Automatic Point Source Detection through Model Stress

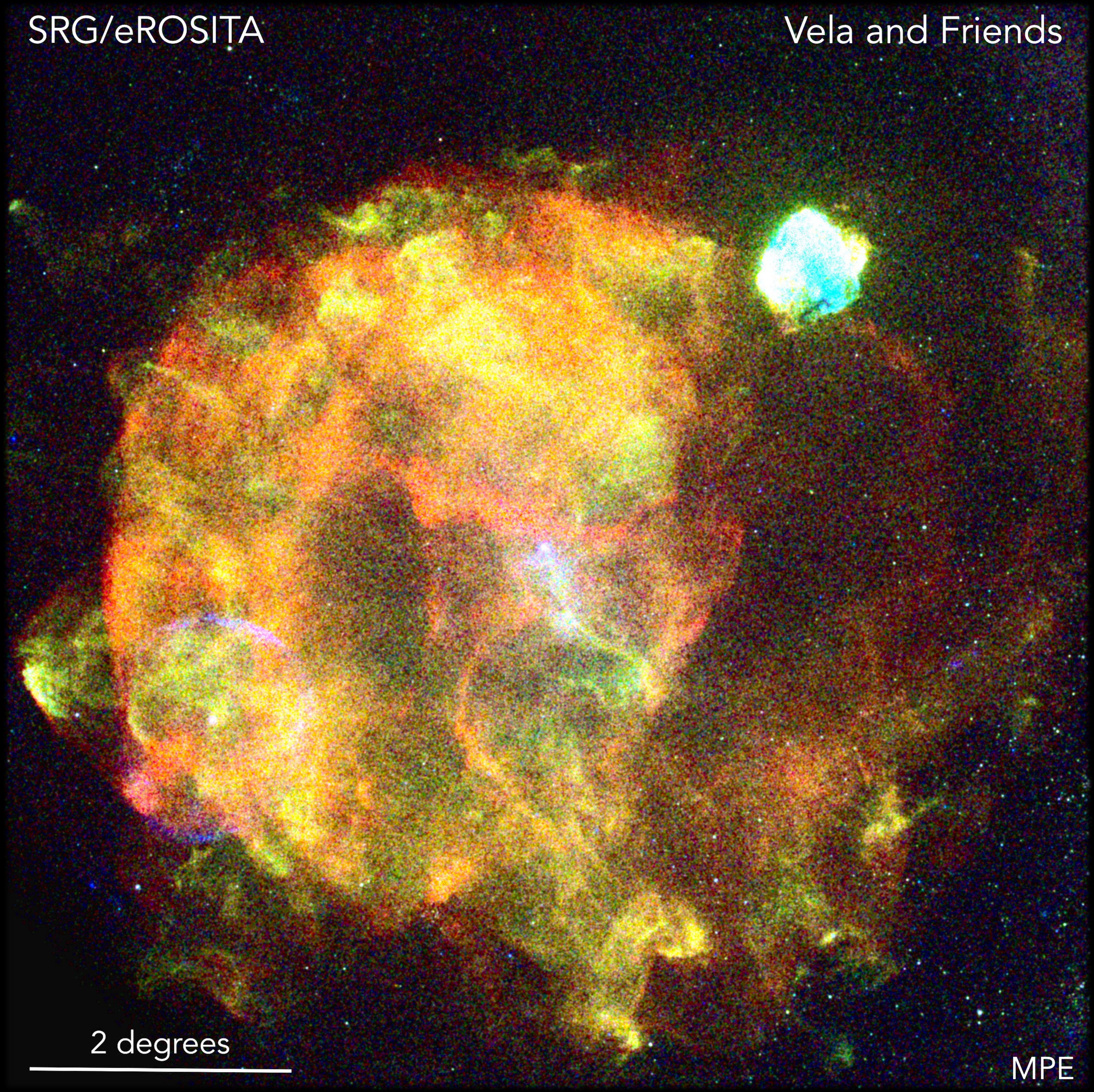
Matteo Guardiani, Vincent Eberle, Margret Westerkamp,
Philipp Frank, and Torsten Enßlin

**First Results from the SRG/eROSITA All-Sky Survey:
From Stars to Cosmology, September 19th 2024,
TUM Campus, Garching, Germany**

DLR

MAX PLANCK INSTITUTE
FOR ASTROPHYSICS

The problem



X-ray Imaging with IFT

Information field theory

Bayes' Theorem

$$P(s\,|\,d) = \frac{P(d\,|\,s)\,P(s)}{P(d)}$$

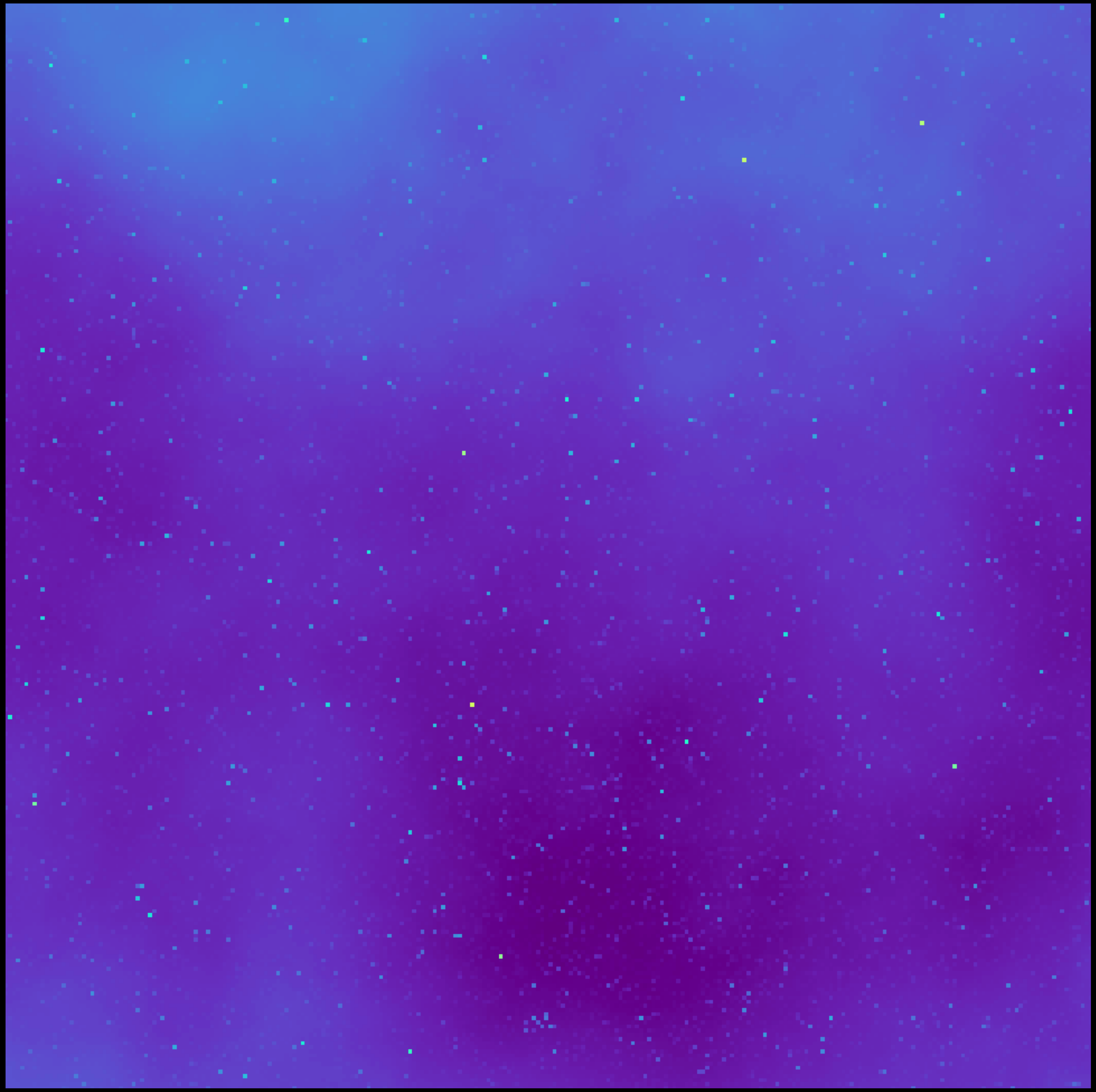
The prior

$$P(s \mid d) = \frac{P(d \mid s)\, P(s)}{P(d)}$$

The prior

Sky

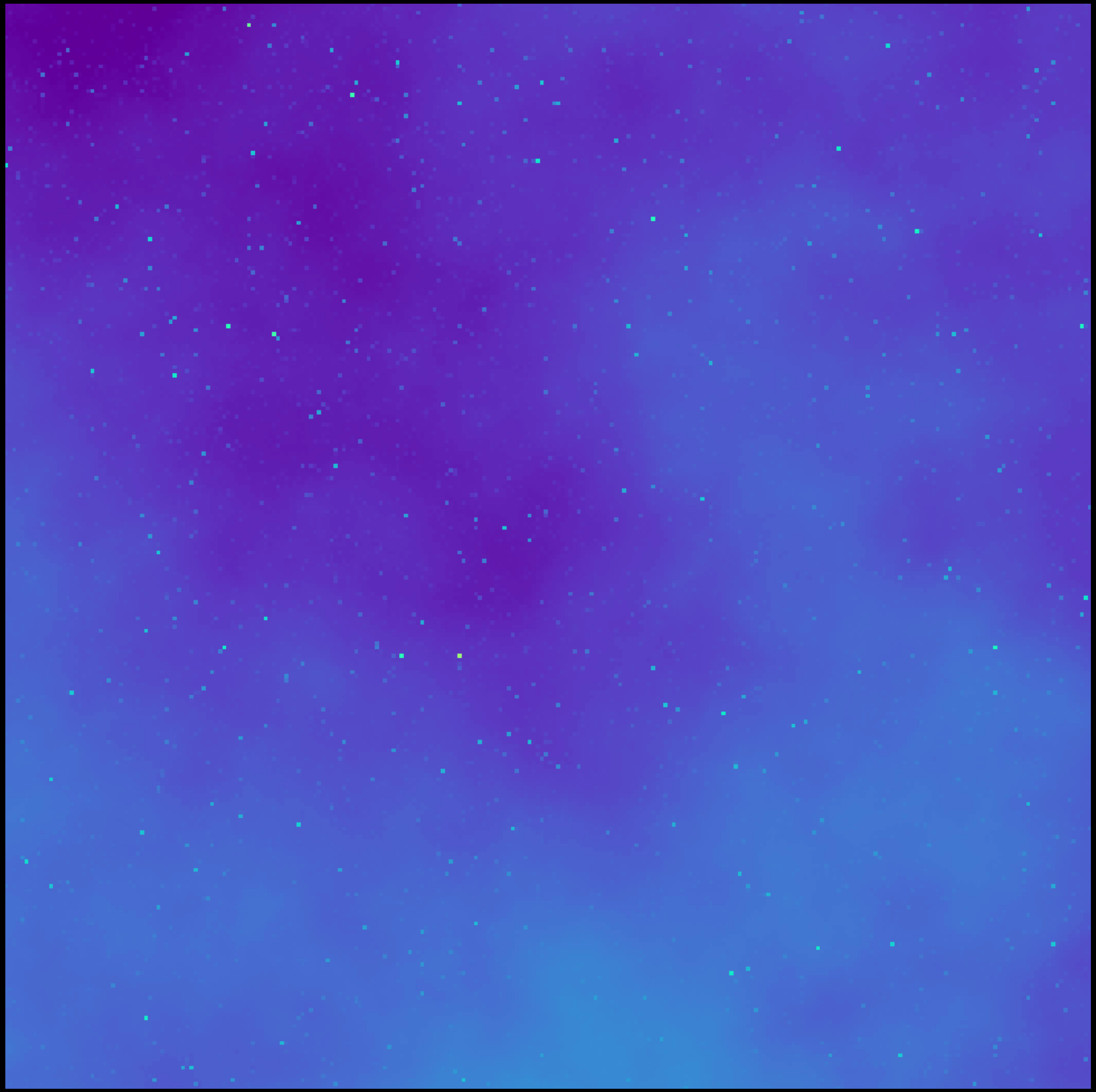
$$P(s)$$



The prior

Sky

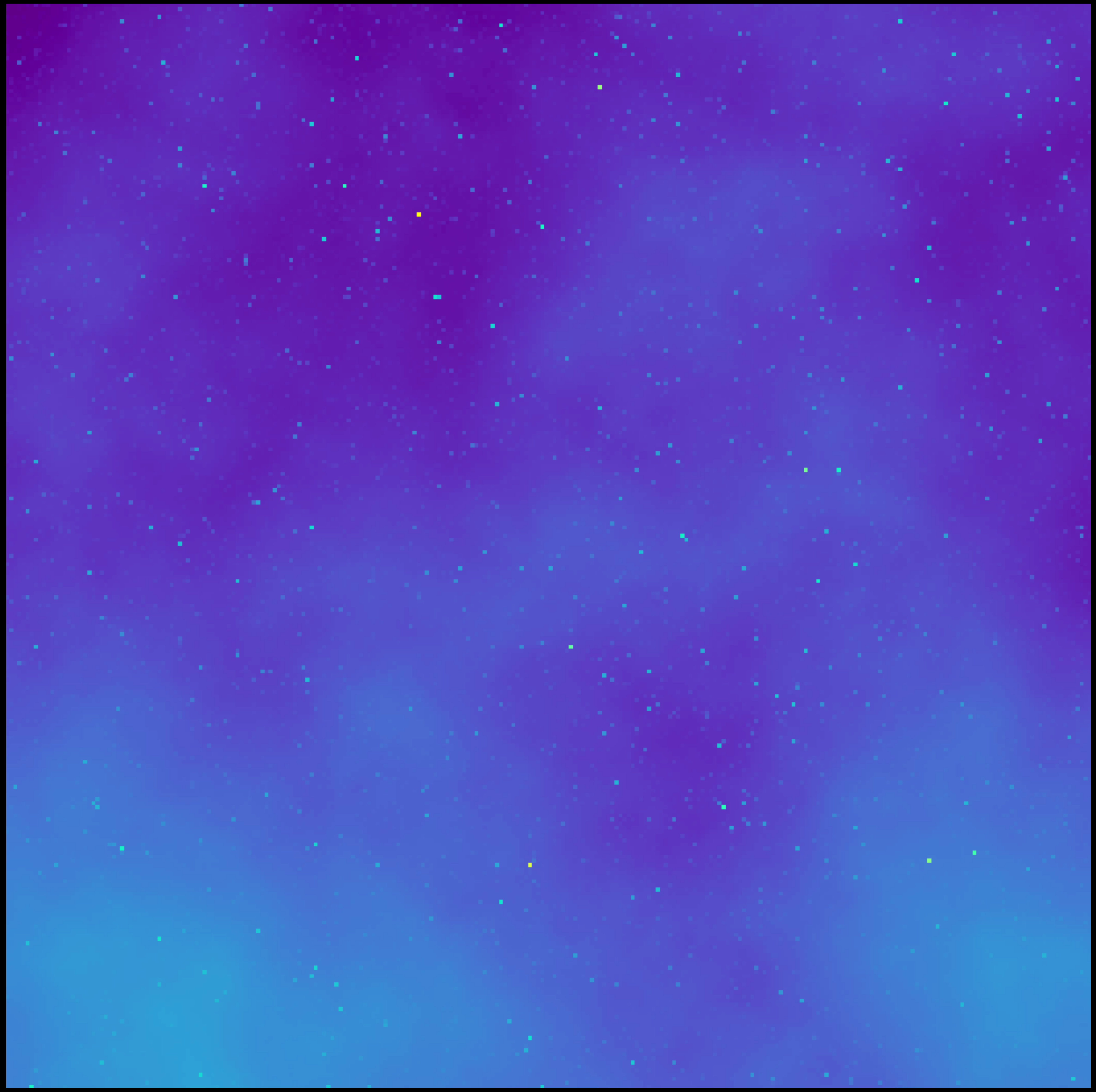
$$P(s)$$



The prior

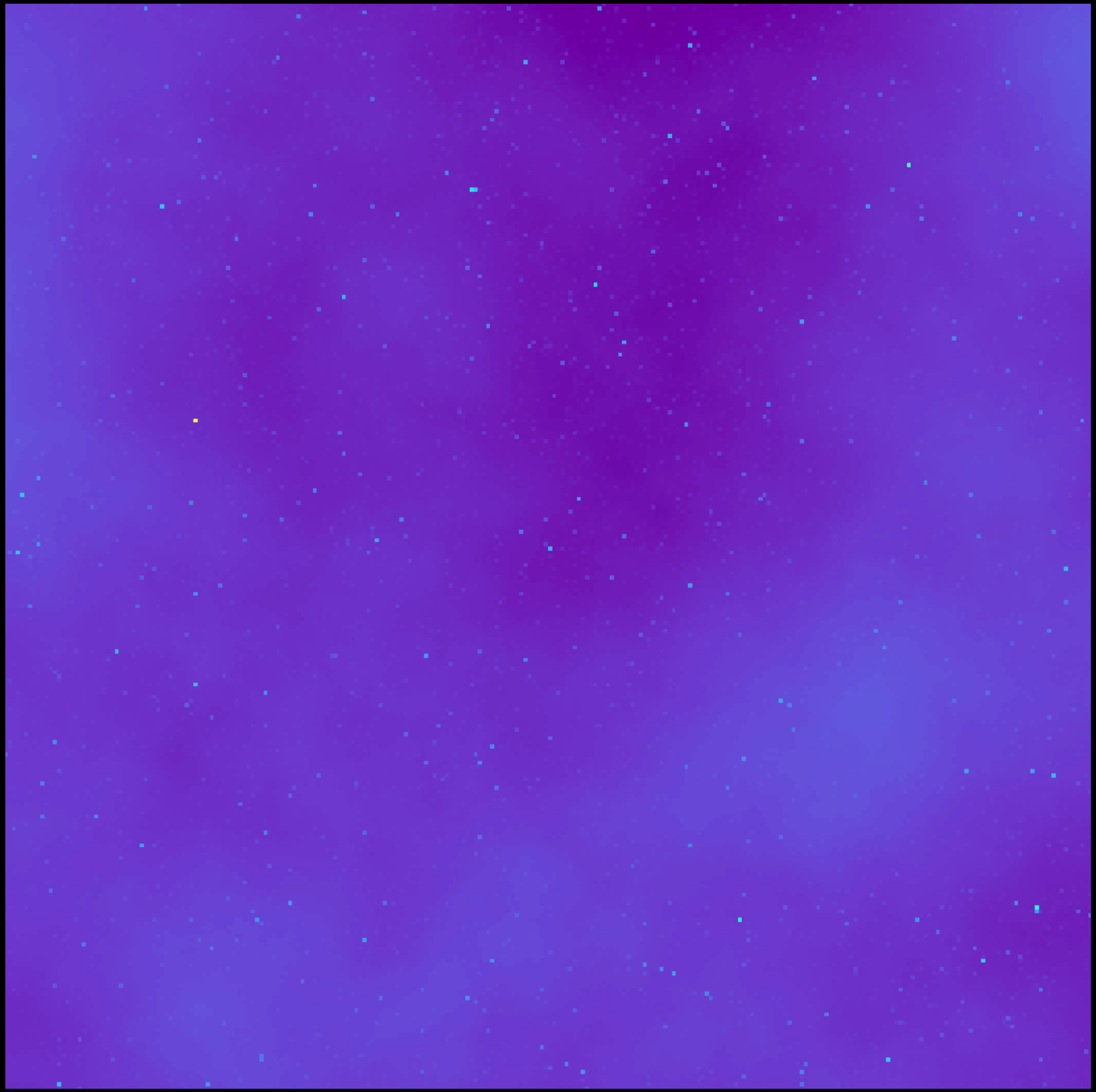
Sky

$$P(s)$$



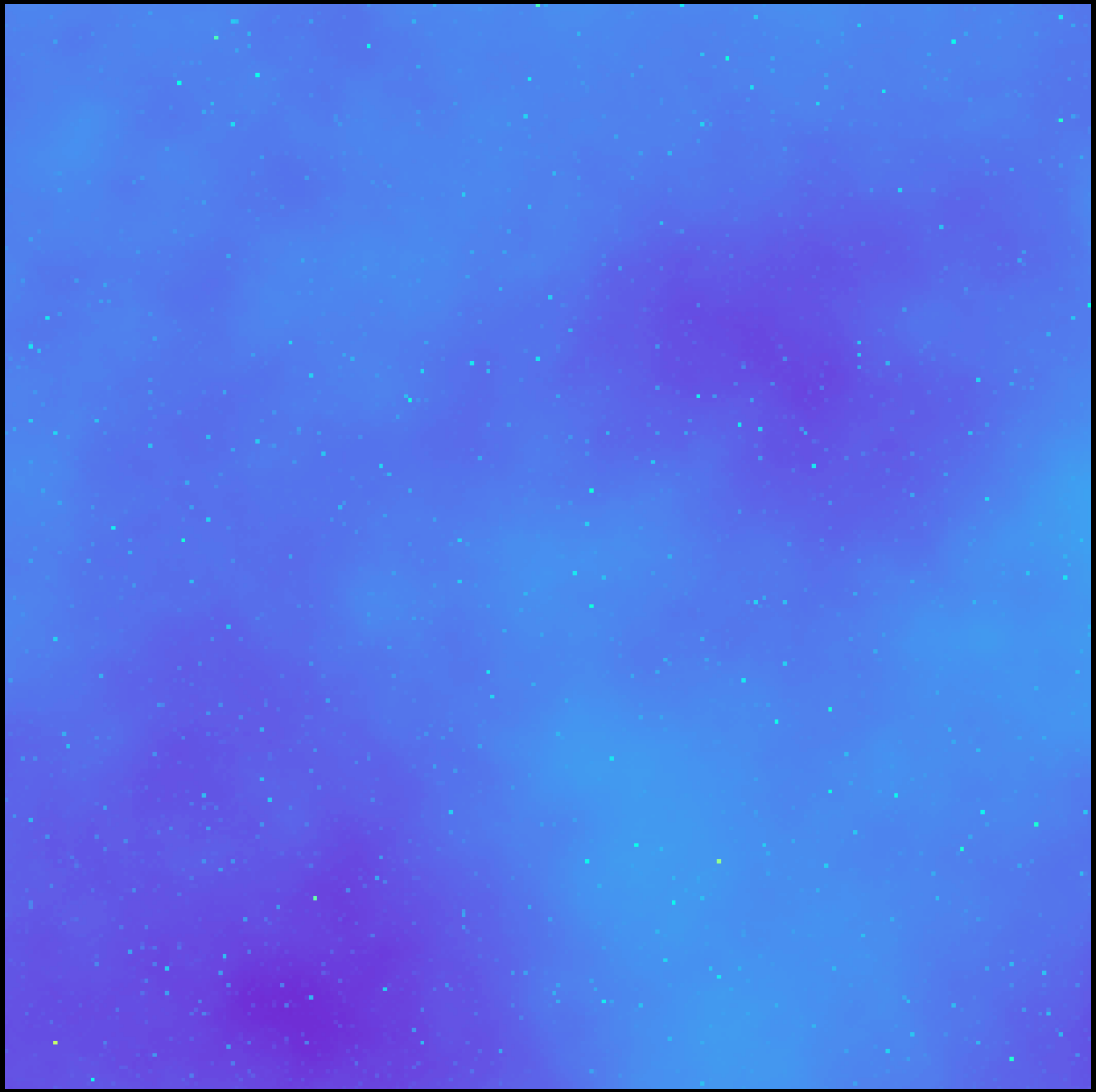
The prior
Sky

$$P(s)$$



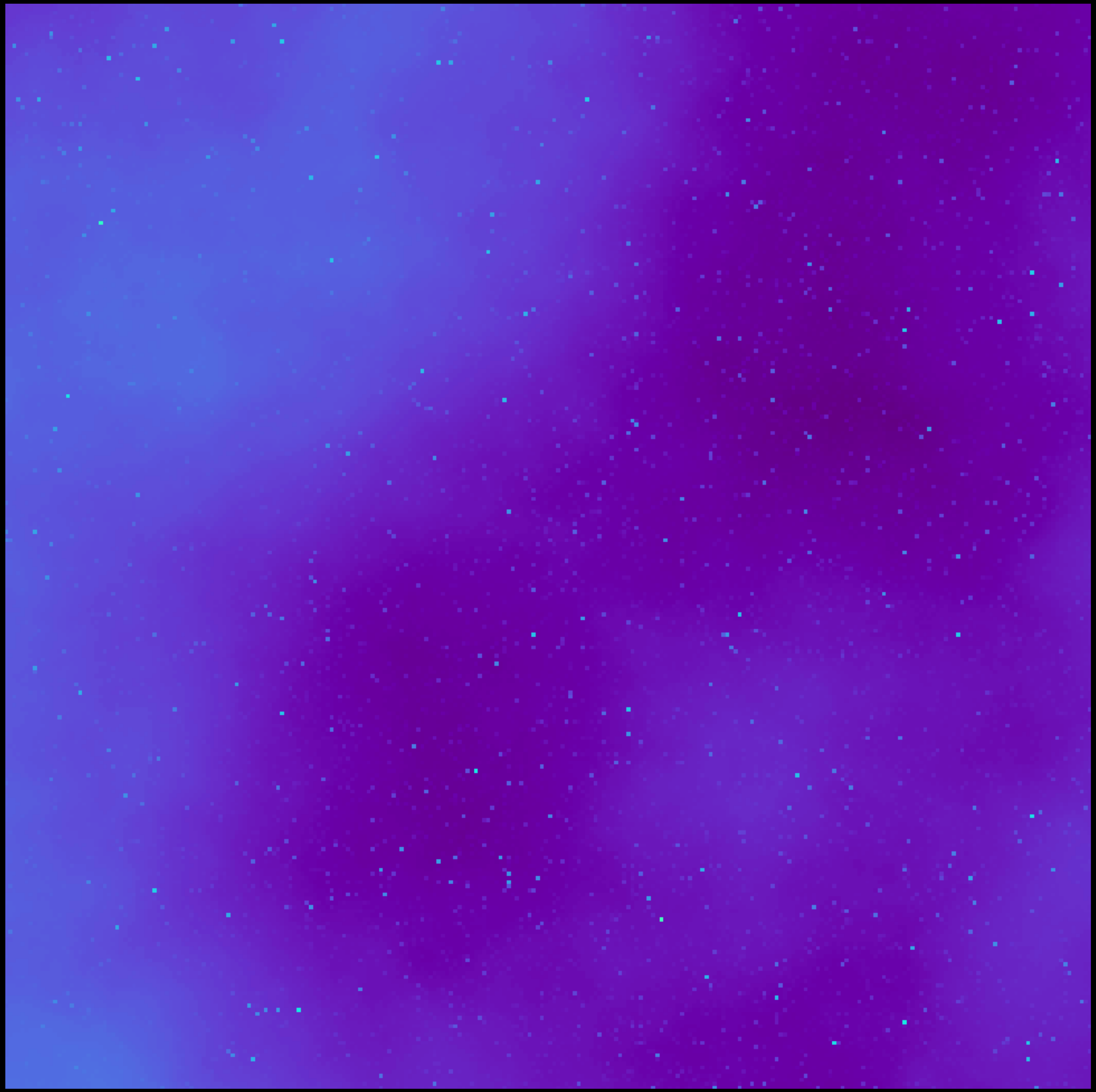
The prior
Sky

$$P(s)$$



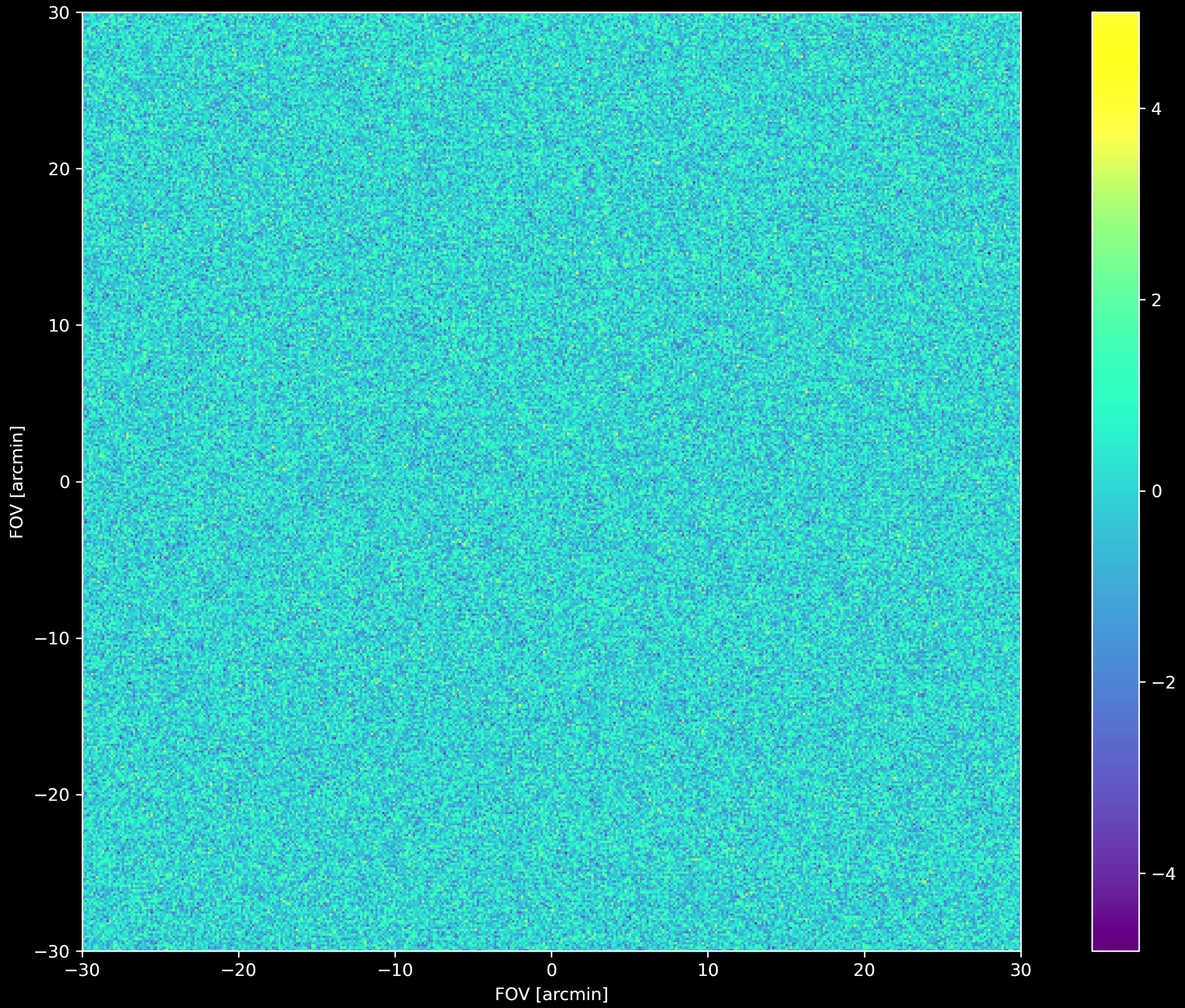
The prior
Sky

$$P(s)$$



The prior
Generative model

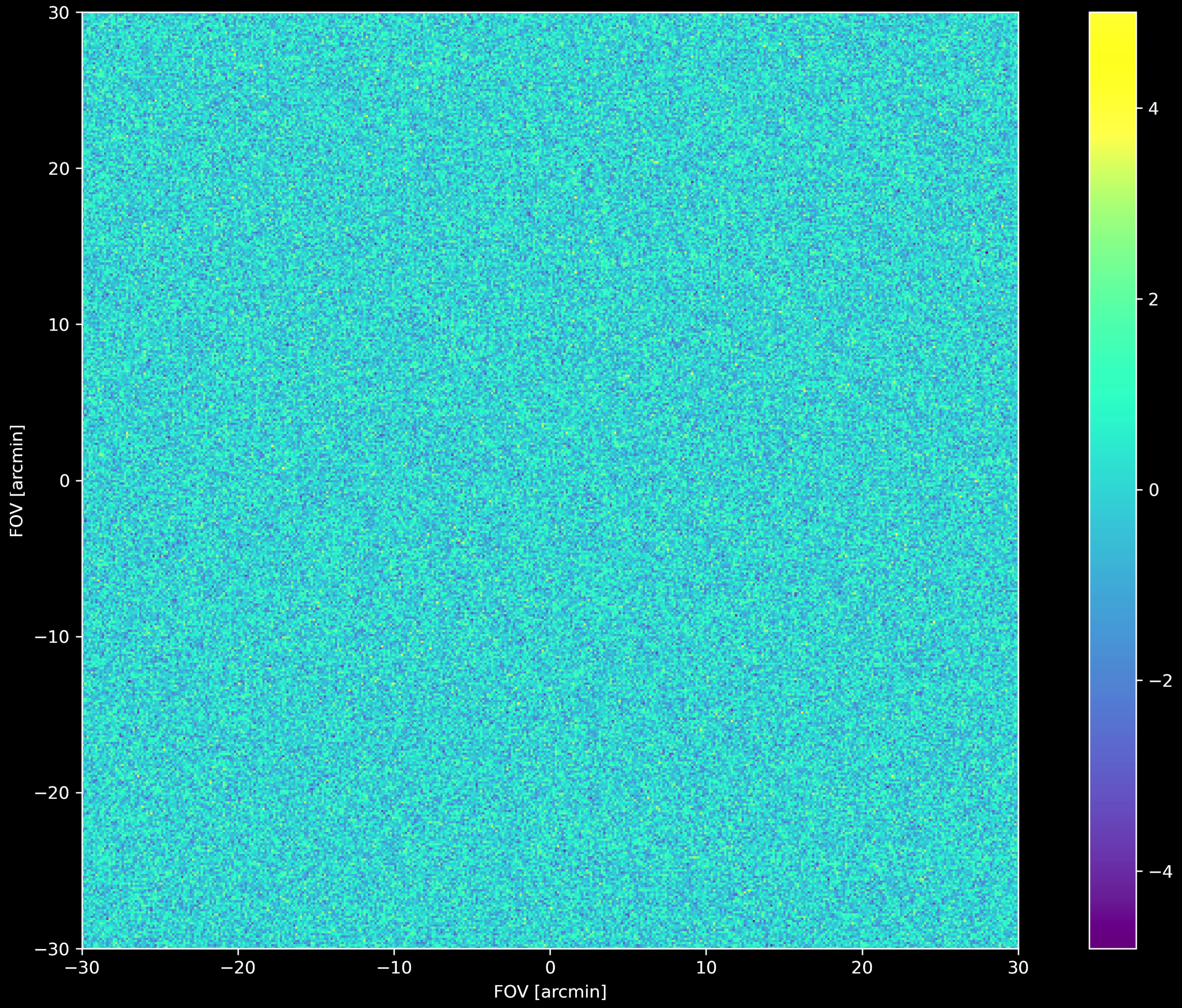
$$P\left(\xi\right) = \mathcal{N}\left(\mathbf{0}, \mathbb{I}\right)$$



Latent space prior distribution

The prior
Generative model

$$P(s) = P\left(\xi\right)\left|\frac{\partial \xi}{\partial s}\right|$$

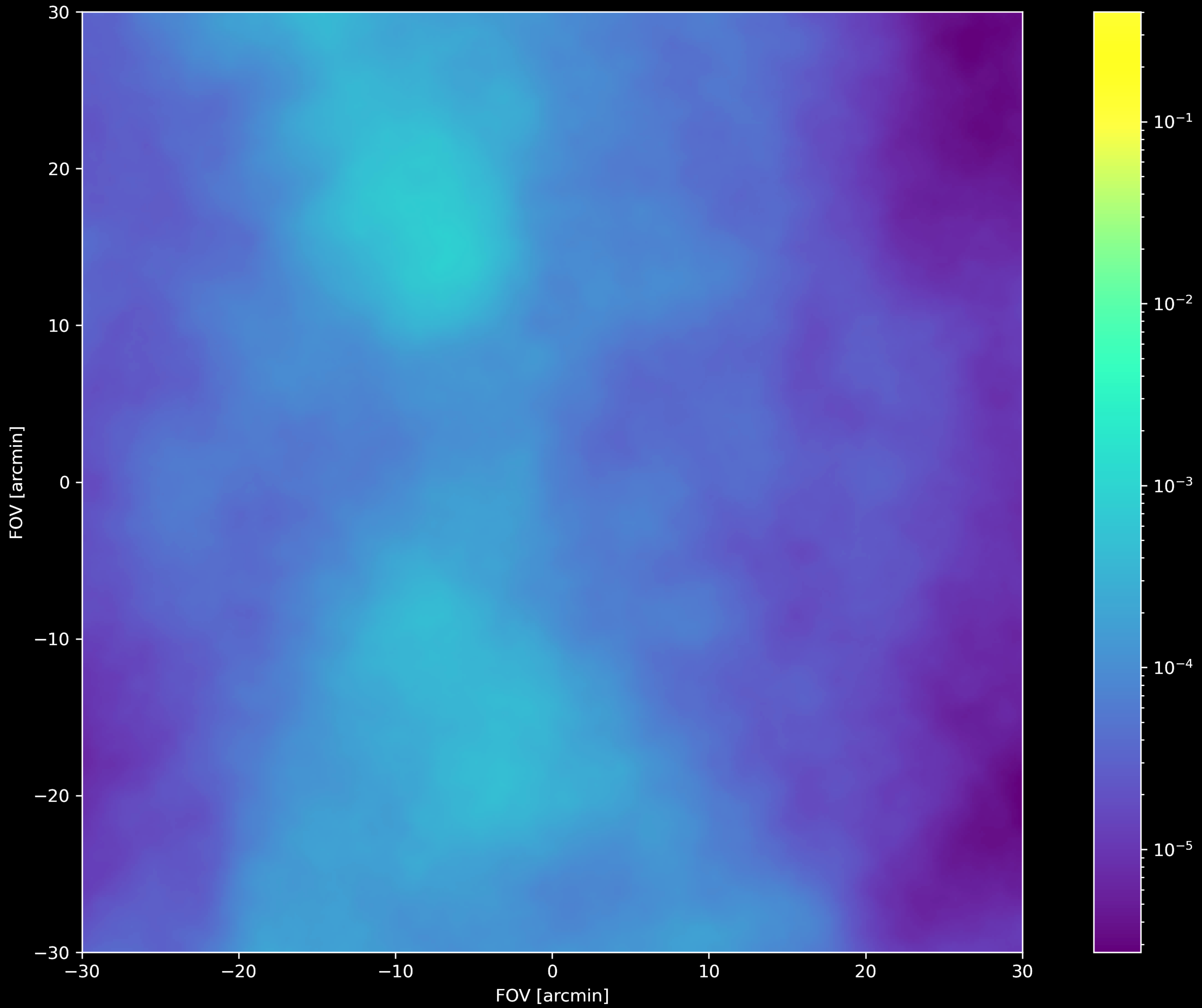


Latent space prior distribution

The prior

Generative model

$$P(s) = \mathcal{N}\left(\mathbf{0}, \mathbb{1}\right) \left| \frac{\partial \xi}{\partial s} \right|$$

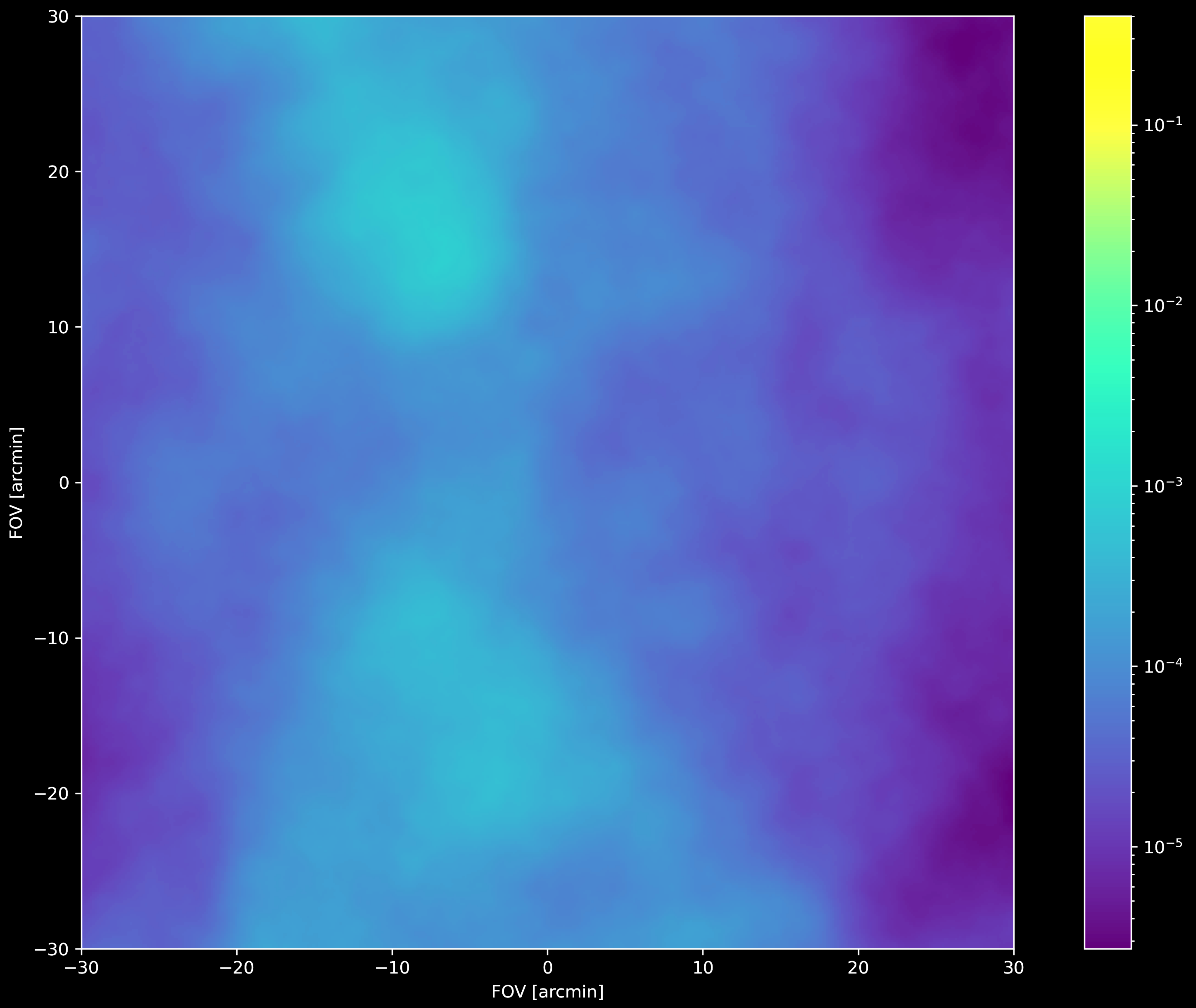


Signal space prior sample

The prior

Generative model

$$P(s) = \mathcal{N}\left(\mathbf{0}, \mathbb{1}\right) \star A(x, y)$$

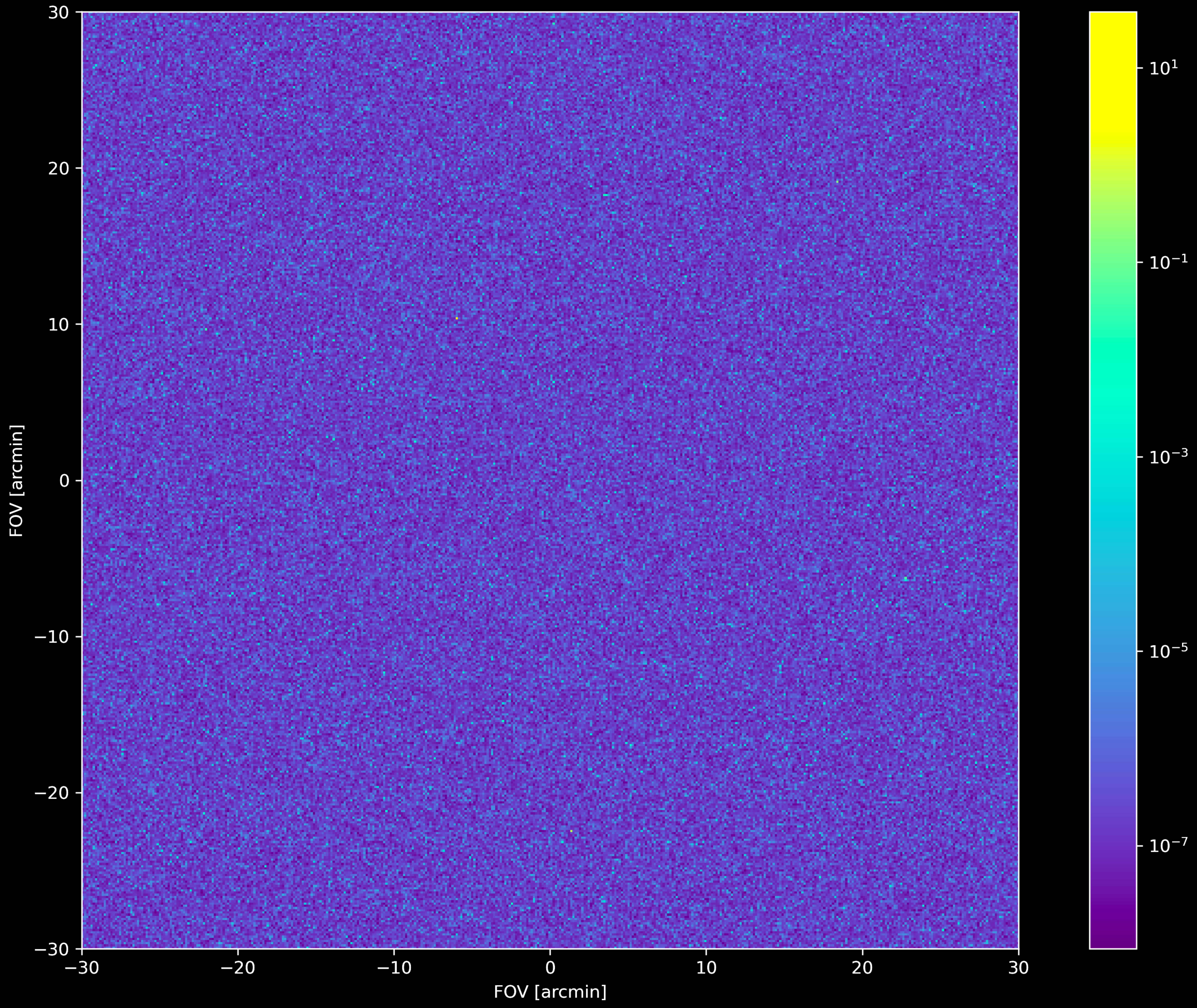


Signal space prior sample

The prior

Generative model

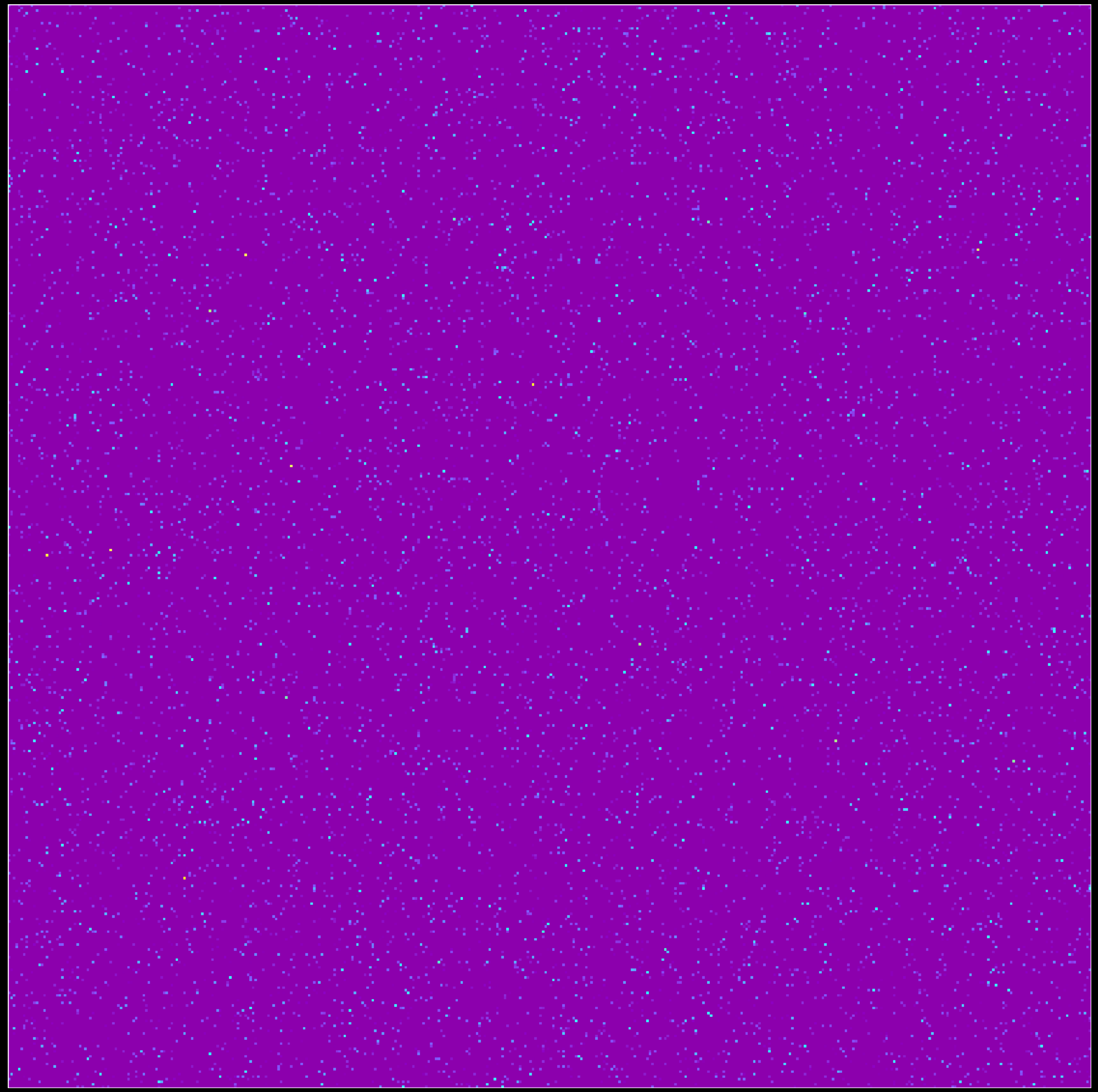
$$P(s) = \mathcal{N}\left(\mathbf{0}, \mathbb{1}\right) \left| \frac{\partial \xi}{\partial s} \right|$$



Signal space prior sample

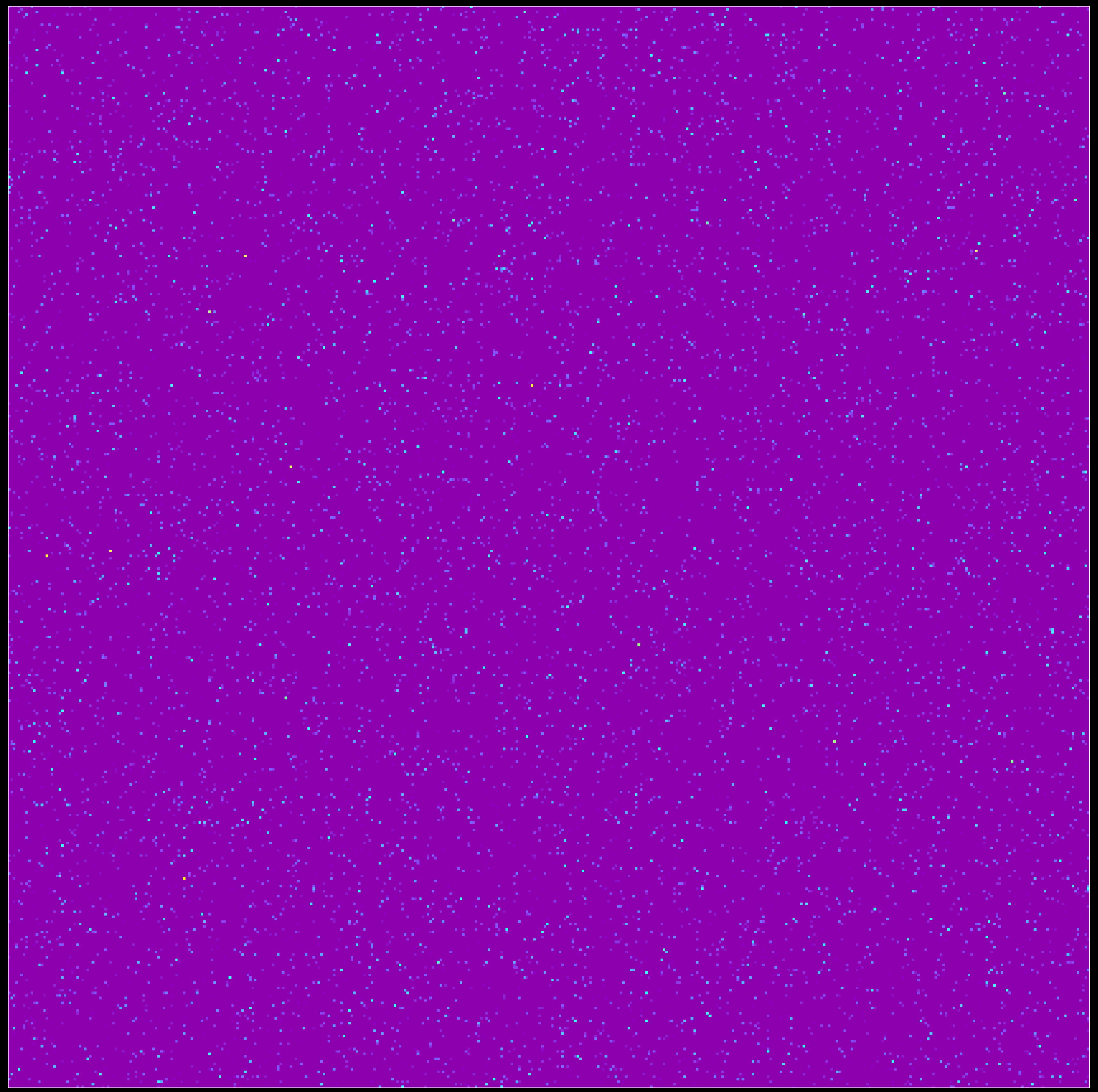
The prior

Sky

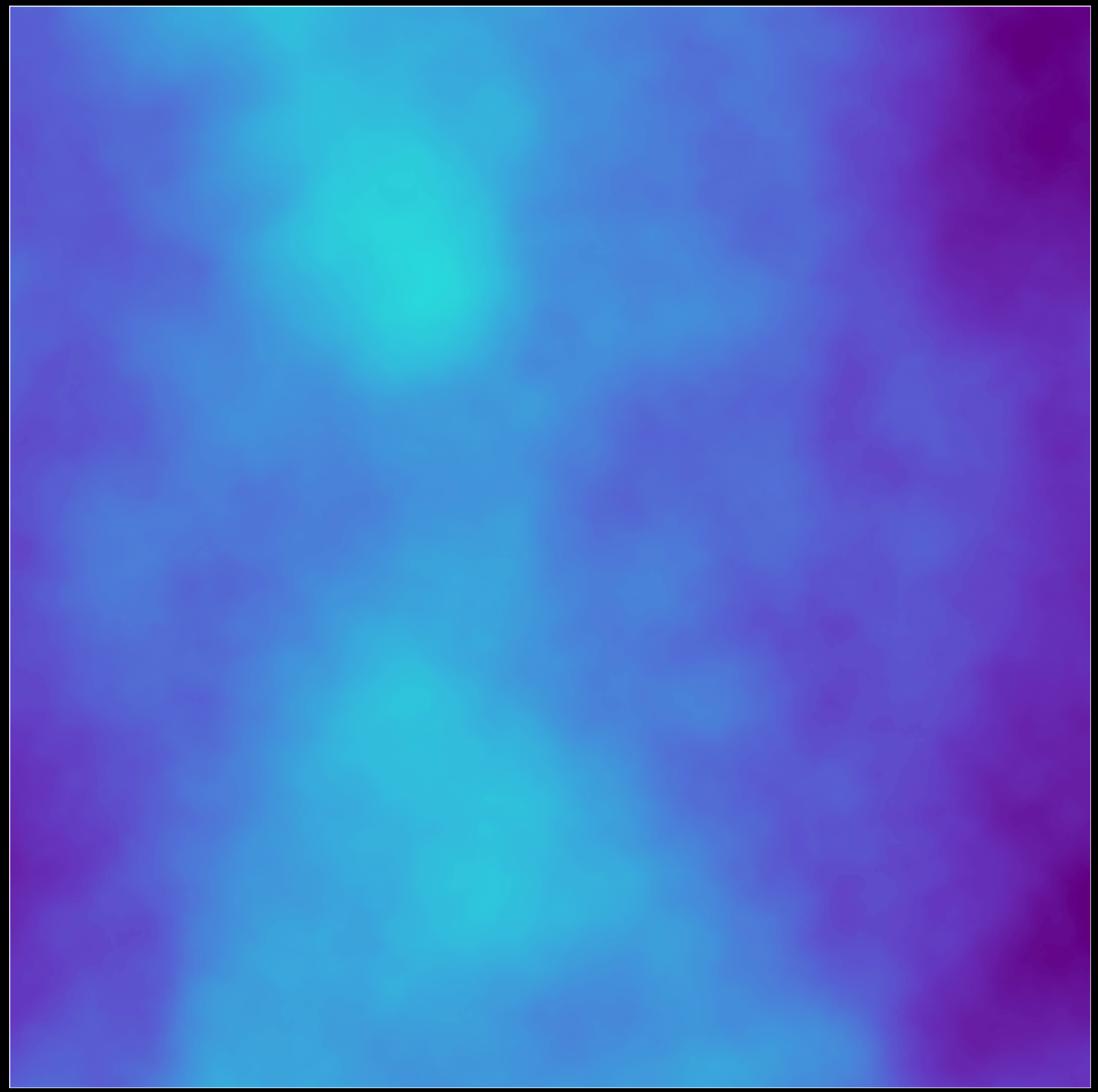


Point sources

The prior
Sky



+



Point sources

Diffuse emission

The prior

Sky

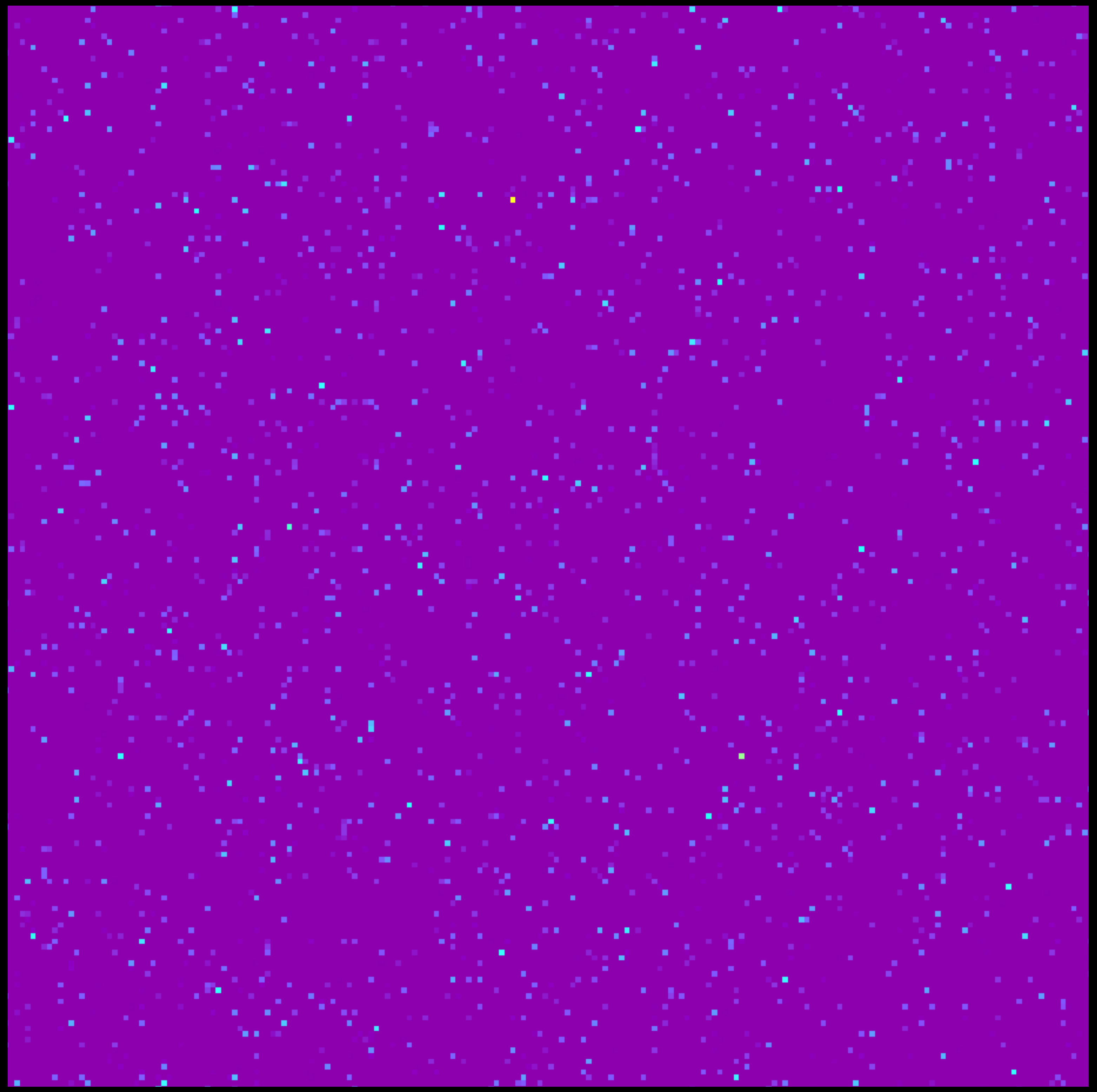
Point sources

Diffuse emission

Sky signal

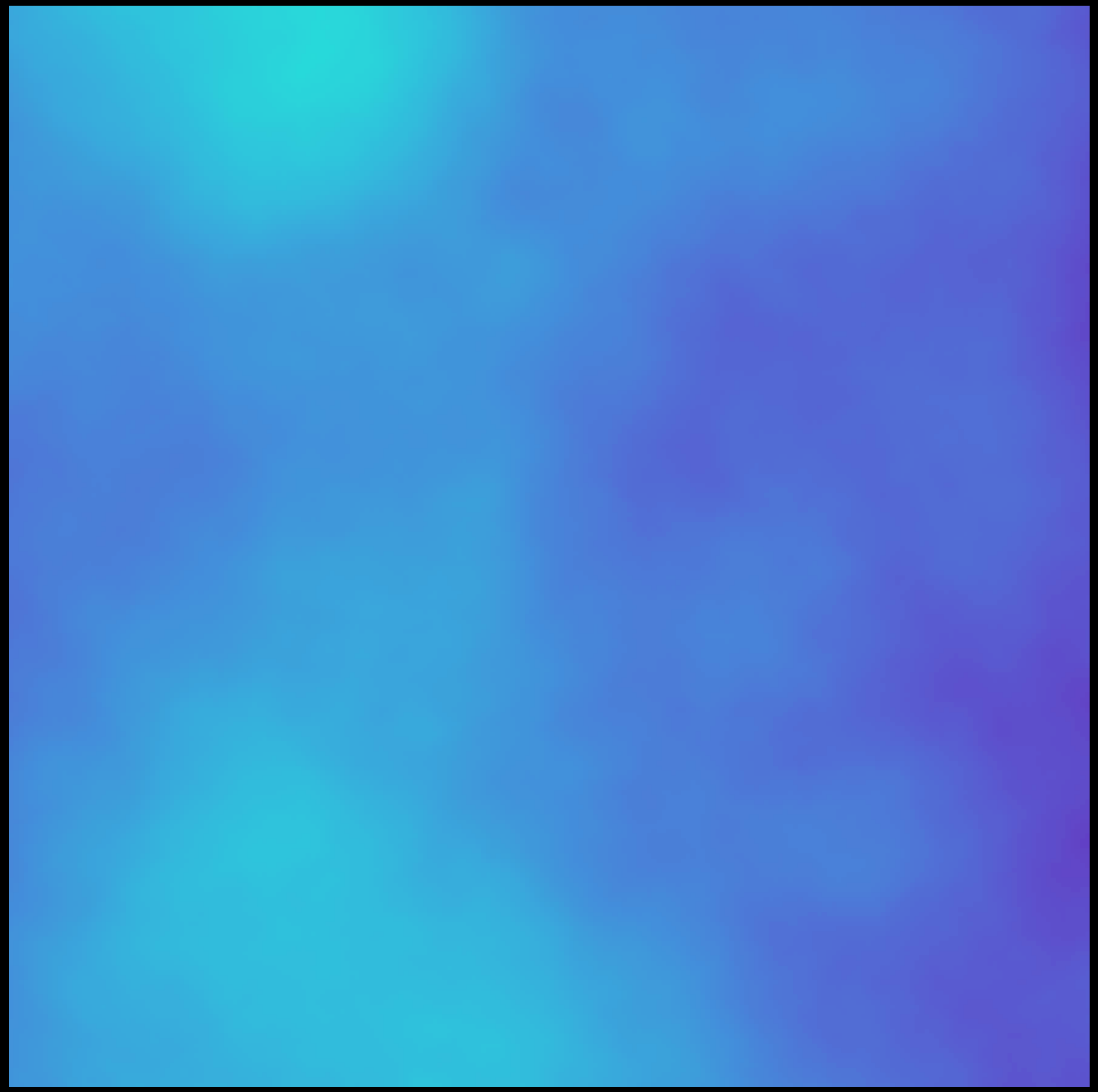
The prior

Sky



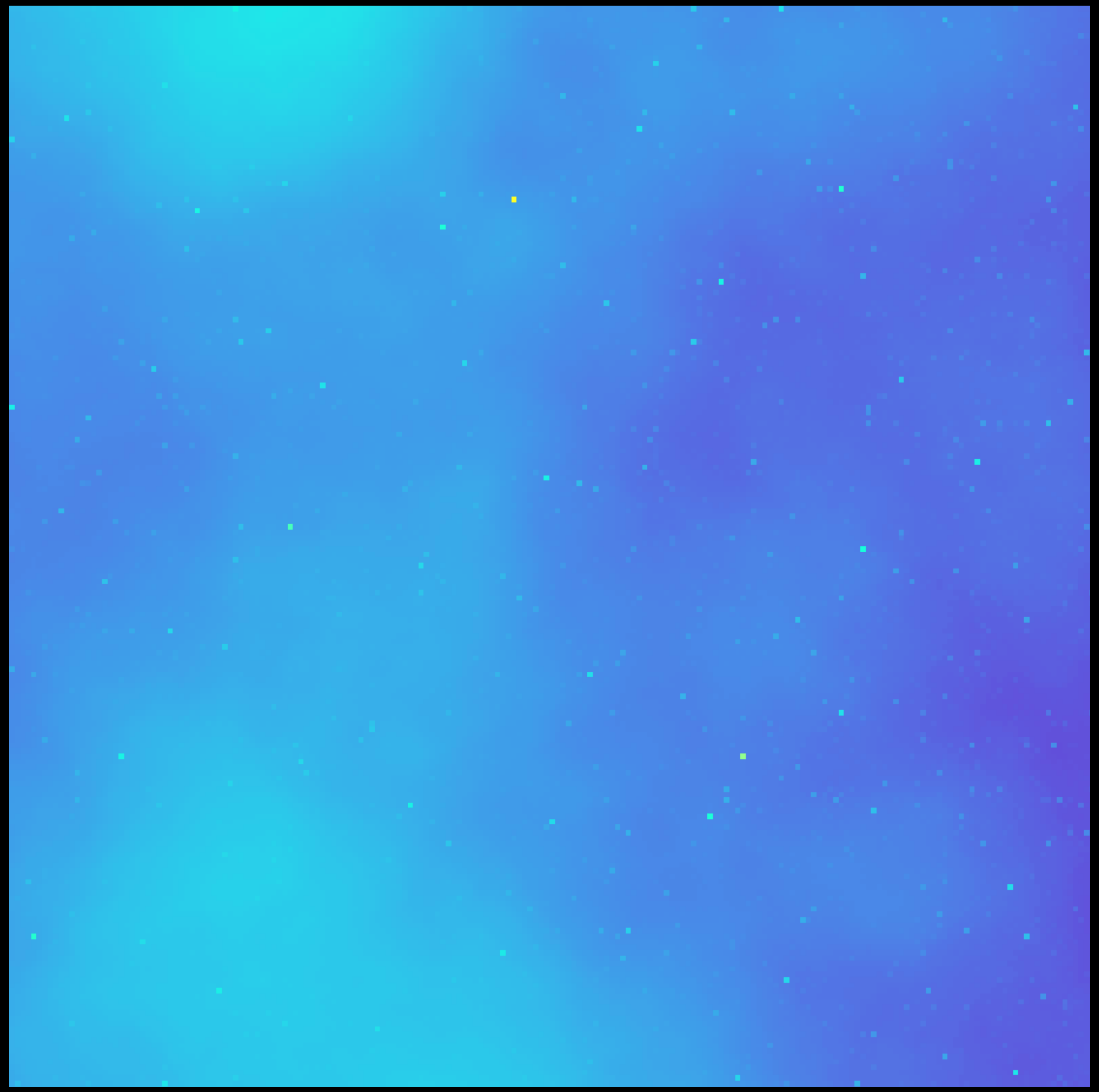
Point sources

+



Diffuse emission

=



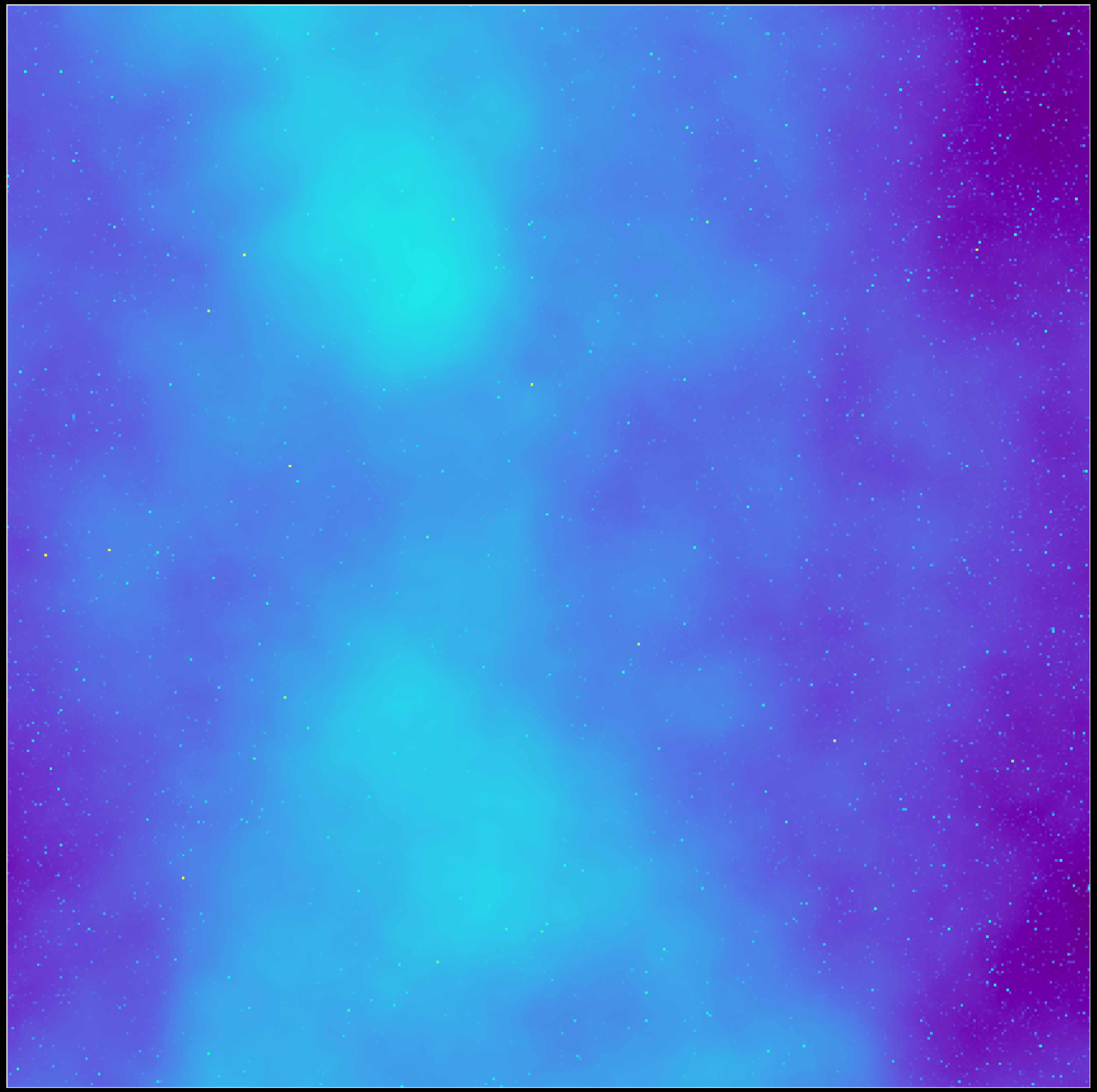
Sky signal

The Likelihood

$$P(s \mid d) = \frac{P(d \mid s)\, P(s)}{P(d)}$$

The Likelihood

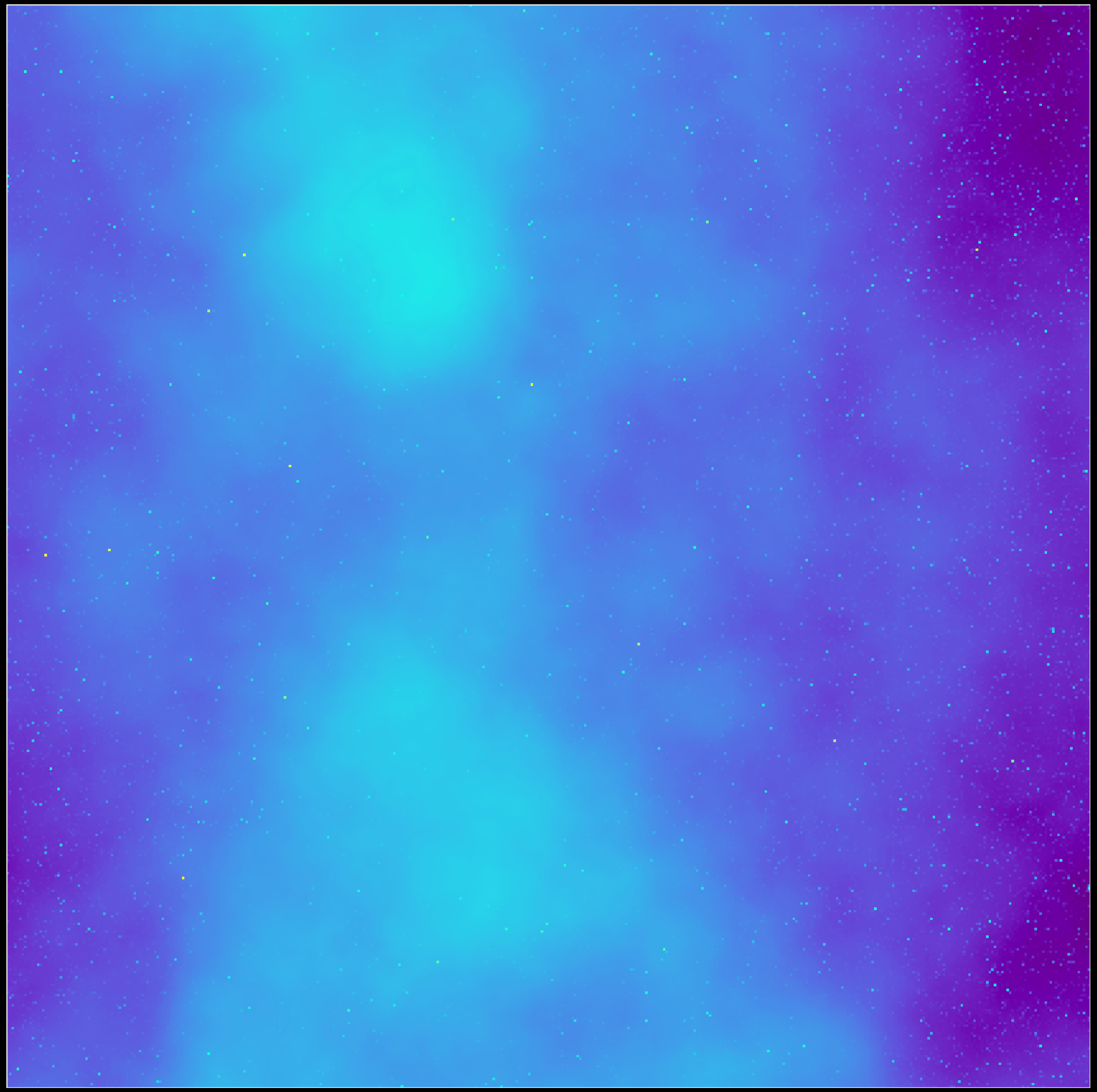
Instrument response



Sky signal

The Likelihood

Instrument response

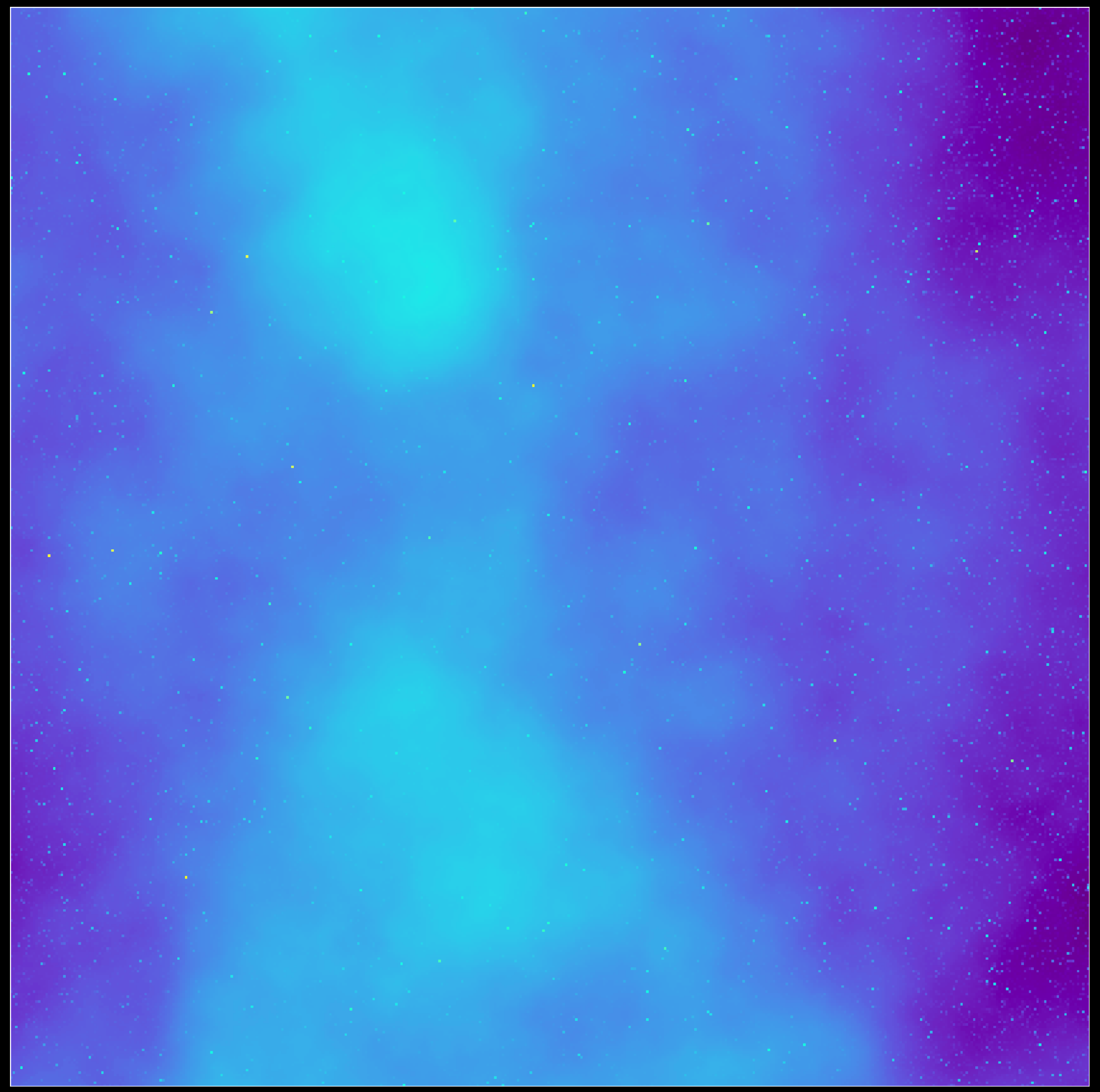


Sky signal

eROSITA on SRG

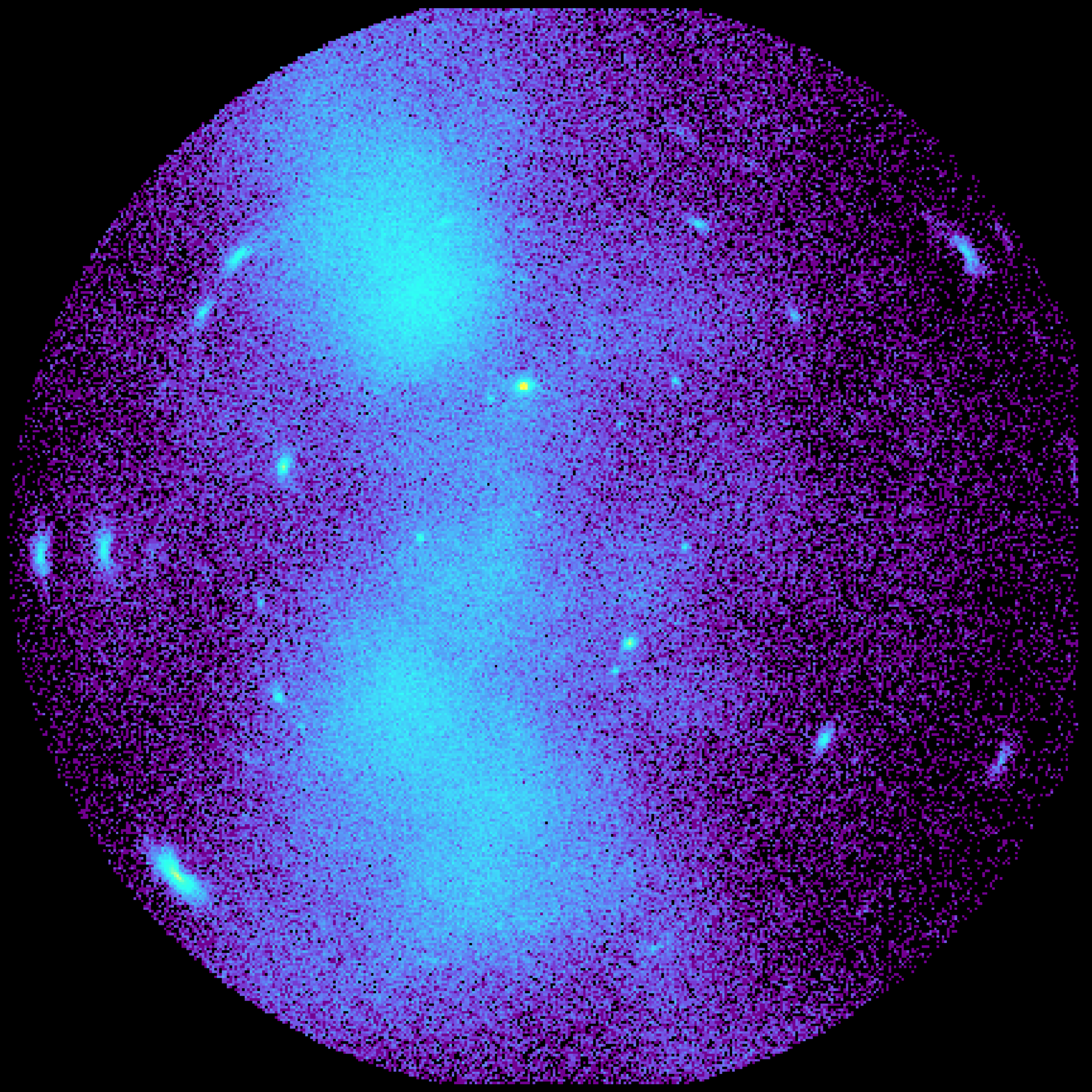
Credits @ Roscosmos

The Likelihood
Instrument response



Sky signal

eROSITA on SRG

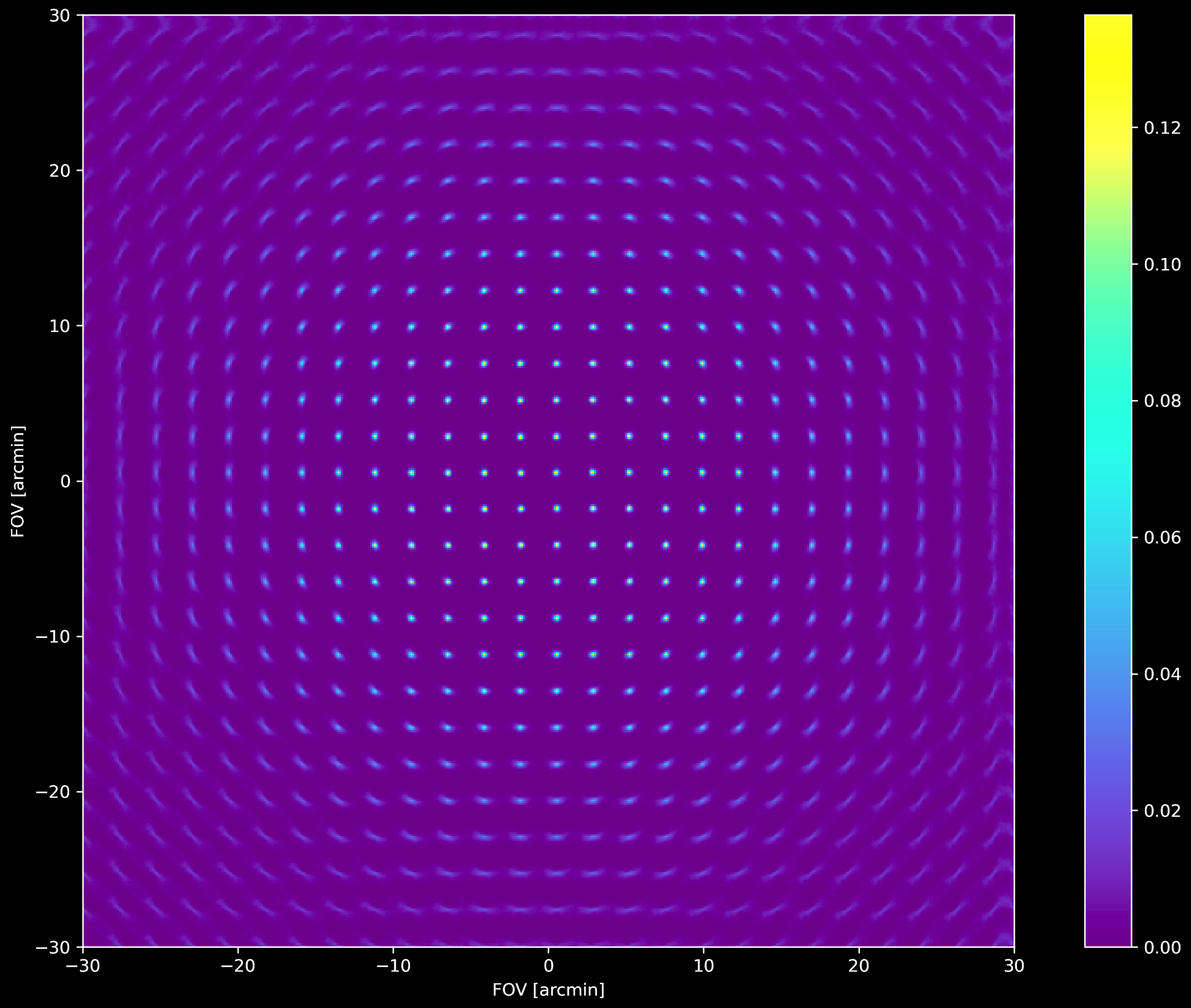


Sky data on earth

Credits @ Roscosmos

The Likelihood
Point-spread function

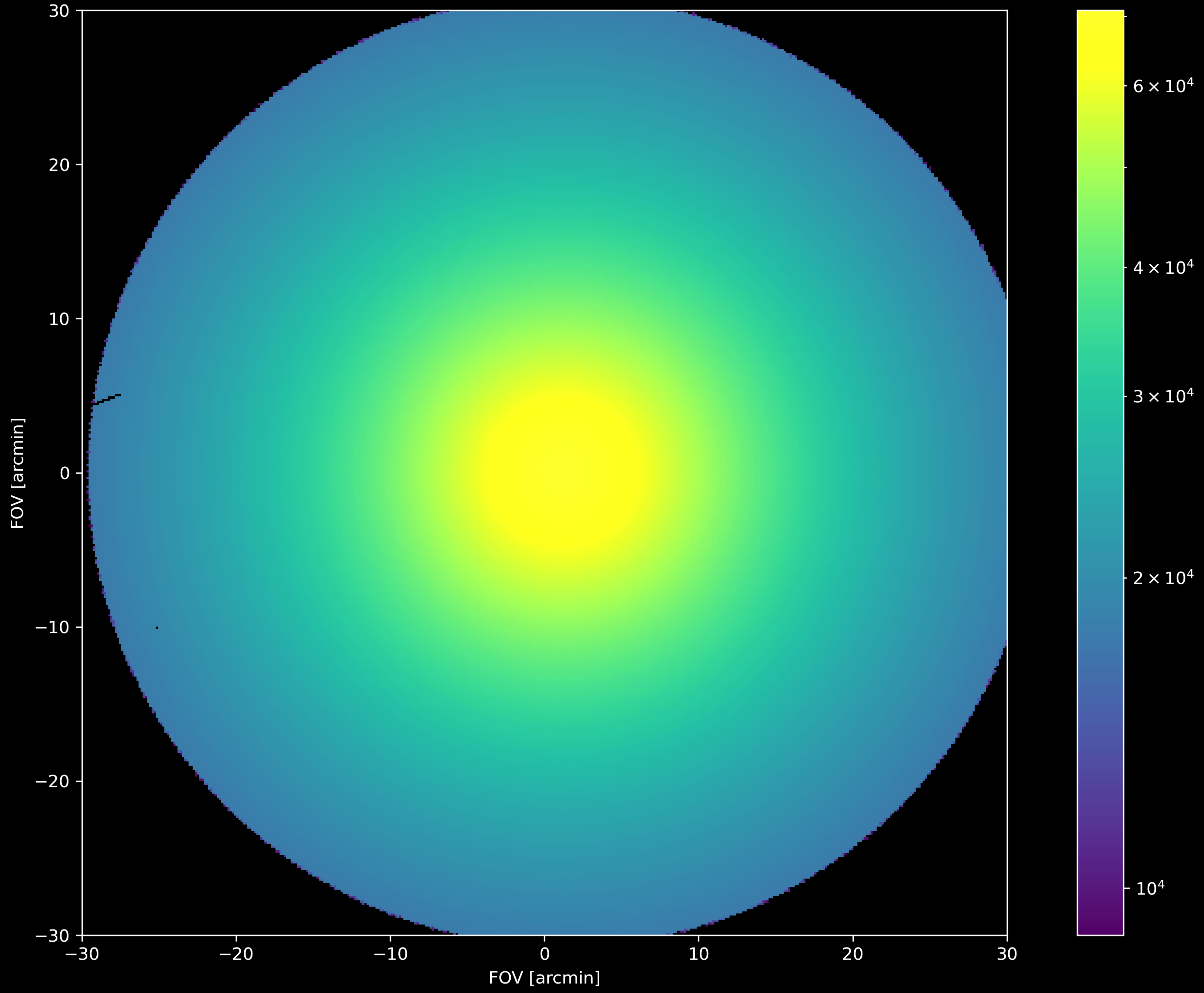
- $R = \text{PSF}$



eROSITA TM1 PSF (1.0 keV)

The Likelihood
Exposure

- $R = \mathsf{E}$

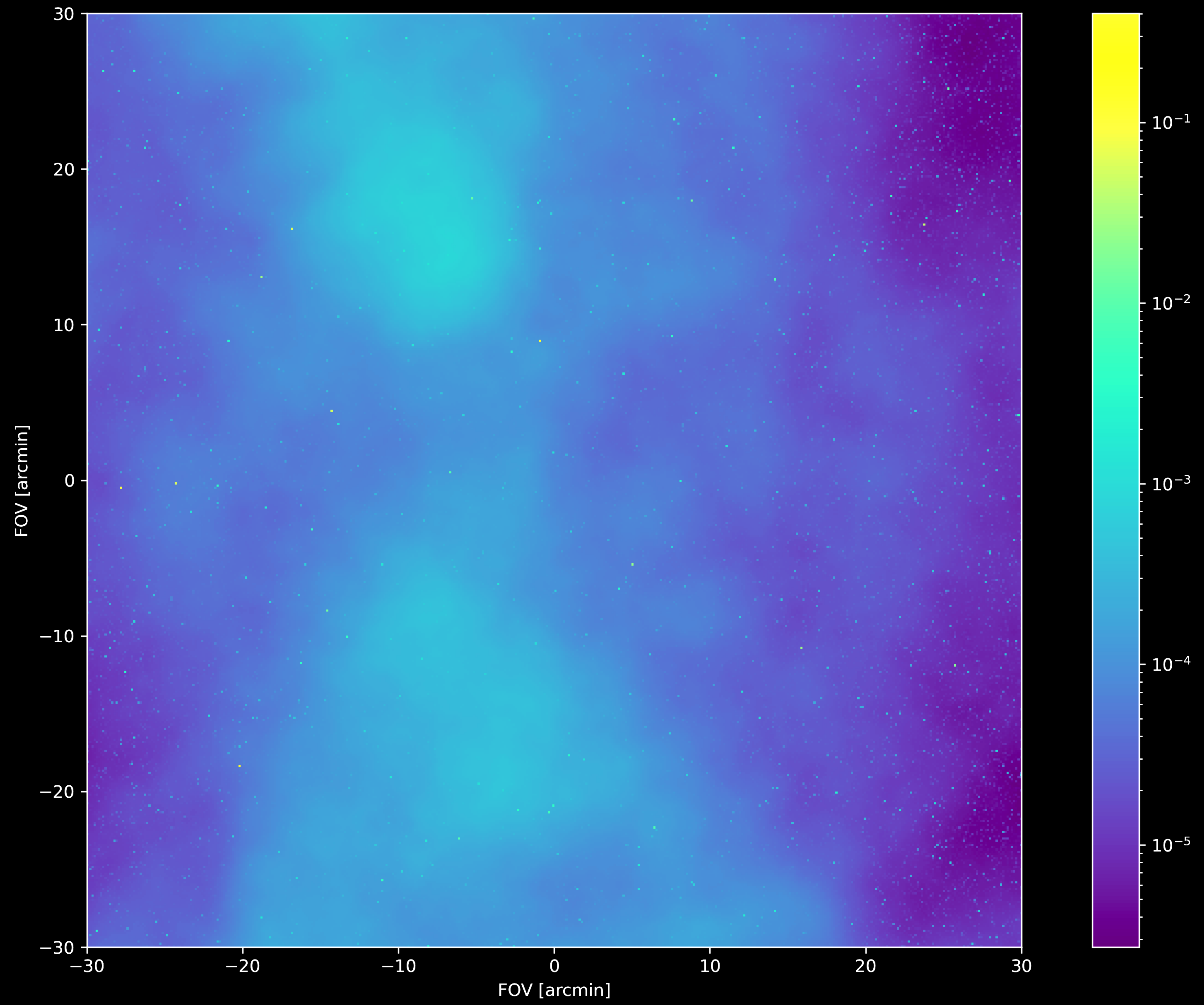


eROSITA TM1 exposure

The Likelihood

Signal

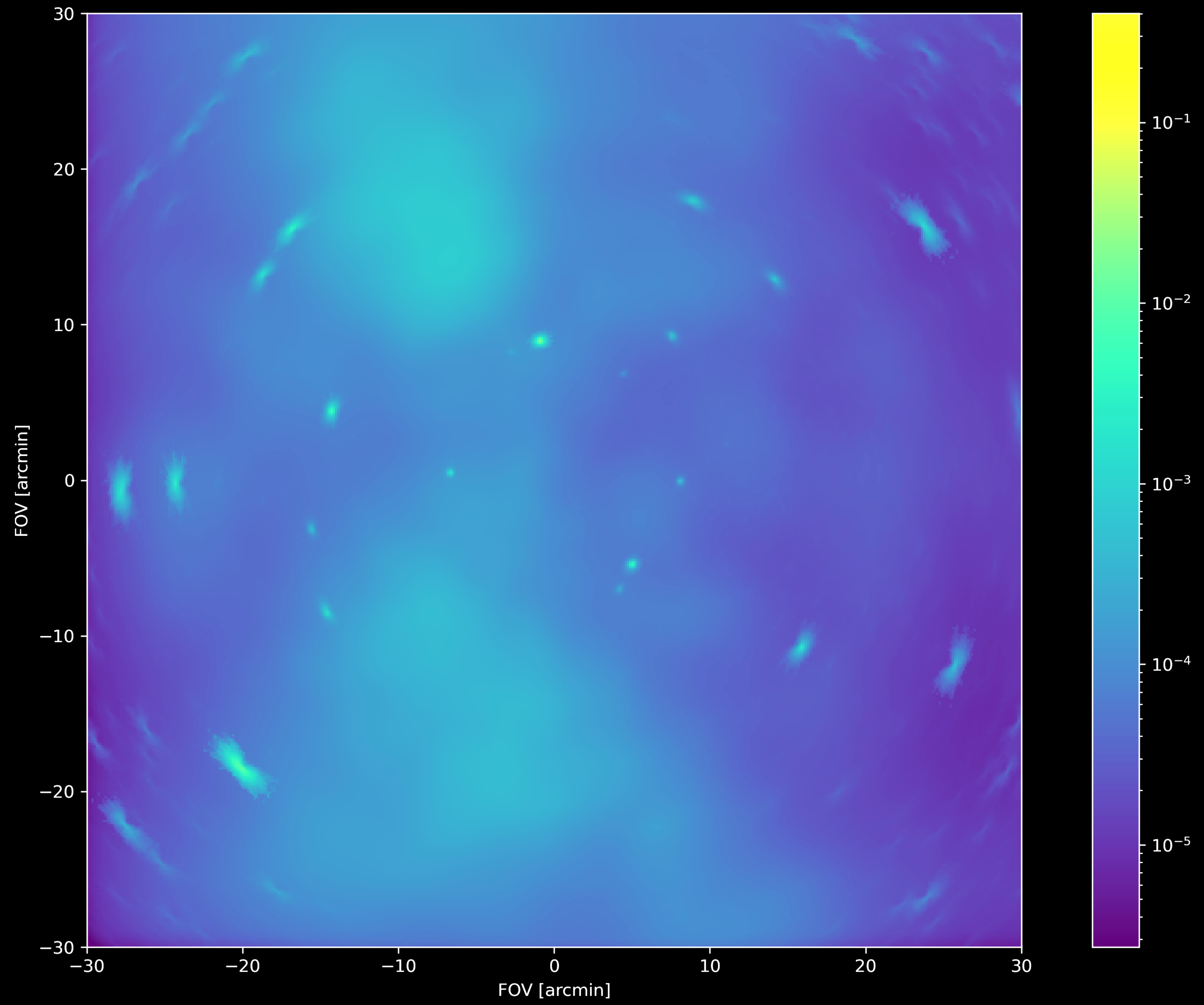
S



The Likelihood

Signal response

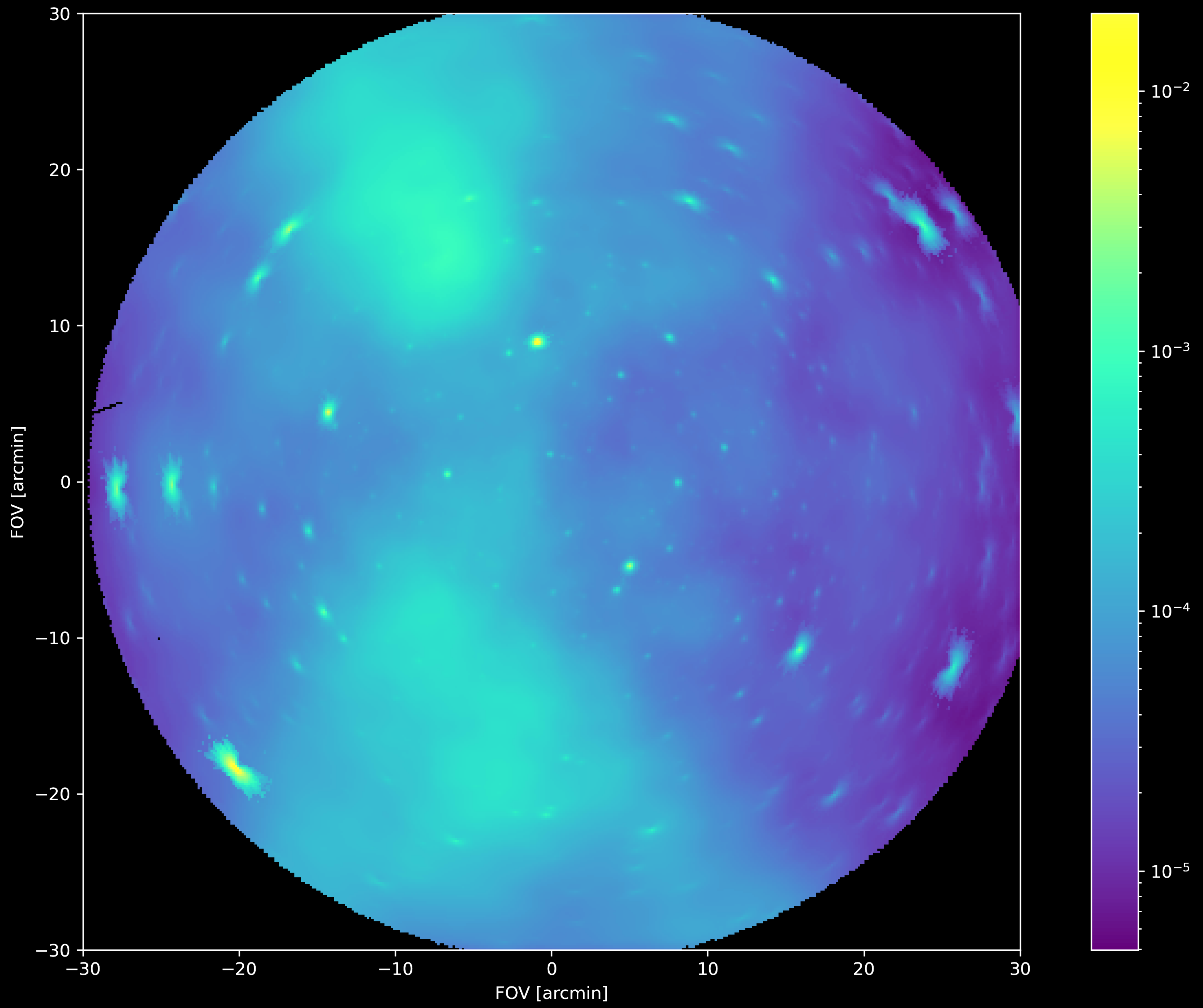
$$\mathrm{PSF}\,(s)$$



The Likelihood

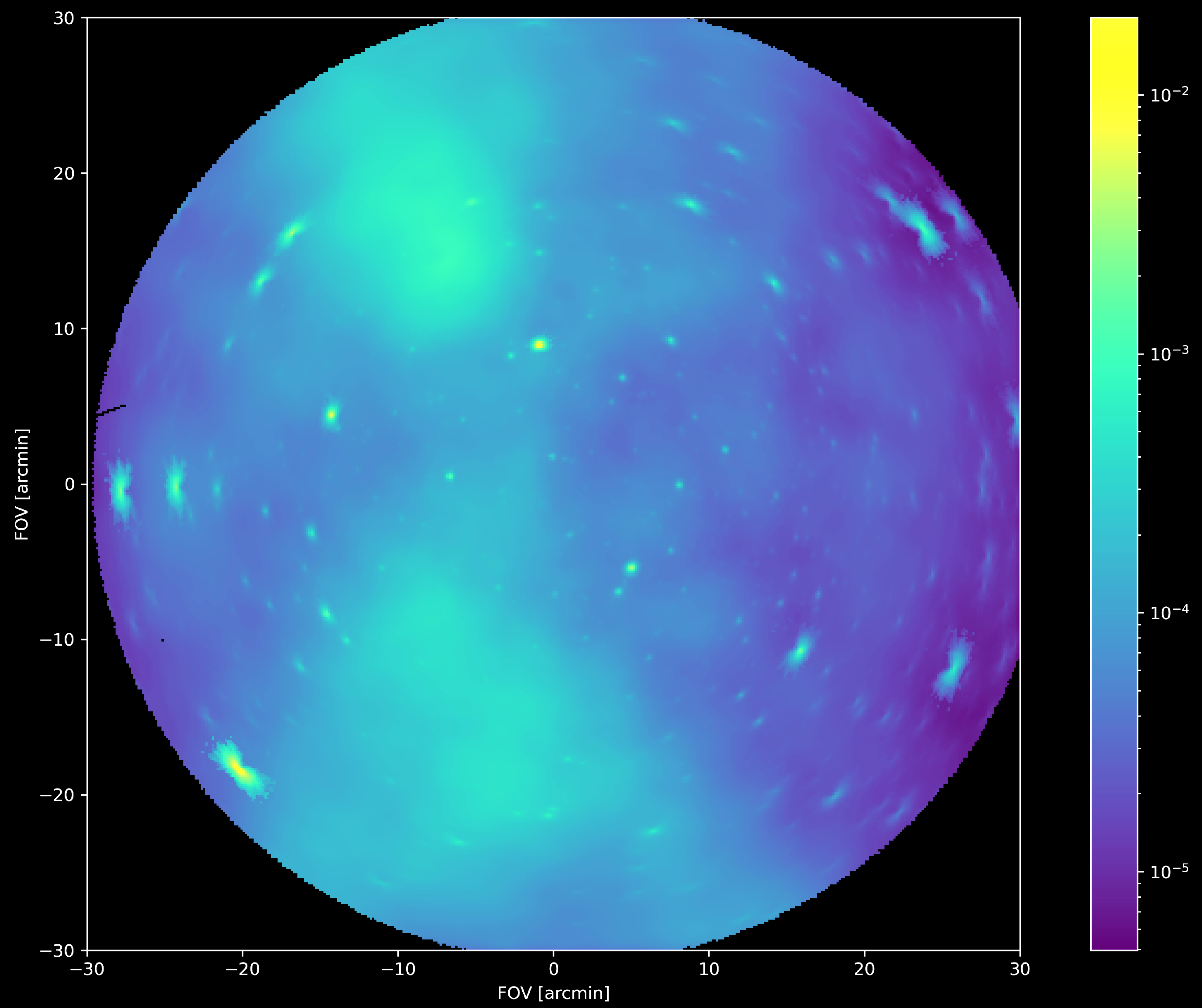
Signal response

$$R s = \mathrm{E}\left(\mathrm{PSF}\left(s\right)\right)$$



The Likelihood
Signal response

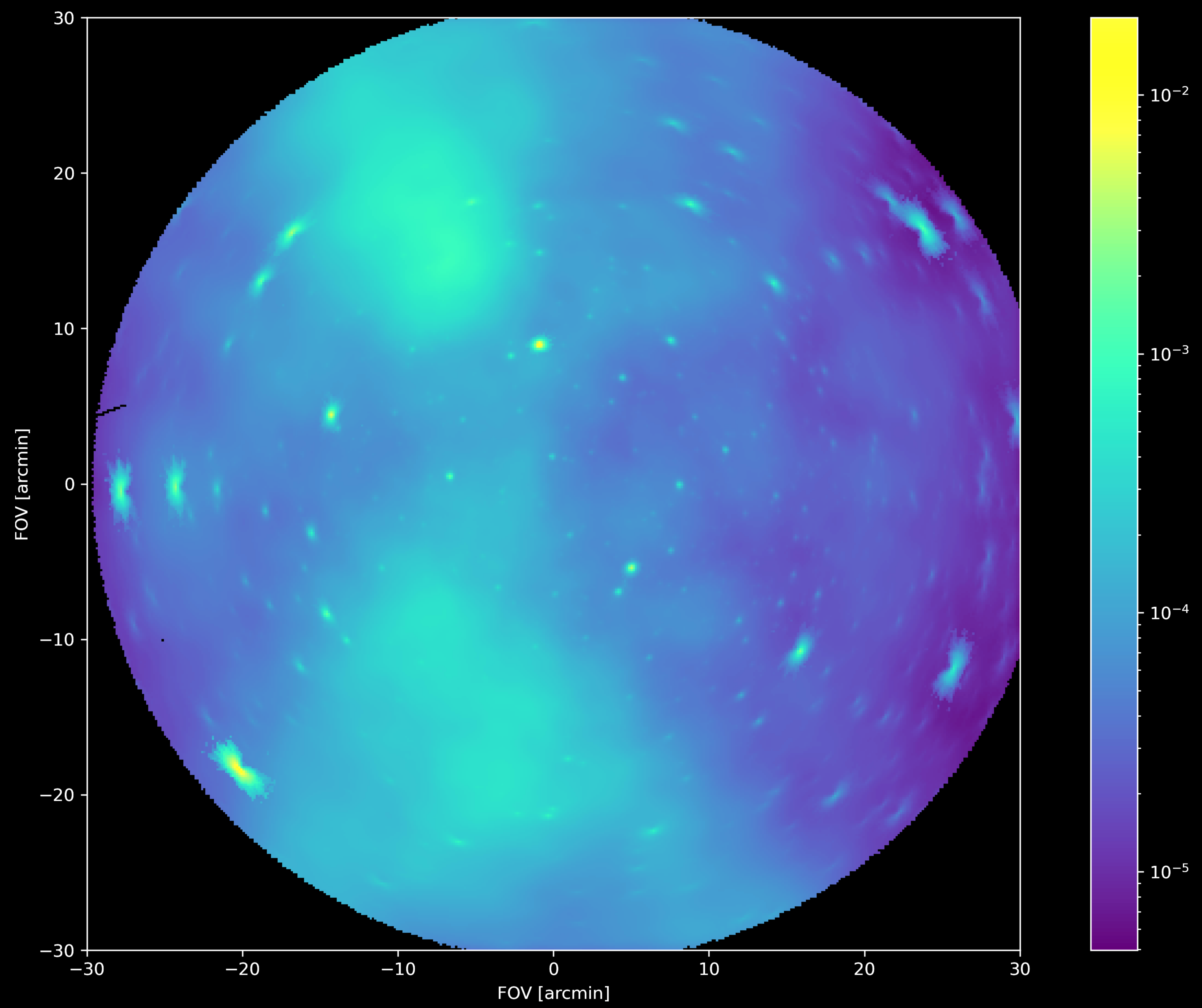
$$\lambda = R s$$



The Likelihood

Poissonian noise

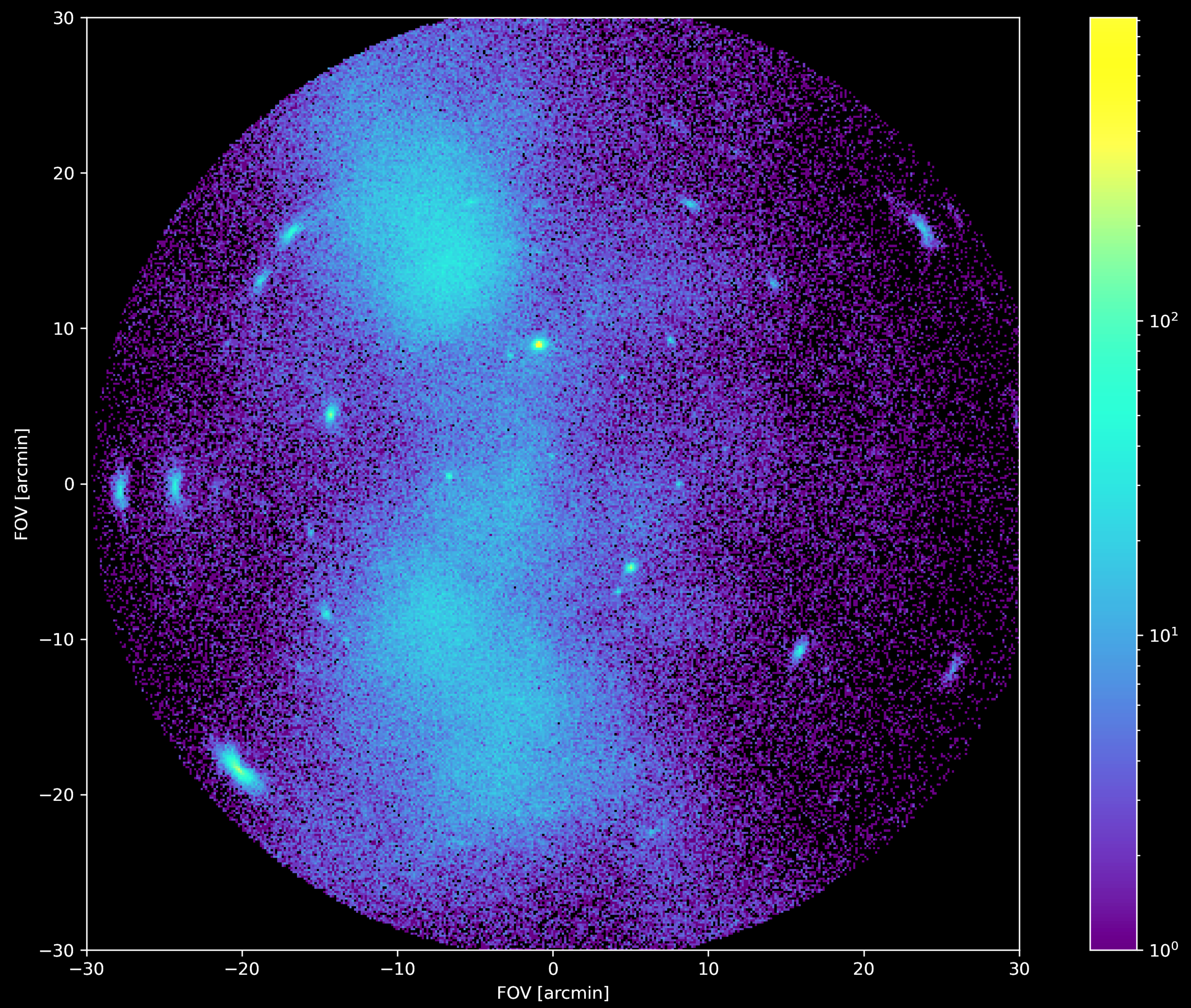
$$P(d\,|\,\lambda) = \prod_{i=1}^{N} \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



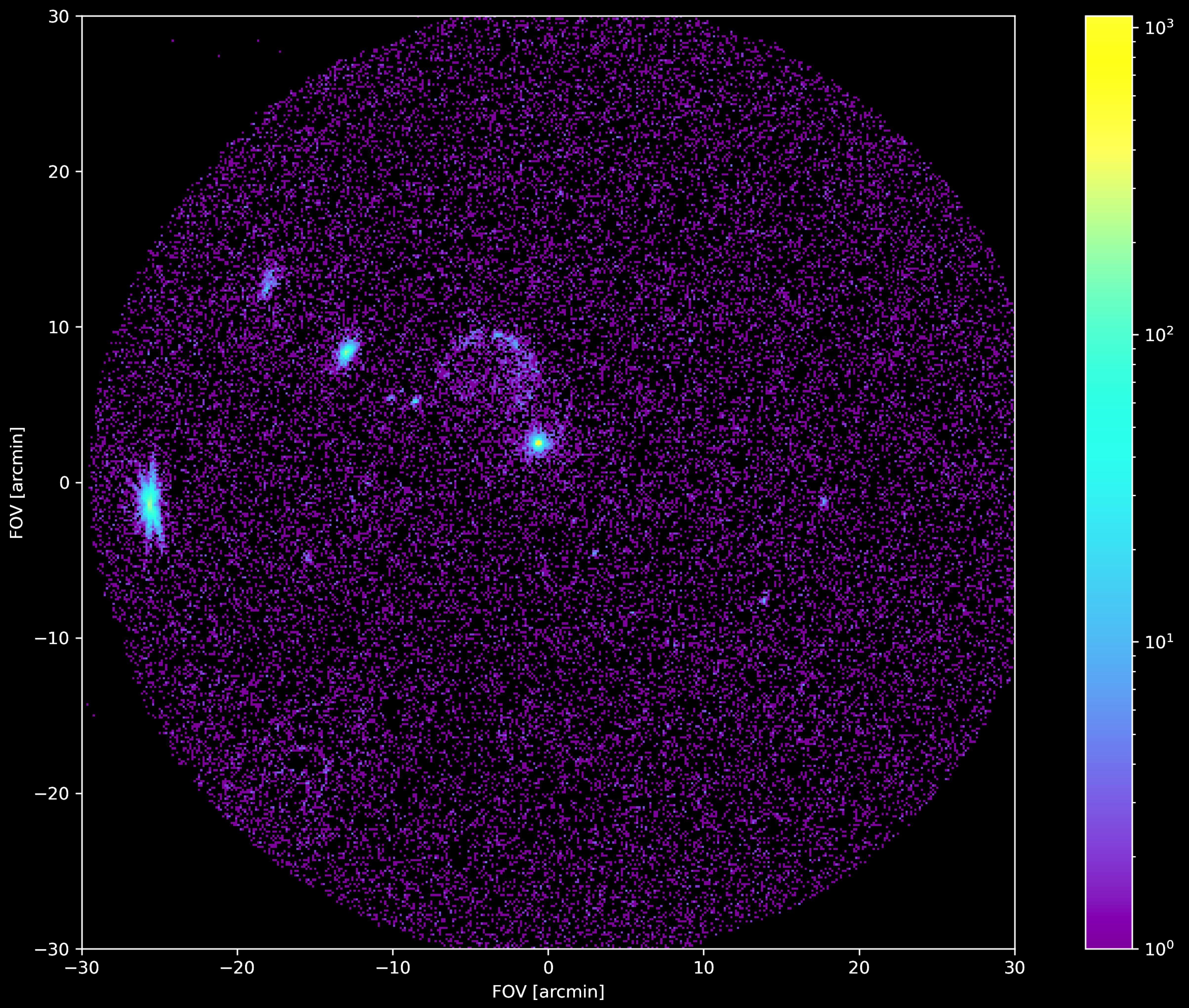
The Likelihood

Poissonian noise

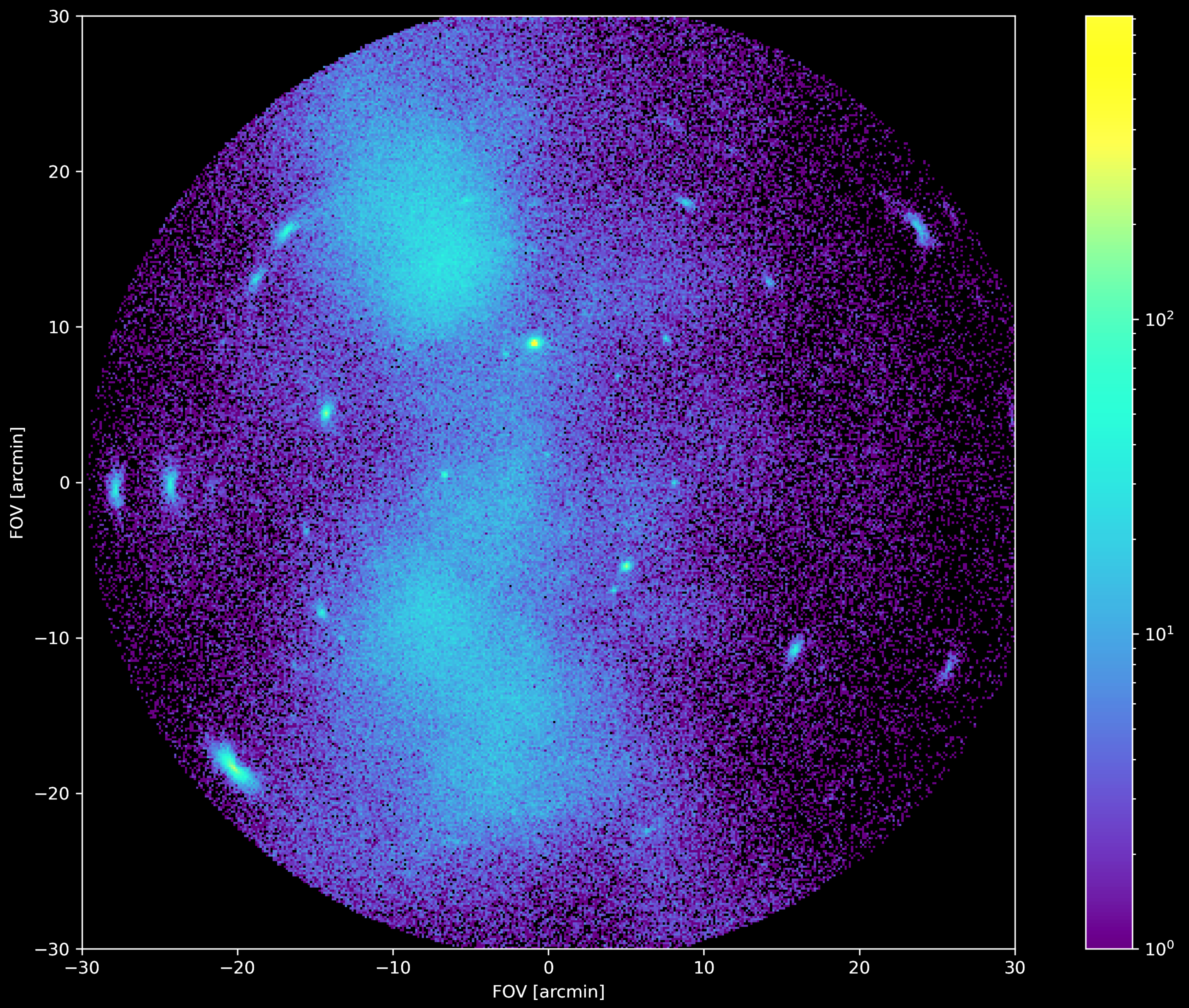
$$P(d\,|\,\lambda) = \prod_{i=1}^{N} \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



The Data



eROSITA TM1 SN1987A data



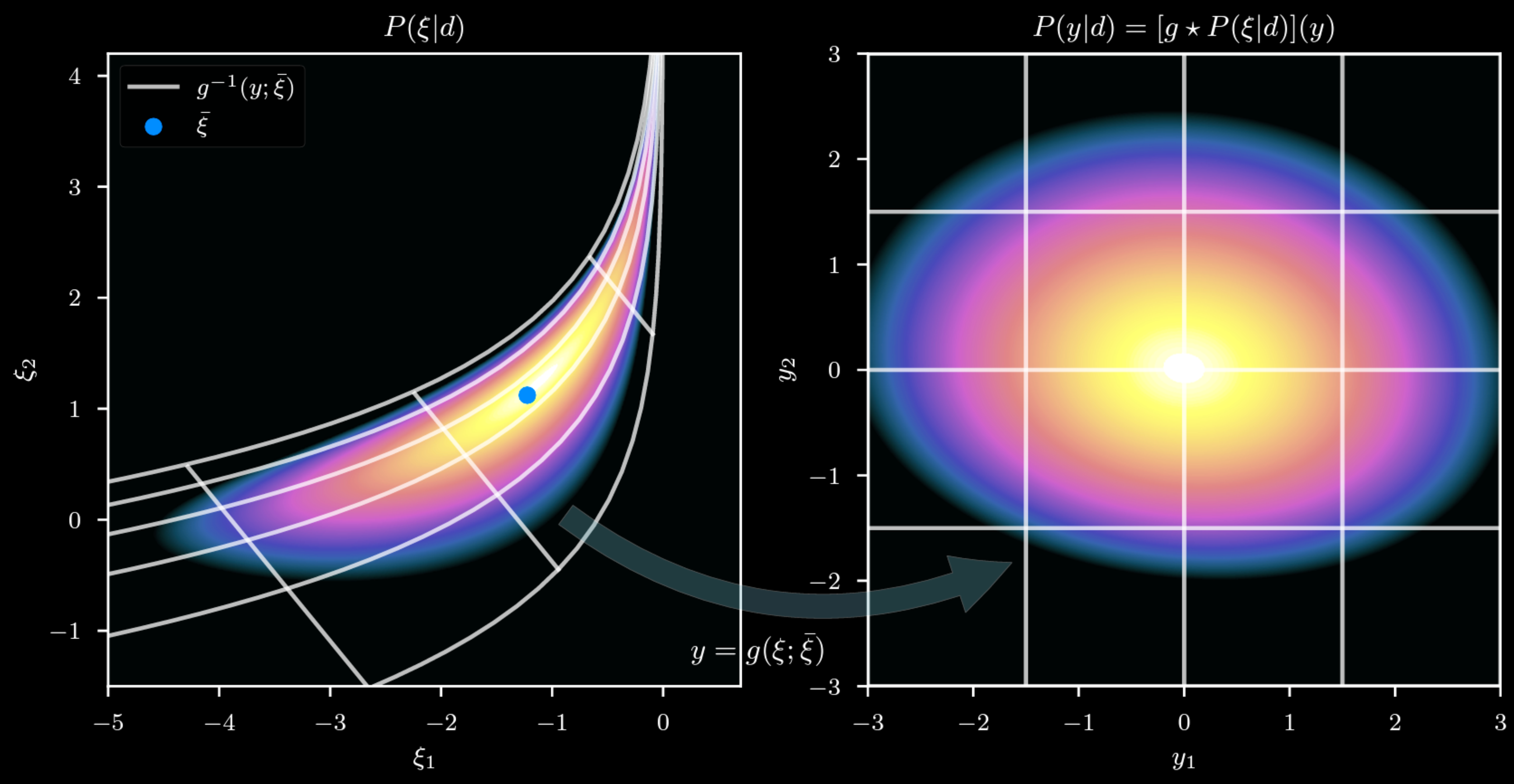
Simulated eROSITA TM1 data

The Posterior

$$P(s \mid d) = \frac{P(d \mid s)\, P(s)}{P(d)}$$

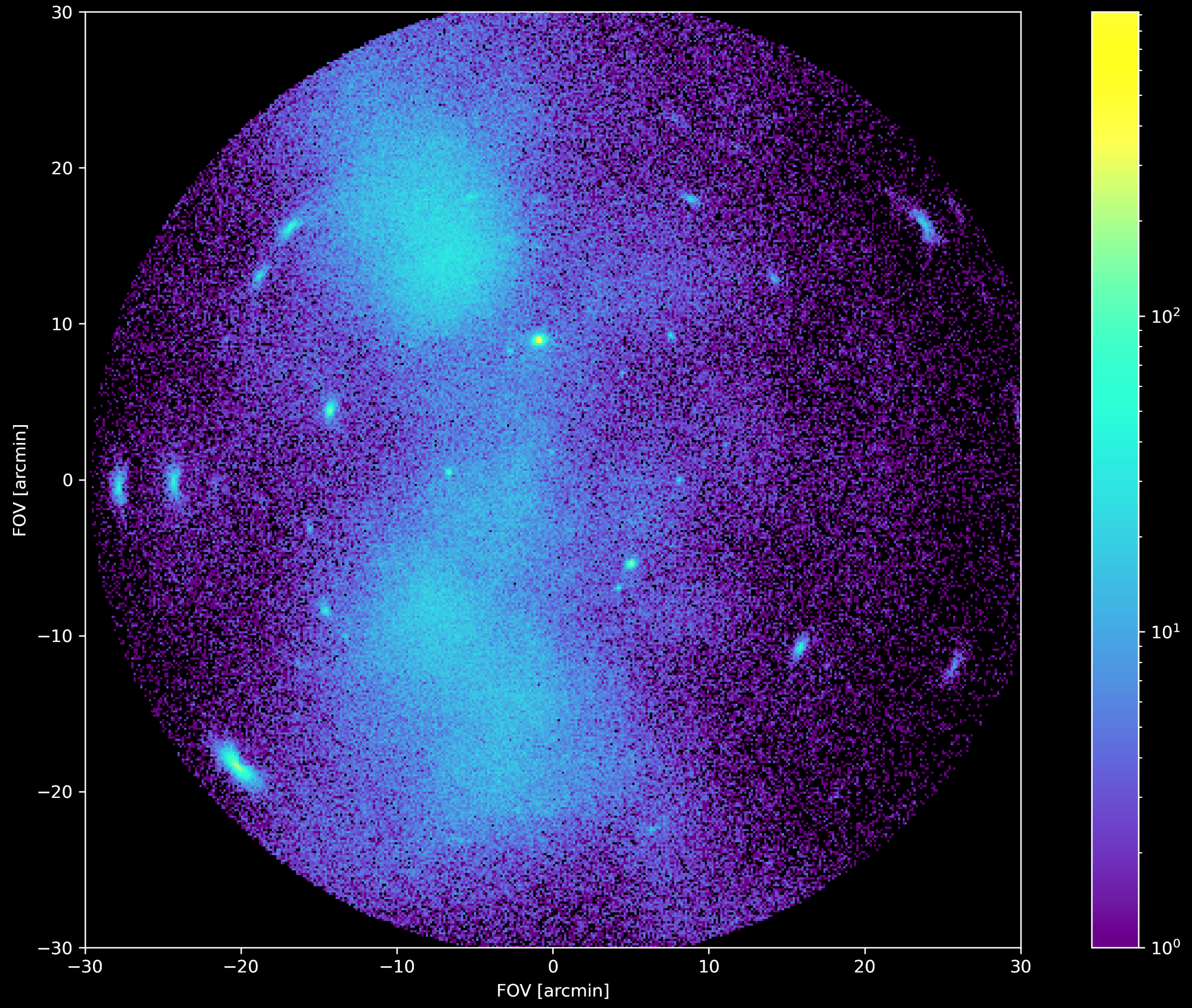
Inference

geometric Variational Inference



Credits @ Frank, P.; Leike, R.; Enßlin, T.A. Geometric Variational Inference. *Entropy* **2021**, *23*, 853.

The Data

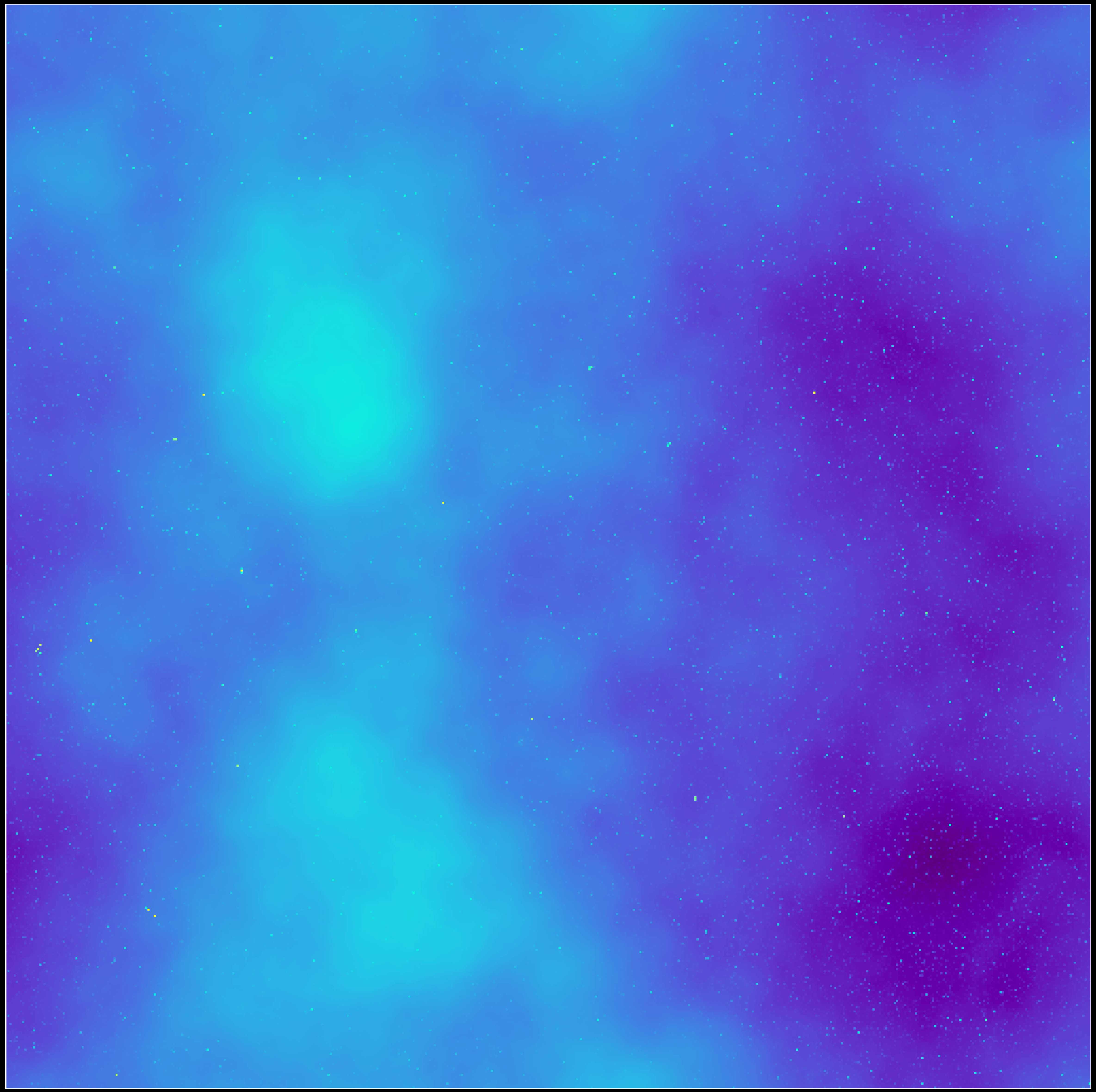


Simulated eROSITA TM1 data

Inference

Posterior

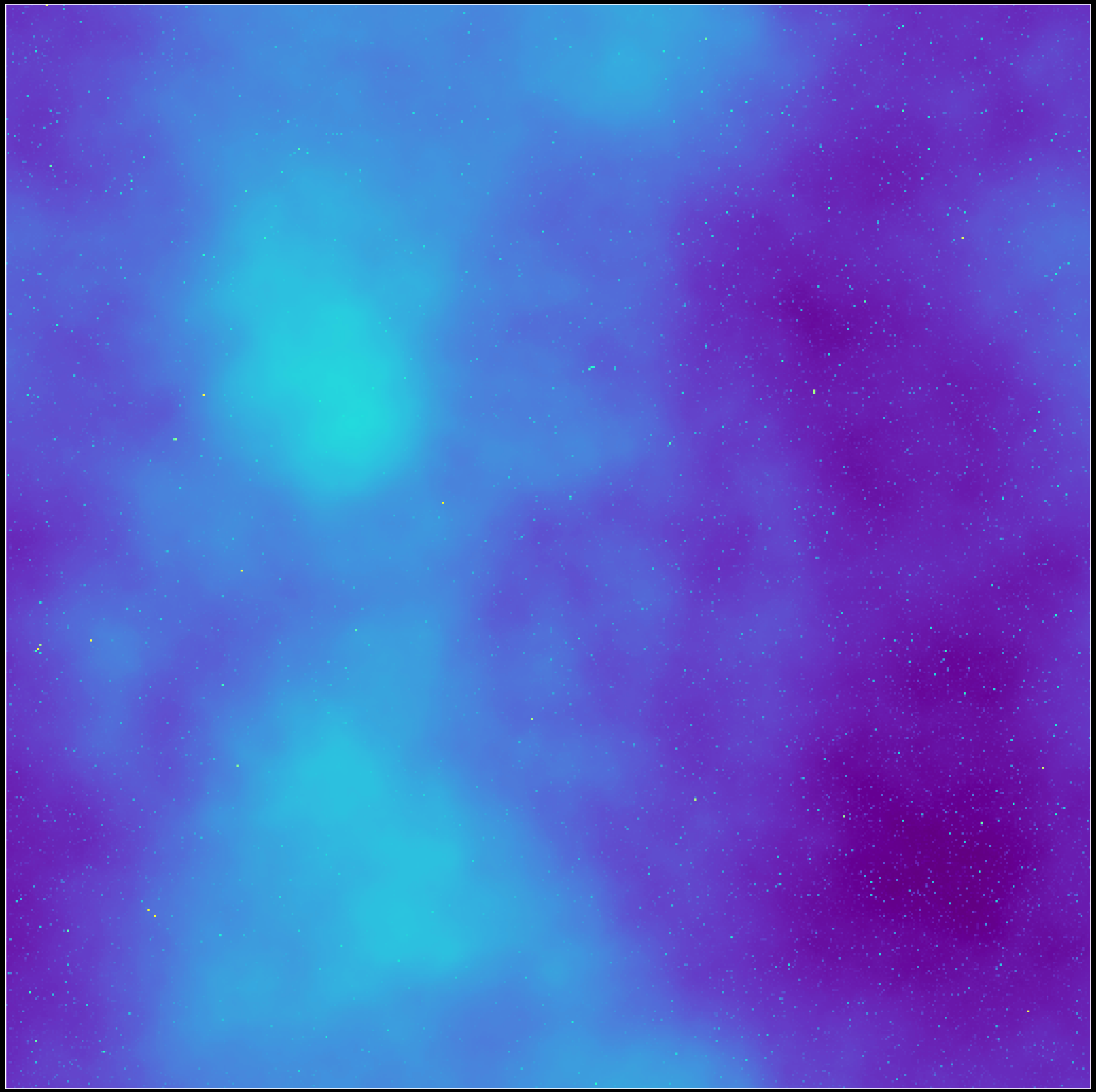
$$P(s \mid d)$$



Inference

Posterior

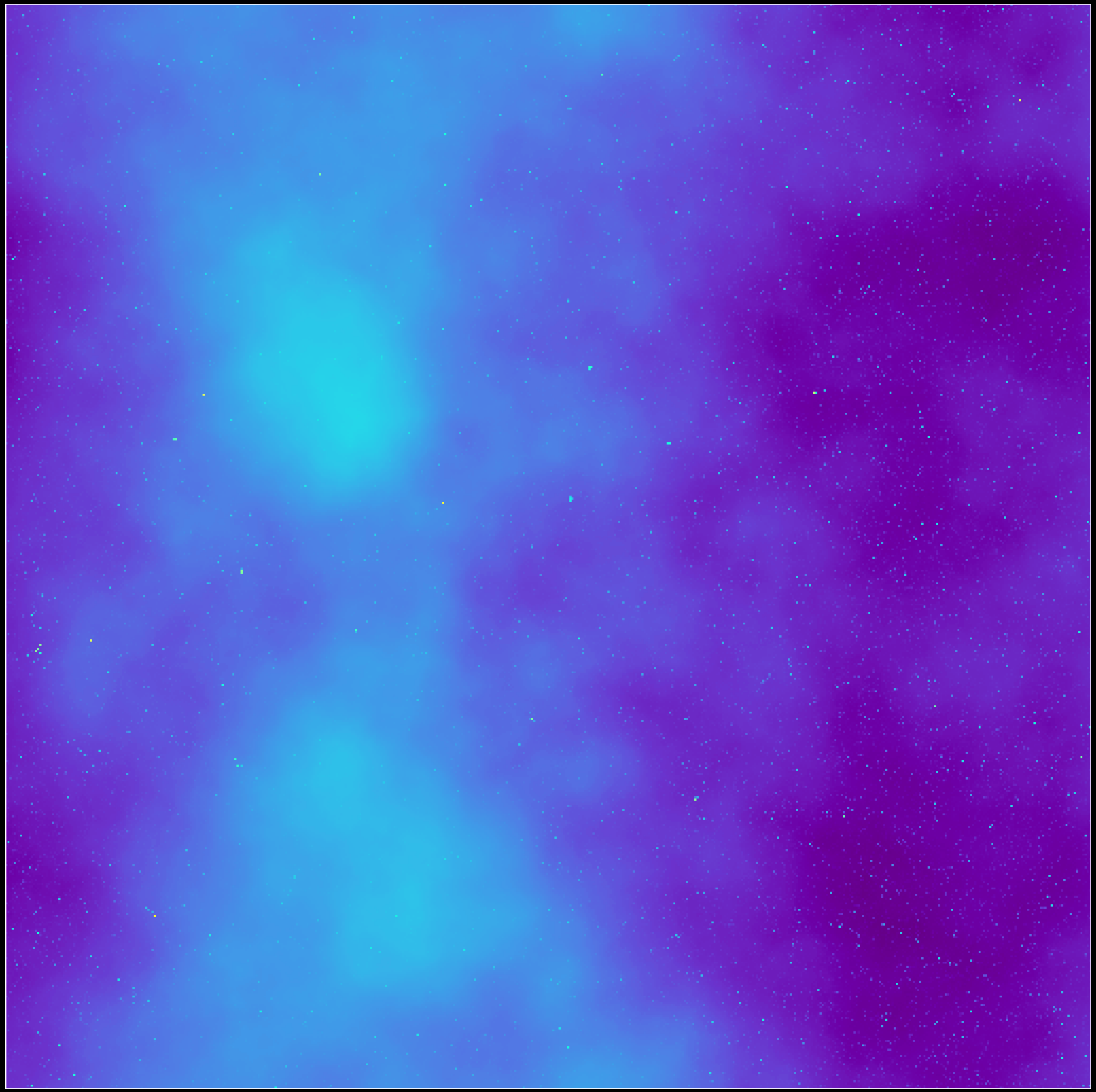
$$P(s \mid d)$$



Inference

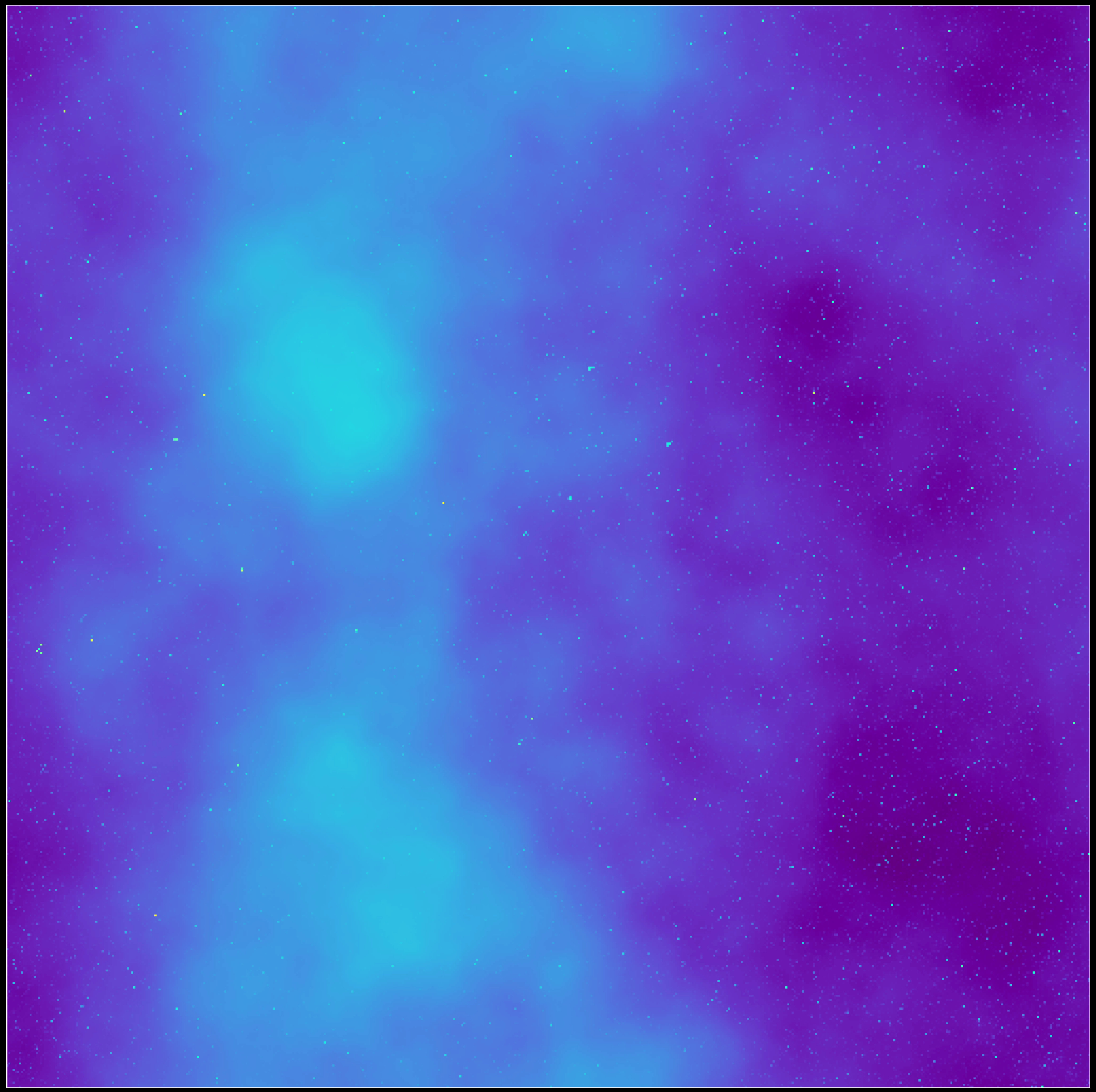
Posterior

$$P(s \mid d)$$



Inference
Posterior

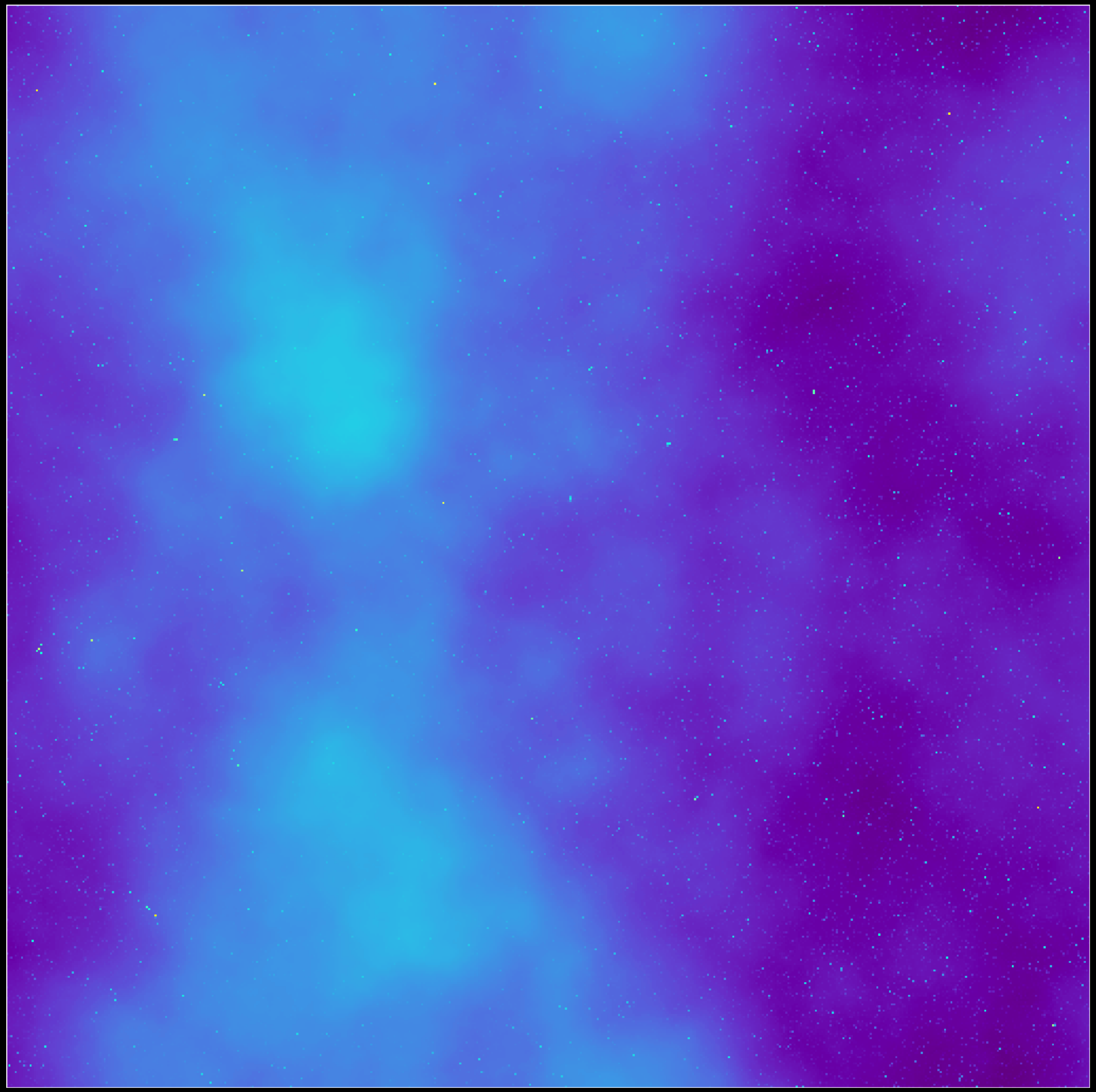
$$P(s\,|\,d)$$



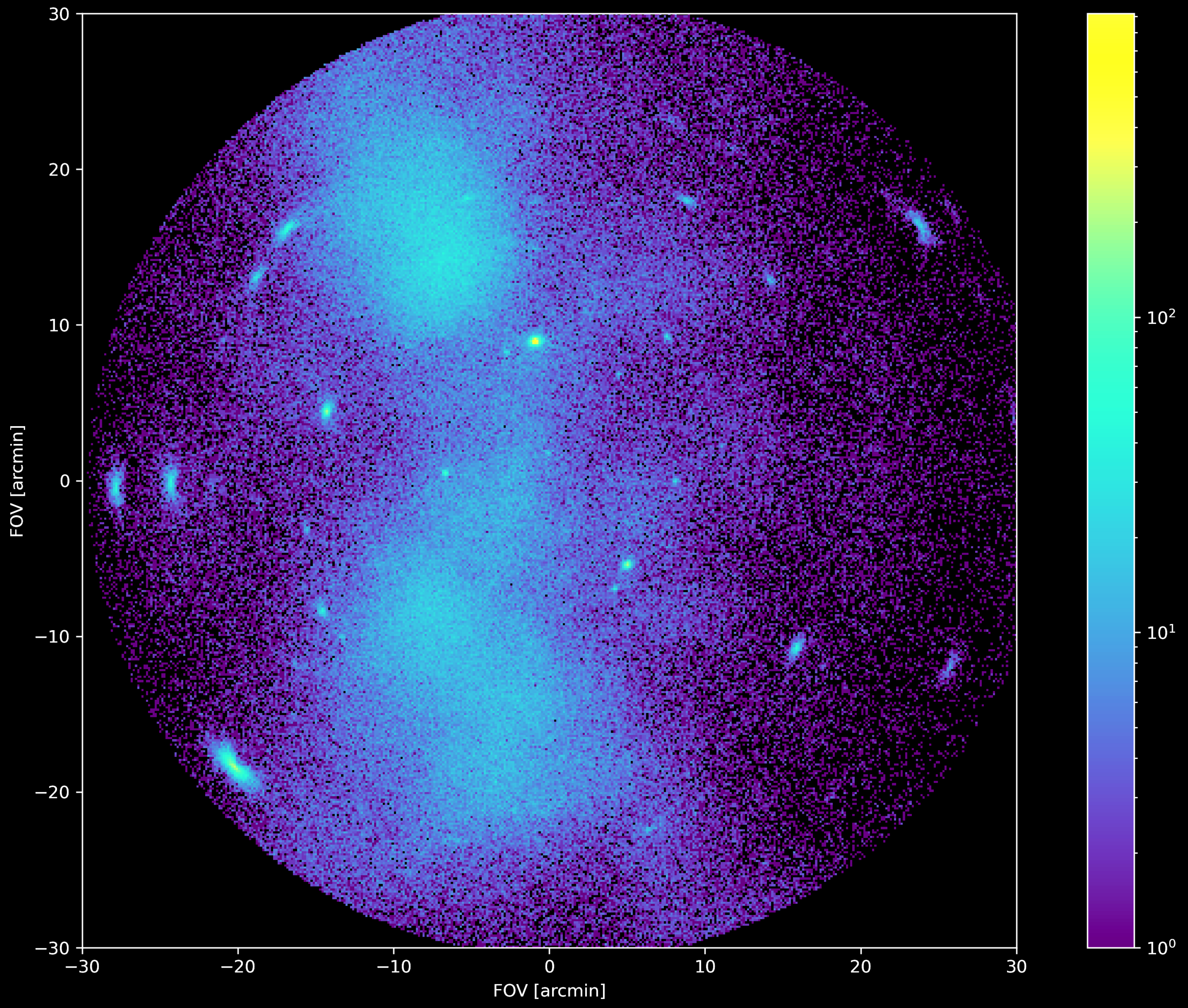
Inference

Posterior

$$P(s \mid d)$$

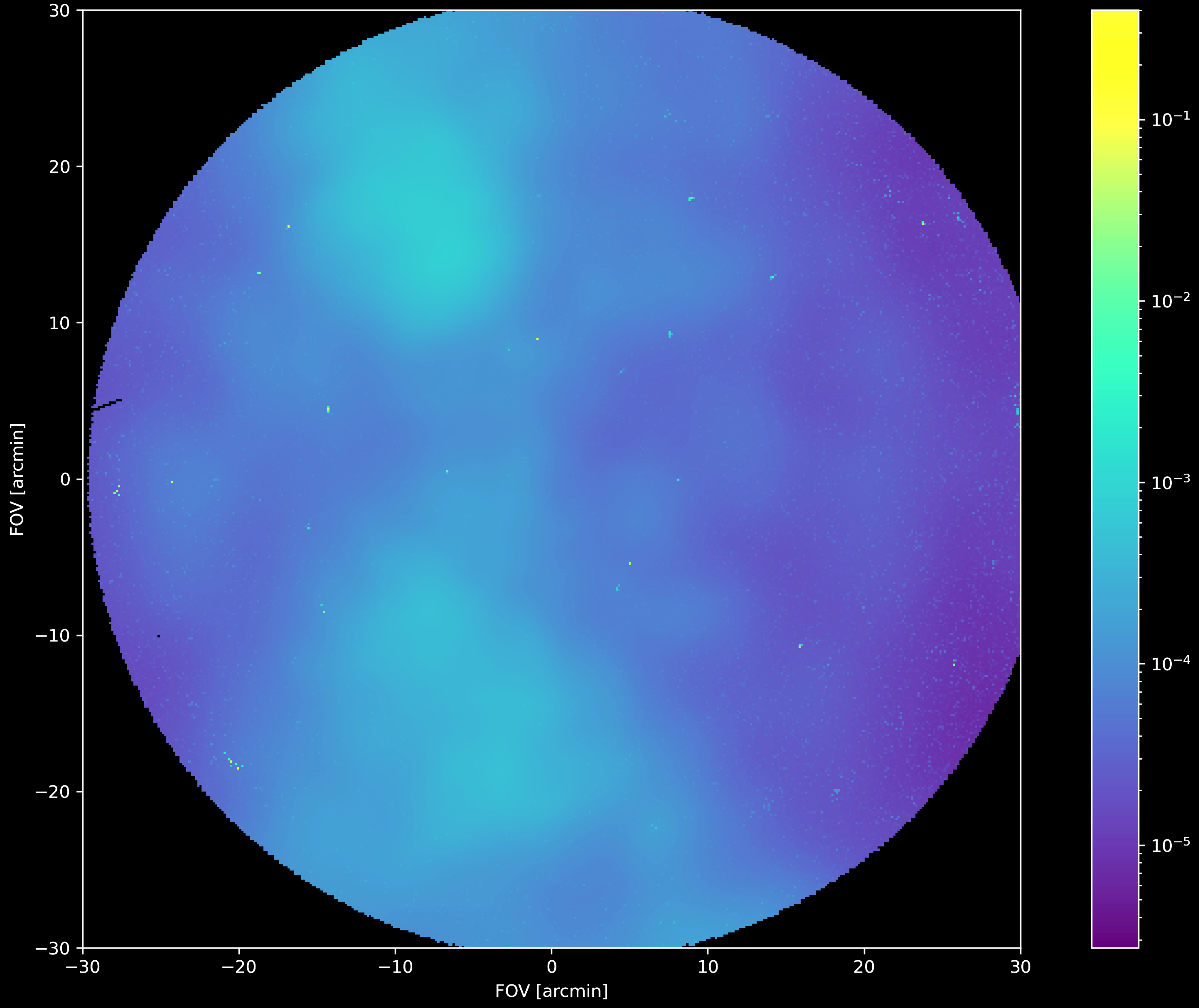


Inference



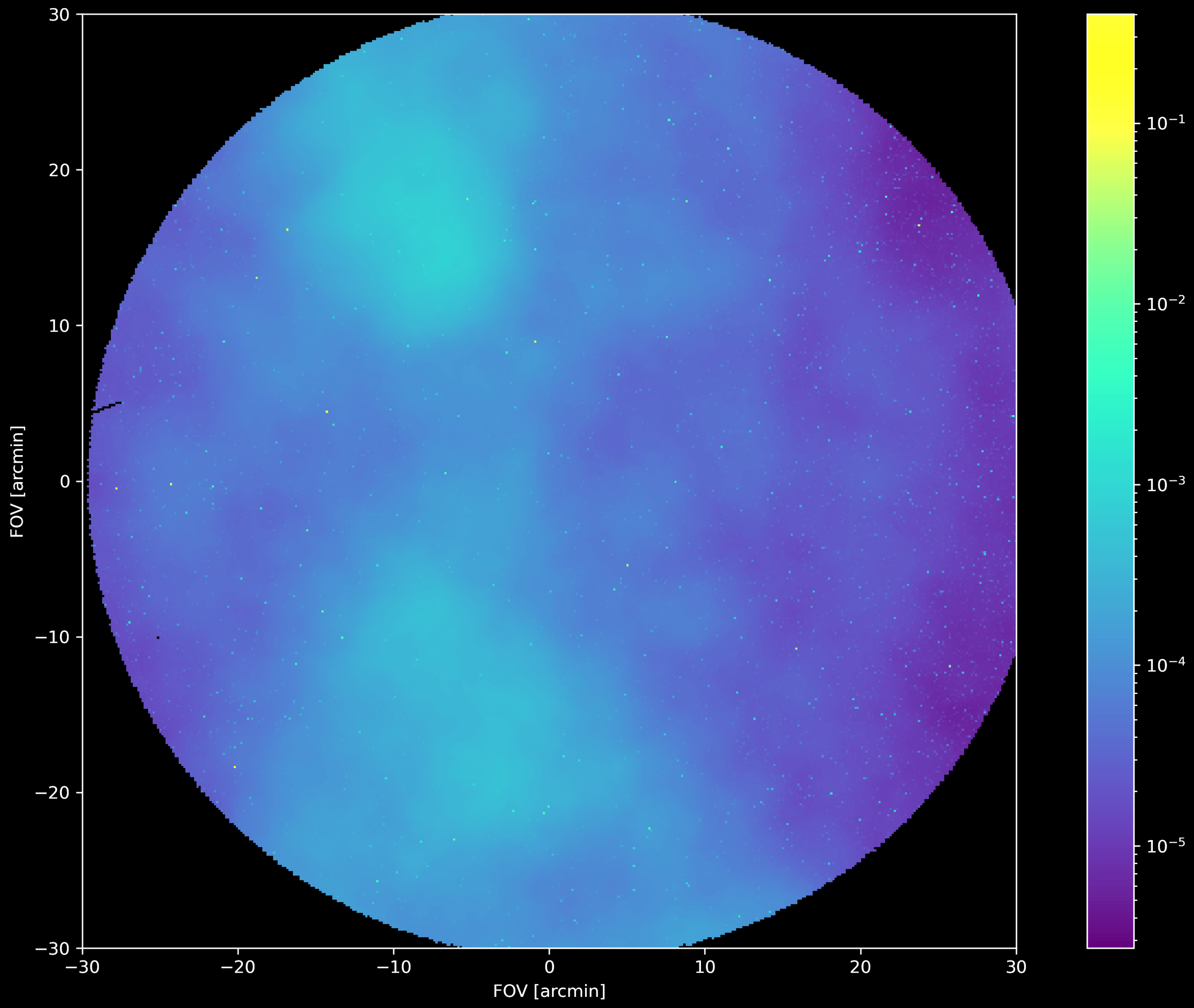
Data

Inference



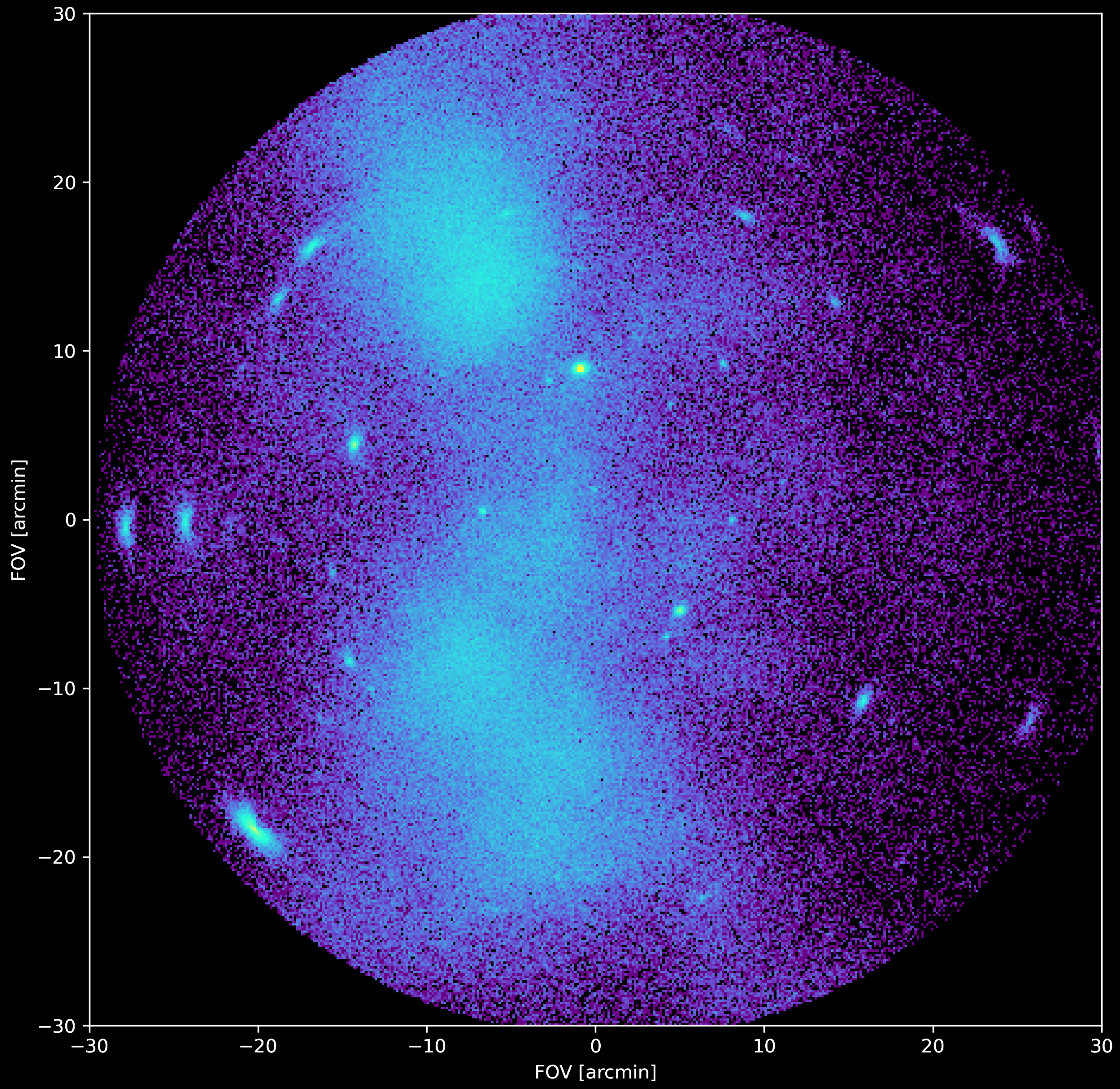
Posterior mean reconstructed sky

Inference

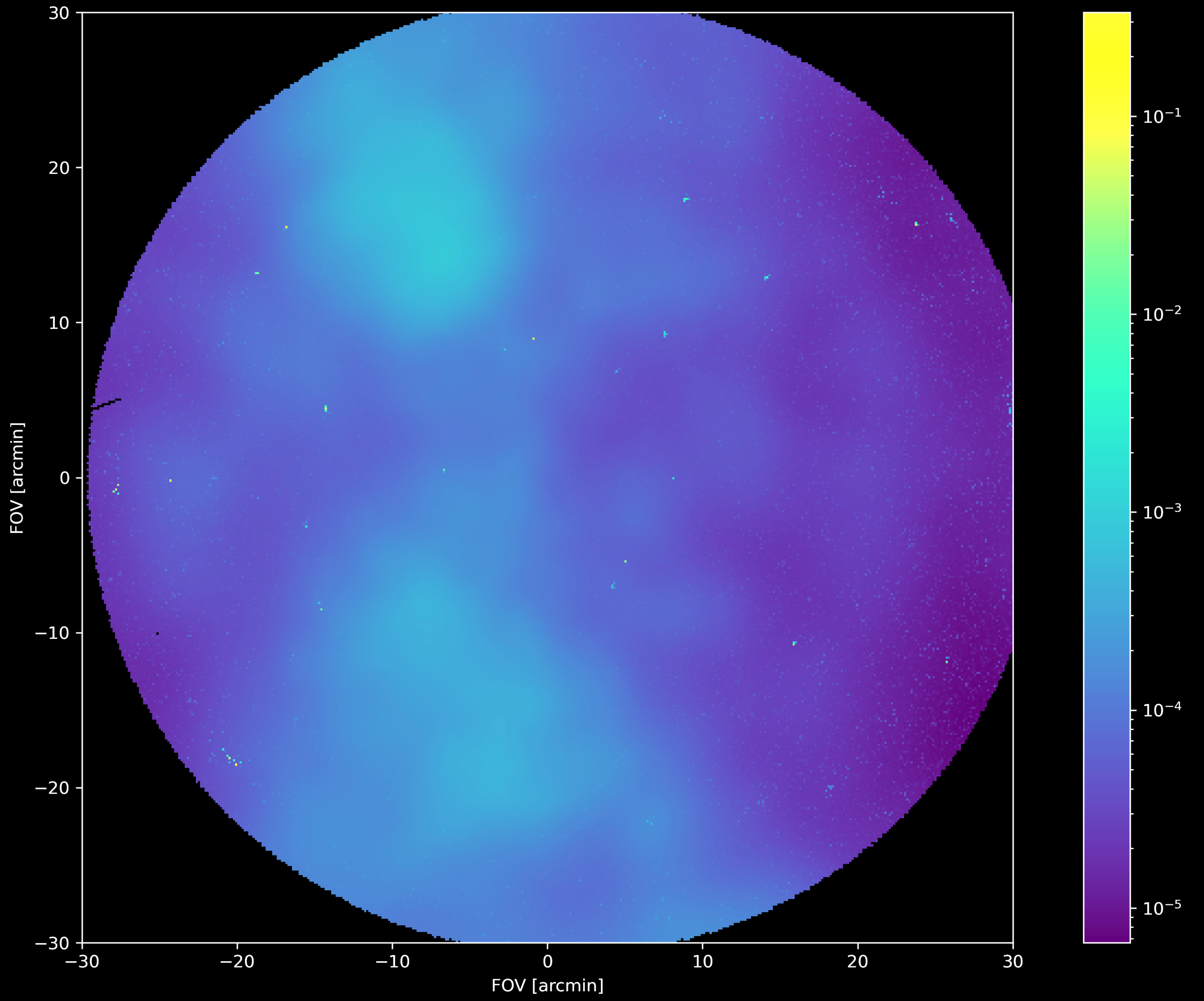


Ground truth sky

Inference



Data

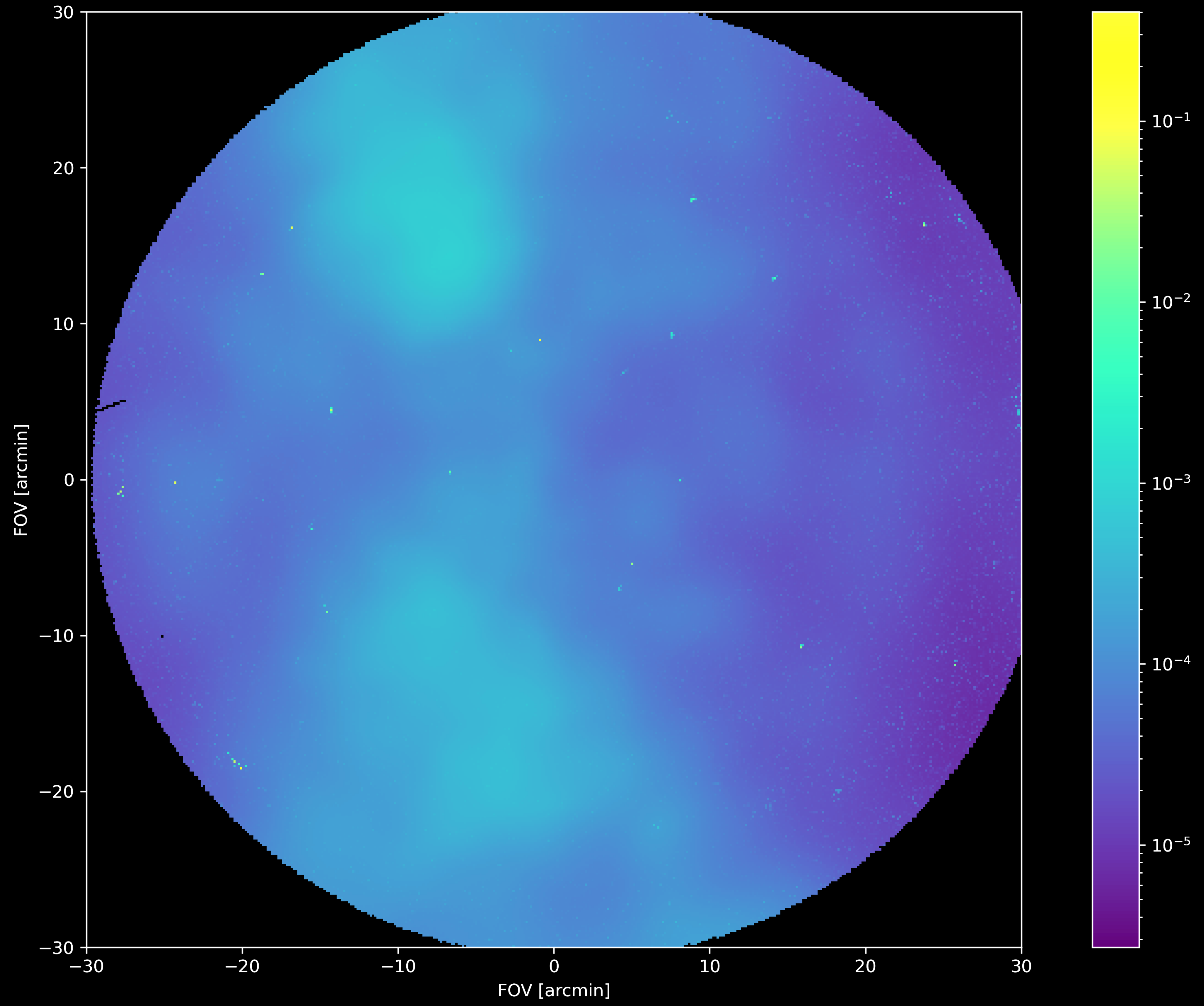


Posterior mean sky reconstruction

Point source detection

Point source detection

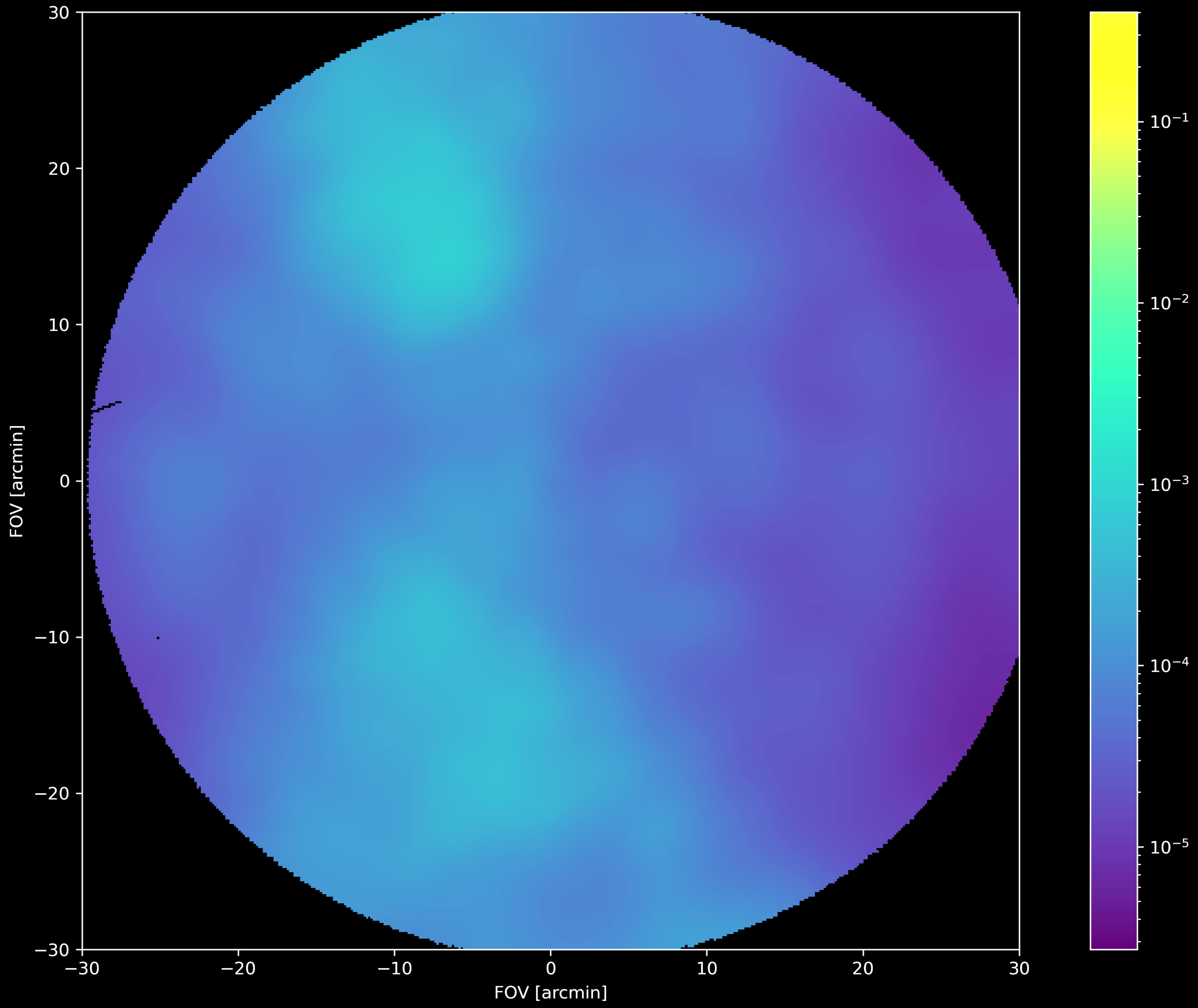
Component separation



Posterior mean sky reconstruction

Point source detection

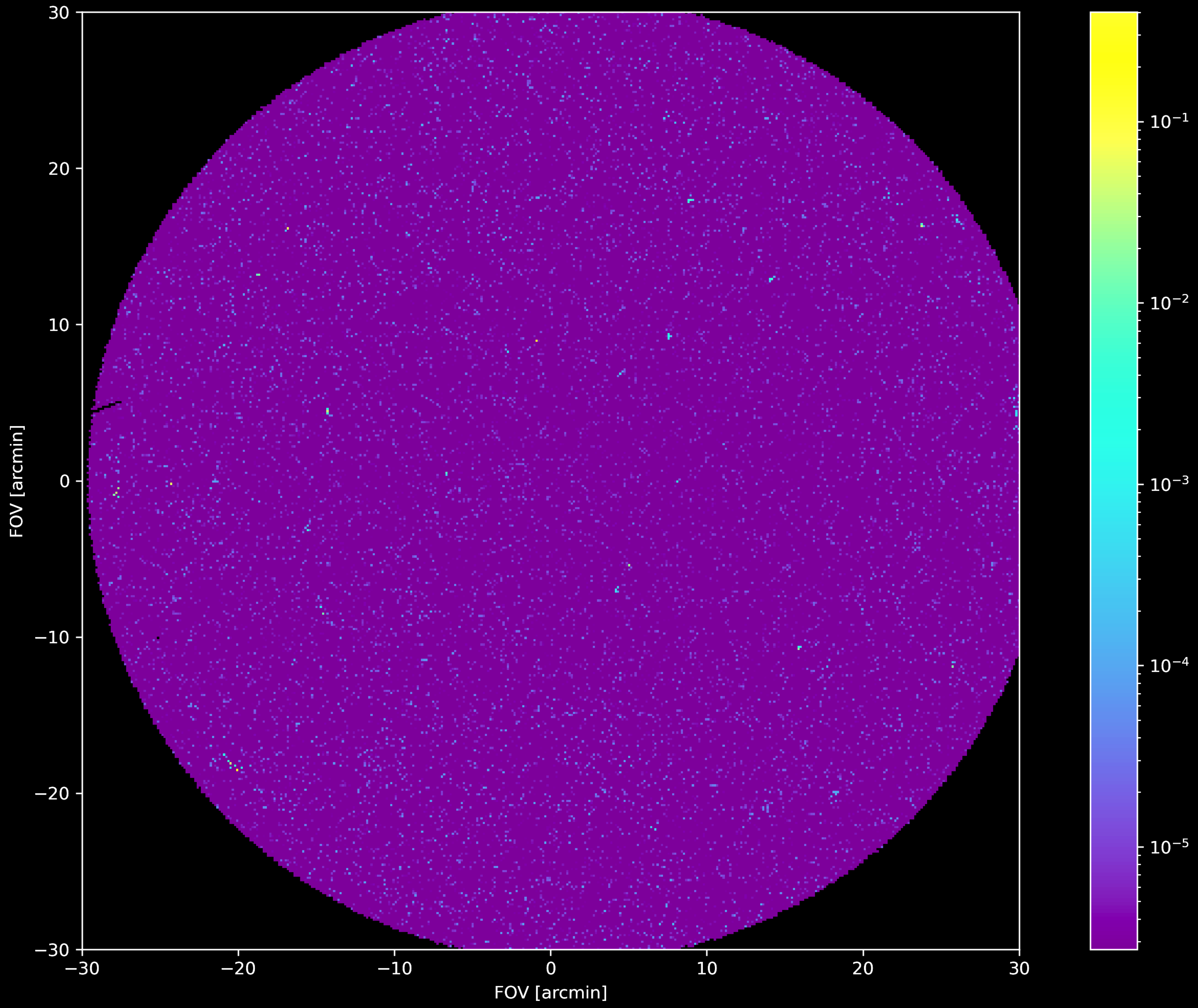
Component separation



Posterior mean diffuse reconstruction

Point source detection

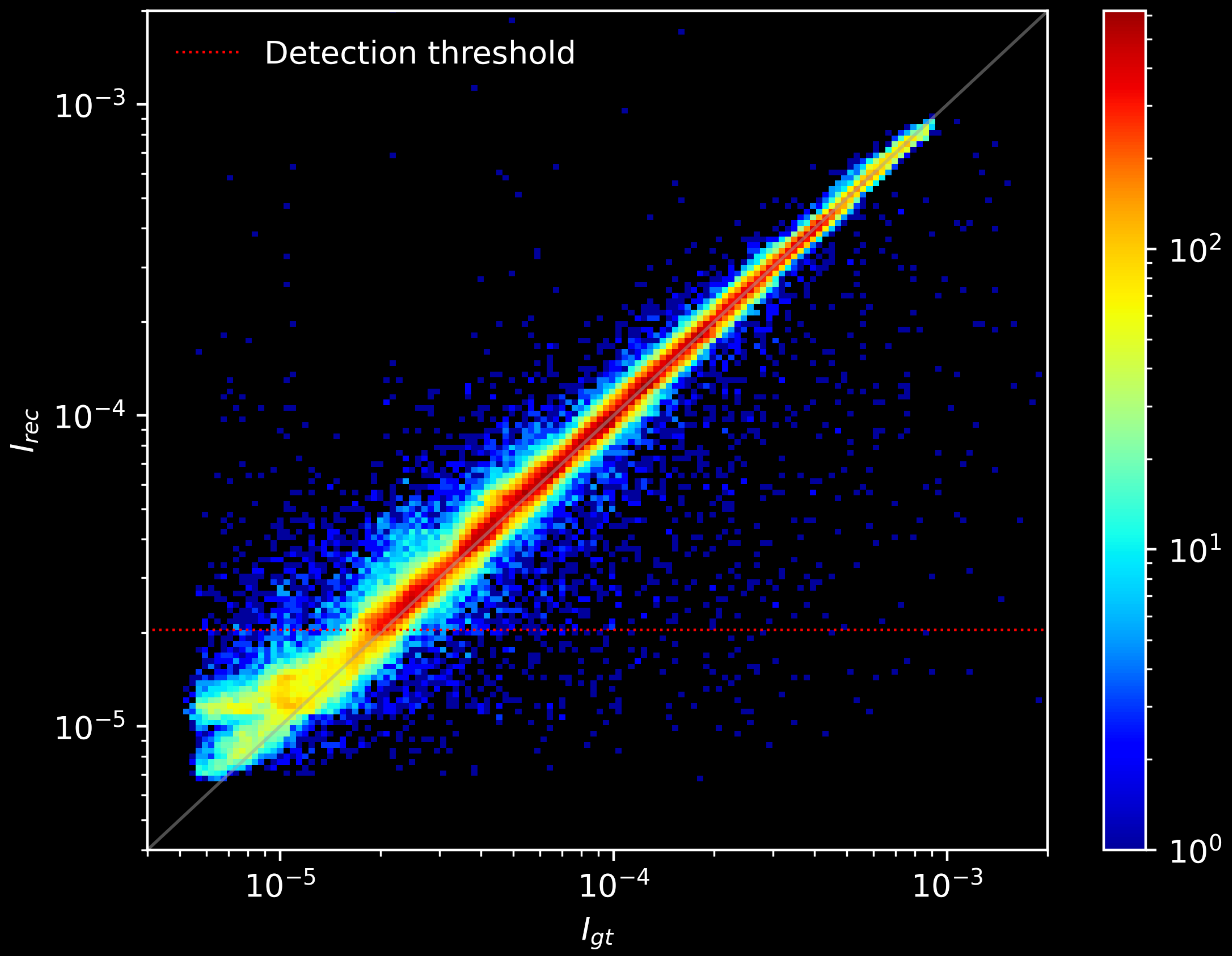
Component separation



Posterior mean point source reconstruction

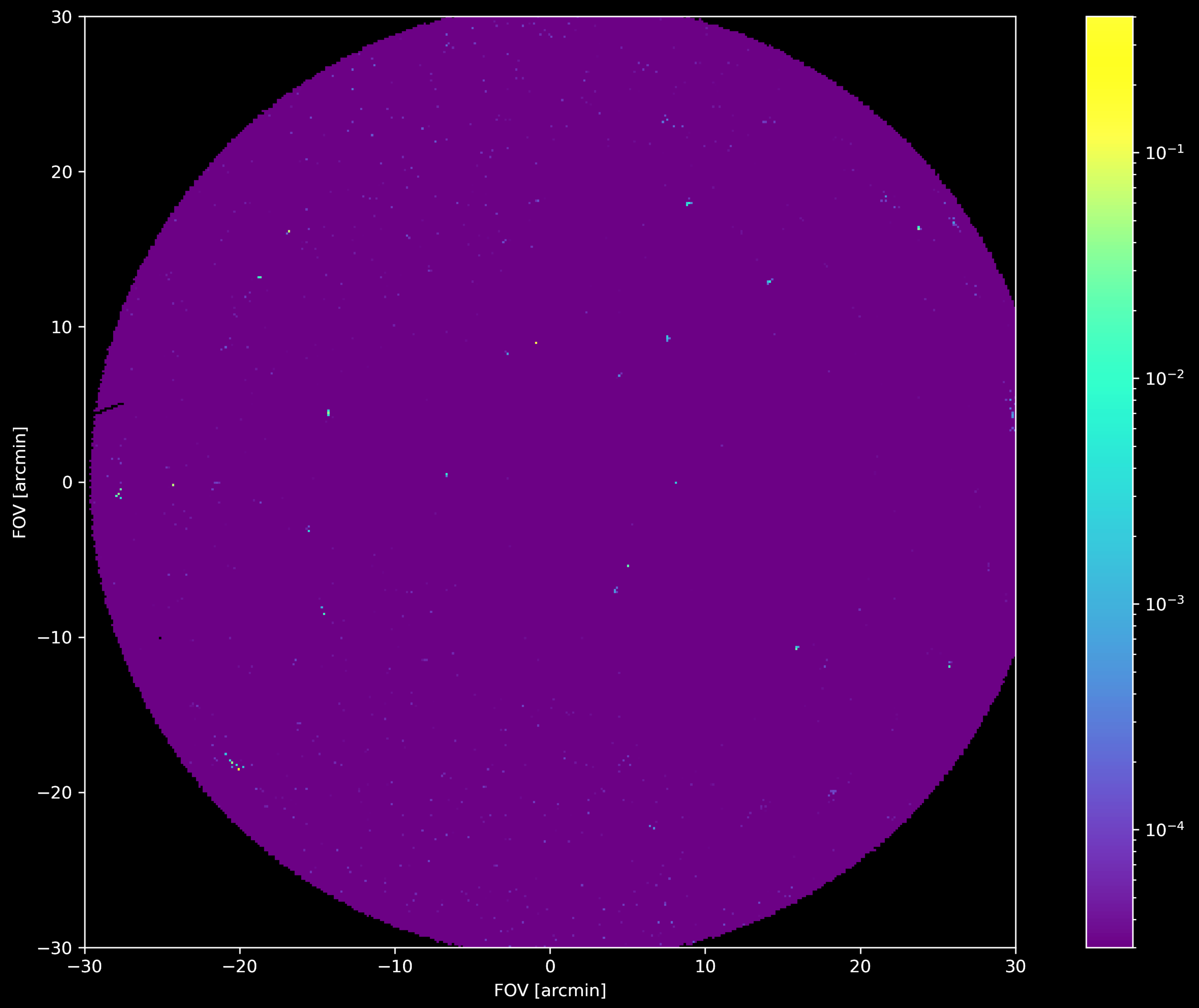
Point source detection

Detection thresholds from synthetic data



Point source detection

Issues?

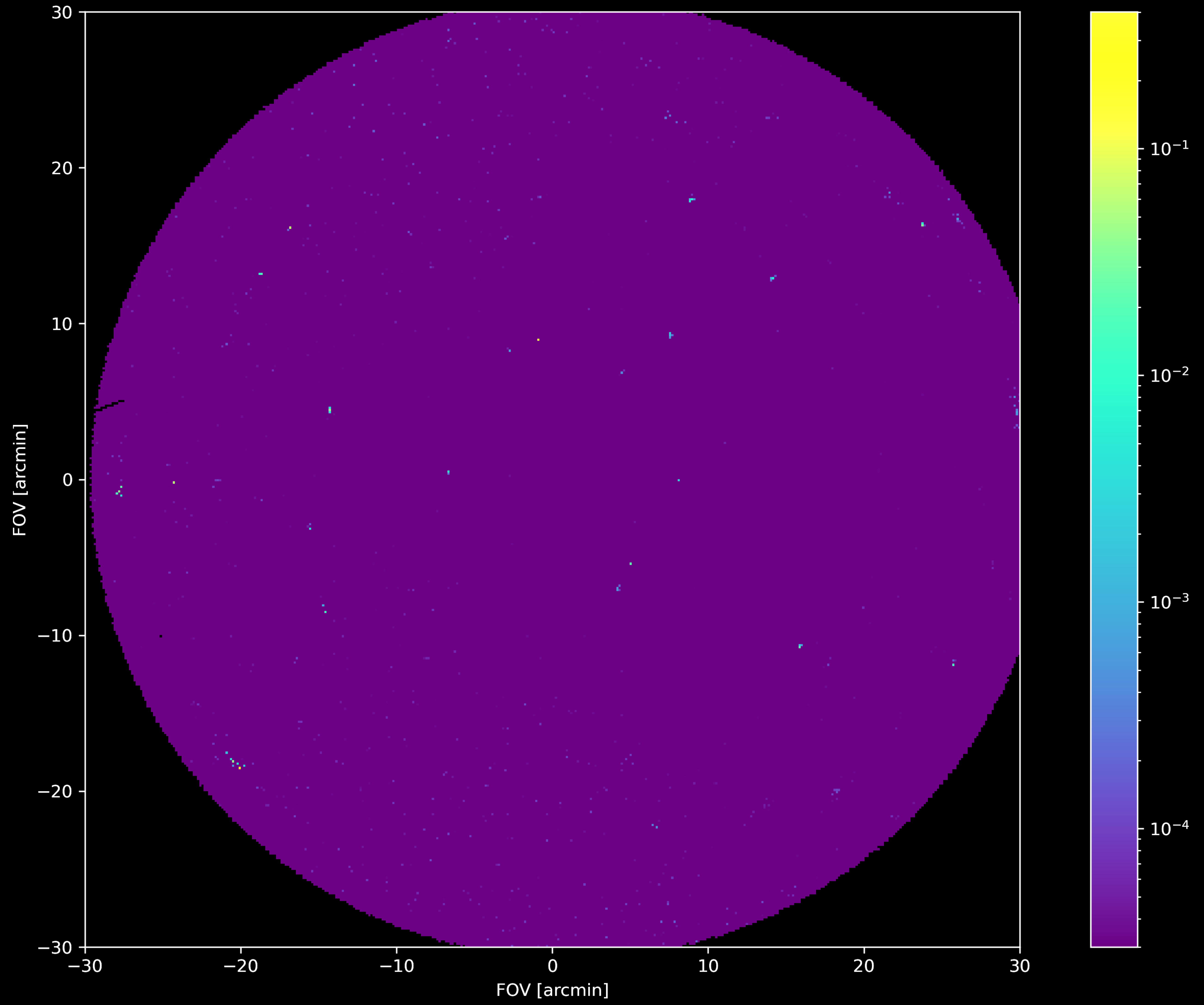


Detected point sources in posterior mean

Point source detection

Issues?

- **Prior driven**

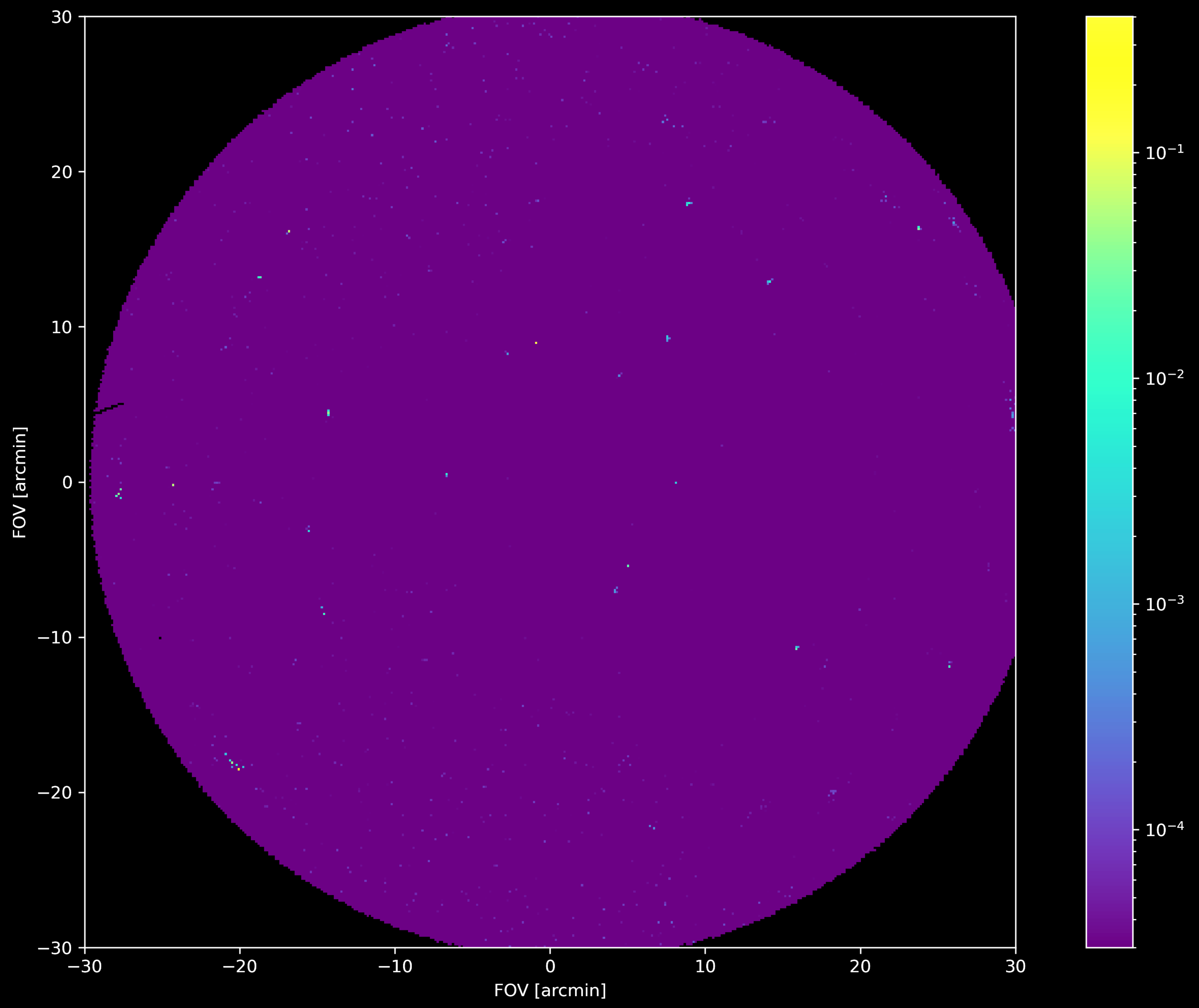


Detected point sources in posterior mean

Point source detection

Issues?

- **Prior driven**
- **A point source in every pixel**

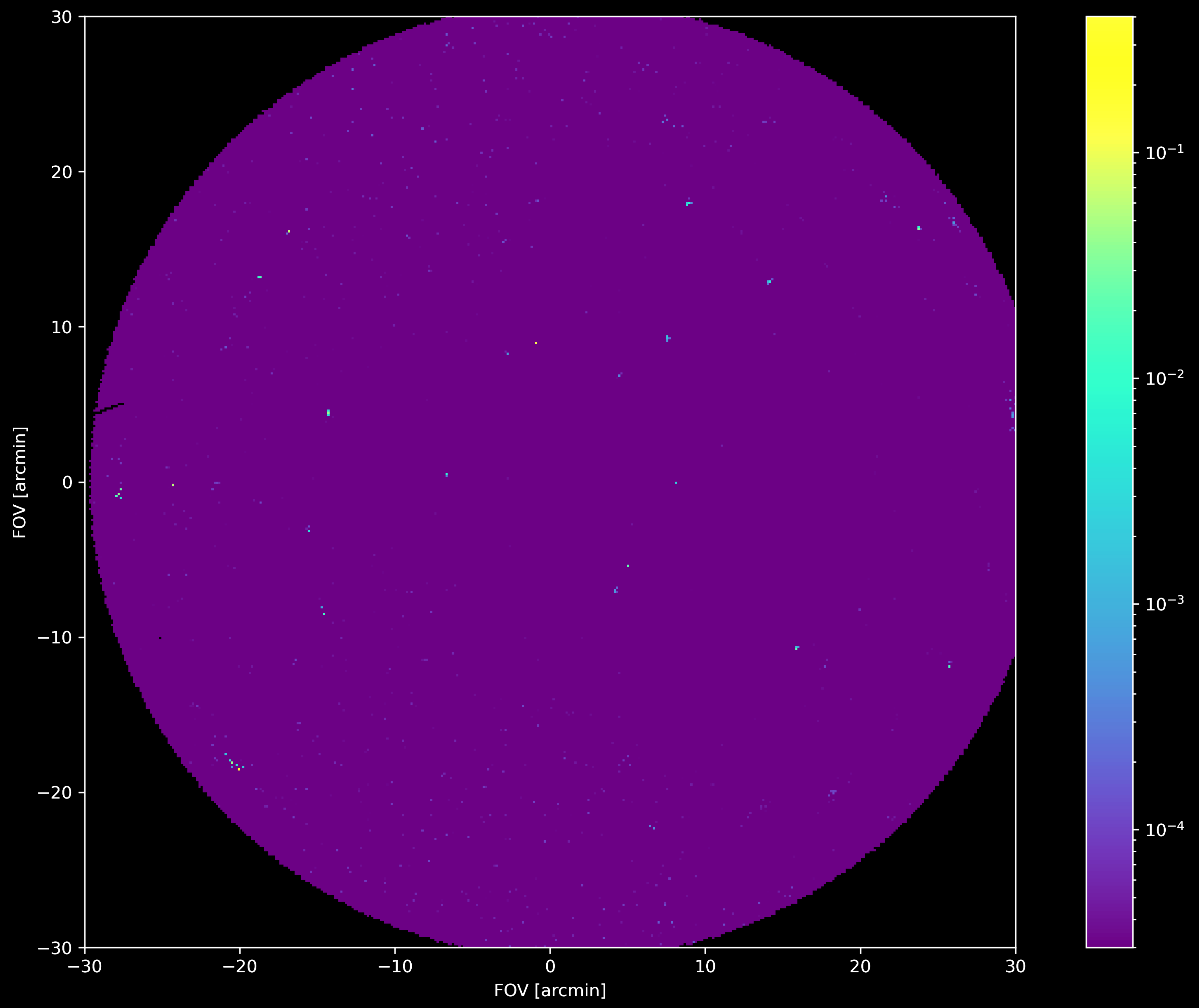


Detected point sources in posterior mean

Point source detection

Issues?

- **Prior driven**
- **A point source in every pixel**
- **Hard optimization**



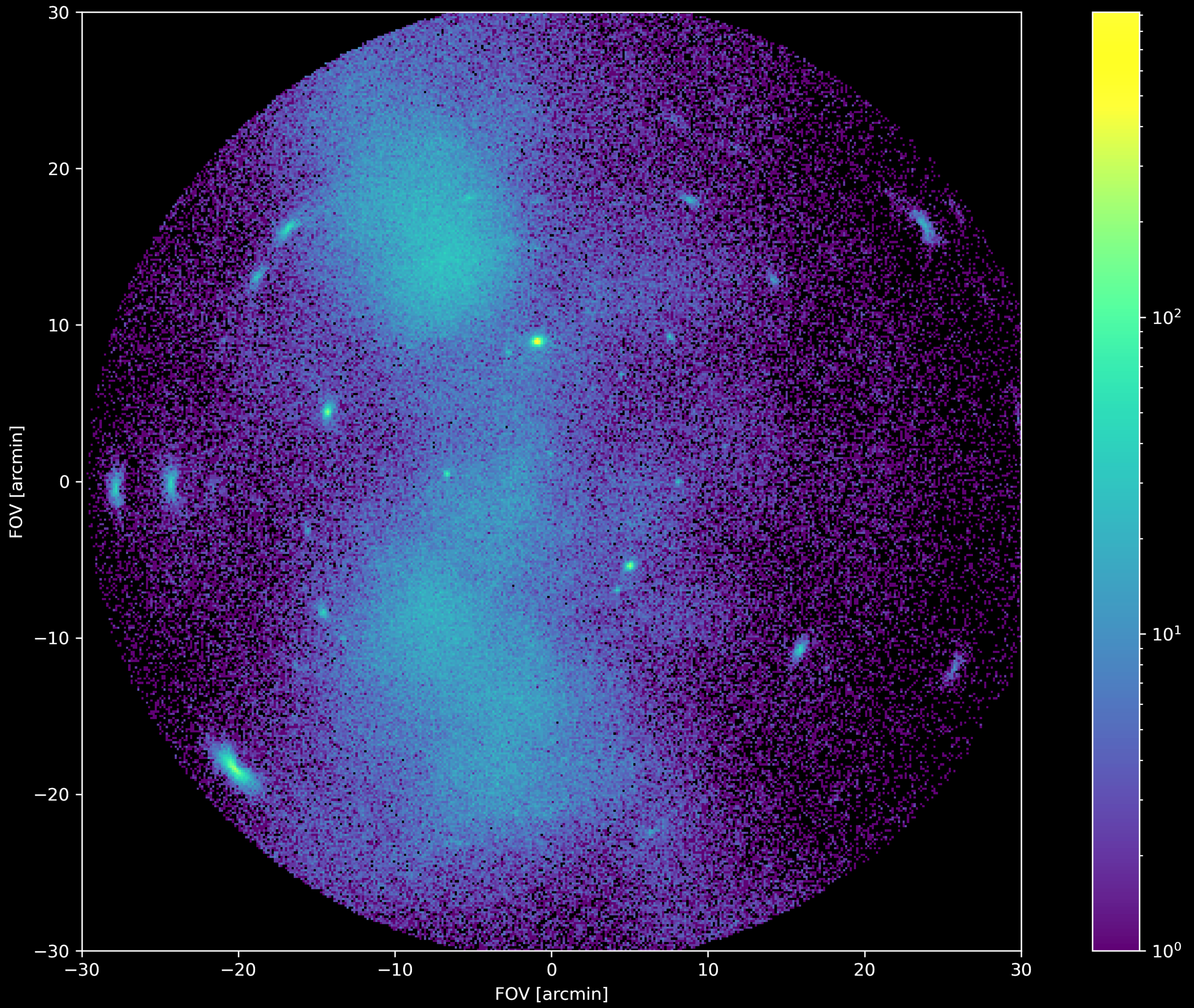
Detected point sources in posterior mean

Automatic point source detection

Let’s use a different model…

Point source detection

Diffuse-only fit



Data

Point source detection

Diffuse-only fit

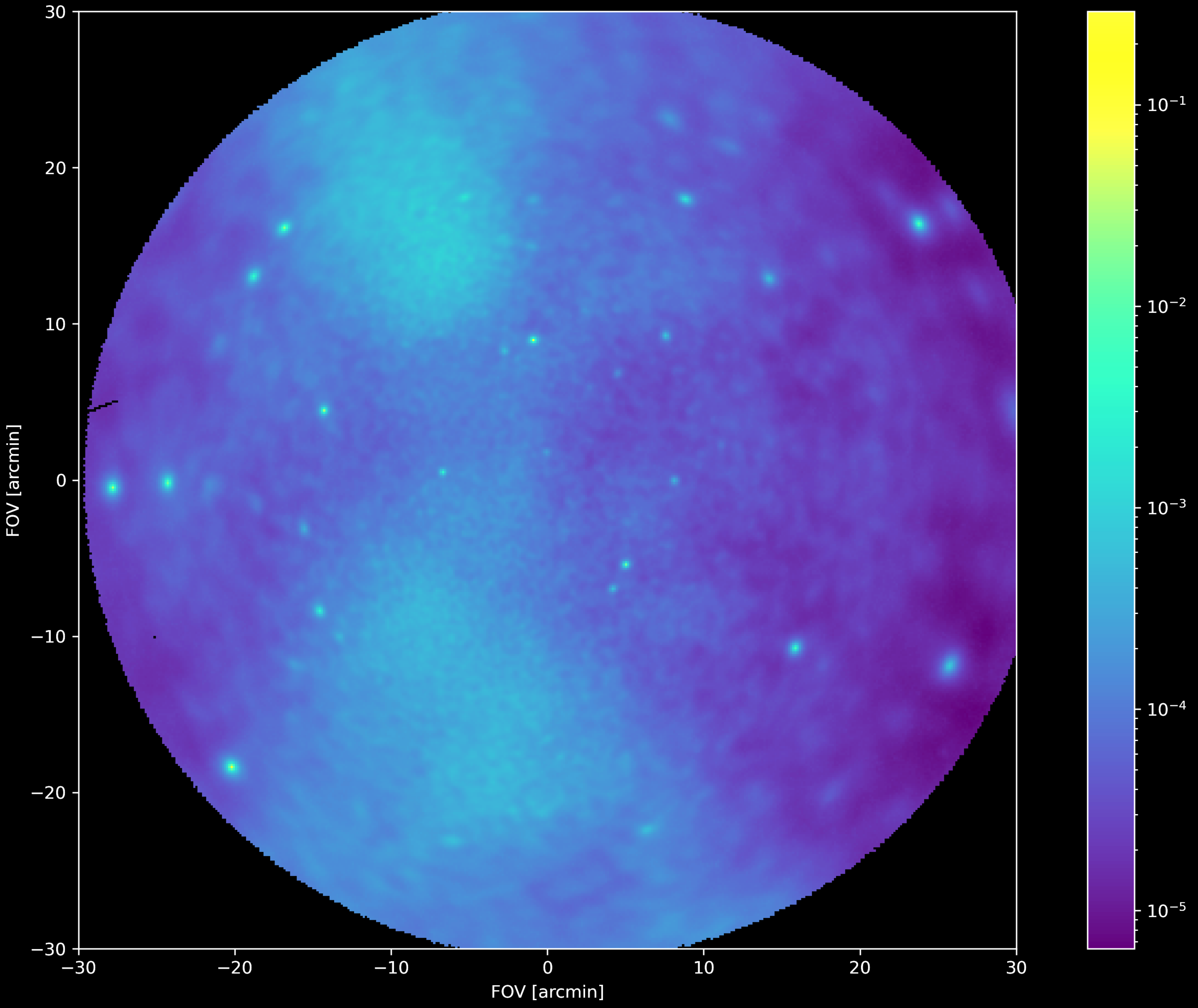
Point sources

Diffuse emission

Sky signal

Point source detection

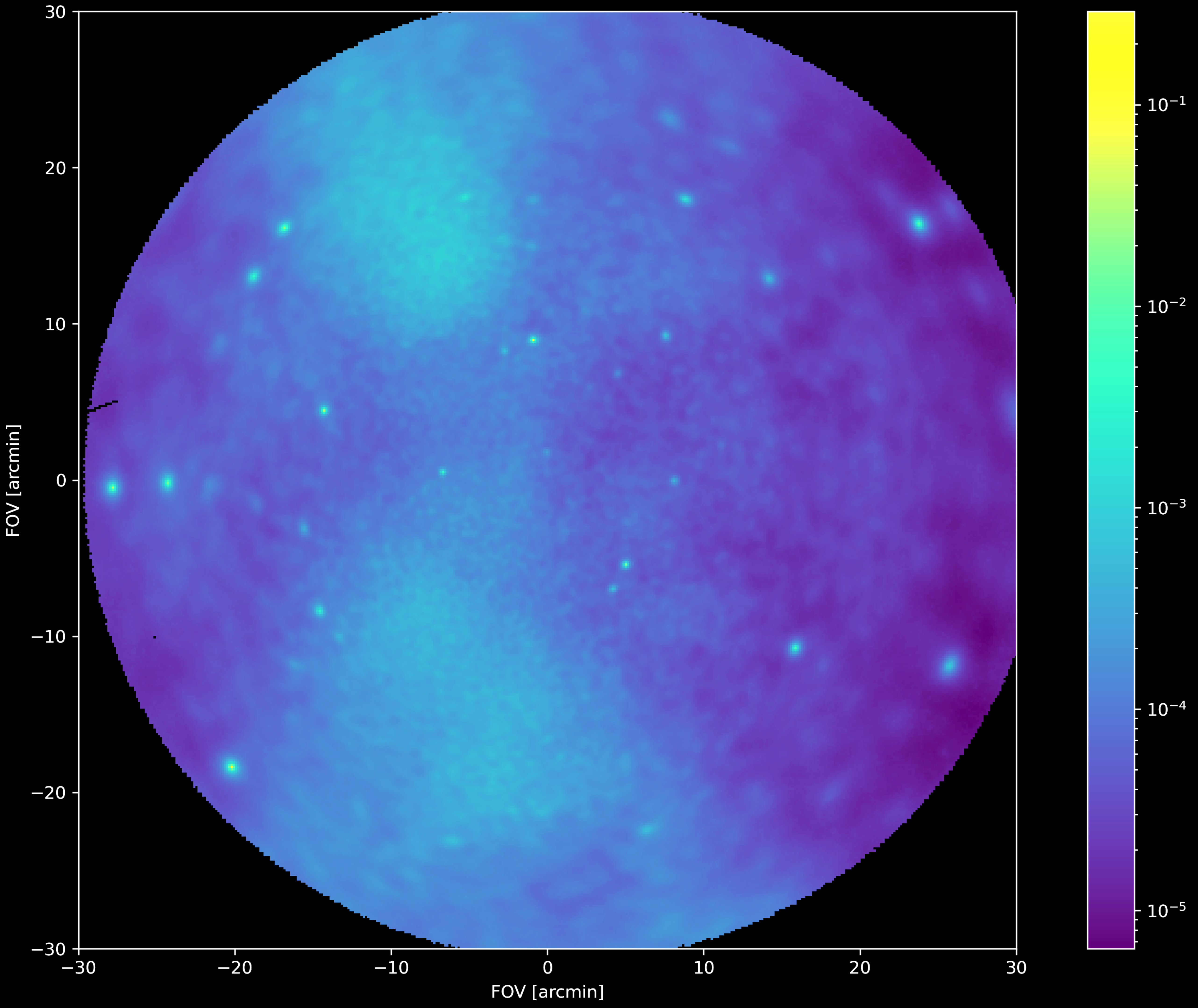
Diffuse-only fit



Posterior mean diffuse-only reconstruction

Point source detection

Diffuse-only fit

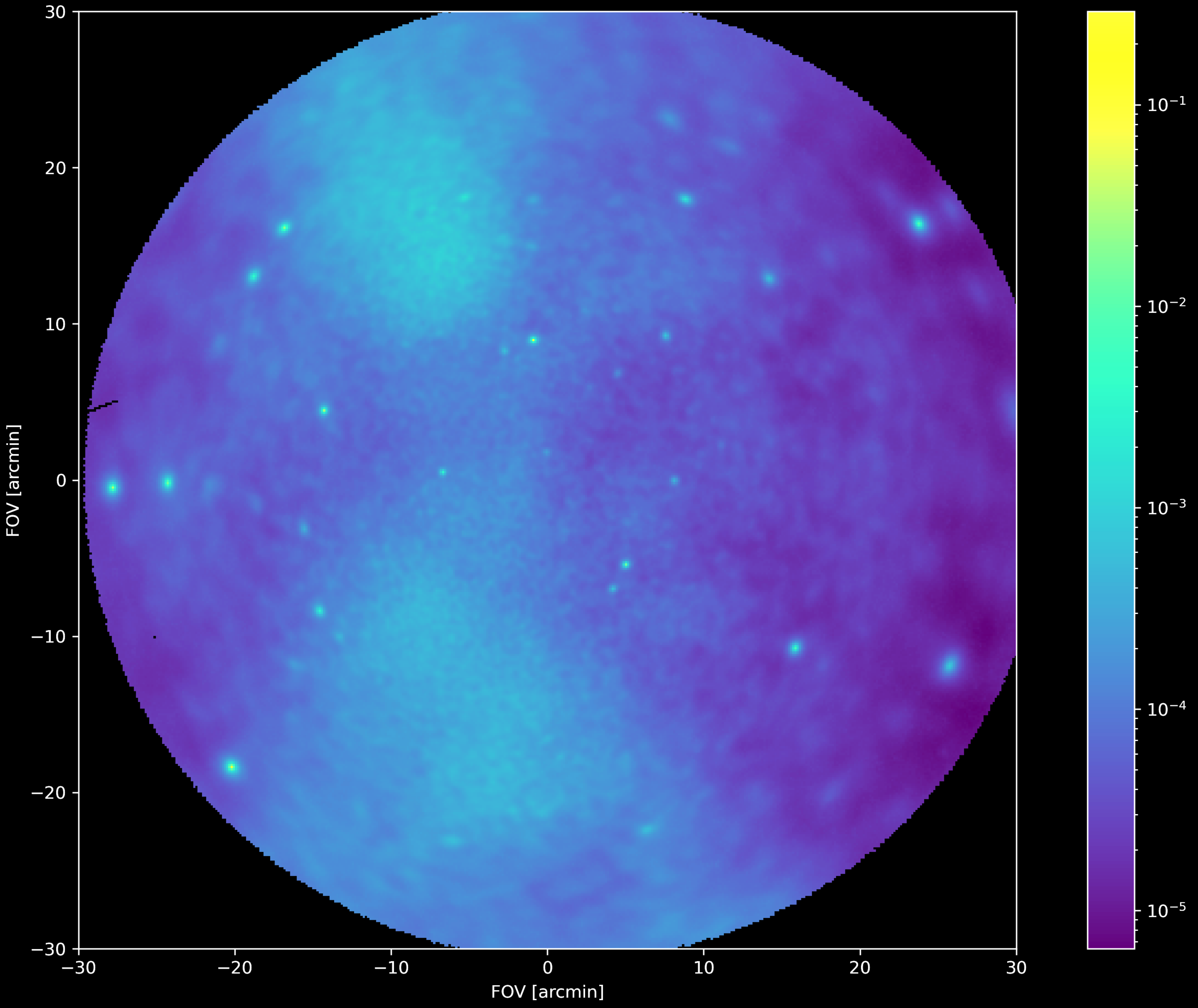


Posterior mean diffuse-only reconstruction

- **Spatially correlated**

Point source detection

Diffuse-only fit

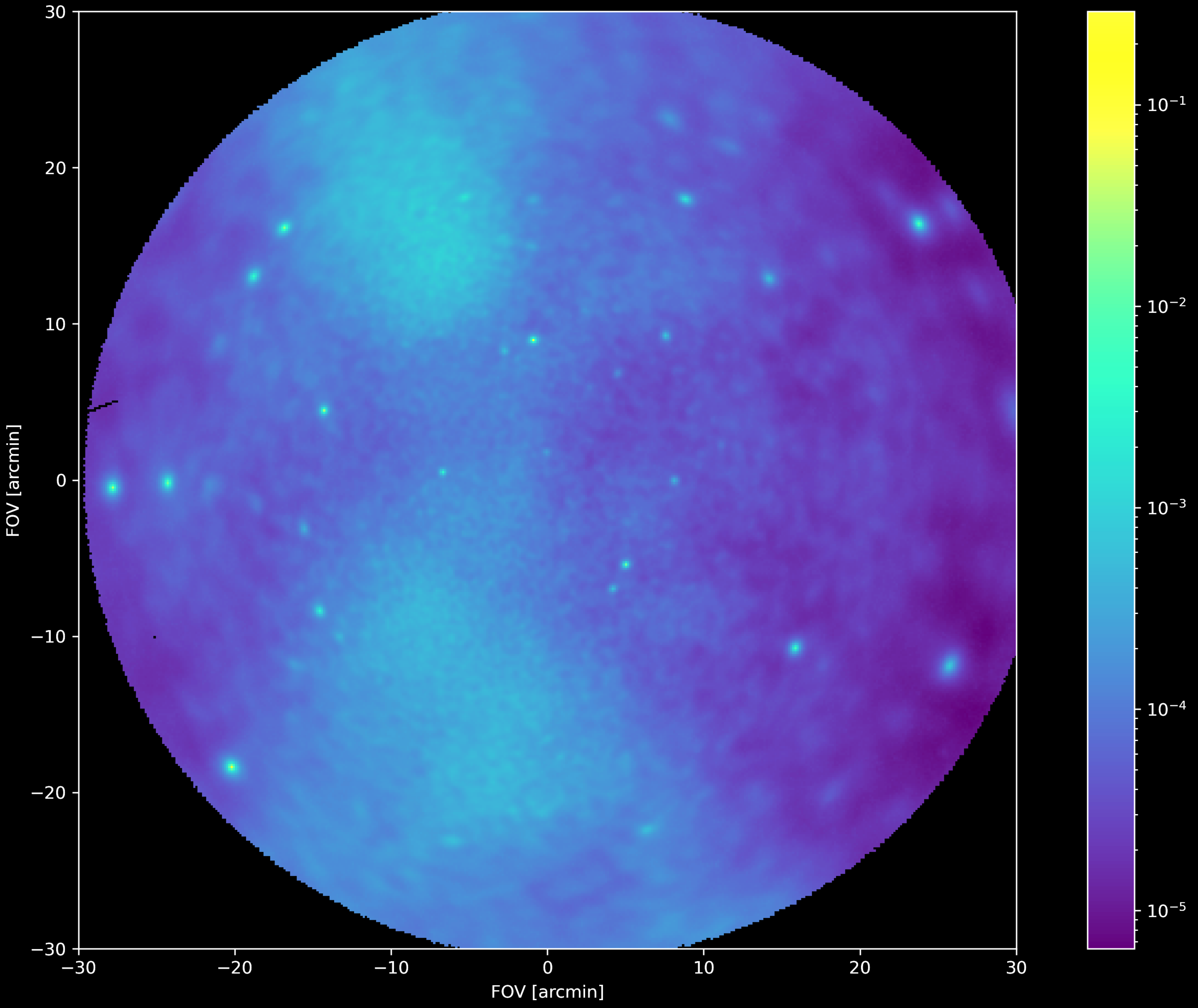


Posterior mean diffuse-only reconstruction

- **Spatially correlated**
- **Spectrally dependent from the background**

Point source detection

Diffuse-only fit



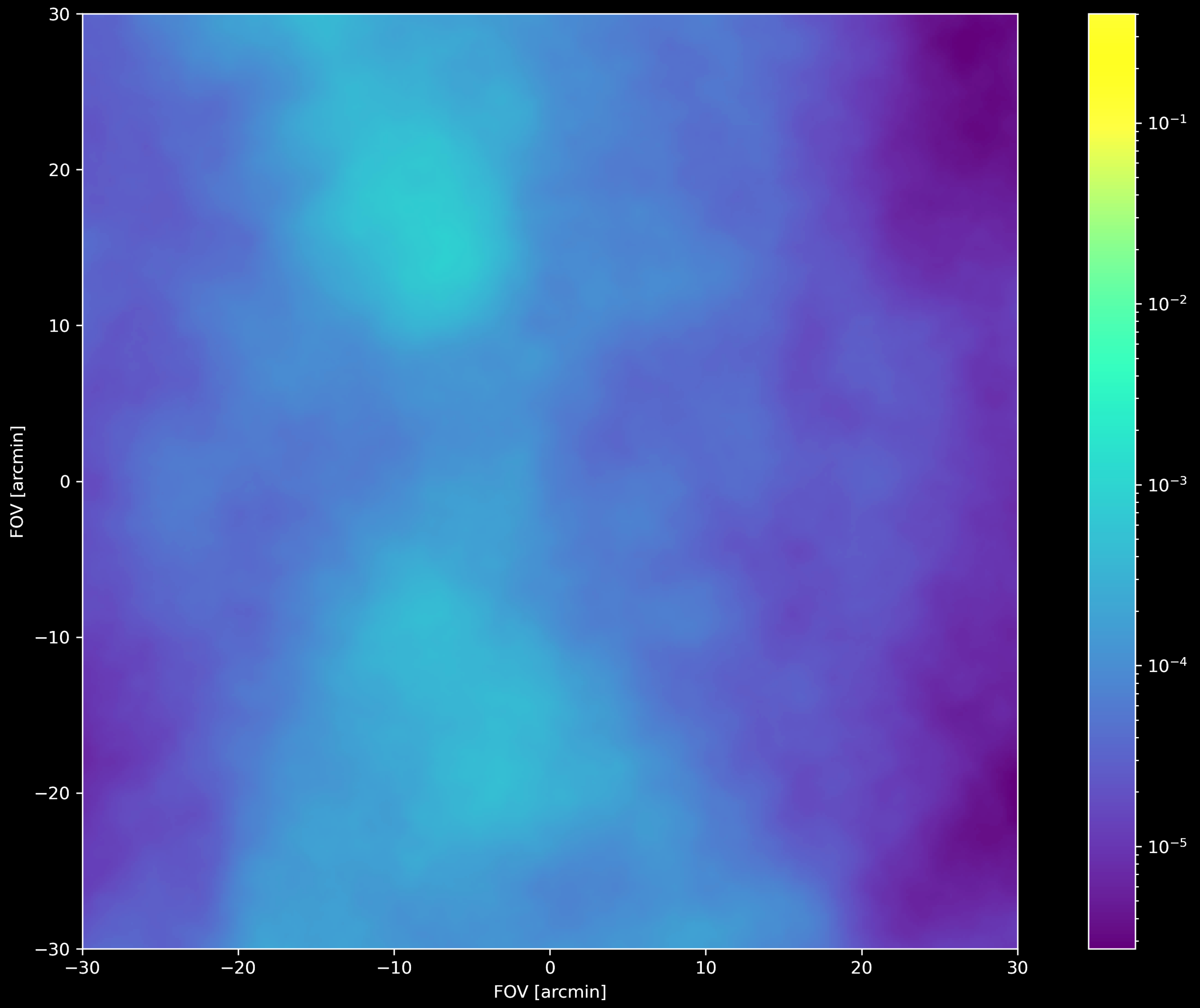
Posterior mean diffuse-only reconstruction

- **Spatially correlated**
- **Spectrally dependent from the background**
- **Live on a grid**

Point source detection

Diffuse prior model

$$P(s) = \mathcal{N}\left(\mathbf{0}, \square\right) \star A(x, y)$$

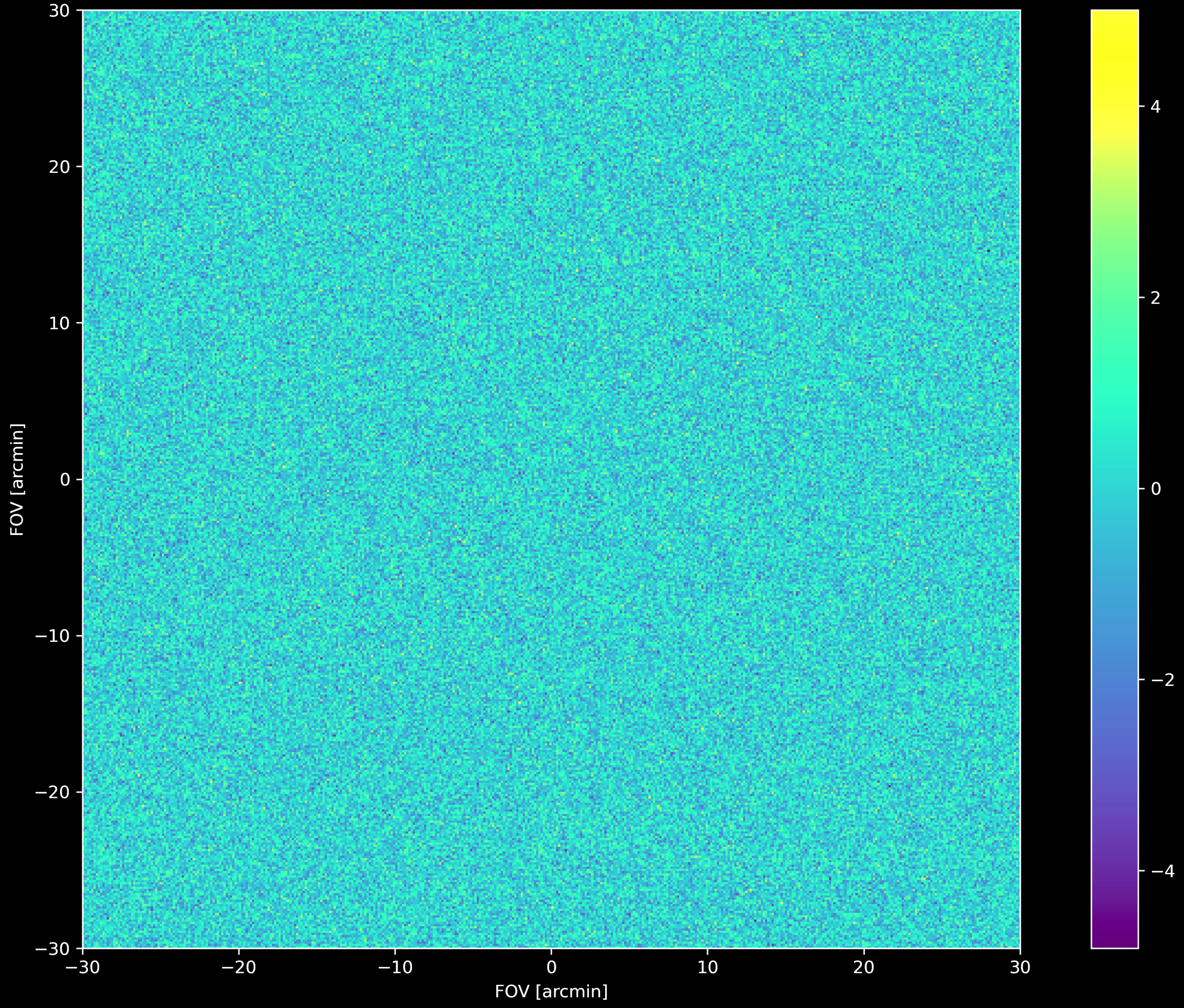


Signal space prior sample

Point source detection

Model stress?

$$P\left(\xi\right) = \mathcal{N}\left(\mathbf{0}, \mathbb{1}\right)$$

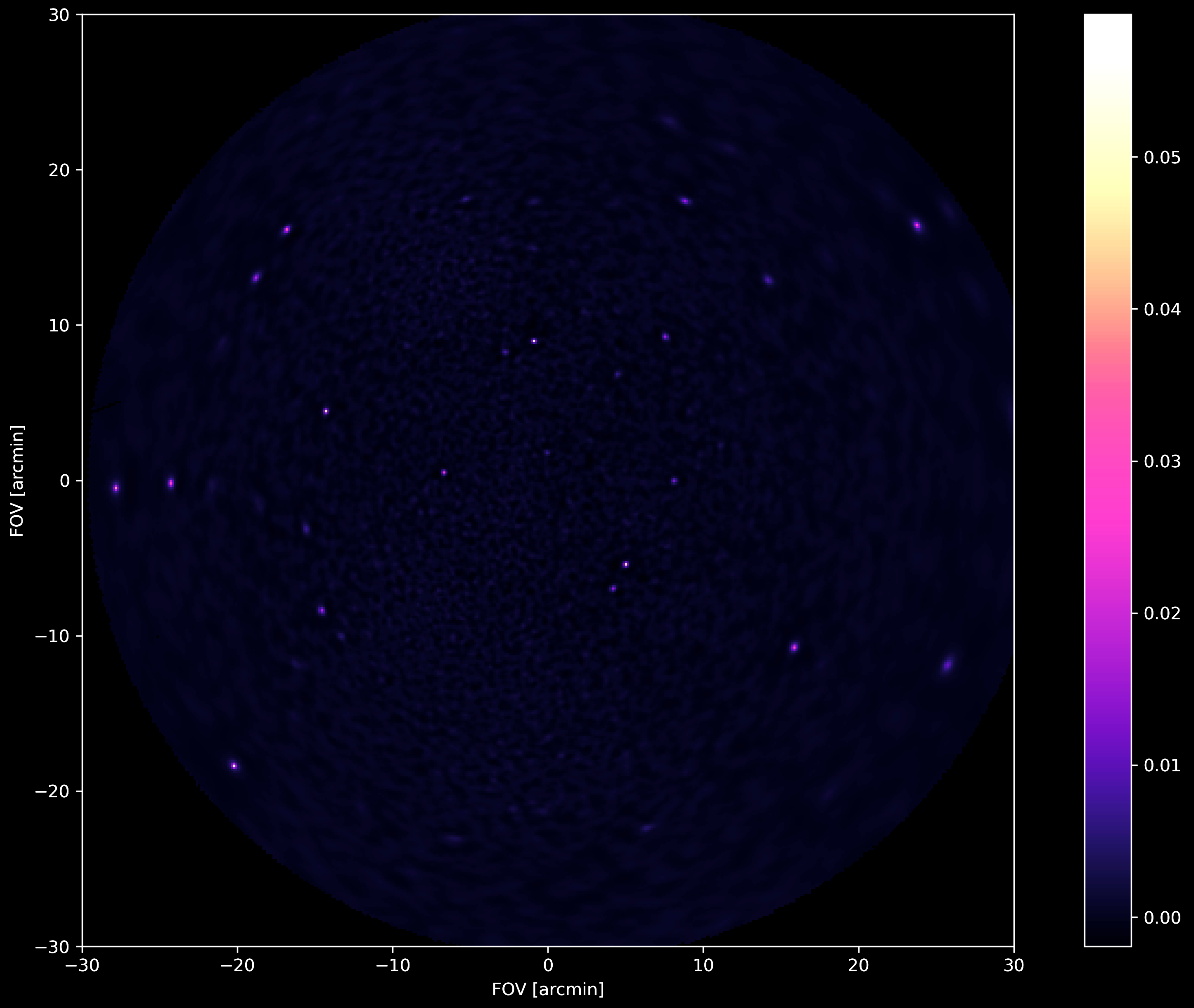


Prior latent ξ excitations

Point source detection

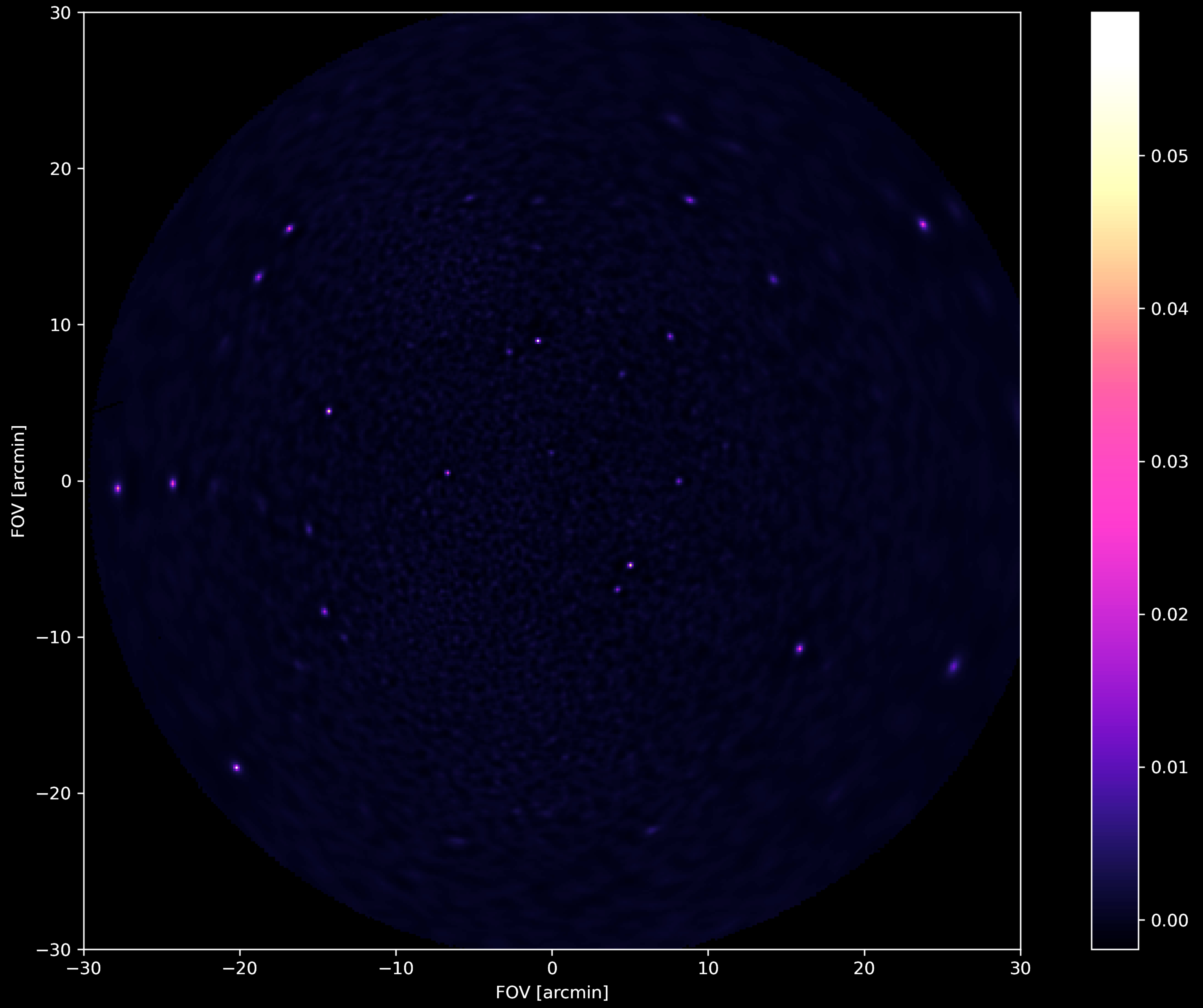
Model stress?

$$P\left(\xi\,|\,\mathbf{d}\right) \neq \mathcal{N}\left(\mathbf{0}, \mathbb{1}\right)$$



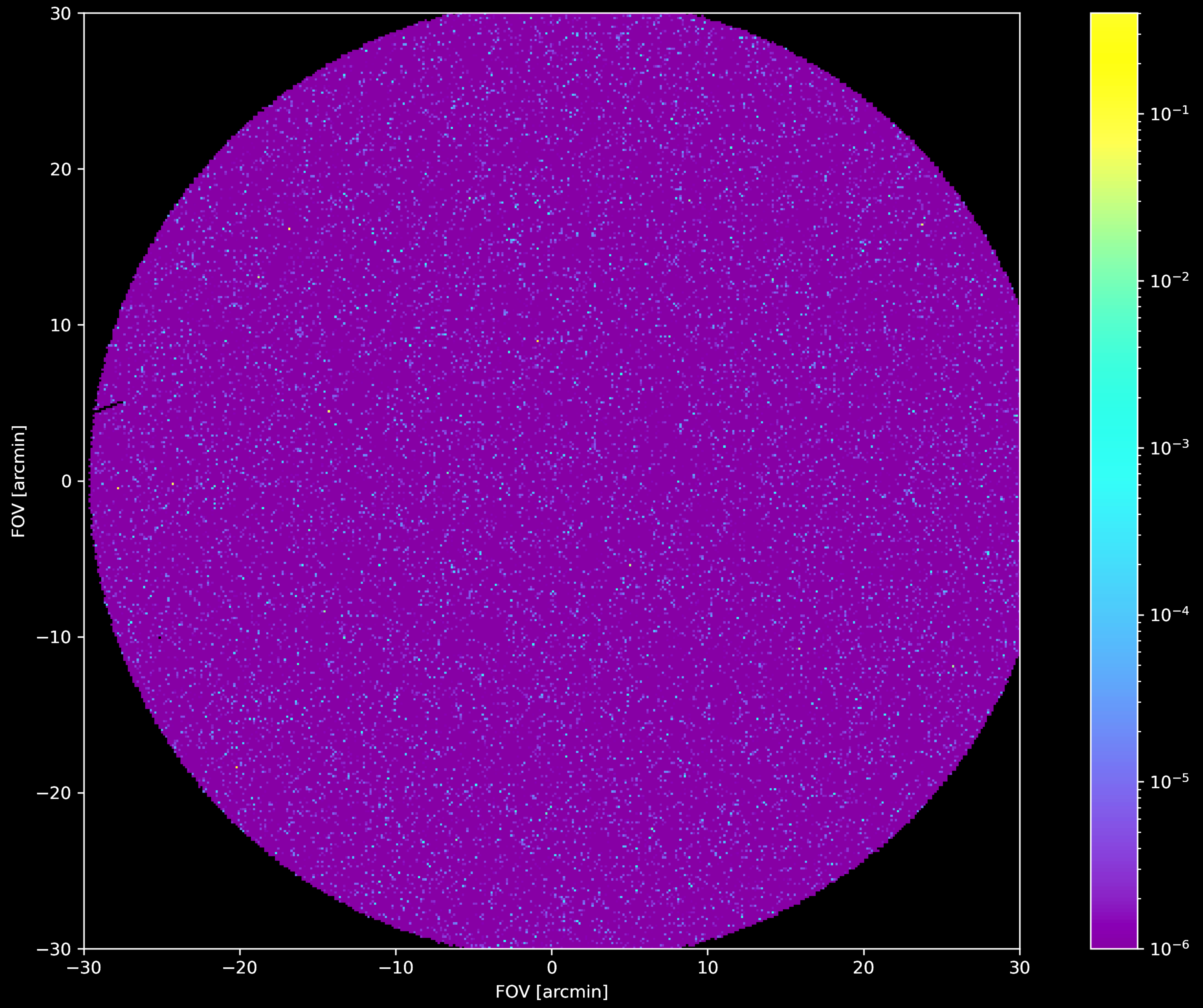
Posterior latent ξ excitations

Point source detection
Model stress, yessir!



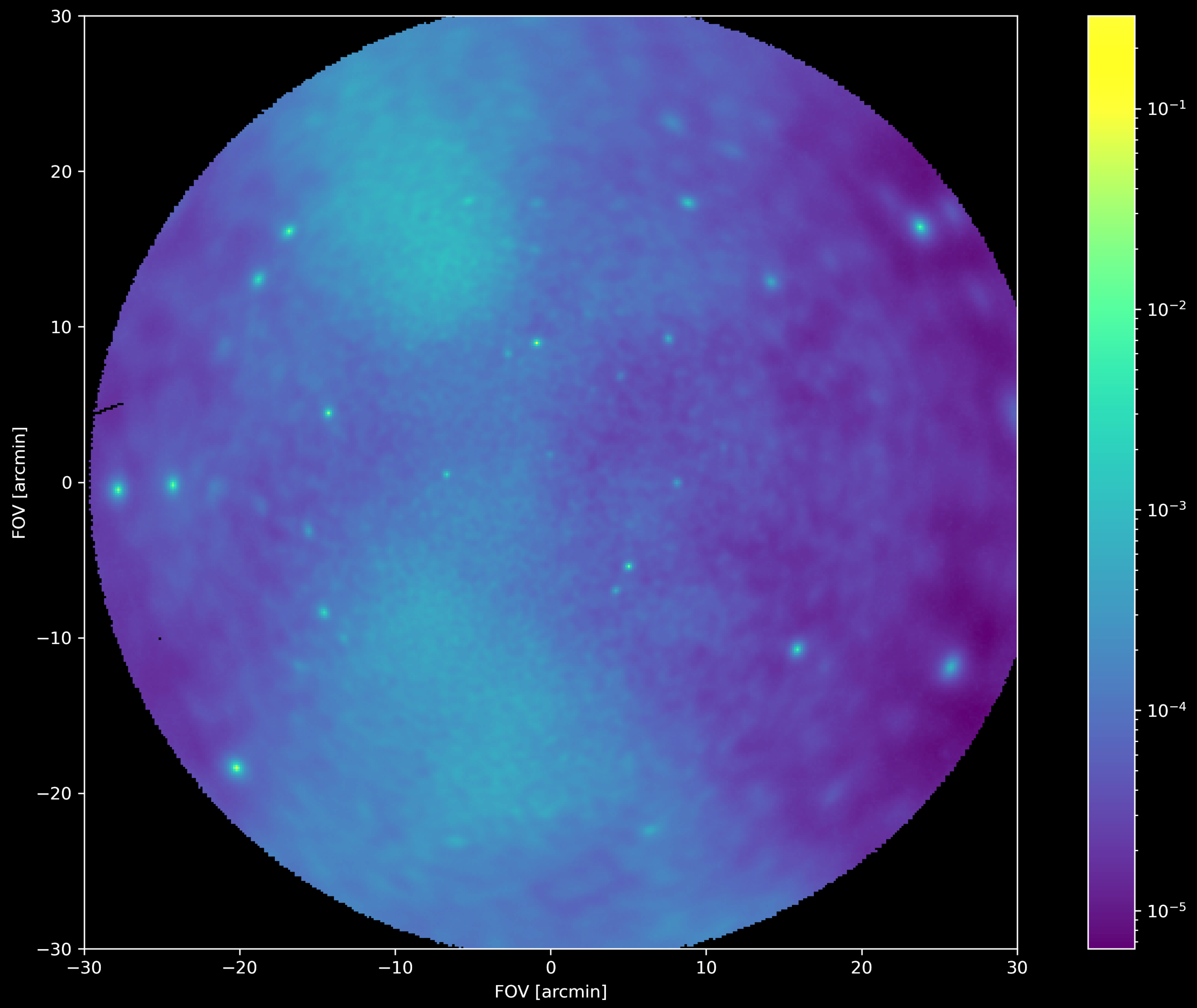
Latent ξ excitations

Point source detection
Model stress, yessir!



Point source ground truth

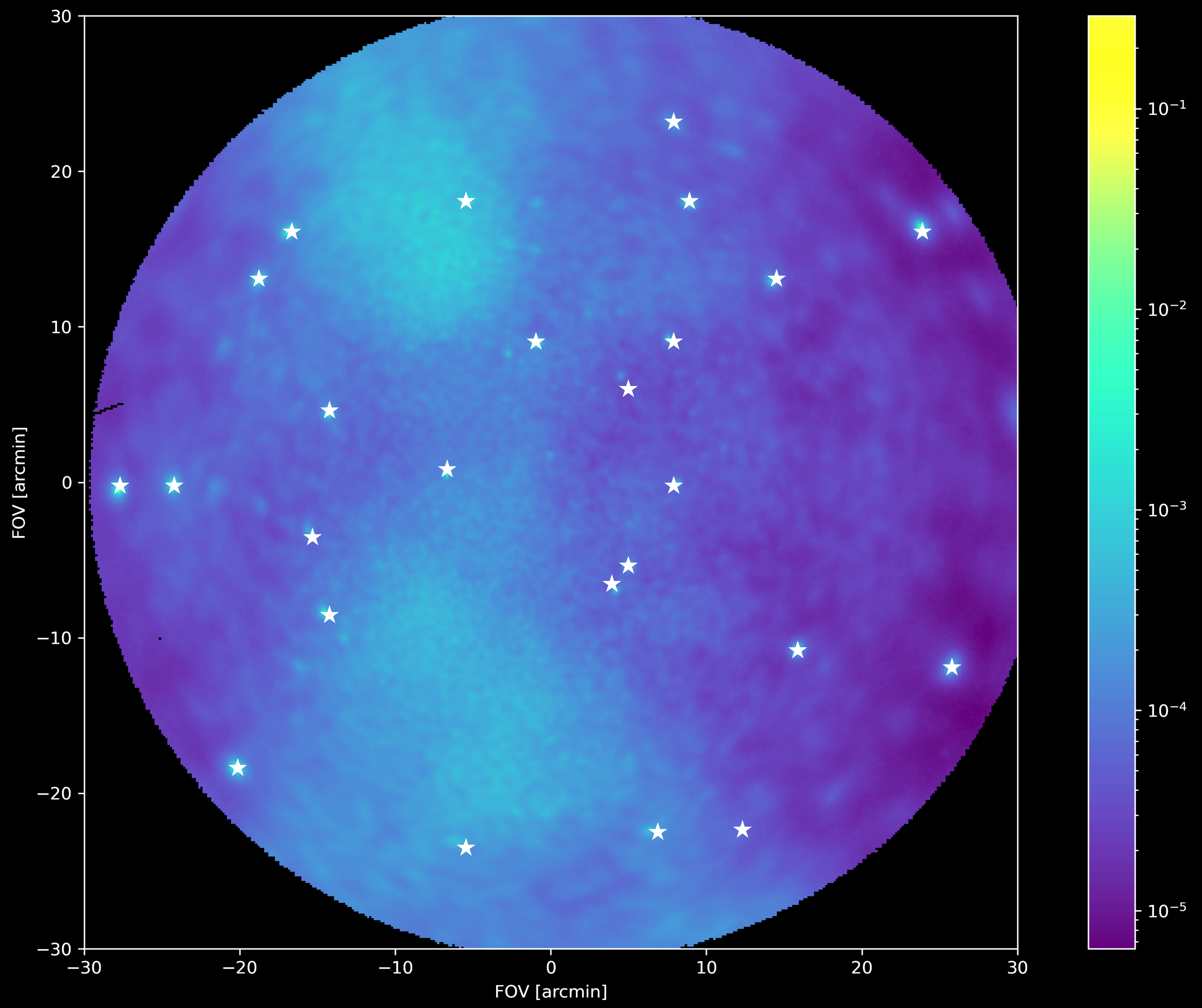
Point source detection
Automatic detection



Posterior mean diffuse-only reconstruction

Point source detection

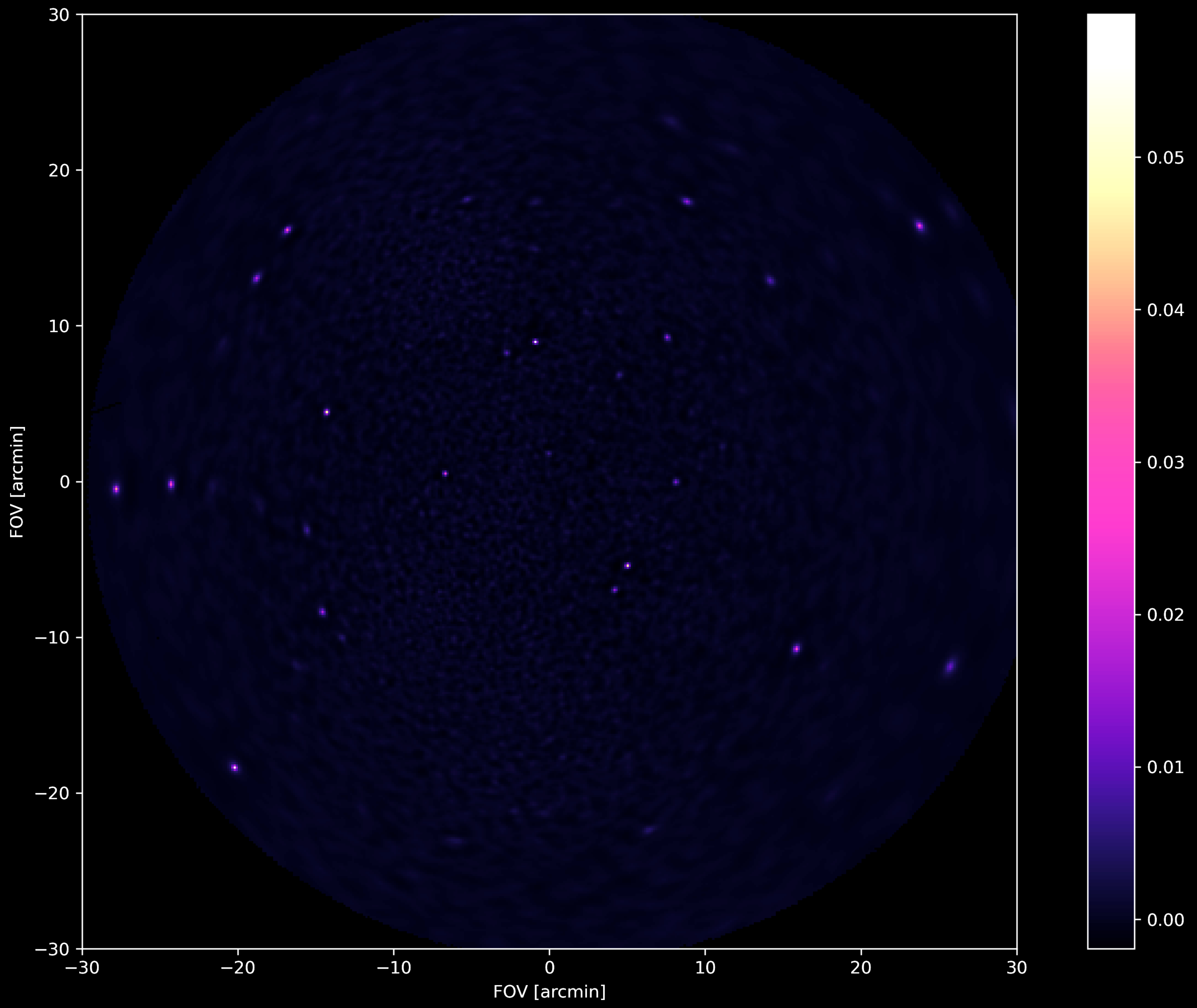
Automatic detection



Diffuse-only reconstruction + point source model

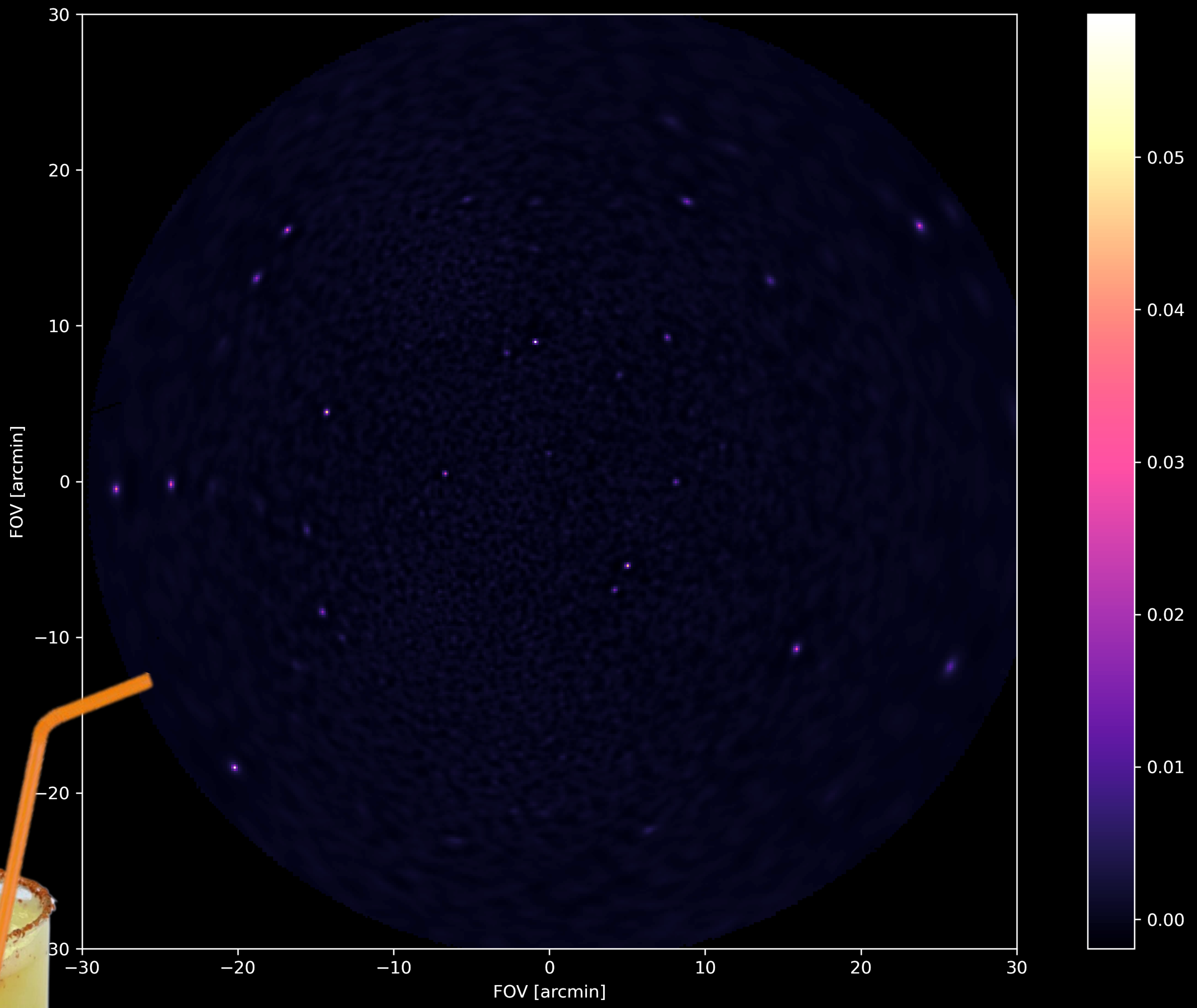
Point source detection

Relax excitations!



Latent ξ excitations

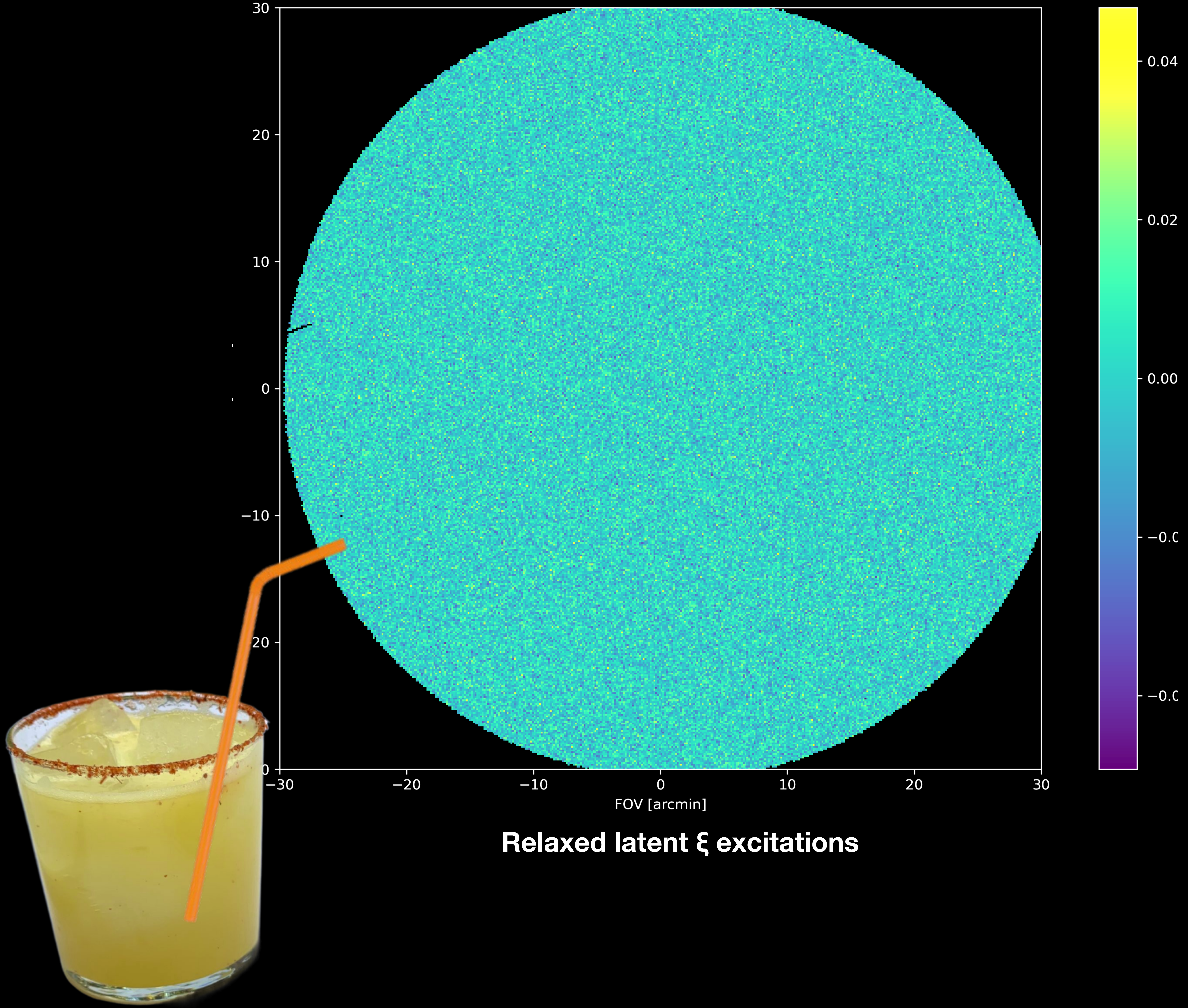
Point source detection
Relax excitations!



Latent ξ excitations

Point source detection

Relaxed excitations



Relaxed latent ξ excitations

Point source model

Some theory…

What is a point source?

Some theory…

What is a point source?

- Spatially uncorrelated

Some theory…

What is a point source?

- Spatially uncorrelated
- Spectrally independent from background

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What is a point source?

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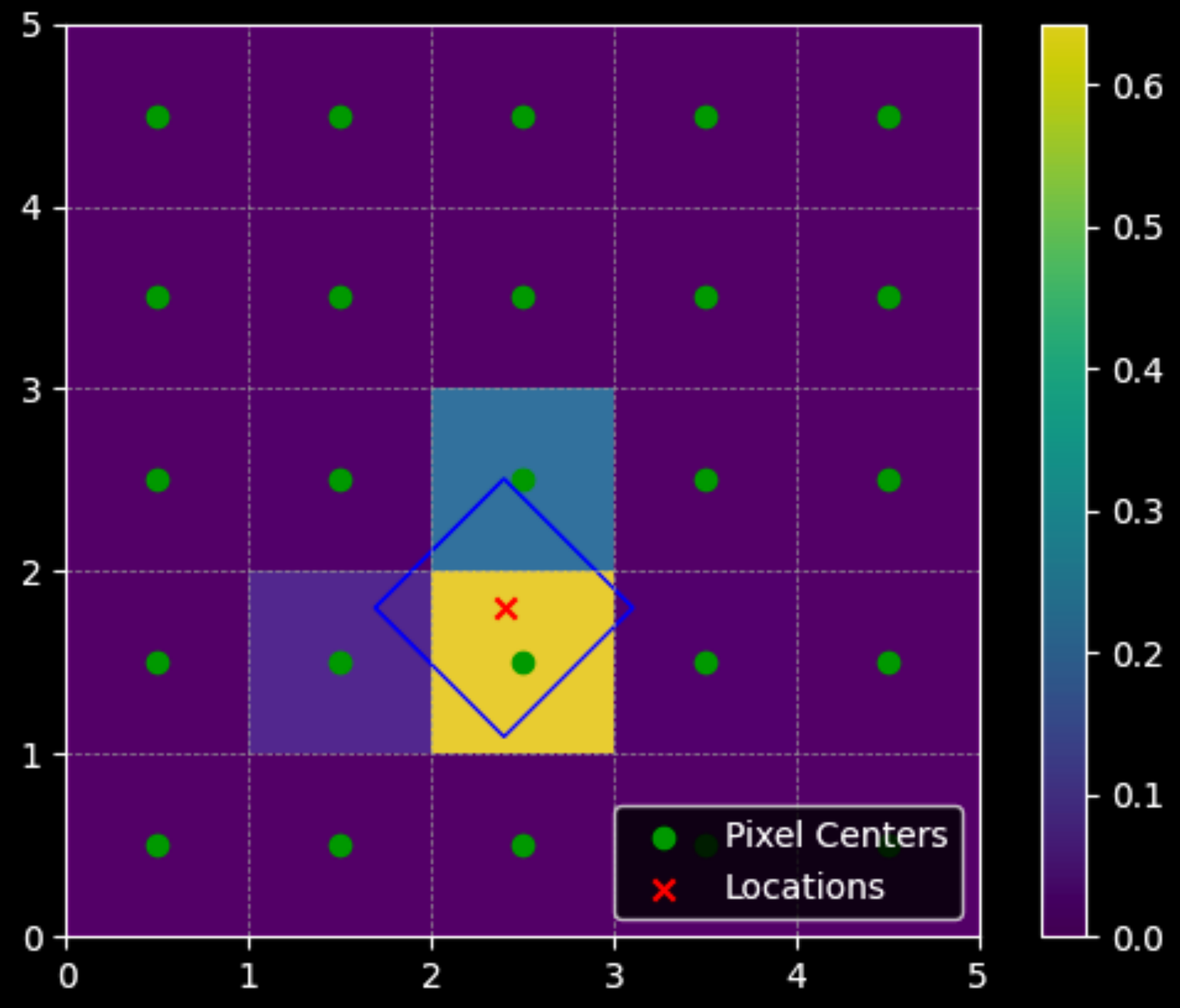
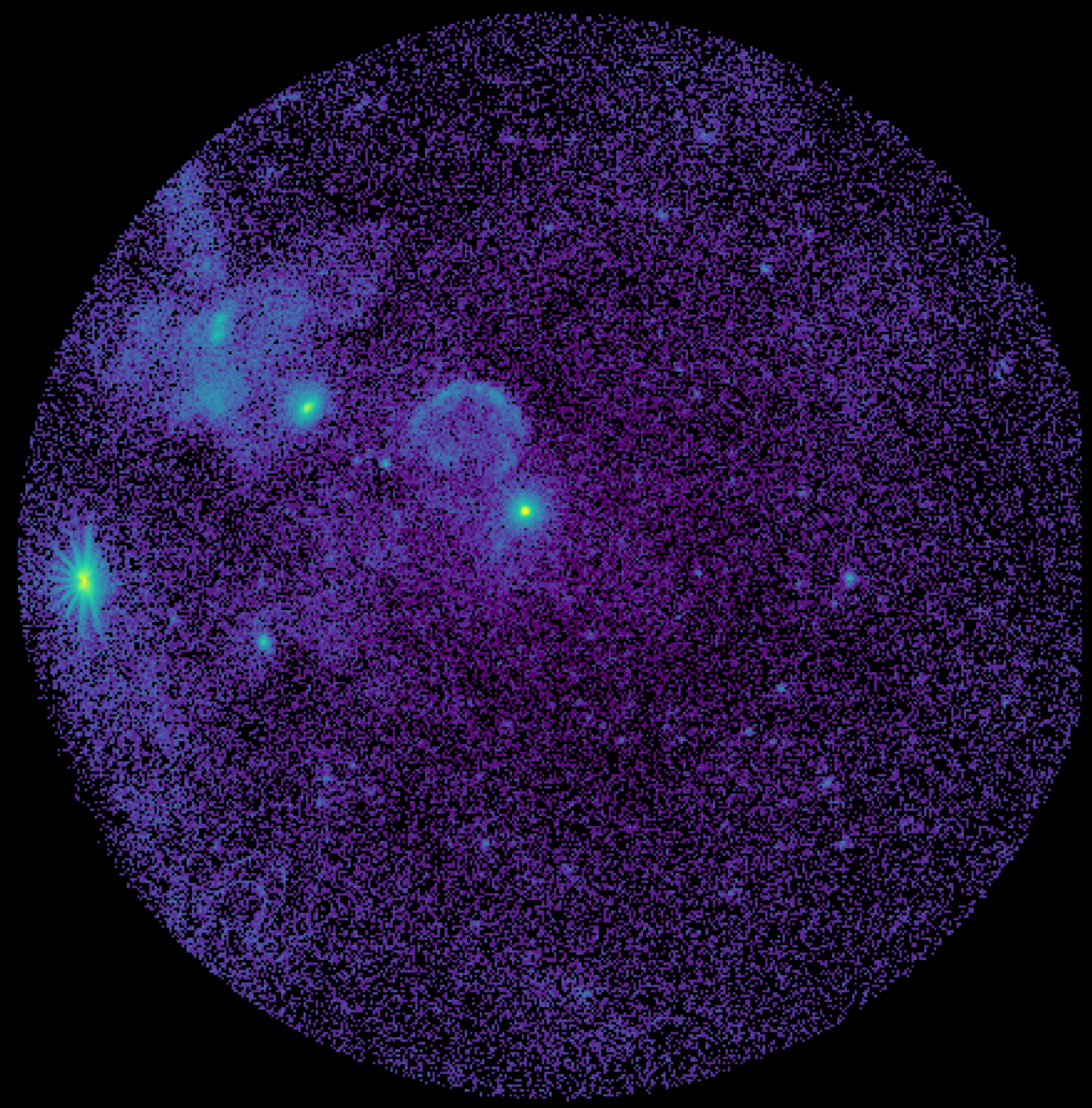


Real data

Point source detection
Single-frequency information

TM1

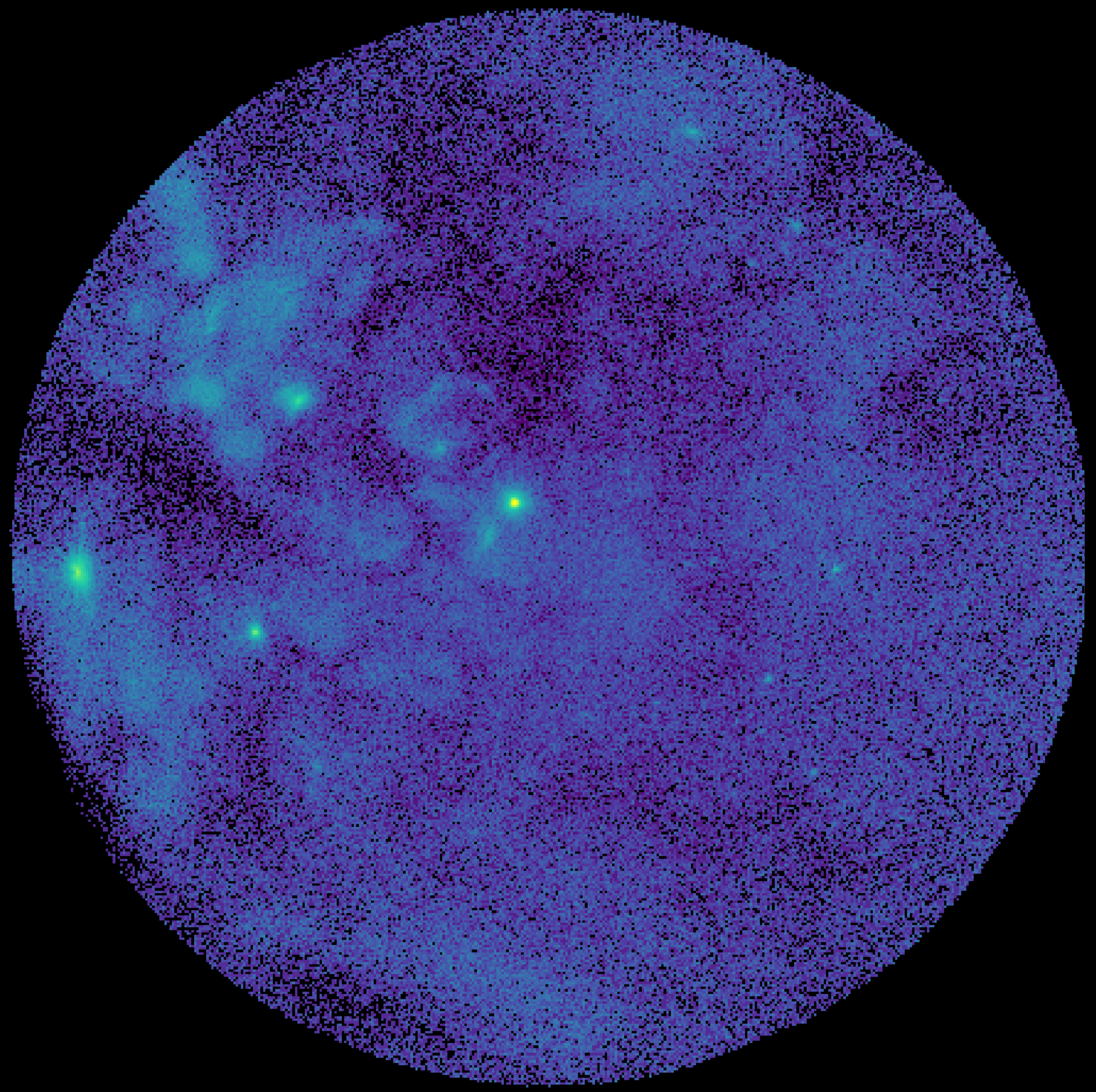


1.0 - 2.0 keV

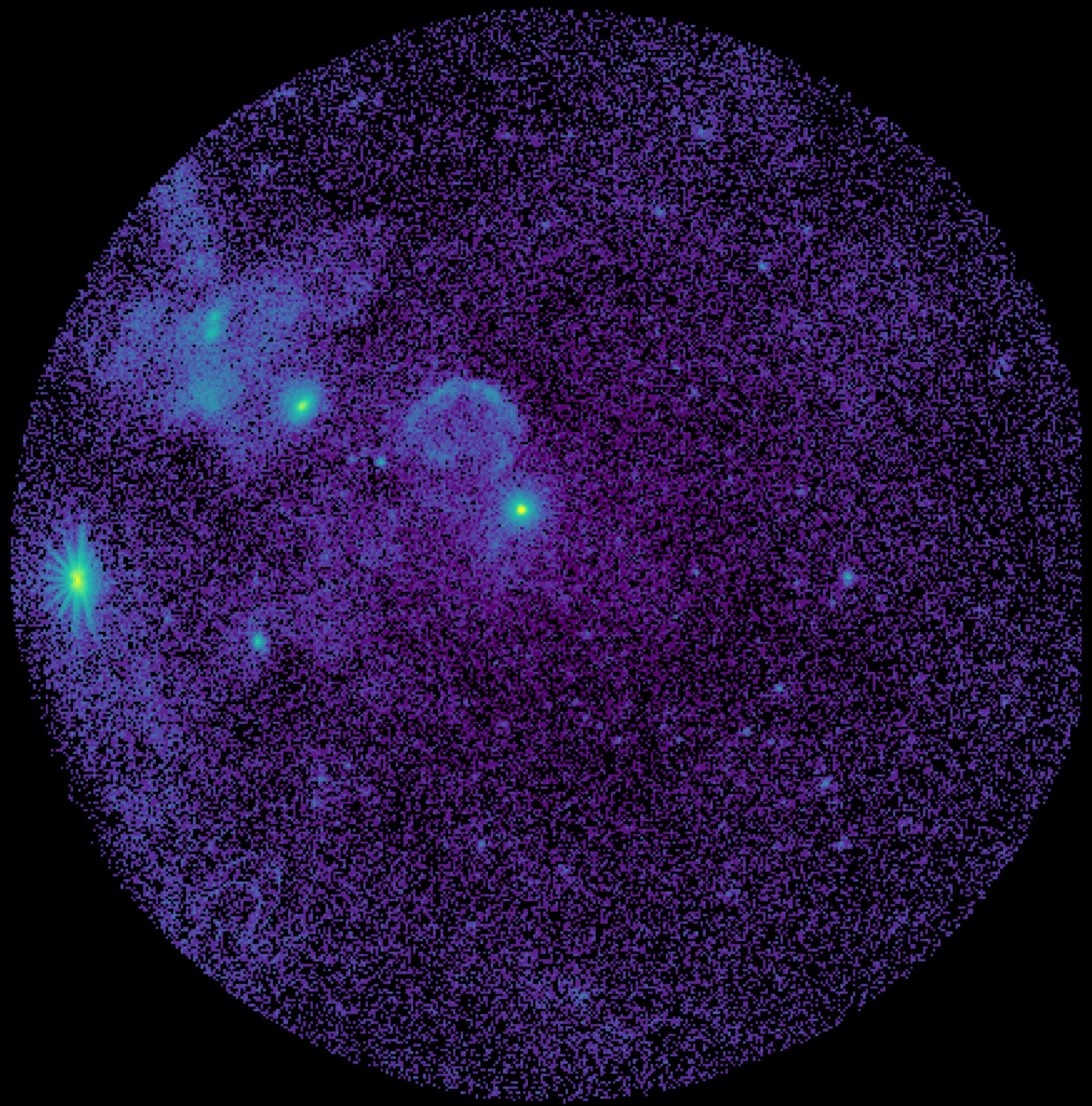
Point source detection

Multi-frequency information

TM1



0.2 - 1.0 keV



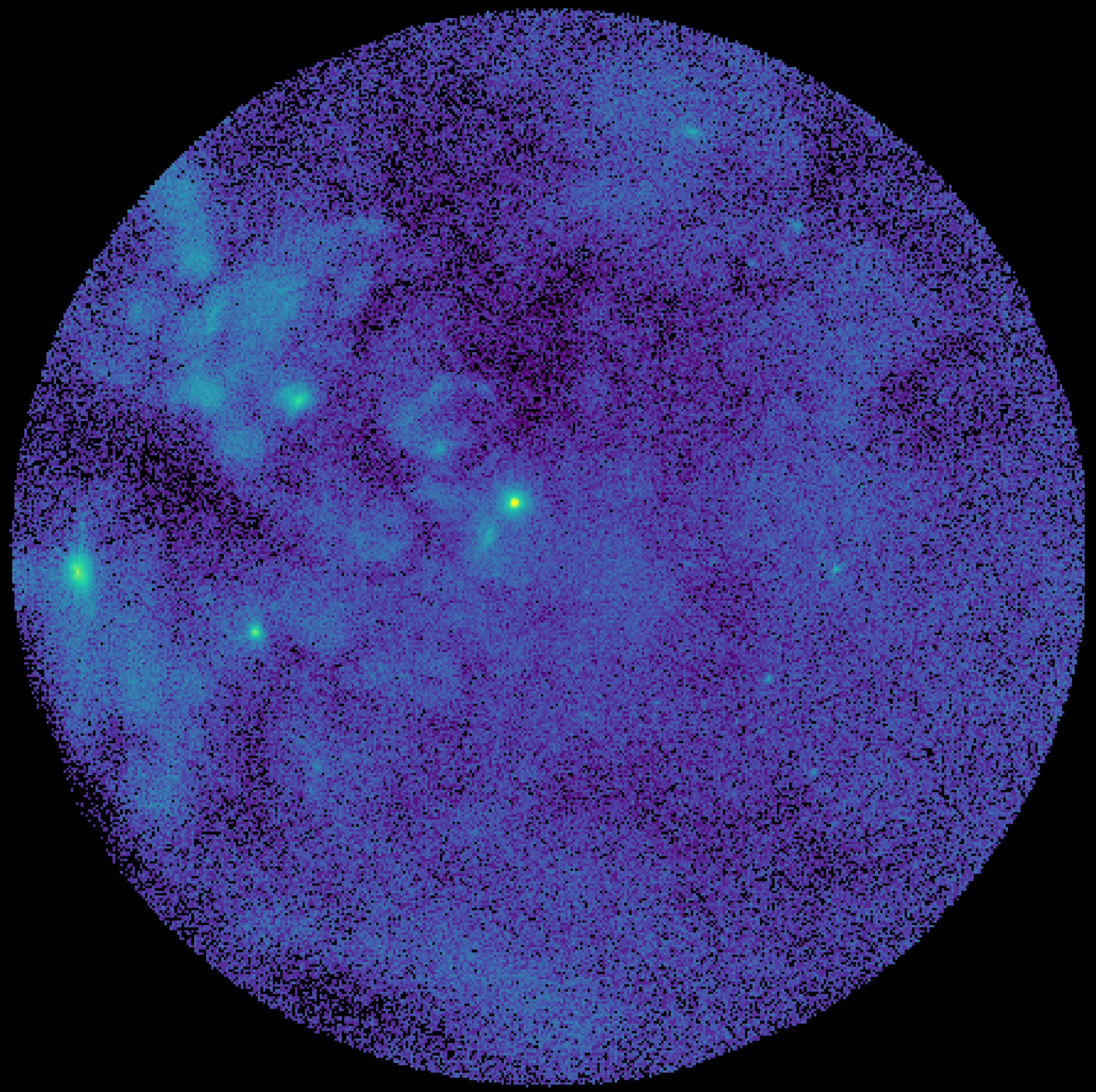
1.0 - 2.0 keV

2.0 - 4.5 keV

Point source detection

Multi-frequency information

TM1



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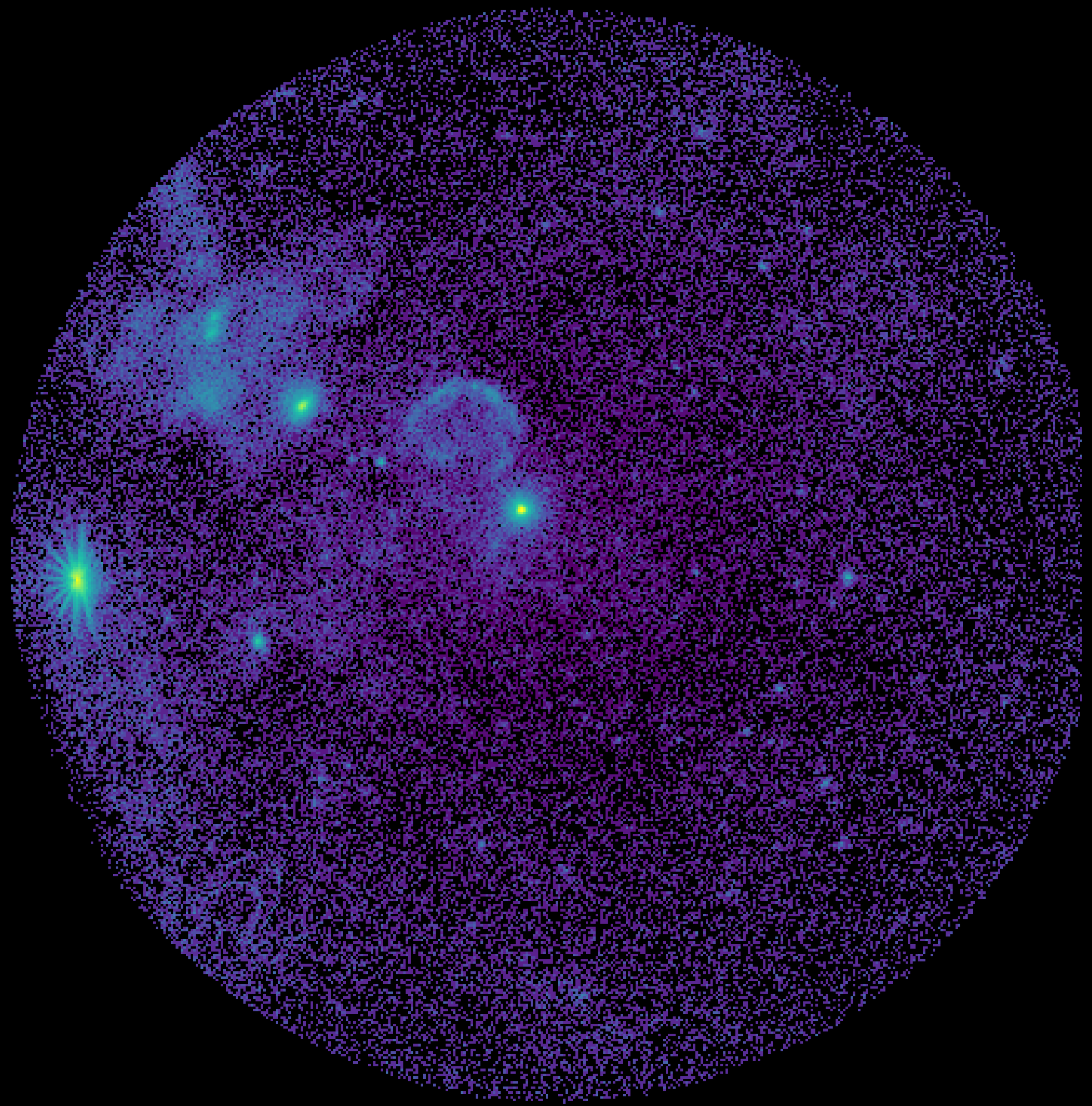

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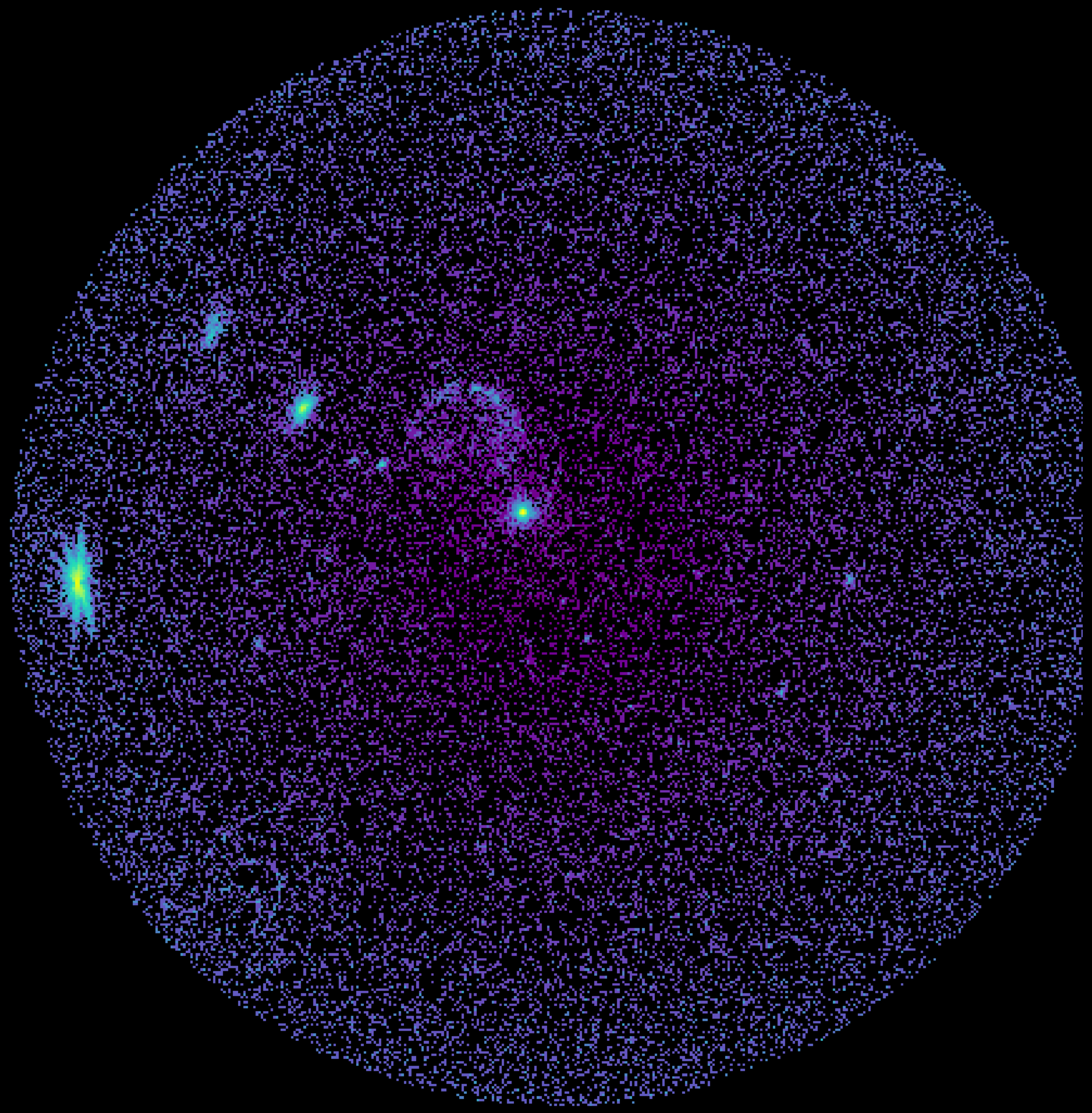
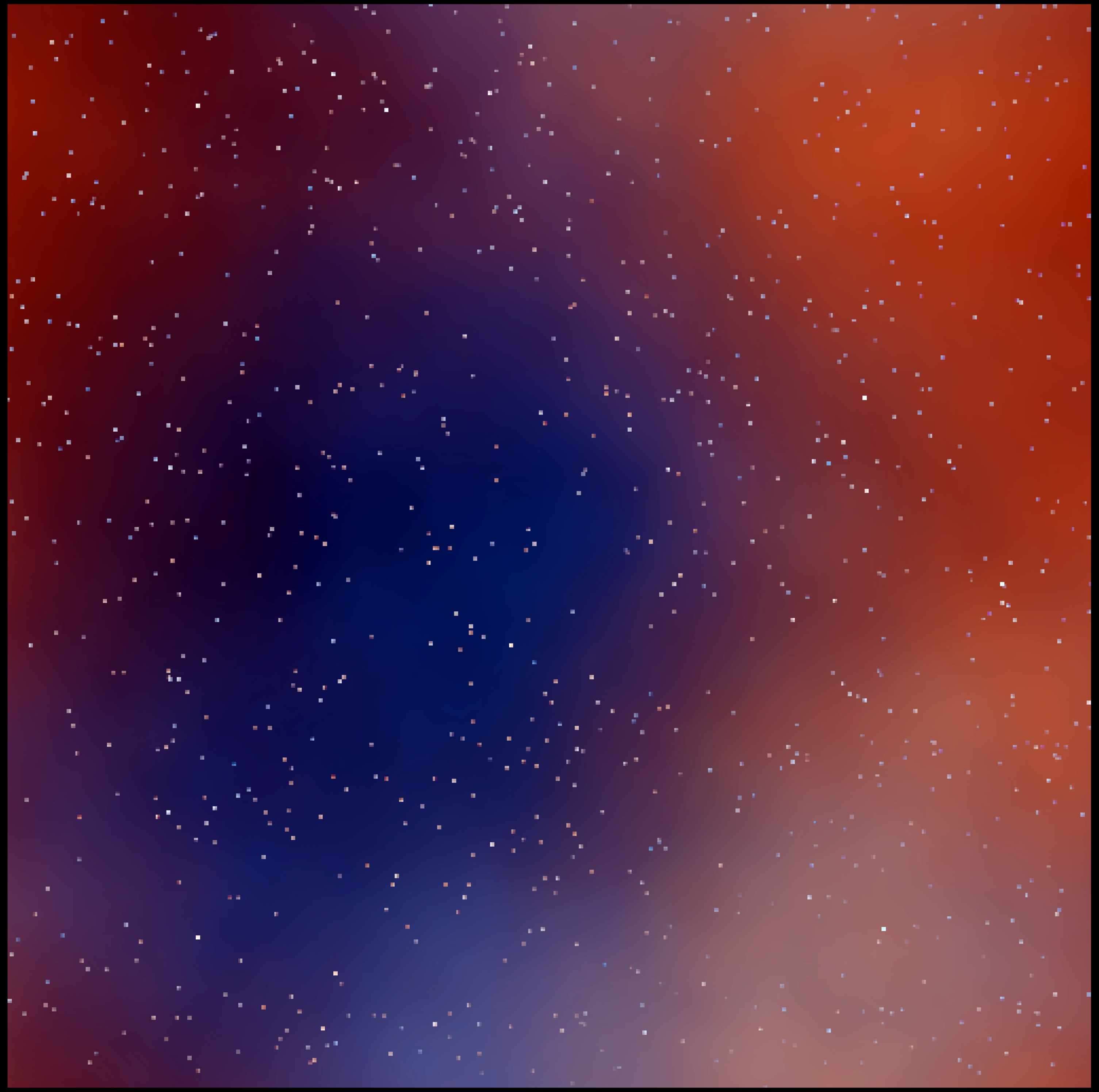
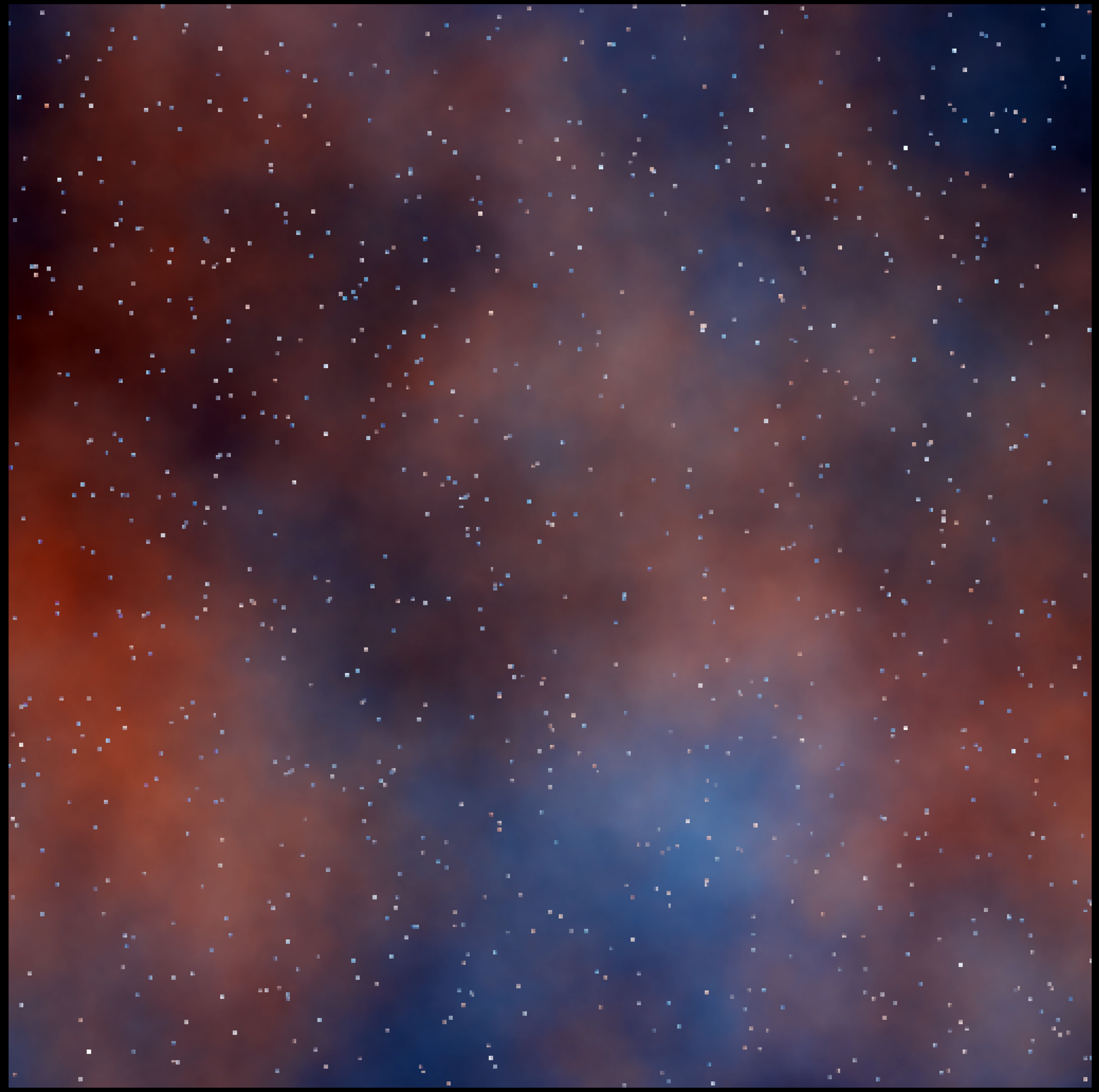
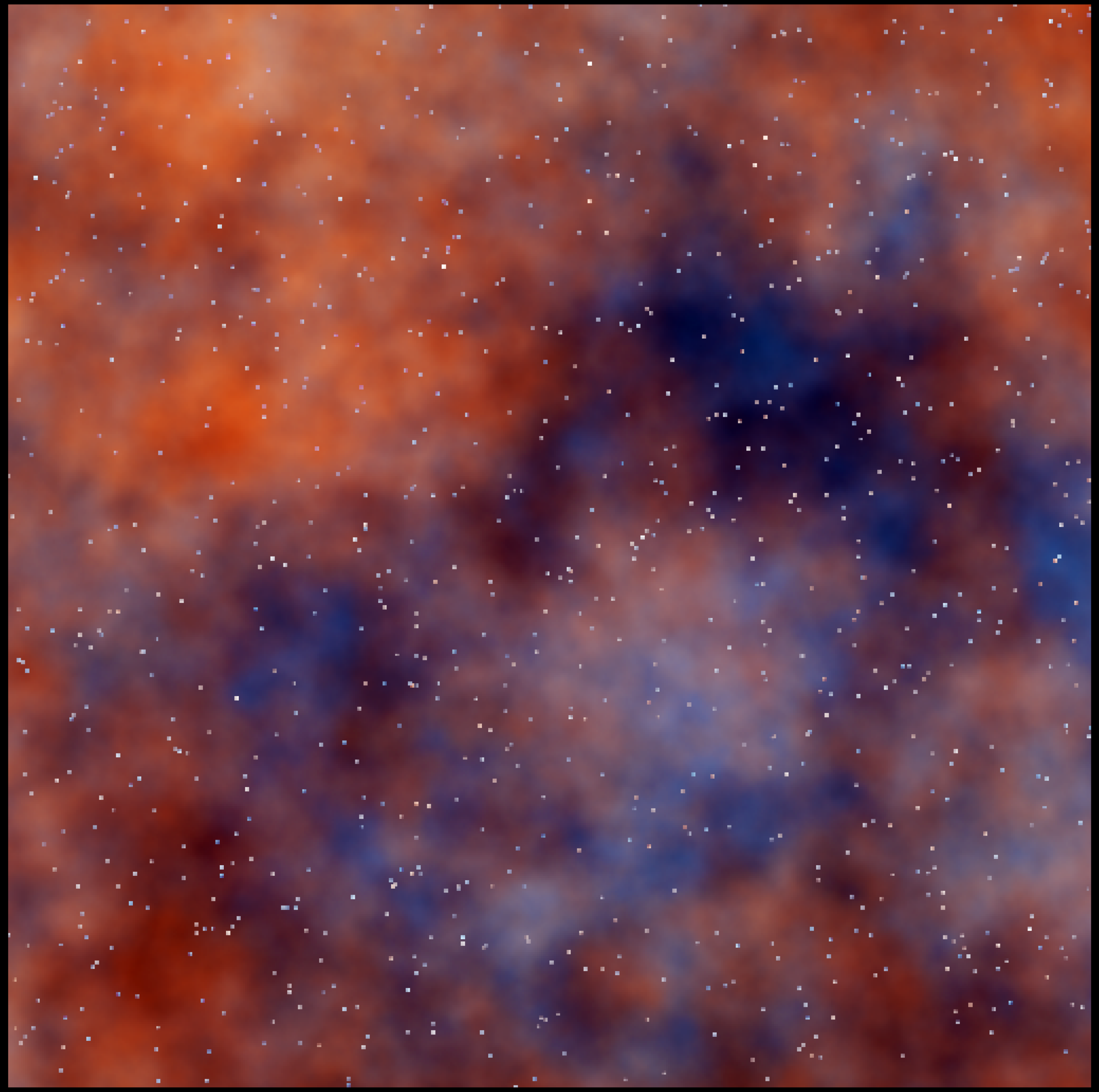


2.0 - 4.5 keV

Point source detection
Multi-frequency model

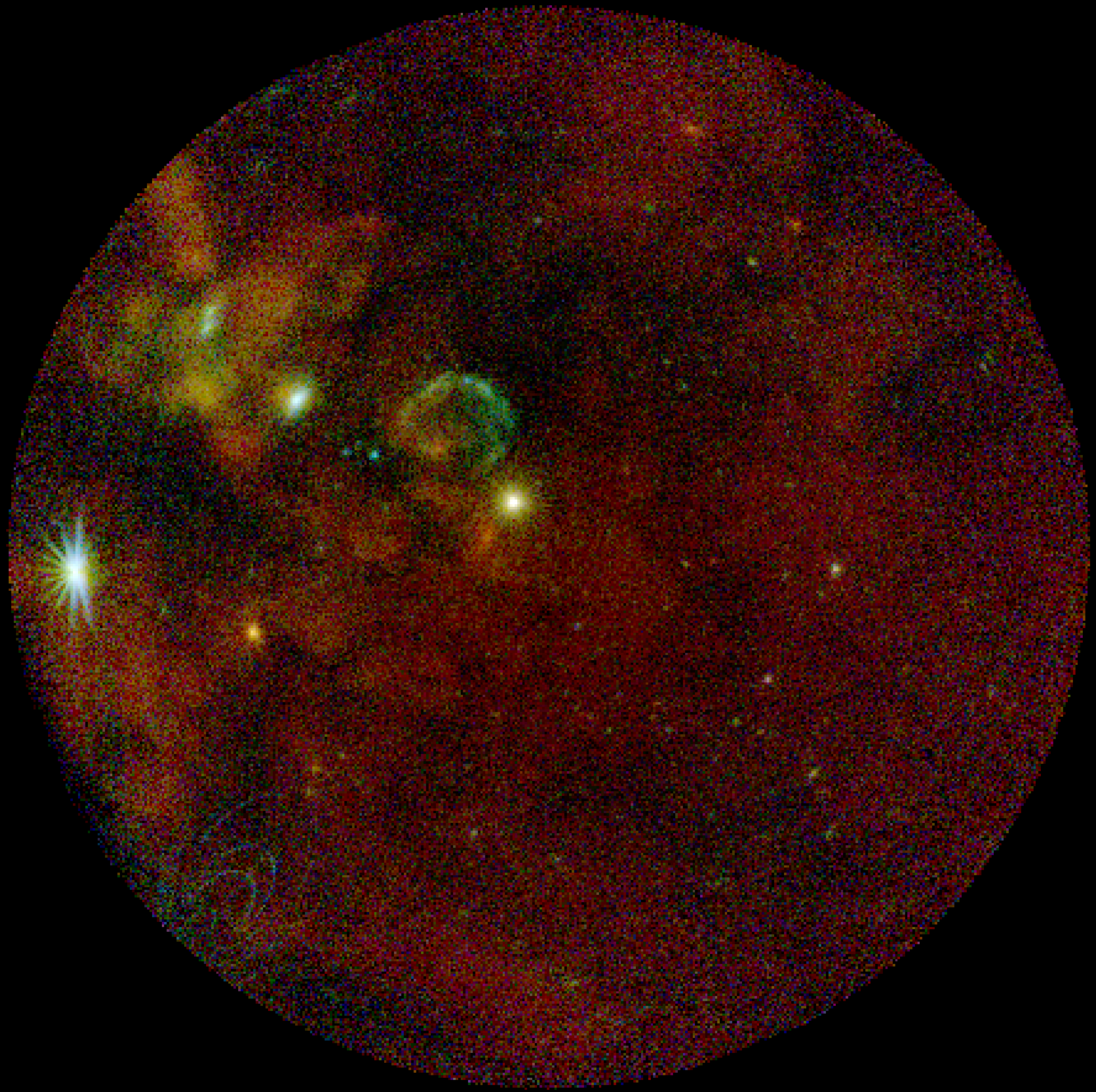
Point source detection

Multi-frequency model

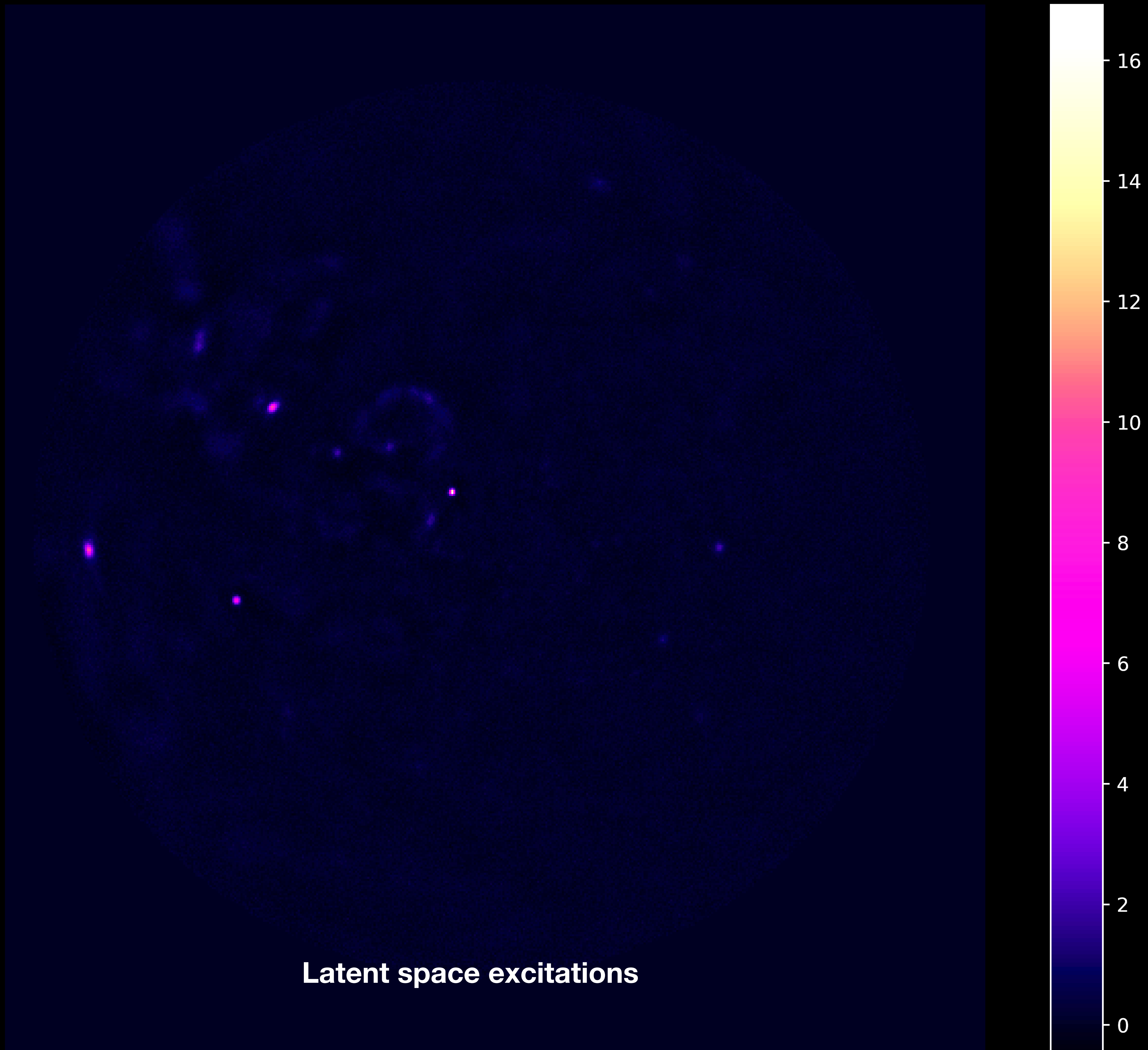
Point source detection

Multi-frequency model

TM1

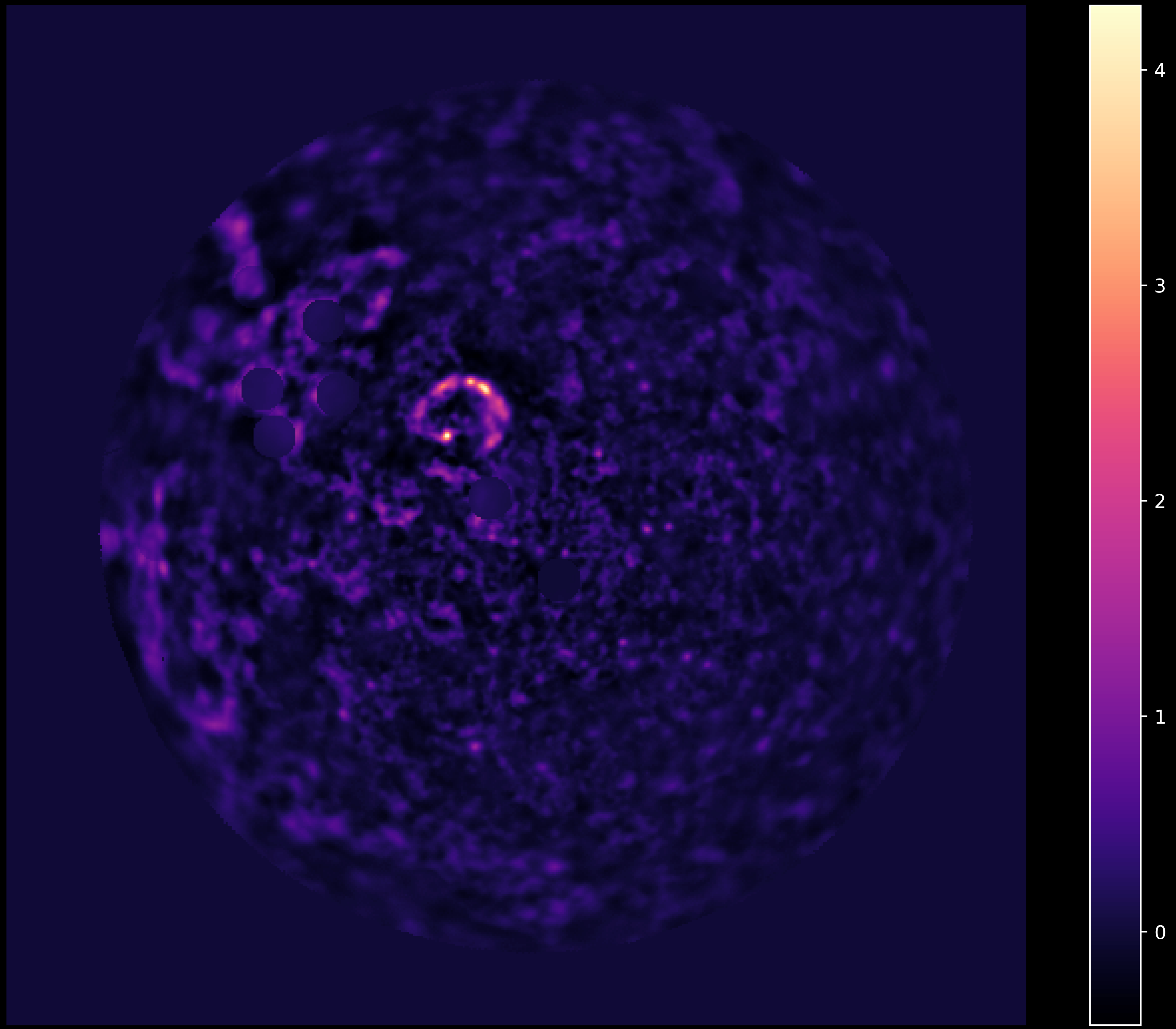


Point source detection
Multi-frequency model latent excitations



Point source detection

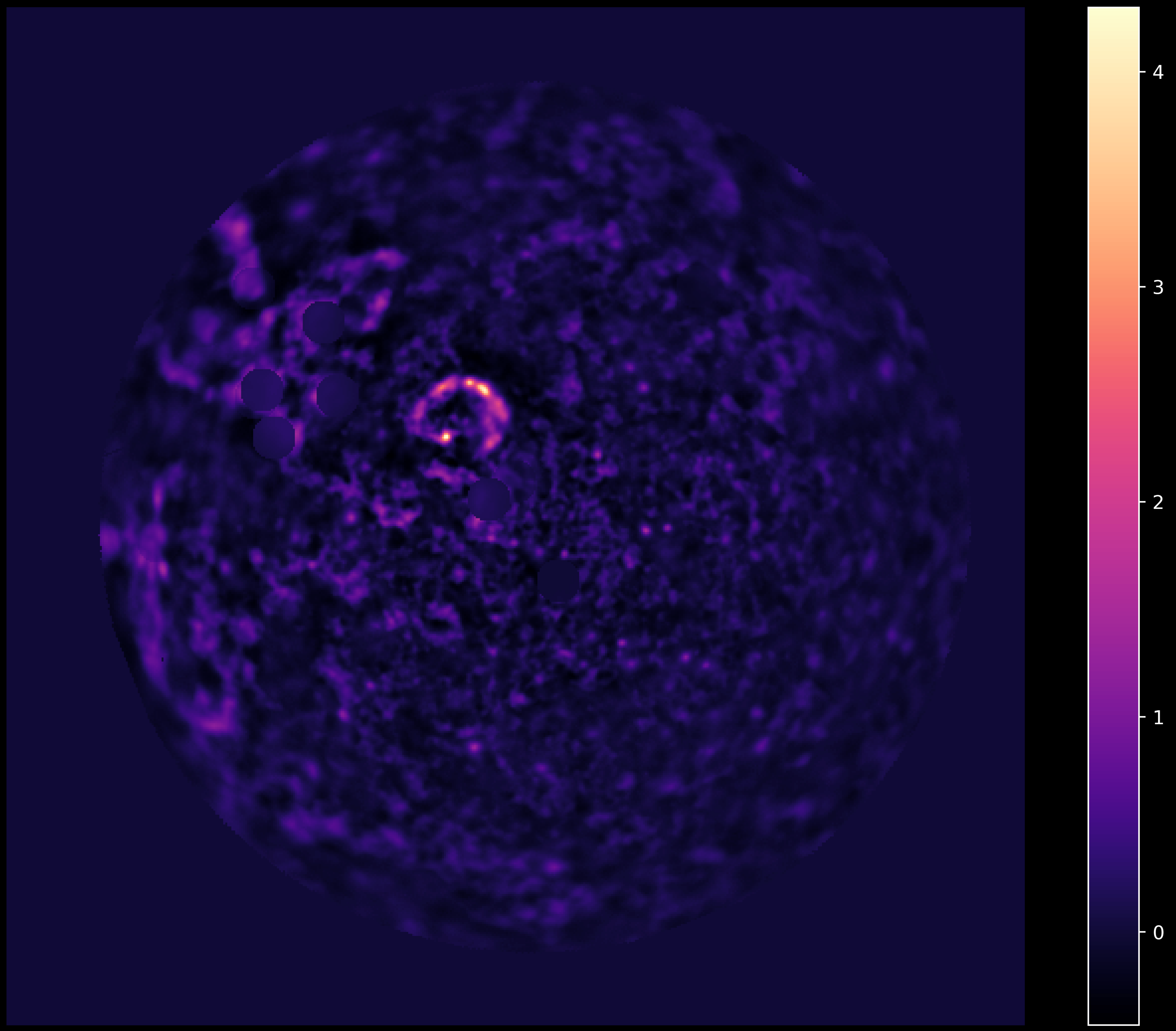
Multi-frequency model latent excitations



Latent space excitations

Point source detection

Generalizable to extended sources!

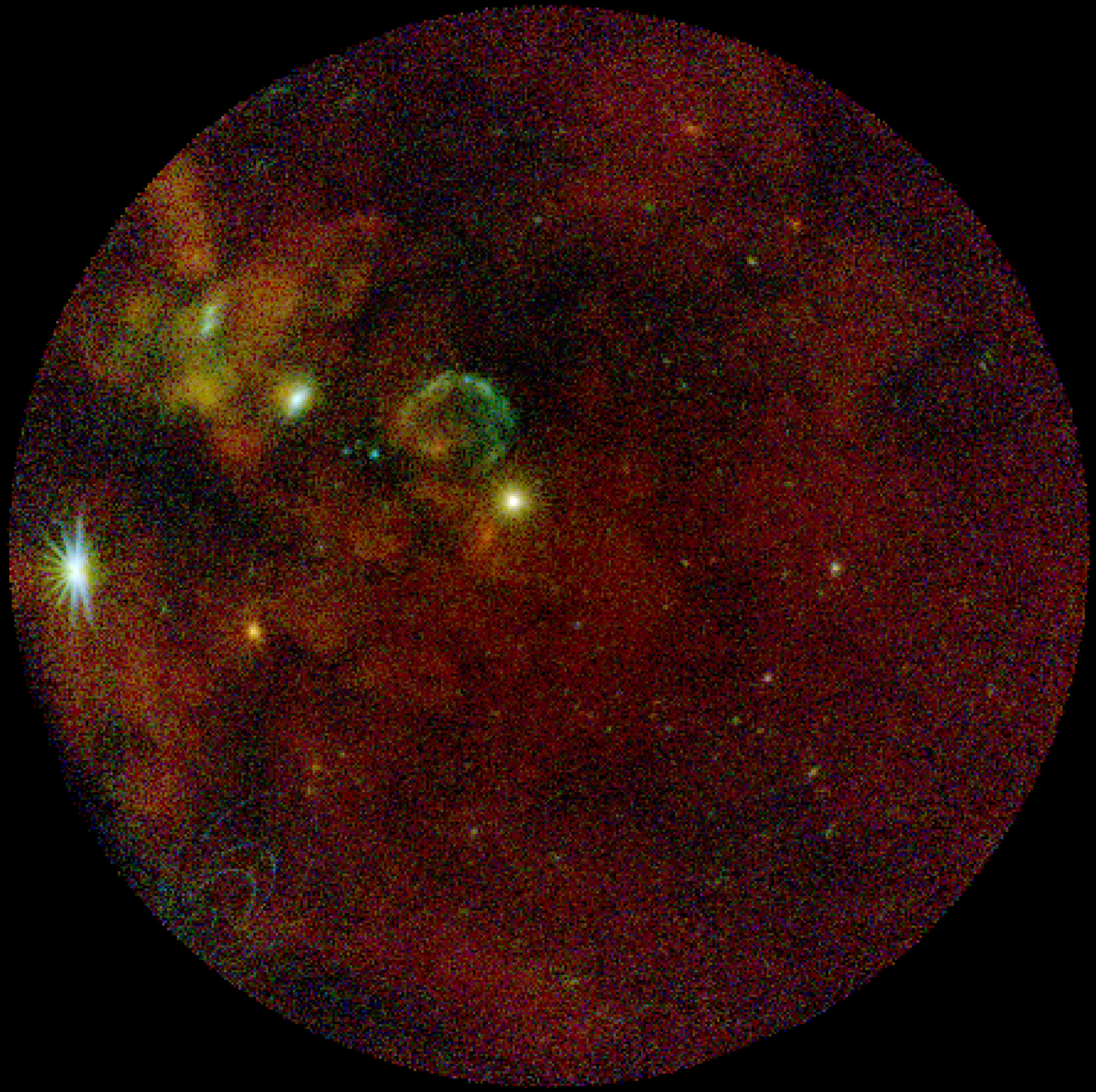


Latent space excitations

Point source detection

Preliminary results

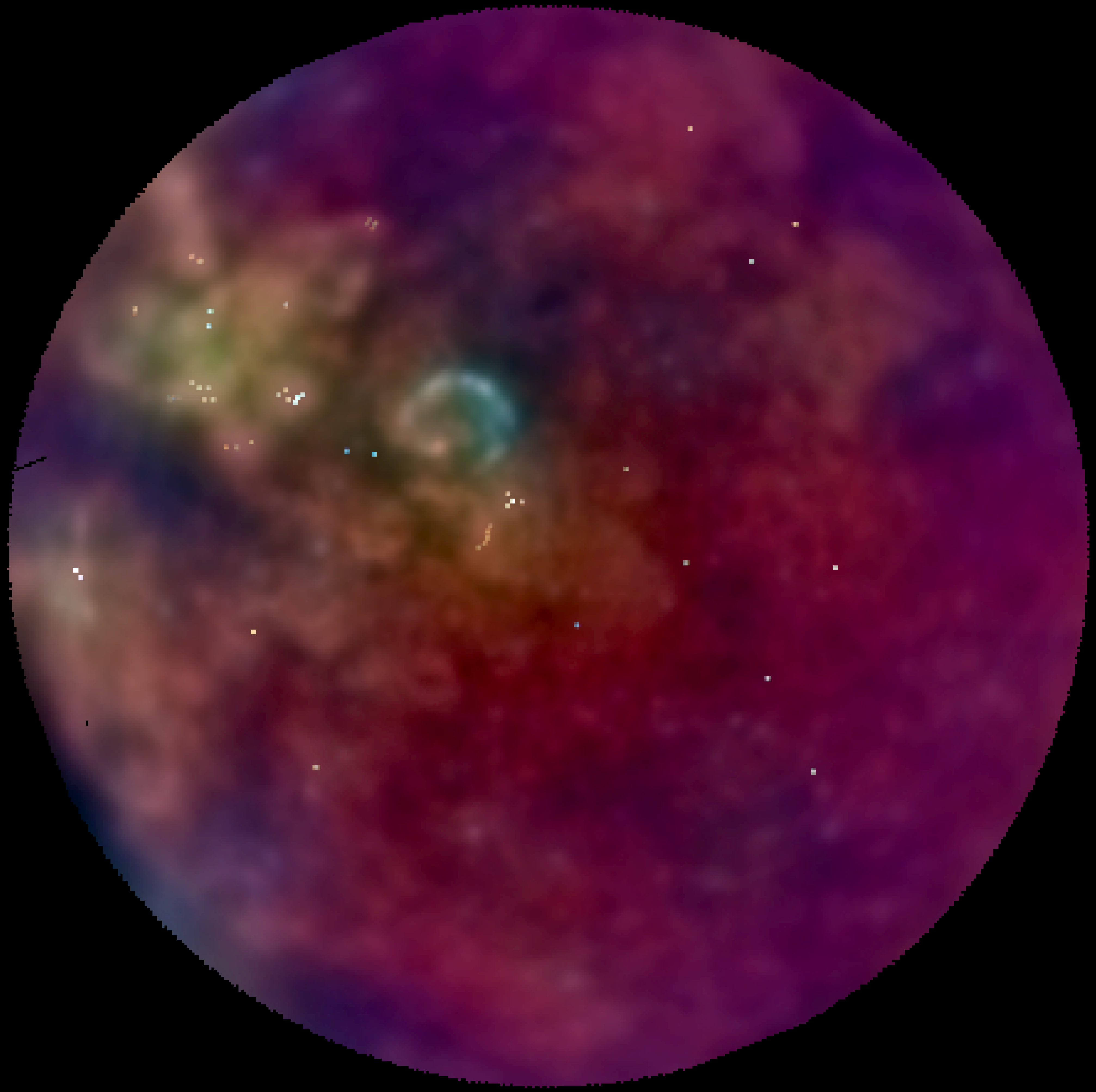
TM1



Point source detection

Preliminary results

TM1



Point source detection

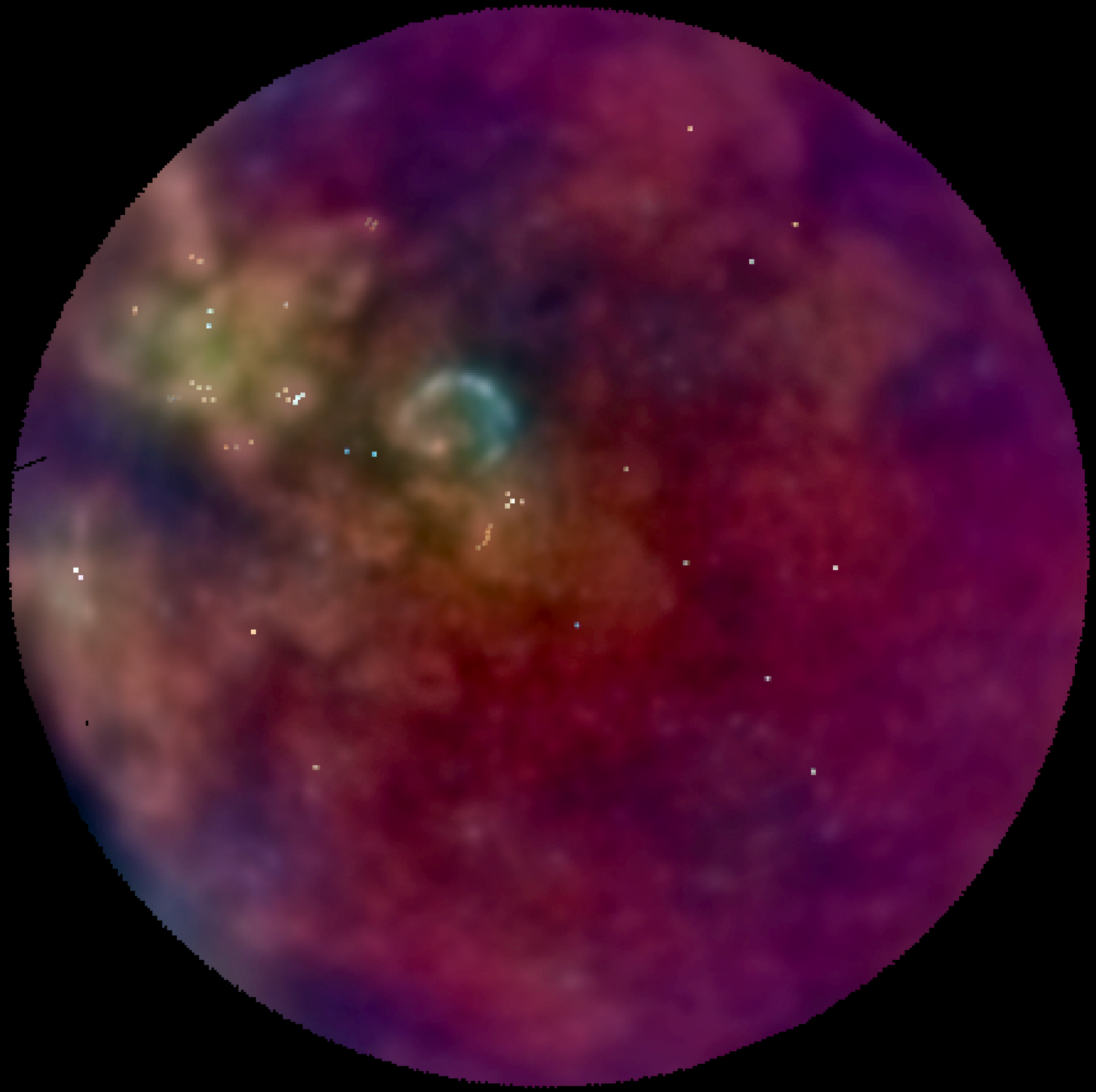
Preliminary results

TM1

Point source detection

Preliminary results

TM1



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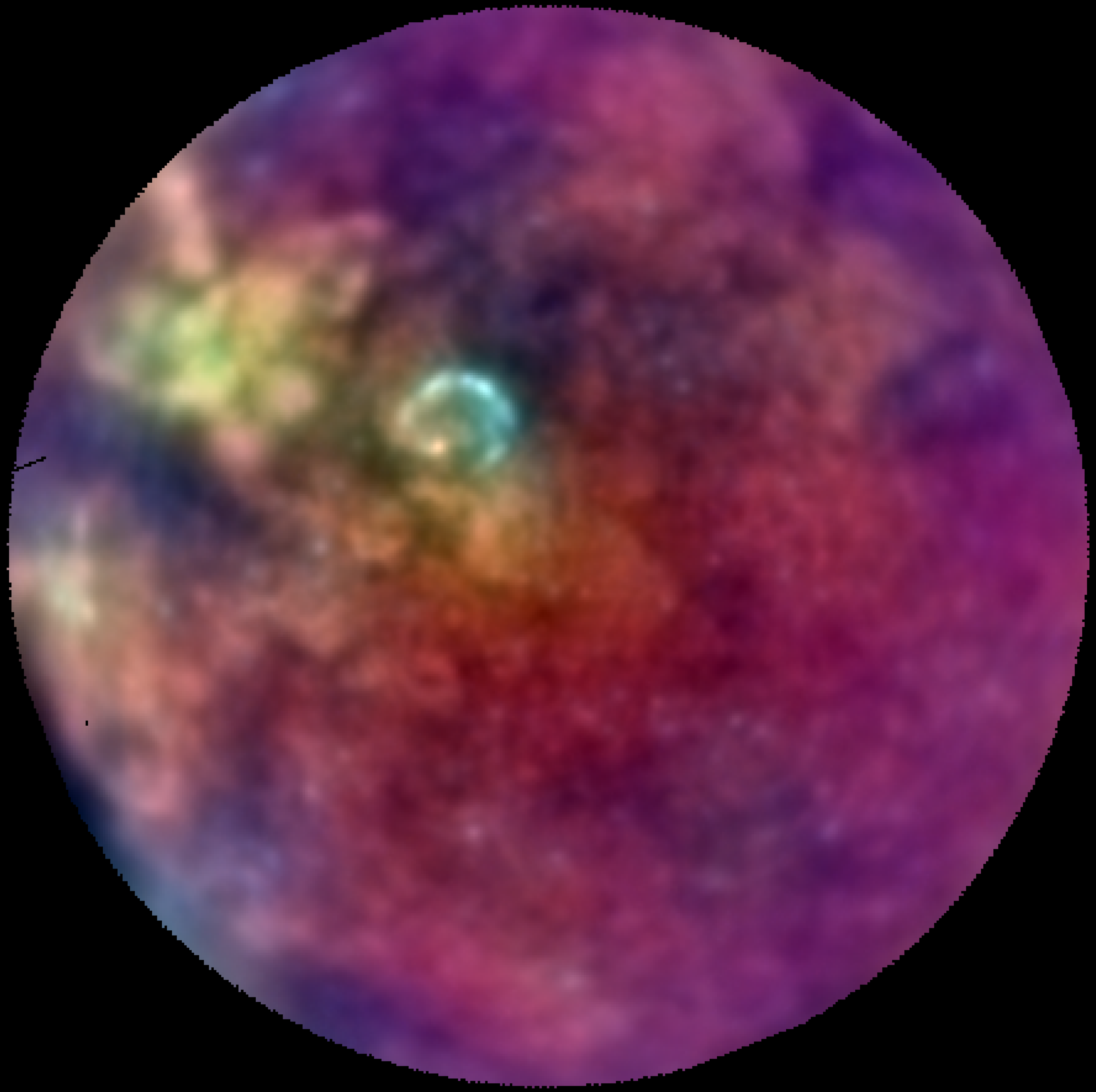

Outlook

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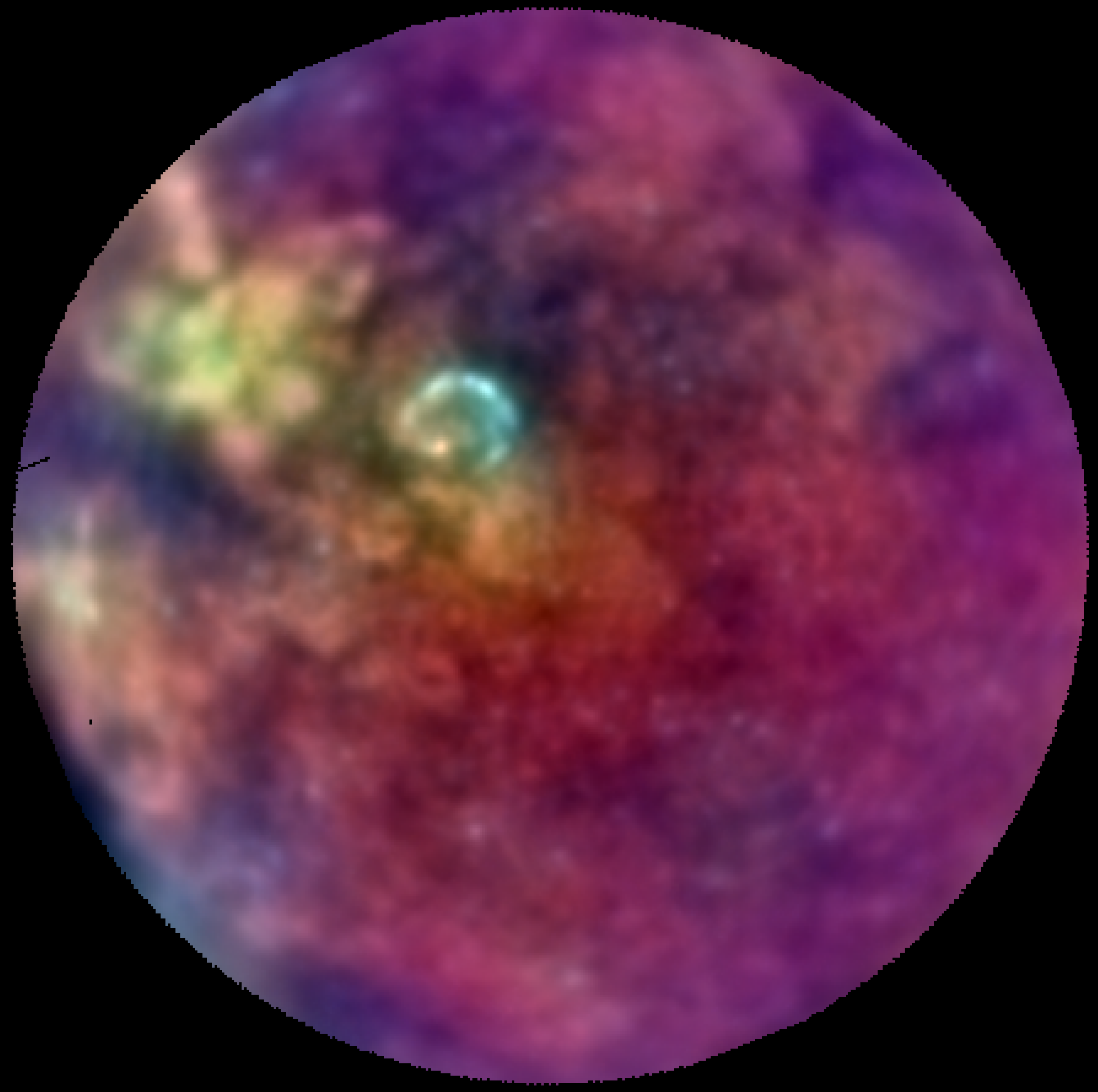
- **Model stress can rescue component separation!**

Outlook



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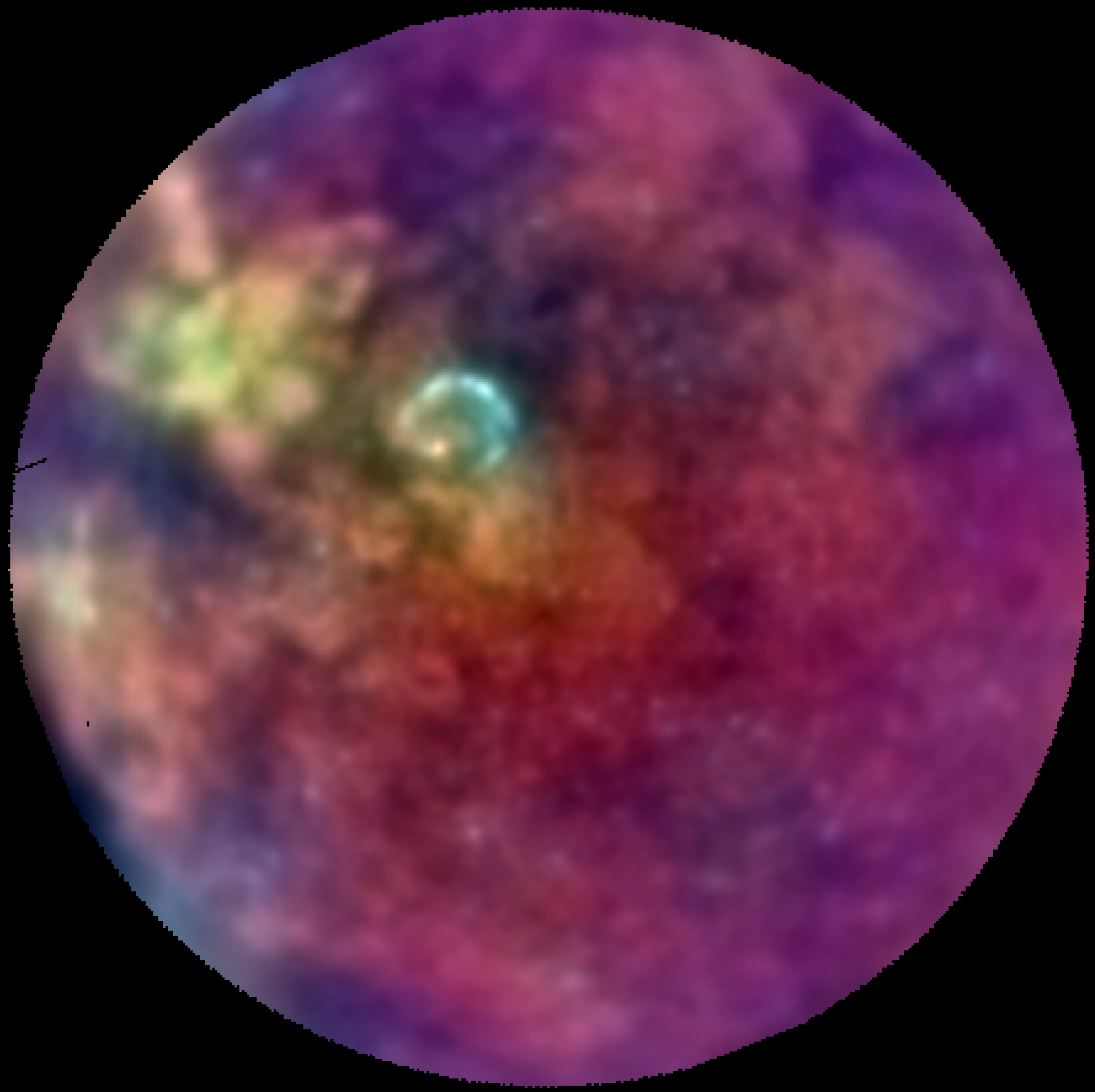

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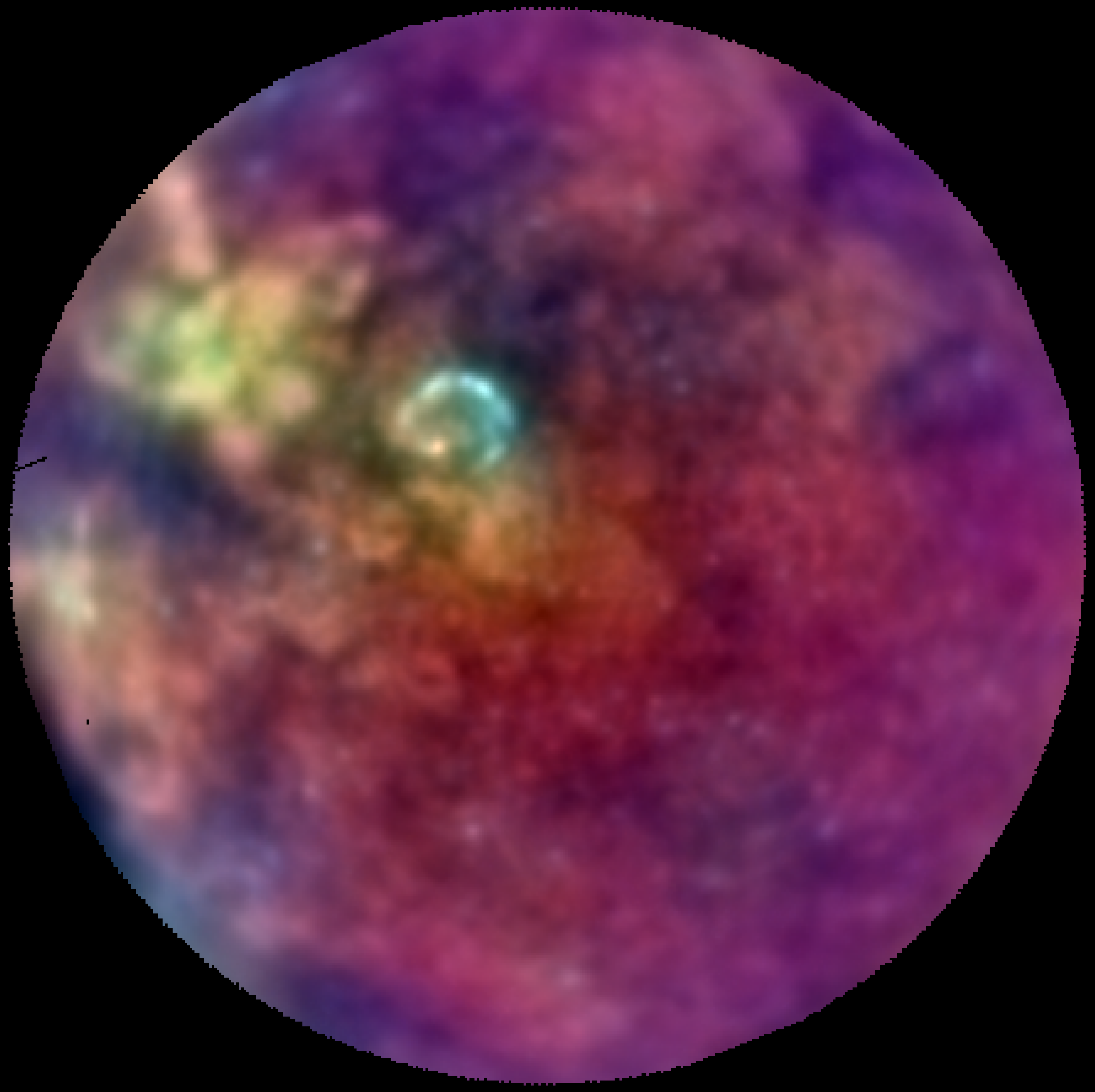

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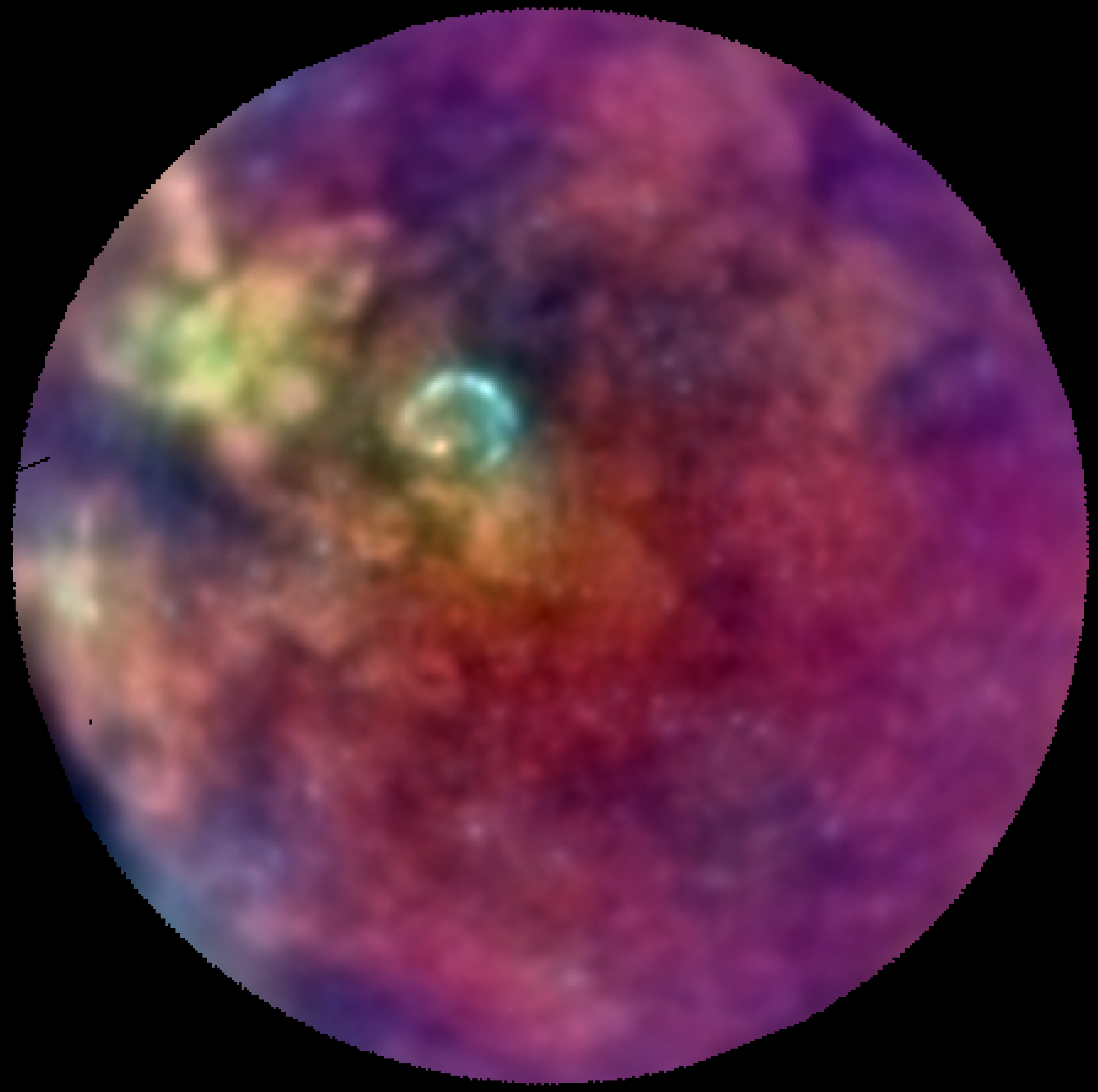
Outlook



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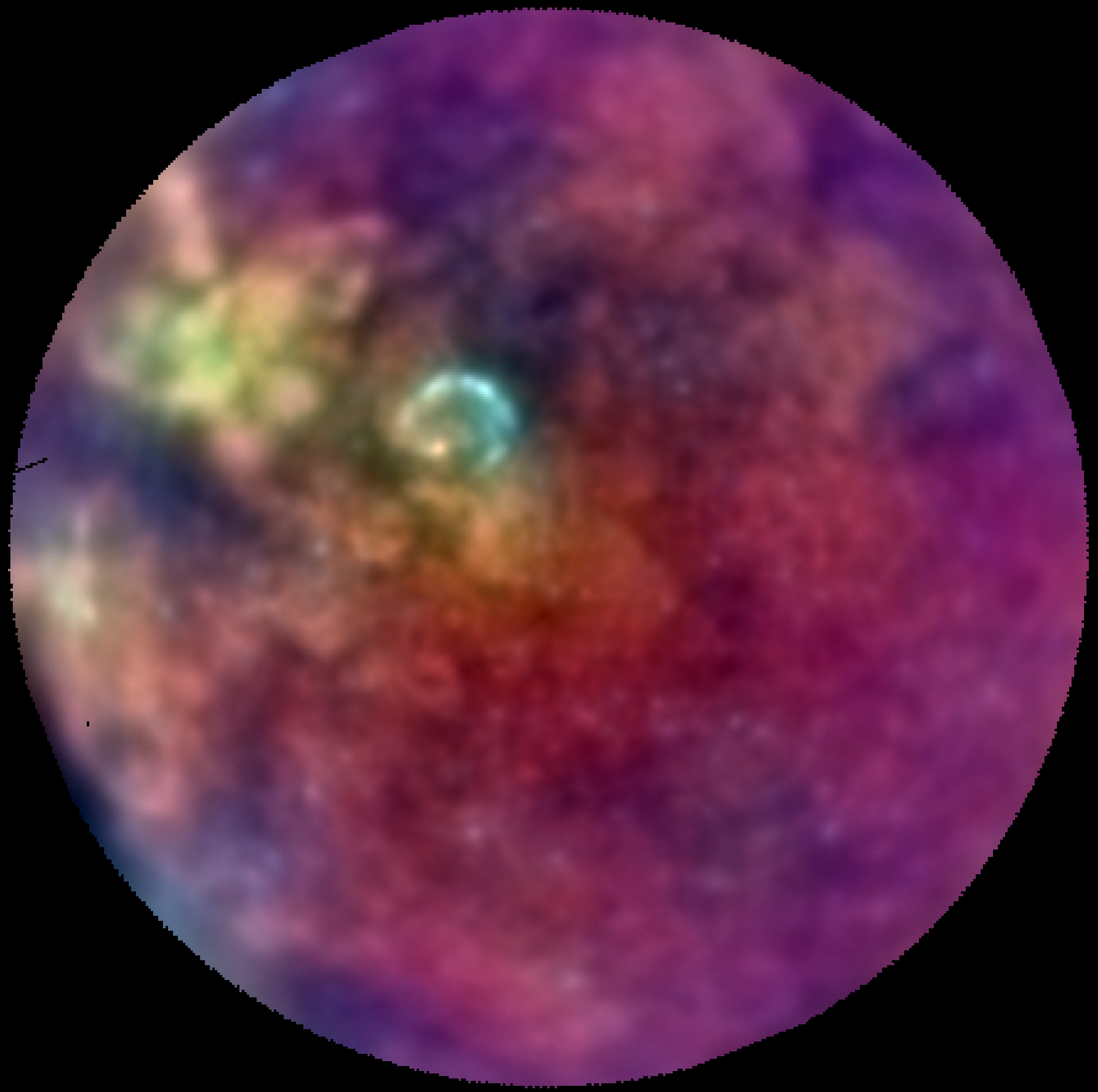

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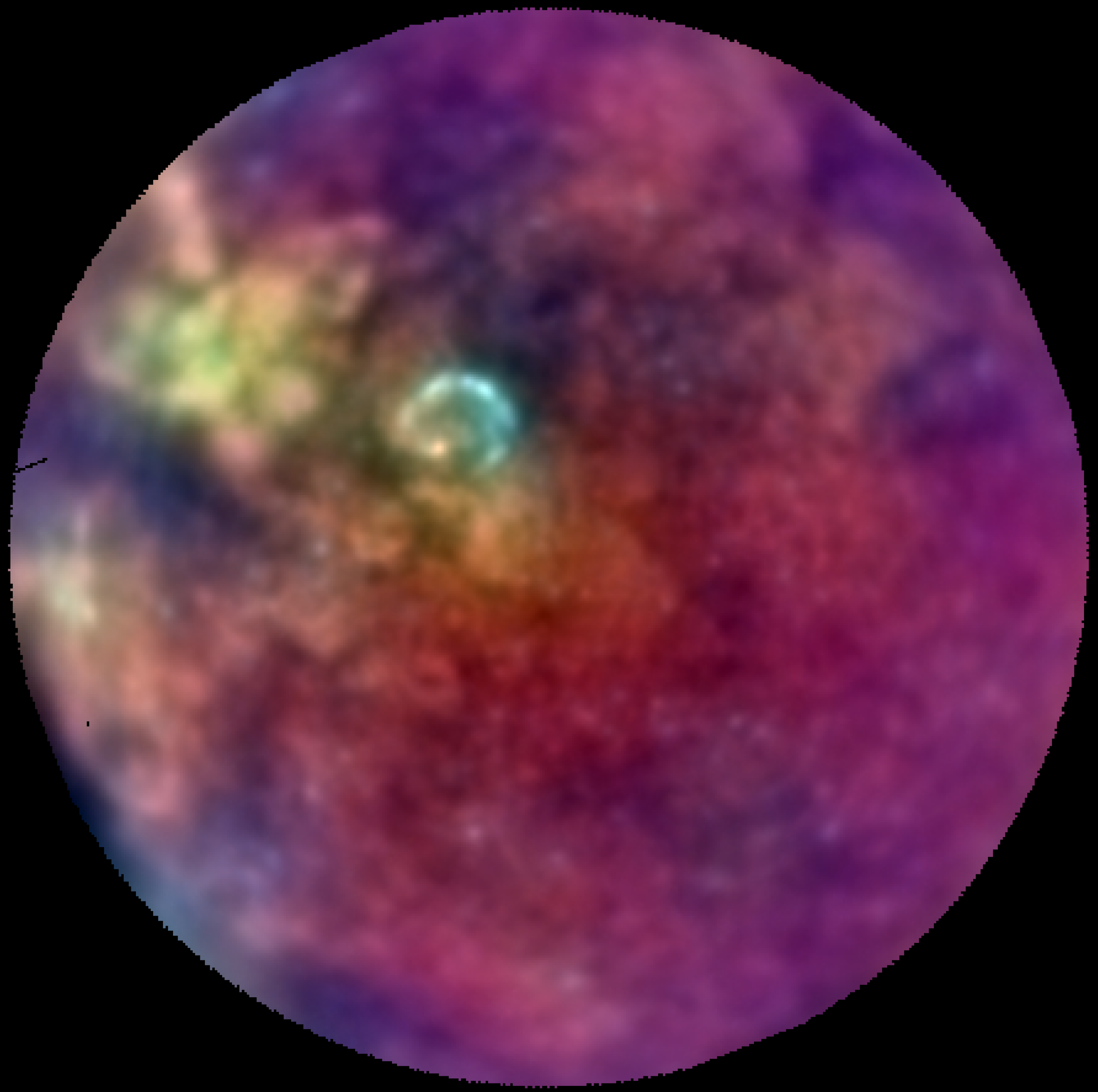
- **Soon preprint on arxiv!**



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Thank you!

matteani@mpa-garching.mpg.de

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FOR ASTROPHYSICS

Thank you!

Looking for PostDocs!

matteani@mpa-garching.mpg.de

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