Introducing LensCharm

Charming Bayesian Generative Strong Lensing

Matteo Guardiani, Julian Rüstig,
Jakob Roth, Philipp Frank, and Torsten Enßlin

MACHINE LEARNING FOR ASTROPHYSICS
2ND EDITION
CATANIA, 8-12 JULY, 2024

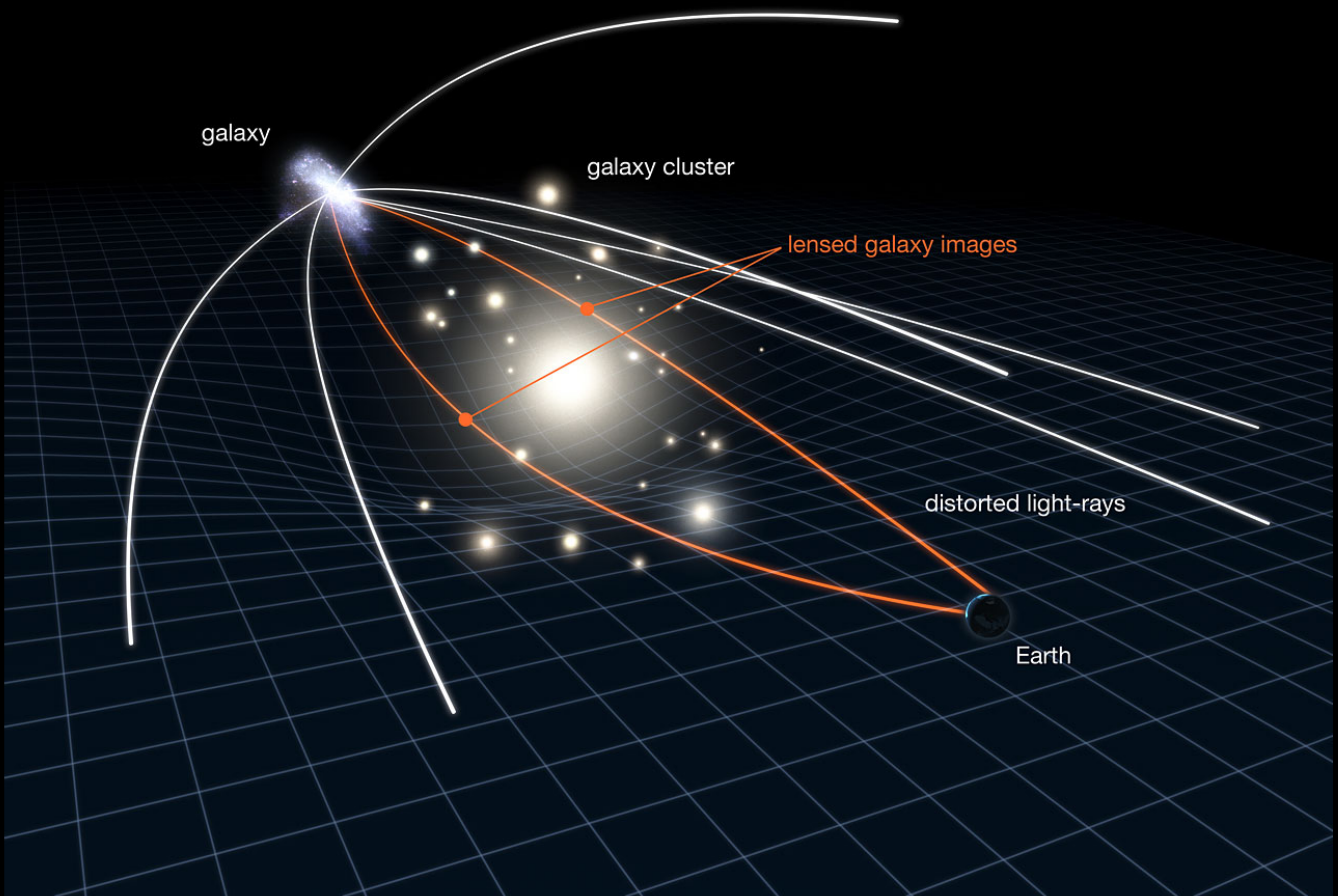
DLR

MAX PLANCK INSTITUTE FOR ASTROPHYSICS

The problem

Credits @ ESA/Hubble & NASA

The problem


galaxy
galaxy cluster
lensed galaxy images
distorted light-rays
Earth

Strong lensing with IFT

Information field theory

Bayes' Theorem

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

Information field theory

Bayes' Theorem

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

Information field theory

Bayes' Theorem

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

Information field theory

Bayes' Theorem

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

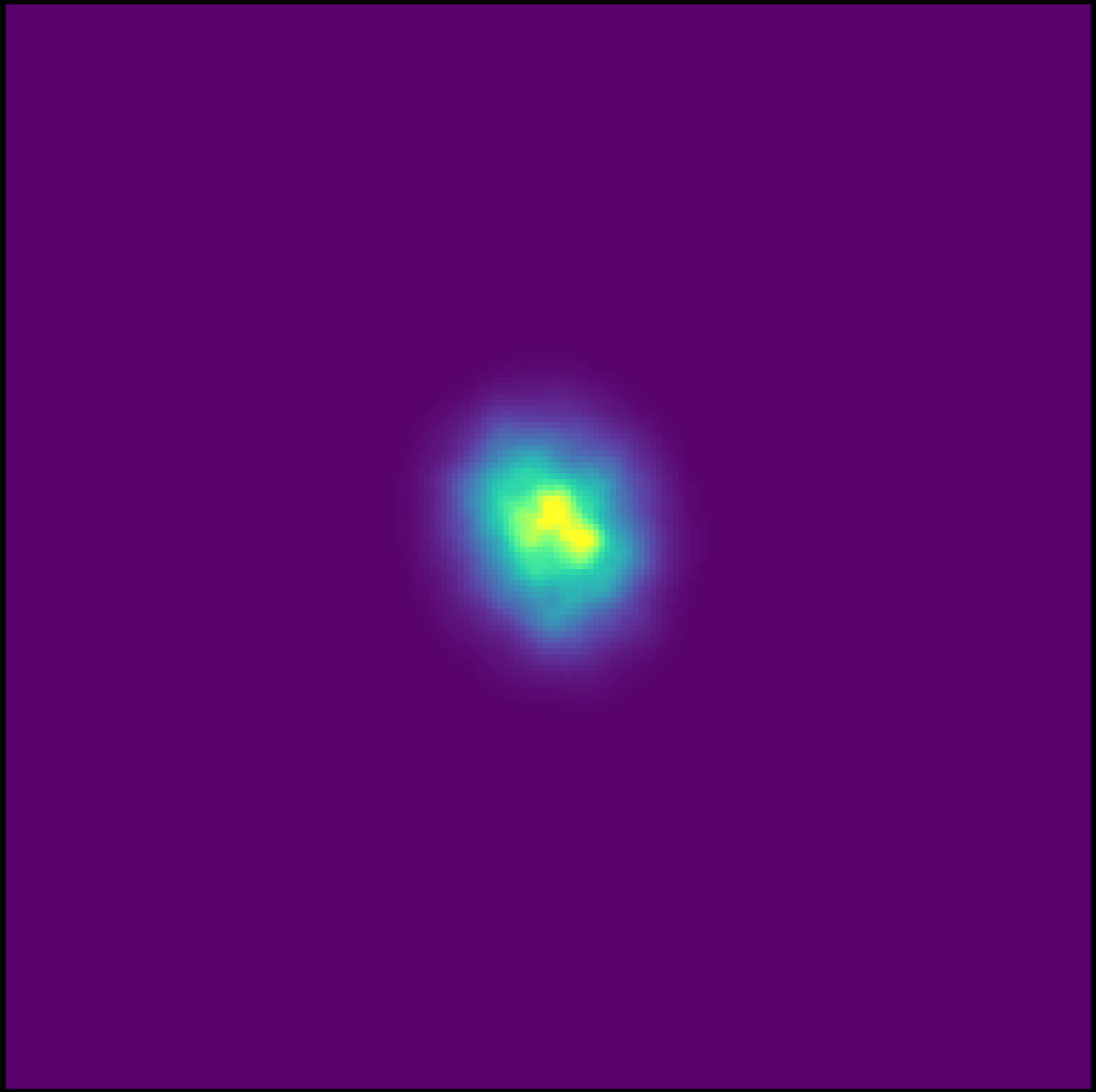
The prior

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

The prior

Source galaxy

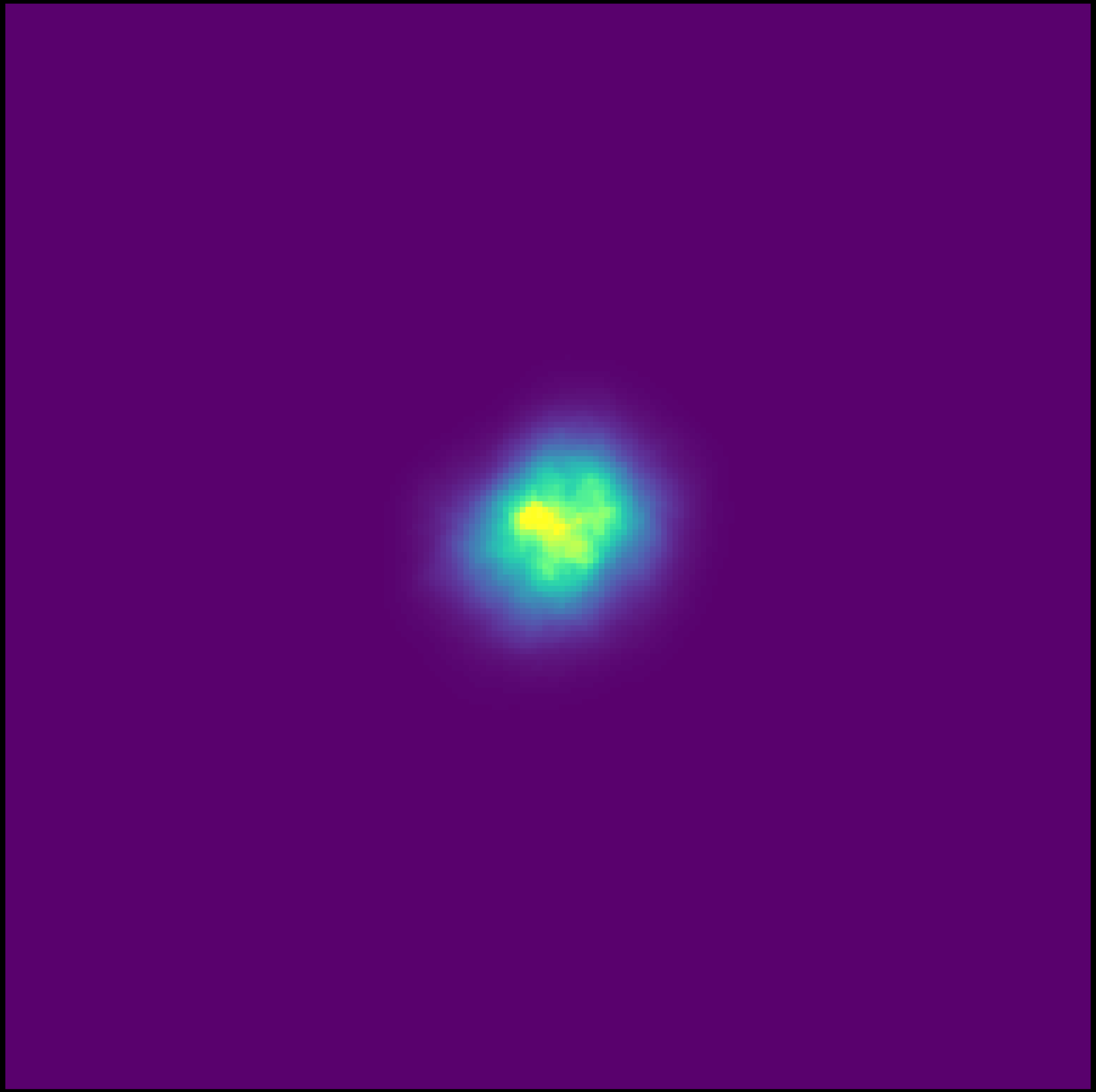
$$P(s)$$



The prior

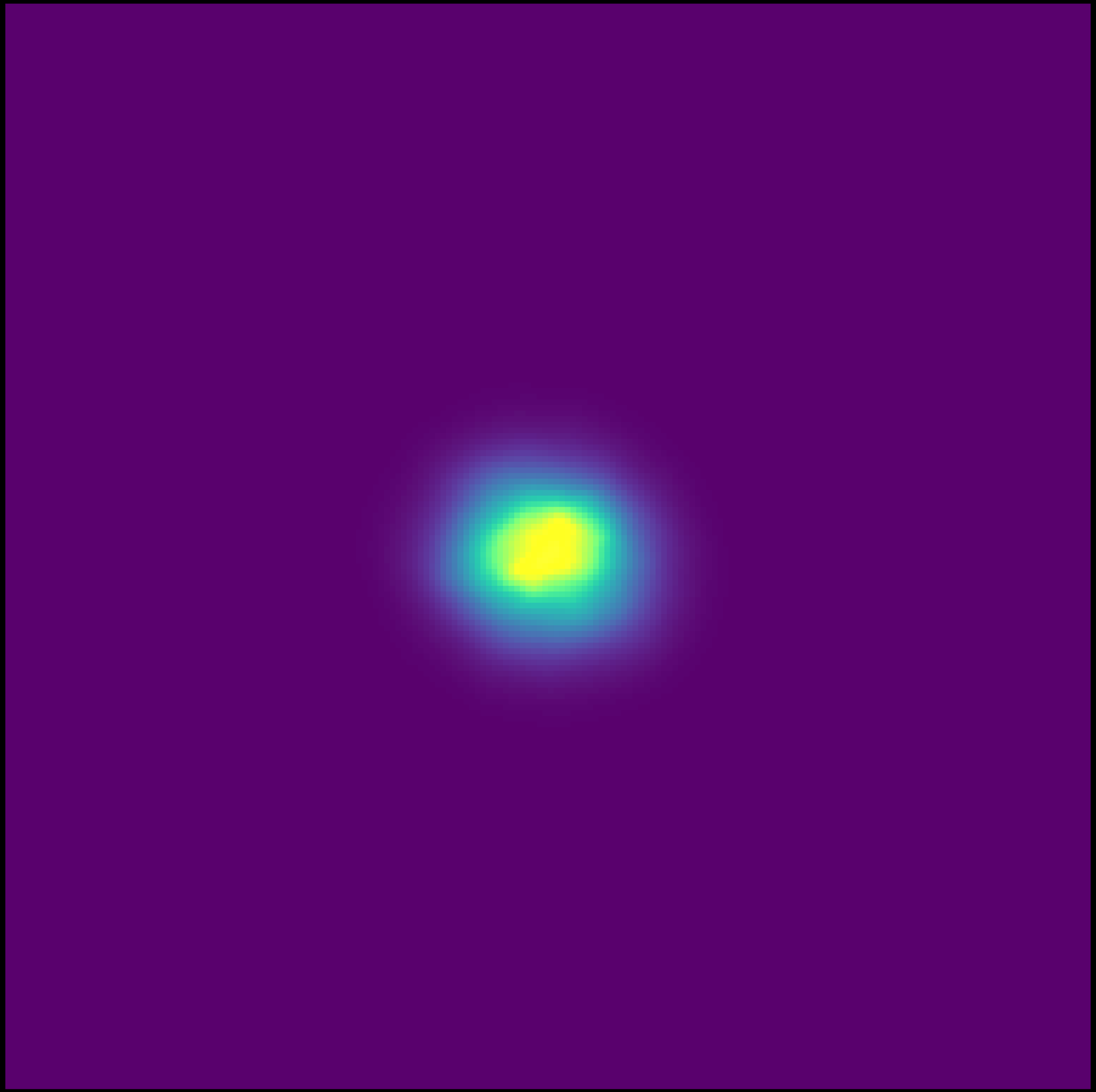
Source galaxy

$$P(s)$$



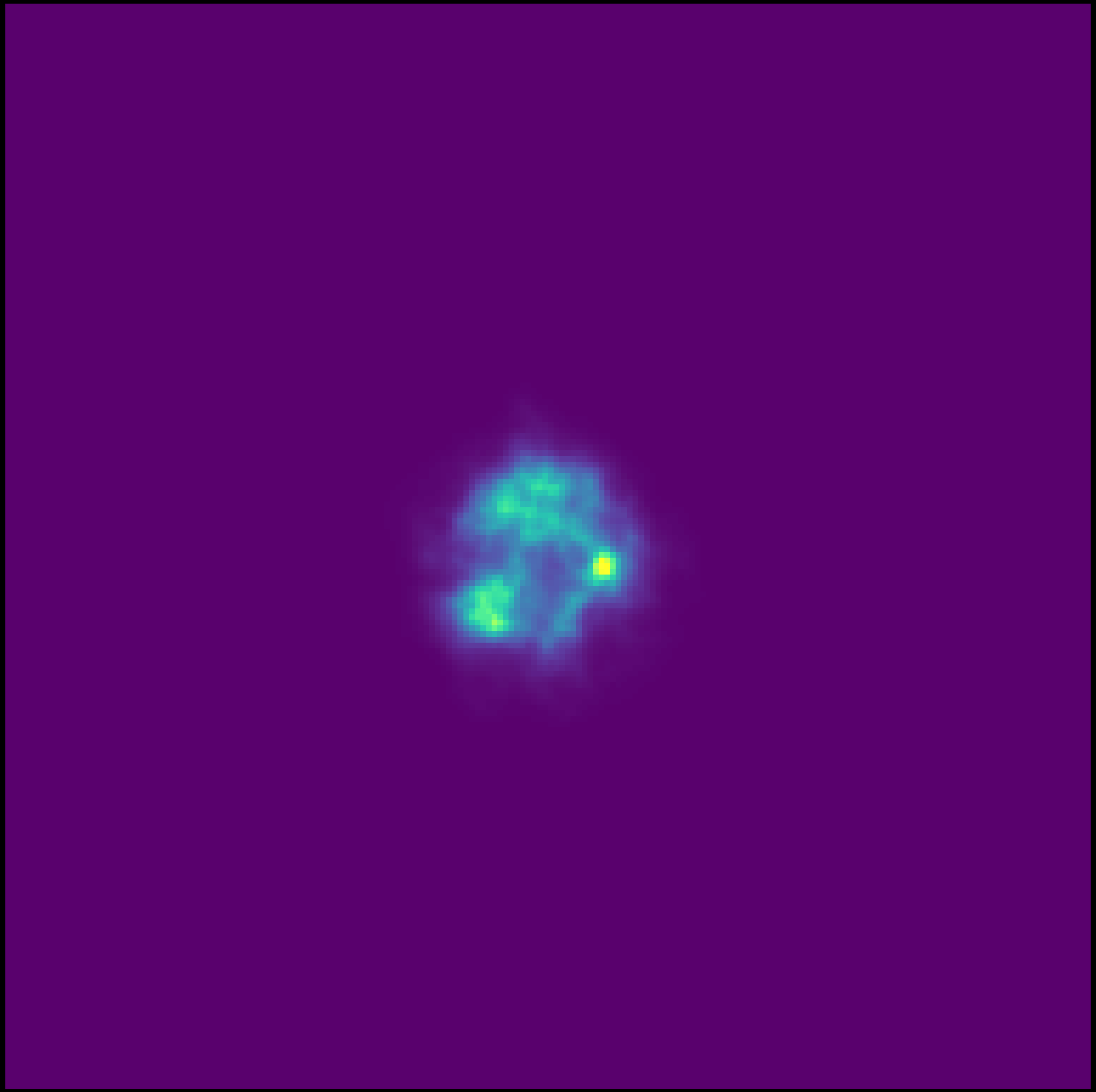
The prior
Source galaxy

$$P(s)$$



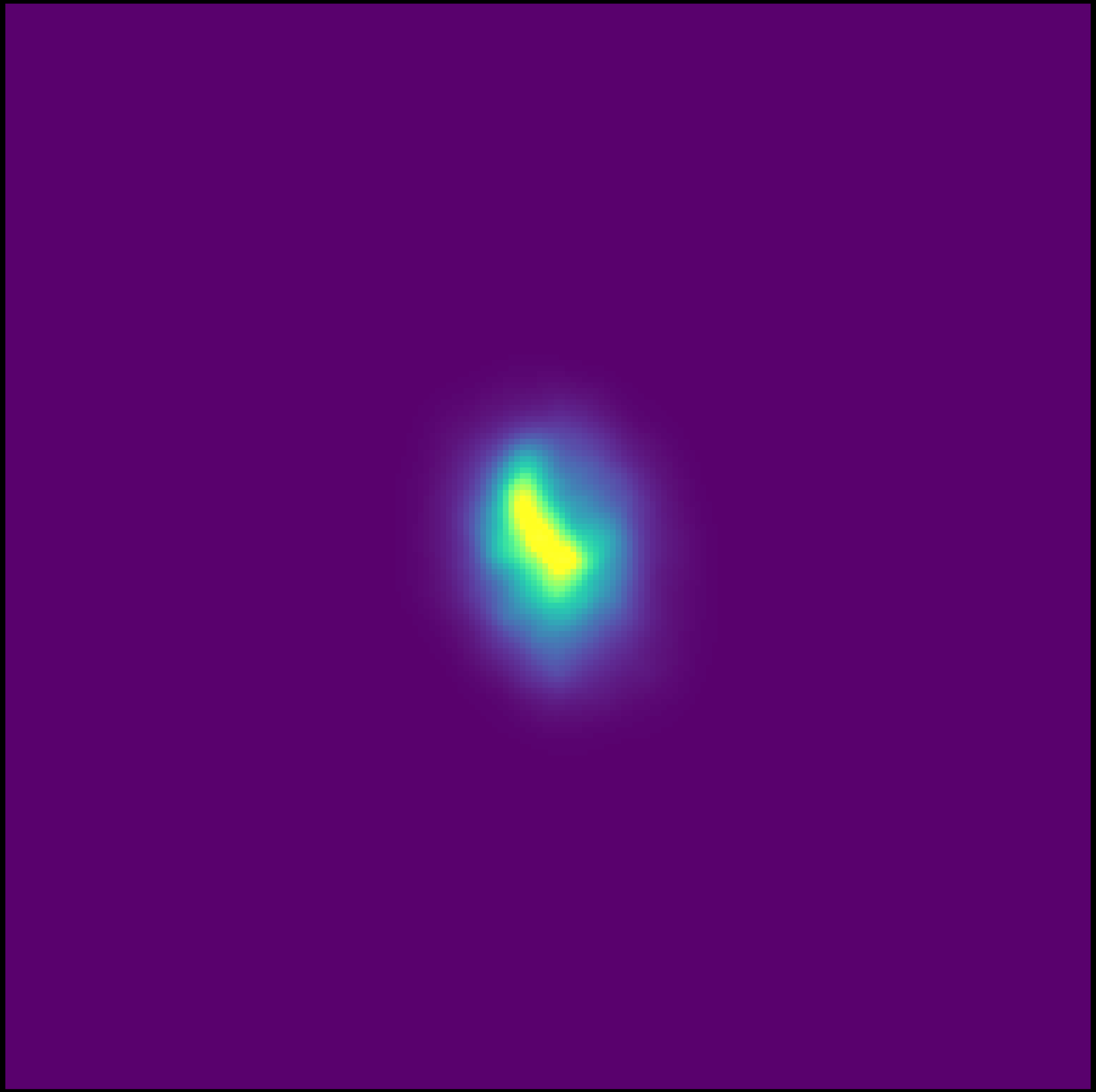
The prior
Source galaxy

$$P(s)$$



The prior
Source galaxy

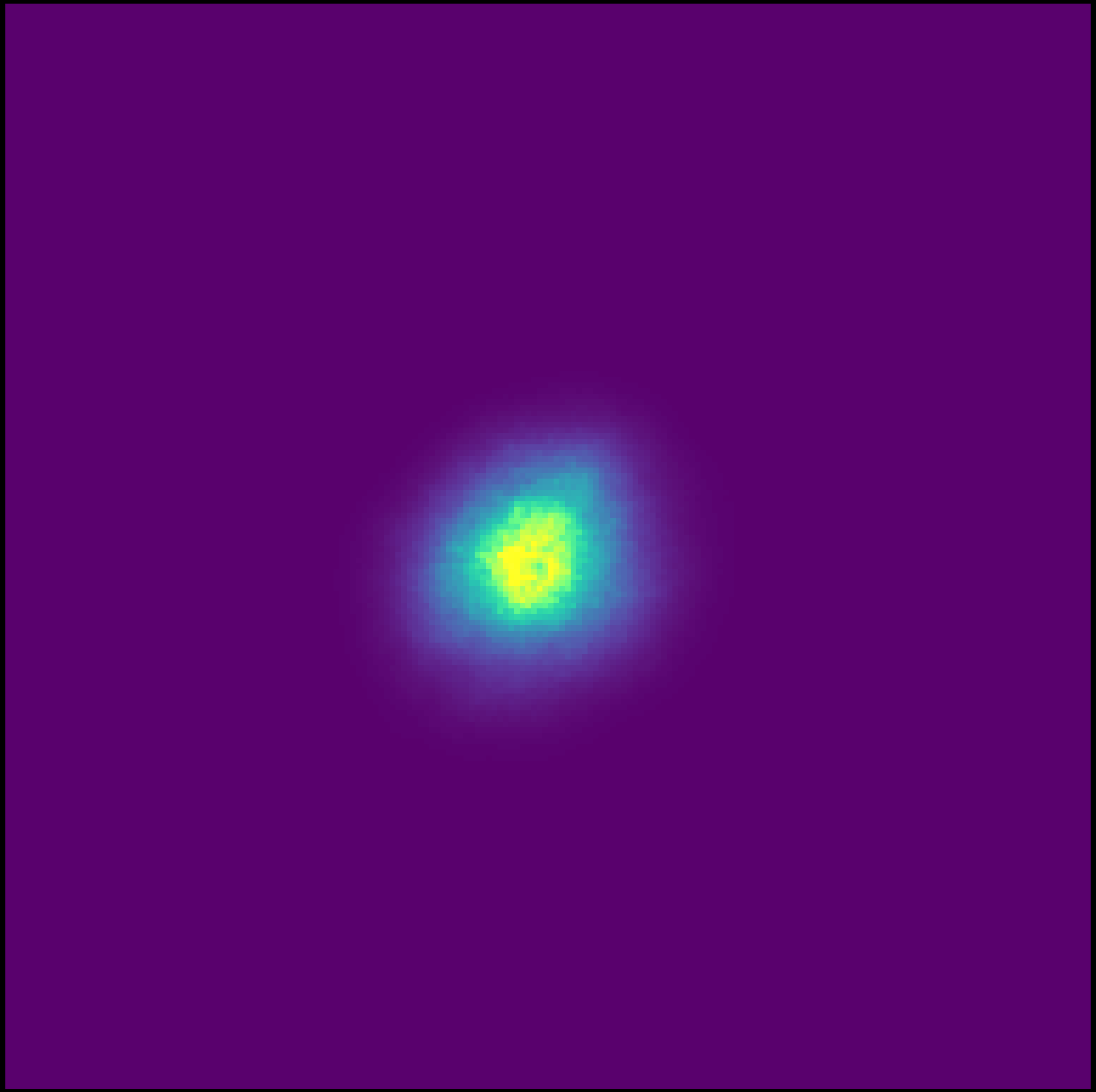
$$P(s)$$



The prior

Source galaxy

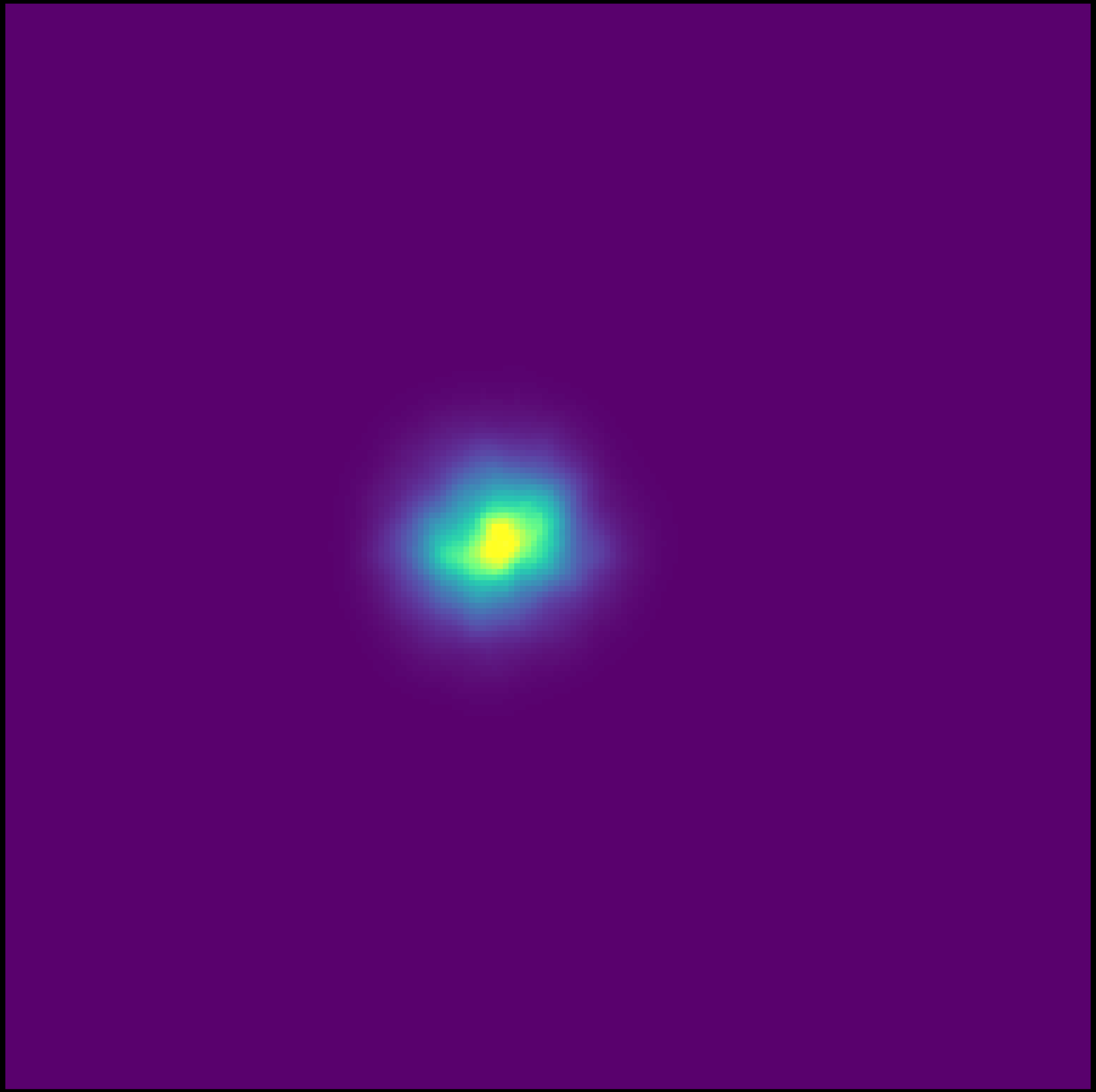
$$P(s)$$



The prior

Source galaxy

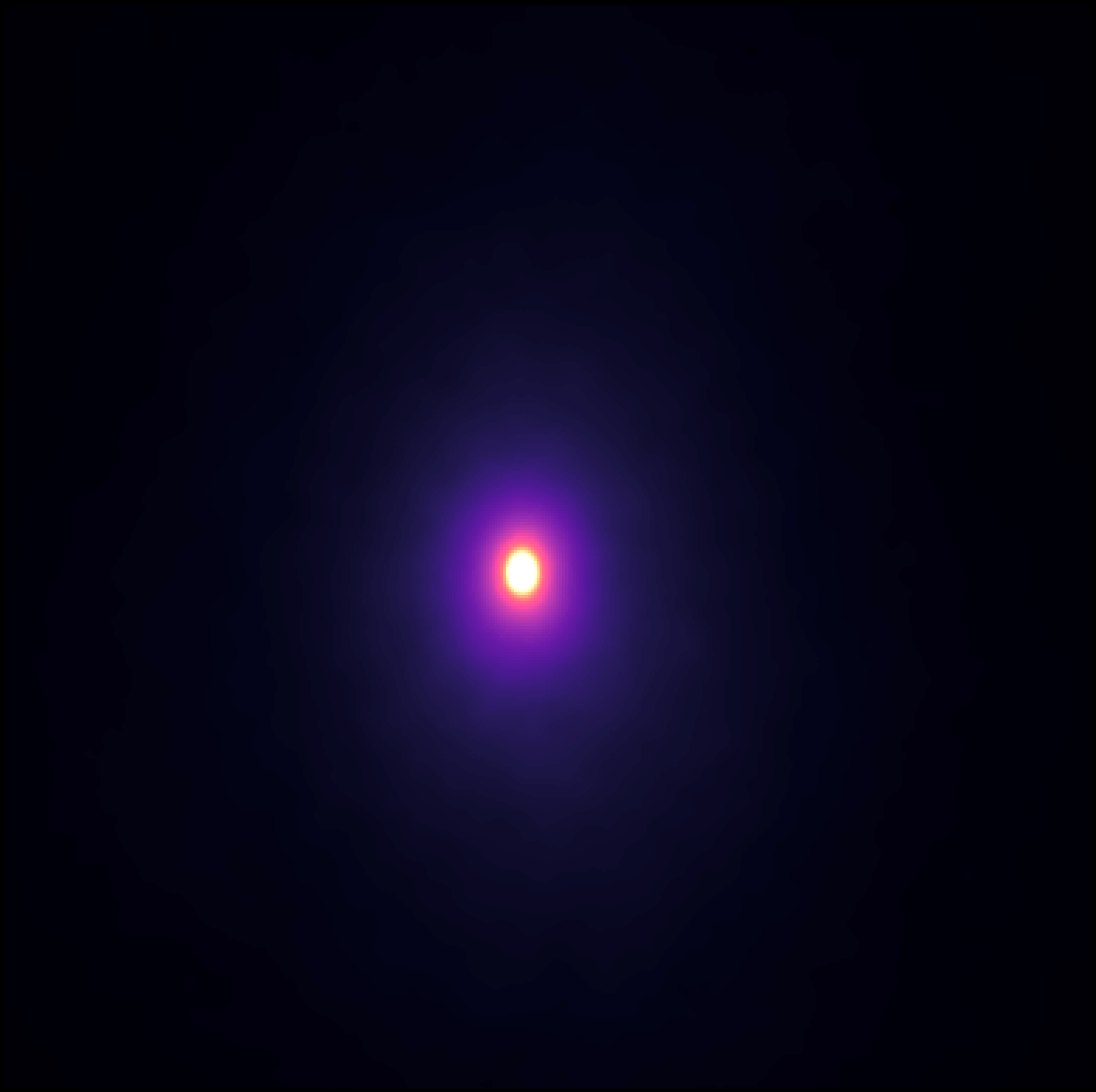
$$P(s)$$



The prior

Convergence

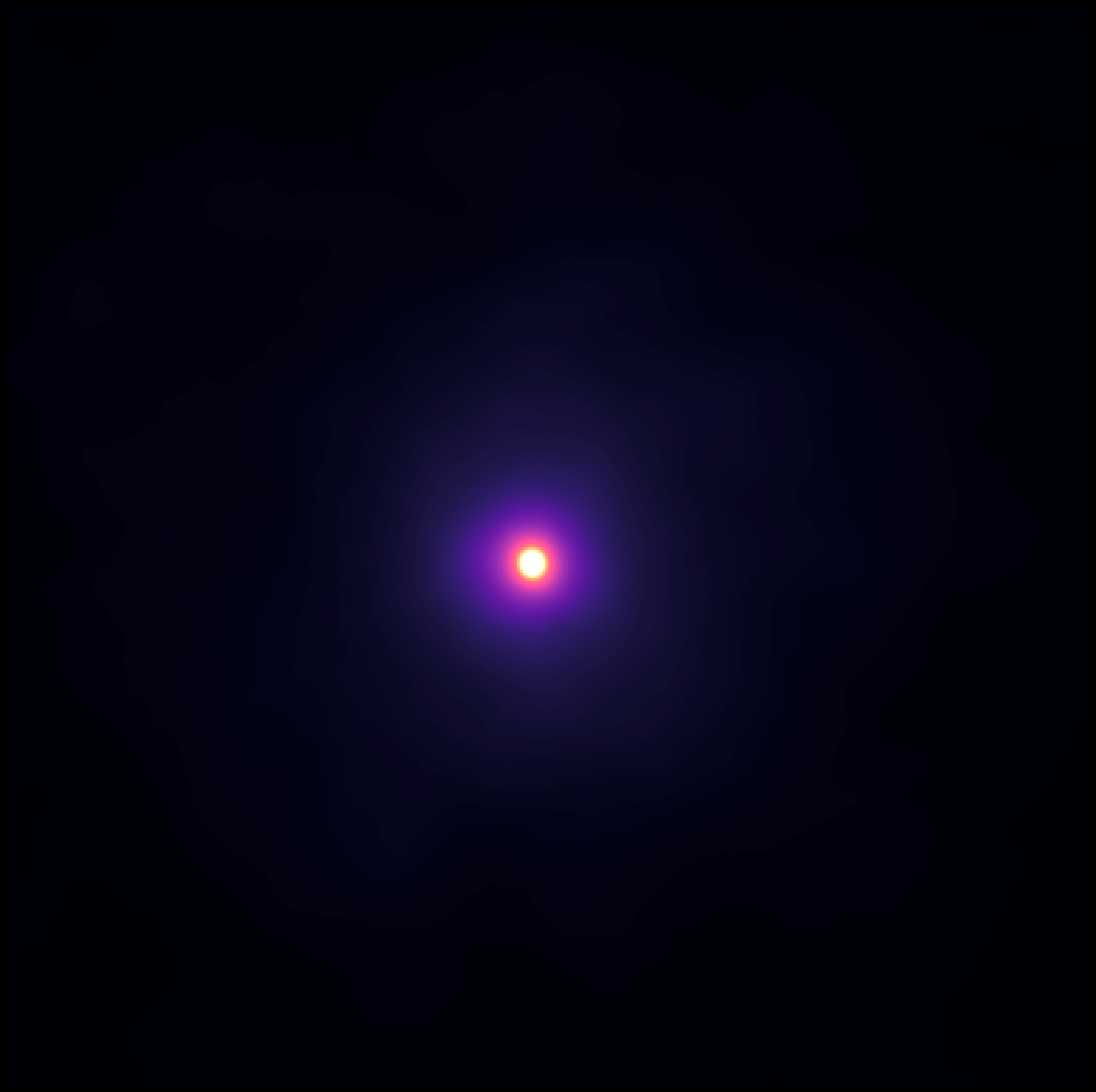
$$P(s)$$



The prior

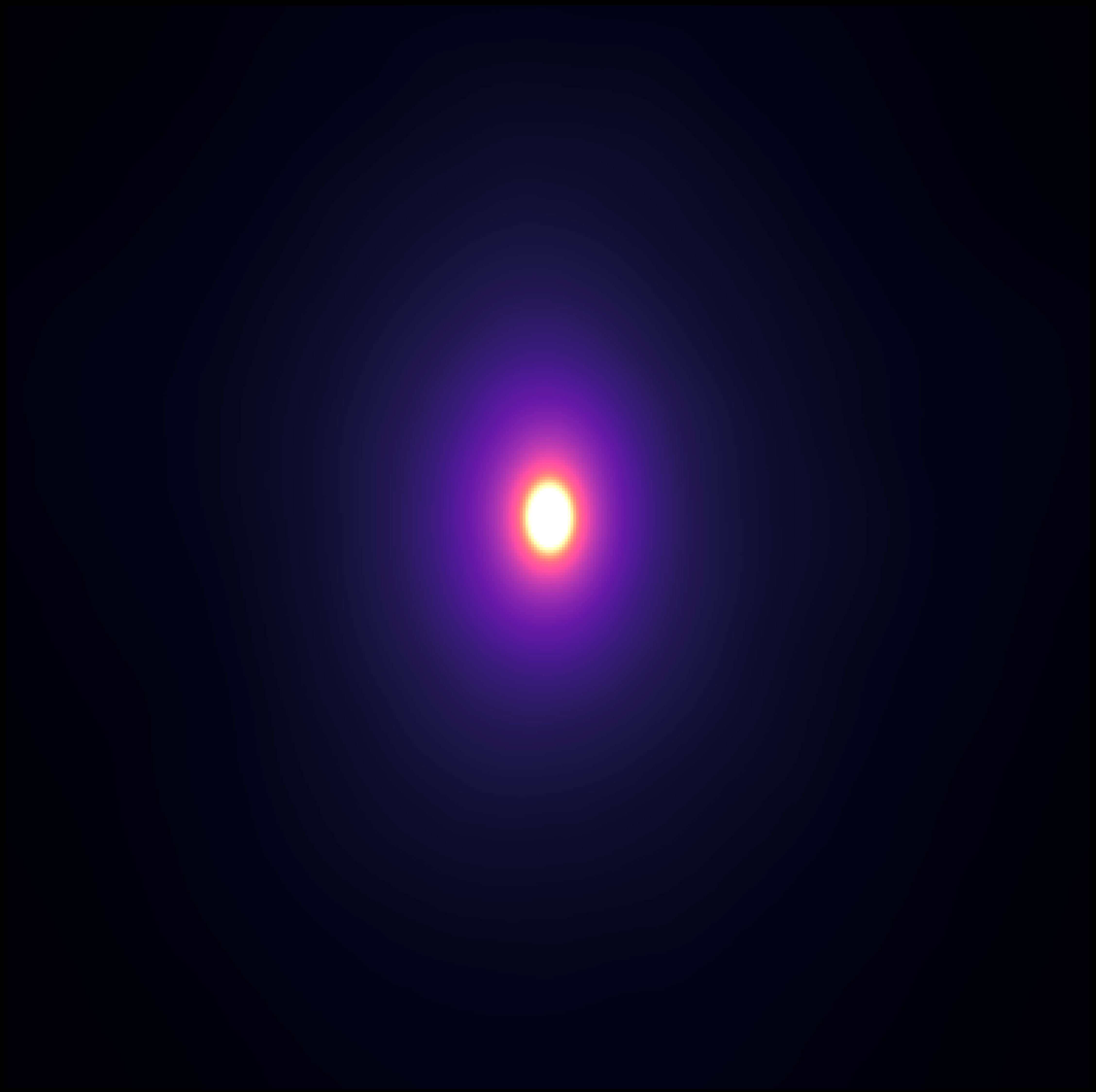
Convergence

$$P(s)$$



The prior
Convergence

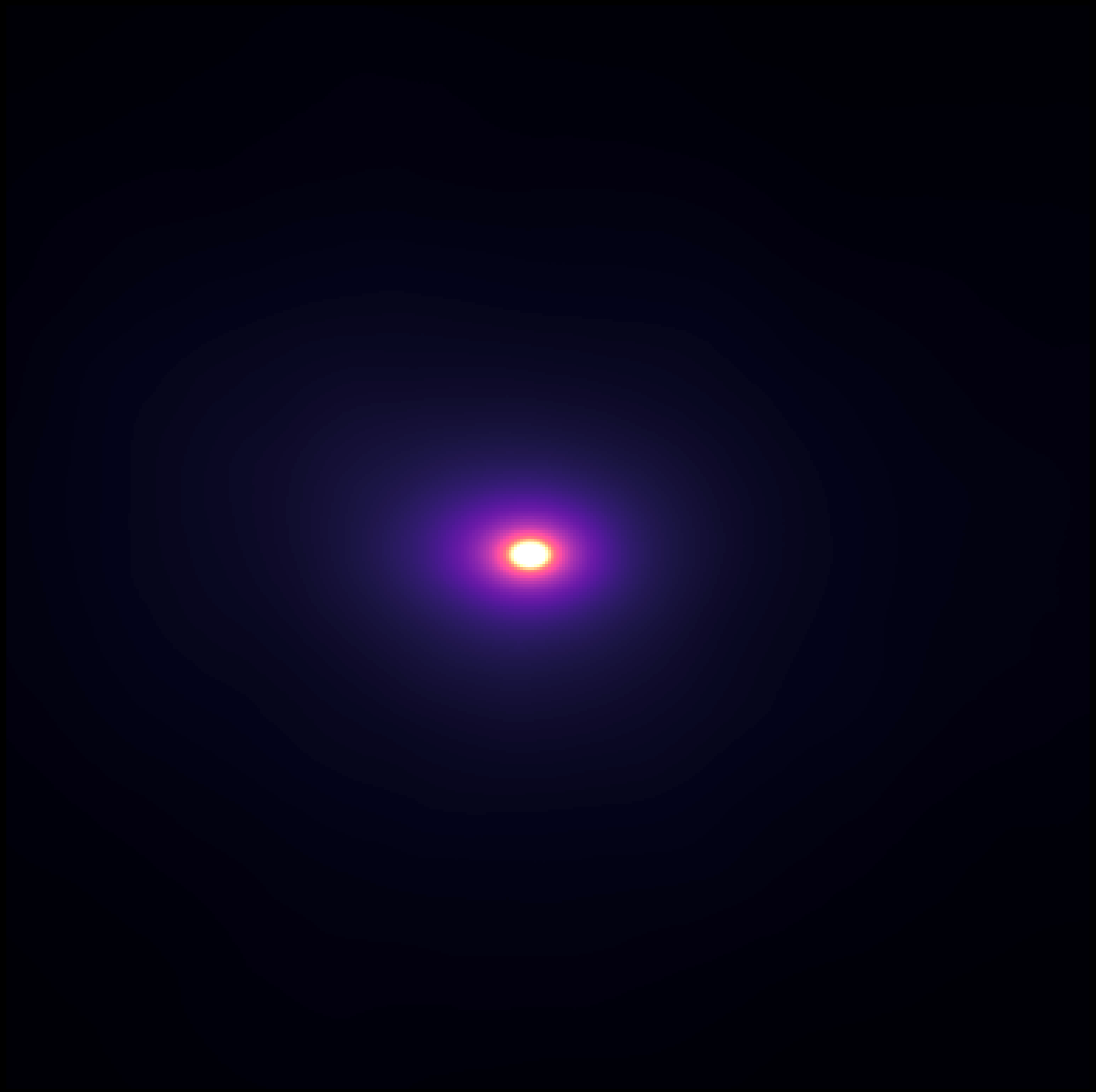
$$P(s)$$



The prior

Convergence

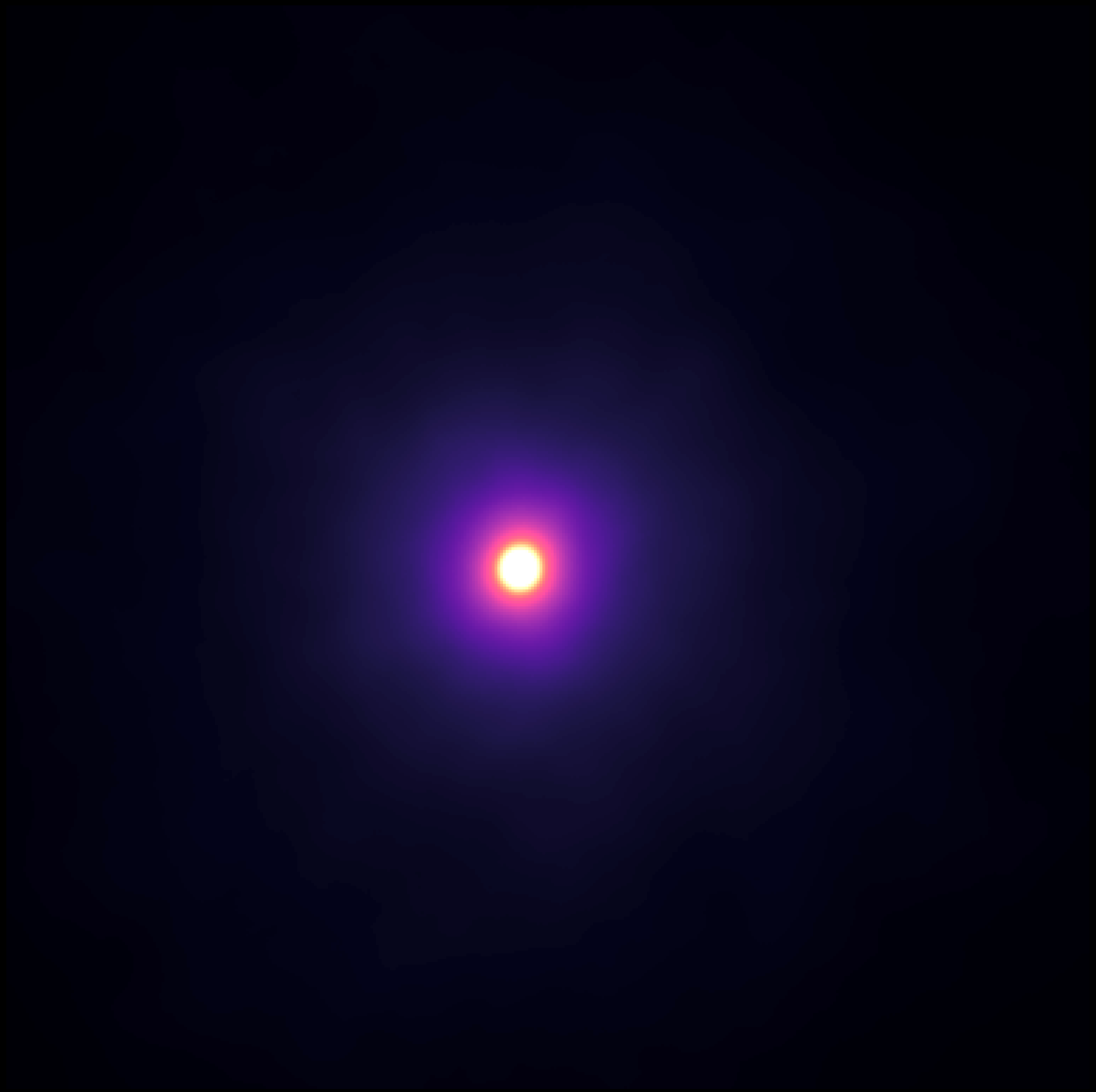
$$P(s)$$



The prior

Convergence

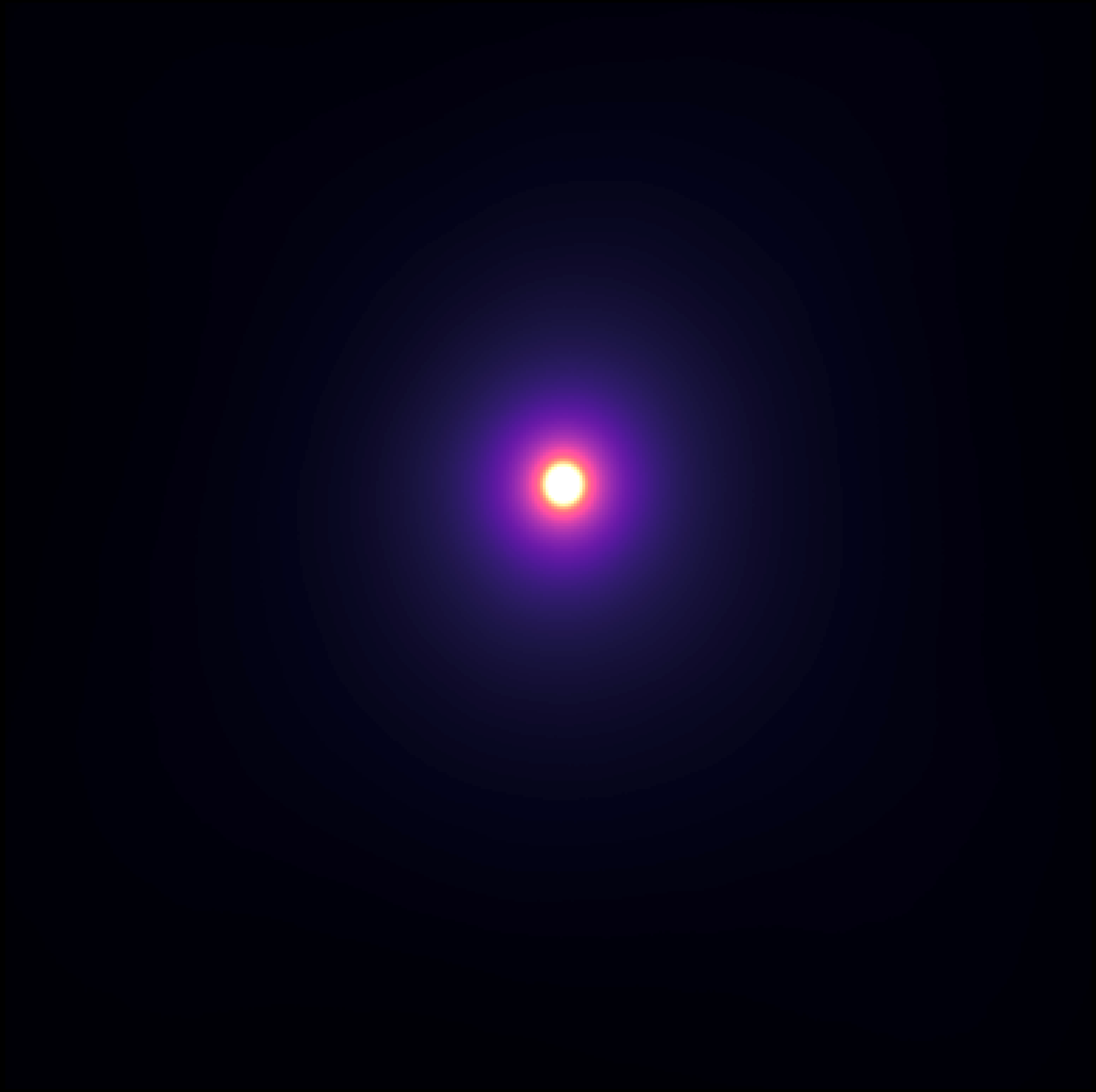
$$P(s)$$



The prior

Convergence

$$P(s)$$

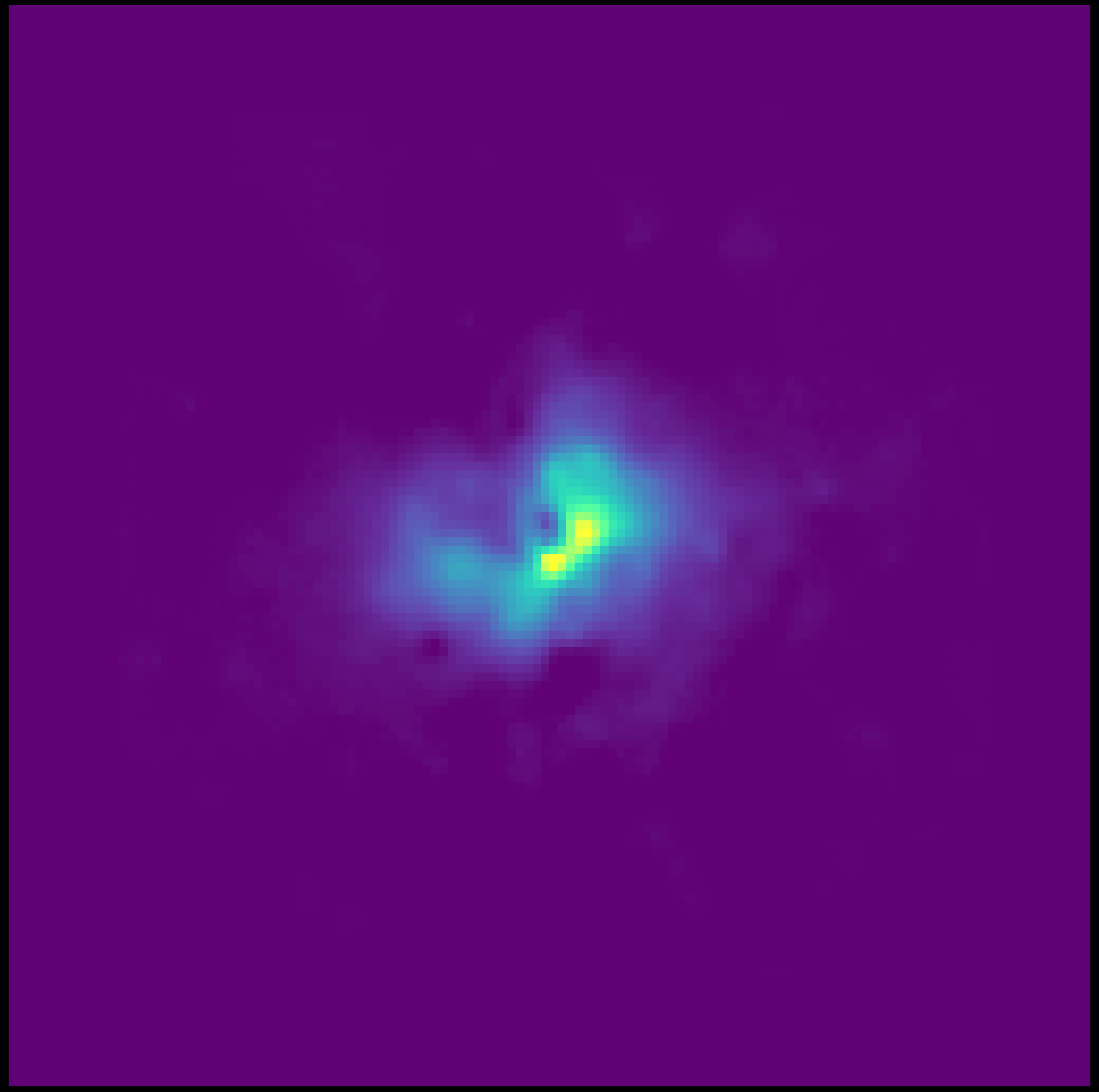


The Likelihood

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

The Likelihood

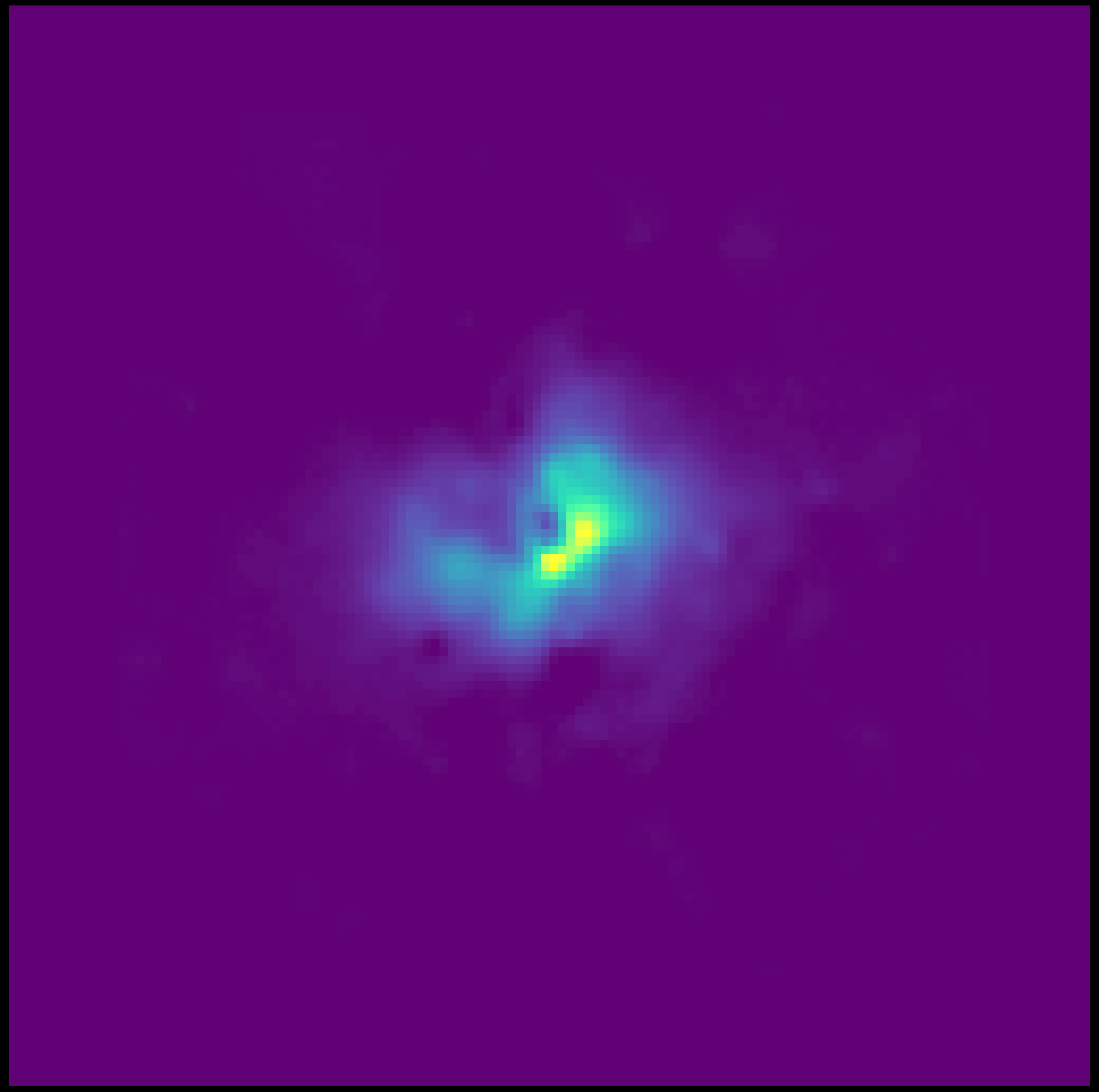
Strong lensing response



Source galaxy

The Likelihood

Strong lensing response

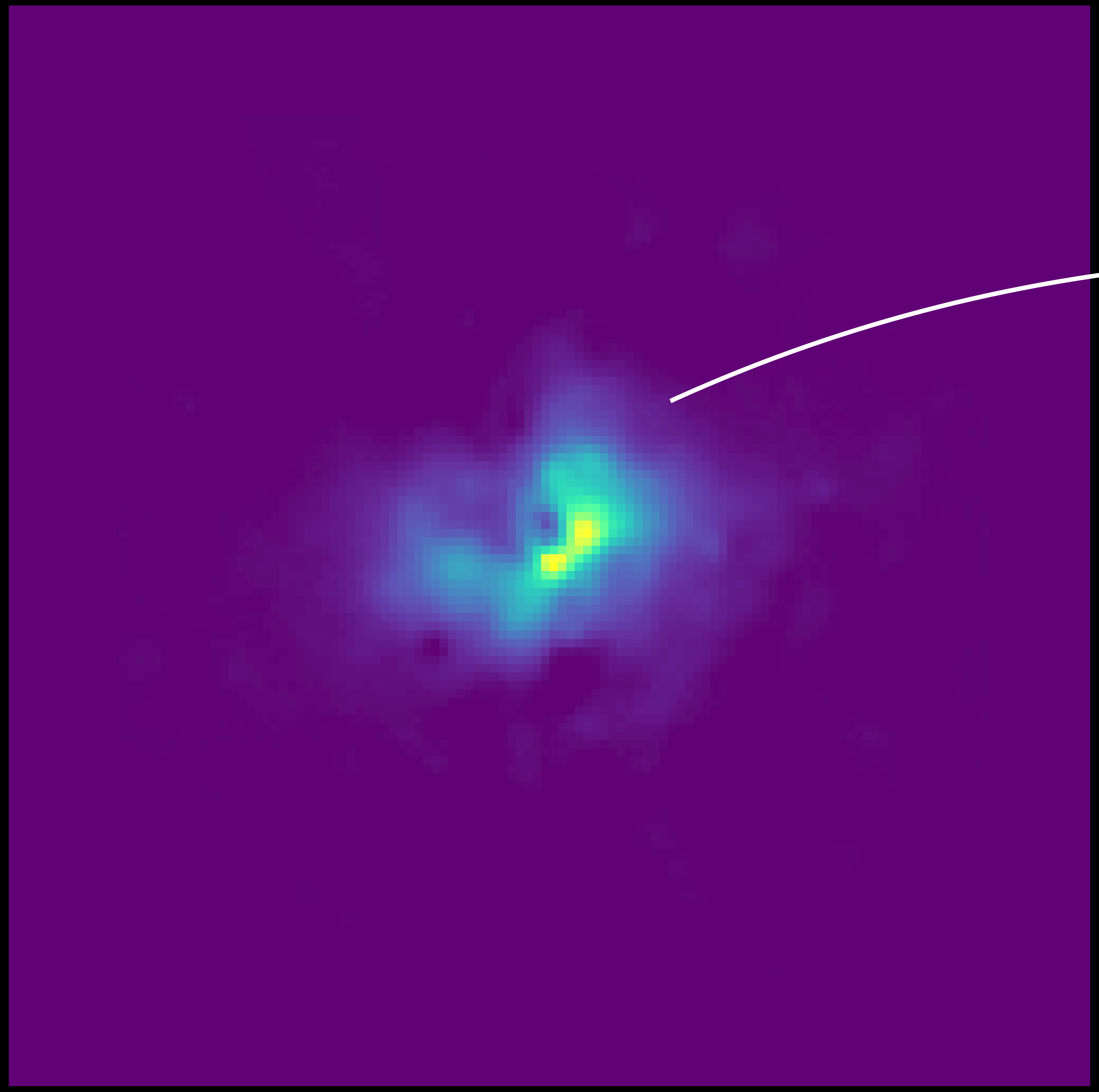


Source galaxy

DM halo mass profile

The Likelihood

Strong lensing response

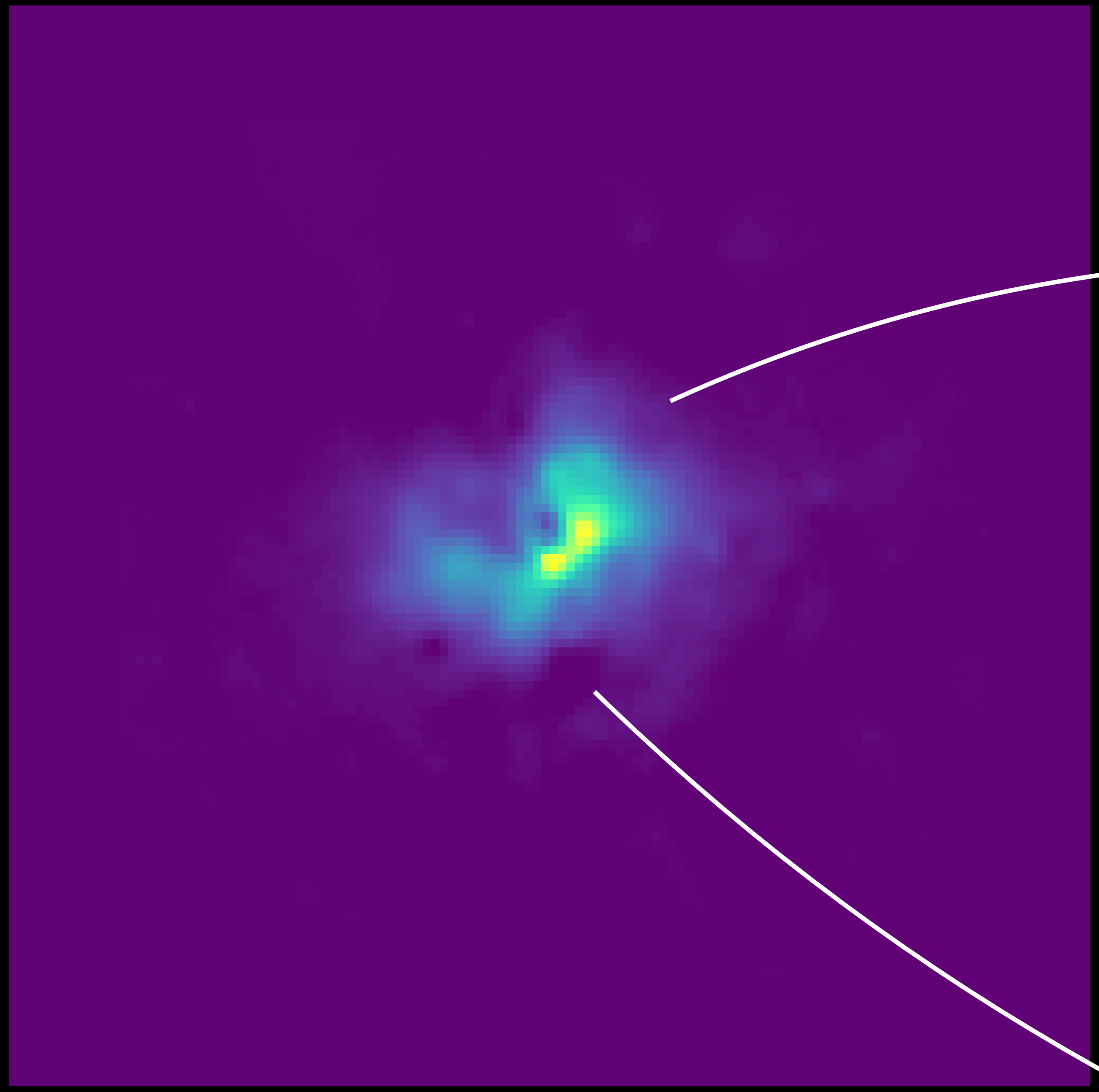


Source galaxy

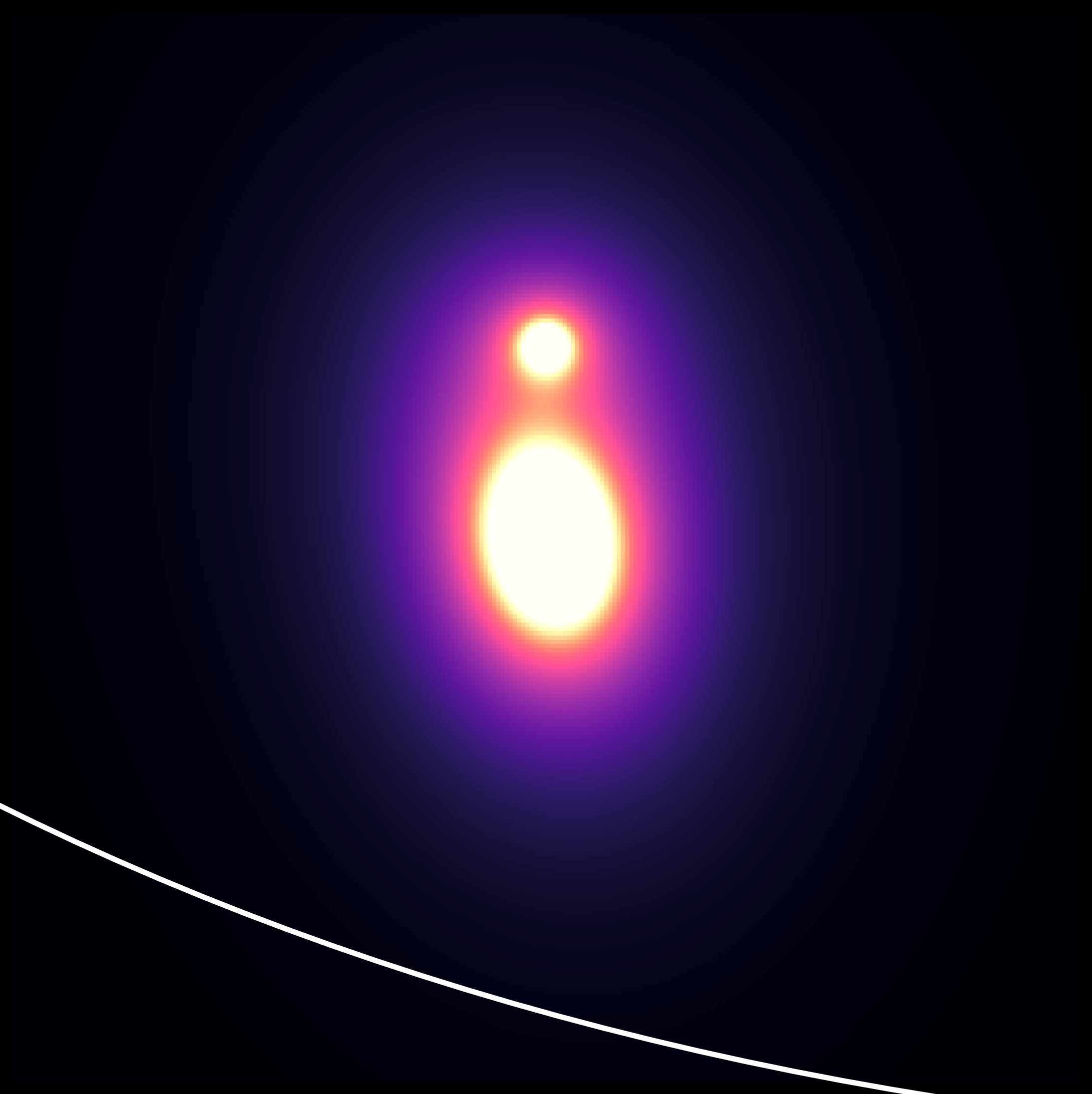
DM halo mass profile

The Likelihood

Strong lensing response



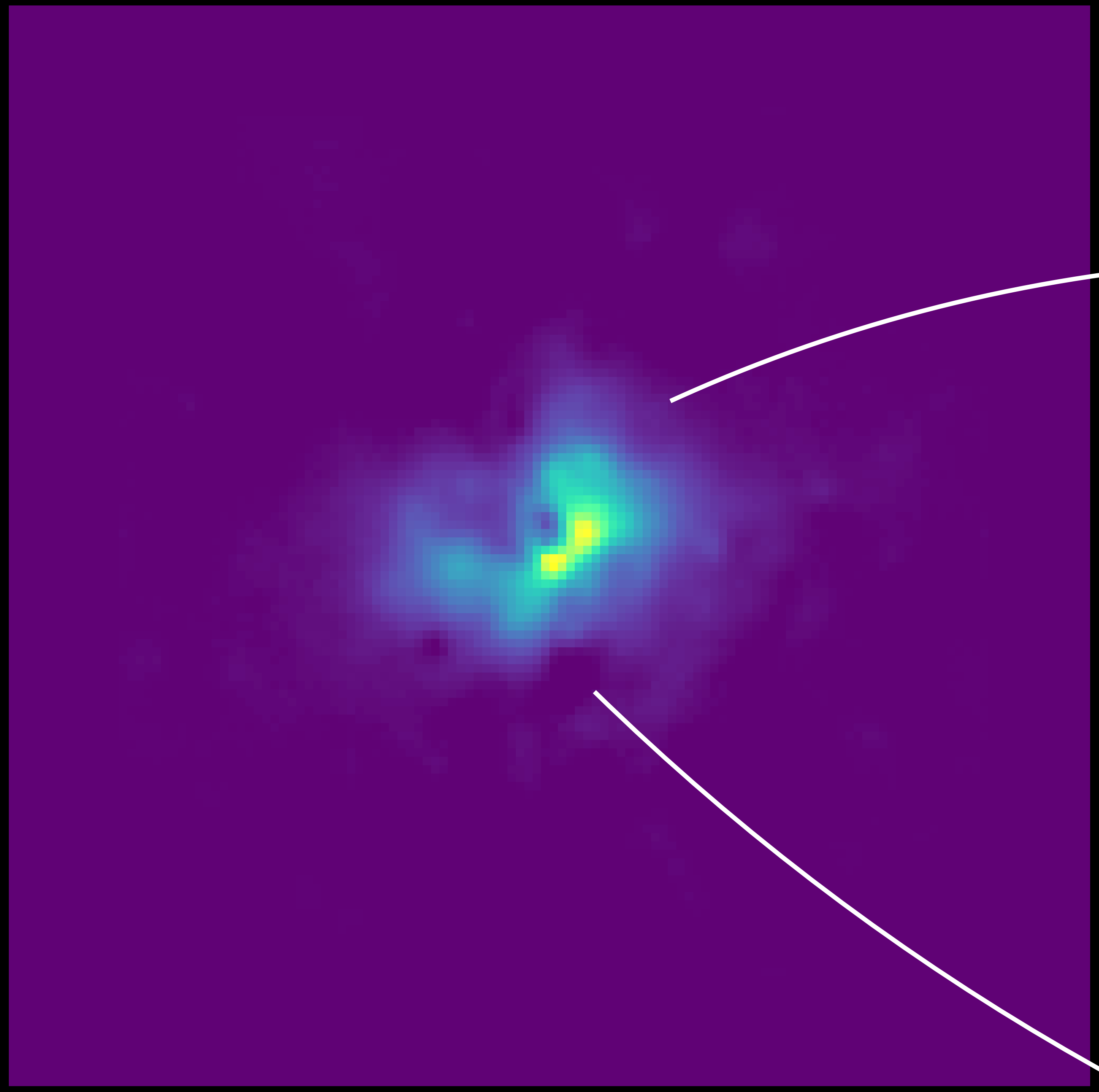
Source galaxy



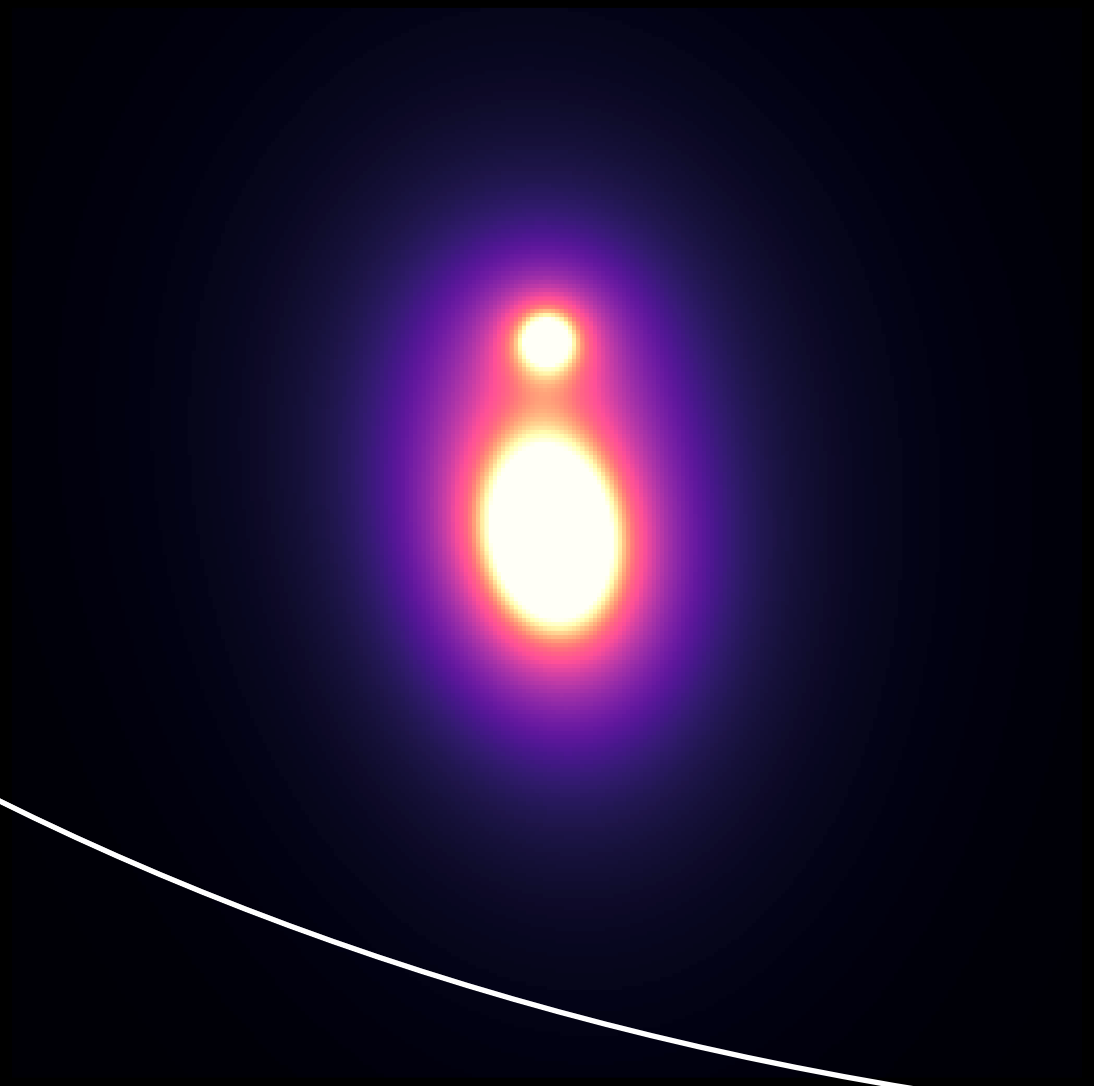
DM halo mass profile

The Likelihood

Strong lensing response



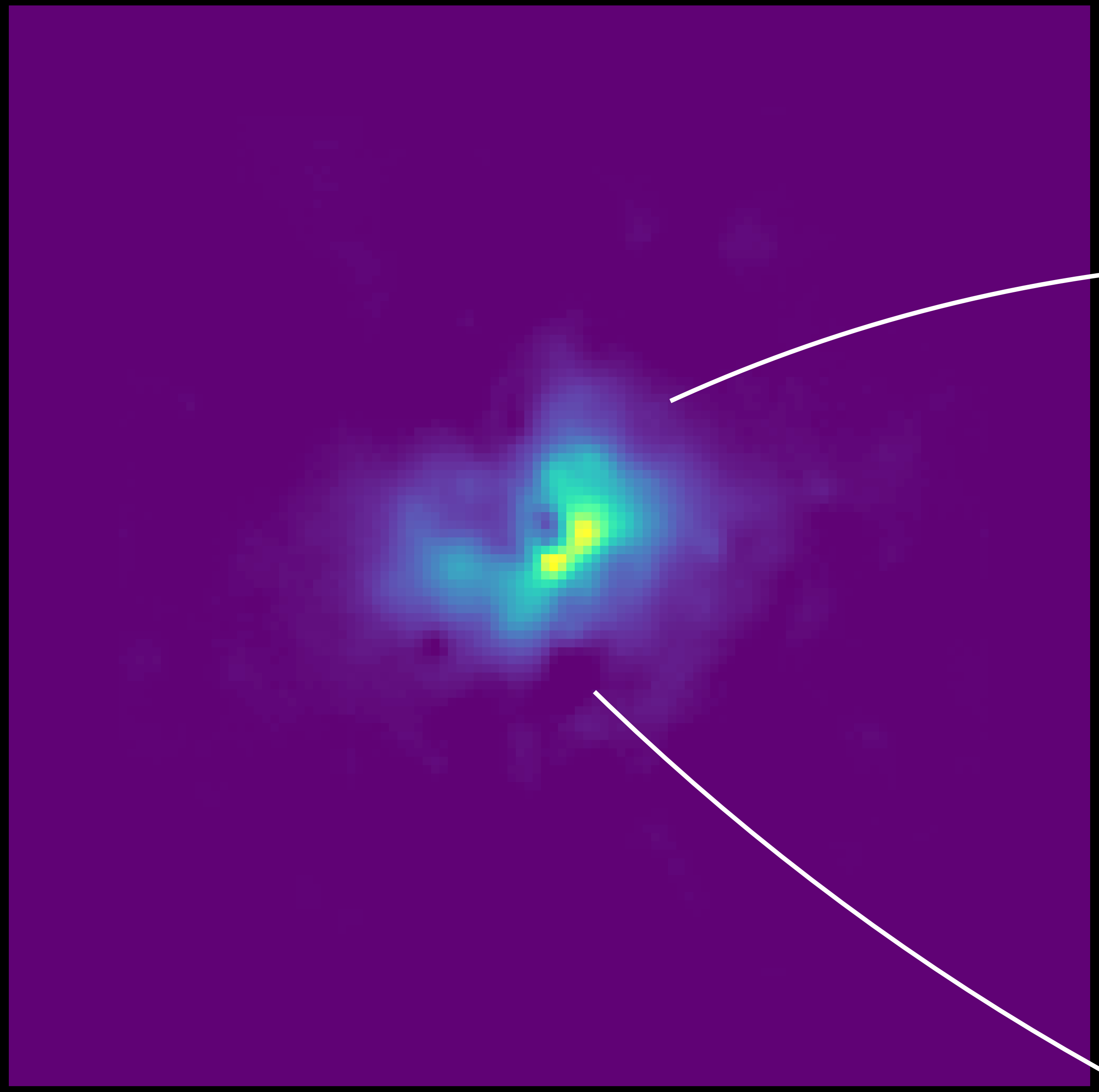
Source galaxy



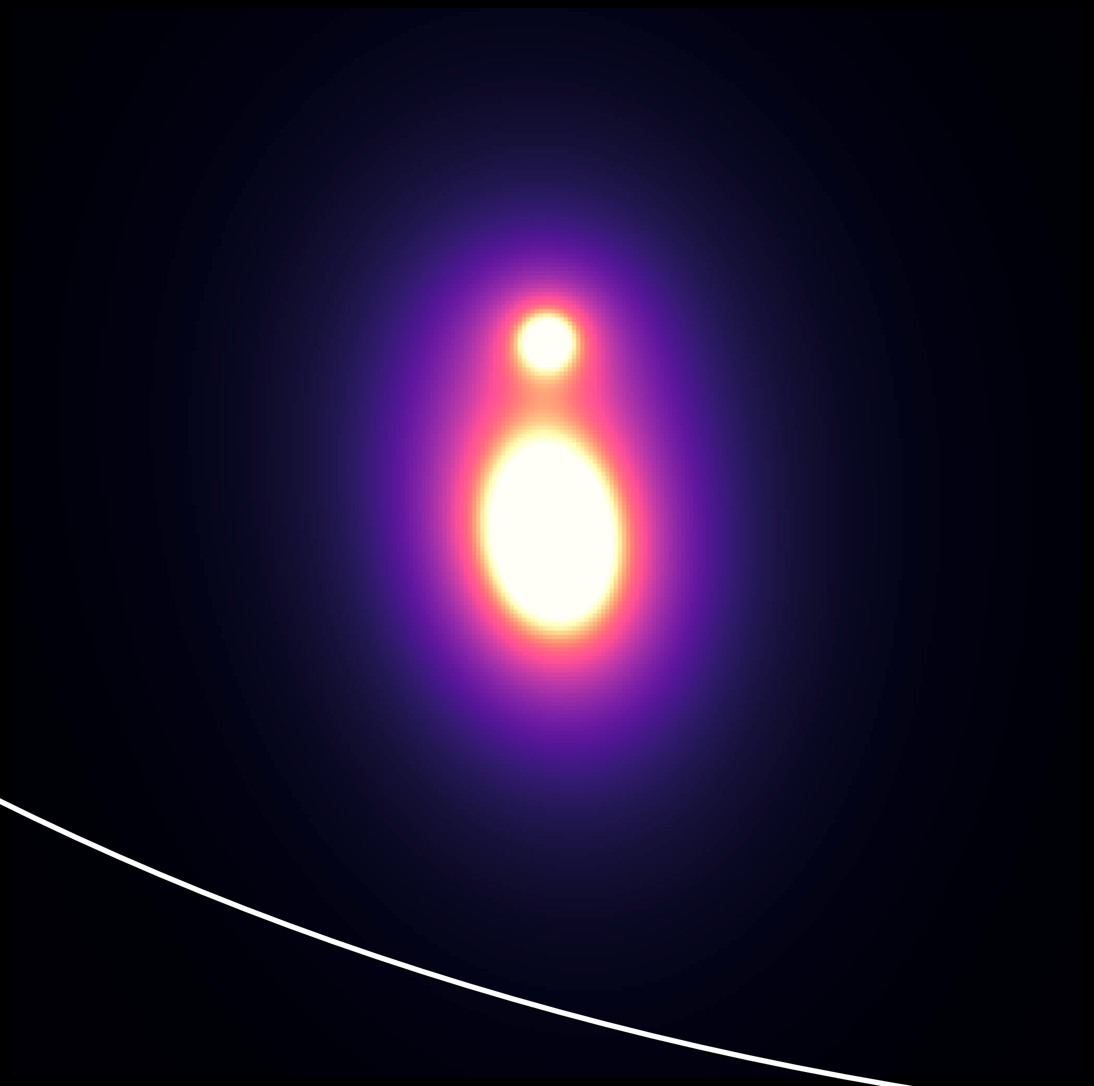
DM halo mass profile

The Likelihood

Strong lensing response



Source galaxy

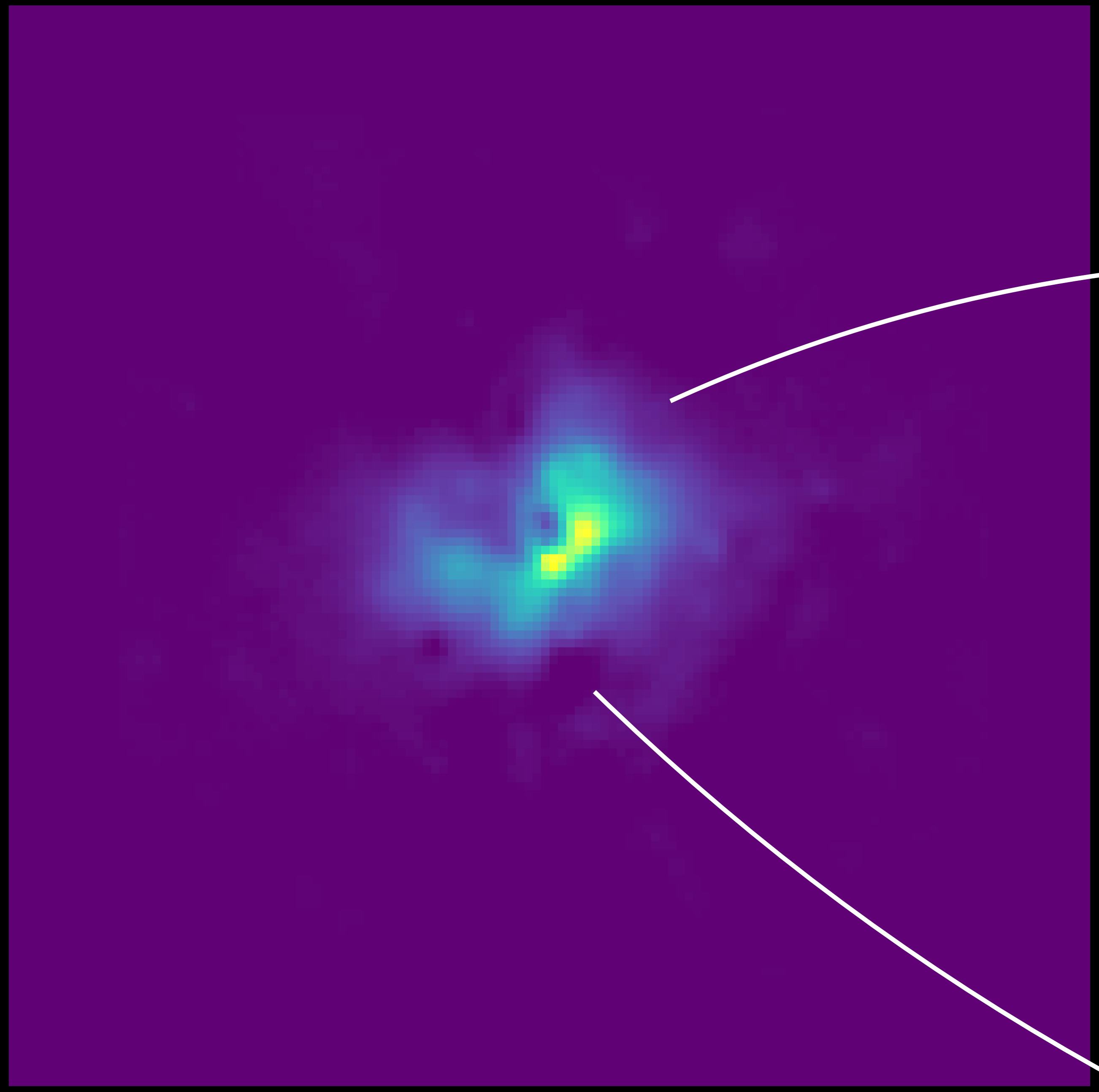


DM halo mass profile

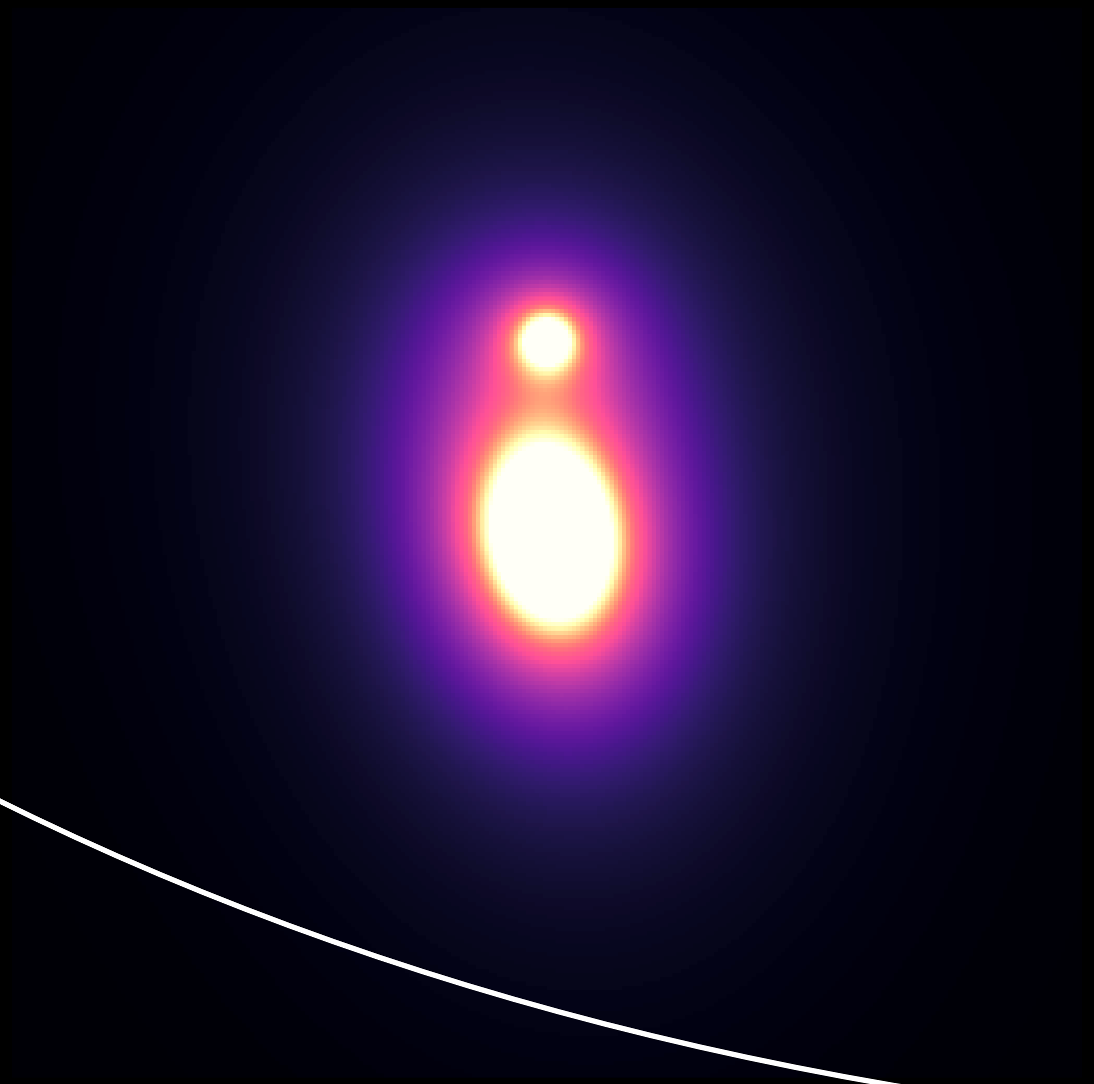
$$\nabla \cdot \kappa = 2\ \alpha$$

The Likelihood

Strong lensing response

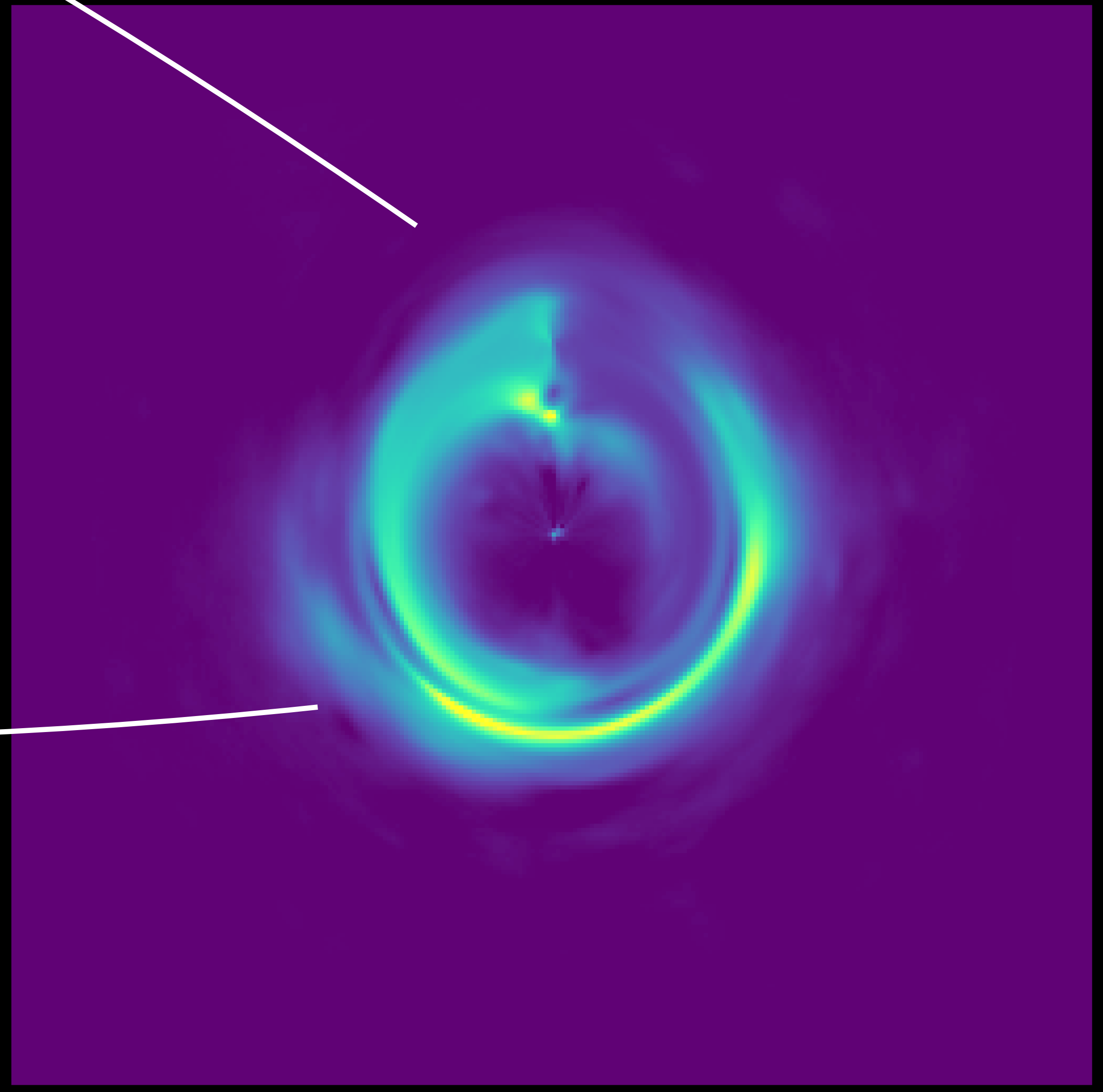


Source galaxy



DM halo mass profile

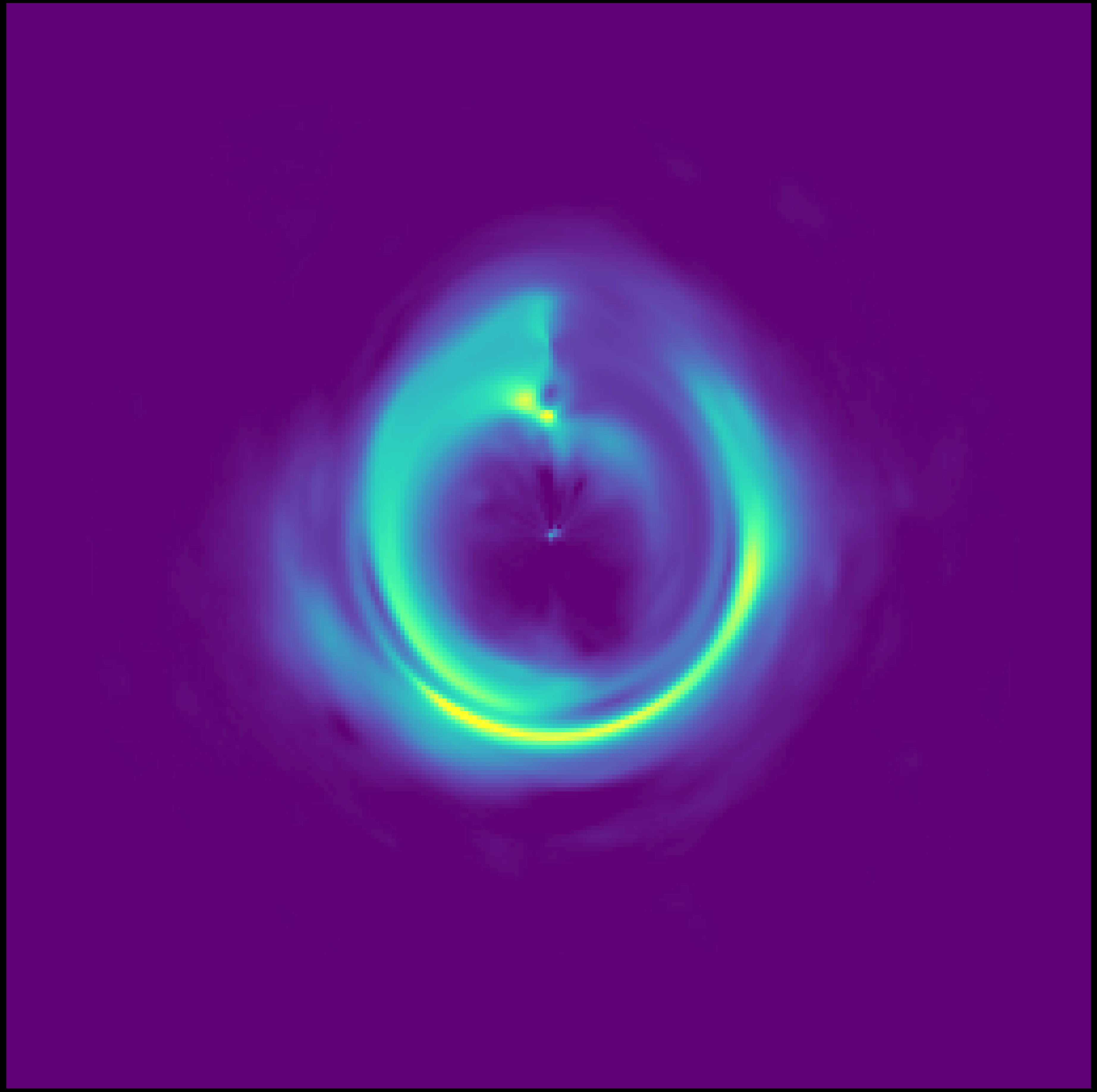
$$\nabla \cdot \kappa = 2\ \alpha$$



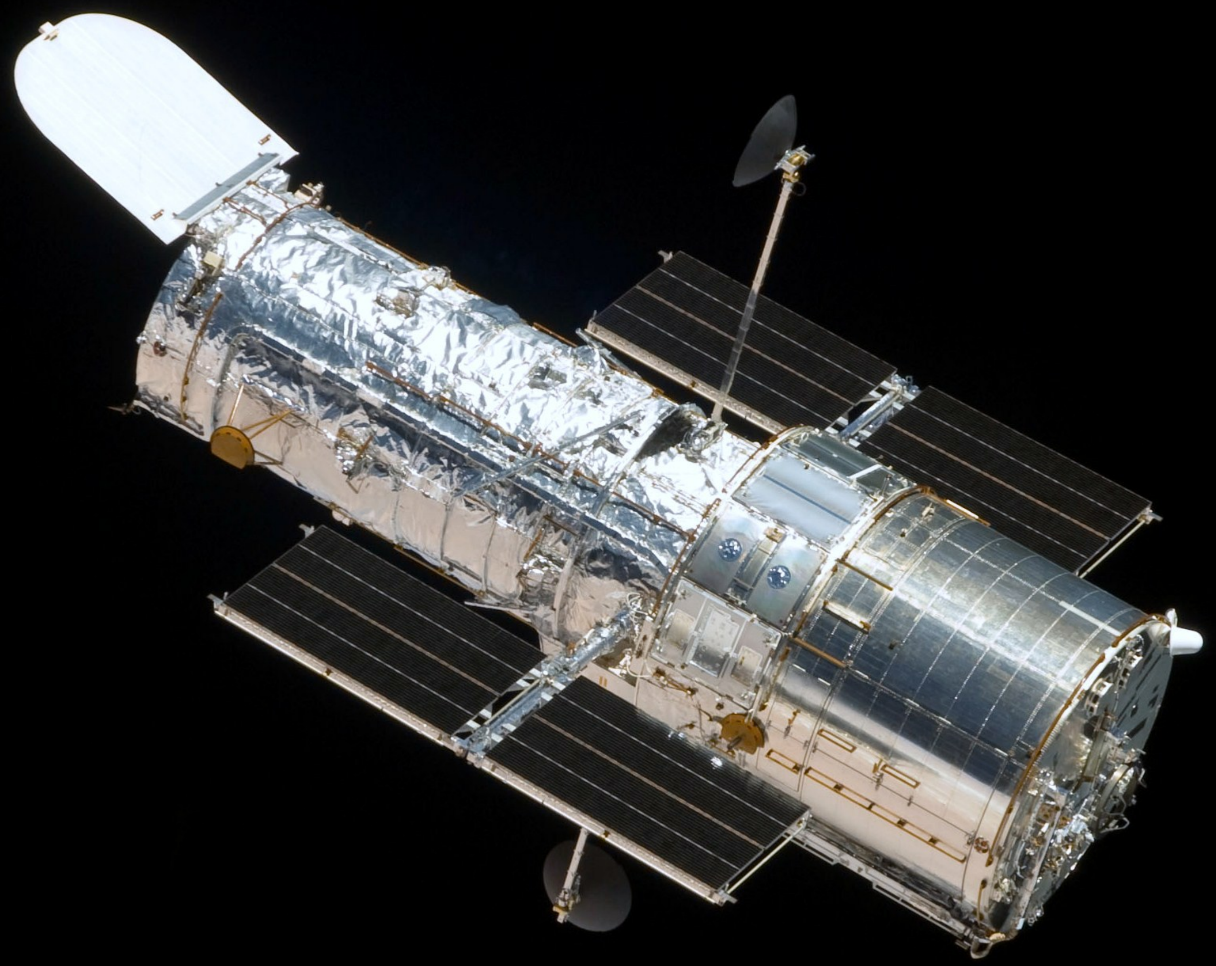
$$y = x - \alpha(x)$$

The Likelihood

Instrument response



Lensed galaxy signal

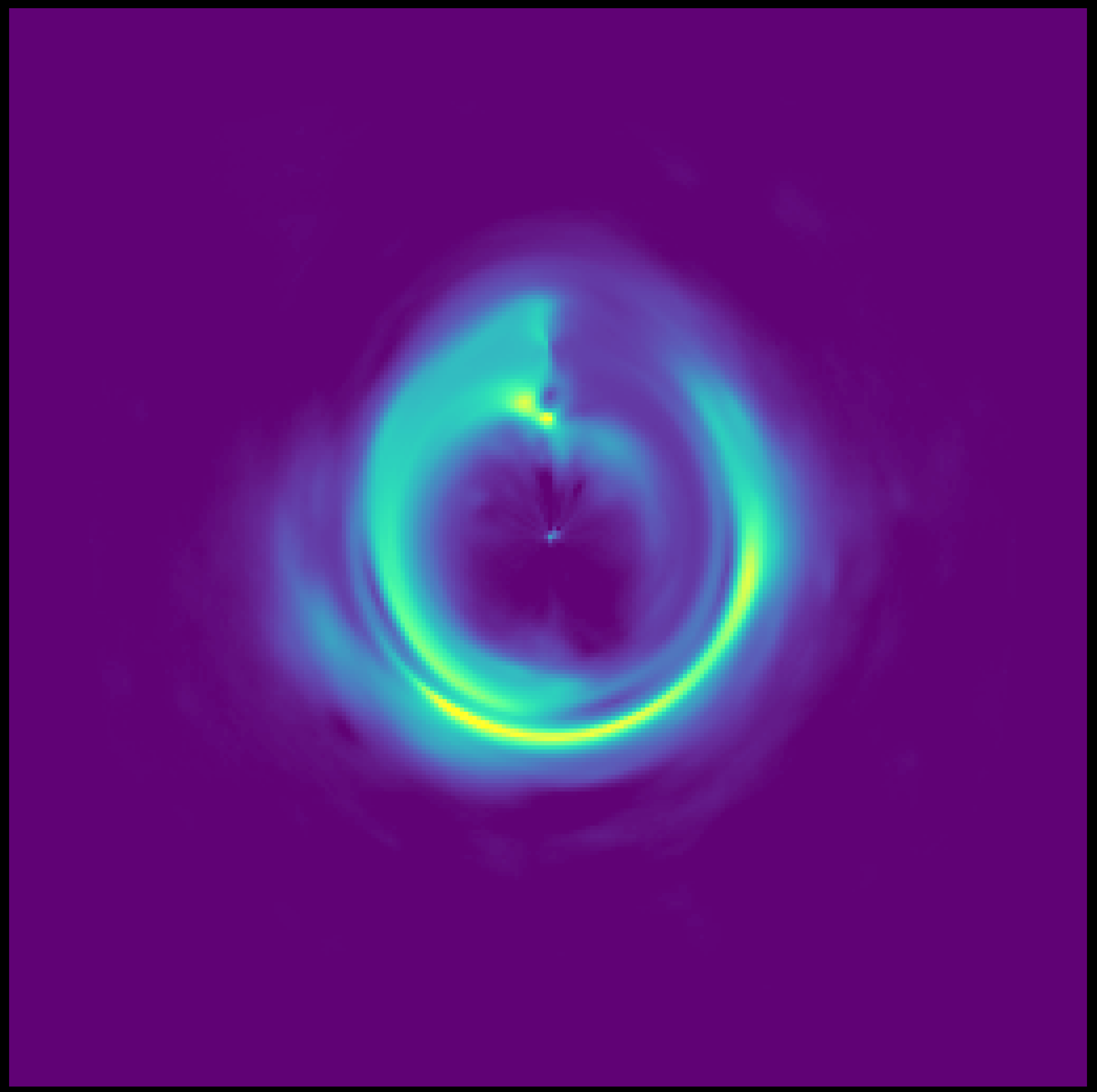


Hubble Space Telescope

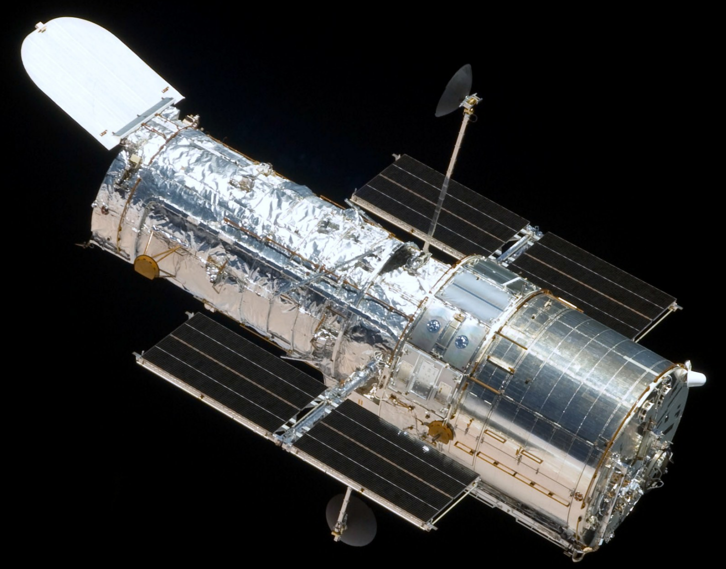
Credits @ Ruffnax (Crew of STS-125)

The Likelihood

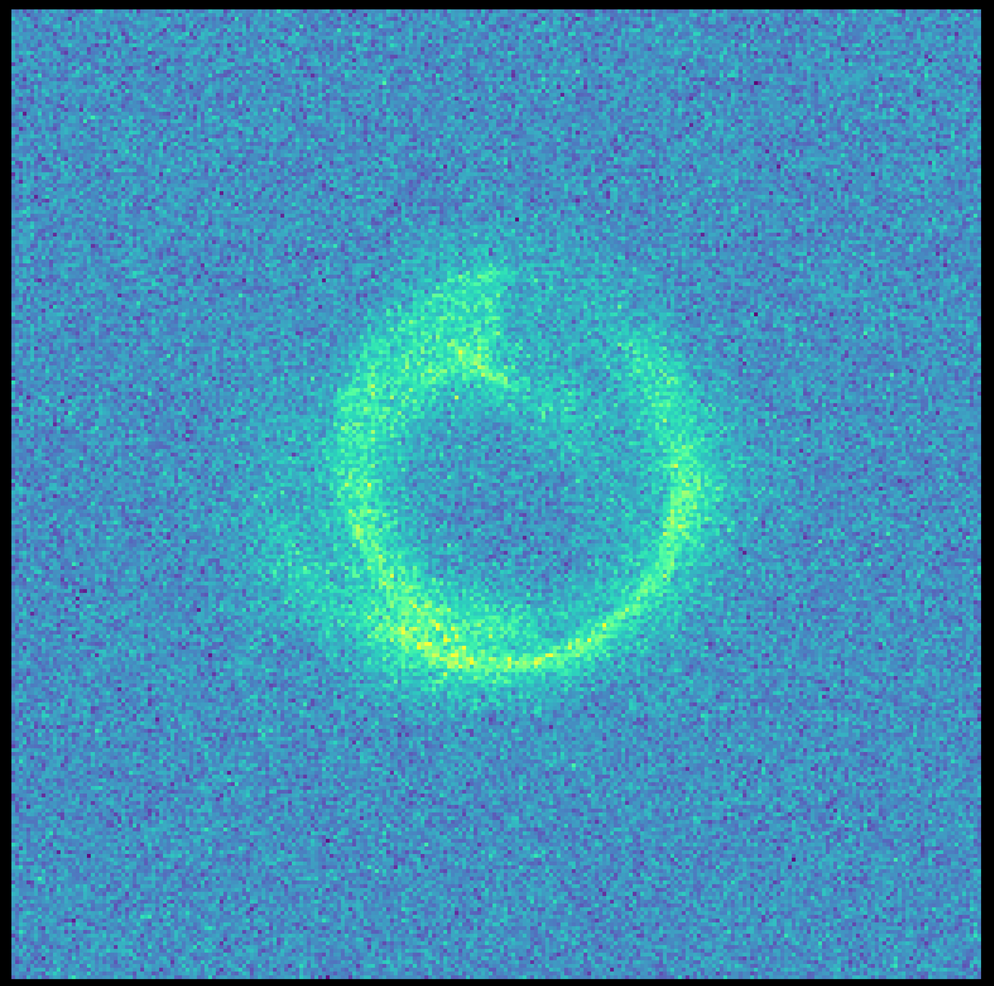
Instrument response



Lensed galaxy signal



Hubble Space Telescope

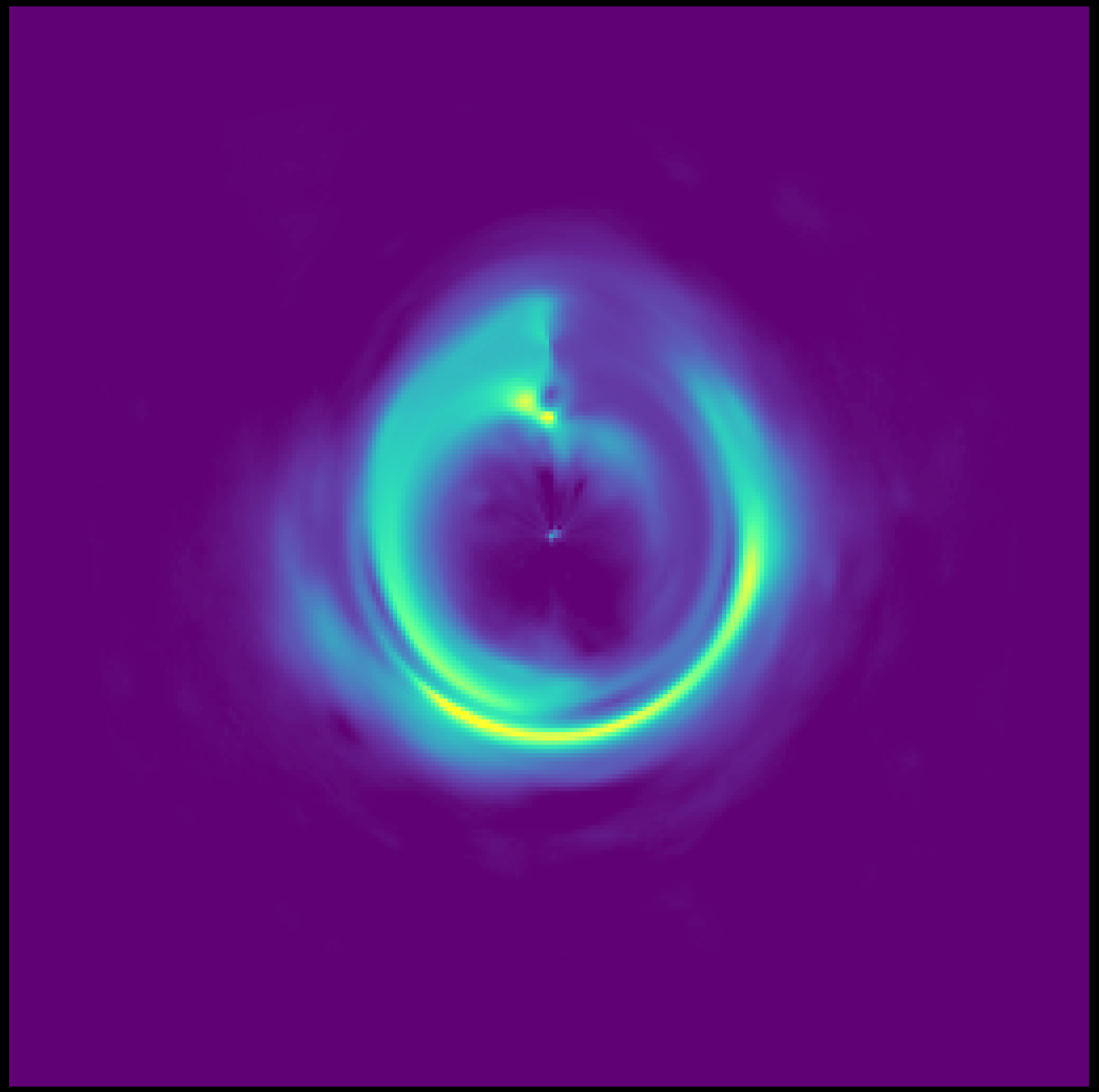


Data on Earth

Credits @ Ruffnax (Crew of STS-125)

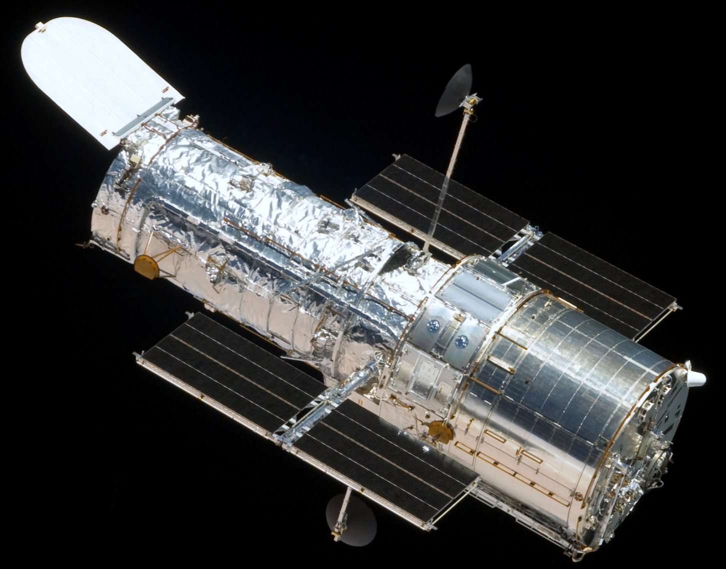
The Likelihood

Instrument response



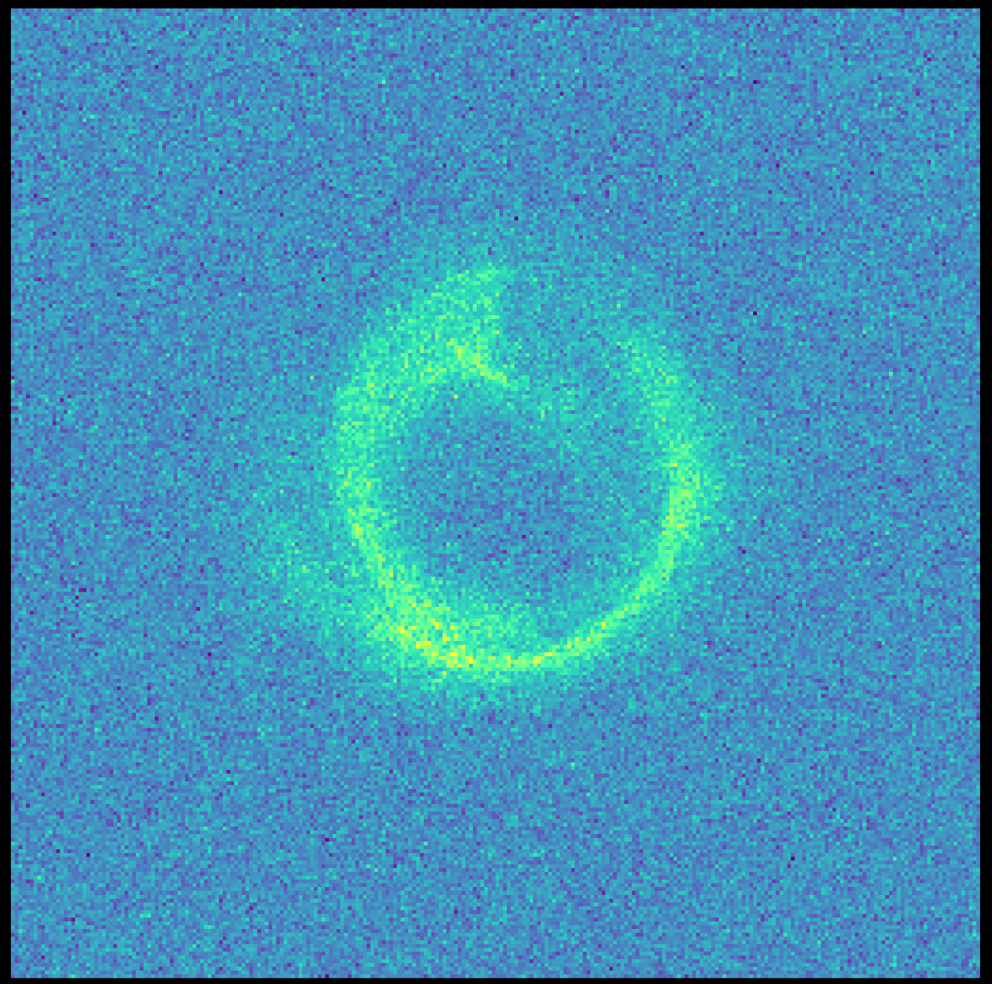
Lensed galaxy signal

$$L(s)$$



Hubble Space Telescope

$$RL(s)$$



Data on Earth

$$P(d\,|\,s) = \mathcal{G}(RL(s) - d,\, \sigma_h)$$

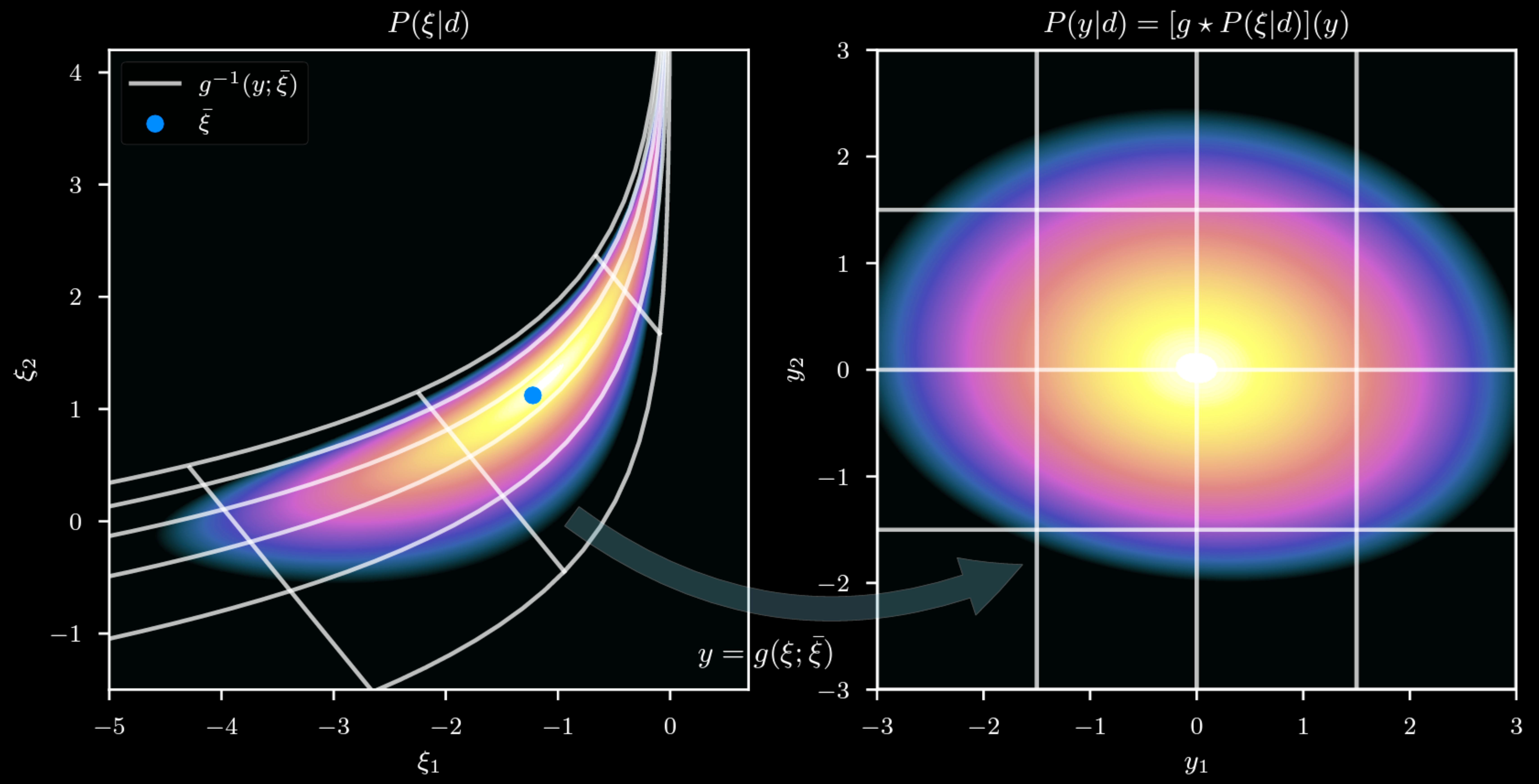
Credits @ Ruffnax (Crew of STS-125)

The Posterior

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

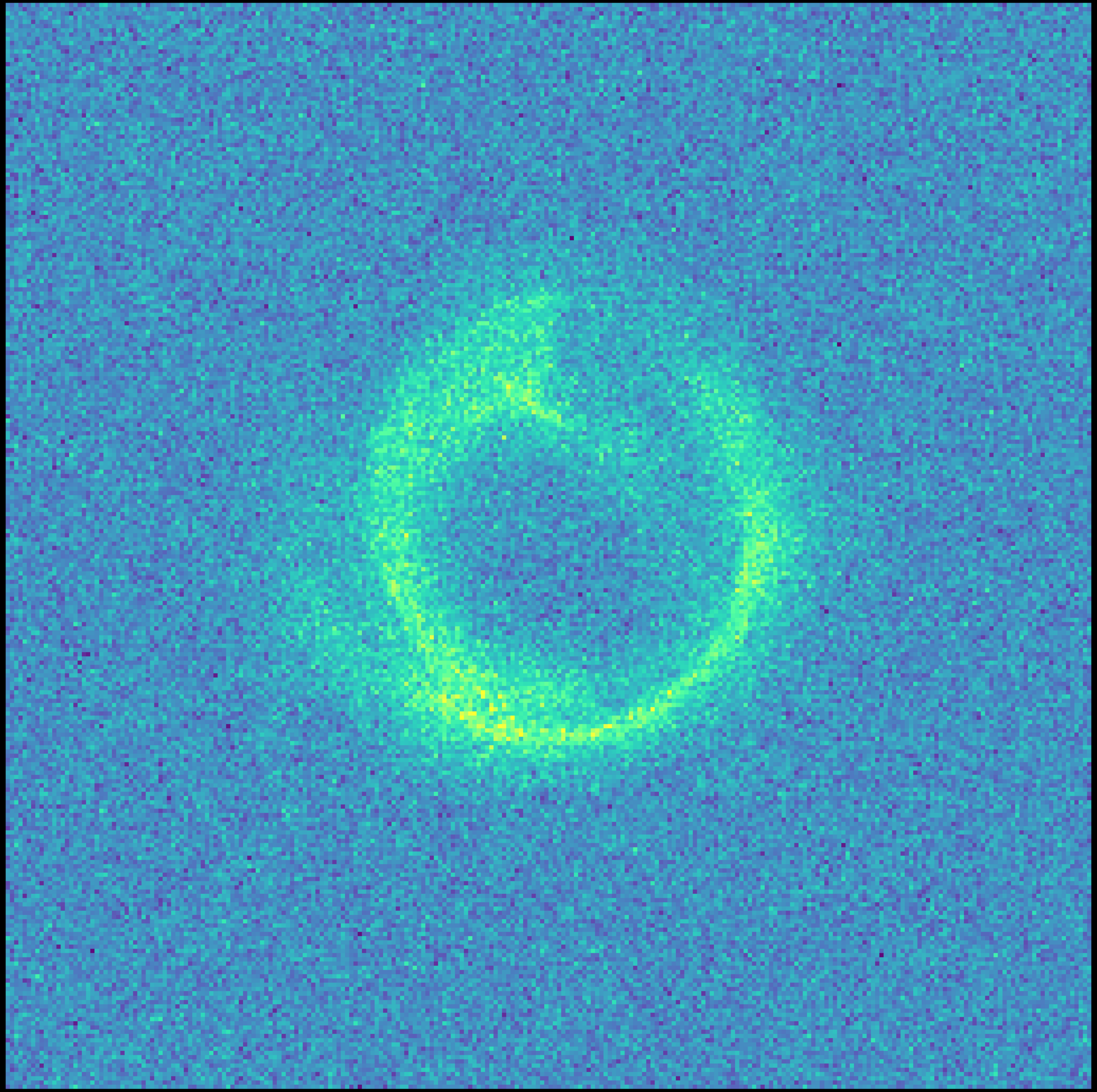
Inference

geometric Variational Inference



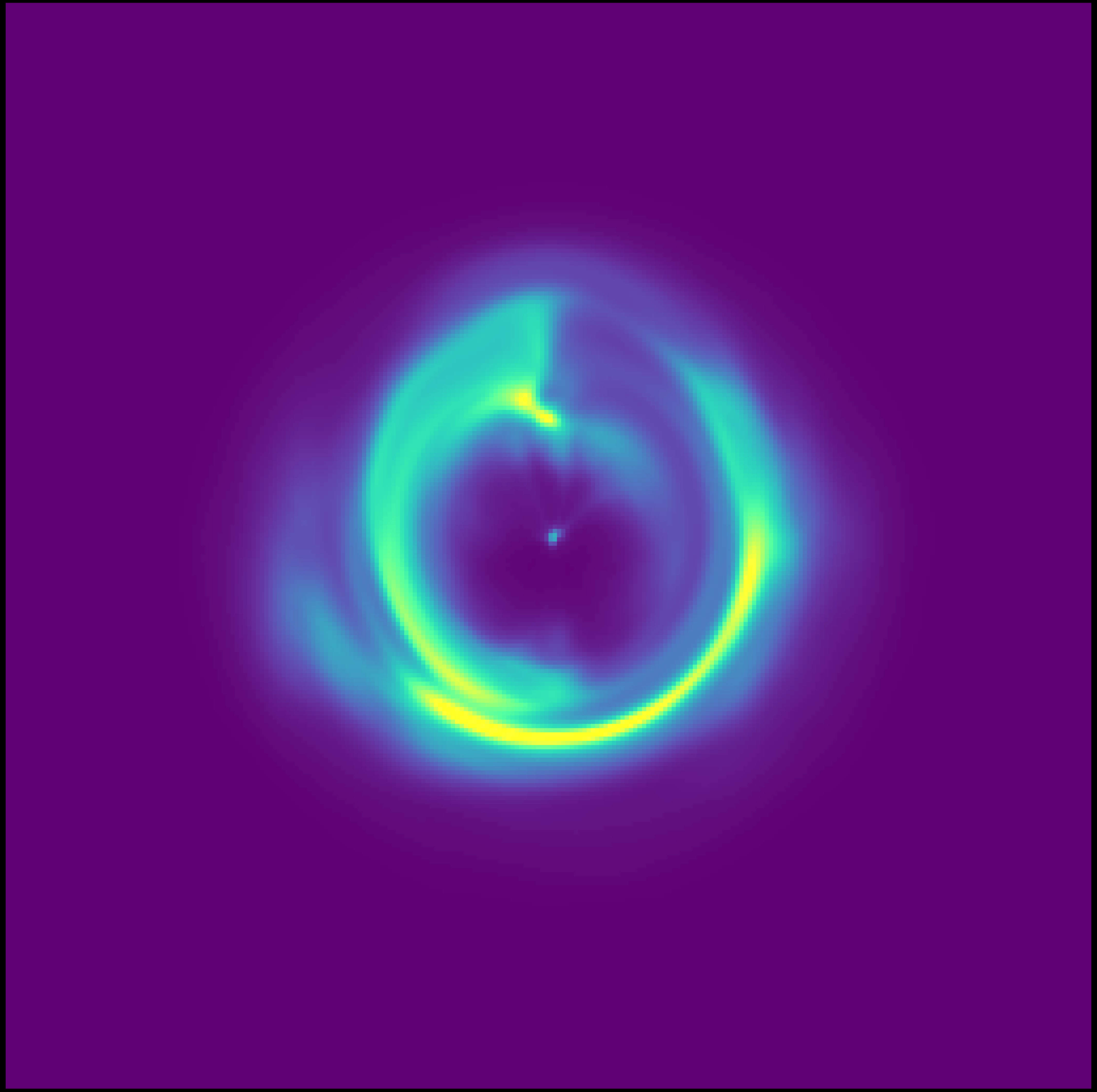
Credits @ Frank, P.; Leike, R.; Enßlin, T.A. Geometric Variational Inference. *Entropy* **2021**, *23*, 853.

The Data



Simulated HST data

The Reconstruction

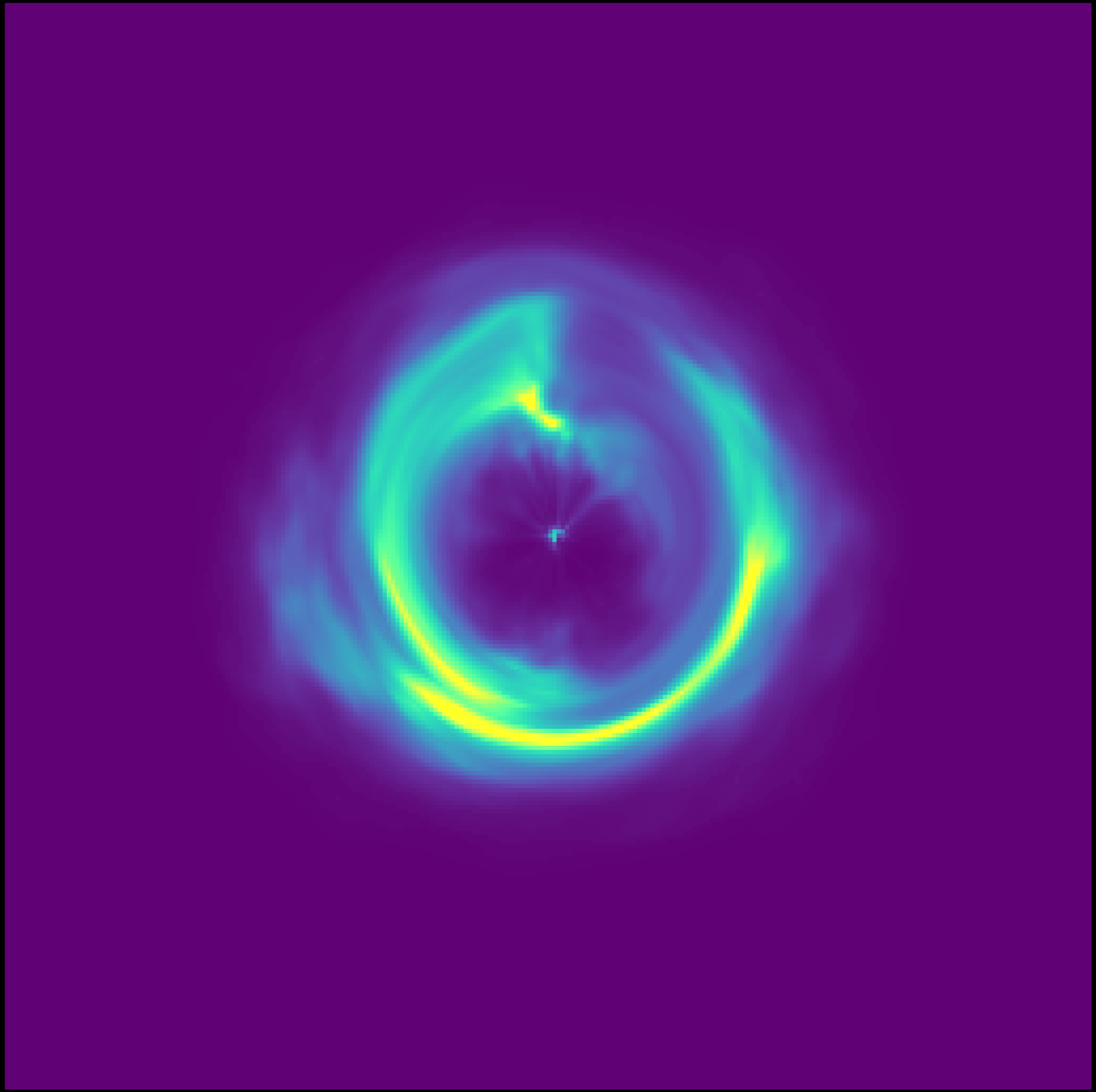


Lensed source light

Inference

Posterior (Ls)

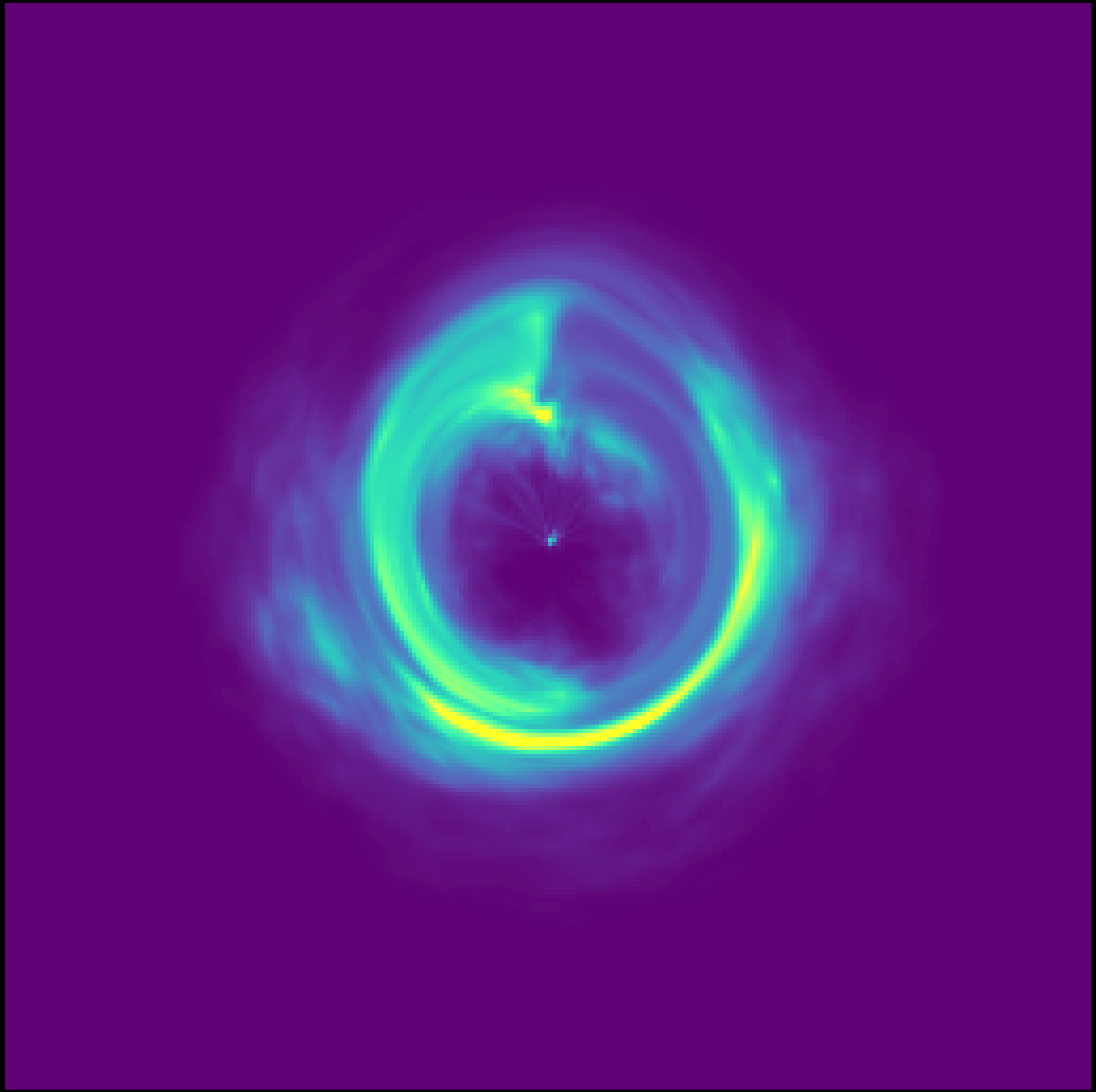
$$P(s\,|\,d)$$



Inference

Posterior (Ls)

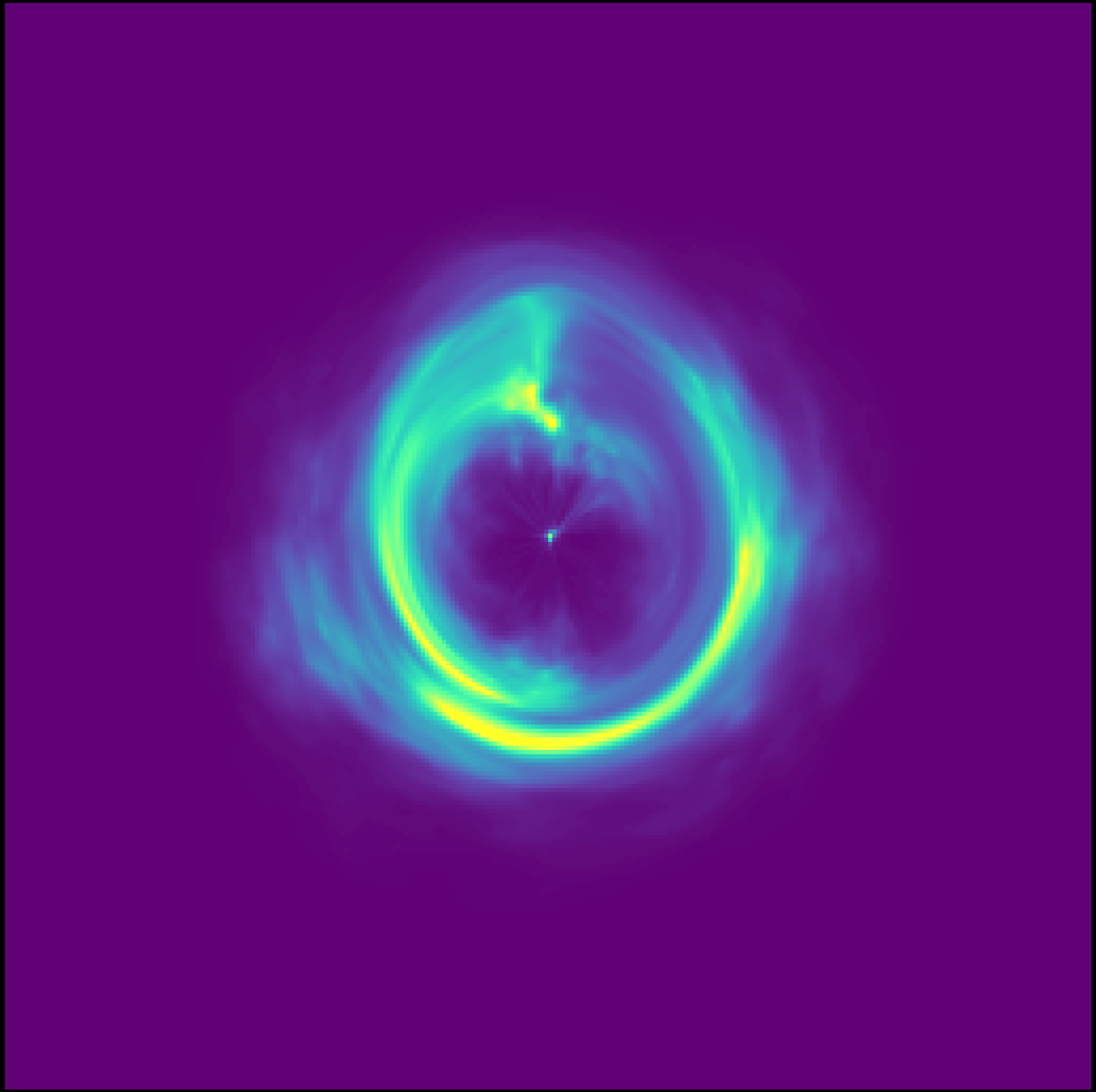
$$P(s \mid d)$$



Inference

Posterior (Ls)

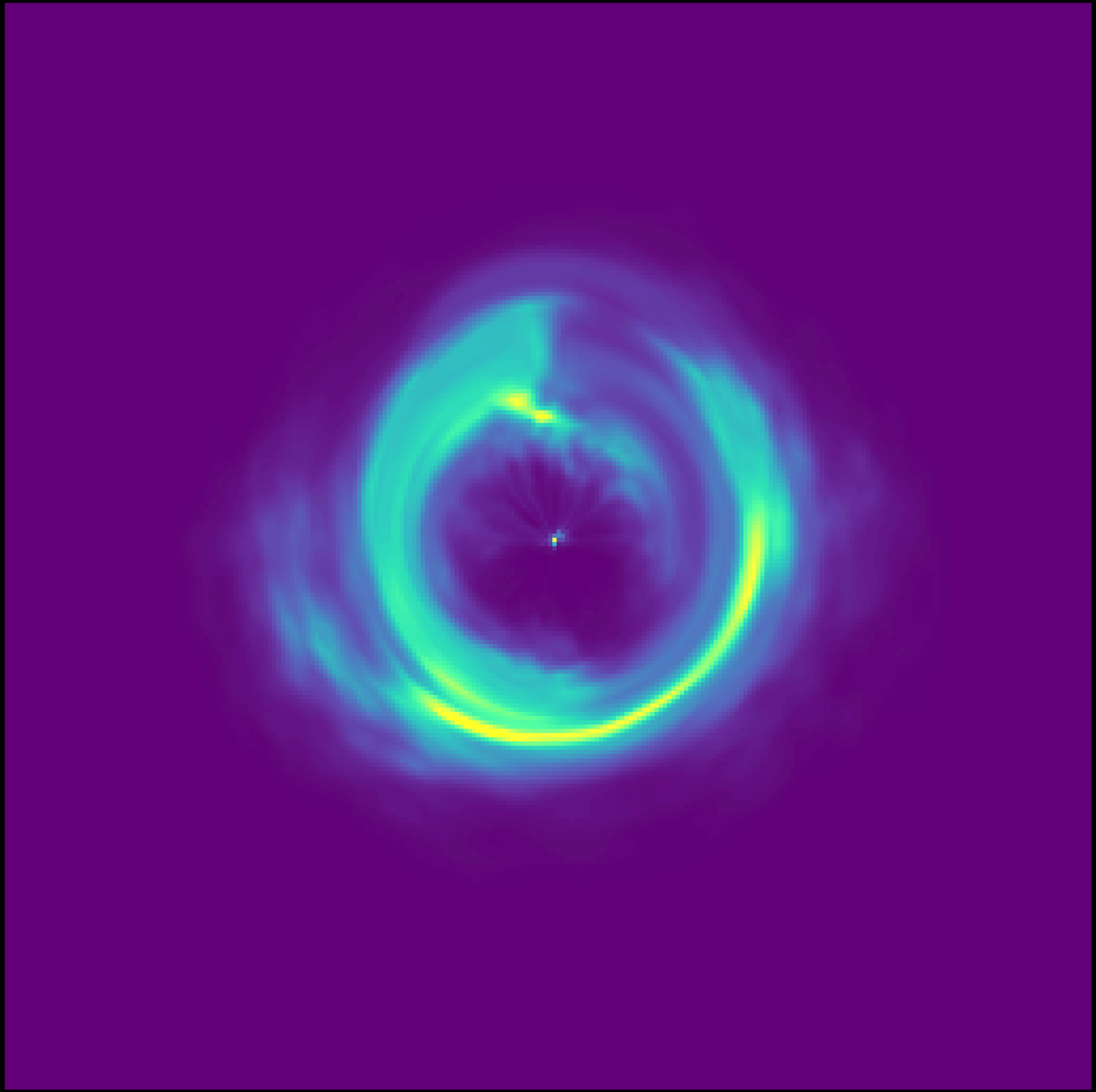
$$P(s \mid d)$$



Inference

Posterior (Ls)

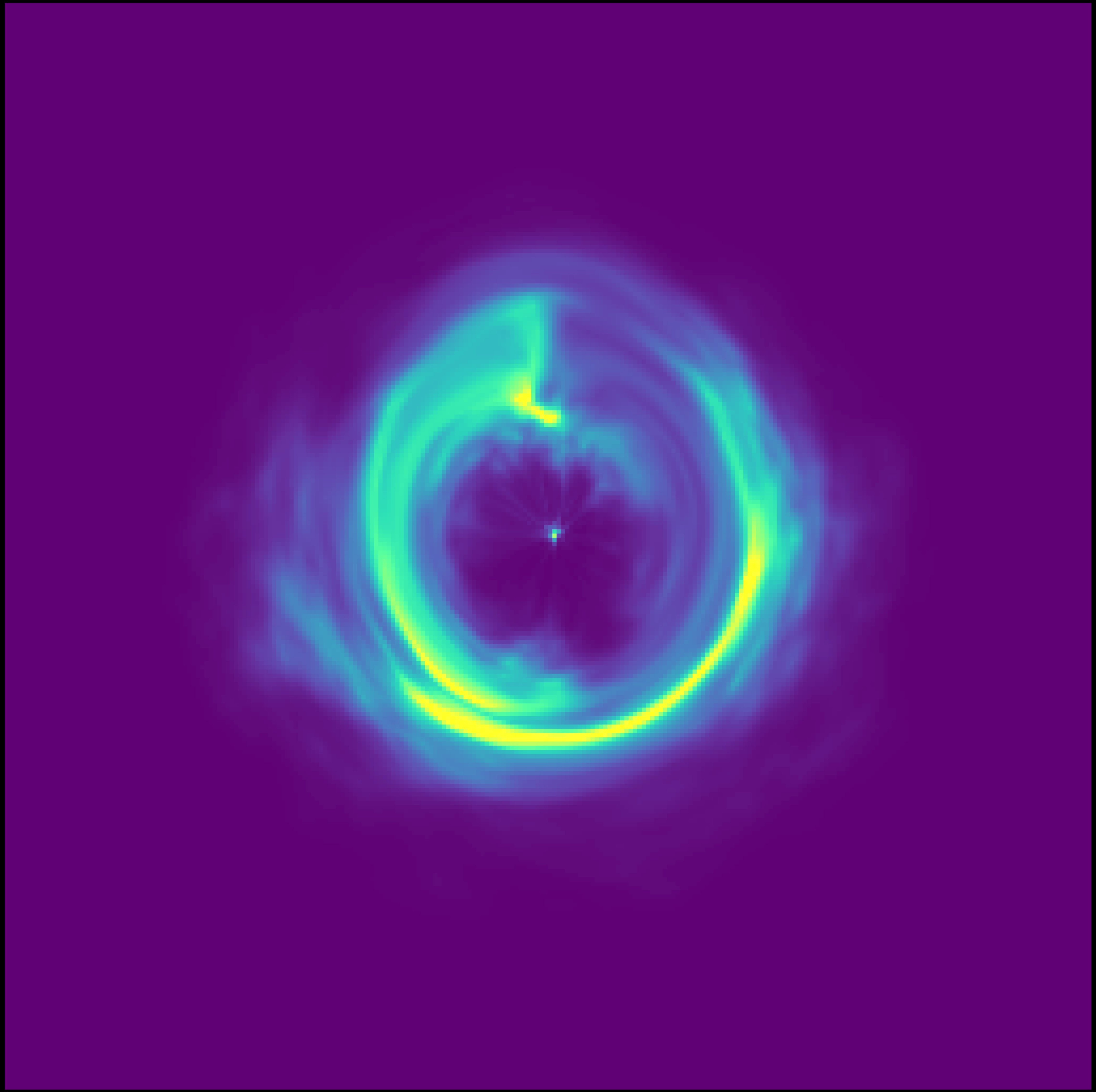
$$P(s \mid d)$$



Inference

Posterior (Ls)

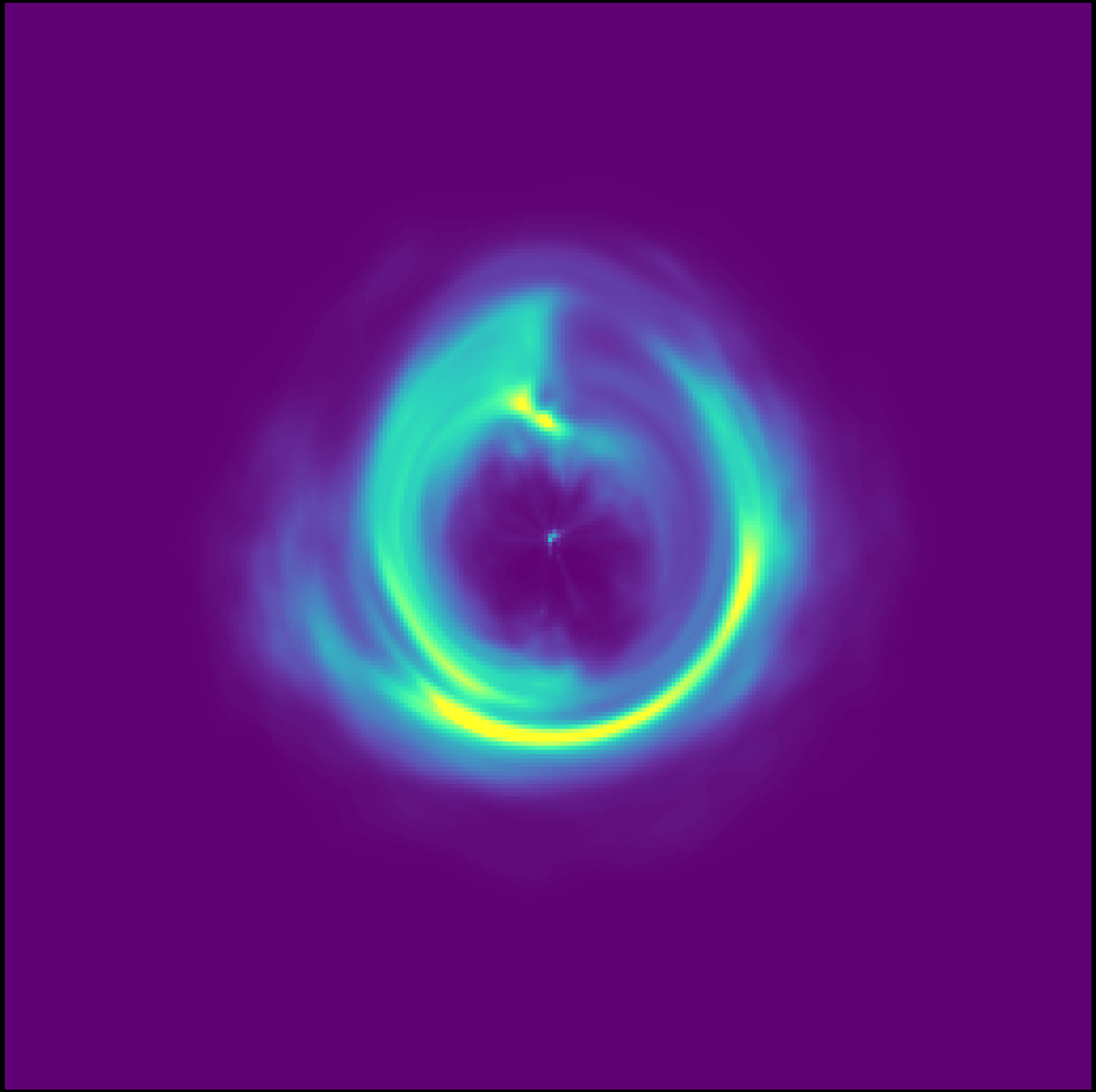
$$P(s \mid d)$$



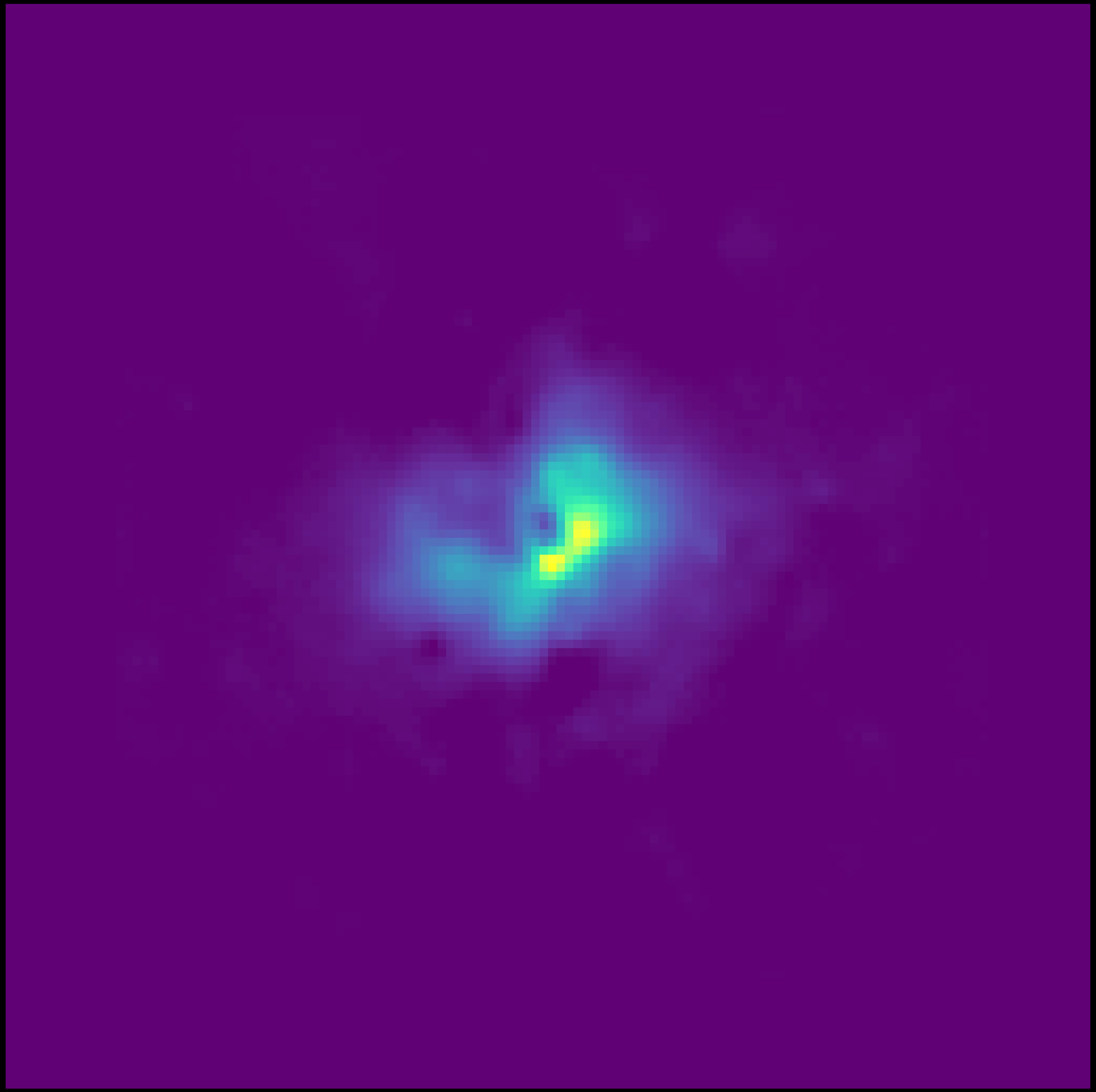
Inference

Posterior (Ls)

$$P(s \mid d)$$

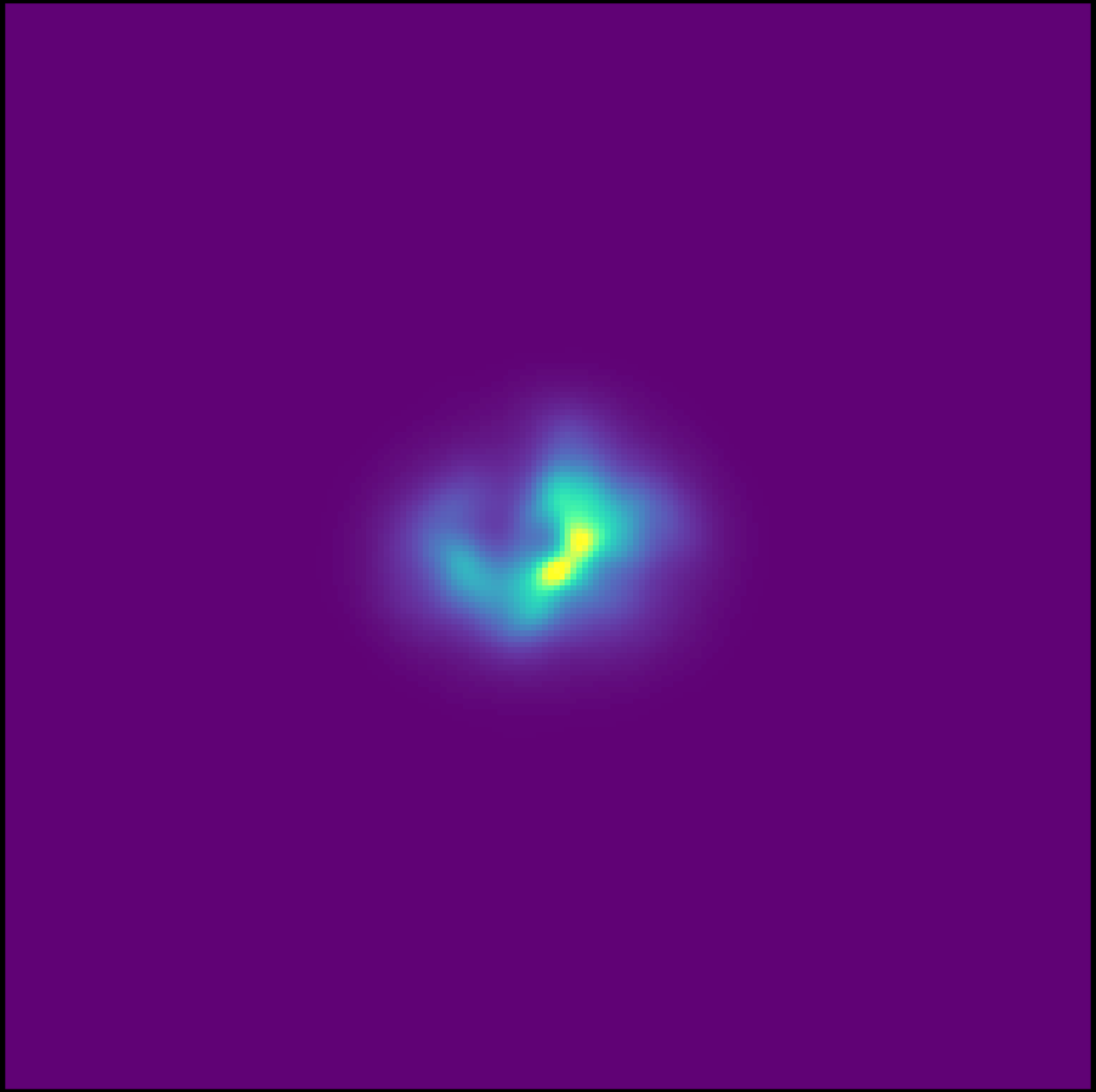


The Source



Ground truth

The Source

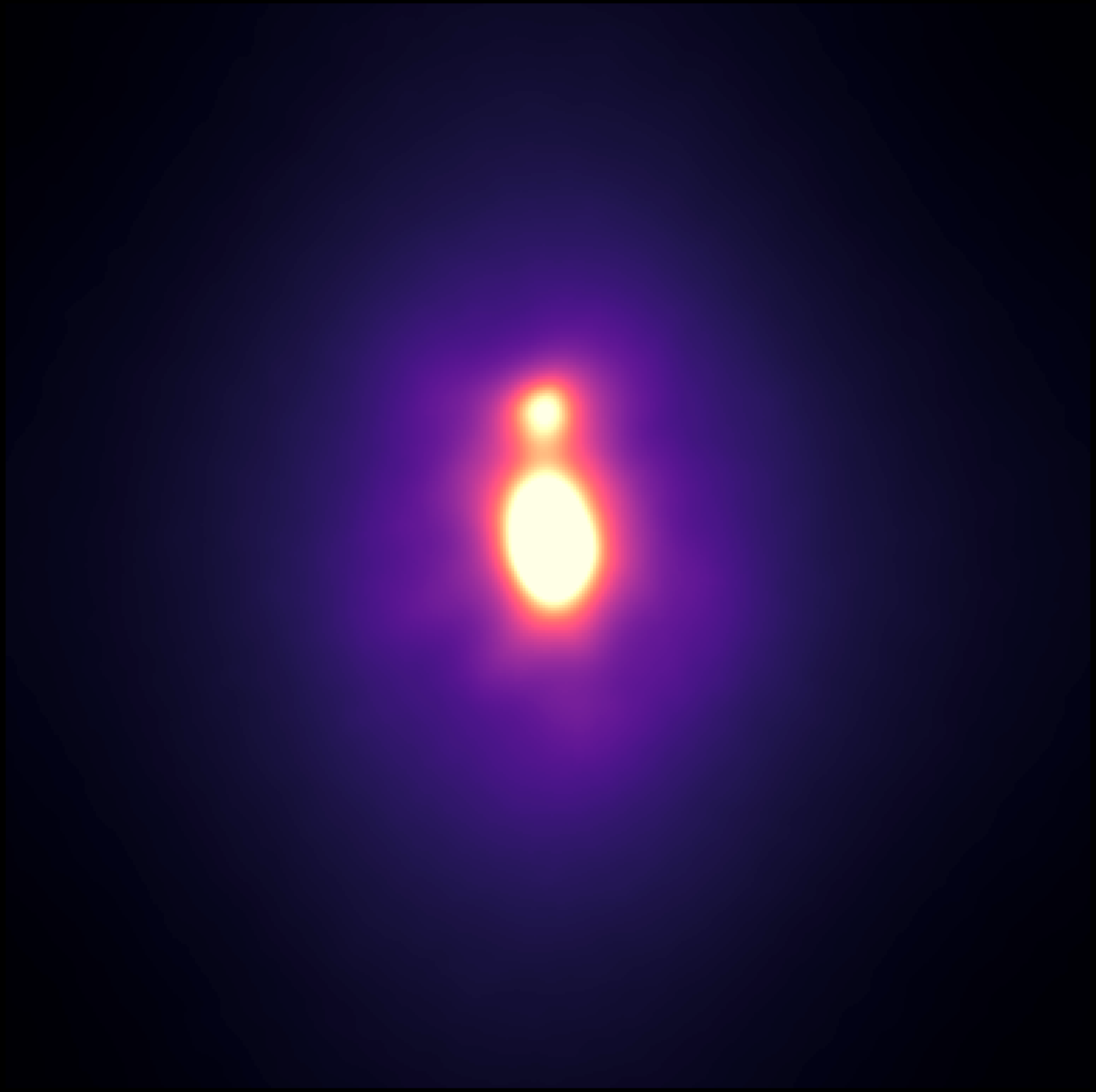


Posterior mean

The Convergence

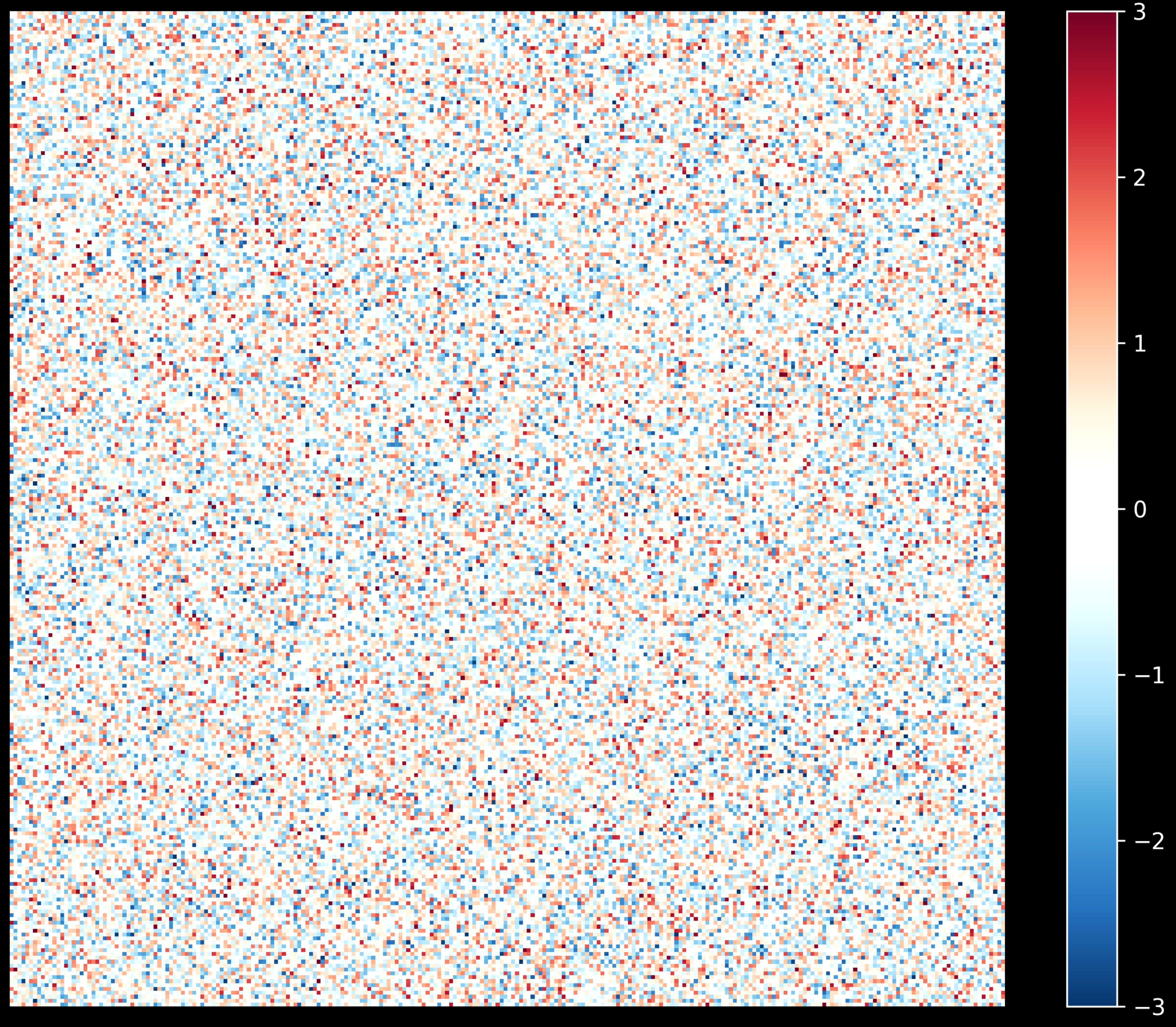
Ground truth mass distribution

The Reconstruction



Reconstructed projected mass distribution

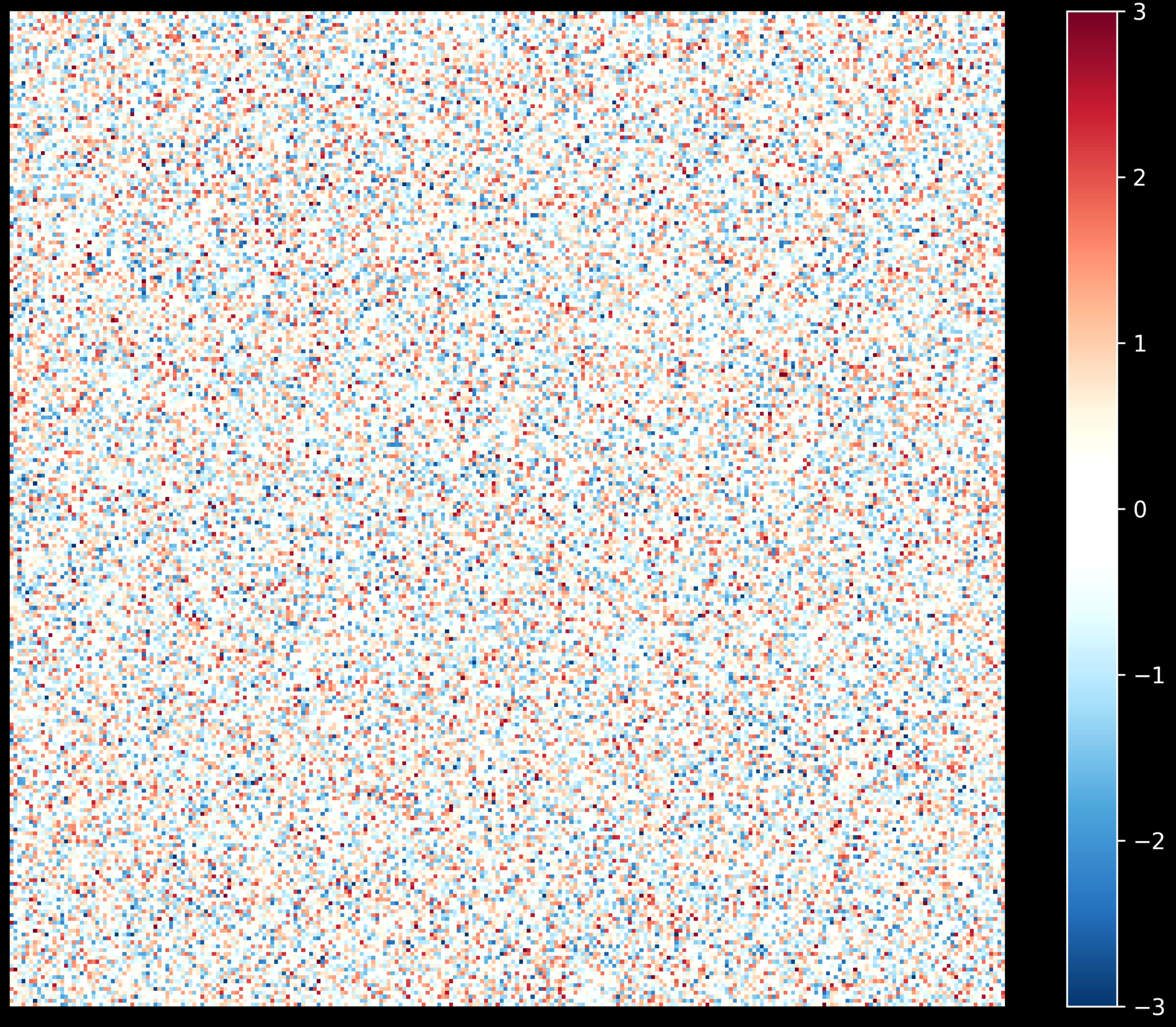
Take home



Lensed light noise-weighted residuals

Take home

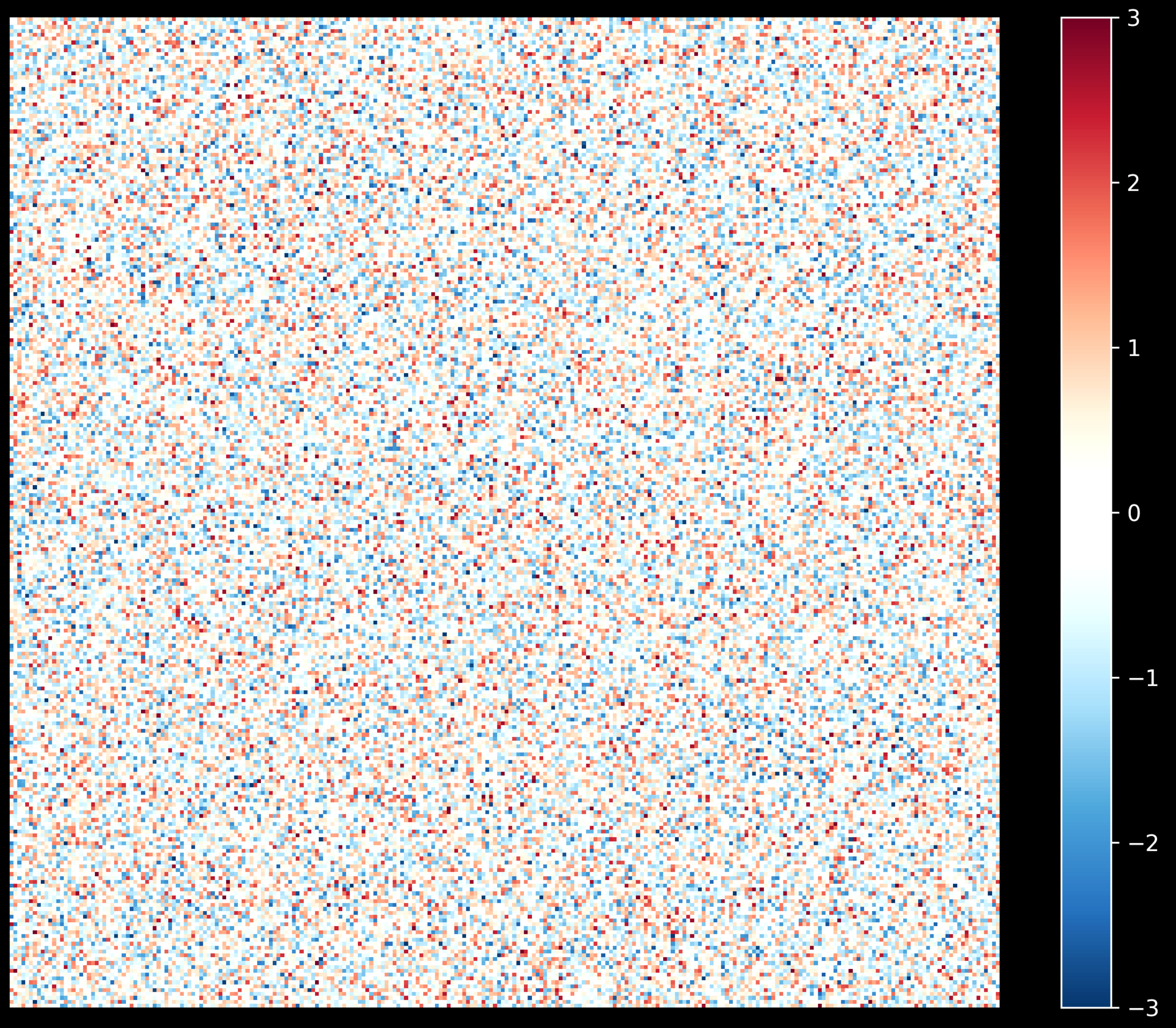
- Flexible source brightness distribution models



Lensed light noise-weighted residuals

Take home

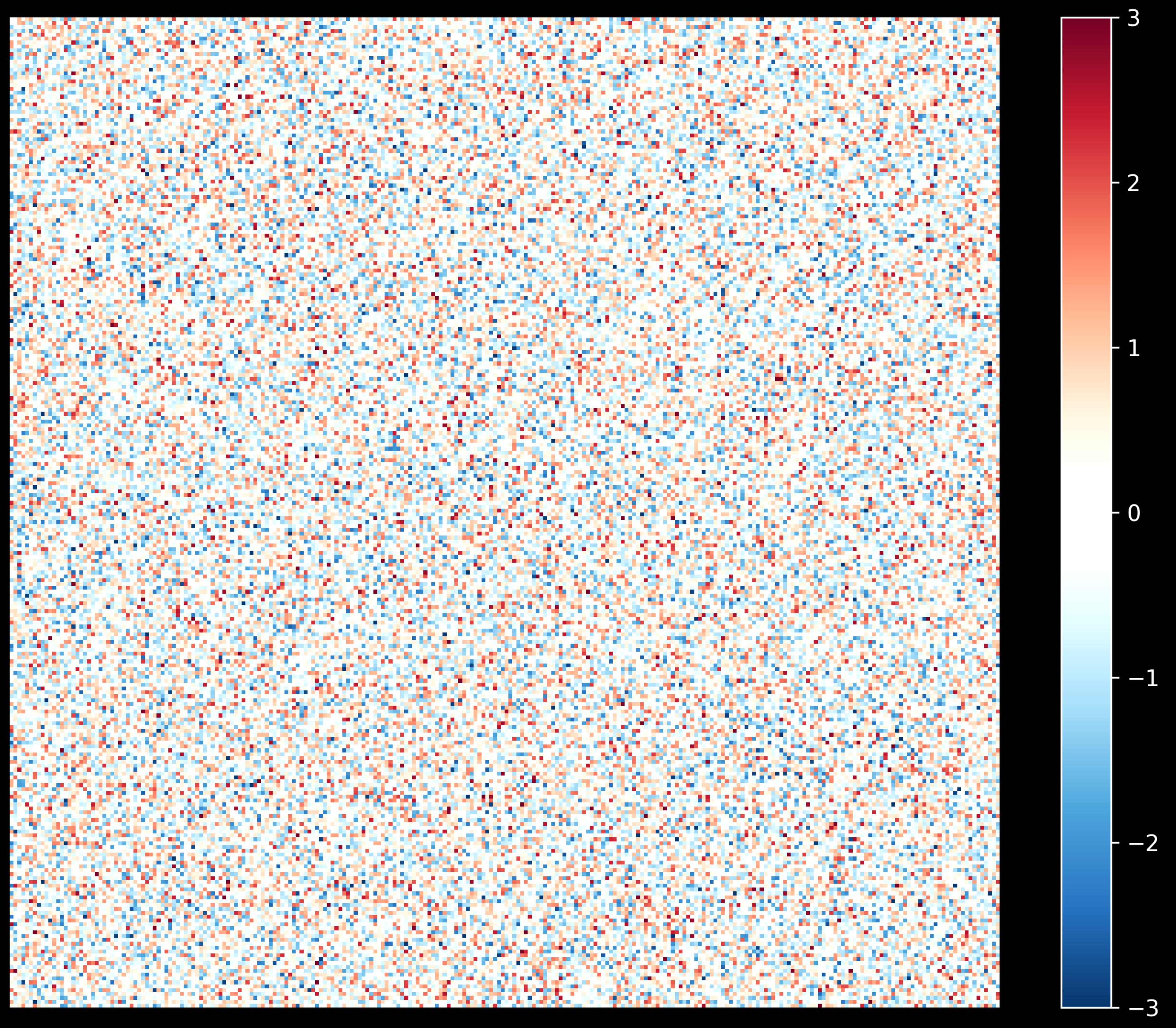
- Flexible source brightness distribution models
- Flexible mass distribution models



Lensed light noise-weighted residuals

Take home

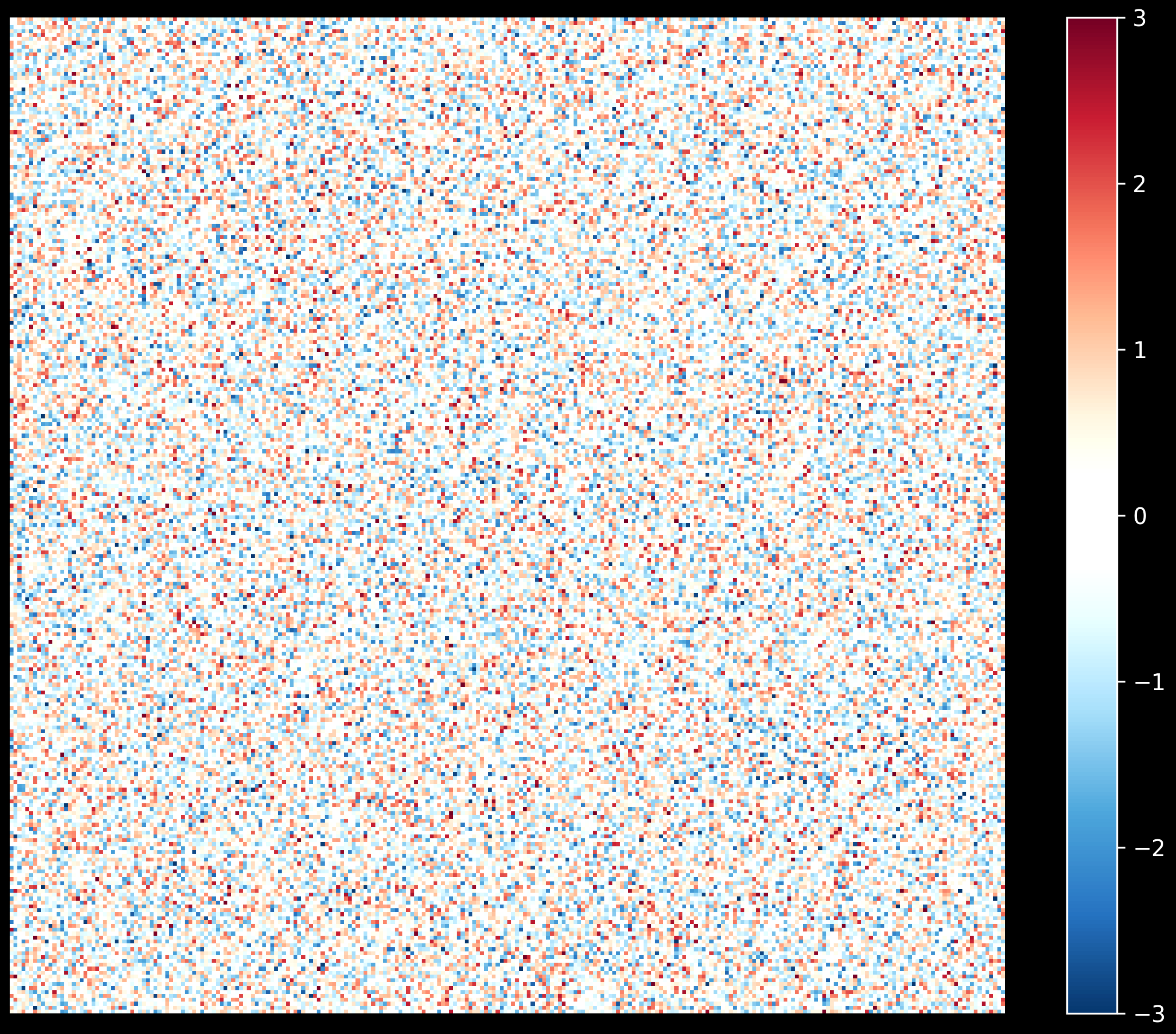
- Flexible source brightness distribution models
- Flexible mass distribution models
- Instrumental effects



Lensed light noise-weighted residuals

Take home

- Flexible source brightness distribution models
- Flexible mass distribution models
- Instrumental effects
- Uncertainty estimates

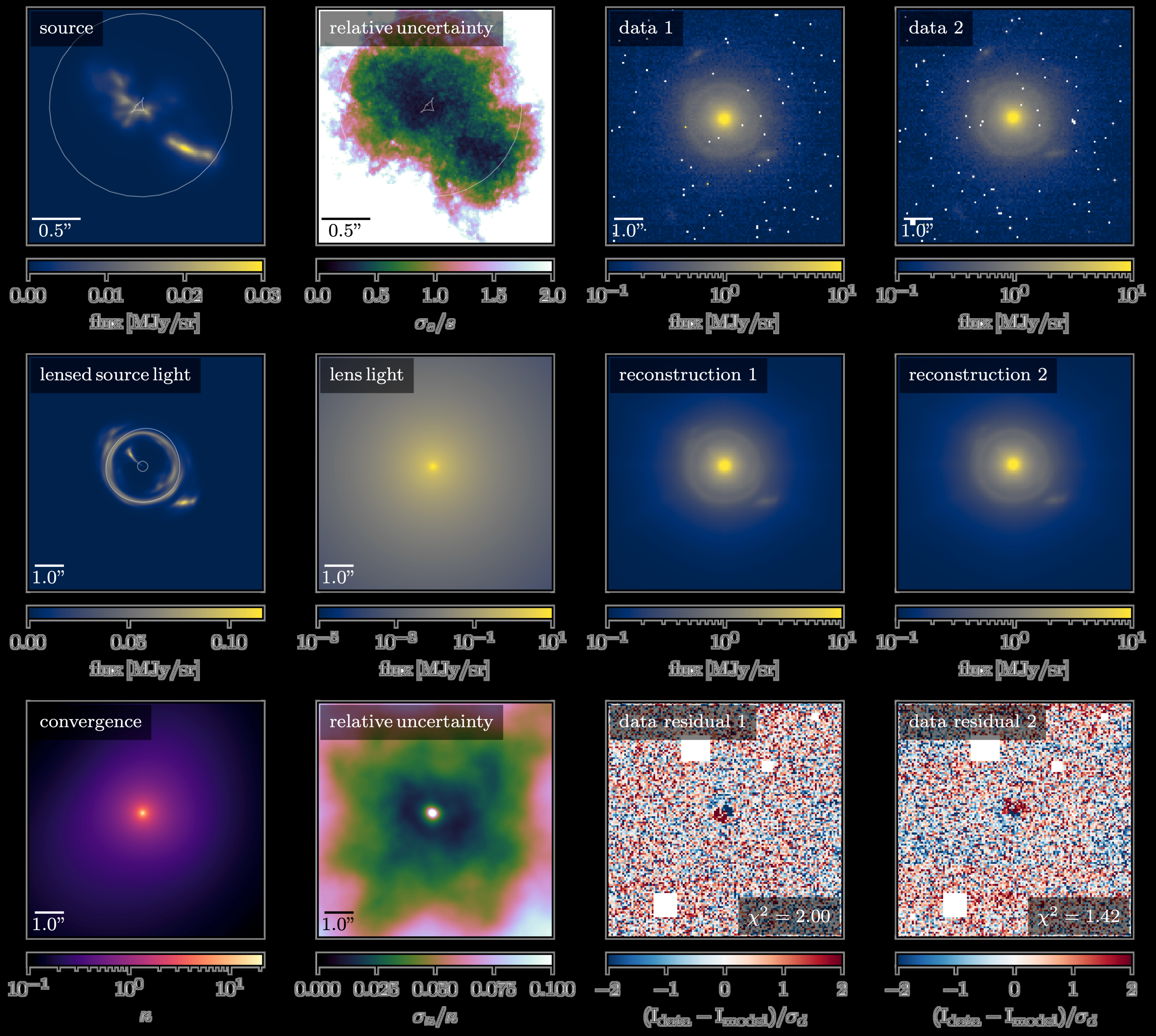


Lensed light noise-weighted residuals

Future Work

Future Work

- Improve mass models and substructure detection
- Incorporate multi-wavelength observations (radio -> X-ray)
- Enlarge charming models library :)
- And more…



SPT-0418 JWST data application

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Thank you!

Astronomy & Astrophysics

Rüstig J., Guardiani M. et al., Introducing LensCharm
A charming Bayesian strong lensing reconstruction framework
https://doi.org/10.1051/0004-6361/202348256

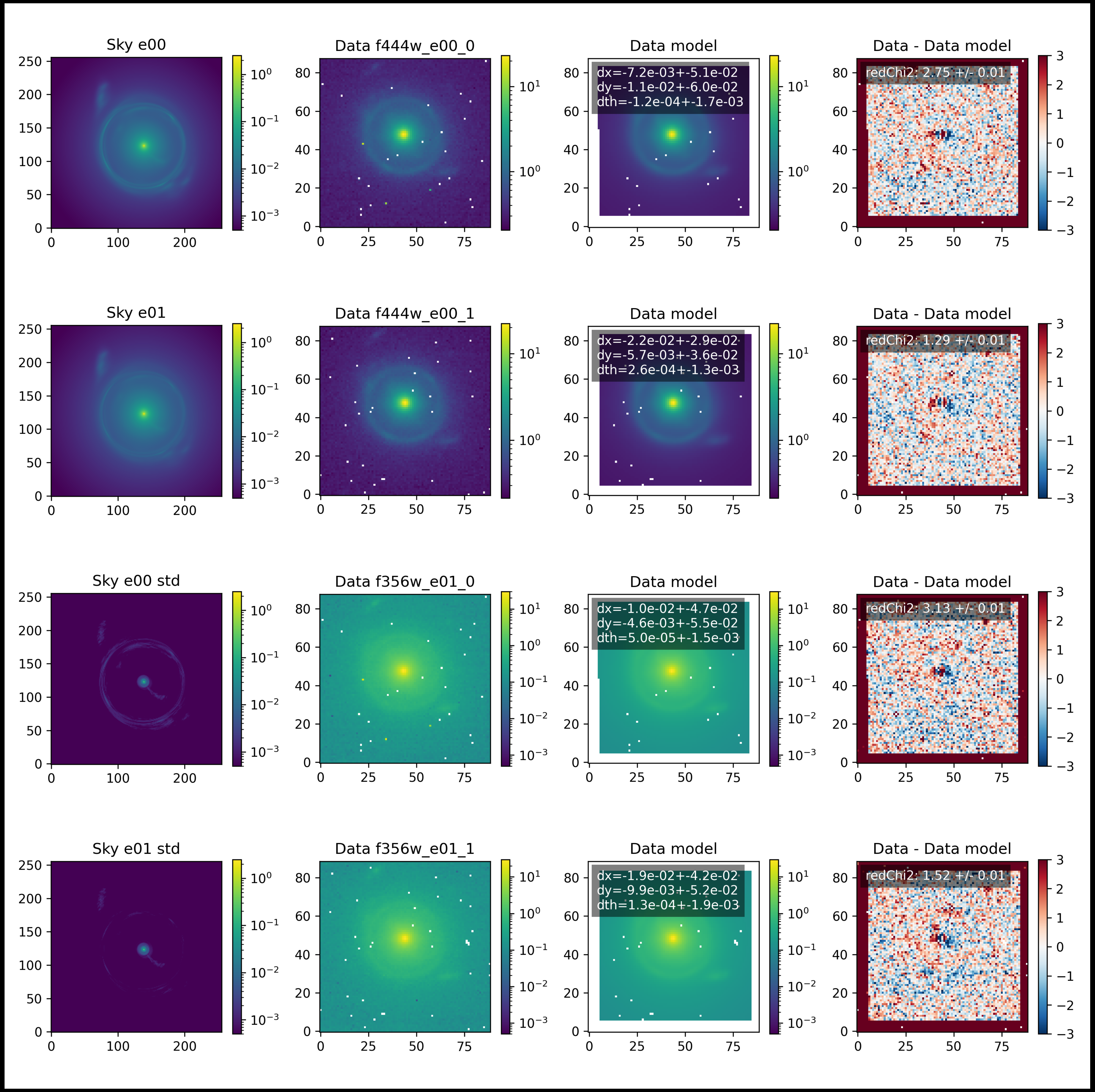
matteani@mpa-garching.mpg.de

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

DLR
MAX PLANCK INSTITUTE FOR ASTROPHYSICS

Backup

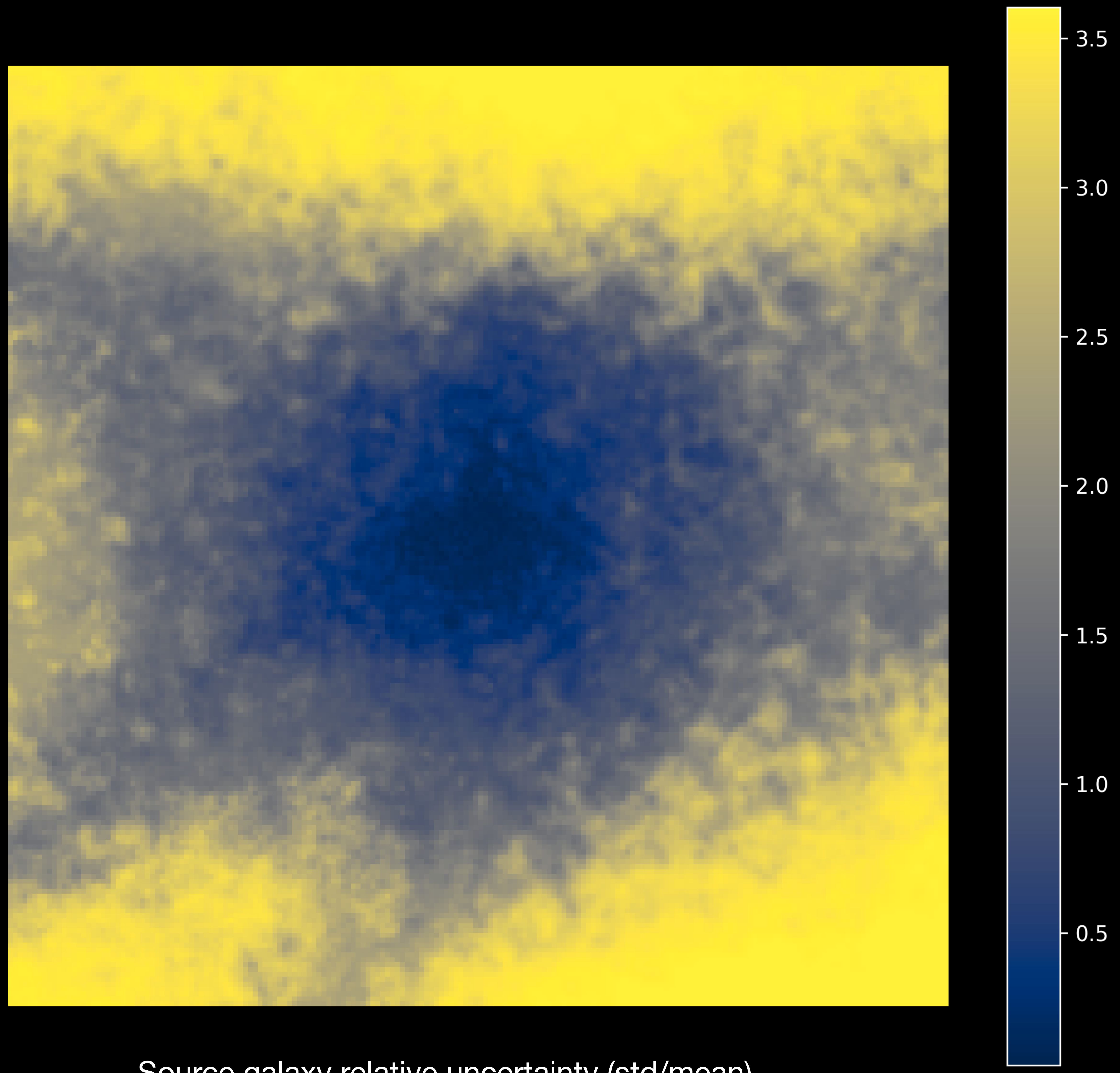
Multi-frequency SPT0418-47 (preliminary)



Guardiani M., Rüstig J. et al., in prep.

Backup

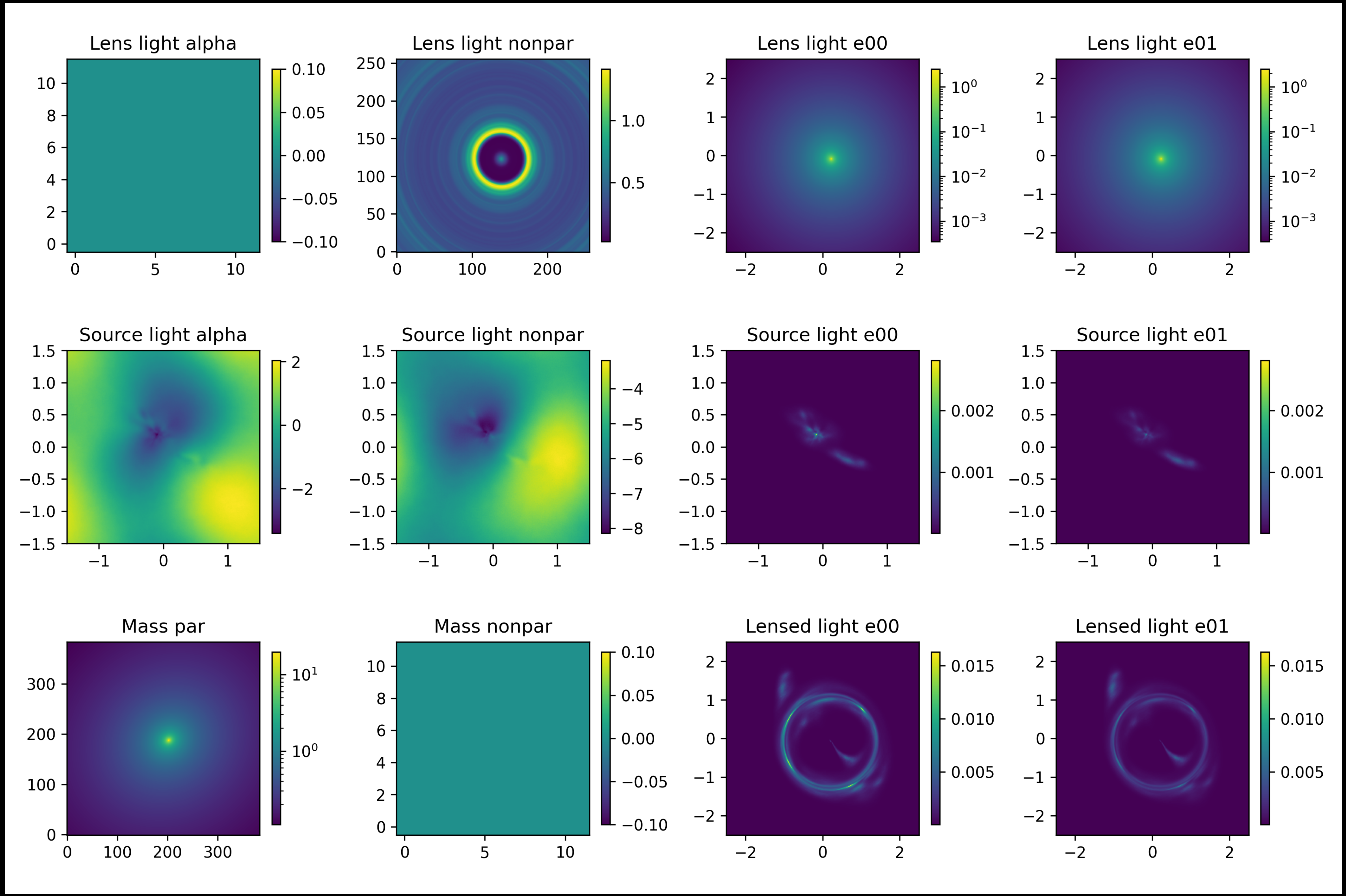
More uncertainties



Source galaxy relative uncertainty (std/mean)

Backup

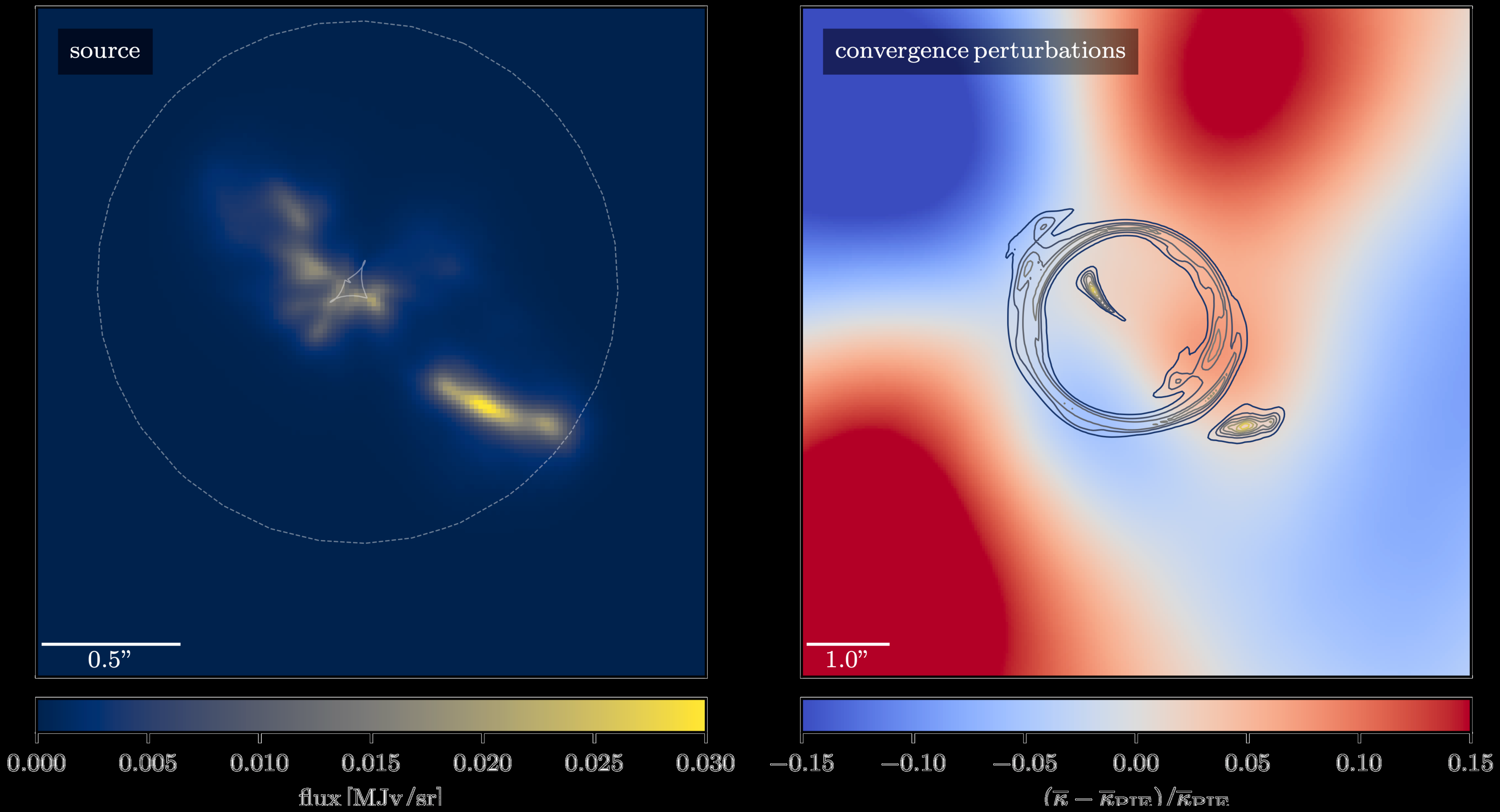
Multi-frequency SPT0418-47 (preliminary)



Guardiani M., Rüstig J. et al., in prep.

Backup

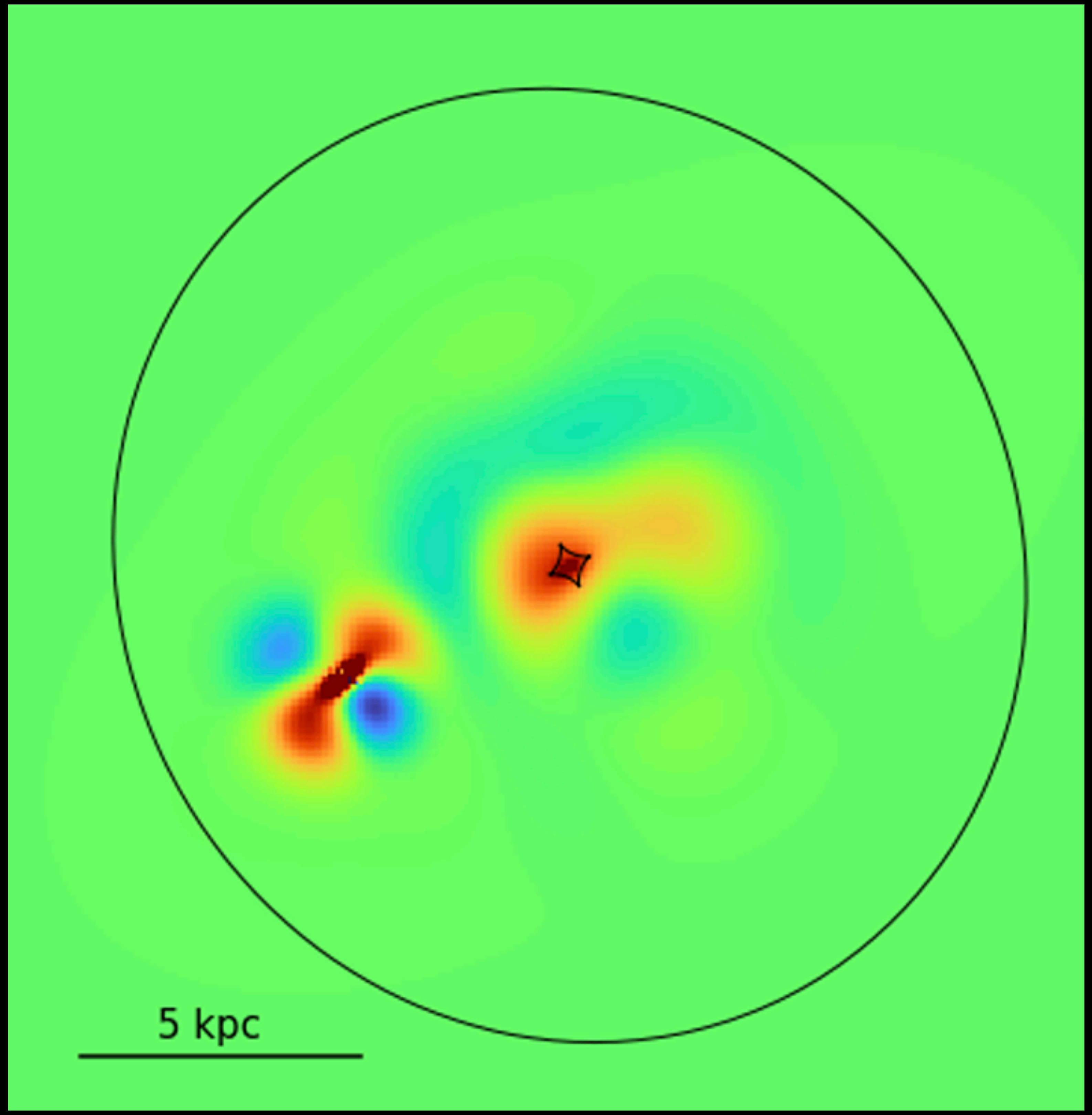
Single-frequency SPT0418-47

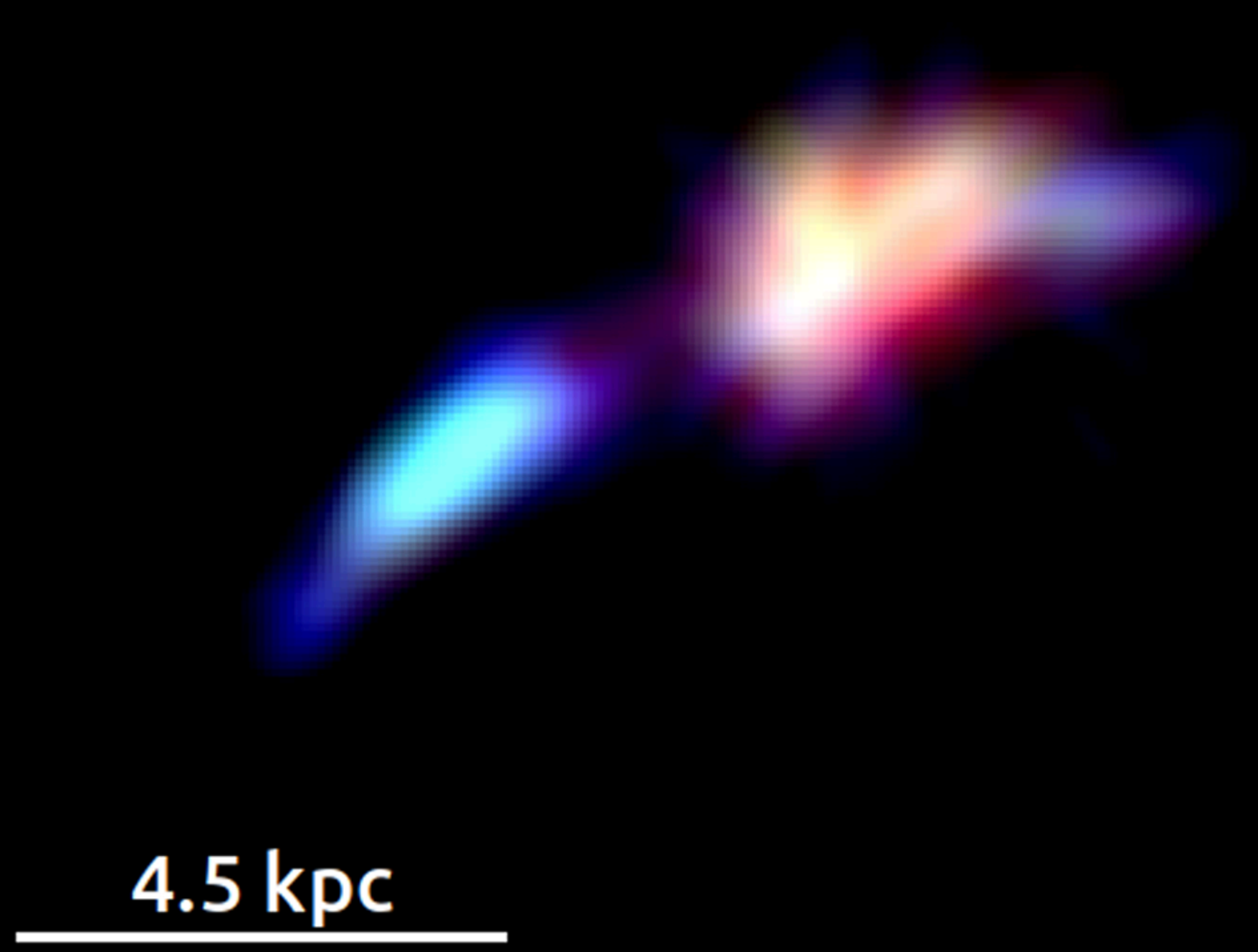


Rüstig J., Guardiani M., et al., A&A 2024

Backup

SPT0418-47





Cathey et al., arXiv:2307.10115