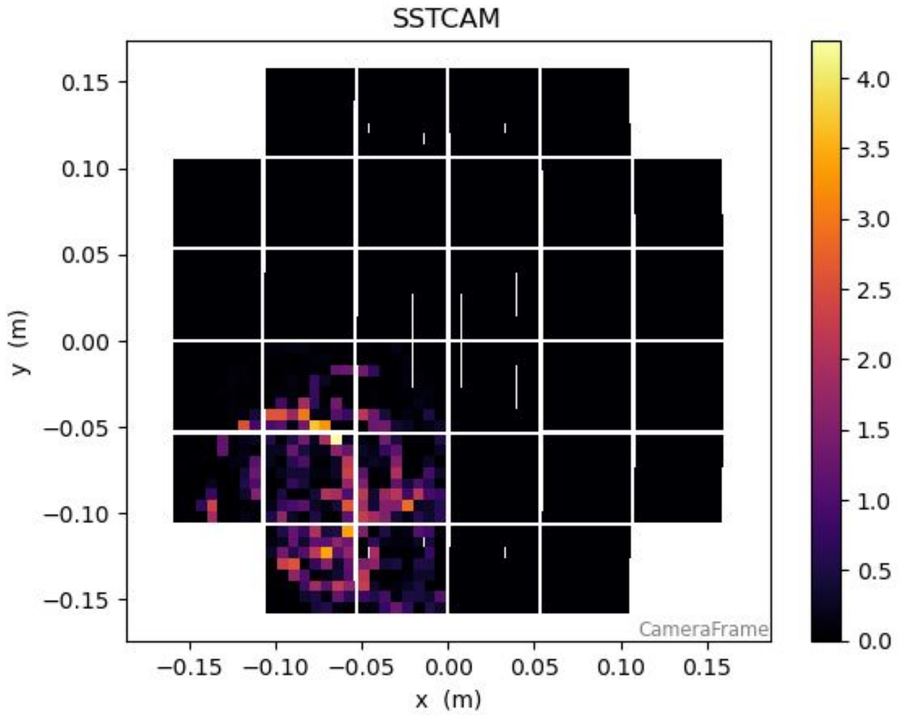
edge effect



Muon Tagging consistency: MC vs Tenerife (QCAMi)

exclusion_zone	**MC (*trig_eff*)**	**Tenerife* (# μ rings)**
0.6 * np.max(d)	0.029 Hz (62.2 %)	0.016 Hz (9 rings)
0.5 * np.max(d)	0.052 Hz (83.3 %)	0.050 Hz (28 rings)
0.4 * np.max(d)	0.081 Hz (96.7 %)	0.081 Hz (45 rings)
0.3 * np.max(d)	0.131 Hz (97.8 %)	0.127 Hz (71 rings)

**Run: d250724T2208/Run00049*



Backup

Impact distance/parameter