Information field theory

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Information Field Theory

signal field: ∞ degrees of freedom
data set: finite
→ additional information needed

information:
physical laws, symmetries, continuity,
statistical homogeneity/isotropy, ...

most important:
space, time, & fields
are continuous

combining concrete (data) &
abstract (knowledge) information
→ **information theory for fields**

Information Field Theory

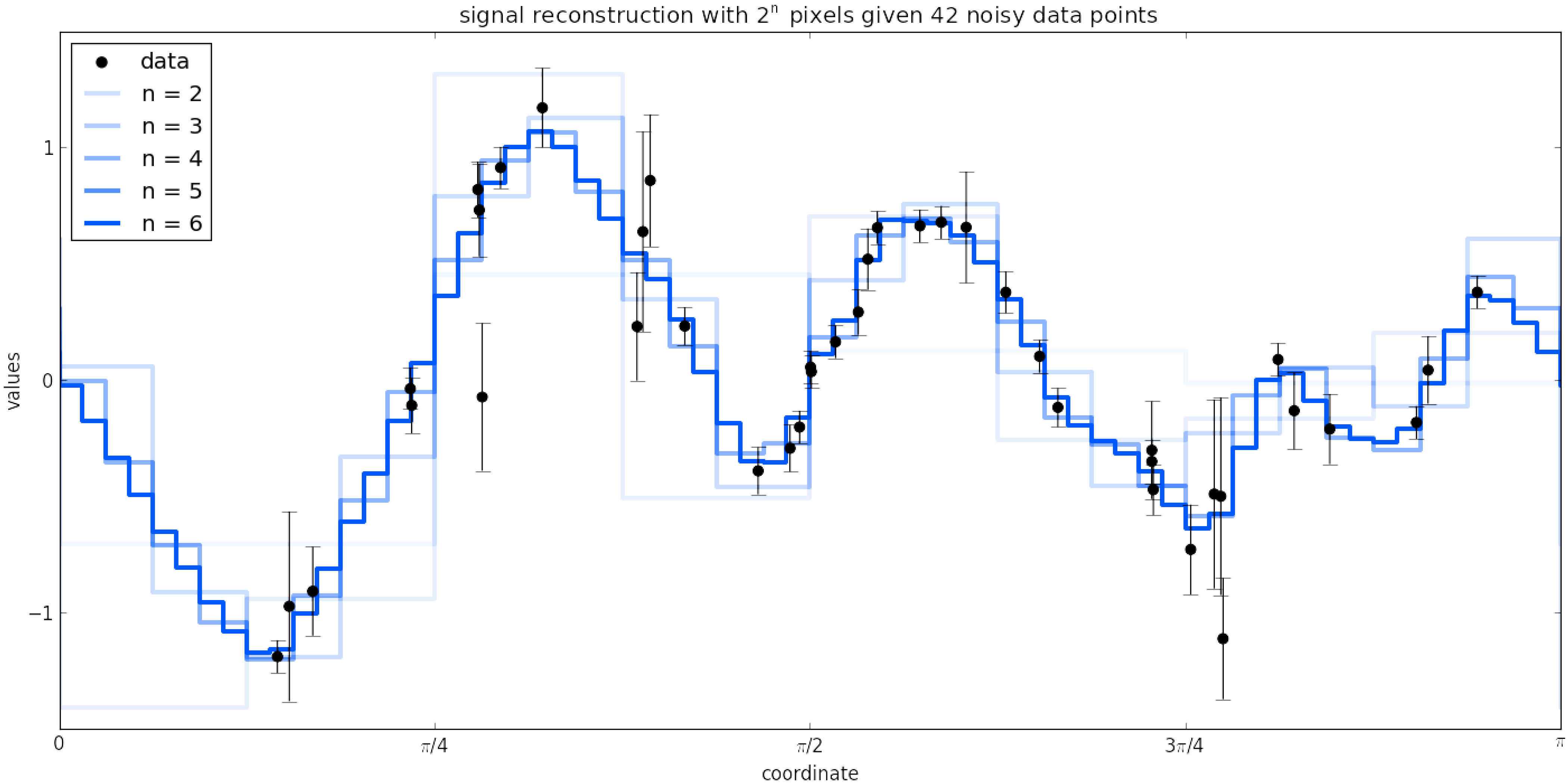
$s =$ signal

$d =$ data

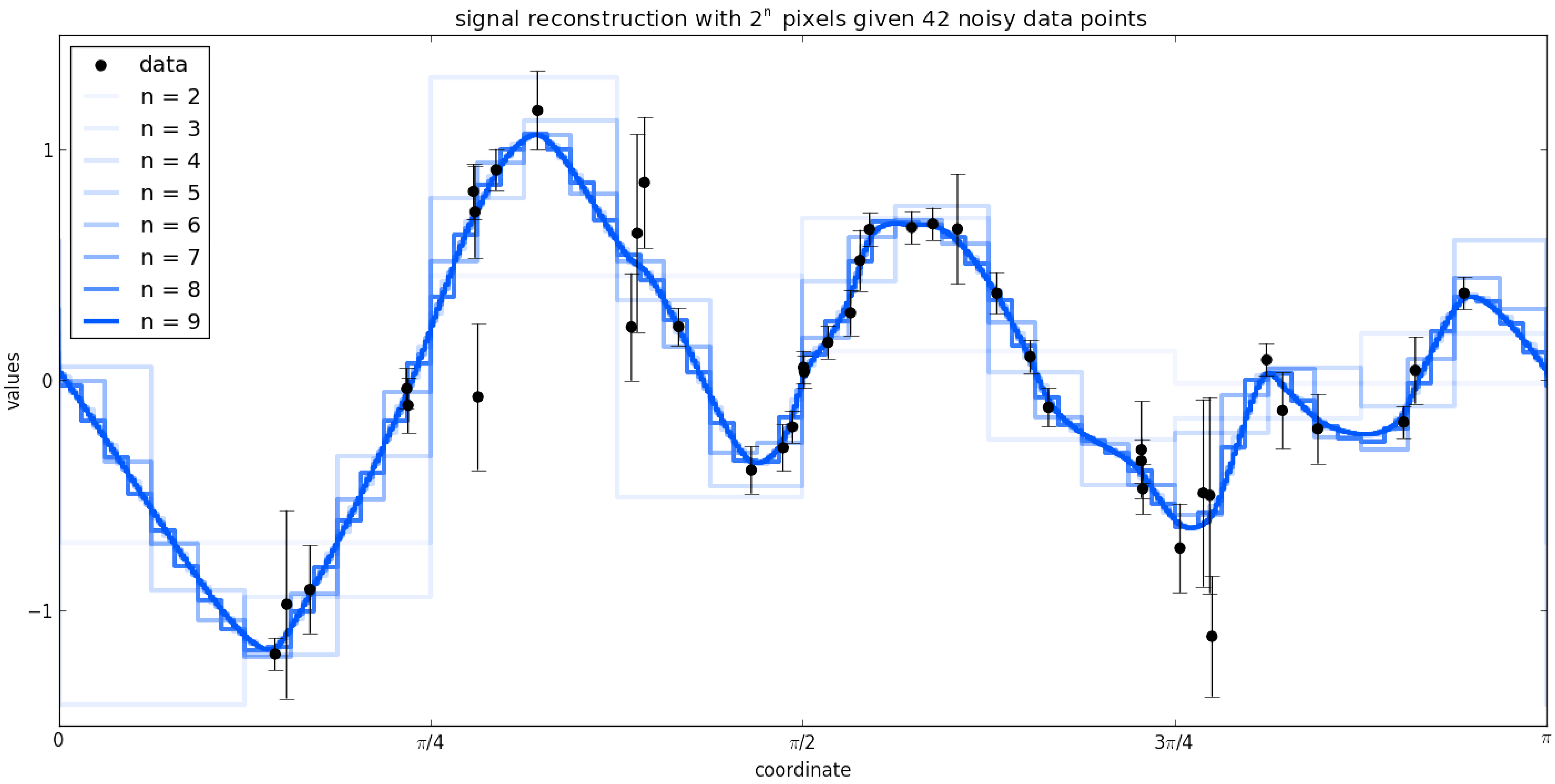
$$\mathcal{P}(s|d) = \frac{\mathcal{P}(d|s)\,\mathcal{P}(s)}{\mathcal{P}(d)}$$

$$\begin{aligned} H(d,s) &= -\log \mathcal{P}(d,s) \\ Z(d) &= \int \mathcal{D}s\, \mathcal{P}(d,s) \end{aligned}$$


Correlations
information field theory
in continuous space
calculations in discretized spaces



signal reconstruction with 2ⁿ pixels given 42 noisy data points
data
n = 2
n = 3
n = 4
n = 5
n = 6
1
0
−1
values
0
π/4
π/2
3π/4
π
coordinate

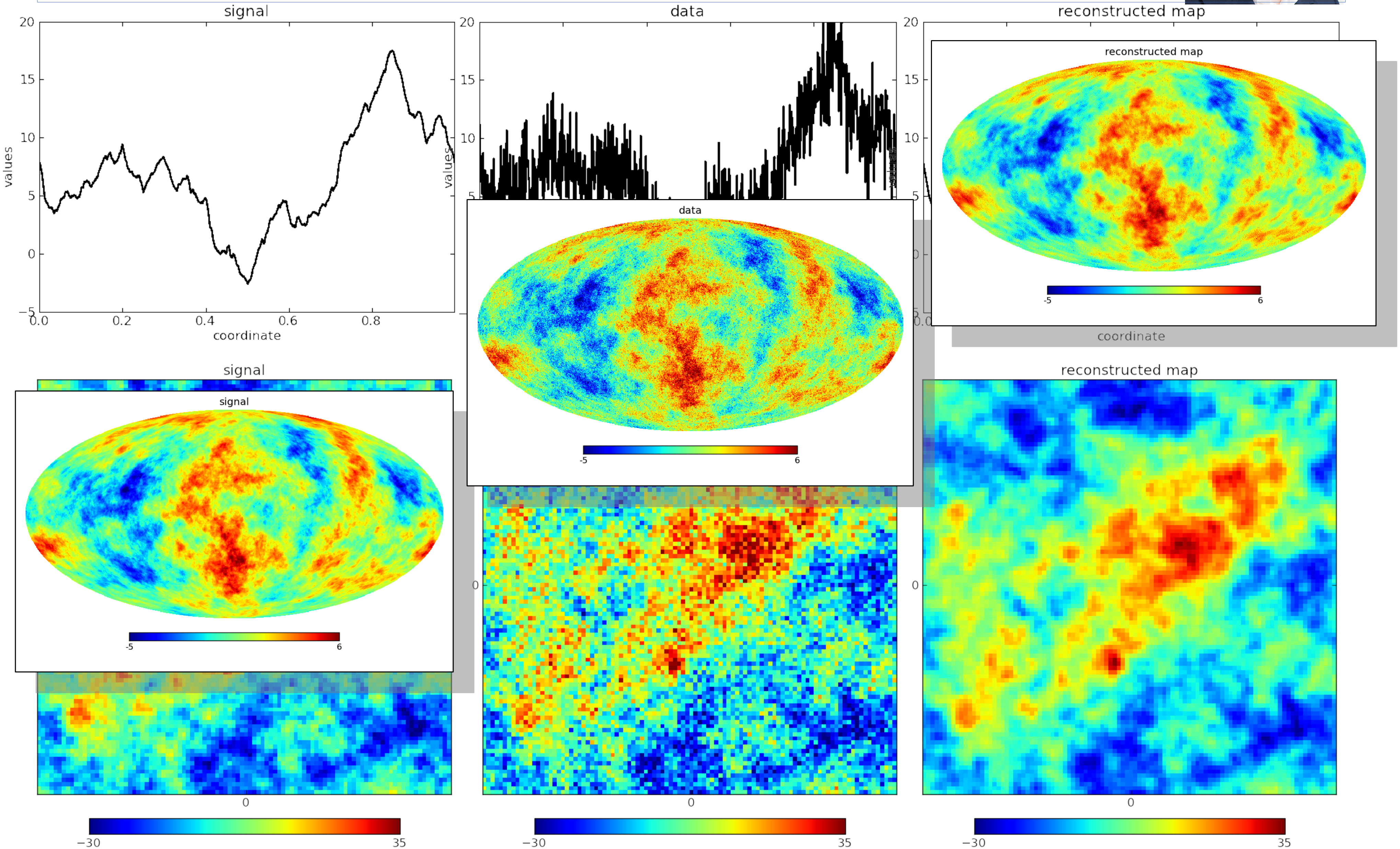


signal reconstruction with 2^n pixels given 42 noisy data points
data
n = 2
n = 3
n = 4
n = 5
n = 6
n = 7
n = 8
n = 9
values
1
0
−1
0
π/4
π/2
3π/4
π
coordinate

NIFTy - Numerical Information Field Theory

Selig et al. (2013), Steininger et al. (sub.)

Code @ https://gitlab.mpcdf.mpg.de/ift/NIFTy




Extended VLA
LOFAR
RESOLVE
ALMA
Junklewitz et al.
Arras et al.
APERTIF
Meerkat
ASKAP

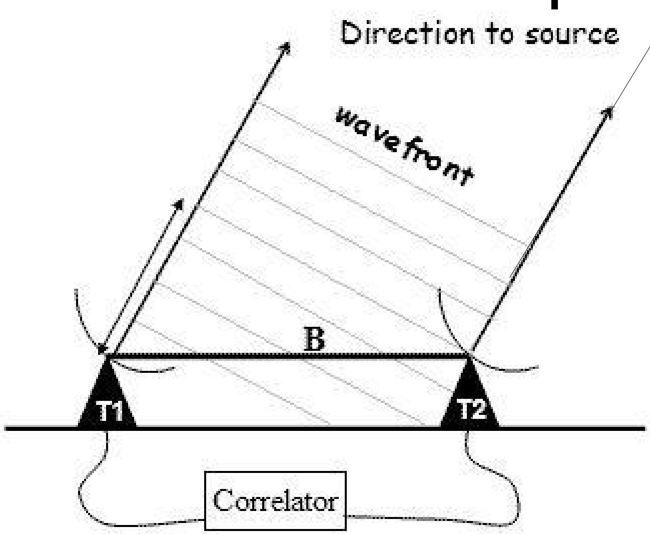
Data model

$$d = R\, e^{\color{red}{s}} + \color{red}{n}$$

known

unknown

known response



Gaussian priors:

$\mathcal{P}(s) = \mathcal{G}(s, \color{red}{S})$ unknown

$\mathcal{P}(n) = \mathcal{G}(n, N)$ known

Information Hamiltonian

$$\mathcal{H}(\boldsymbol{d}, \boldsymbol{s}, \boldsymbol{\tau}) = -\log \mathcal{P}(\boldsymbol{d}, \boldsymbol{s}, \boldsymbol{\tau})$$

likelihood

$$= \frac{1}{2}\left(\boldsymbol{d} - \boldsymbol{R}\mathrm{e}^{\boldsymbol{s}}\right)^{\dagger} \boldsymbol{N}^{-1}\left(\boldsymbol{d} - \boldsymbol{R}\mathrm{e}^{\boldsymbol{s}}\right) + \frac{1}{2}\log\left(\det\left[\boldsymbol{N}\right]\right)$$

prior / regularization

$$+ \frac{1}{2}\boldsymbol{s}^{\dagger}\boldsymbol{S}^{-1}\boldsymbol{s} + \frac{1}{2}\log\left(\det\left[\boldsymbol{S}\right]\right)$$

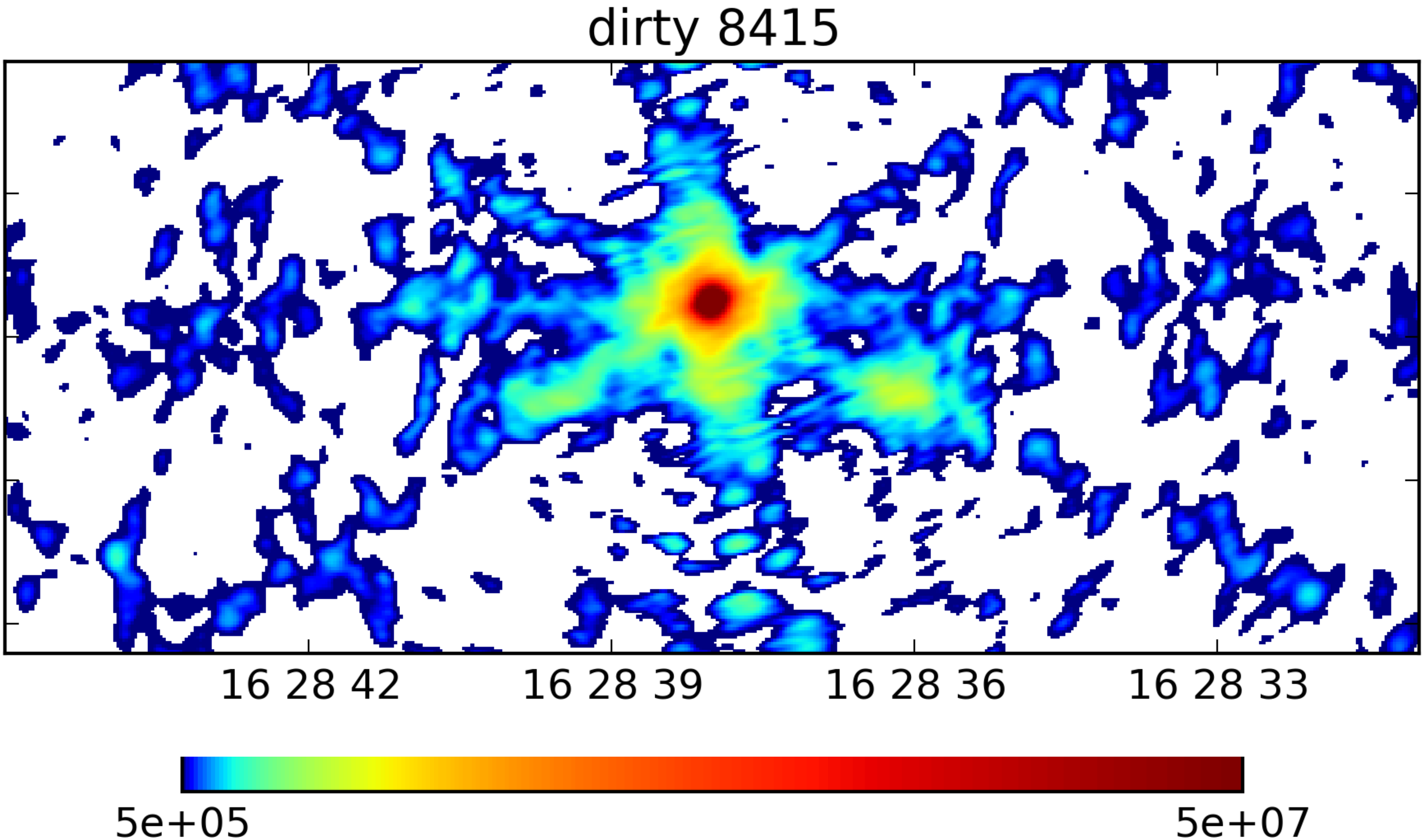
hyper-prior / intelligence

$$+ (\boldsymbol{\alpha} - \boldsymbol{1})^{\dagger}\boldsymbol{\tau} + \boldsymbol{q}^{\dagger}\mathrm{e}^{-\boldsymbol{\tau}} + \frac{1}{2}\boldsymbol{\tau}^{\dagger}\boldsymbol{T}\boldsymbol{\tau}$$

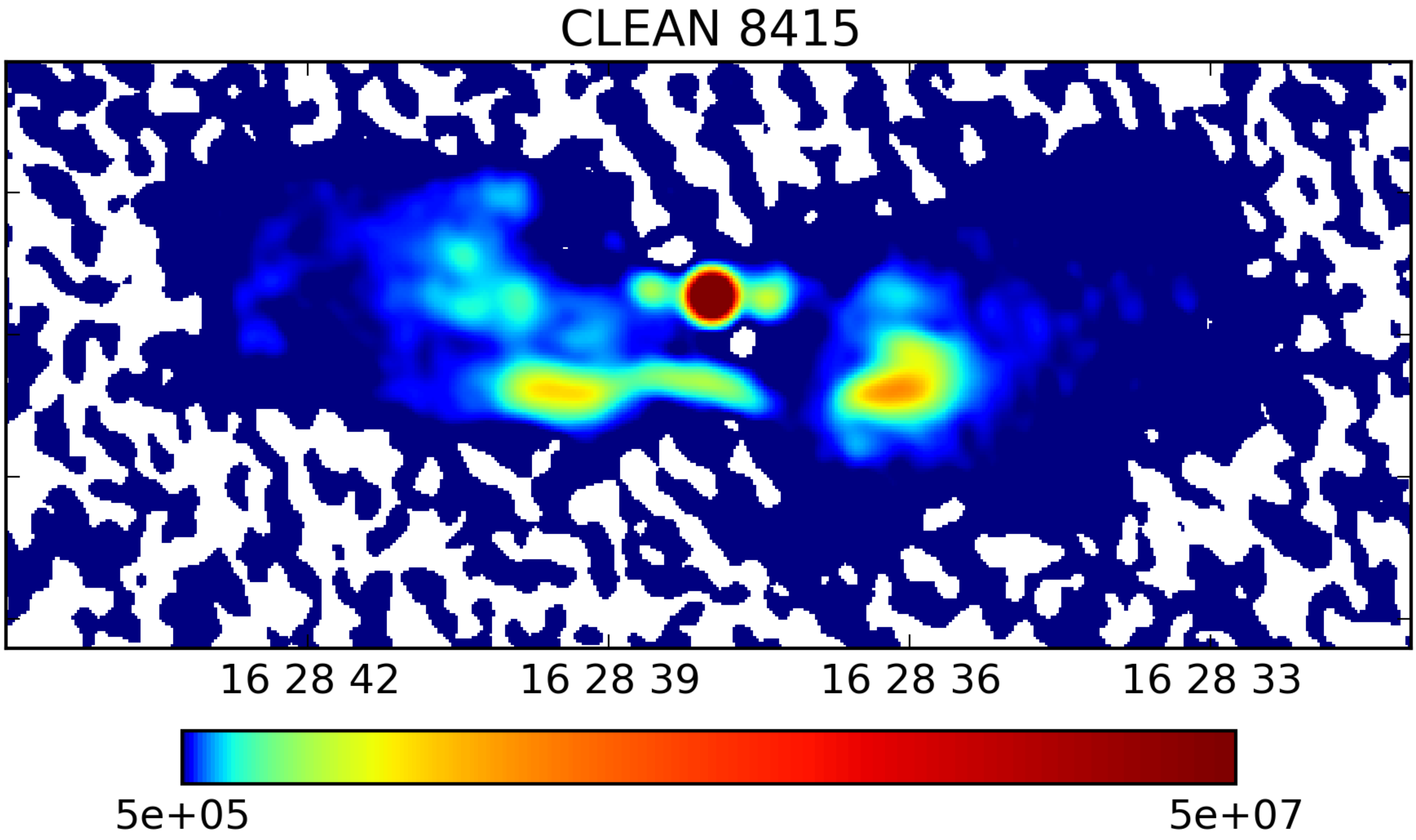
correlation structure

$$\boldsymbol{S} = \sum_{k} \mathrm{e}^{\tau_k}\boldsymbol{S}_k$$

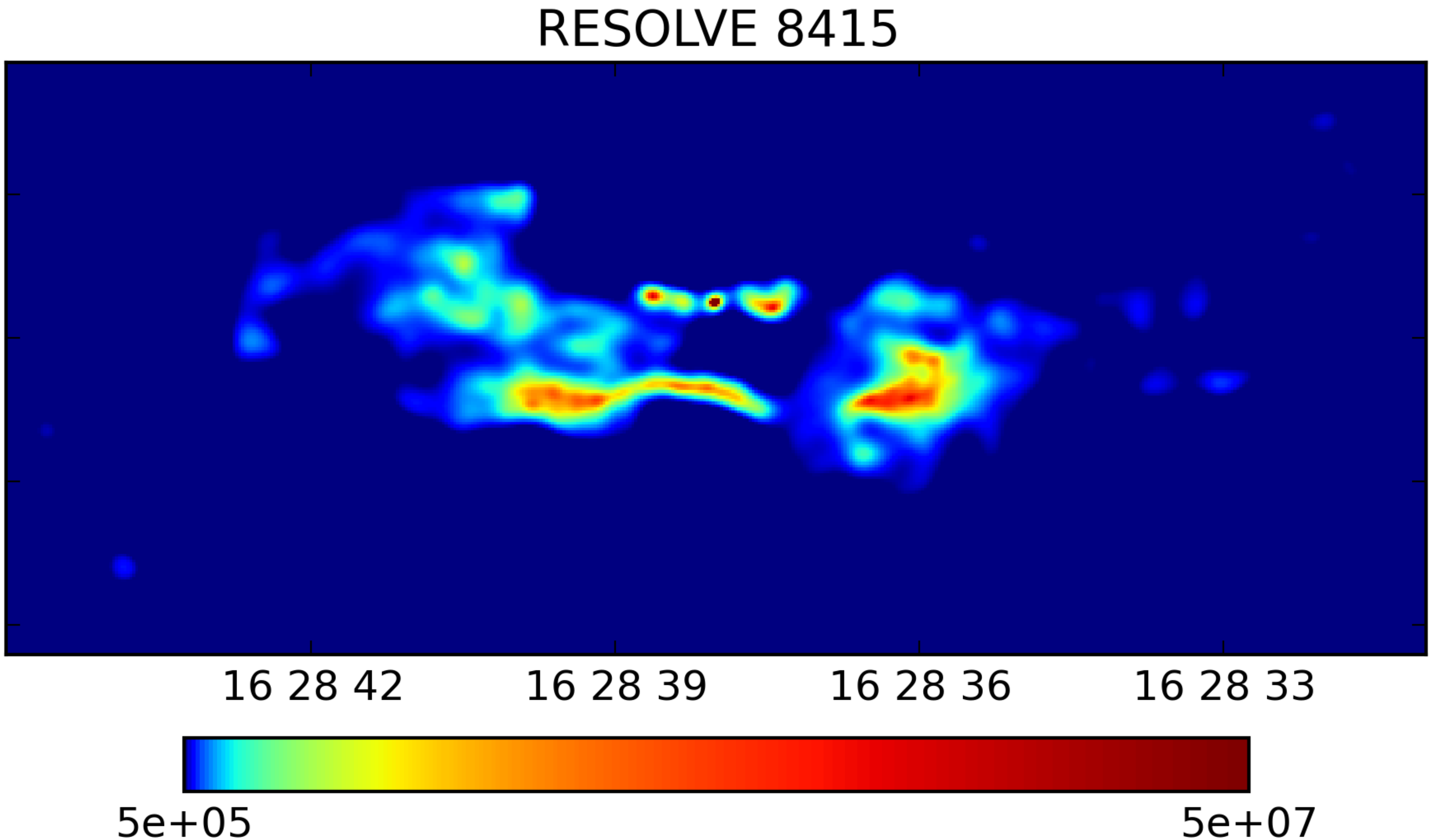
Abell 2219 @ 8415 MHz - data by Valentina Vacca



Abell 2219 @ 8415 MHz - CLEAN map by Valentina Vacca



Abell 2219 @ 8415 MHz – **fast-RESOLVE** map by Maksim Greiner



IFT gang

Maksim Greiner
fastRESOLVE

Data fusion

single dish

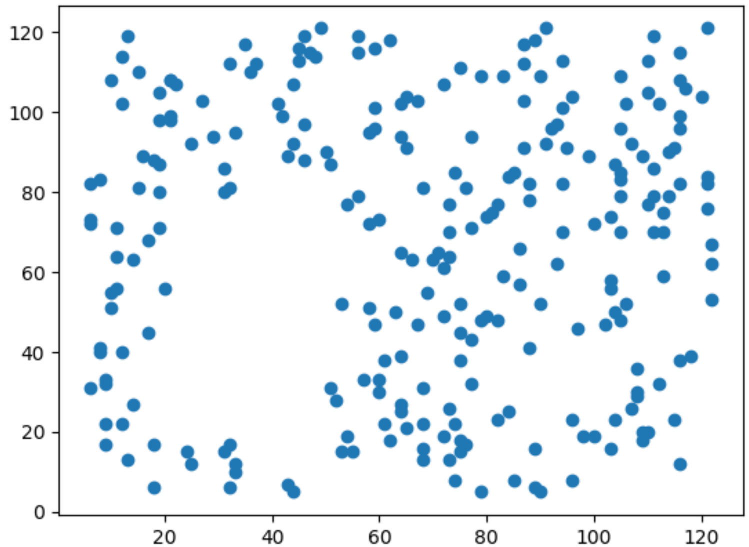
interferometer

Data fusion

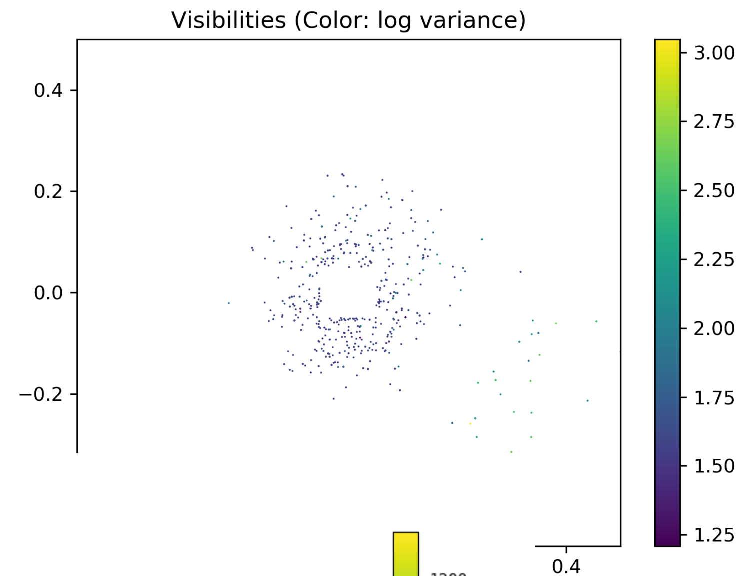
$$\mathcal{P}(d_1, d_2, s) = \mathcal{P}(d_1|s)\,\mathcal{P}(d_2|s)\,\mathcal{P}(s)\cdot\mathcal{H}(s)$$

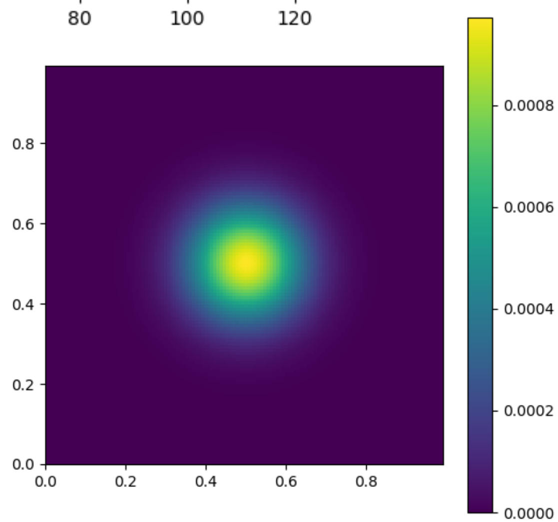
single dish

pointing

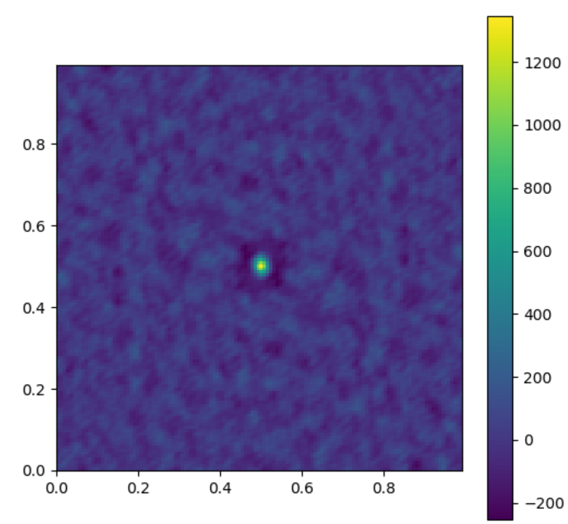


interferometer



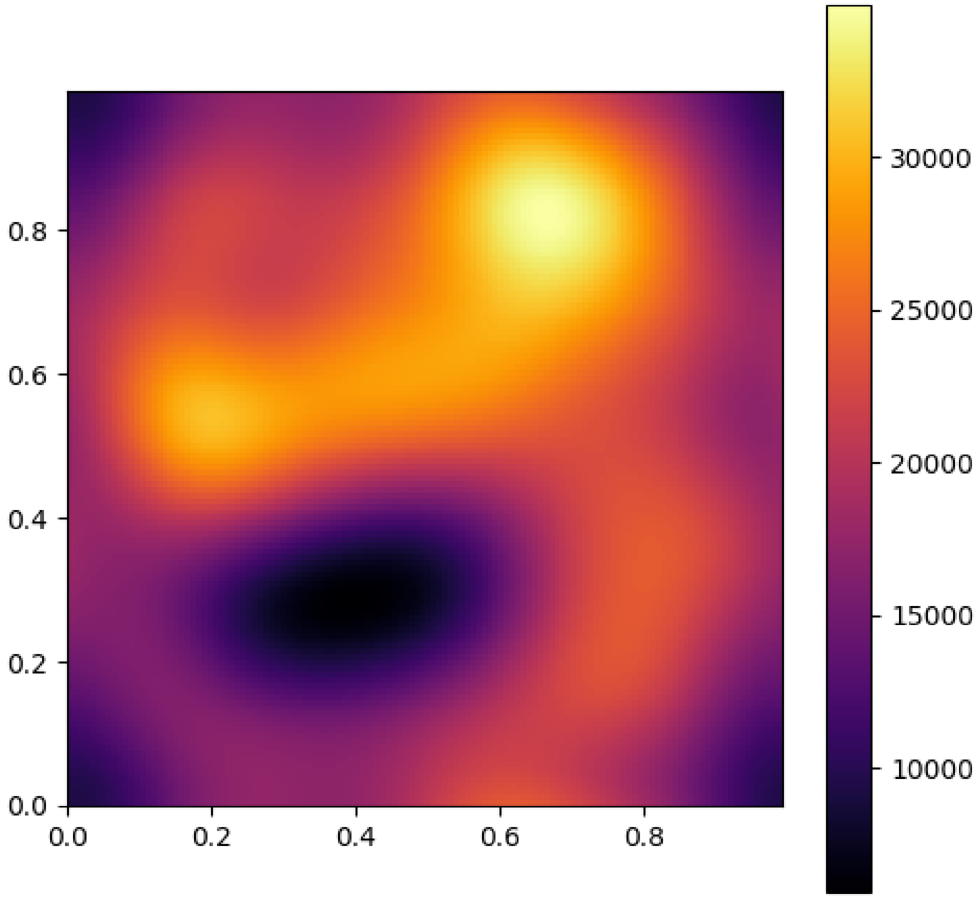


point spread function

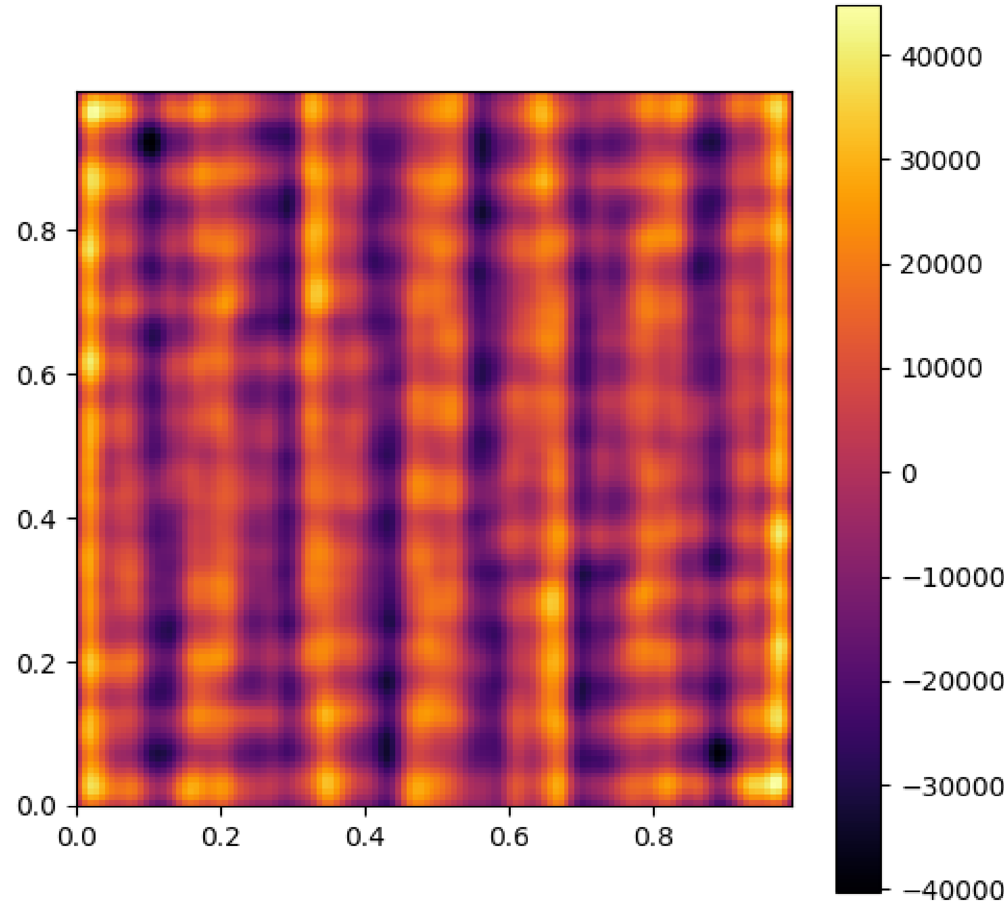


Dirty images

single dish

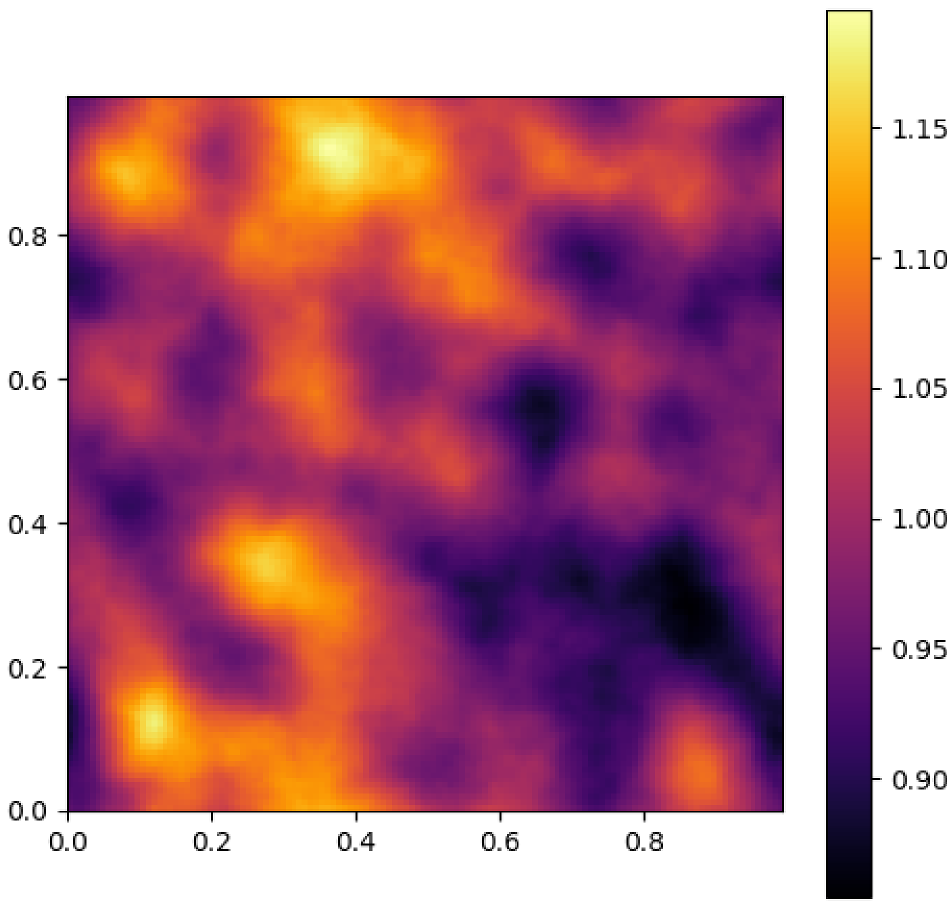


interferometer

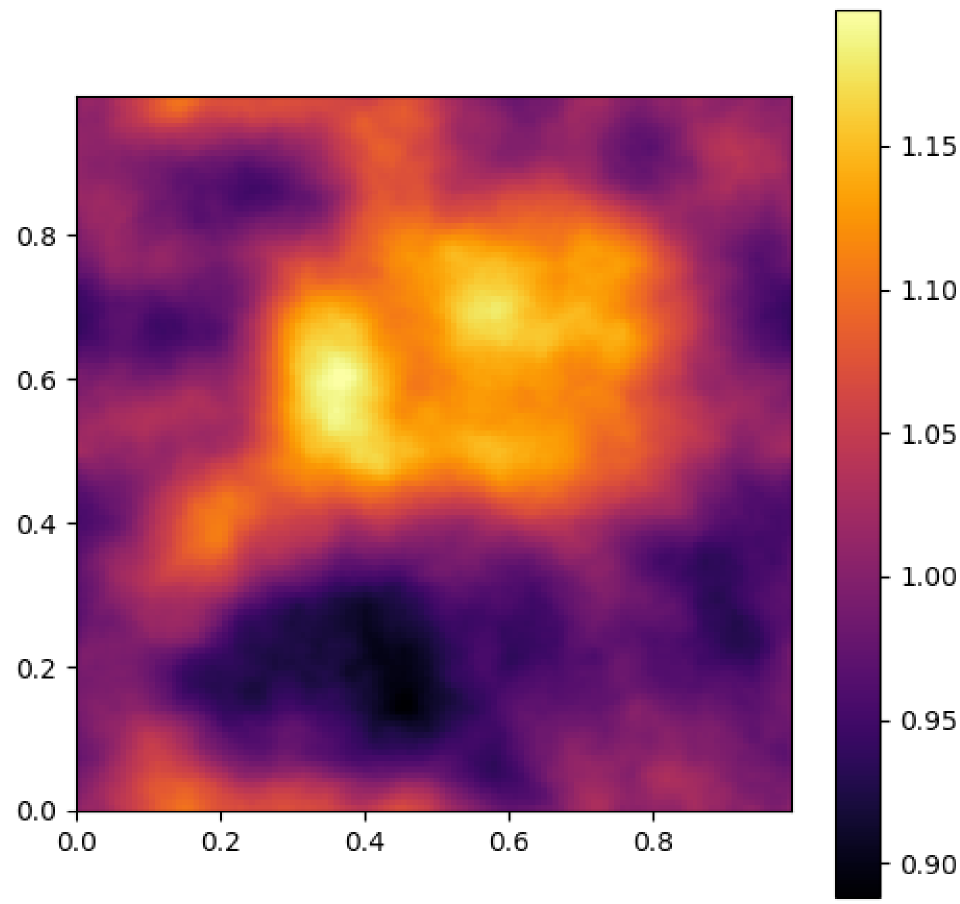


Images

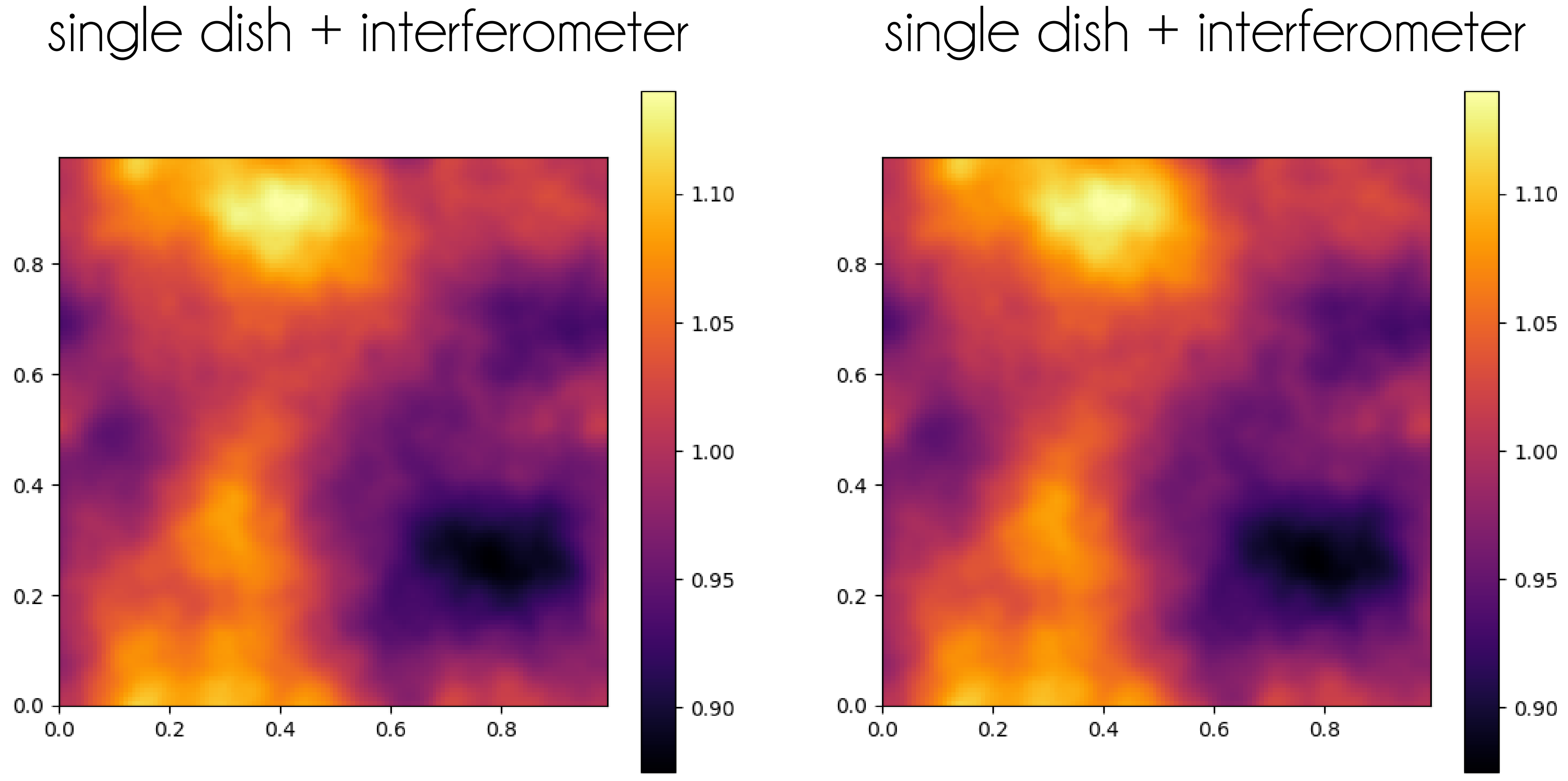
single dish



interferometer

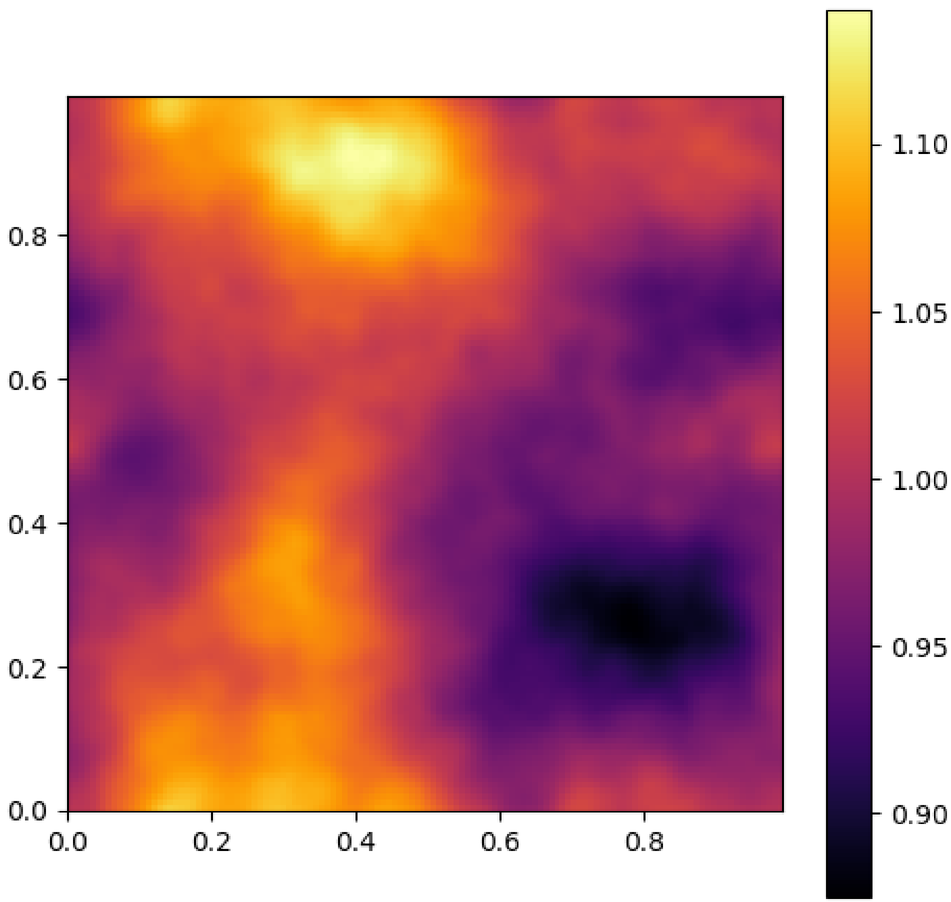


Image

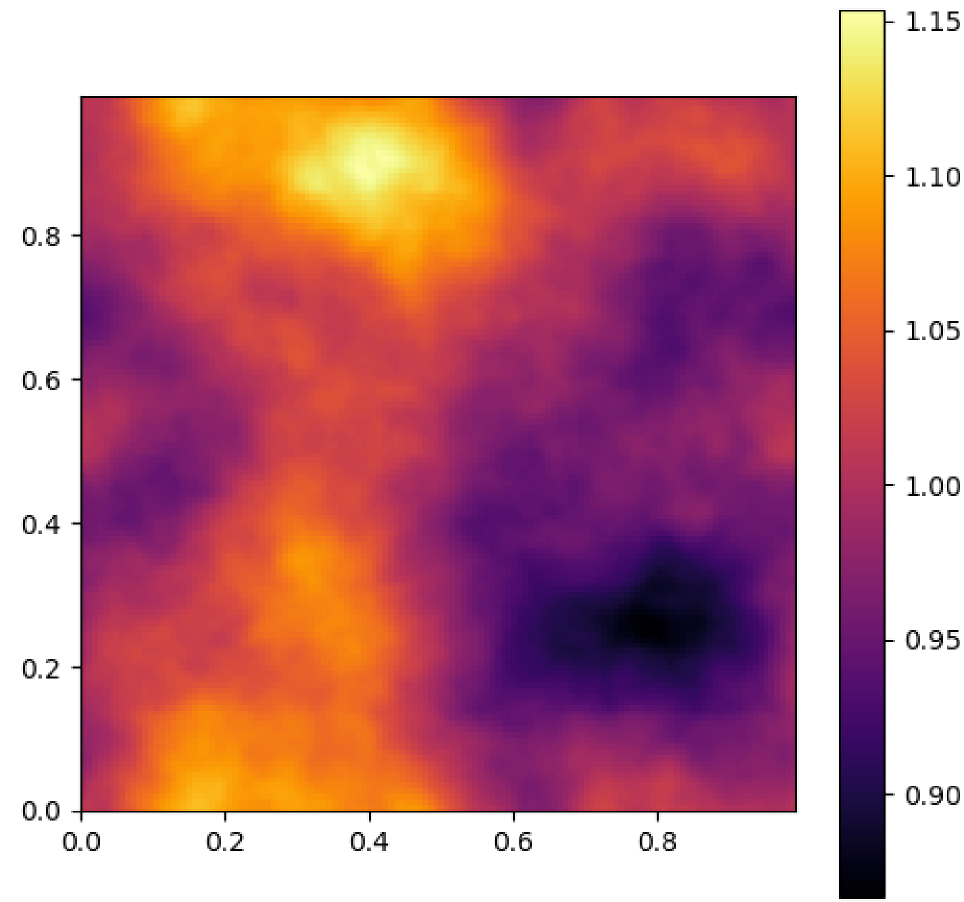

single dish + interferometer
single dish + interferometer
0.0
0.2
0.4
0.6
0.8
0.90
0.95
1.00
1.05
1.10

Image

single dish + interferometer



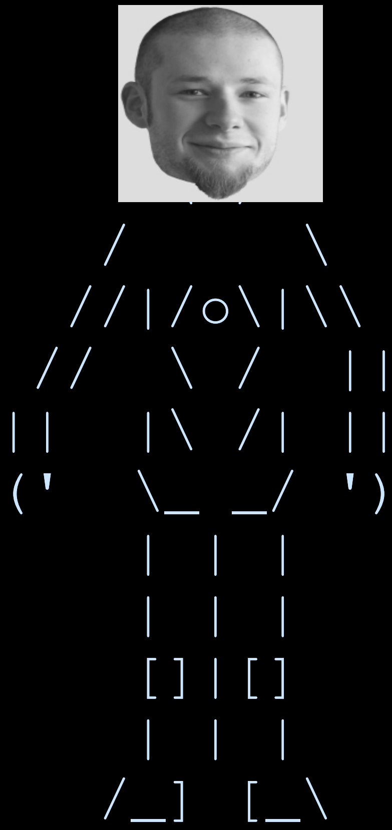
real sky



Denoising, Deconvolving, and Decomposing Photon Observations

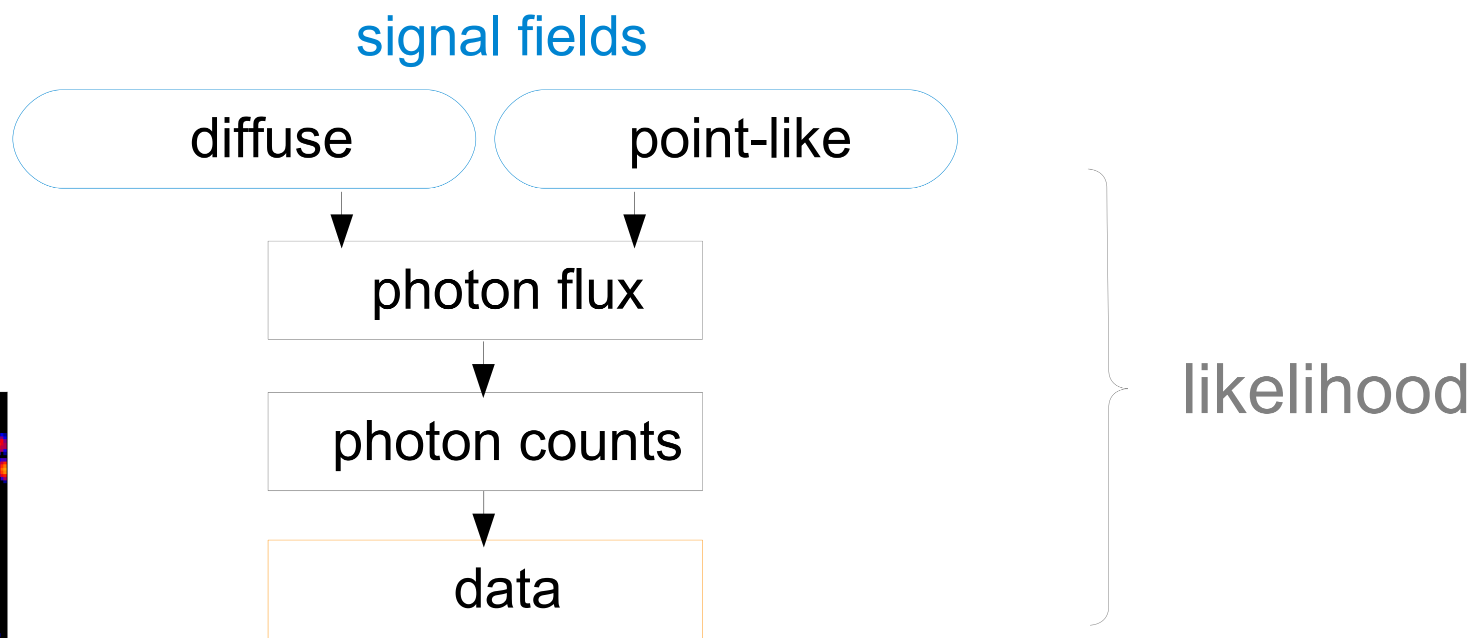
Selig et al. (2014)
www.mpa-garching.mpg.de/ift/d3po

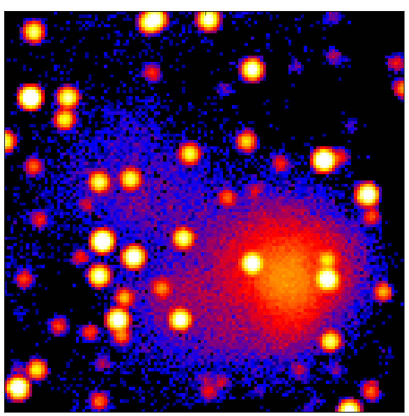
D^{3}PO



D³PO – challenges & assumptions

Selig & Enßlin
(2014)
arXiv: 1311.1888





D^3PO – challenges & assumptions

Selig & Enßlin (2014)
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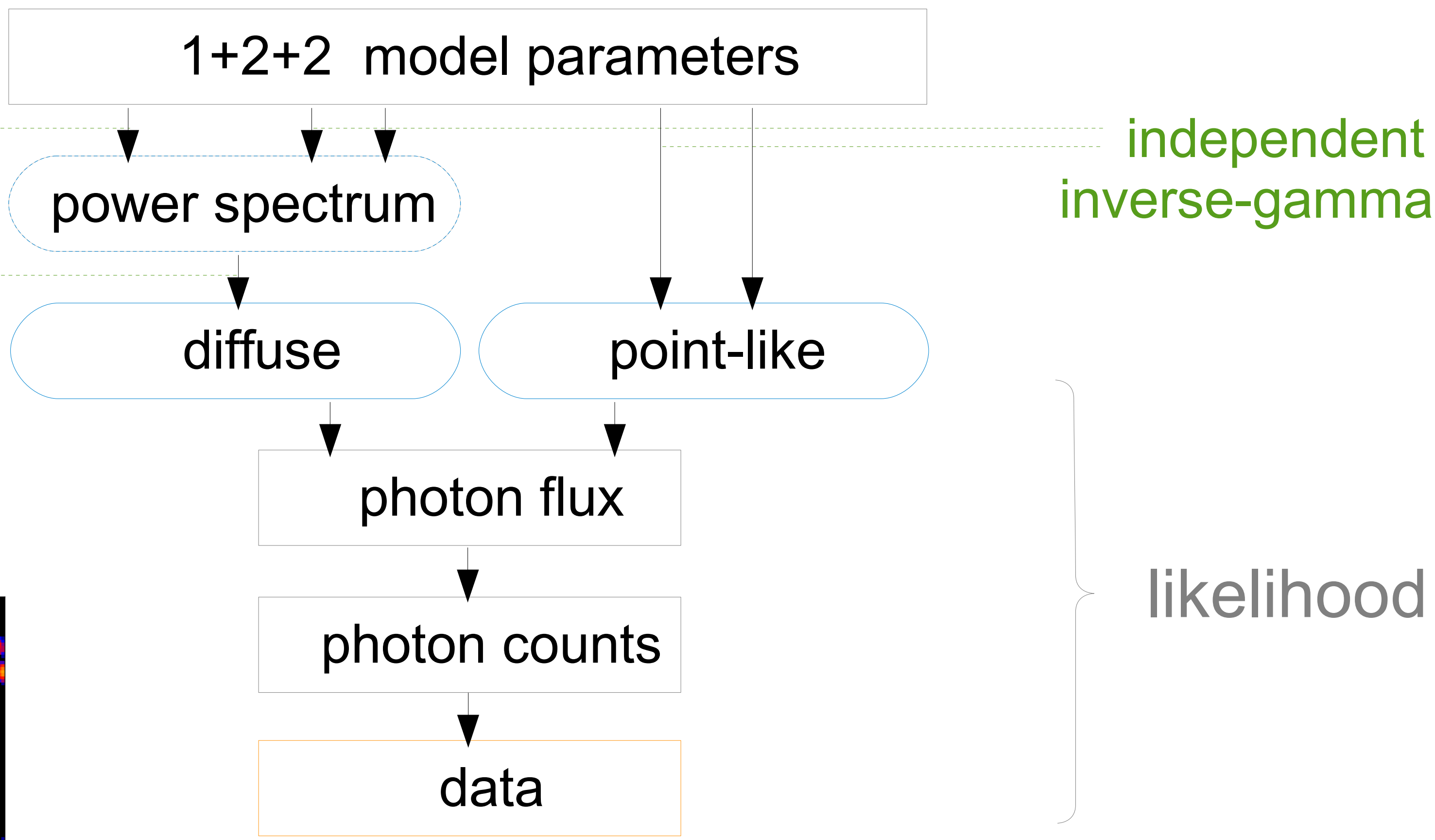
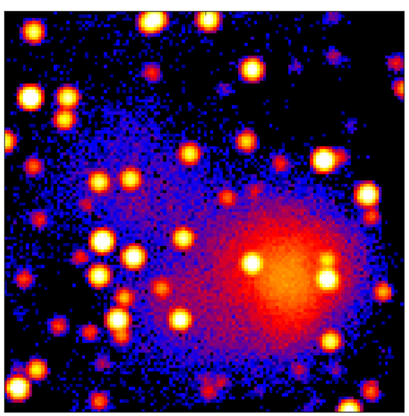
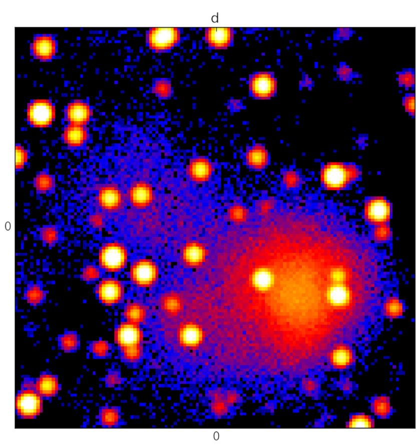




D[3]PO – challenges & assumptions

Selig & Enßlin
(2014)
arXiv: 1311.1888

$$\mathcal{H}(\boldsymbol{s},\boldsymbol{\tau},\boldsymbol{u}|\boldsymbol{d}) = -\log \mathcal{P}(\boldsymbol{s},\boldsymbol{\tau},\boldsymbol{u}|\boldsymbol{d})$$
$$= H_0 + \boldsymbol{1}^\dagger \boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right) - \boldsymbol{d}^\dagger \log\left(\boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right)\right)$$
$$+ \frac{1}{2}\log\left(\det\left[\boldsymbol{S}\right]\right) + \frac{1}{2}\boldsymbol{s}^\dagger \boldsymbol{S}^{-1}\boldsymbol{s}$$
$$+ (\boldsymbol{\alpha} - \boldsymbol{1})^\dagger \boldsymbol{\tau} + \boldsymbol{q}^\dagger \mathrm{e}^{-\boldsymbol{\tau}} + \frac{1}{2}\boldsymbol{\tau}^\dagger \boldsymbol{T}\boldsymbol{\tau}$$
$$+ (\boldsymbol{\beta} - \boldsymbol{1})^\dagger \boldsymbol{u} + \boldsymbol{\eta}^\dagger \mathrm{e}^{-\boldsymbol{u}}$$

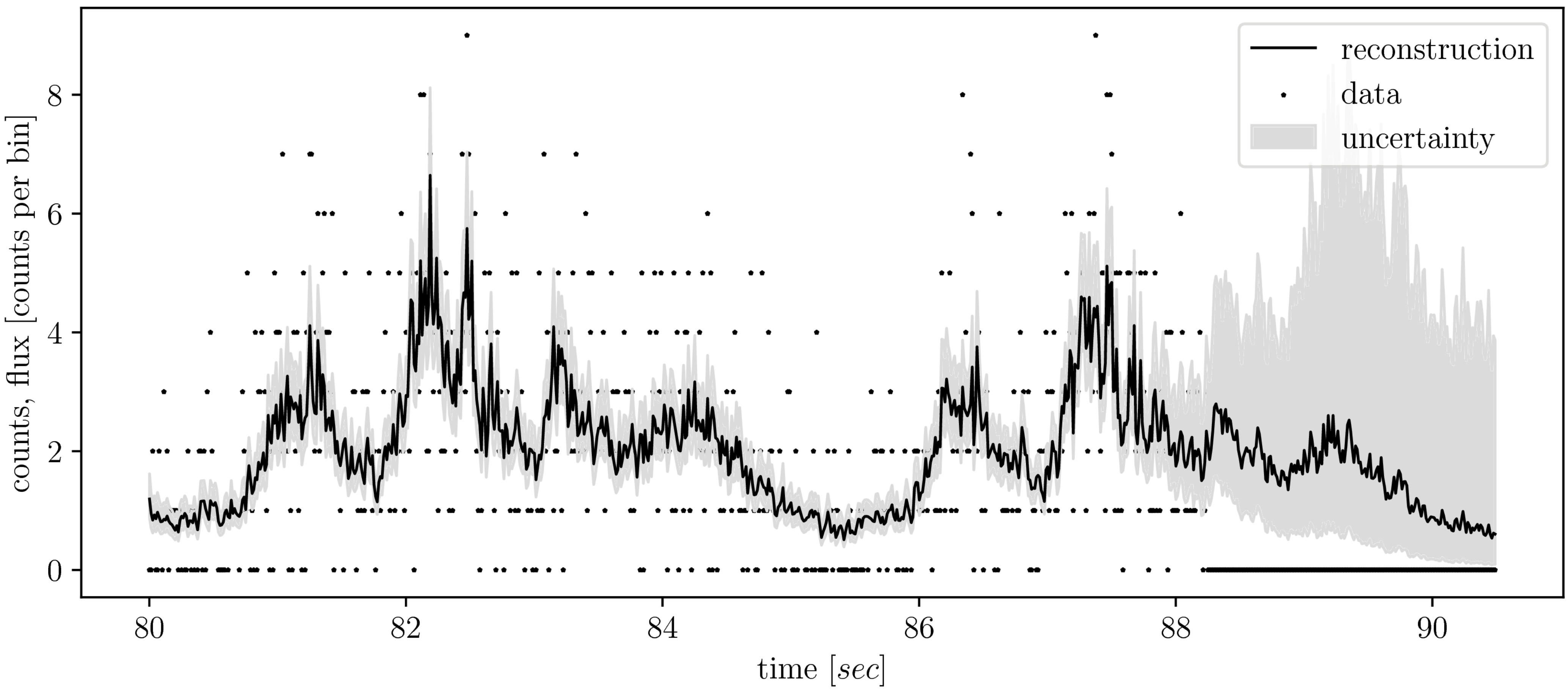


$$\boldsymbol{S} = \sum_k \mathrm{e}^{\tau_k} \boldsymbol{S}_k$$

D³PO in 1D & QPOs

Magnetar flare SGR 1900+14

Pumpe et al. arXiv:1708.05702



D³PO in 1D & QPOs

Magnetar flare SGR 1900+14

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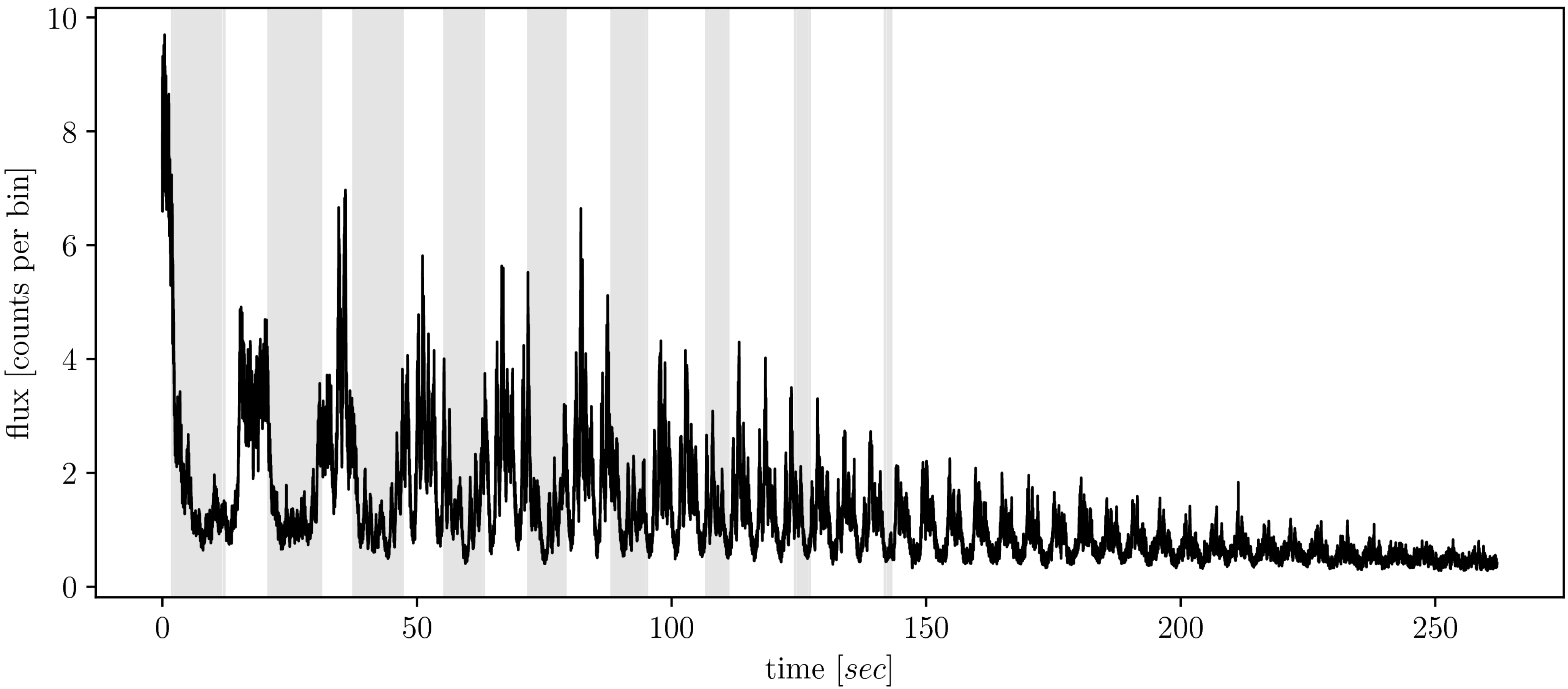

D³PO in 1D & QPOs

Magnetar flare SGR 1900+14

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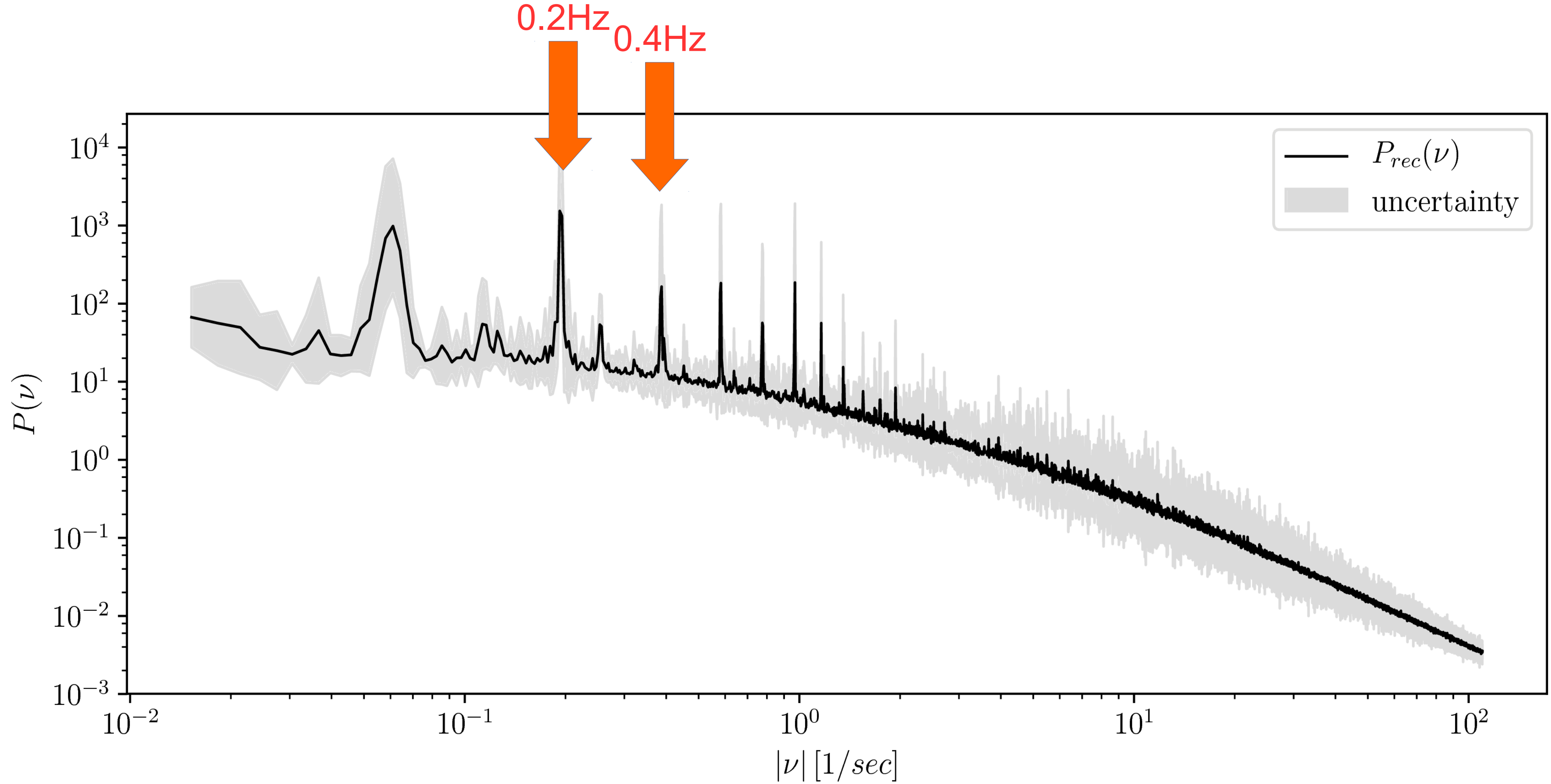
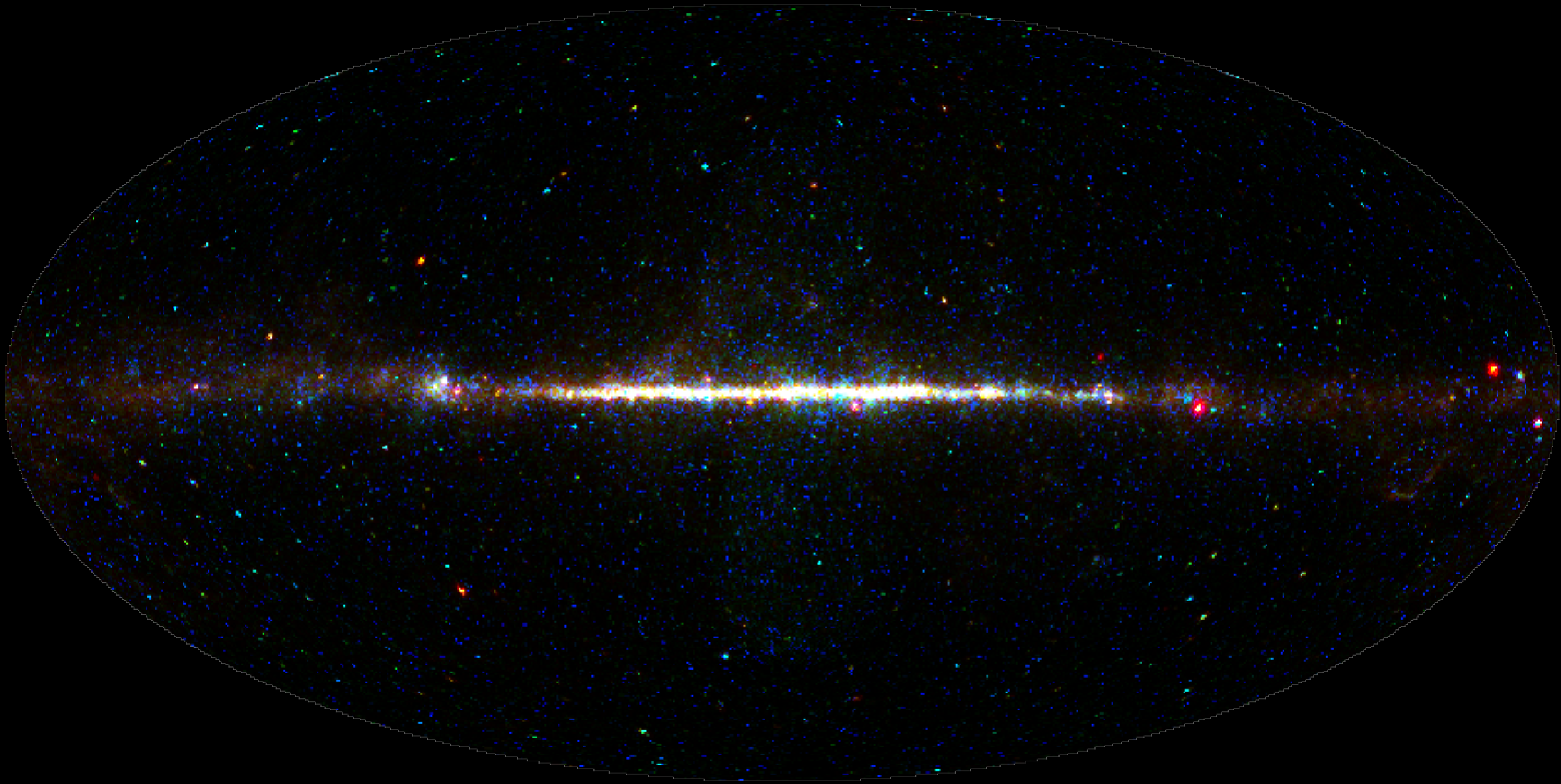
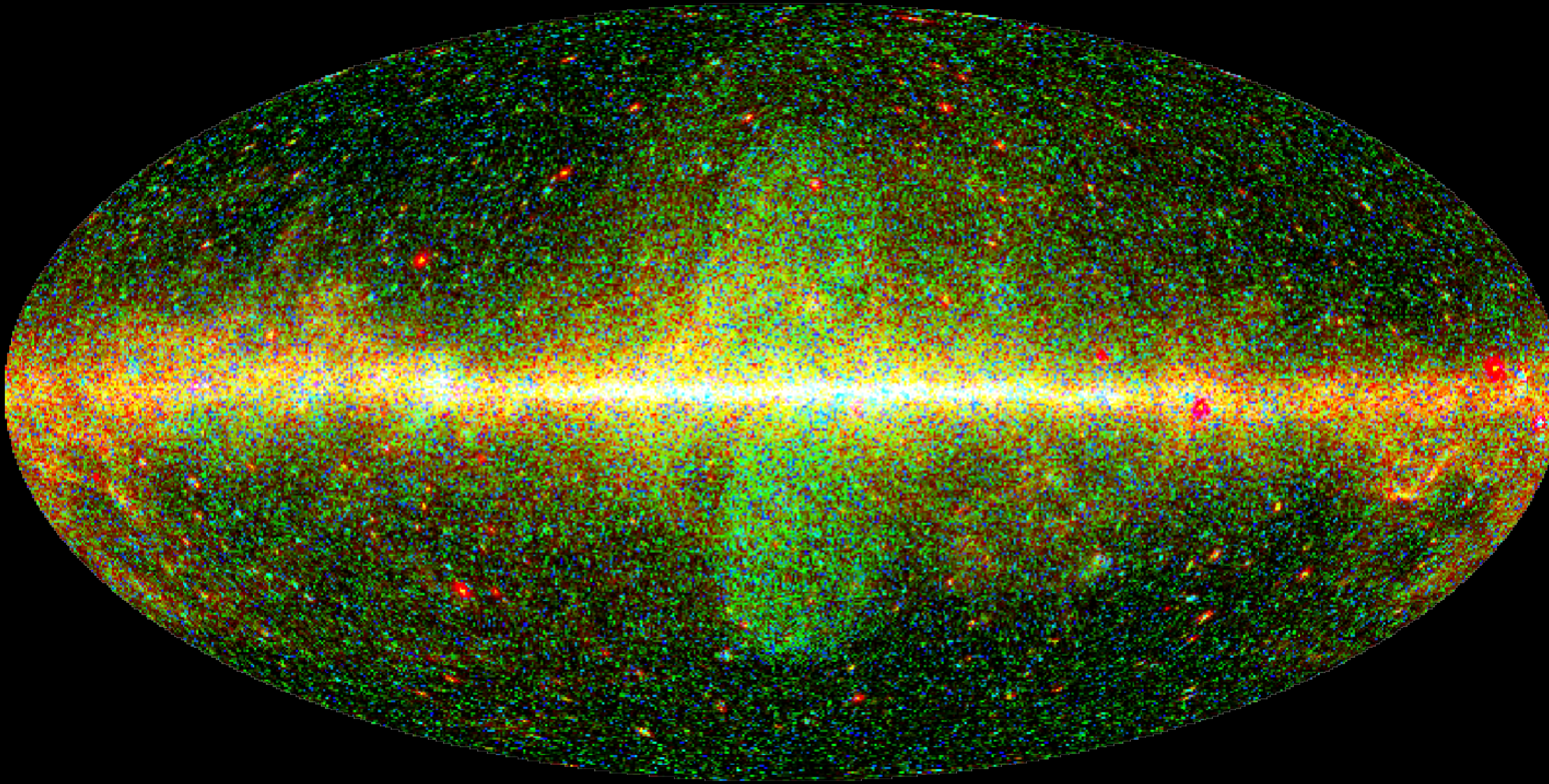
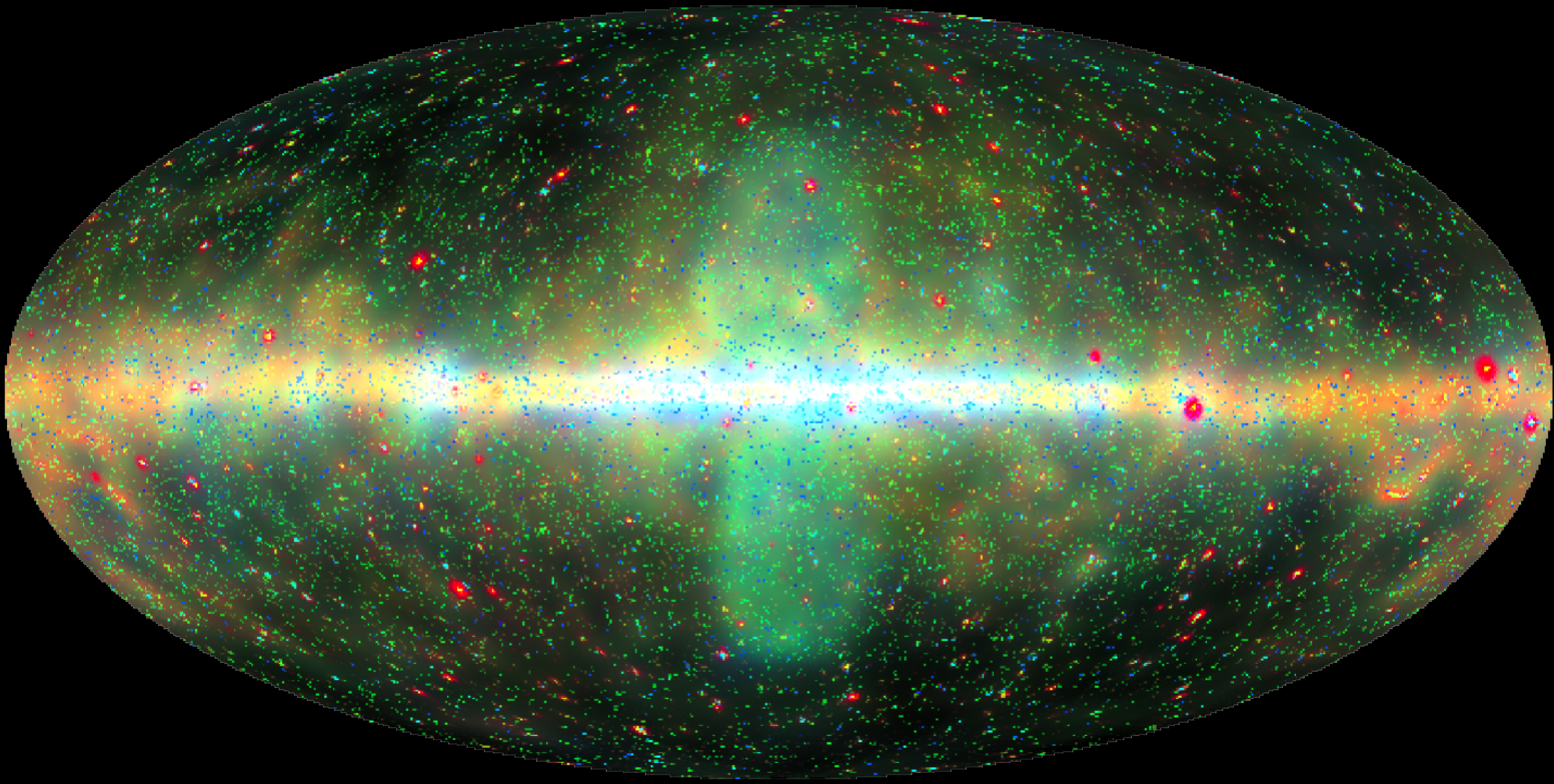




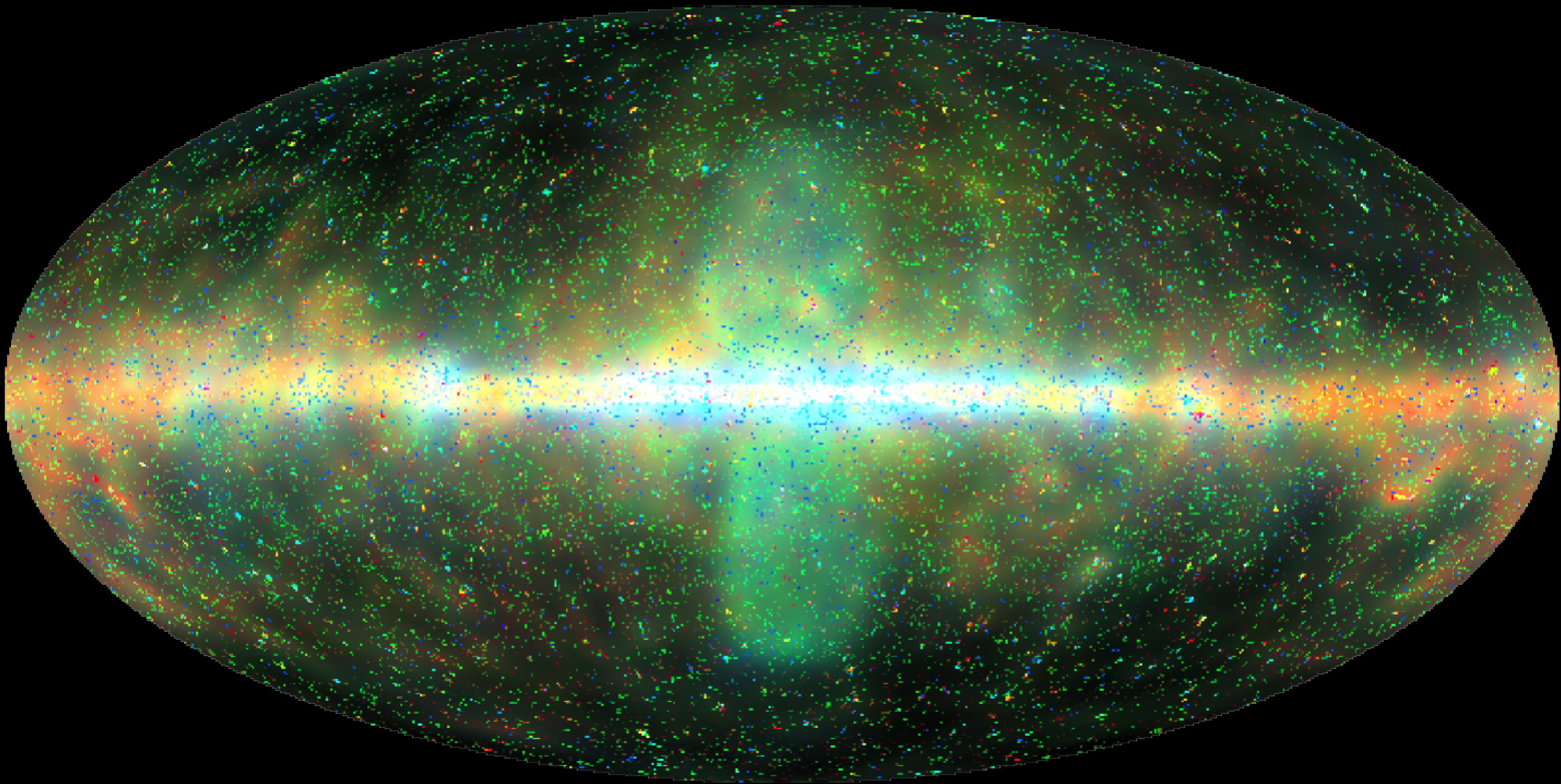
data



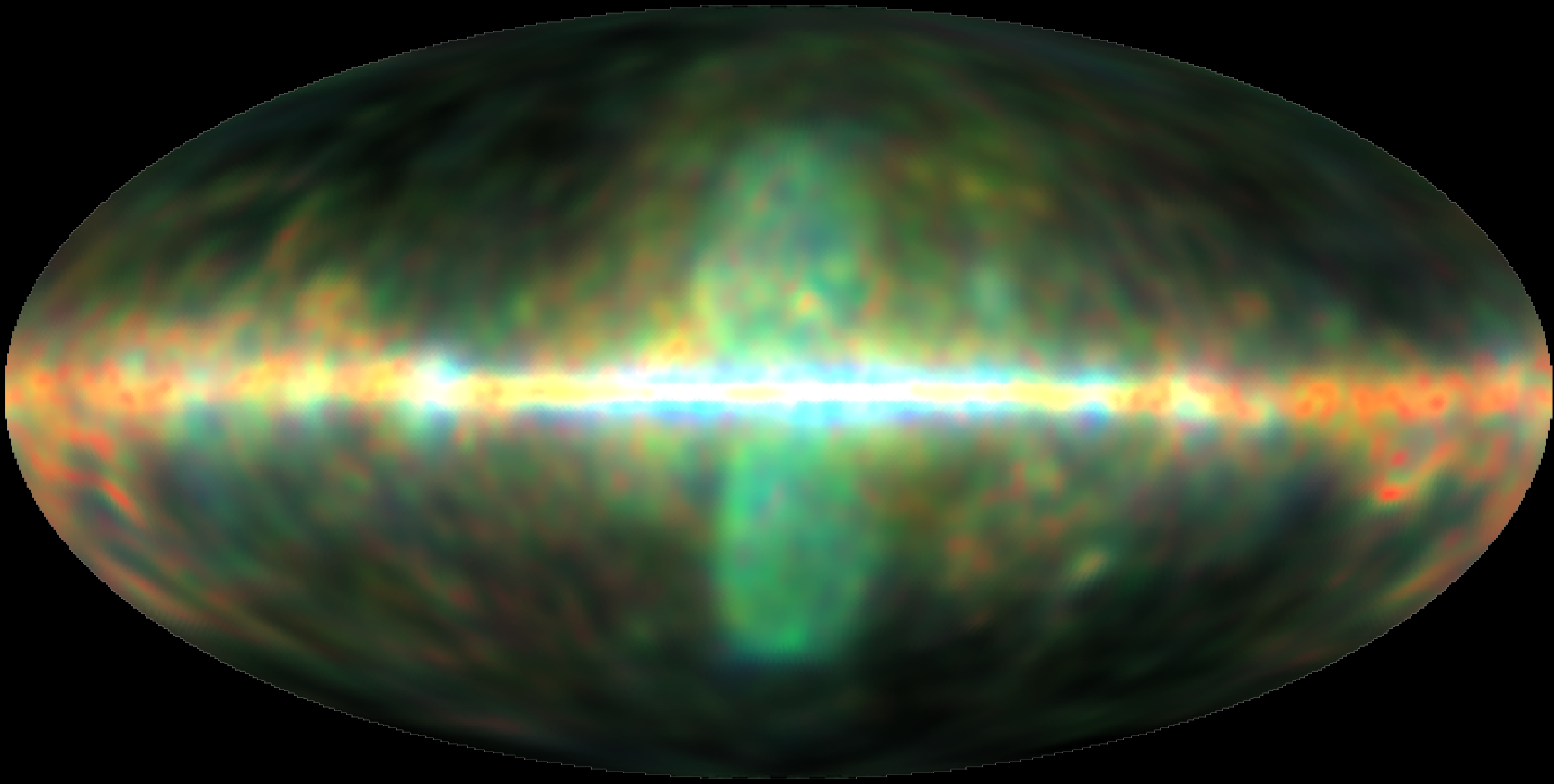
log-data



log-data … denoised

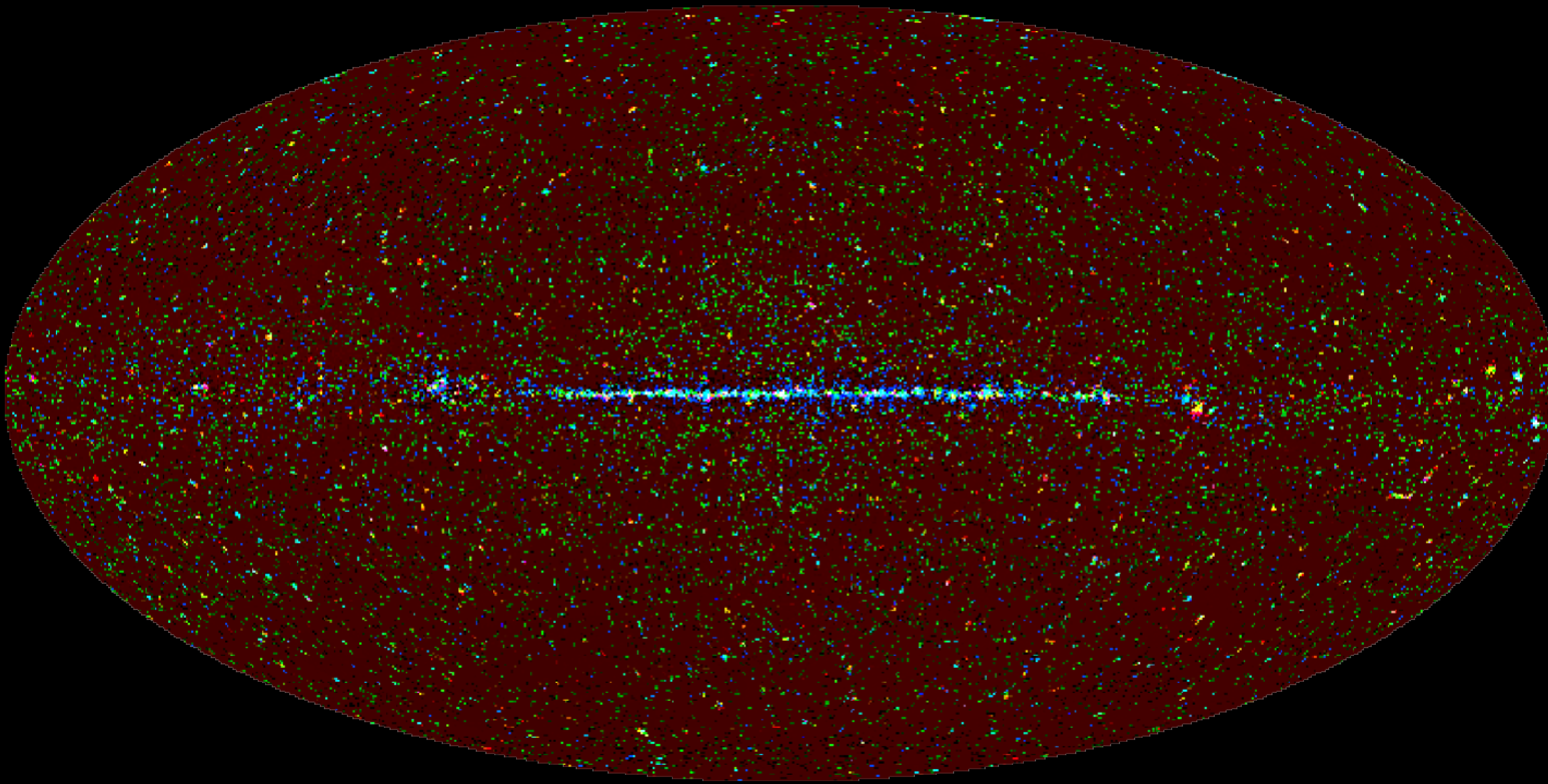


log-data … denoised … deconvolved



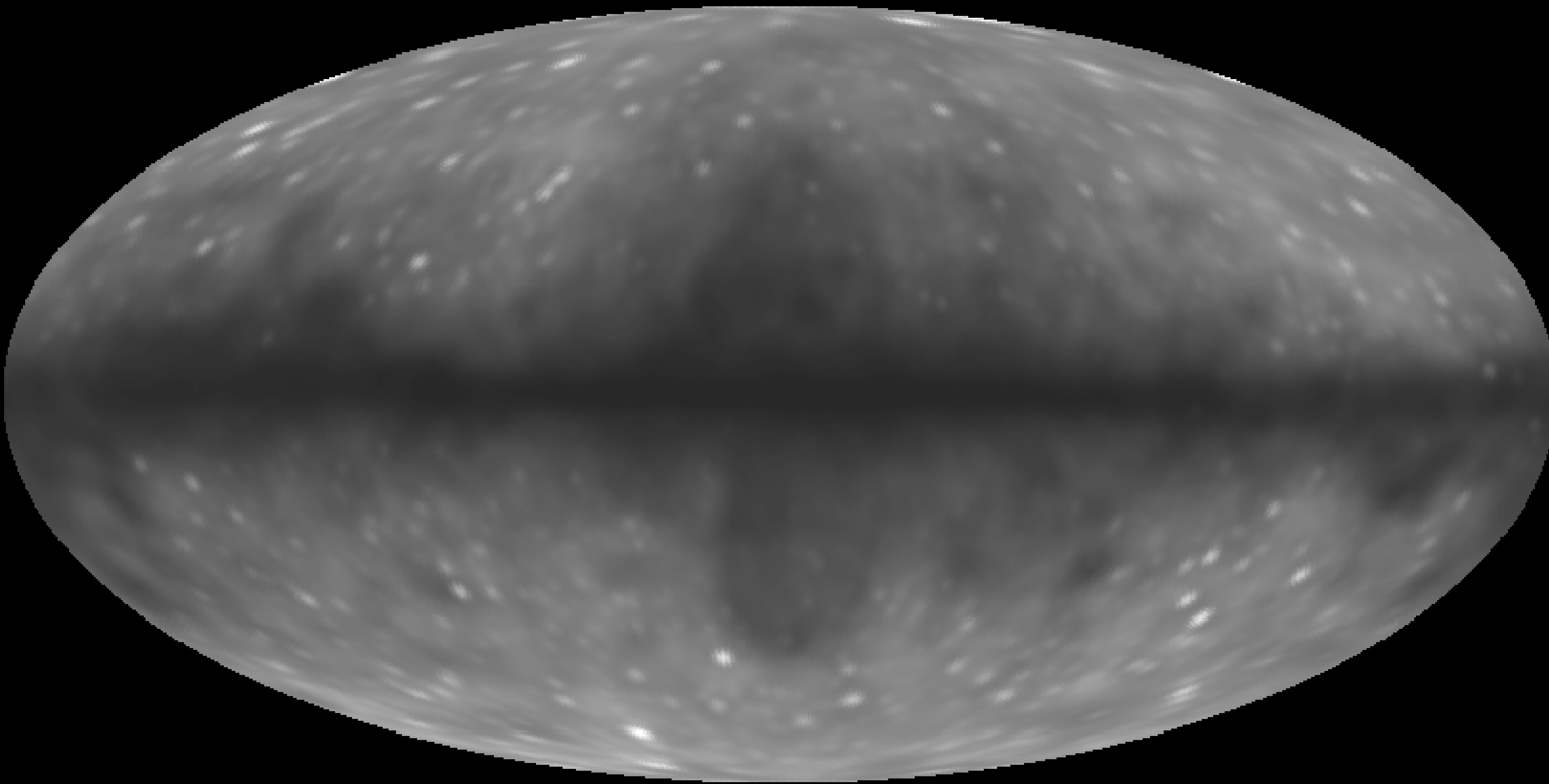
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)



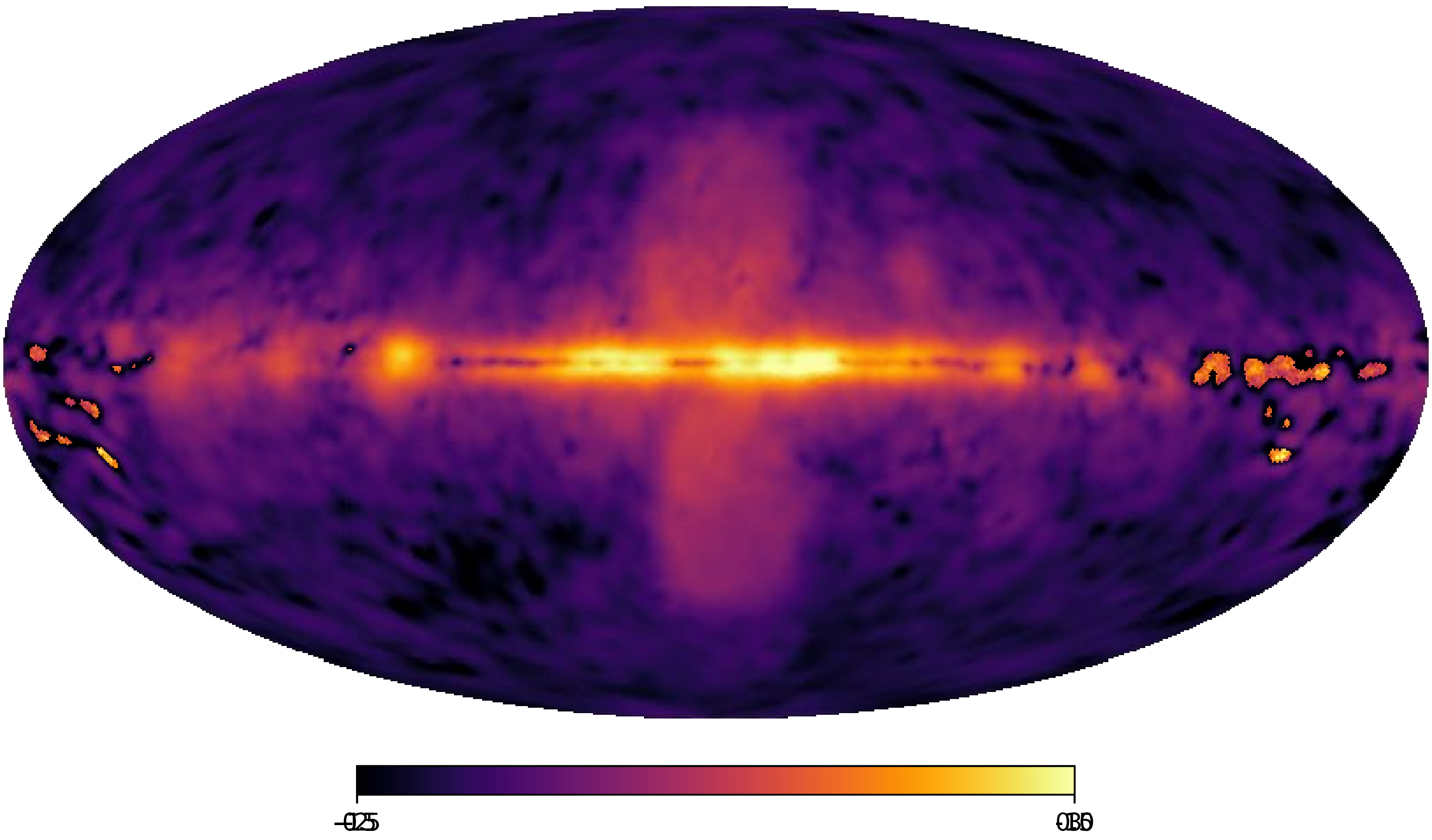
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)

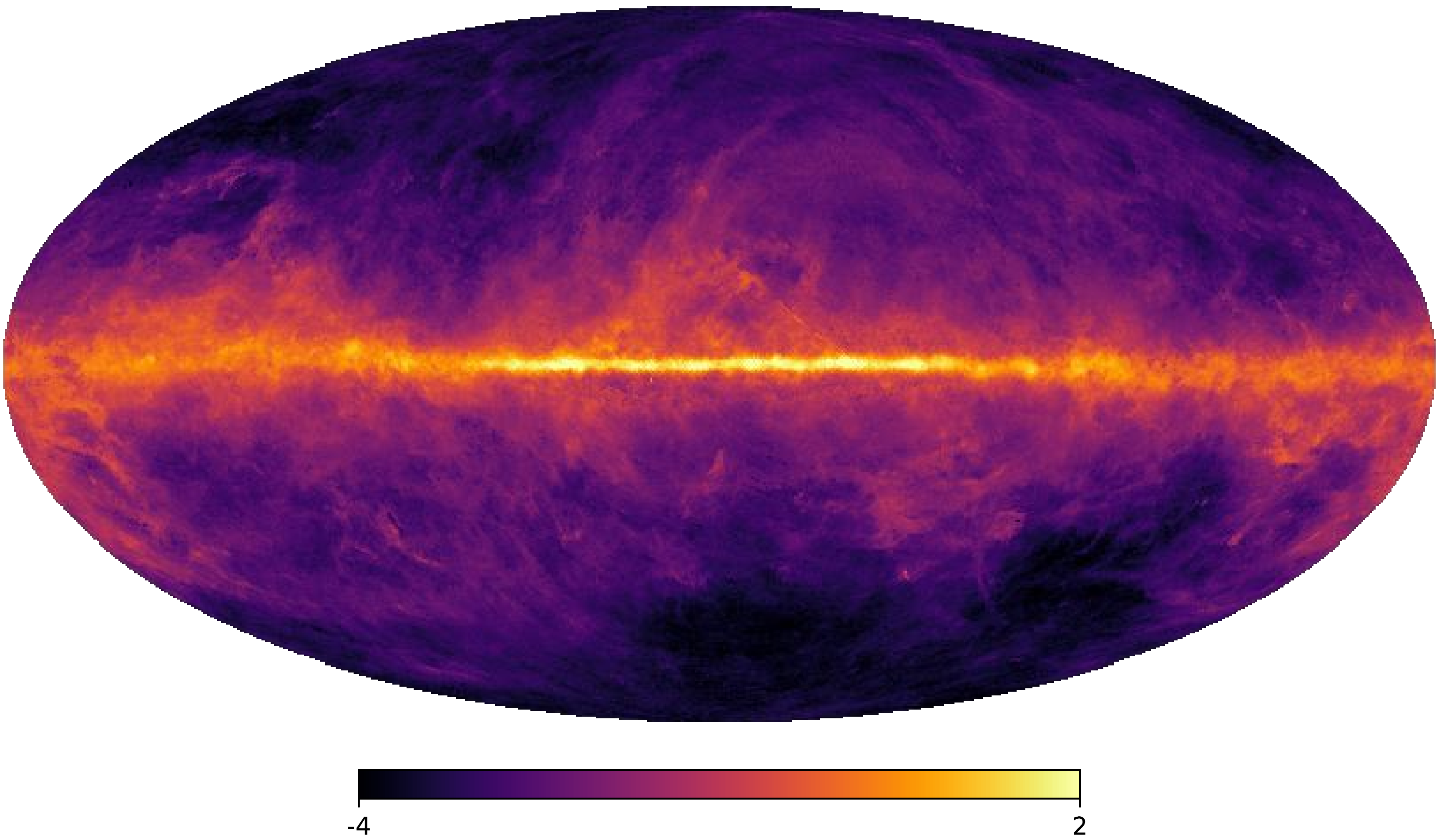


relative uncertainty of diffuse emission

Sharpening up the gamma-ray sky



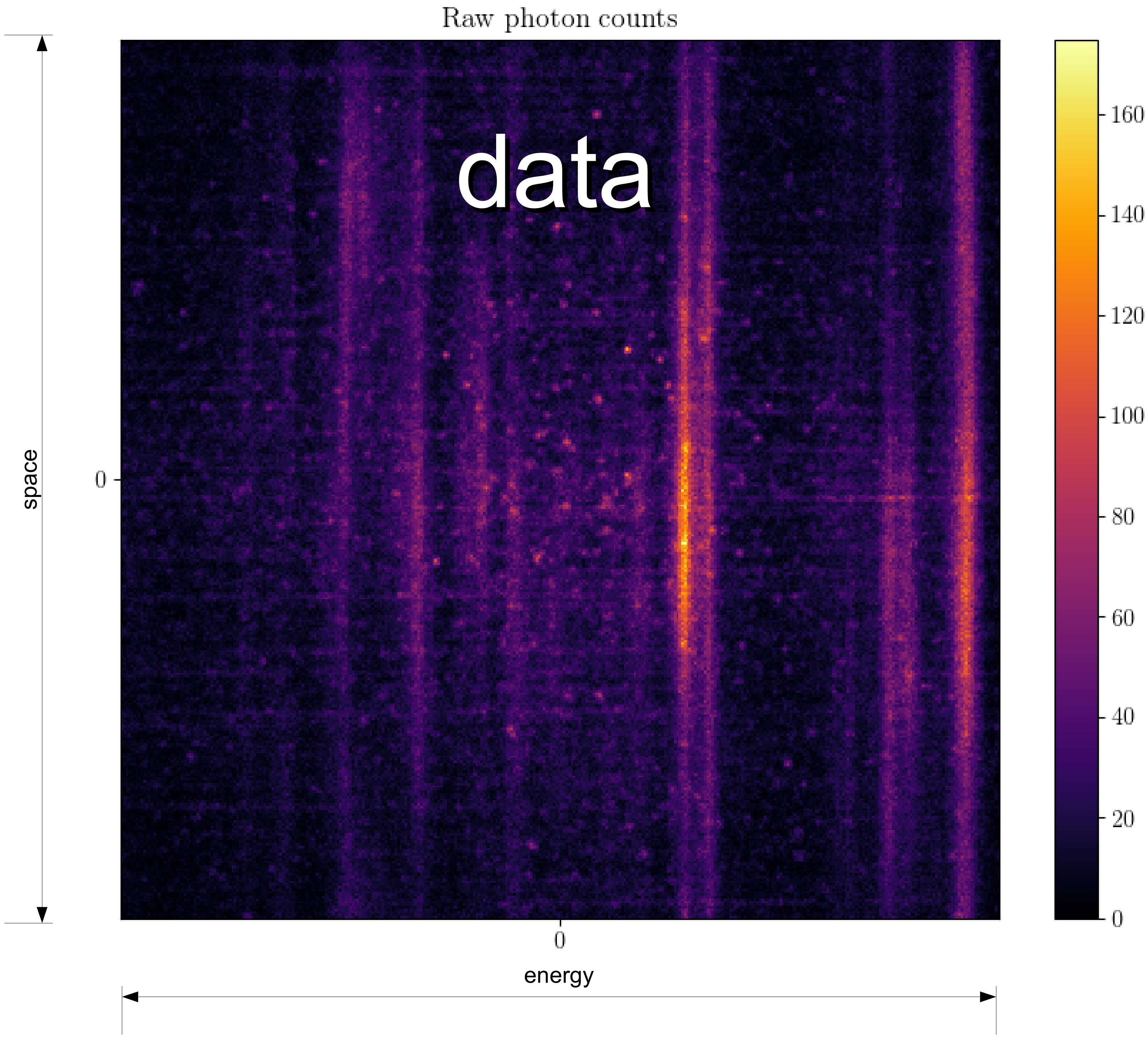
Restoring the hadronic sky



Glimpses into the future

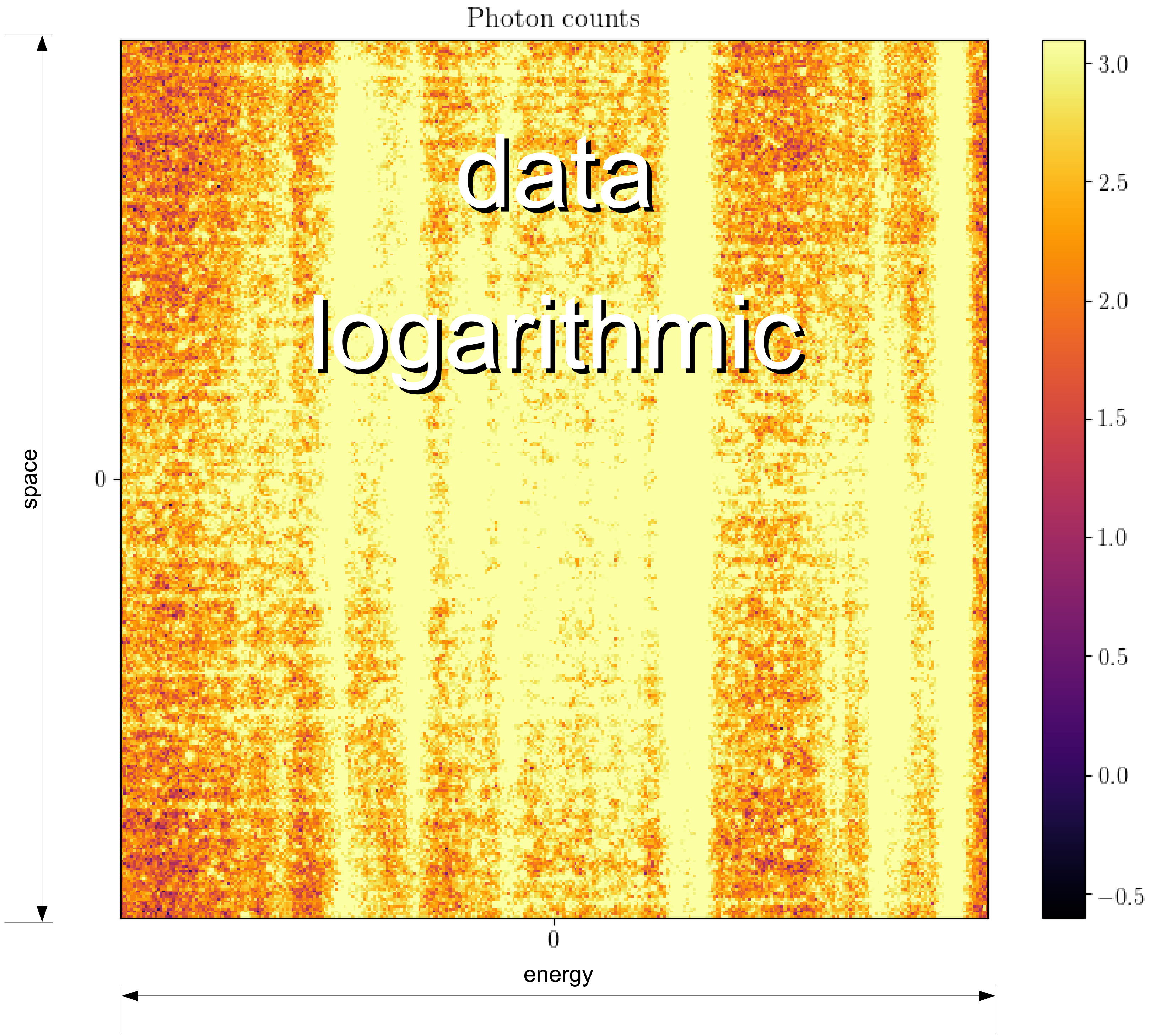
Daniel Pumpe: D^4PO

arXiv:1802.020135

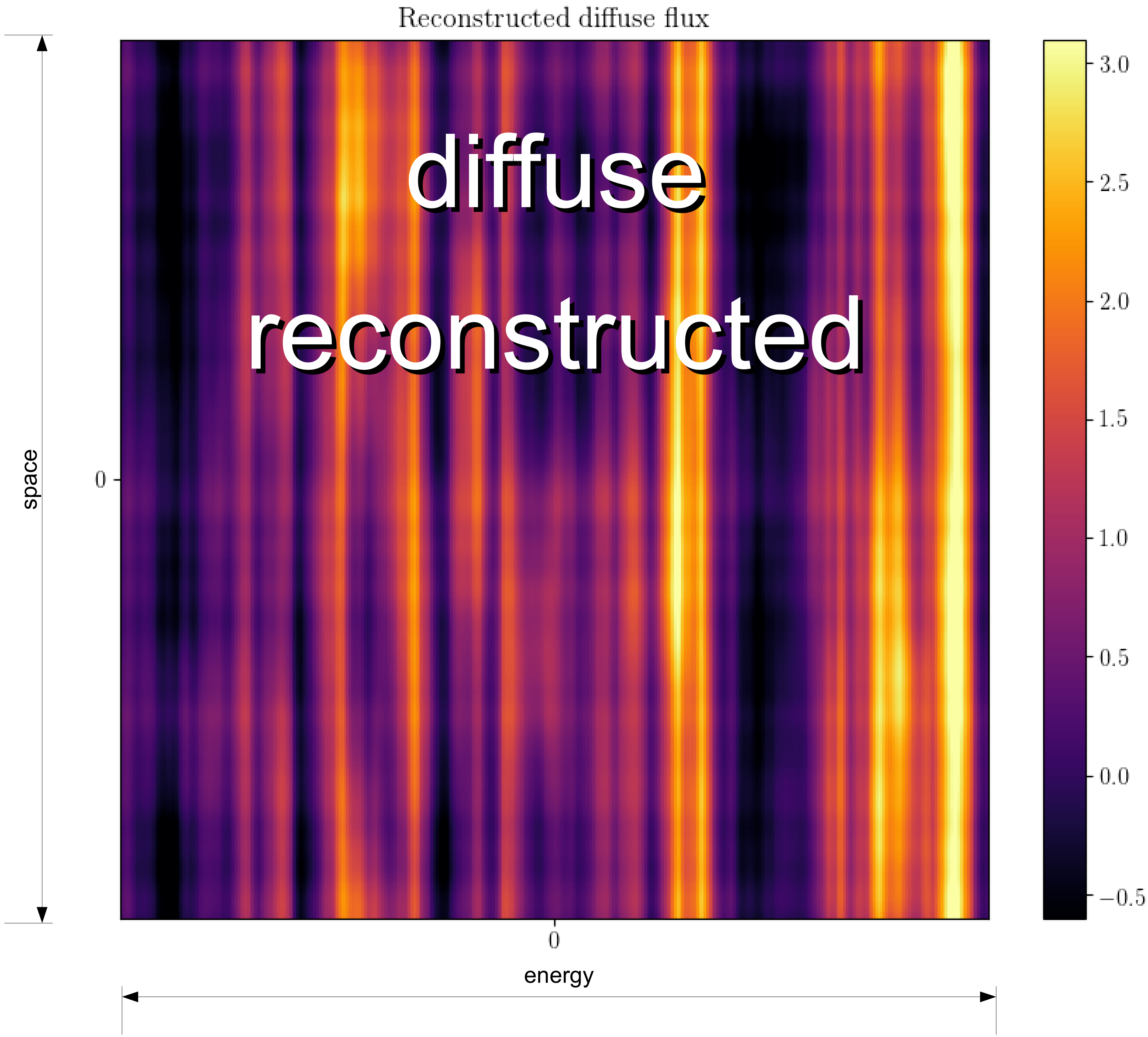


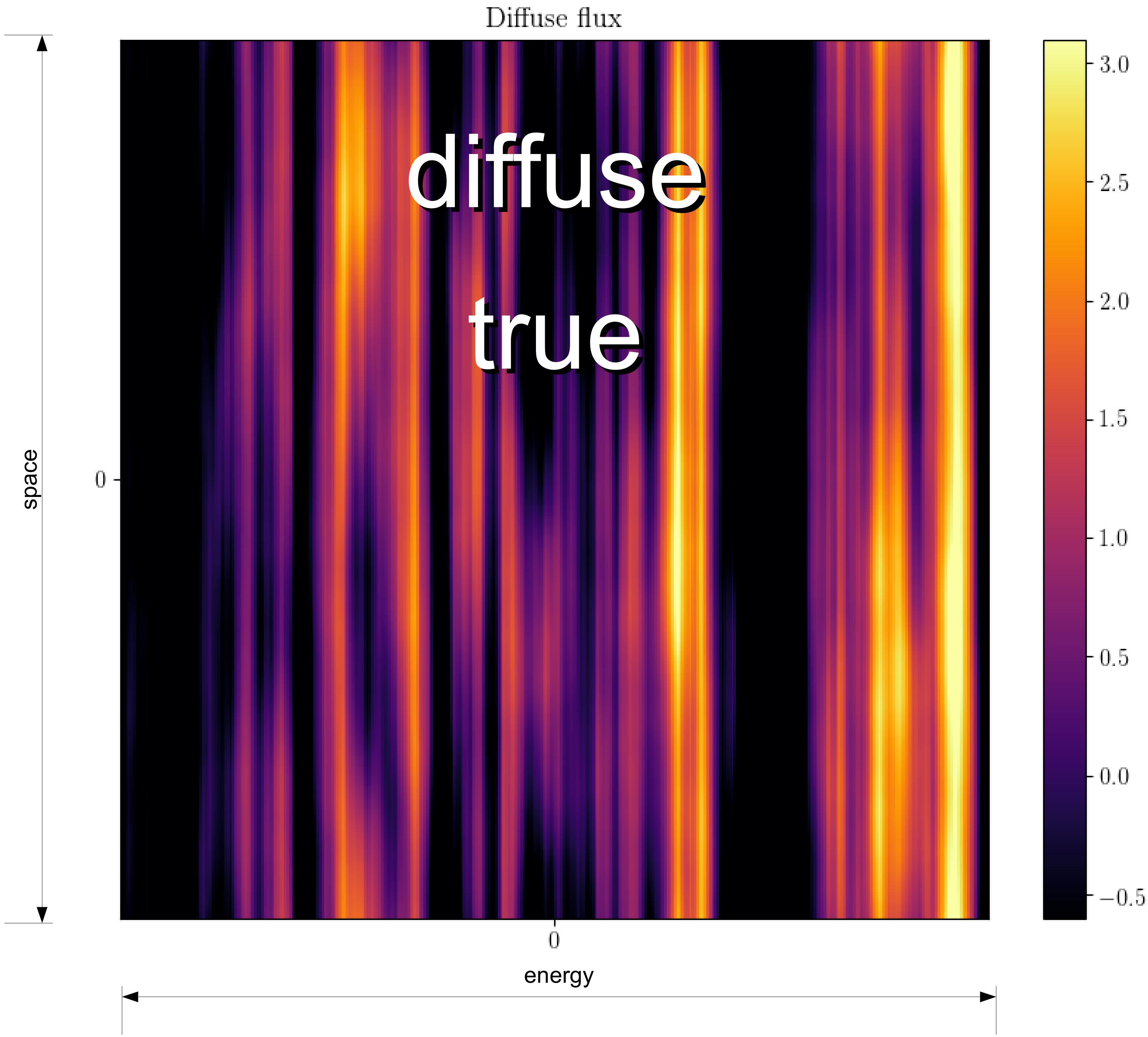
Raw photon counts
data
space
0
0
energy
160
140
120
100
80
60
40
20
0

2018

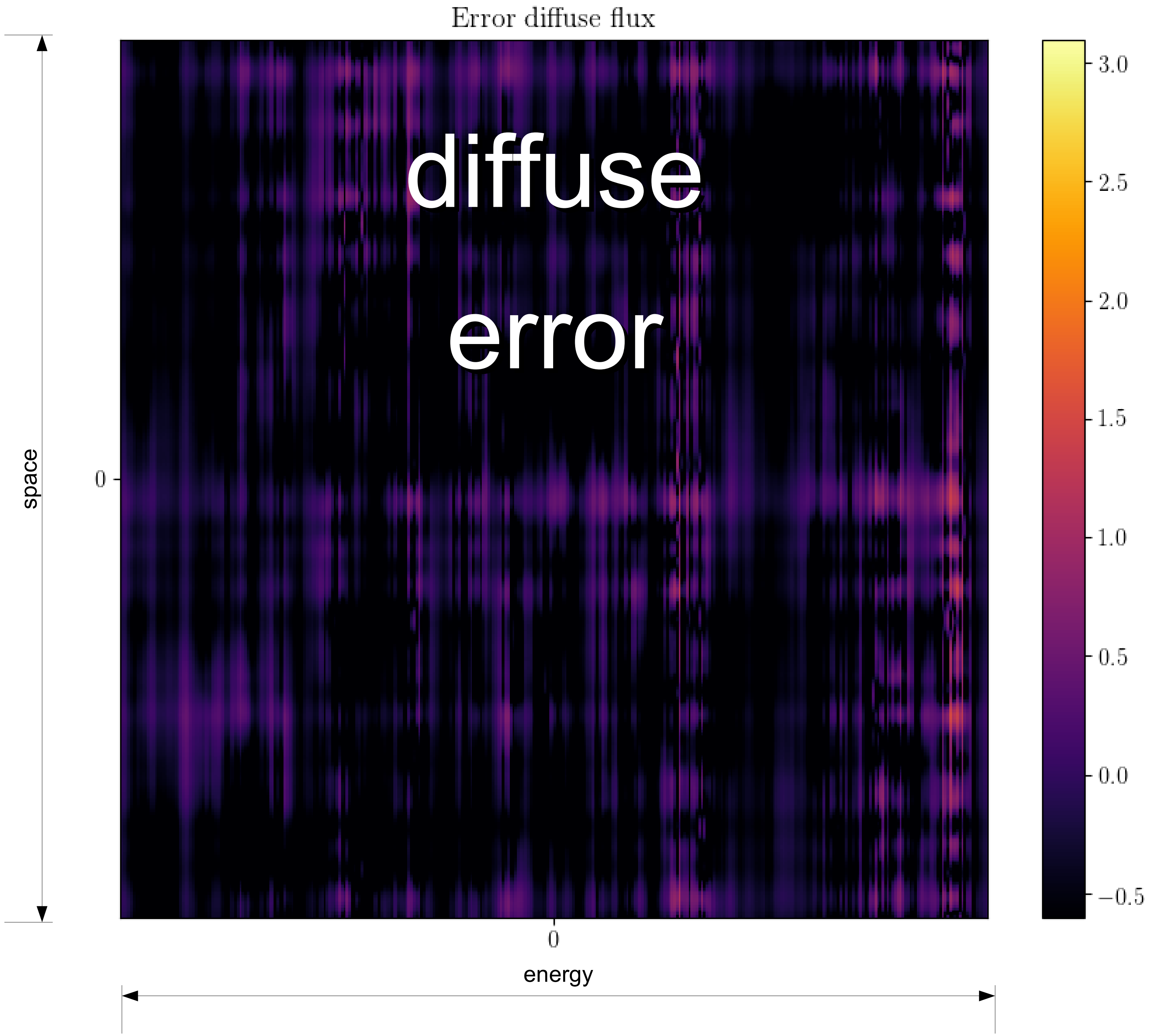


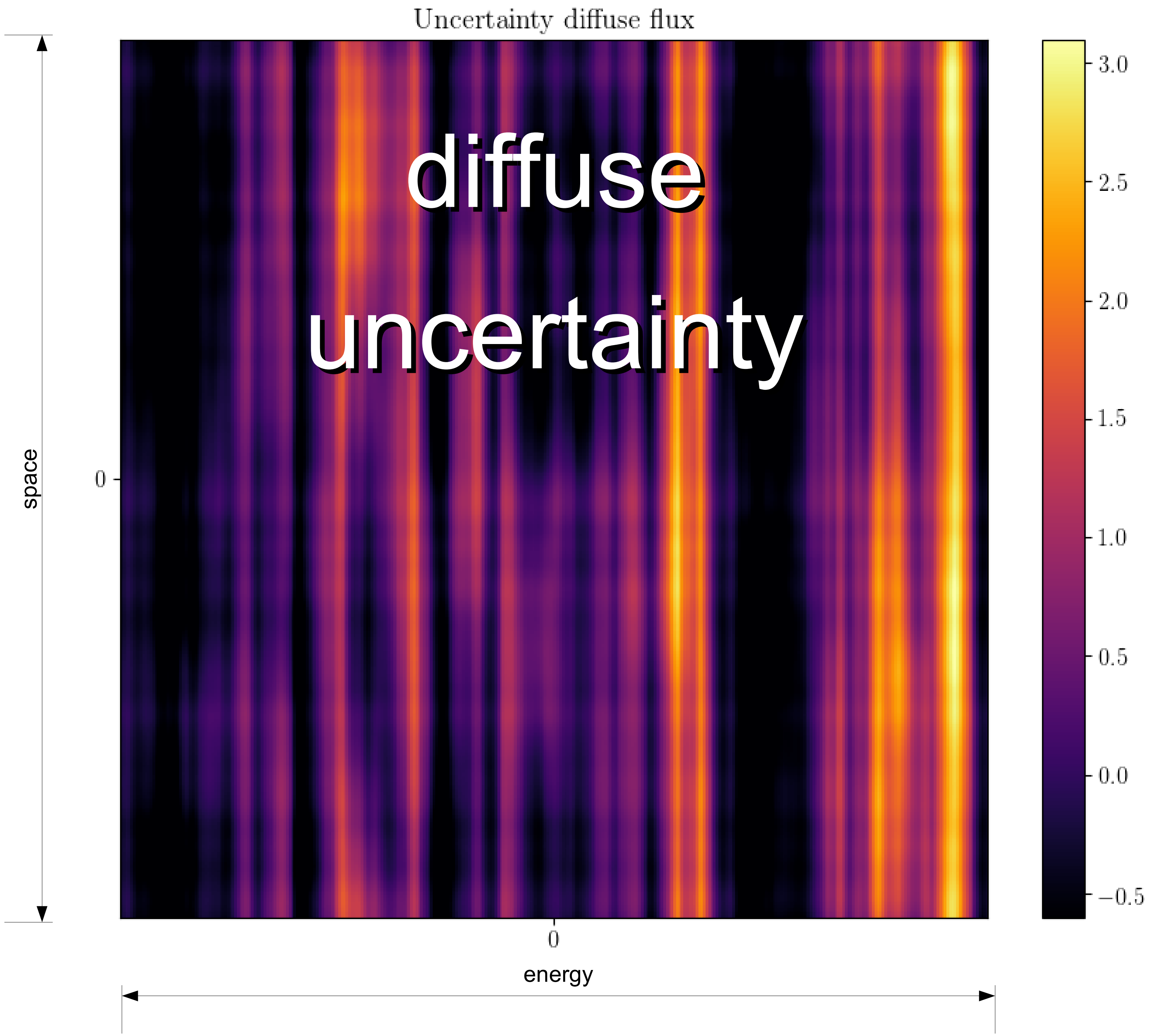
Photon counts
data
logarithmic
space
0
energy
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

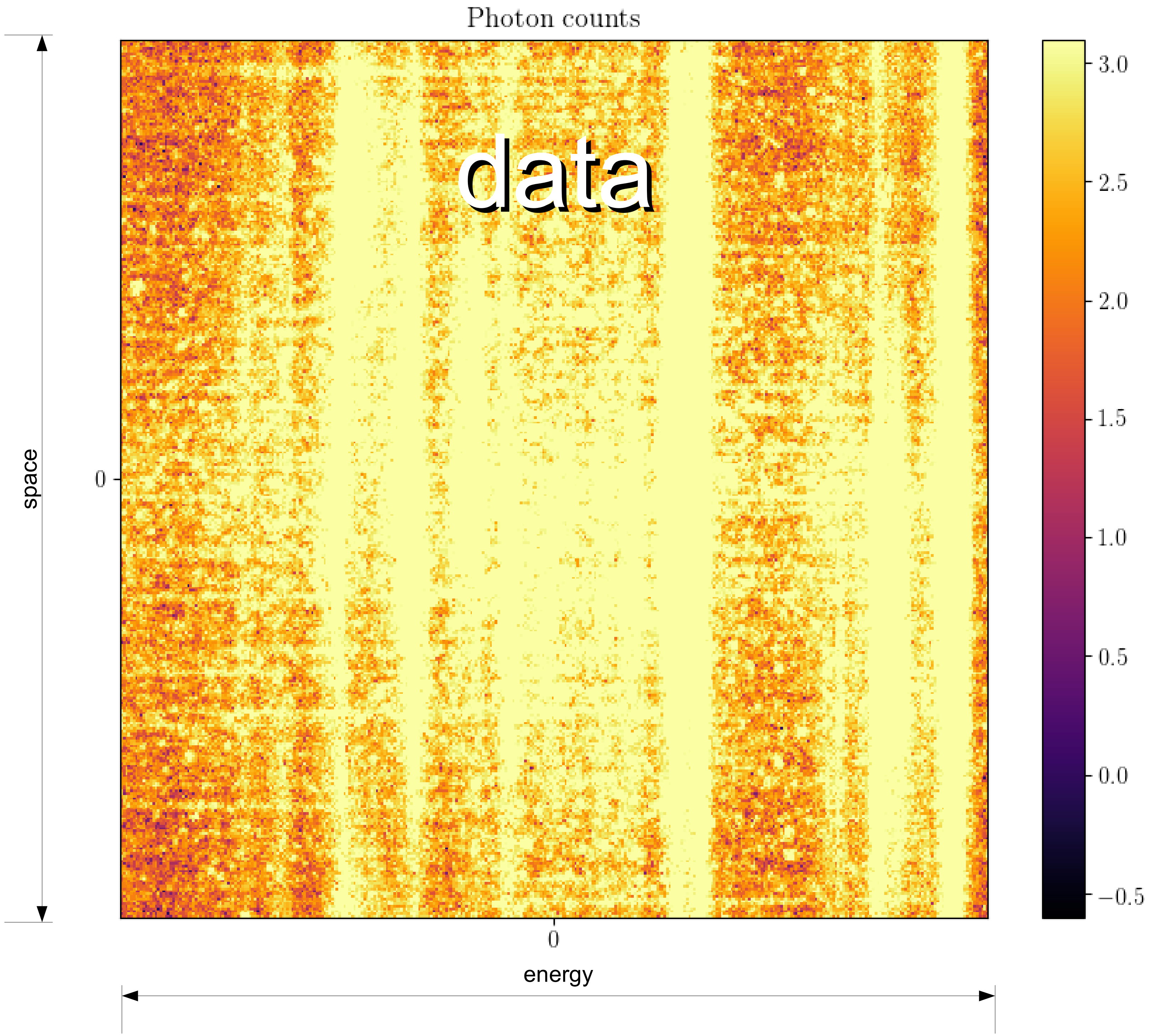

Reconstructed diffuse flux
diffuse
reconstructed
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

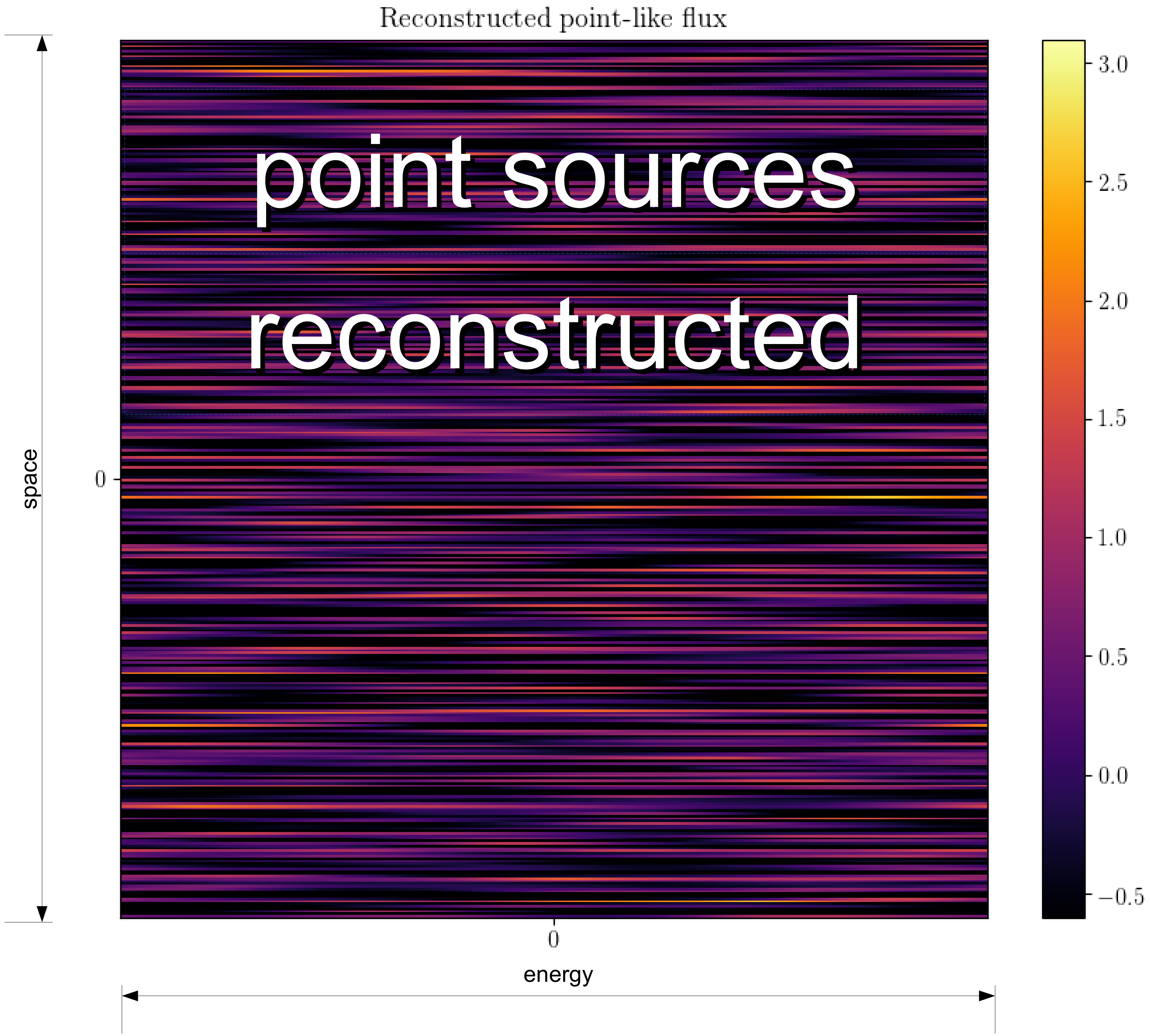


Diffuse flux
diffuse
true
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

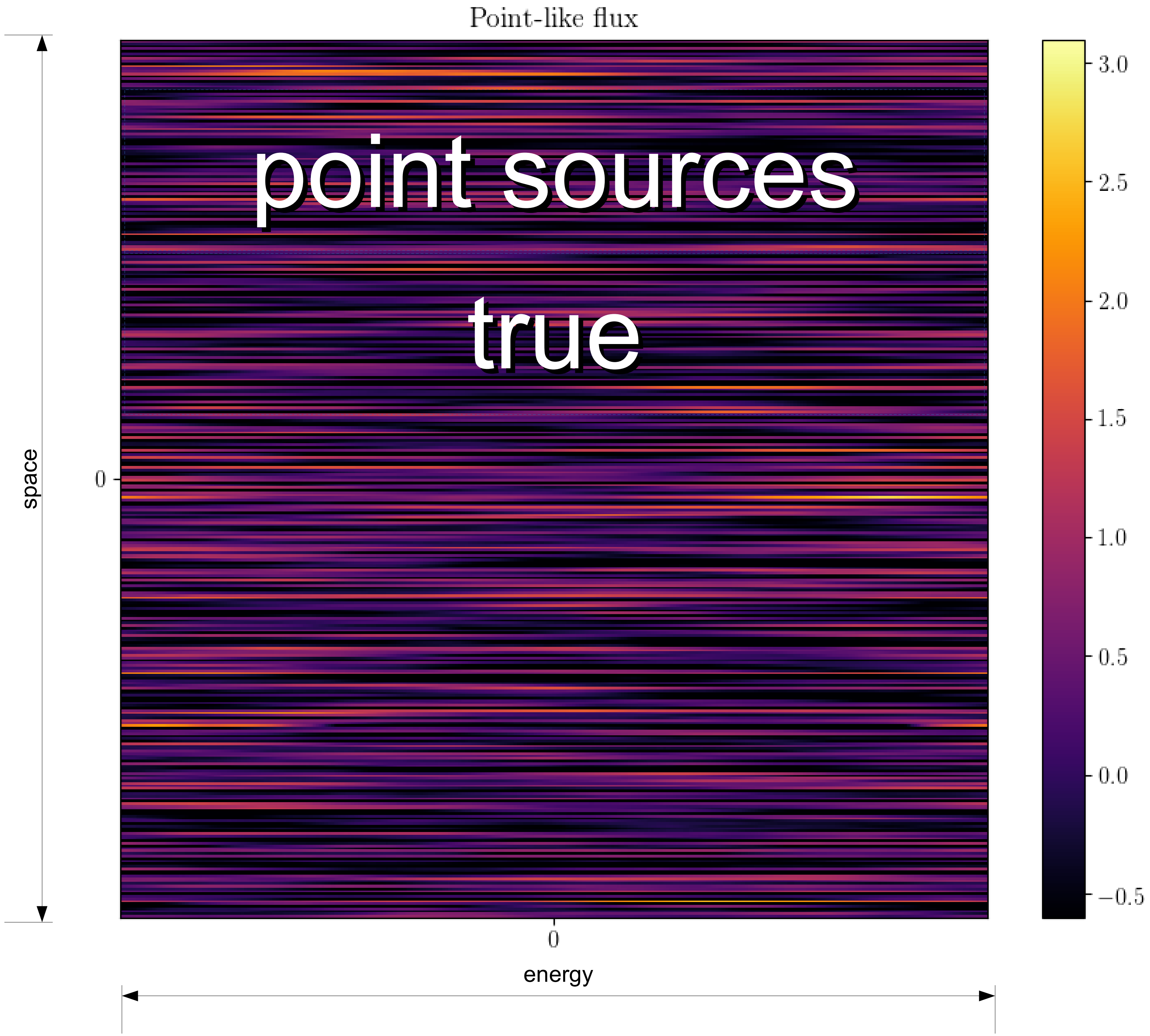

Error diffuse flux
diffuse
error
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5


Uncertainty diffuse flux
diffuse
uncertainty
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5


Photon counts
data
space
0
energy
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

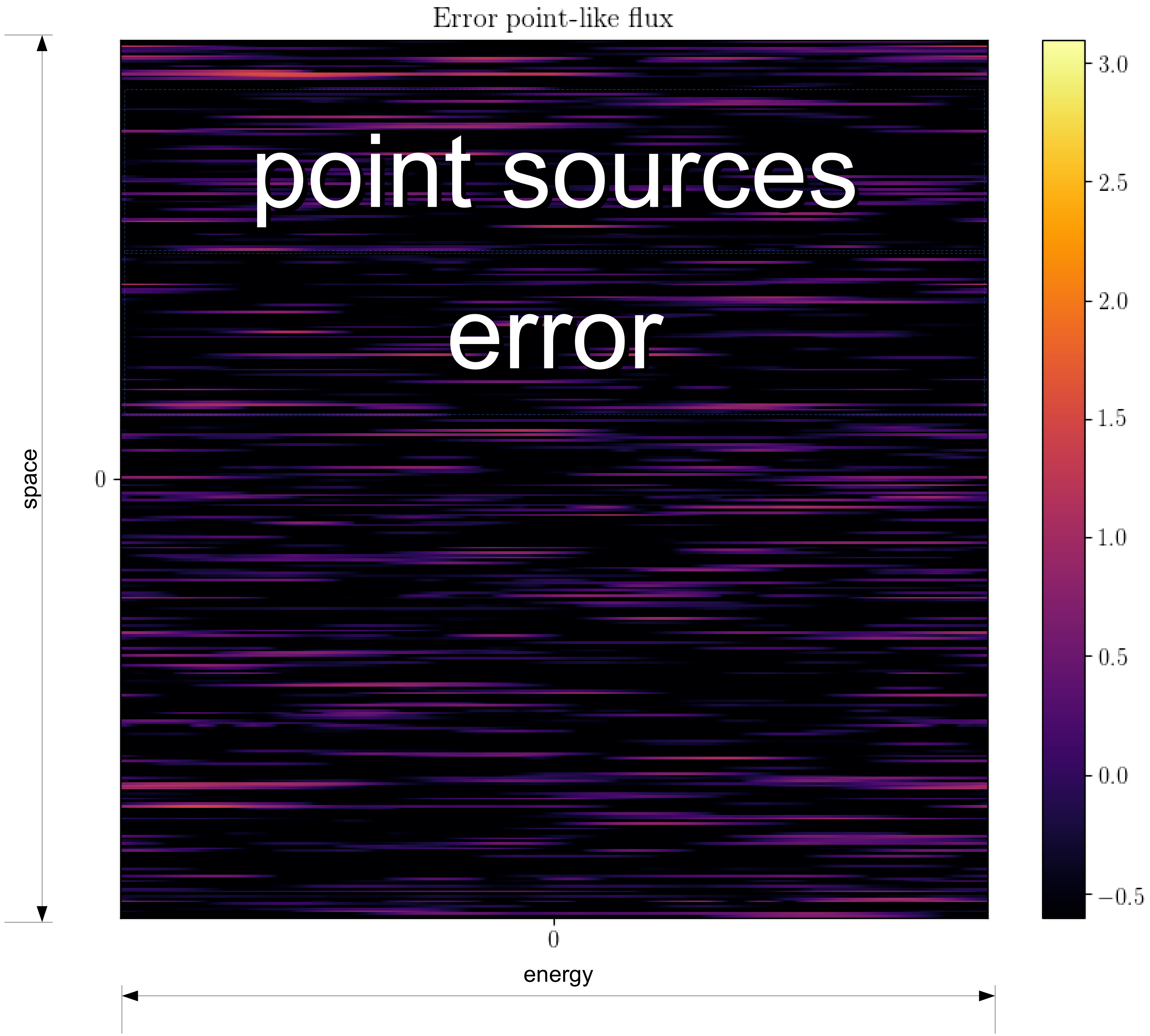

Reconstructed point-like flux
point sources
reconstructed
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

2018

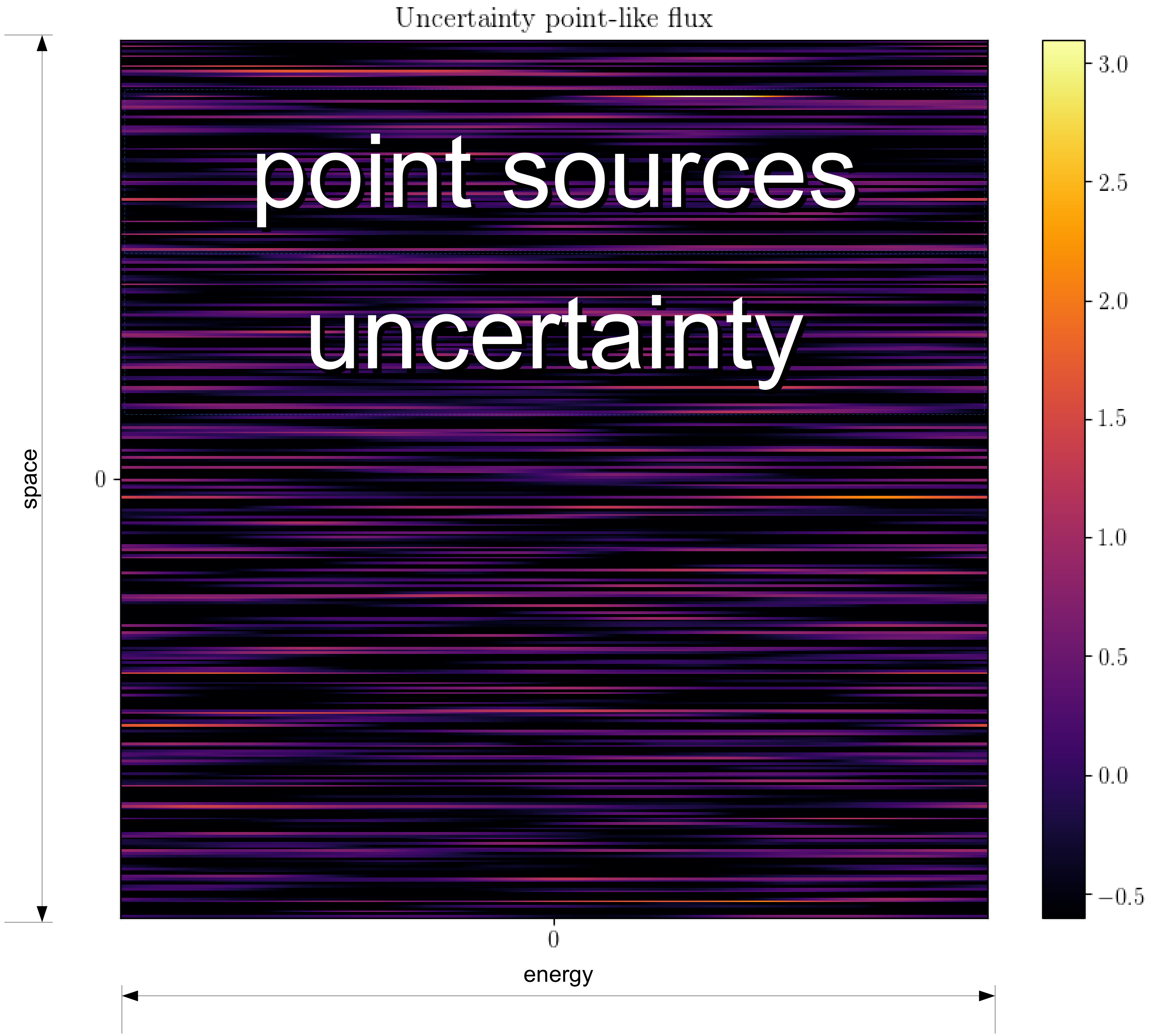


Point-like flux
point sources
true
space
0
energy
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

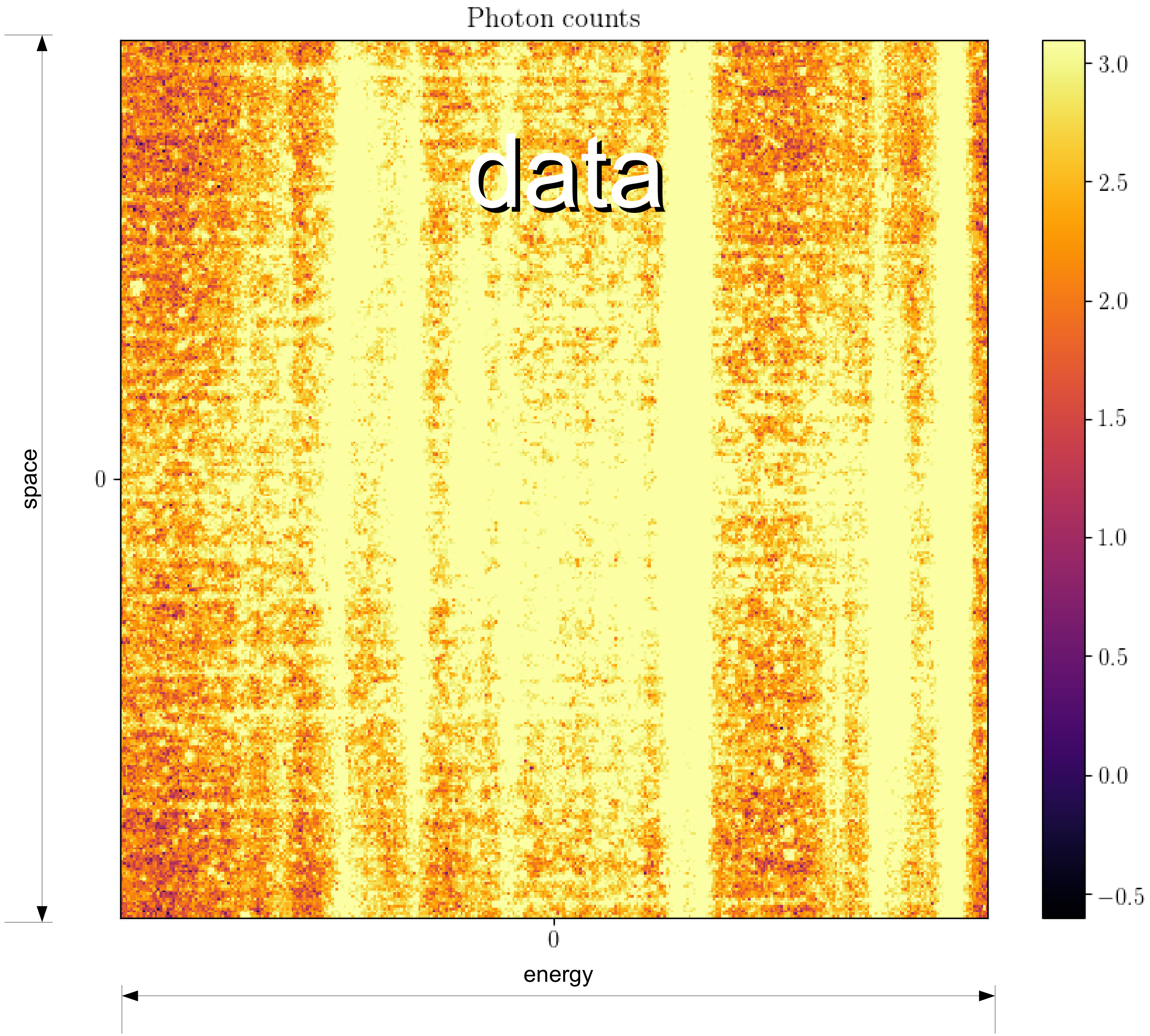
2018

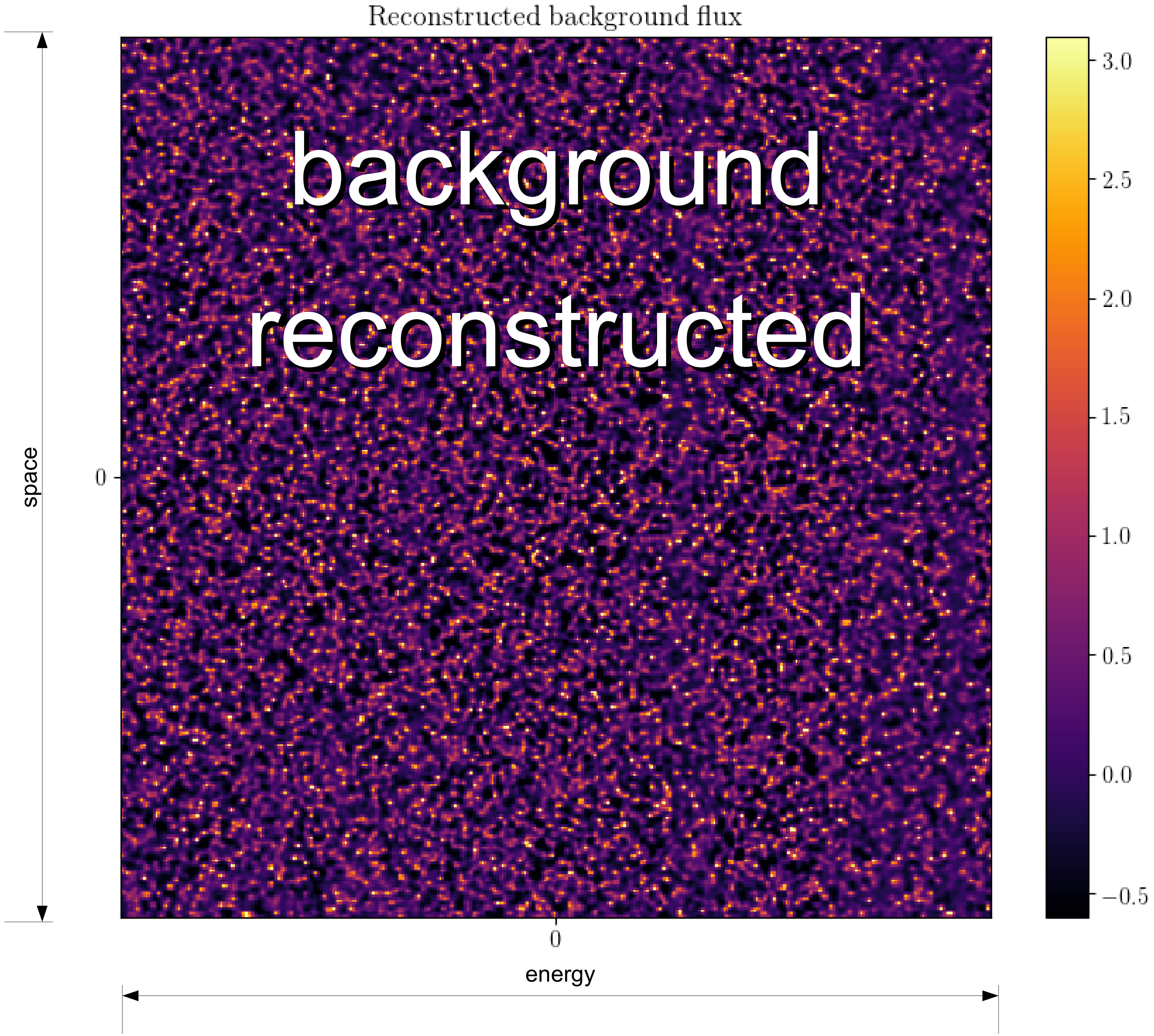

Error point-like flux
point sources
error
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
space
0
0
energy

2018

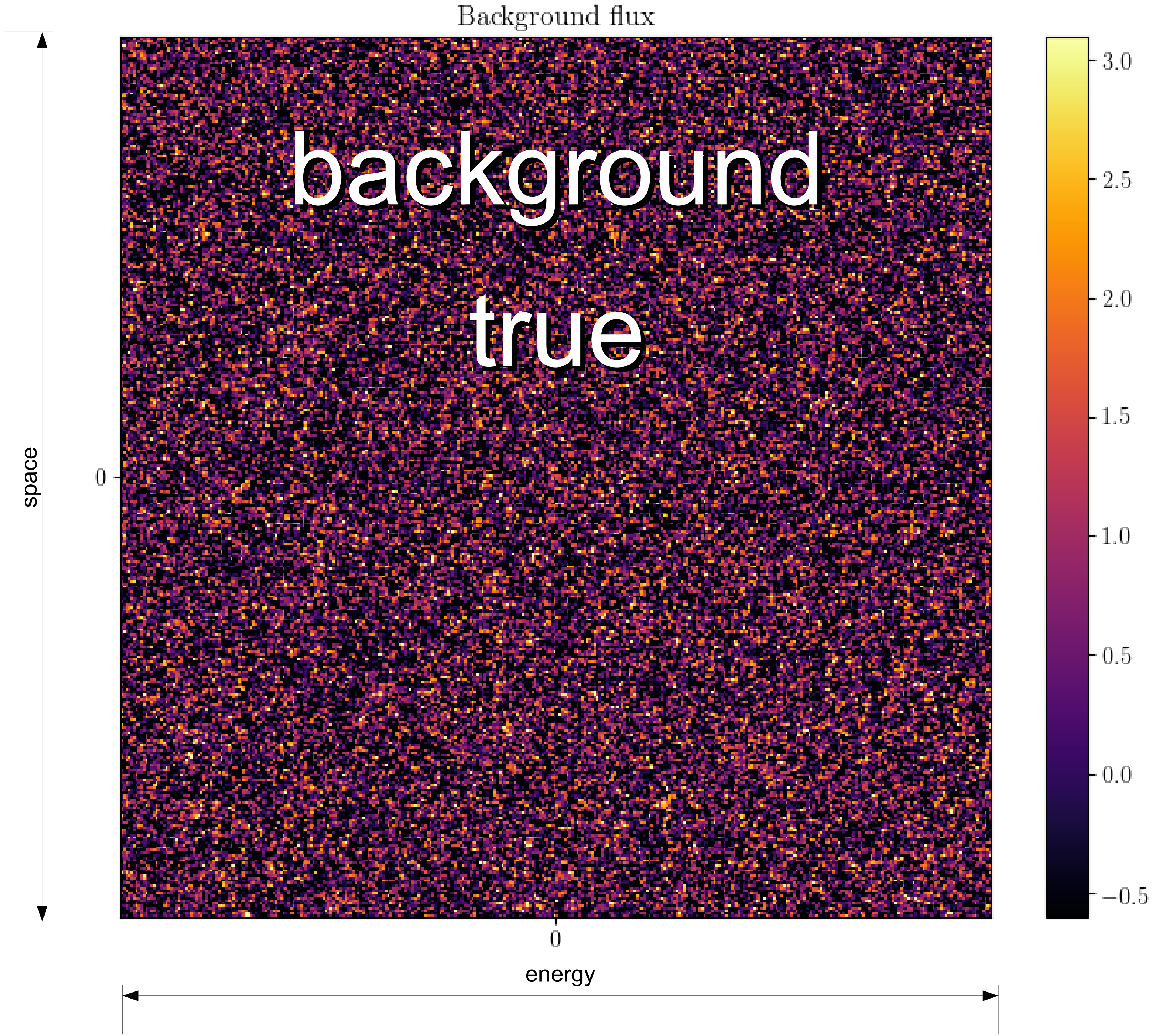

Uncertainty point-like flux
point sources
uncertainty
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

2018

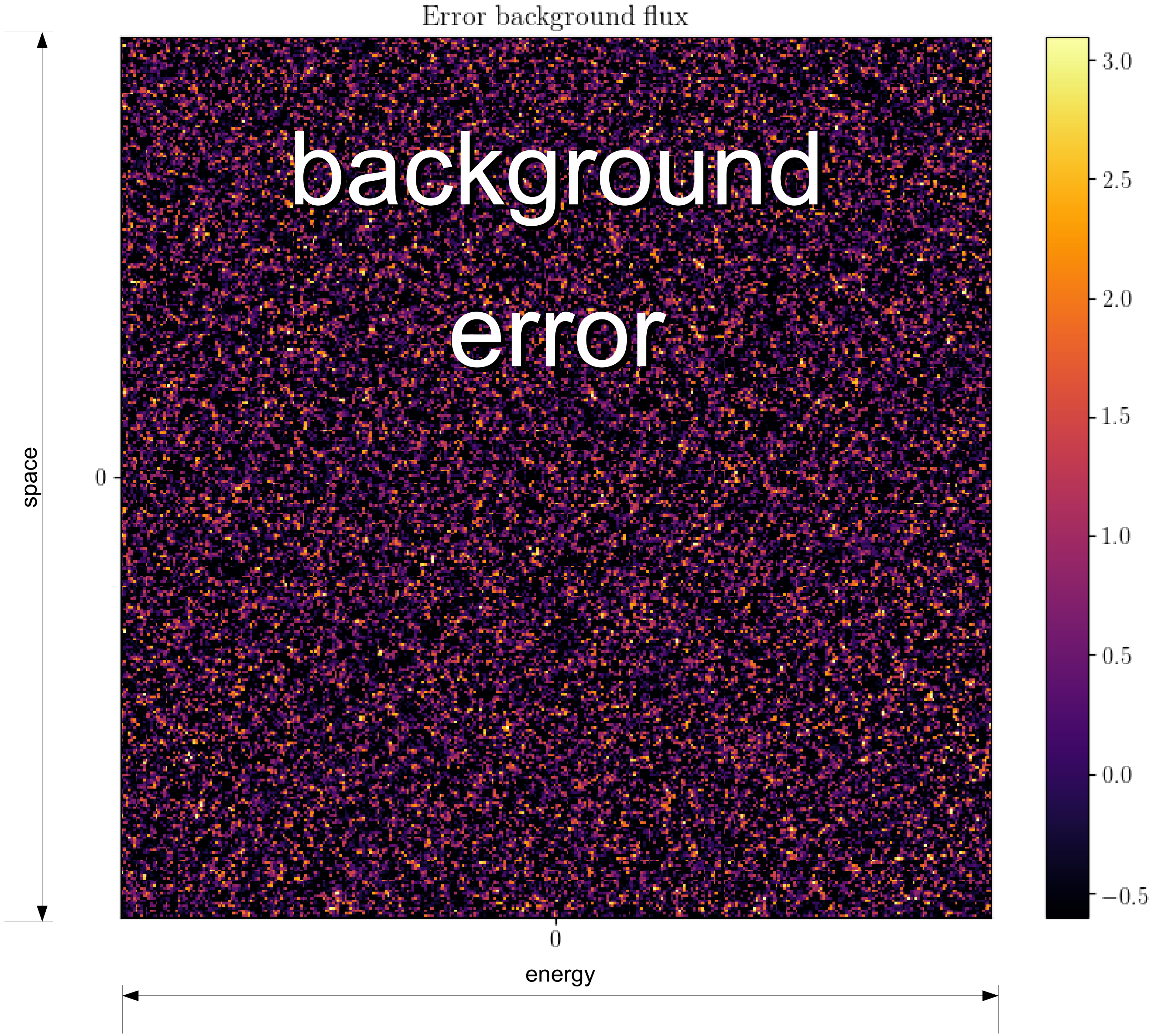

Photon counts
data
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

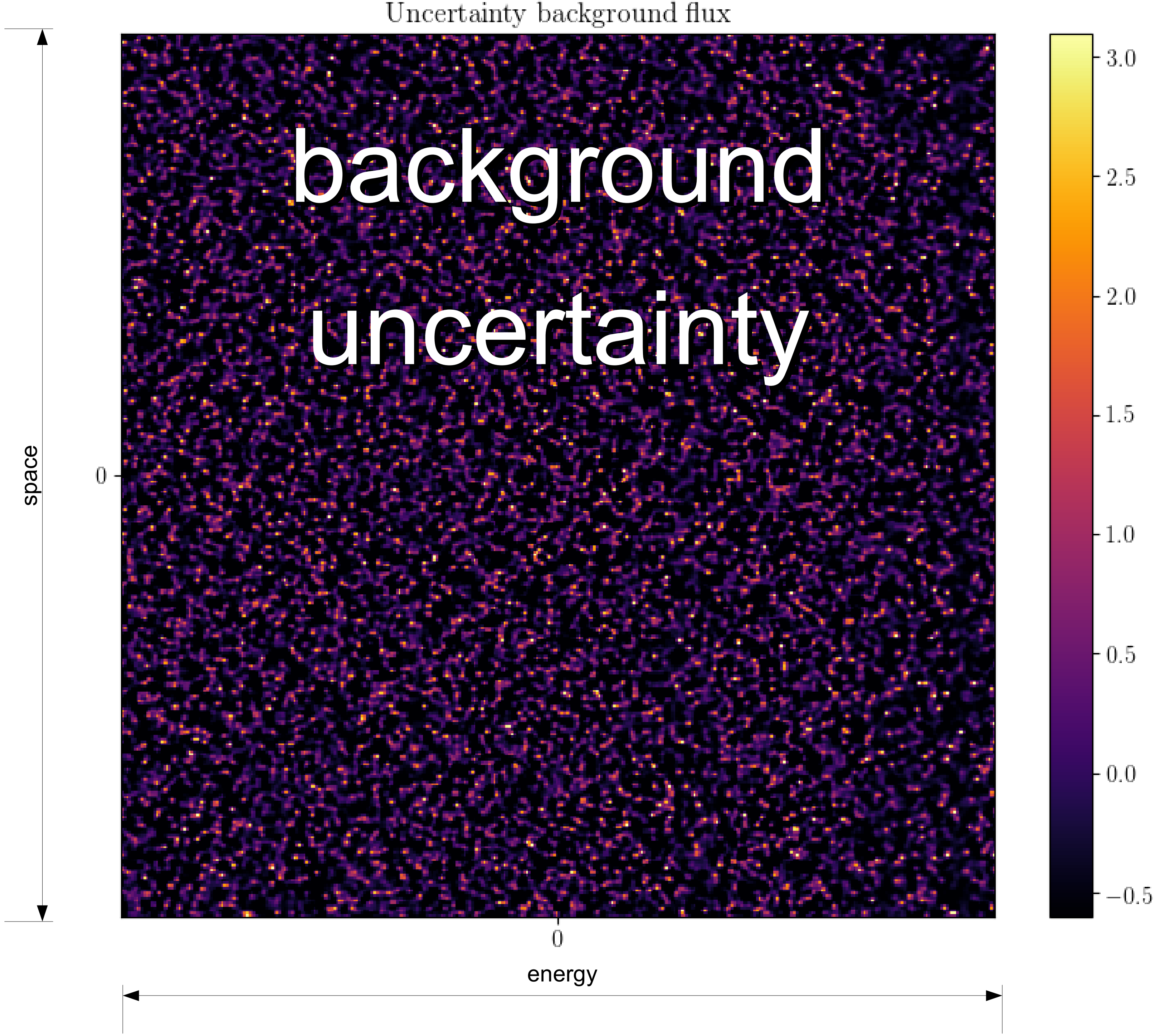


Reconstructed background flux
background
reconstructed
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5



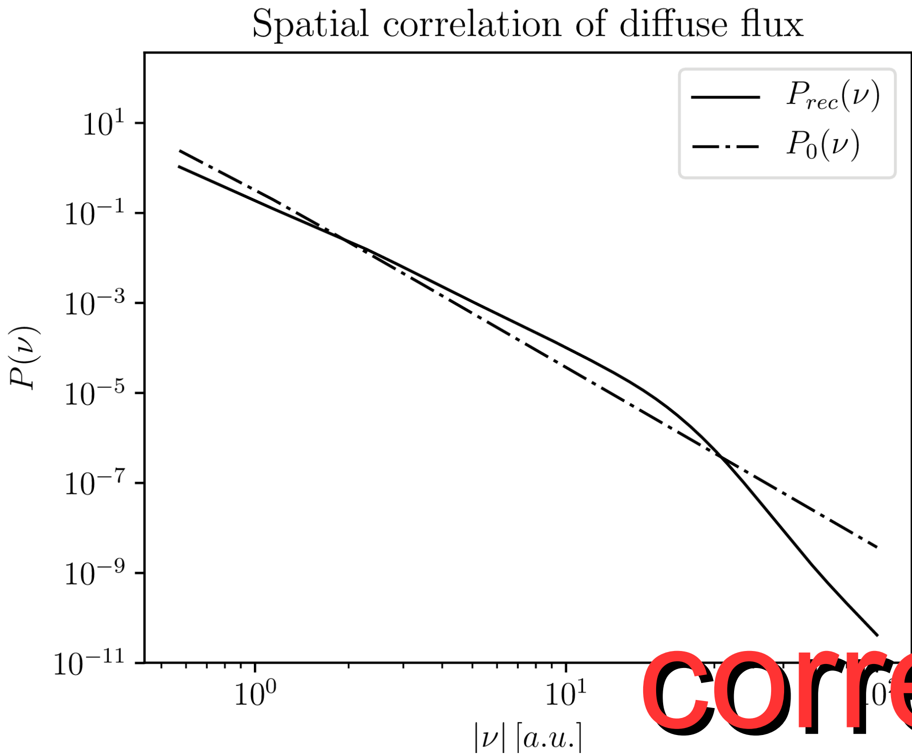
Background flux
background
true
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

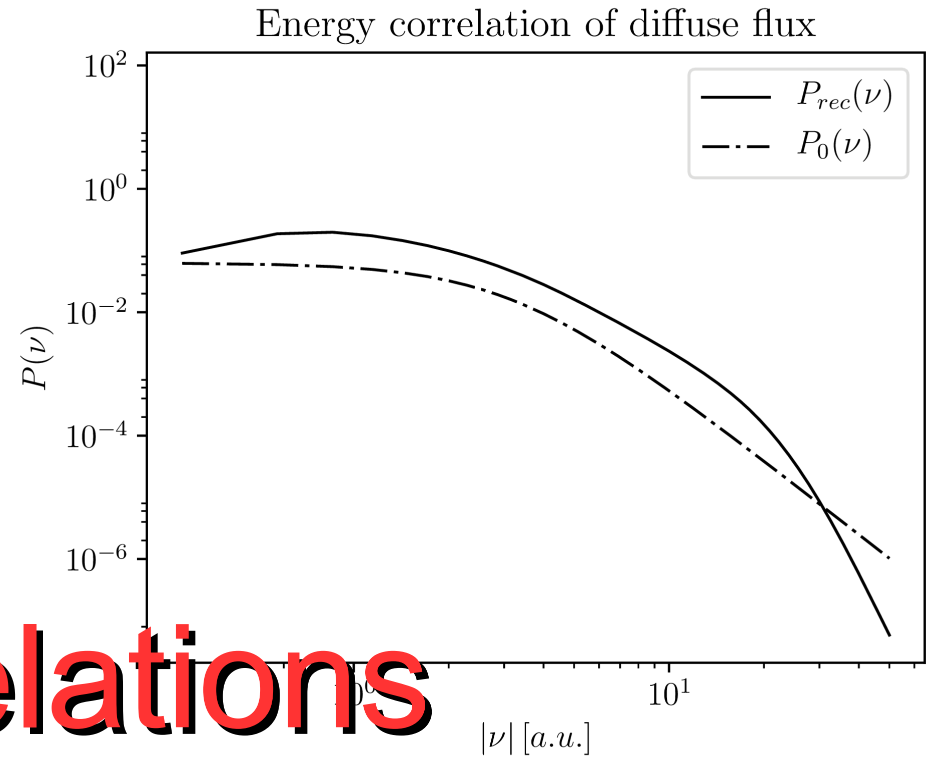

Error background flux
background
error
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

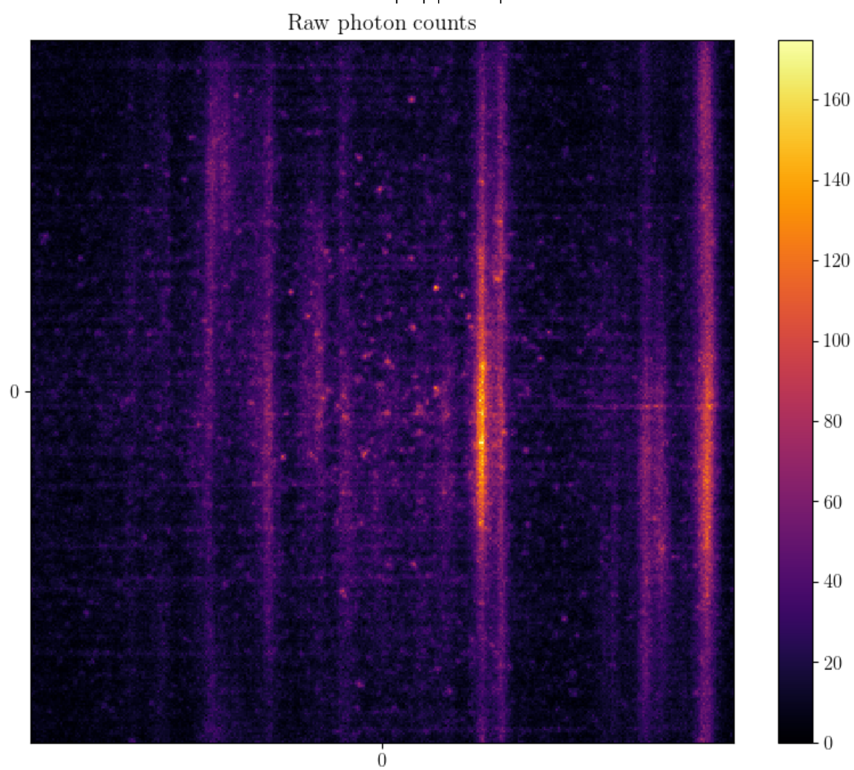


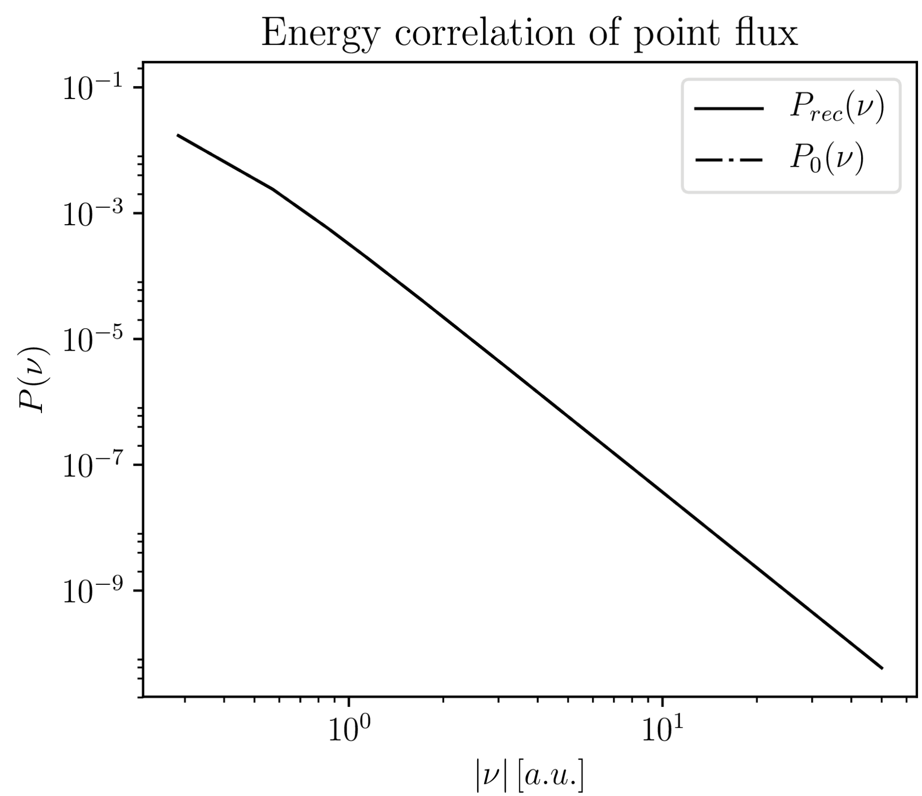
Uncertainty background flux
background
uncertainty
space
0
energy
0
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

correlations

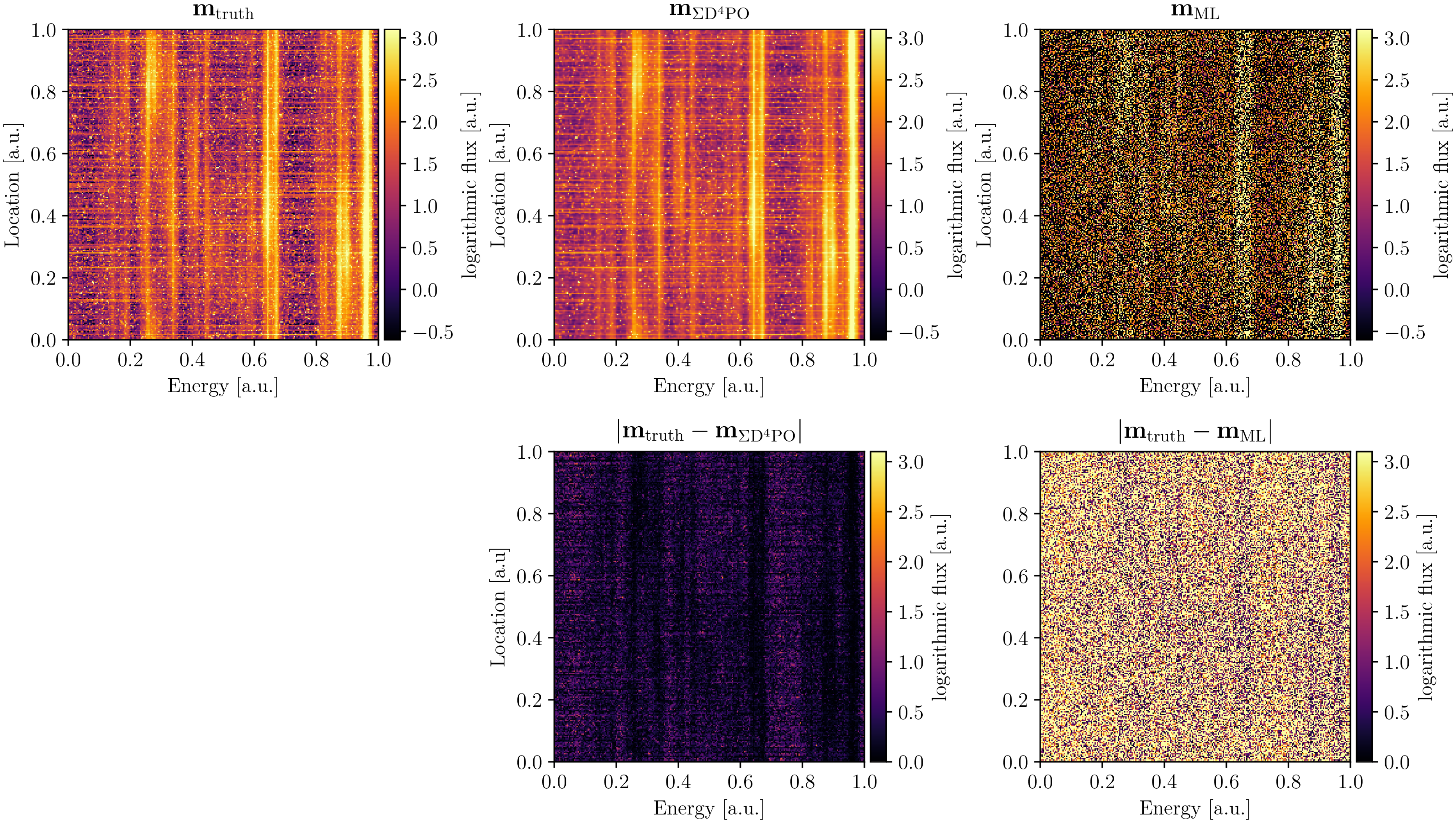








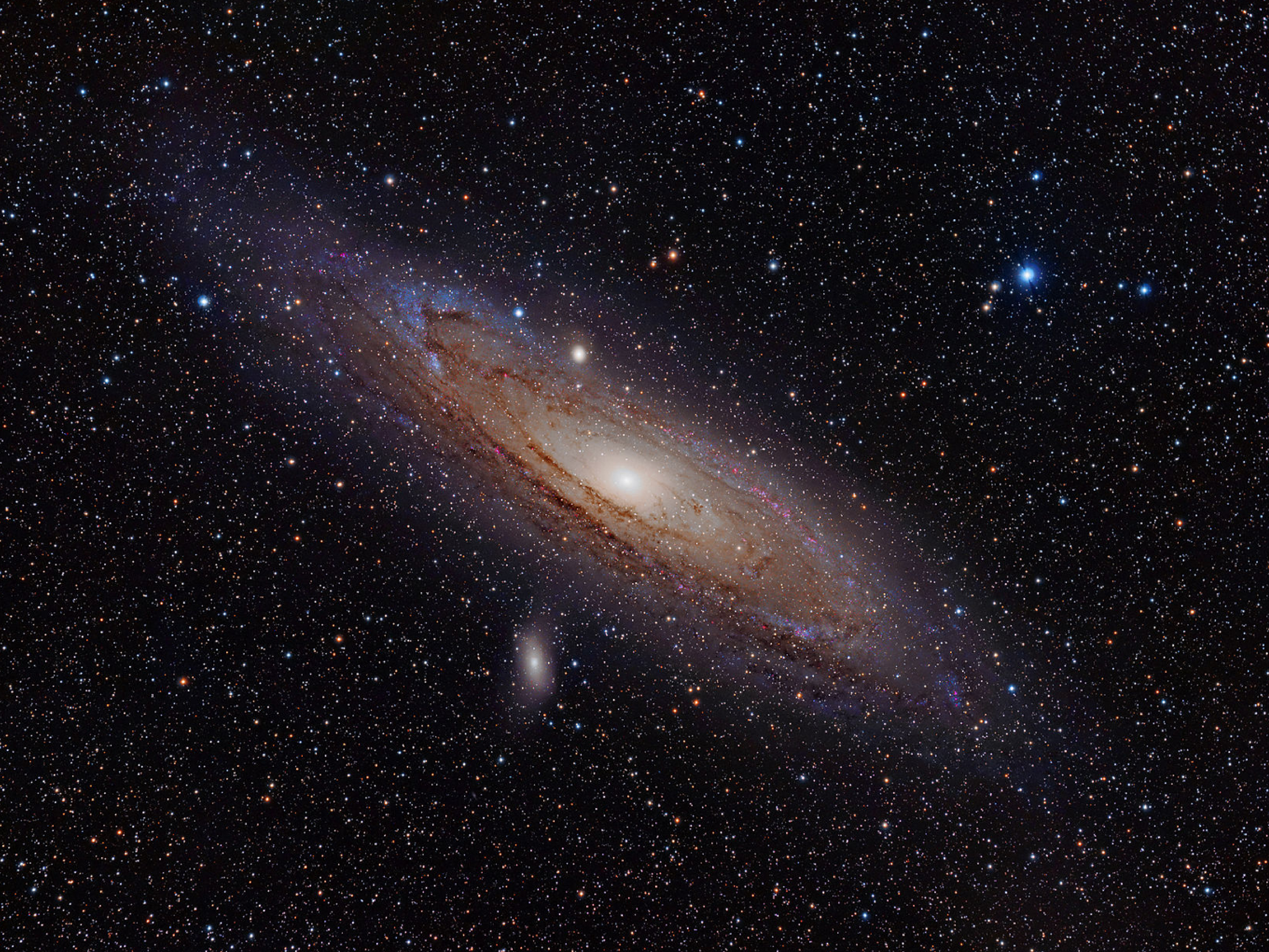
D^{4}PO vs ML

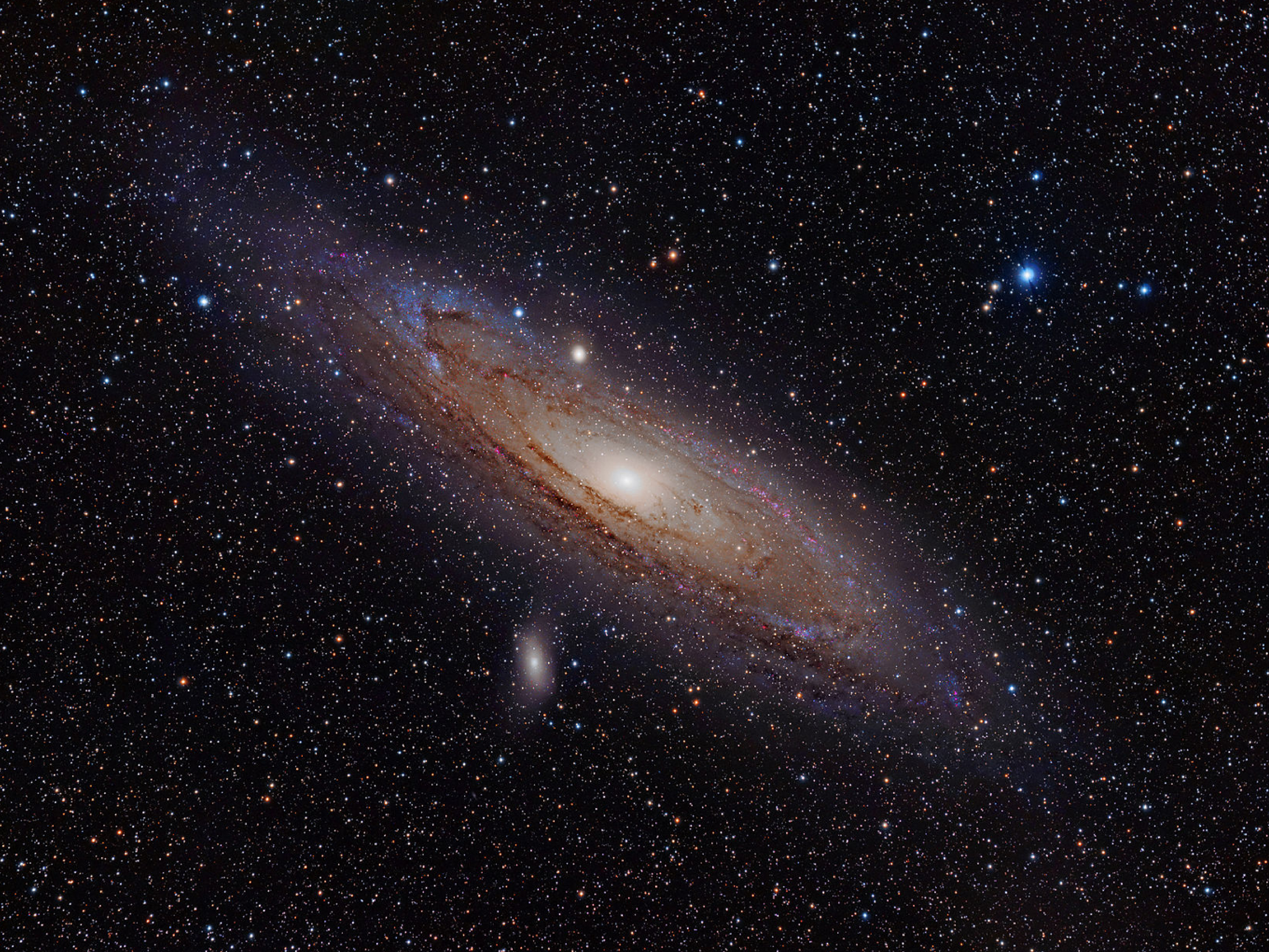


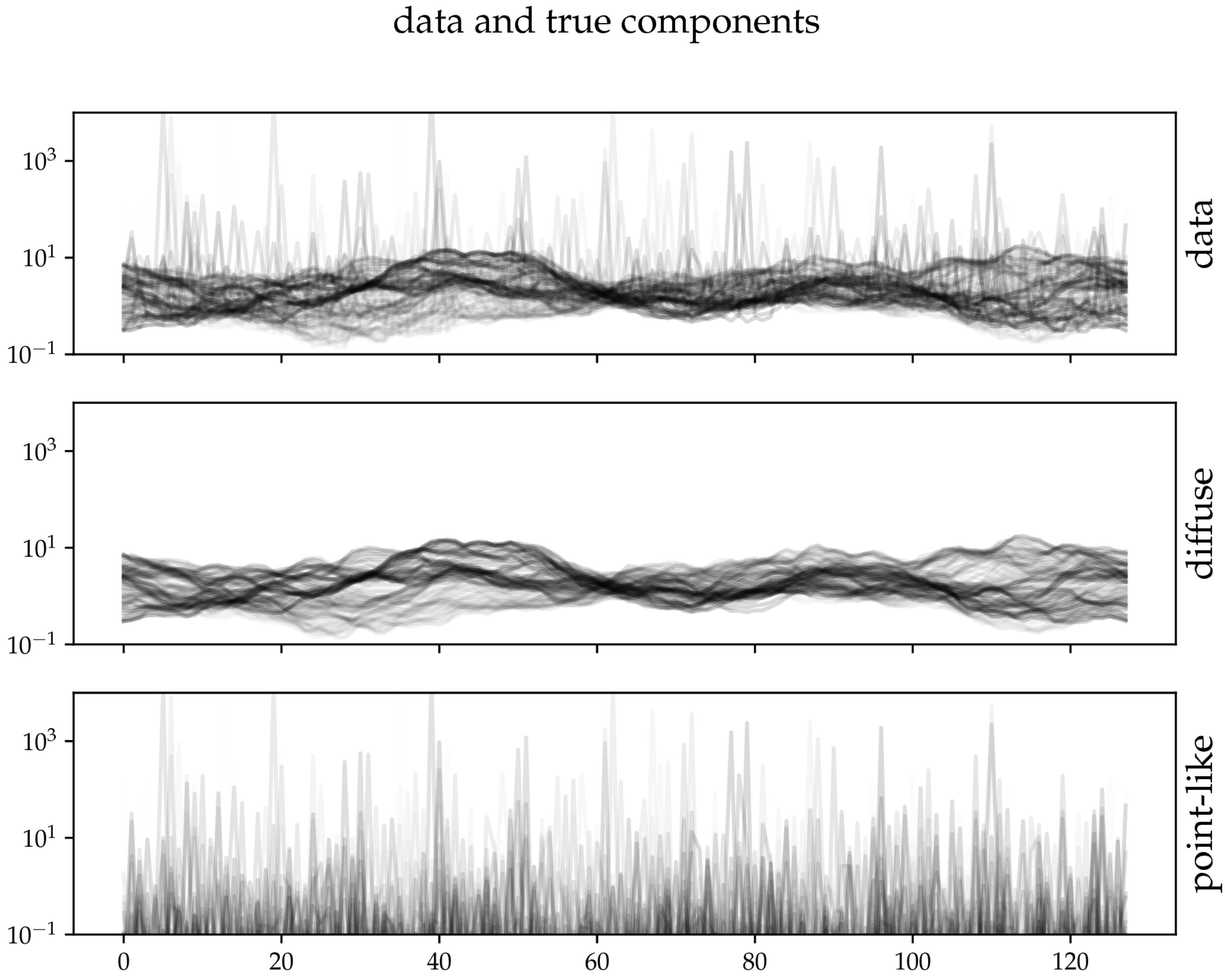
$\mathbf{m}_{\text{truth}}$
$\mathbf{m}_{\Sigma\text{D}^4\text{PO}}$
$\mathbf{m}_{\text{ML}}$
$|\mathbf{m}_{\text{truth}} - \mathbf{m}_{\Sigma\text{D}^4\text{PO}}|$
$|\mathbf{m}_{\text{truth}} - \mathbf{m}_{\text{ML}}|$
Location [a.u.]
Location [a.u]
Energy [a.u.]
logarithmic flux [a.u.]
0.0
0.2
0.4
0.6
0.8
1.0
−0.5
0.5
1.5
2.0
2.5
3.0

Glimpses into the future

Jakob Knollmüller
`starblade`

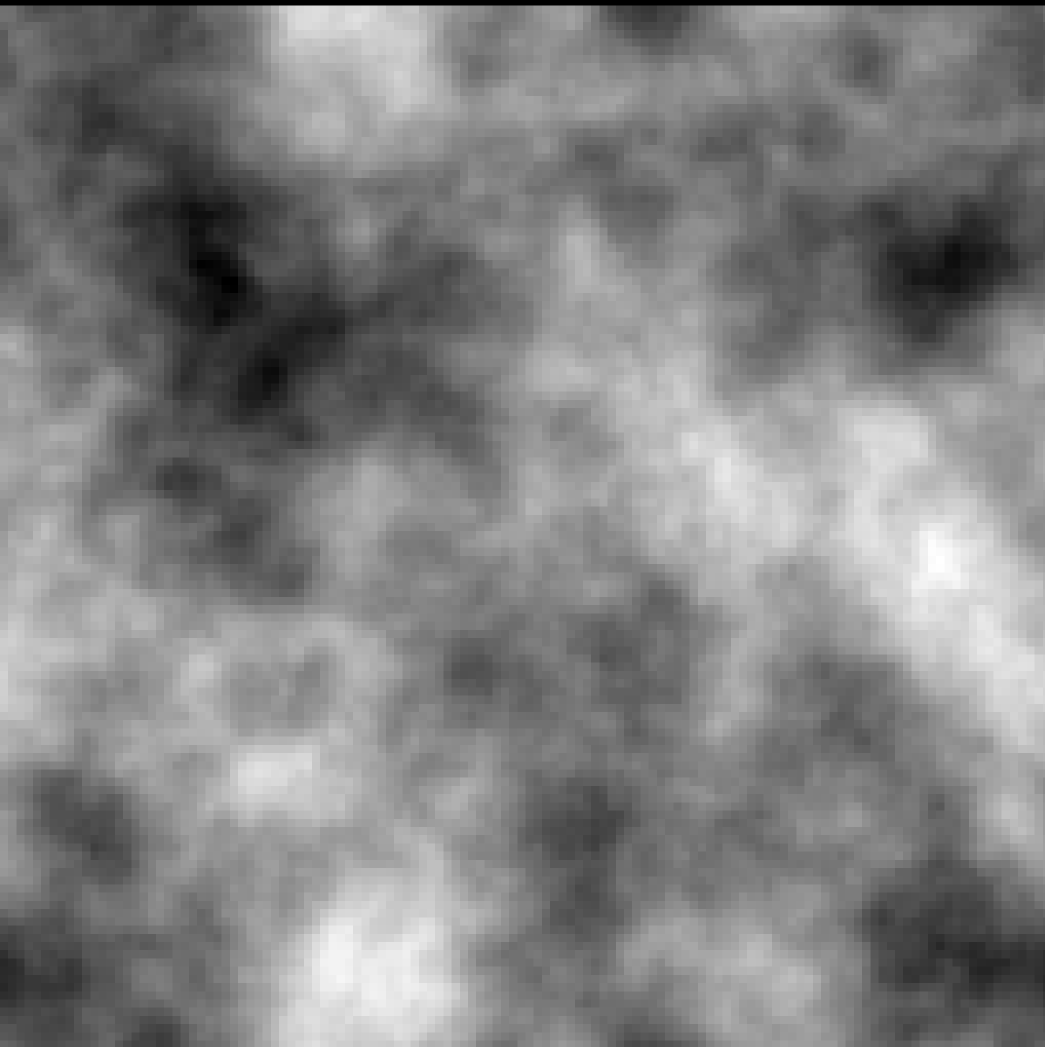




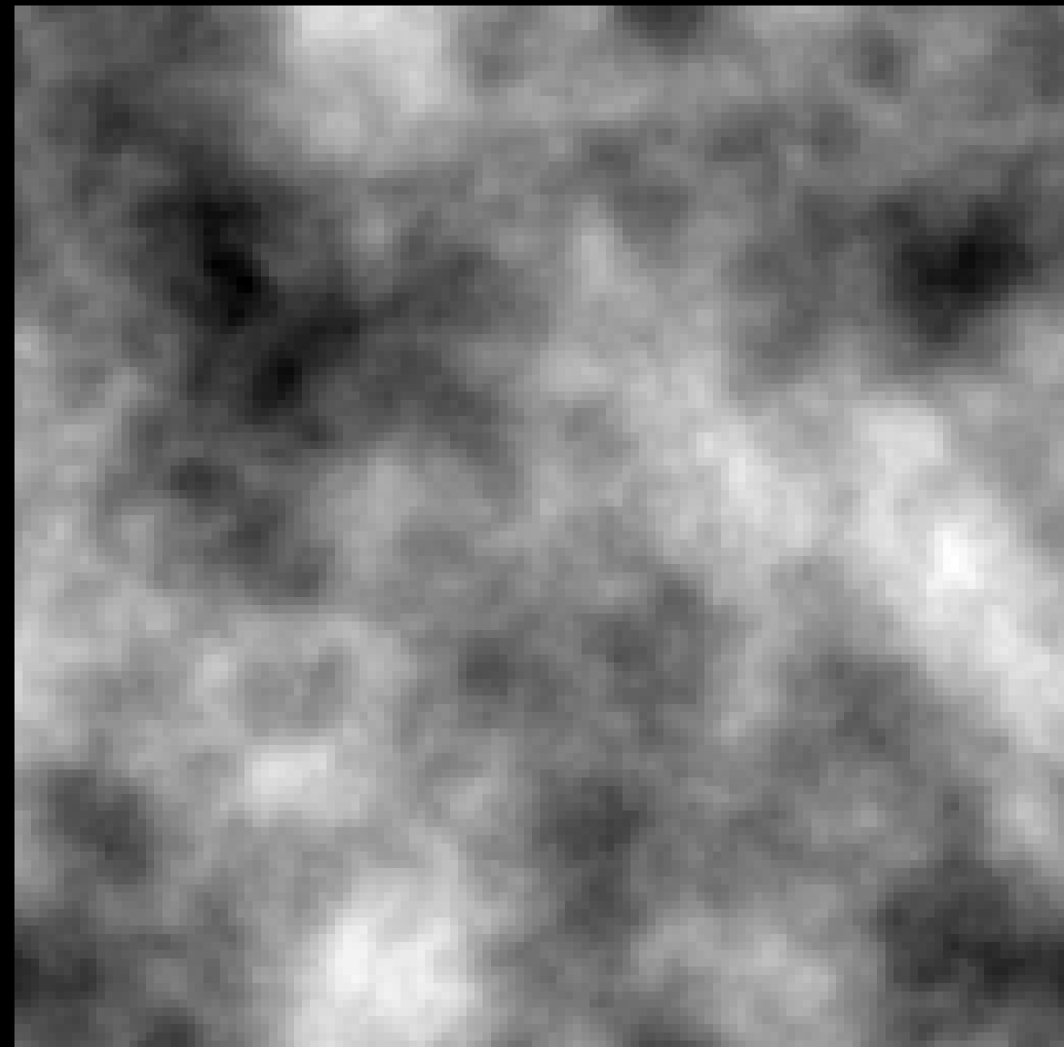


data and true components
data
diffuse
point-like
10^3
10^1
10^{-1}
0
20
40
60
80
100
120

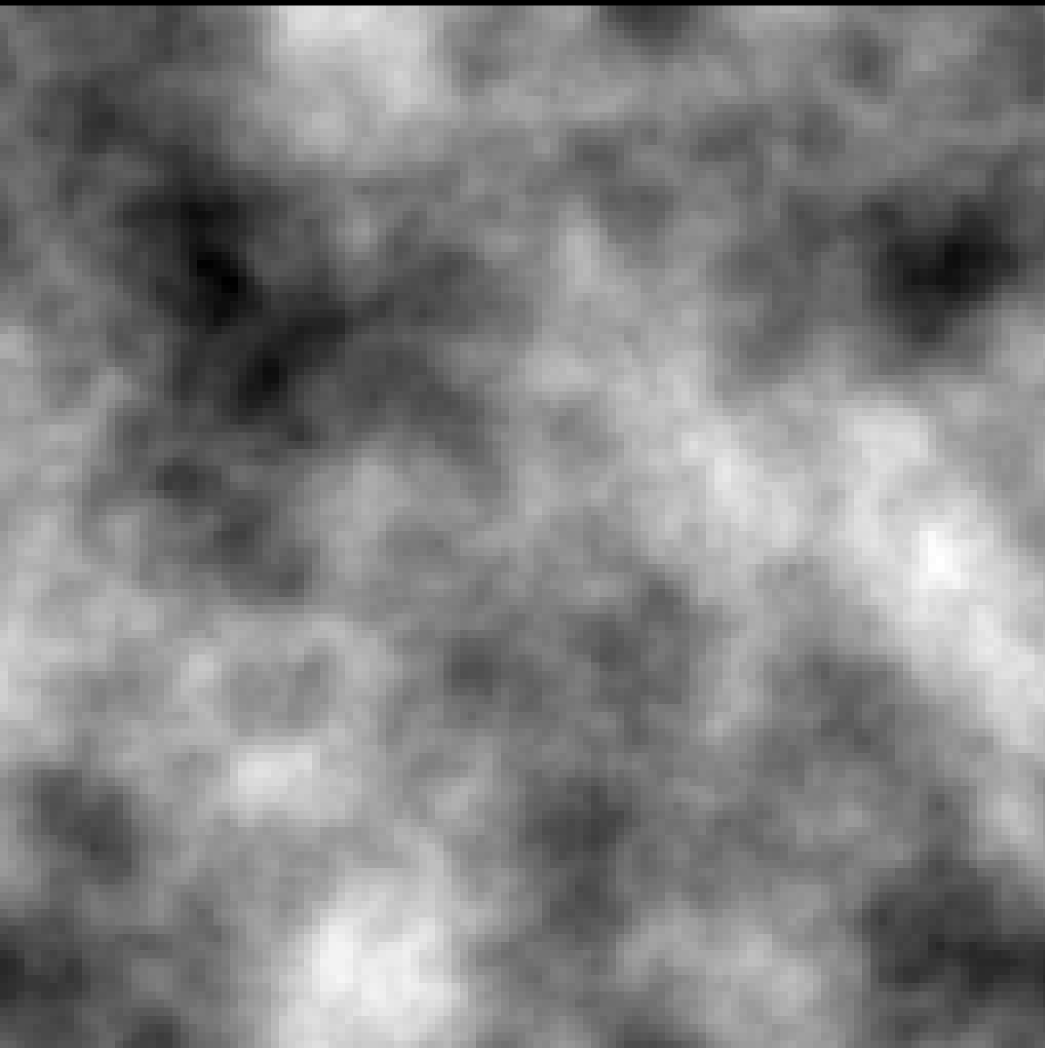
ground truth / starblade



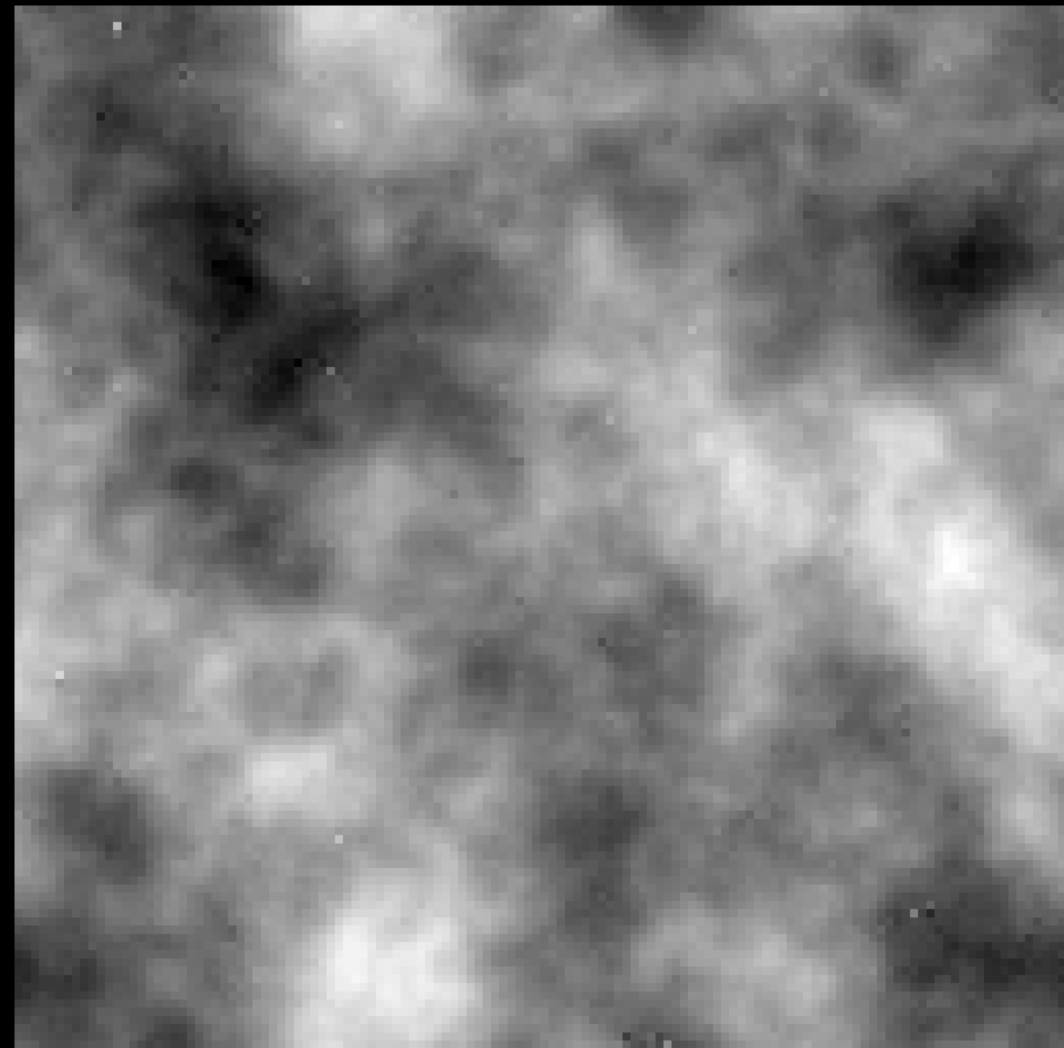
ground truth / autoencoder

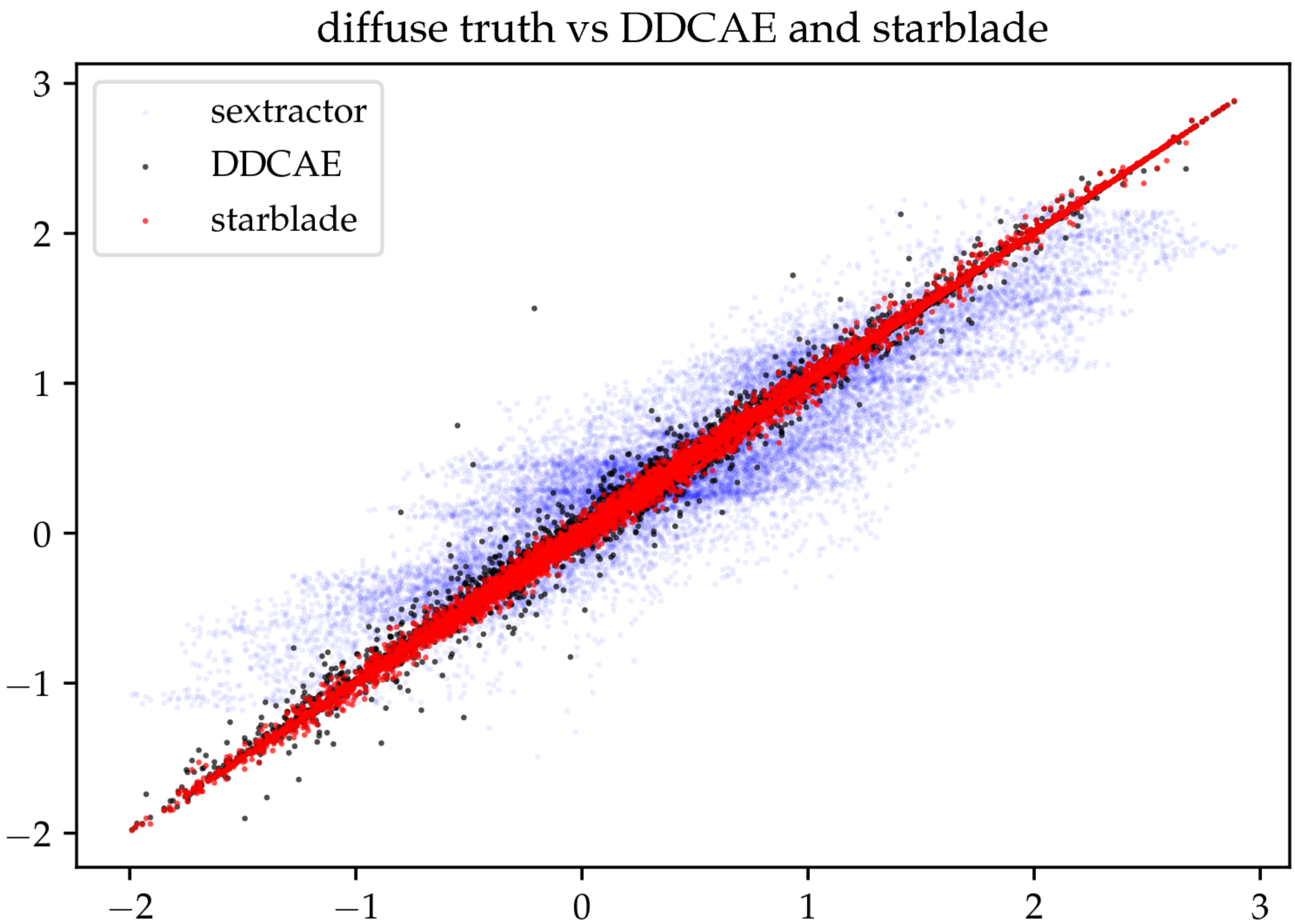


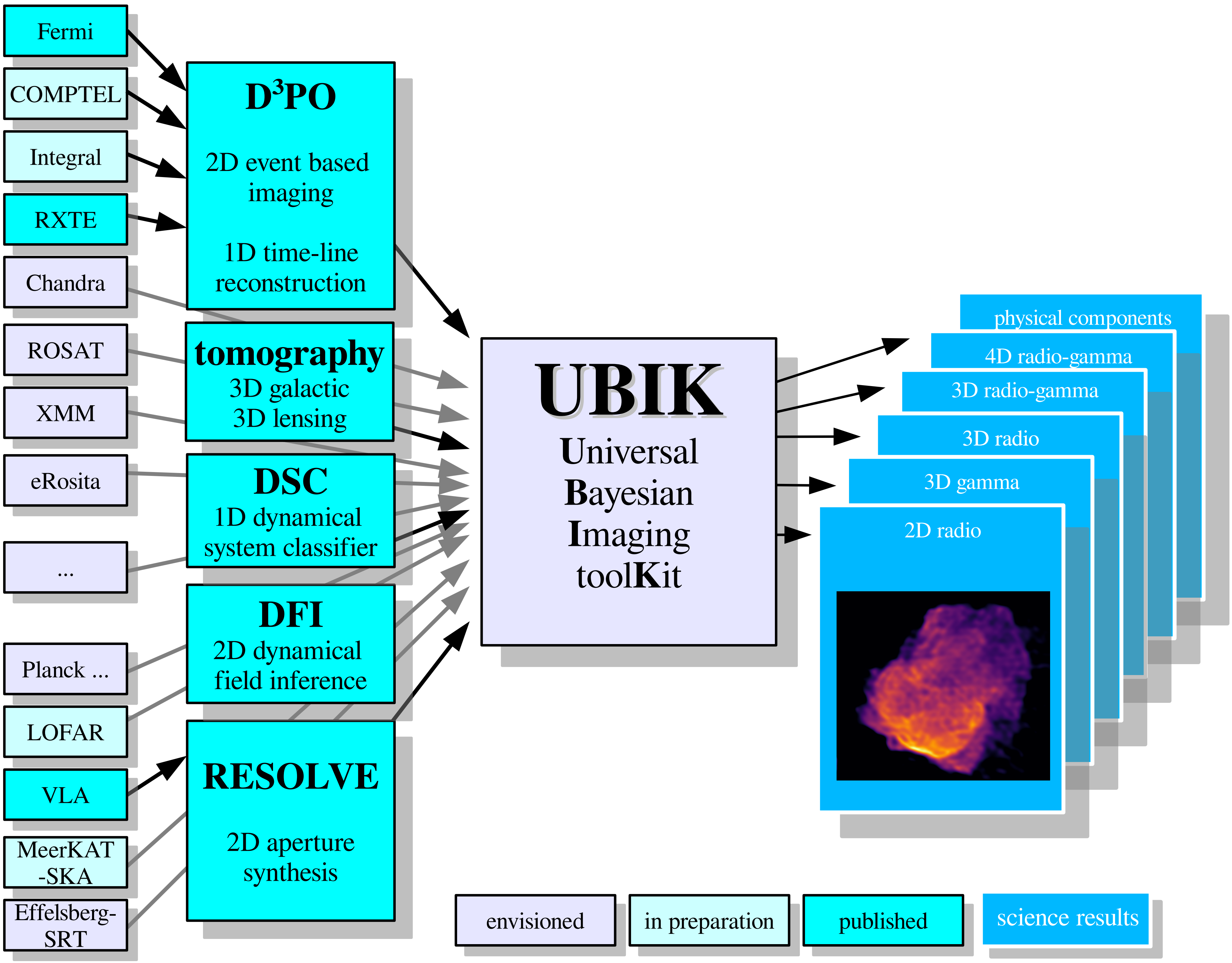
ground truth / starblade

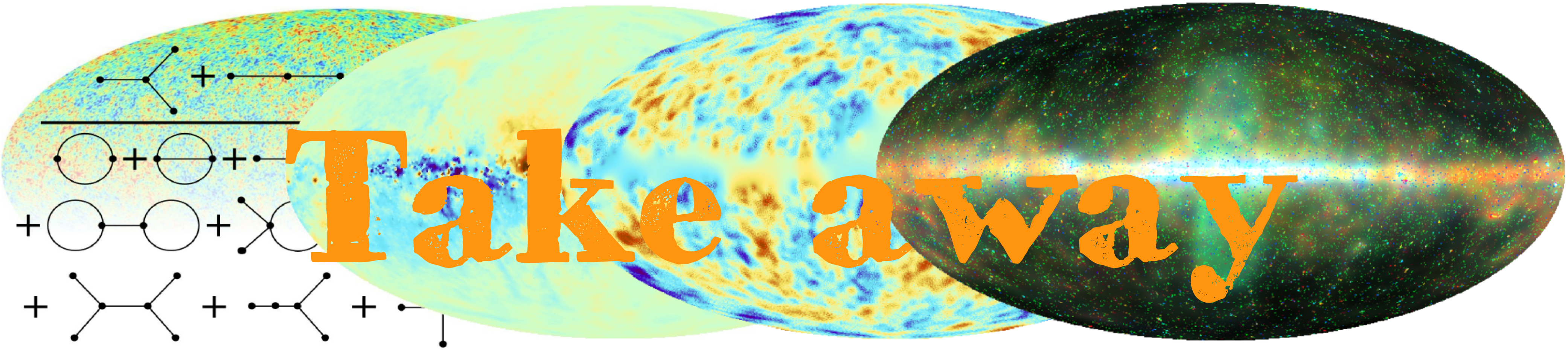


ground truth / autoencoder




diffuse truth vs DDCAE and starblade
sextractor
DDCAE
starblade
3
2
1
0
−1
−2
−2
−1
0
1
2
3

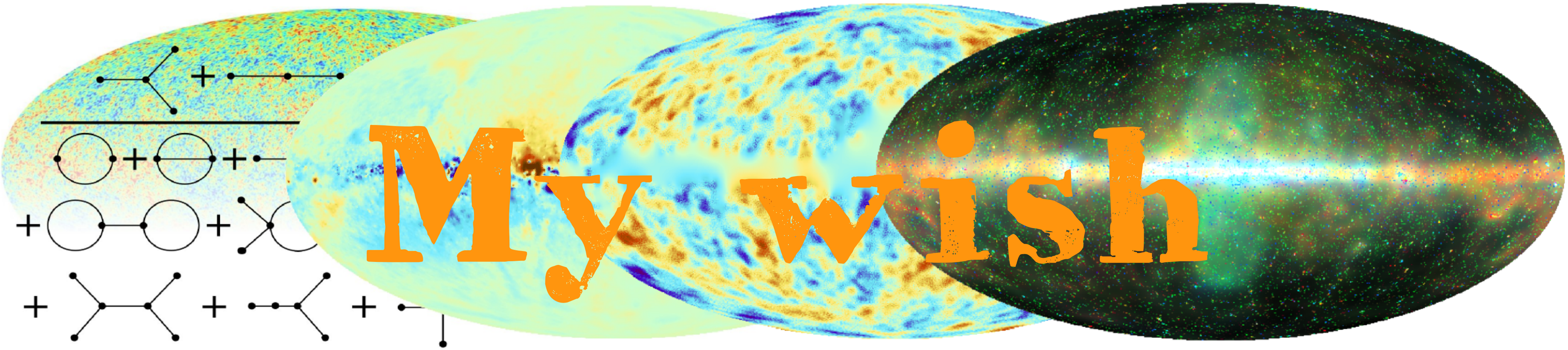

Fermi
COMPTEL
Integral
RXTE
Chandra
ROSAT
XMM
eRosita
...
Planck ...
LOFAR
VLA
MeerKAT
-SKA
Effelsberg-
SRT
D3PO
2D event based
imaging
1D time-line
reconstruction
tomography
3D galactic
3D lensing
DSC
1D dynamical
system classifier
DFI
2D dynamical
field inference
RESOLVE
2D aperture
synthesis
UBIK
Universal
Bayesian
Imaging
toolKit
physical components
4D radio-gamma
3D radio-gamma
3D radio
3D gamma
2D radio
envisioned
in preparation
published
science results



Take away

Imaging goes inference

IFT	-	information field theory
NIFTy	-	numerical IFT in Python
UBIK	-	multi-instrument & -dimension imaging & tomography

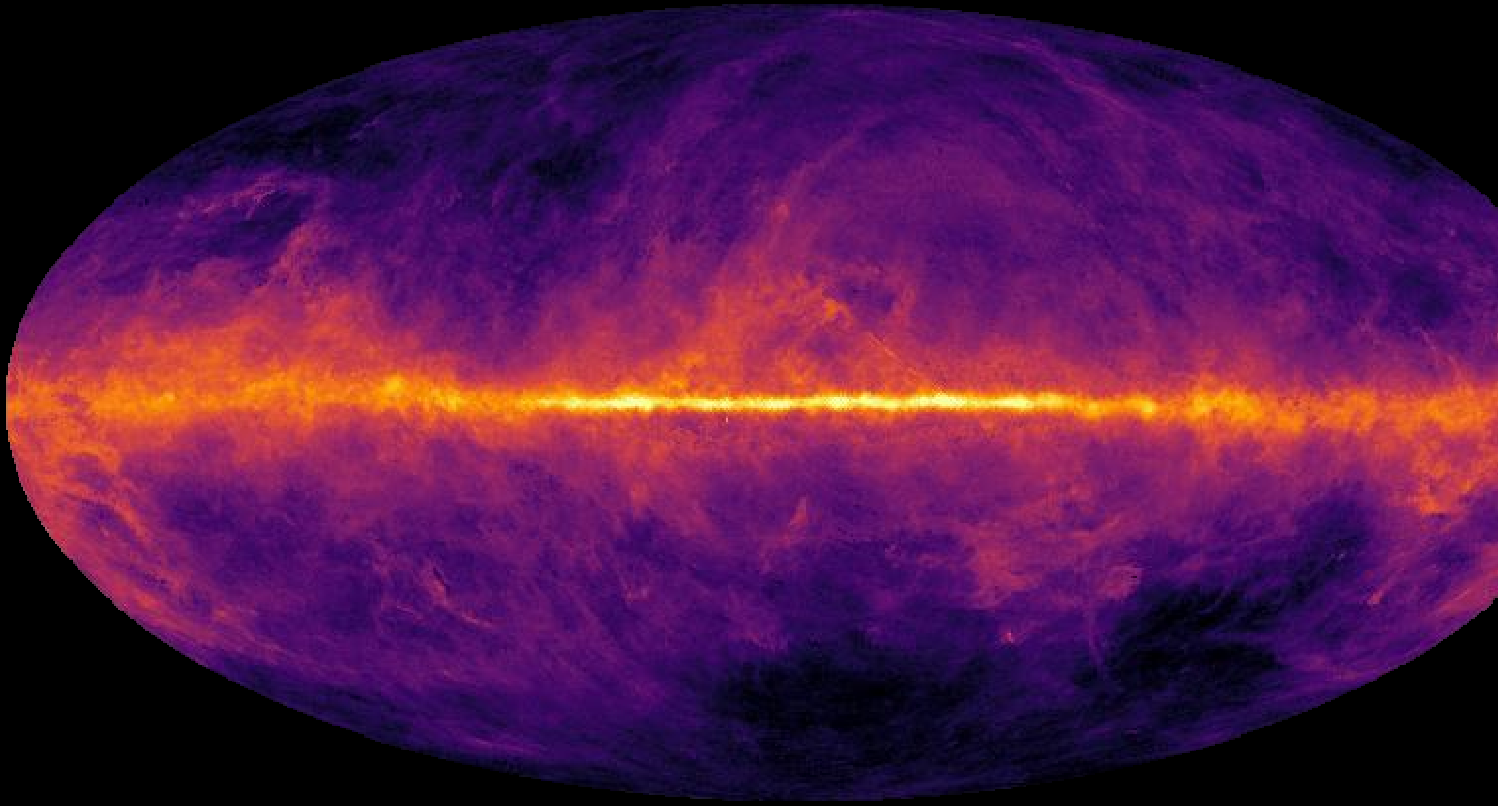


My wish

If you build an instrument please provide

- a fast response code
  R: sky → data
- its derivative
  R' = dR/dsky: (sky, dsky) → ddata
- its adjoint
  $R'^{\dagger}$: (sky, ddata) → dsky

and UBIK will be your friend.



Thank you!

www.mpa-garching.mpg.de/ift