

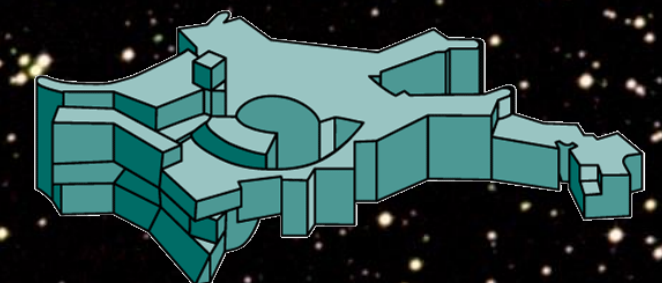
Automatic Component Detection for Astrophysical Imaging

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

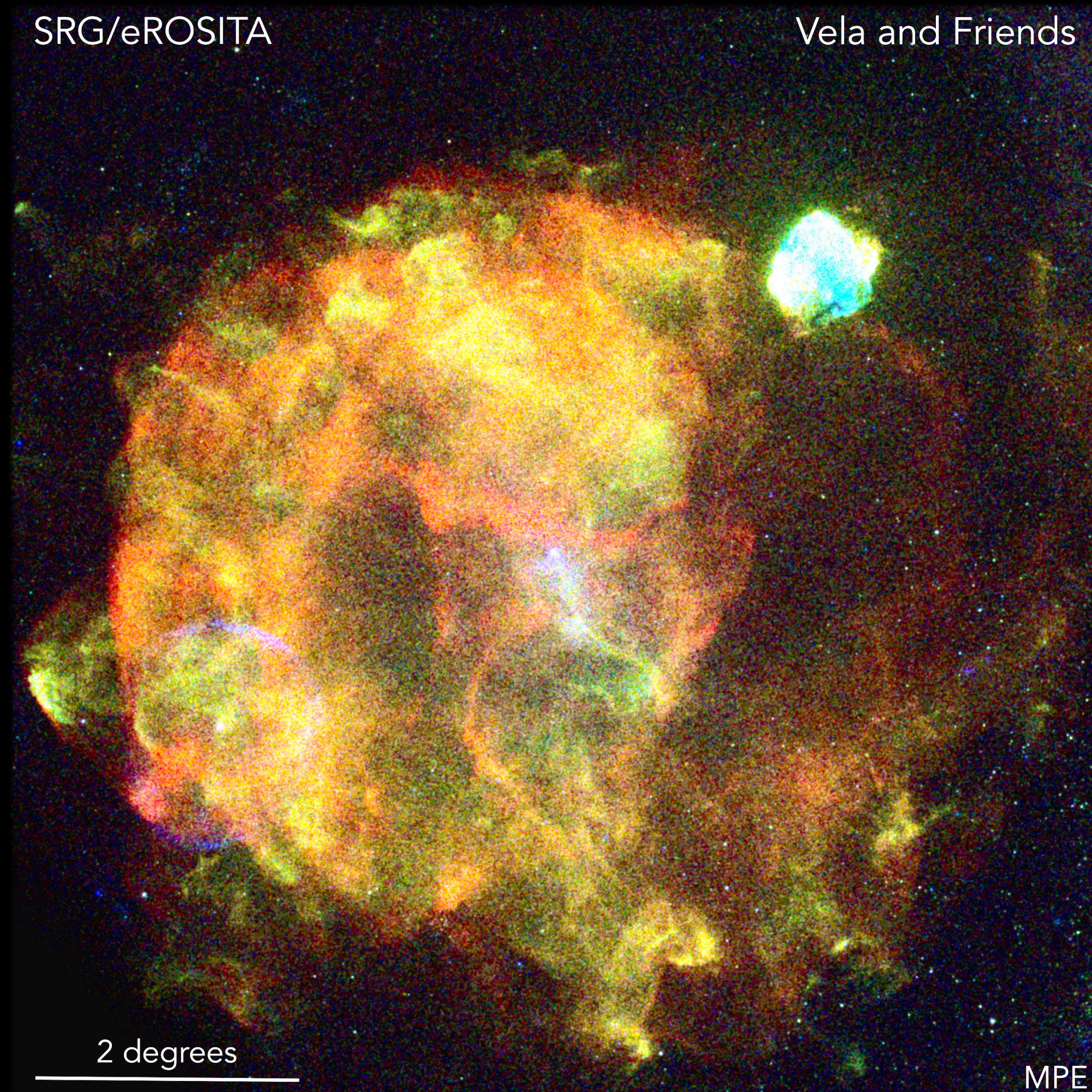
November 5th 2025
CHASC AstroStatistics Seminar
Center for Astrophysics (CfA)
Harvard University, Cambridge, USA



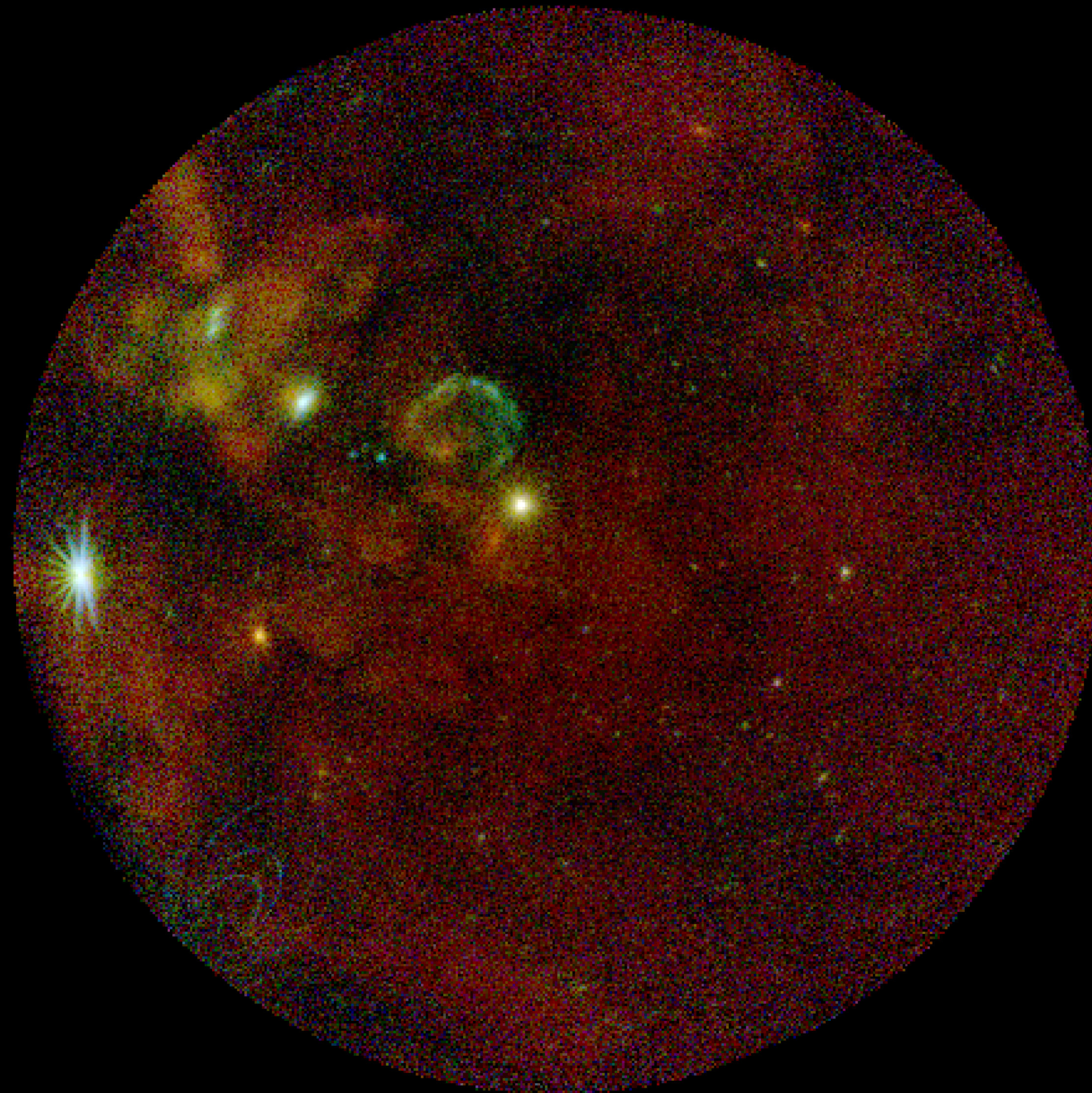
MAX PLANCK INSTITUTE
FOR ASTROPHYSICS



The problem



The problem

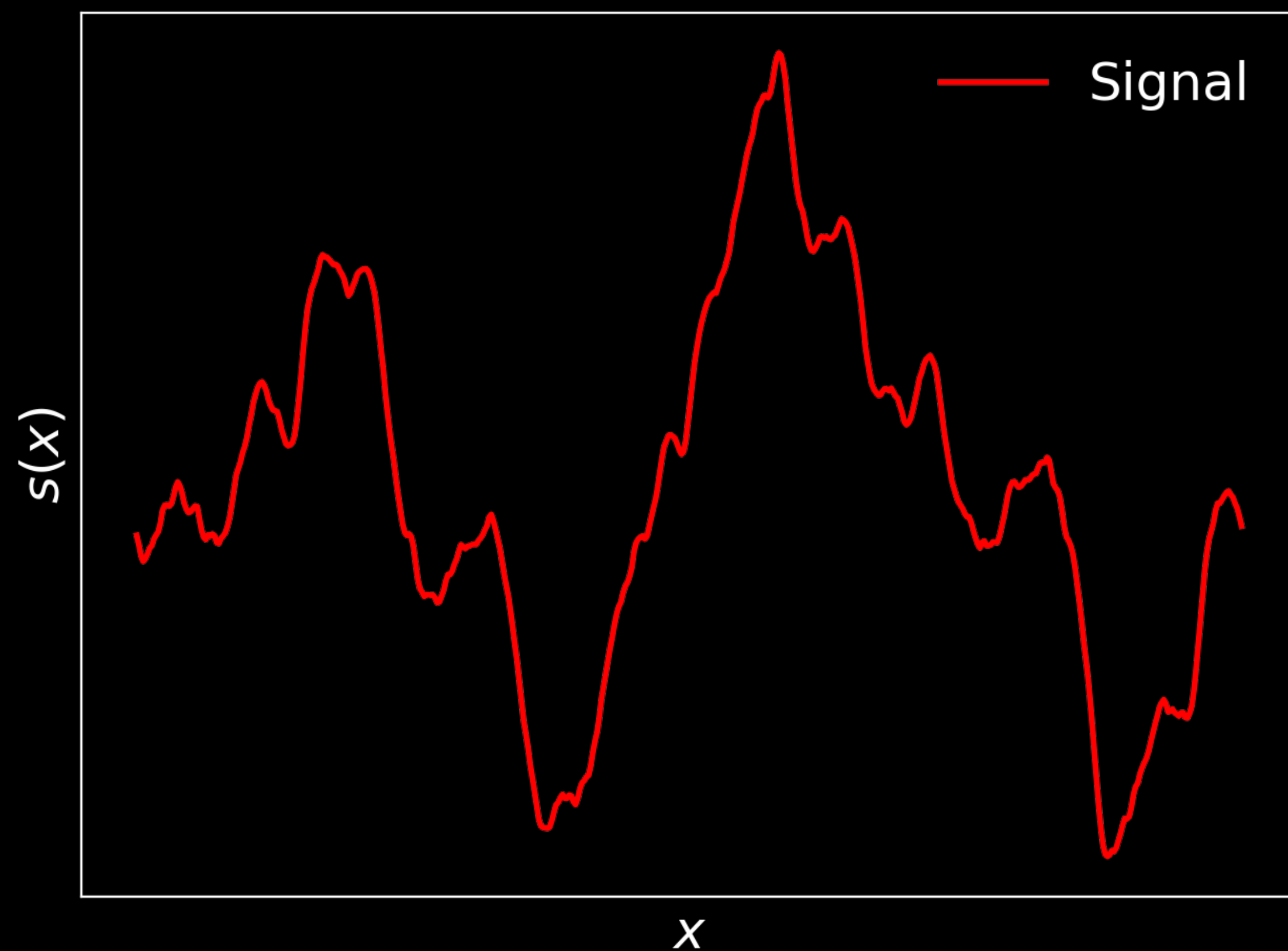


eROSITA
LMC SN 1987A
TM1 dataset

Imaging with IFT

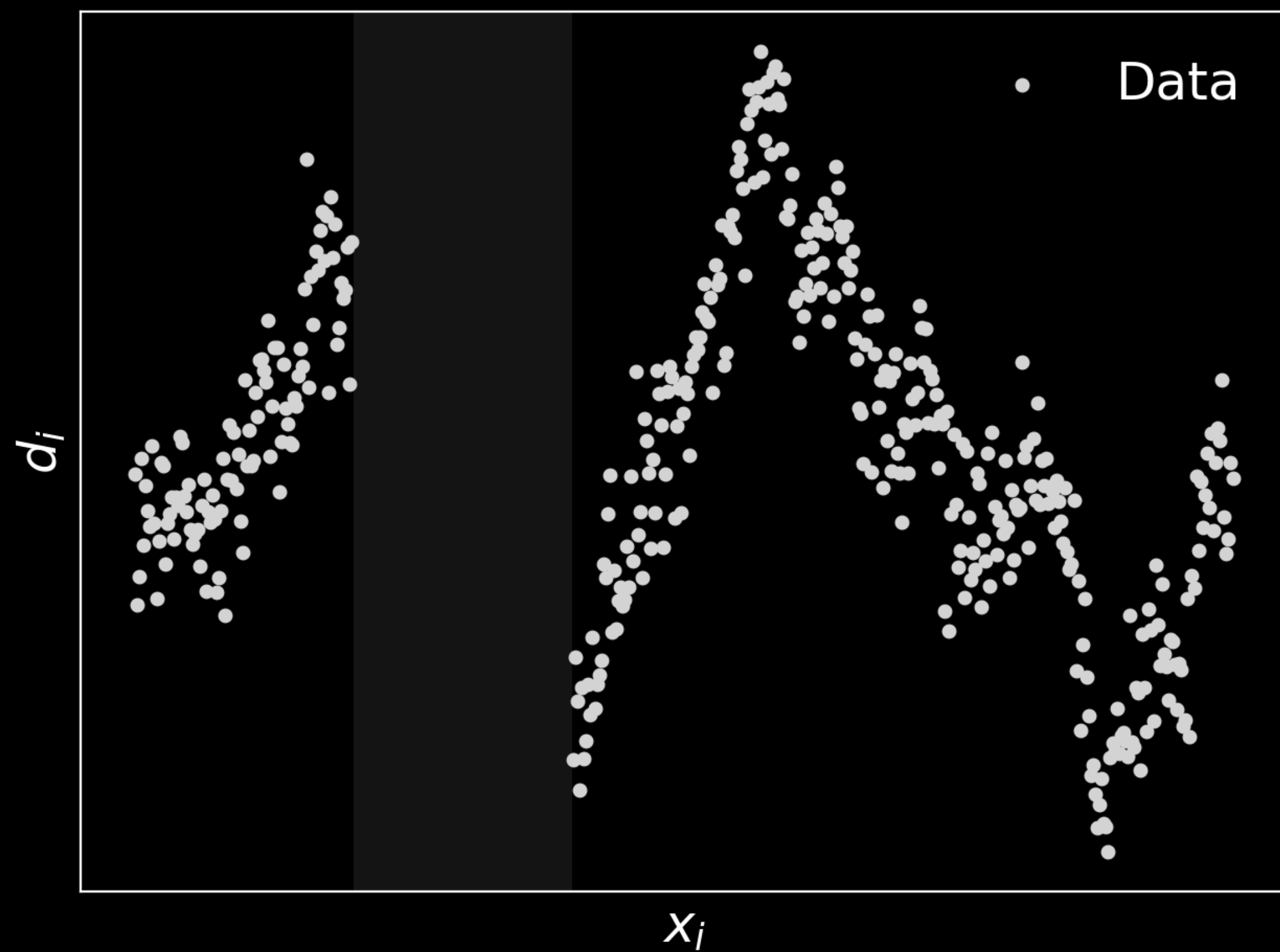
Information field theory

Toy model



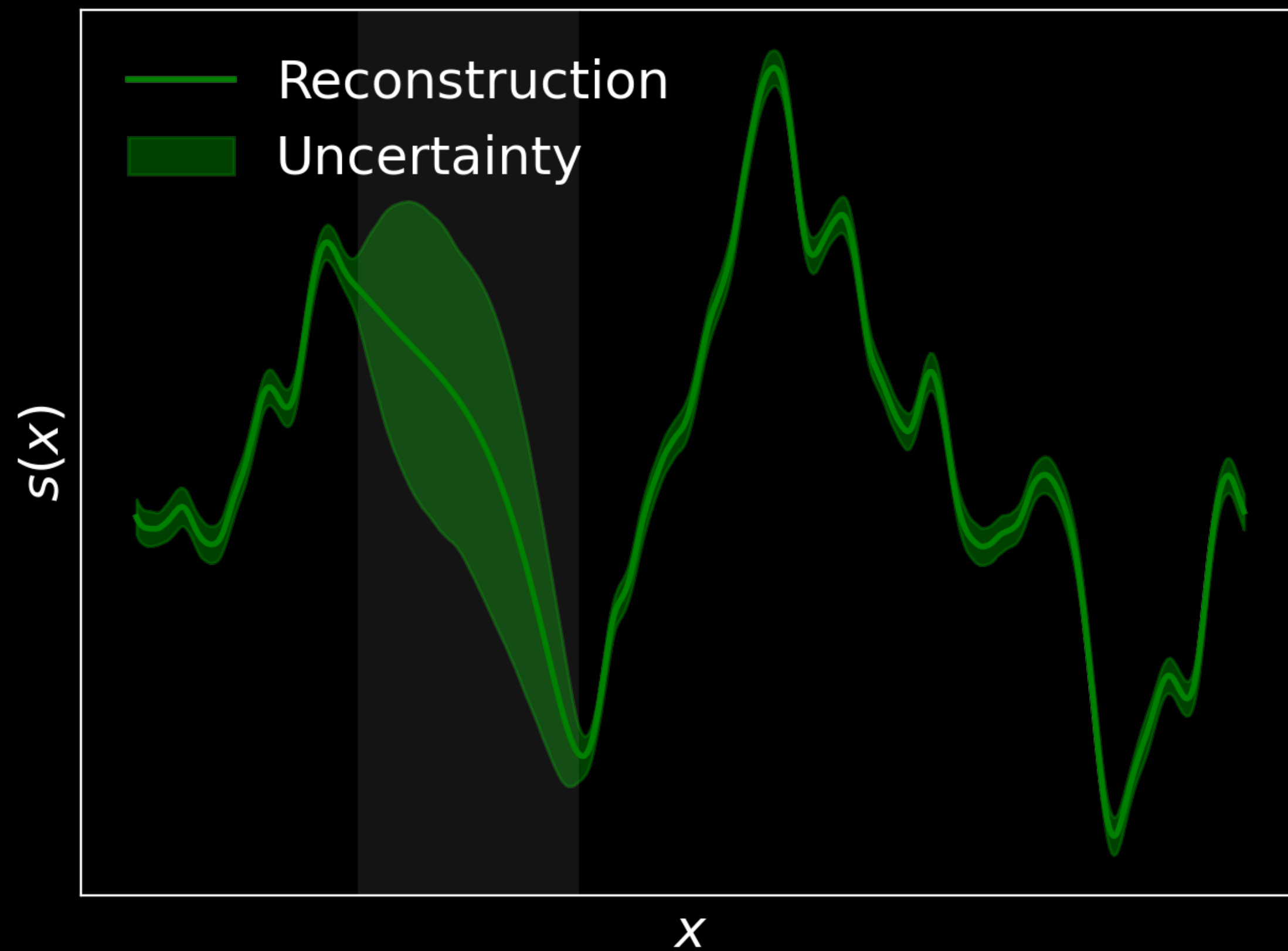
Information field theory

Toy model



Information field theory

Toy model



Information field theory

Bayes' Theorem

$$P(s \mid d) =$$

Information field theory

Bayes' Theorem

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

Information field theory

Bayes' Theorem

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

Information field theory

Bayes' Theorem

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

The prior

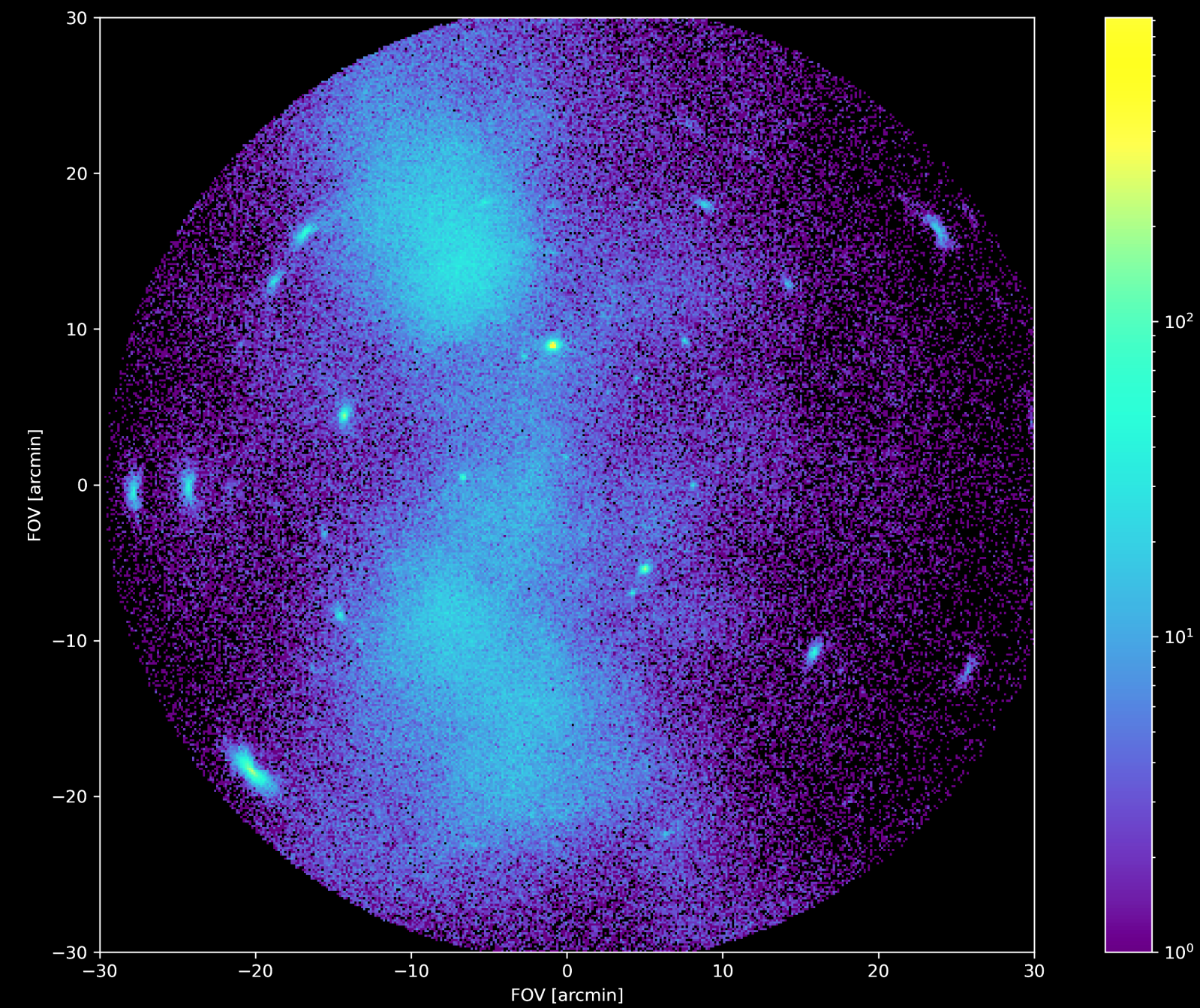
$$P(s | d) = \frac{P(d | s) P(s)}{P(d)}$$

Information field theory

Modeling data

Information field theory

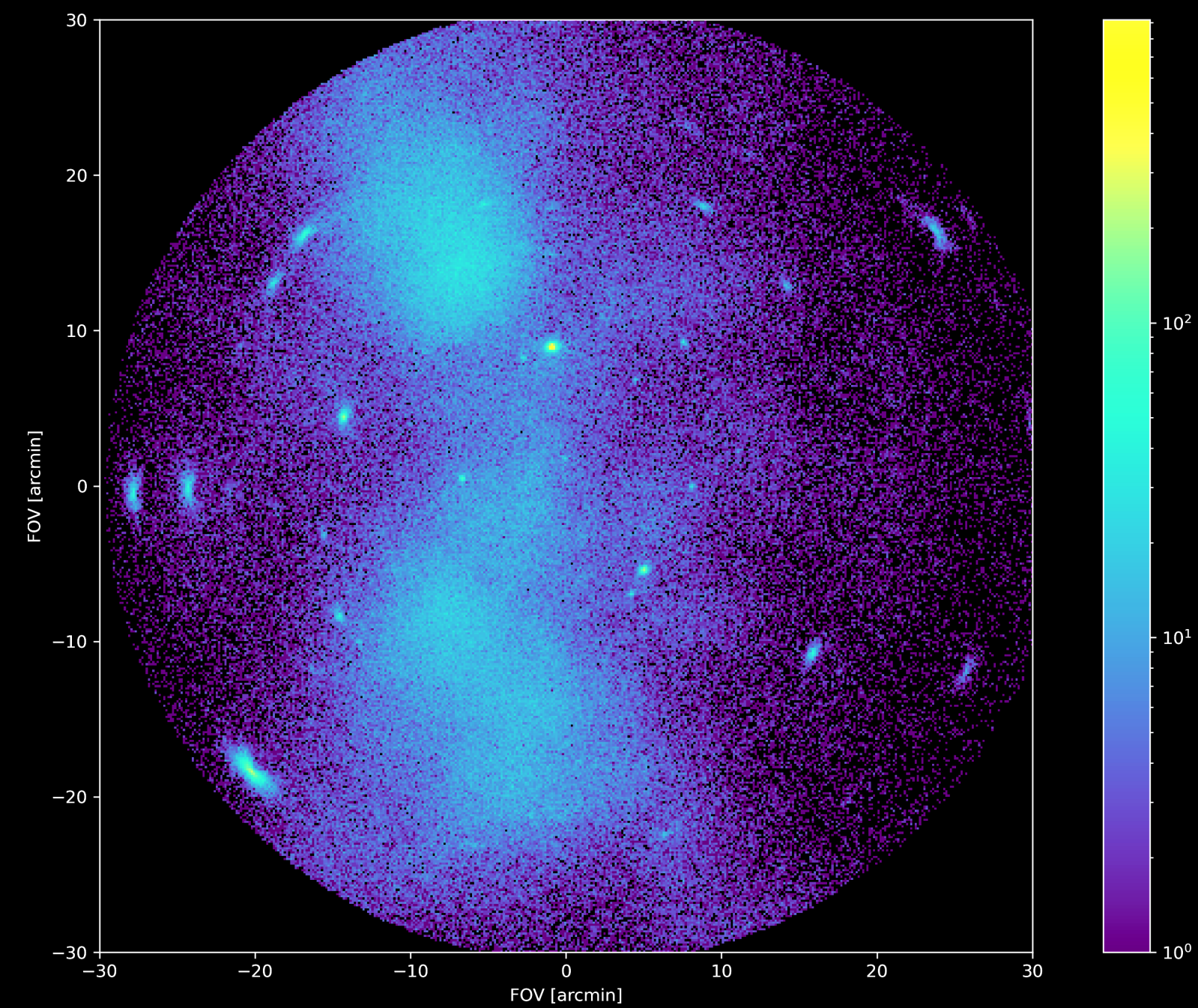
Modeling data



Data

Information field theory

Modeling data

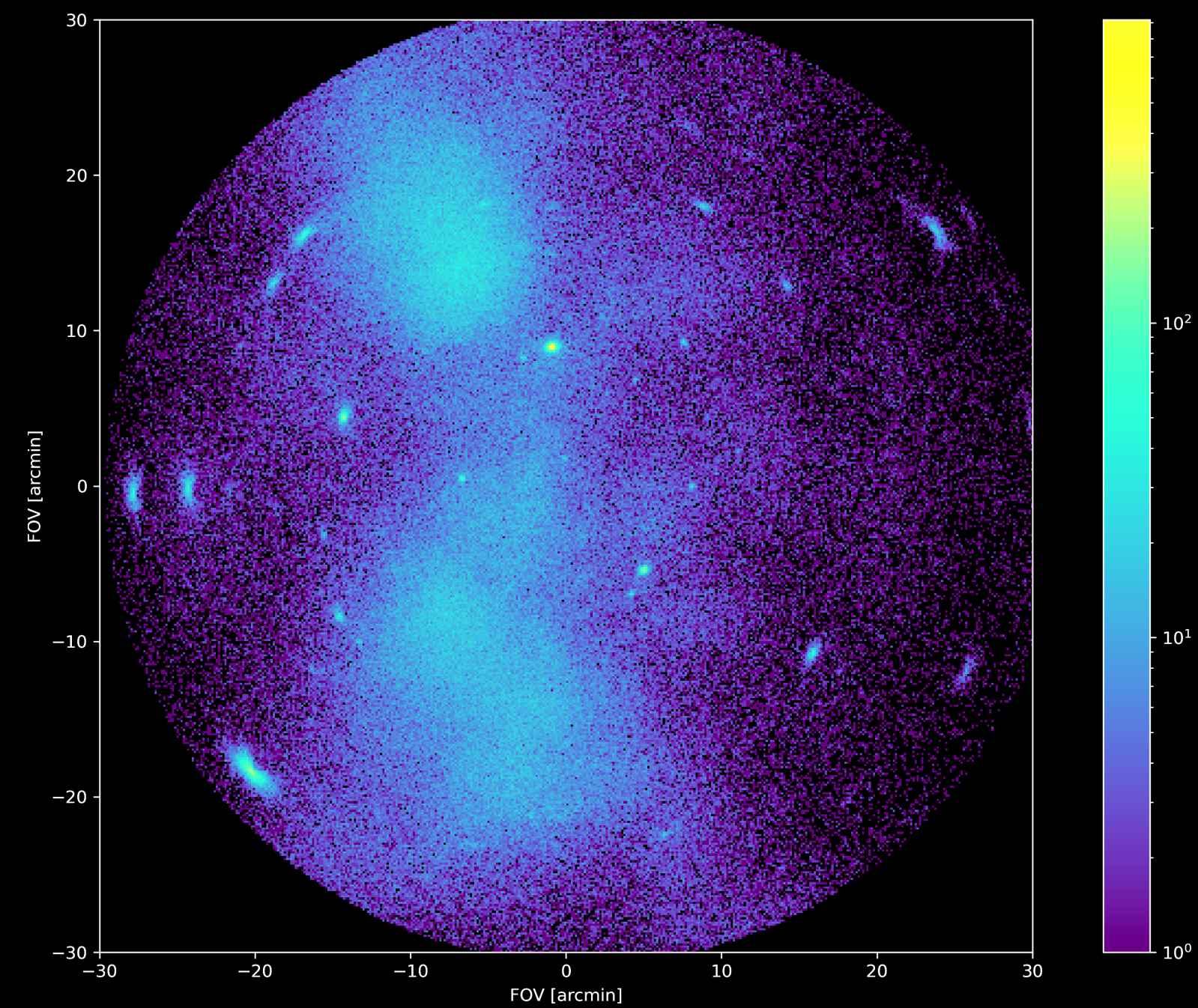


Data

- Finite-dimensional

Information field theory

Modeling data

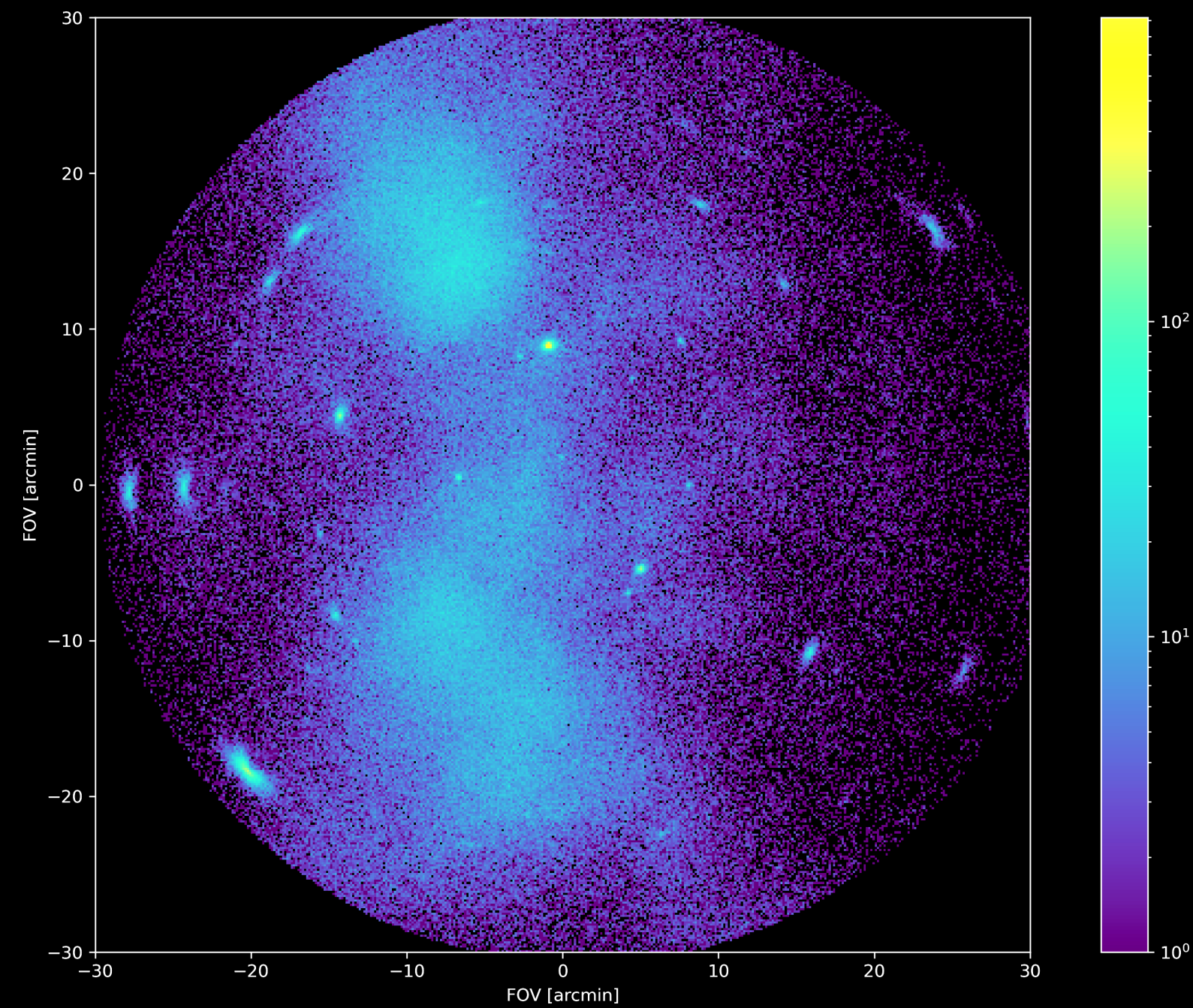


Data

- **Finite-dimensional**
- **Noisy**

Information field theory

Modeling data

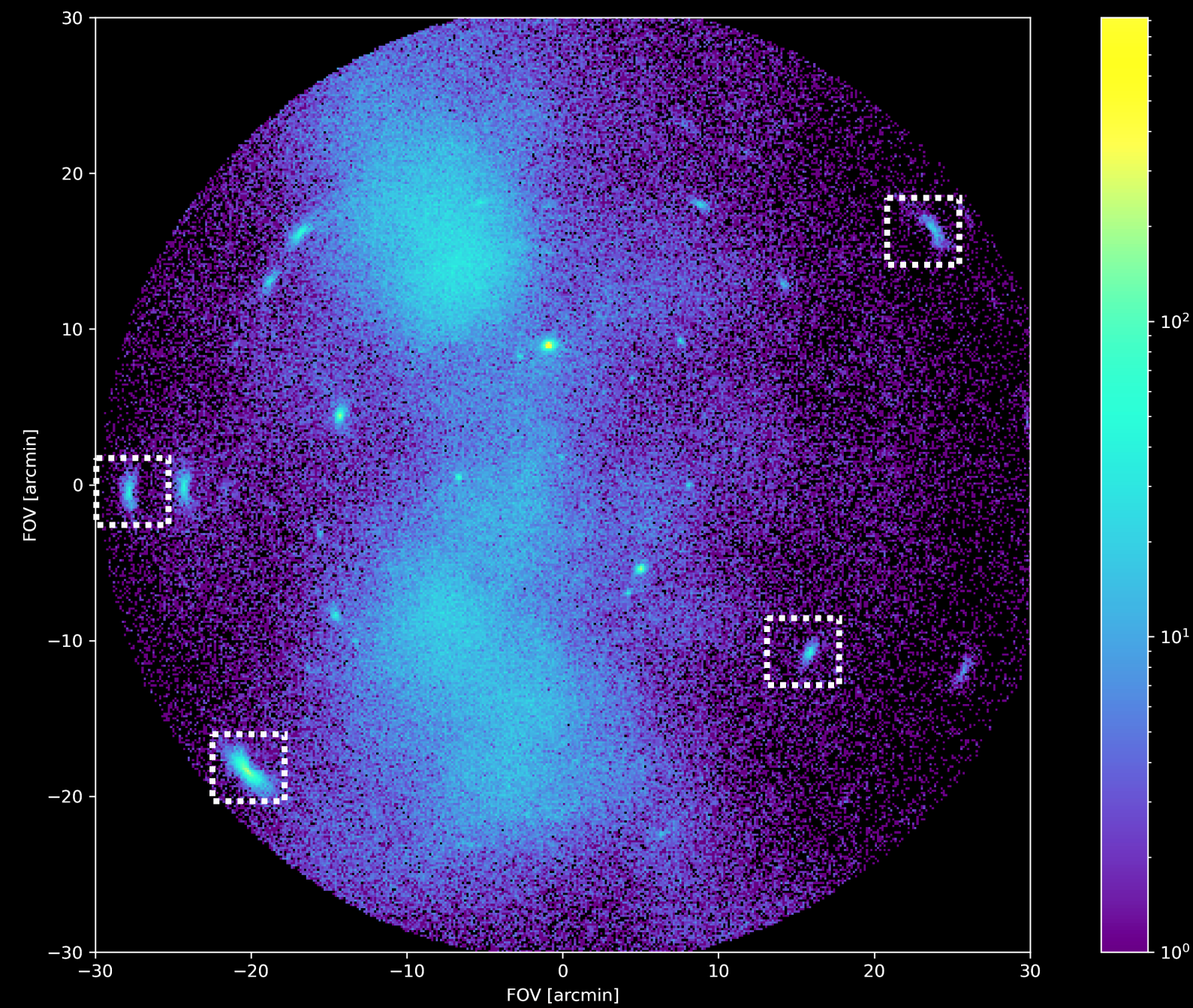


Data

- **Finite-dimensional**
- **Noisy**
- **Contains non-invertible instrumental artifacts**

Information field theory

Modeling data

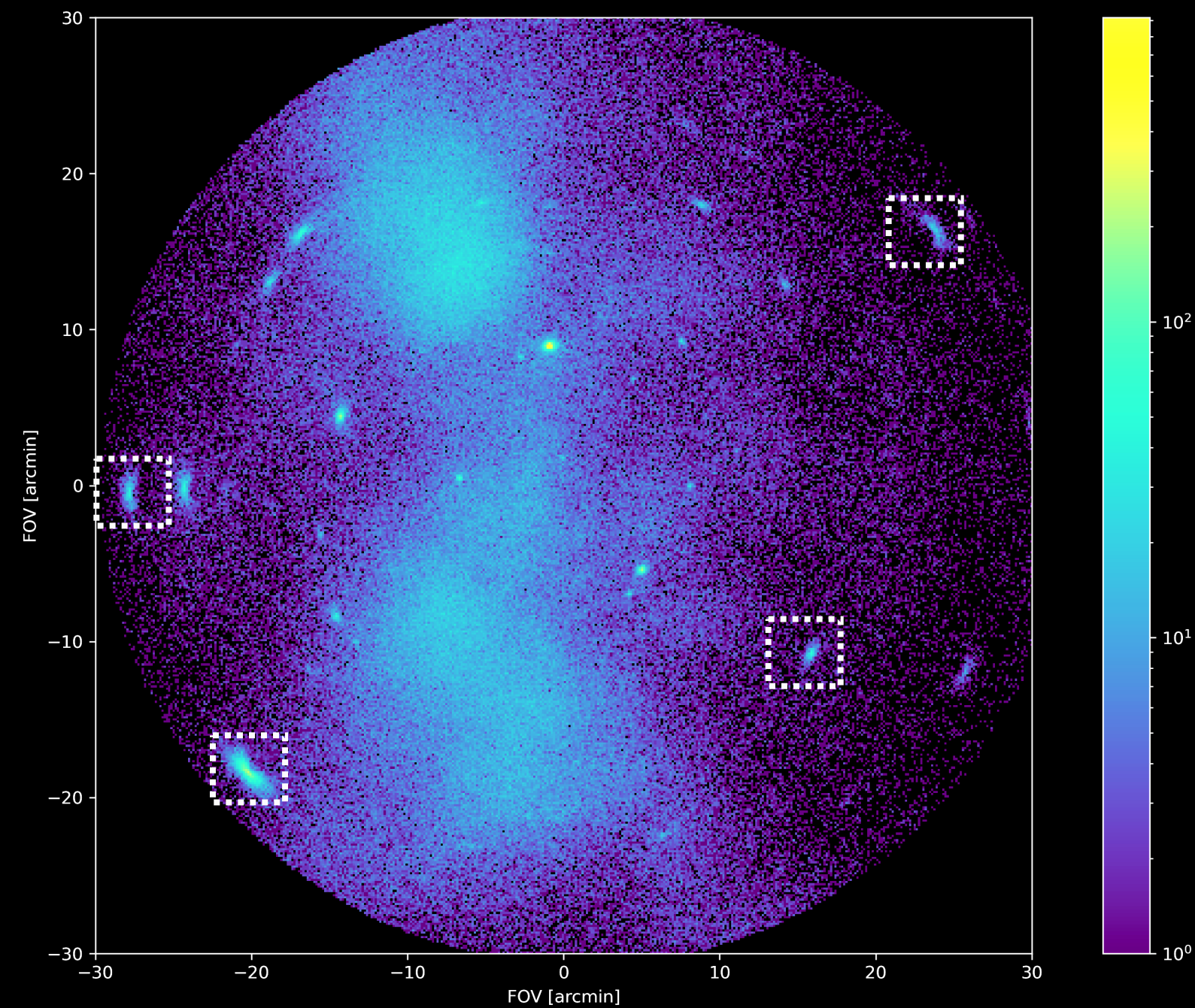


Data

- **Finite-dimensional**
- **Noisy**
- **Contains non-invertible instrumental artifacts**
 - **PSF**
 - **Pile-up**
 - **...**

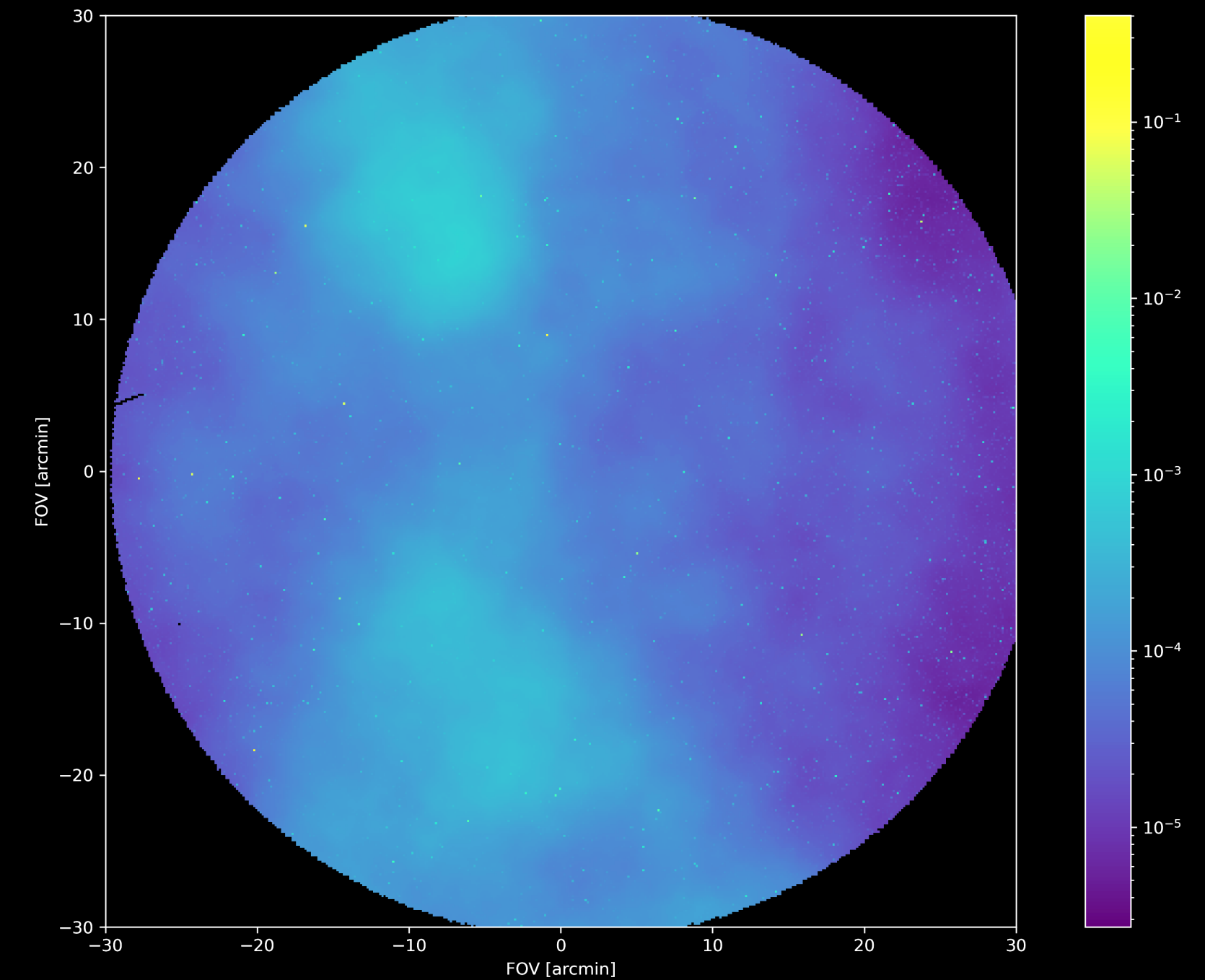
Information field theory

Modeling data



Data

- Finite-dimensional
- Noisy
- Contains non-invertible instrumental artifacts
 - PSF
 - Pile-up
 - ...



Fields

- Infinite dimensional (continuous)
- Variable in space, time, energy, ...
- Don't know about the instrument!

A sky brightness prior

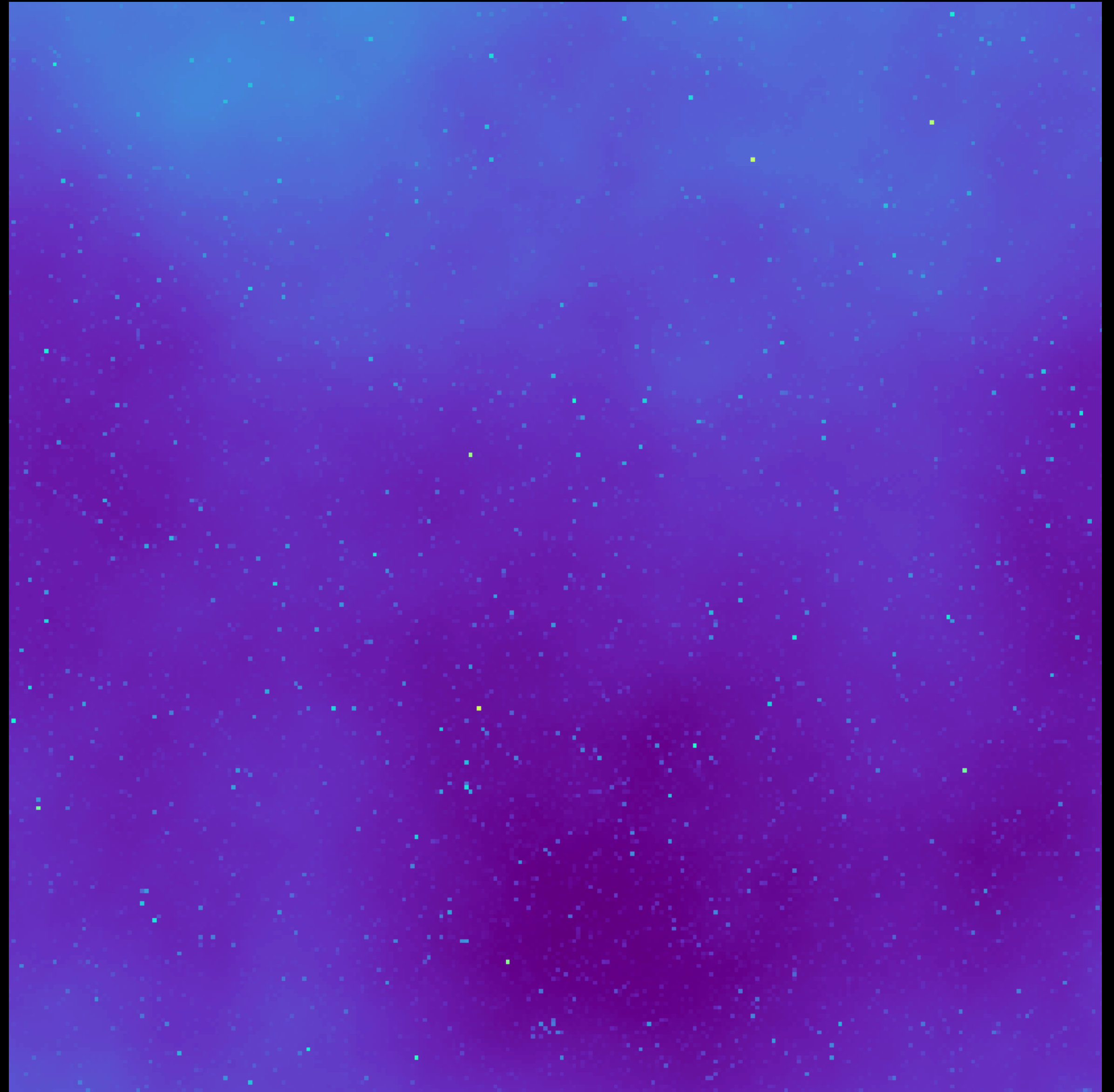
The prior

Sky

The prior

Sky

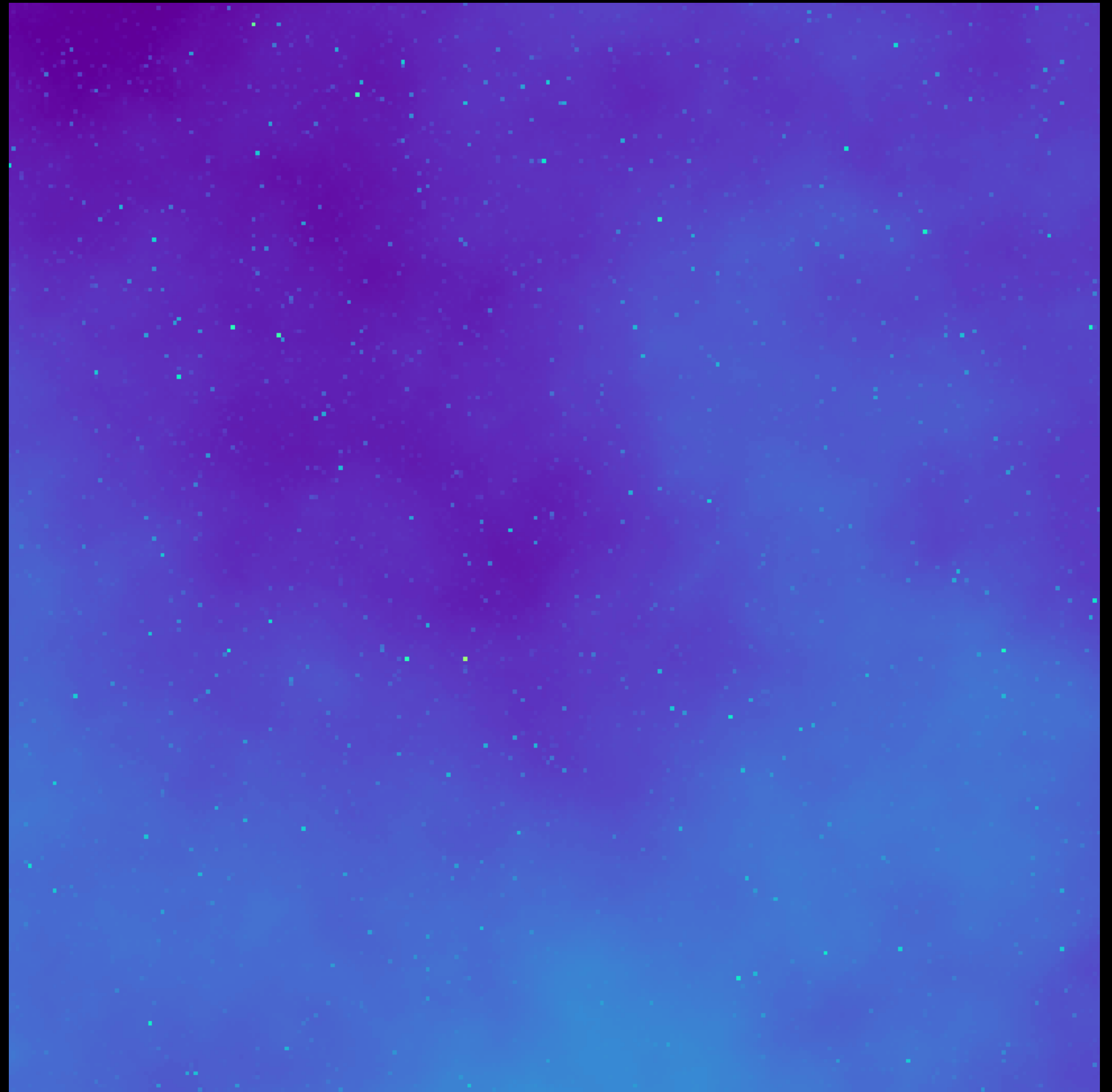
$$P(s)$$



The prior

Sky

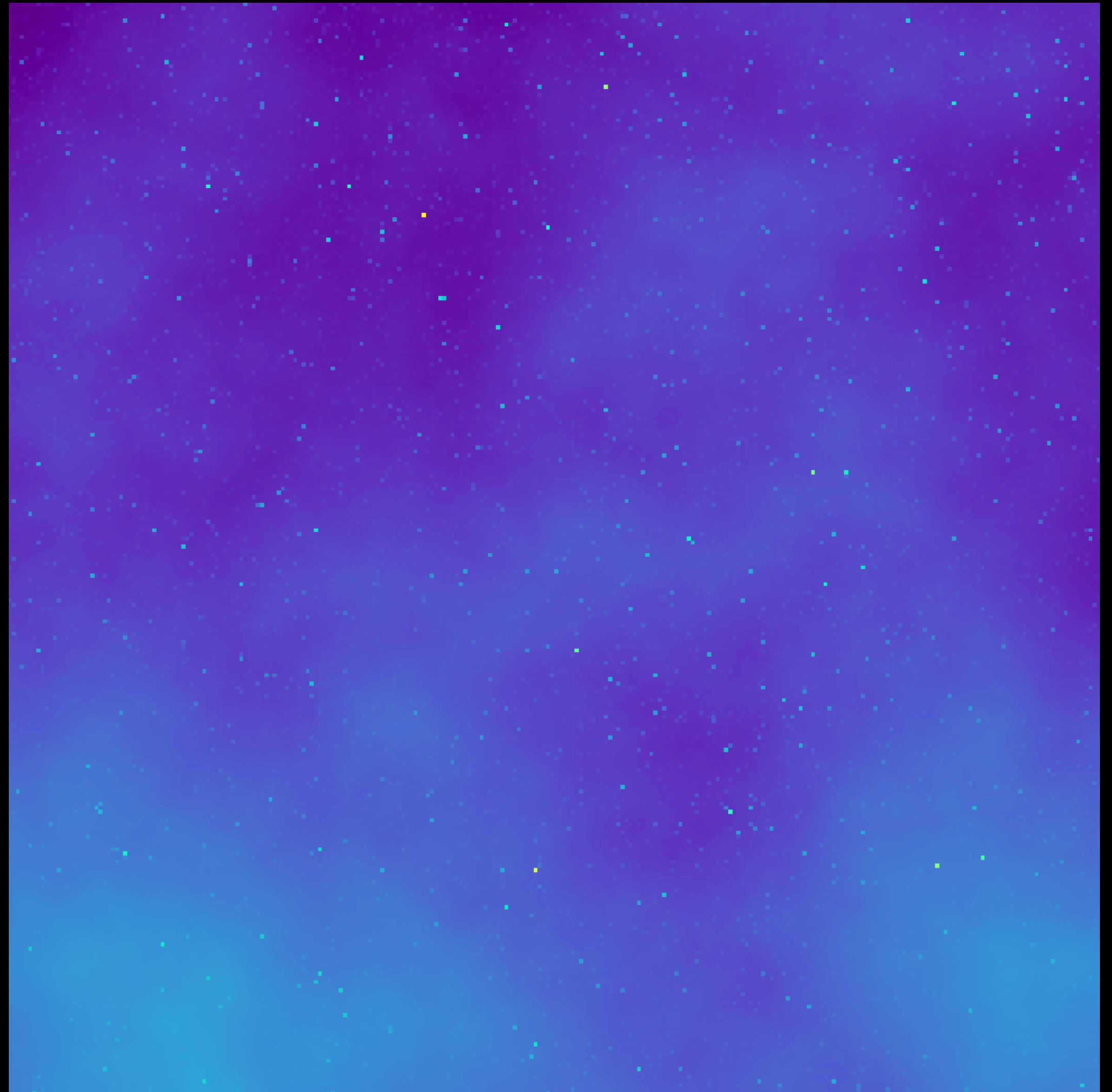
$$P(s)$$



The prior

Sky

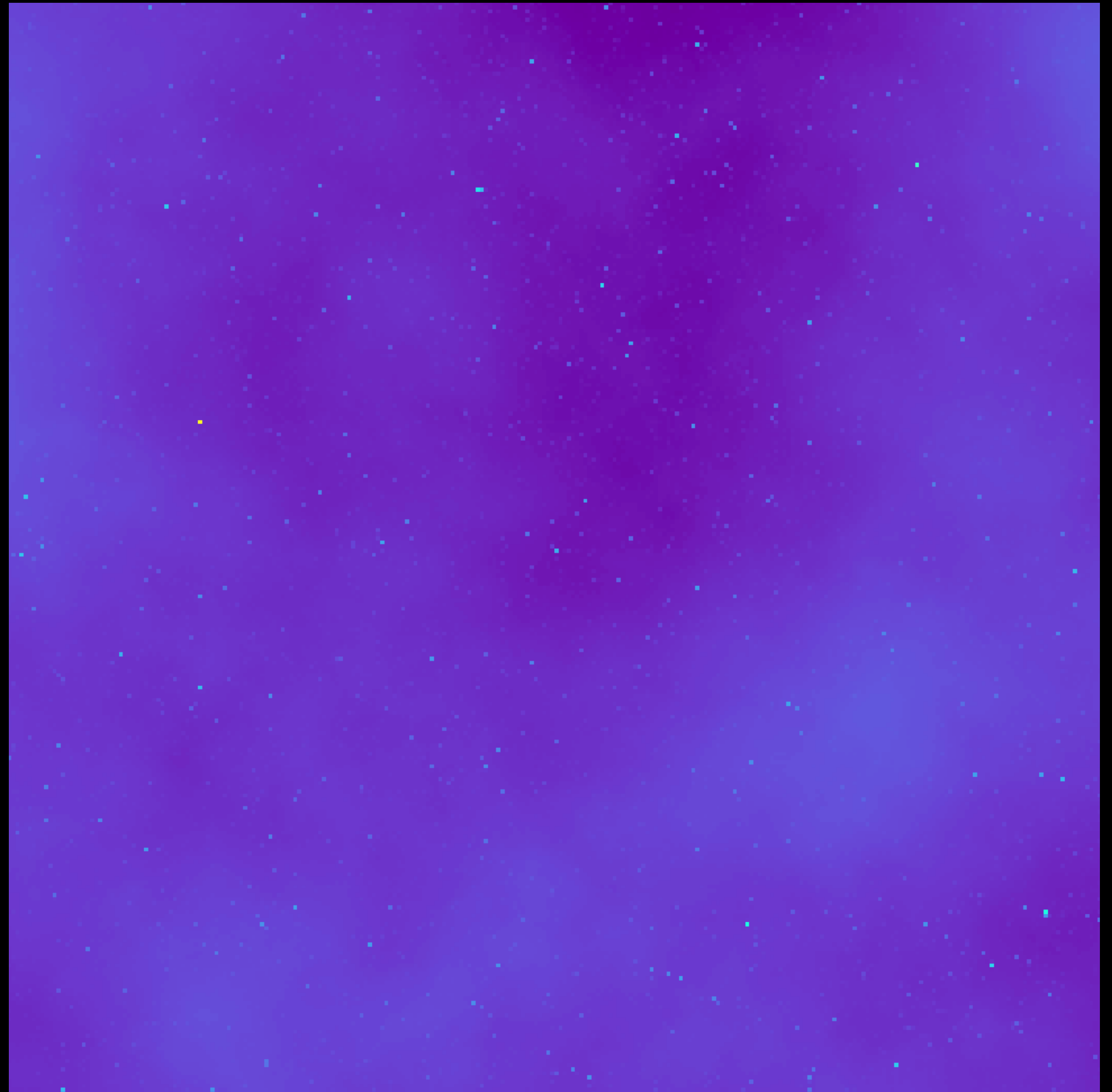
$$P(s)$$



The prior

Sky

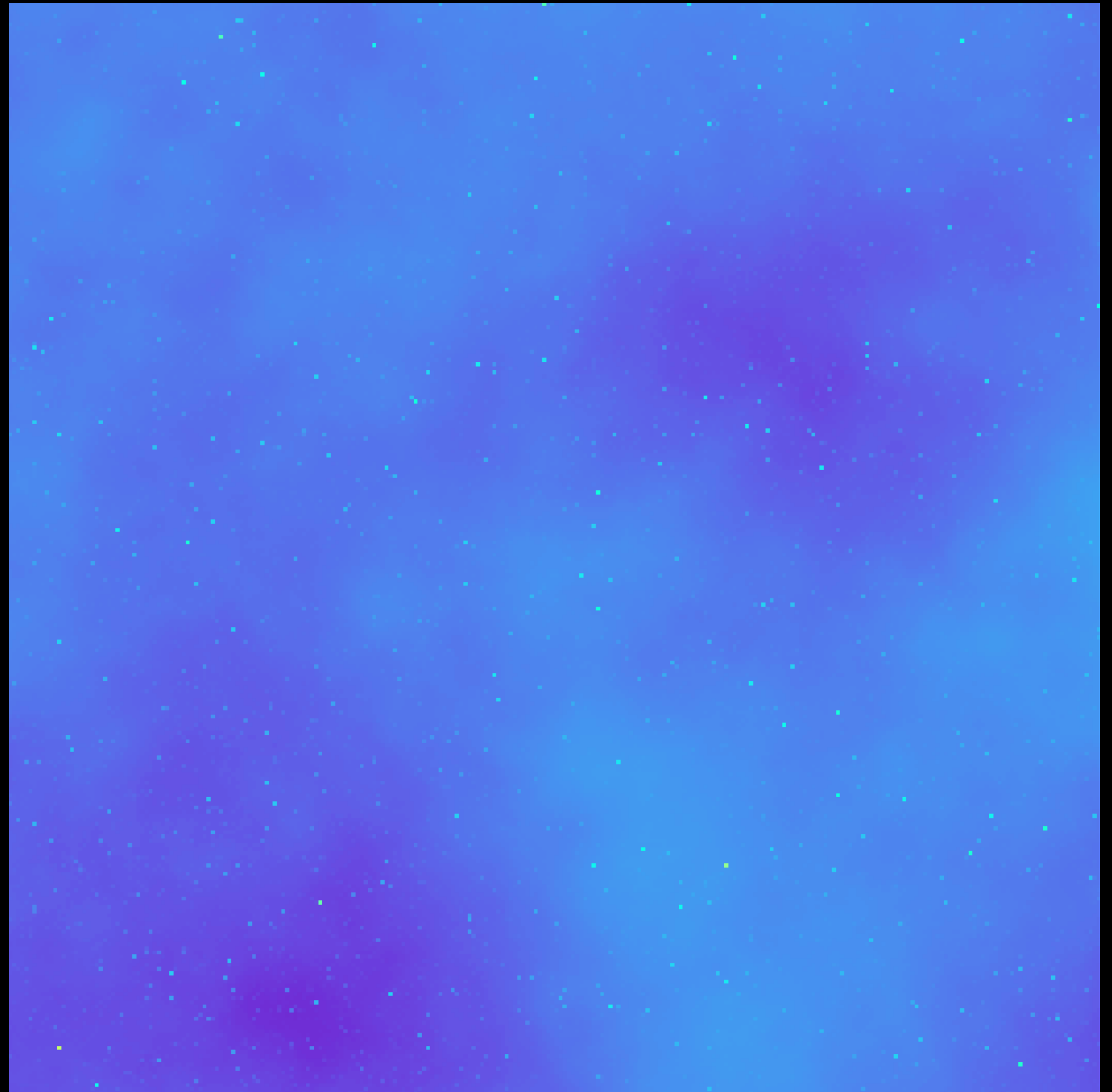
$$P(s)$$



The prior

Sky

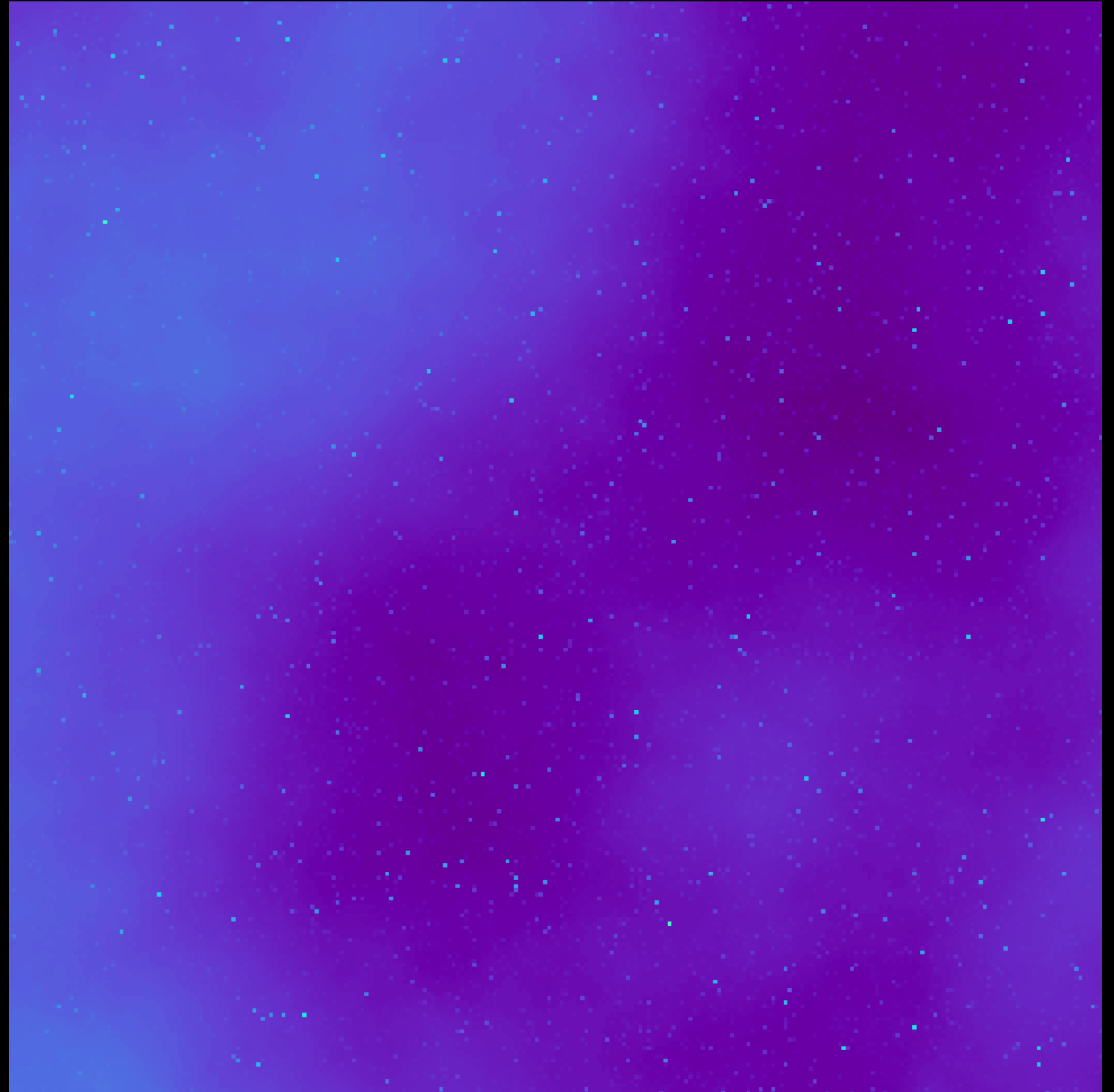
$$P(s)$$



The prior

Sky

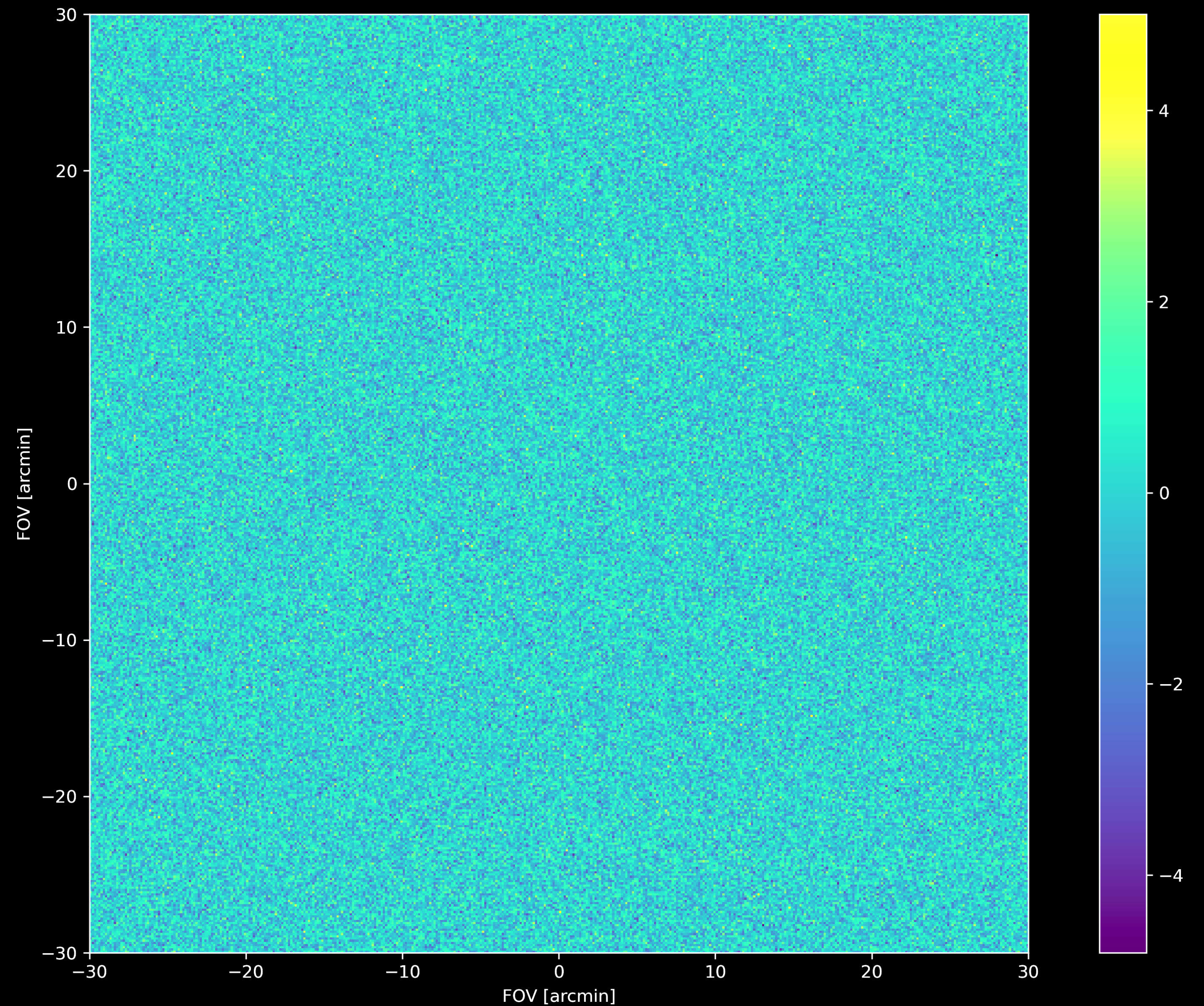
$$P(s)$$



The prior

Generative model

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

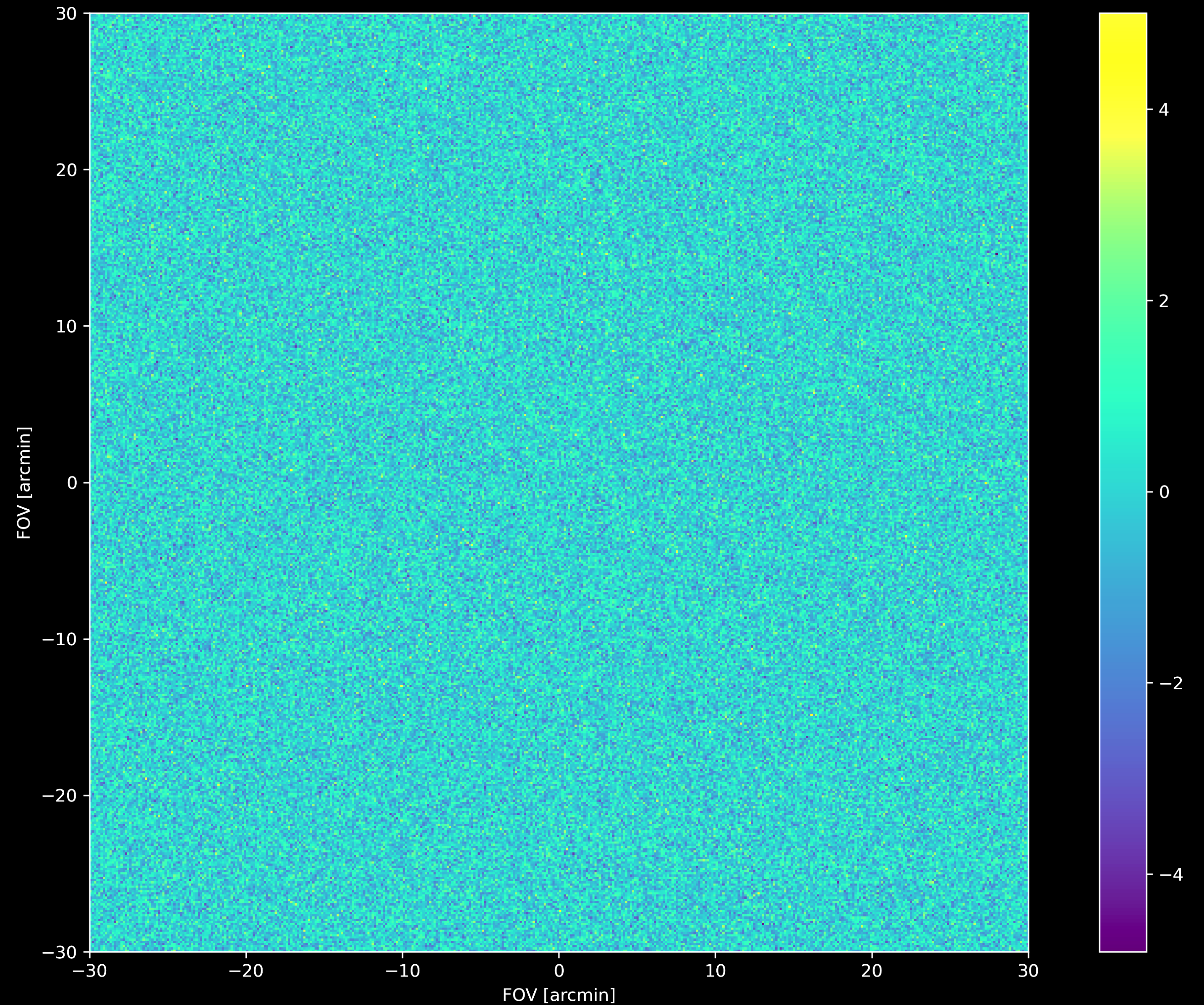


Latent space prior distribution

The prior

Generative model

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

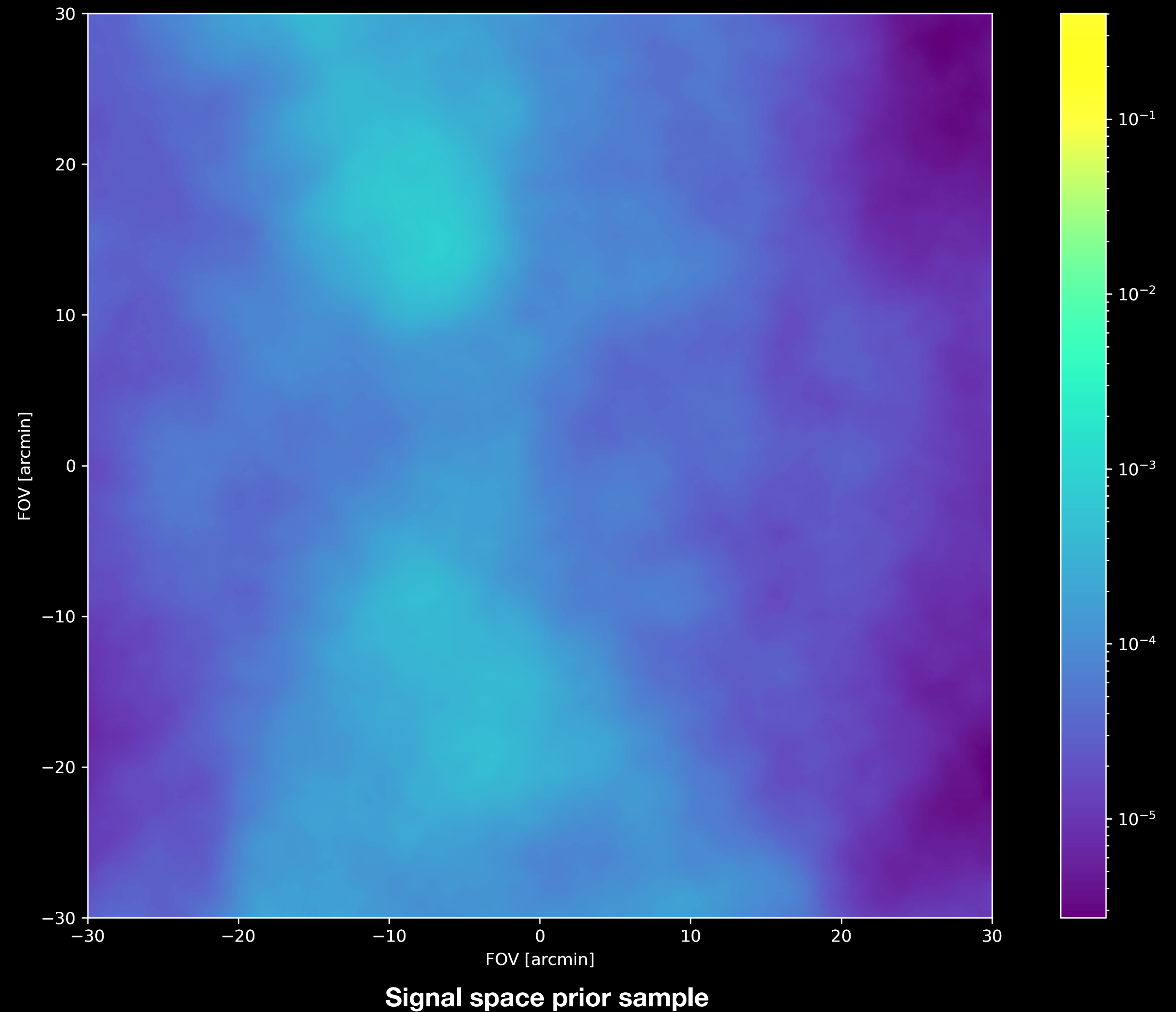


Latent space prior distribution

The prior

Generative model

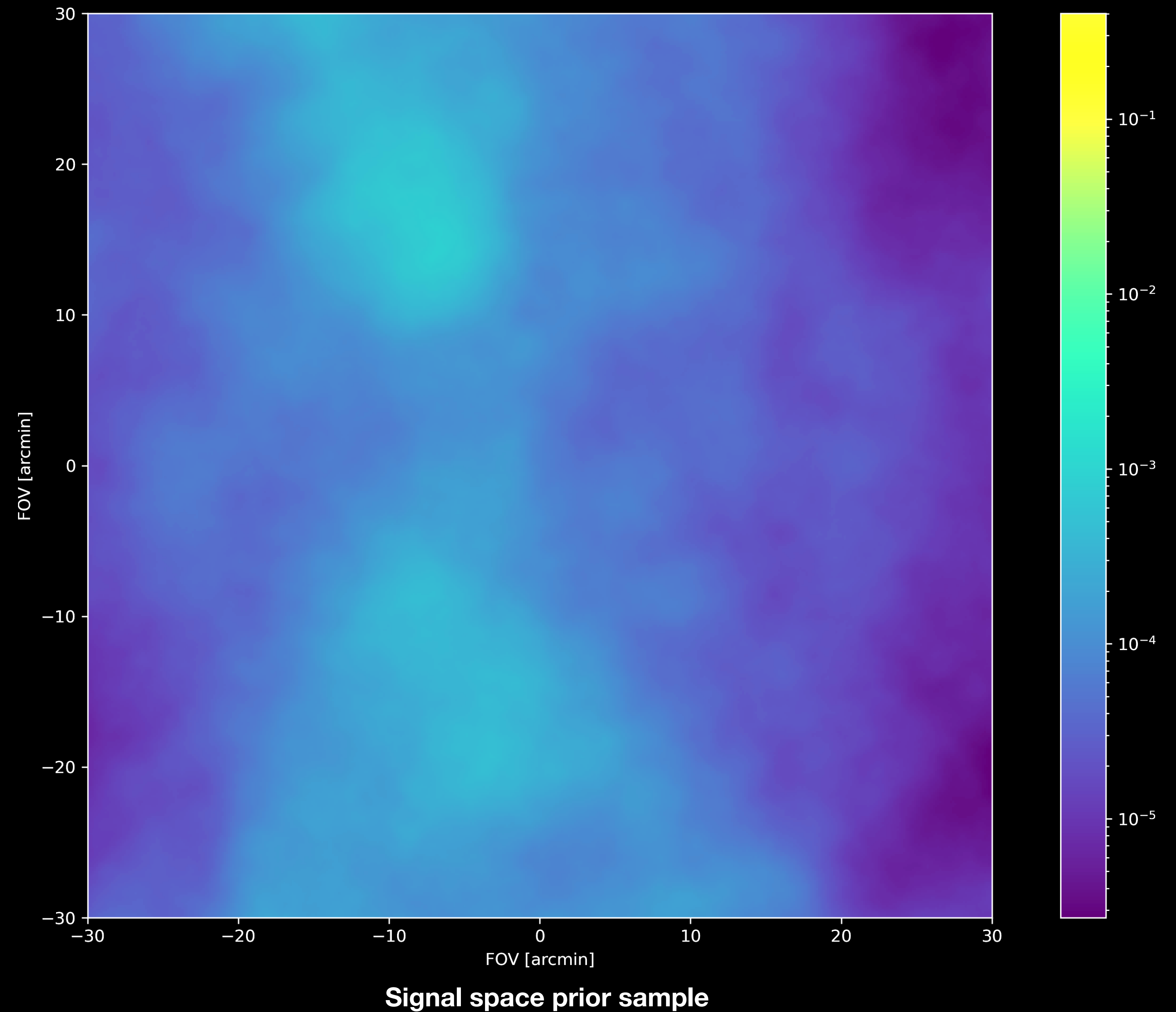
$$P(s) = \mathcal{N}(\mathbf{0}, \mathbb{I}) \left| \frac{\partial \xi}{\partial s} \right|$$



The prior

Generative model

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



The prior

Generative model (Gaussian process)

The prior

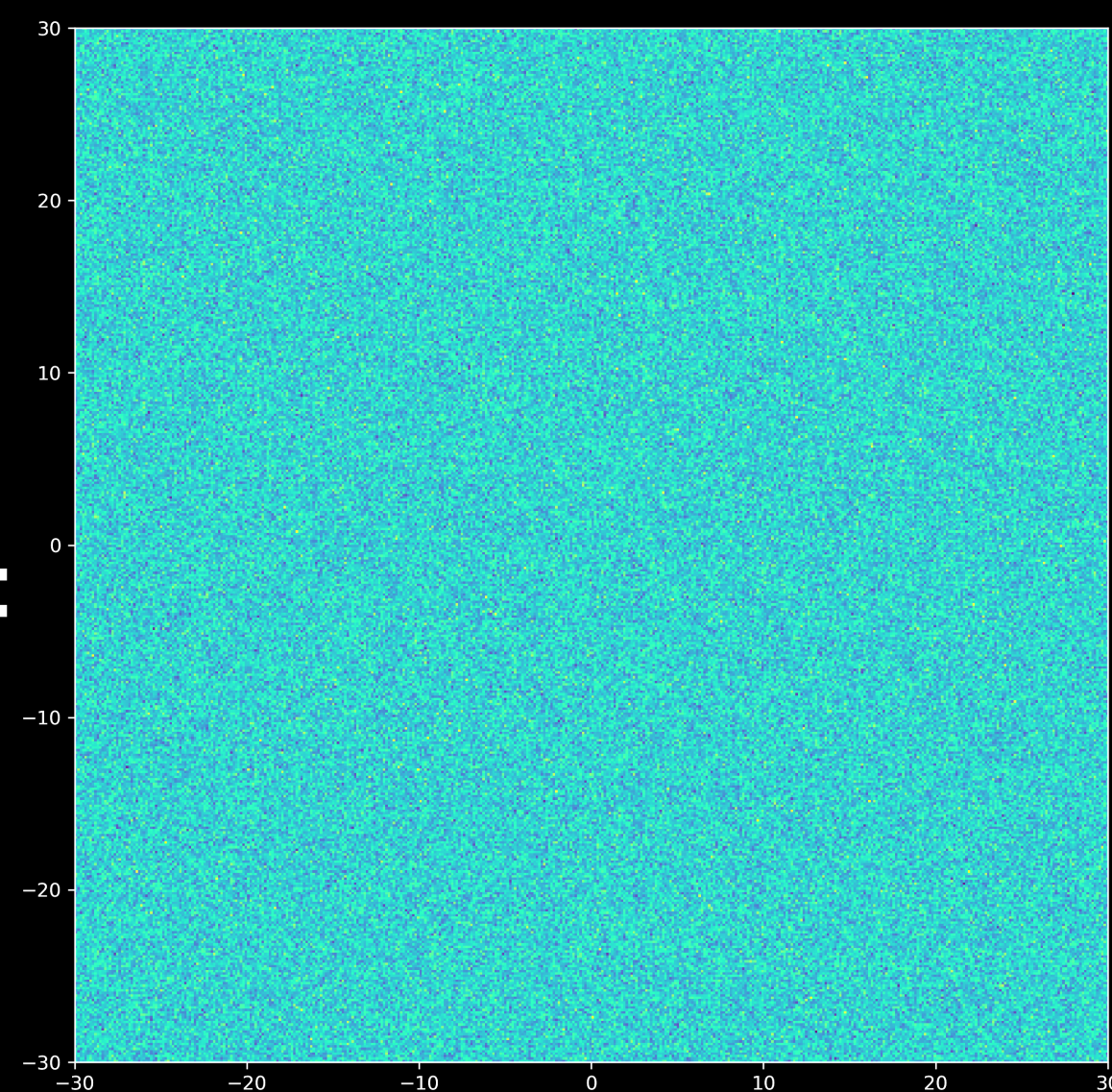
Generative model (Gaussian process)

$$P(s) =$$

The prior

Generative model (Gaussian process)

$P(s) =$

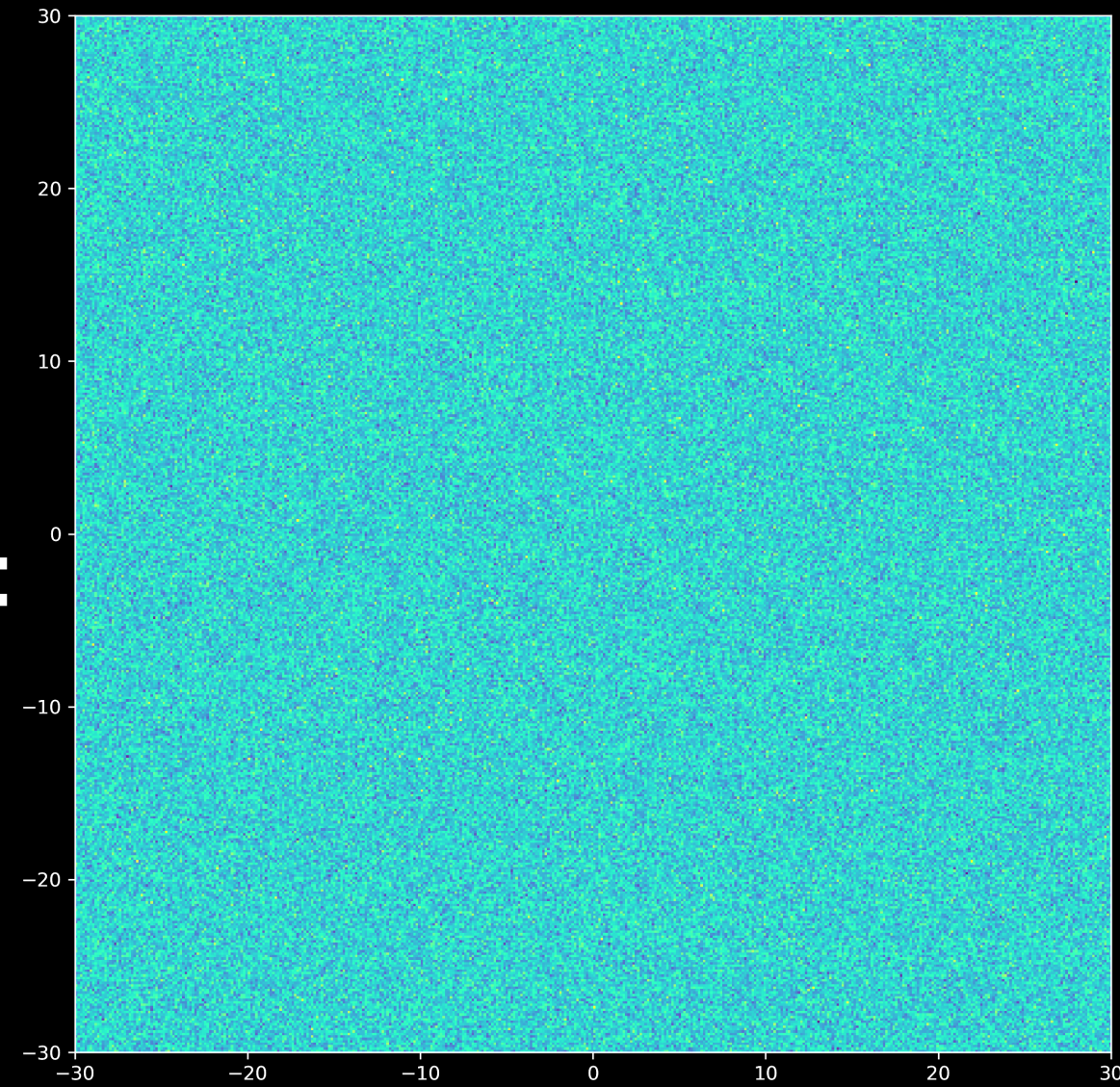


$$\mathcal{N}(\mathbf{0}, \mathbb{I})$$

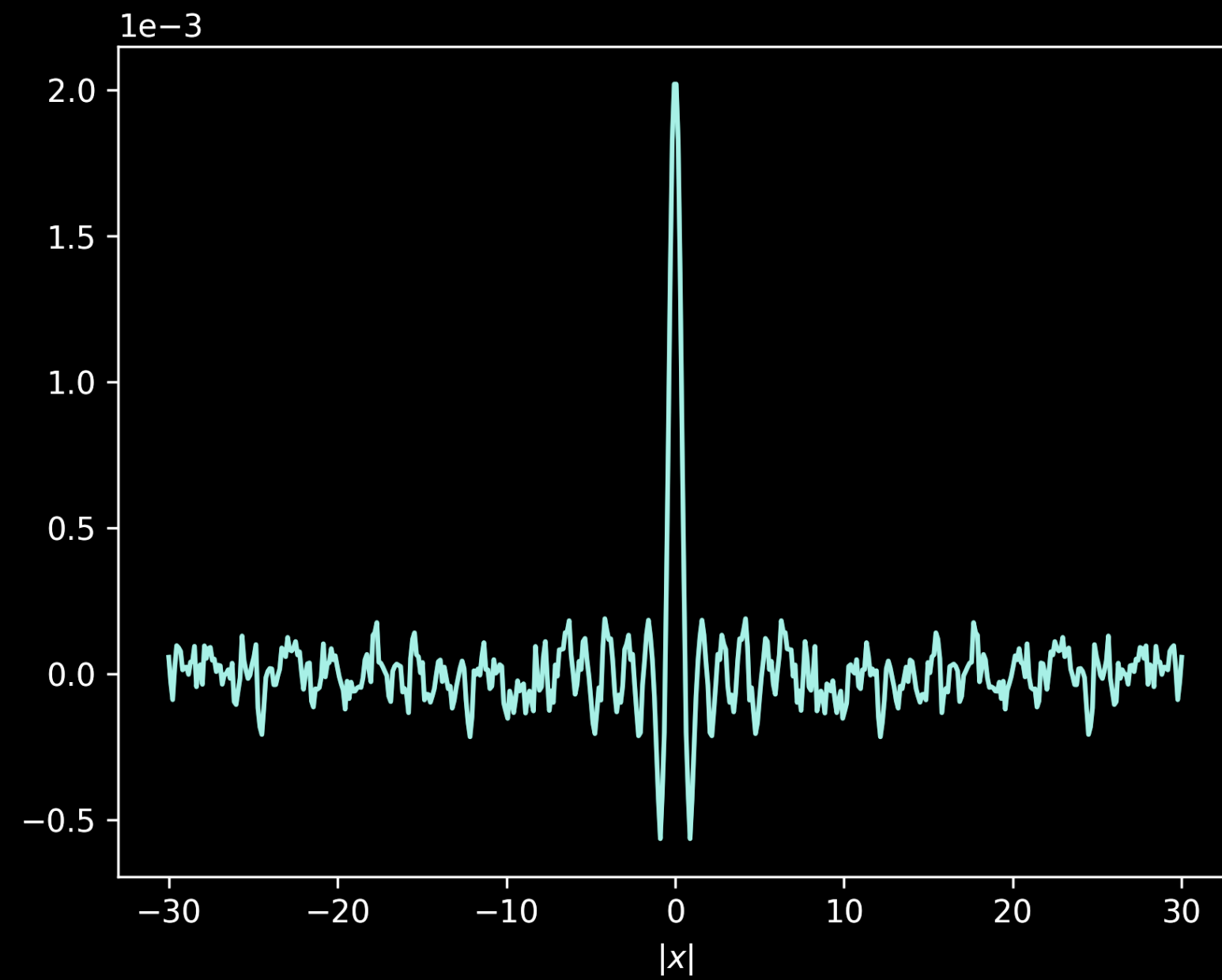
The prior

Generative model (Gaussian process)

$$P(s) =$$



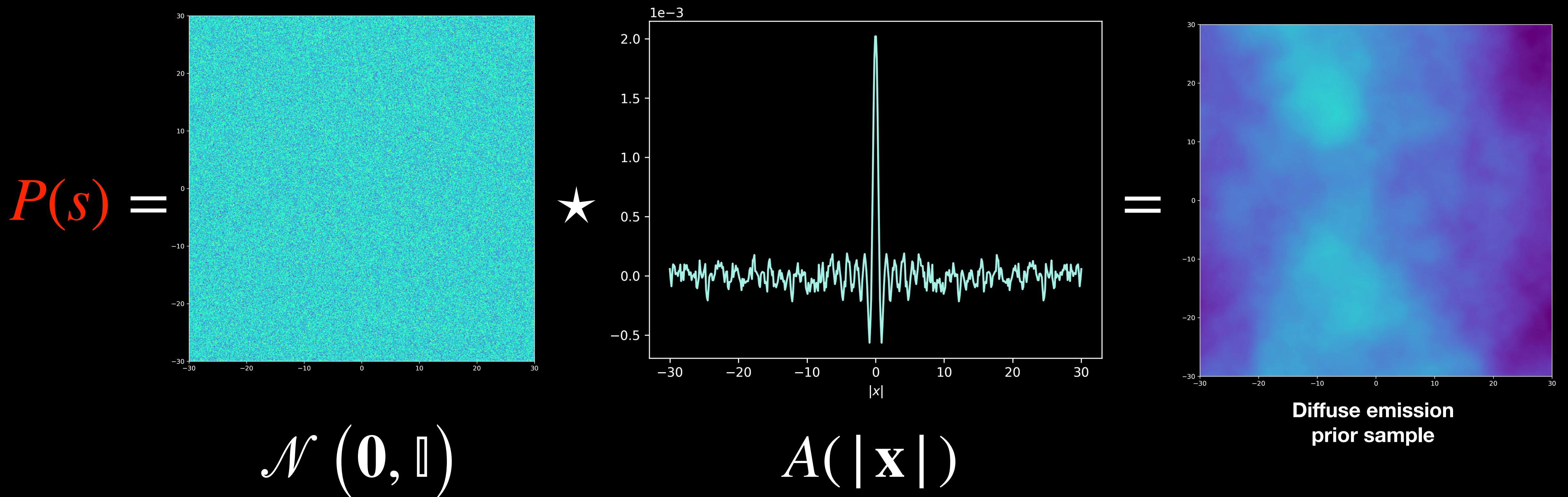
$$\mathcal{N}(\mathbf{0}, \mathbb{I})$$



$$A(|\mathbf{x}|)$$

The prior

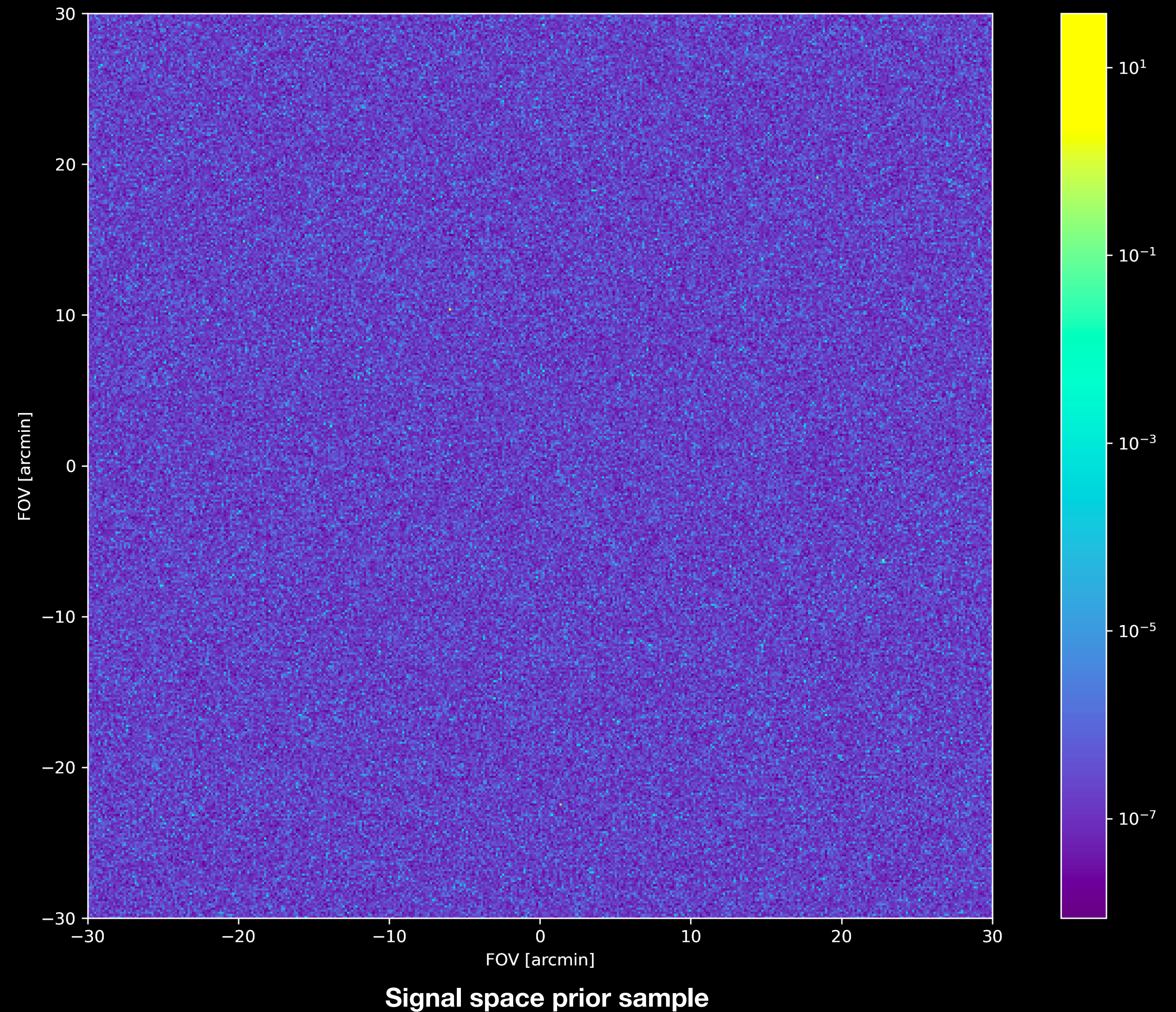
Generative model (Gaussian process)



The prior

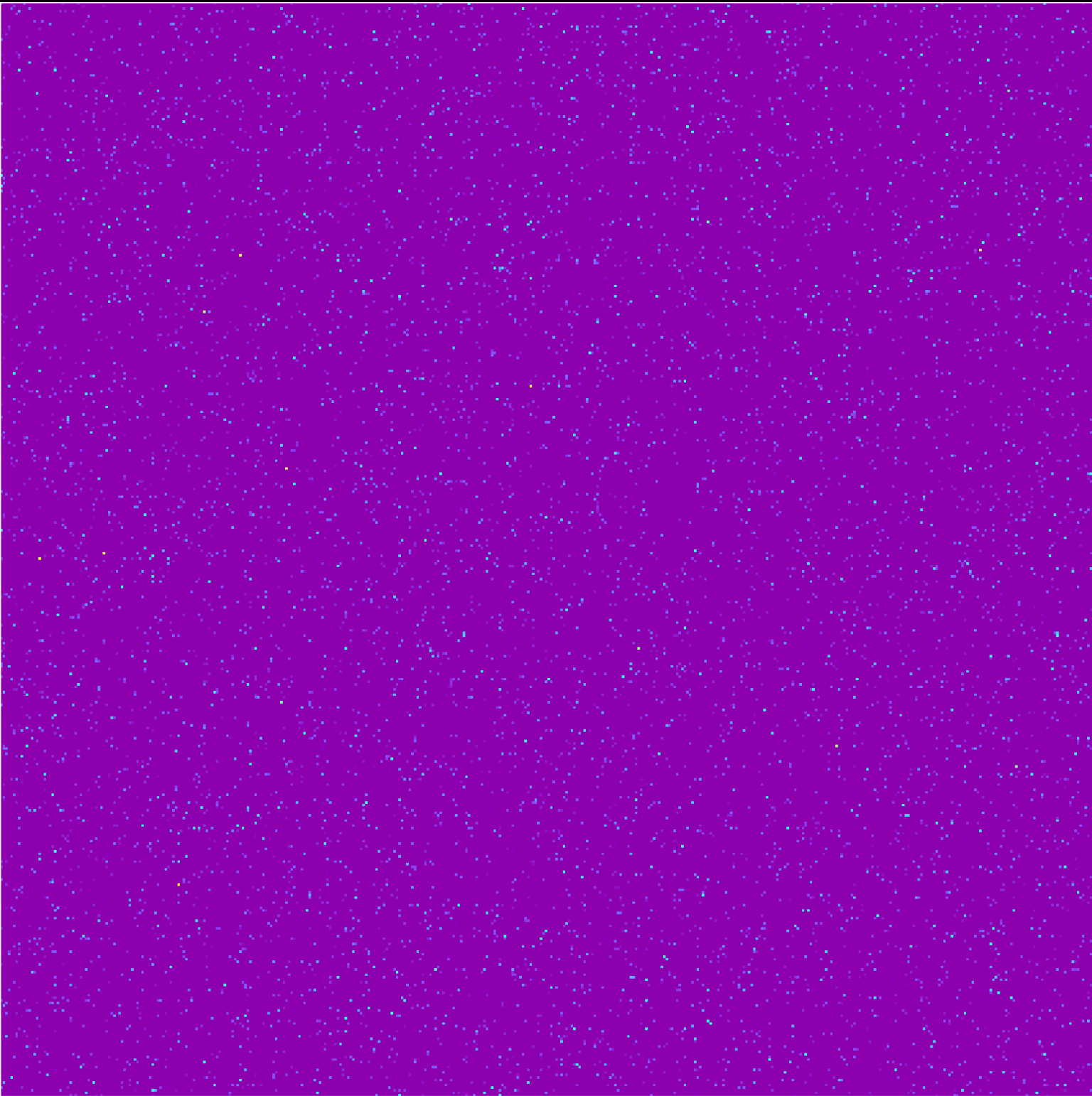
Generative model

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



The prior

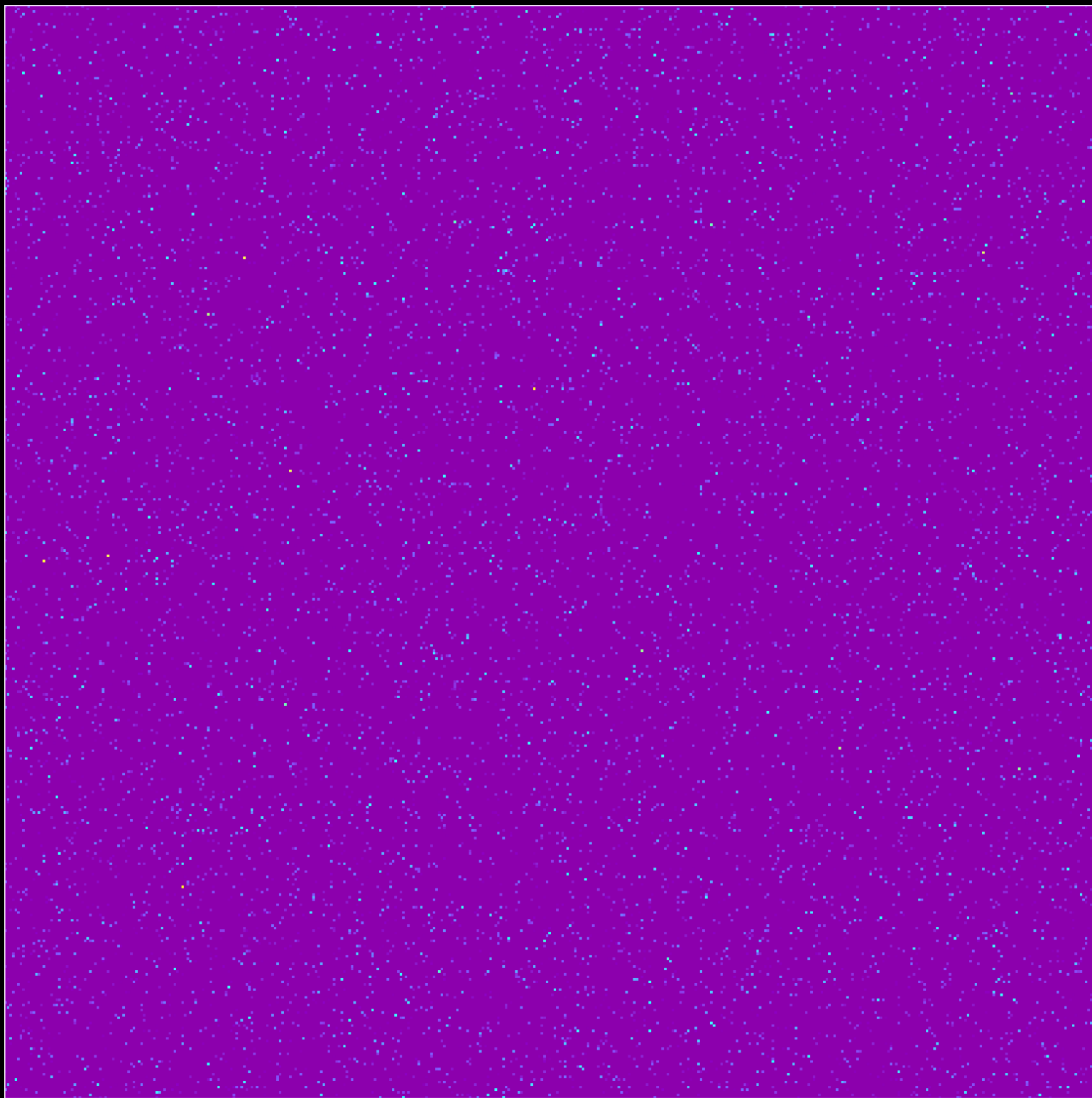
Sky



Point sources

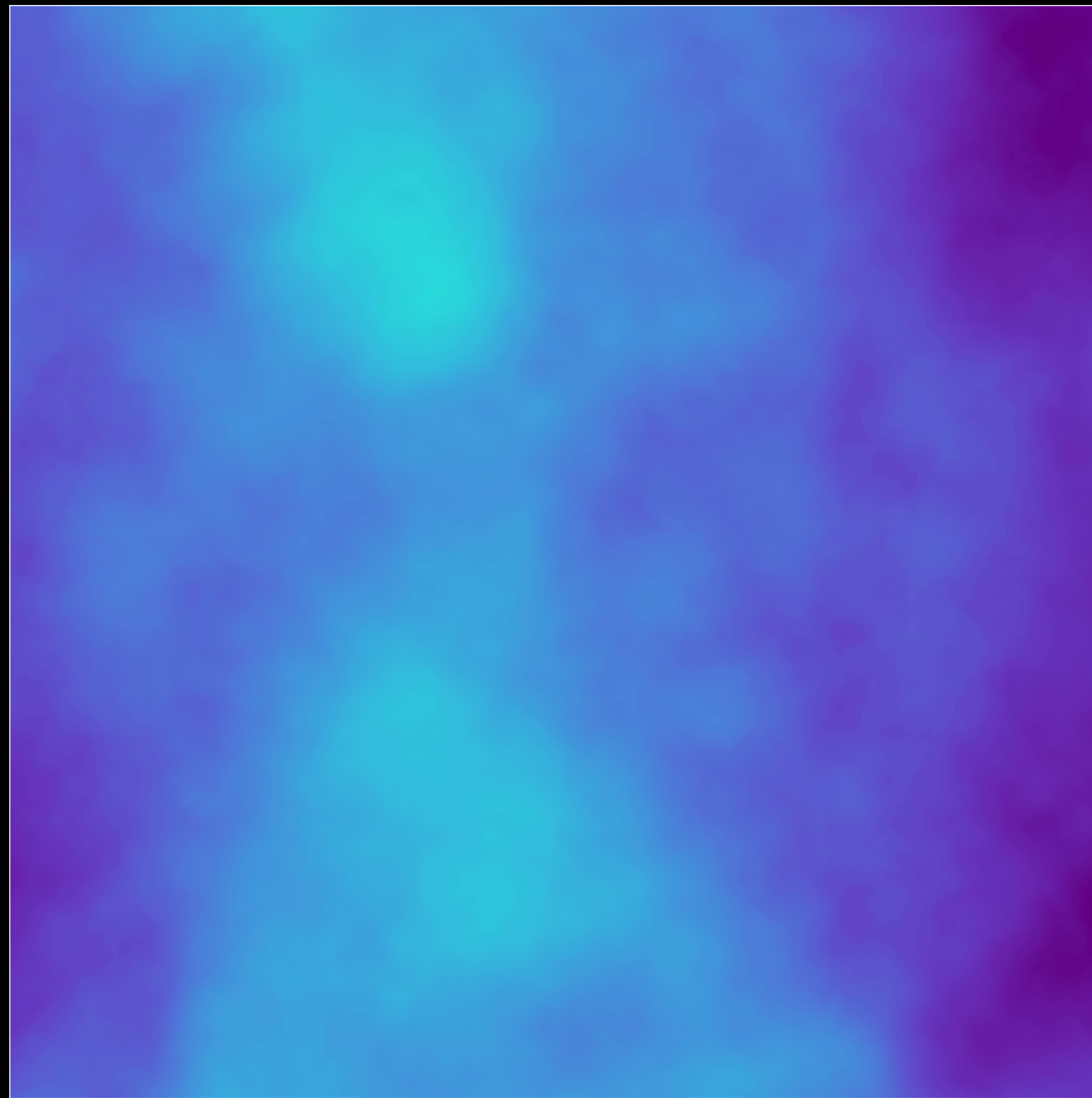
The prior

Sky



Point sources

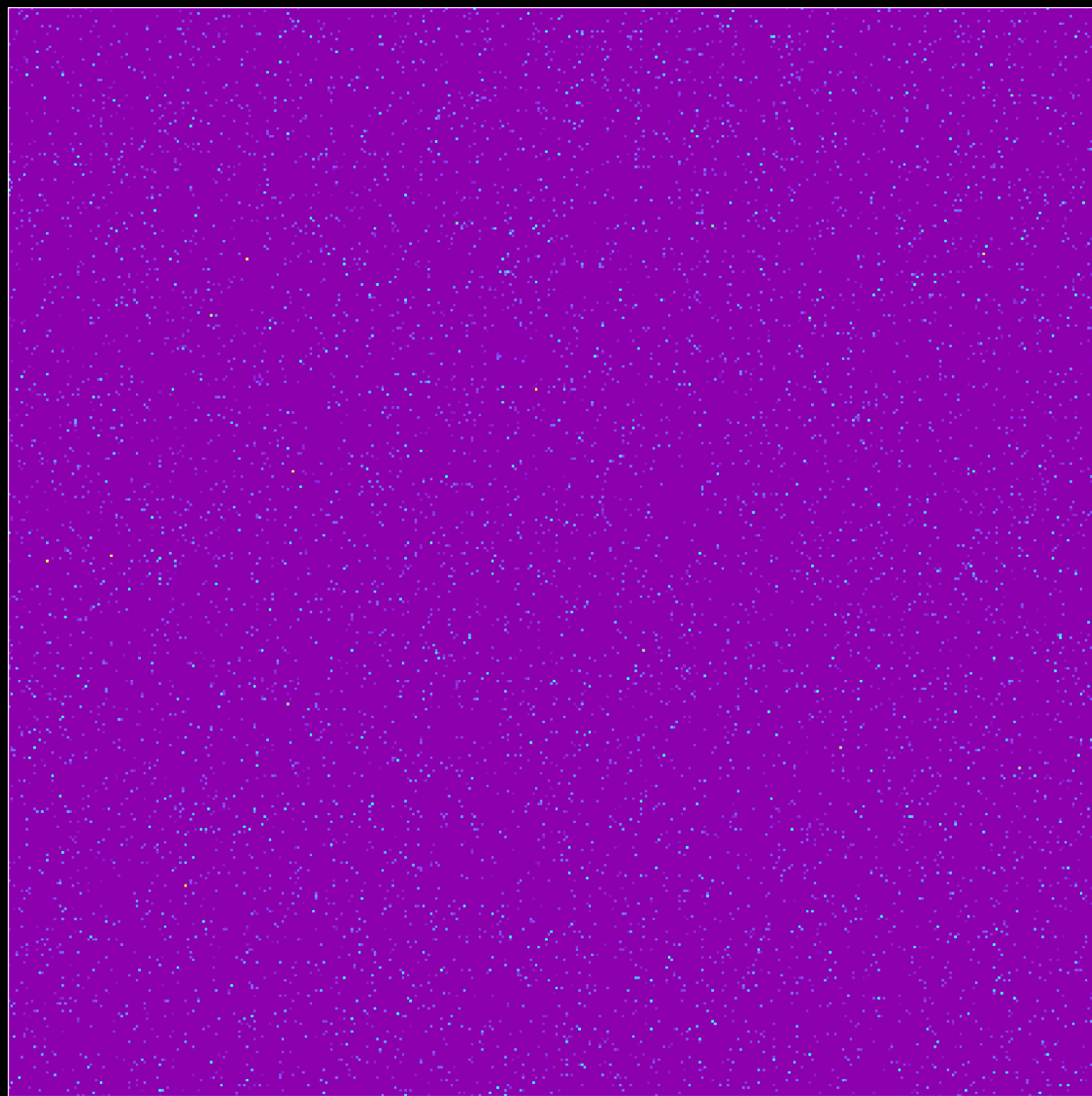
+



Diffuse emission

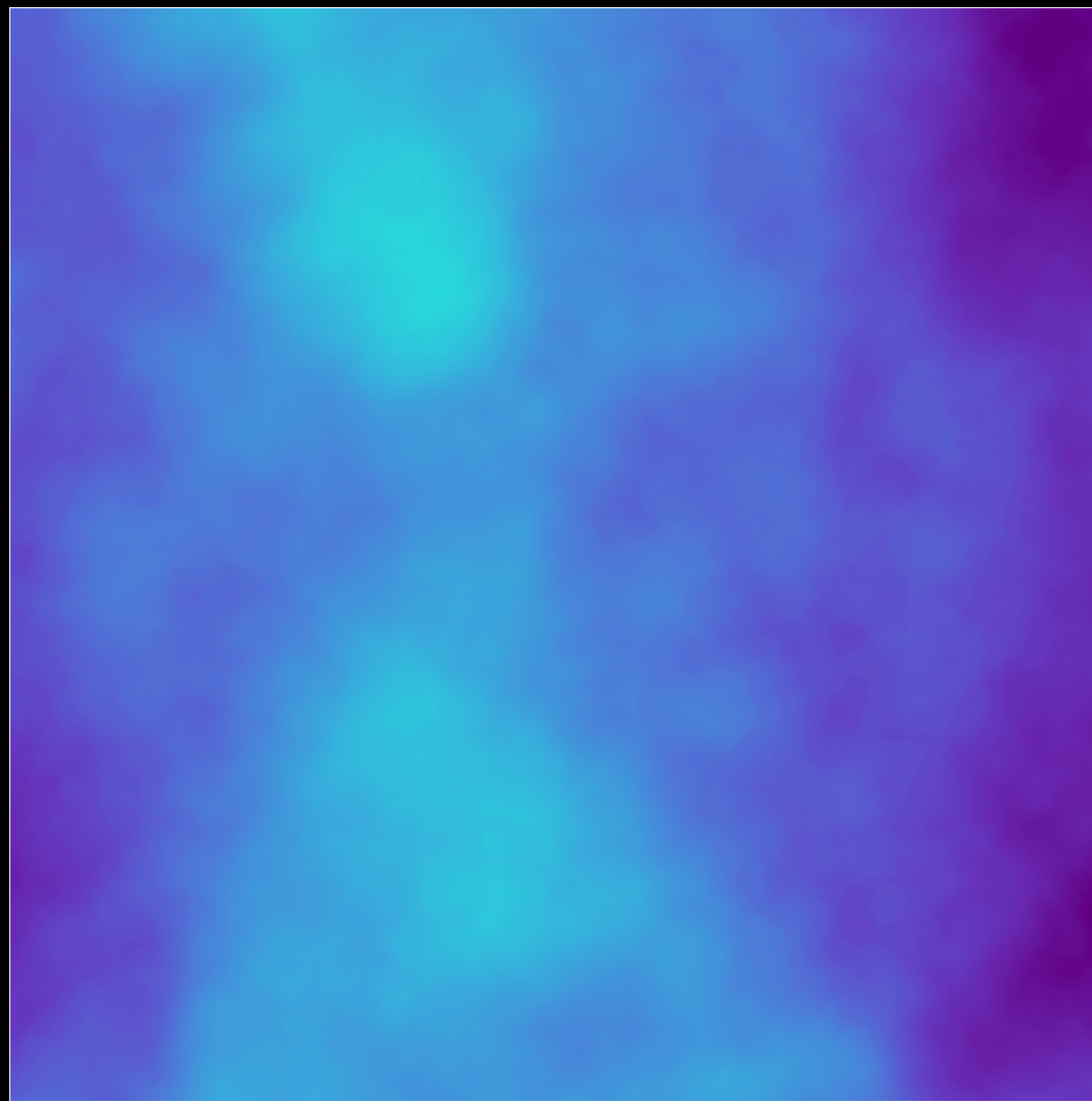
The prior

Sky



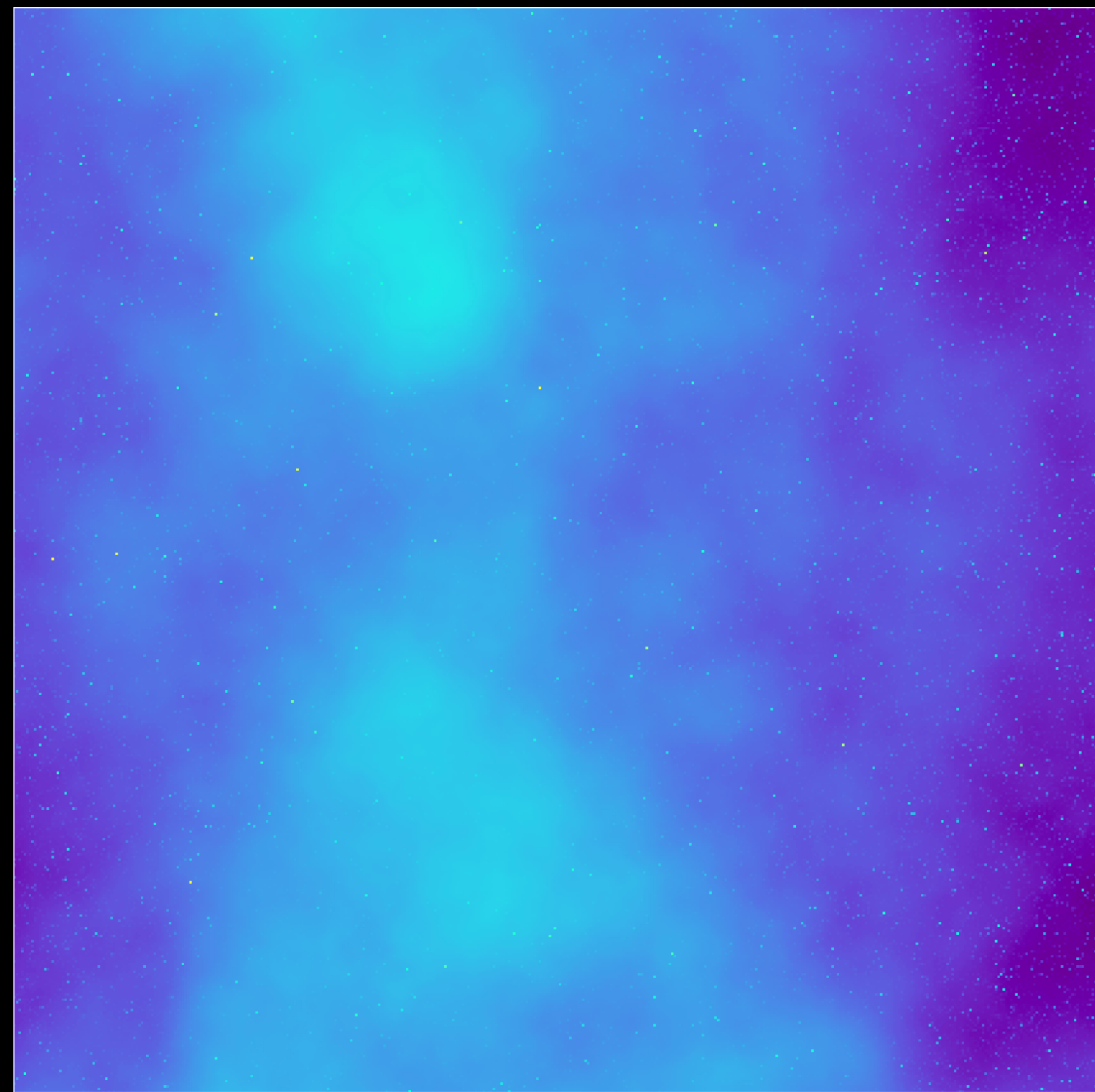
Point sources

+



Diffuse emission

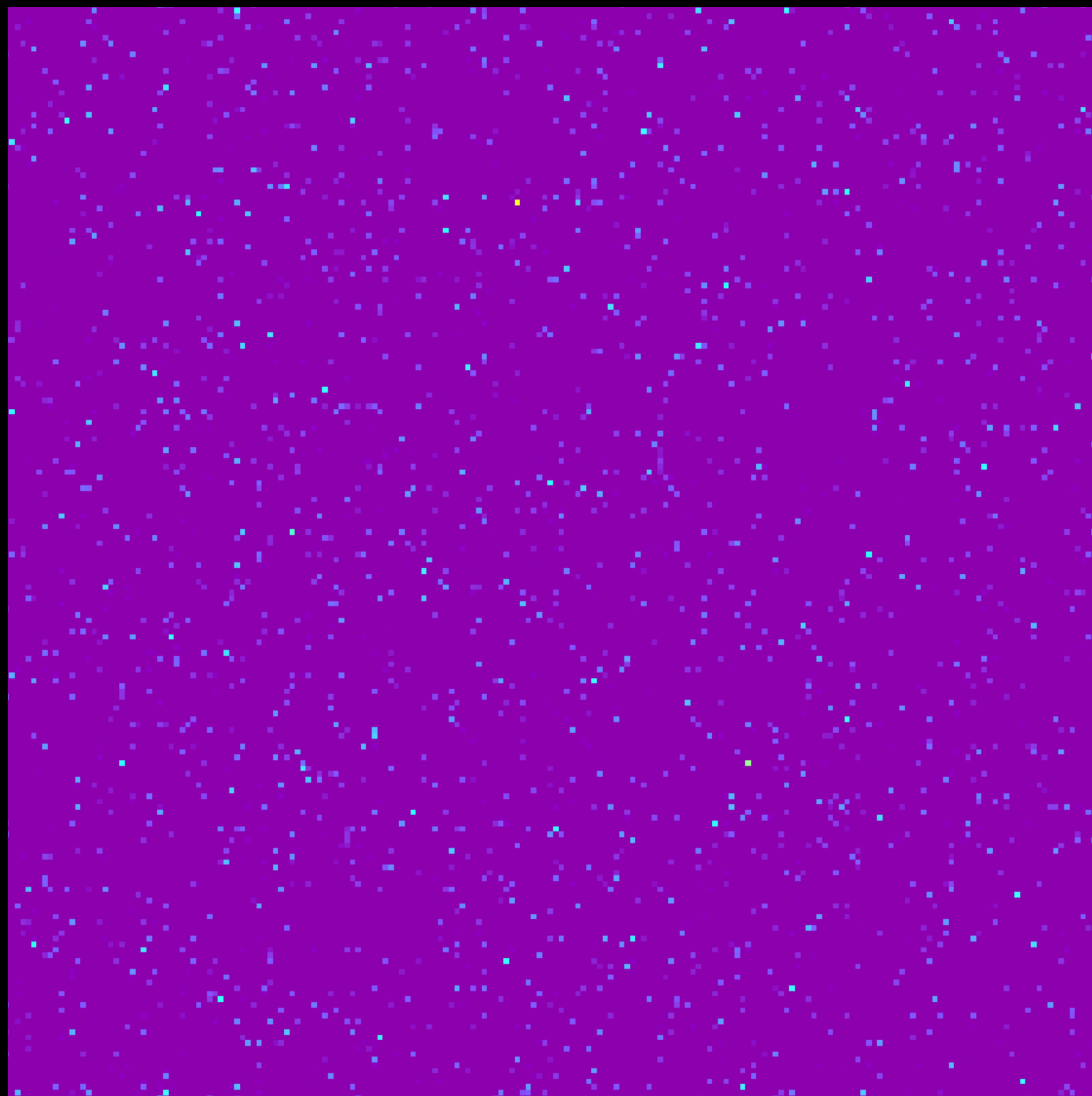
=



Sky signal

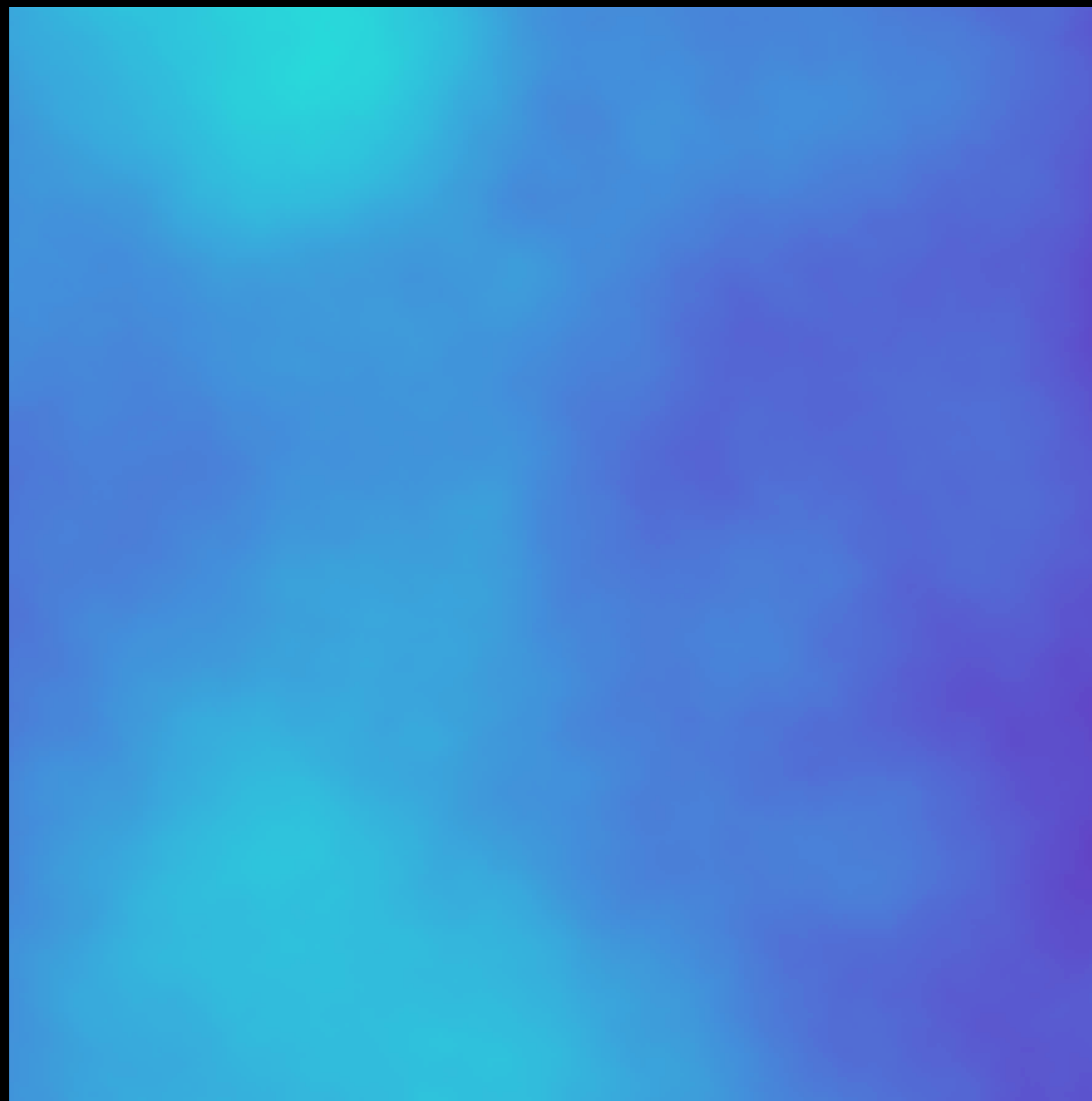
The prior

Sky



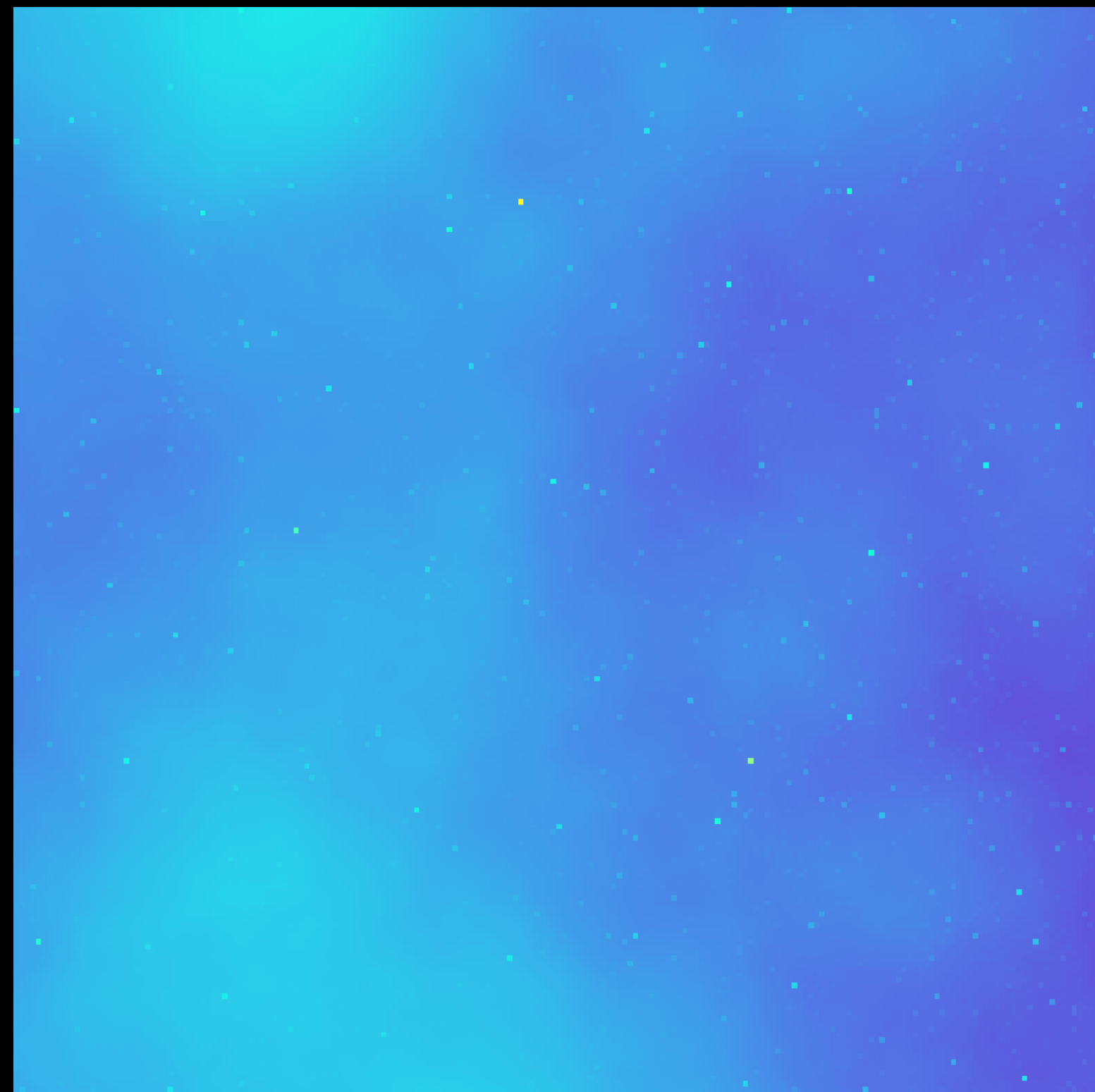
Point sources

+



Diffuse emission

=



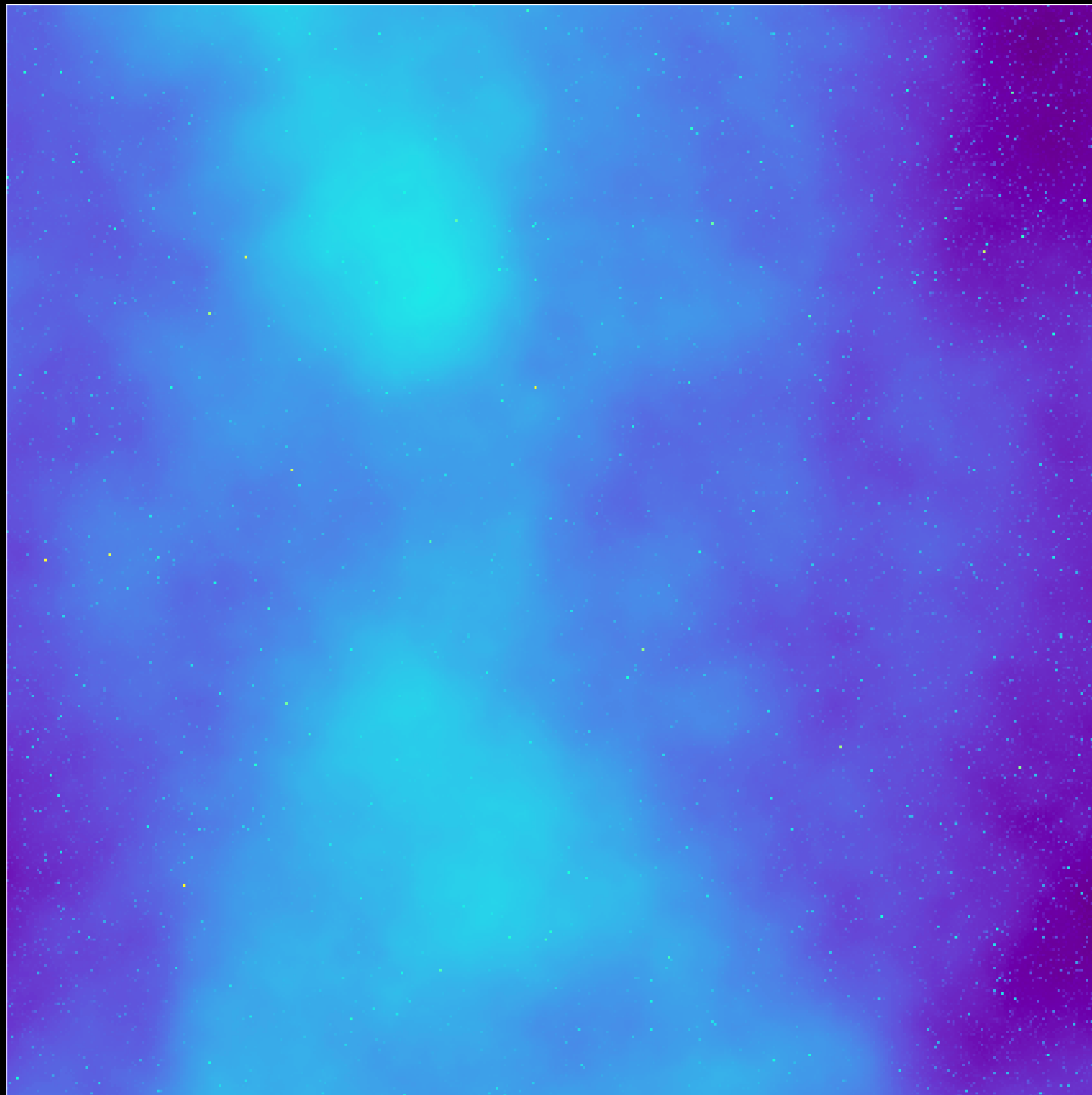
Sky signal

The Likelihood

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

The Likelihood

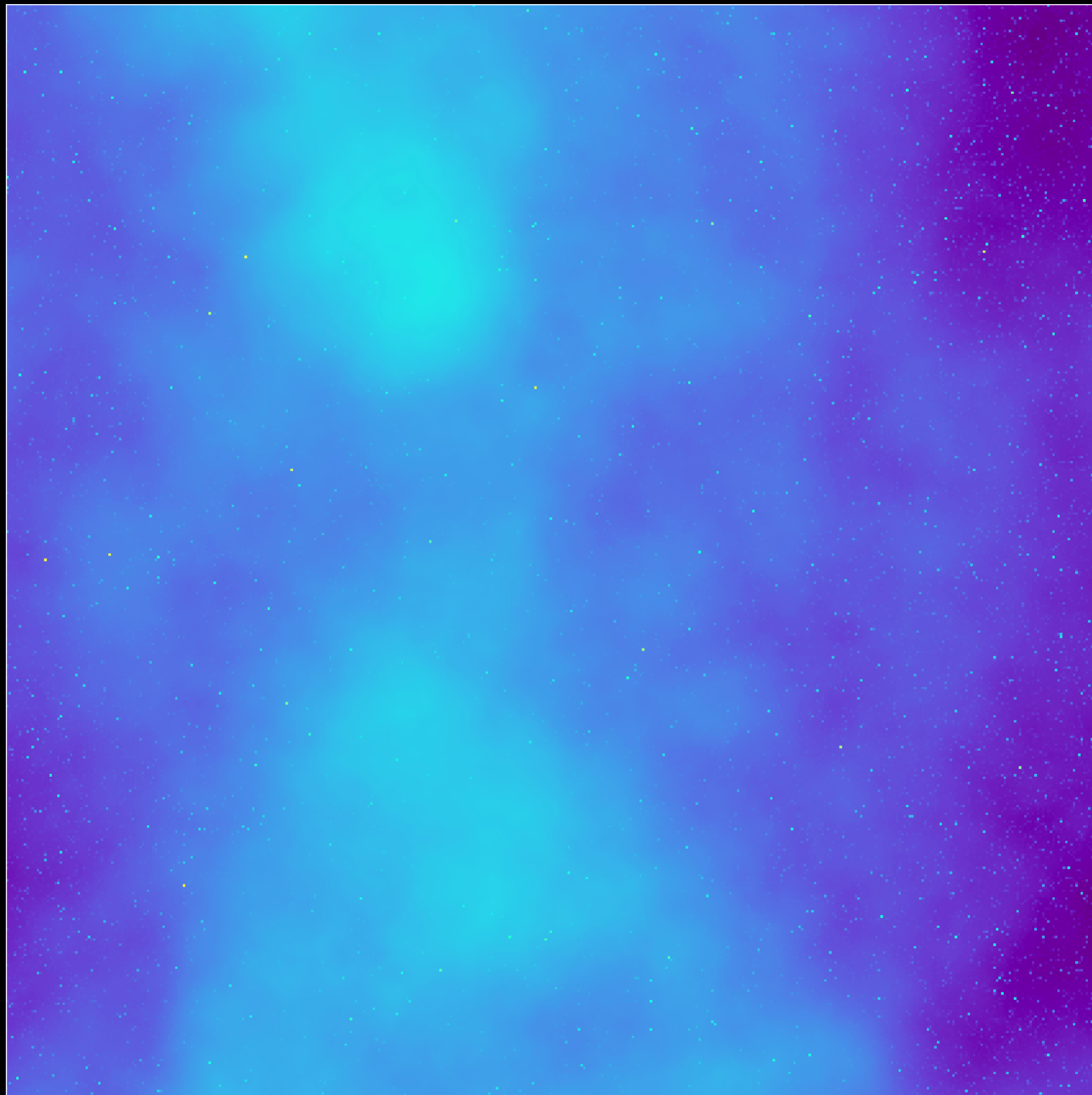
Instrument response



Sky signal

The Likelihood

Instrument response



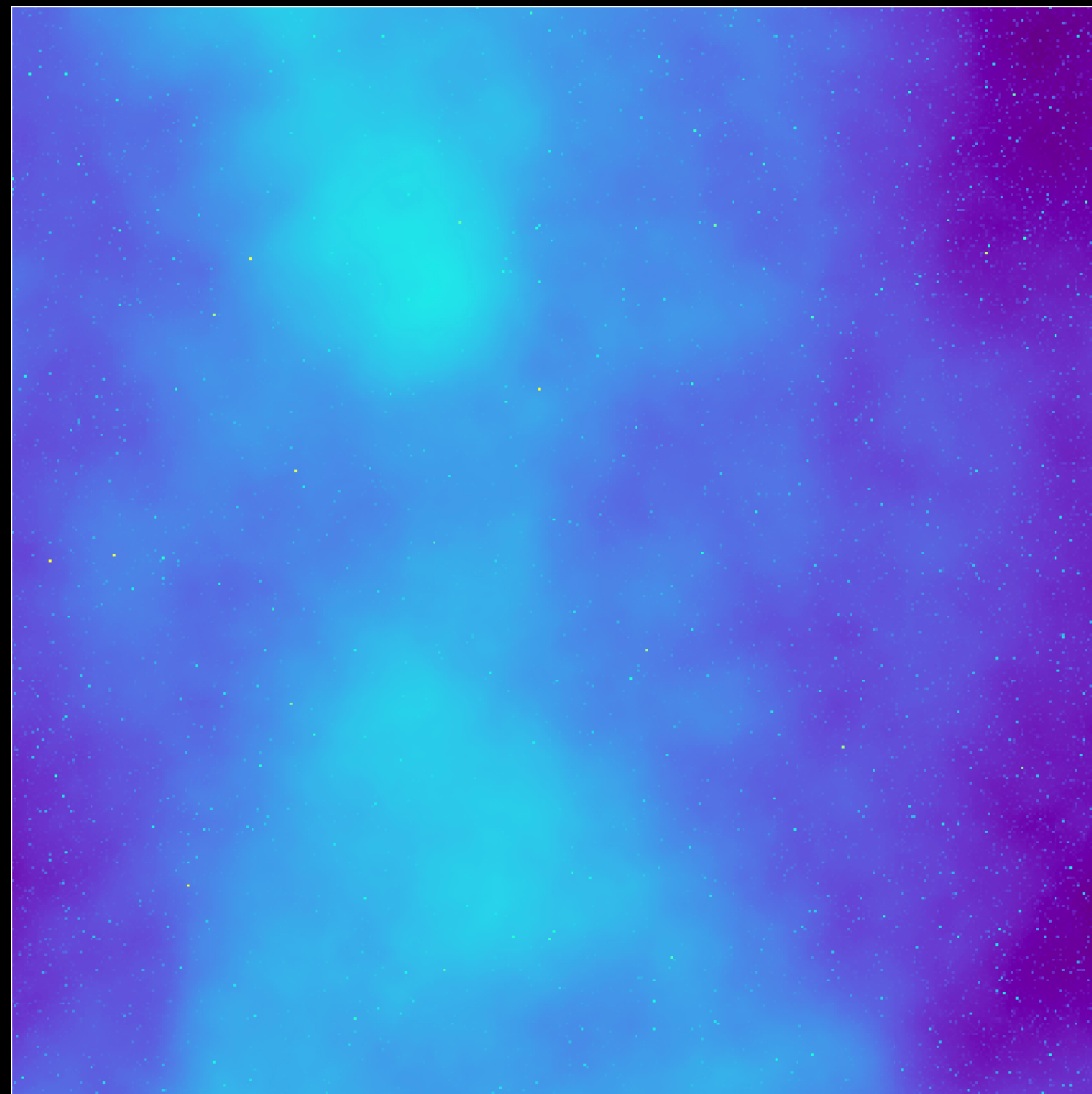
Sky signal



eROSITA on SRG

The Likelihood

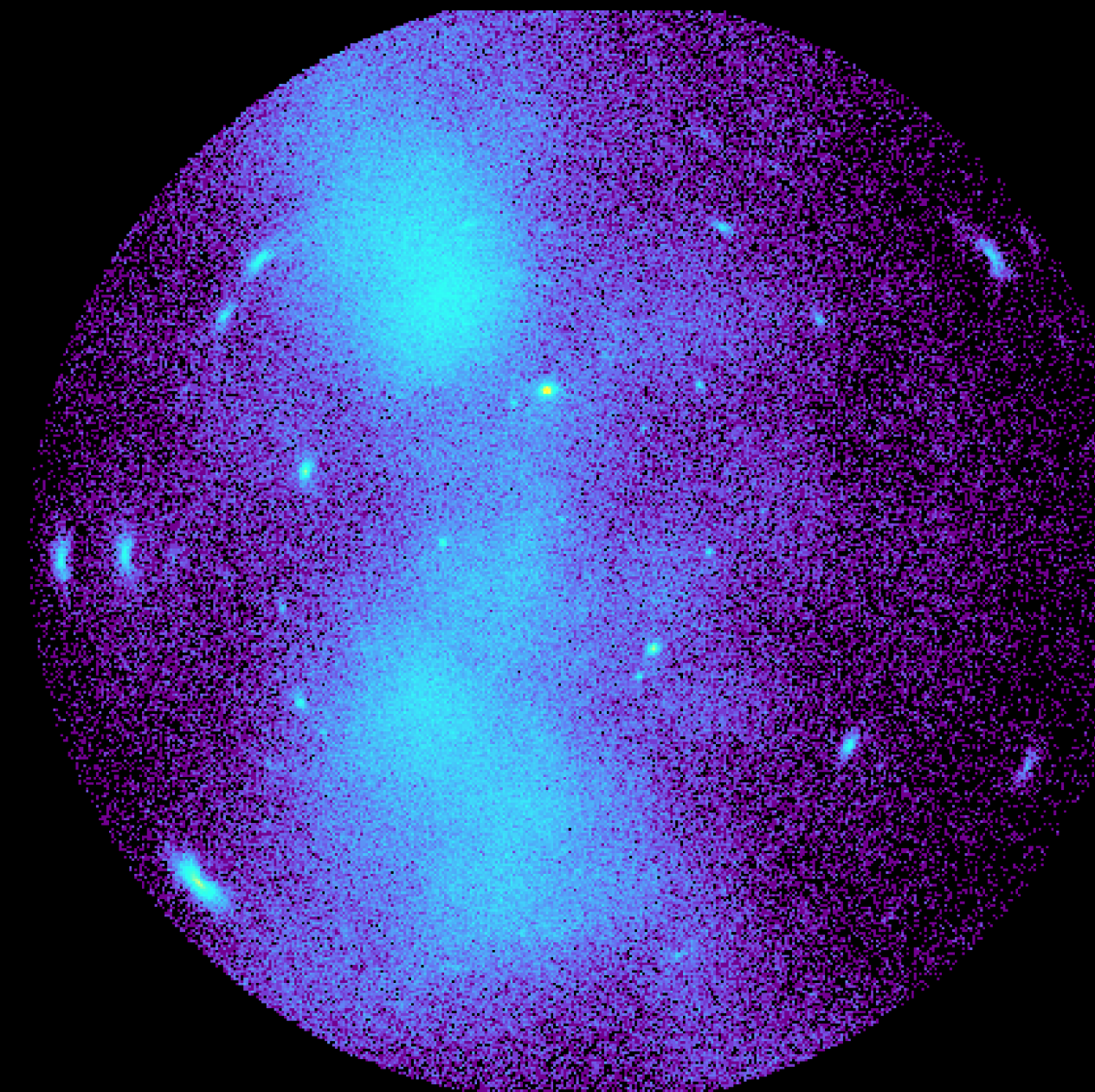
Instrument response



Sky signal



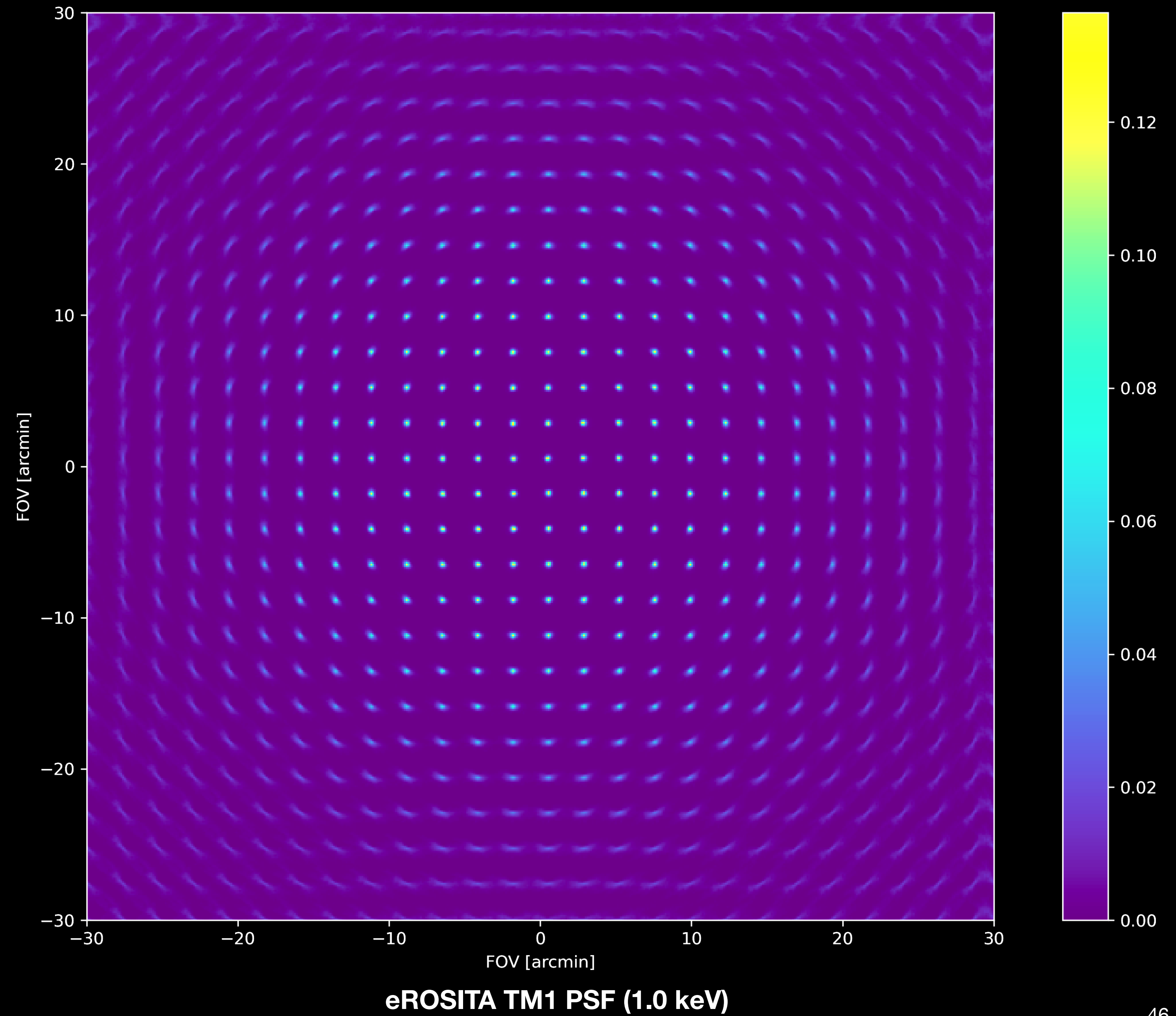
eROSITA on SRG



Sky data on earth

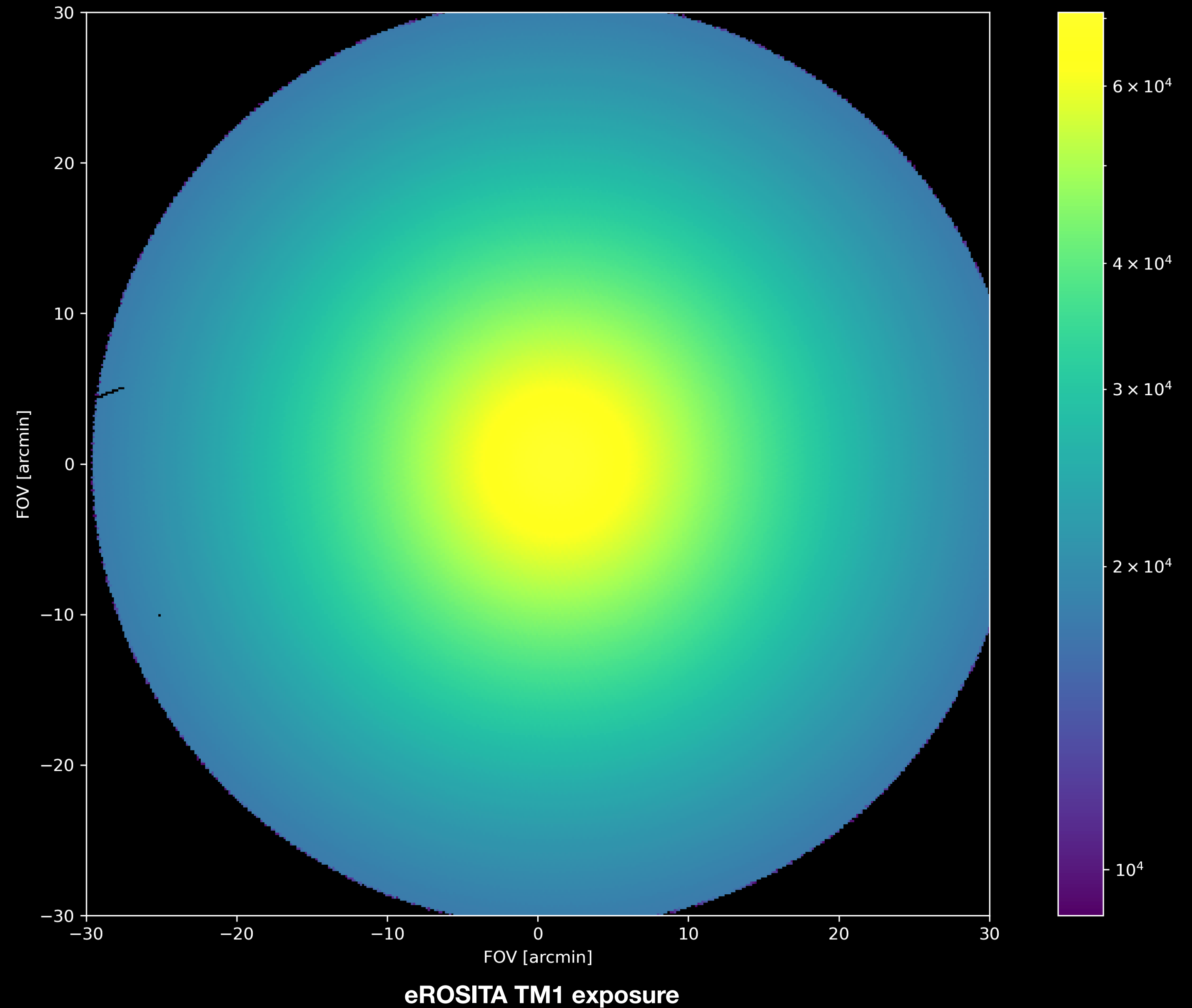
The Likelihood Point-spread function

- $R = \text{PSF}$



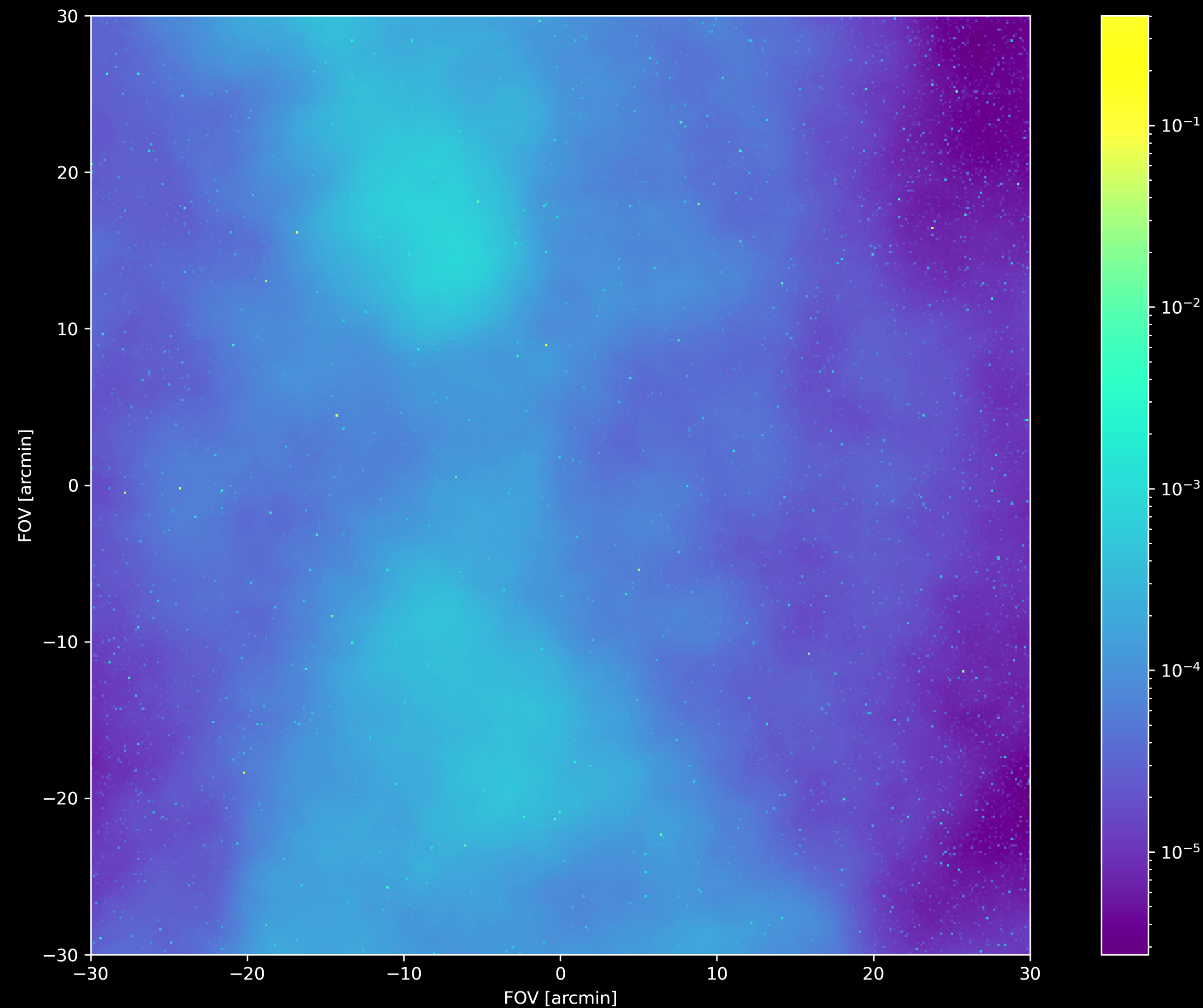
The Likelihood Exposure

- $R = E$



The Likelihood Signal

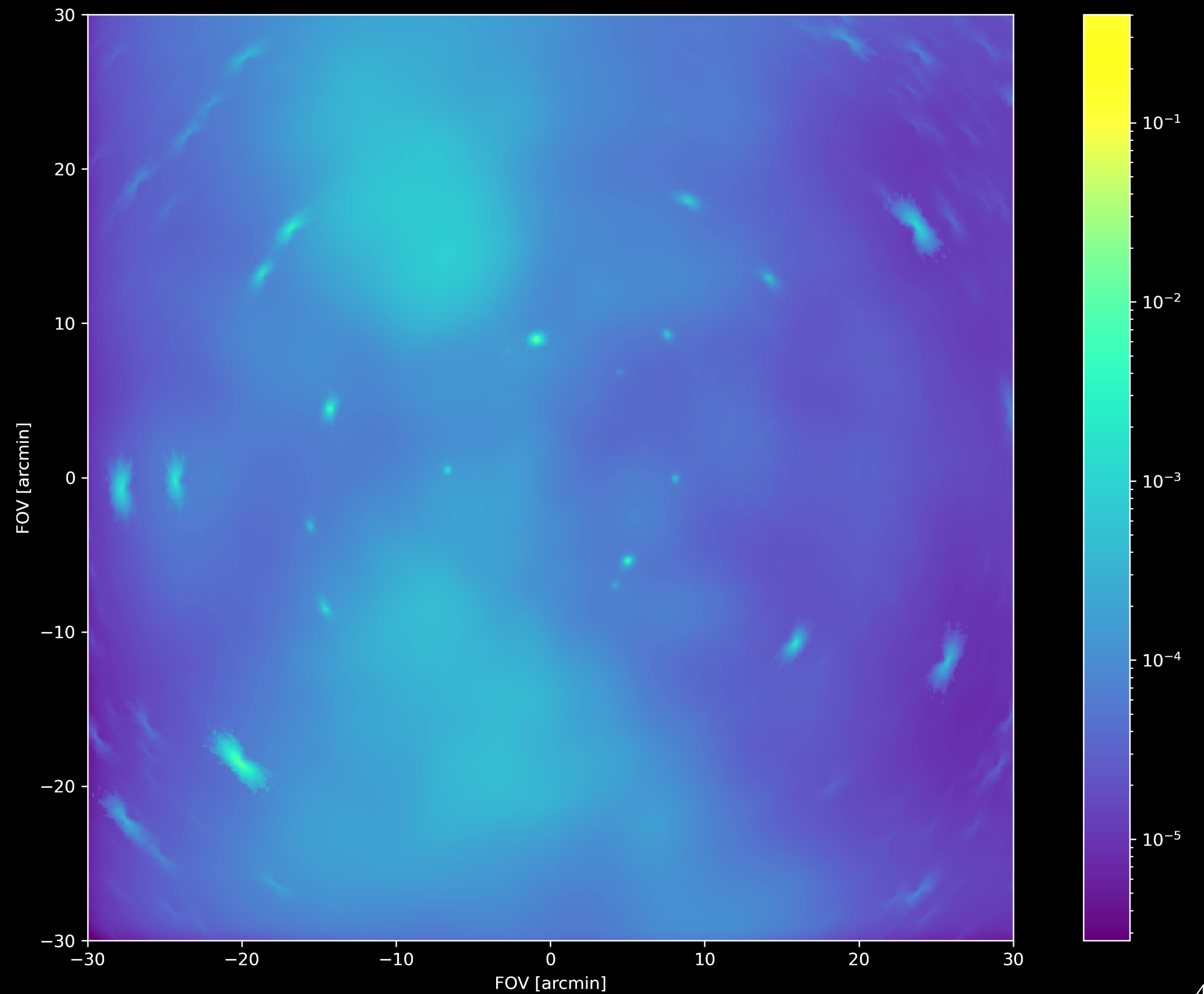
S



The Likelihood

Signal response

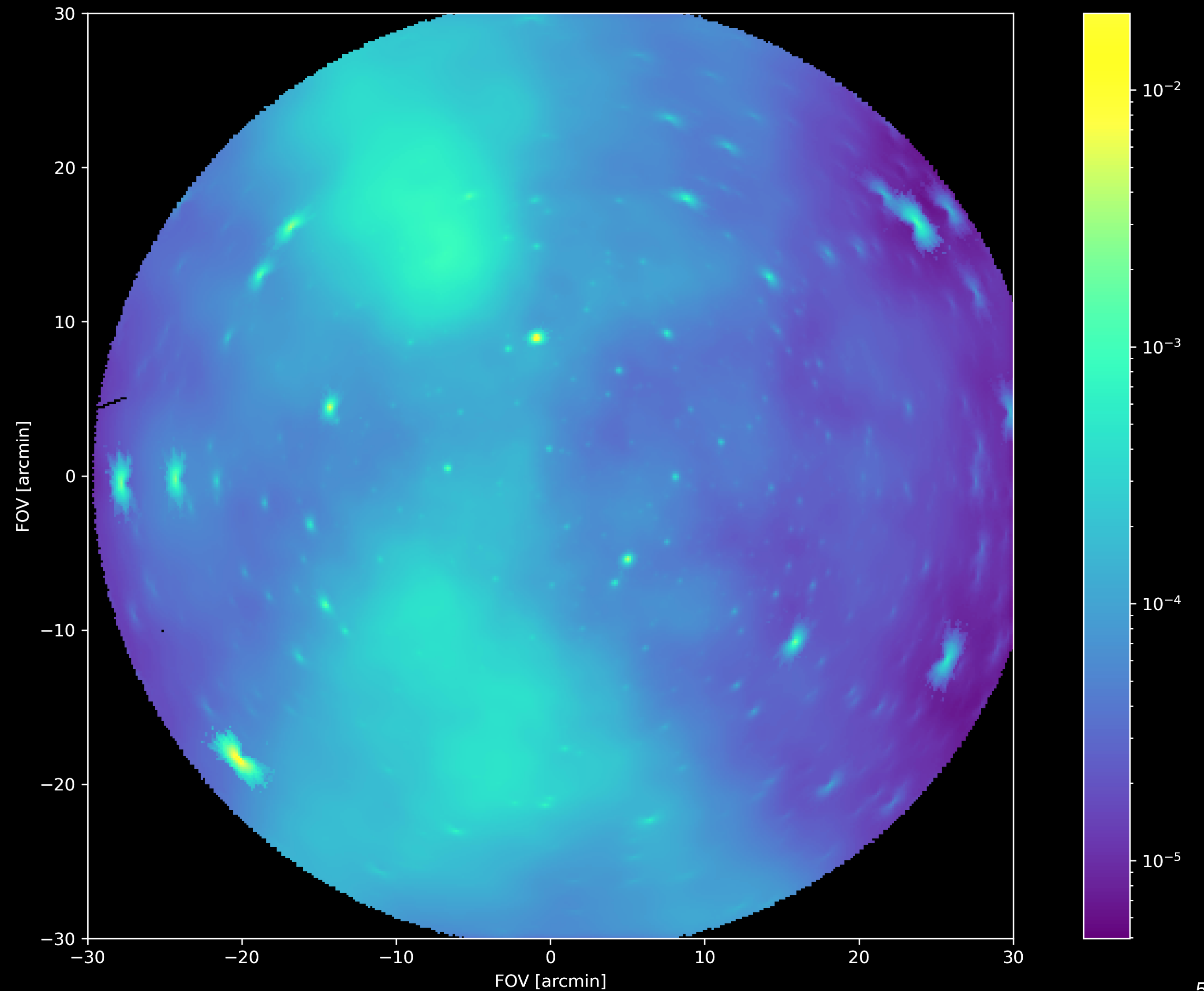
PSF (*S*)



The Likelihood

Signal response

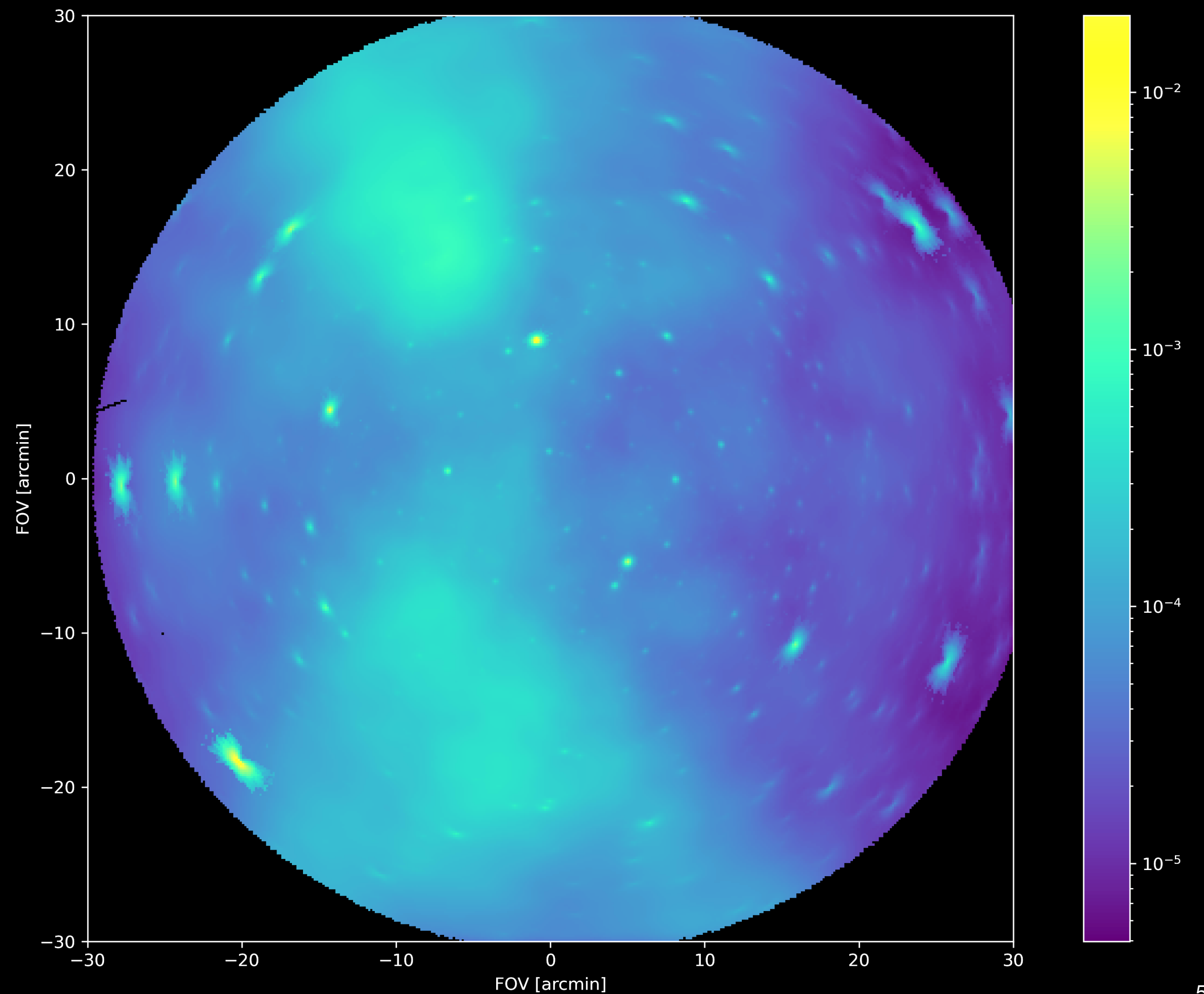
$$R_s = E \left(\text{PSF} (s) \right)$$



The Likelihood

Signal response

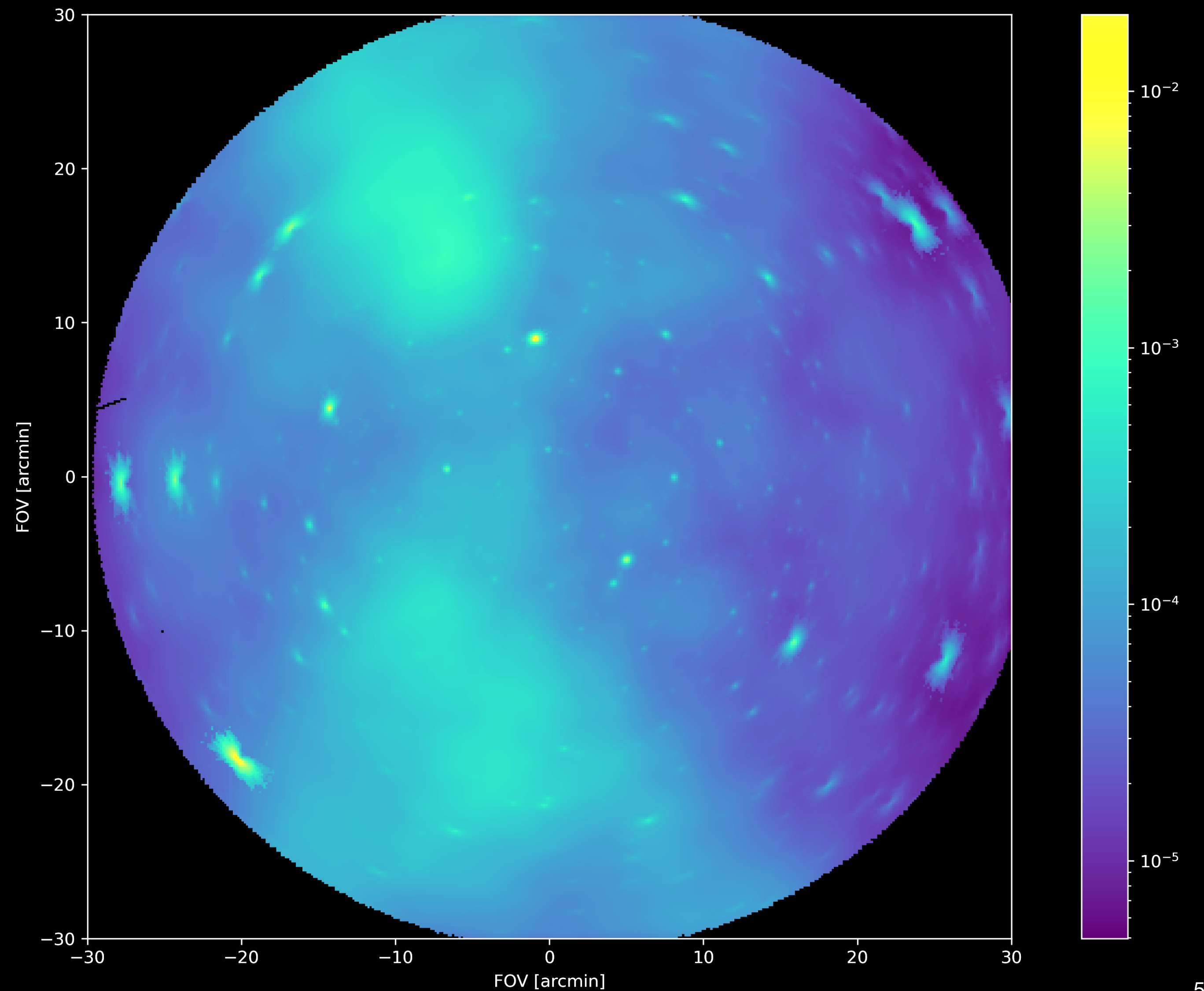
$$\lambda = R_s$$



The Likelihood

Poissonian noise

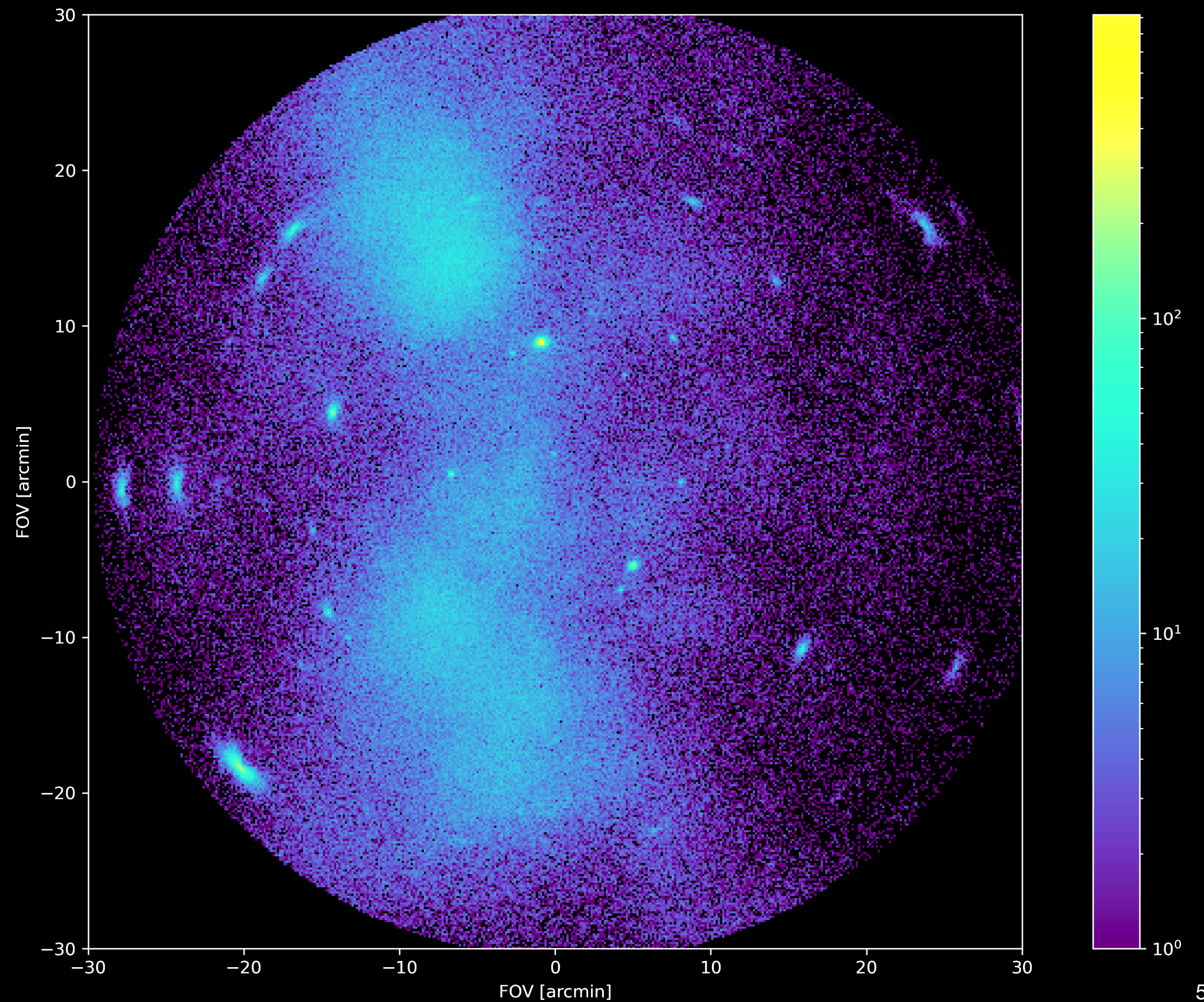
$$P(d|\lambda) = \prod_{i=1}^N \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



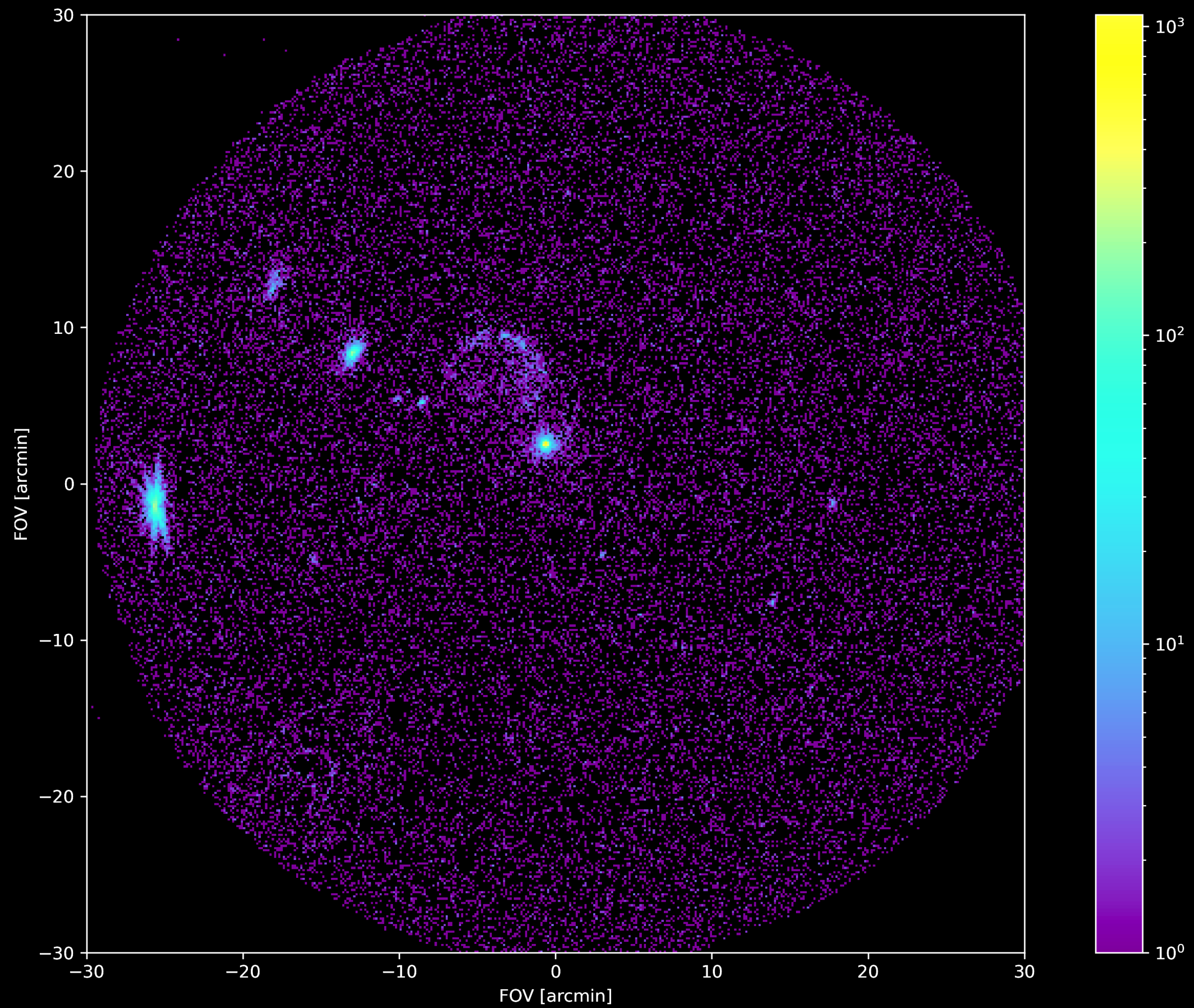
The Likelihood

Poissonian noise

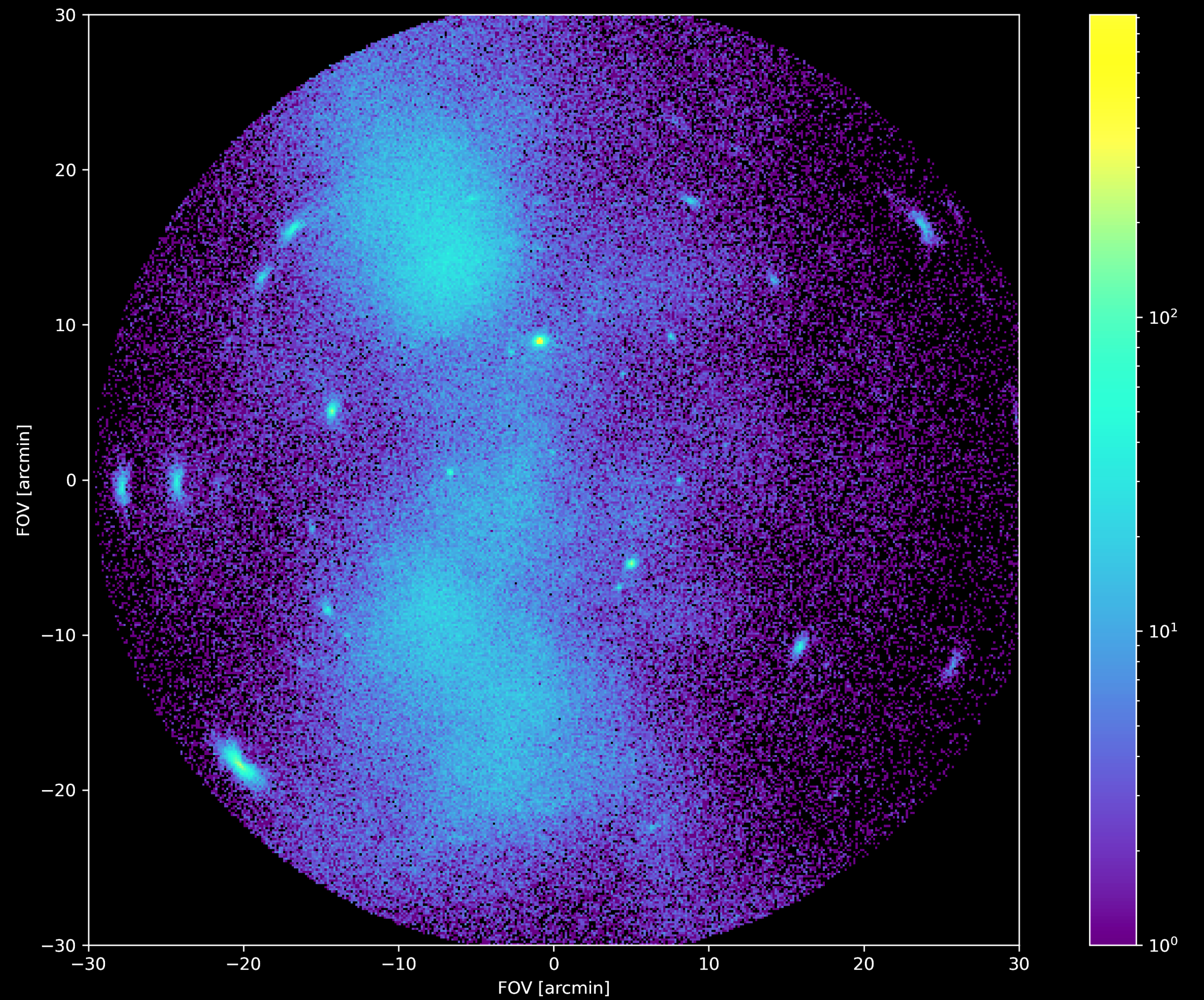
$$P(d|\lambda) = \prod_{i=1}^N \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



The Data



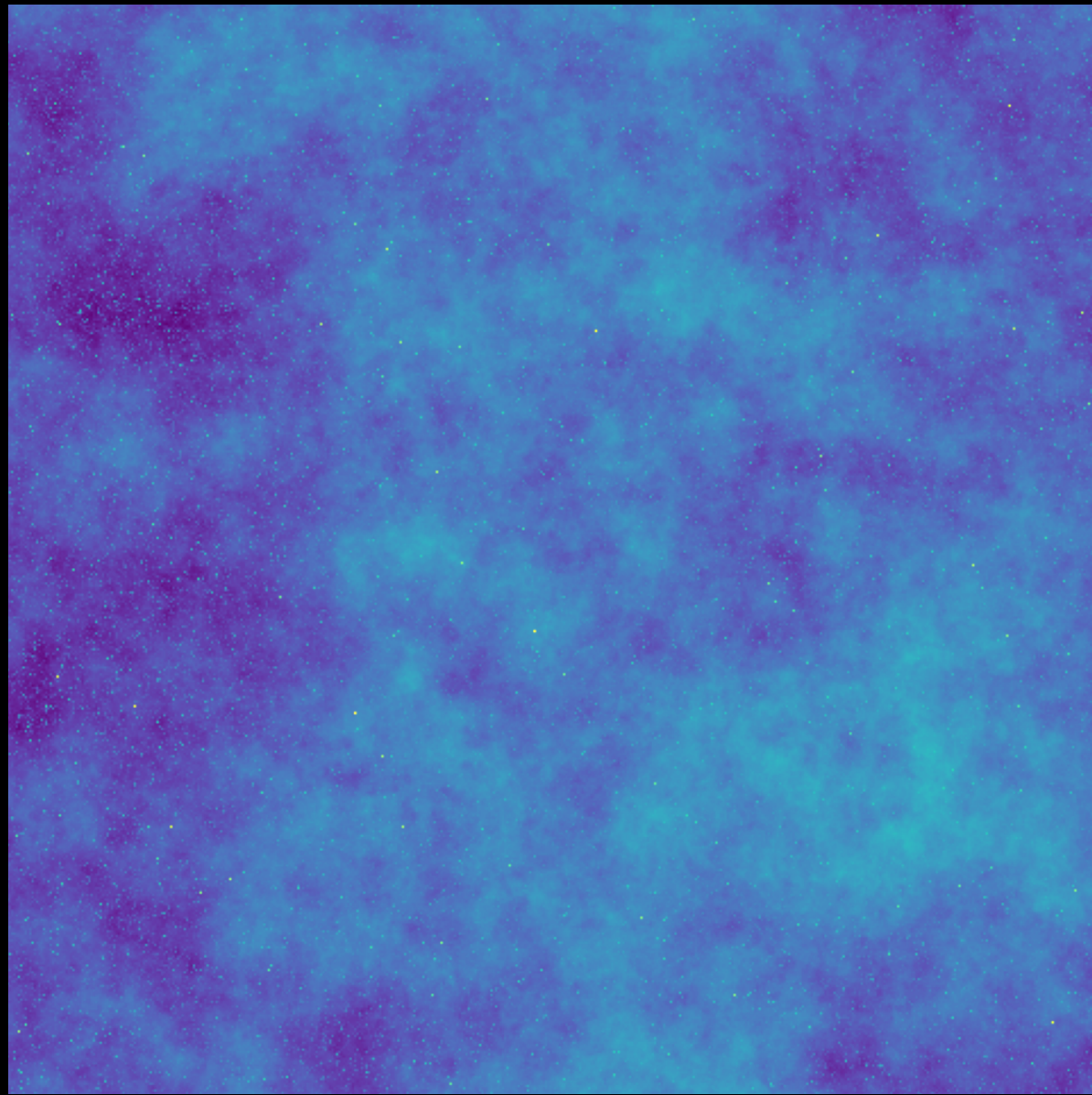
eROSITA TM1 SN1987A data



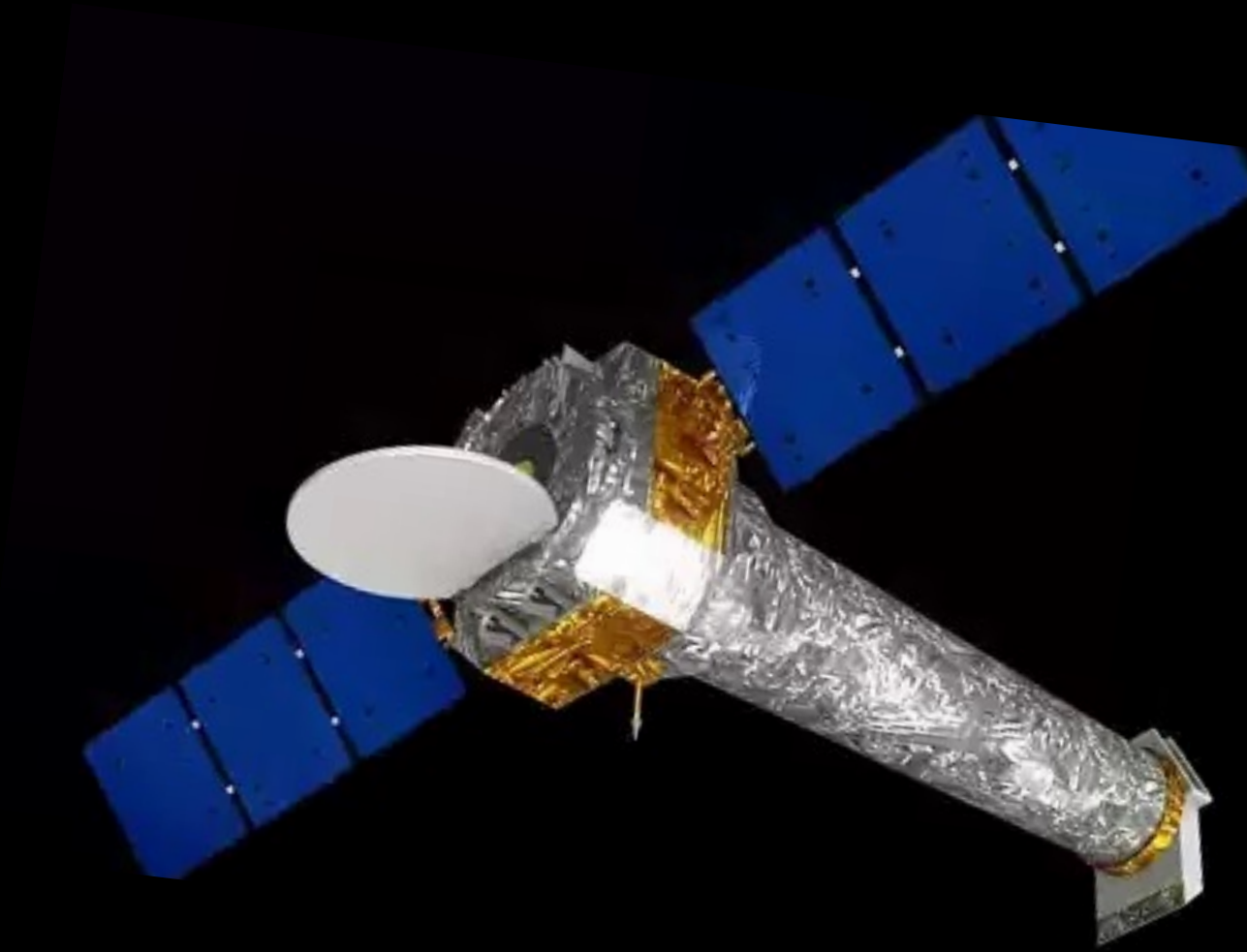
Simulated eROSITA TM1 data

The Likelihood

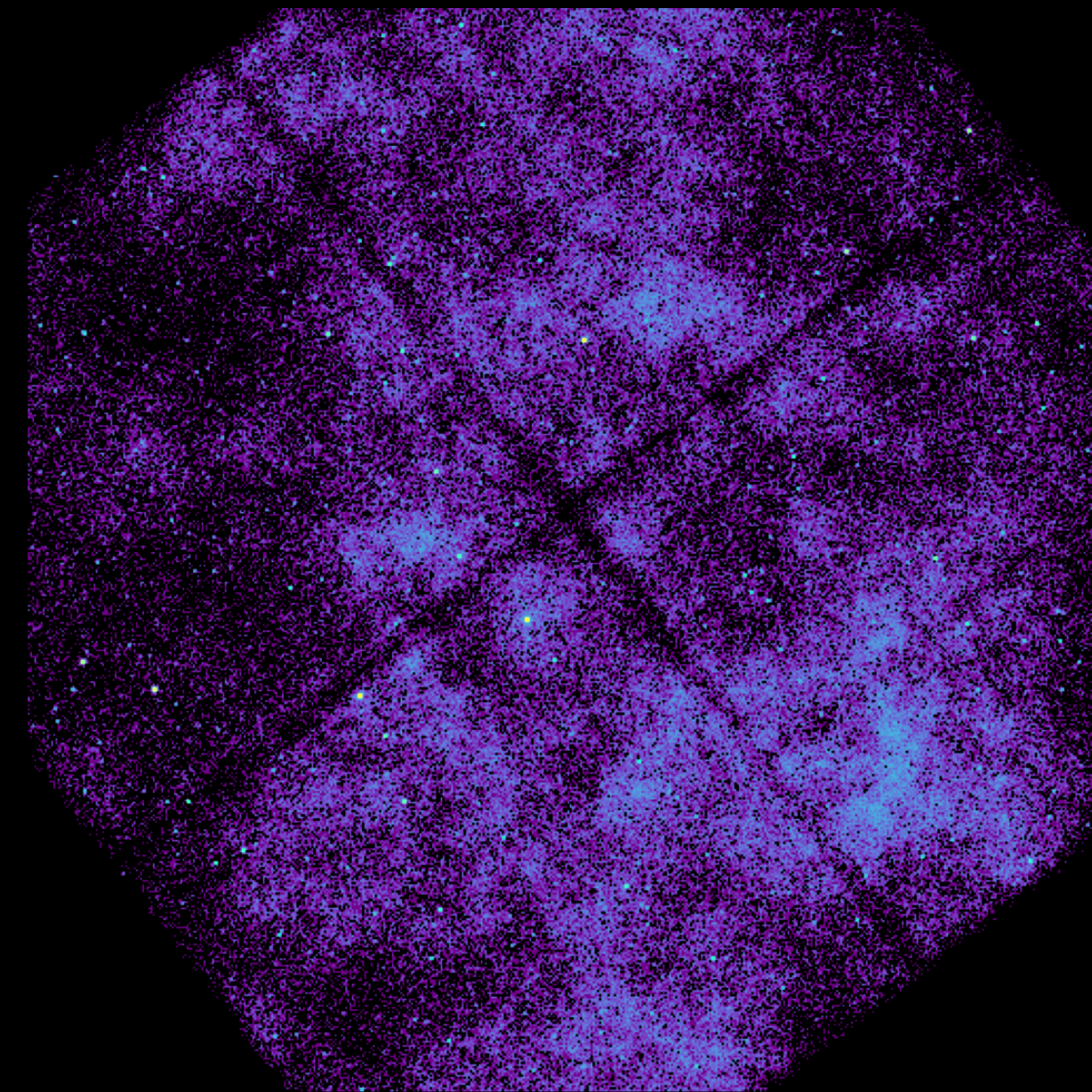
Chandra instrument response



Sky signal



Chandra X-ray observatory

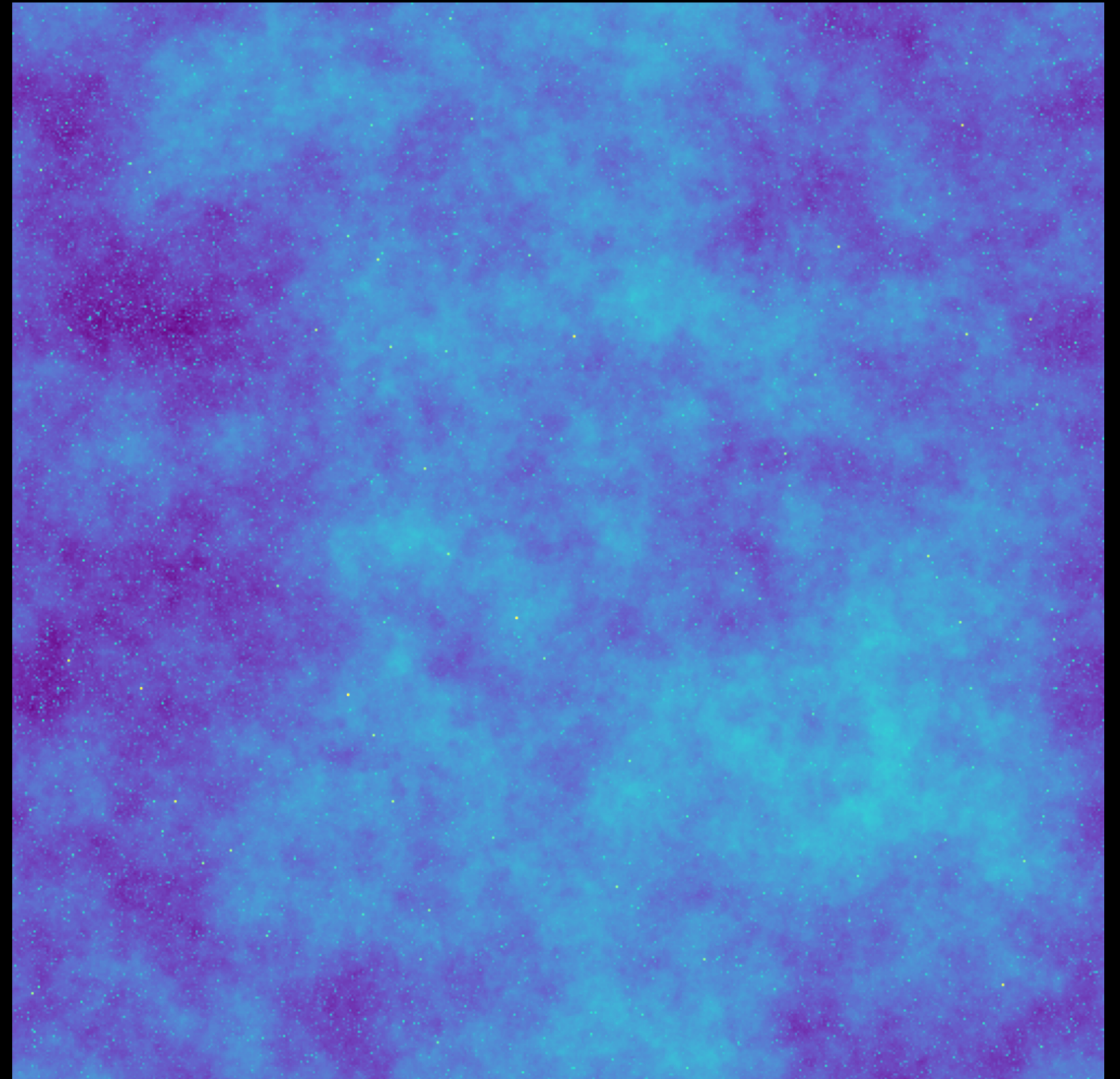


Sky data on earth



The Likelihood Signal

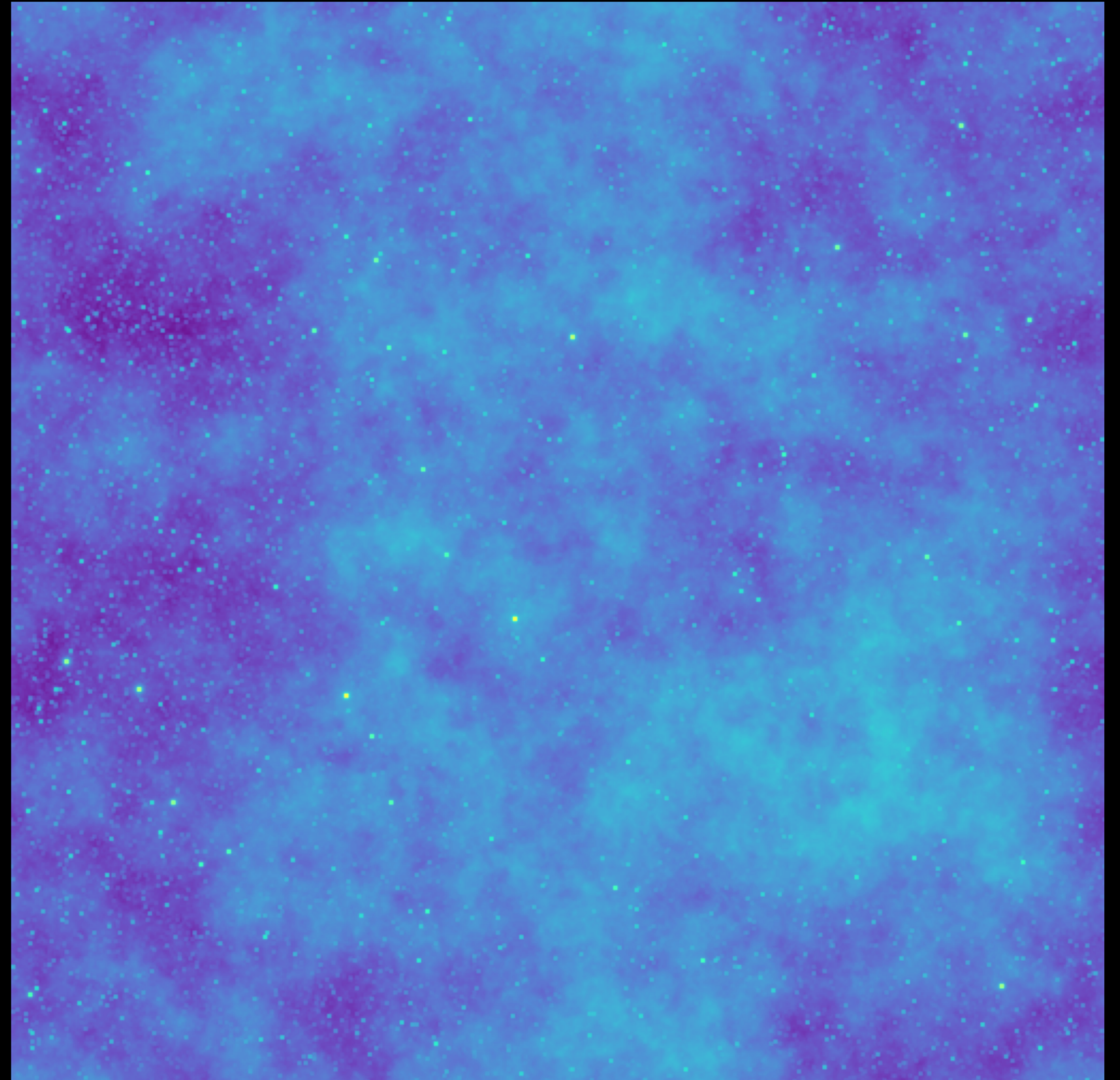
S



The Likelihood

Signal response

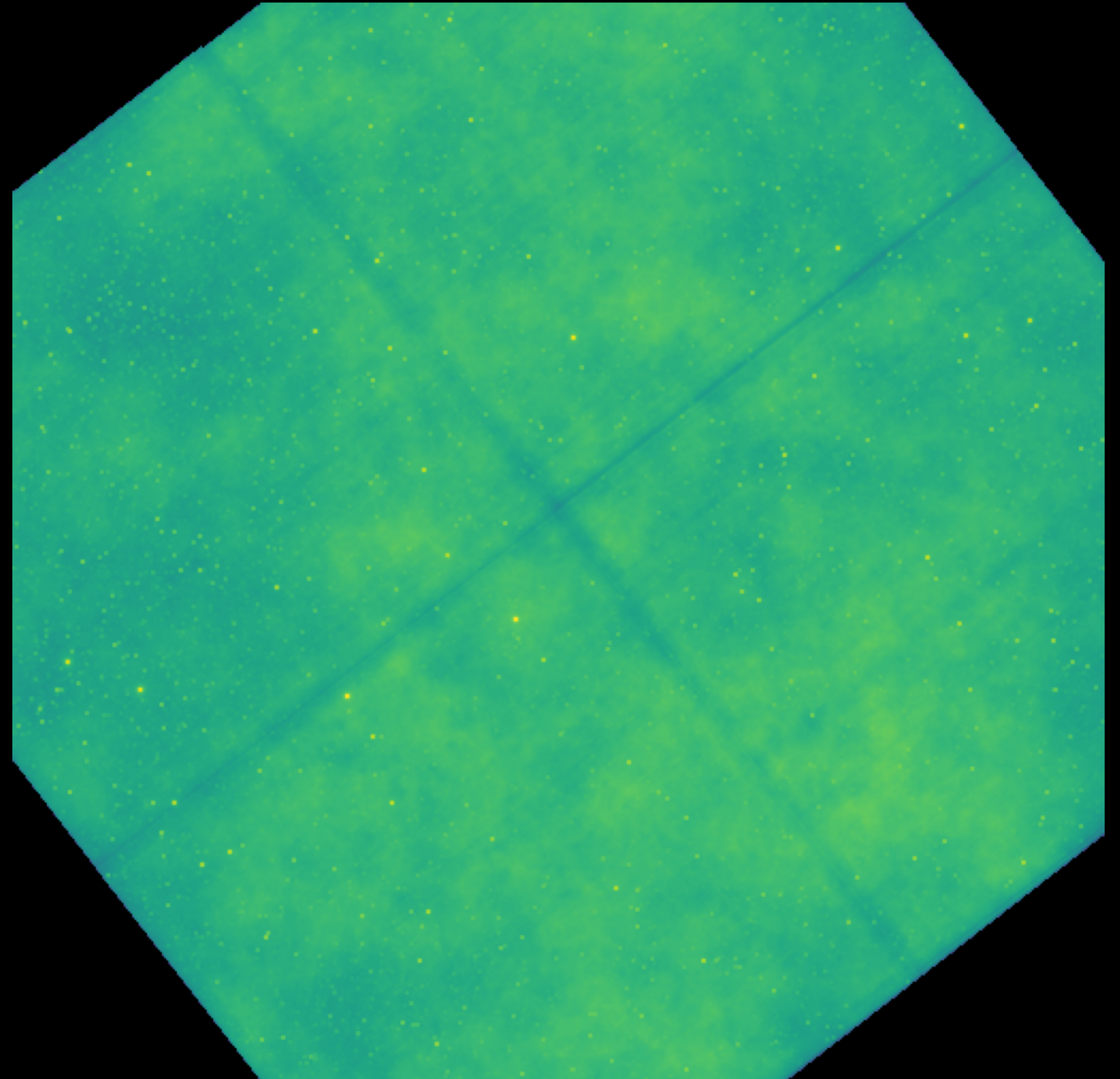
PSF (*s*)



The Likelihood

Signal response

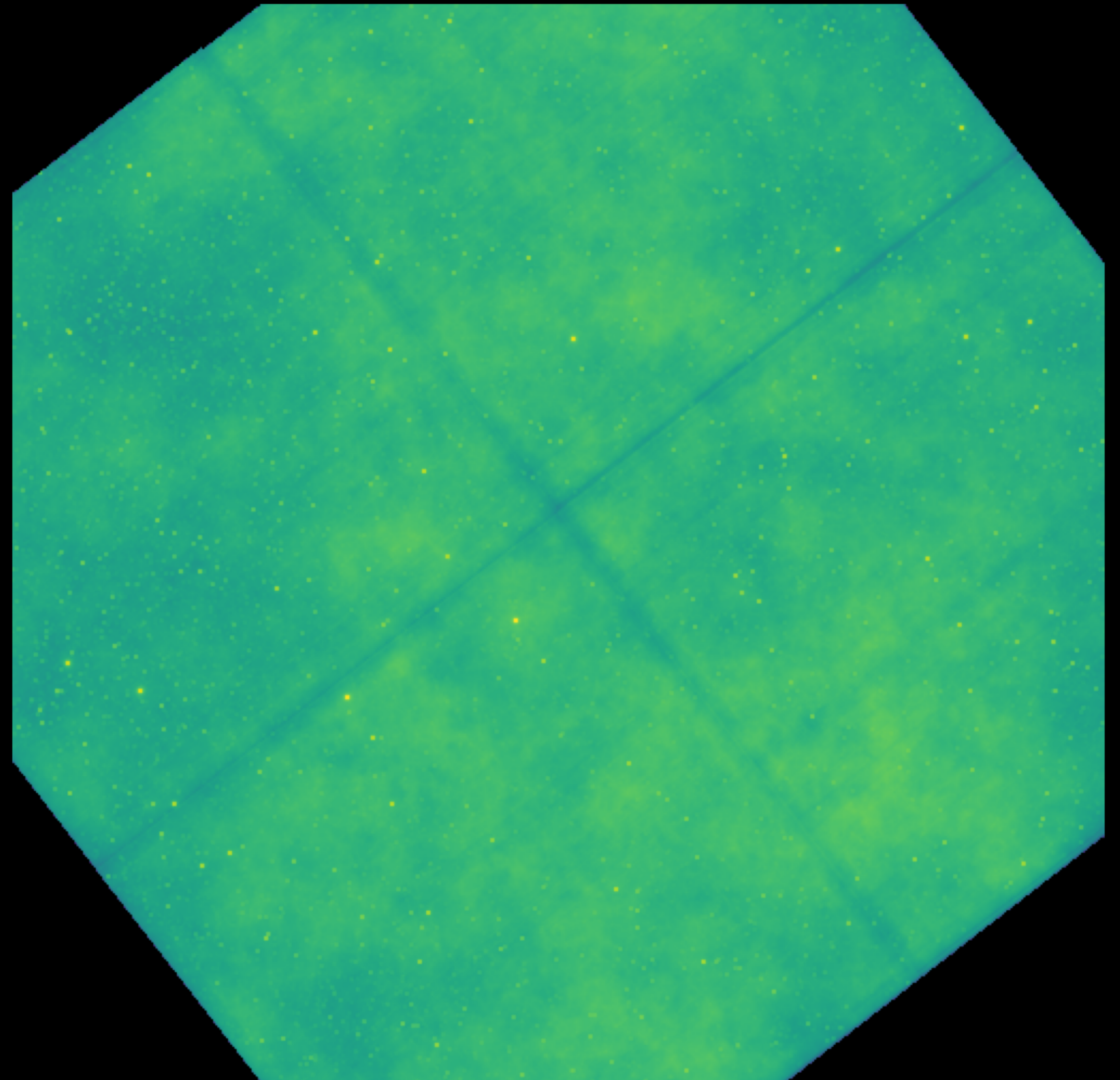
$$R_s = E \left(\text{PSF} (s) \right)$$



The Likelihood

Signal response

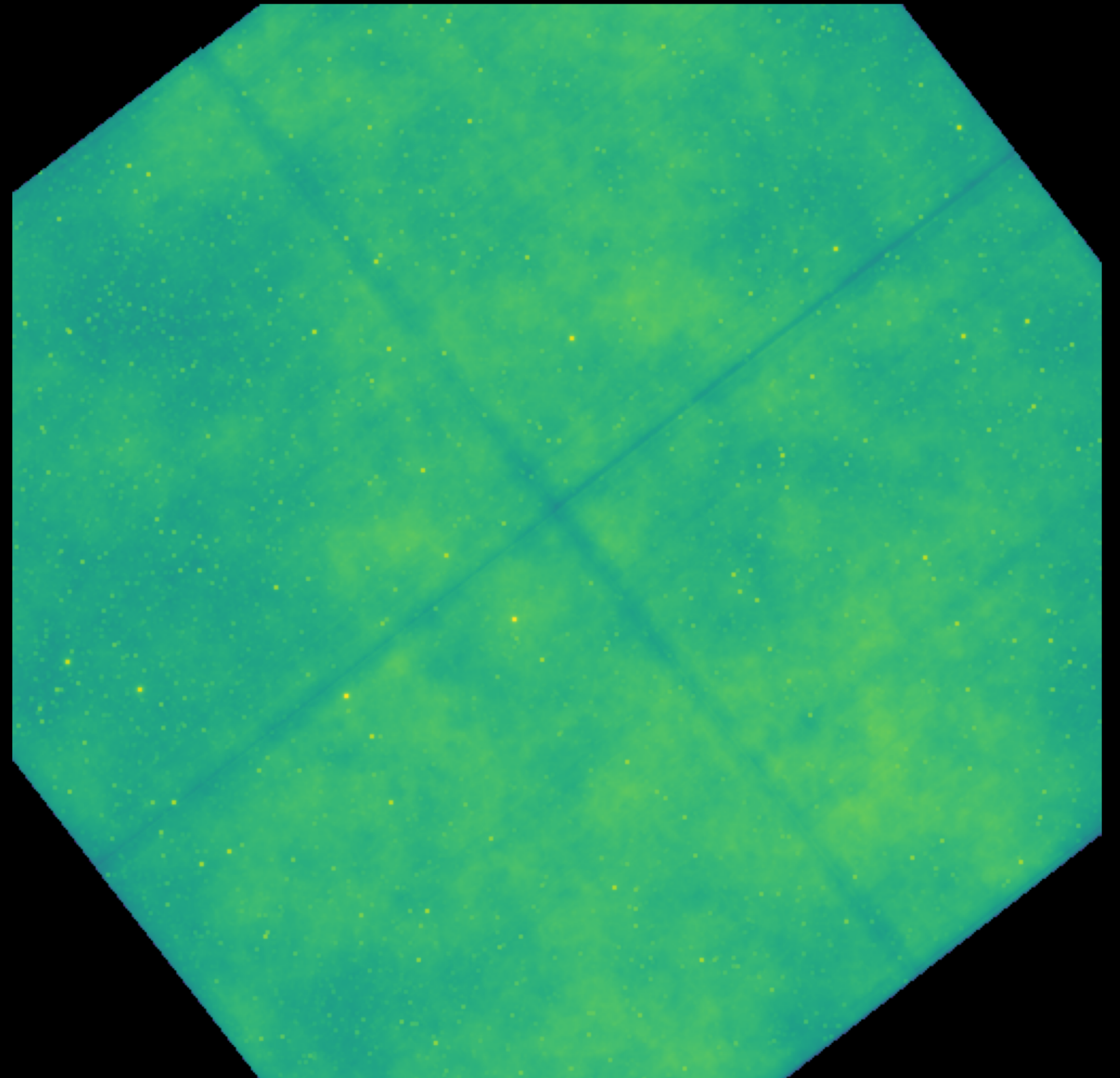
$$\lambda = R_s$$



The Likelihood

Poissonian noise

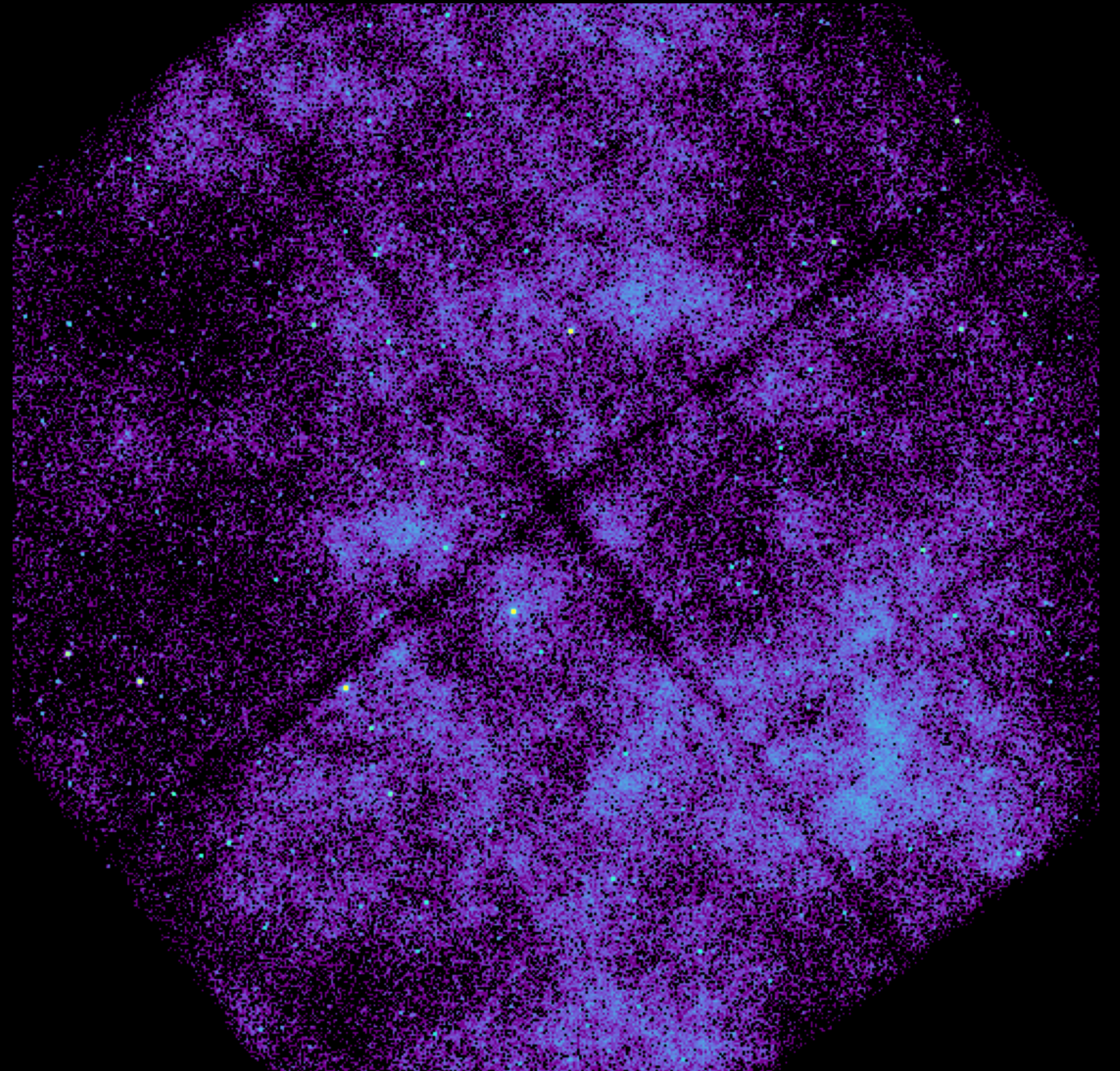
$$P(d|\lambda) = \prod_{i=1}^N \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



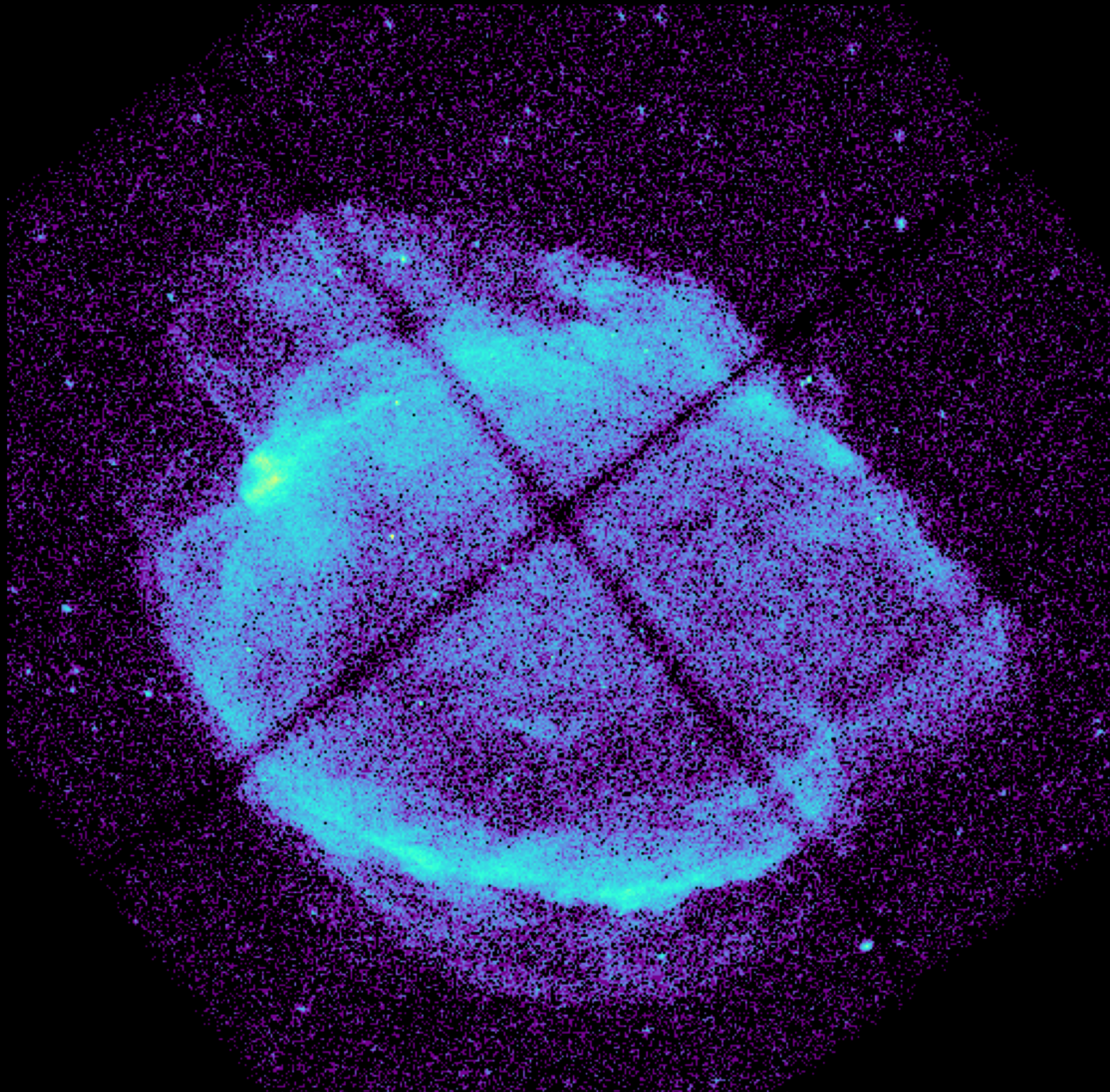
The Likelihood

Poissonian noise

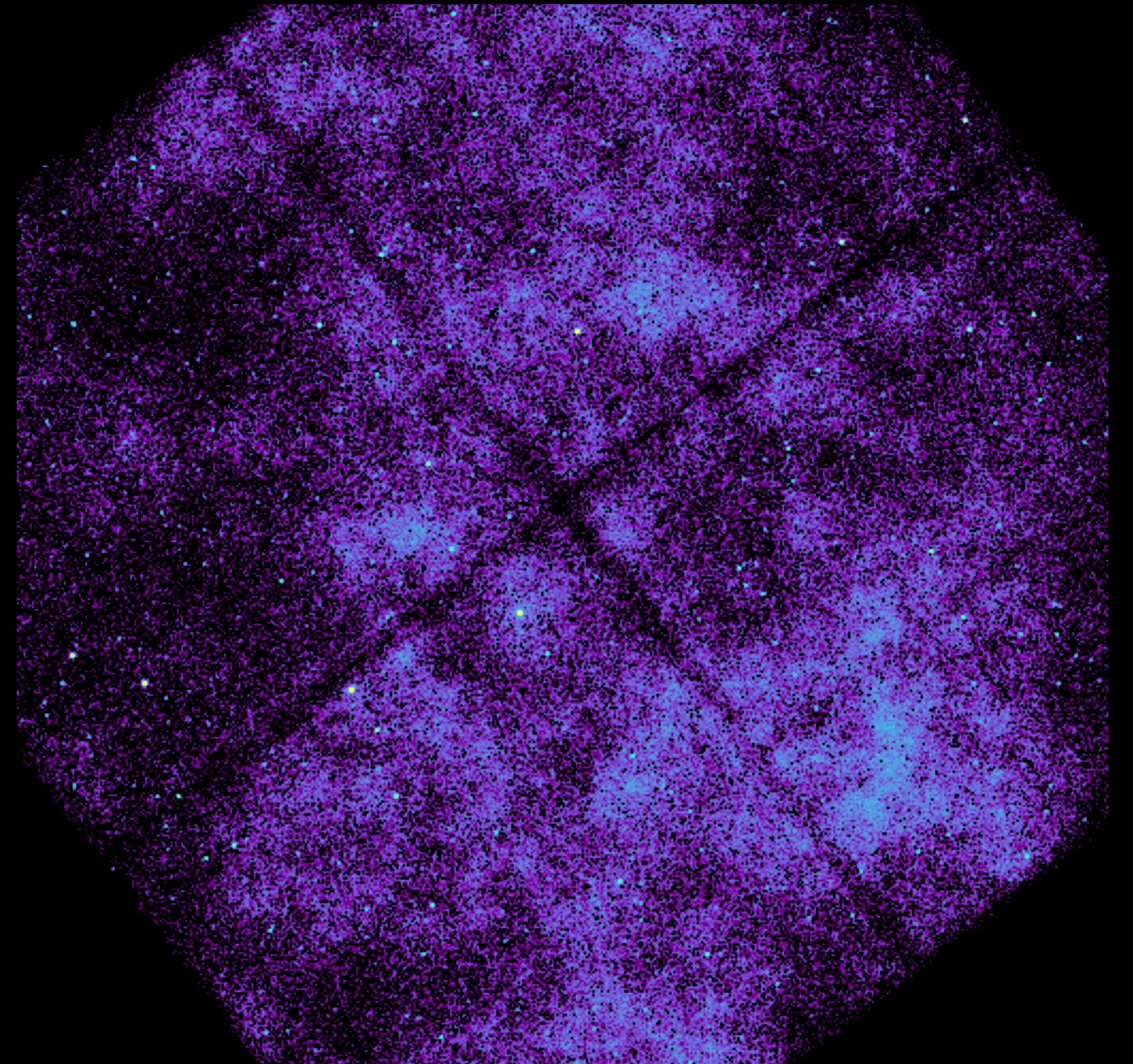
$$P(d|\lambda) = \prod_{i=1}^N \frac{\lambda_i^{d_i} e^{-\lambda_i}}{d_i!}$$



The Data



Chandra SNR G299.2-2.9 data



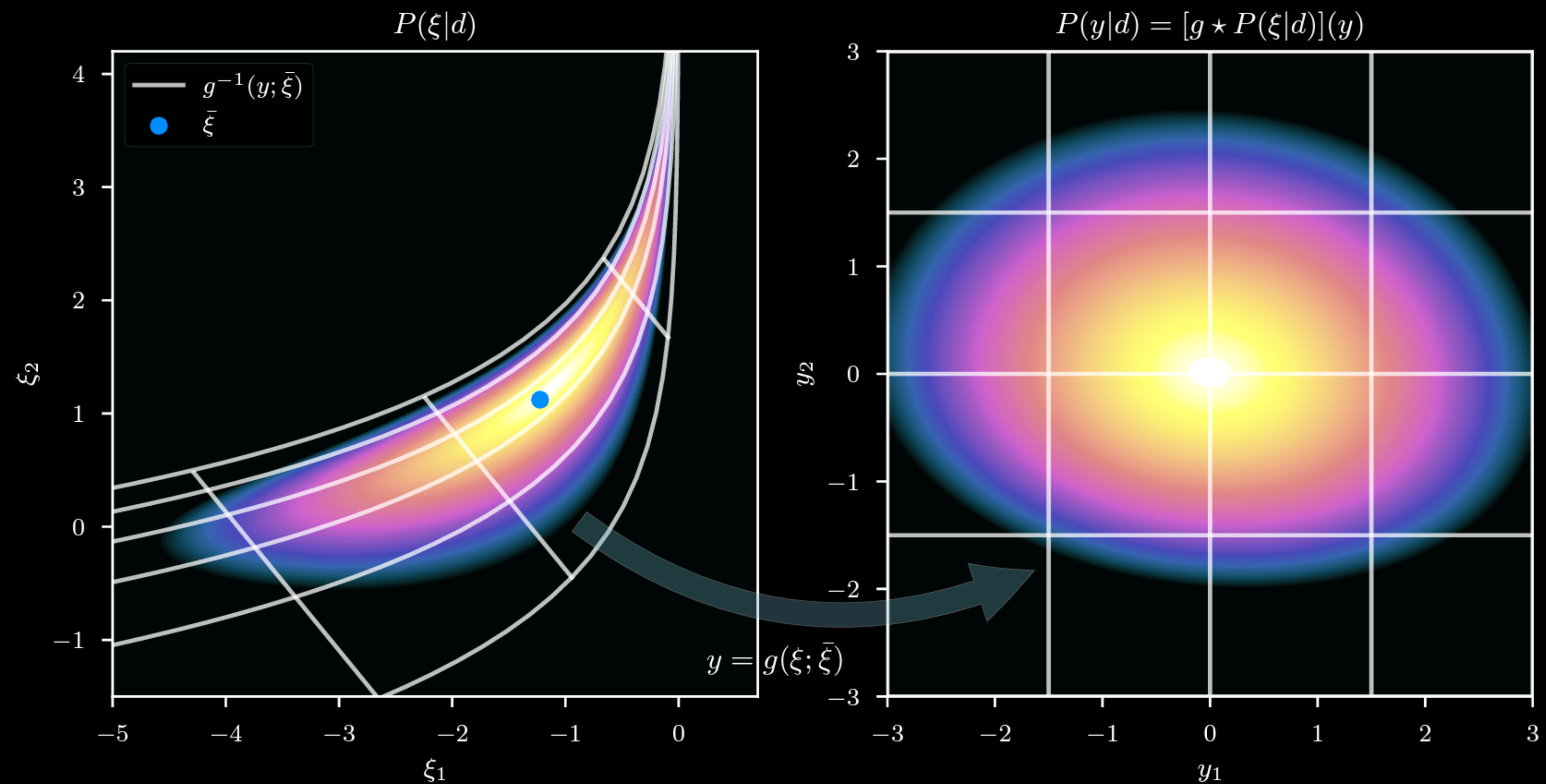
Simulated Chandra data

The Posterior

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

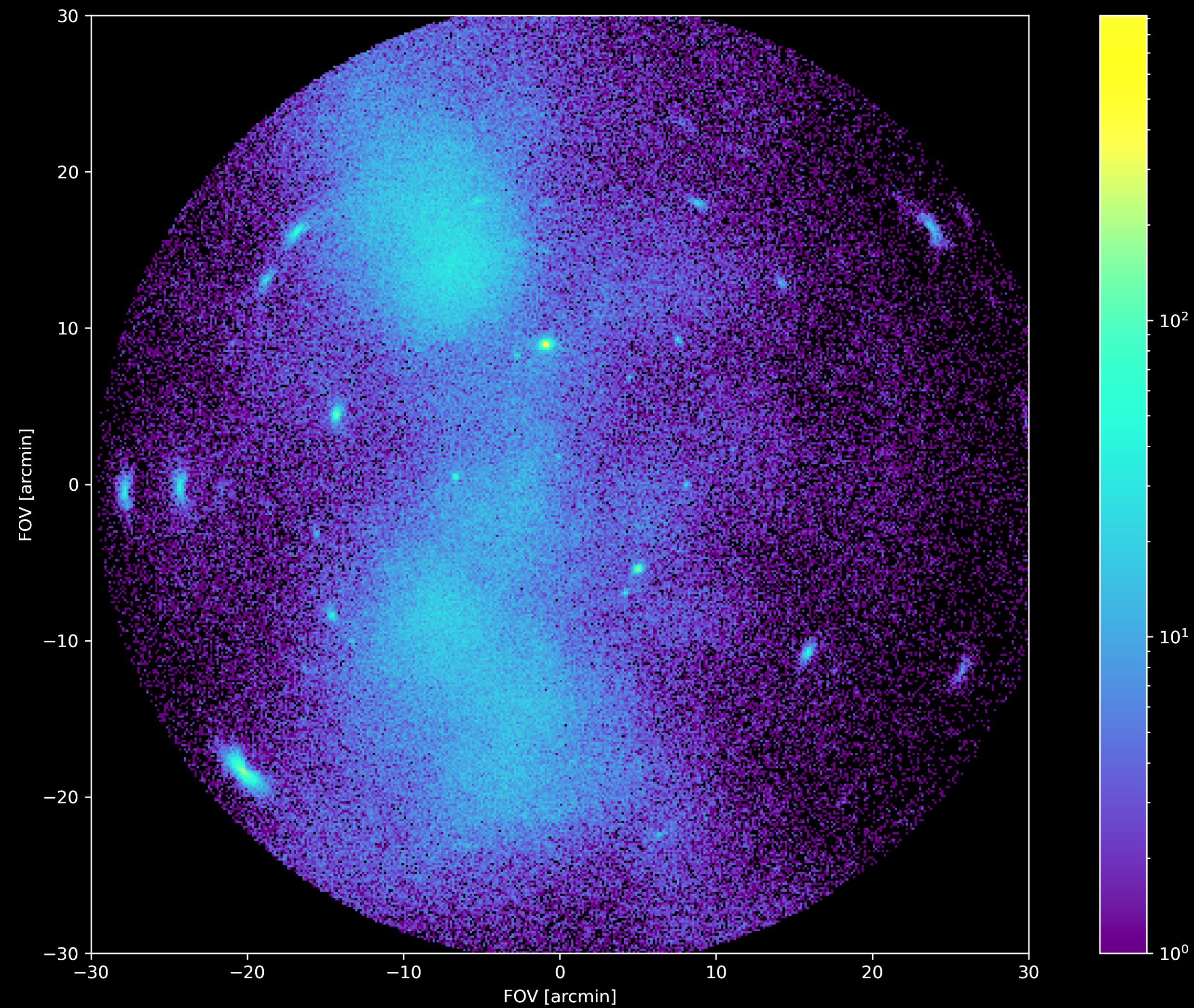
Inference

geometric Variational Inference



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

The Data

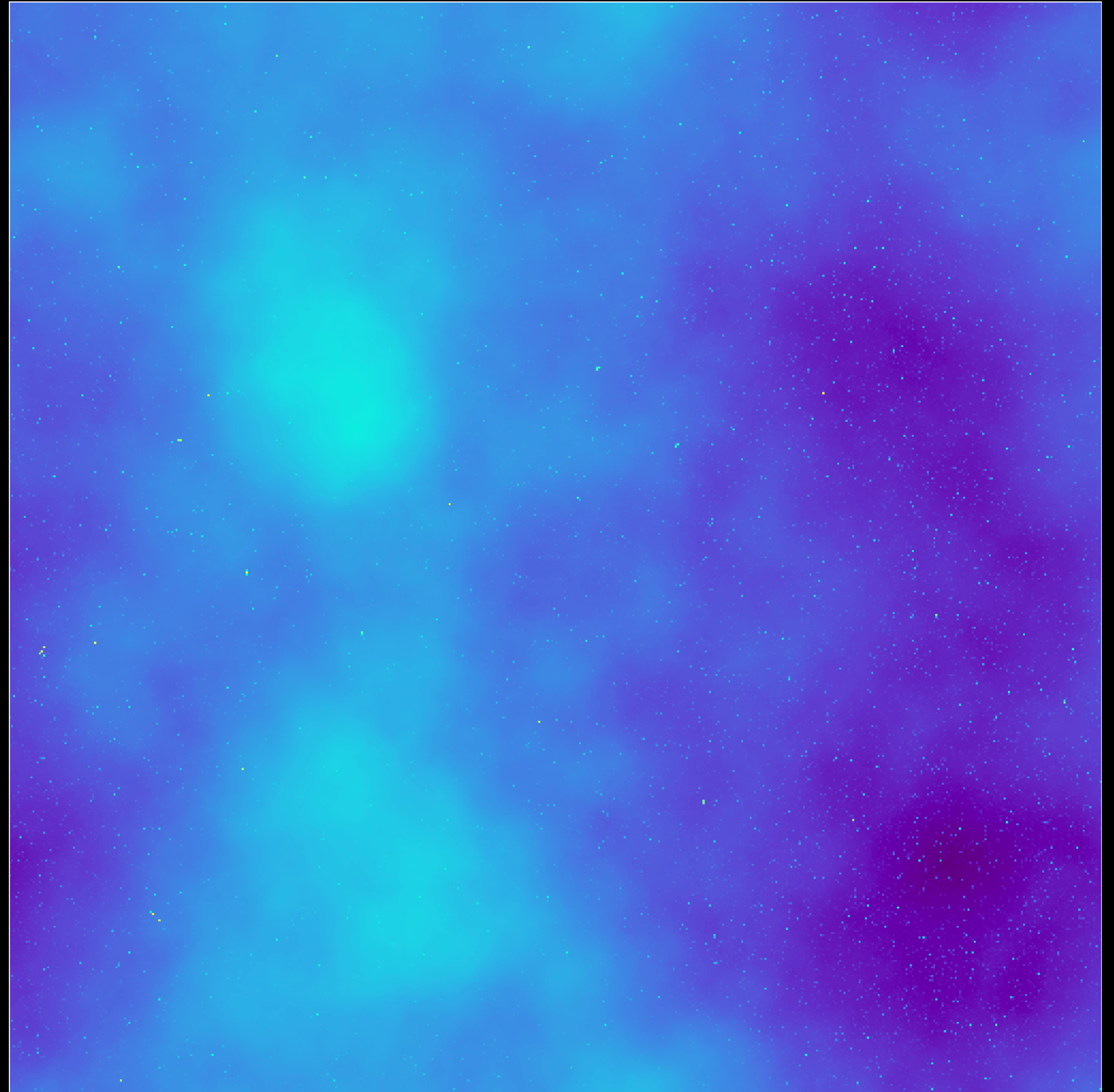


Simulated eROSITA TM1 data

Inference

Posterior

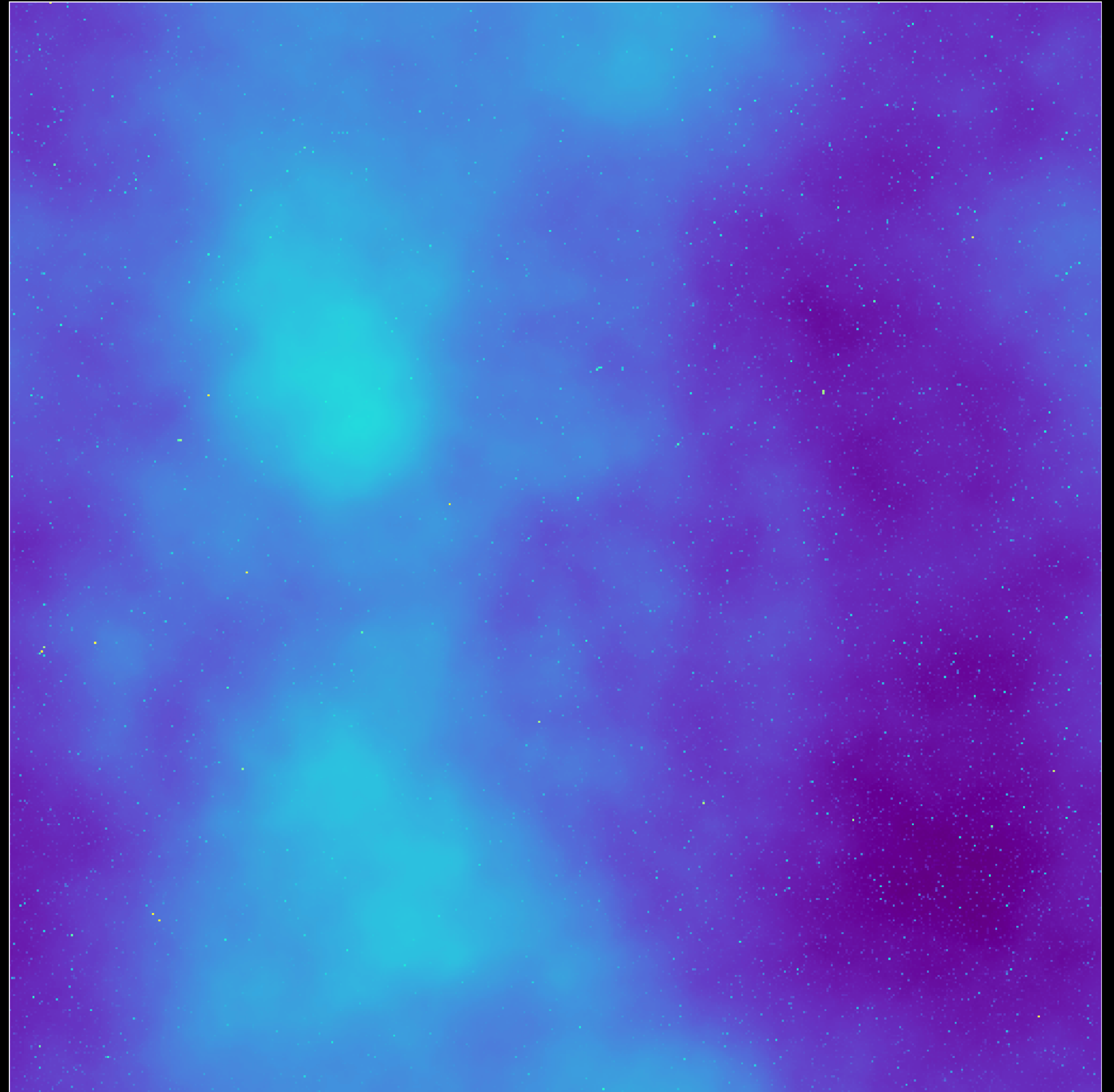
$$P(s \mid d)$$



Inference

Posterior

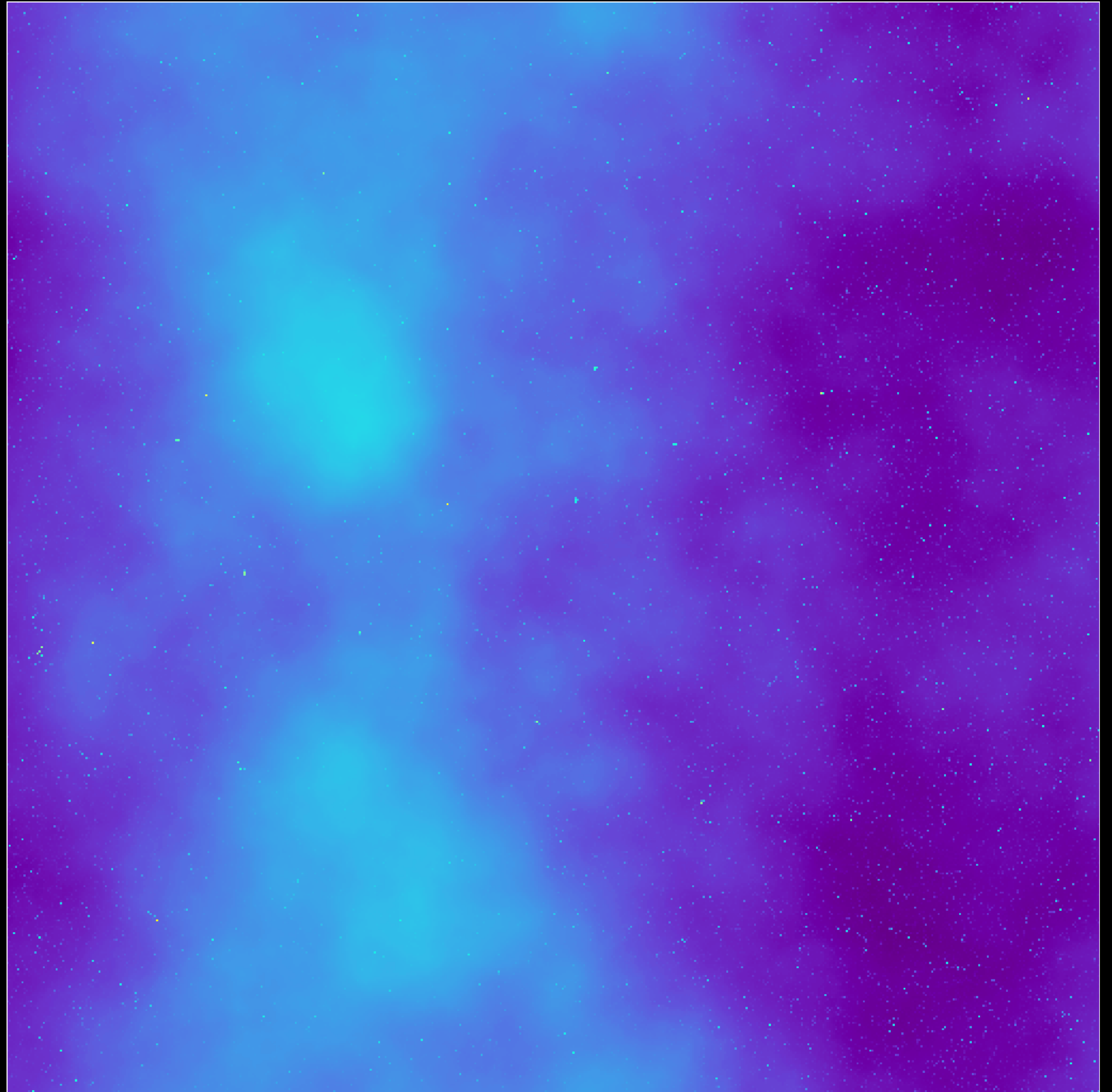
$$P(s \mid d)$$



Inference

Posterior

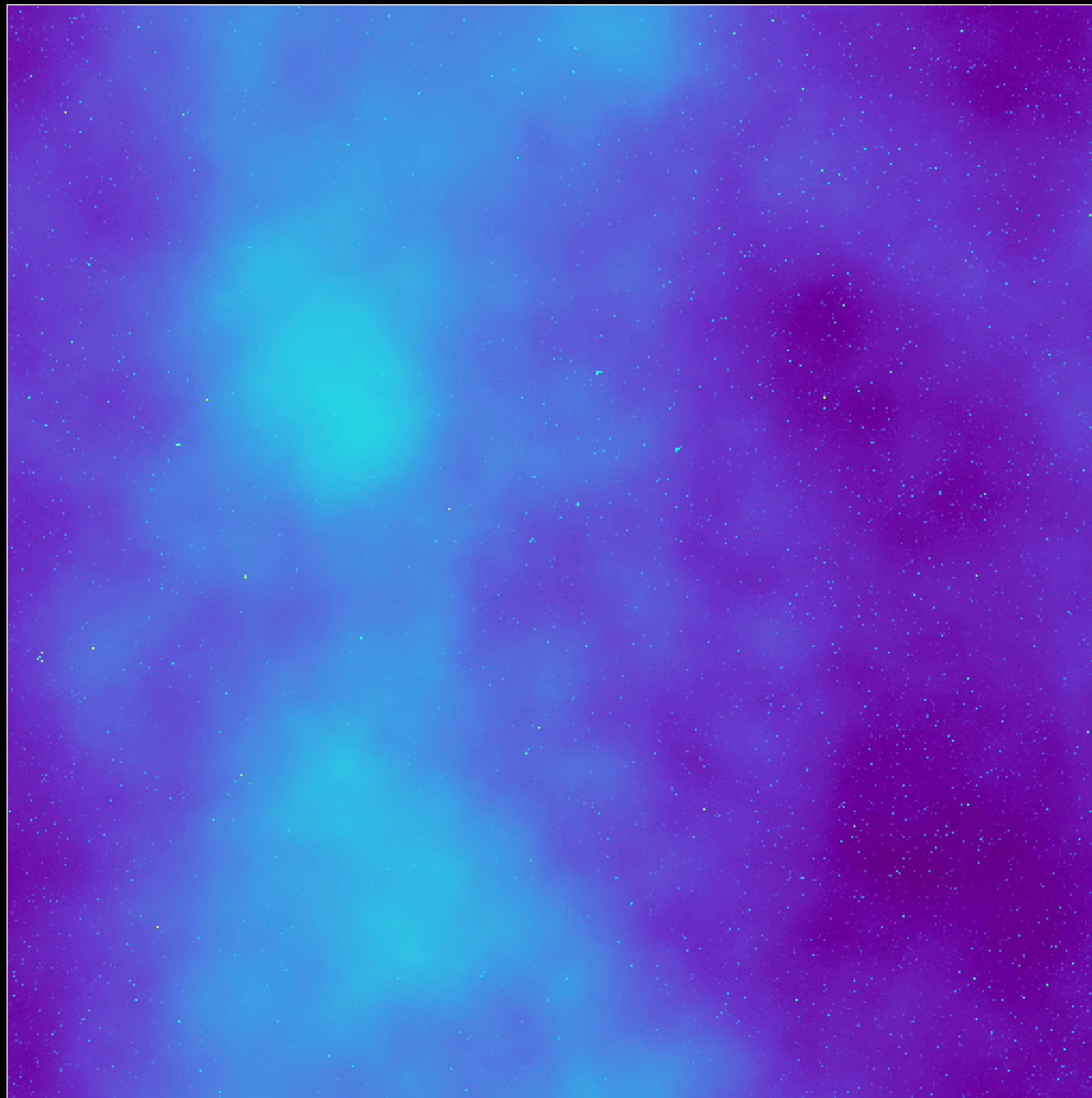
$$P(s \mid d)$$



Inference

Posterior

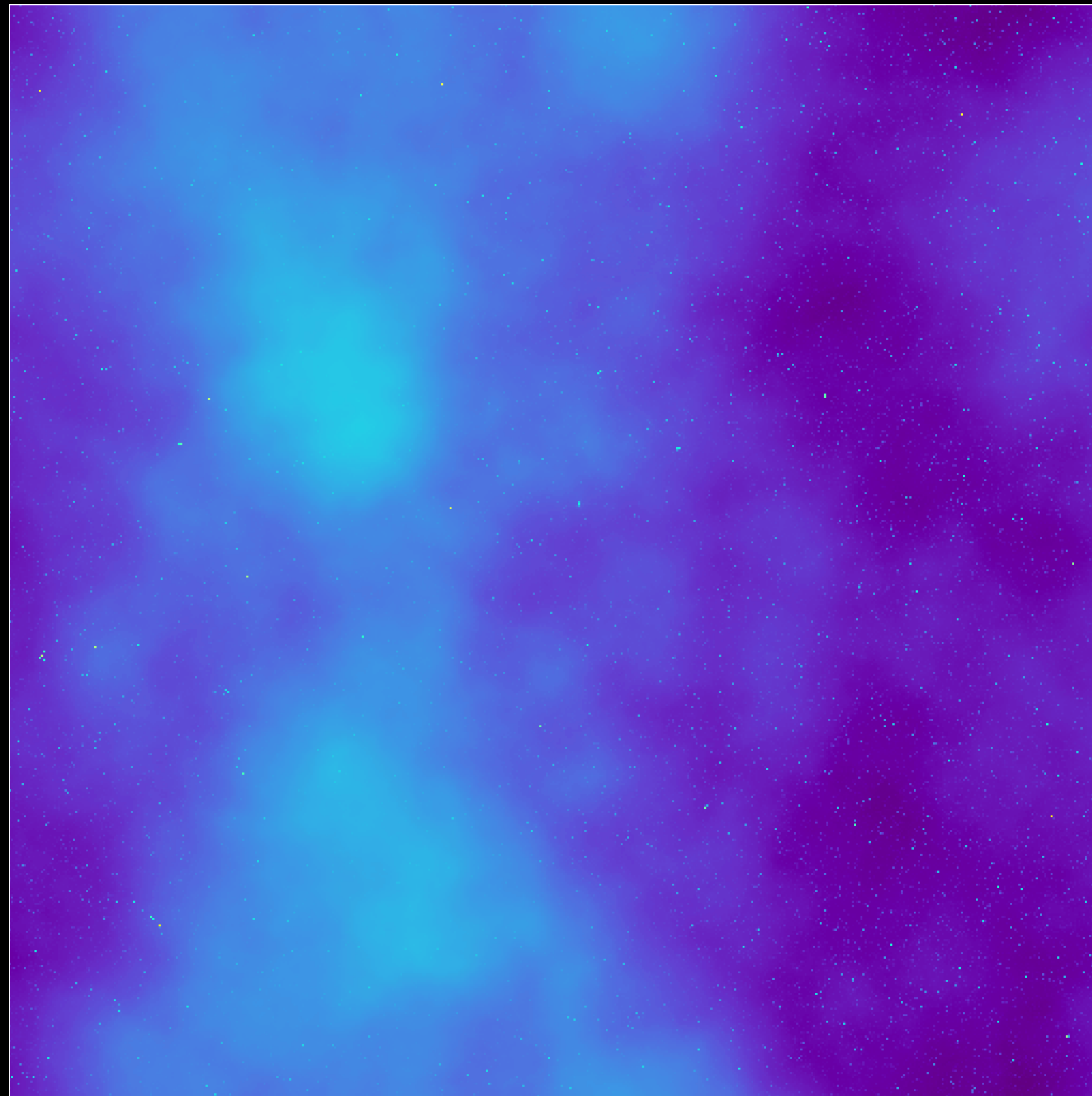
$$P(s \mid d)$$



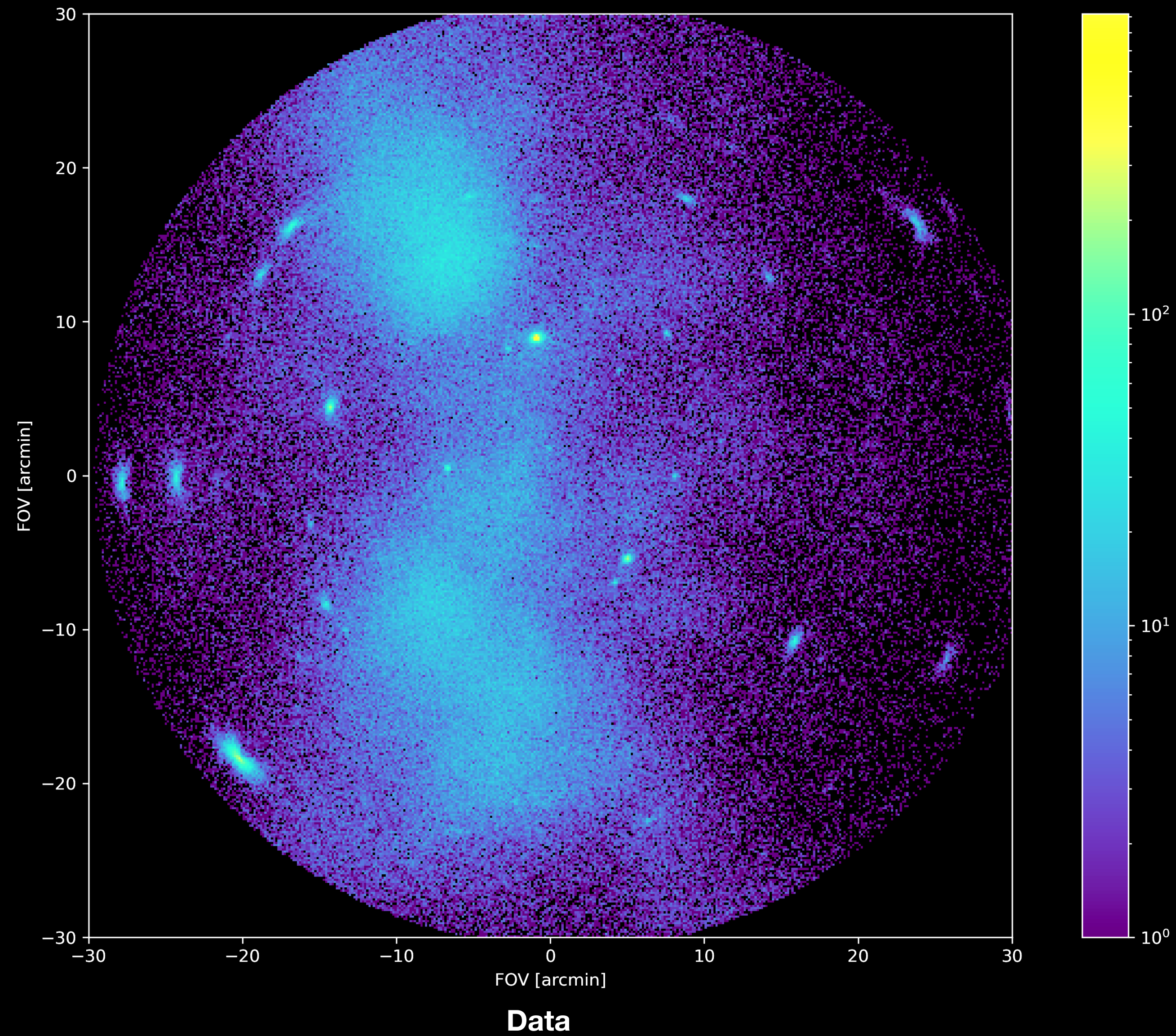
Inference

Posterior

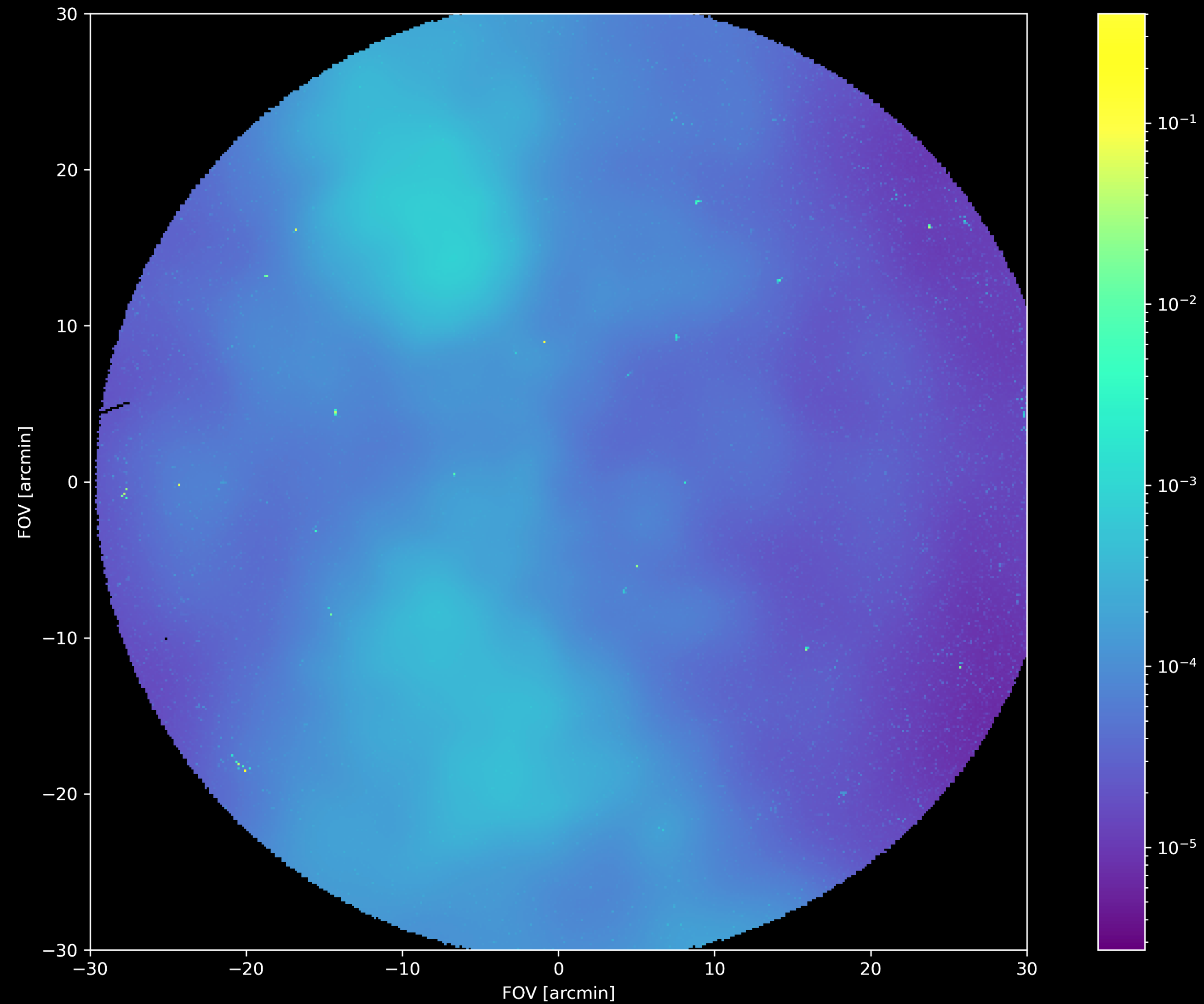
$$P(s \mid d)$$



Inference

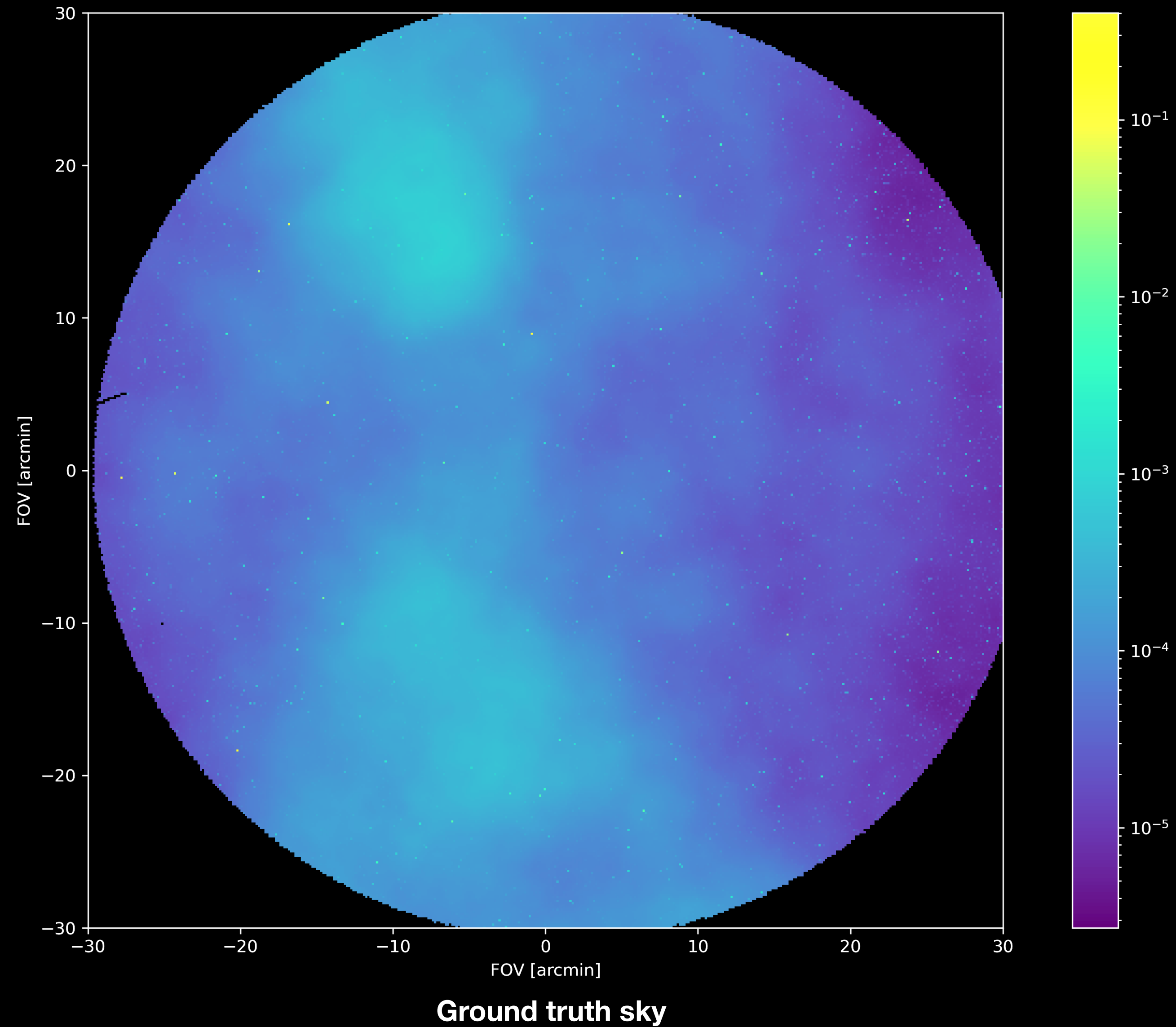


Inference

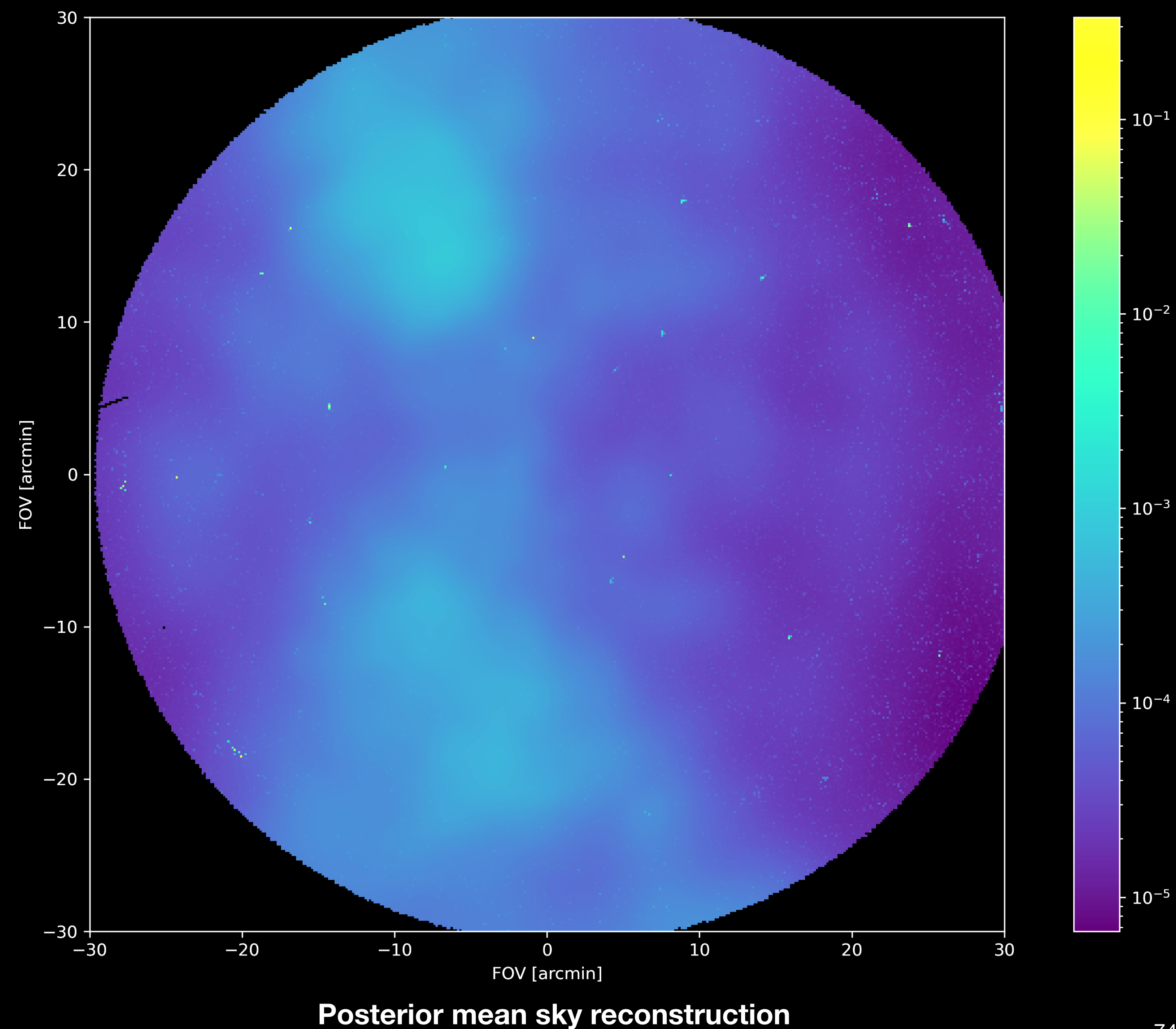
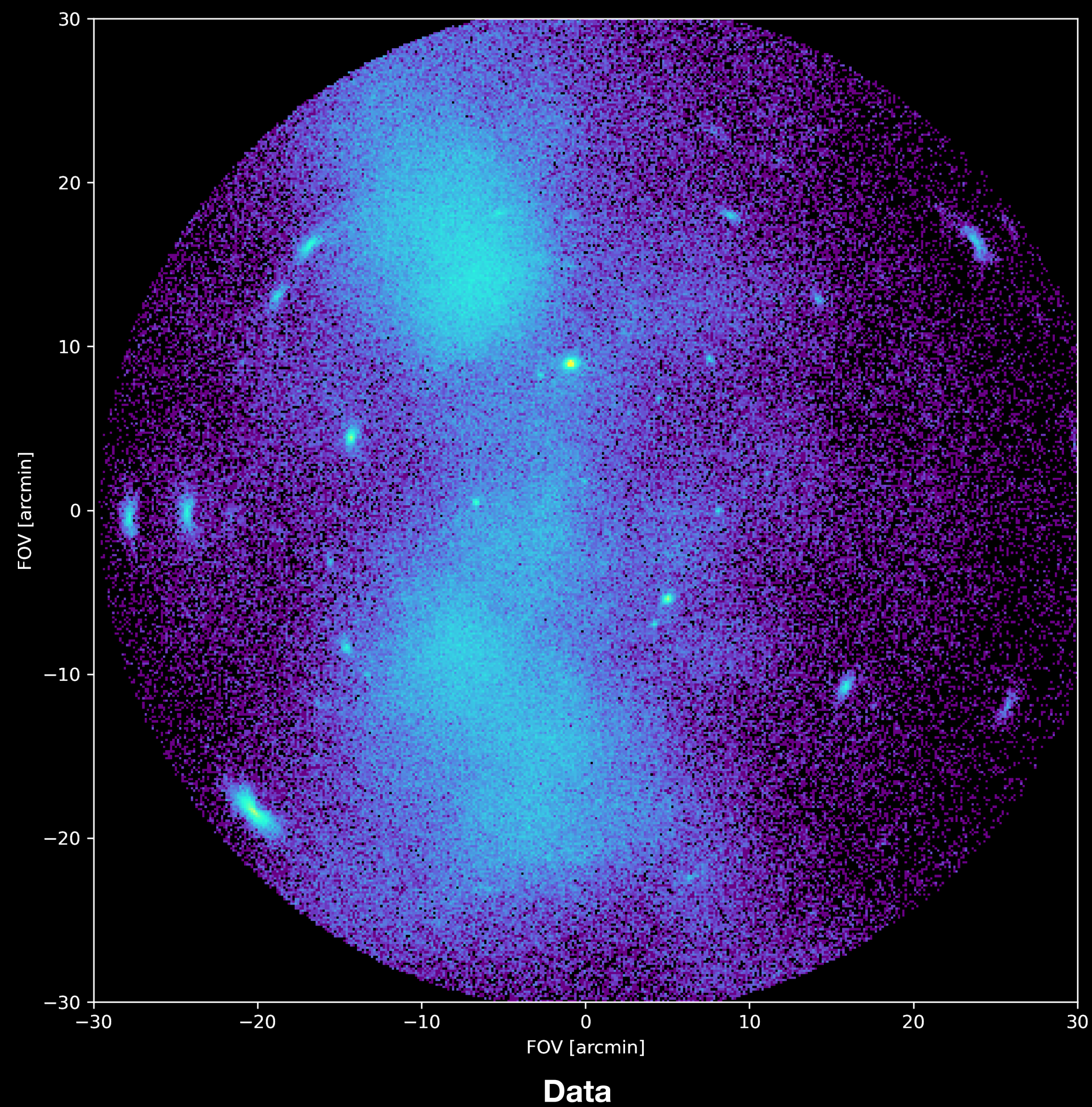


Posterior mean reconstructed sky

Inference



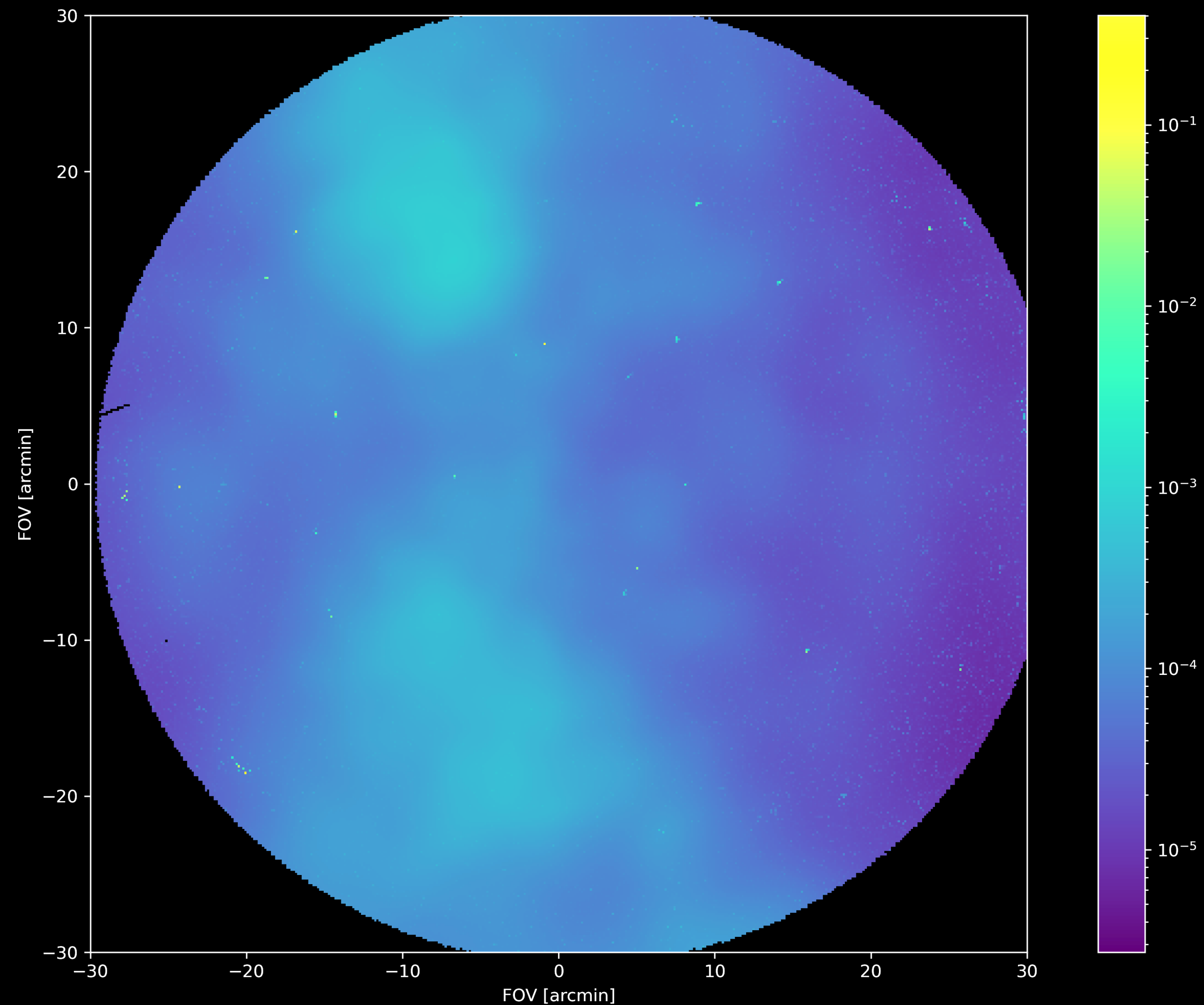
Inference



Point source detection

Point source detection

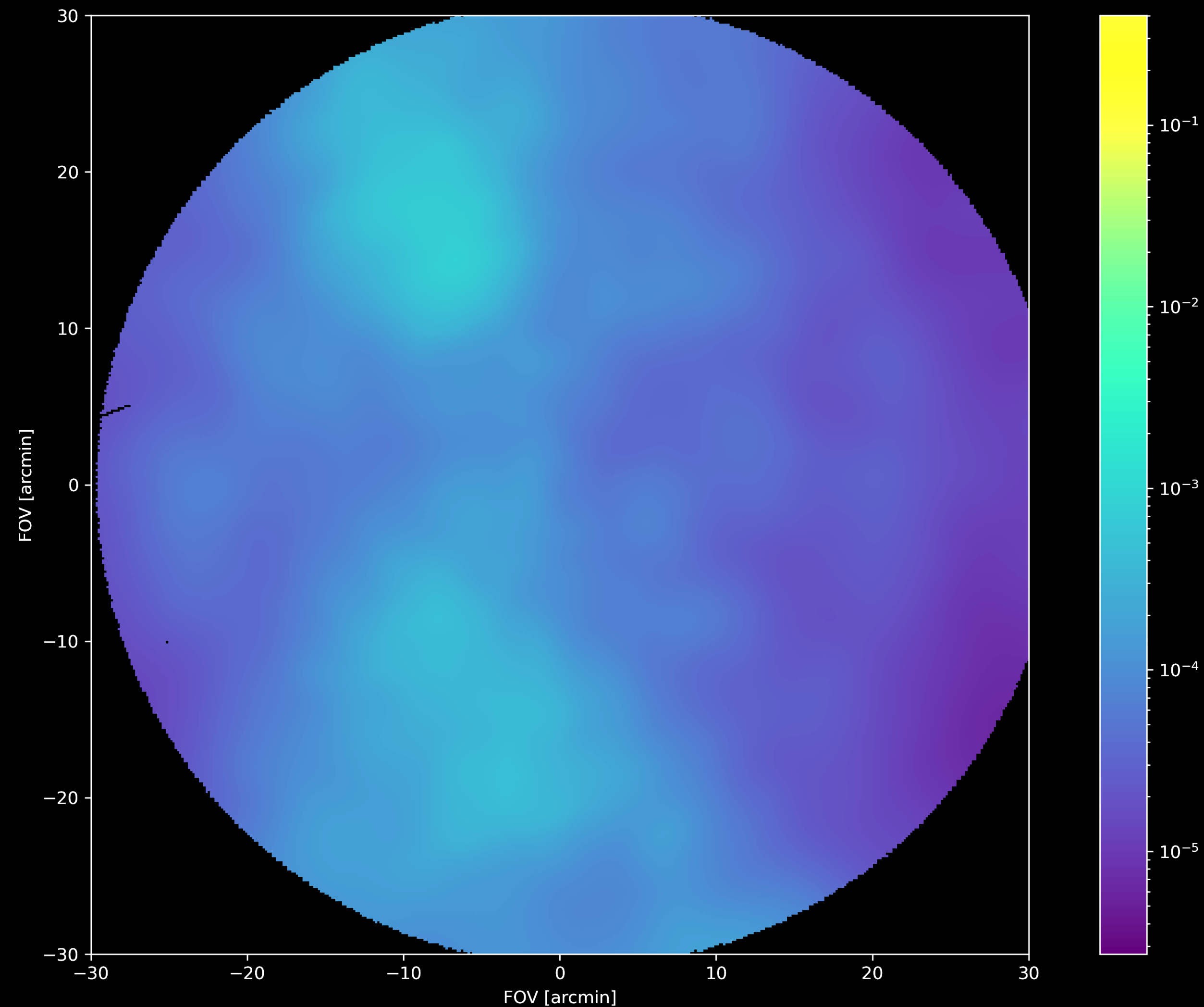
Component separation



Posterior mean sky reconstruction

Point source detection

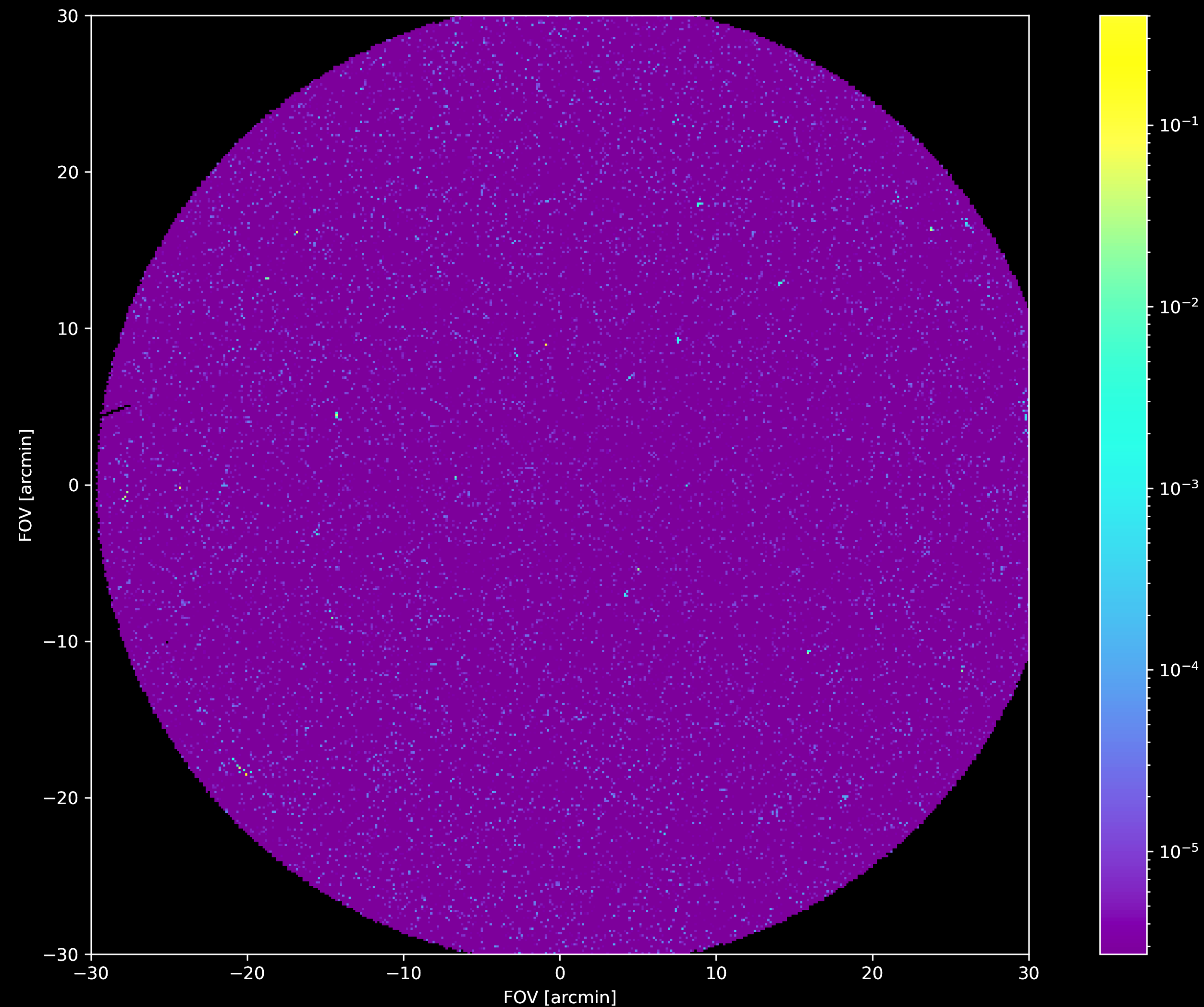
Component separation



Posterior mean diffuse reconstruction

Point source detection

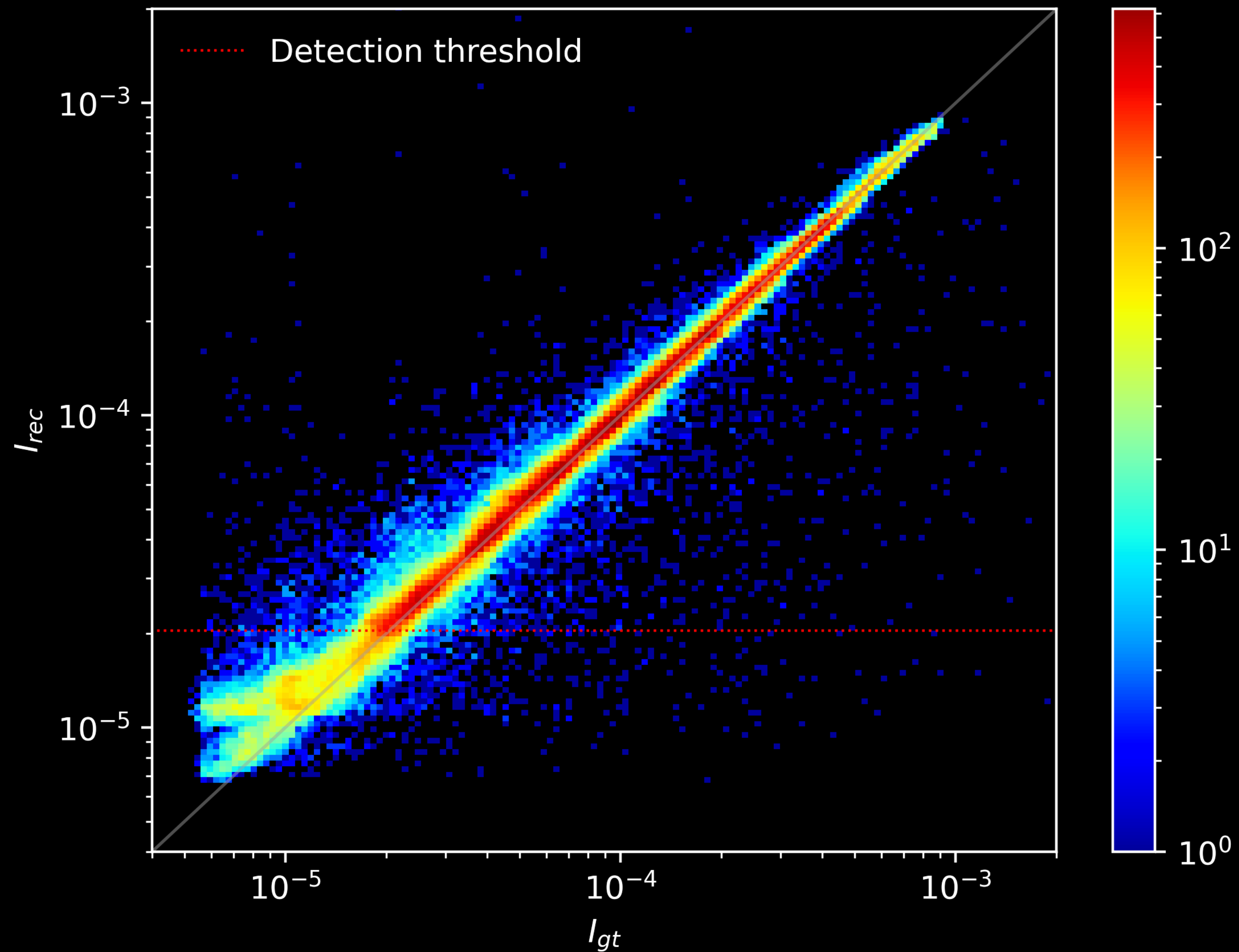
Component separation



Posterior mean point source reconstruction

Point source detection

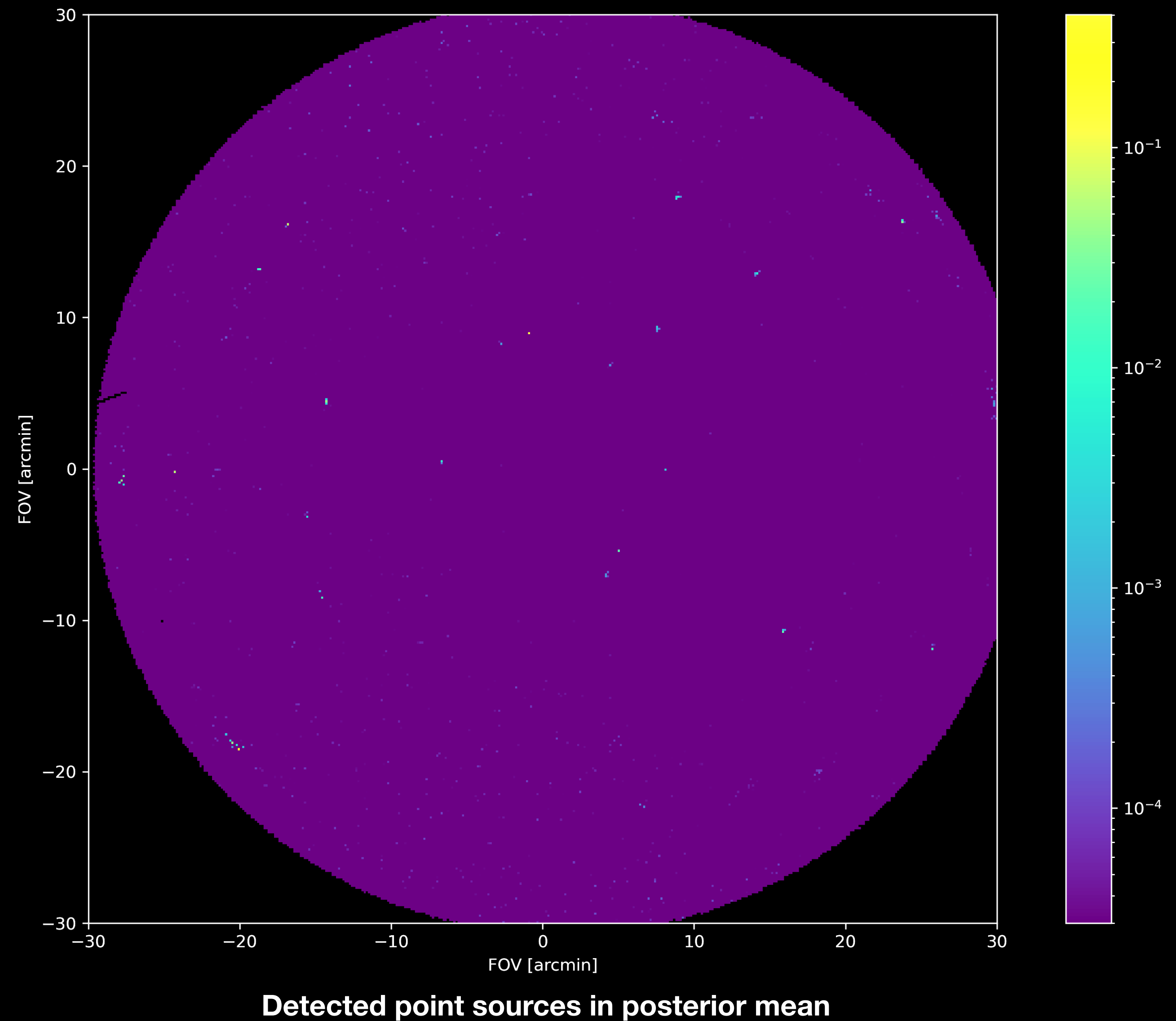
Detection thresholds from synthetic data



Point source detection

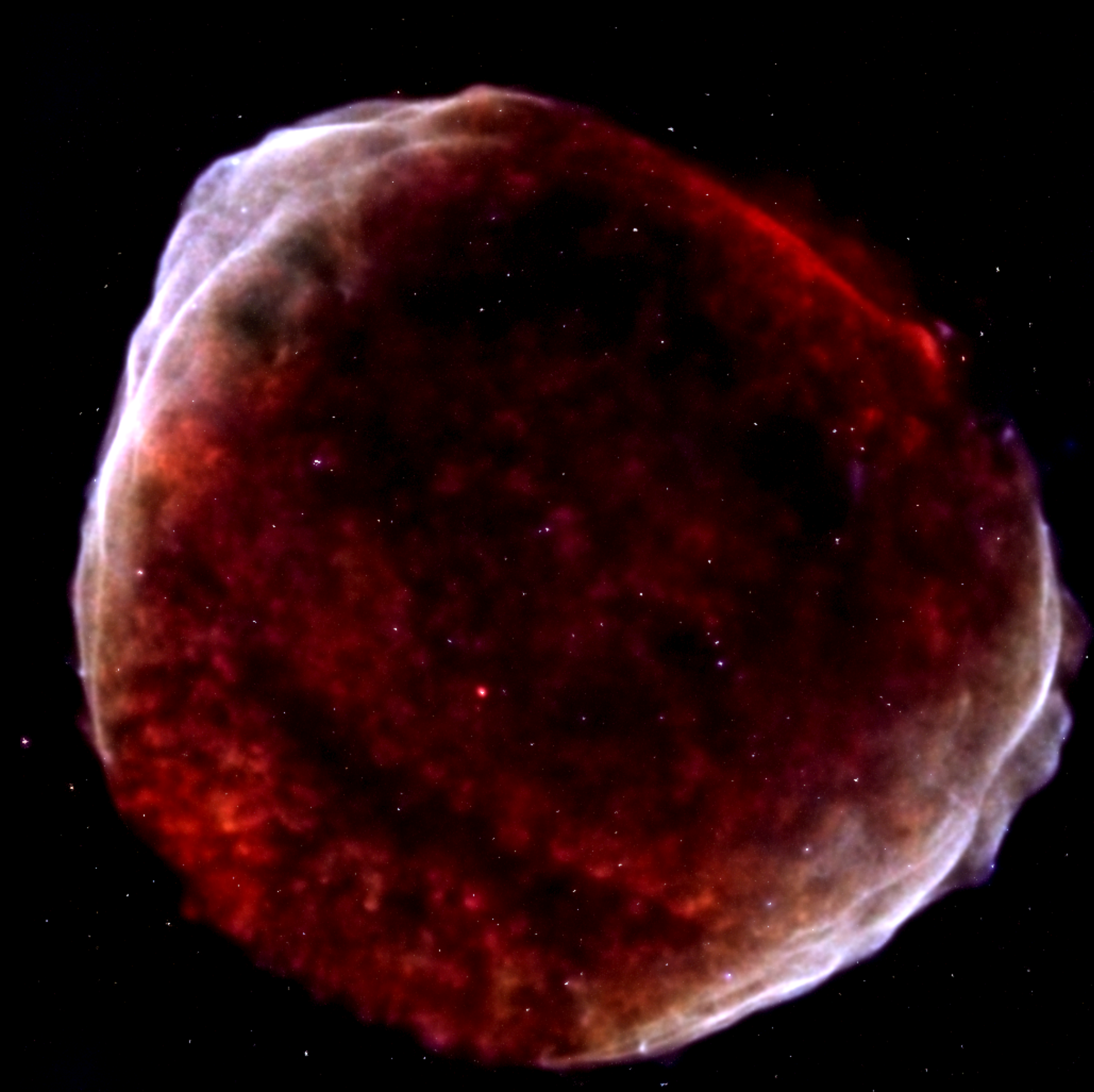
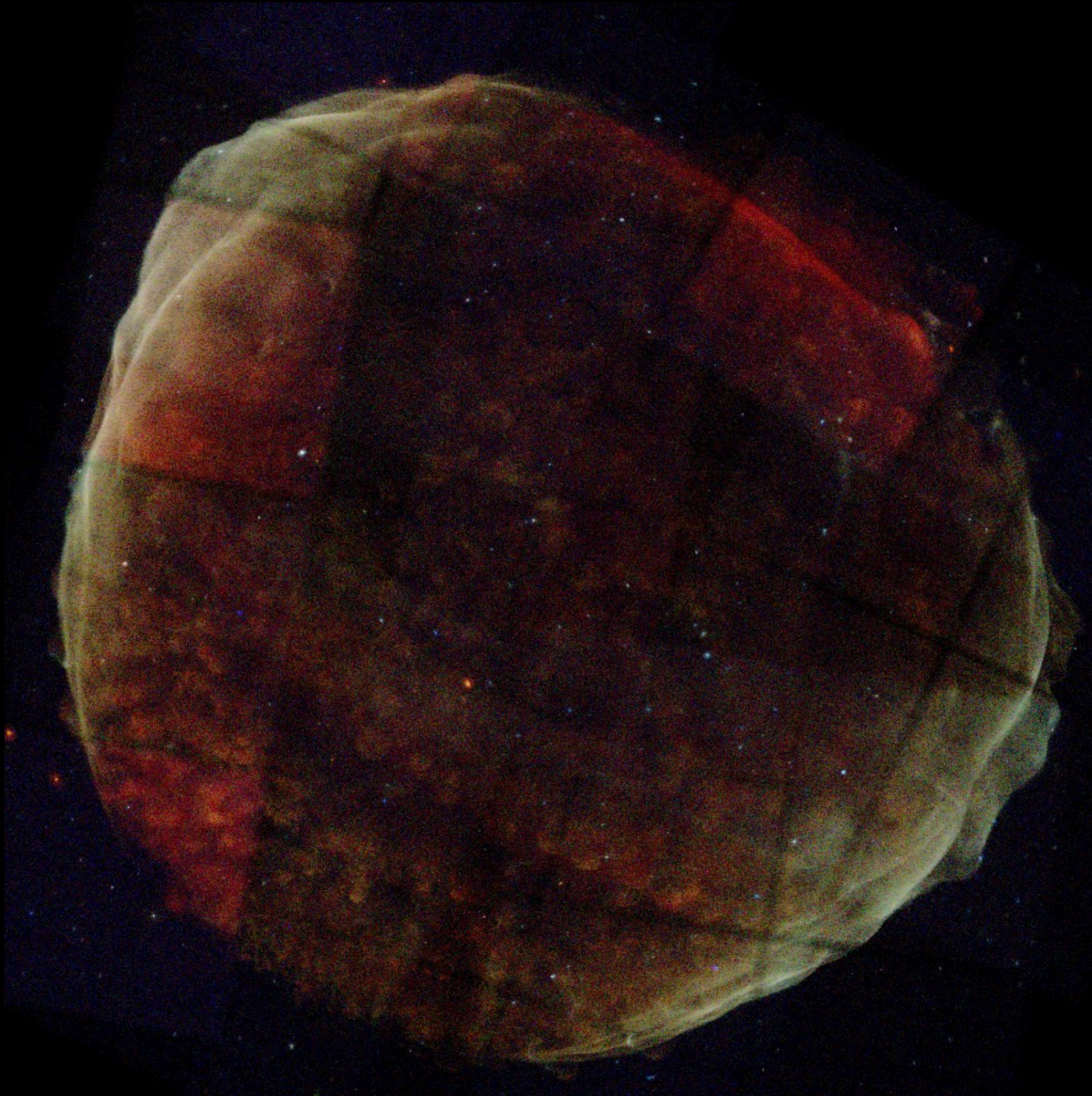
Issues?

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



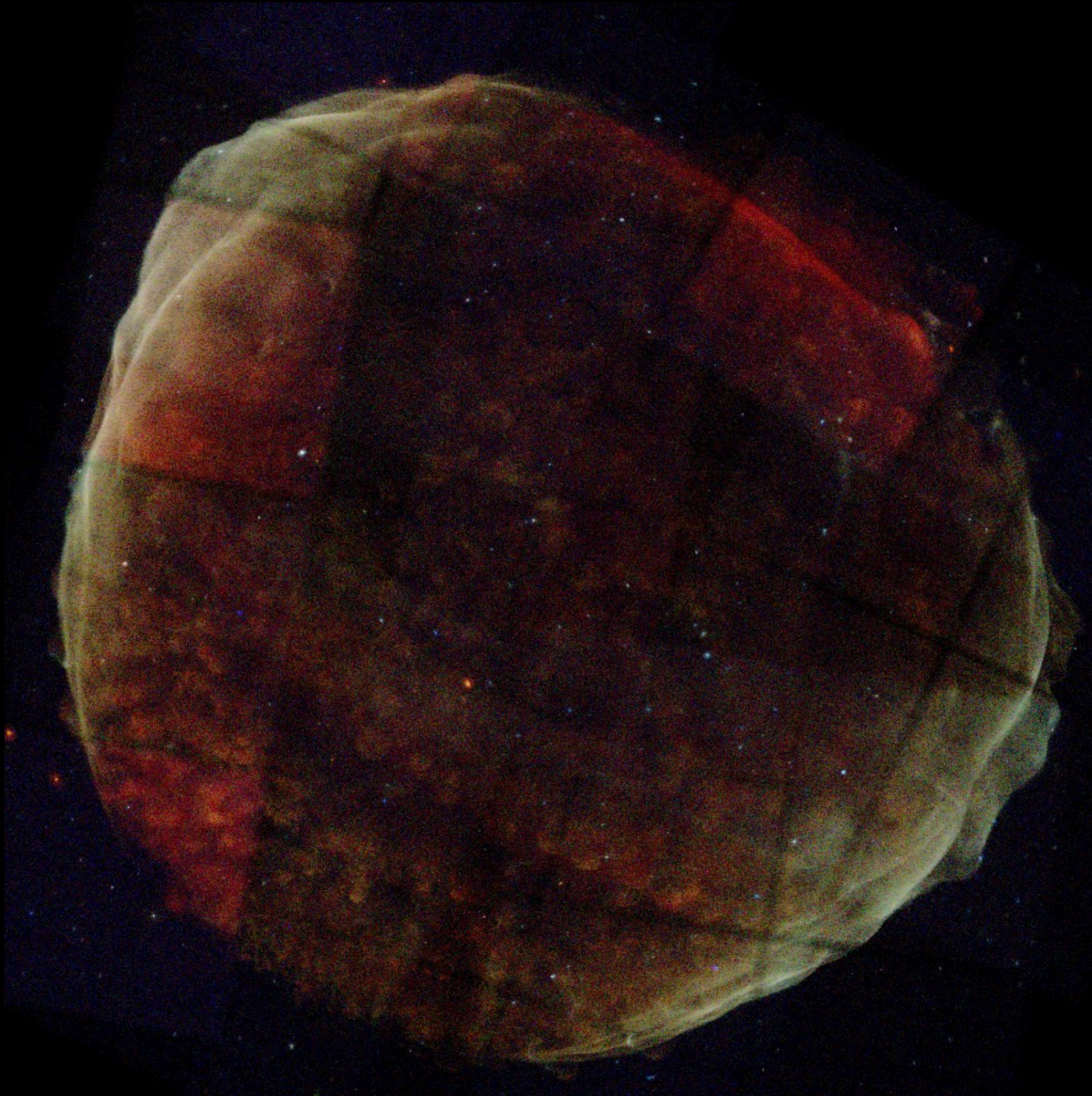
Point source detection

Detection thresholds from synthetic data



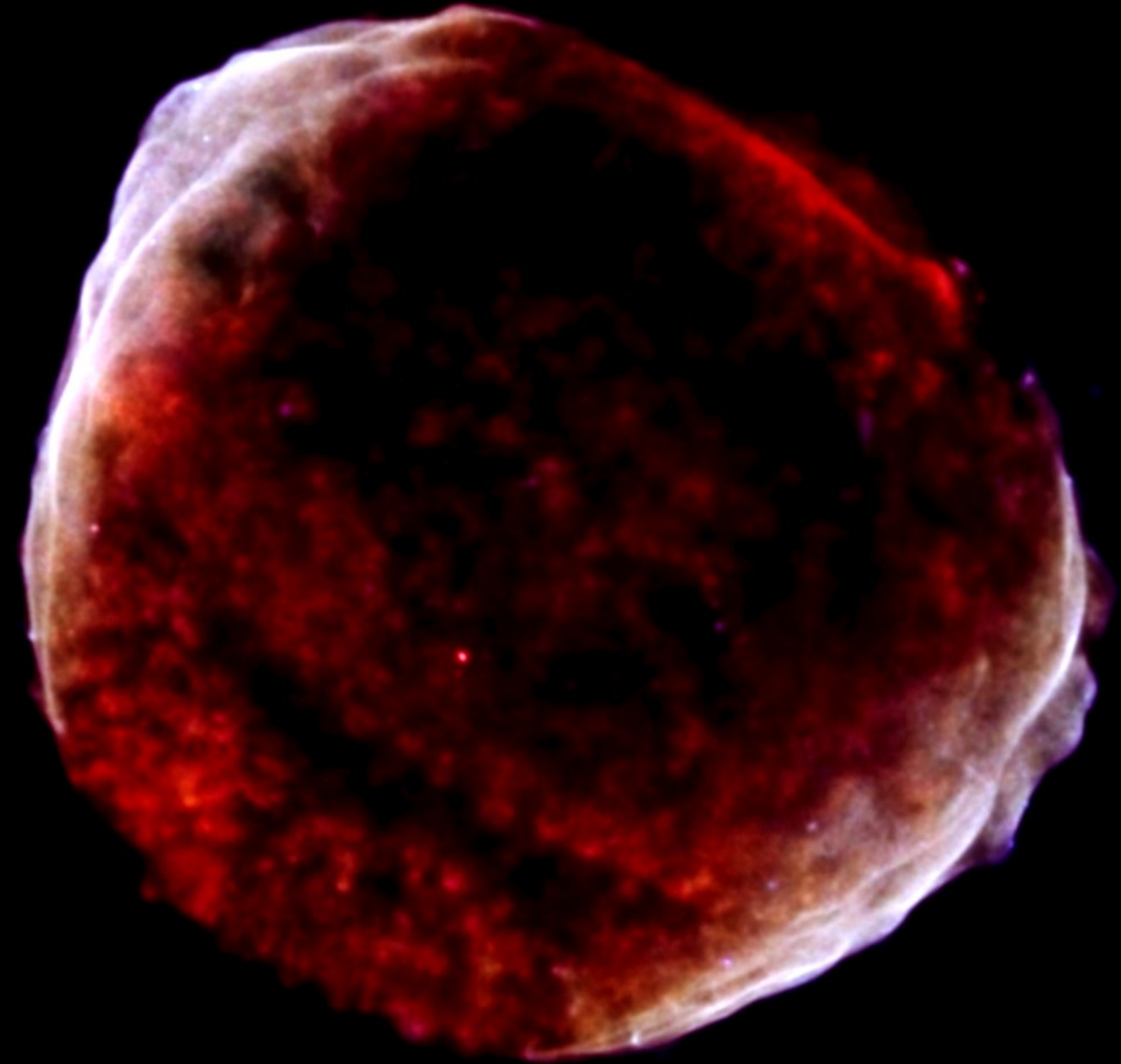
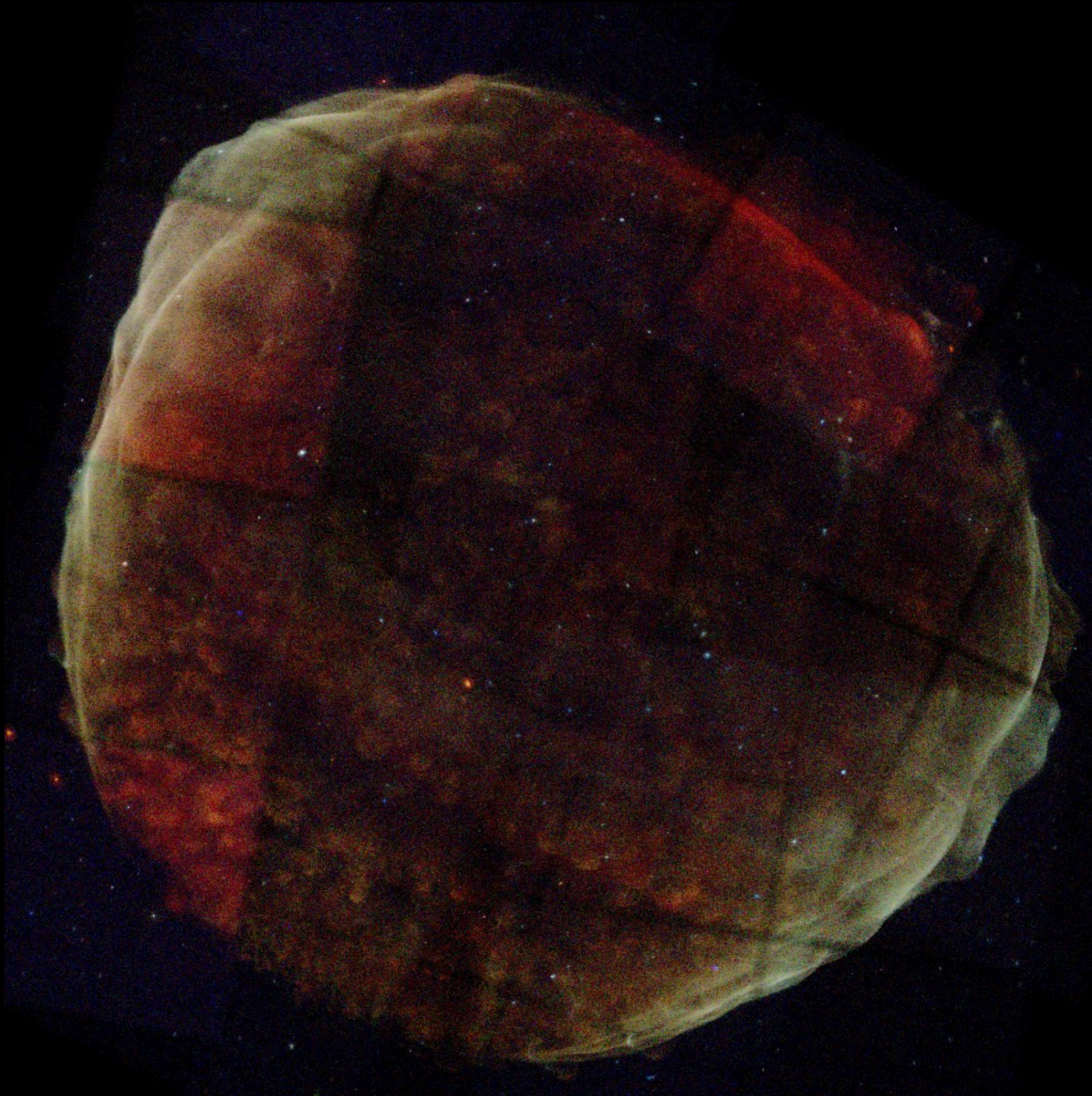
Point source detection

Detection thresholds from synthetic data



Point source detection

Detection thresholds from synthetic data

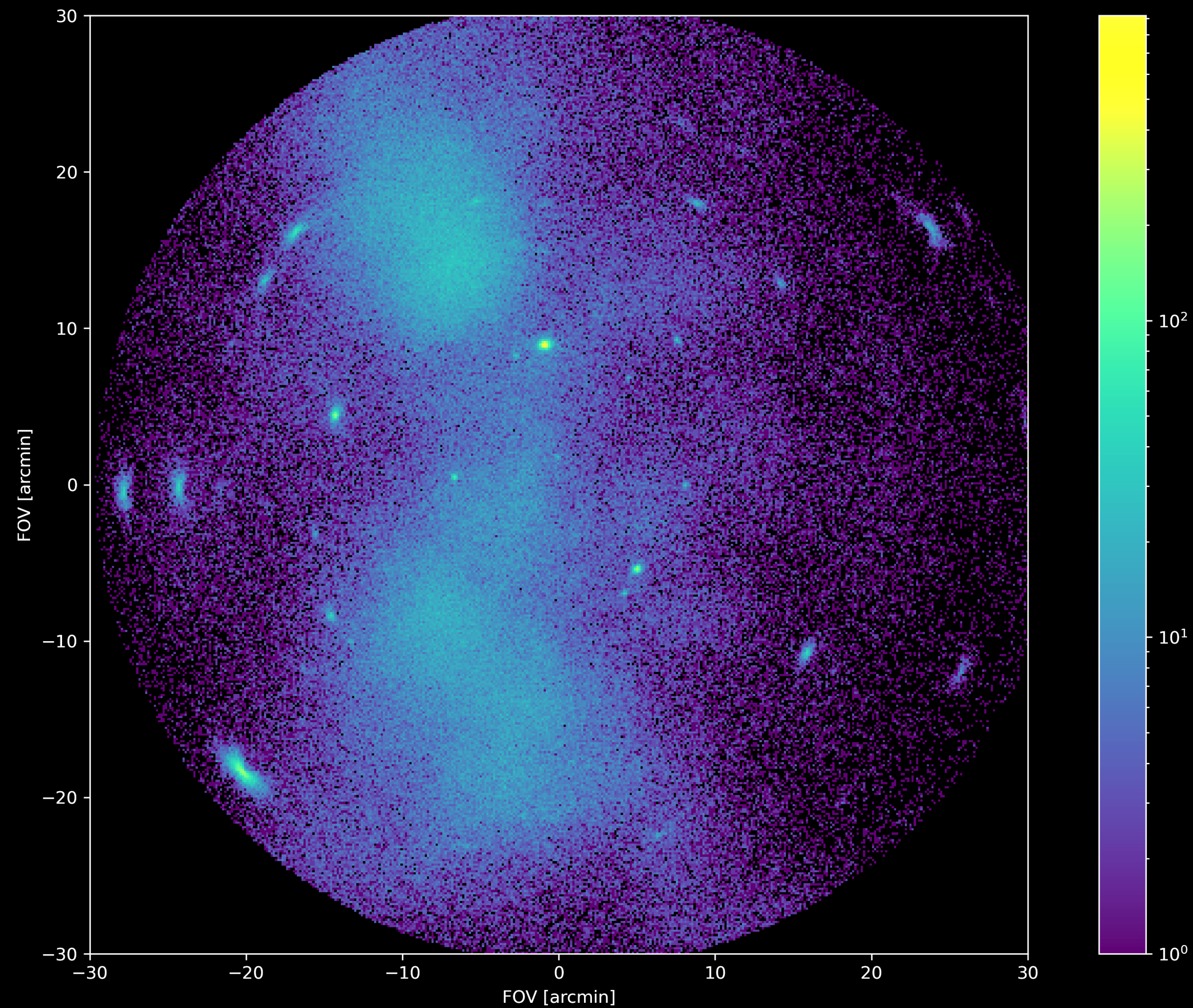


Automatic point source detection

Let's use a different model...

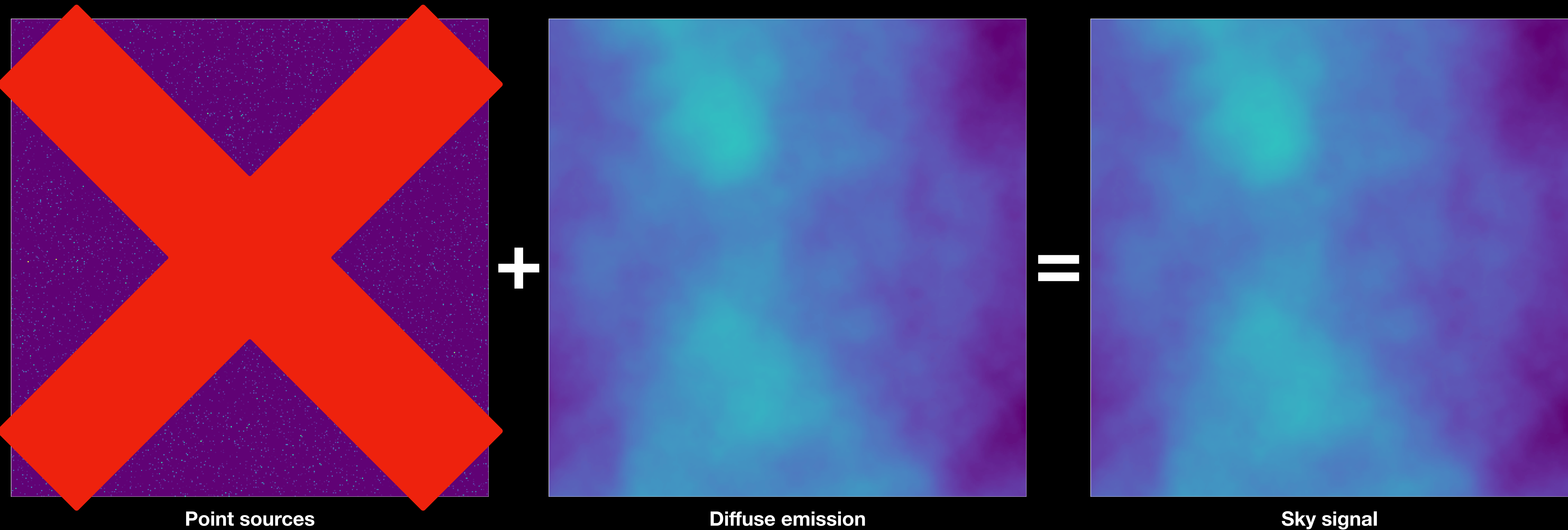
Point source detection

Diffuse-only fit



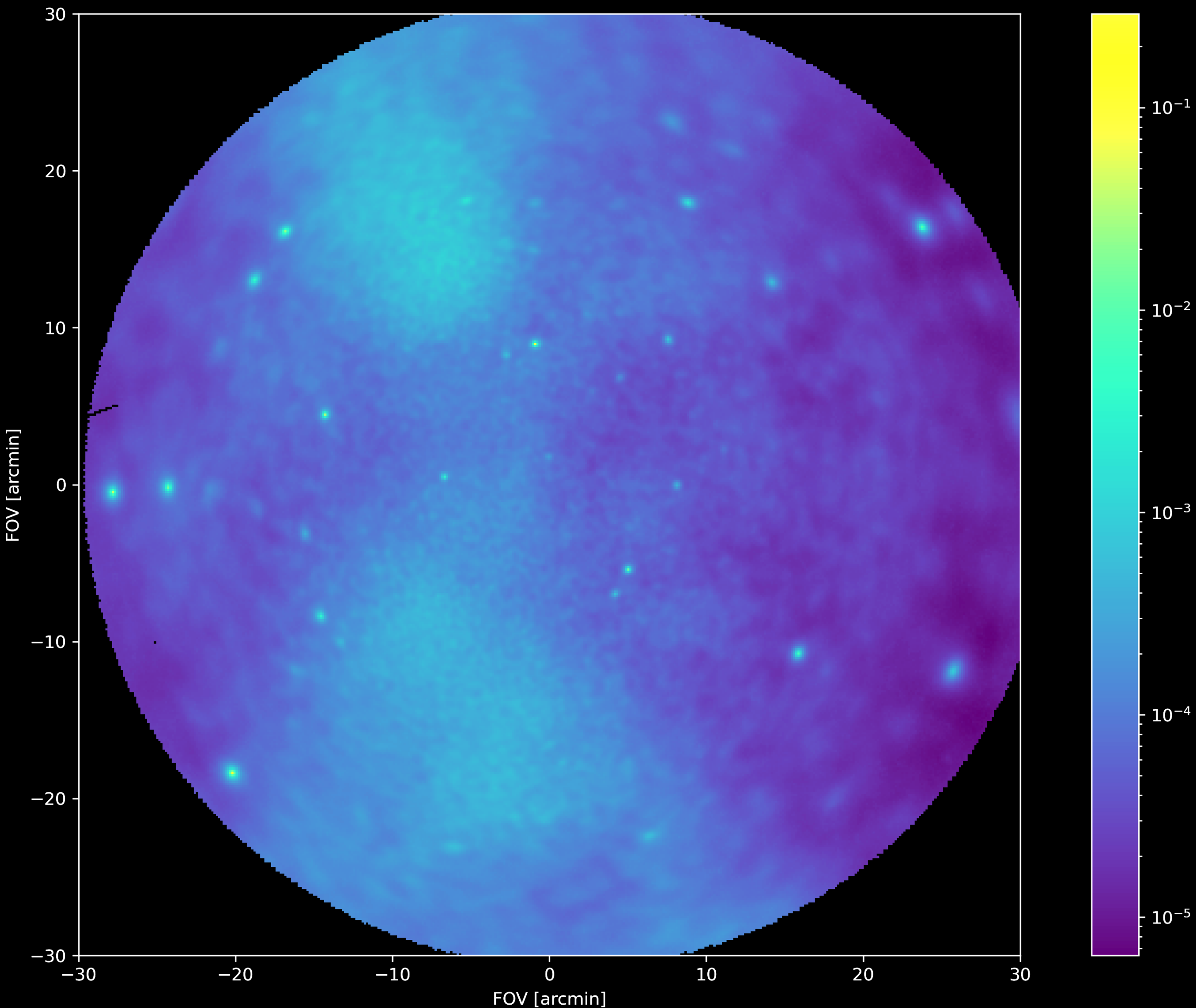
Point source detection

Diffuse-only fit



Point source detection

Diffuse-only fit



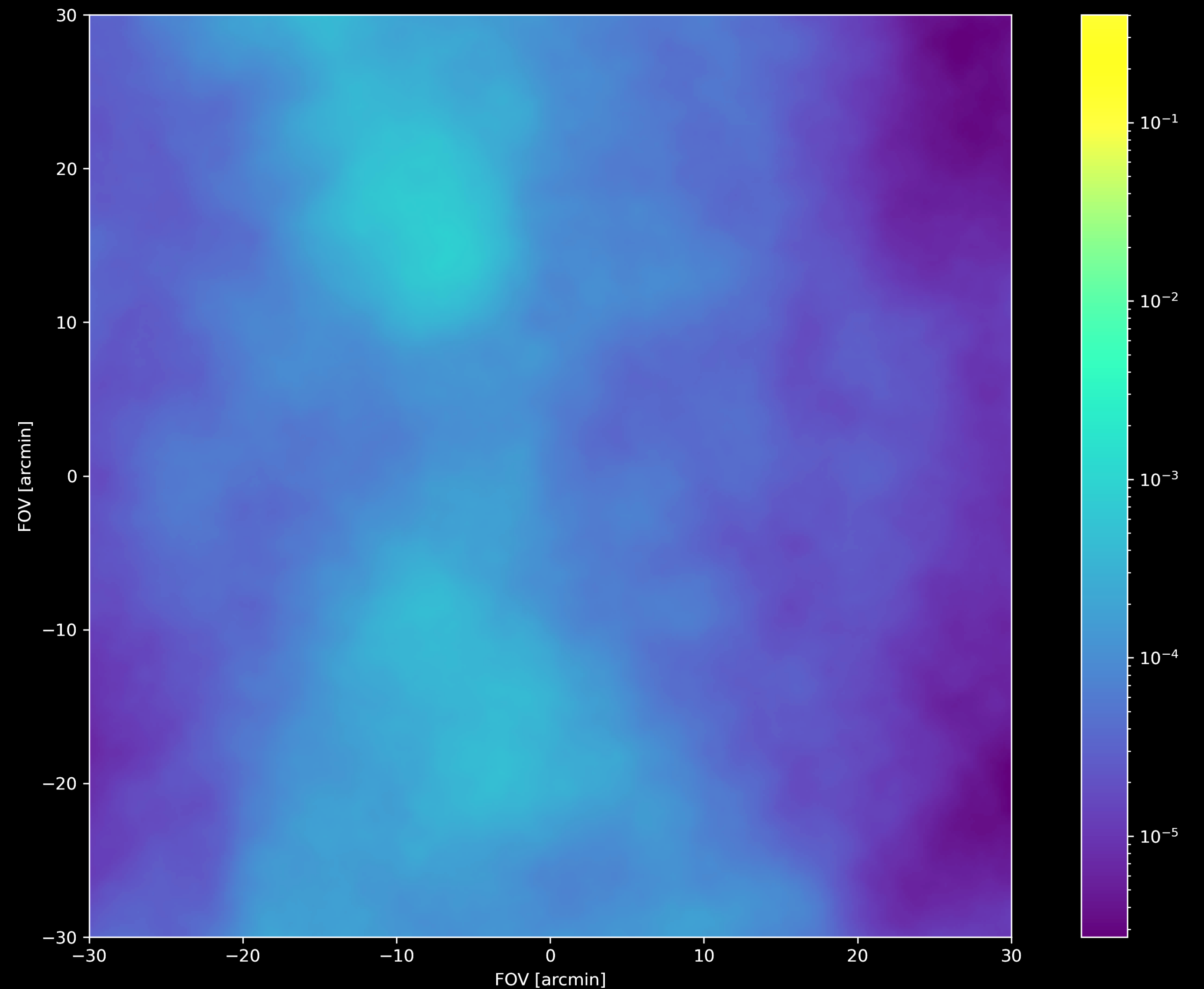
Posterior mean diffuse-only reconstruction

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

Point source detection

Diffuse prior model

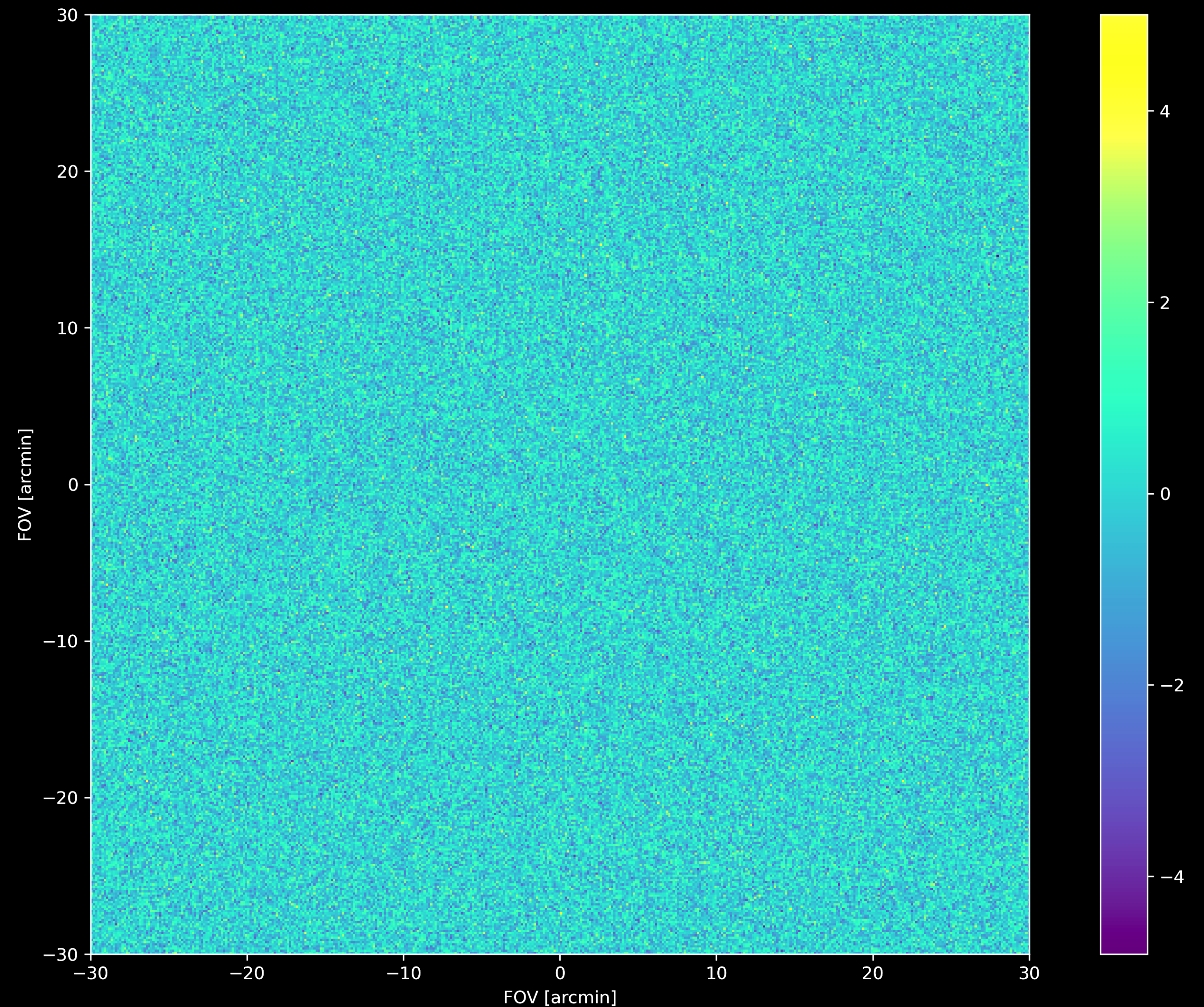
$$P(s) = \mathcal{N}(\mathbf{0}, \mathbb{I}) \star A(x, y)$$



Point source detection

Model stress?

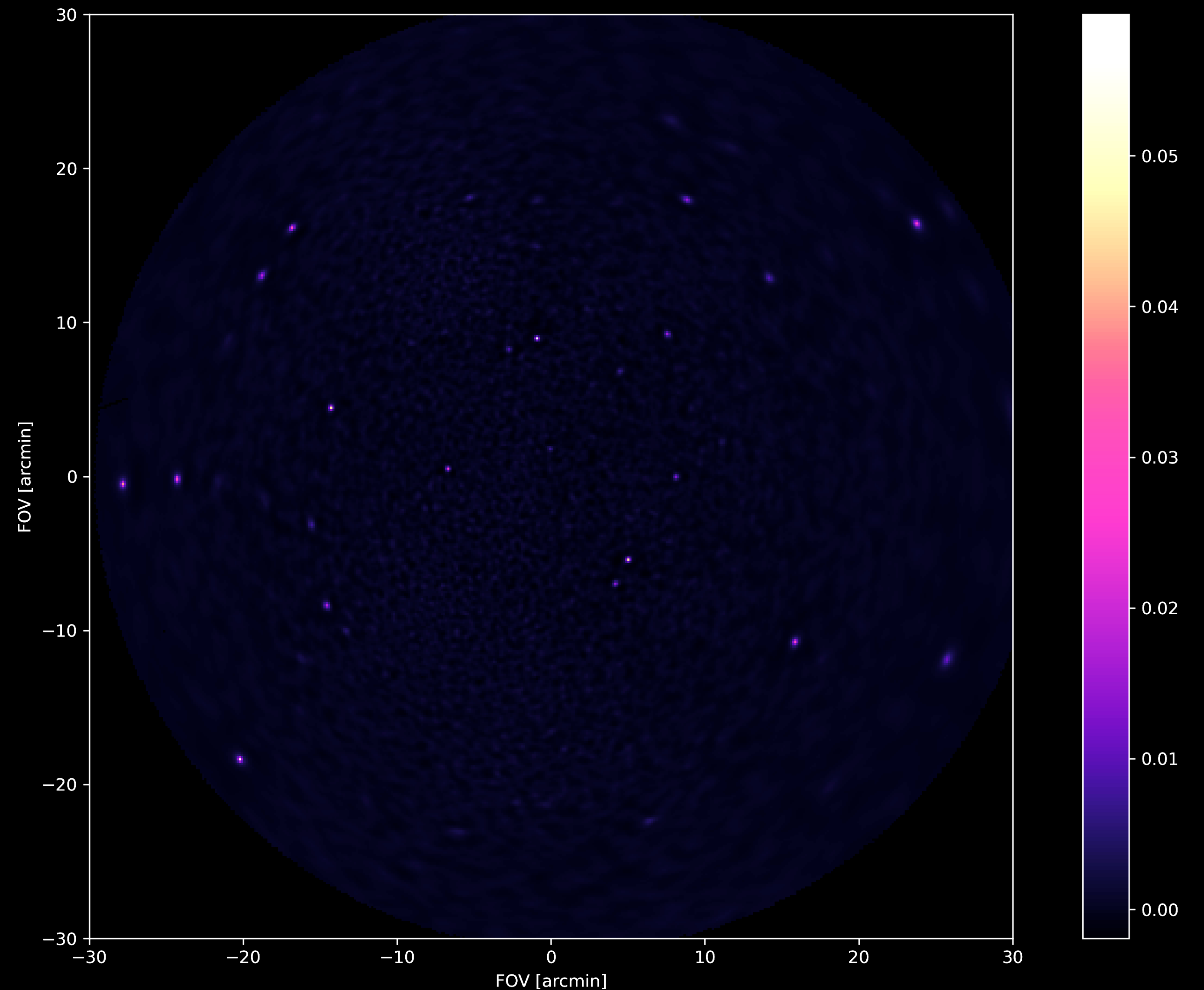
$$P(\xi) = \mathcal{N}(\mathbf{0}, \mathbb{I})$$



Point source detection

Model stress?

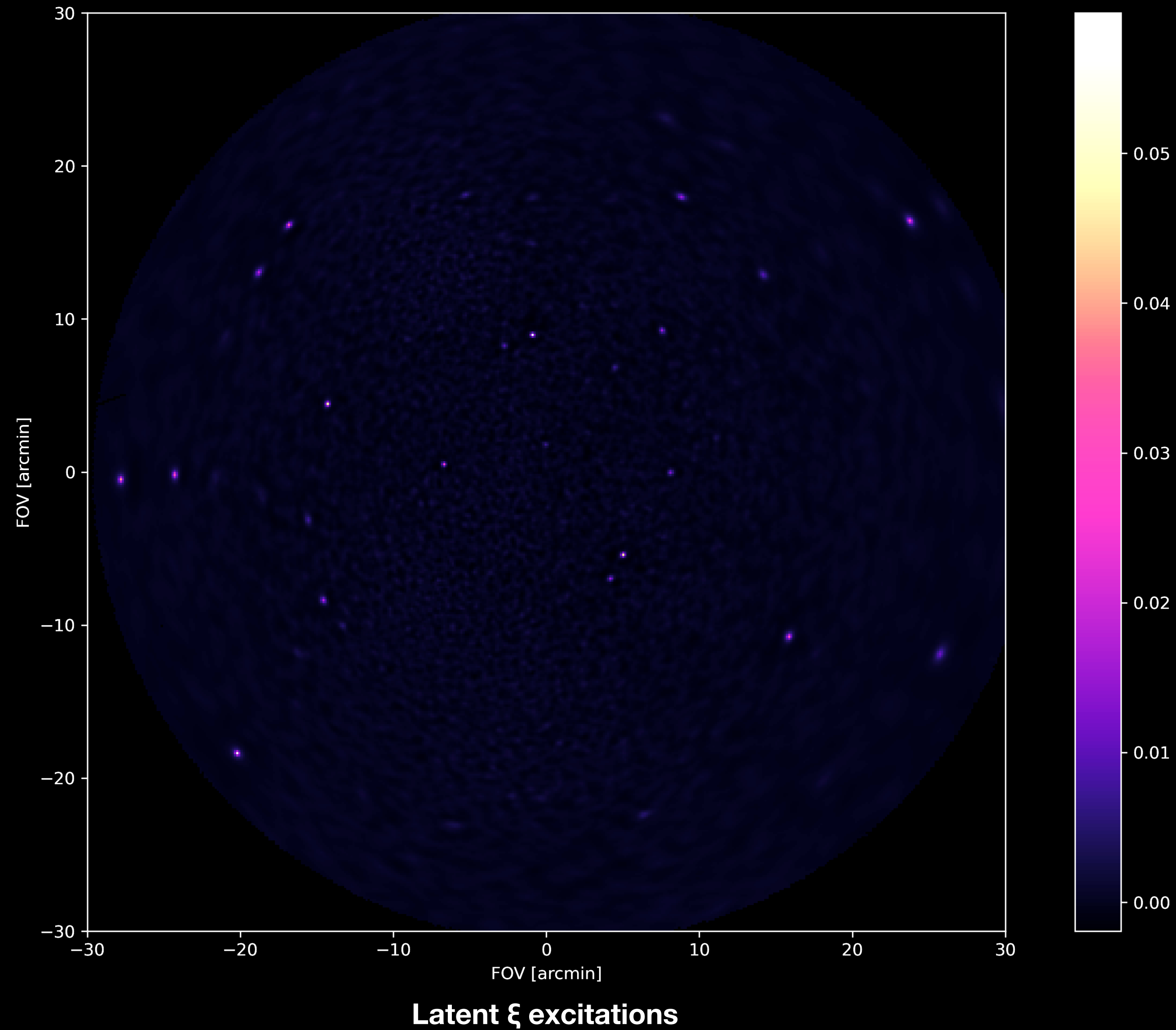
$$P(\xi | \mathbf{d}) \neq \mathcal{N}(\mathbf{0}, \mathbb{I})$$



Posterior latent ξ excitations

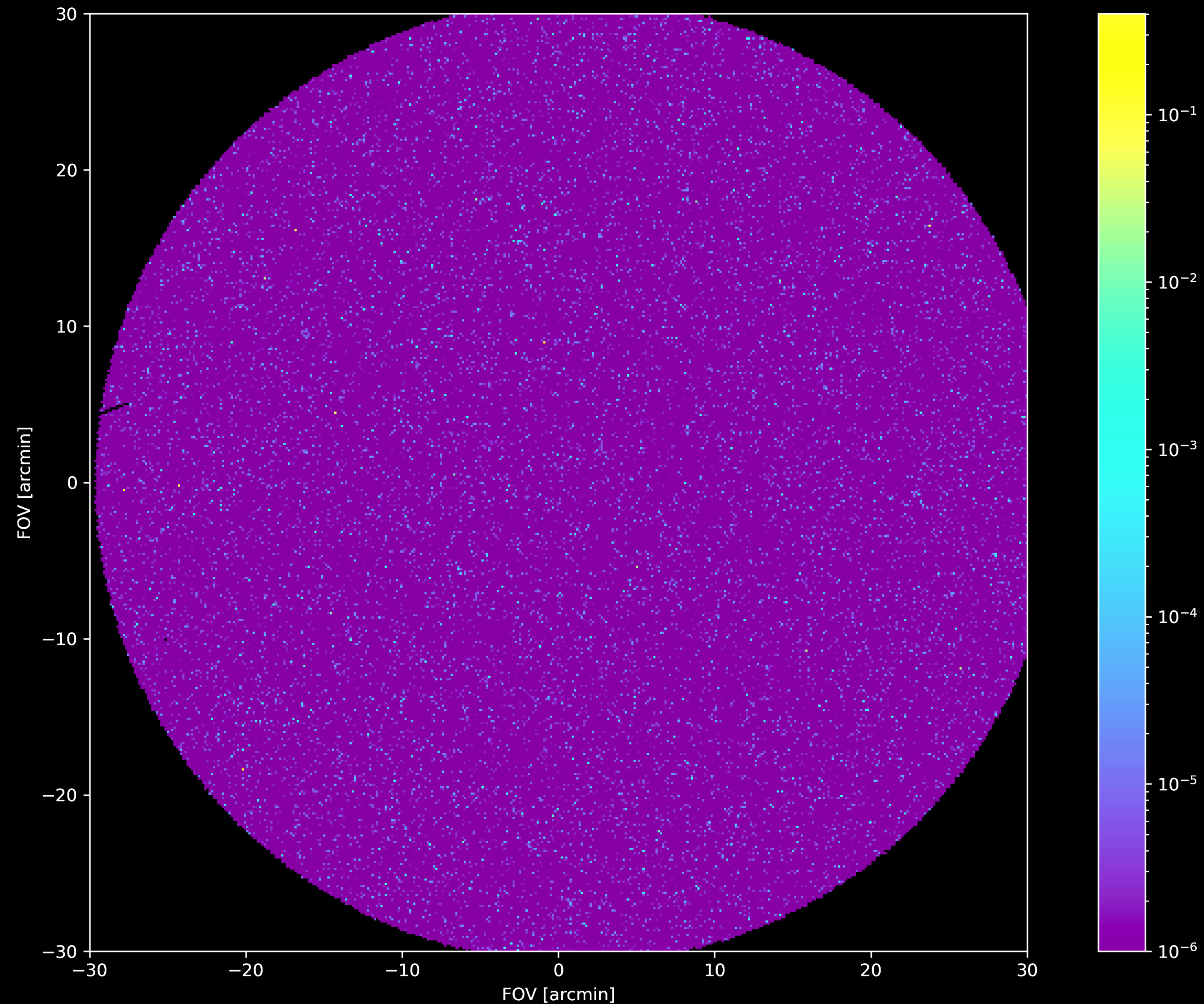
Point source detection

Model stress, yessir!



Point source detection

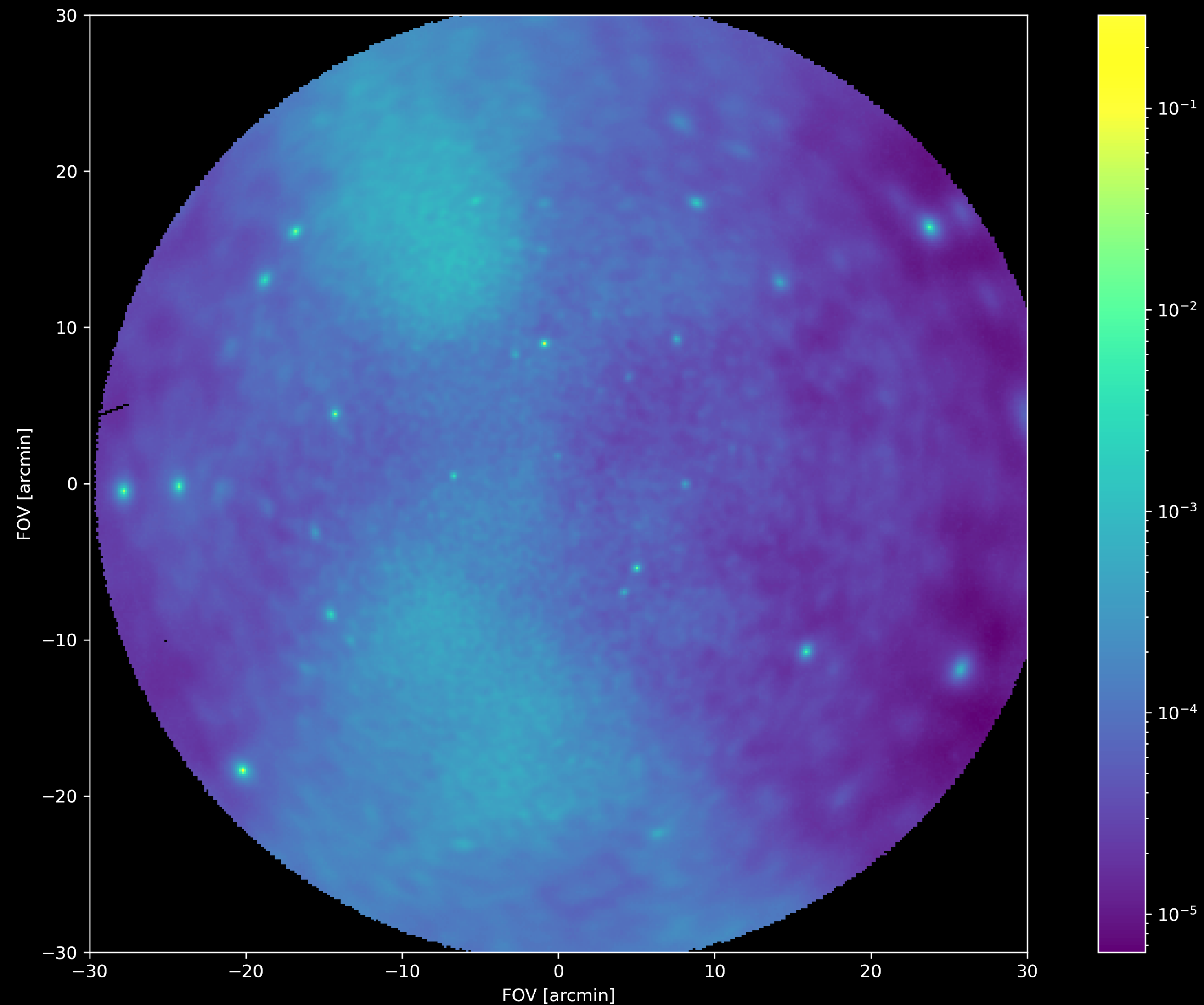
Model stress, yessir!



Point source ground truth

Point source detection

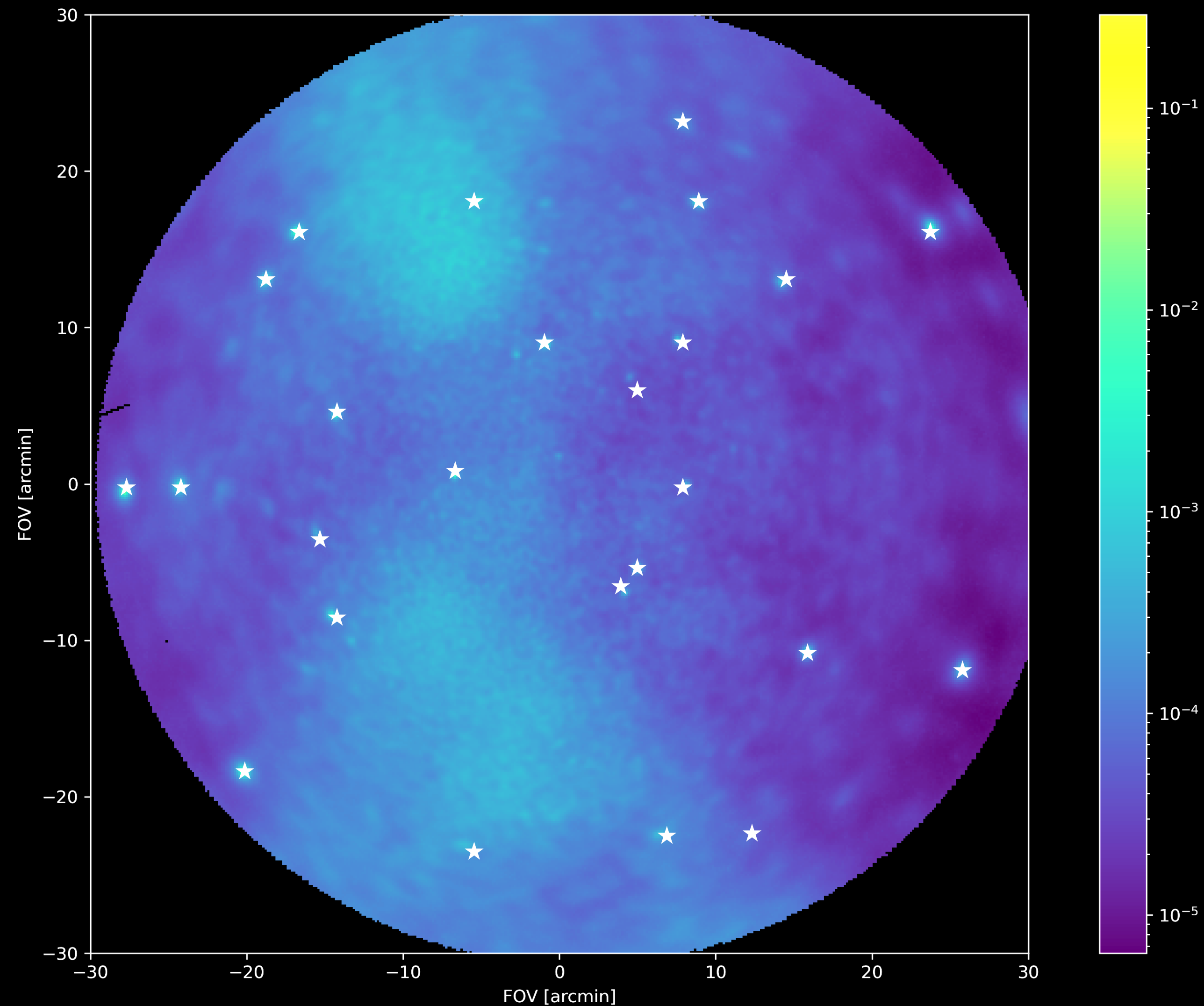
Automatic detection



Posterior mean diffuse-only reconstruction

Point source detection

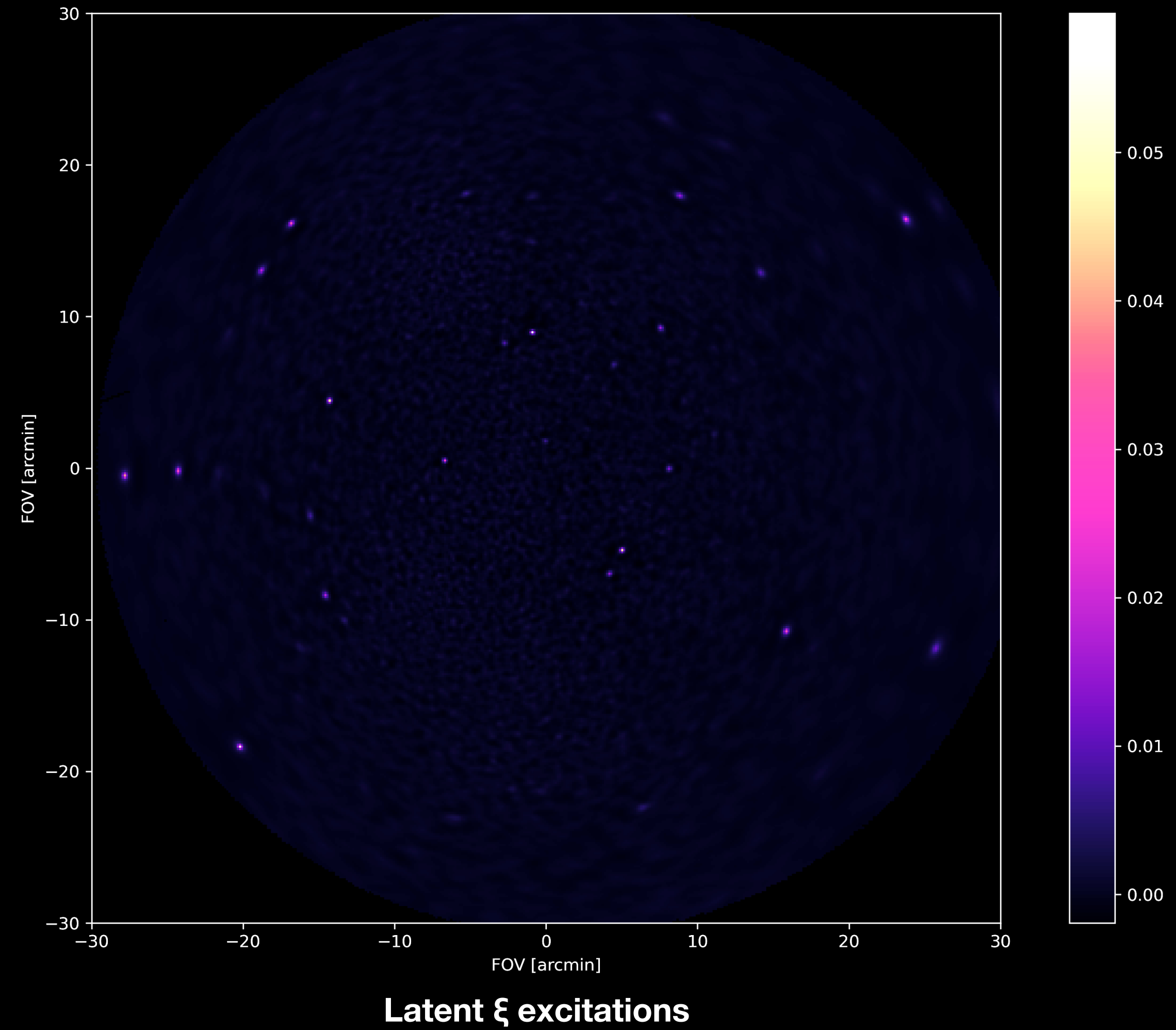
Automatic detection



Diffuse-only reconstruction + point source model

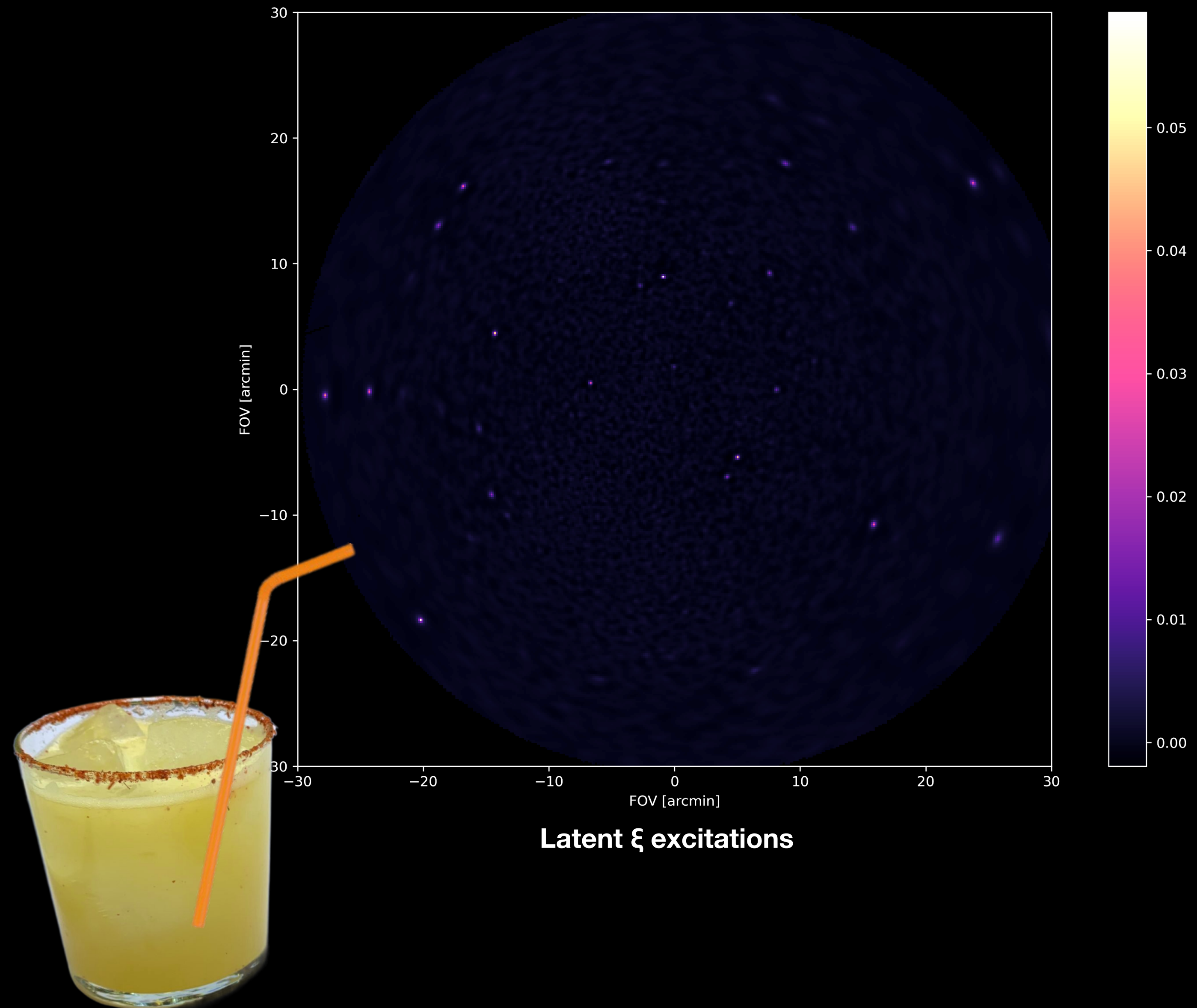
Point source detection

Relax excitations!



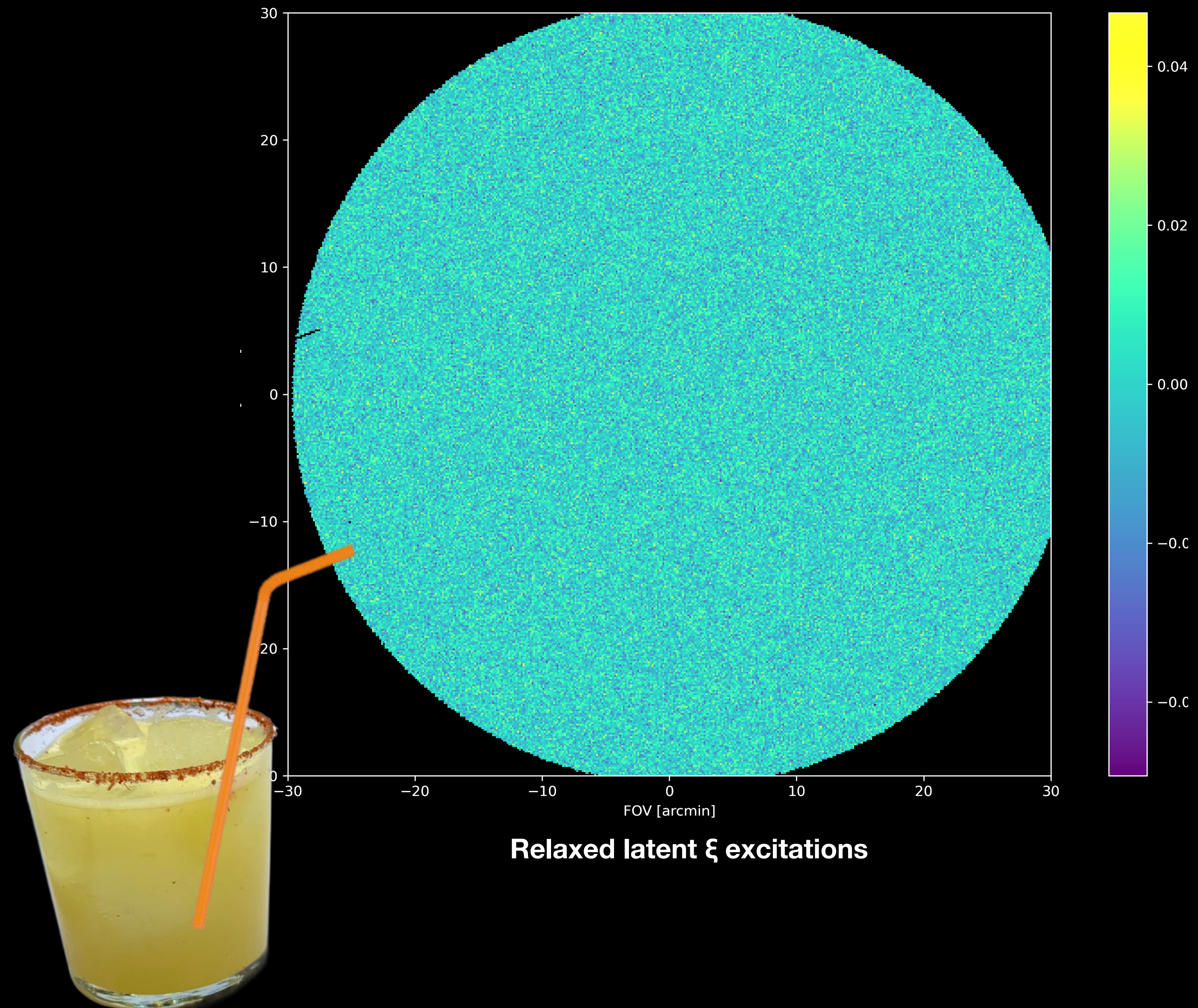
Point source detection

Relax excitations!



Point source detection

Relaxed excitations

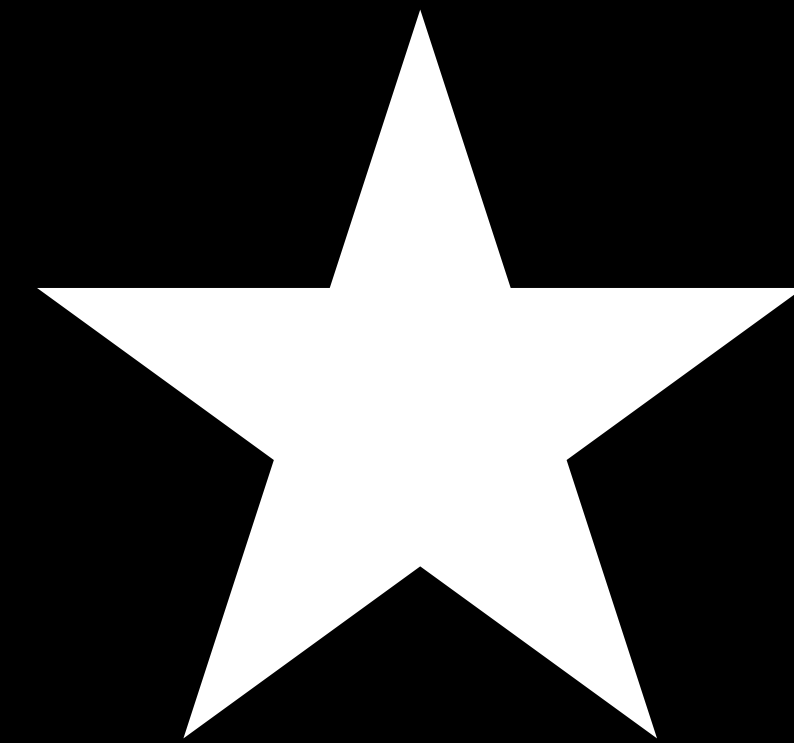


Point source model

Some theory...

What is a point source?

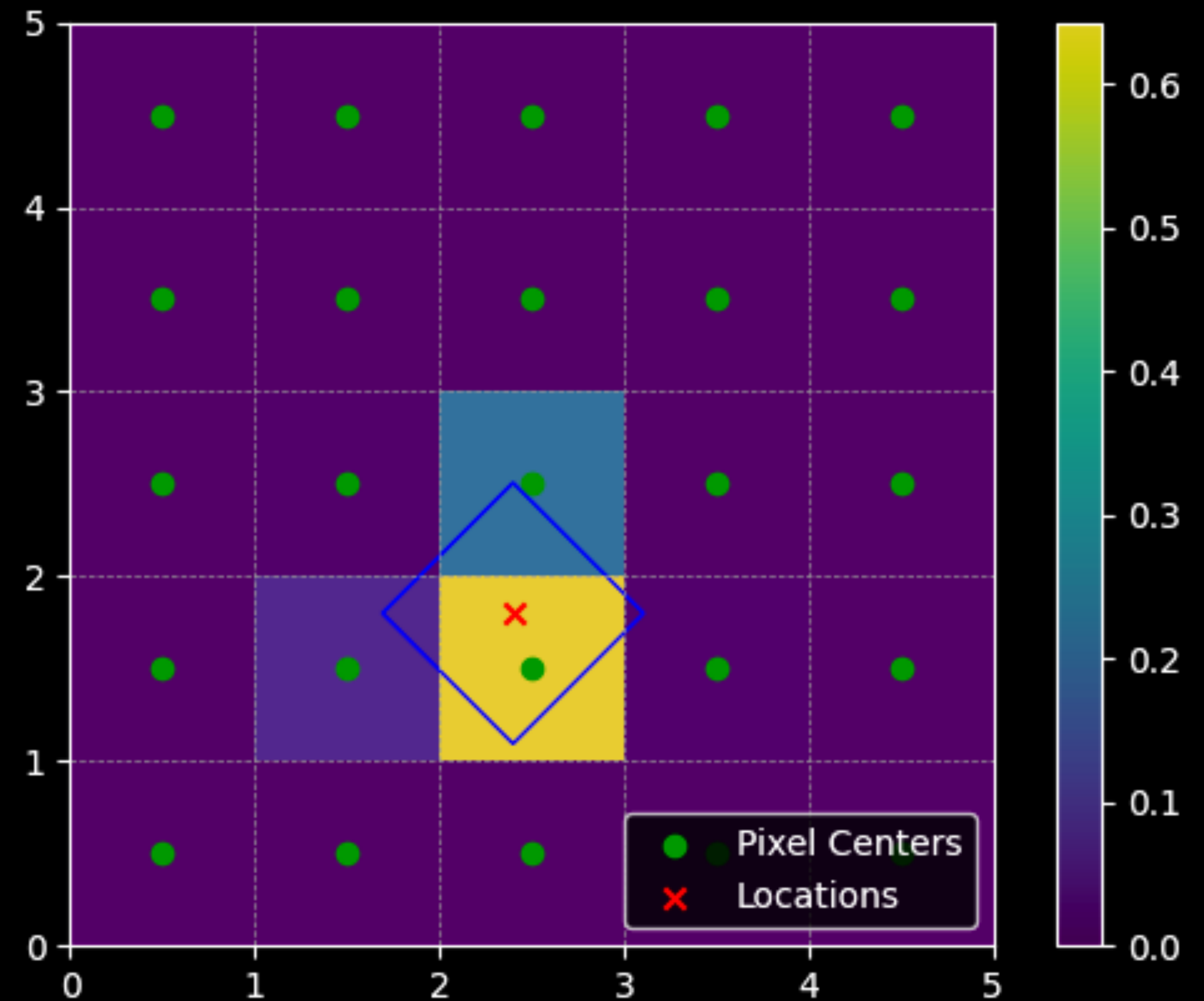
- **Spatially uncorrelated**
- **Spectrally independent from background**
- **Does not live on a grid**



Some theory...

What is a point source?

- **Spatially uncorrelated**
- **Spectrally independent from background**
- **Does not live on a grid**



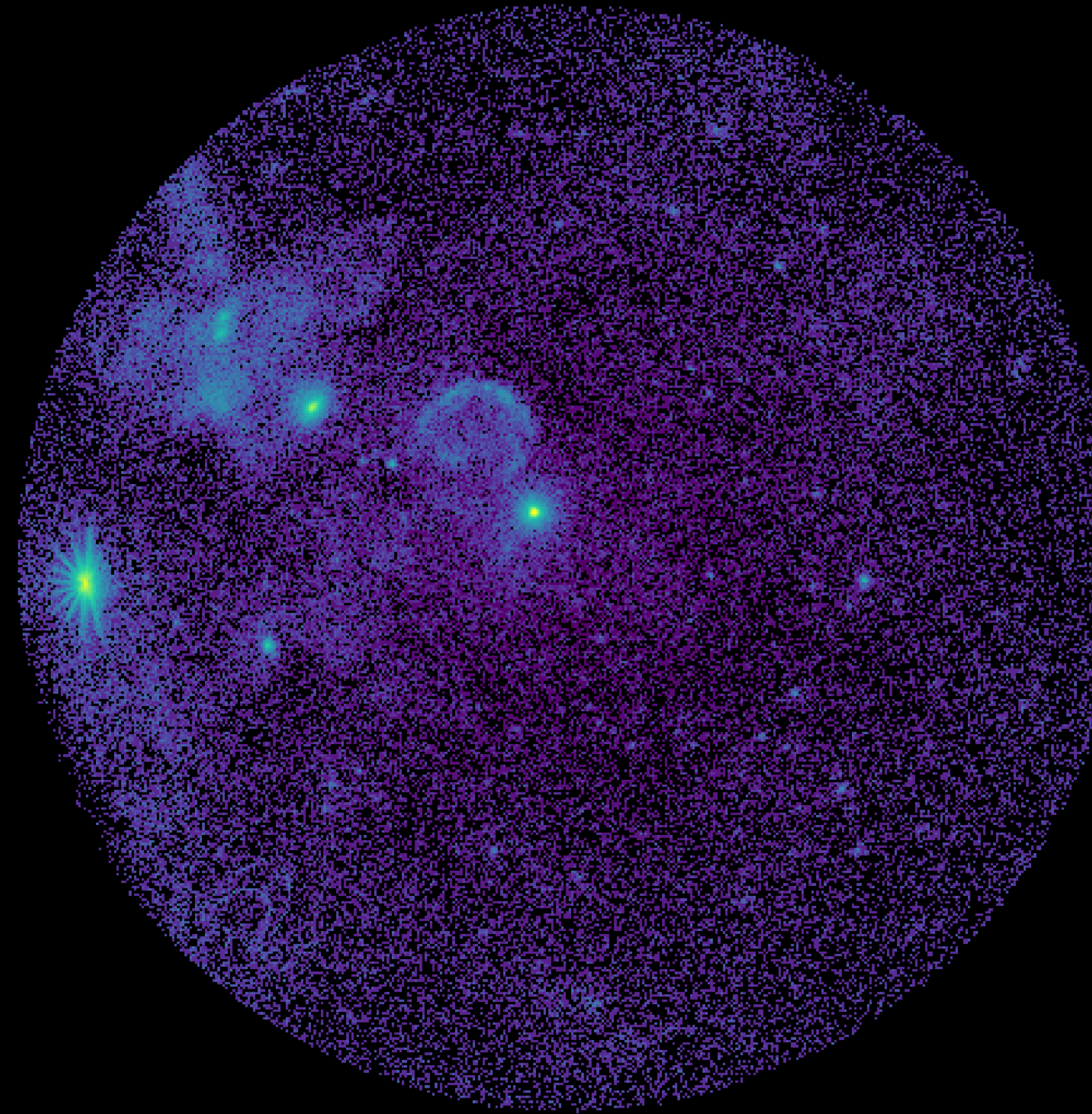
Multi-frequency data

Automatic source detection

Single-frequency information

eROSITA
LMC SN 1987A
dataset

TM1



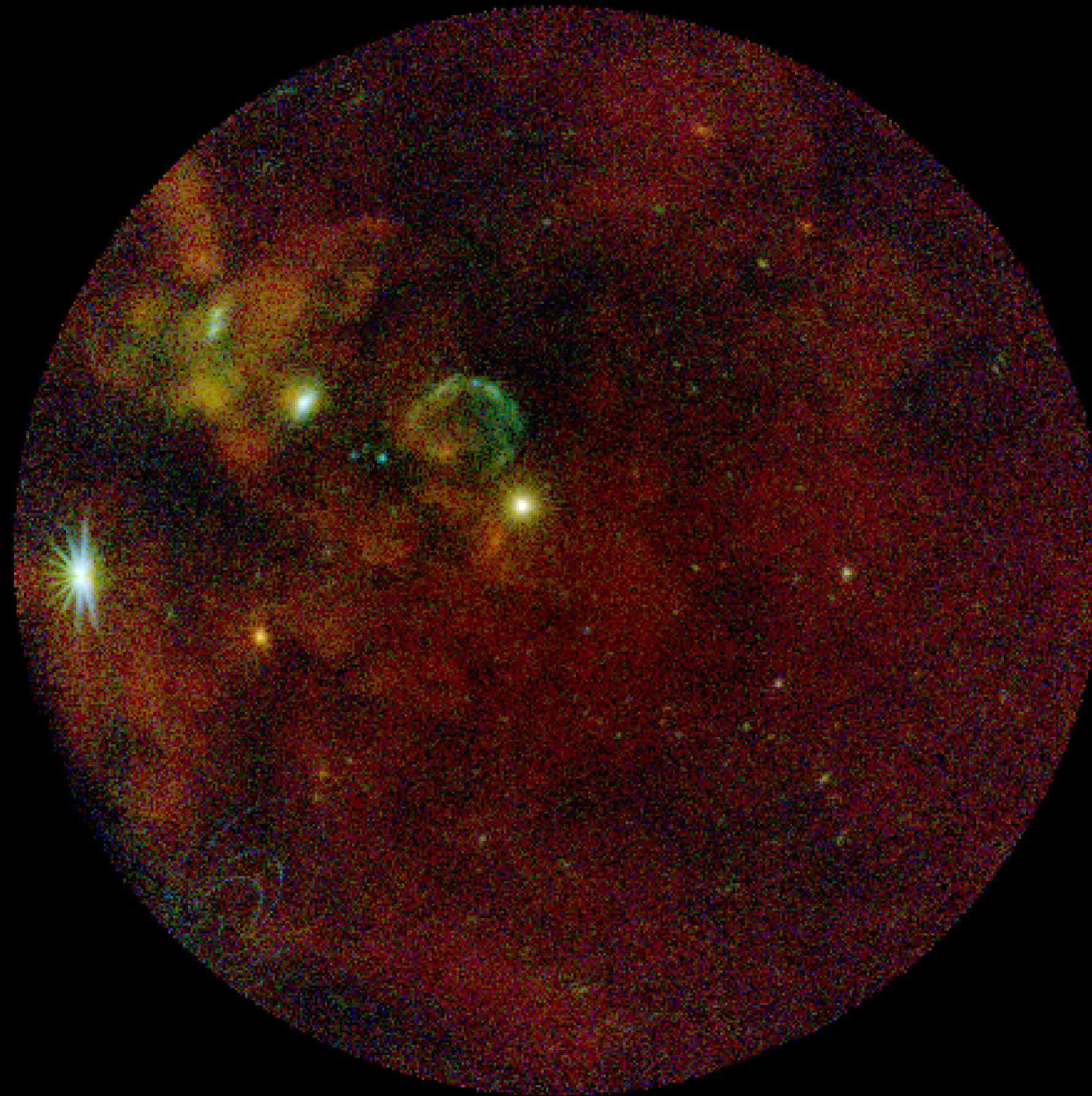
1.0 - 2.0 keV

Automatic source detection

Multi-frequency information

eROSITA
LMC SN 1987A
dataset

TM1

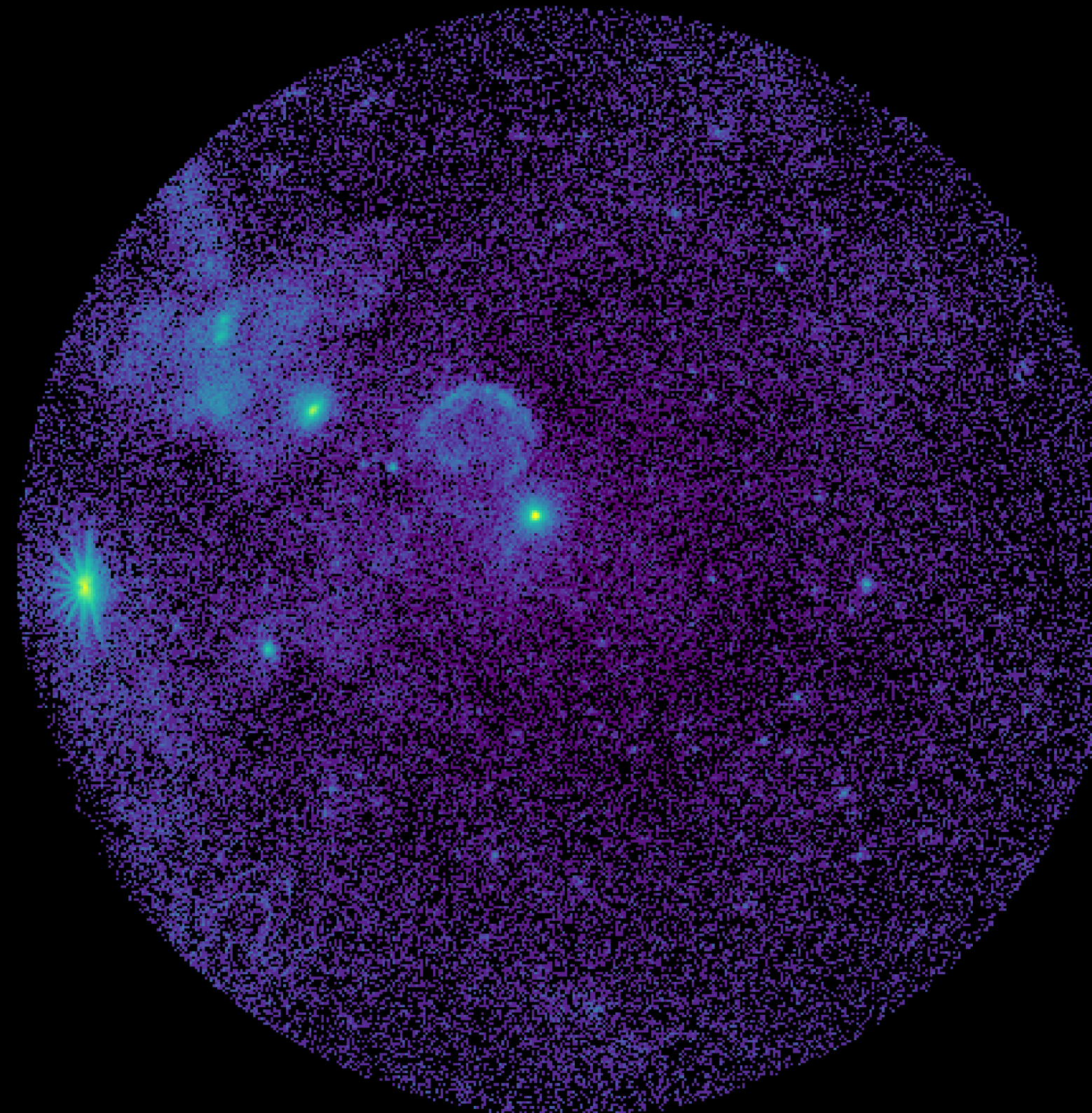


Automatic source detection

Multi-frequency information

eROSITA
LMC SN 1987A
dataset

TM1



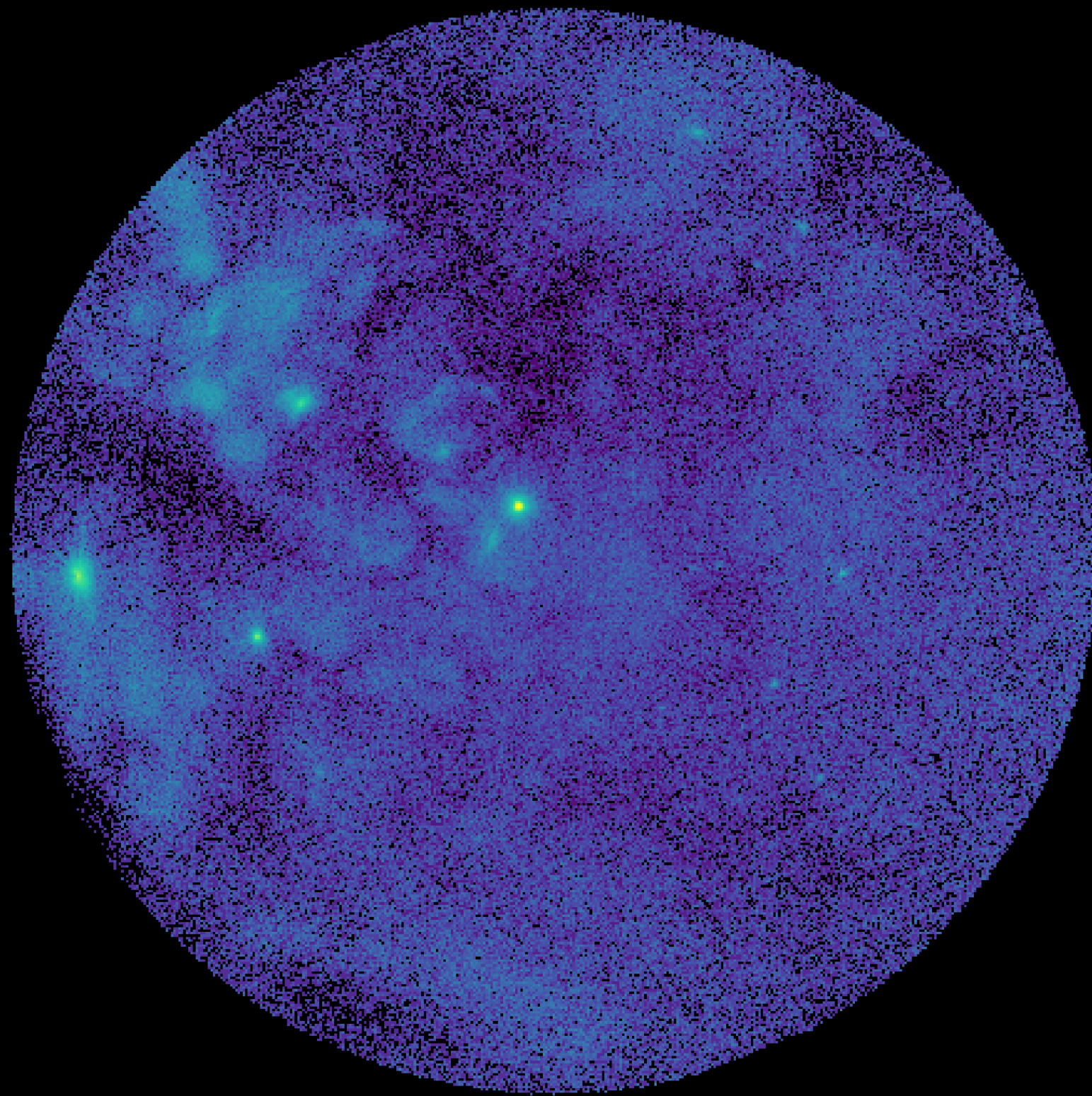
1.0 - 2.0 keV

Automatic source detection

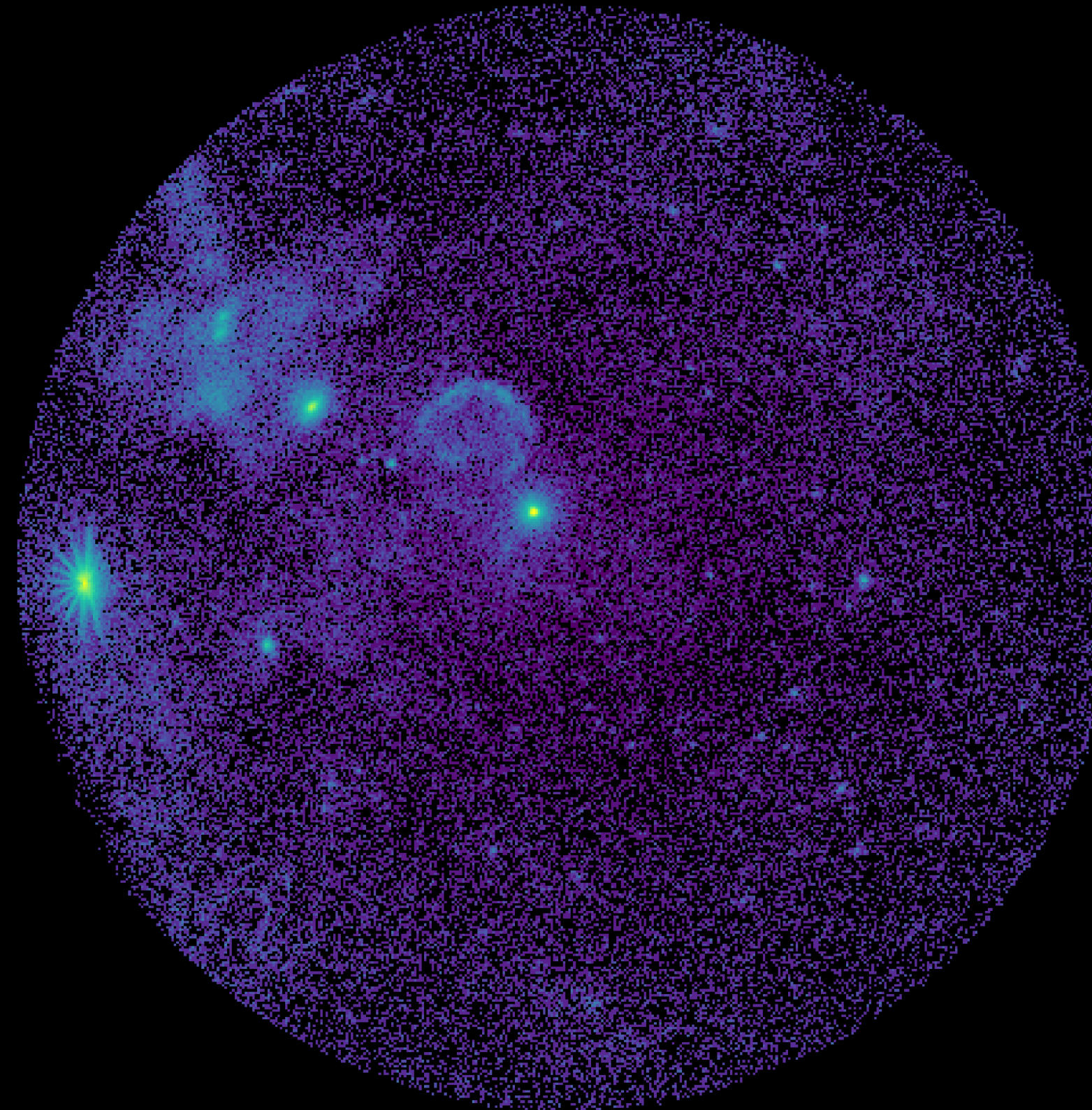
Multi-frequency information

eROSITA
LMC SN 1987A
dataset

TM1



0.2 - 1.0 keV



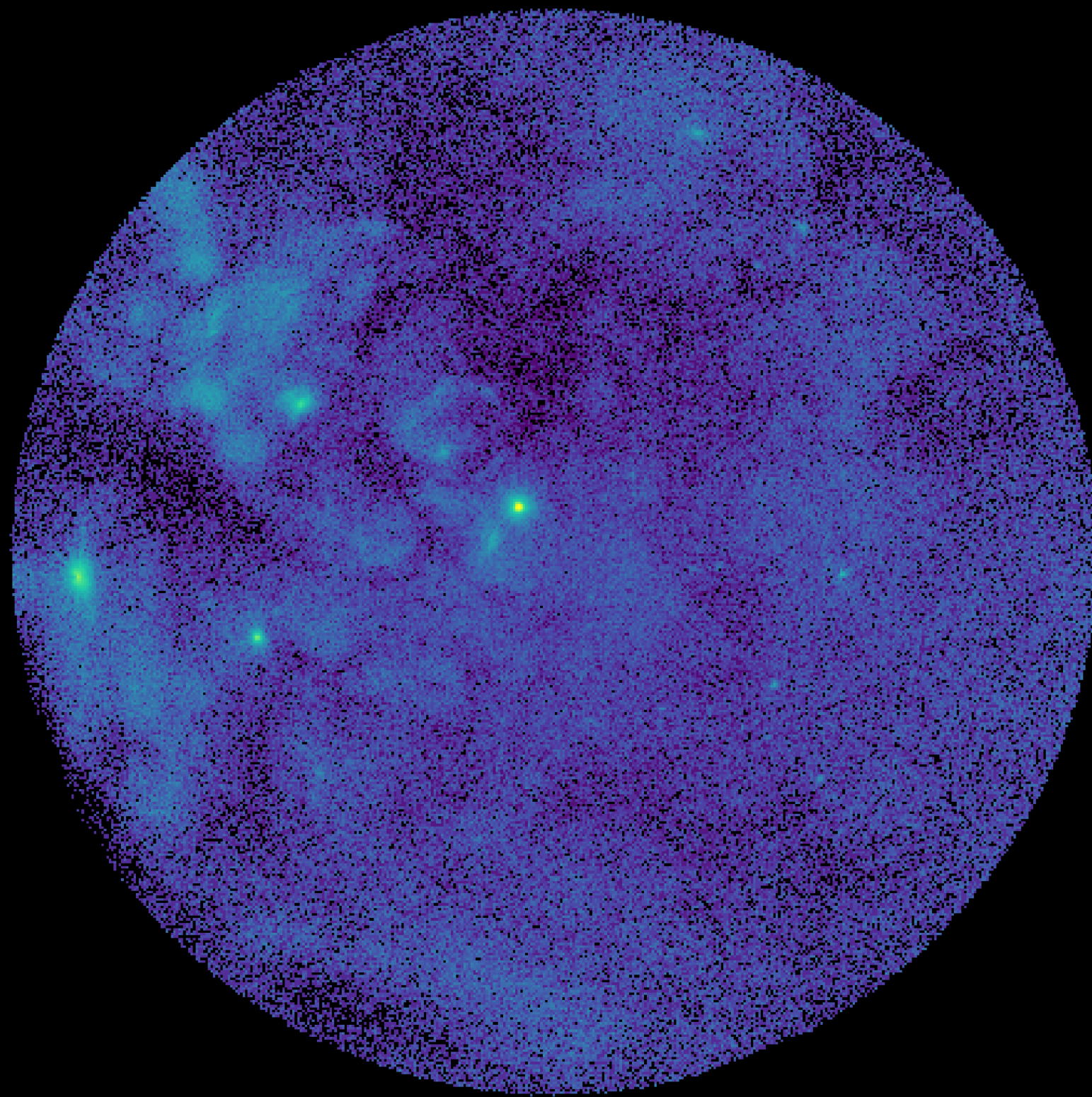
1.0 - 2.0 keV

Automatic source detection

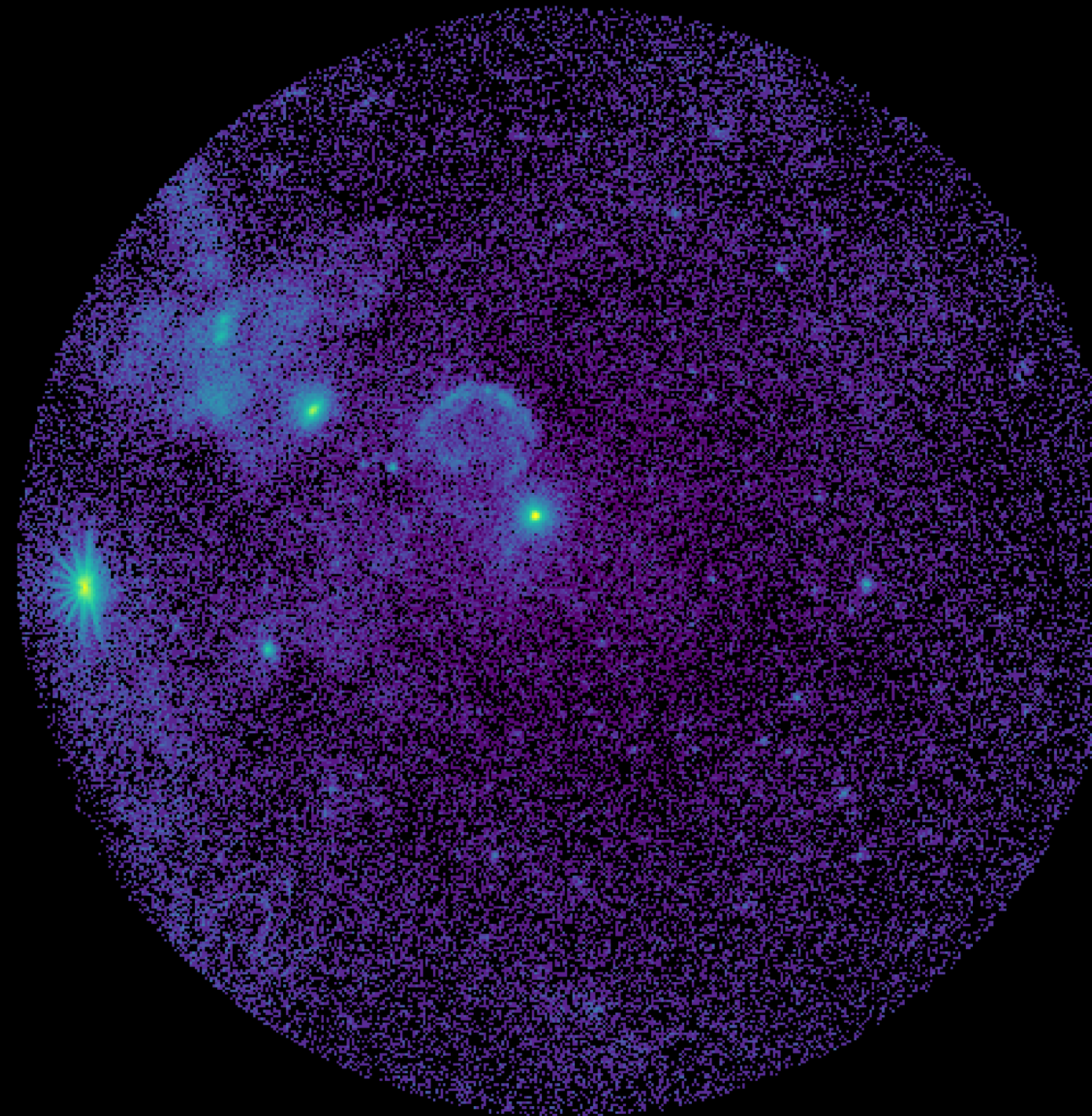
Multi-frequency information

eROSITA
LMC SN 1987A
dataset

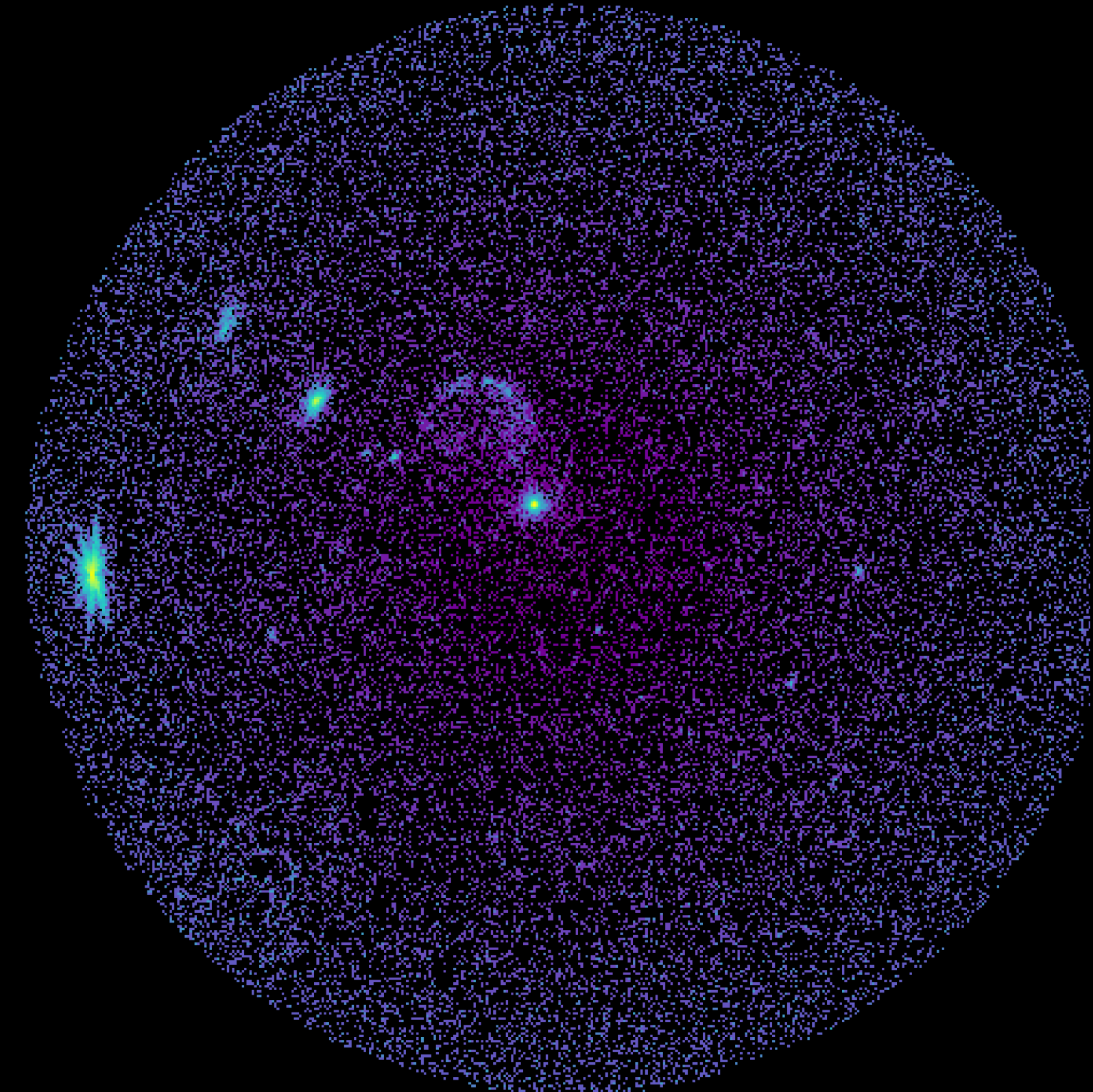
TM1



0.2 - 1.0 keV



1.0 - 2.0 keV



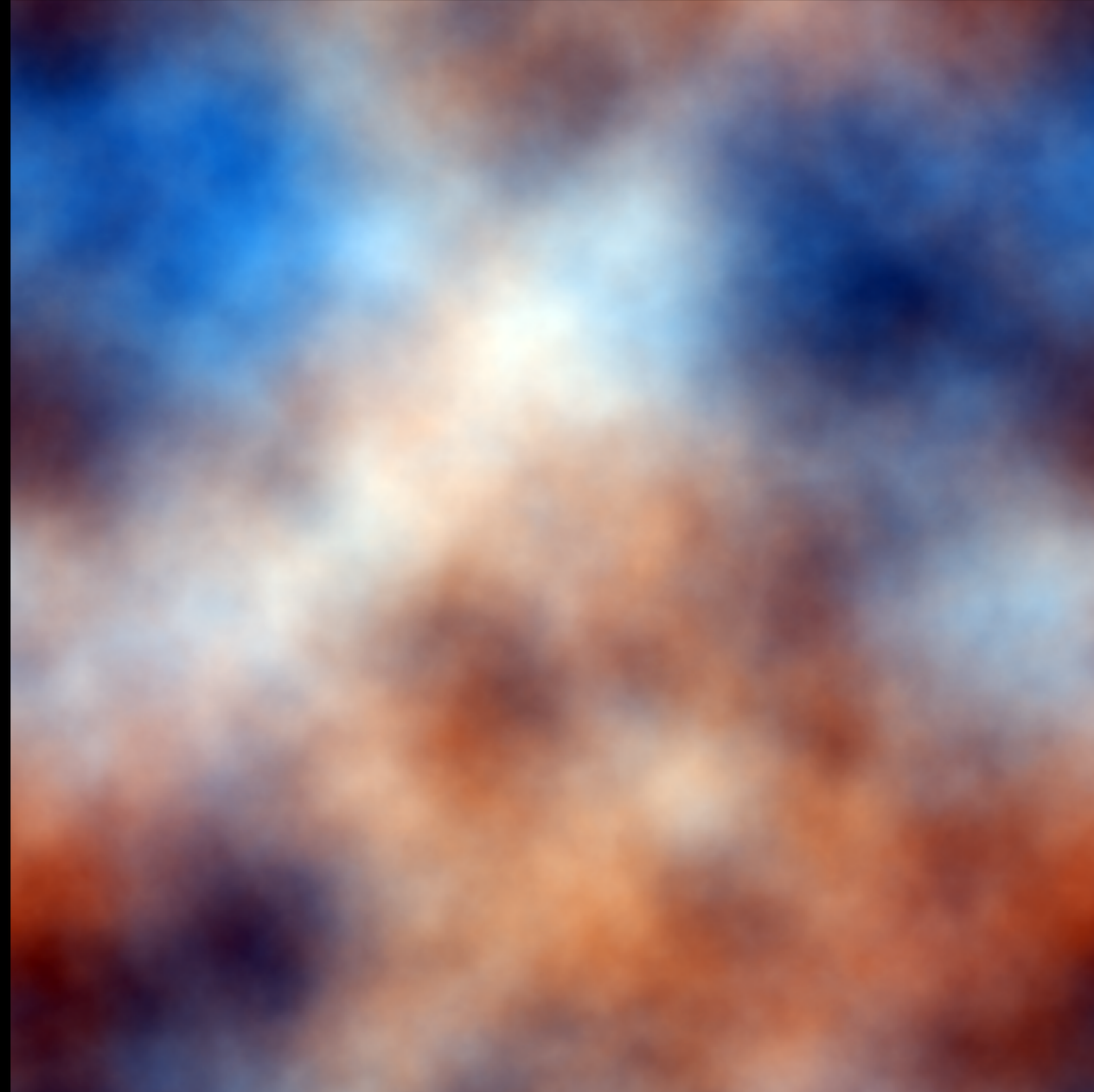
2.0 - 4.5 keV

Automatic source detection

Multi-frequency sky model

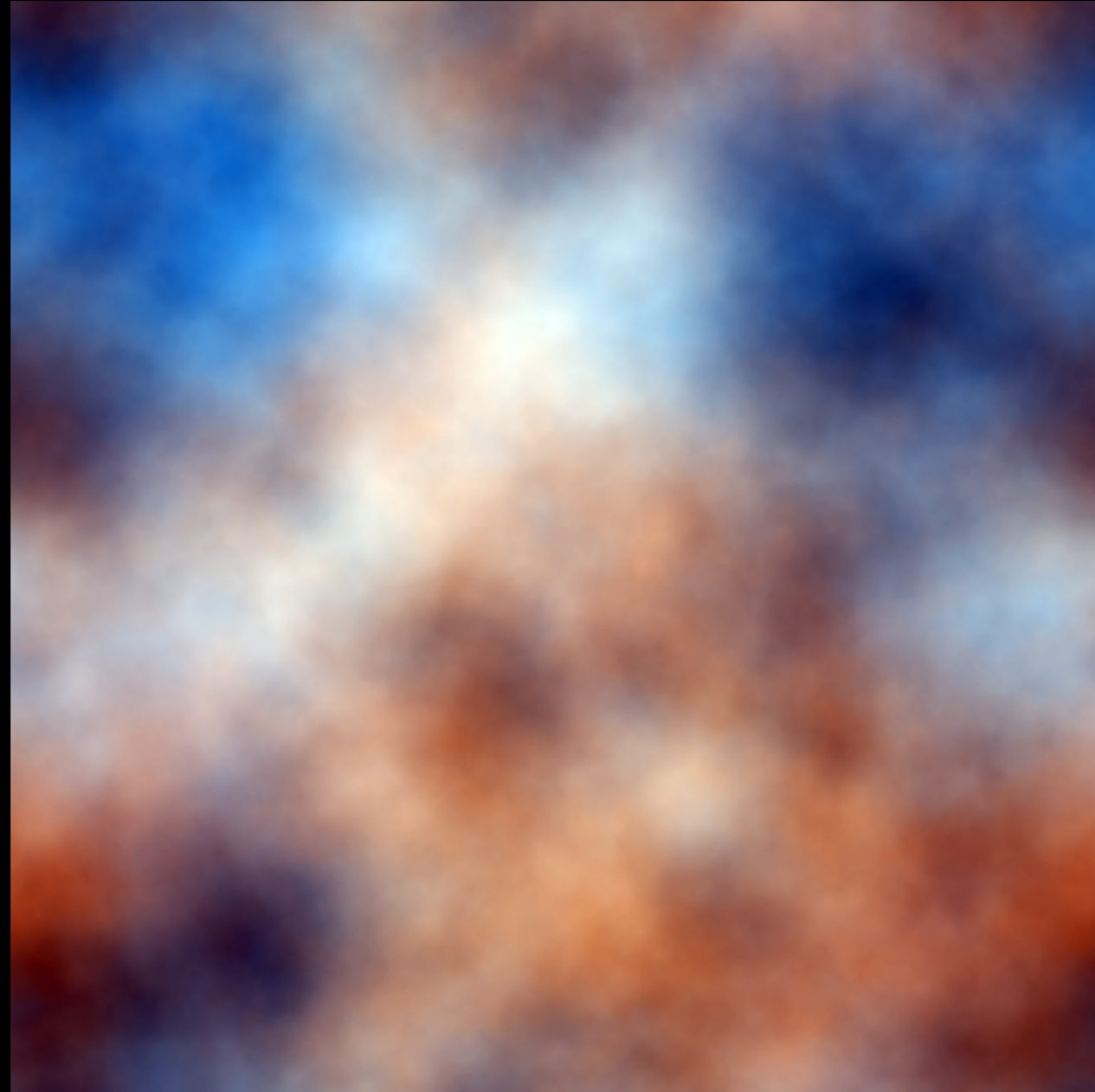
Automatic source detection

Multi-frequency sky model



Automatic source detection

Multi-frequency sky model

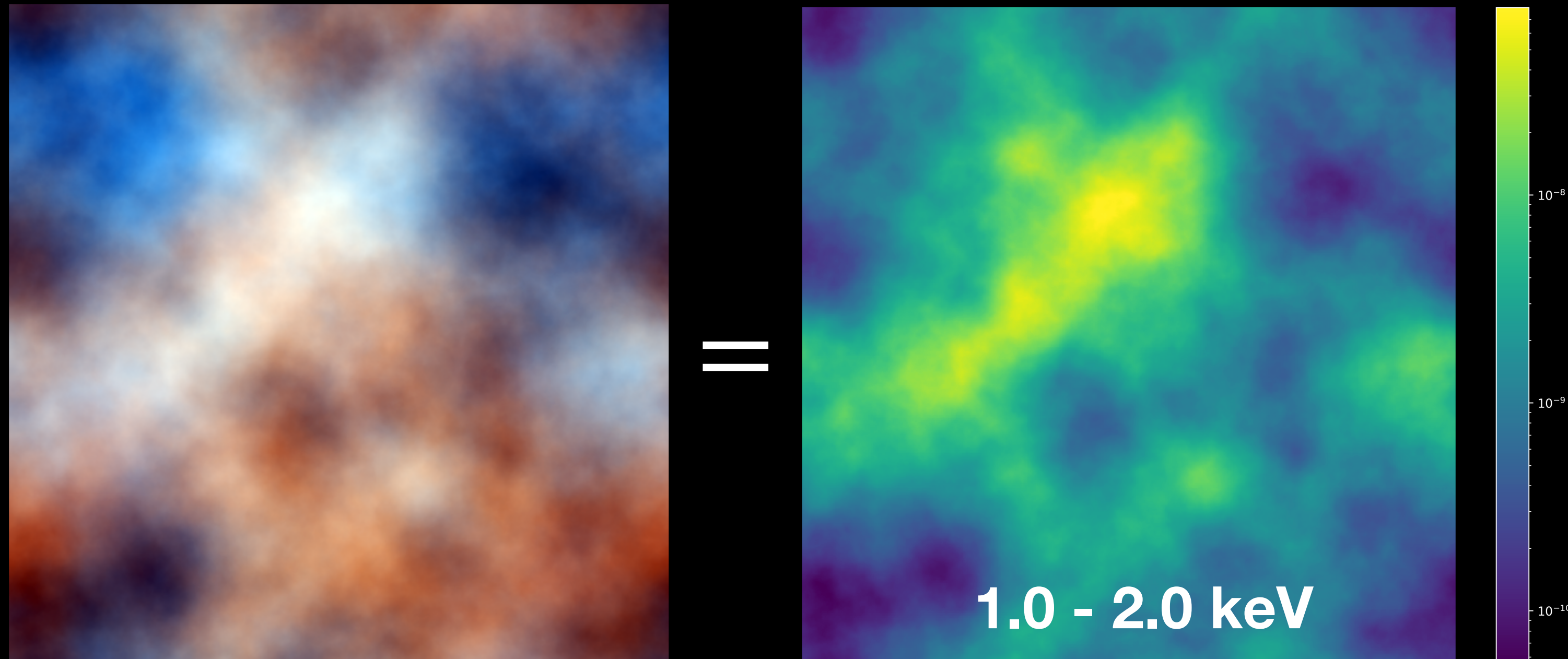


=

$$I(\mathbf{x}, \nu) =$$

Automatic source detection

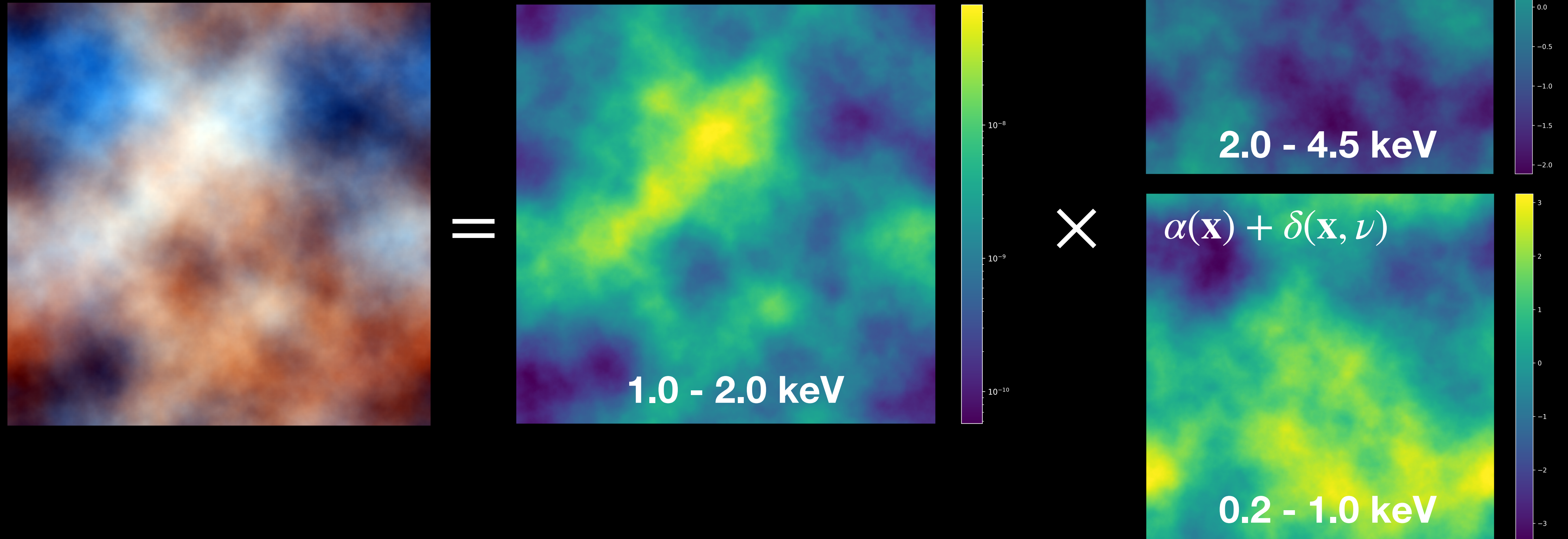
Multi-frequency sky model



$$I(\mathbf{x}, \nu) = I_0(\mathbf{x})$$

Automatic source detection

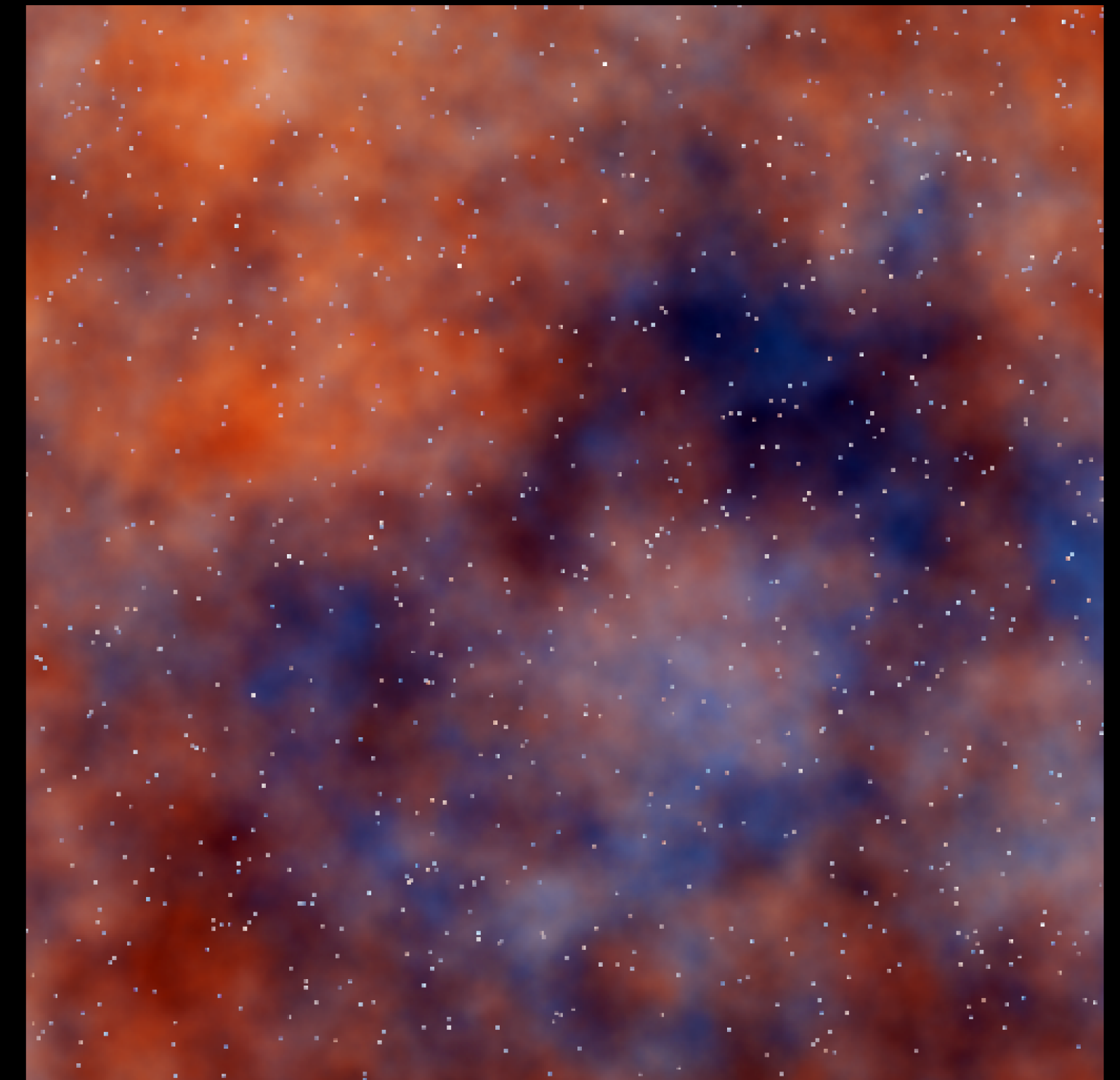
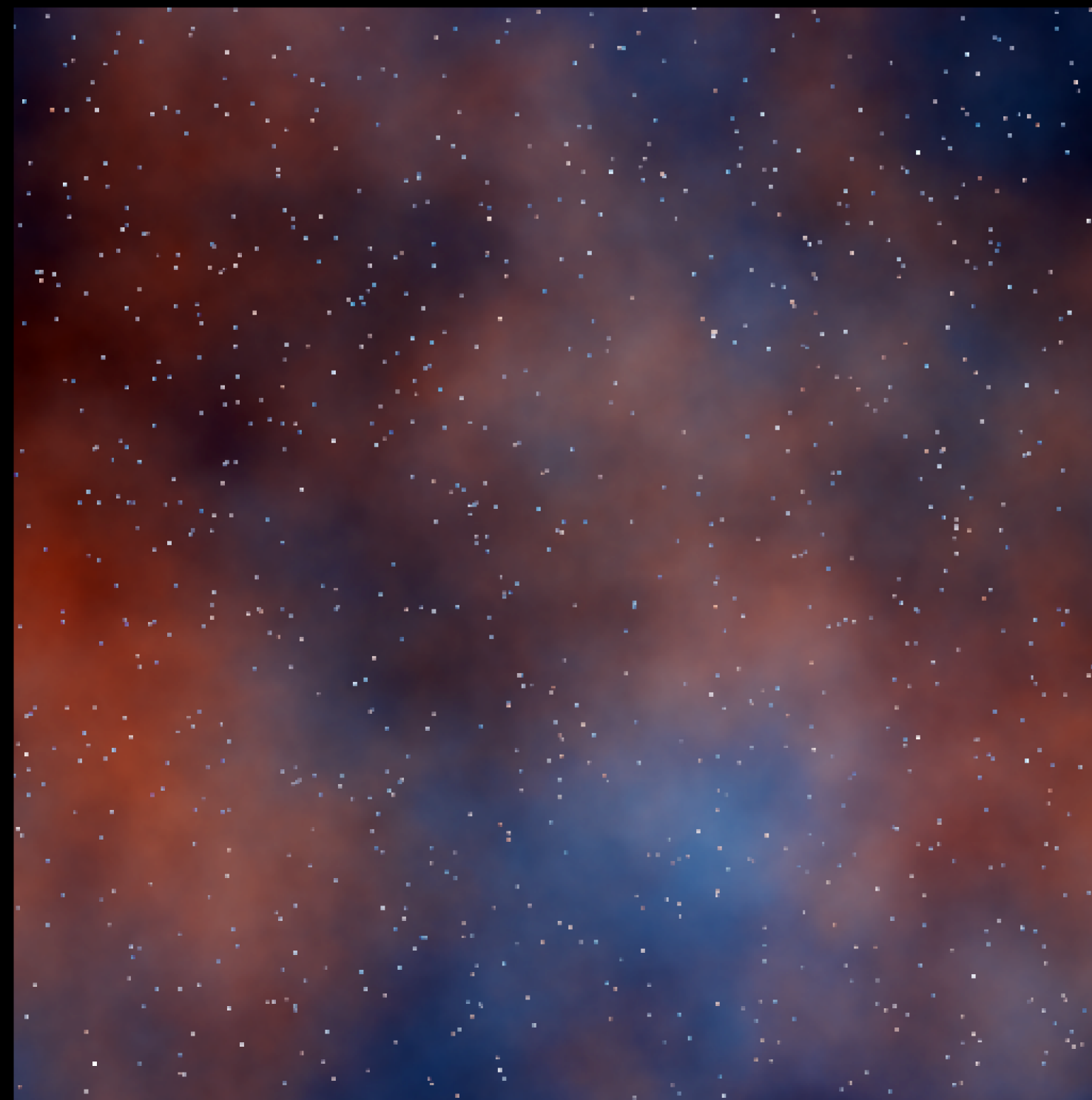
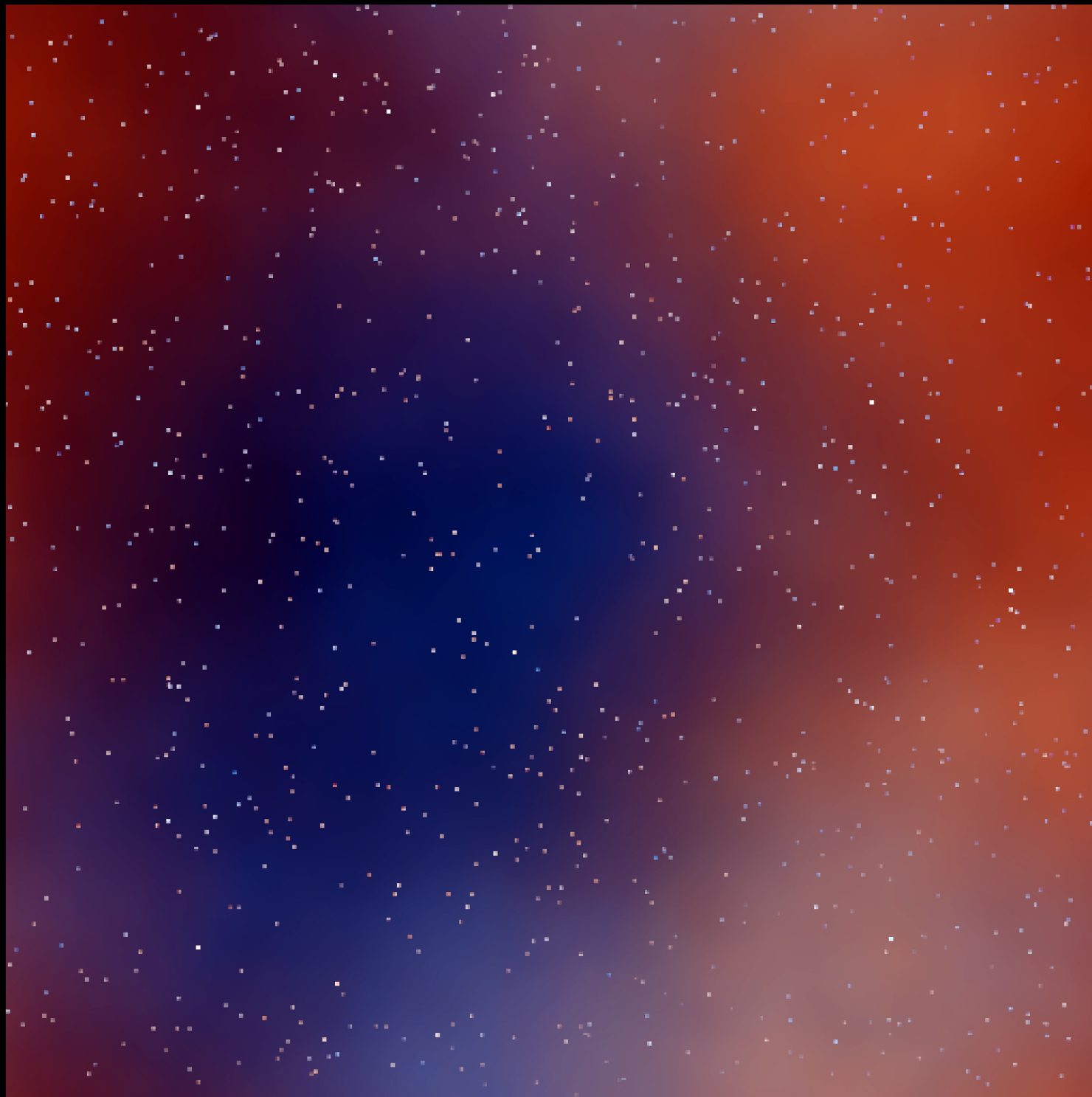
Multi-frequency sky model



$$I(\mathbf{x}, \nu) = I_0(\mathbf{x}) \times \left(\frac{\nu}{\nu_0} \right)^{\alpha(\mathbf{x}) + \delta(\mathbf{x}, \nu)}$$

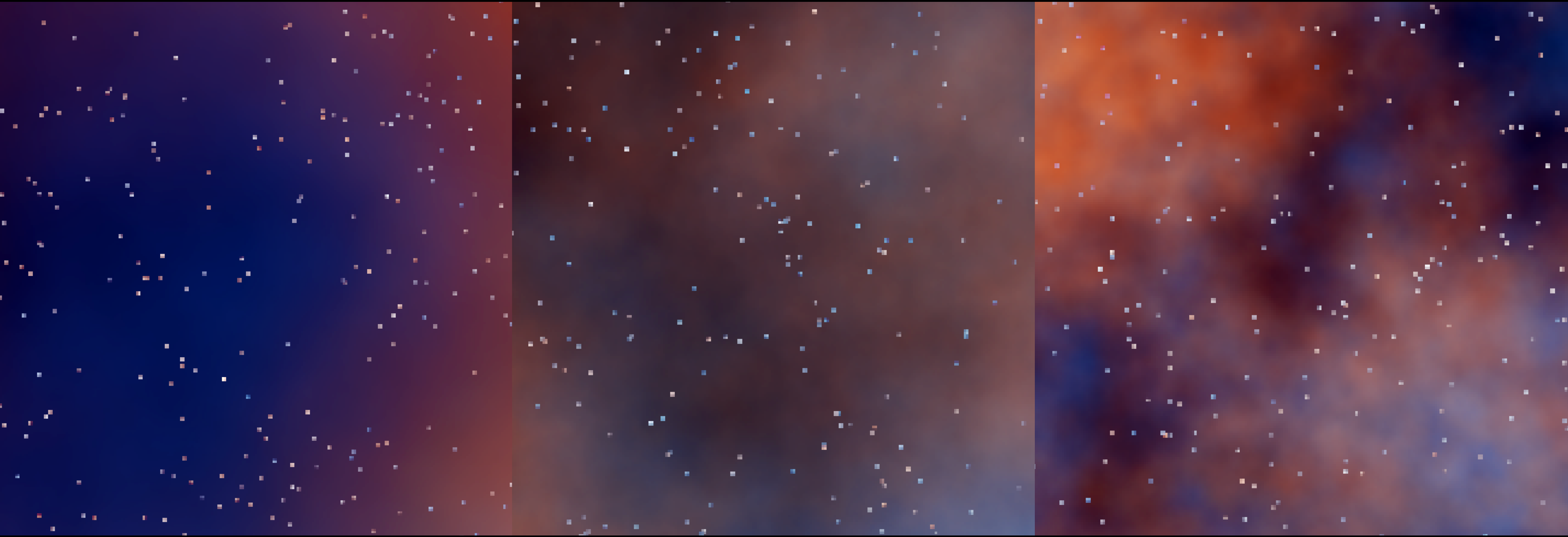
Point source detection

Multi-frequency model



Point source detection

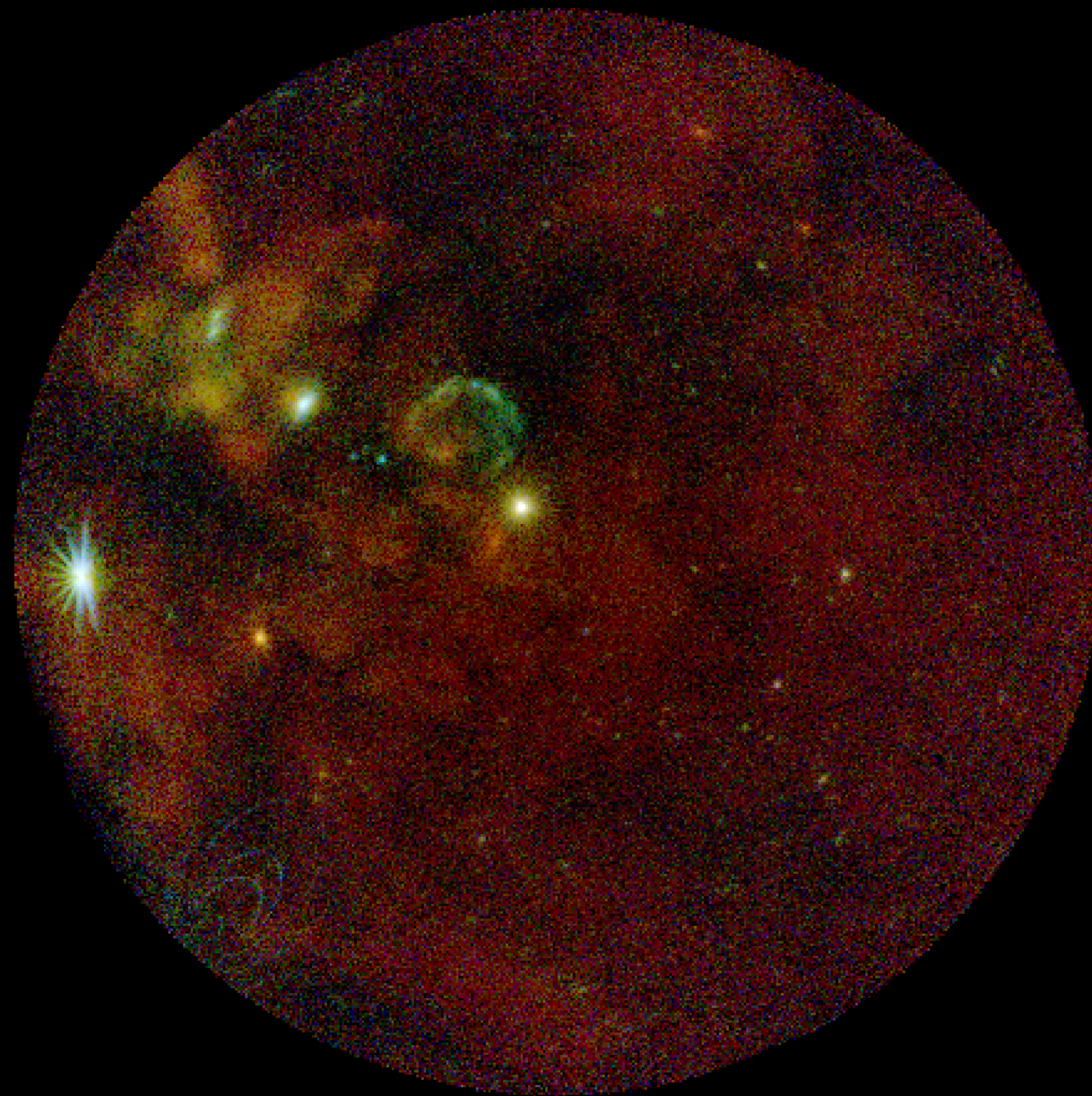
Multi-frequency model



Point source detection

Multi-frequency model

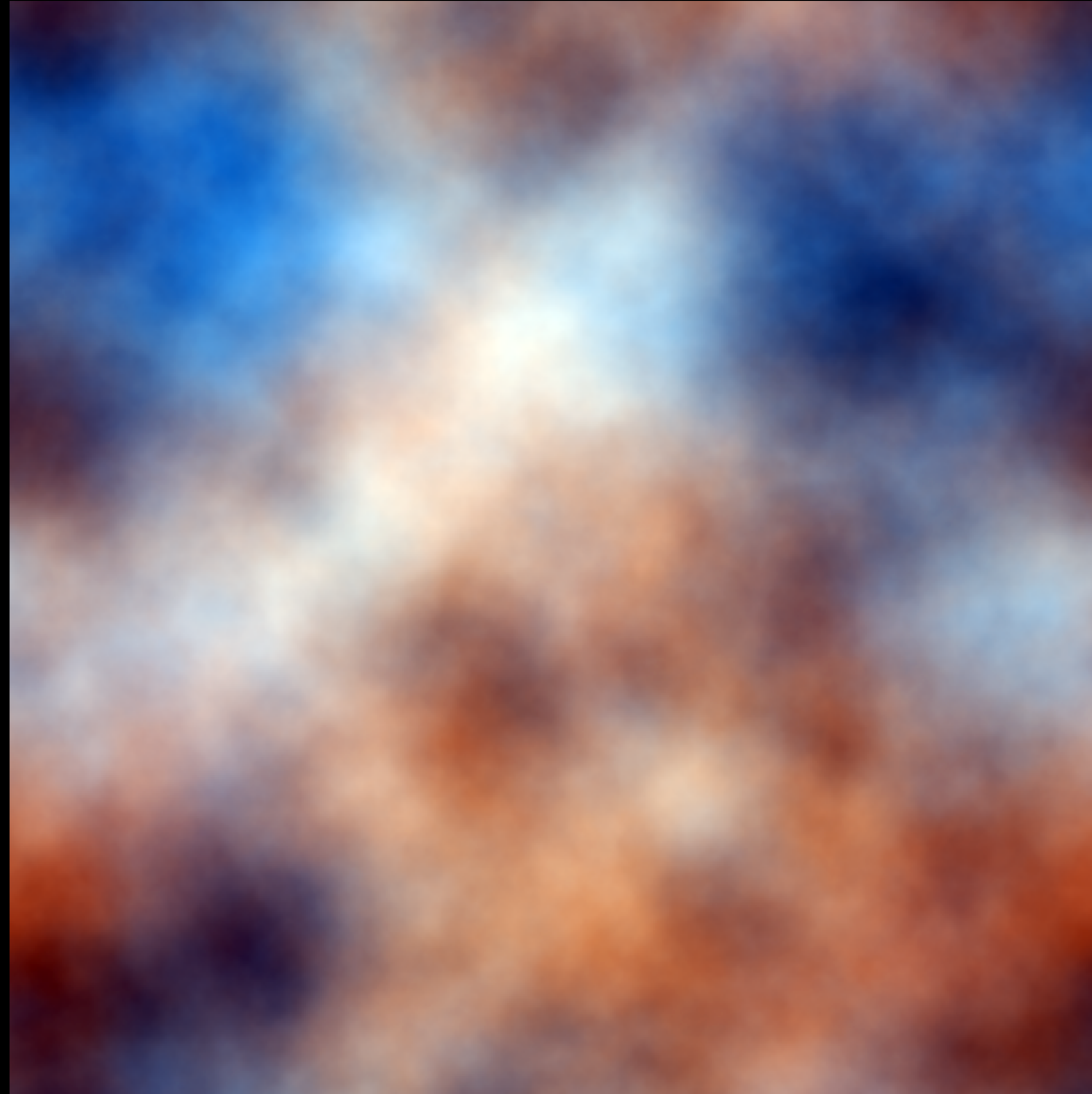
TM1



eROSITA
LMC SN 1987A
dataset

Automatic source detection

Multi-frequency sky model

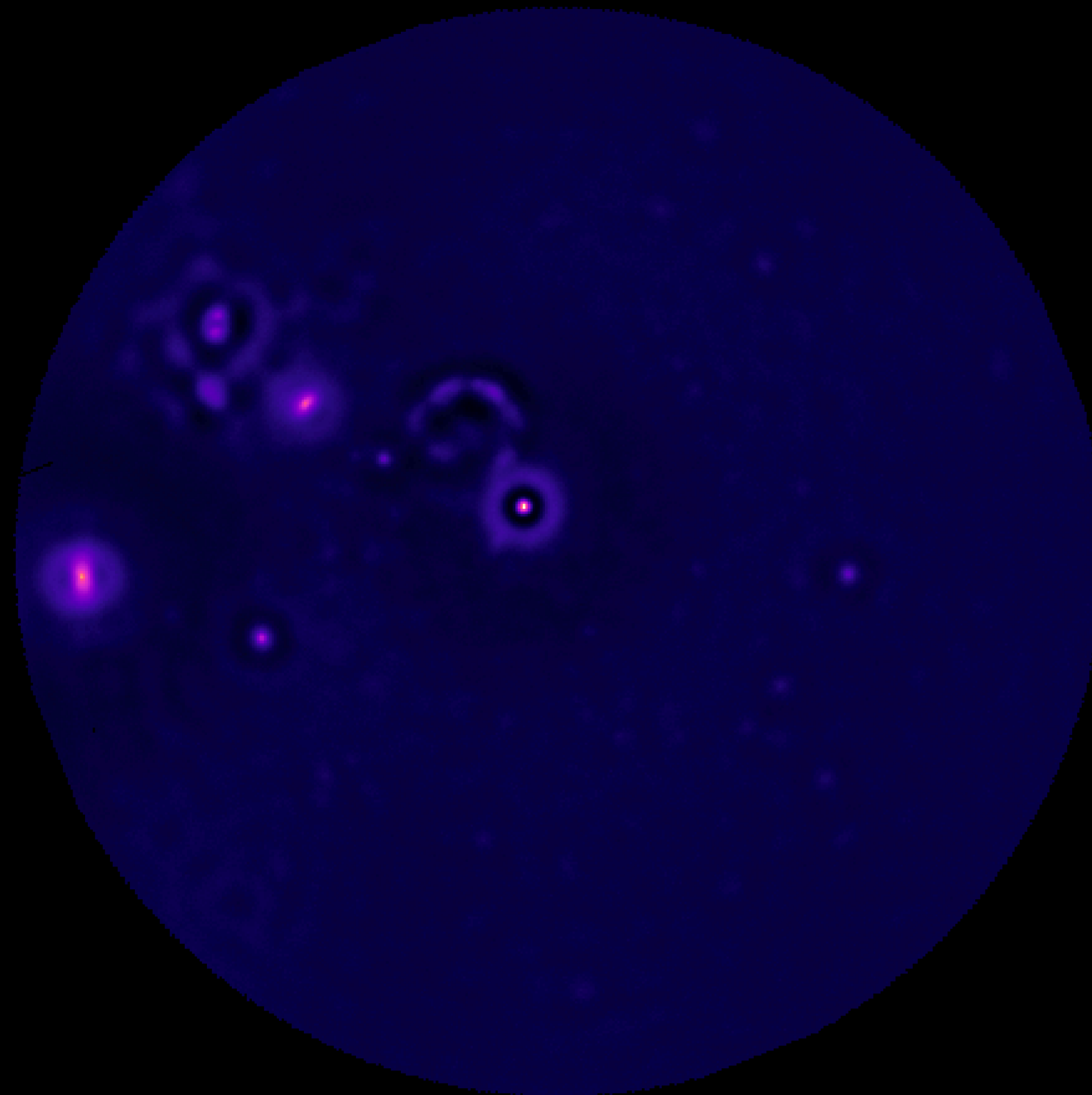


$$I(\mathbf{x}, \nu) = I_0(\mathbf{x}) \left(\frac{\nu}{\nu_0} \right)^{\alpha(\mathbf{x}) + \delta(\mathbf{x}, \nu)}$$

Point source detection

Latent space excitations

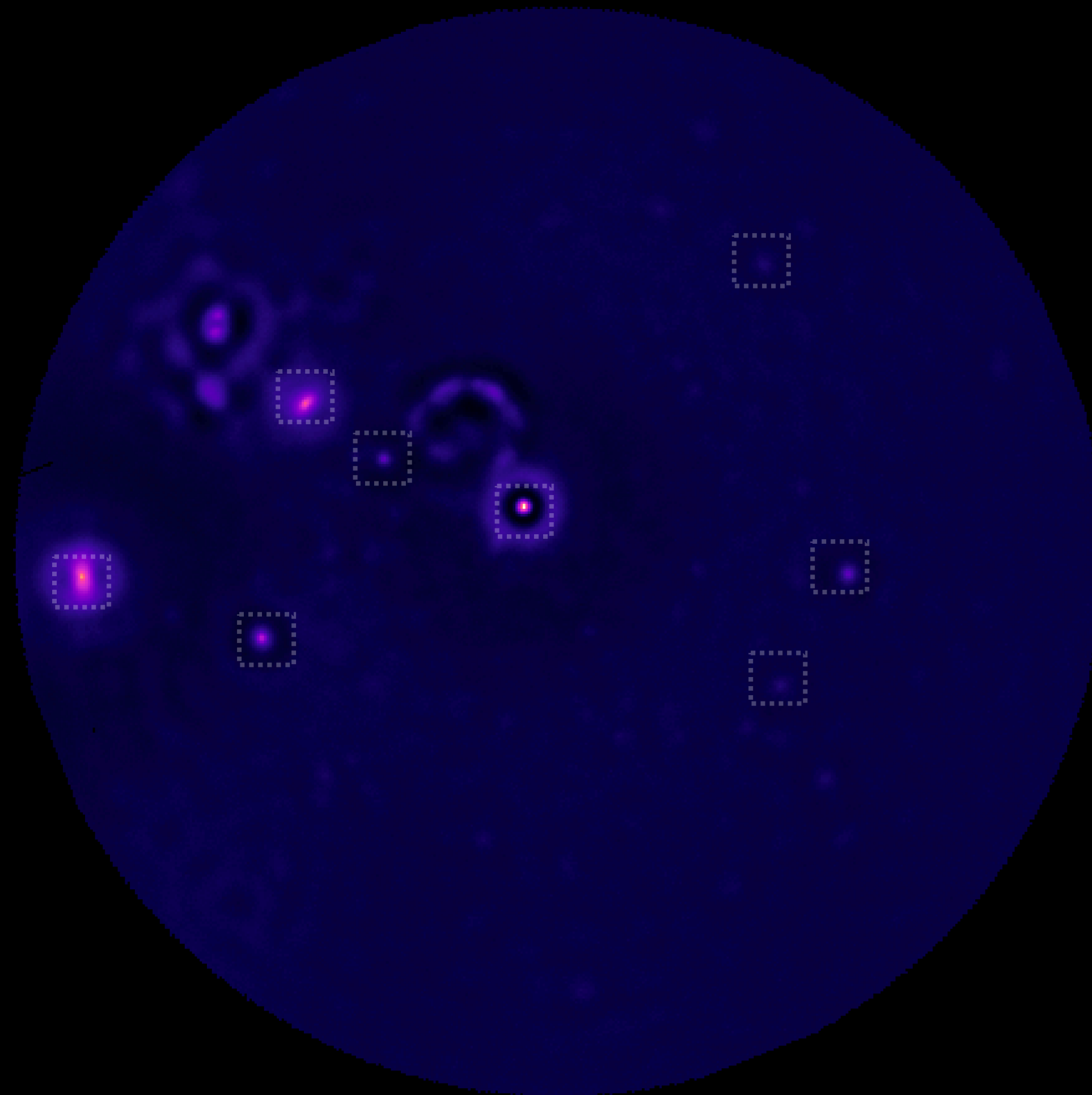
TM1



Point source detection

Latent space excitations

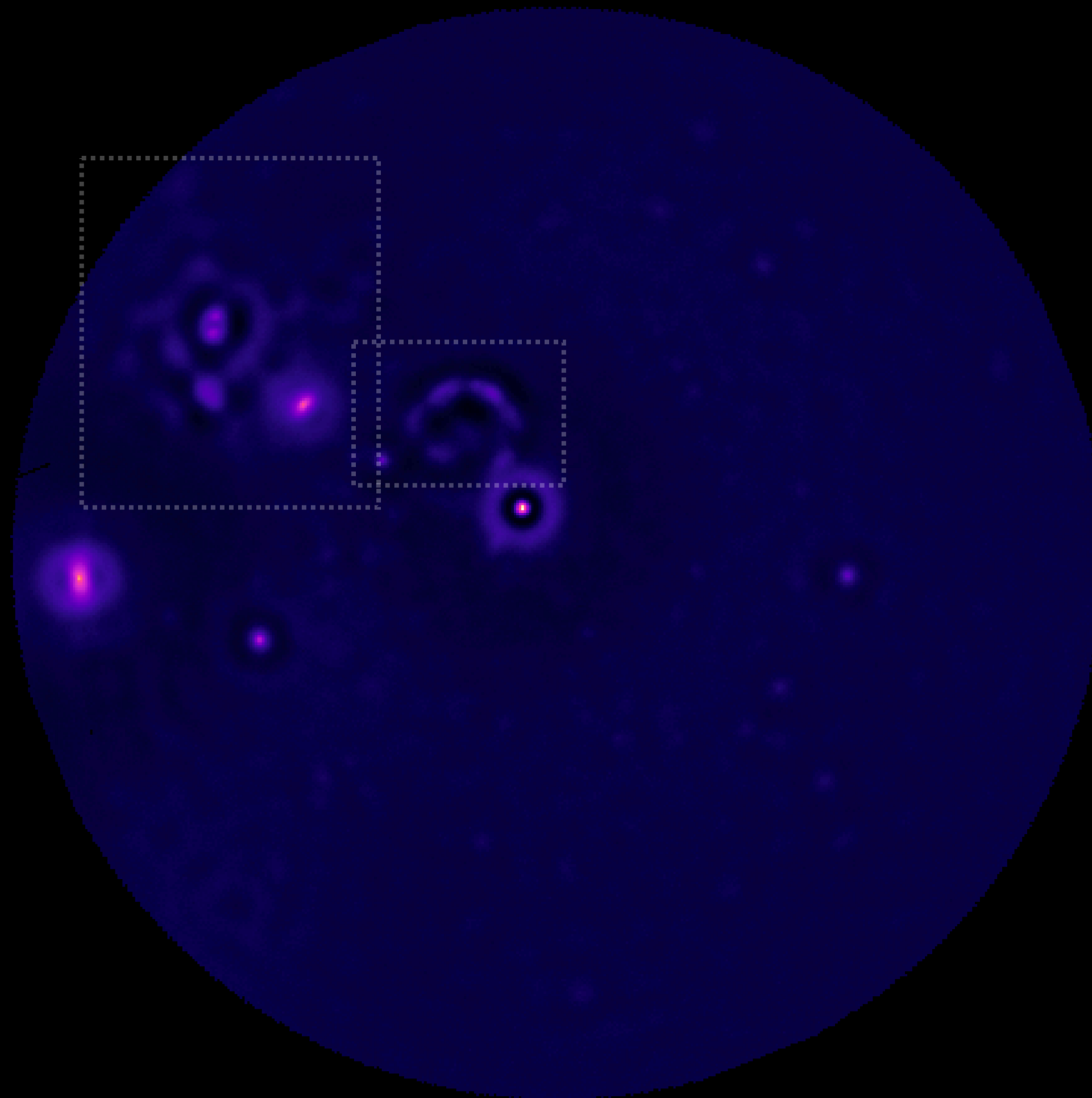
TM1



Extended-source detection!

Latent space excitations

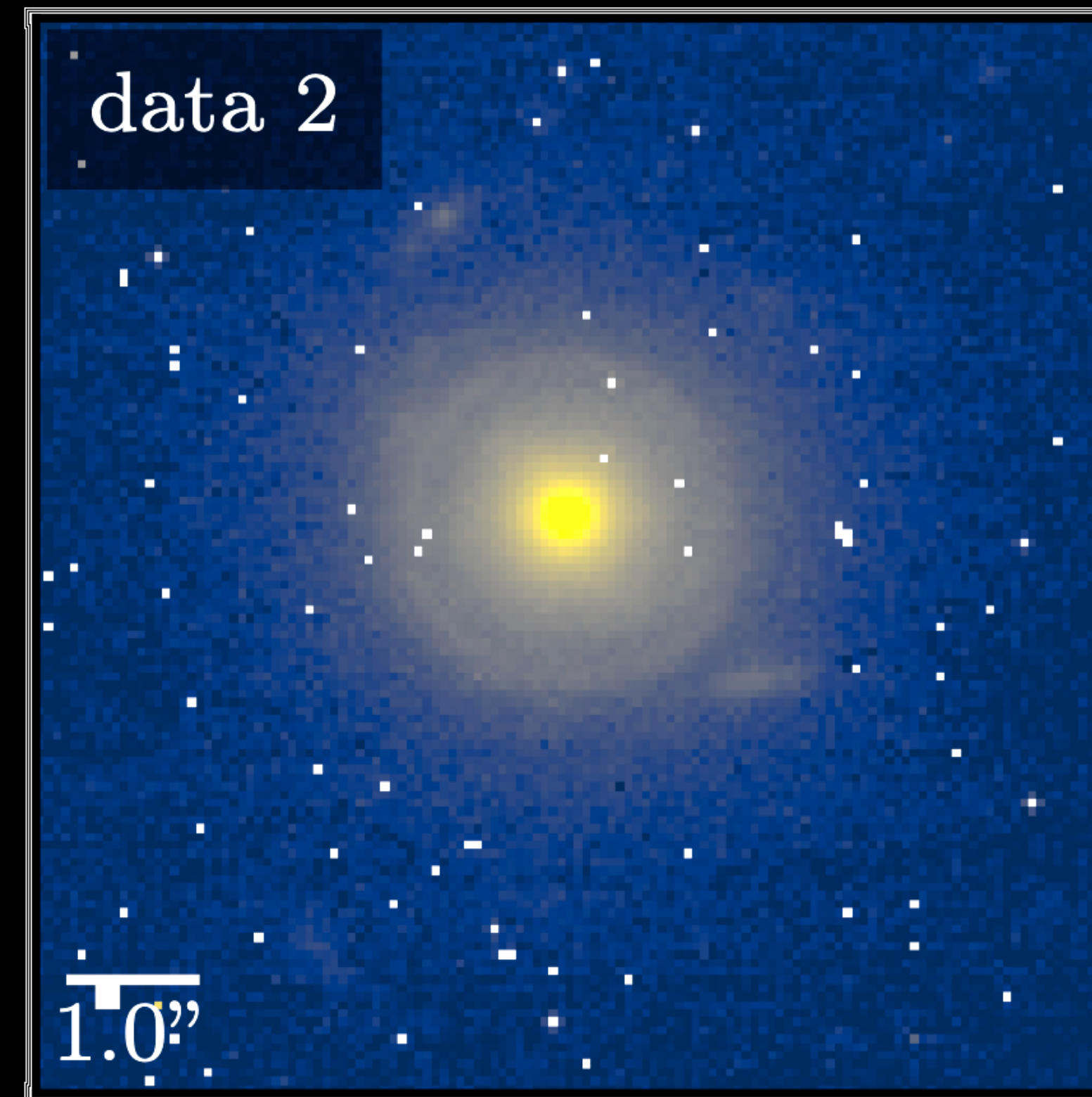
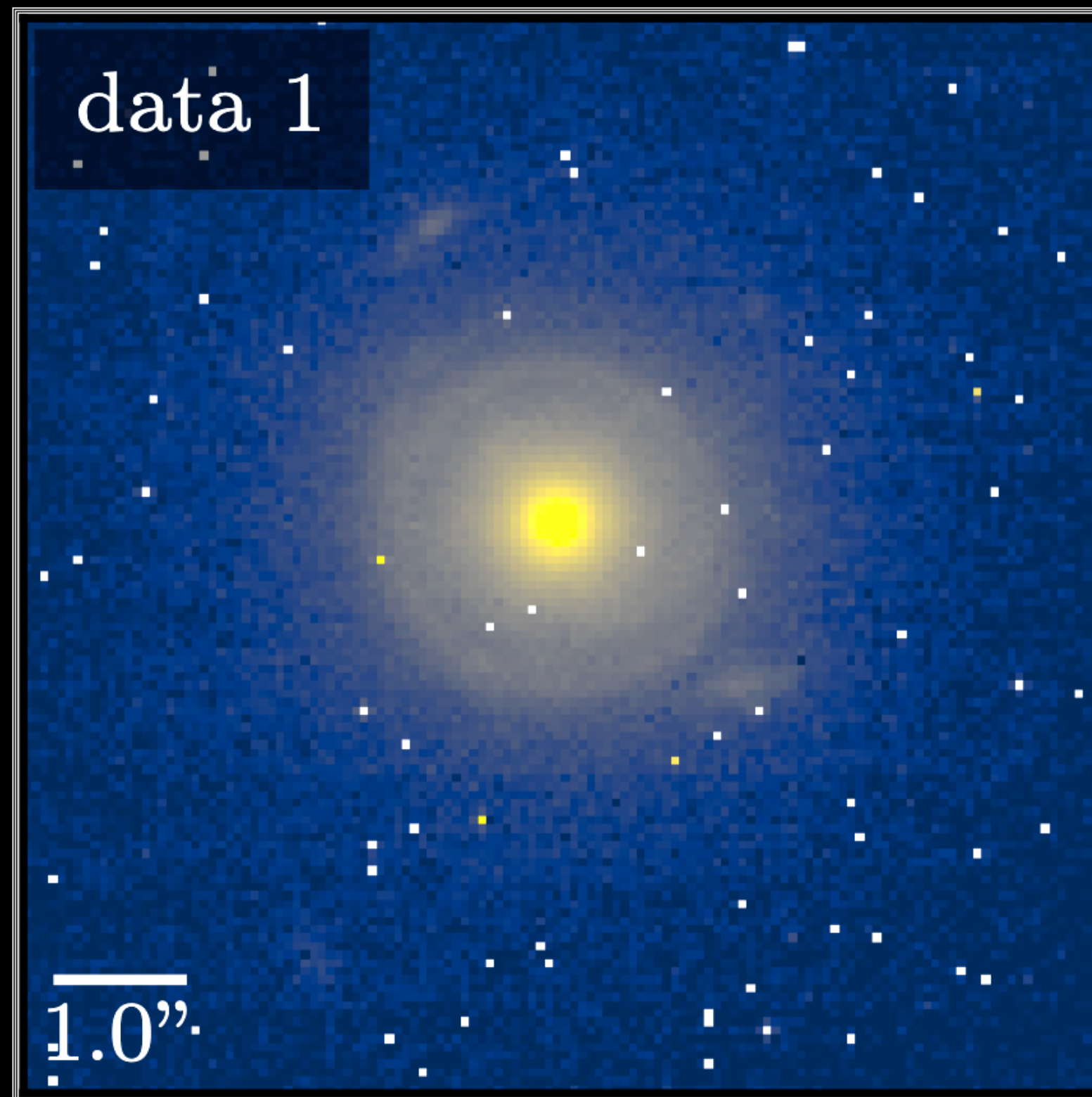
TM1



Extended source model

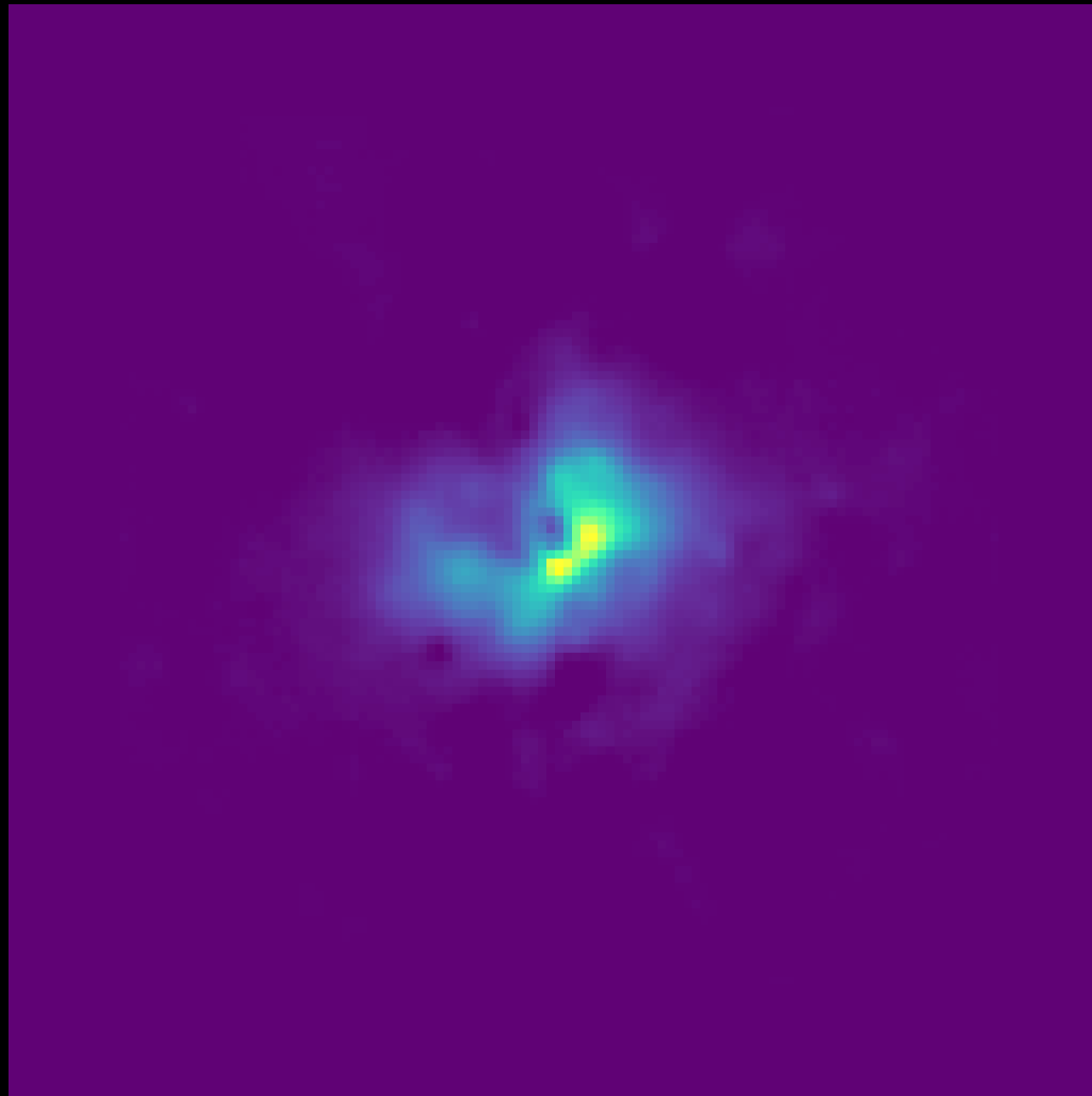
The prior

Developed for strong lensing



The prior

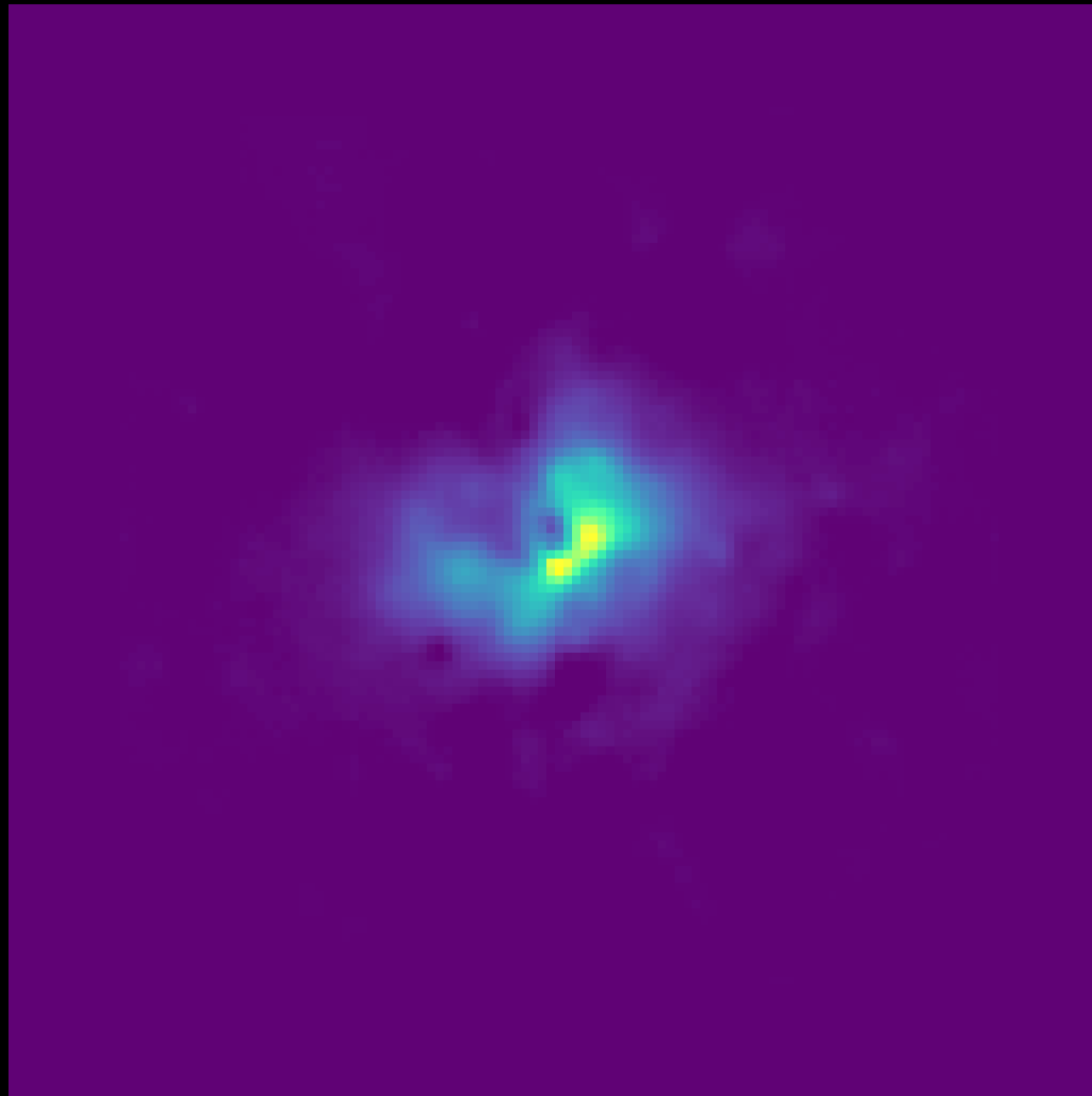
Developed for strong lensing



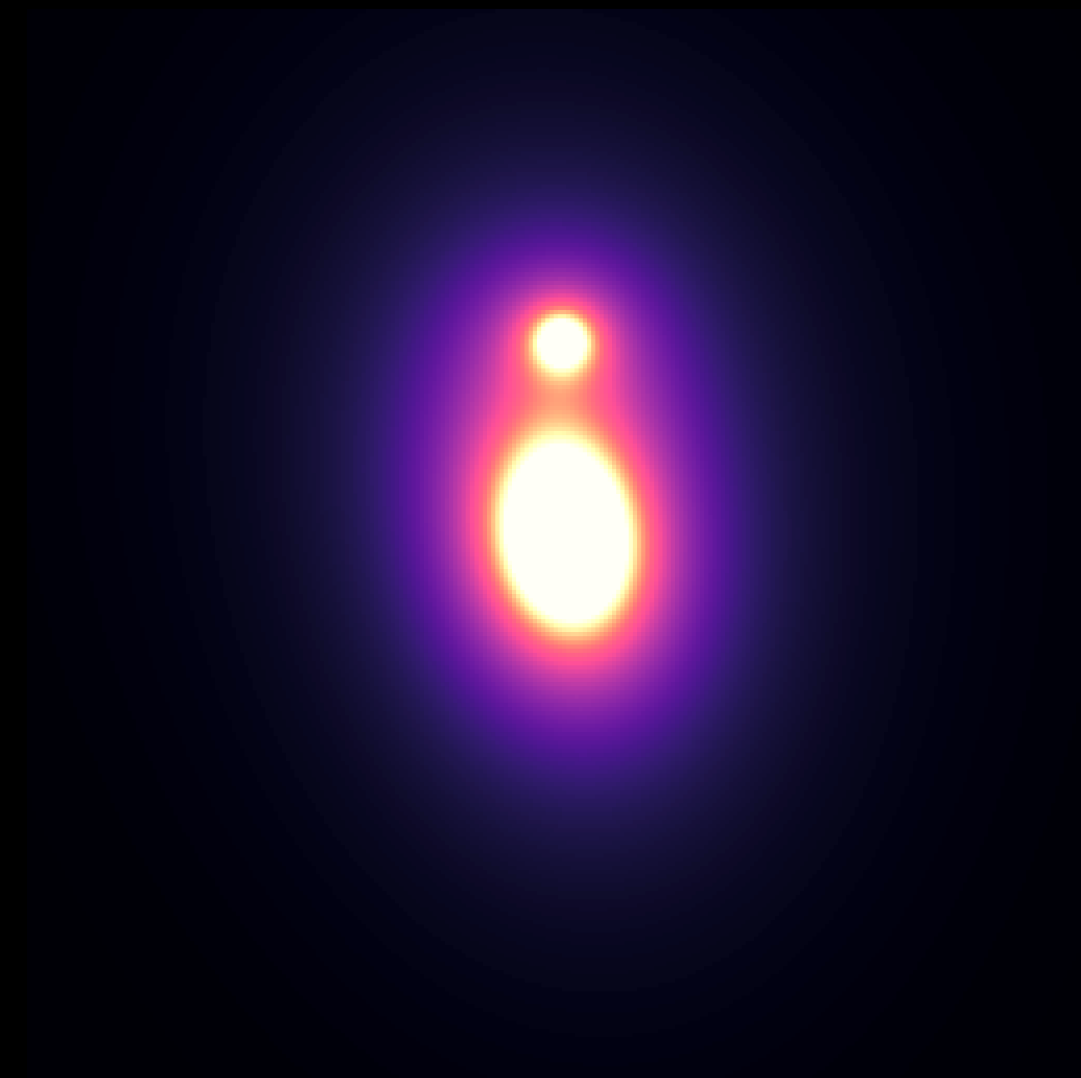
Source galaxy

The prior

Developed for strong lensing



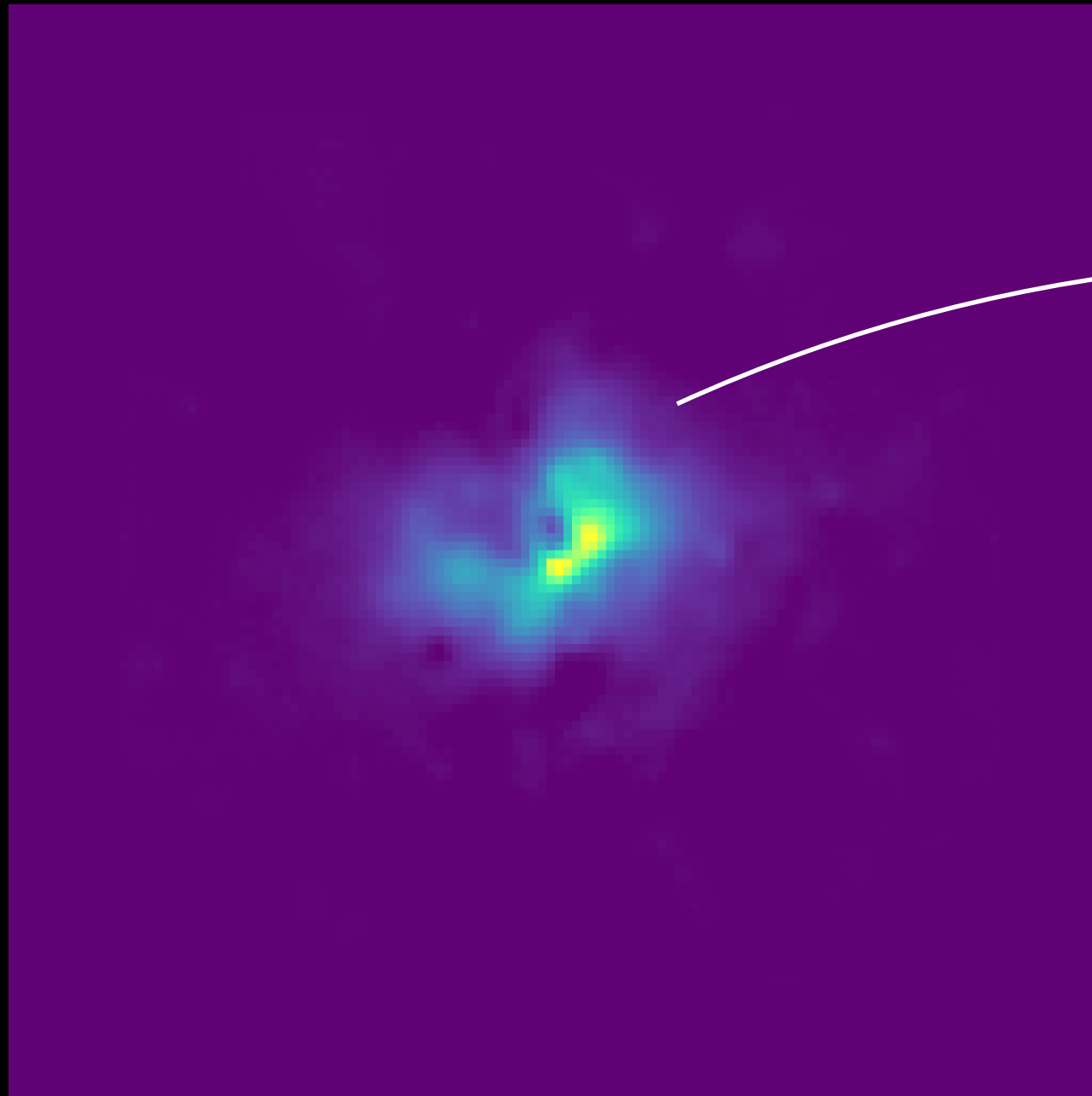
Source galaxy



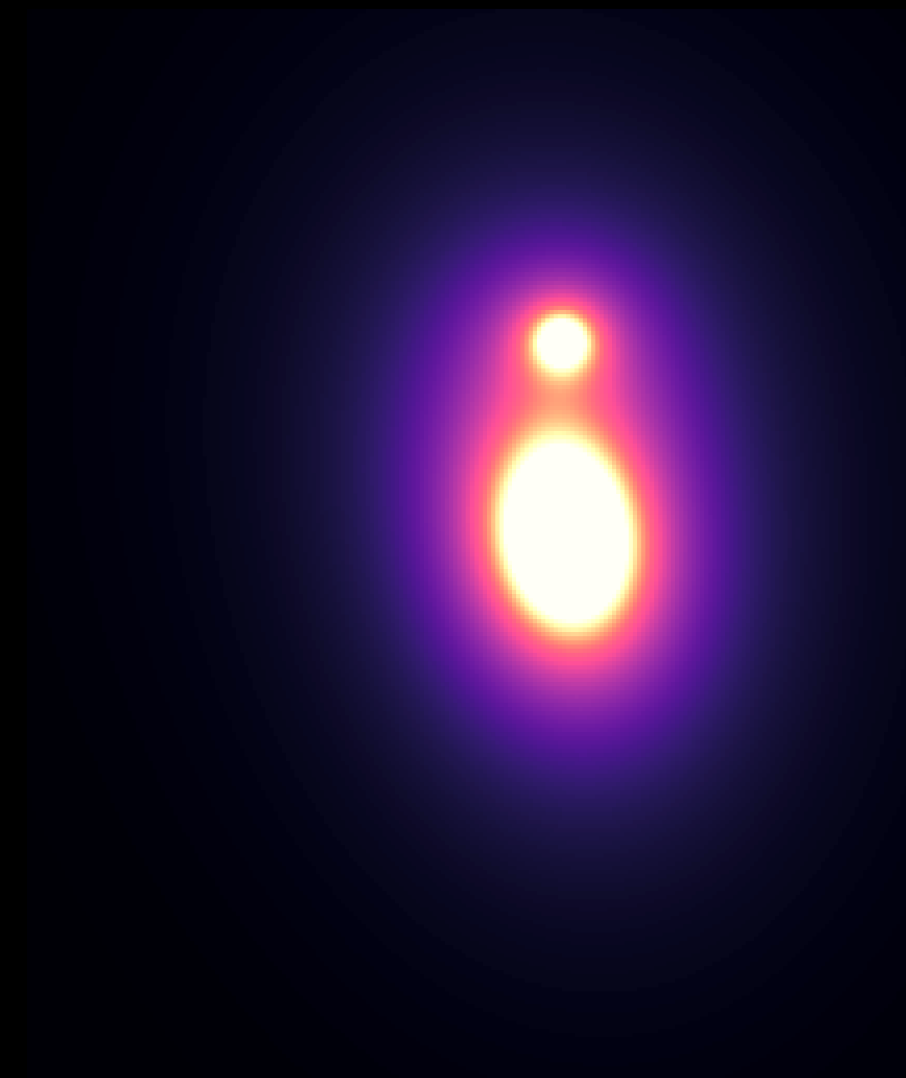
DM halo mass profile

The prior

Developed for strong lensing



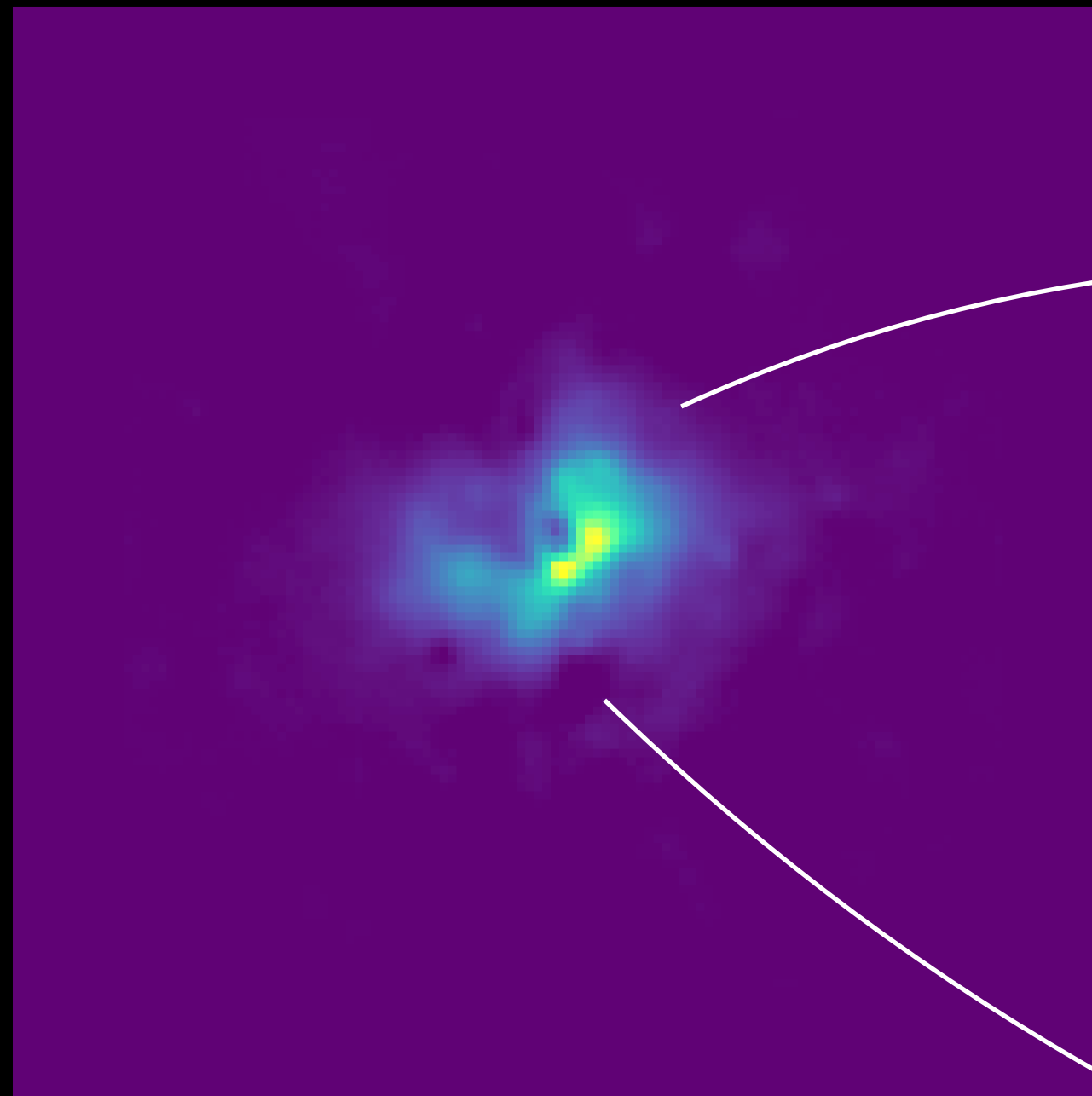
Source galaxy



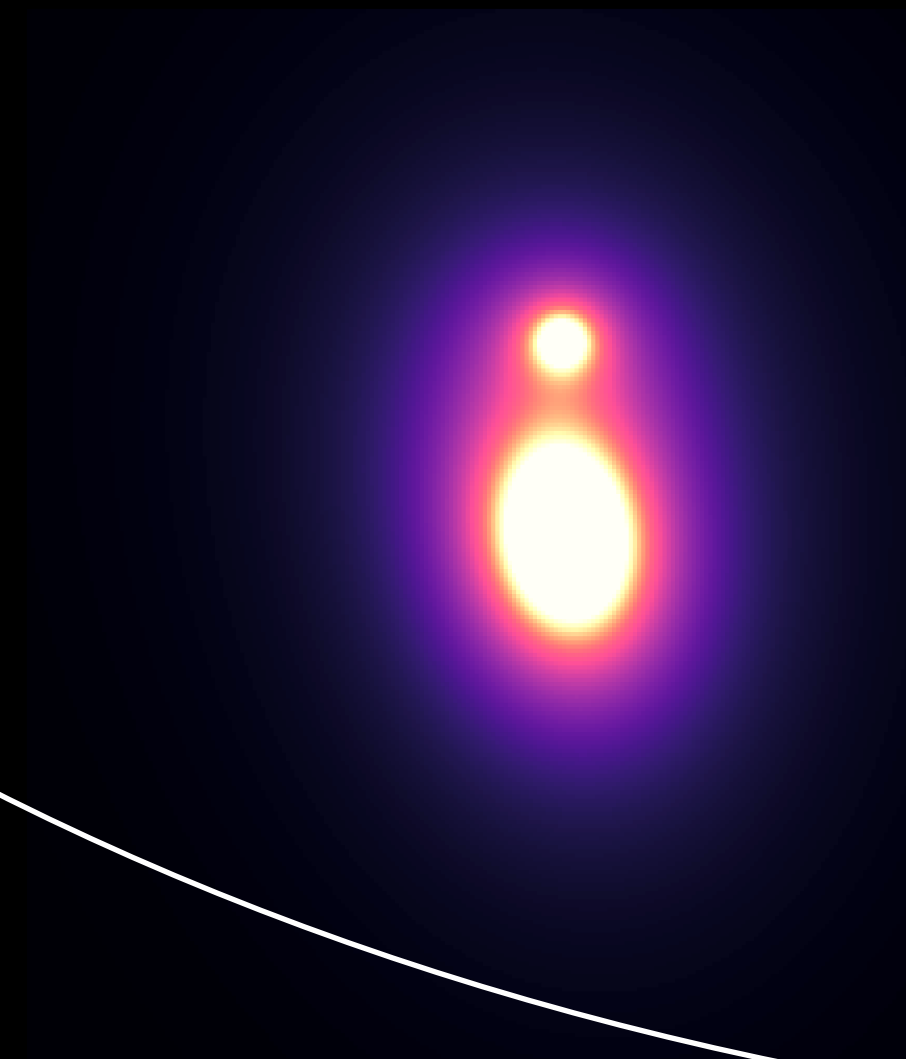
DM halo mass profile

The prior

Developed for strong lensing



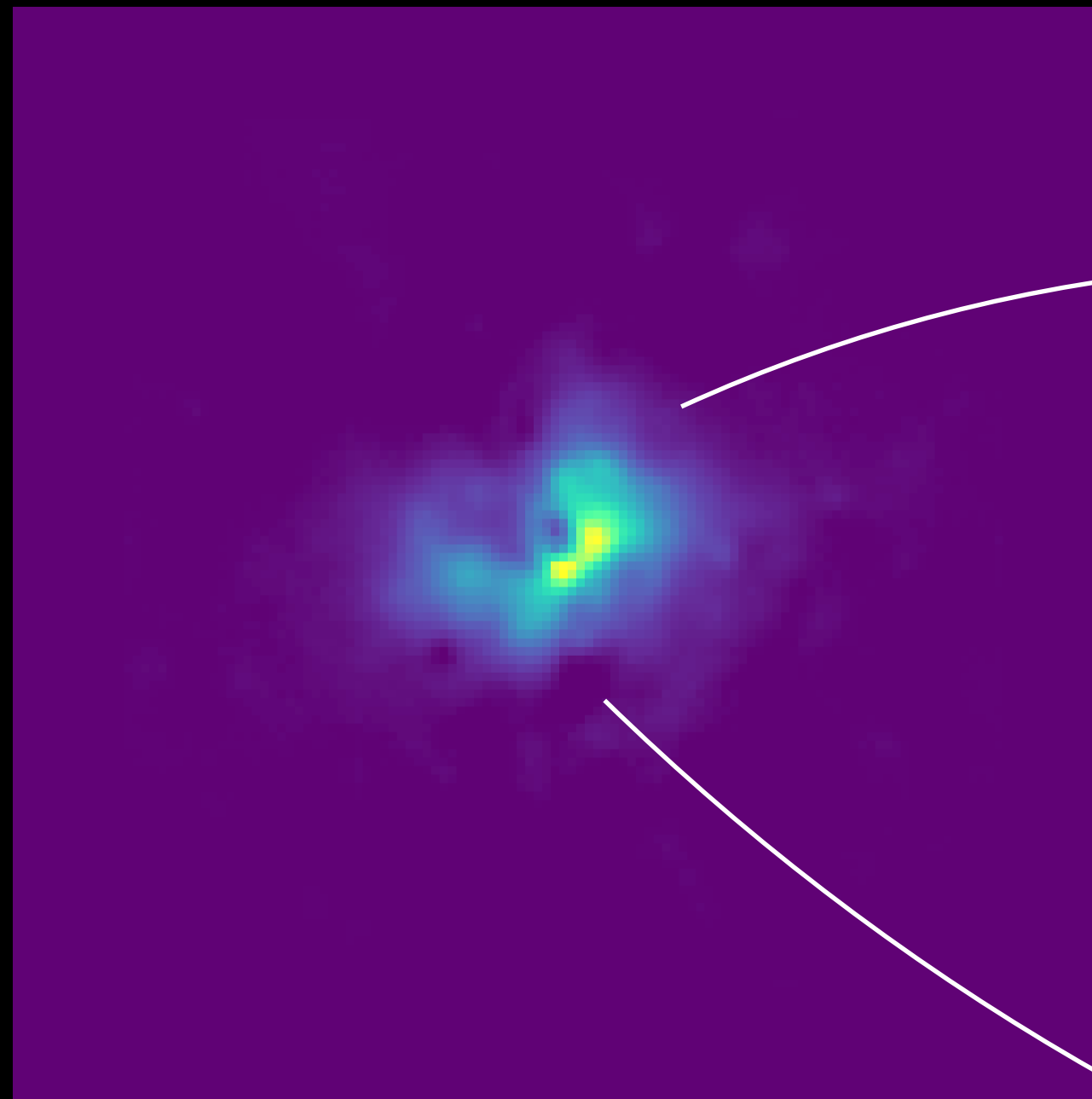
Source galaxy



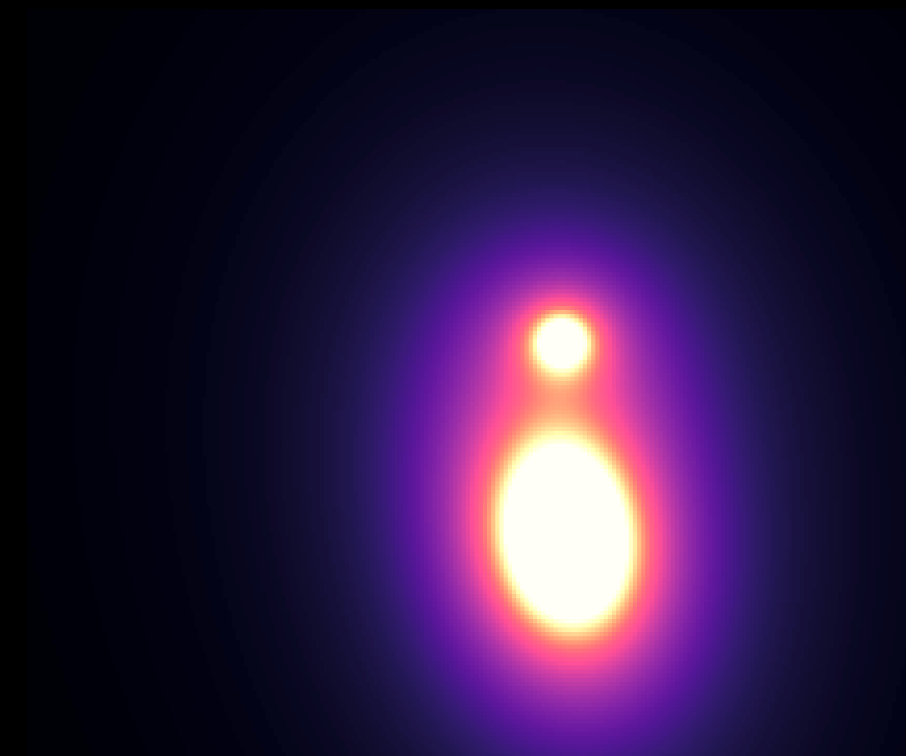
DM halo mass profile

The prior

Developed for strong lensing



Source galaxy

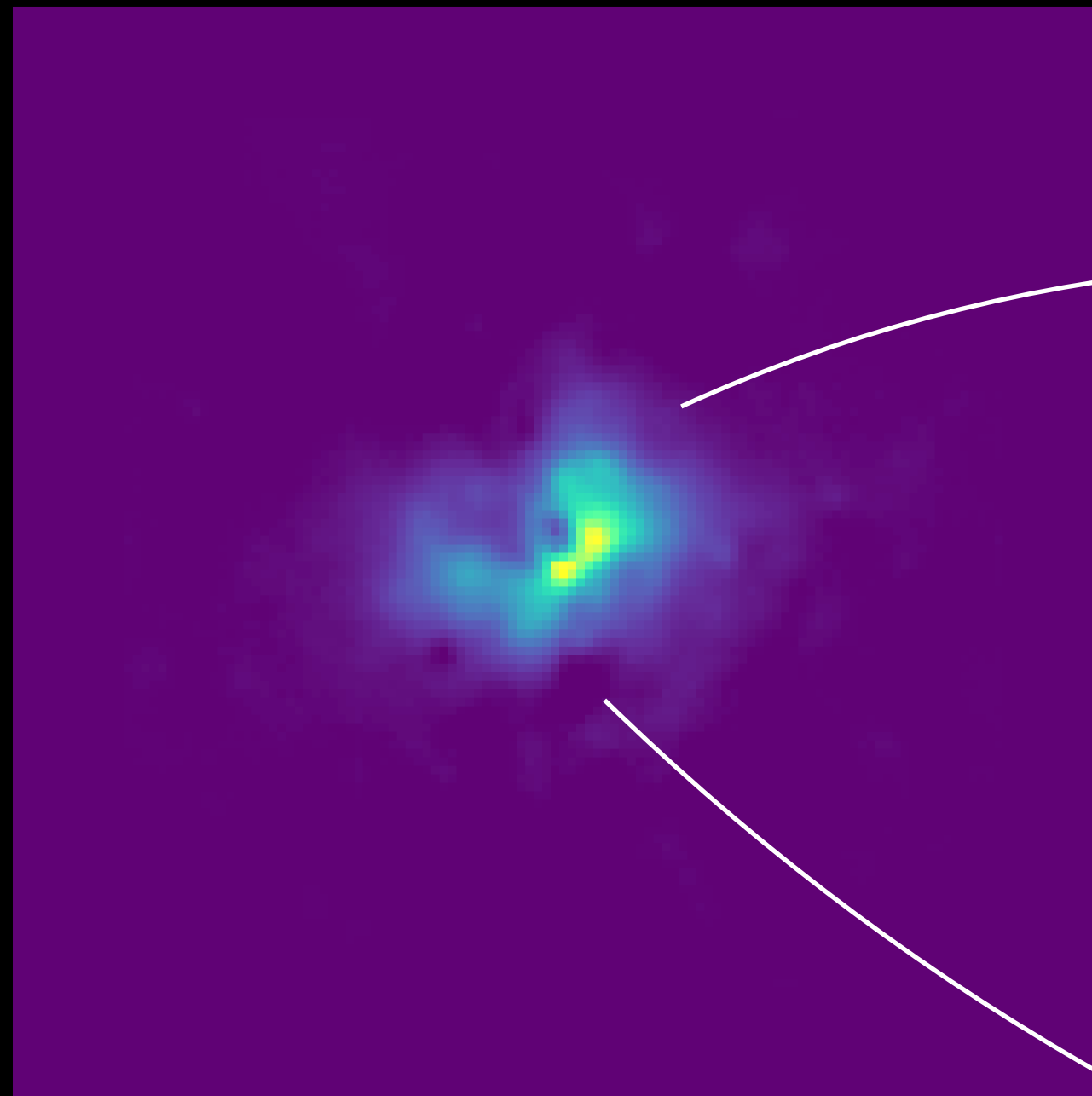


DM halo mass profile

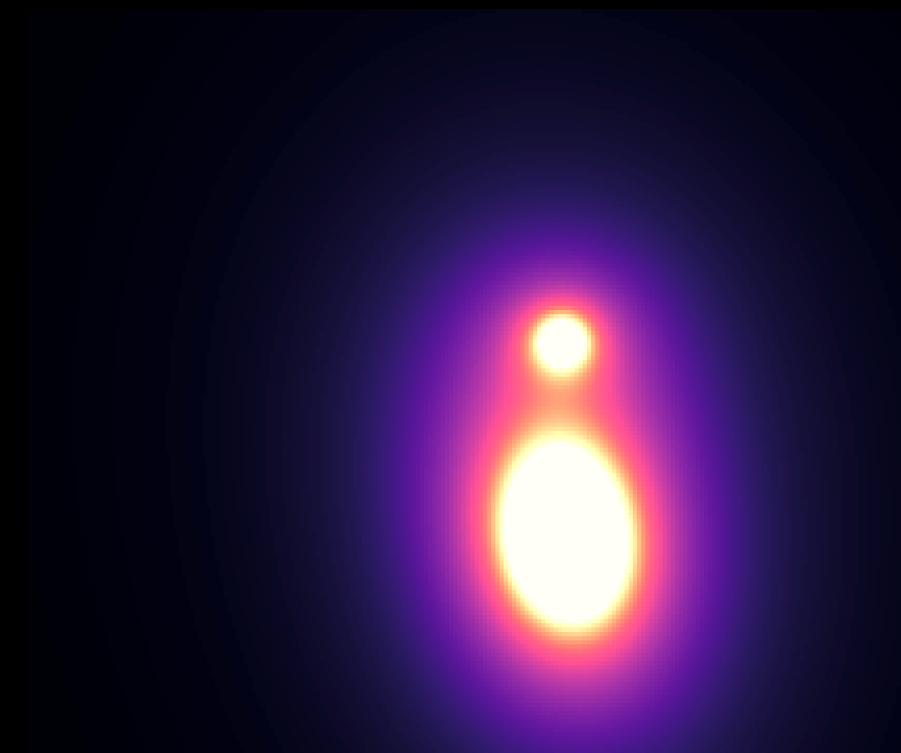
$$\nabla \cdot \alpha = 2 \kappa$$

The prior

Developed for strong lensing

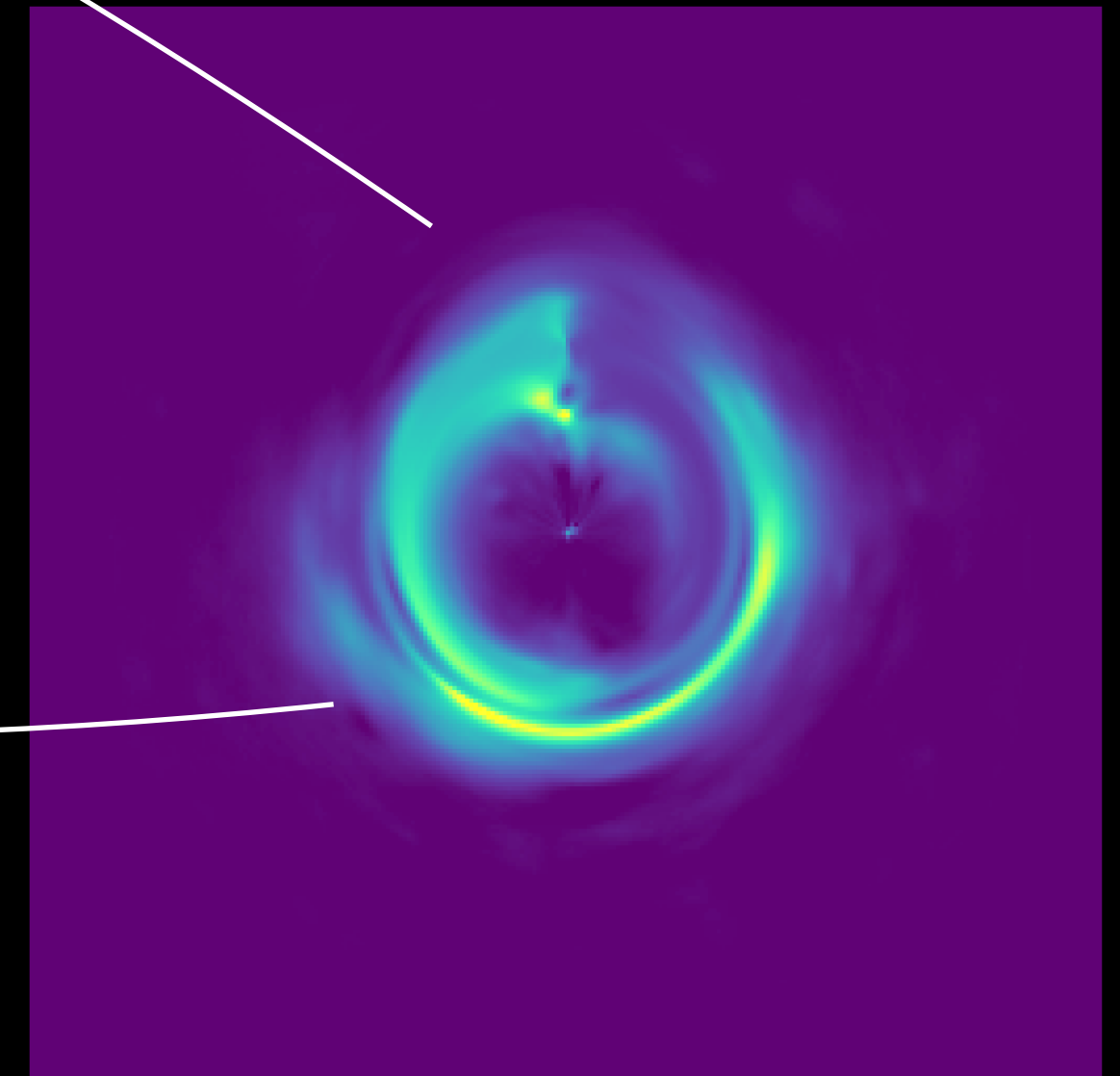


Source galaxy



DM halo mass profile

$$\nabla \cdot \alpha = 2 \kappa$$

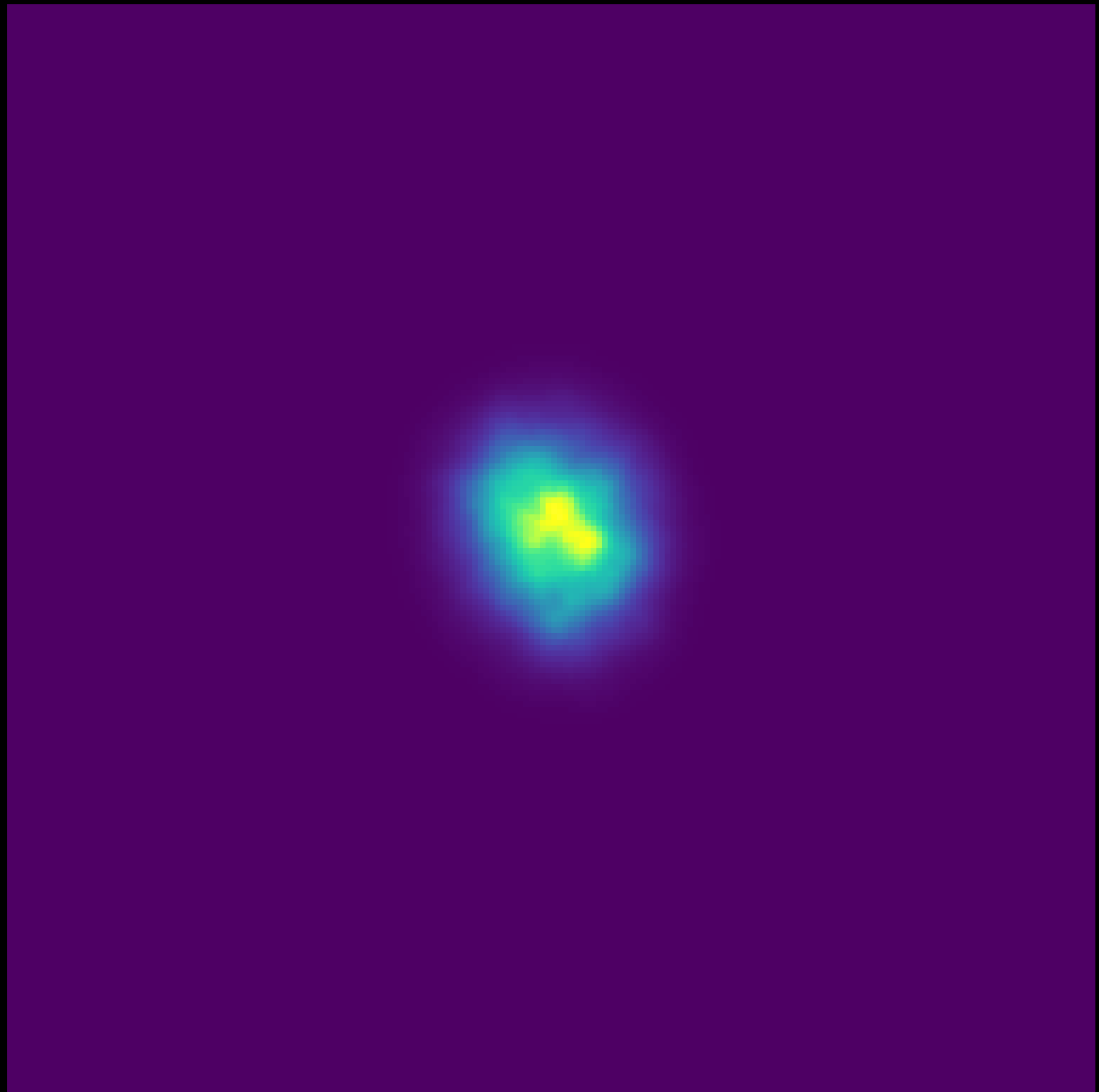


$$y = x - \alpha(x)$$

The prior

Extended sources

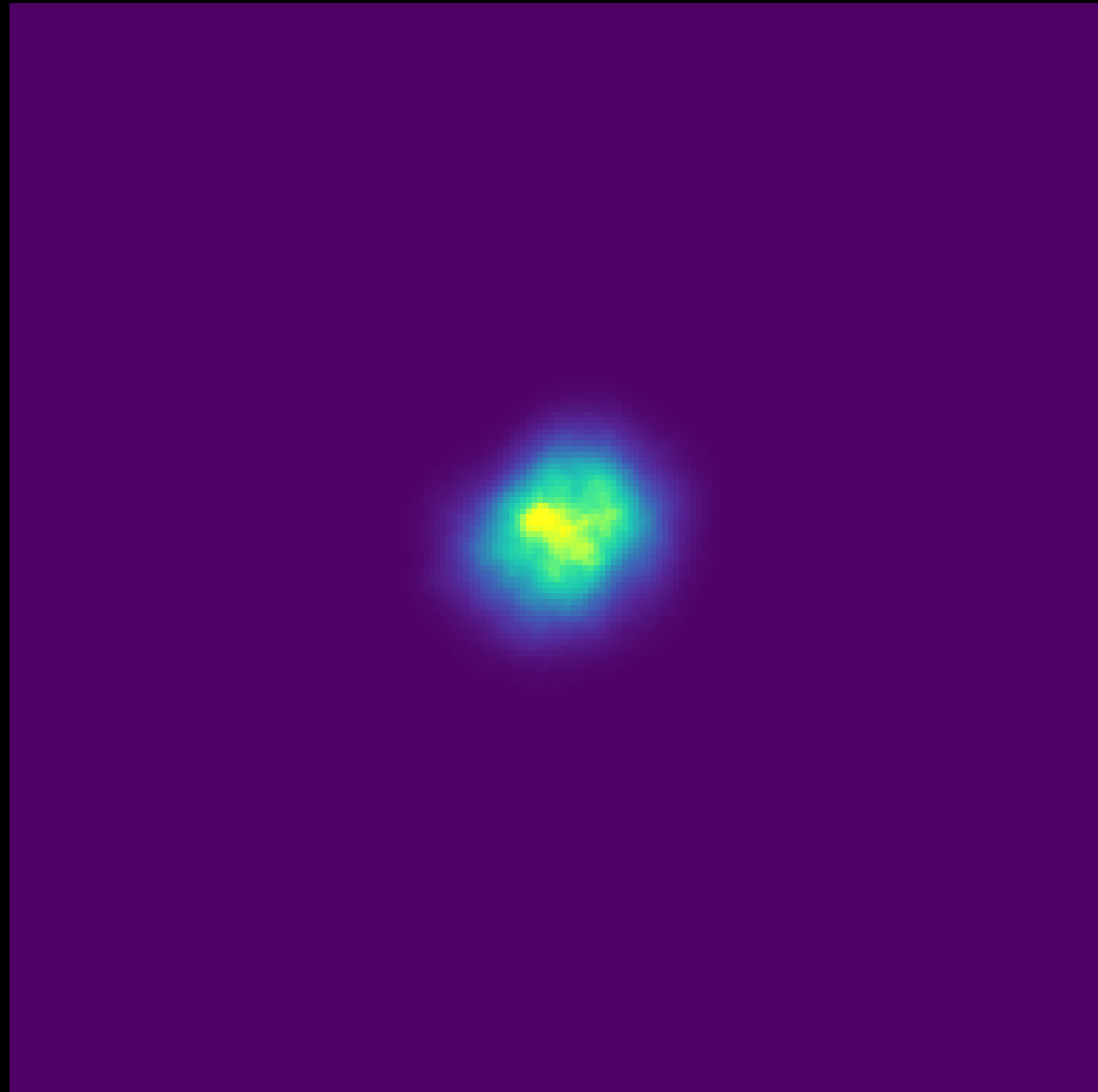
$$P(s)$$



The prior

Extended sources

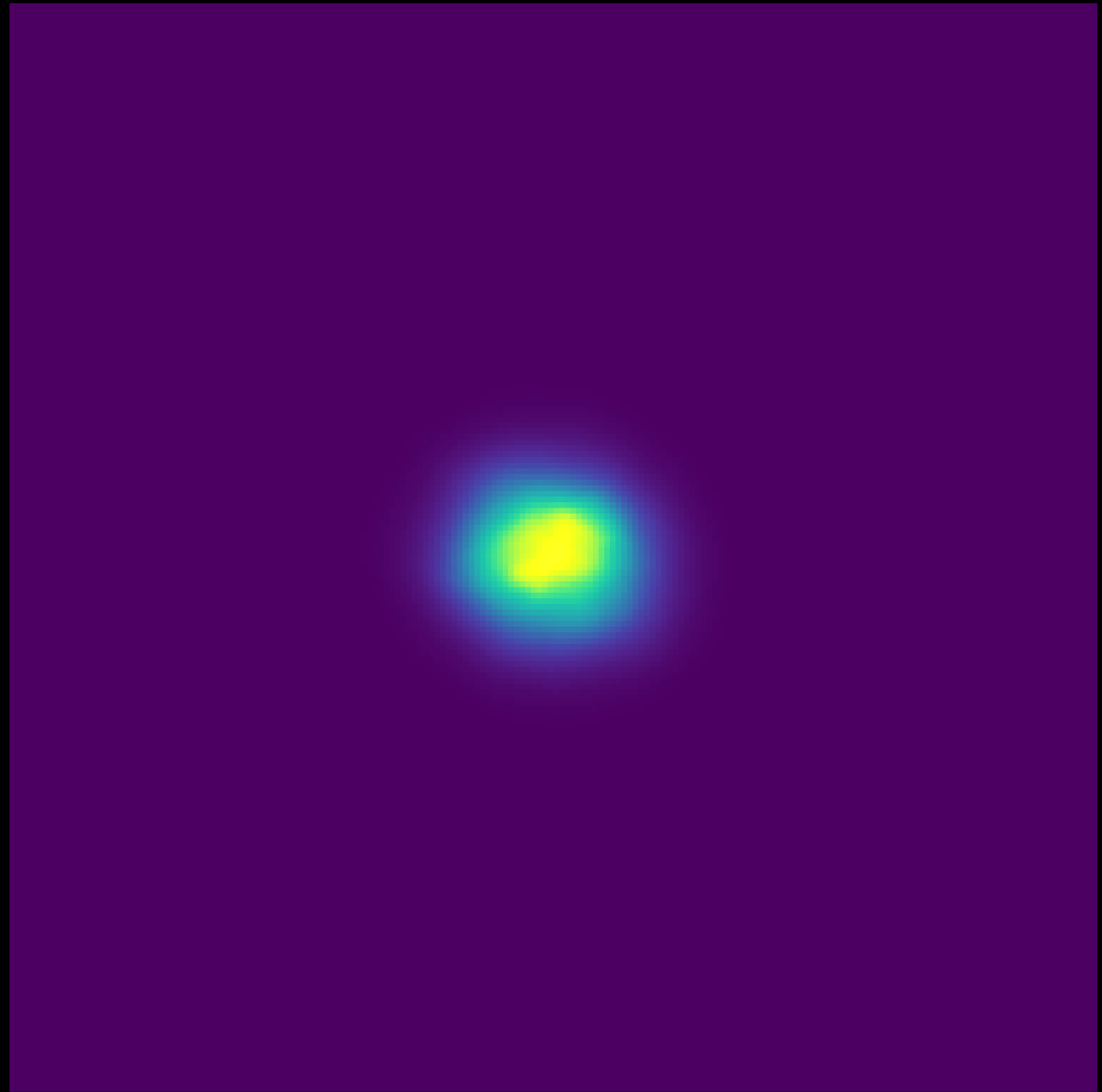
$$P(s)$$



The prior

Extended sources

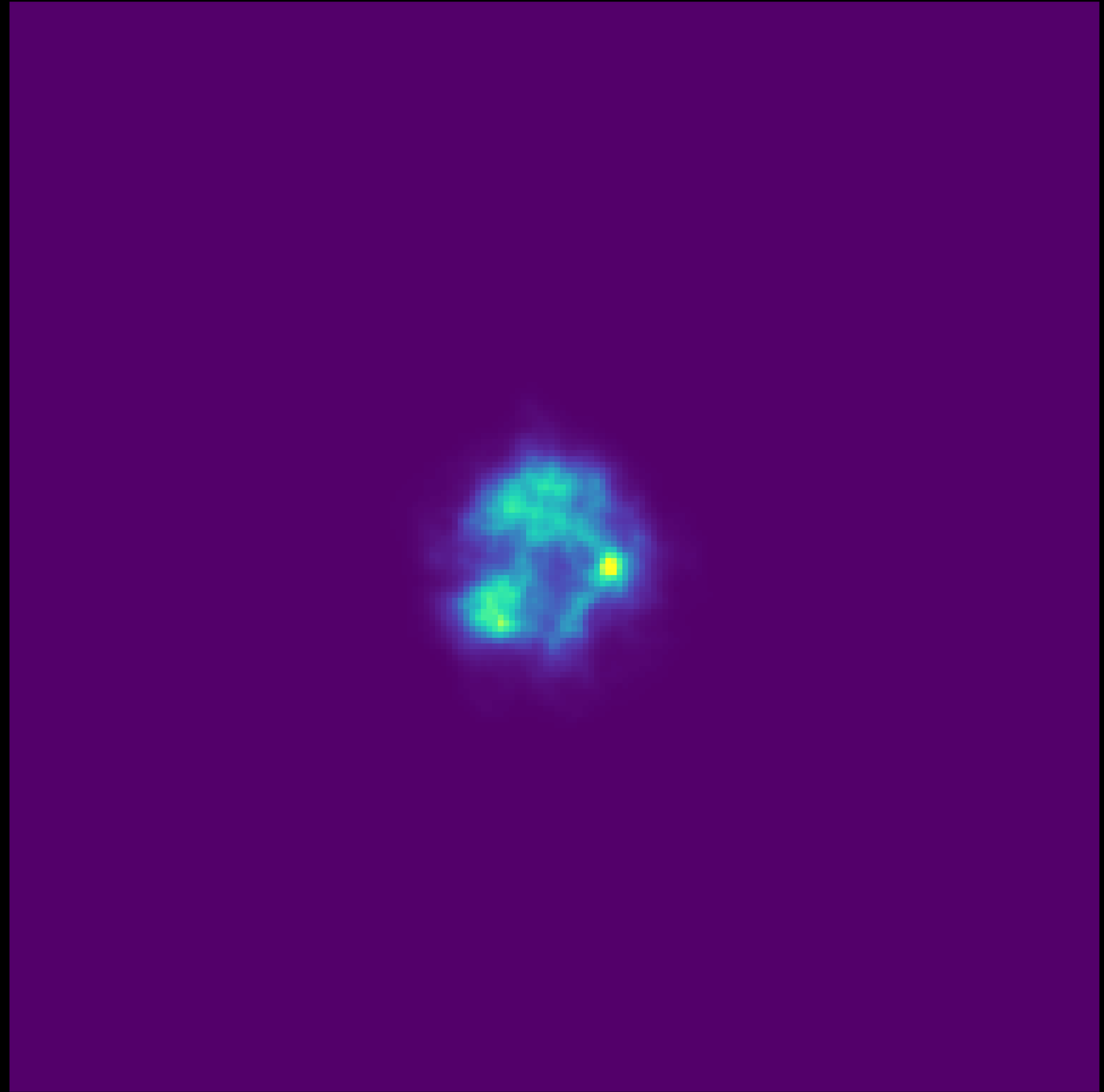
$$P(s)$$



The prior

Extended sources

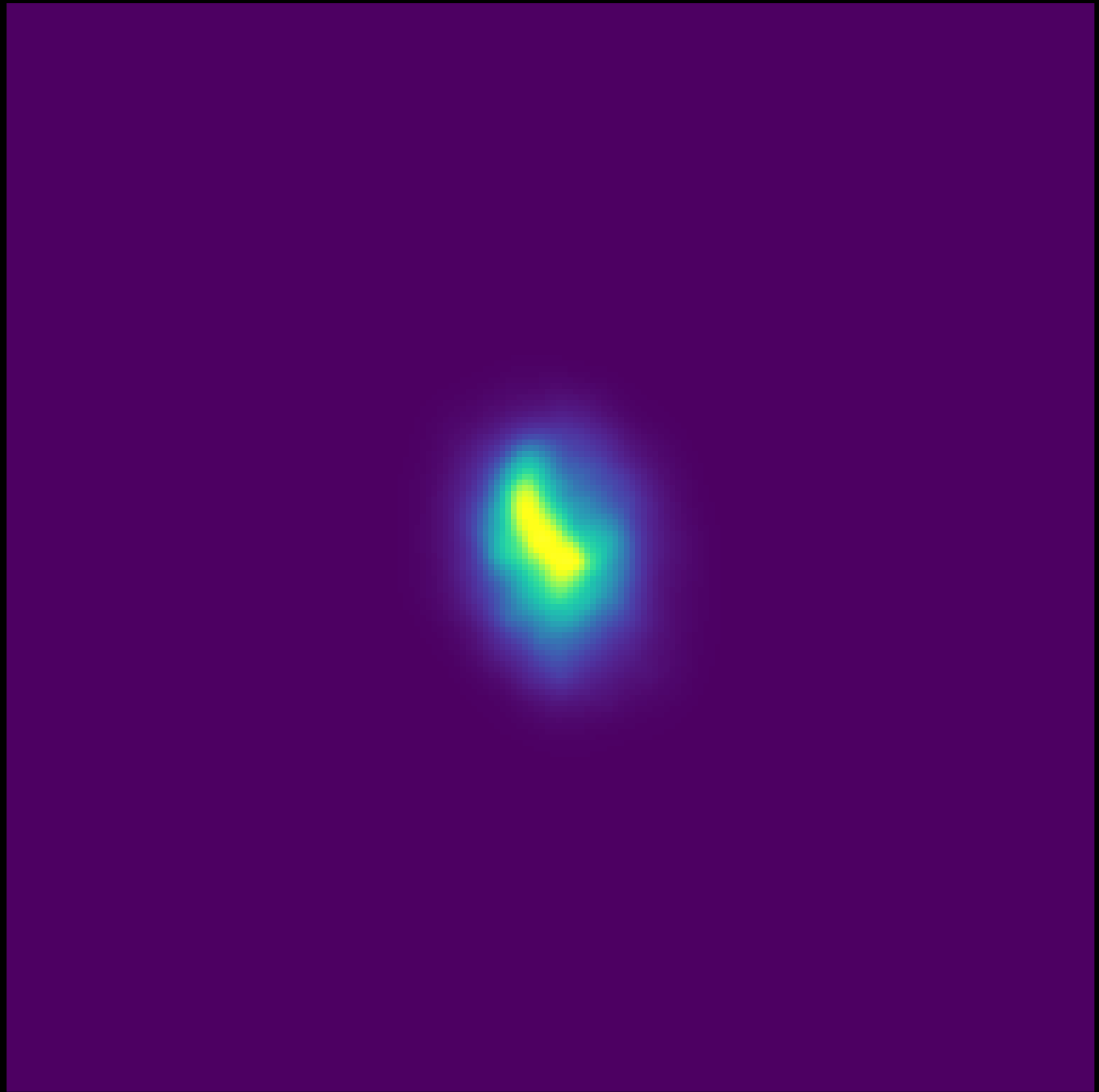
$$P(s)$$



The prior

Extended sources

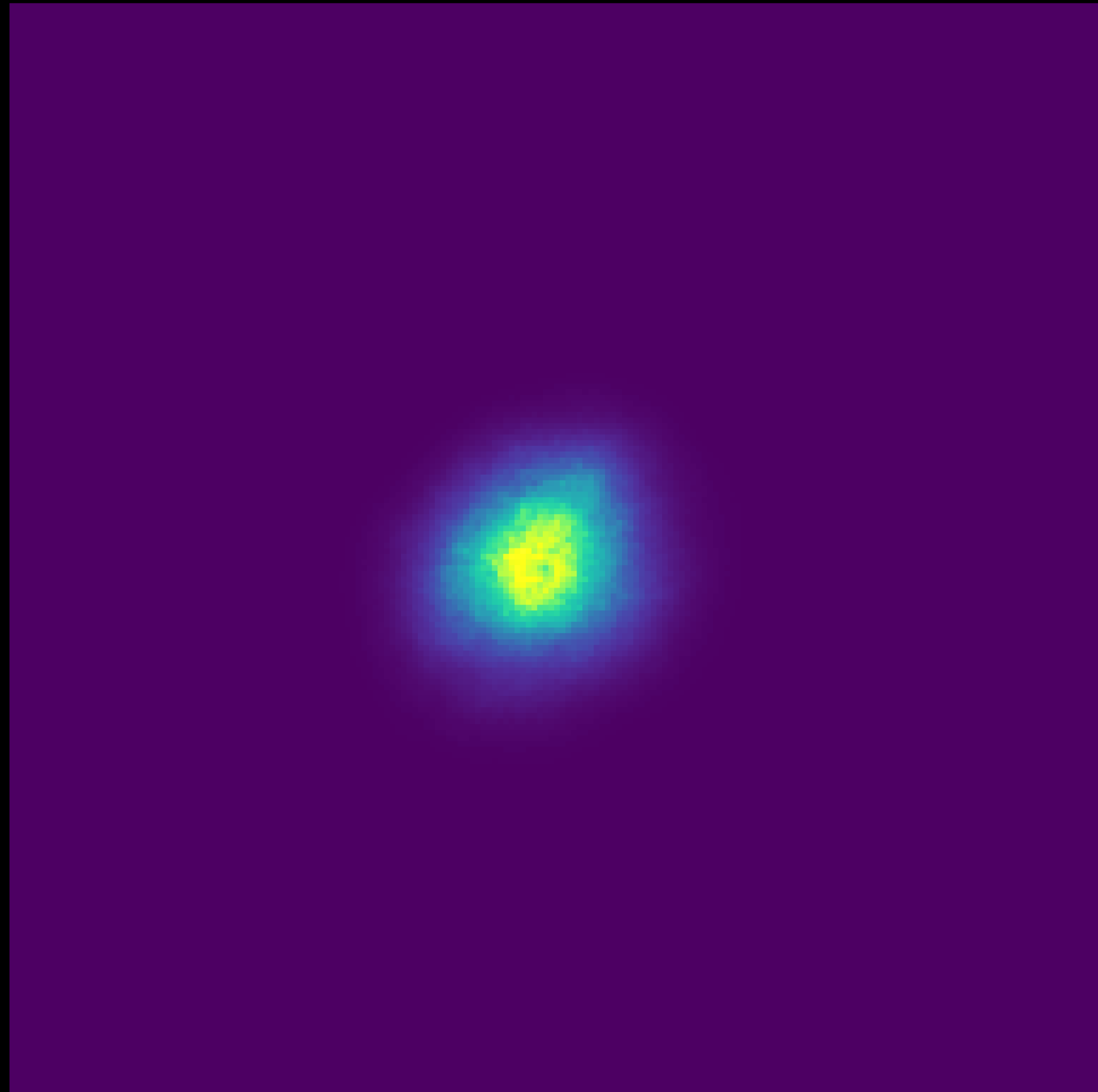
$$P(s)$$



The prior

Extended sources

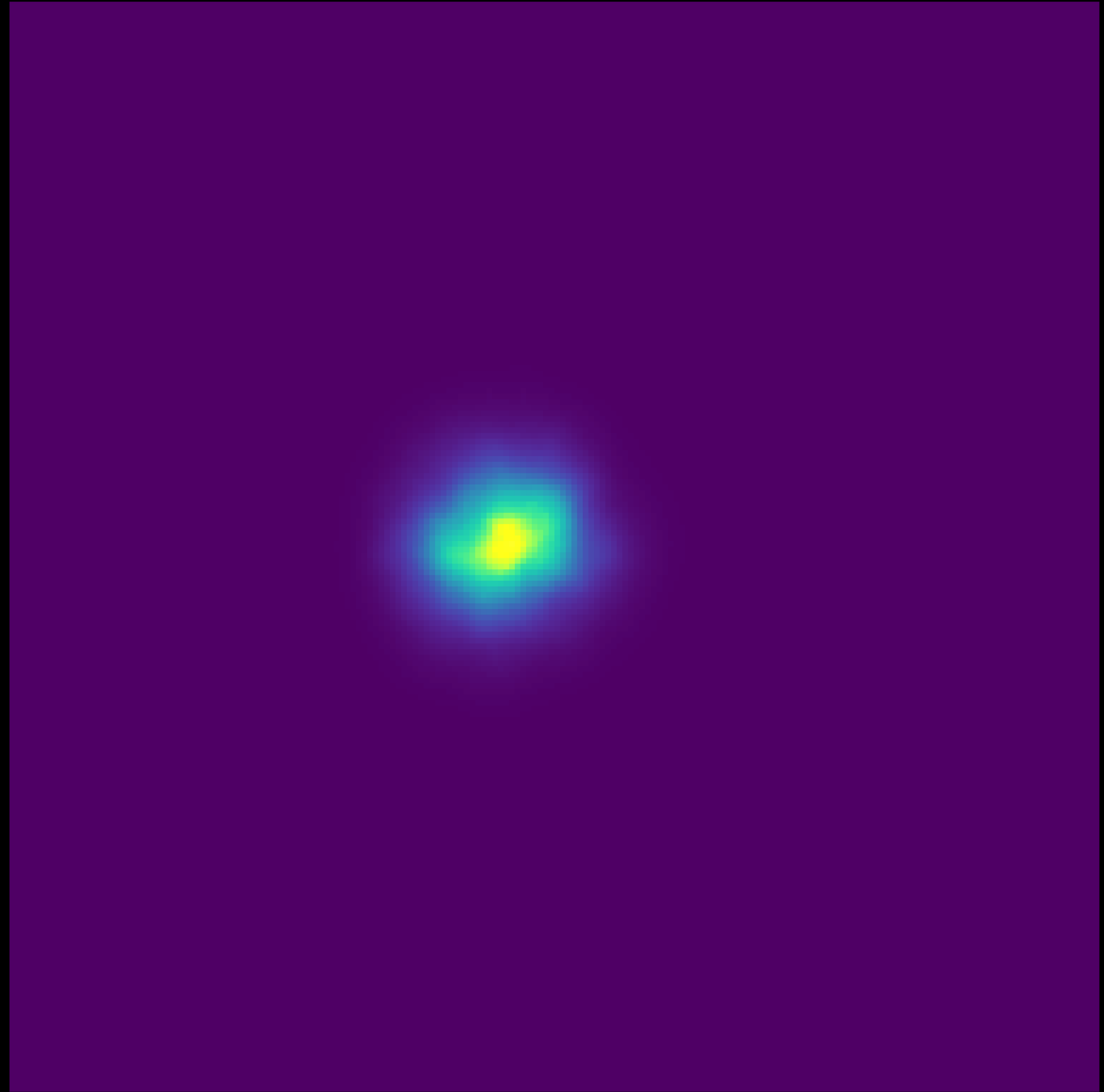
$$P(s)$$



The prior

Extended sources

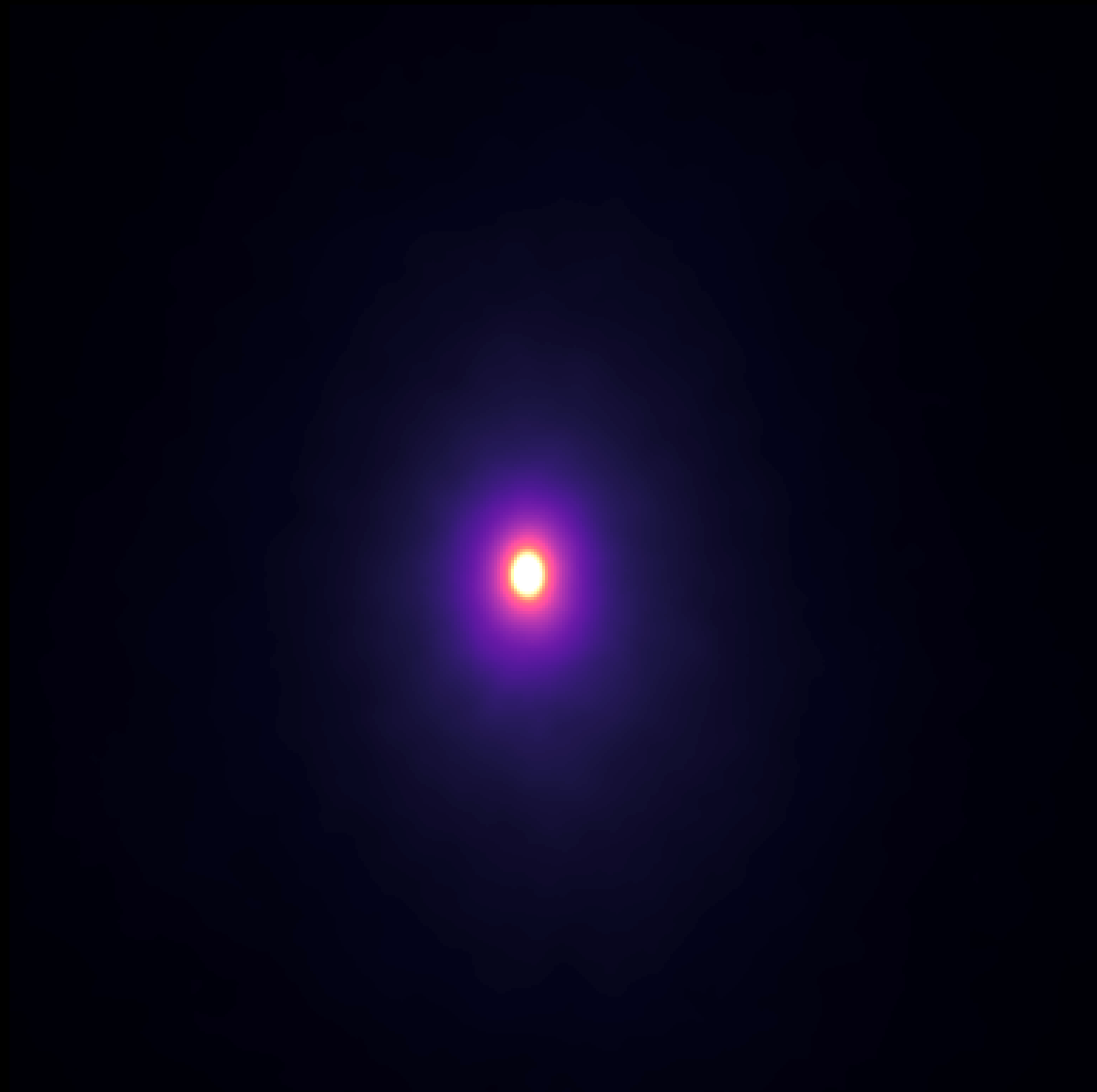
$$P(s)$$



The prior

Lens mass distribution

$$P(s)$$



The prior

Lens mass distribution

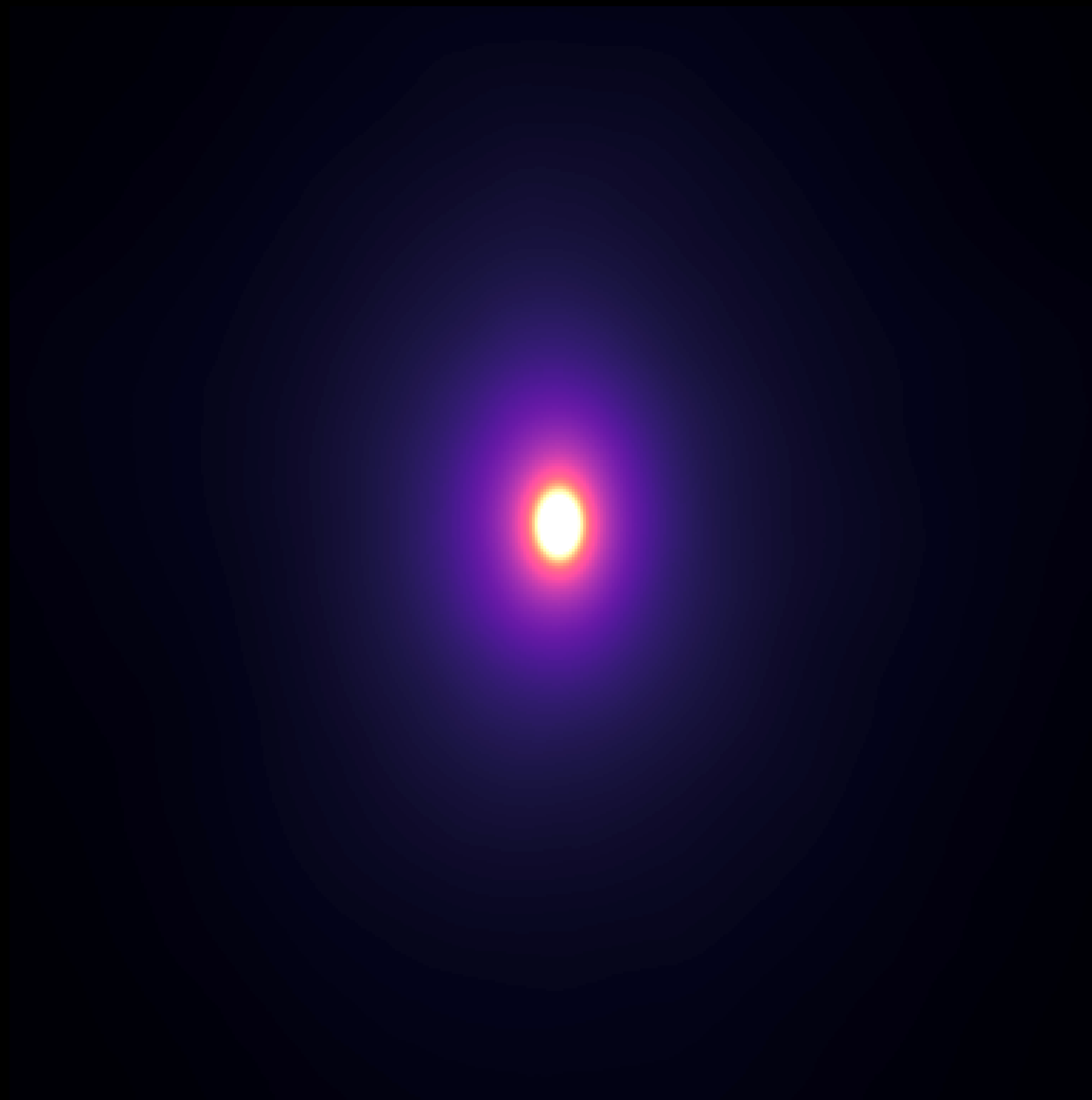
$$P(s)$$



The prior

Lens mass distribution

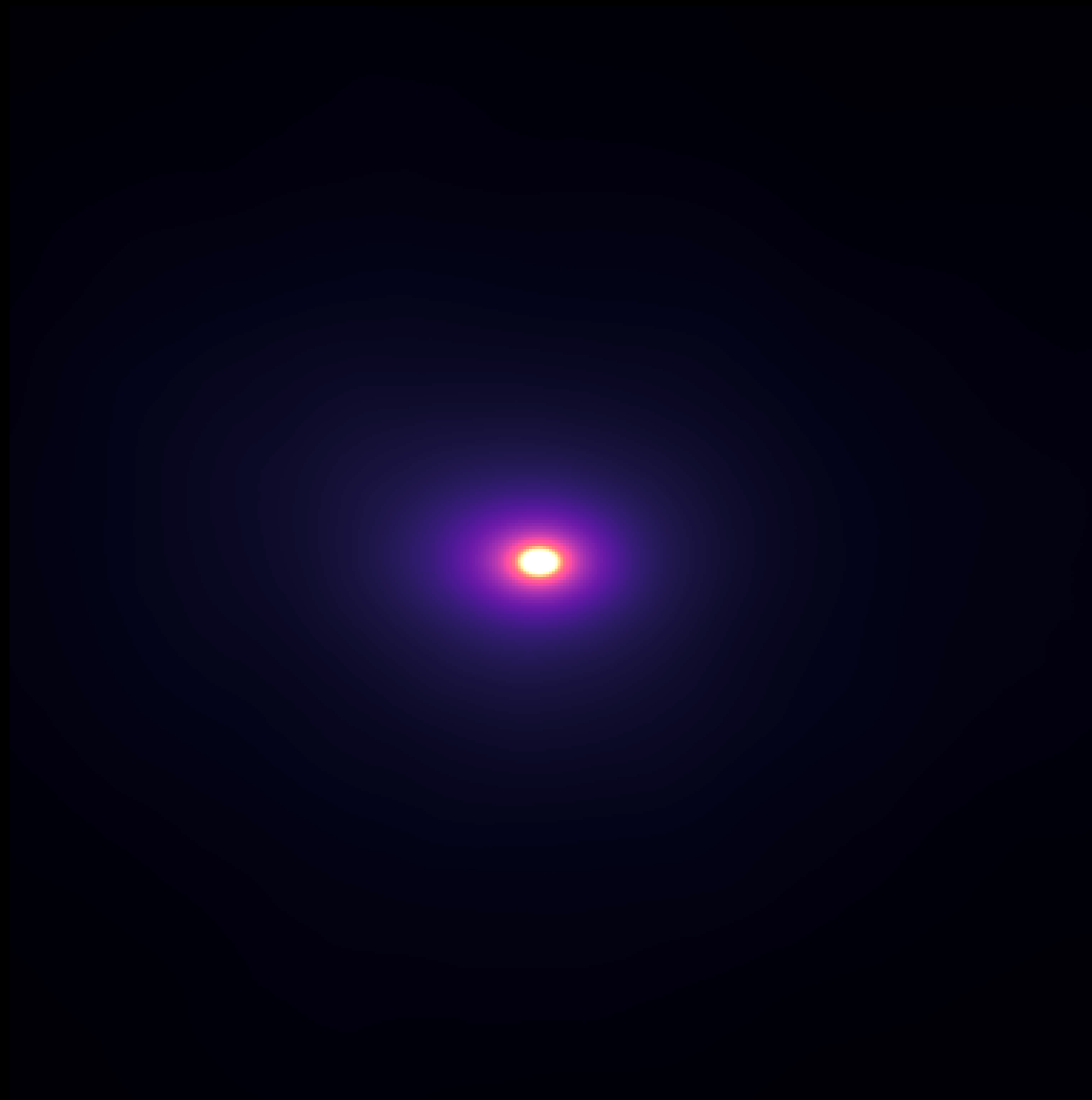
$$P(s)$$



The prior

Lens mass distribution

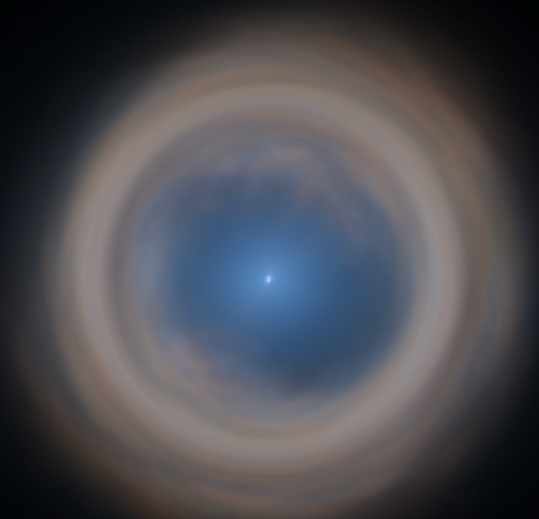
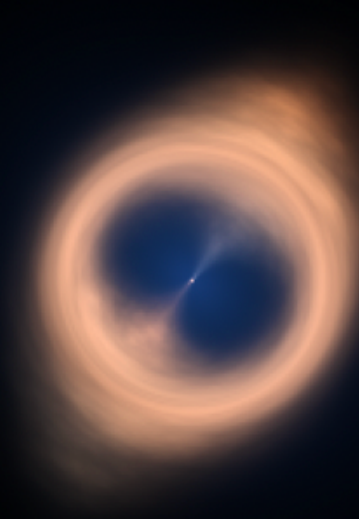
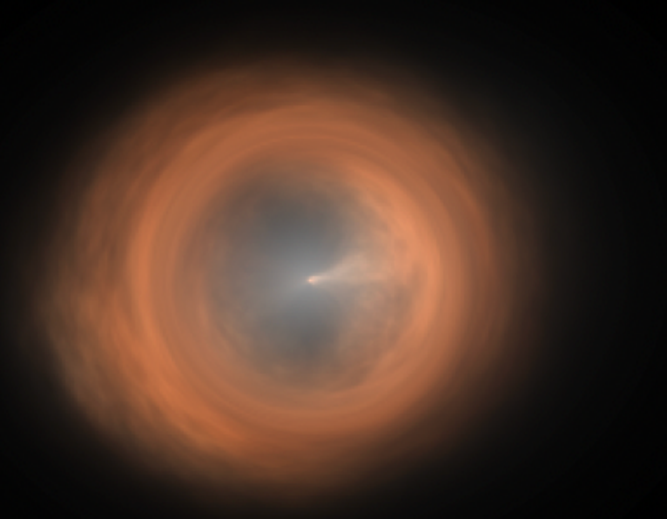
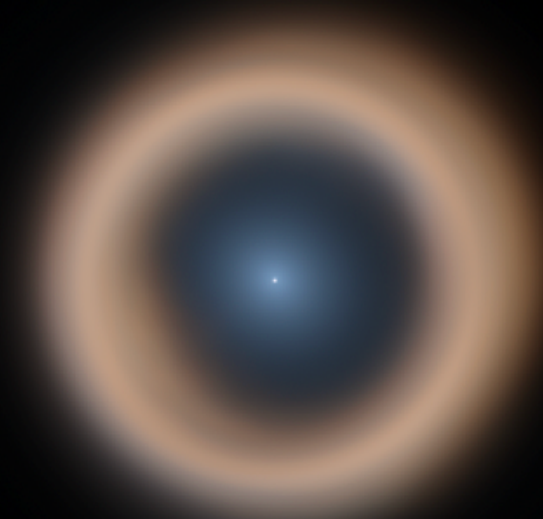
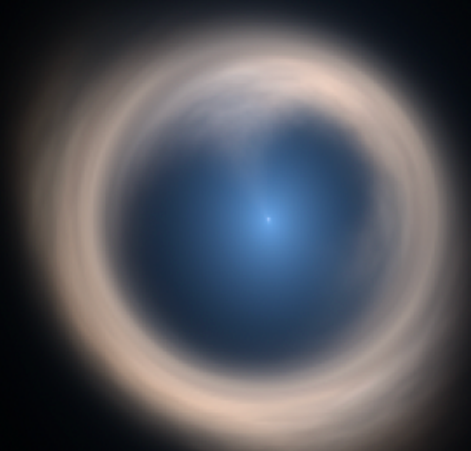
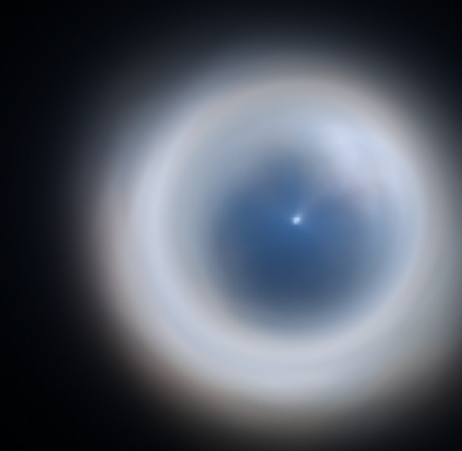
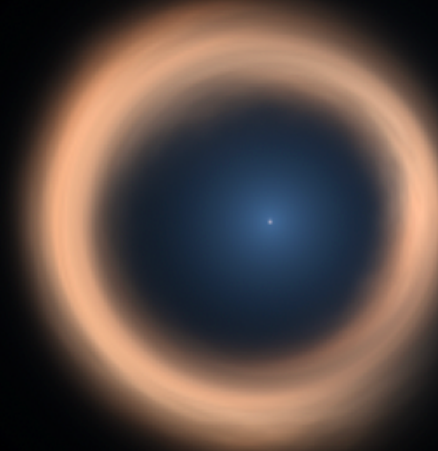
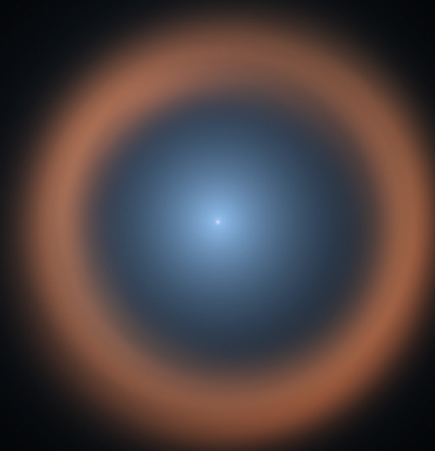
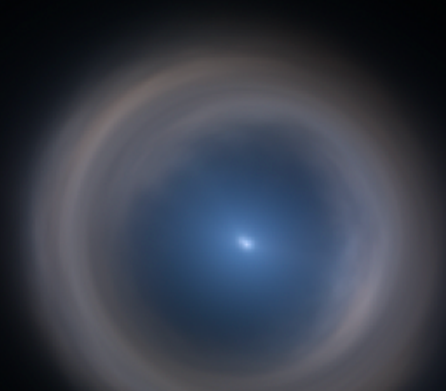
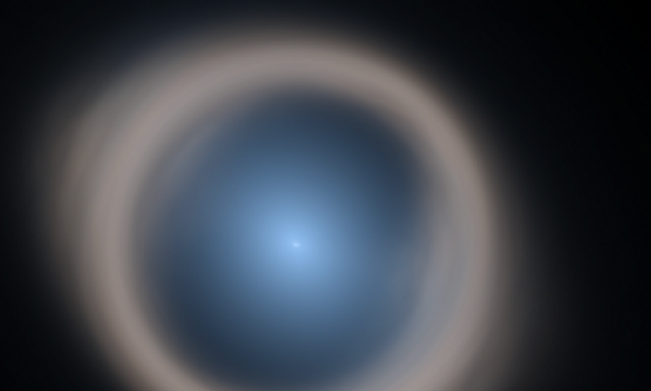
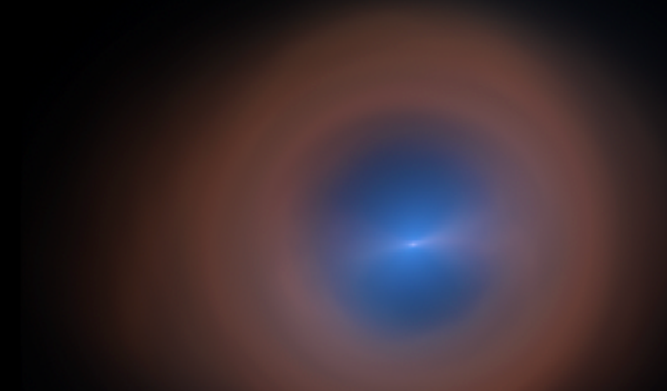
$$P(s)$$



The prior

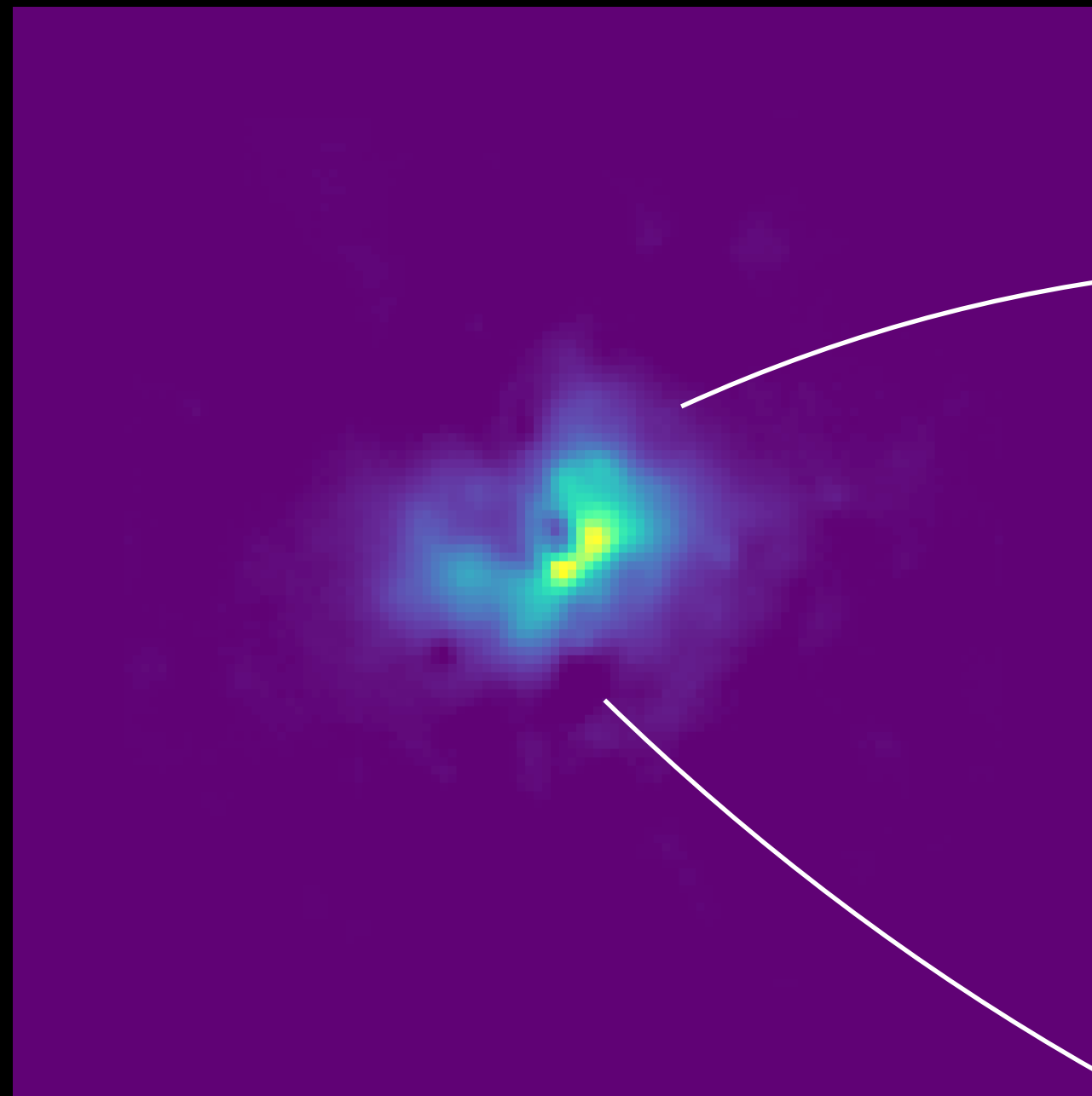
Total light

$P(s)$

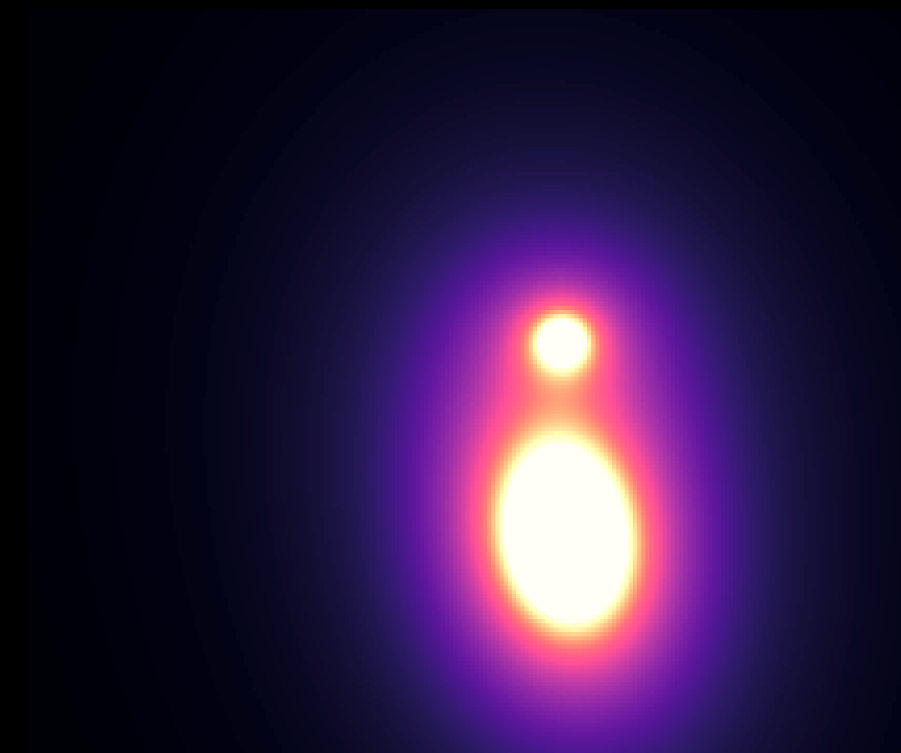


The prior

Developed for strong lensing

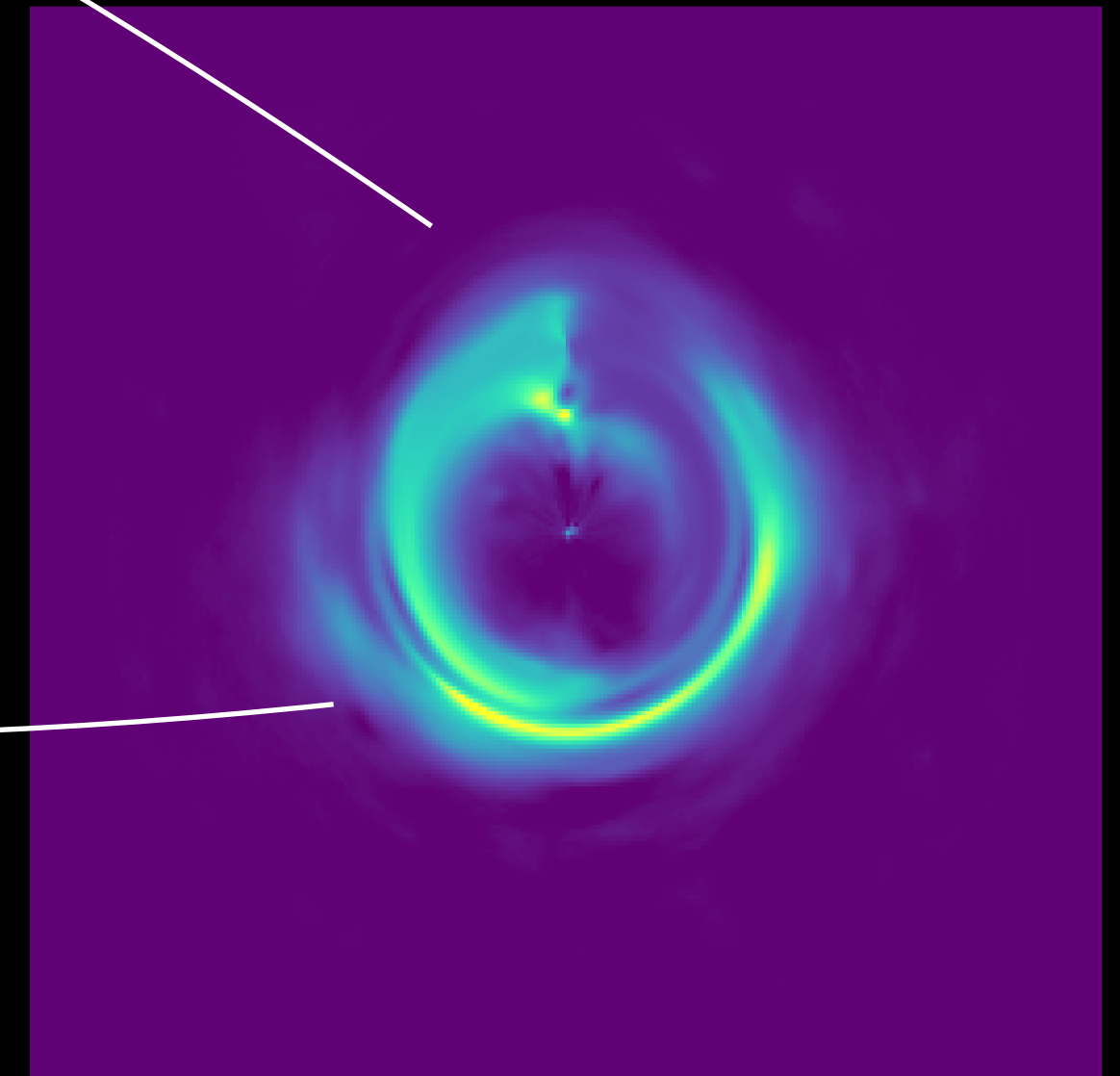


Source galaxy



DM halo mass profile

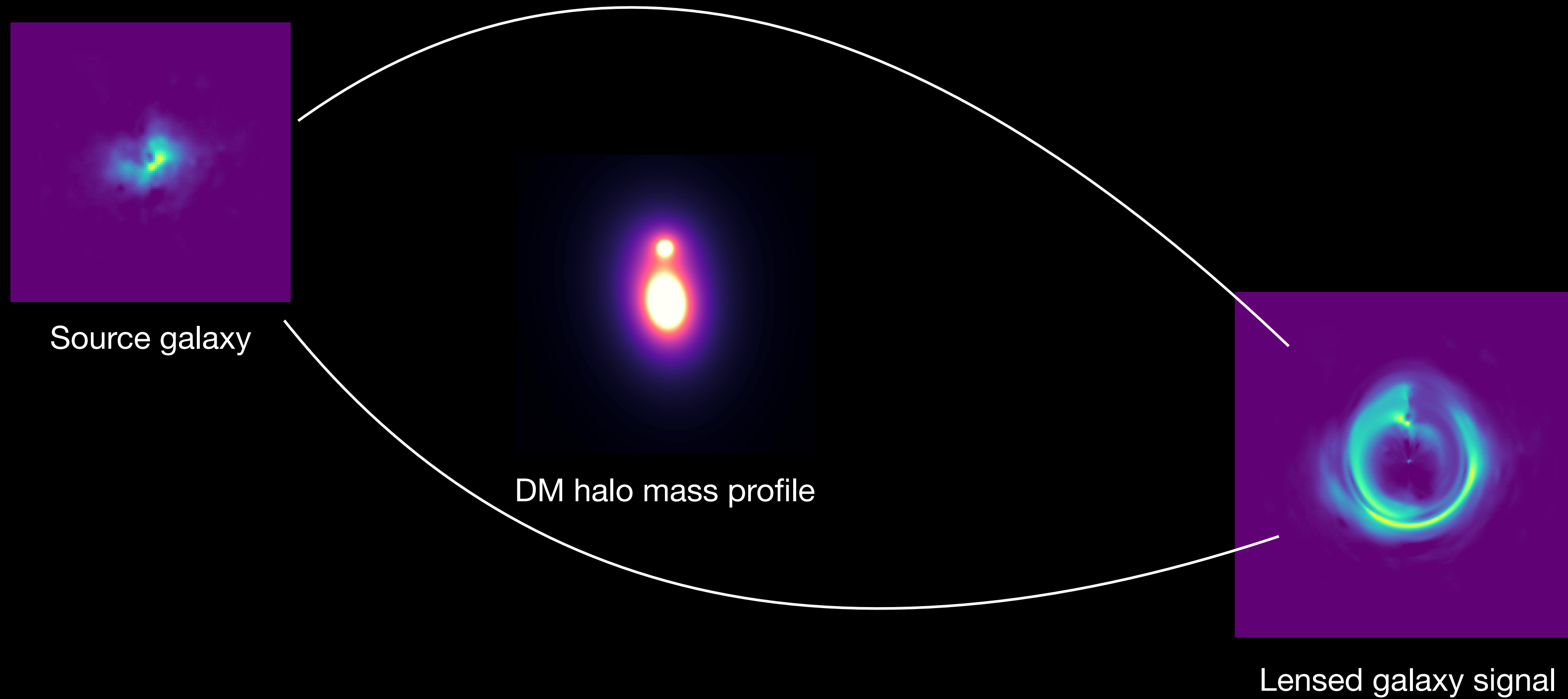
$$\nabla \cdot \kappa = 2 \alpha$$



$$y = x - \alpha(x)$$

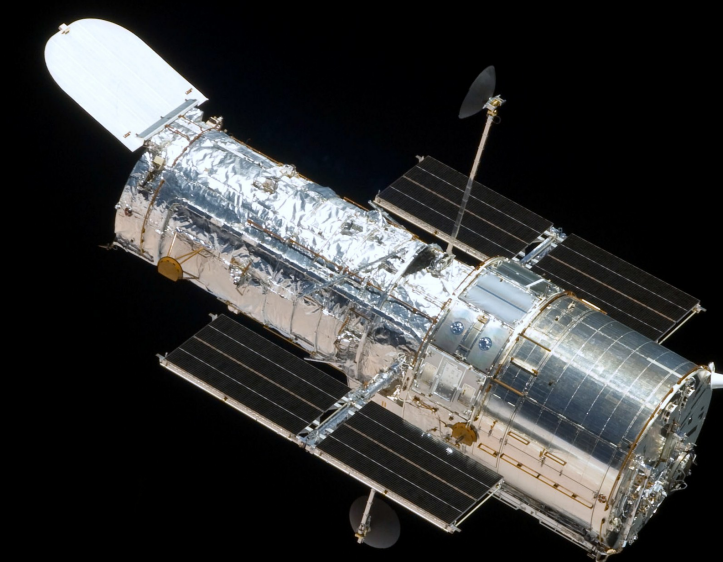
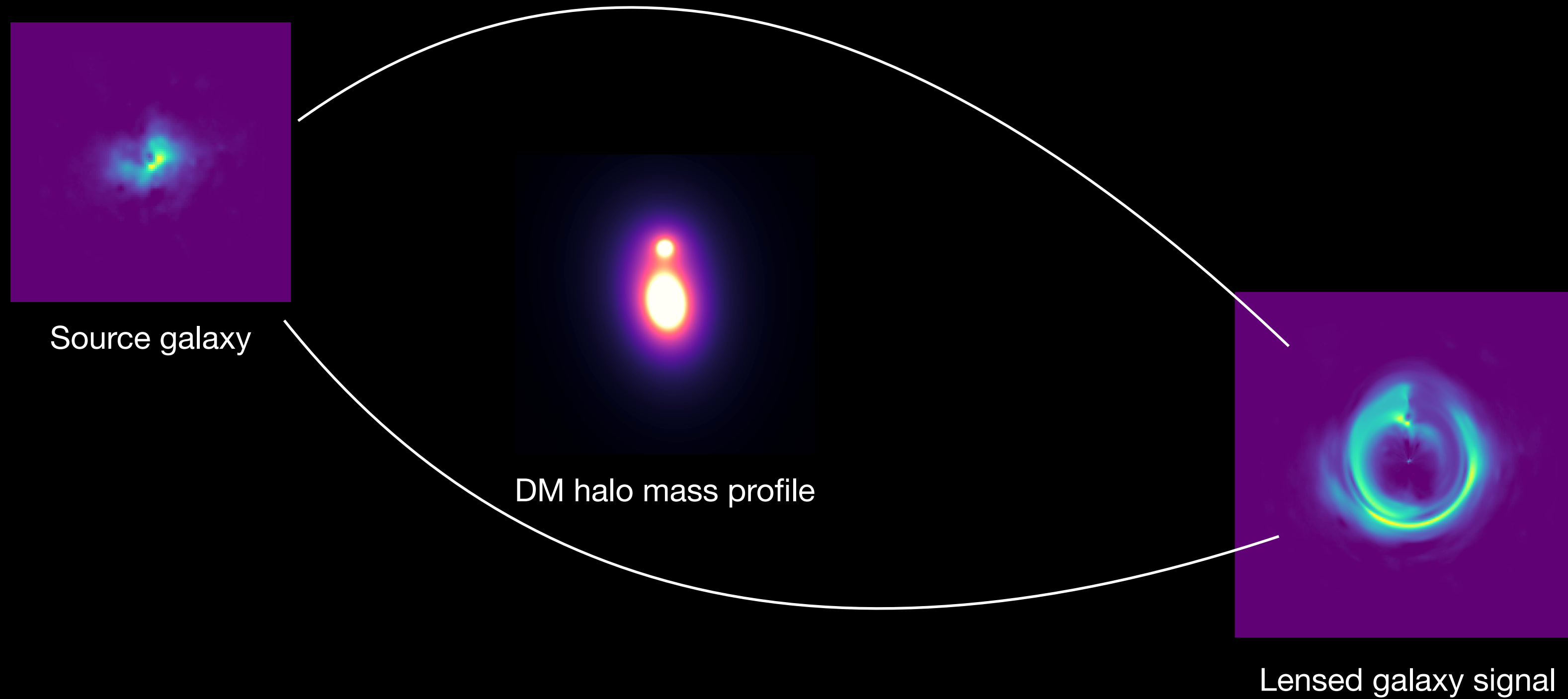
The Likelihood

Instrument response



The Likelihood

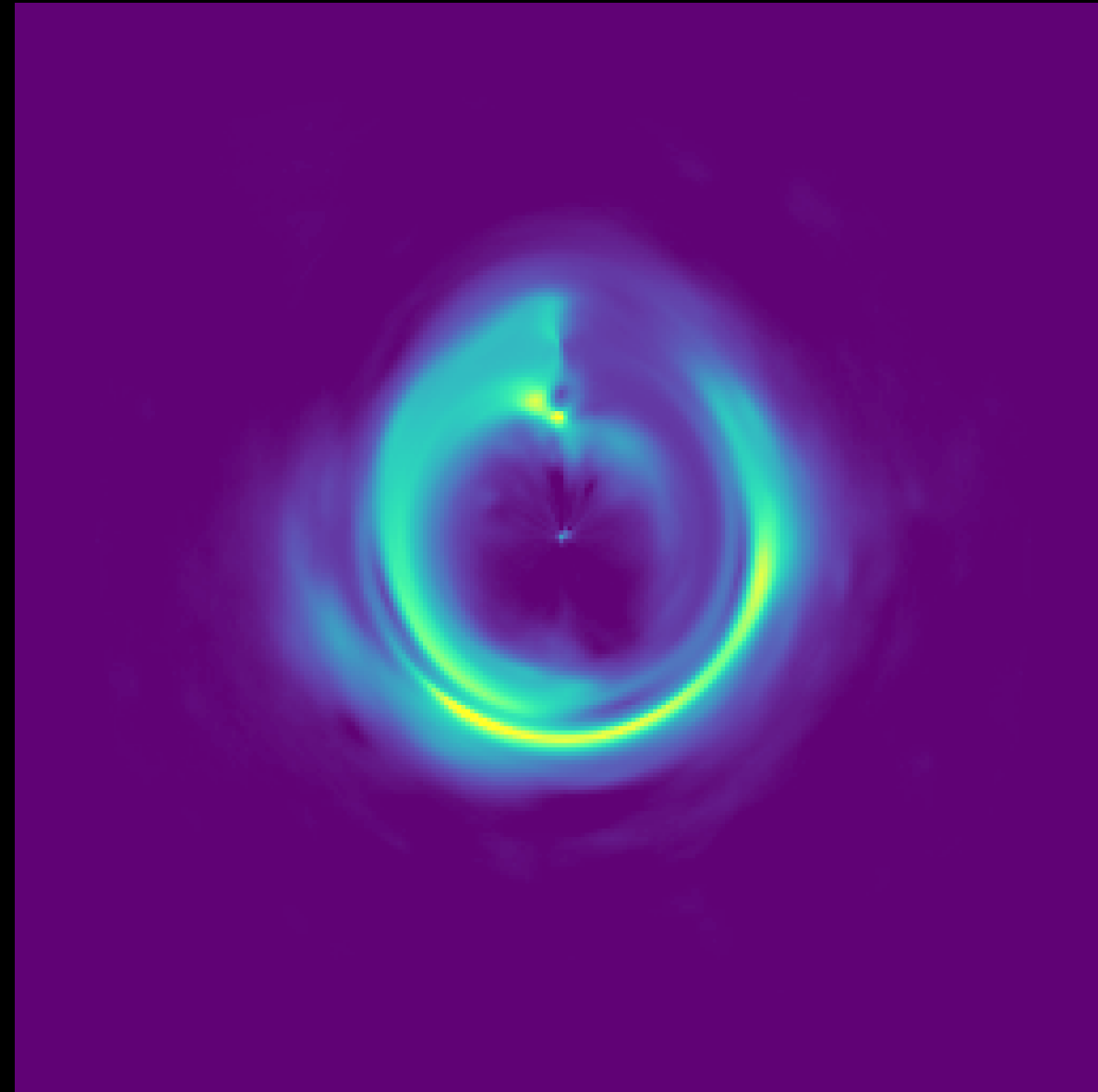
Instrument response



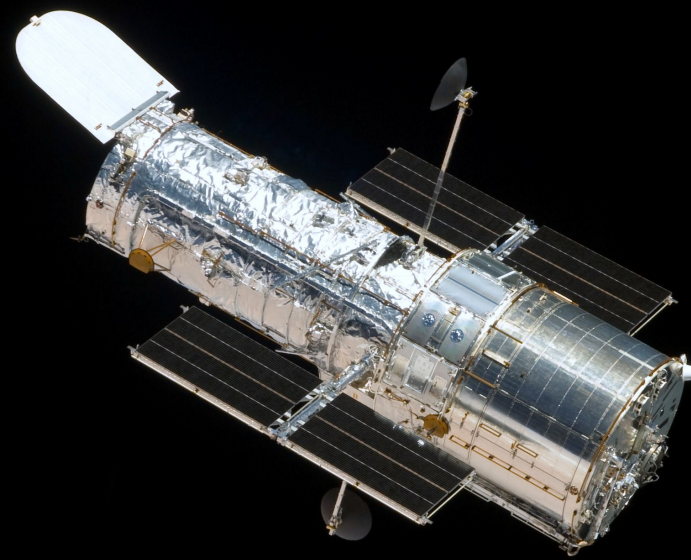
Hubble Space Telescope

The Likelihood

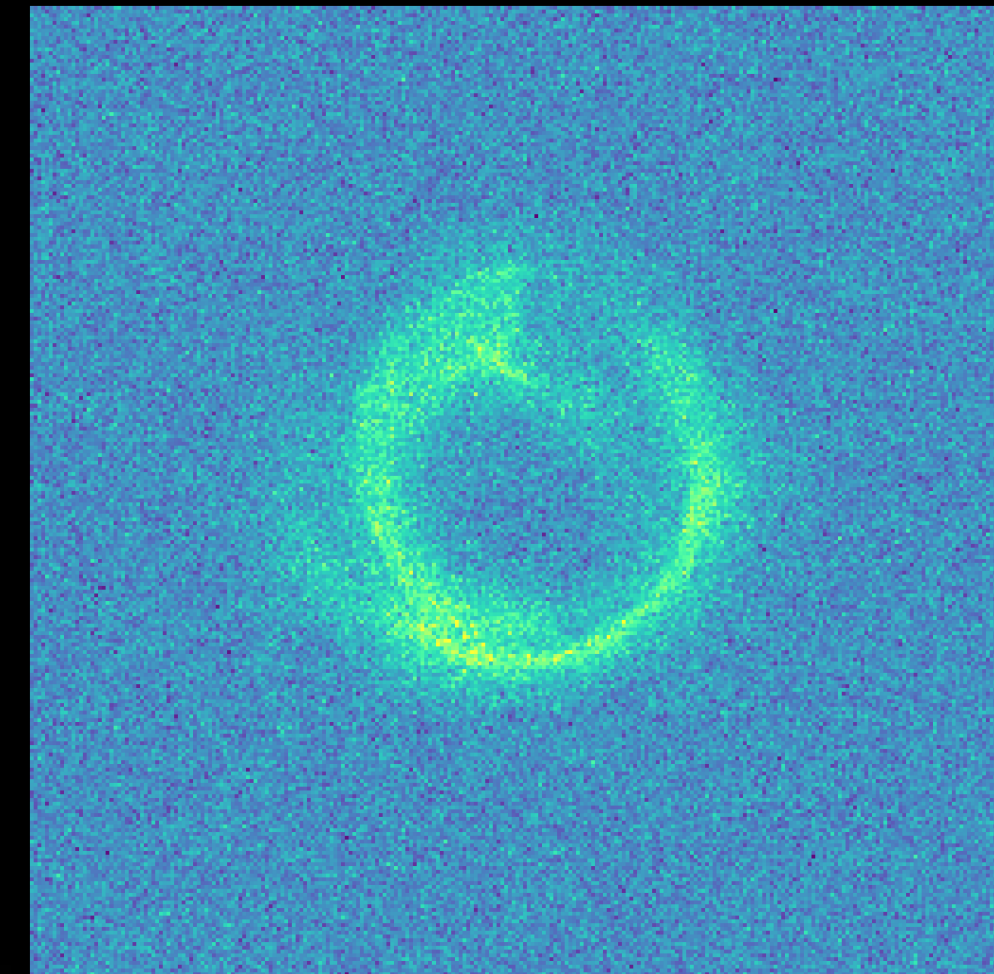
Instrument response



Lensed galaxy signal



Hubble Space Telescope

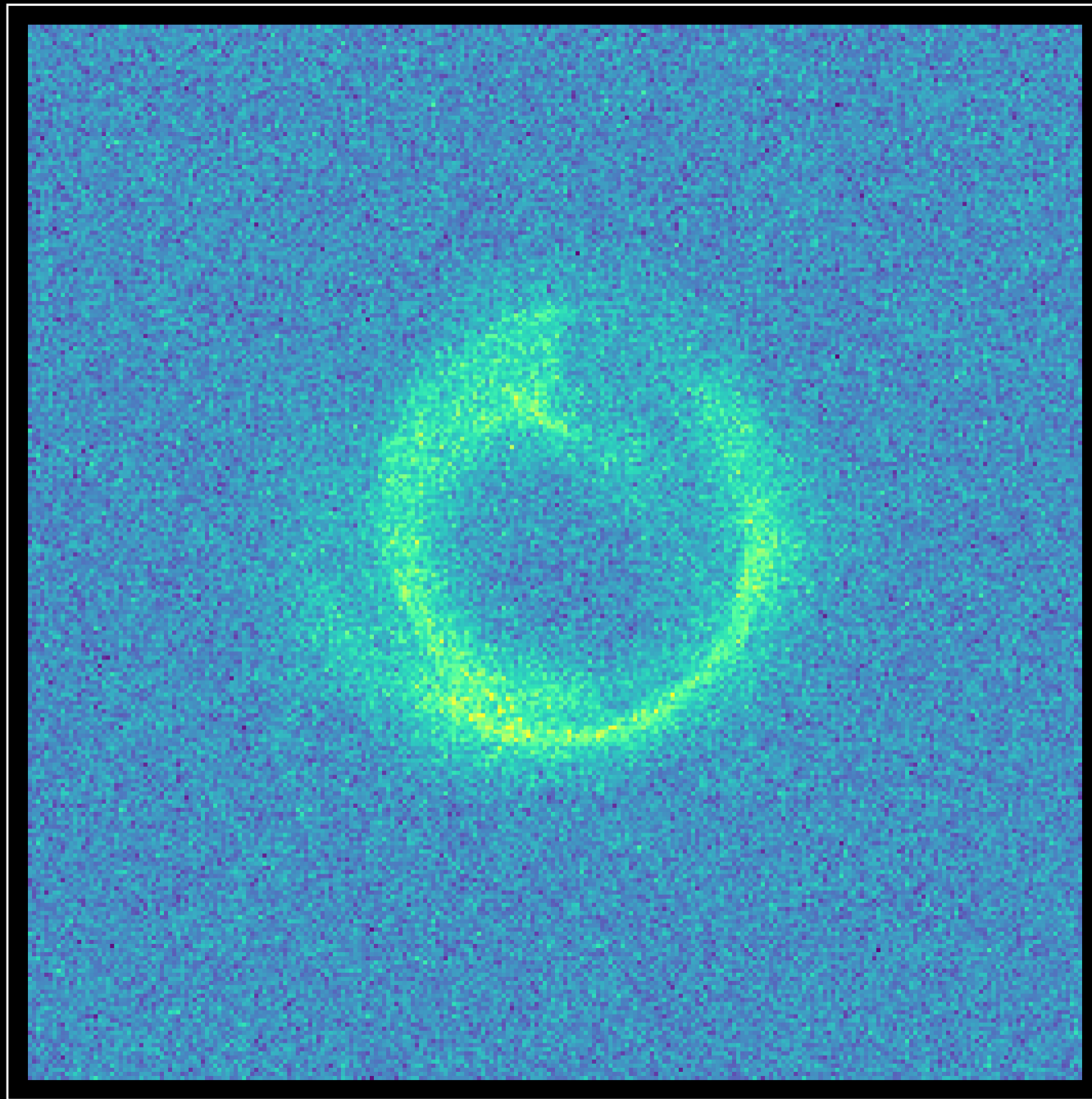


Data on Earth

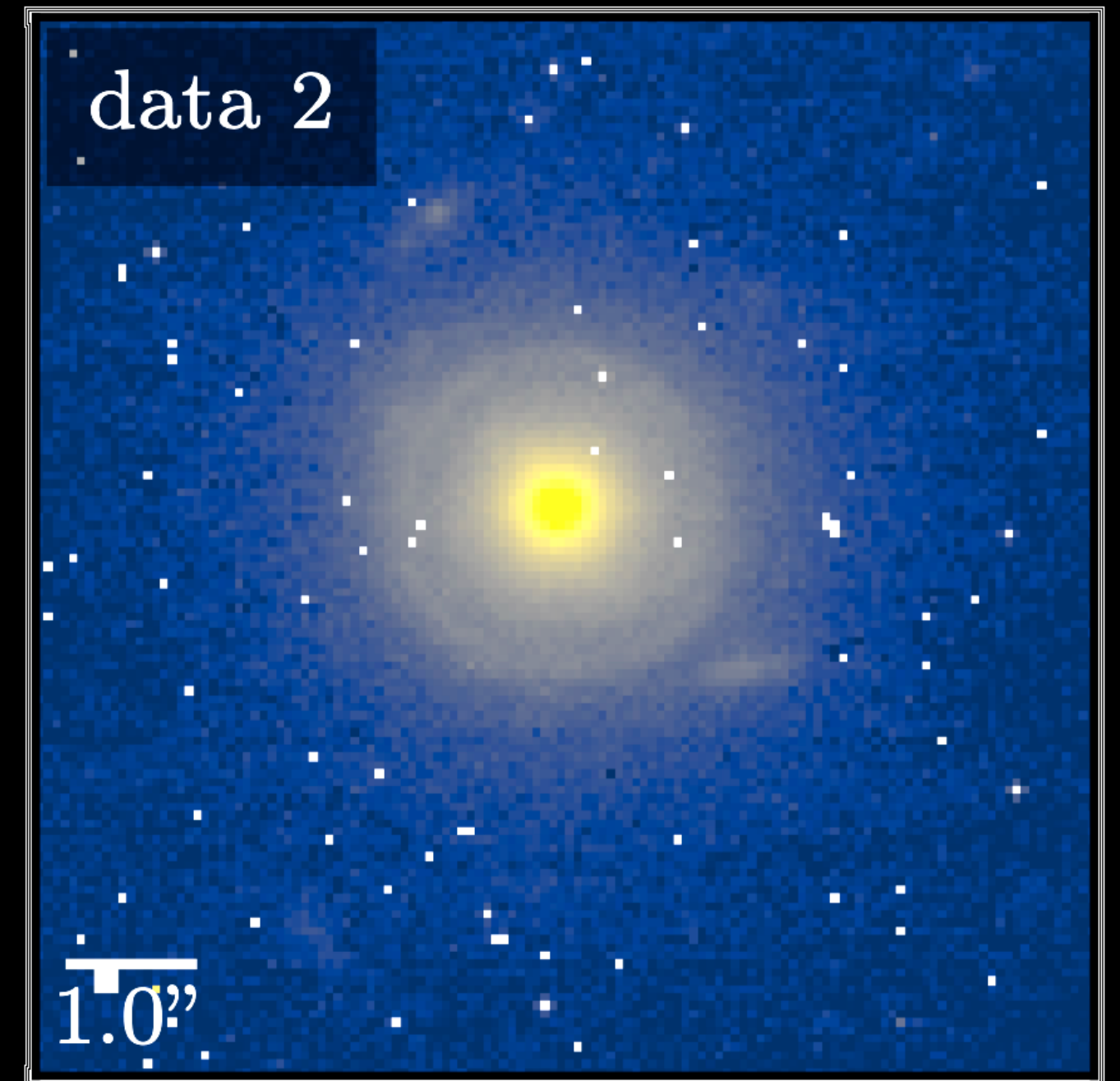
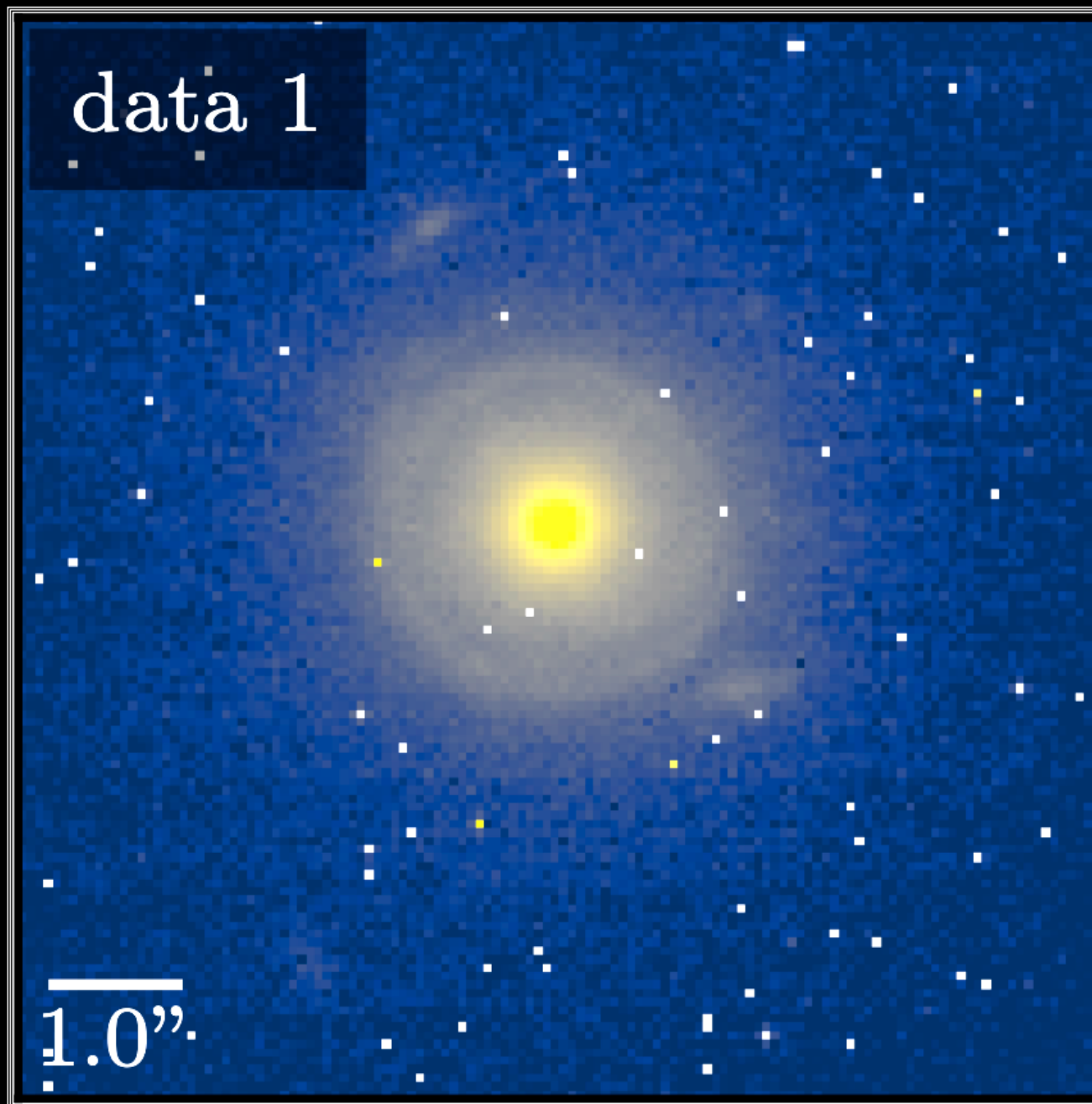


The Likelihood

Instrument response



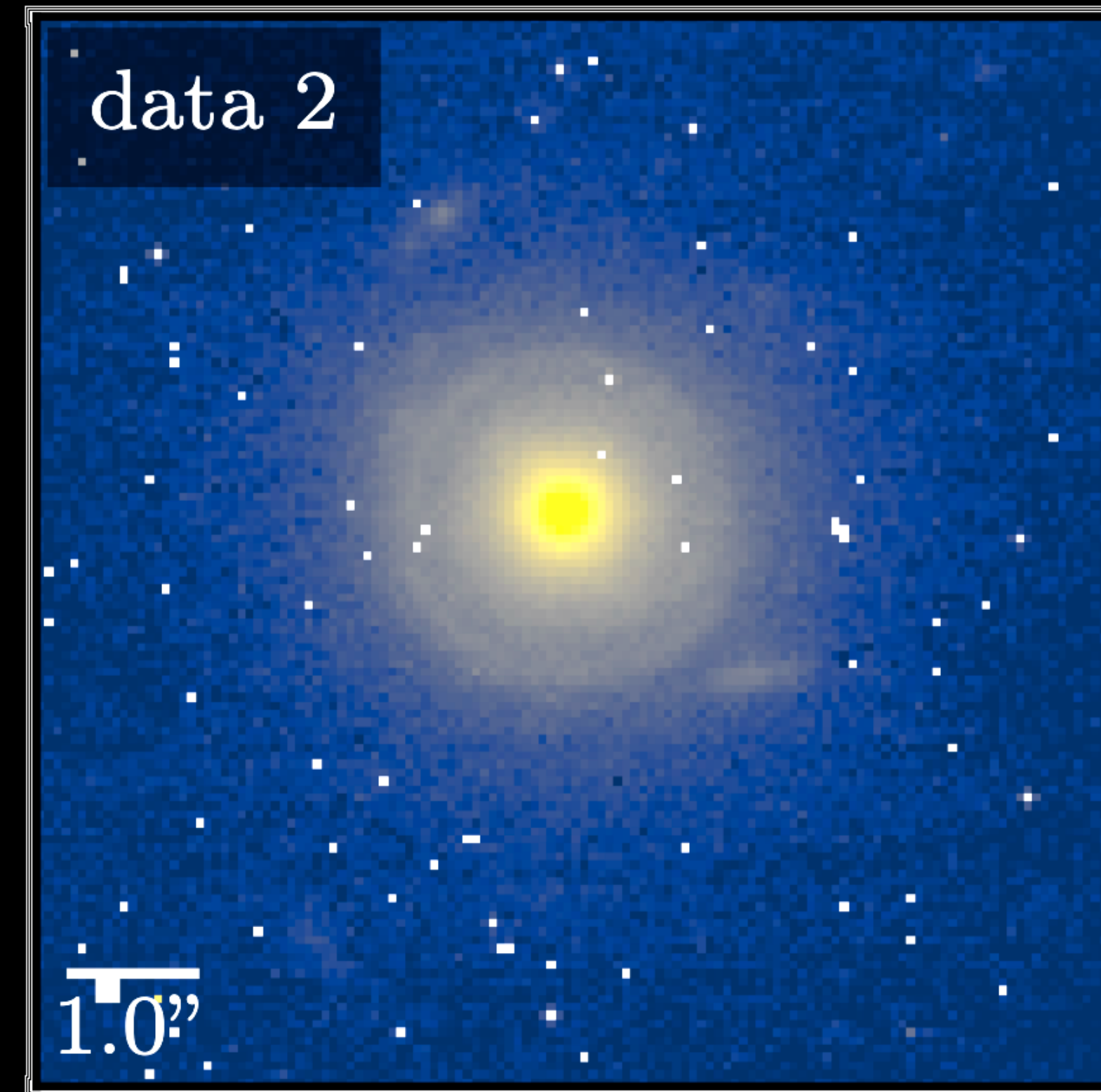
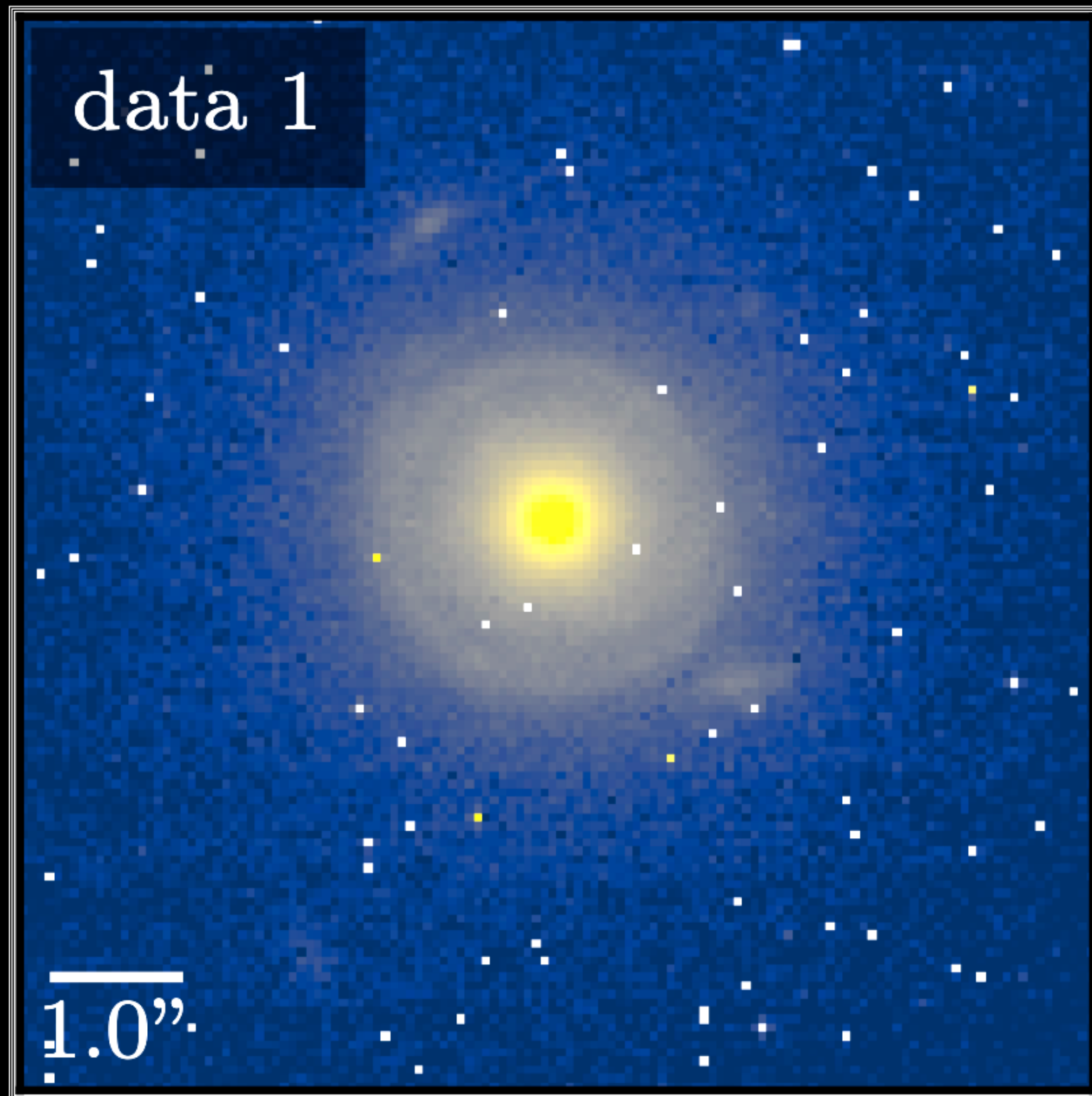
HST synthetic data



Real JWST lensing data

High-redshift galaxy reconstruction with LensCharm

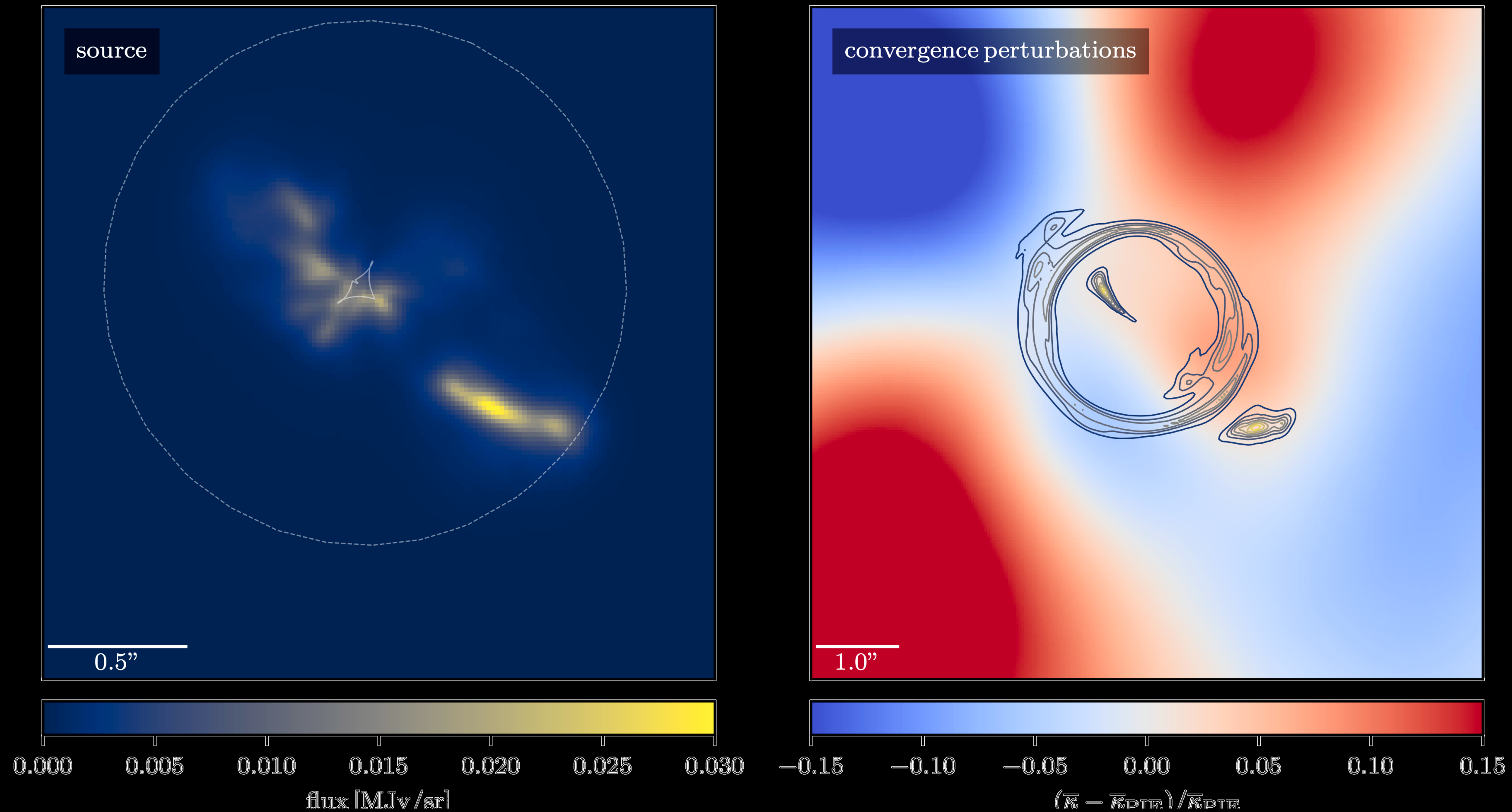
SPT0418-47 ($z=4.22$) data



SPT-0418 JWST data application

High-redshift galaxy reconstruction with LensCharm

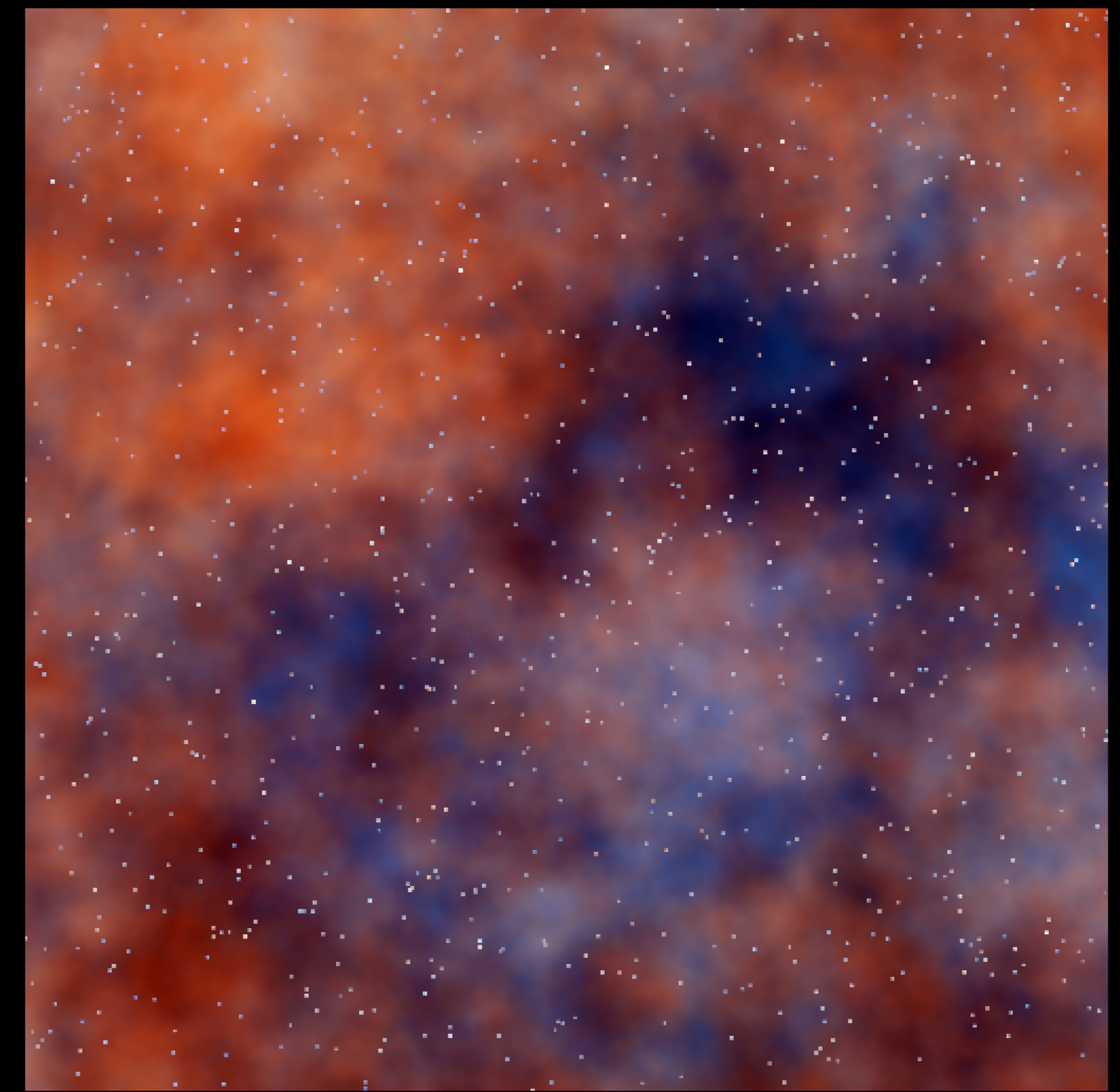
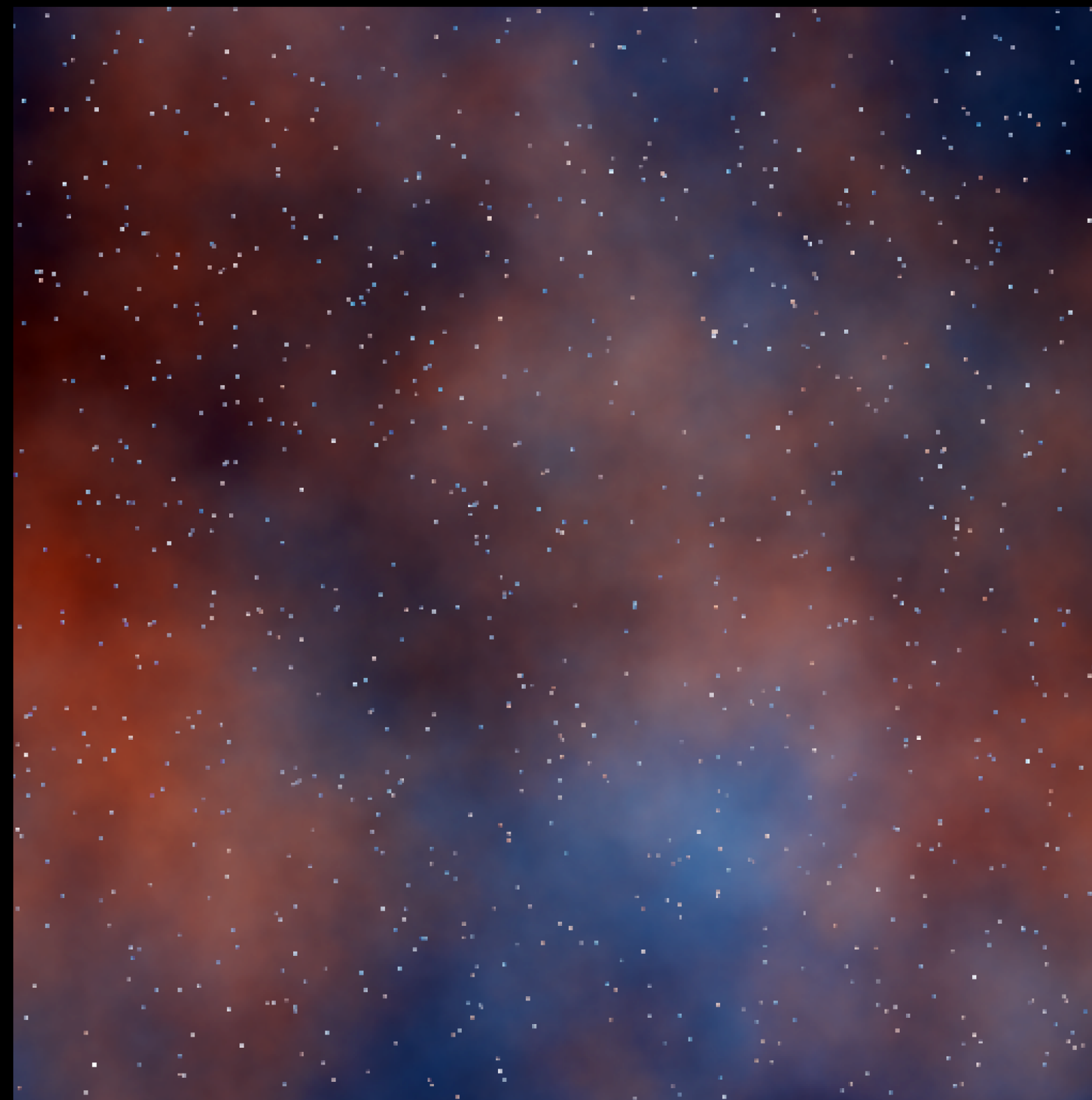
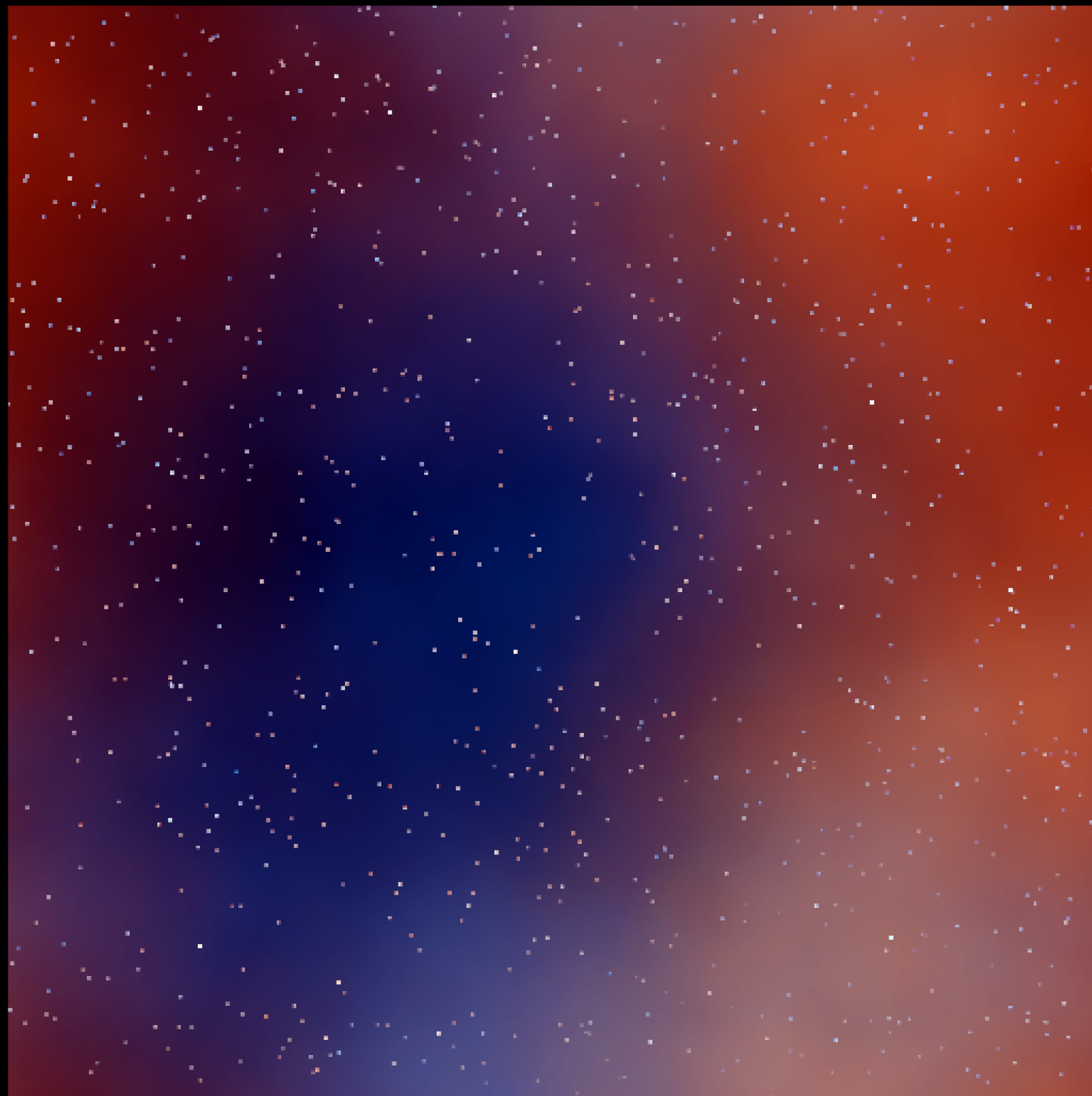
SPT0418-47 ($z=4.22$) reconstruction



... back to imaging

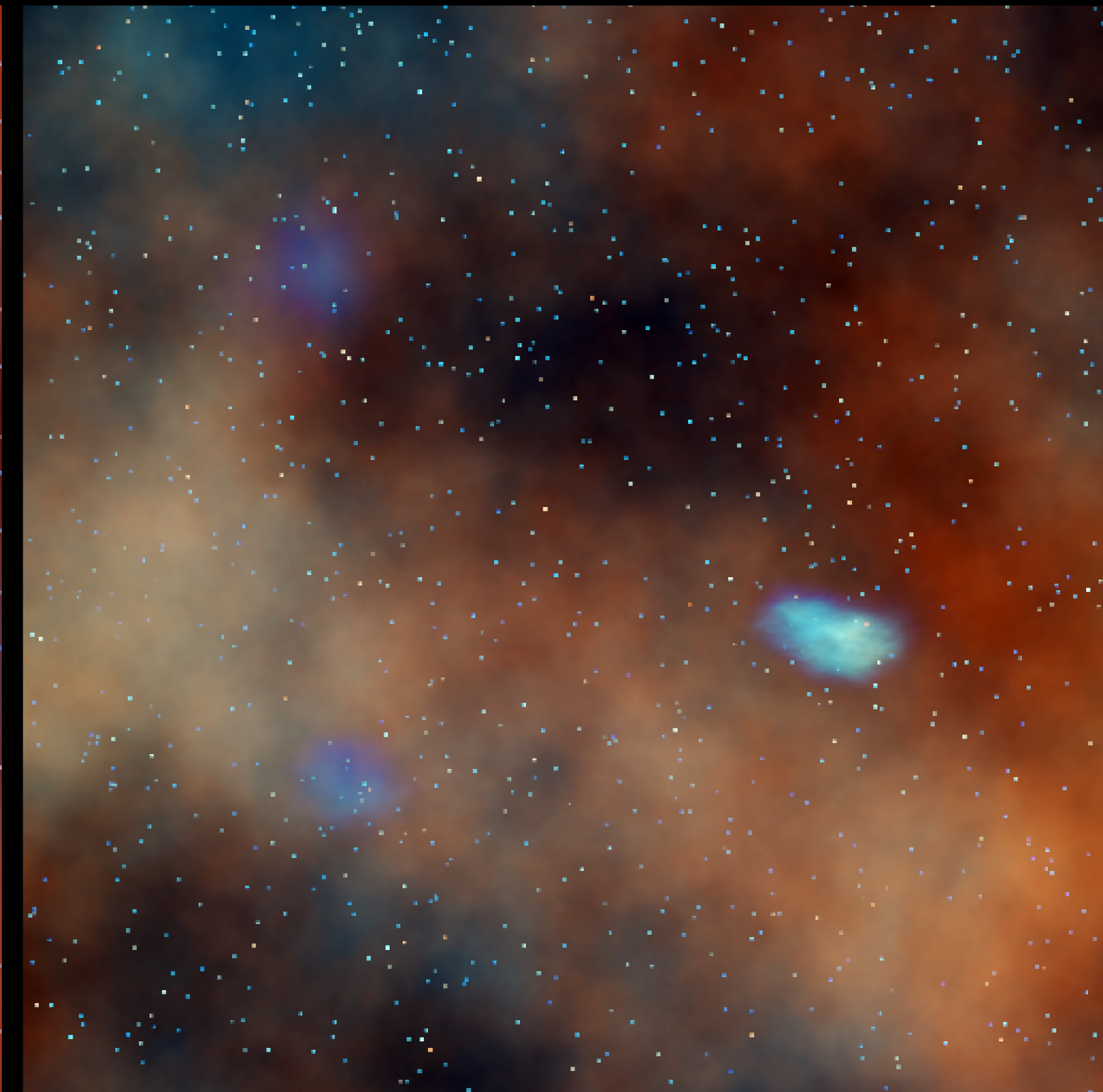
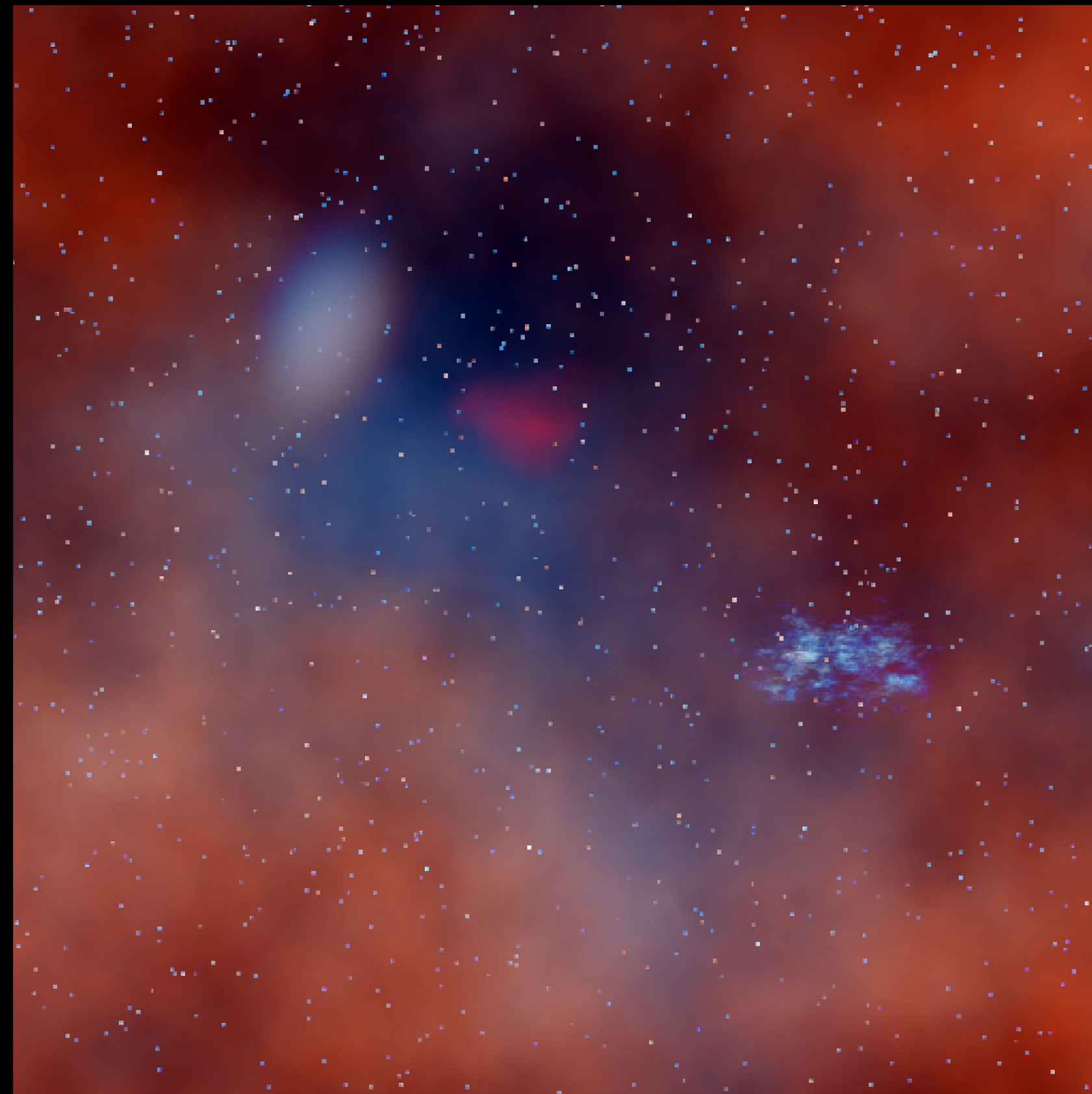
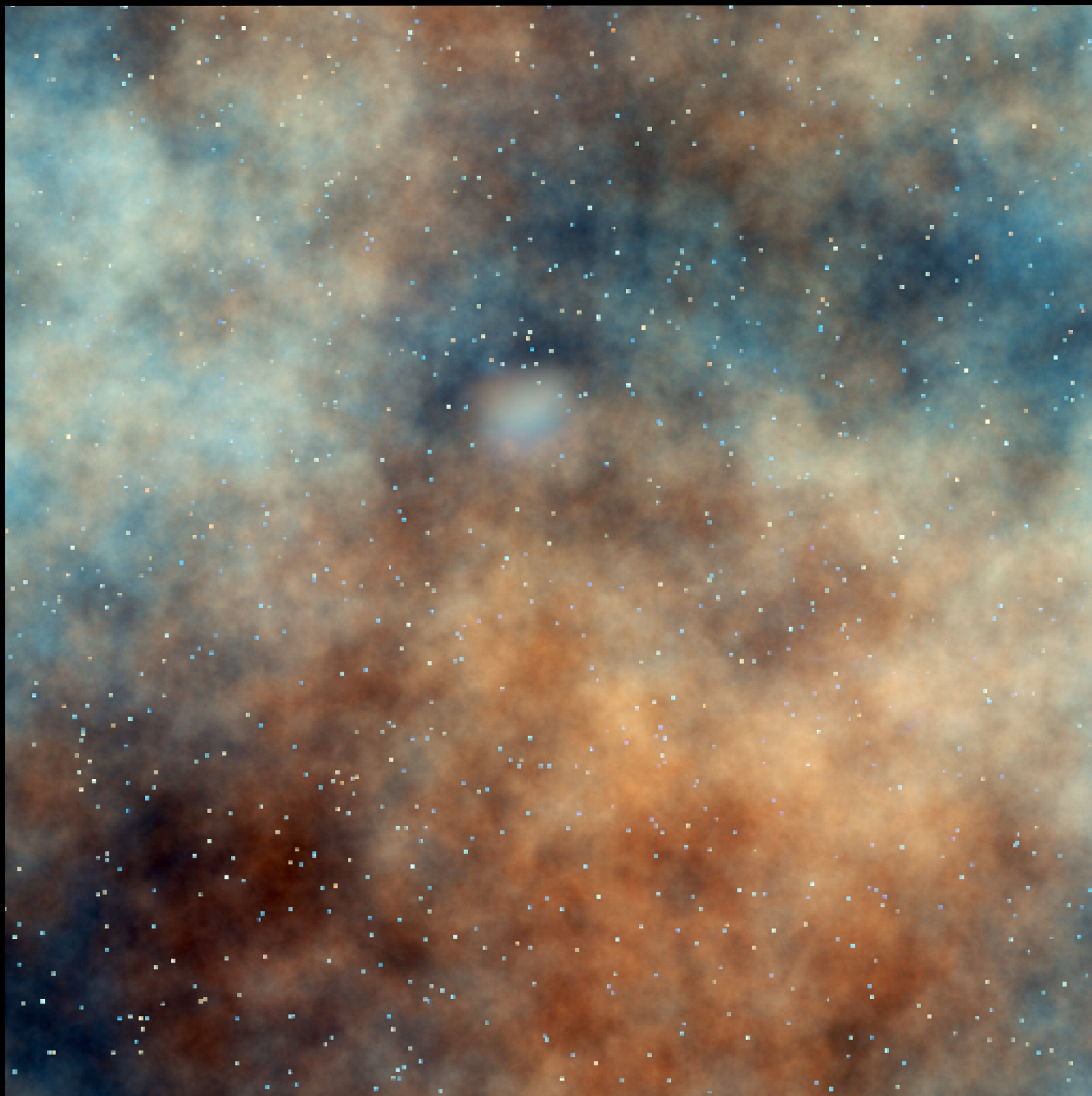
Automatic component modeling

A multi-frequency sky prior model



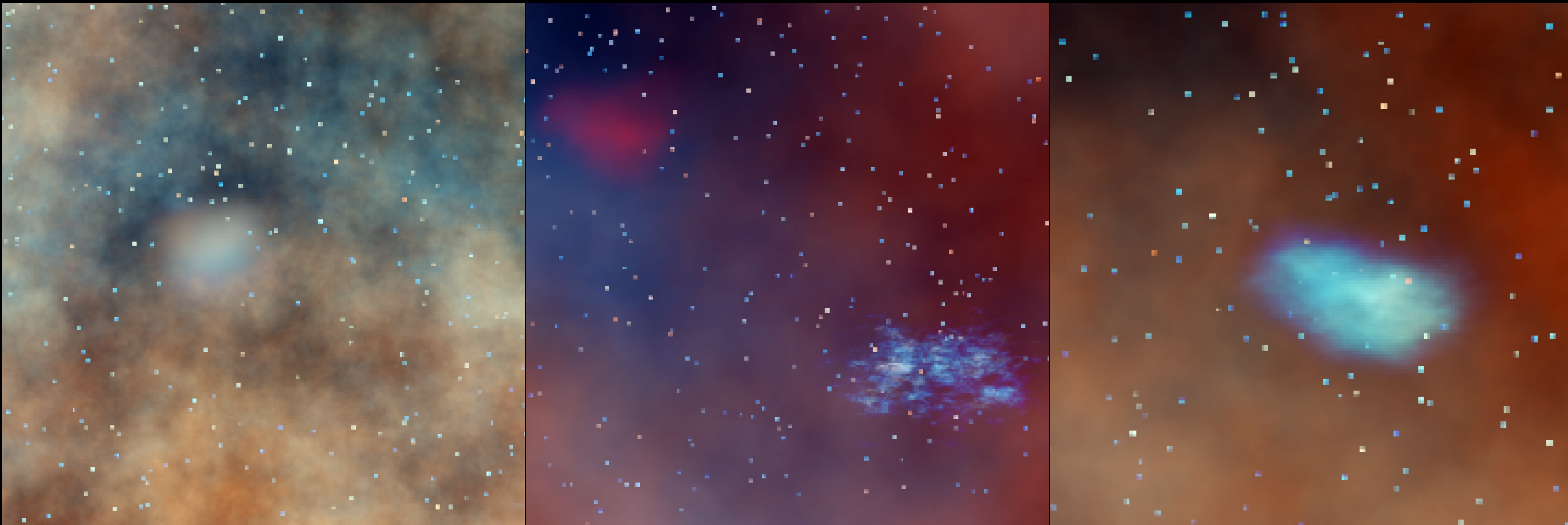
Automatic component modeling

A multi-frequency sky prior model



Automatic component modeling

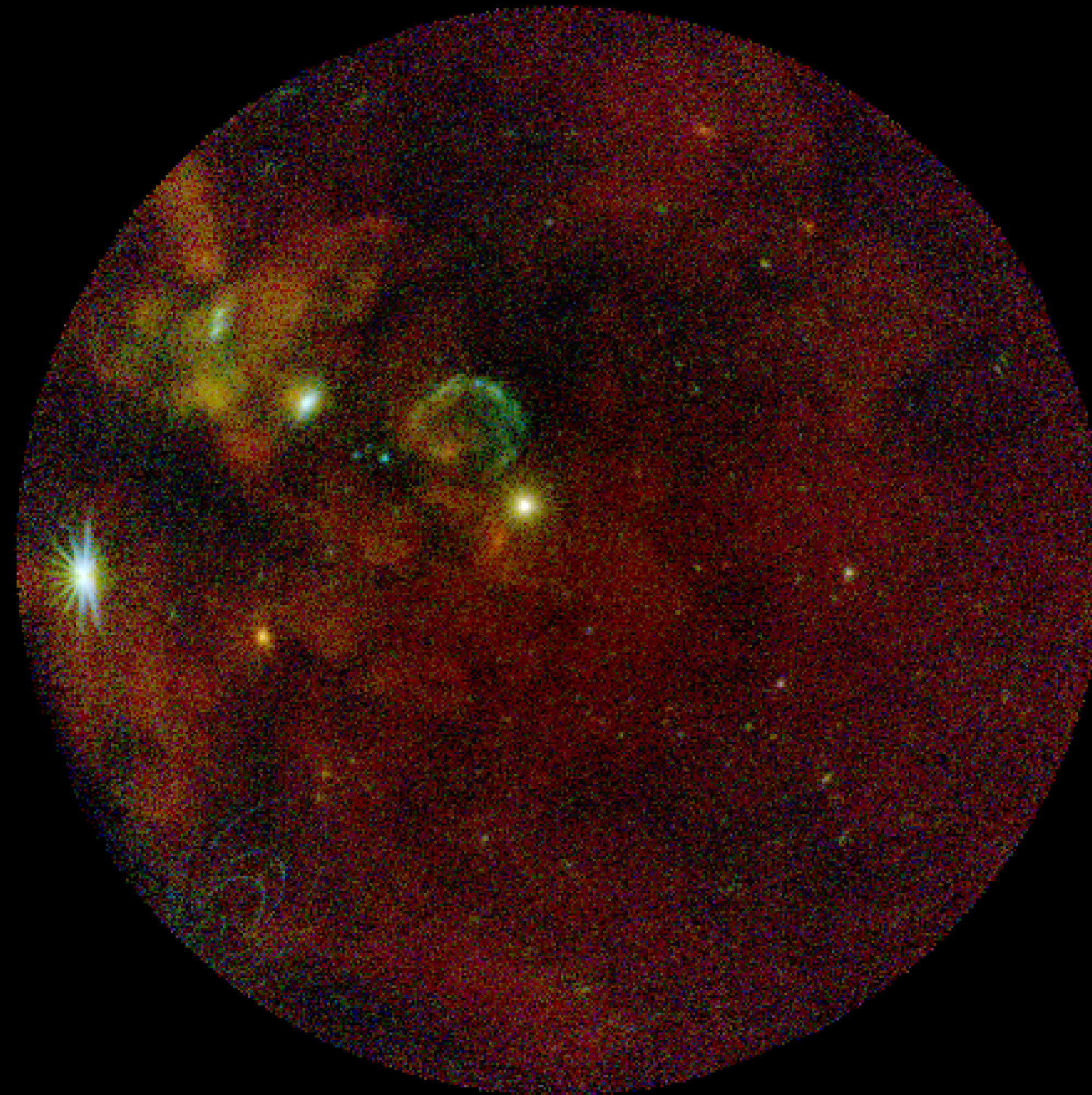
A multi-frequency sky prior model



Automatic component modeling

Preliminary results

TM1

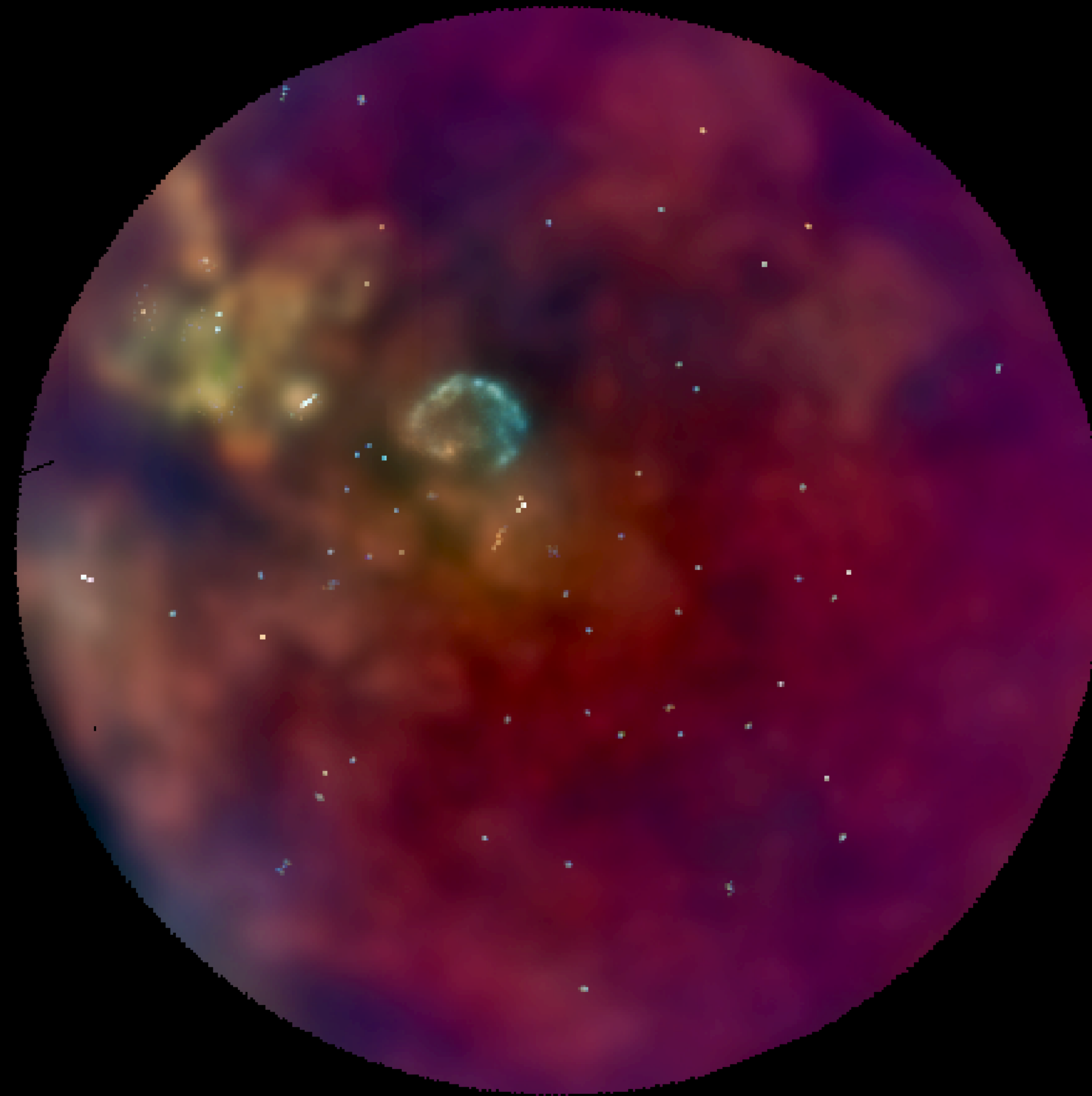


eROSITA
LMC SN 1987A
dataset

Automatic Component Modeling

Preliminary results

TM1



Point source detection

Preliminary results

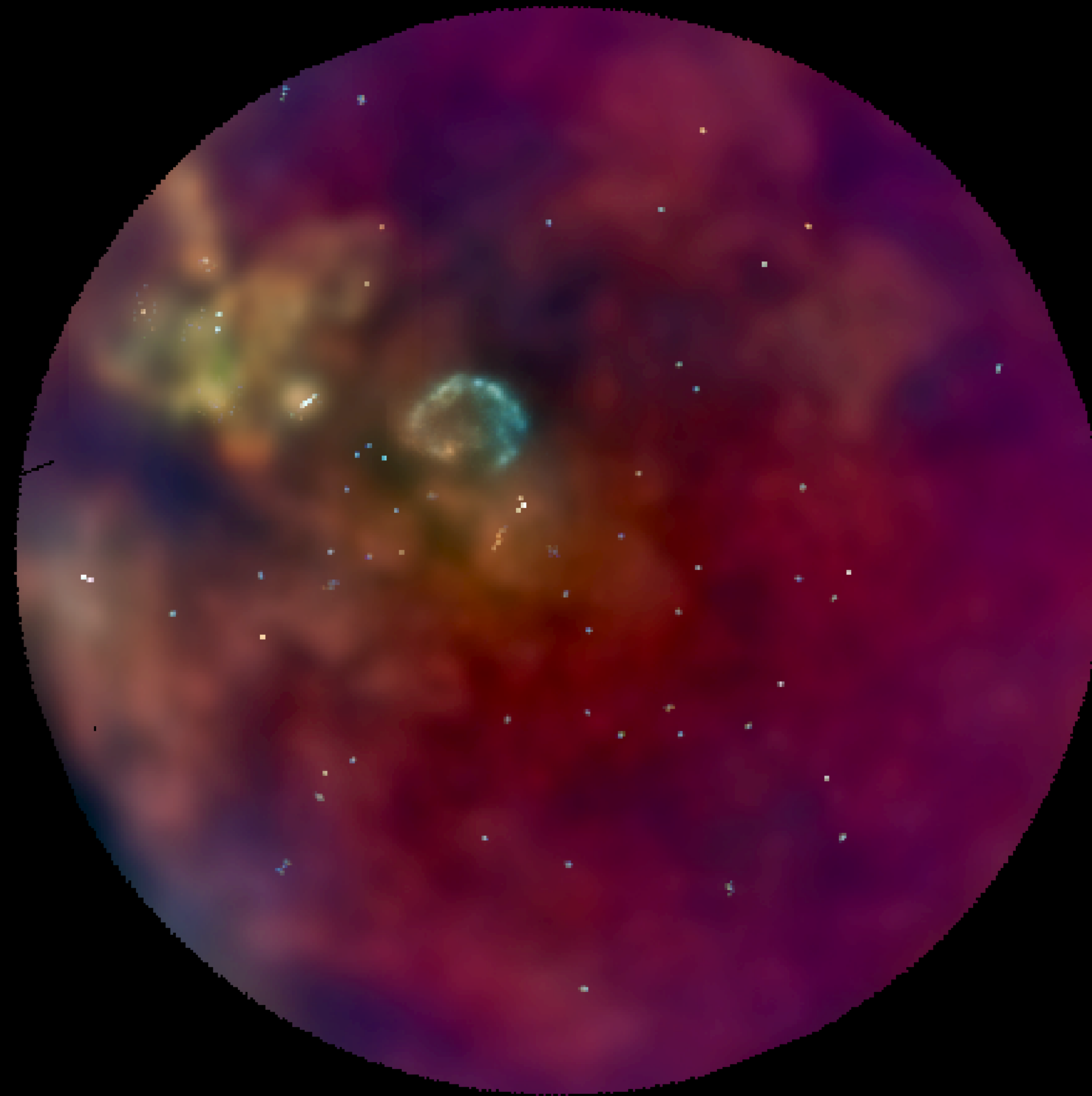
TM1



Automatic Component Modeling

Preliminary results

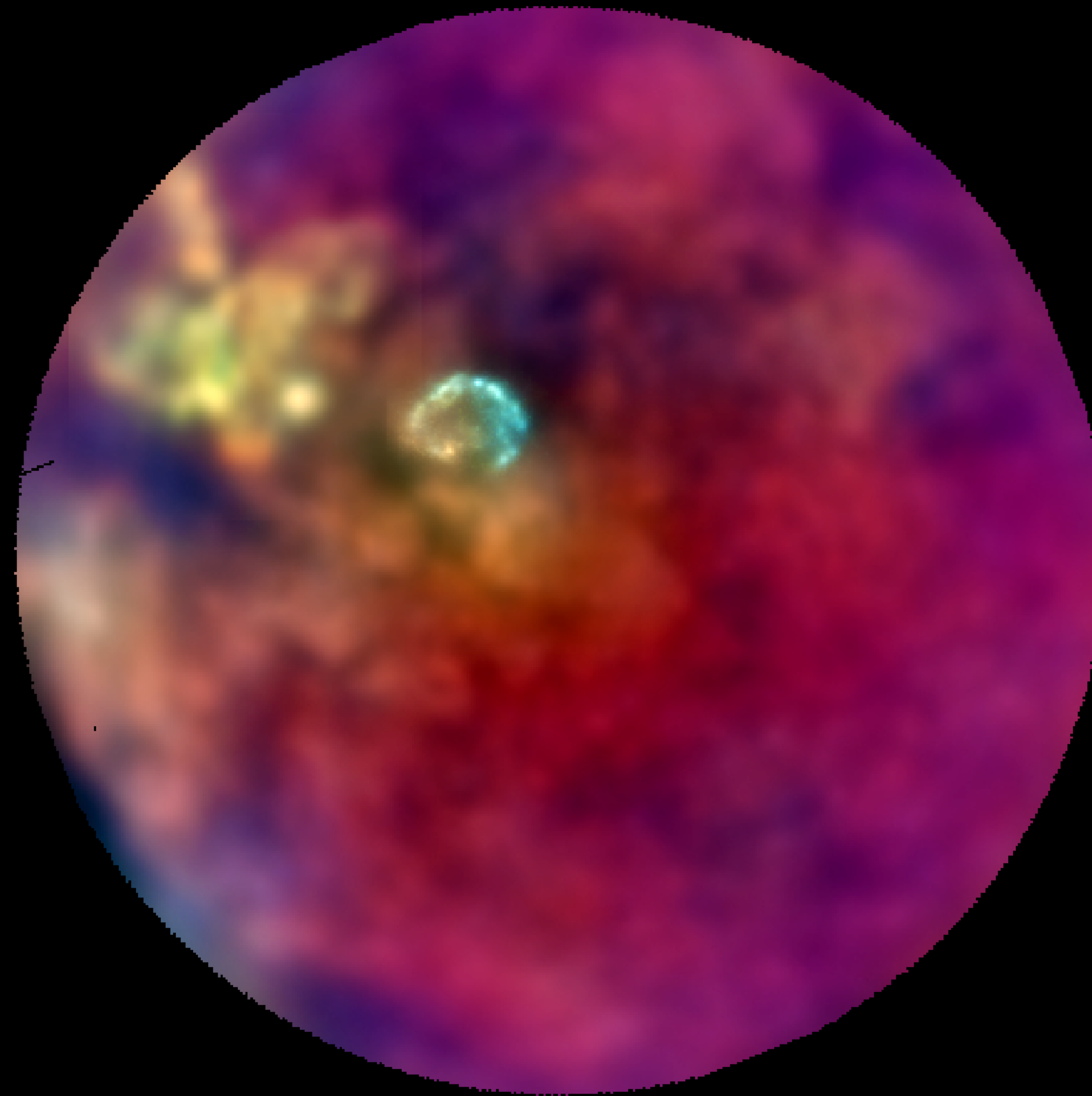
TM1



Automatic Component Modeling

Preliminary results

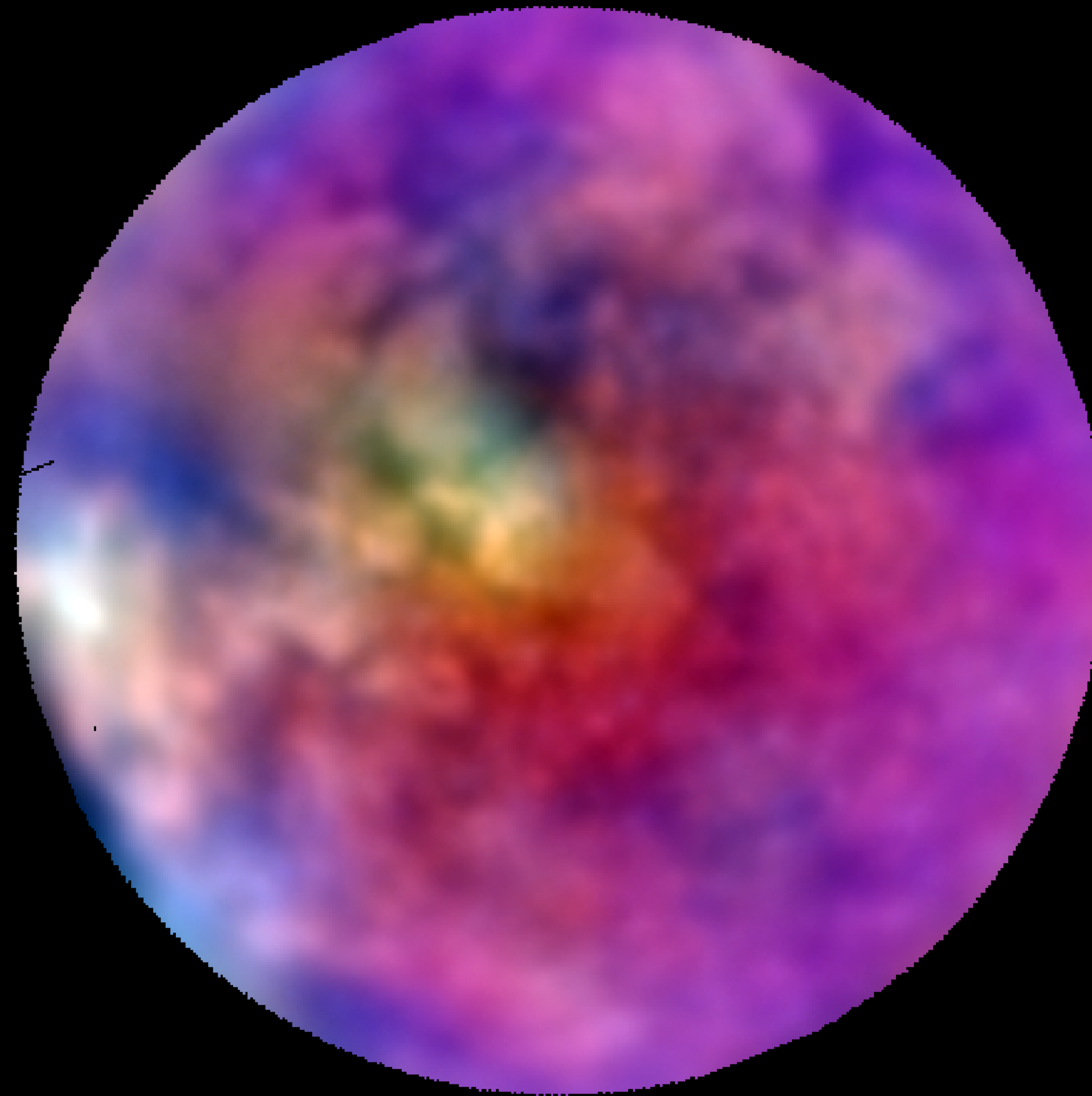
TM1



Automatic Component Modeling

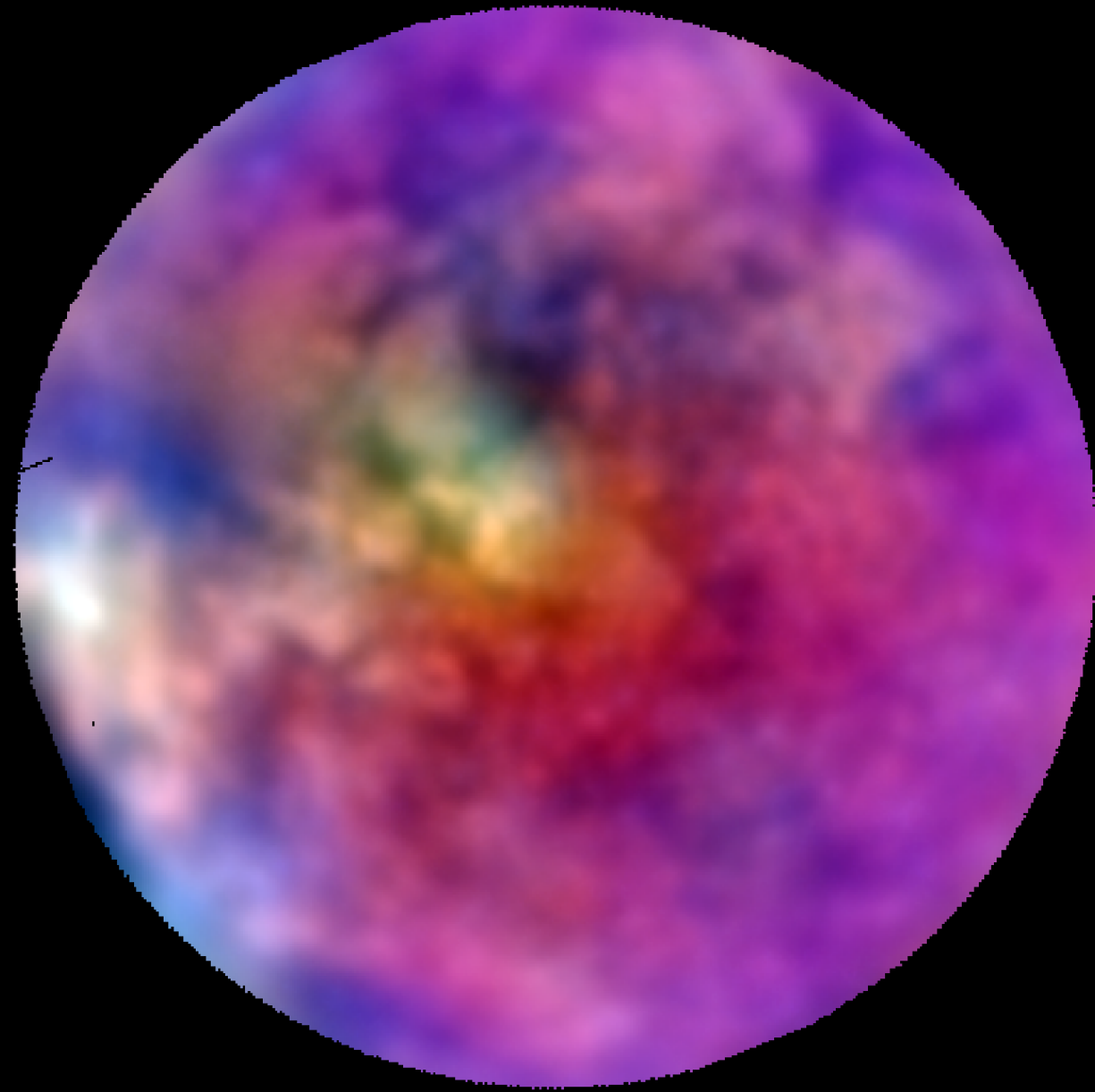
Preliminary results

TM1



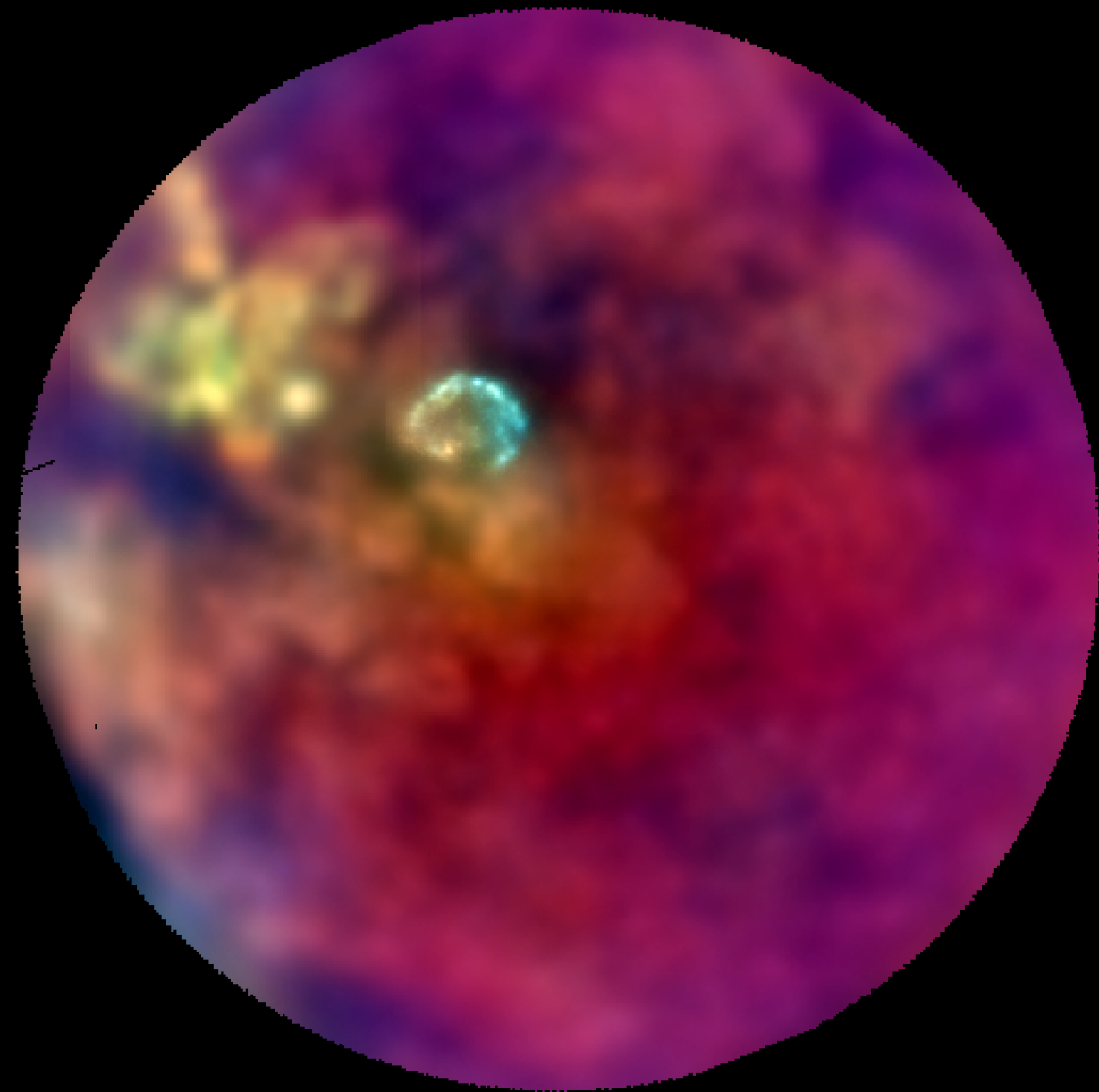
Automatic Component Modeling

Preliminary results



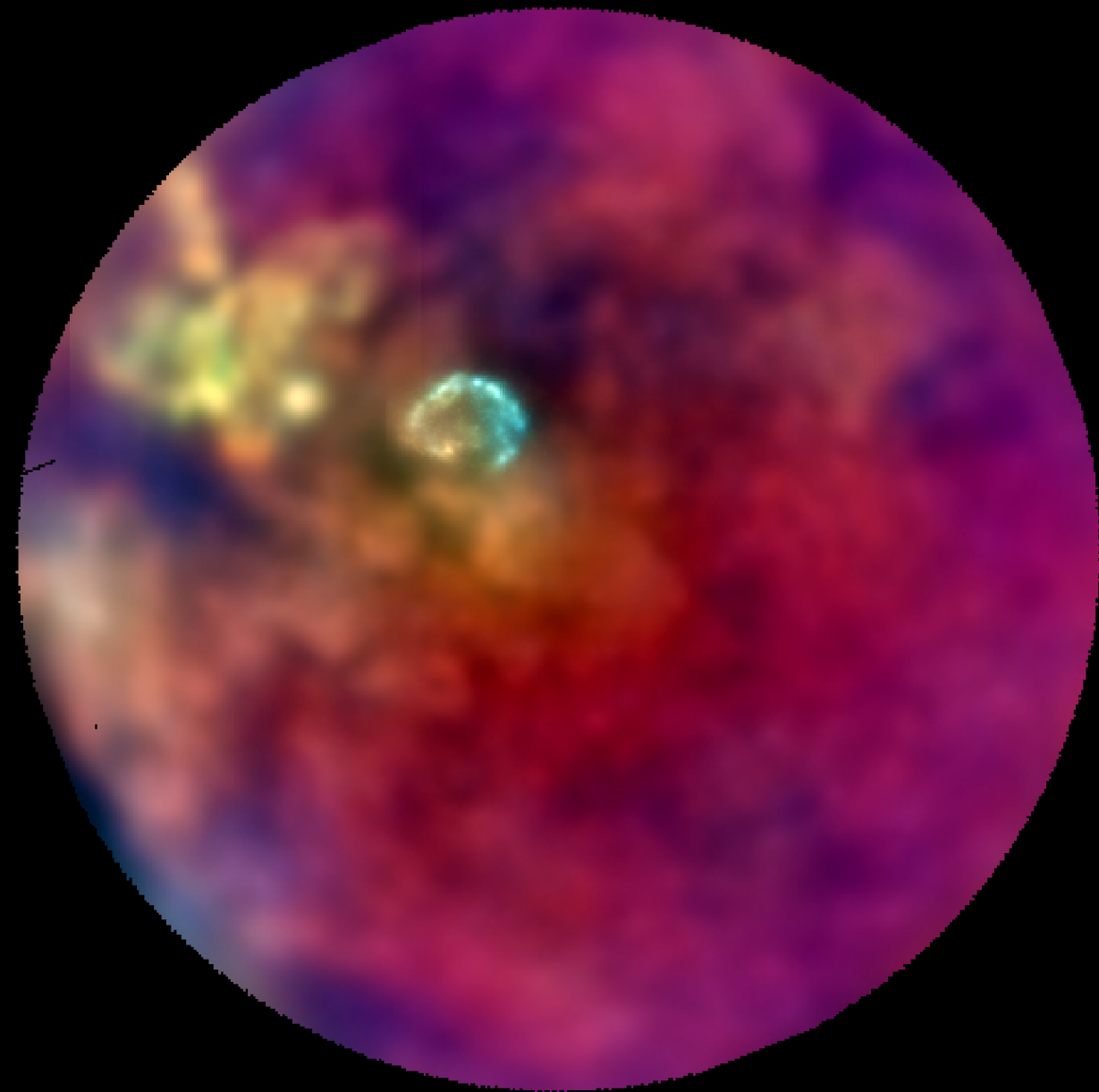
Automatic Component Modeling

Preliminary results (extended sources)



Automatic Component Modeling

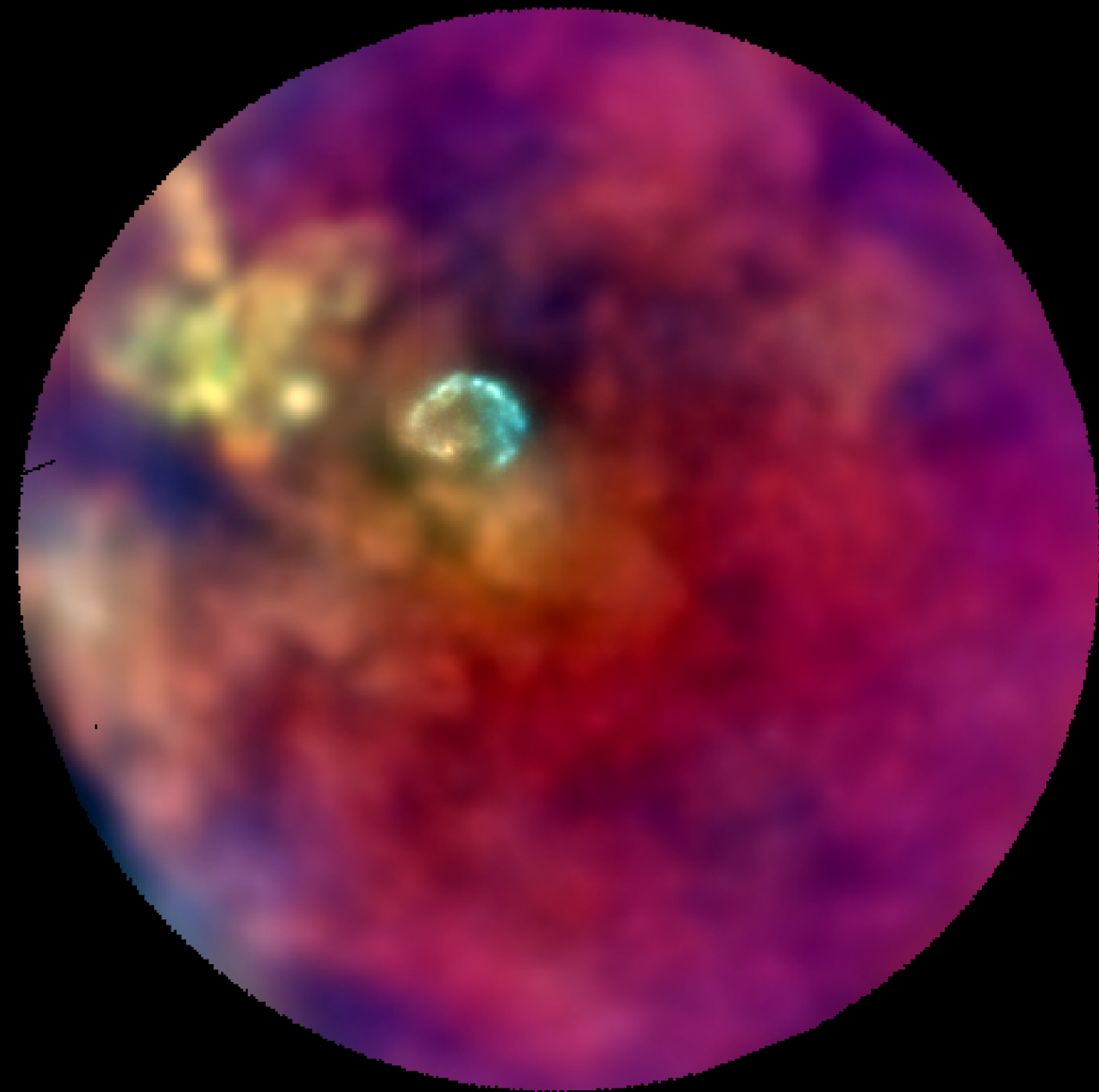
Preliminary results (extended sources)



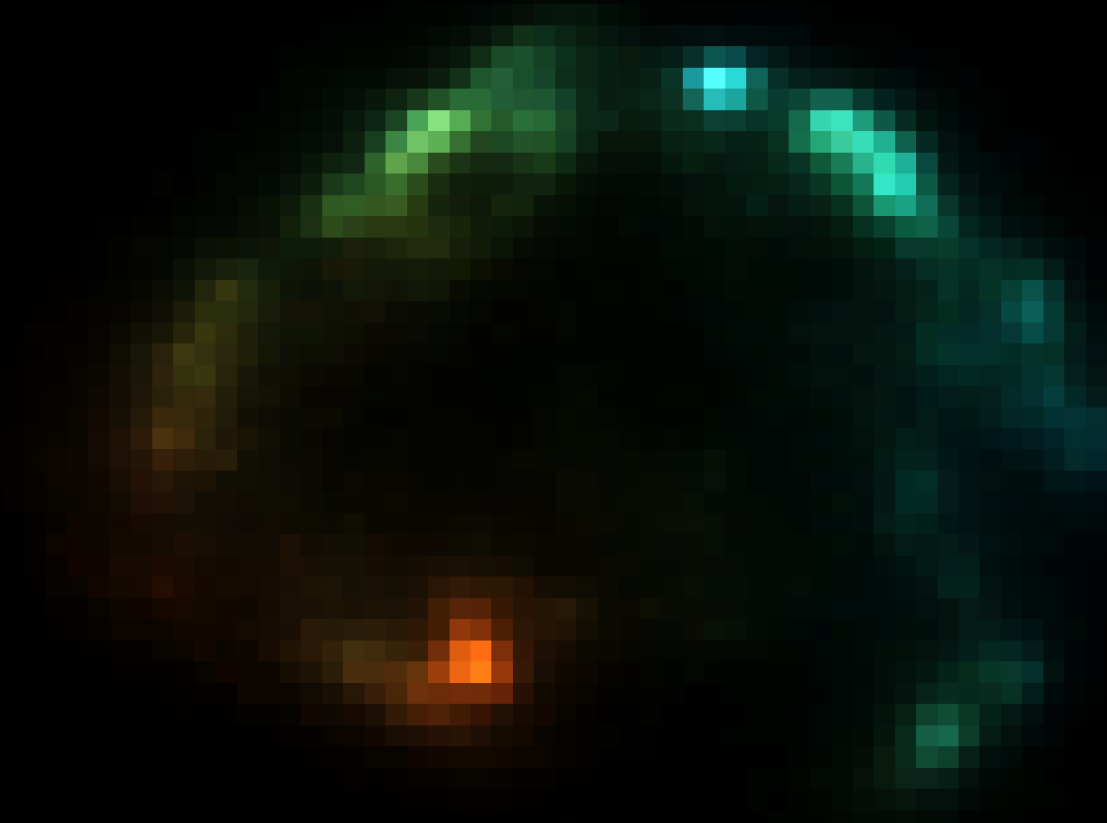
Tarantula nebula

Automatic Component Modeling

Preliminary results (extended sources)



Tarantula nebula



30 Doradus C

Bayesian method

Uncertainties come for free!



Posterior mean

Bayesian method

Uncertainties come for free!



Posterior sample 1

Bayesian method

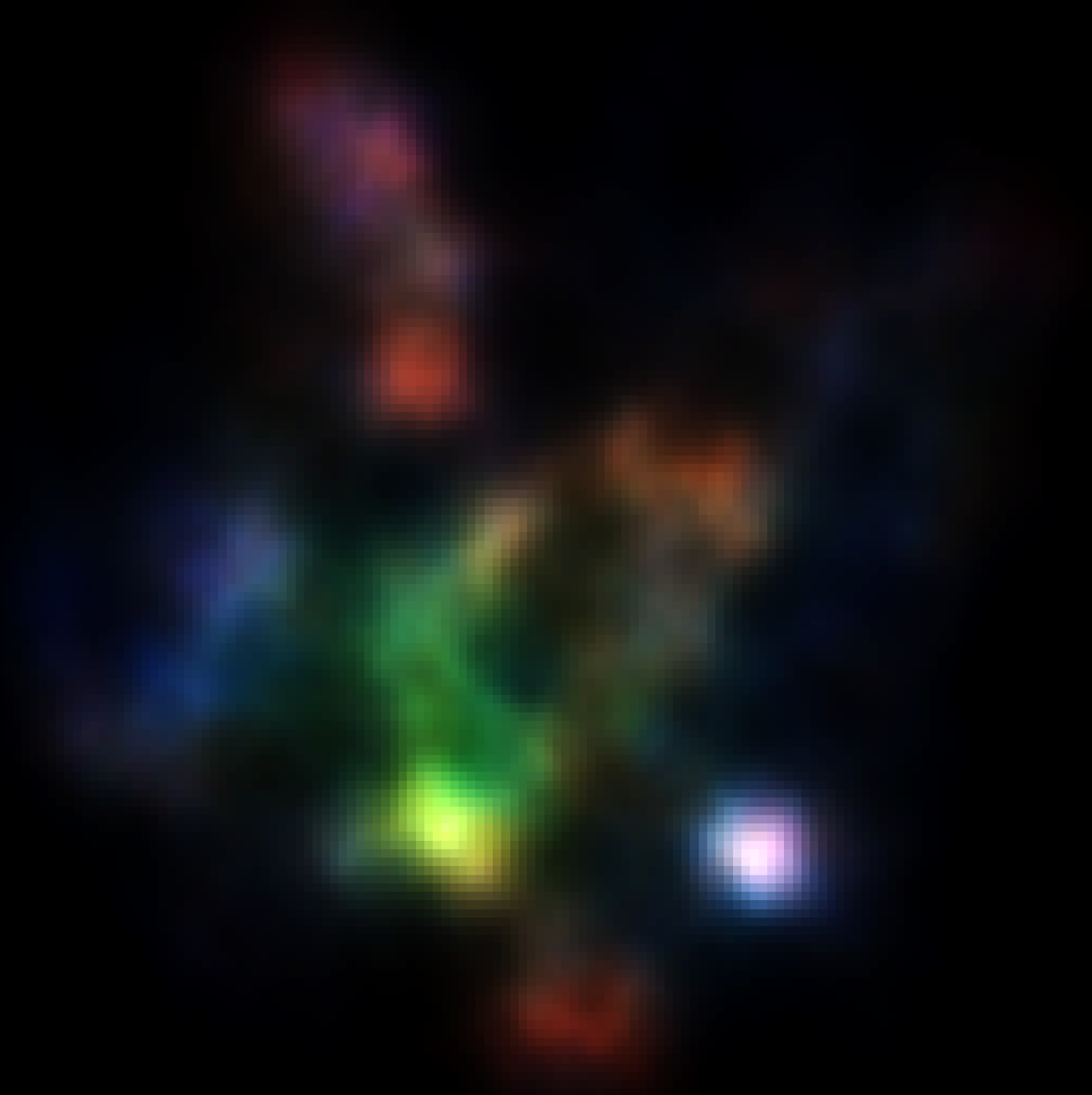
Uncertainties come for free!



Posterior sample 2

Bayesian method

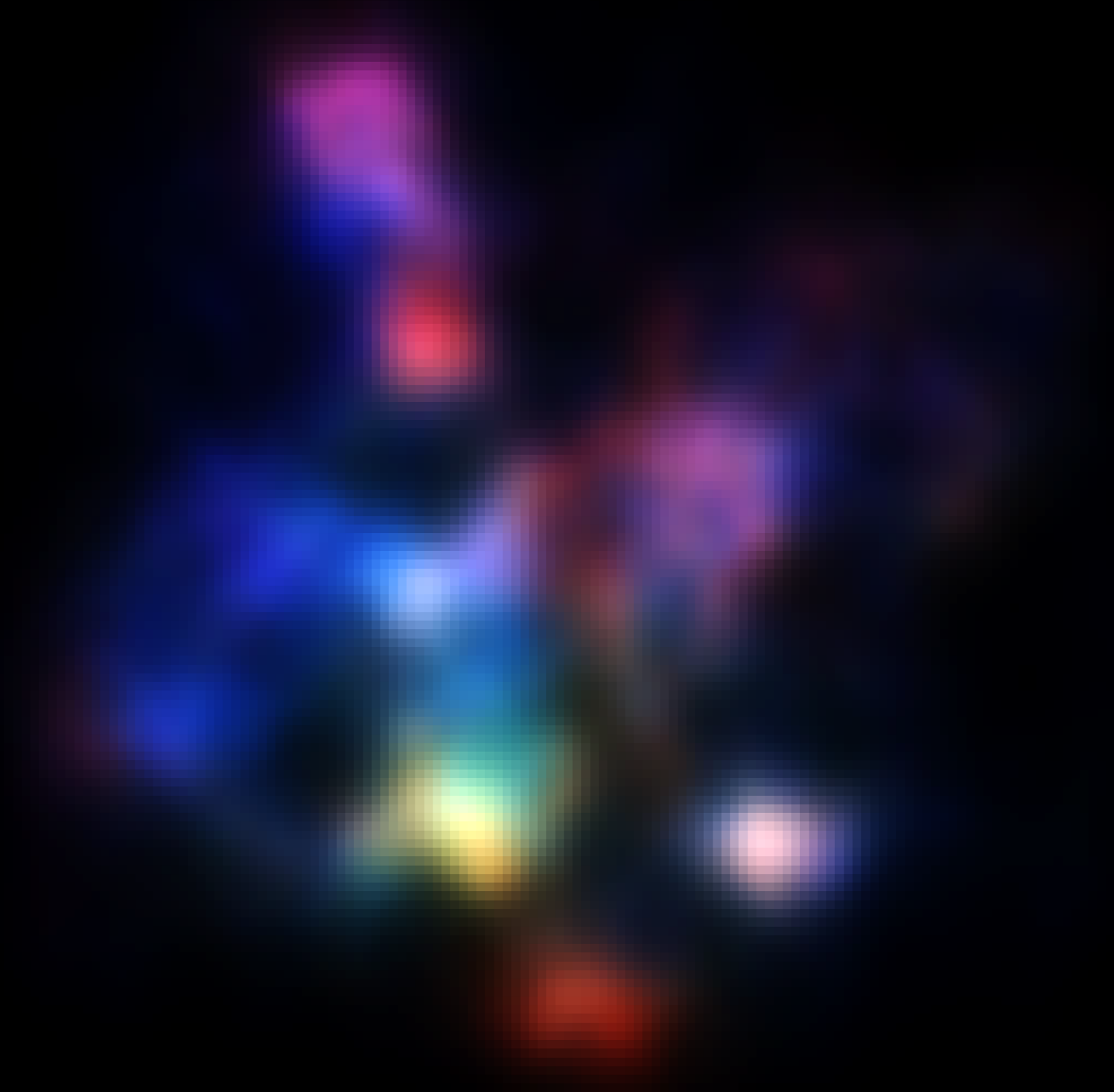
Uncertainties come for free!



Posterior sample 3

Bayesian method

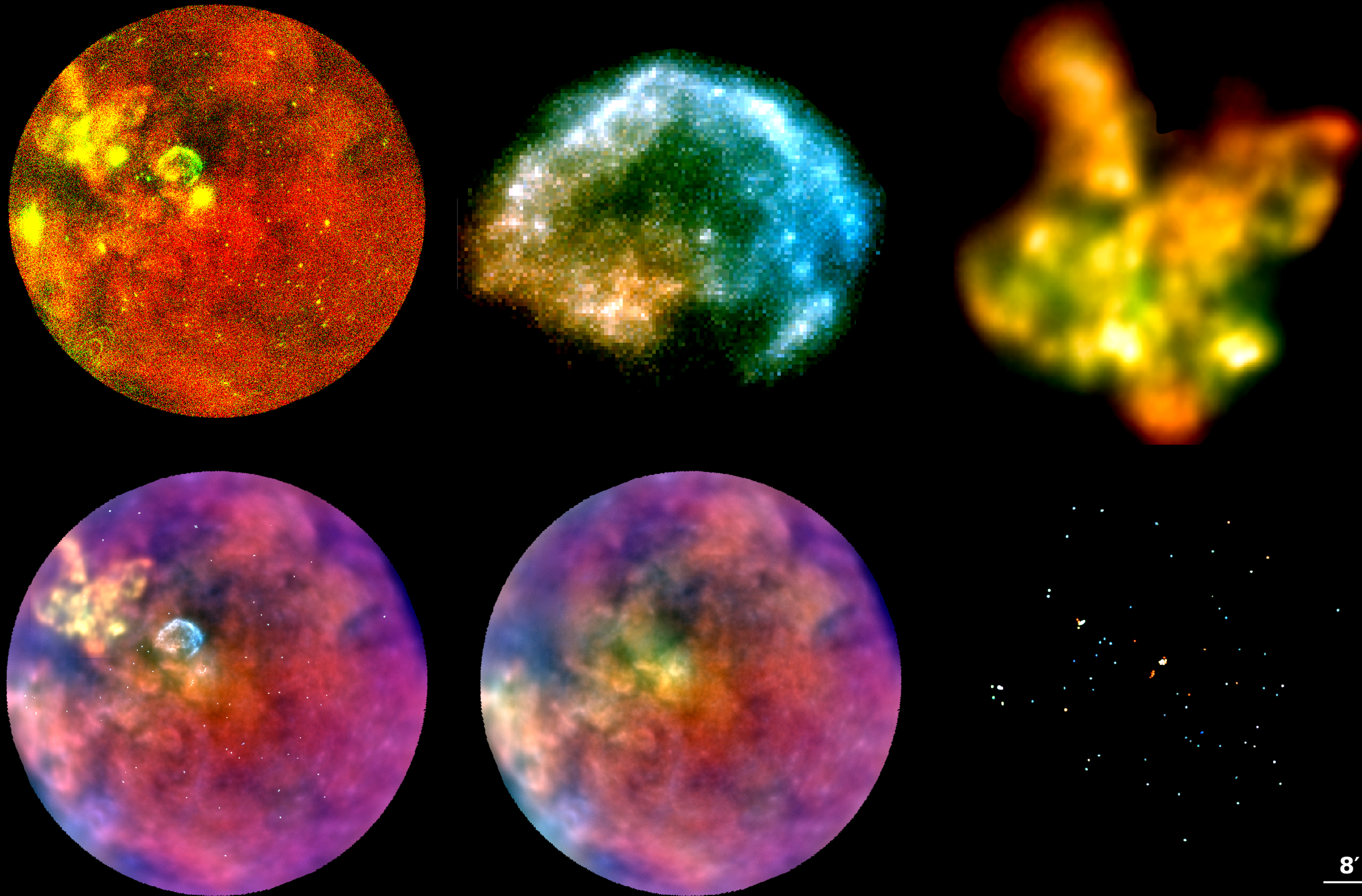
Uncertainties come for free!



Posterior sample 4

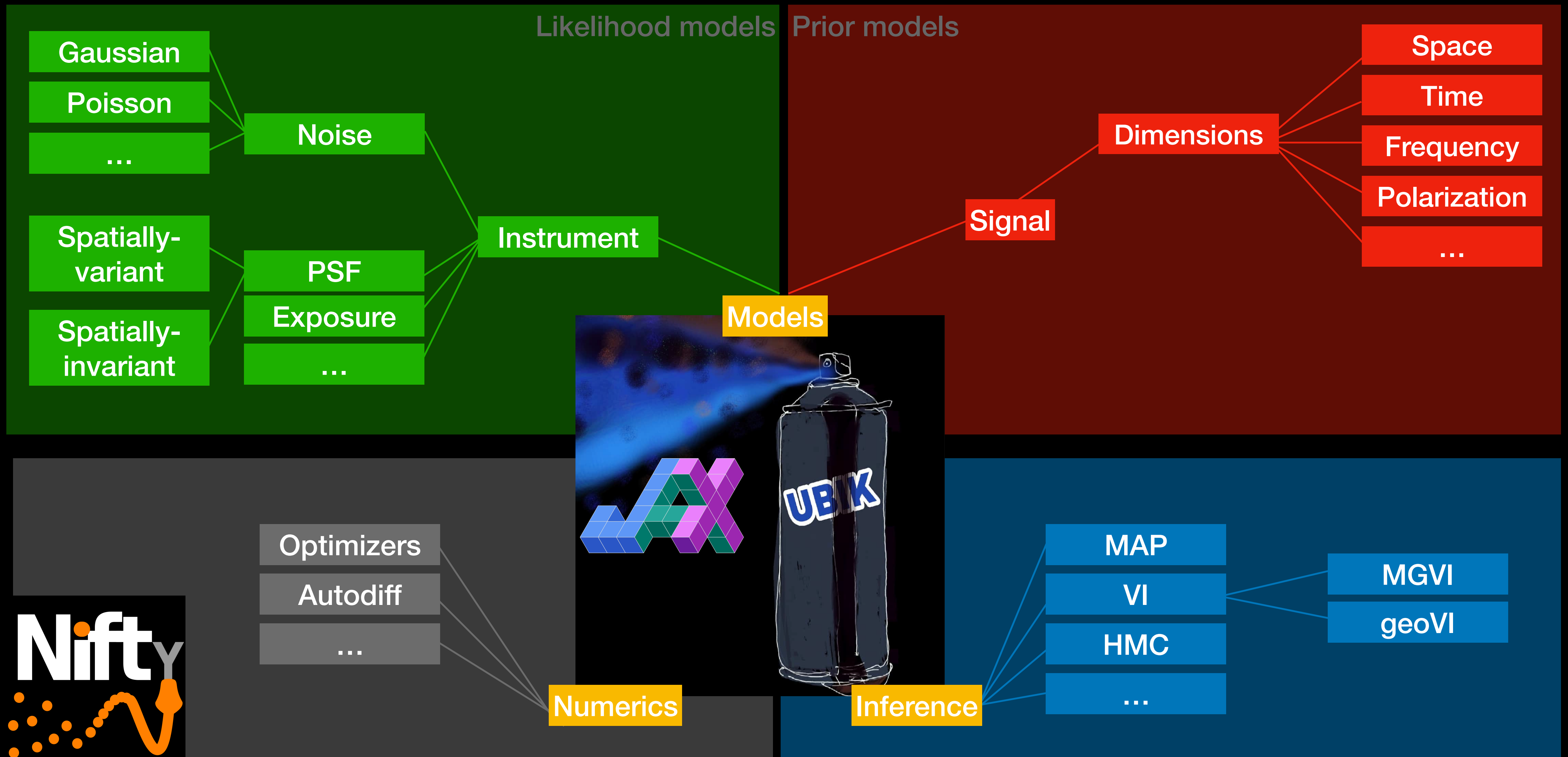
Automatic component modeling

LMC SN1987A



I like it, how can I do this?

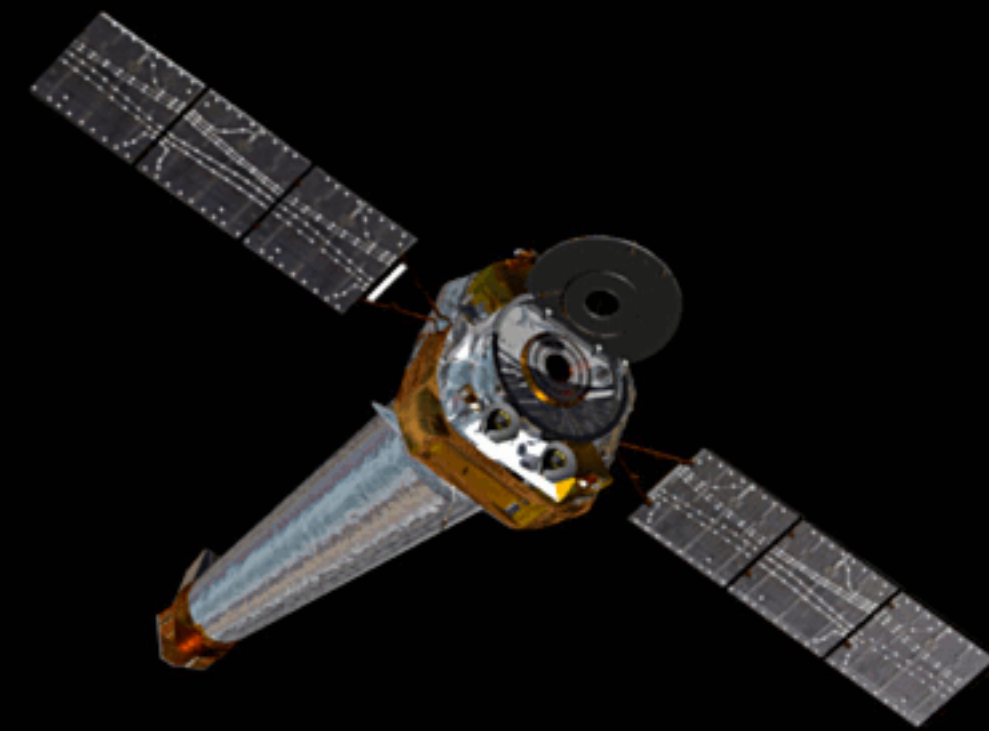
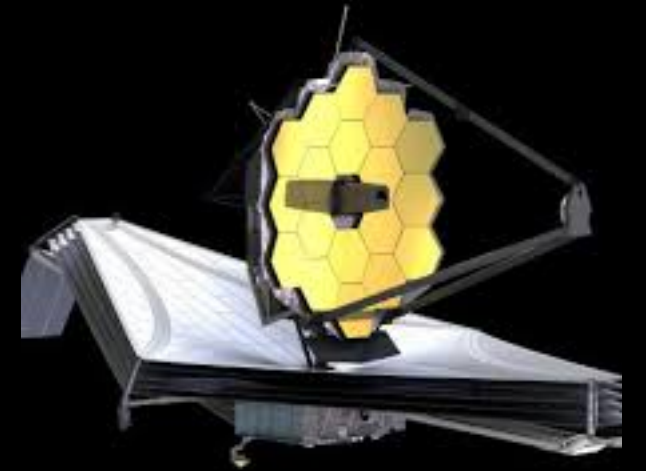
J-UBIK



J-UBIK

Instruments

- X-ray (**Chandra**, **eROSITA**, **Xmm-Newton**, ...)
- Gamma-ray (**Fermi-LAT**)
- Optical (**ELT?** **VLT/MUSE?**)
- Infrared (**JWST**, **GRAVITY?**, **ELT?**)
- Radio (**VLA**, **ALMA**, **MeerKAT**, **EHT**, ...)



Outlook

Outlook

- **Prior knowledge allows to solve ill-posed problems**
- **Detector effects can be effectively removed**
- **Many applications: spectral lines, exoplanets, ...**
- **Many more applications: Optical, Infrared, Interferometry, Strong lensing, ...**



Future work

- **Fuse J-UBIK with resolve (interferometric imaging)**
- **Enlarge library of digital twins (HST, ALMA, ELT, ...)**
- **Enlarge library of calibration models (pile-up, PSFs, ...)**
- **Explore self/cross-calibration**
- **Implement spectral line model**
- **Enhance support for multi-instrument data**



Some advertisement...

- **NIFTy (Numerical Information Field Theory)**
High-dimensional inference & Gaussian processes
- **J-UBIK (Universal Bayesian Imaging Kit)**
Sky models & astronomical instrument responses
- **LensCharm**
Charming strong-lensing signal reconstructions



<https://github.com/NIFTy-PPL/NIFTy>

<https://github.com/NIFTy-PPL/J-UBIK>



GitLab <https://gitlab.mpcdf.mpg.de/ift/lenscharm>



Thank you!

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