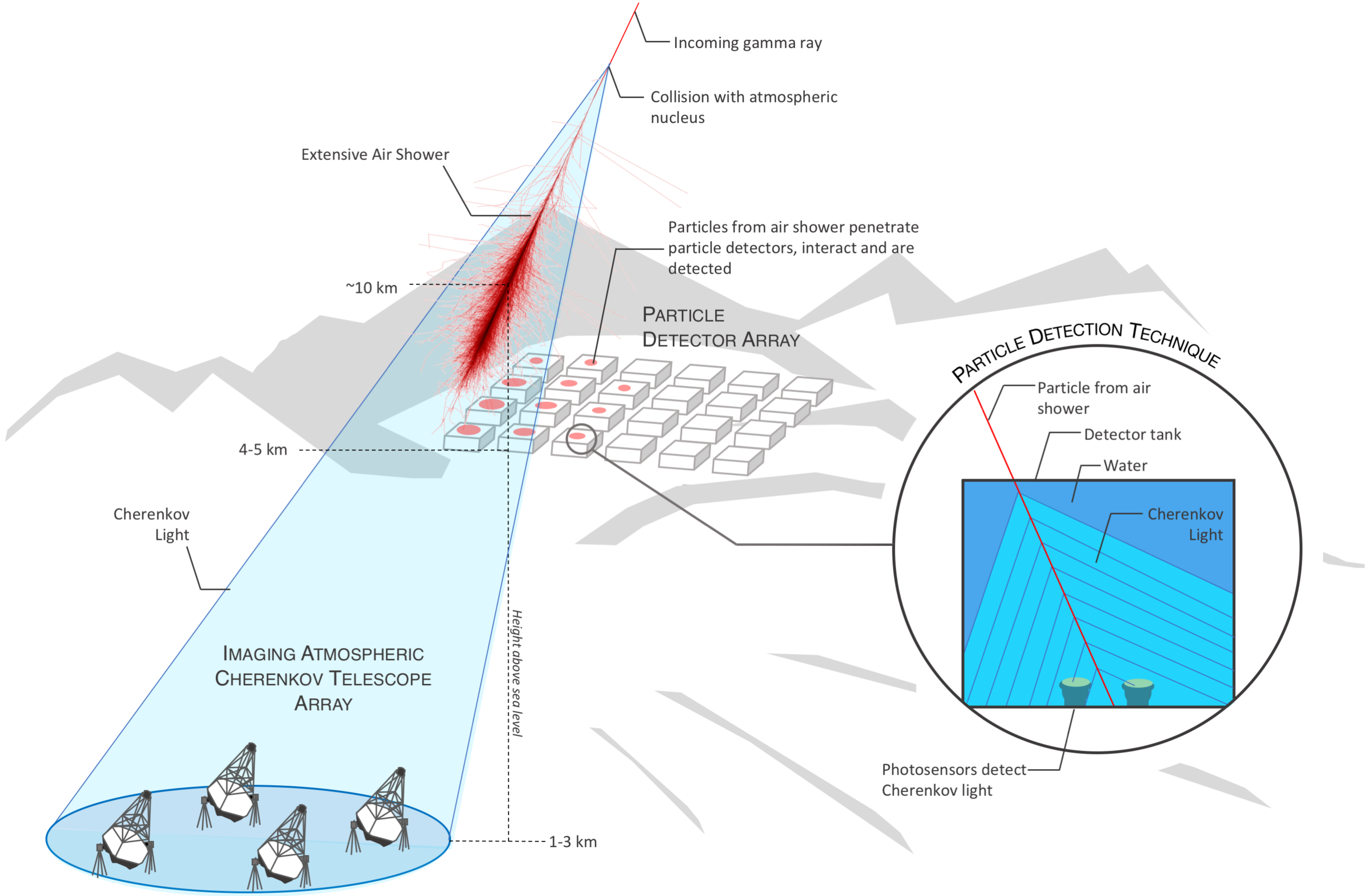
An alternative way to sky maps

Gamma-ray astronomy × statistical physics.

Markus Pirke, 28.07.25

Detection mechanism at the TeV scales

Use atmosphere as a calorimeter.



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Not to scale

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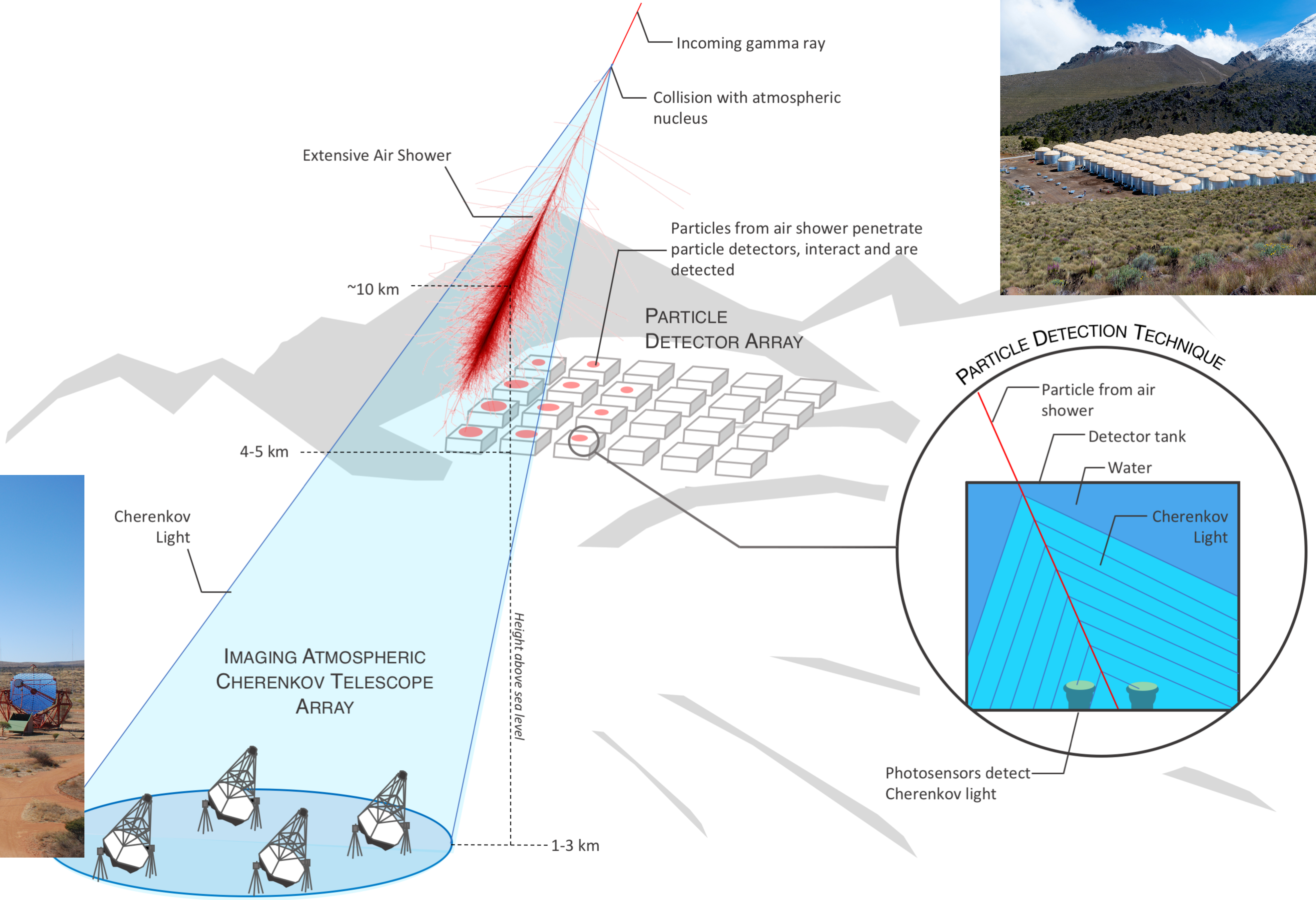

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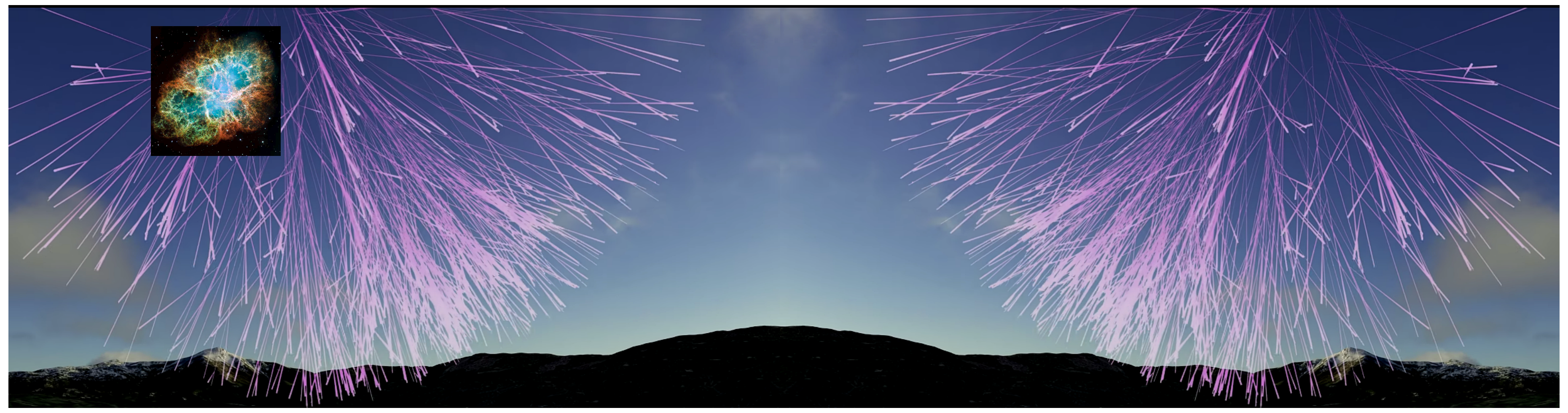
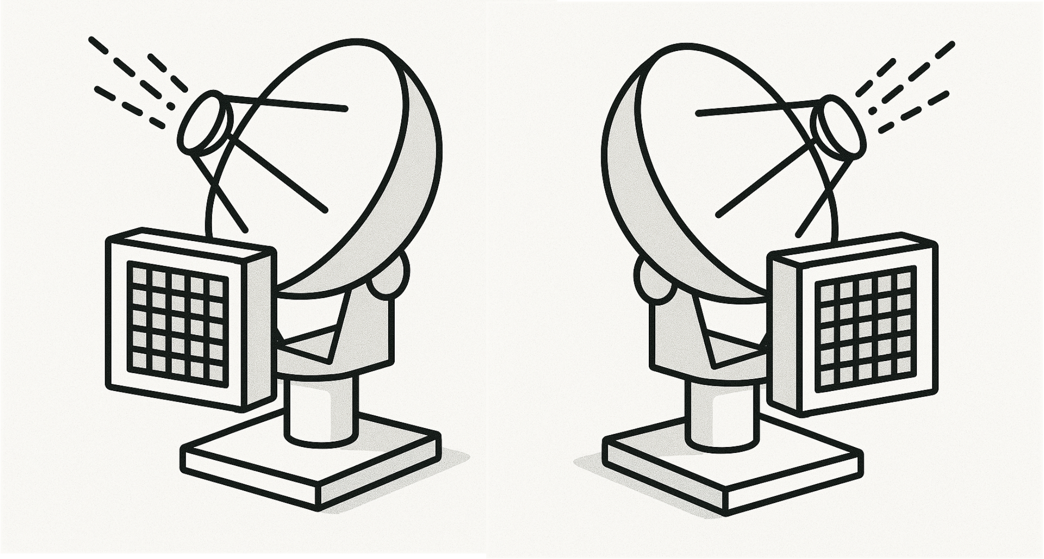
Not to scale

Background modeling

- Gamma/hadron separation is not perfect → hadronic background
- We need to estimate the number of background events in the region of interest





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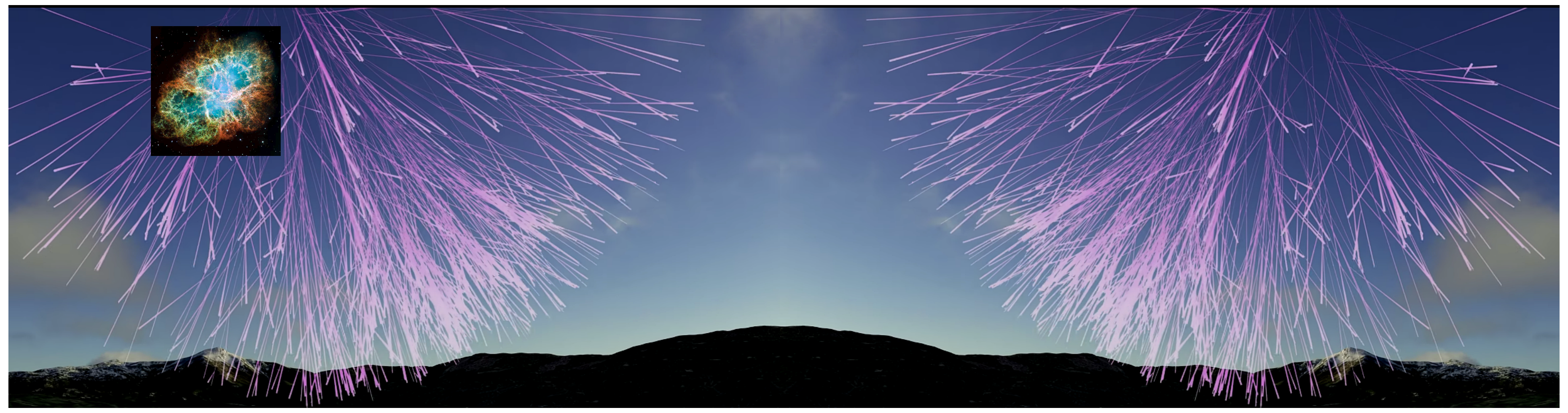
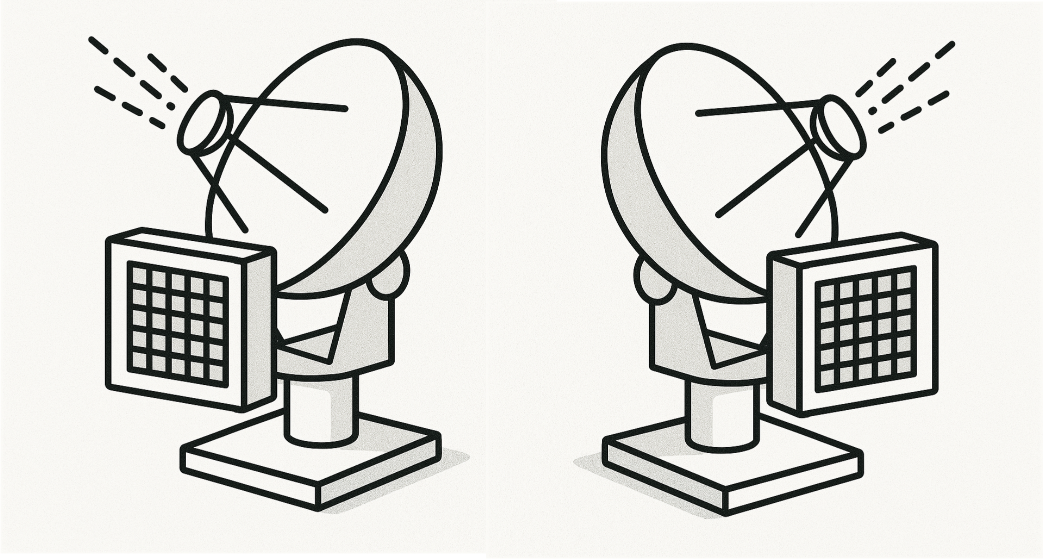
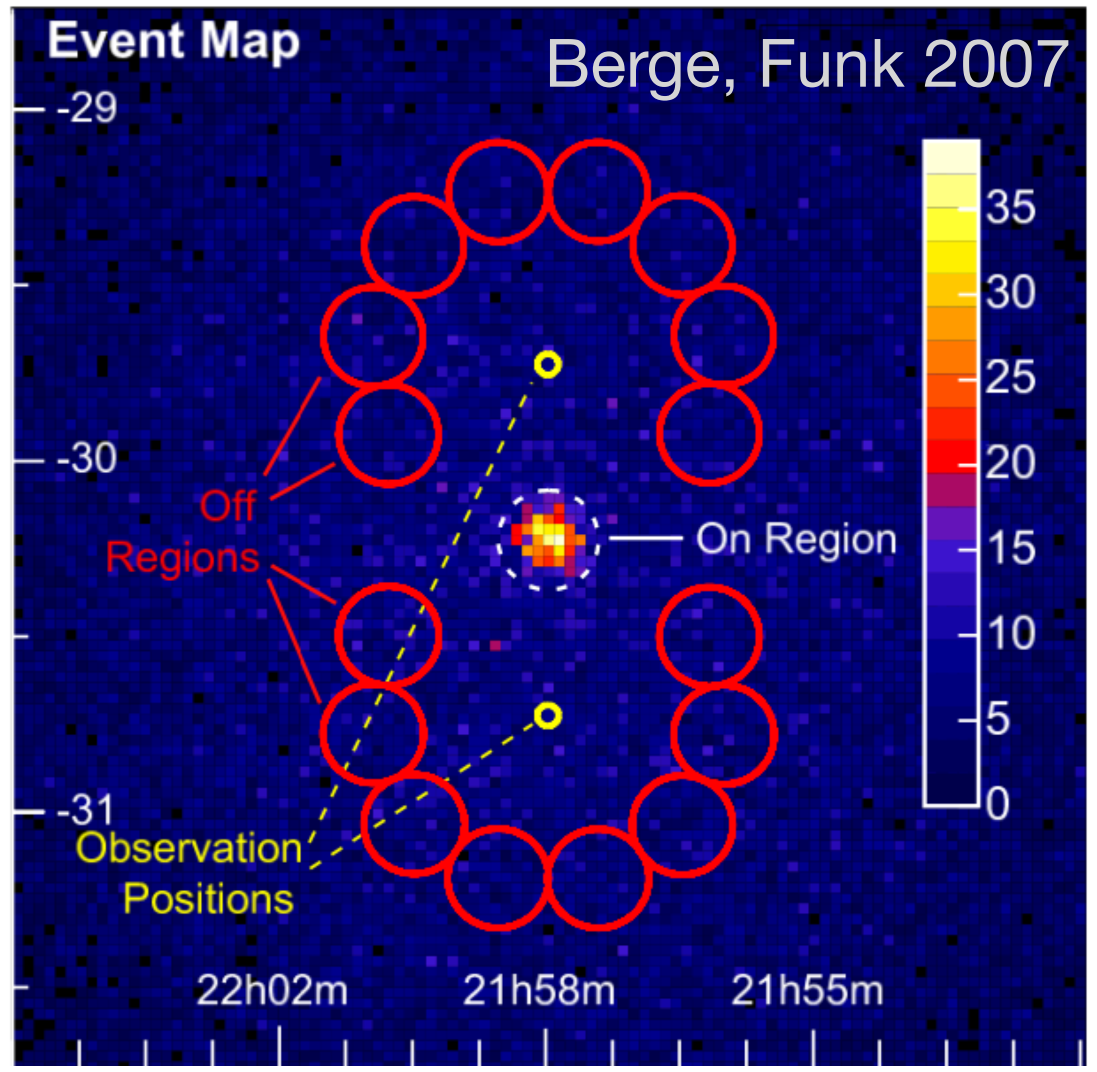




Reflected Background



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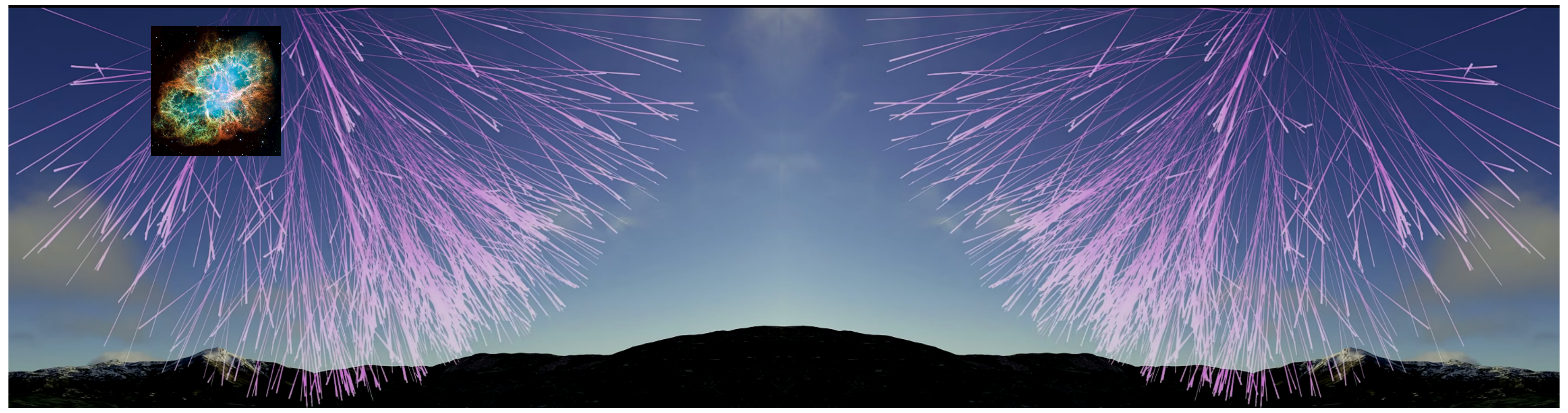

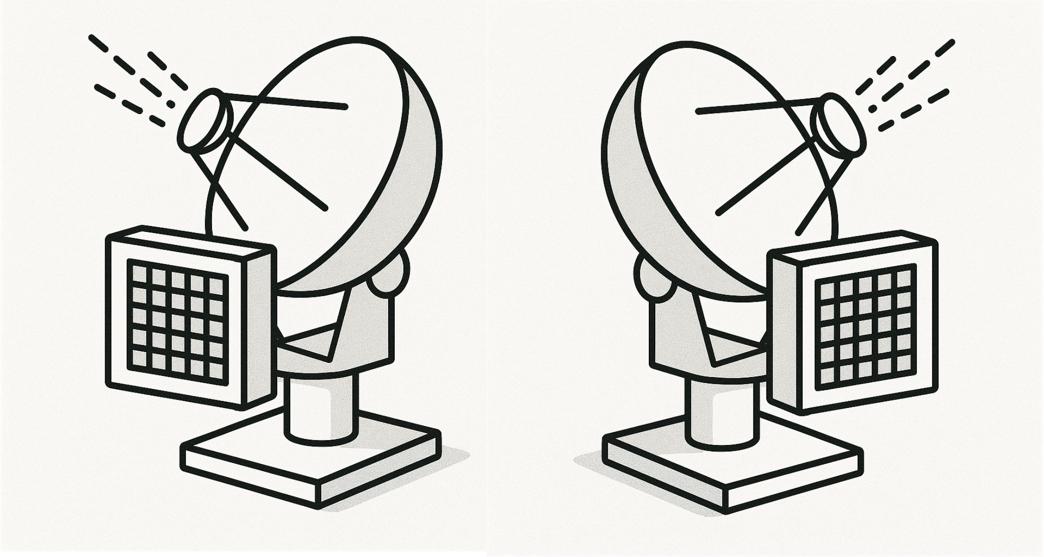

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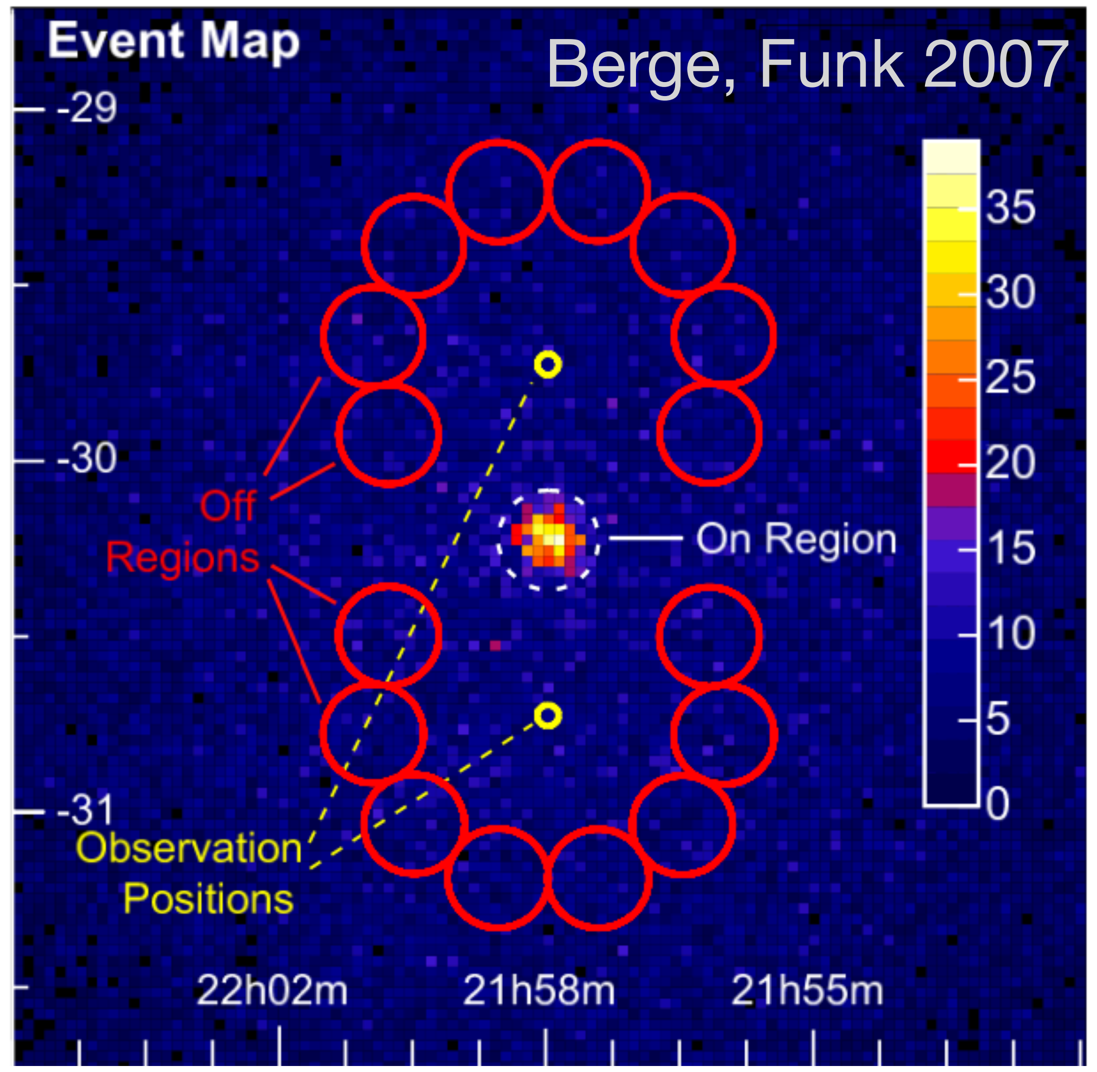
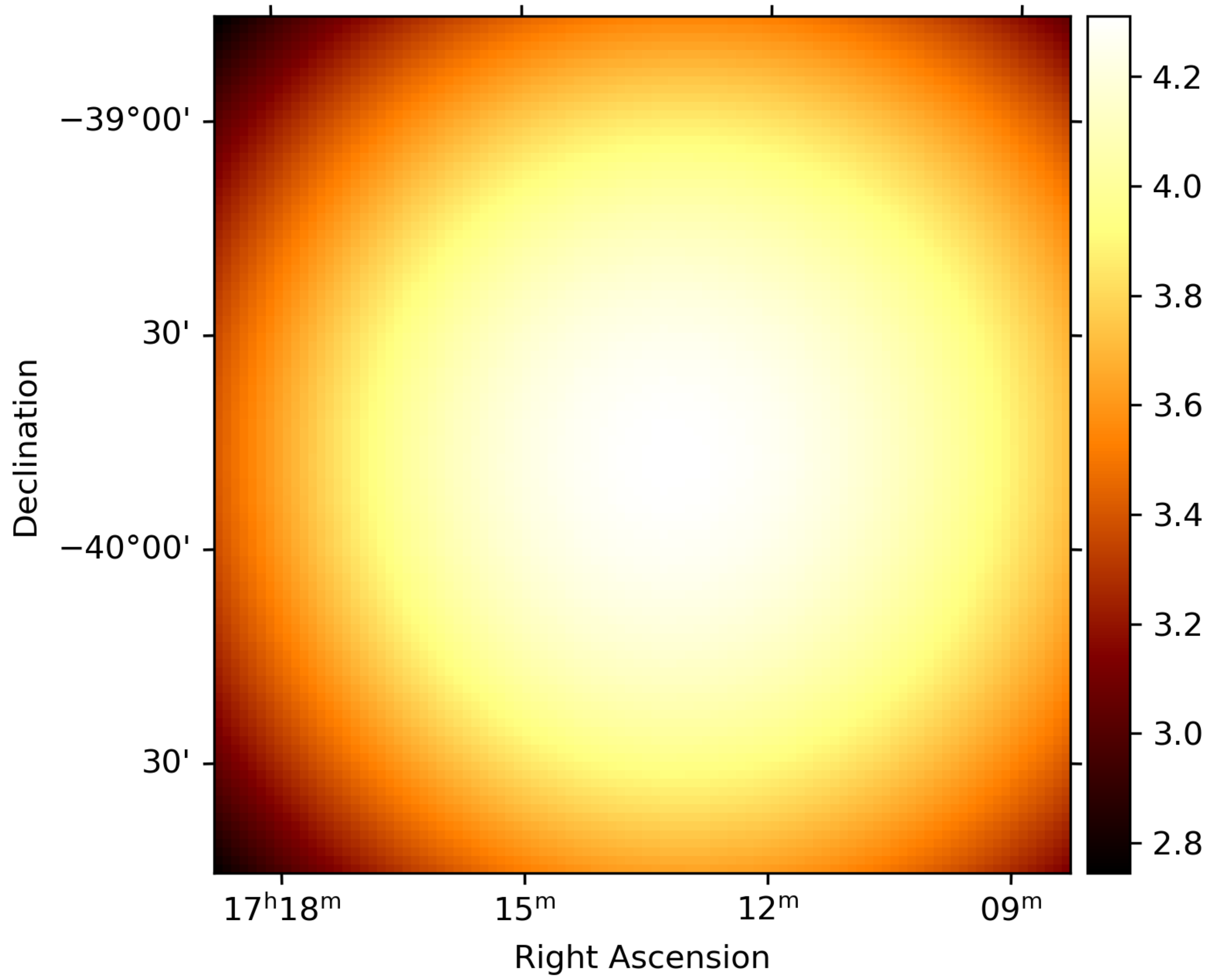


Background template



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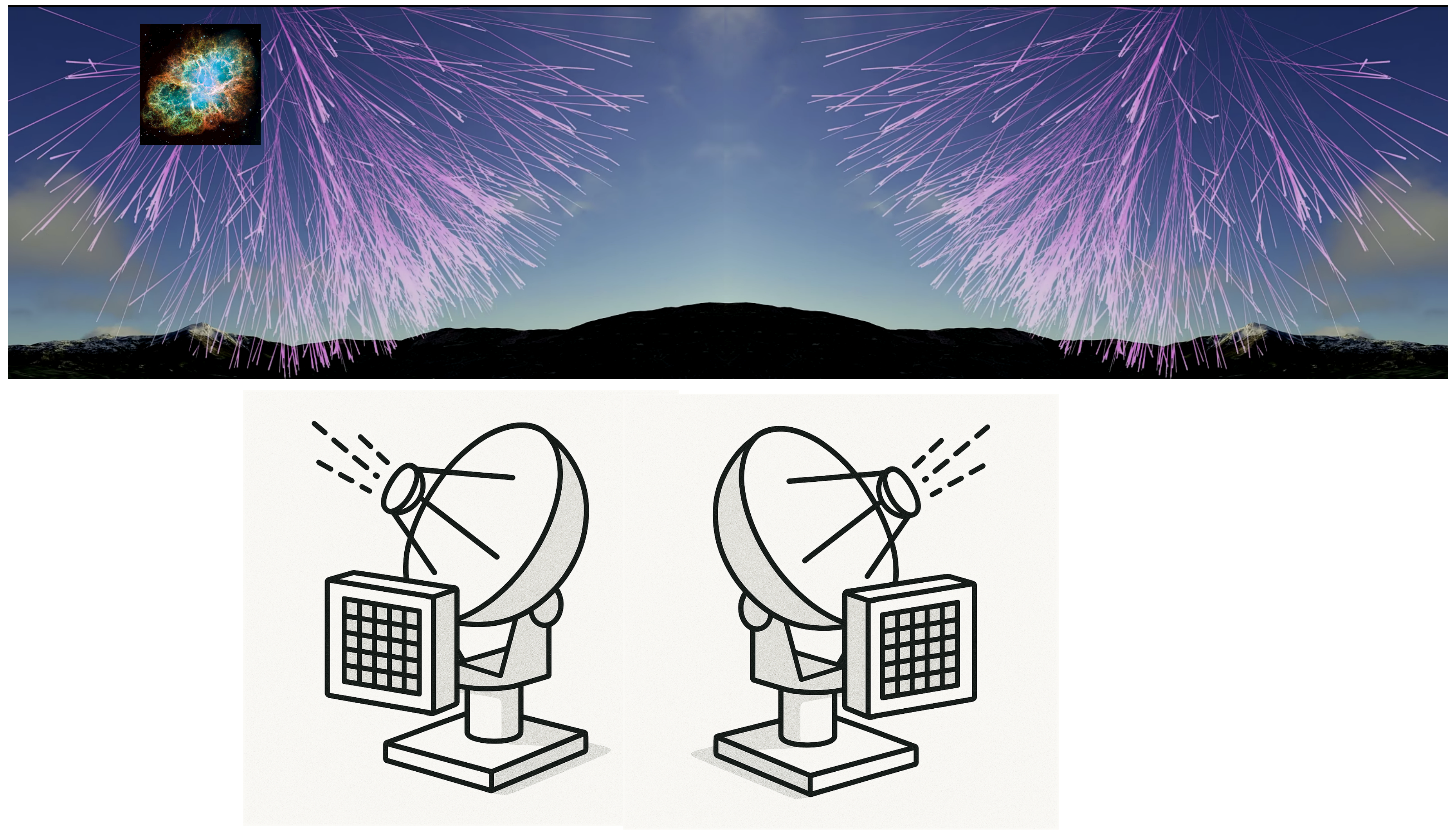

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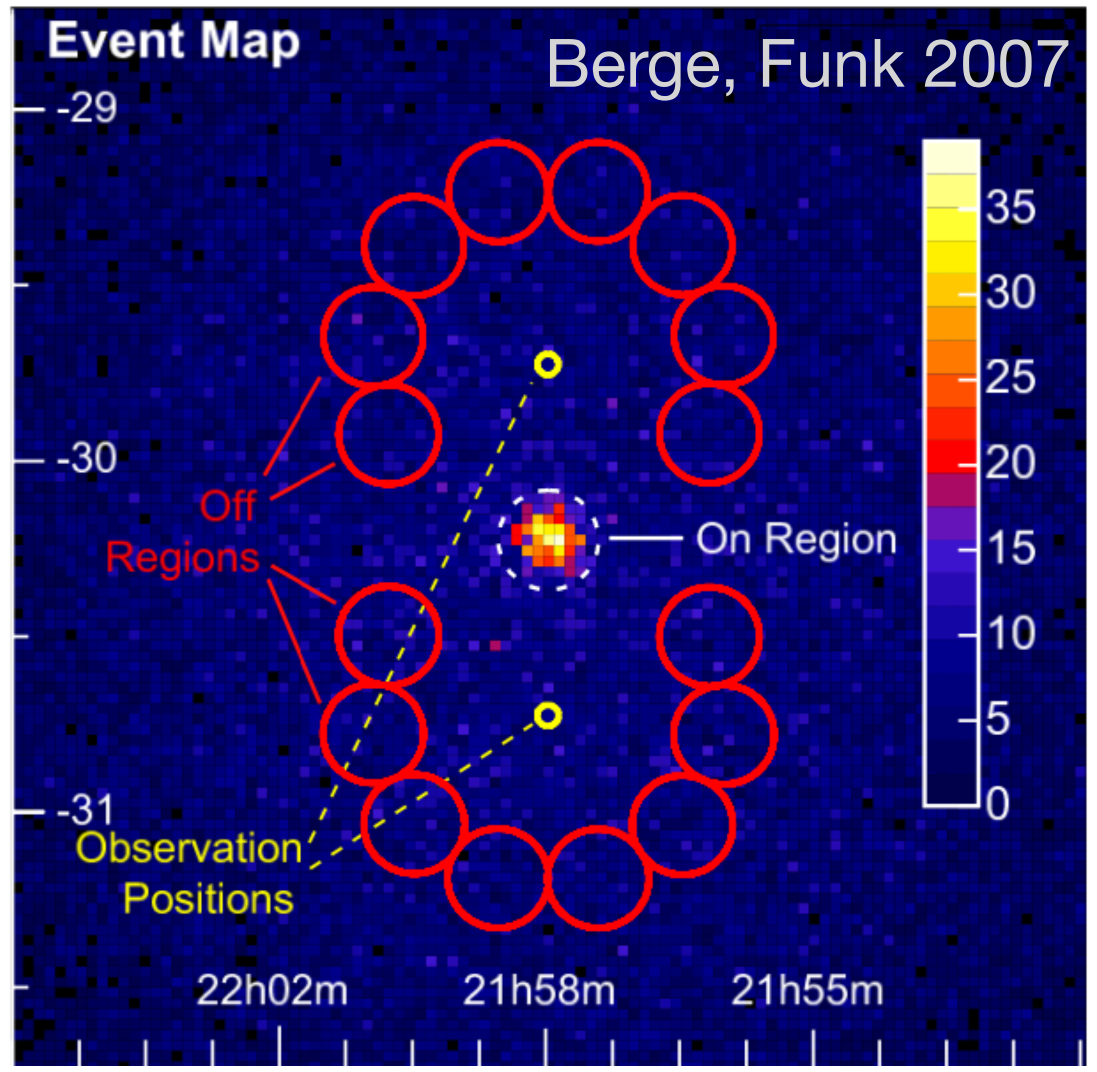

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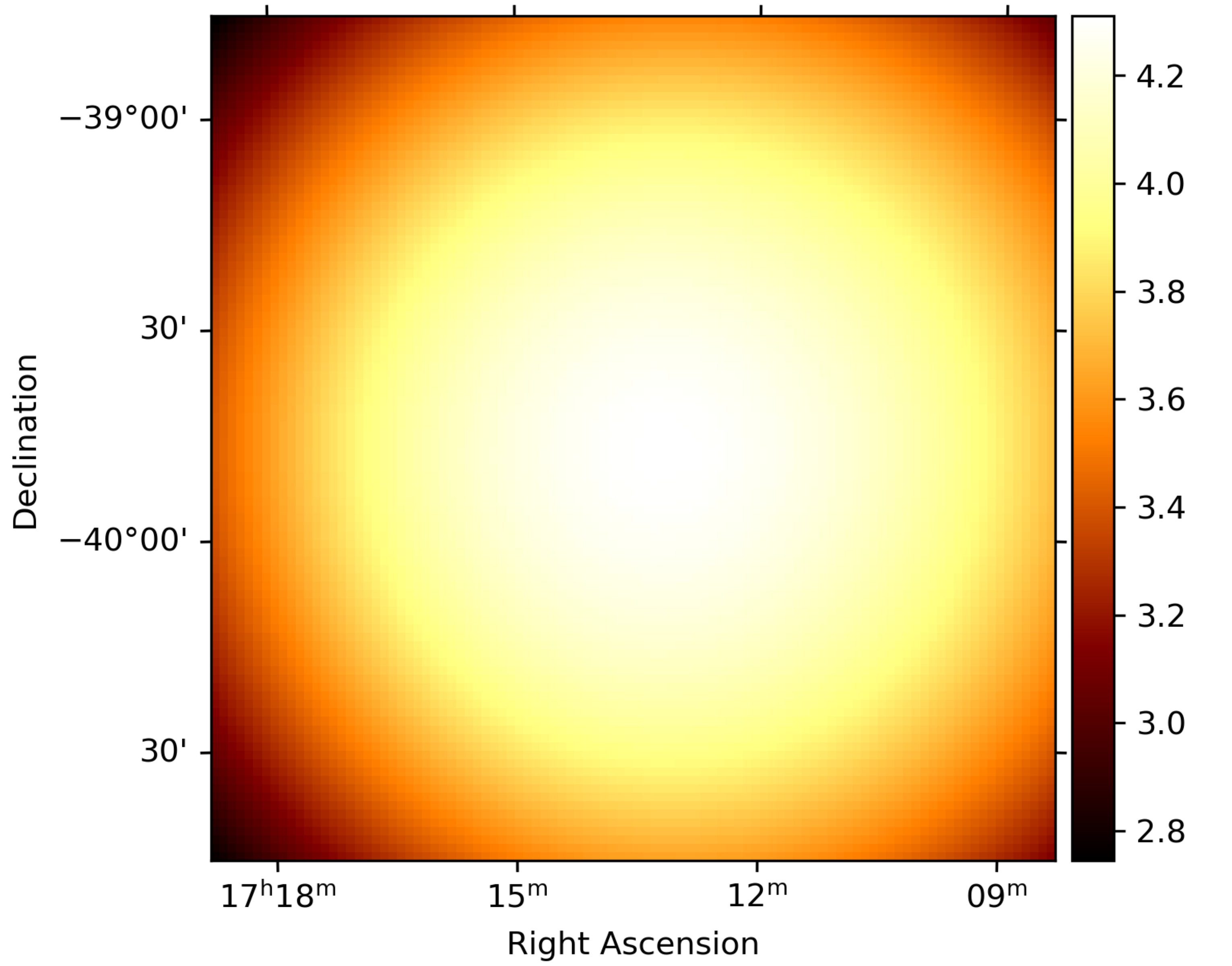


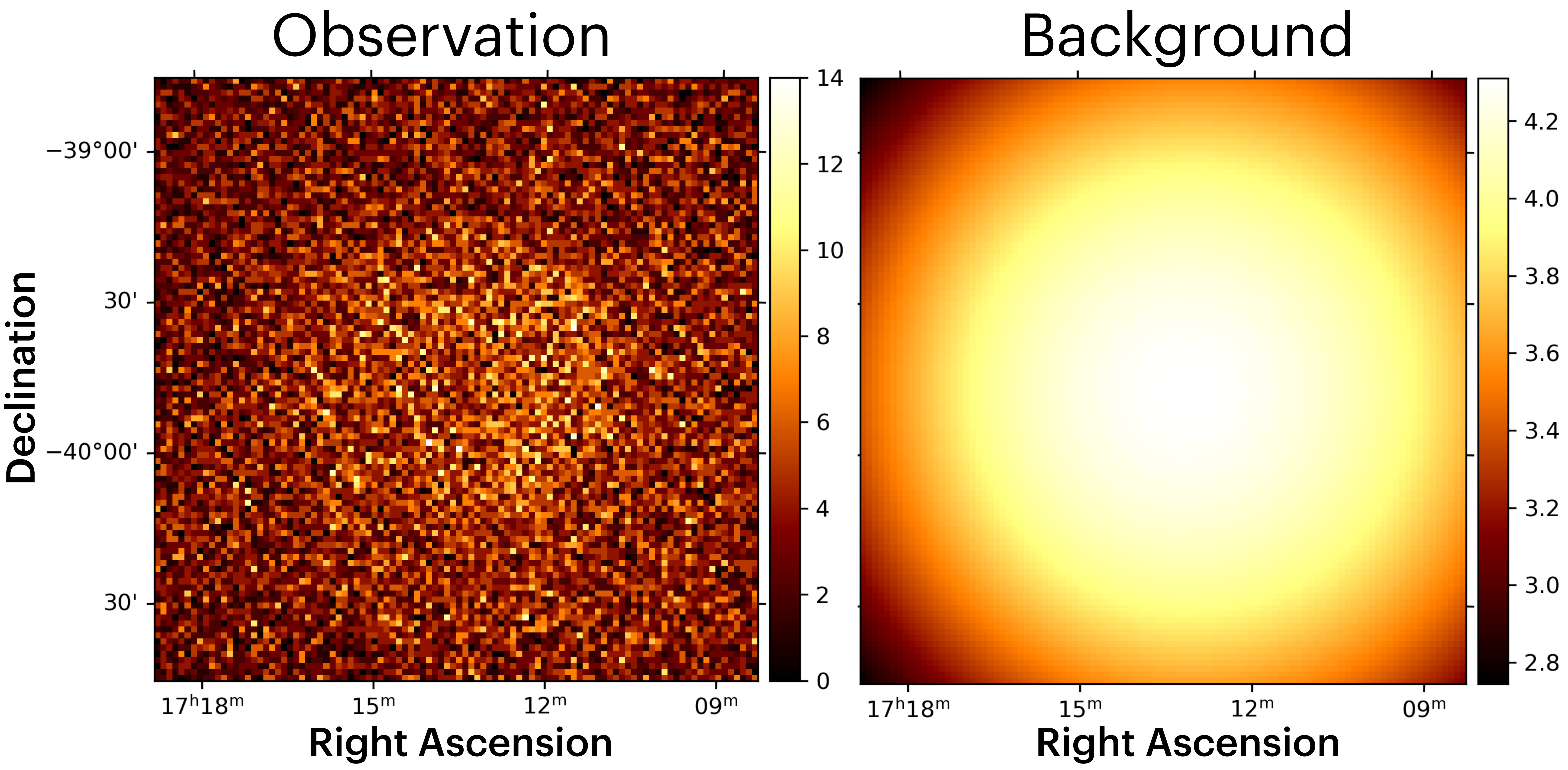
Lima Significance (1983)

$$S(N_{\text{on}}, N_{\text{off}}, \alpha) = \sqrt{-2\ln\Lambda} = \sqrt{2}\left\{N_{\text{on}} \ln\left[\frac{1+\alpha}{\alpha}\frac{N_{\text{on}}}{N_{\text{on}}+N_{\text{off}}}\right] + N_{\text{off}} \ln\left[(1+\alpha)\frac{N_{\text{off}}}{N_{\text{on}}+N_{\text{off}}}\right]\right\}^{1/2}$$

“S quantifies how likely it is that all counts from the “on region” were only due to background”

Example sky maps: RX J1713.7 3946

- 15 observations from 2004 released in HESS open data 2018



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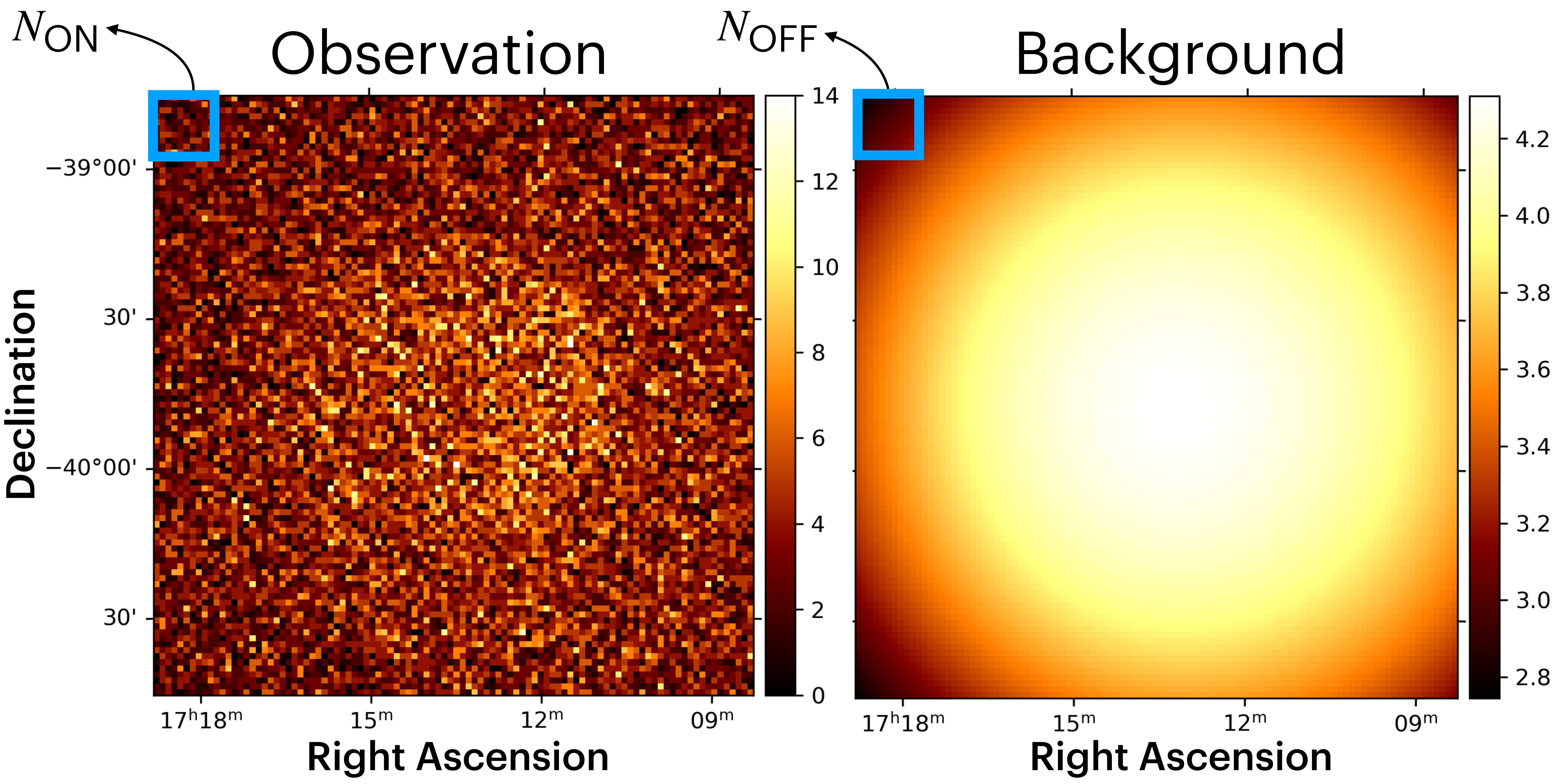

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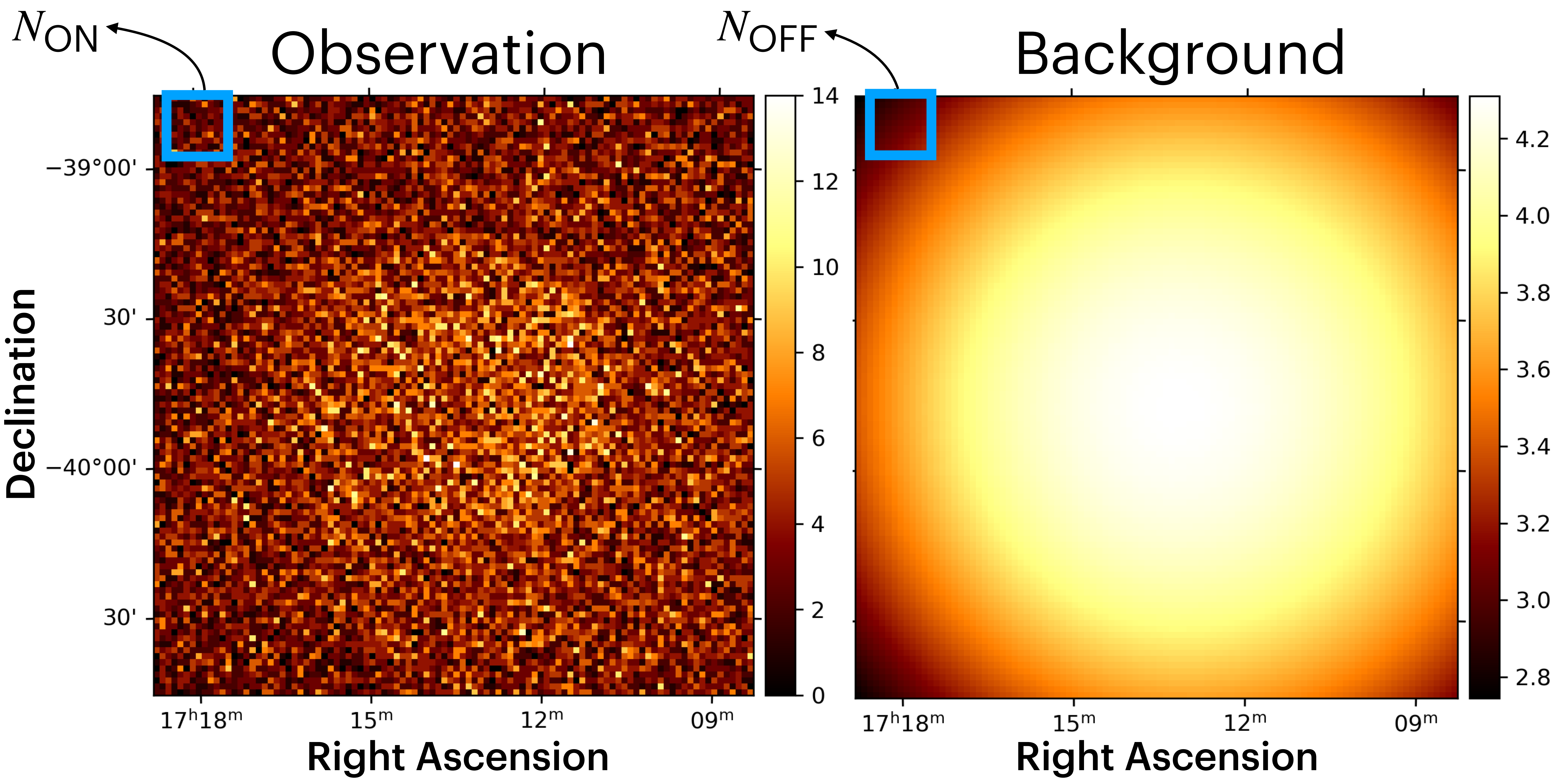

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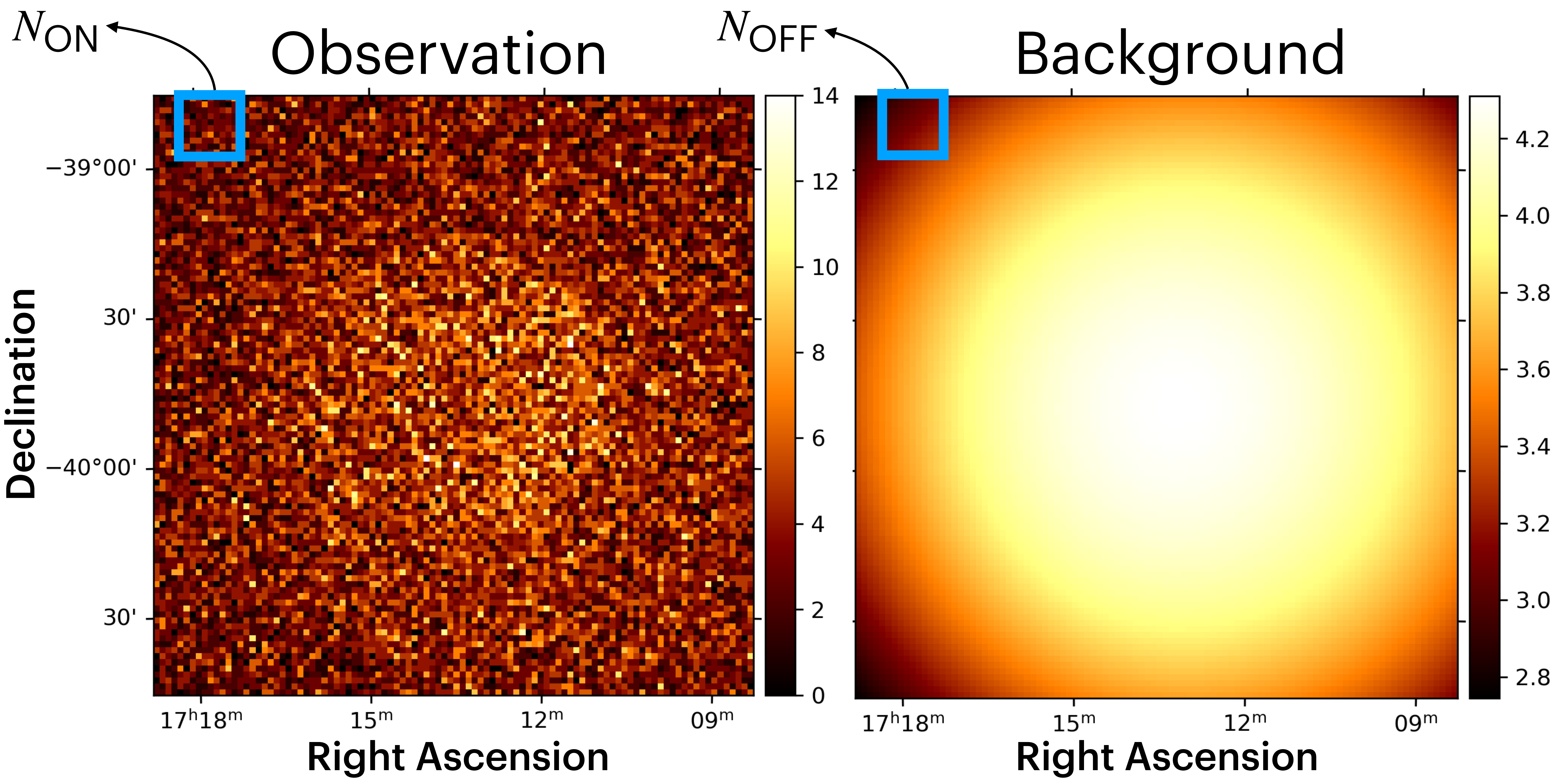

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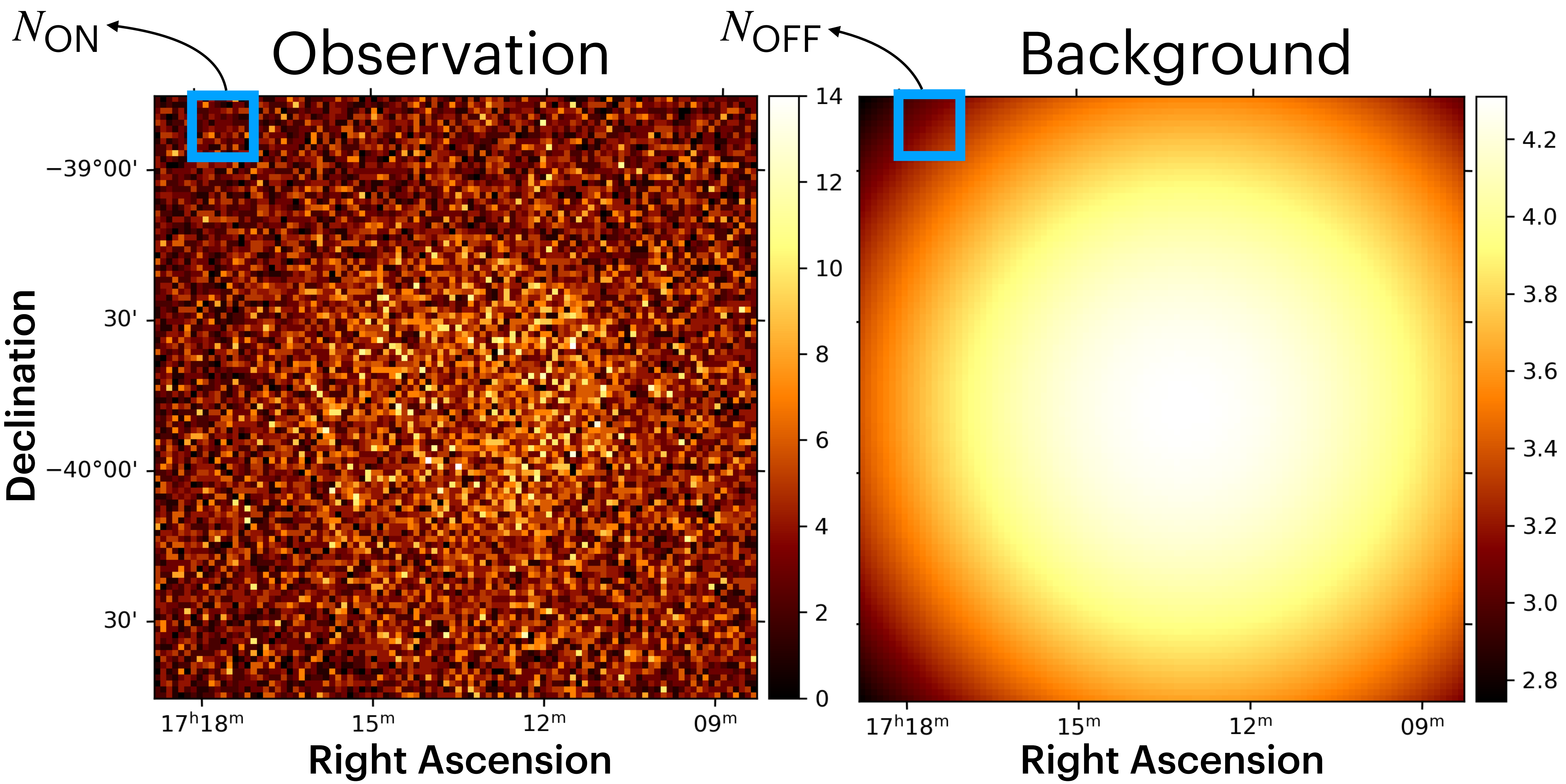

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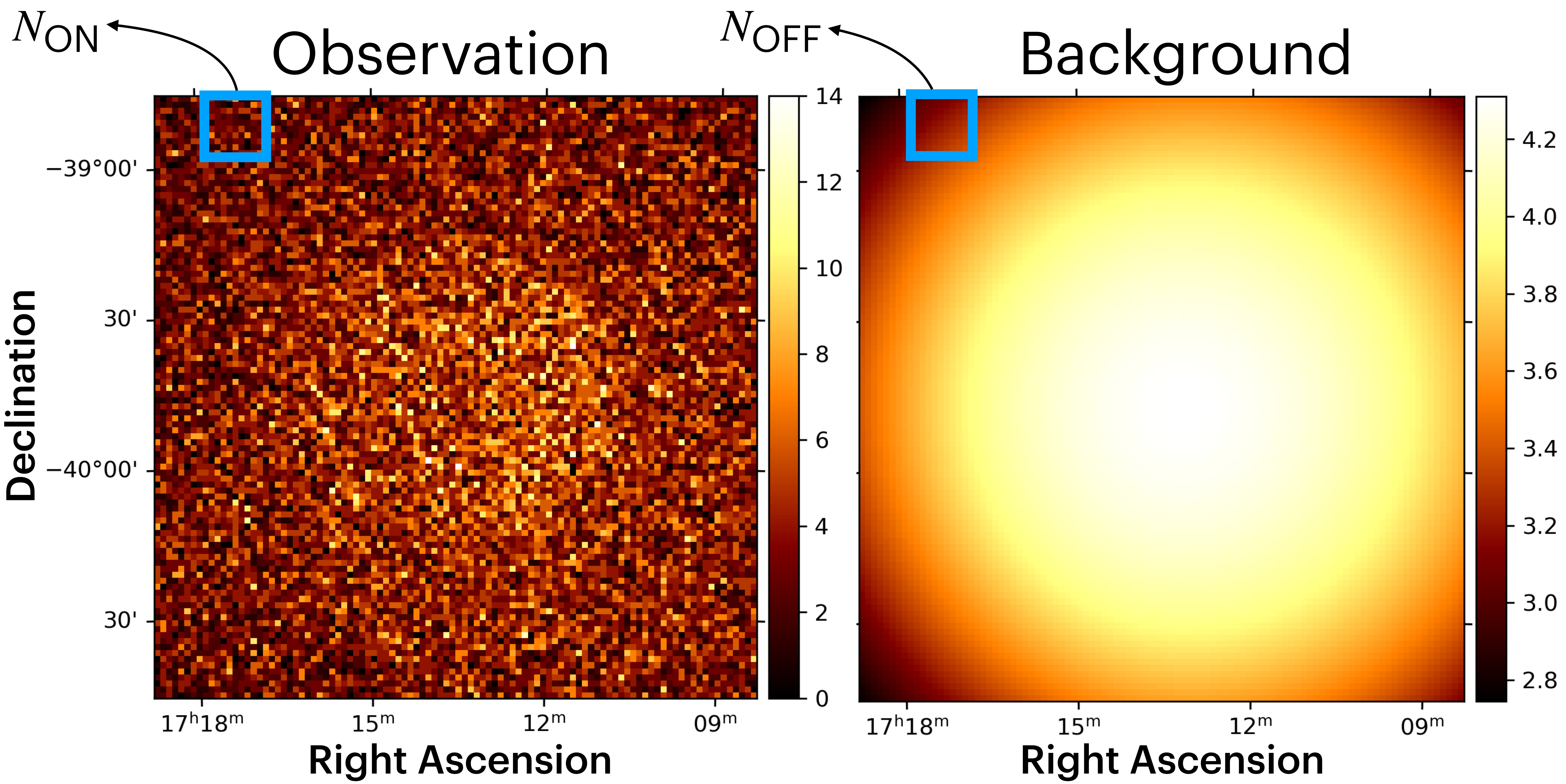

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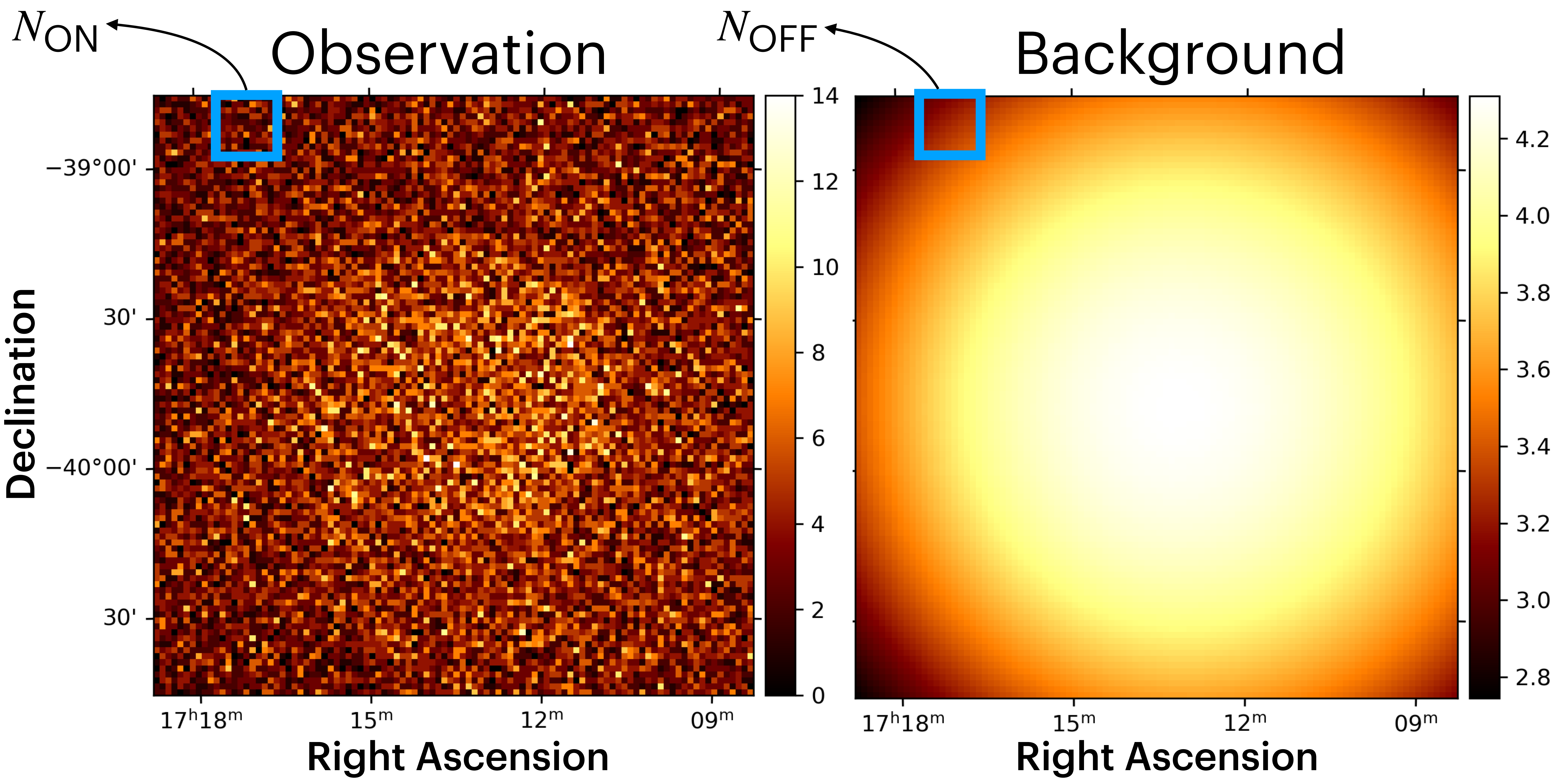

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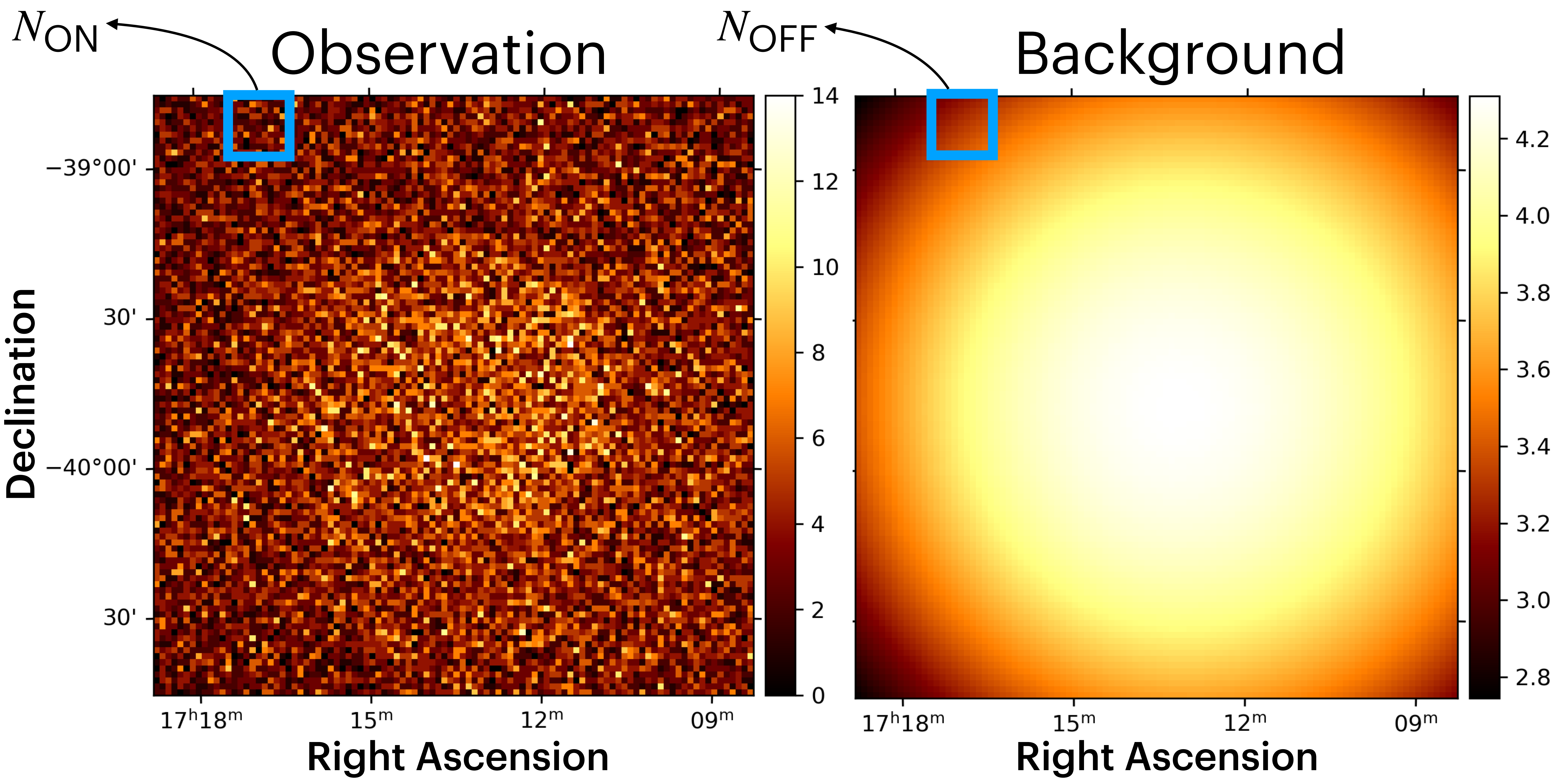

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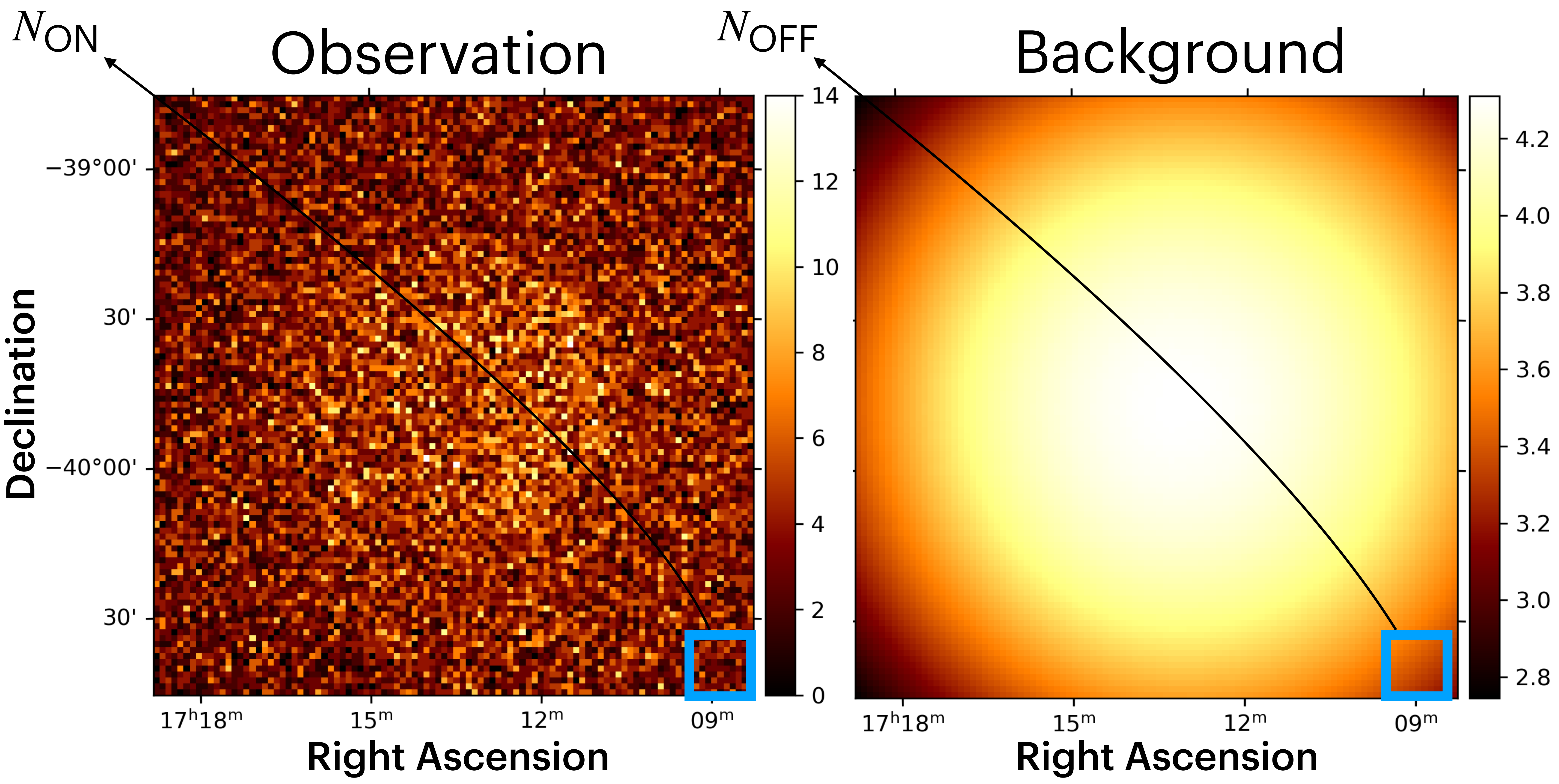

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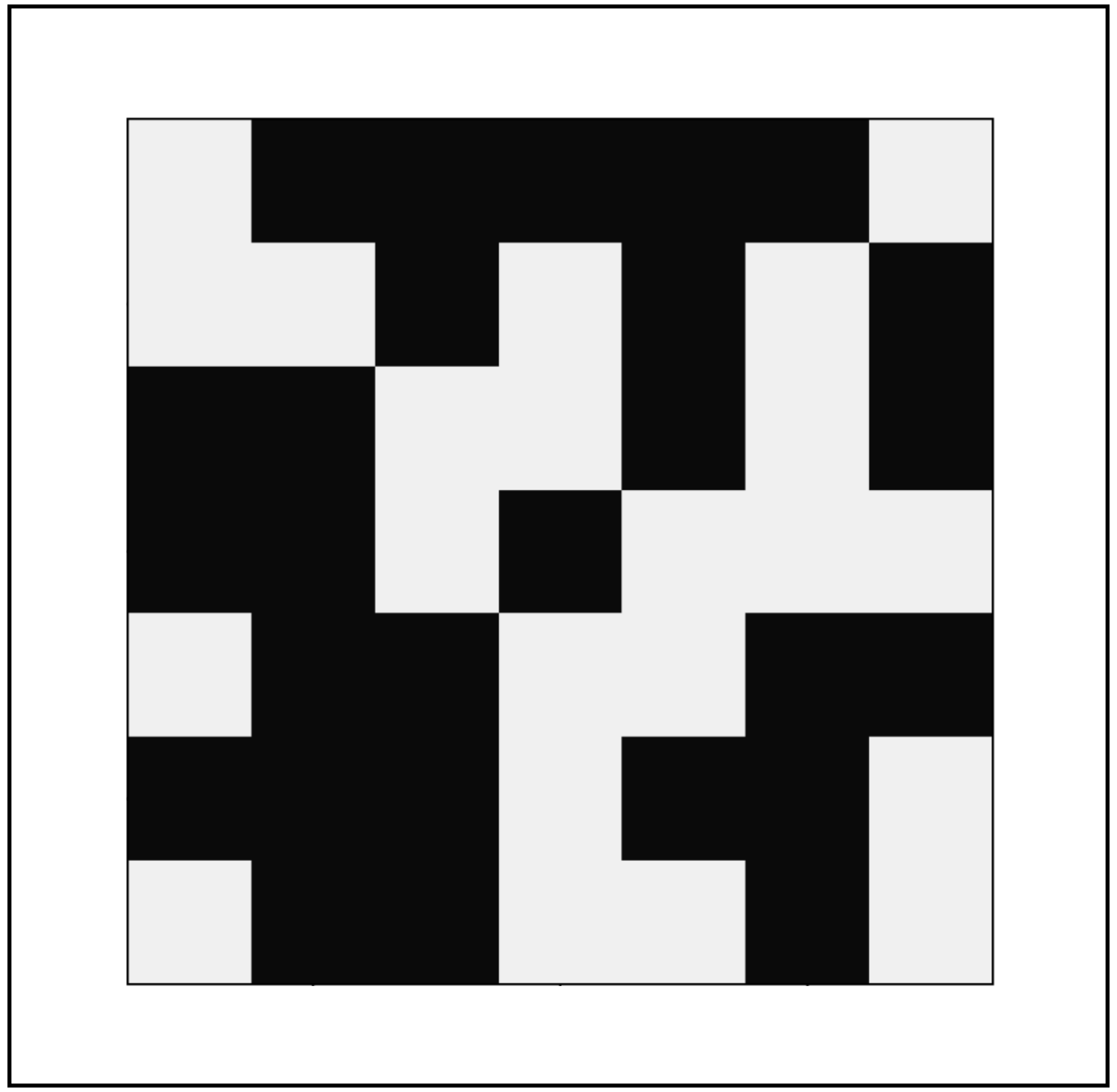
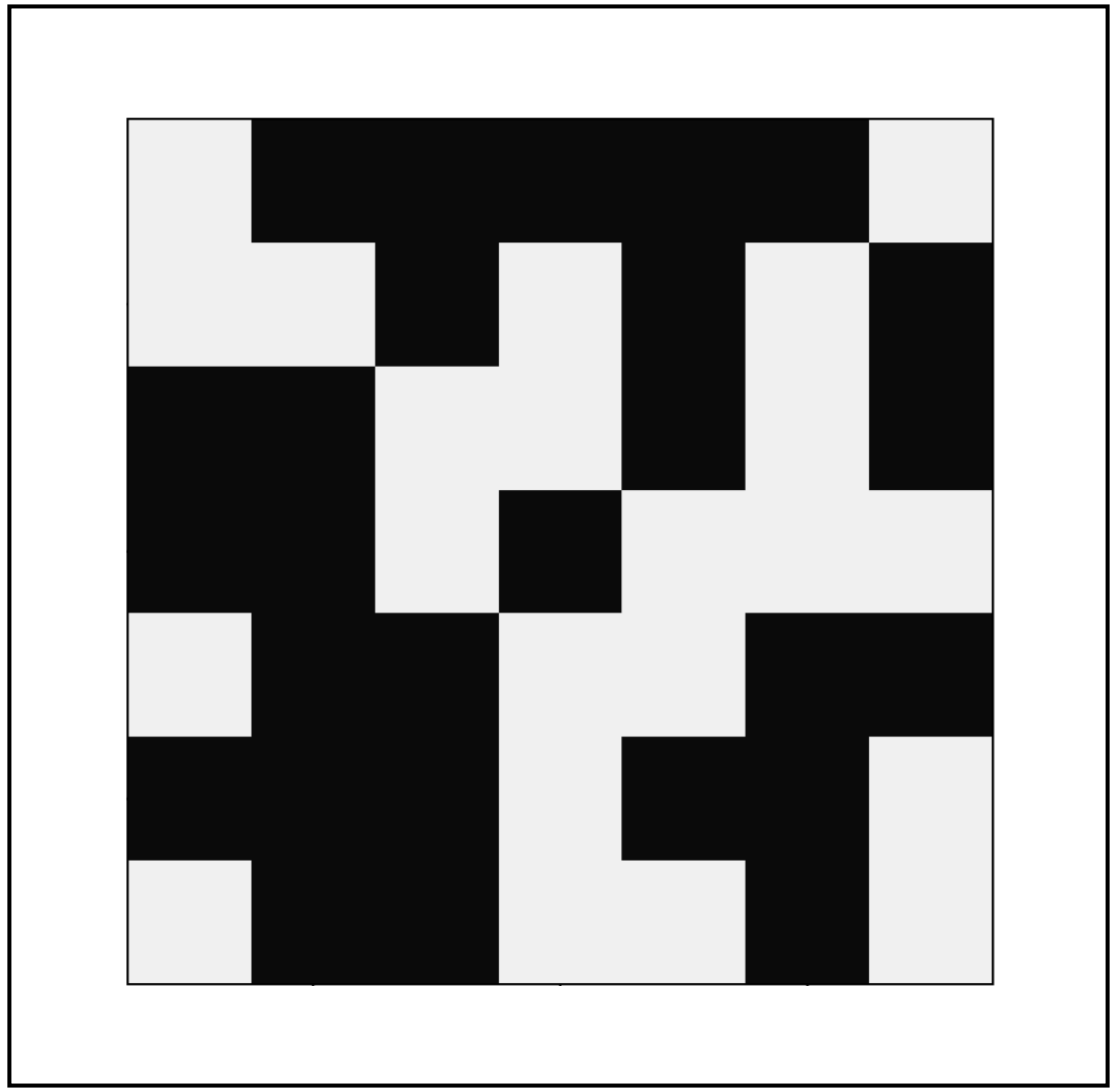
Statistical physics



How can we quantify the structure of the black and white image?



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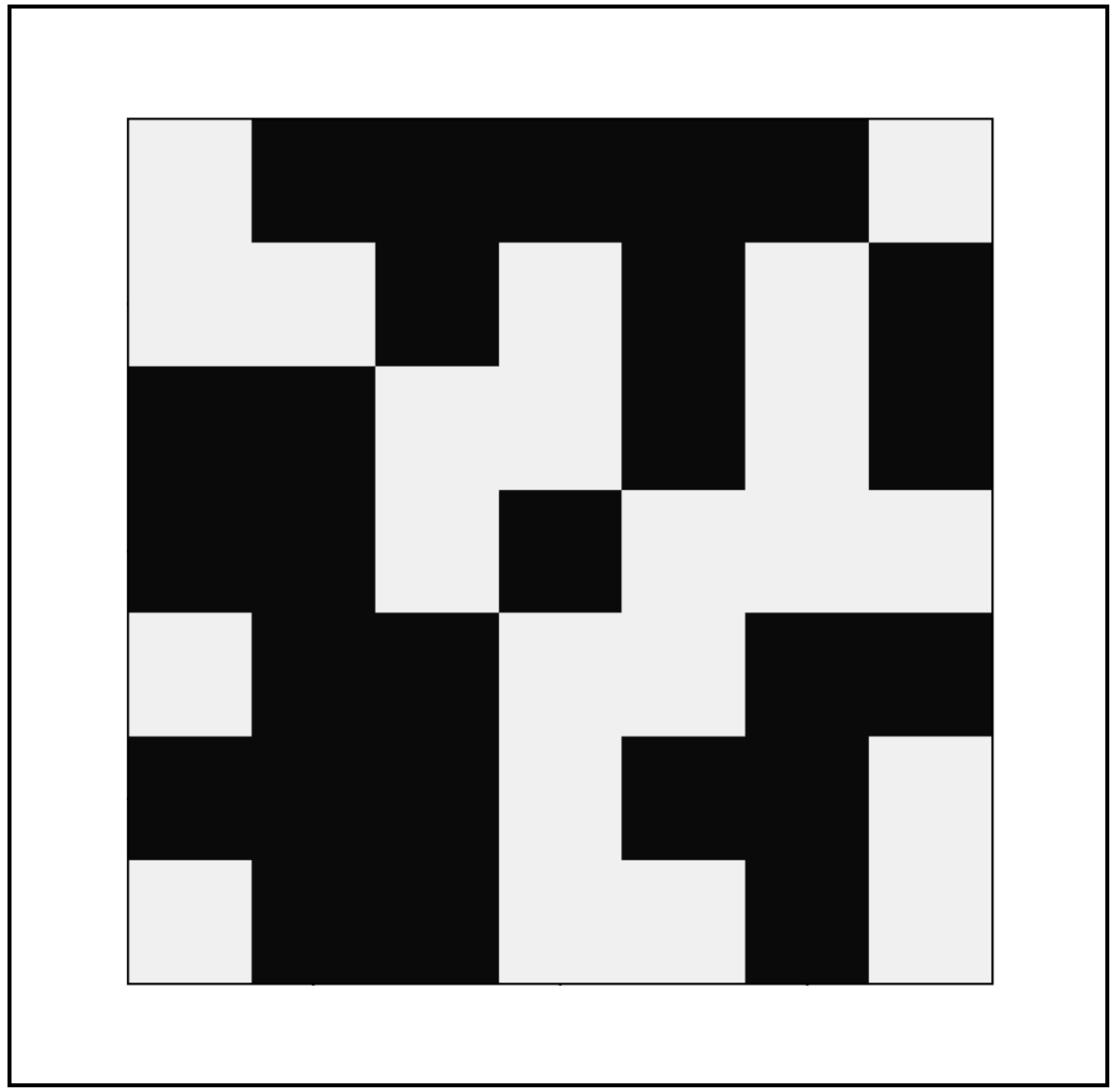
One way: **Minkowski Functionals**

Example

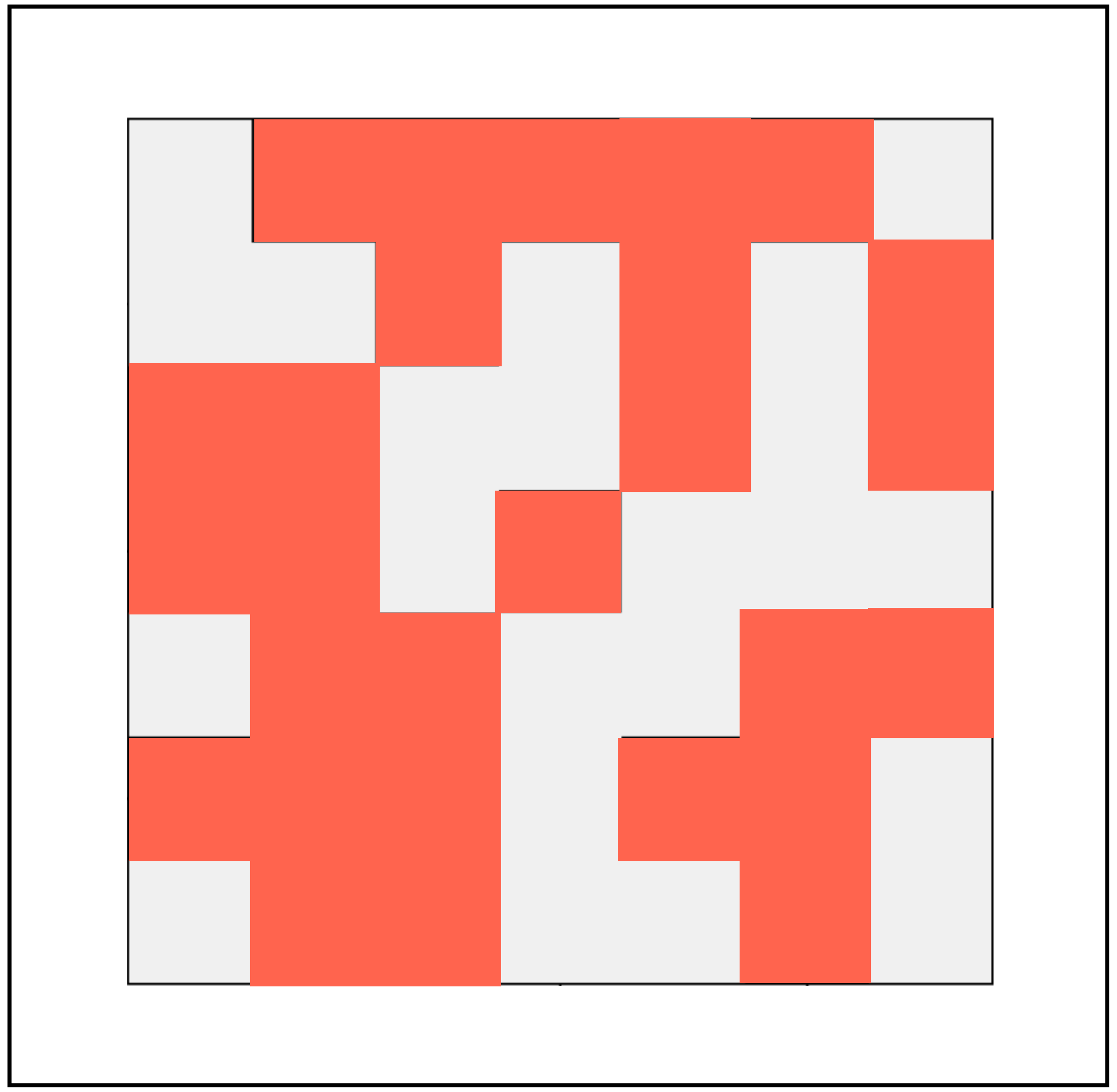
In two dimensions there are 3 such functionals. (fullfilling some desirable properties)



Example

In two dimensions there are 3 such functionals. (fullfilling some desireable properties)

Area: 27



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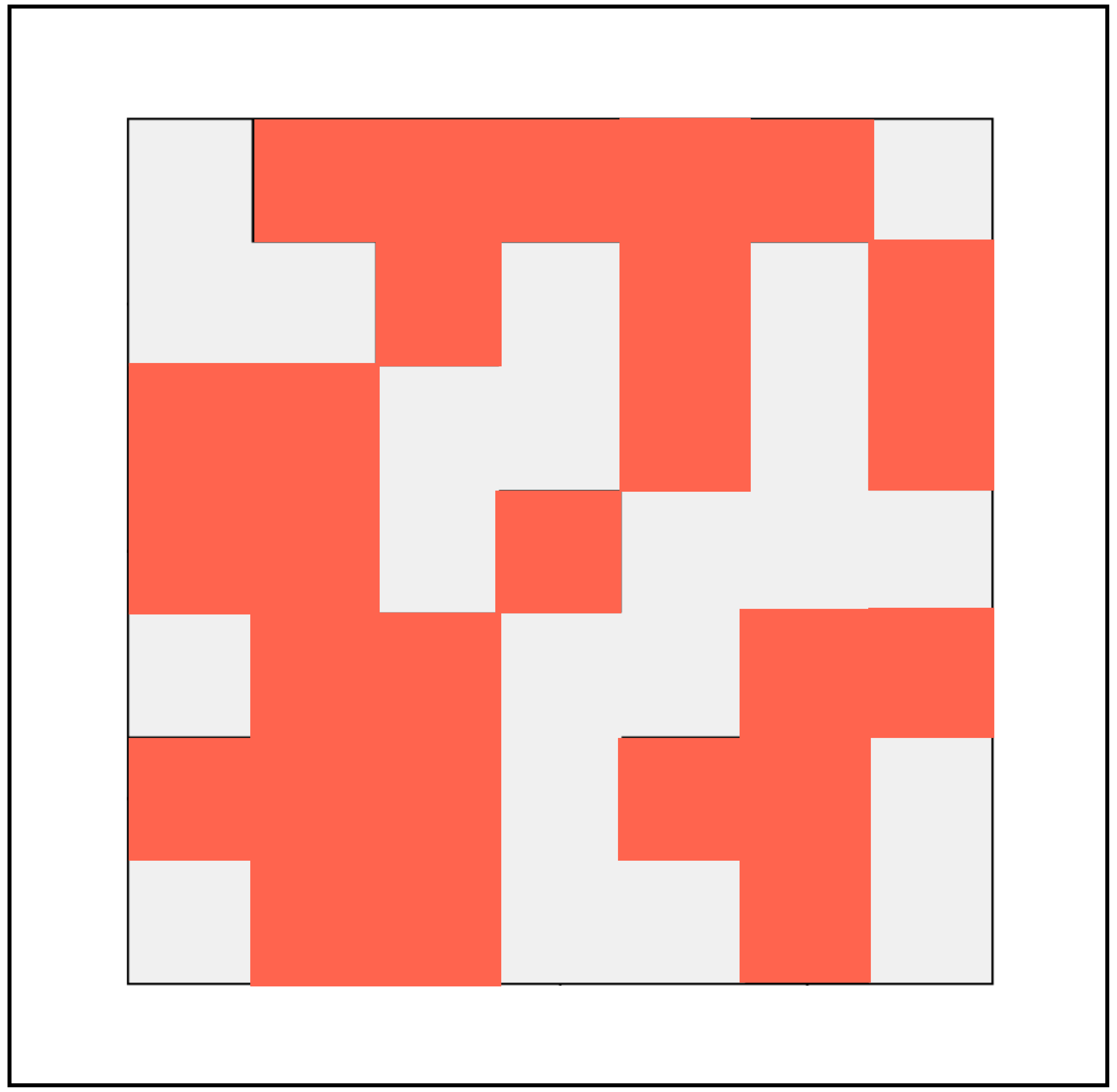
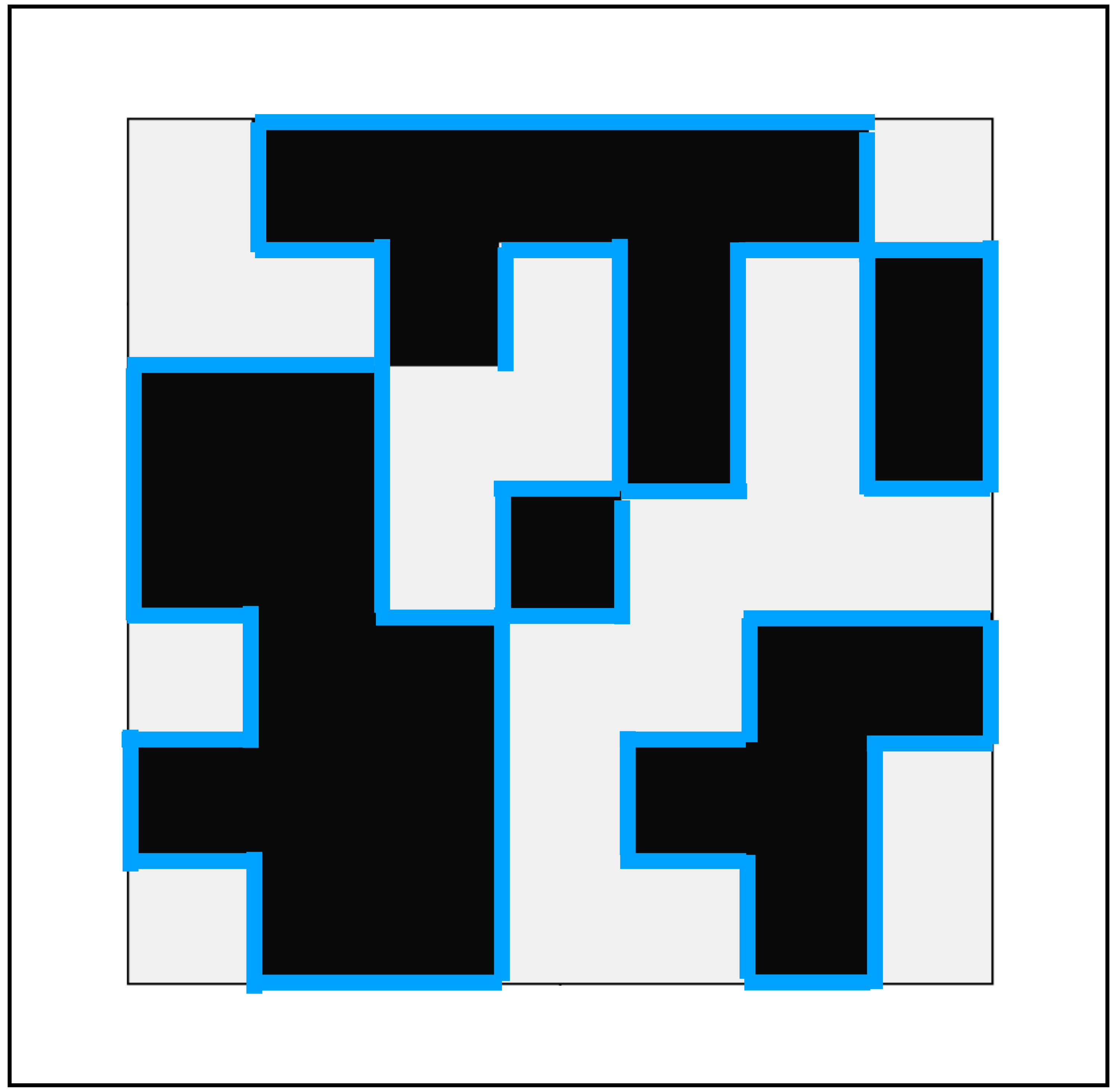


Perimeter: 58



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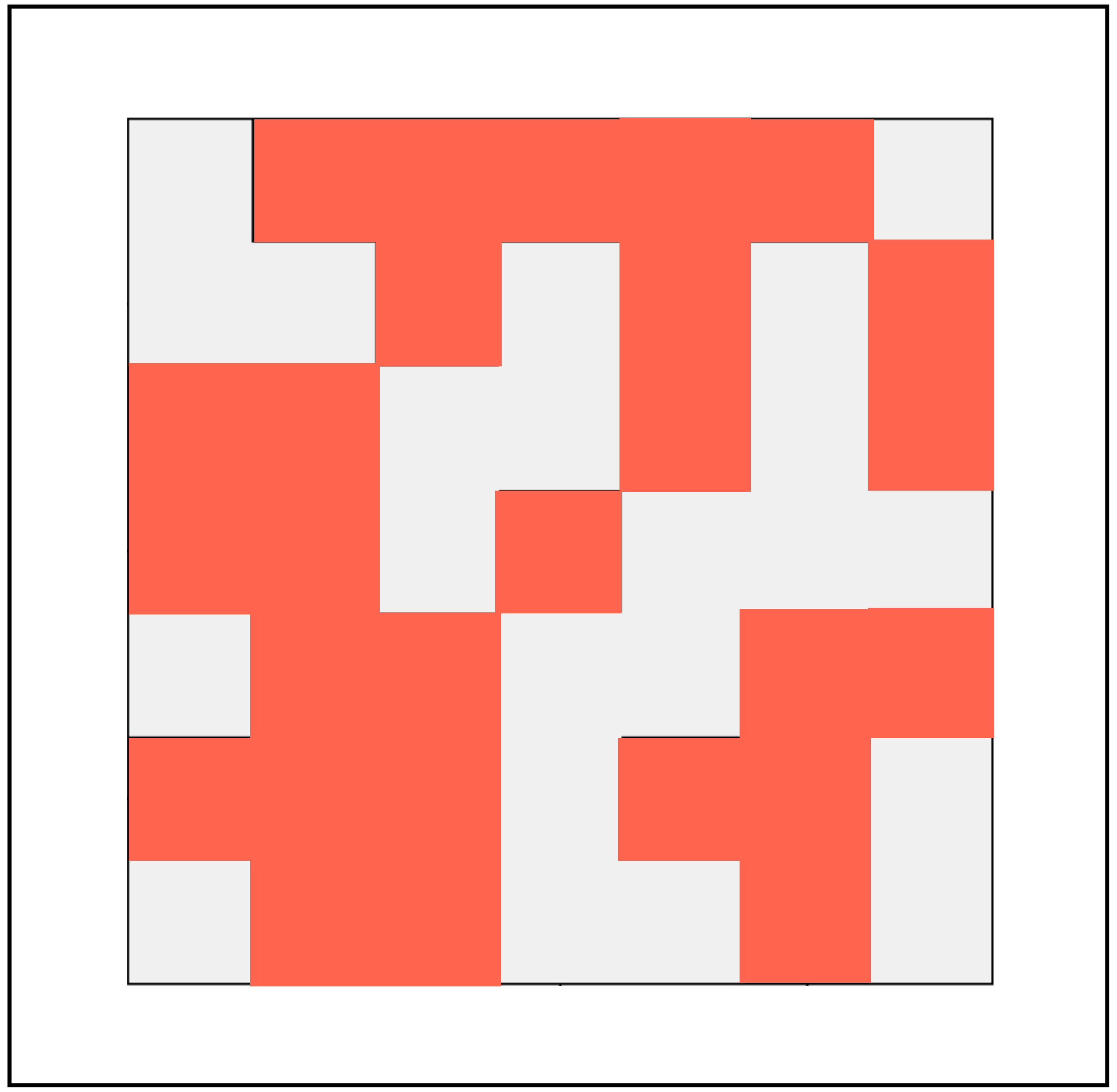

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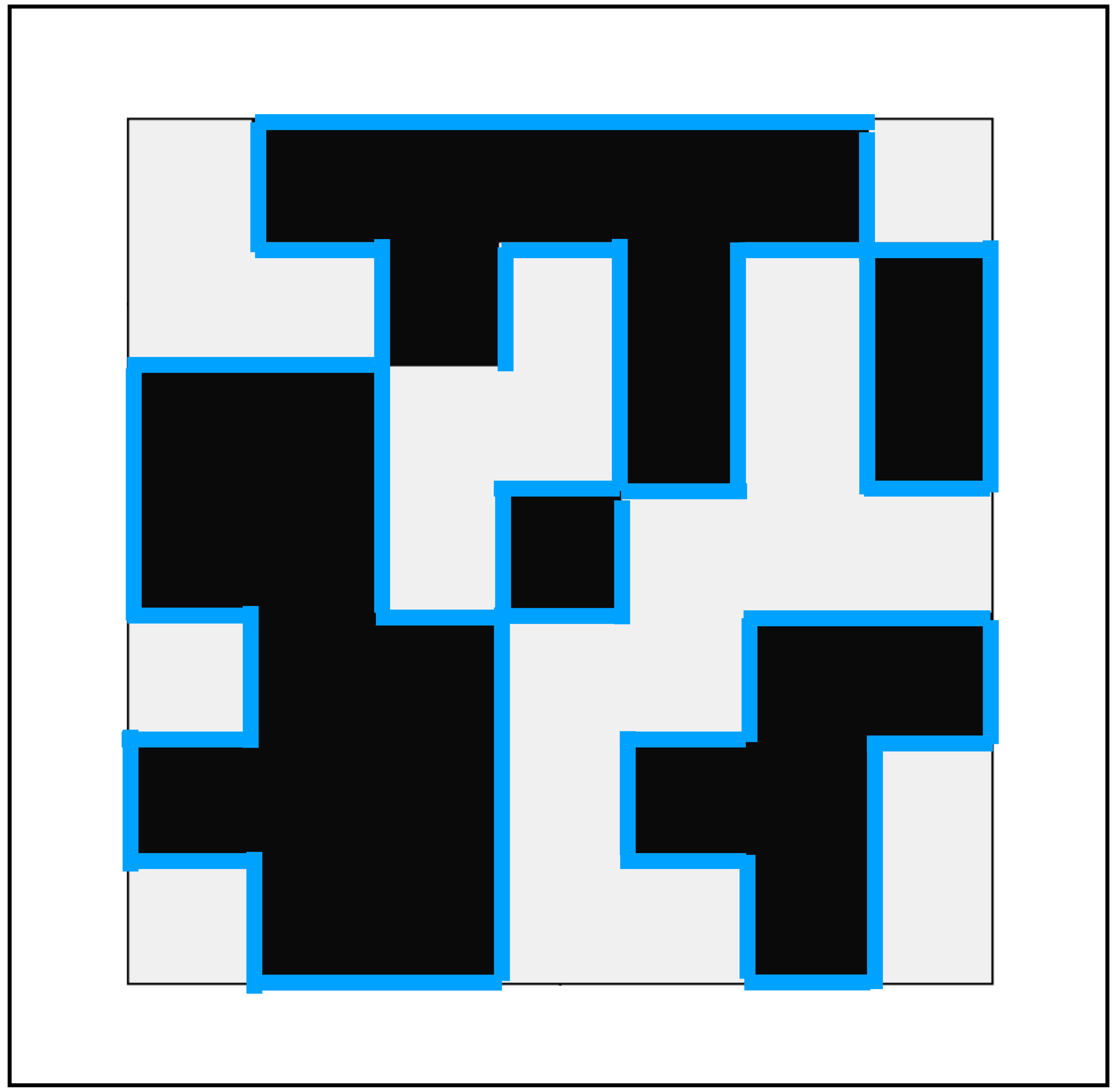
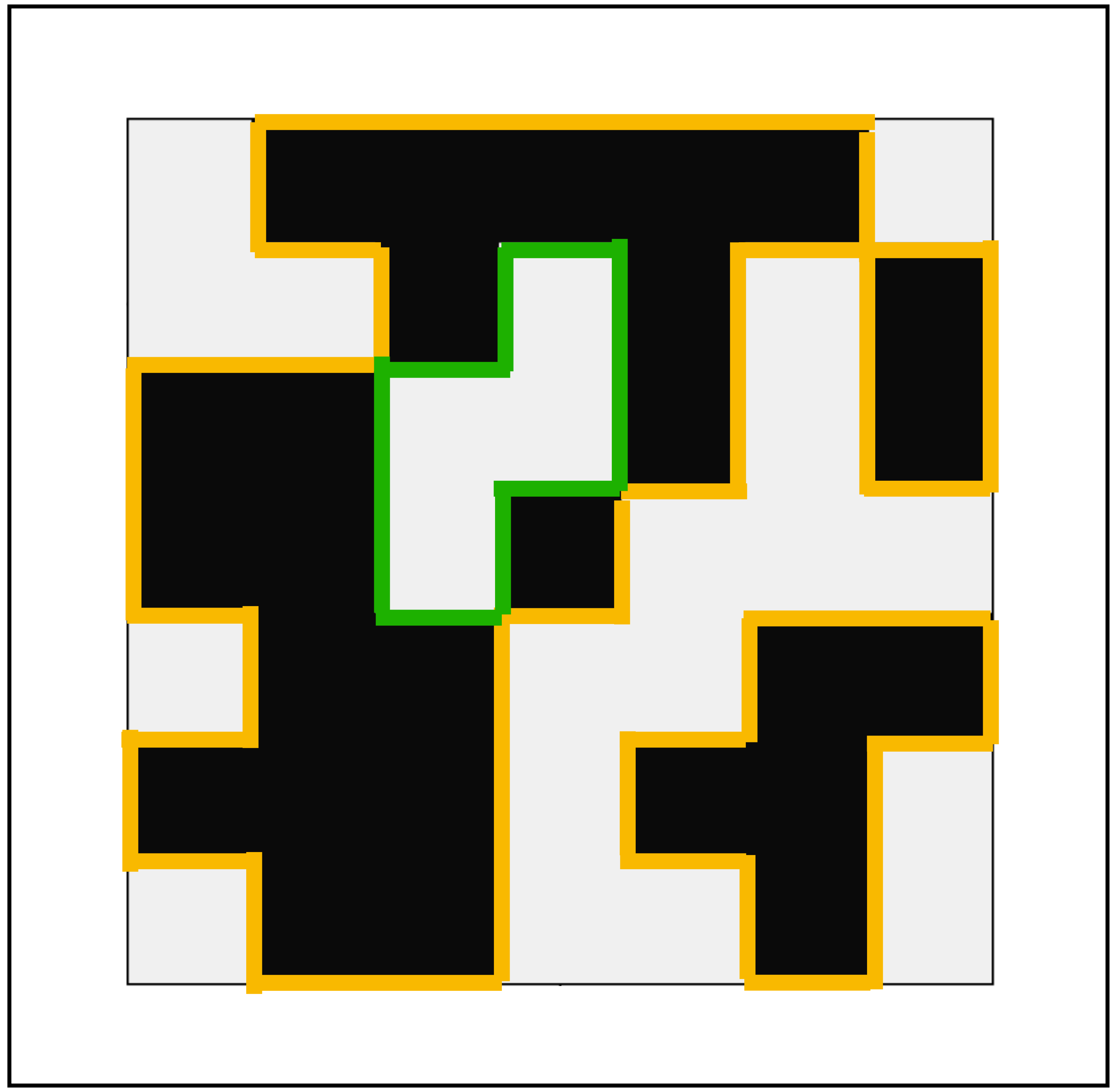
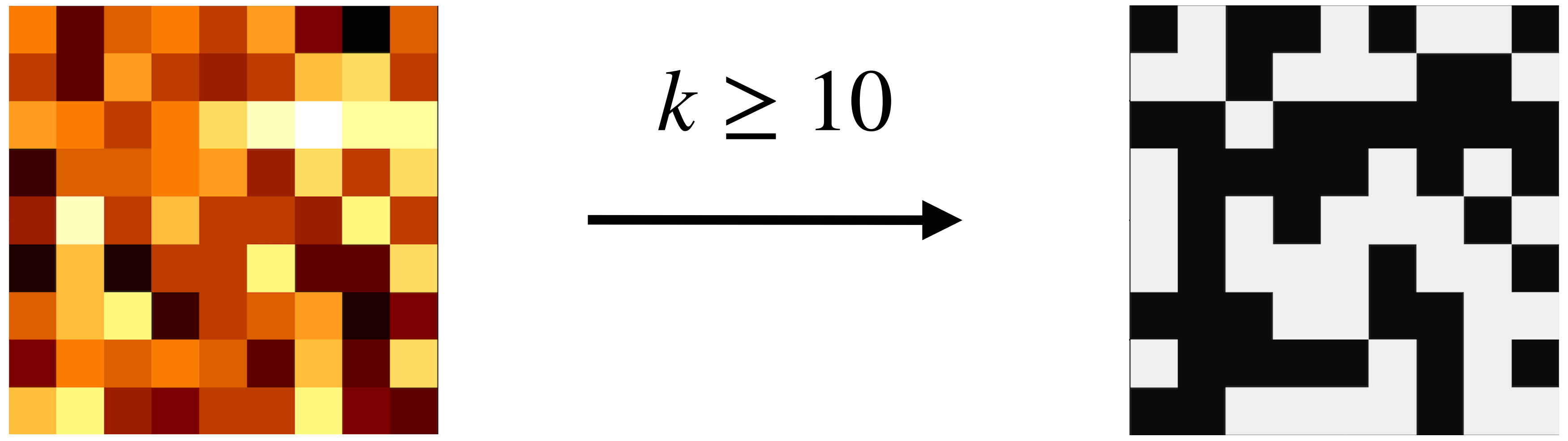


Euler Characteristic: 1



Minkowski functionals and gamma-ray astronomy

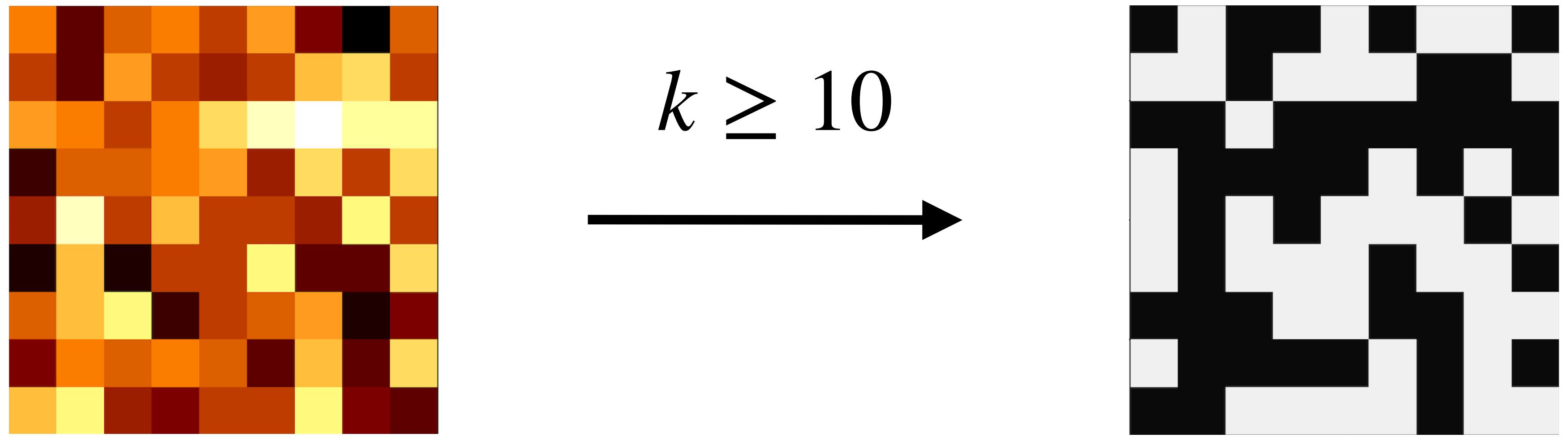
- Cosmic ray events will be isotropically distributed in all directions → homogeneous Poisson background
- Generate black and white images by thresholding



A: 42, P: 96, χ: 1

Minkowski functionals and gamma-ray astronomy

- Cosmic ray events will be isotropically distributed in all directions → homogeneous Poisson background
- Generate black and white images by thresholding
- We can calculate all possible black and white images for a certain system size N → distributions for Minkowski functionals



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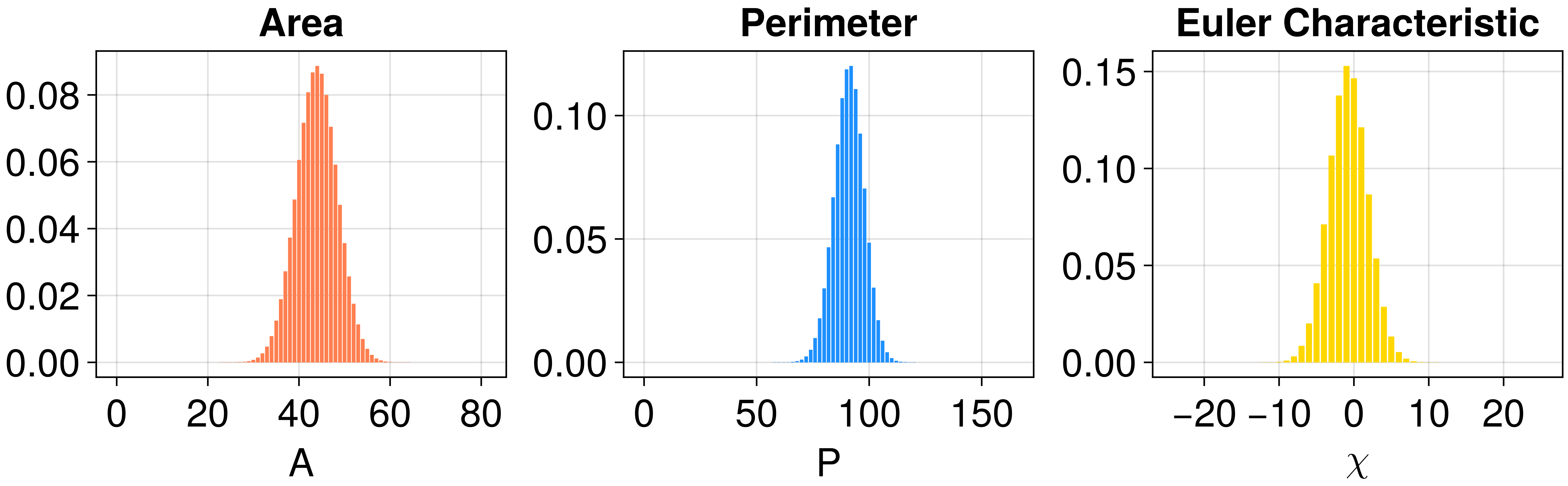

Minkowski functionals and gamma-ray astronomy

Idea: Generate, from a counts map, a series of black and white images by thresholding. (Set pixel black if > threshold otherwise white)

Hypothesis test for each black and white image → **Null hypothesis: Observed black and white image is from a Poisson background with mean λ, at threshold X.**

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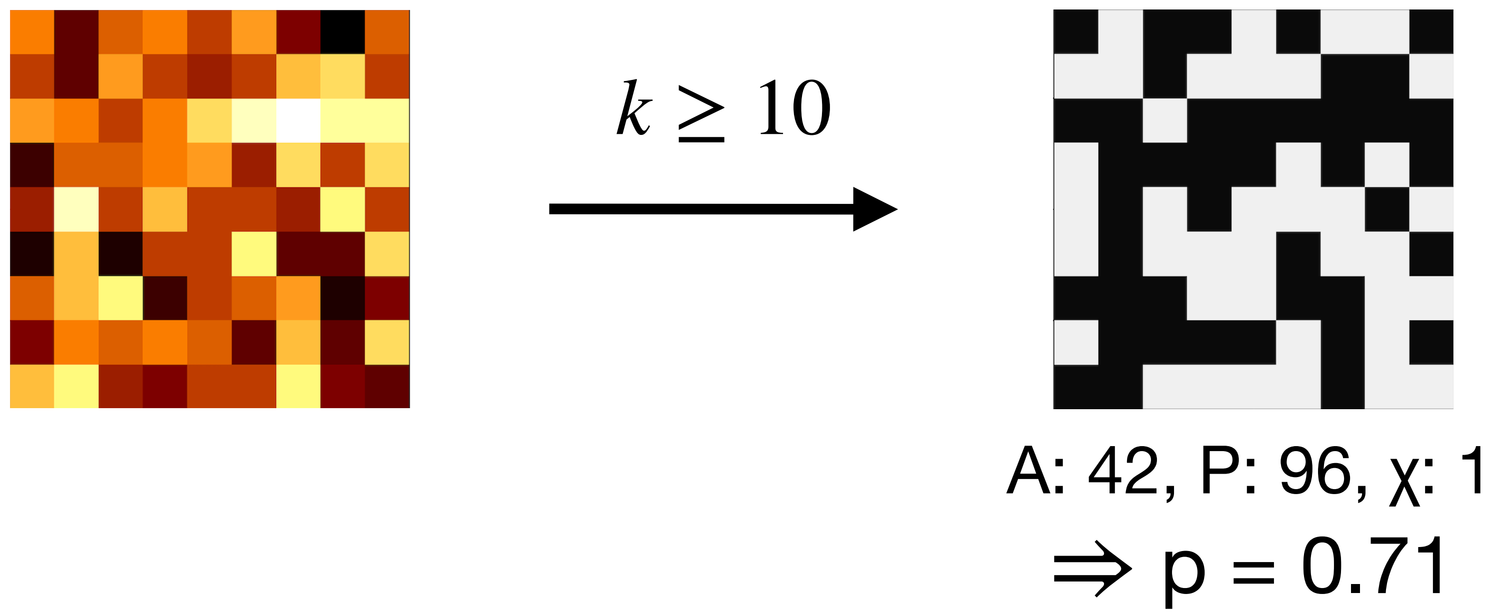

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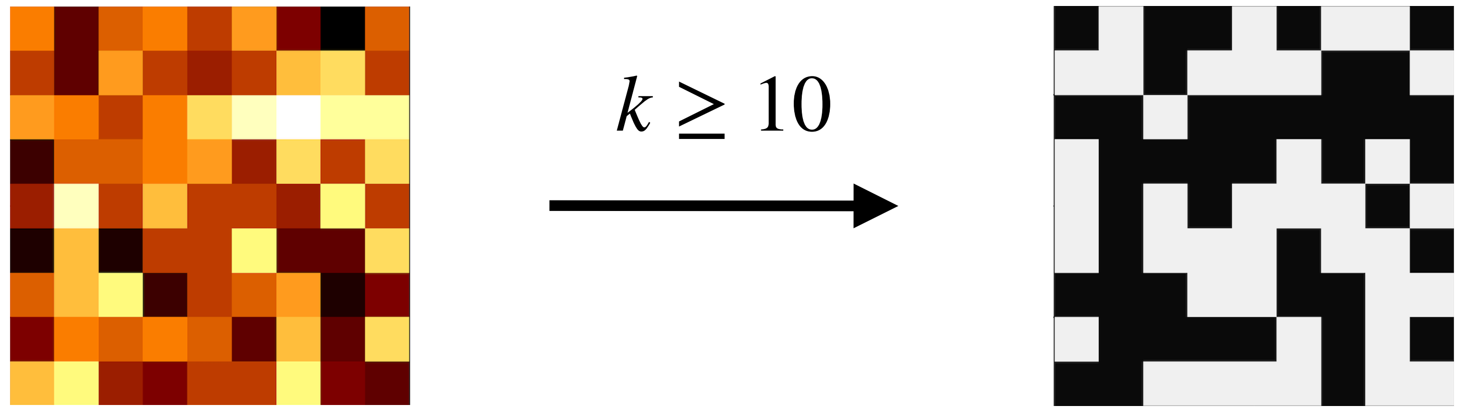

A: 42, P: 96, χ: 1

⇒ p = 0.71

P = 0.71 in words: Given the ***hypothesis is true*** *there is a chance of 71% that this black and white image (at threshold 10) or an even more unlikely one appears.*

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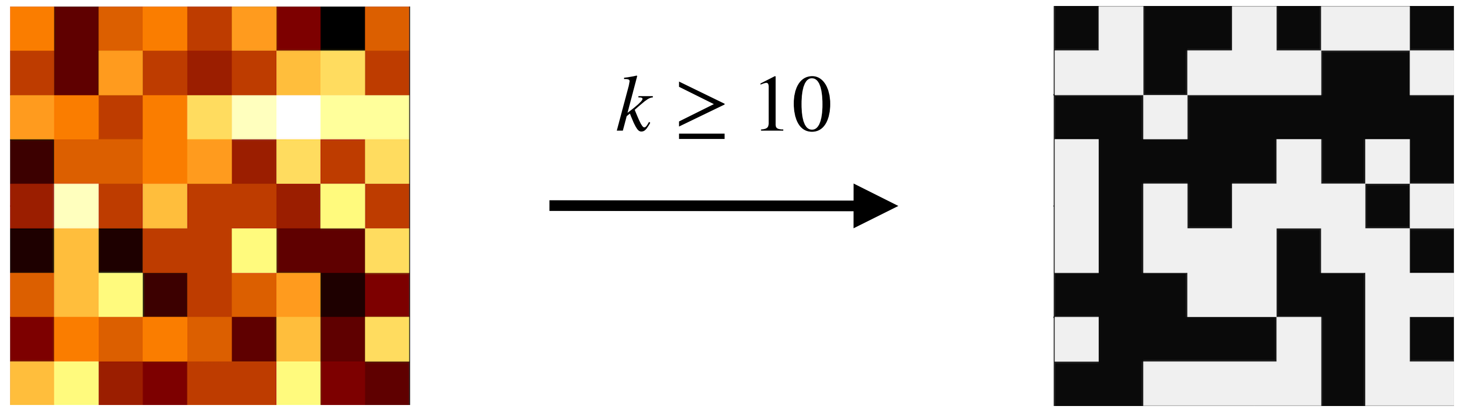
For all possible thresholds:



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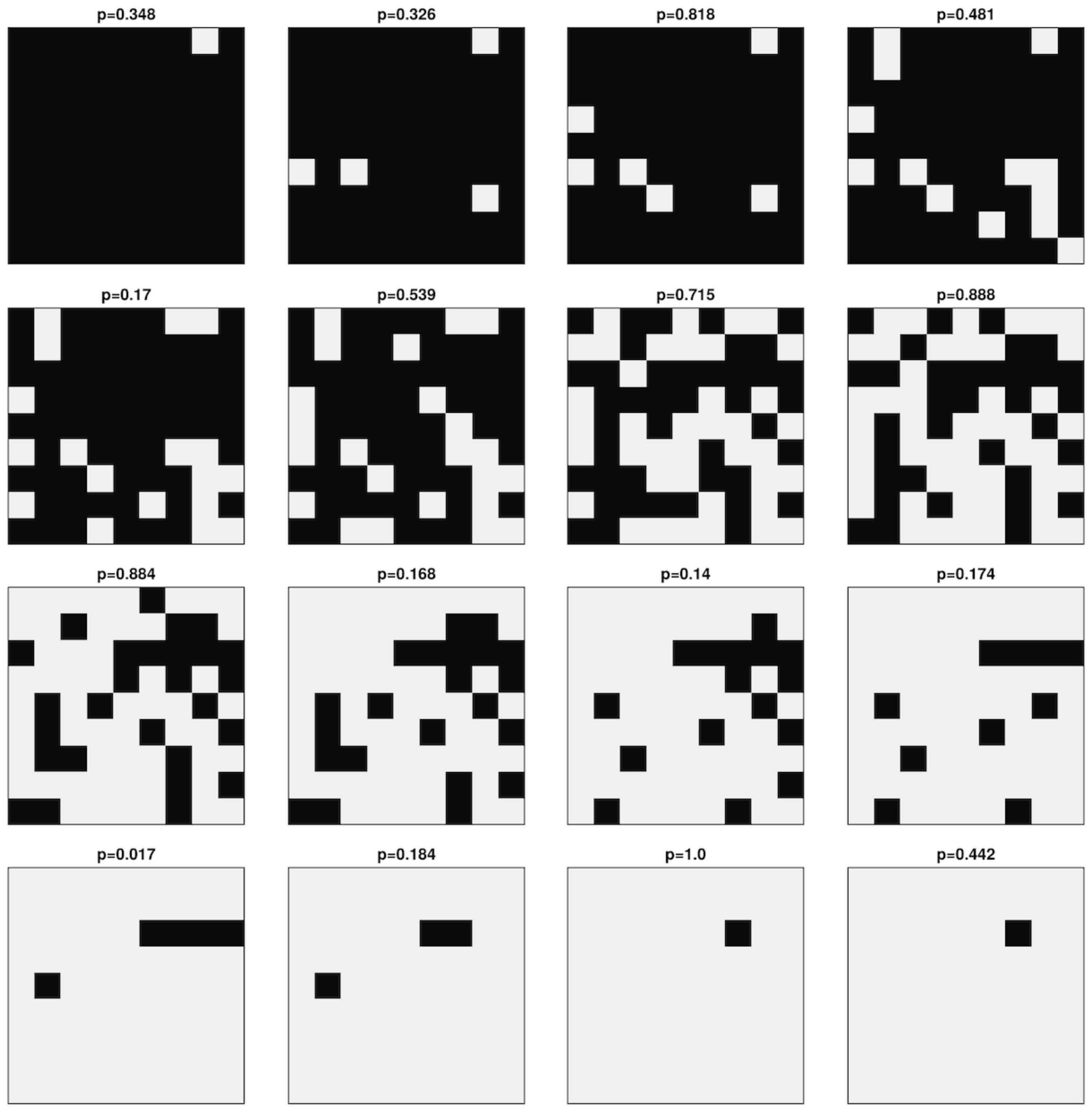

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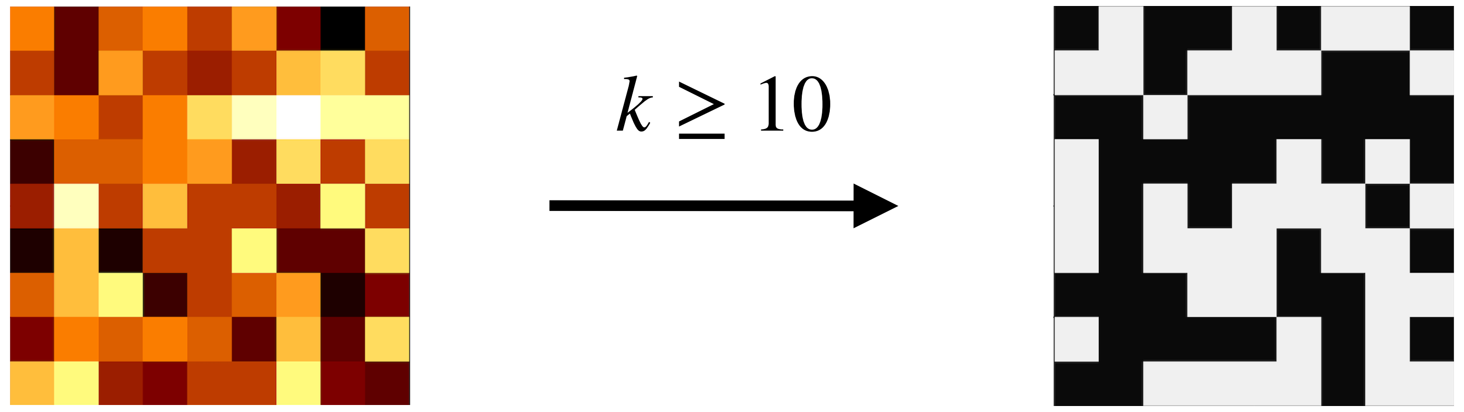

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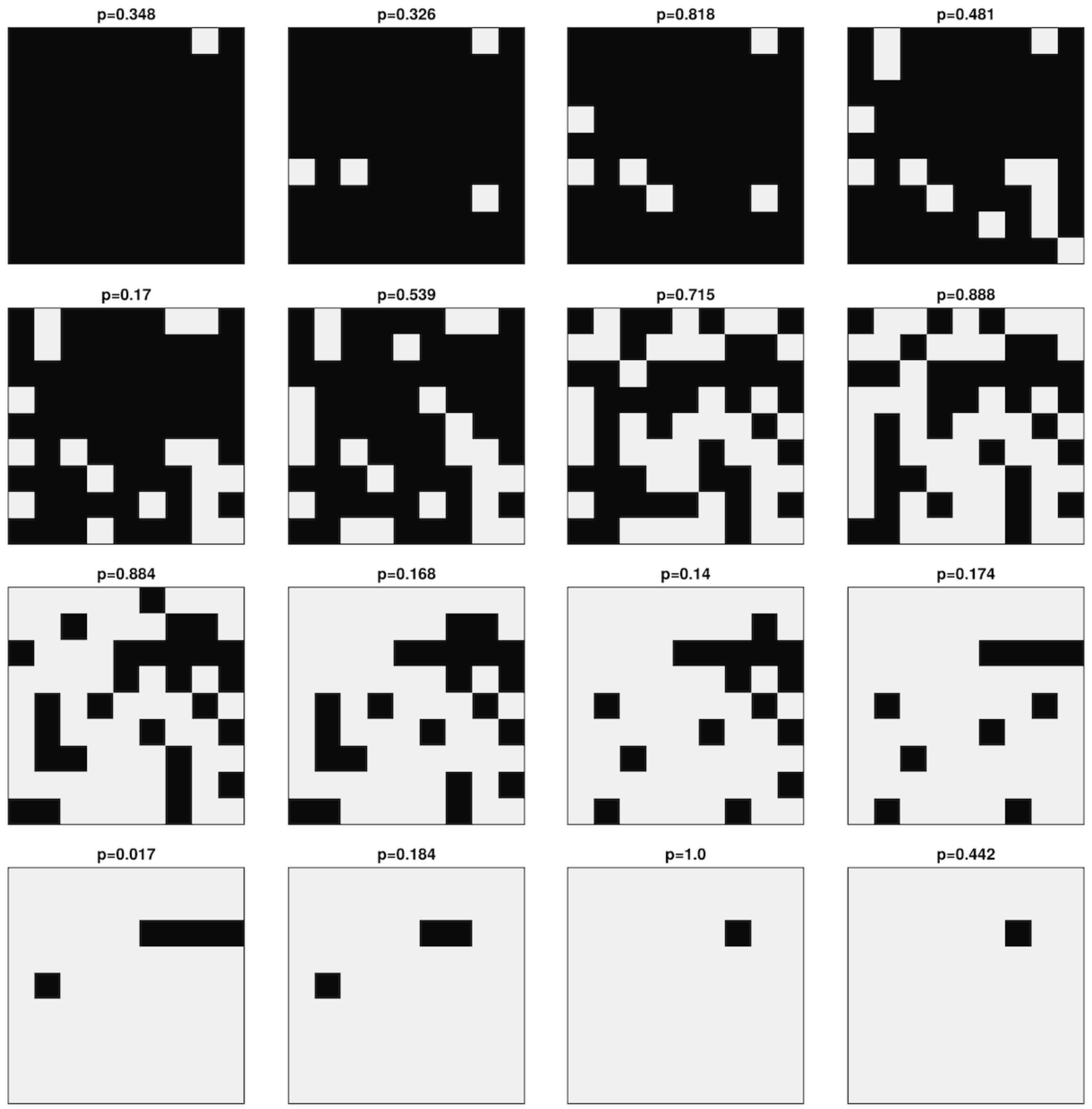

Take **smallest p-value** and **correct for trials** ⇒ p = 0.24

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Minkowski functionals and gamma-ray astronomy

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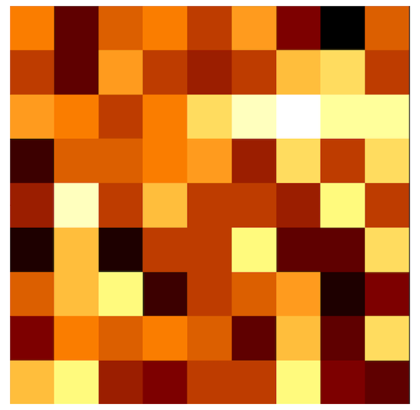
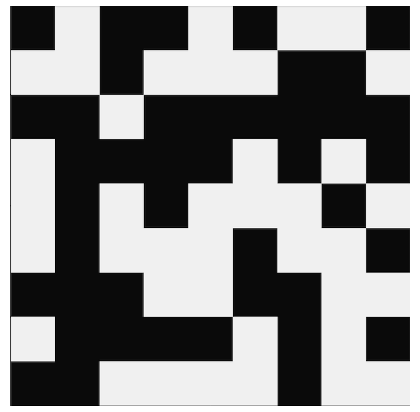


$k \geq 10$ →



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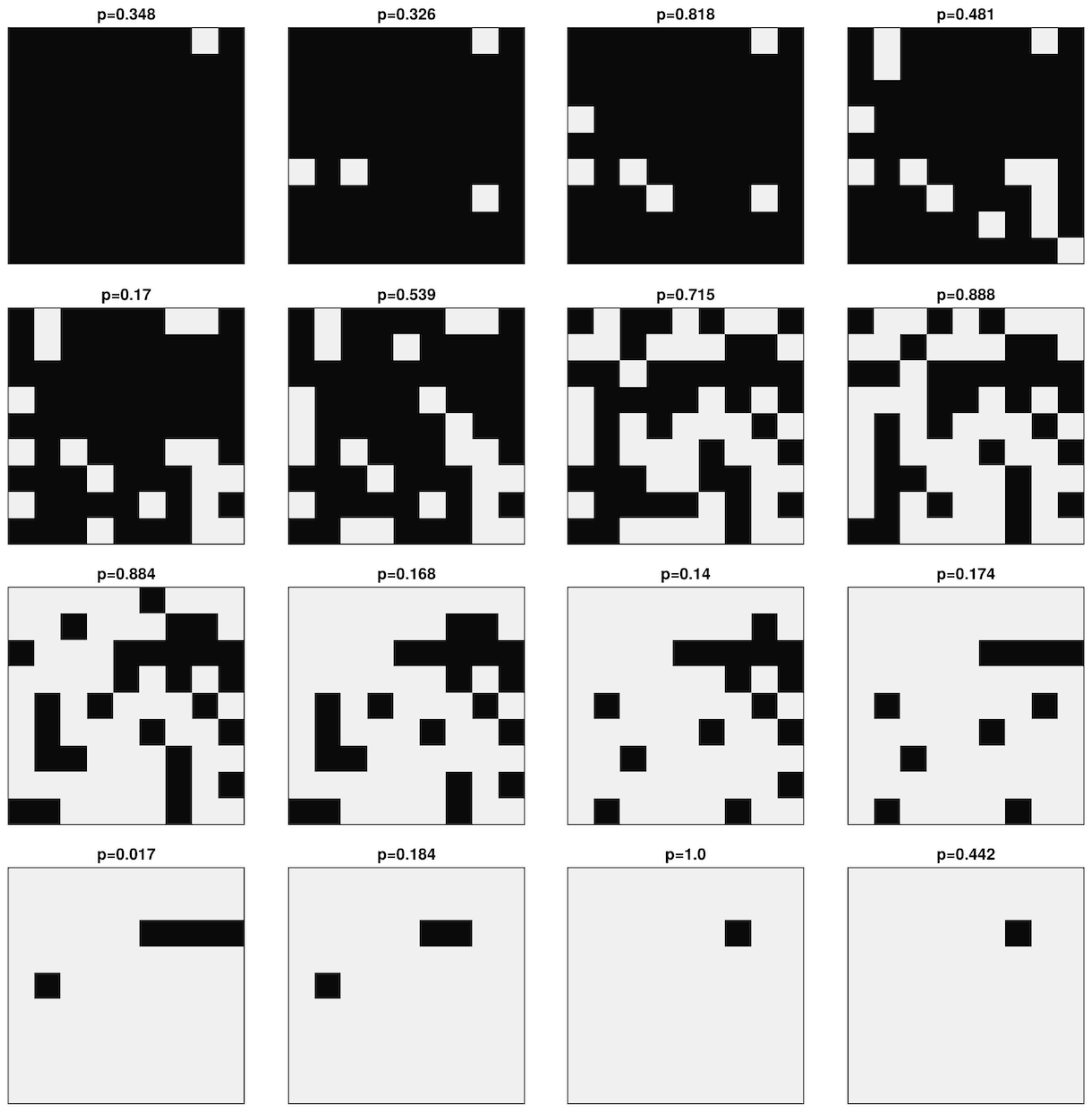

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This we can convert to σ = 1.17,

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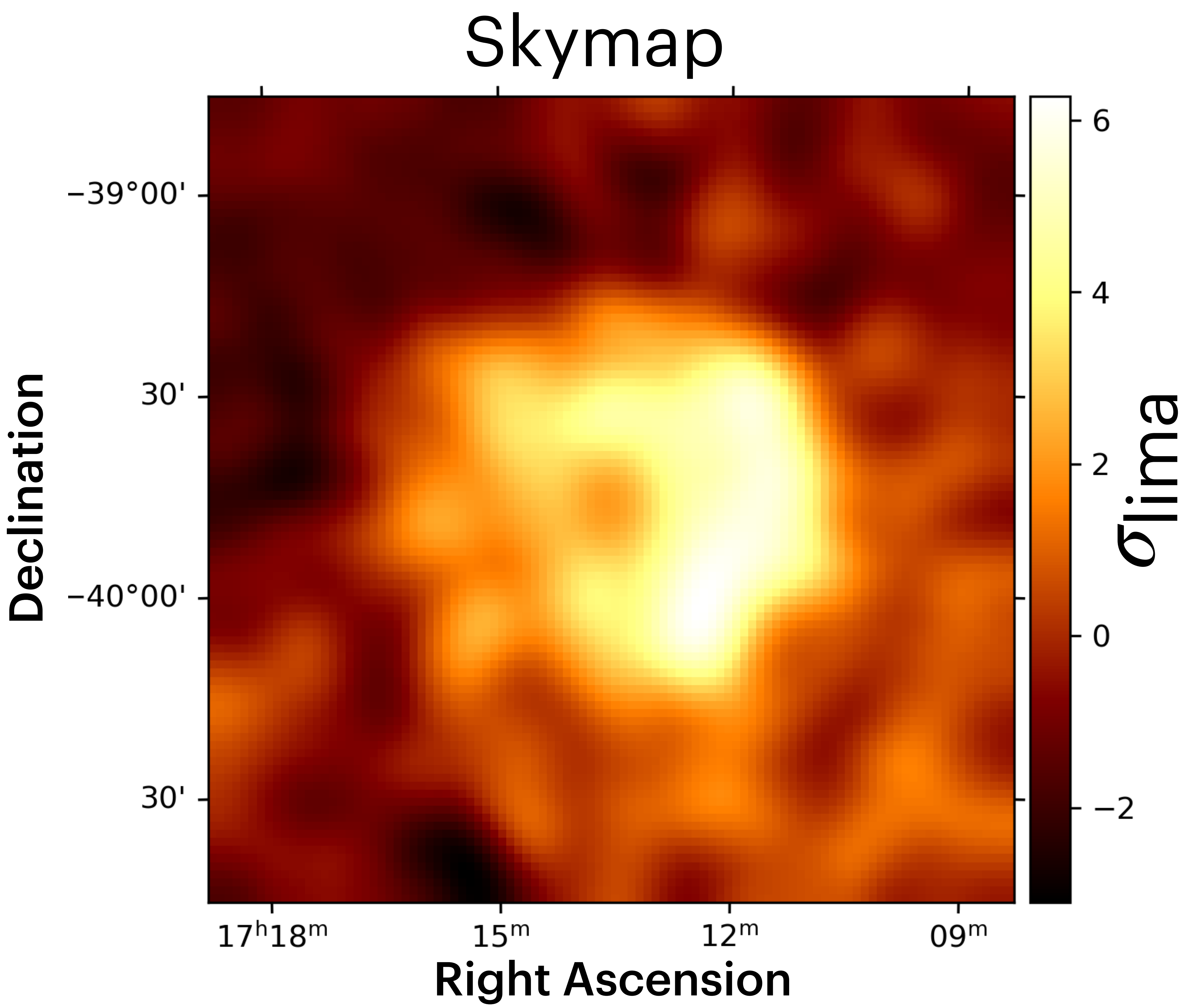

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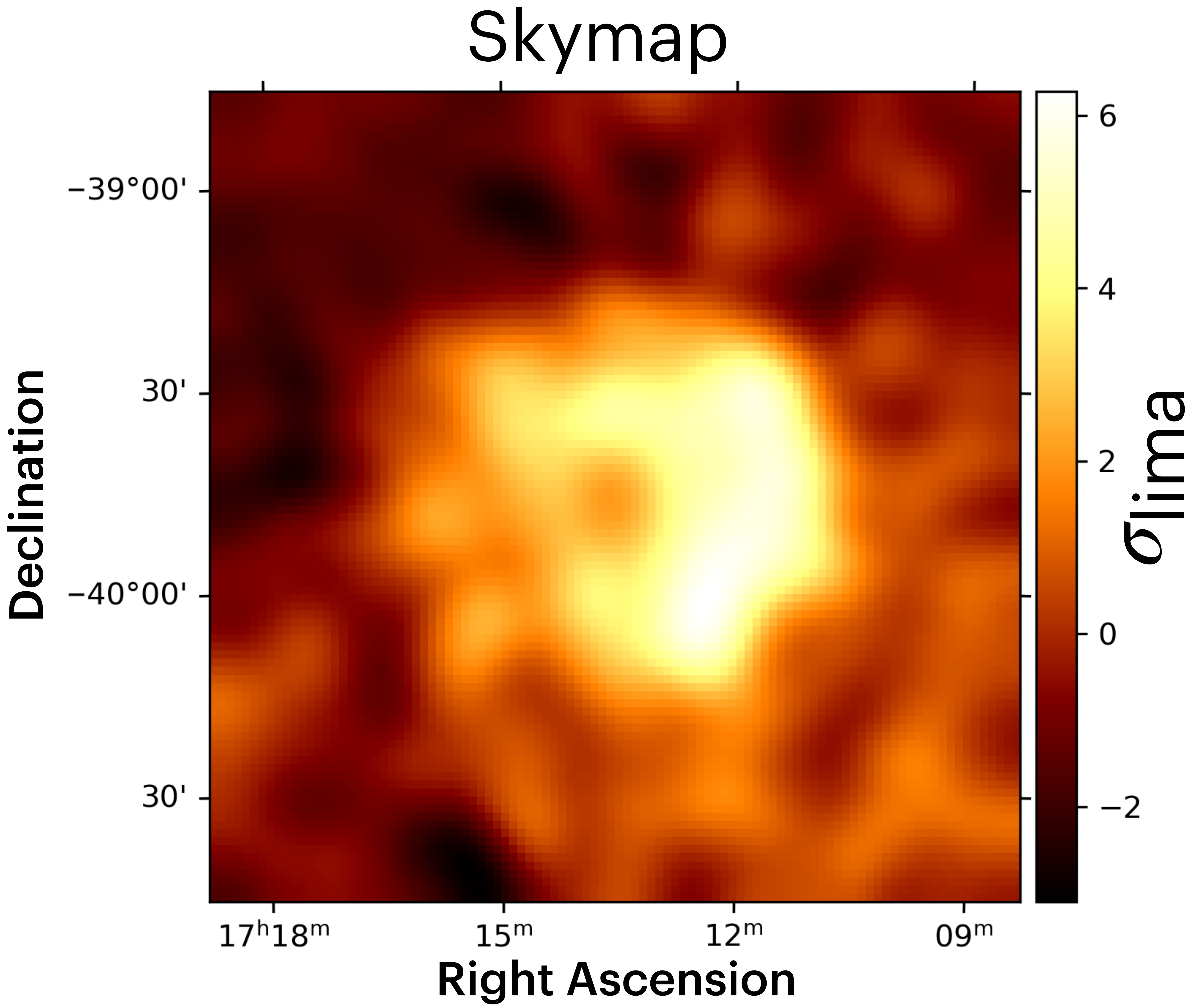
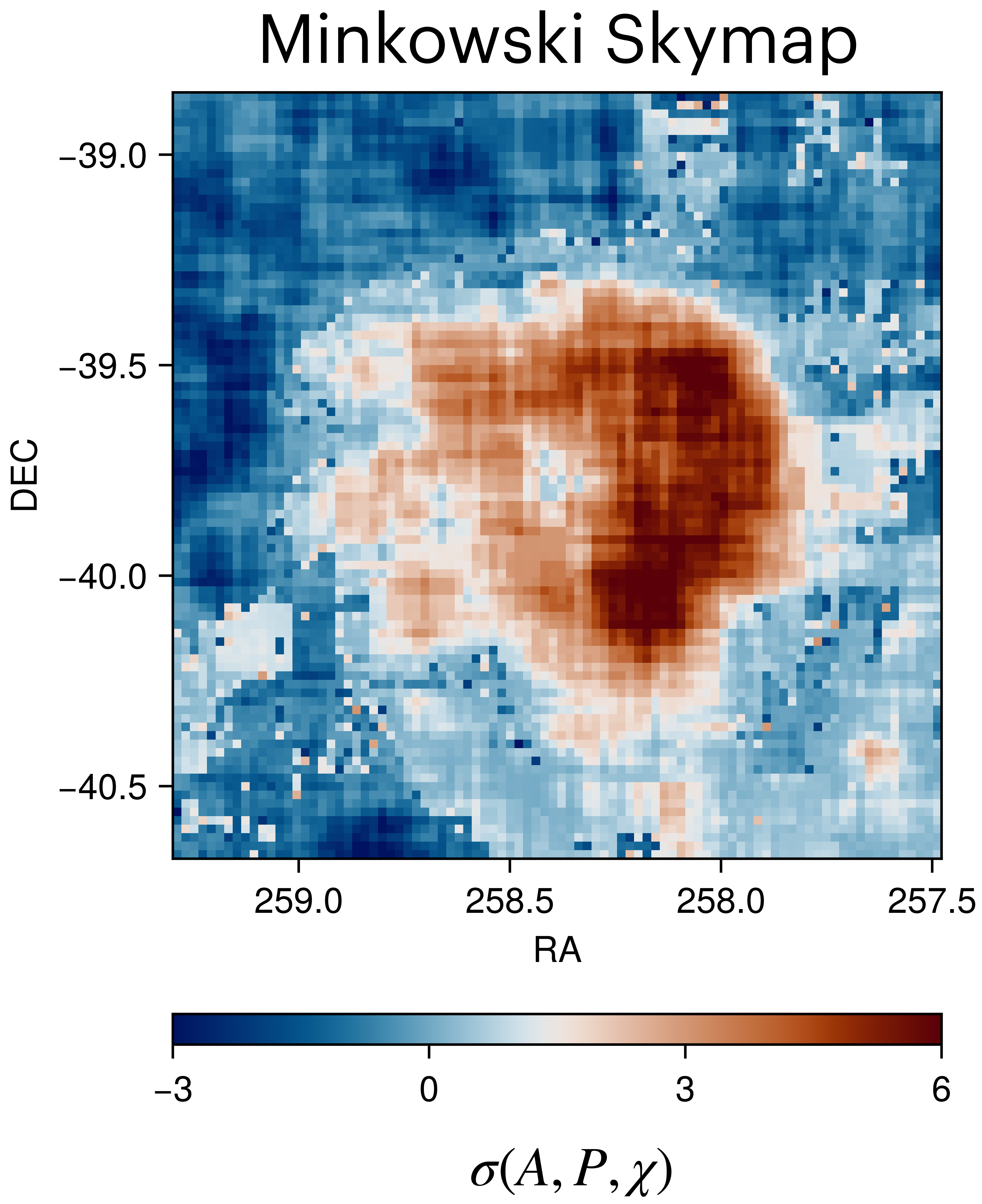




Why Minkowski sky maps

Advantages

- Standard LiMa method only sensitive to excess counts over background
- Minkowski functionals are sensitive to structural information
- Minkowski method can detect structures at different scales using the same kernel size

Disadvantages

- Computationally expensive
- Less sensitive if no complex structure is in the observation

Thank you for your attention!

Backup slides

Minkowski Functionals

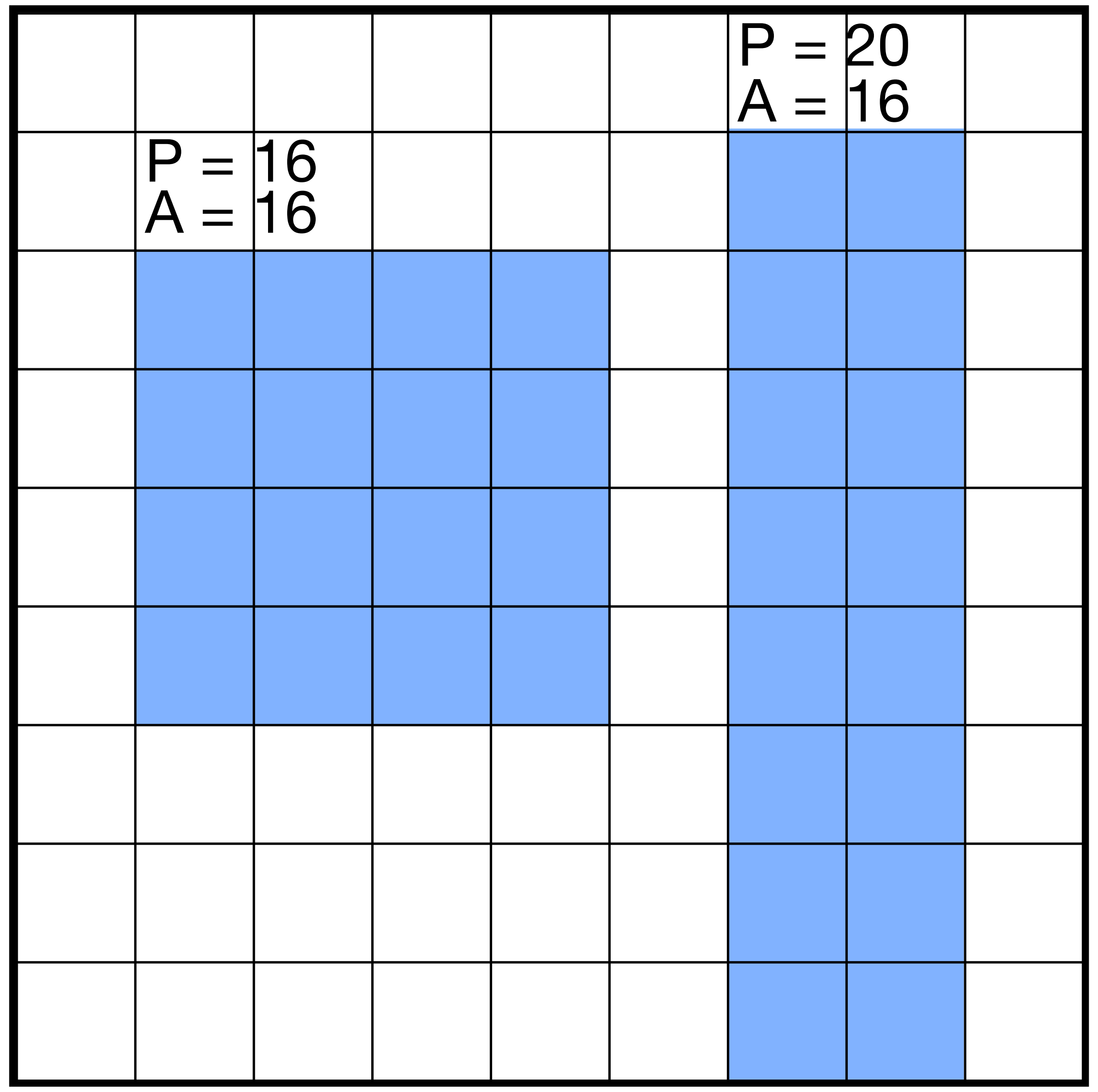
Q: “How to evaluate the “geometry” of a subset of $\mathbb{R}^n$ in a continuous and motion invariant way”

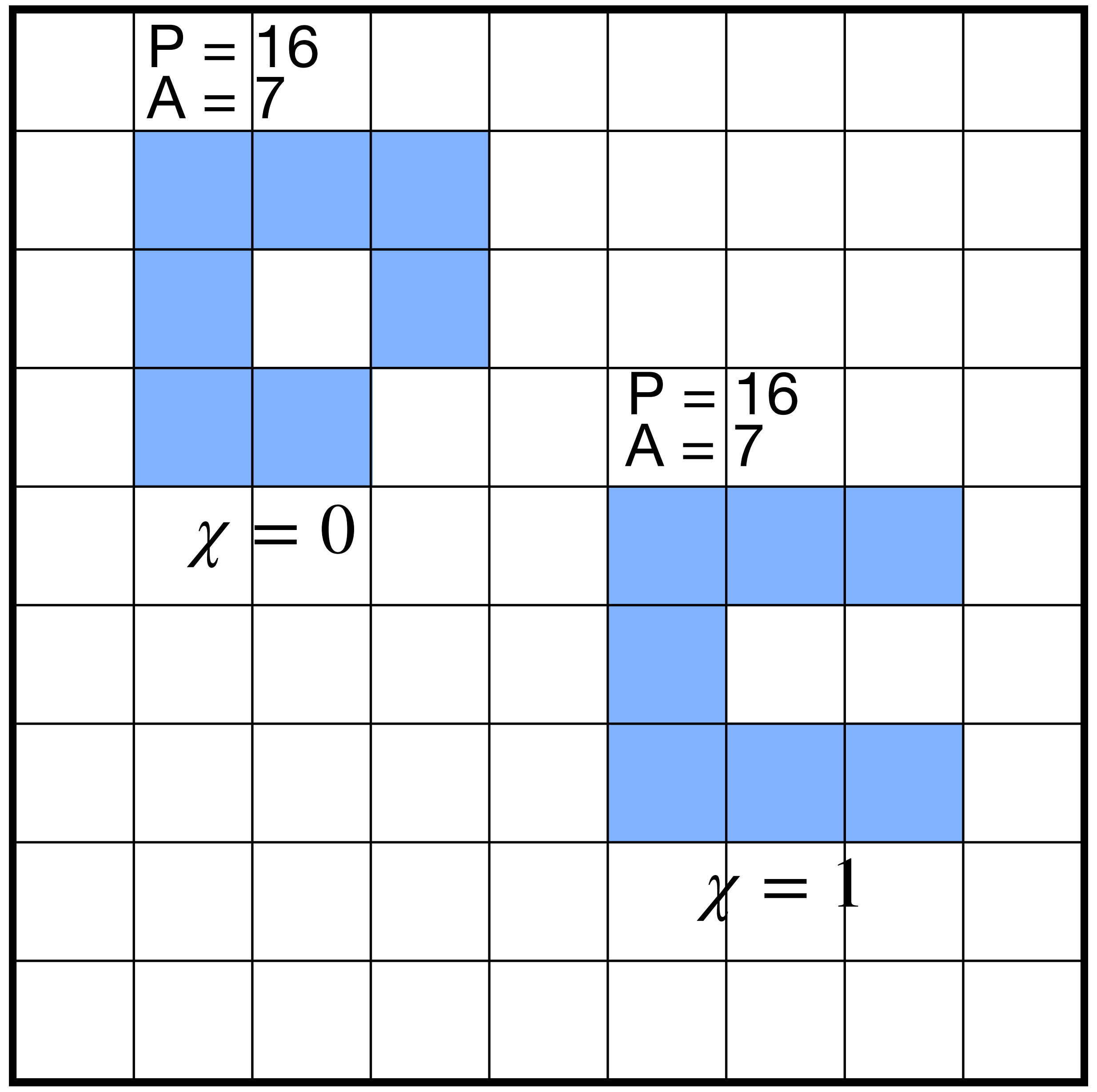
Area (A)

Perimeter (P)

Euler Characteristic (χ)

→Counts “holes”





Hardwiger’s Theorem in mathematics states these are all functionals which exist.

With that we can classify the structure of black and white images.