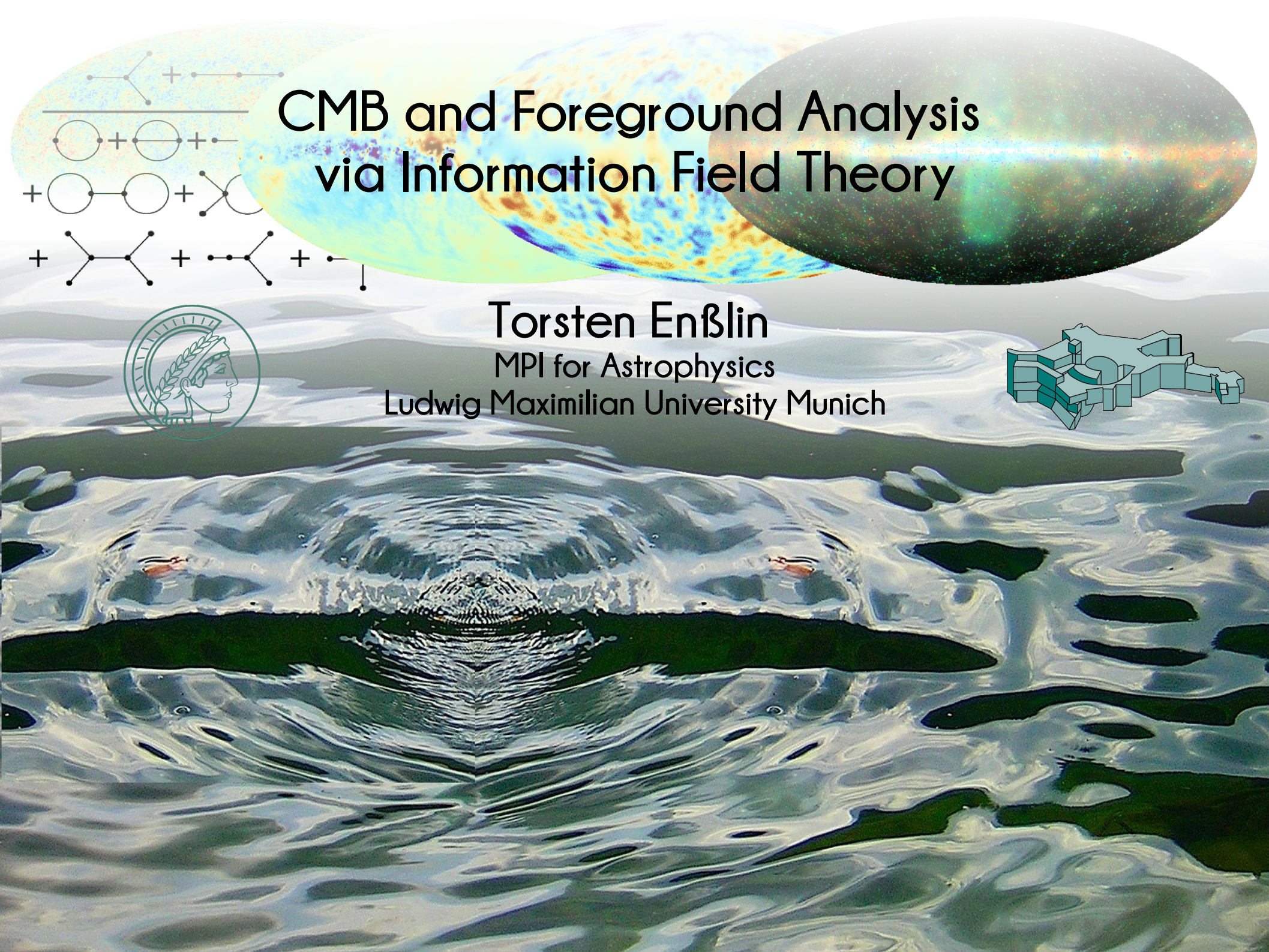
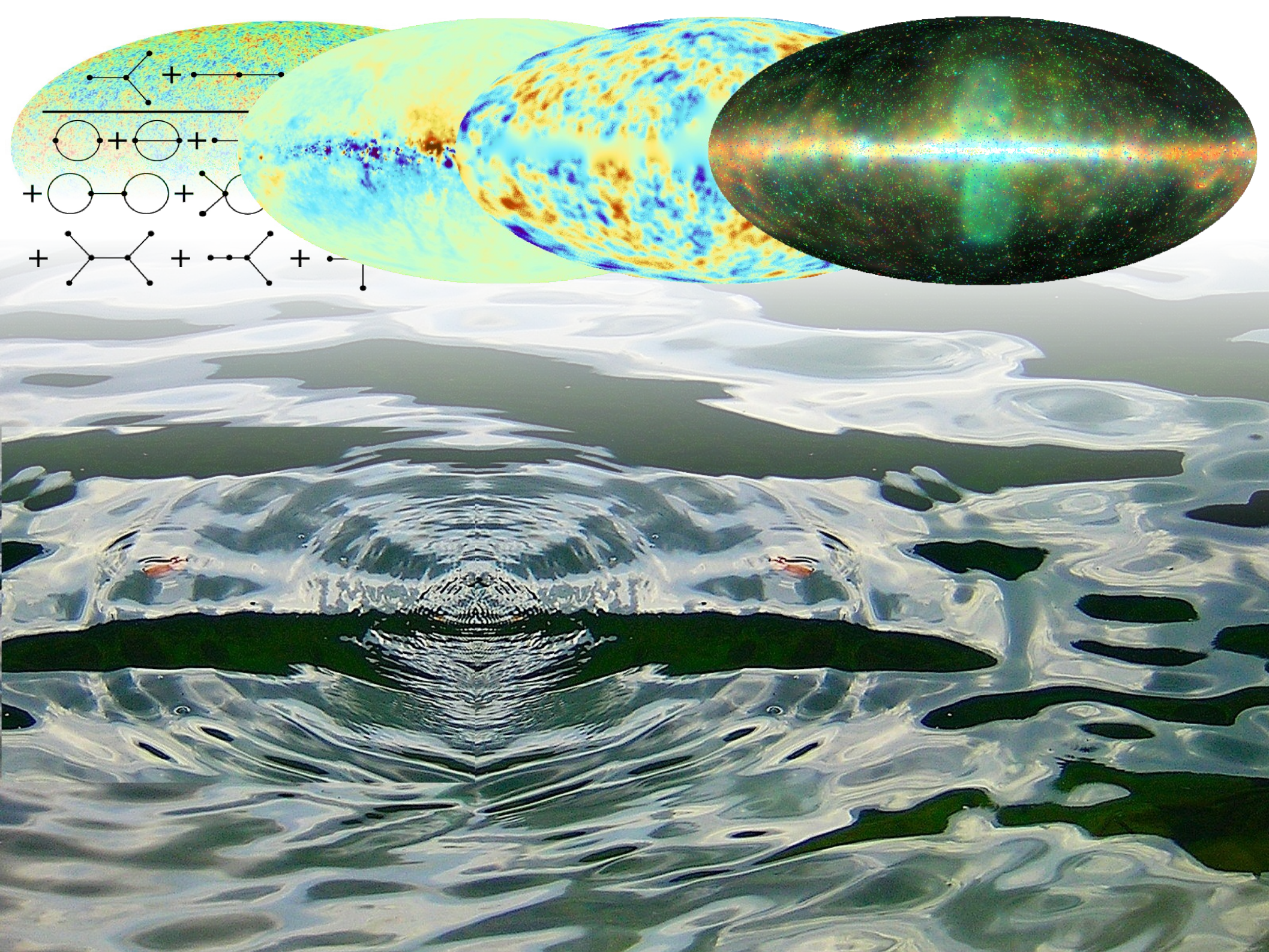


CMB and Foreground Analysis via Information Field Theory

Torsten Enßlin

MPI for Astrophysics

Ludwig Maximilian University Munich



Information Field Theory

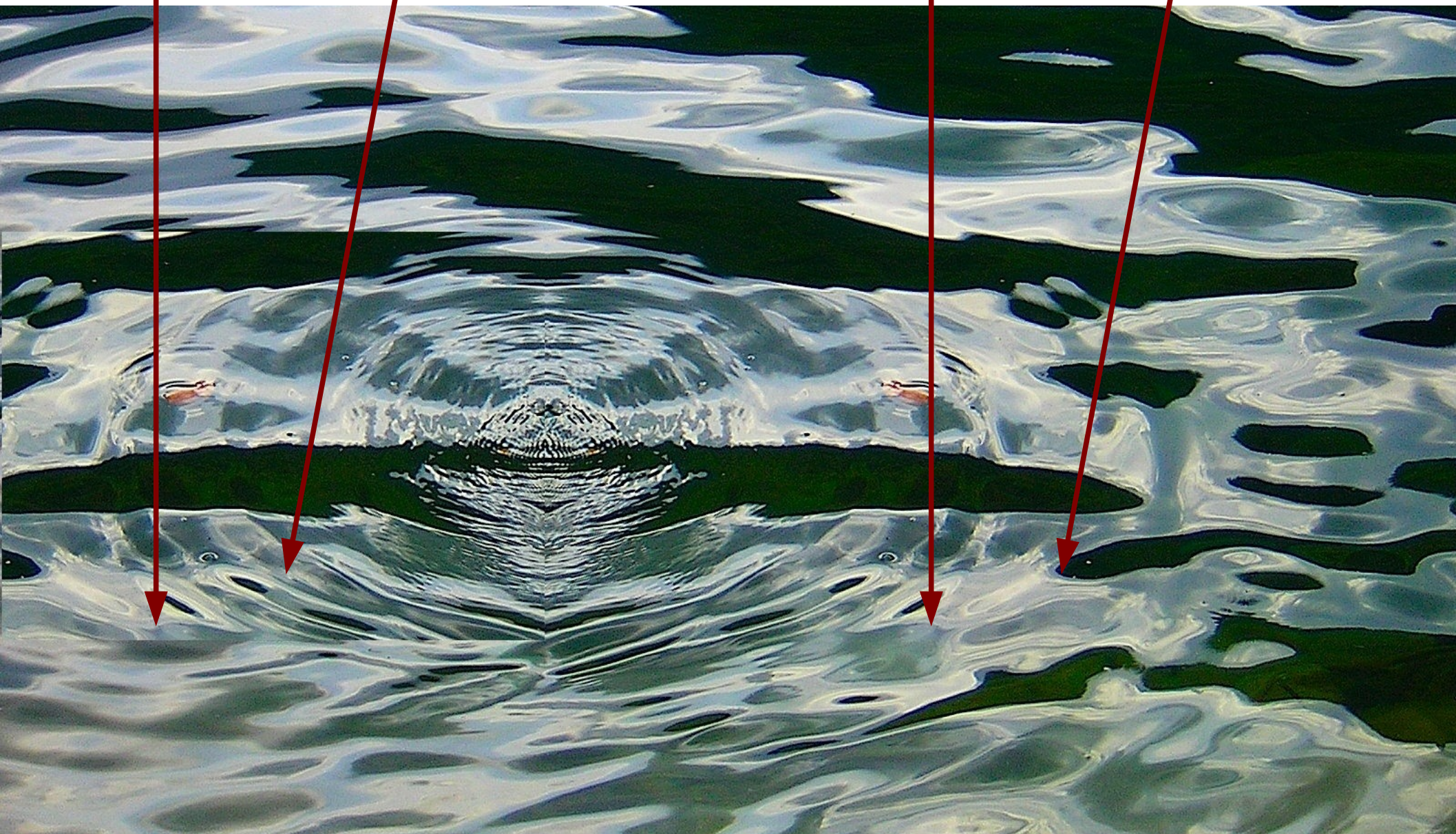
$s =$ signal

$d =$ data

$$\mathcal{P}(s|d) = \frac{\mathcal{P}(d|s)\,\mathcal{P}(s)}{\mathcal{P}(d)} = \frac{1}{Z(d)}\,e^{-H(d,s)}$$

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

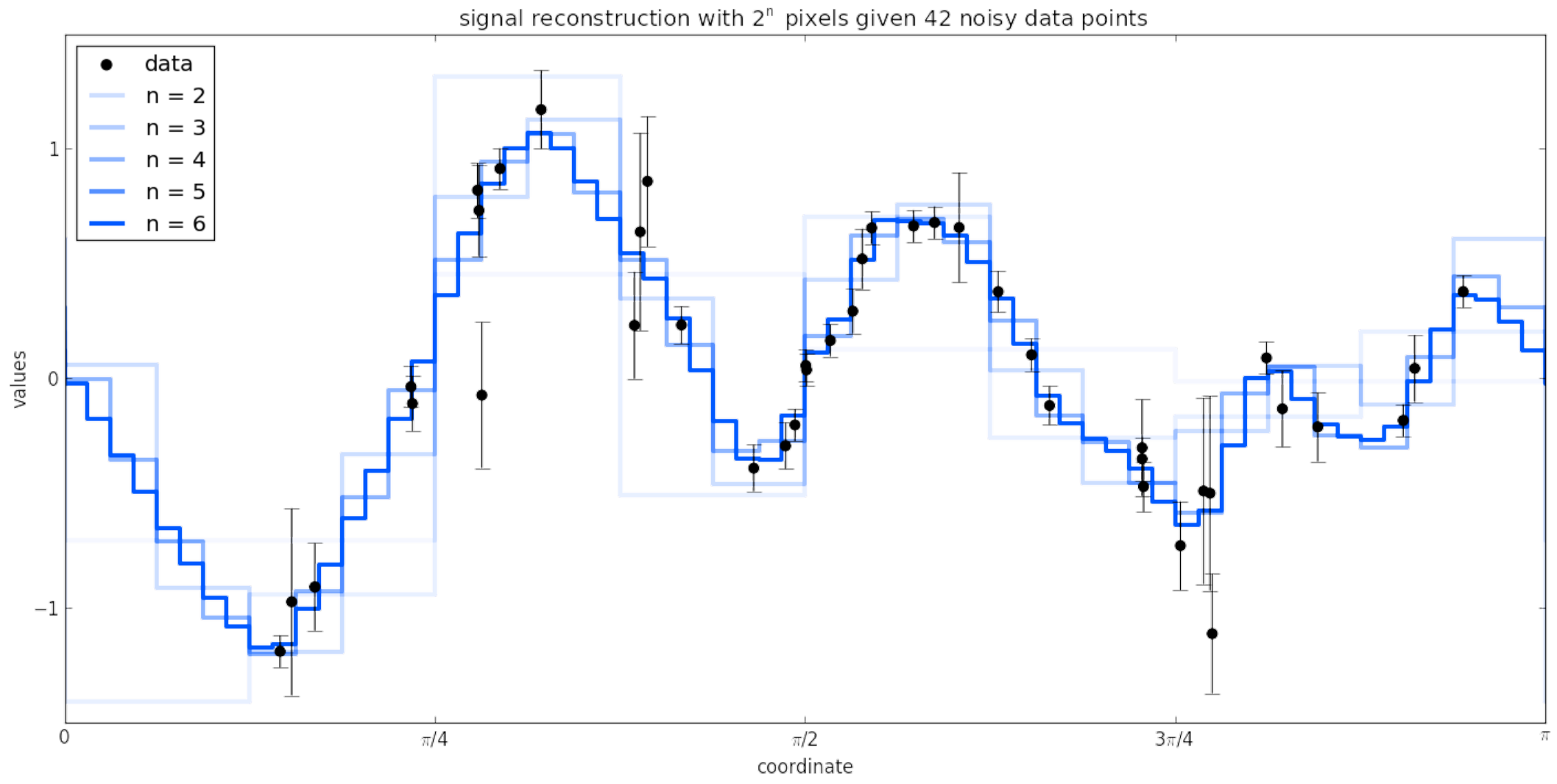
$$\langle s(x_1) \rangle_{P(s|d)} = \int \mathcal{D}s \, s(x_1) \, P(s|d)$$

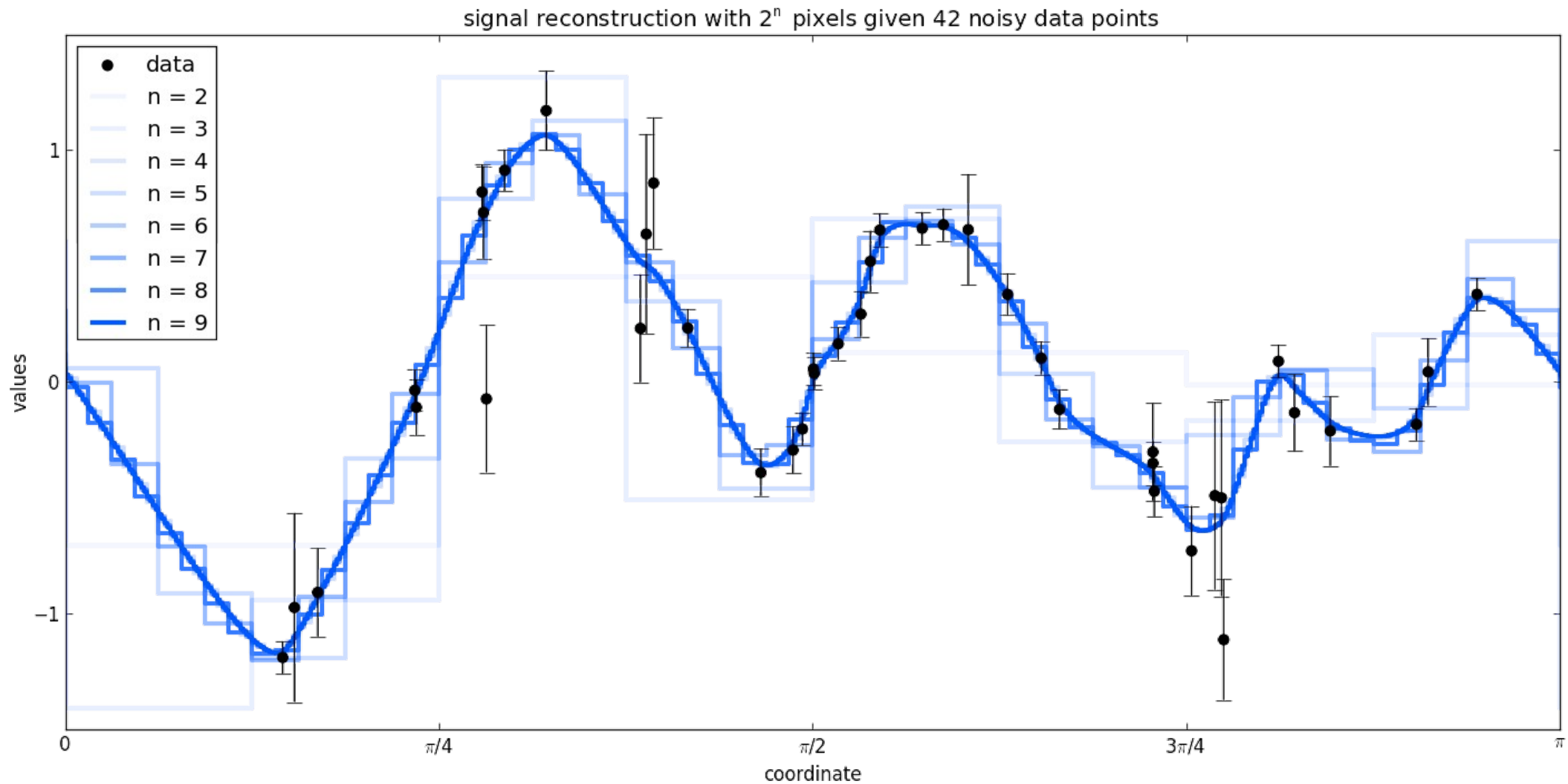


$$\langle s(x_1) \cdots s(x_n) \rangle_{P(s|d)} = \int \mathcal{D}s \, s(x_1) \cdots s(x_n) \, P(s|d)$$

$$\int \mathcal{D}s = \prod_{i=1}^{N_{\mathrm{pix}}} \int ds_i$$

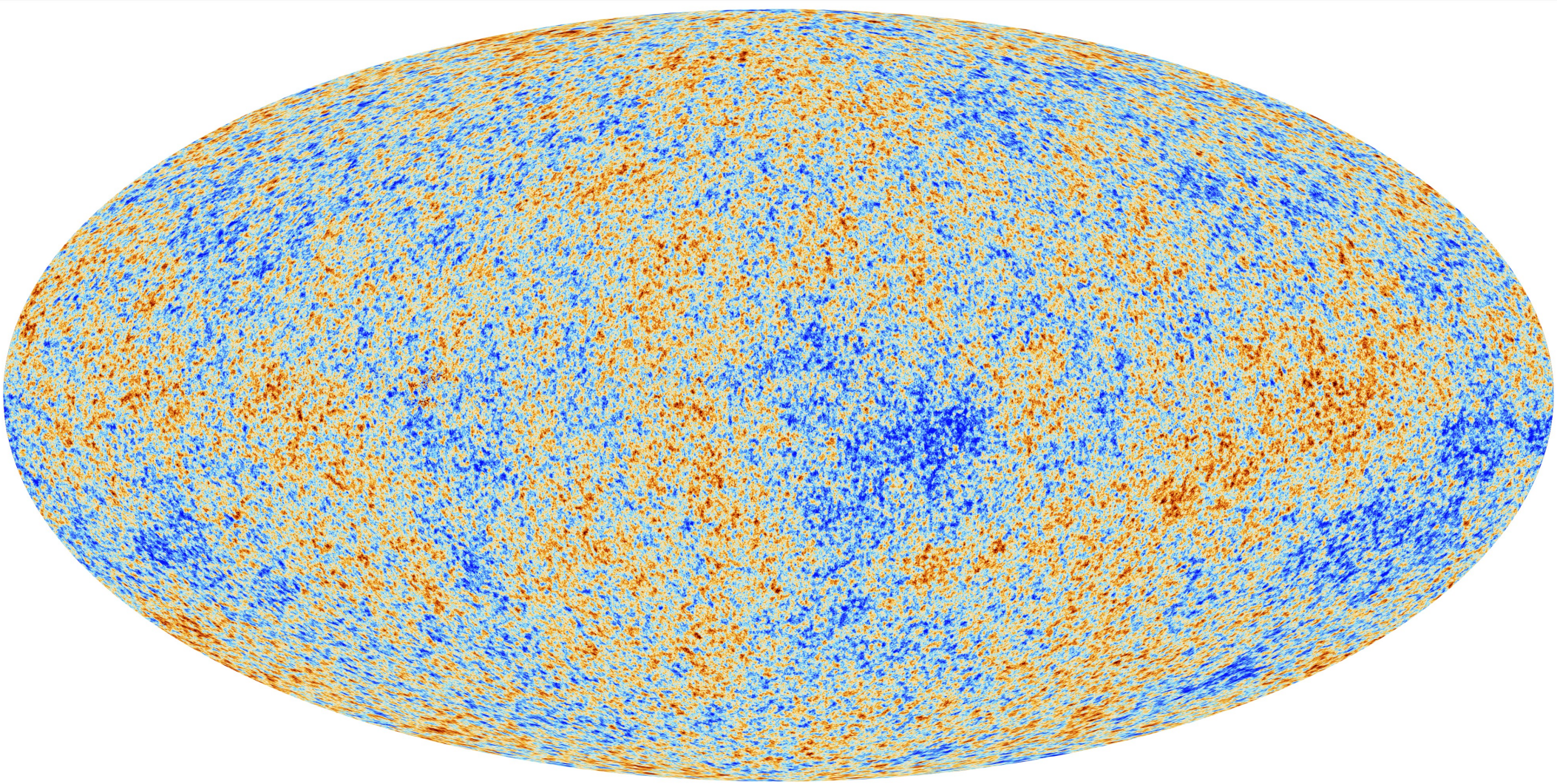

Correlations
information field theory
in continuous space
calculations in discretized spaces


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


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
coordinate
1
0
−1
0
π/4
π/2
3π/4
π

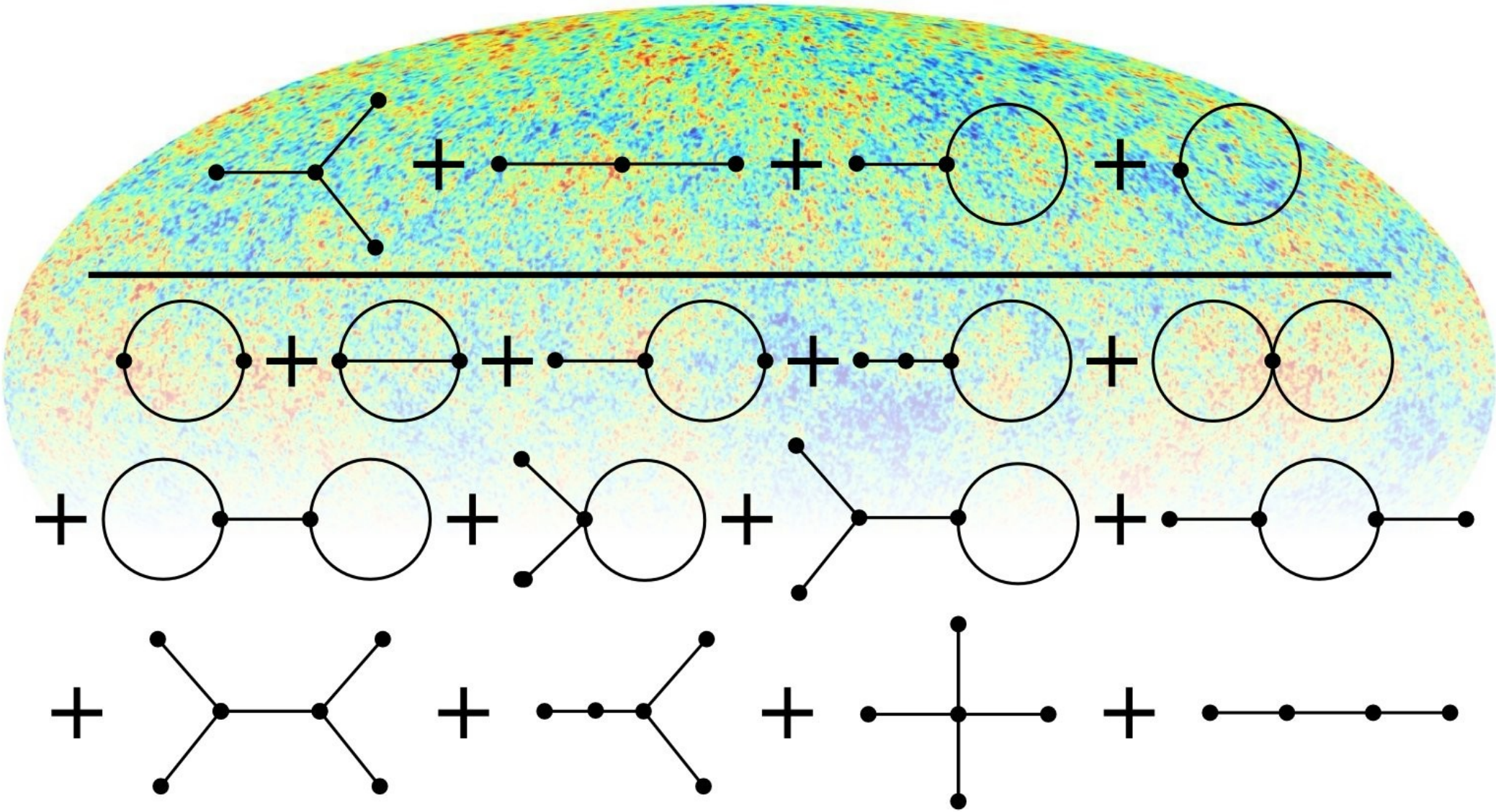
Free Theory

Gaussian signal & noise, linear response

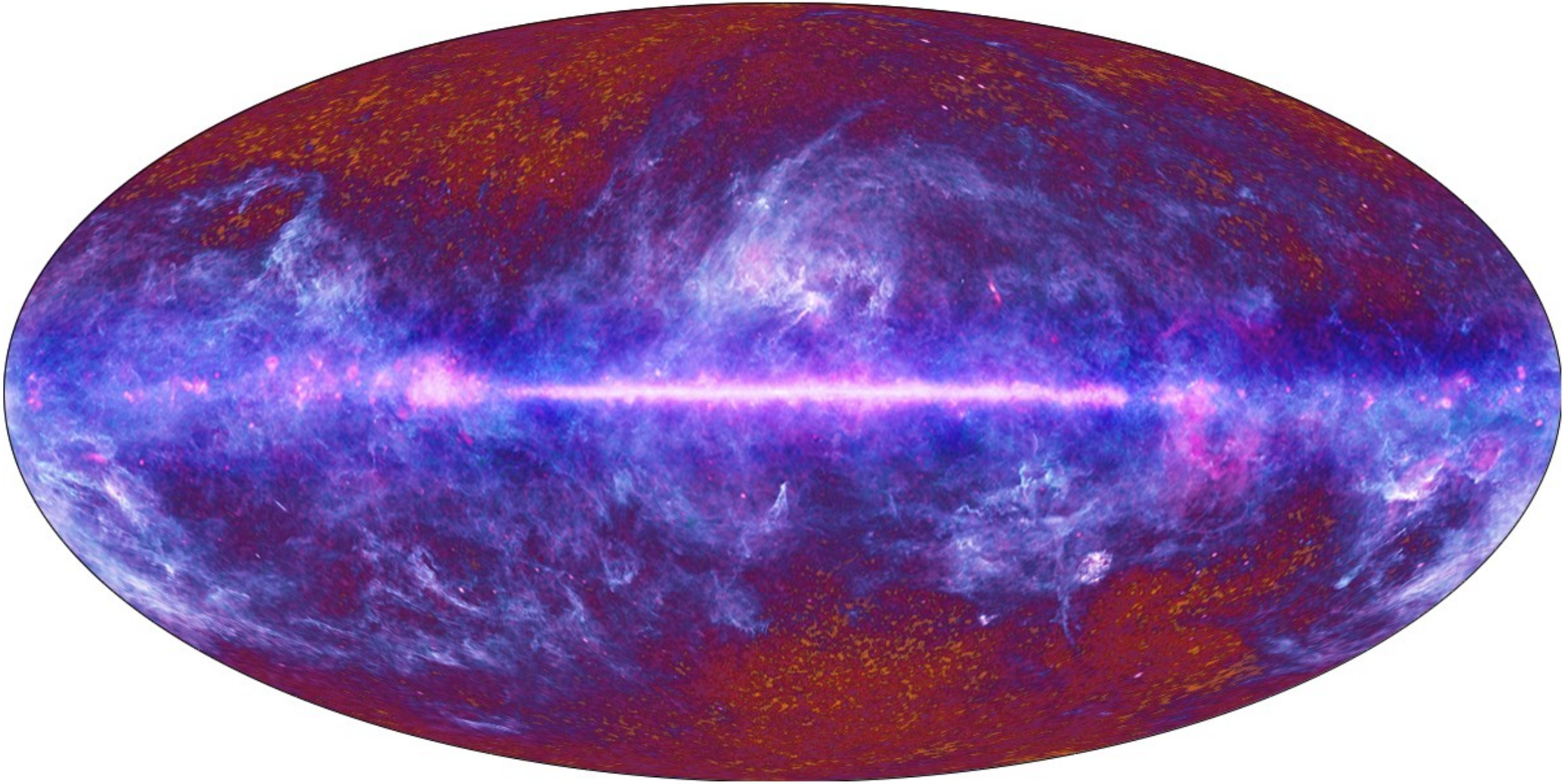


Primordial non-Gaussianity measurement

$$\phi = \varphi + f\left(\varphi^2 - \langle\varphi^2\rangle\right)$$



Interacting Theory
non-Gaussian signal & noise, non-linear response




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

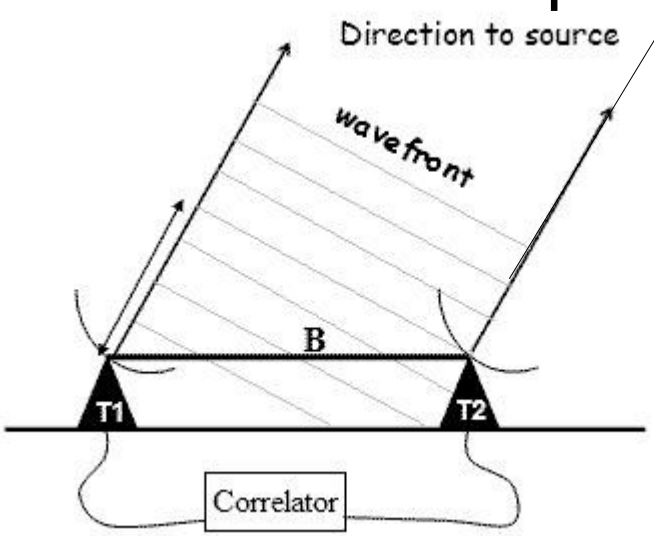
Data model

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

known

unknown

known response



Gaussian priors:

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

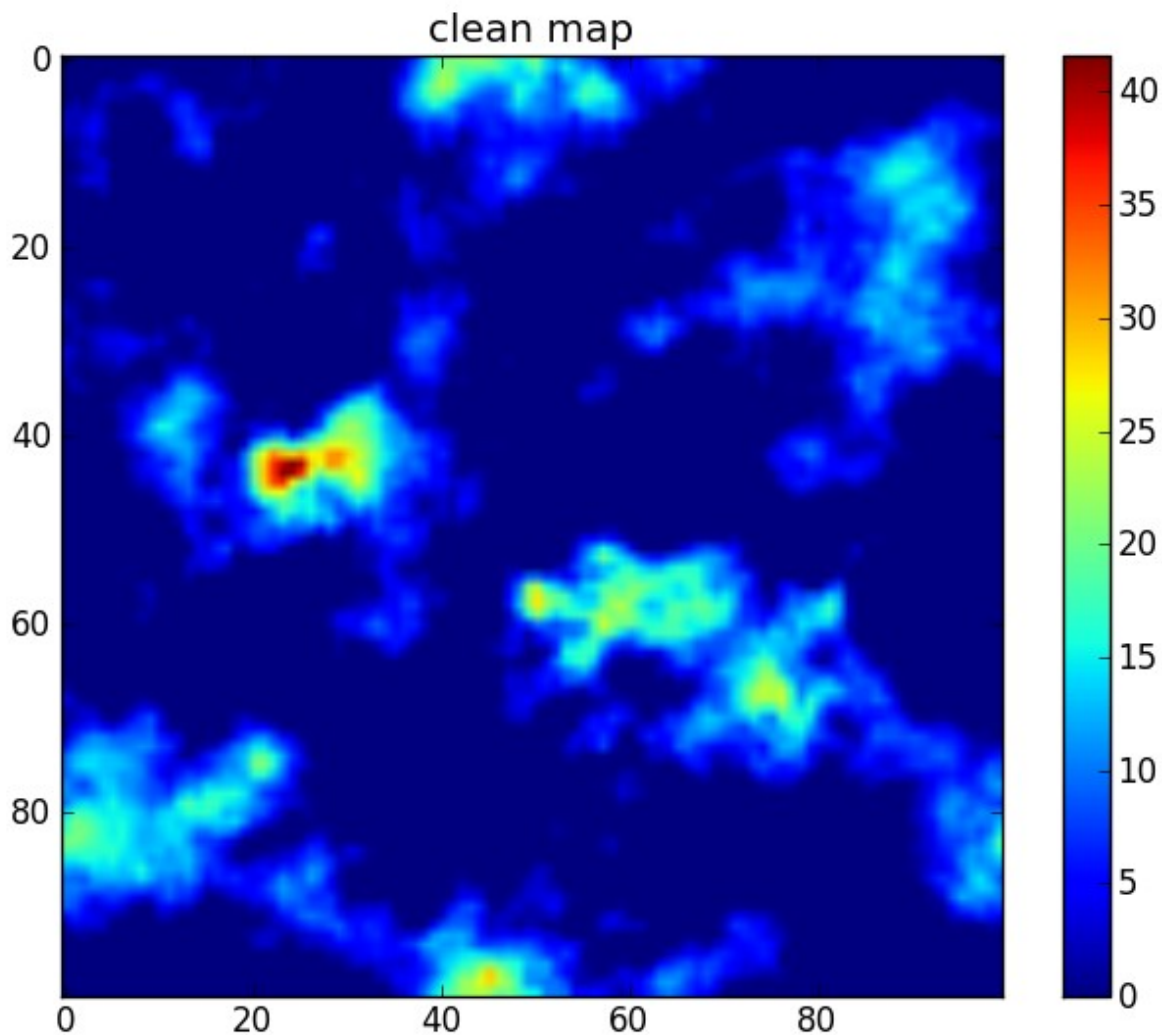
prior / regularization $$+ \frac{1}{2}\boldsymbol{s}^{\dagger}\boldsymbol{S}^{-1}\boldsymbol{s} + \frac{1}{2}\log\left(\det\left[\boldsymbol{S}\right]\right)$$

hyper-prior / intelligence $$+ \left(\boldsymbol{\alpha} - \boldsymbol{1}\right)^{\dagger}\boldsymbol{\tau} + \boldsymbol{q}^{\dagger}\mathrm{e}^{-\boldsymbol{\tau}} + \frac{1}{2}\boldsymbol{\tau}^{\dagger}\boldsymbol{T}\boldsymbol{\tau}$$

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

Radio Interferometry

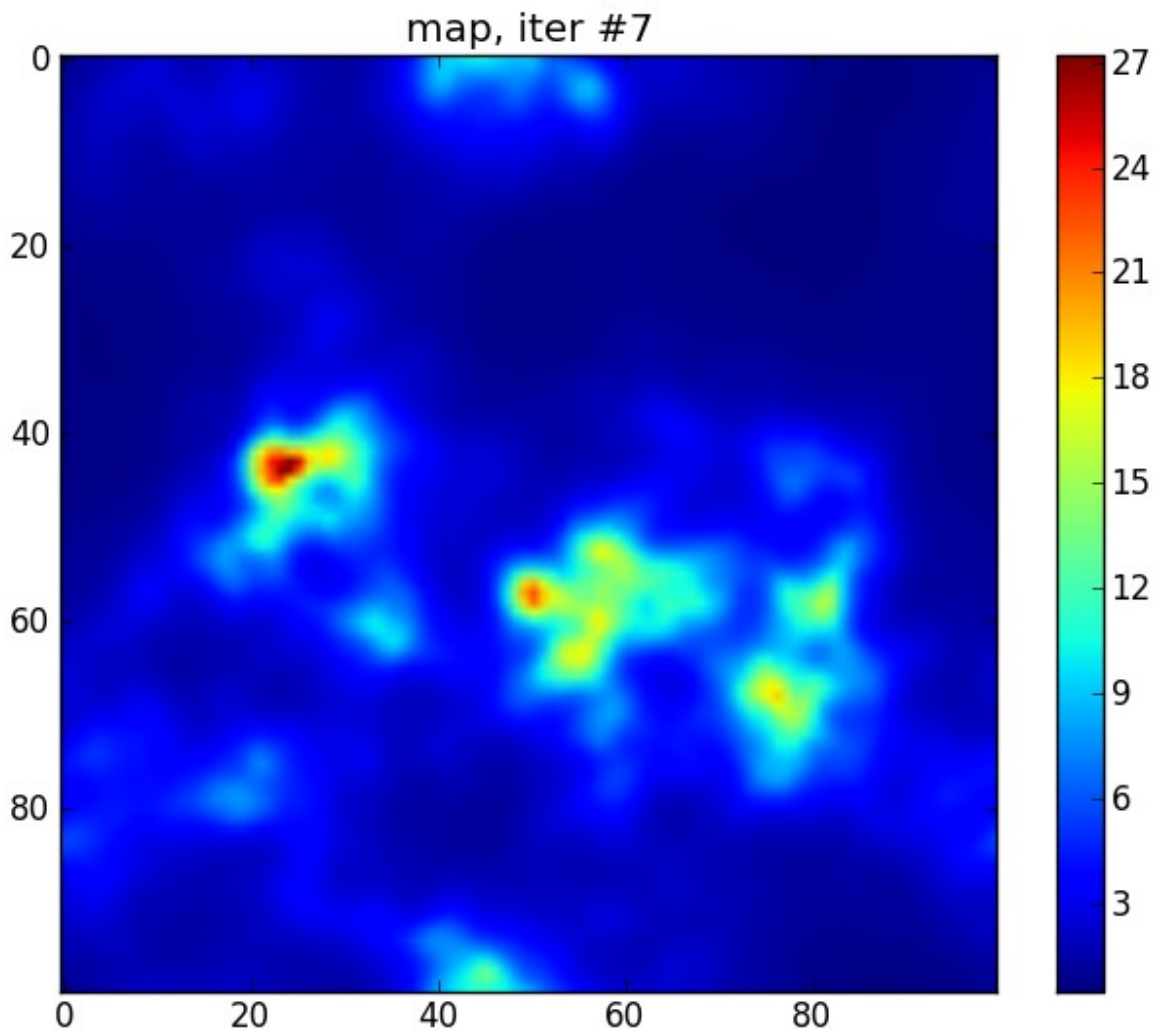
Junklewitz et al. (arXiv:1311.5282)



low noise, 40% uv-coverage

Radio Interferometry

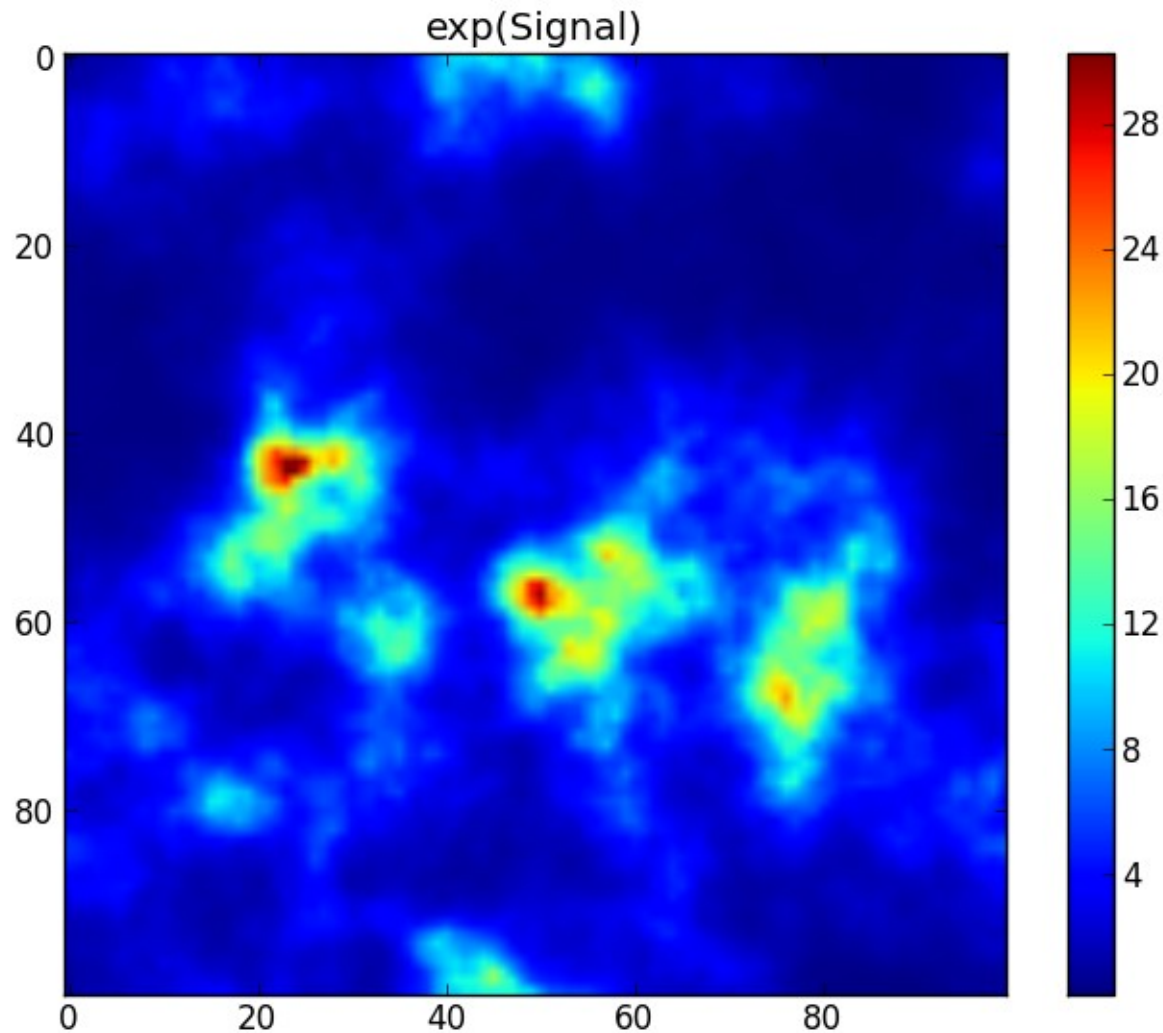
Junklewitz et al. (arXiv:1311.5282)



low noise, 40% uv-coverage

Radio Interferometry

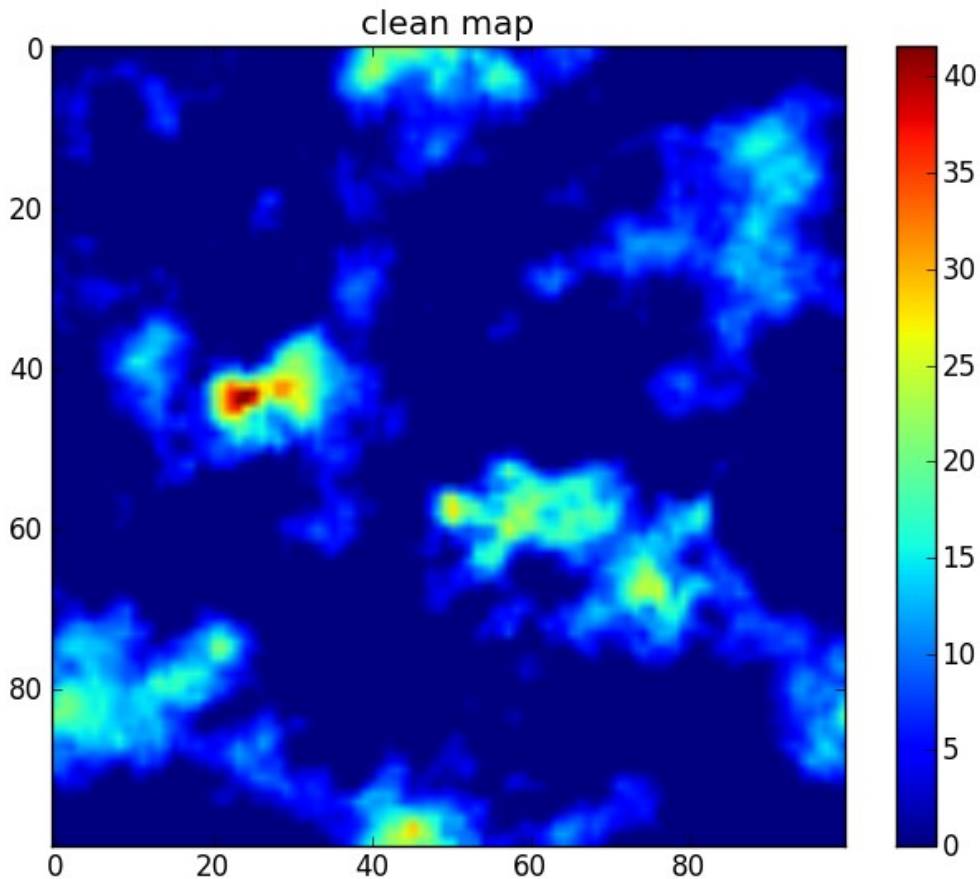
Junklewitz et al. (arXiv:1311.5282)

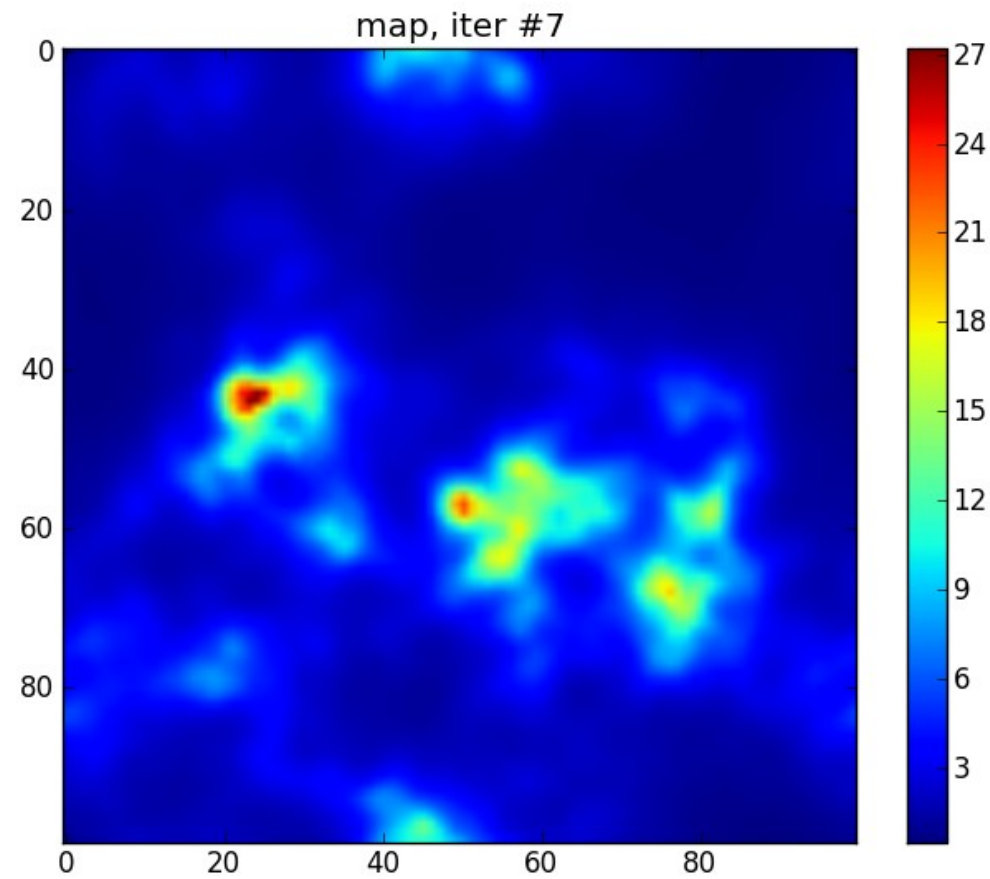


simulated signal

Radio Interferometry

Junklewitz et al. (arXiv:1311.5282)

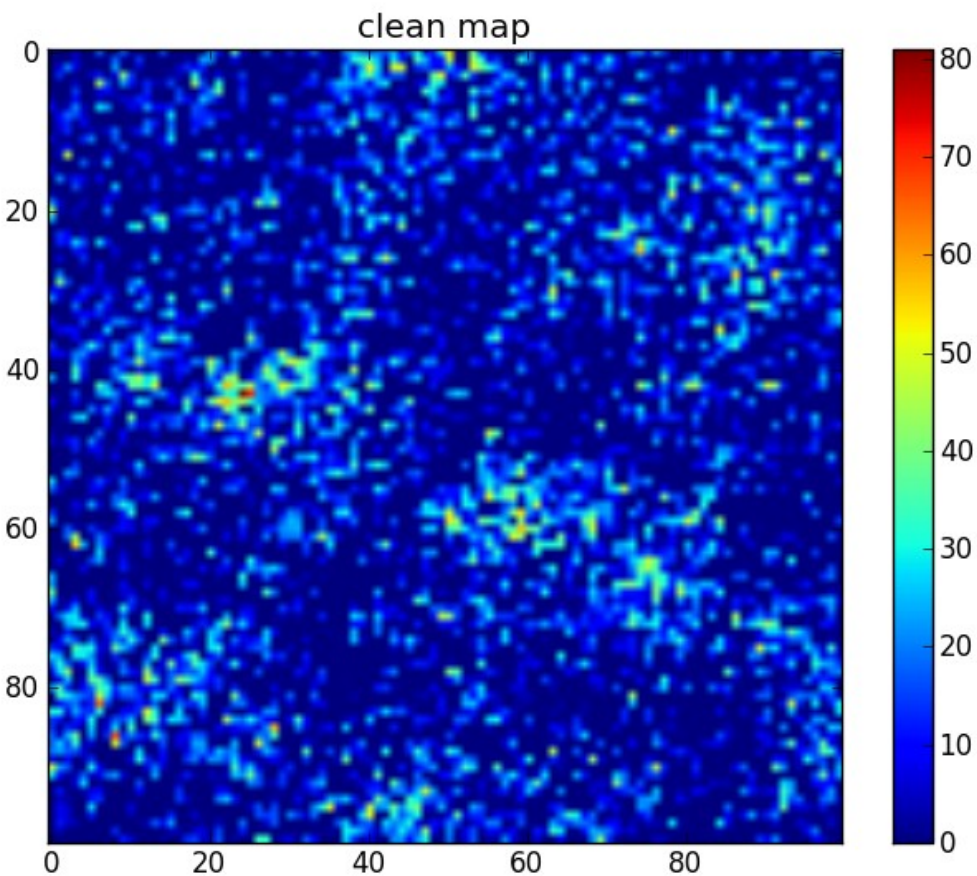


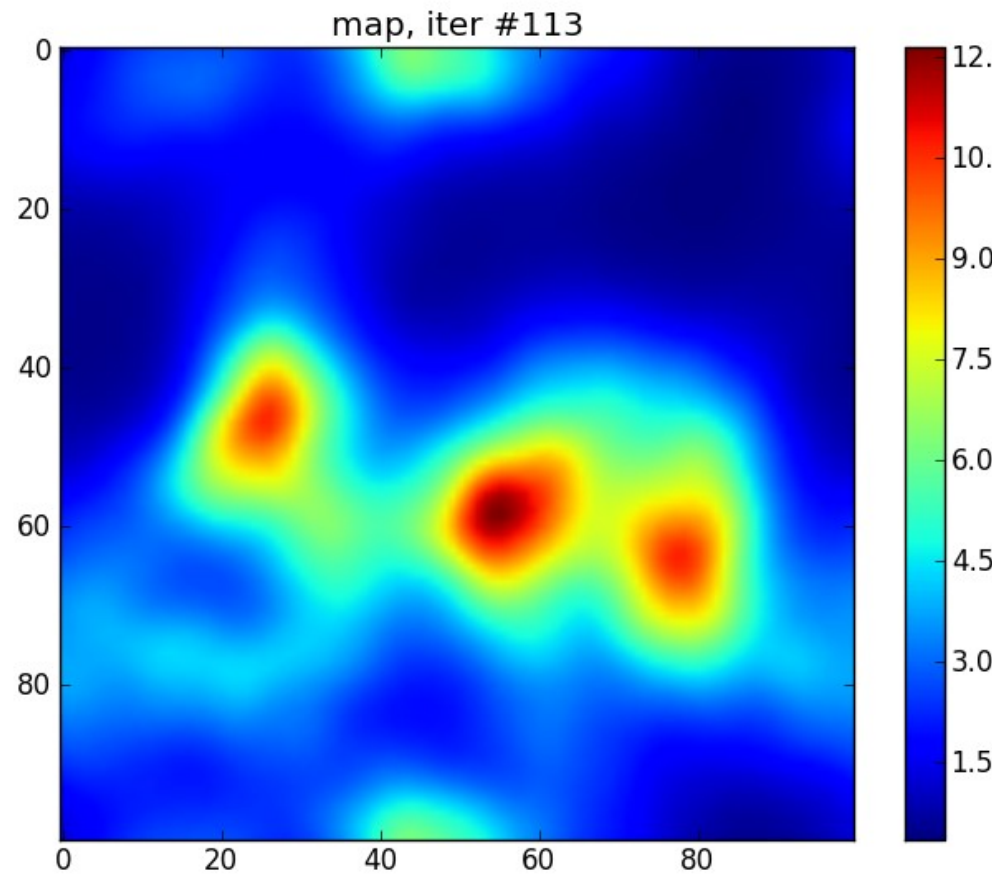


low noise, 40% uv-coverage

Radio Interferometry

Junklewitz et al. (arXiv:1311.5282)

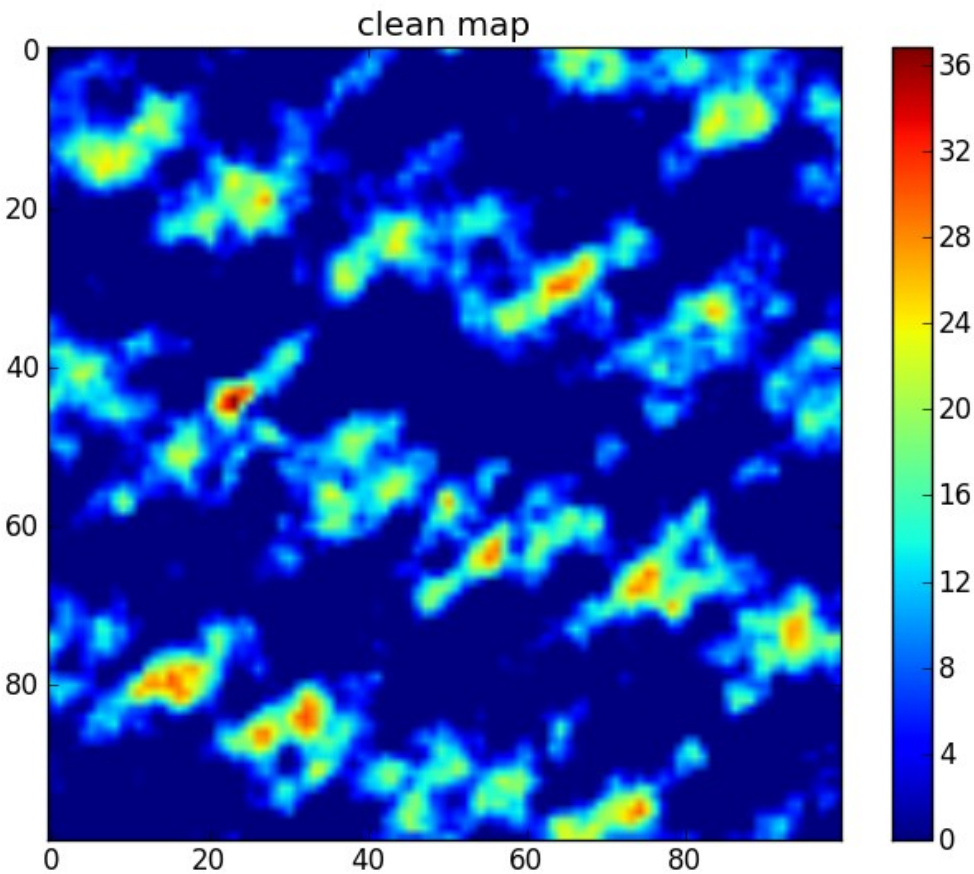


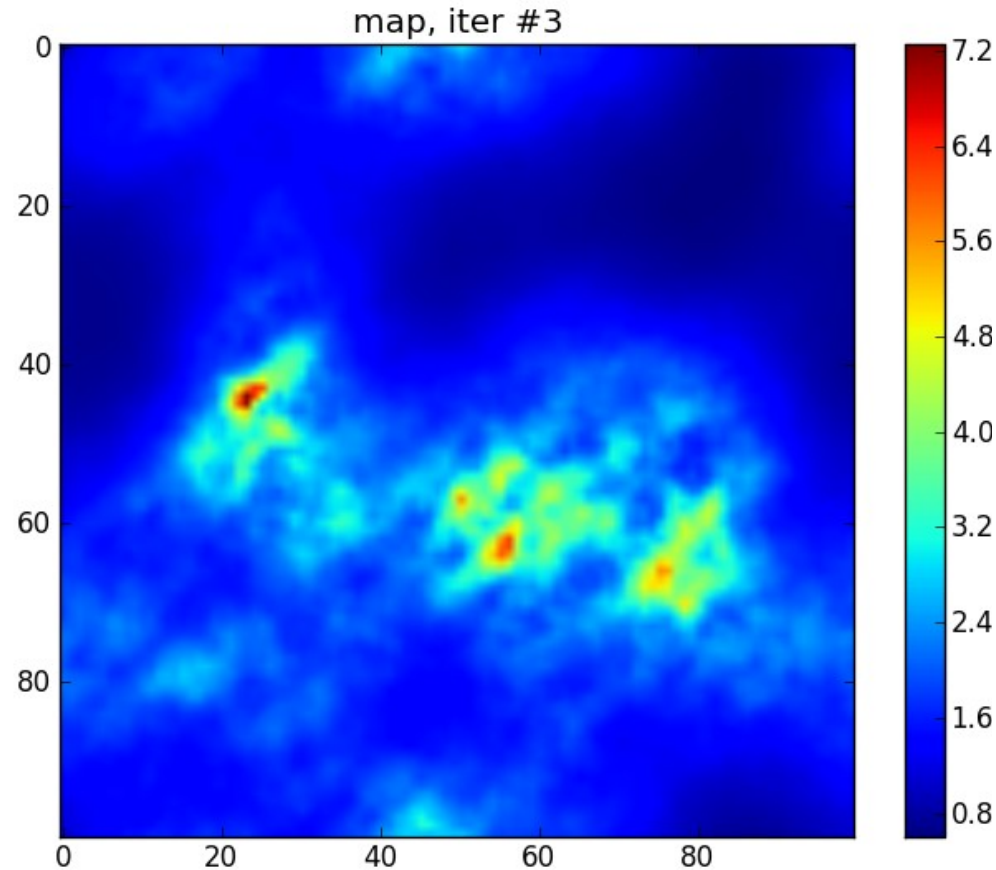


high noise, 40% uv-coverage

Radio Interferometry

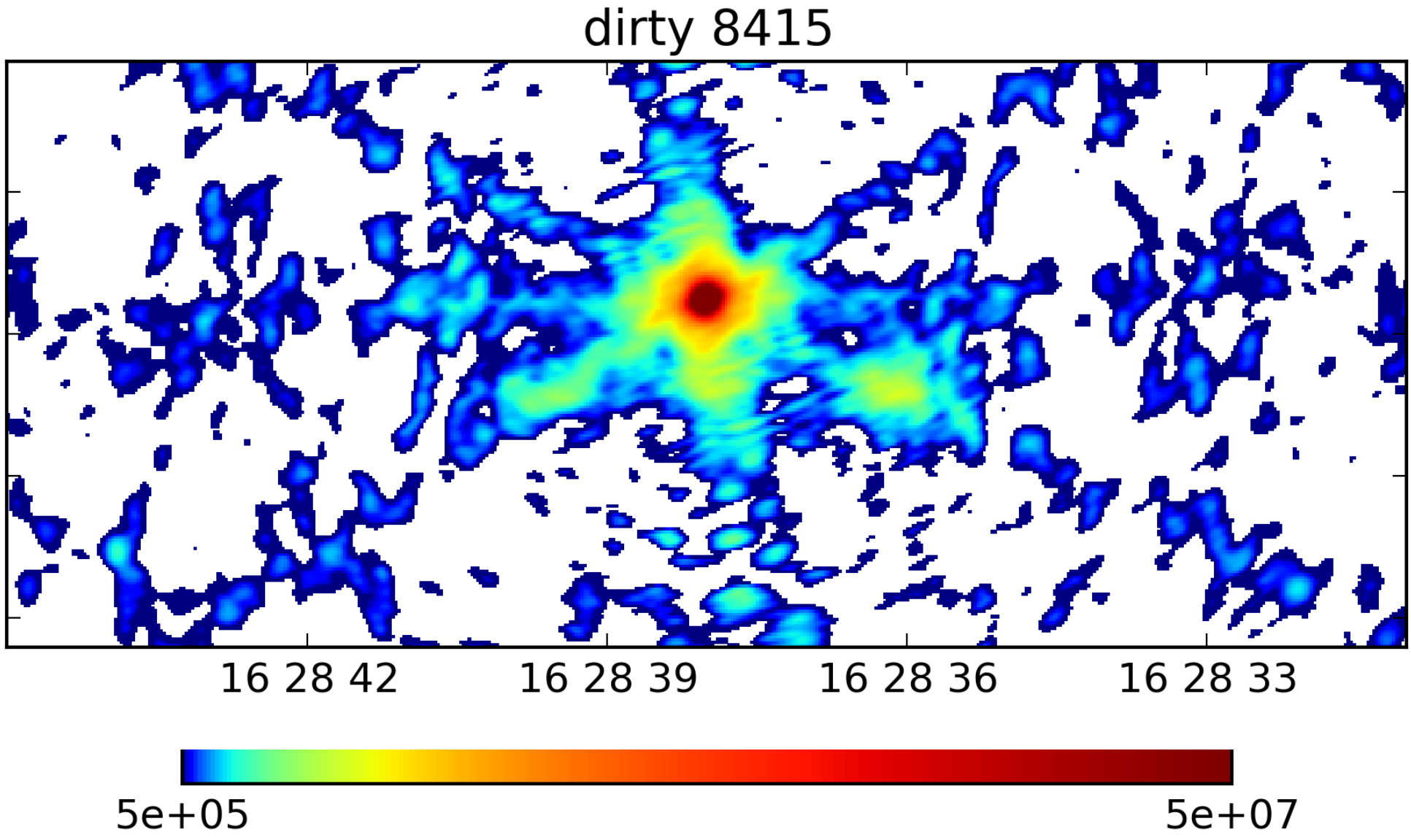
Junklewitz et al. (in prep.)



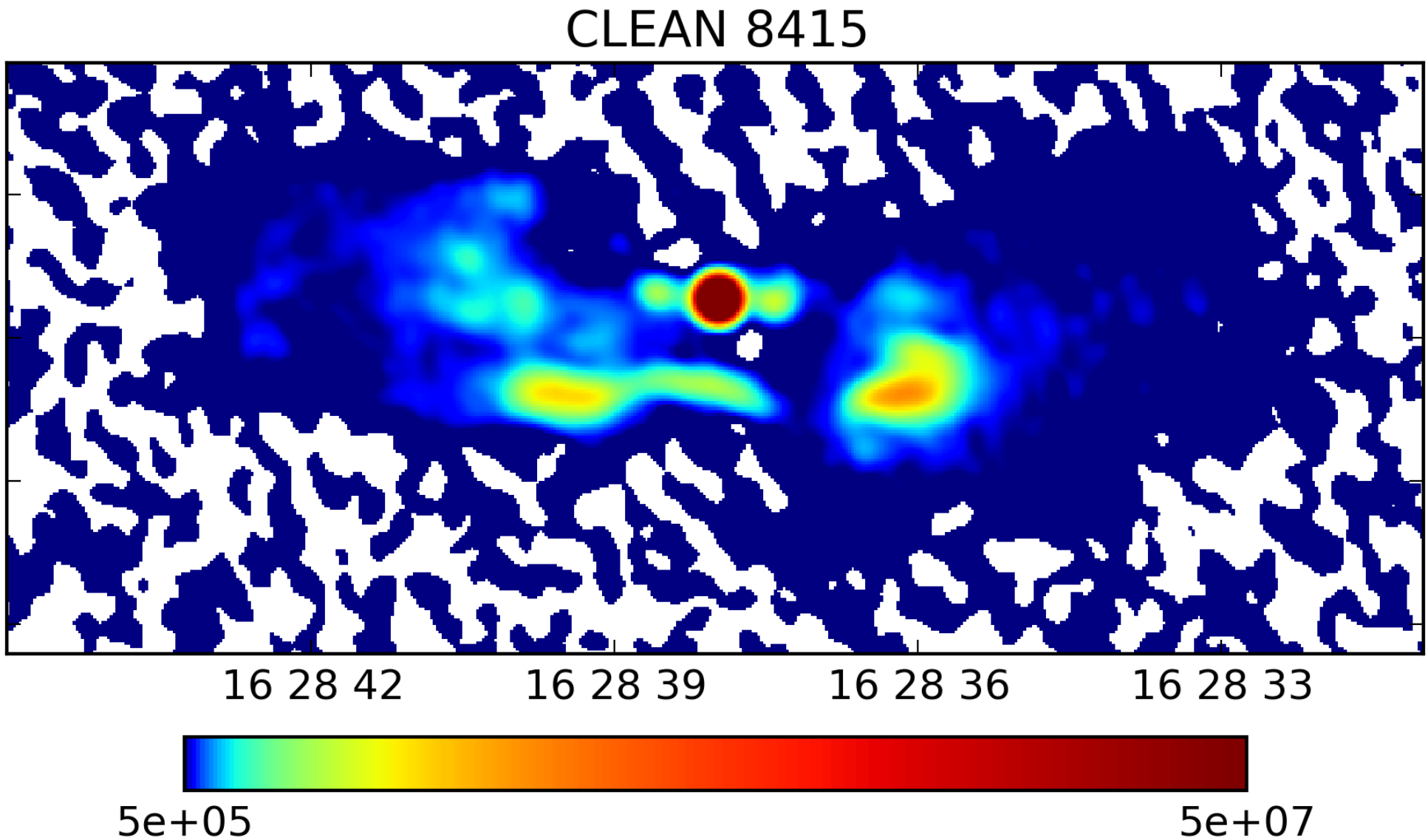


low noise, 10% uv-coverage

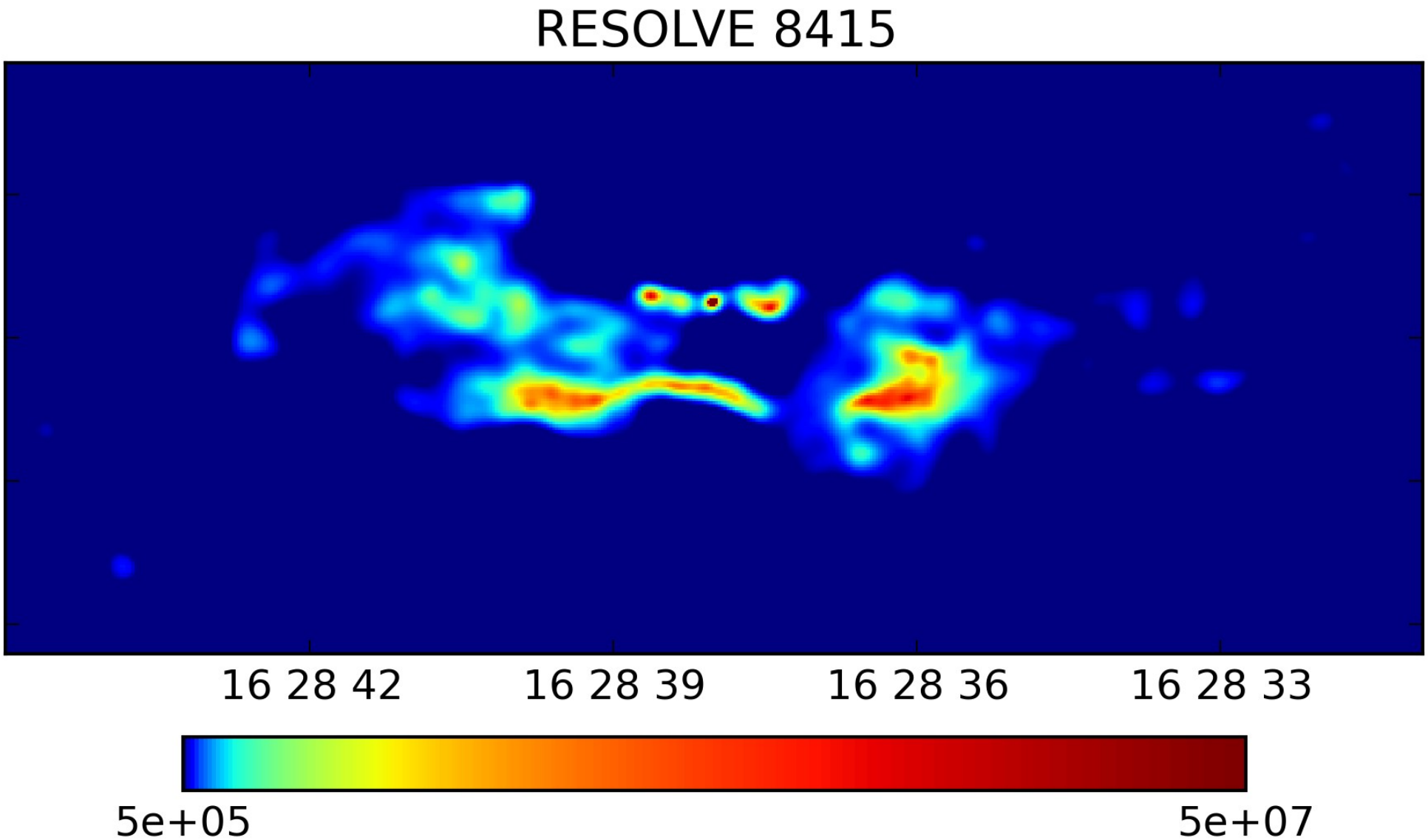
Abell 2219 @ 8415 MHz – data by Valentina Vacca



Abell 2219 @ 8415 MHz – CLEAN map by Valentina Vacca



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



Denoising, Deconvolving, and Decomposing Photon Observations

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

D^{3}PO

```
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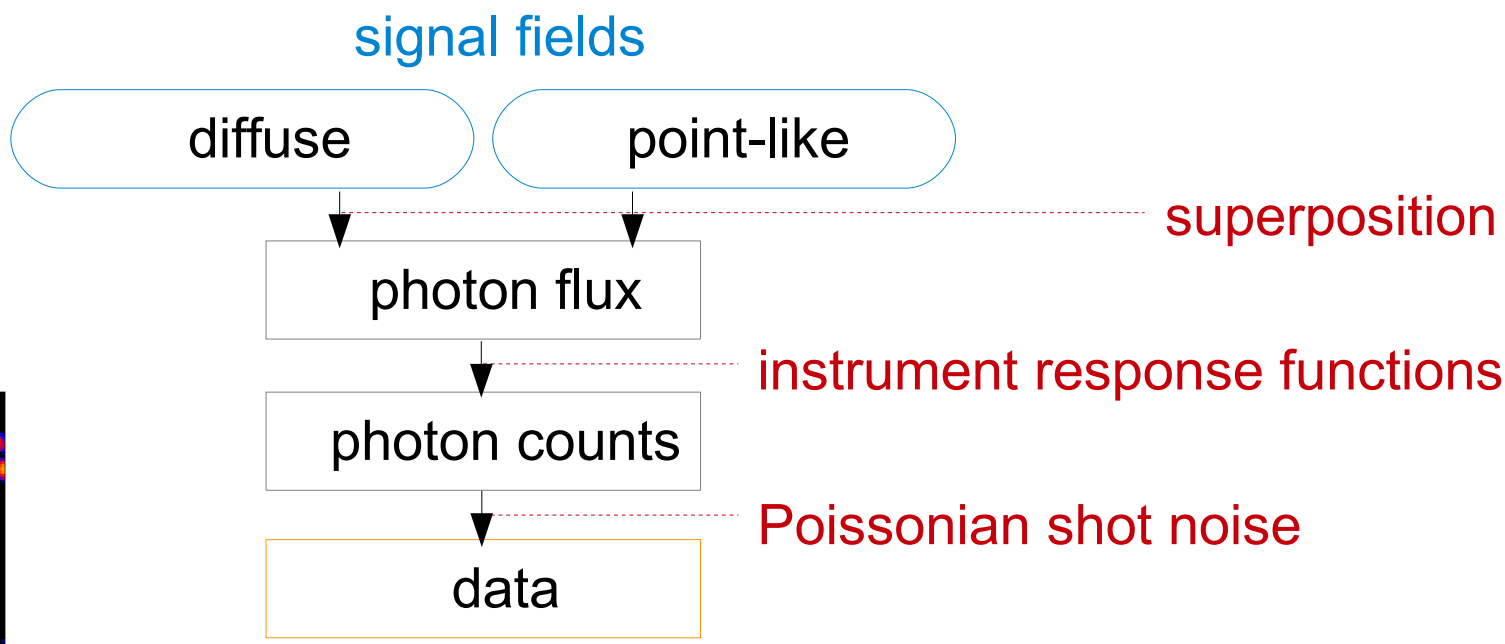
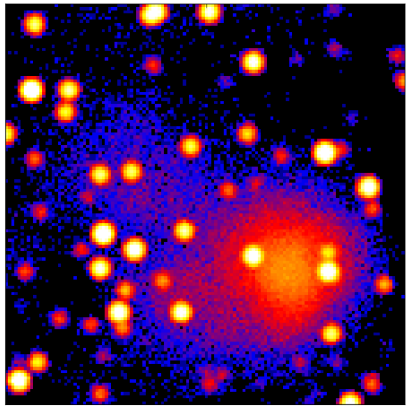
D^3PO – challenges & assumptions

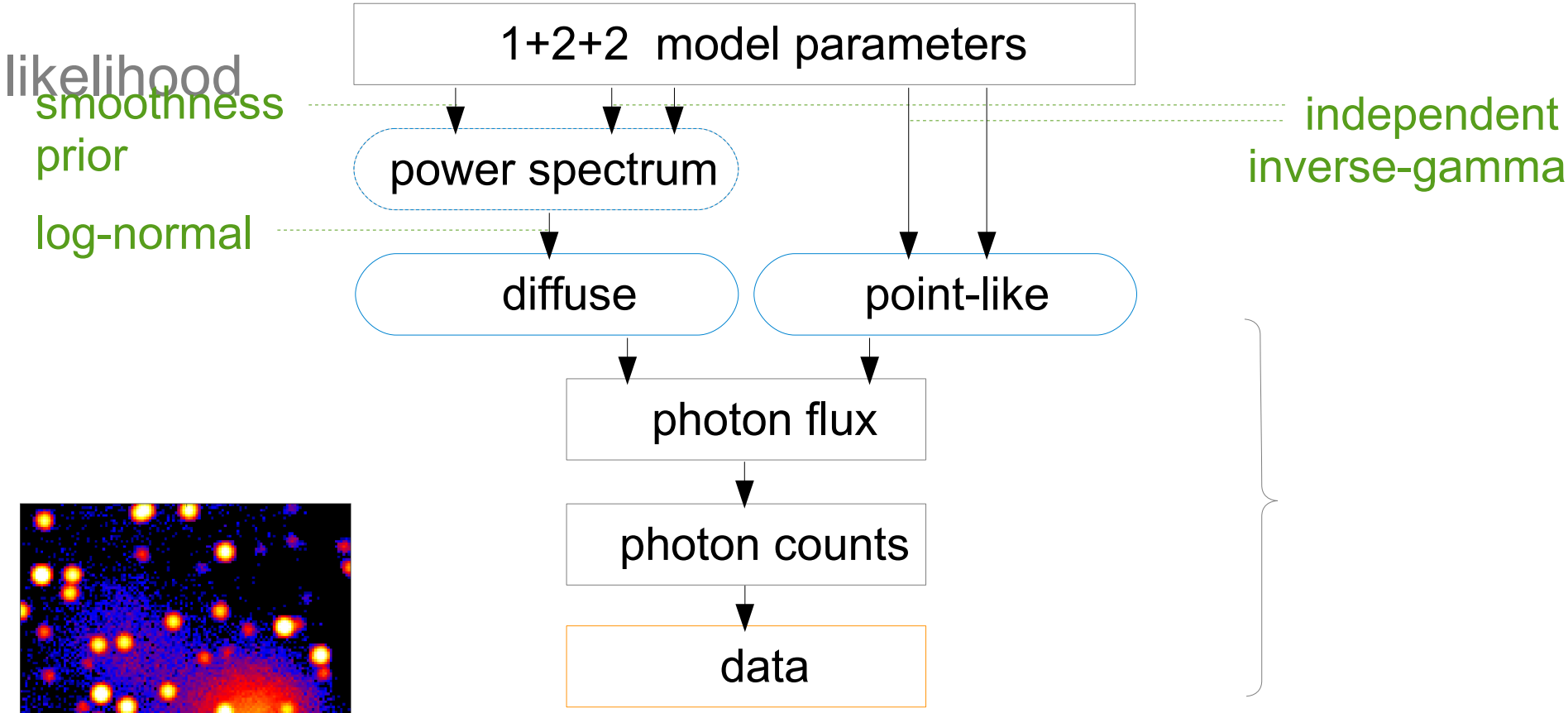
Selig & Enßlin (2014)
arXiv: 1311.1888

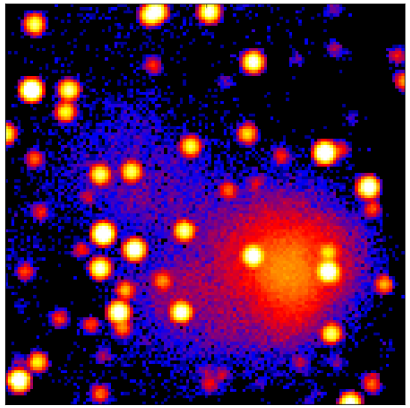




D^{3}PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888

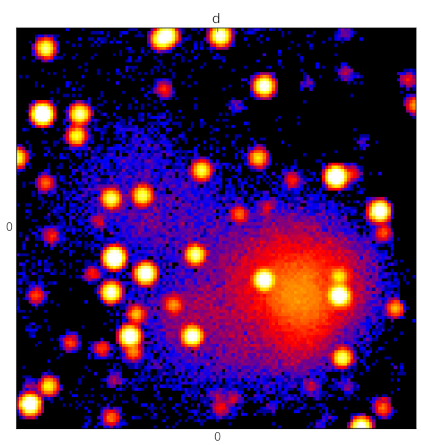




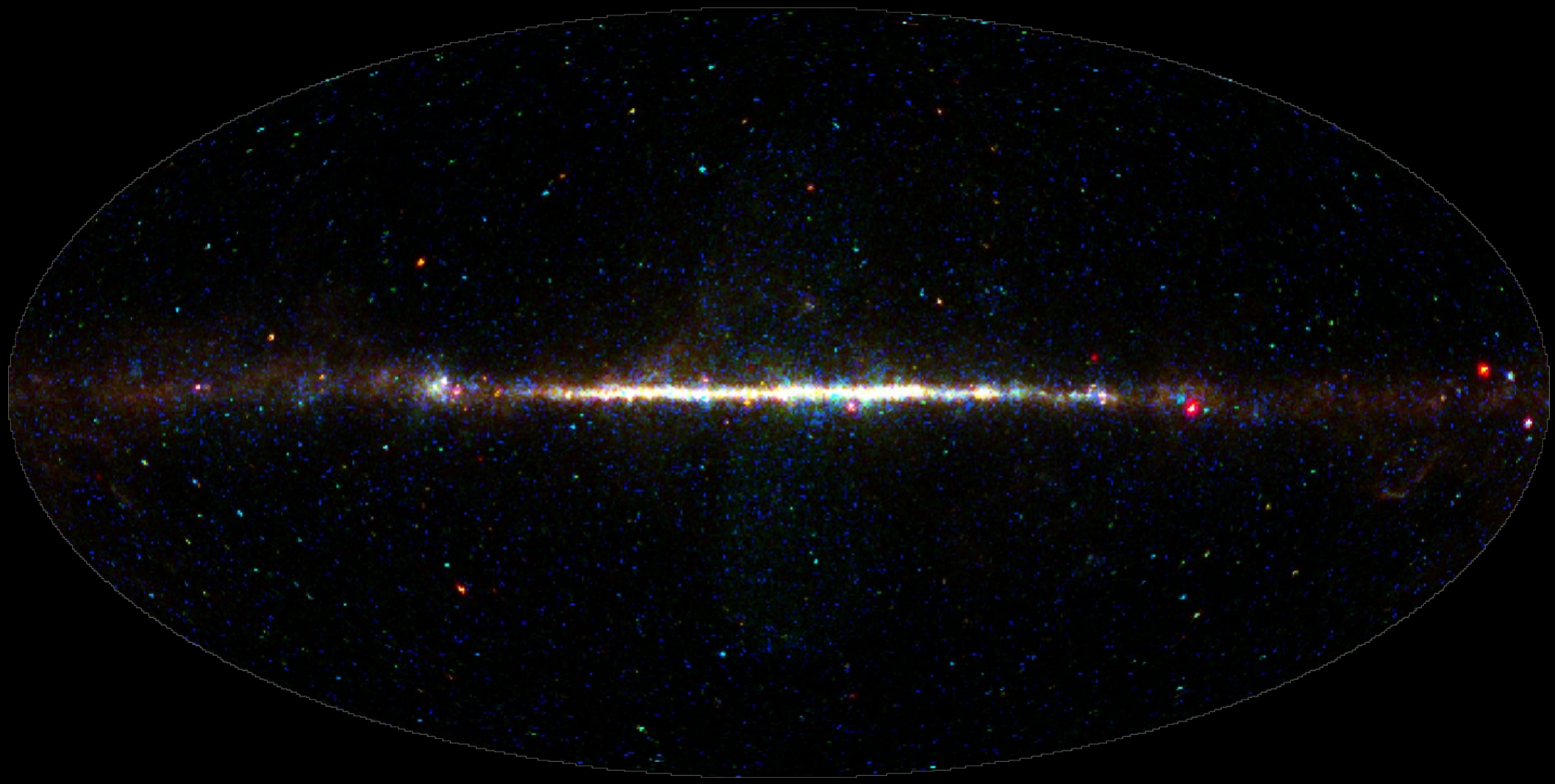
D^{3}PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888

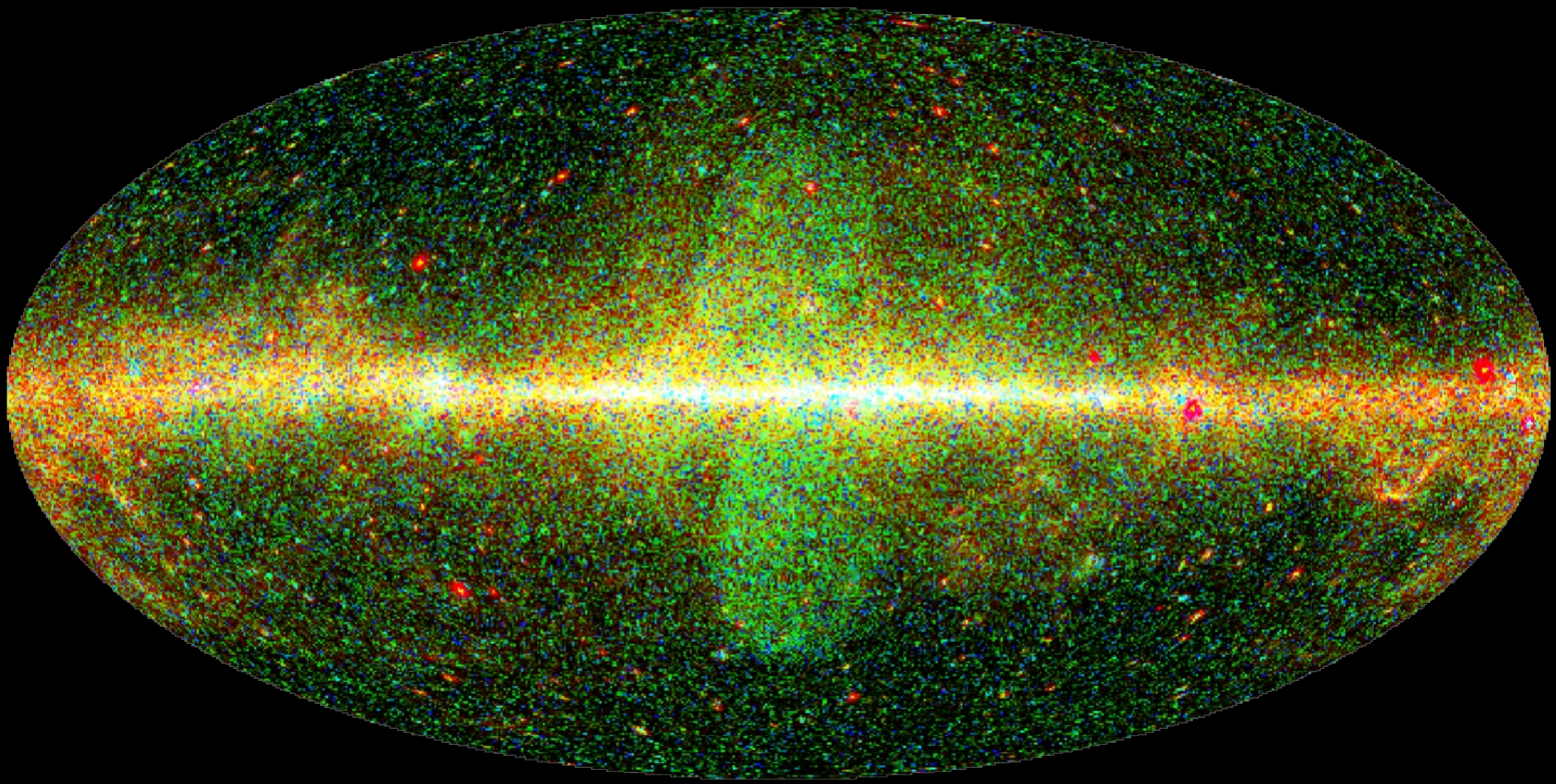
$$
\begin{aligned}
\mathcal{H}(\boldsymbol{s},\boldsymbol{\tau},\boldsymbol{u}|\boldsymbol{d}) &= -\log \mathcal{P}(\boldsymbol{s},\boldsymbol{\tau},\boldsymbol{u}|\boldsymbol{d}) \\
&= H_0 + \boldsymbol{1}^\dagger \boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right) -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



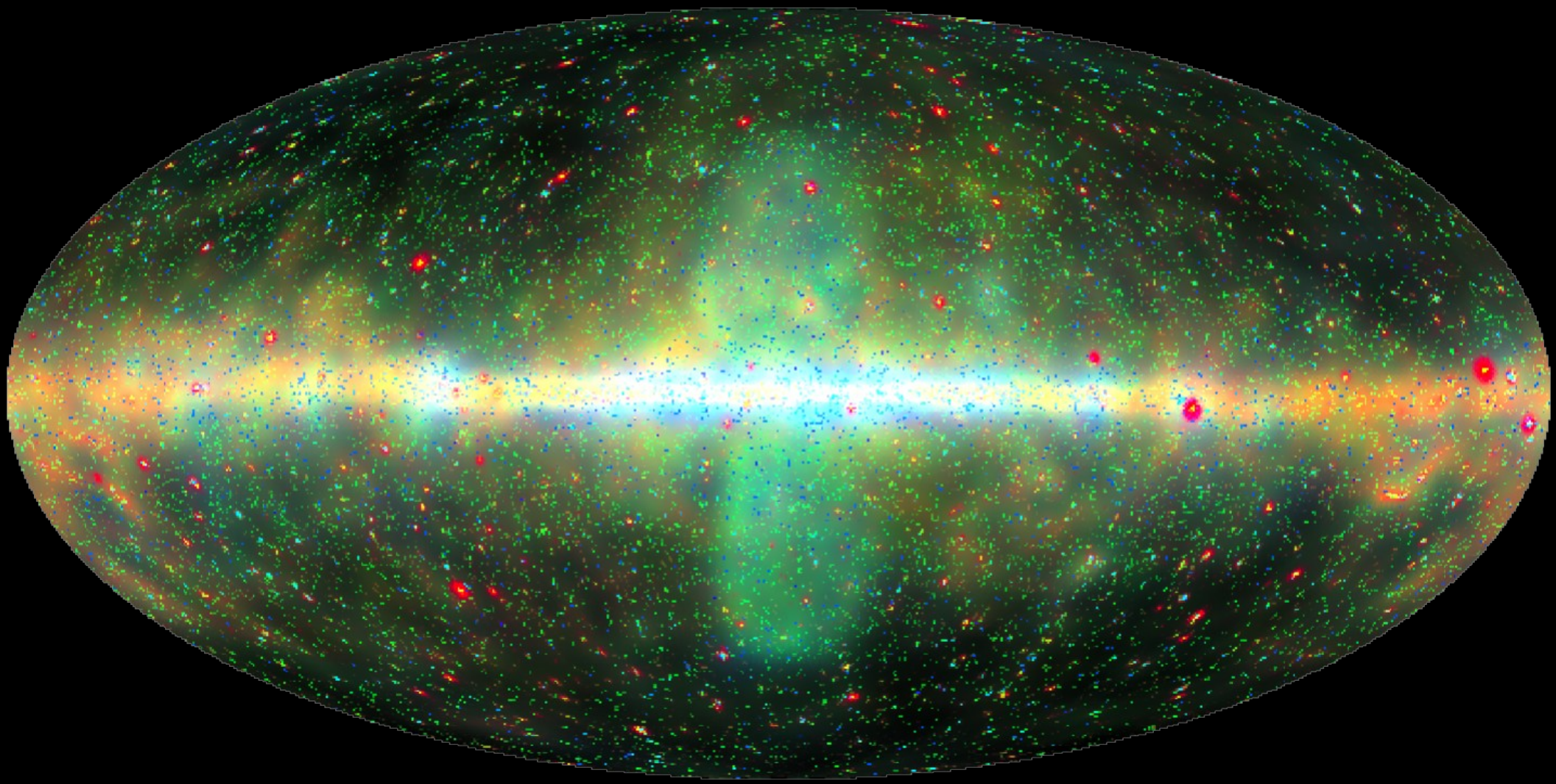
$$
\boldsymbol{S} = \sum_k \mathrm{e}^{\tau_k} \boldsymbol{S}_k
$$



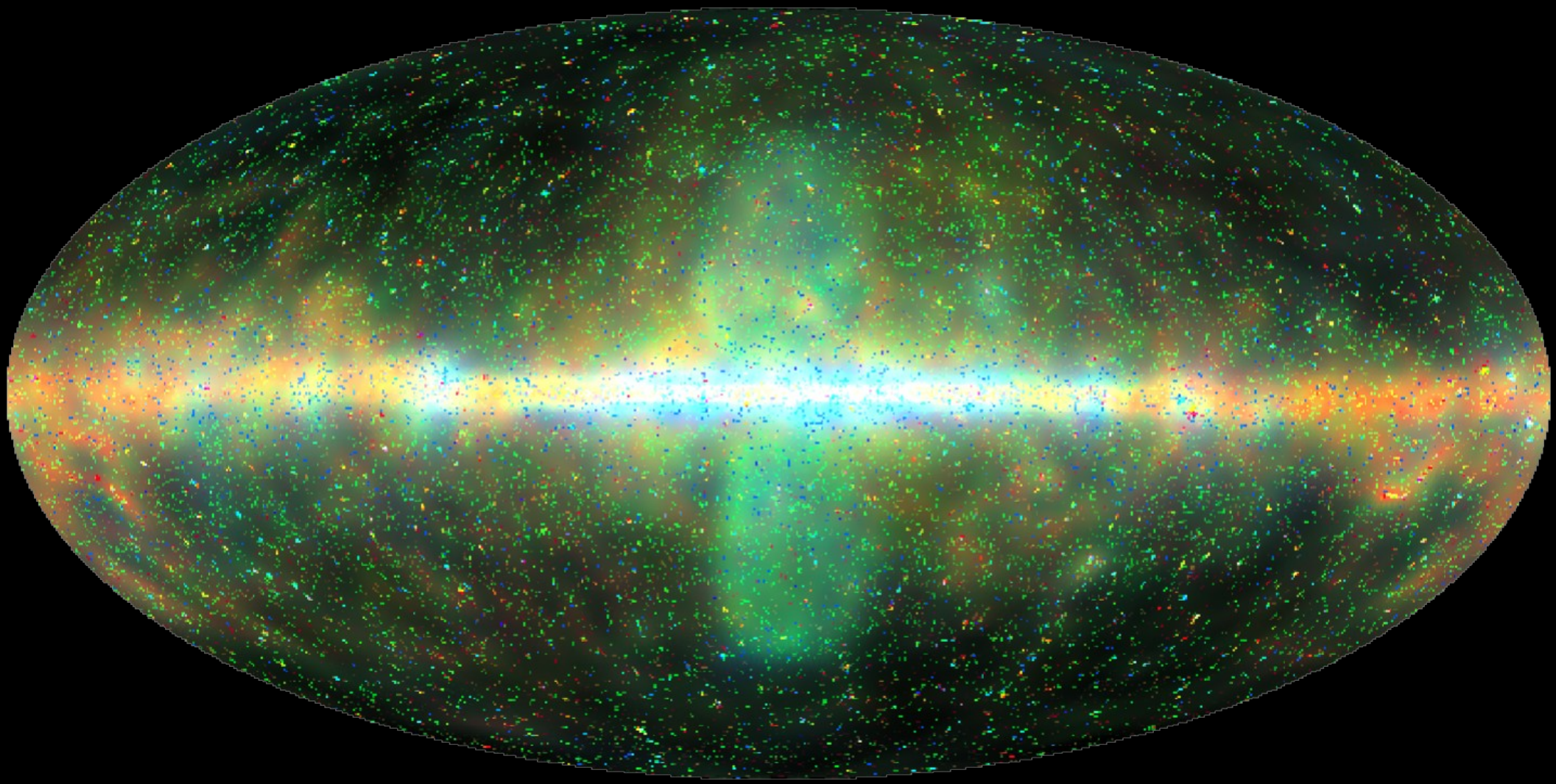
data



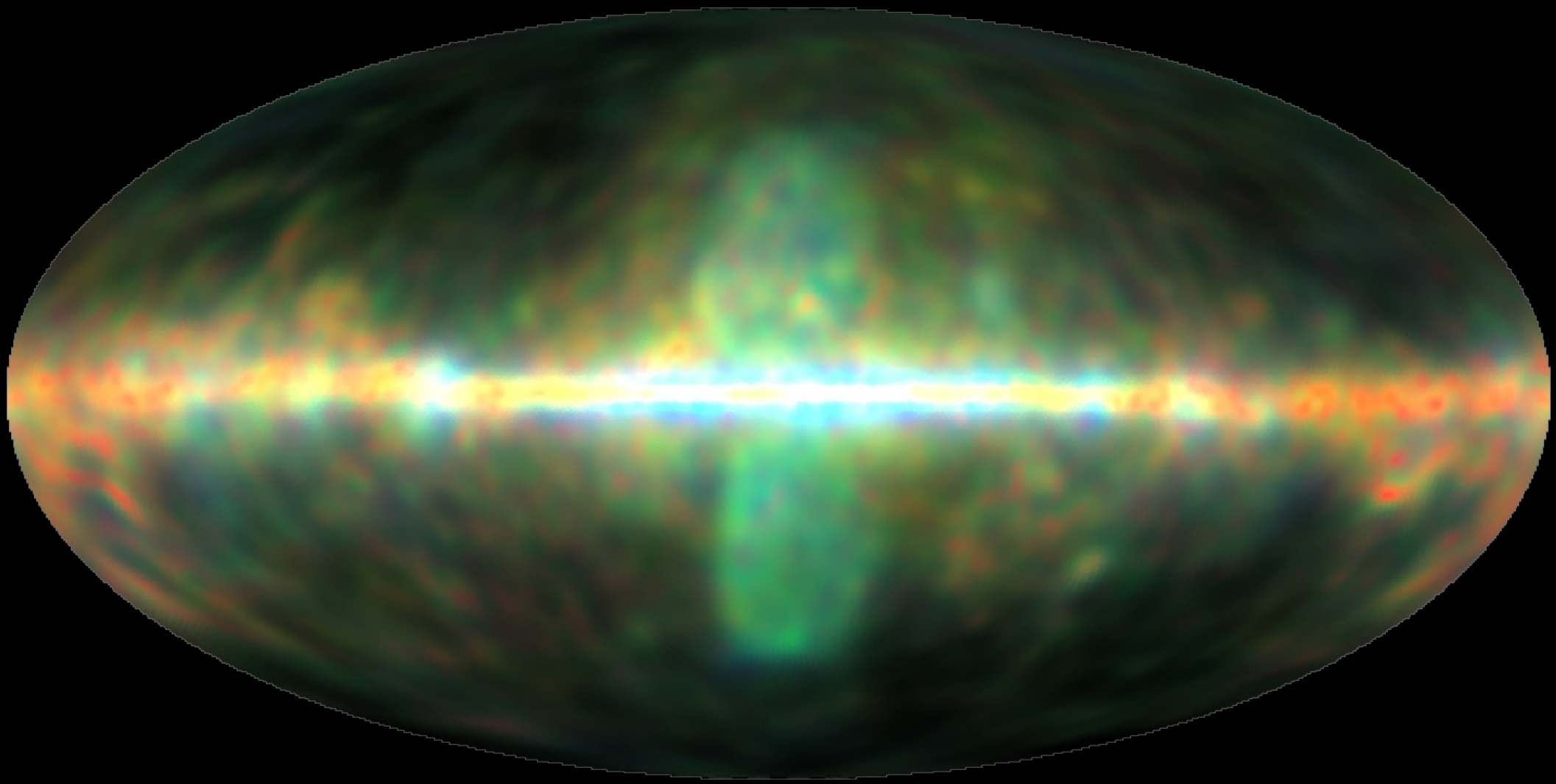
log-data



log-data … denoised

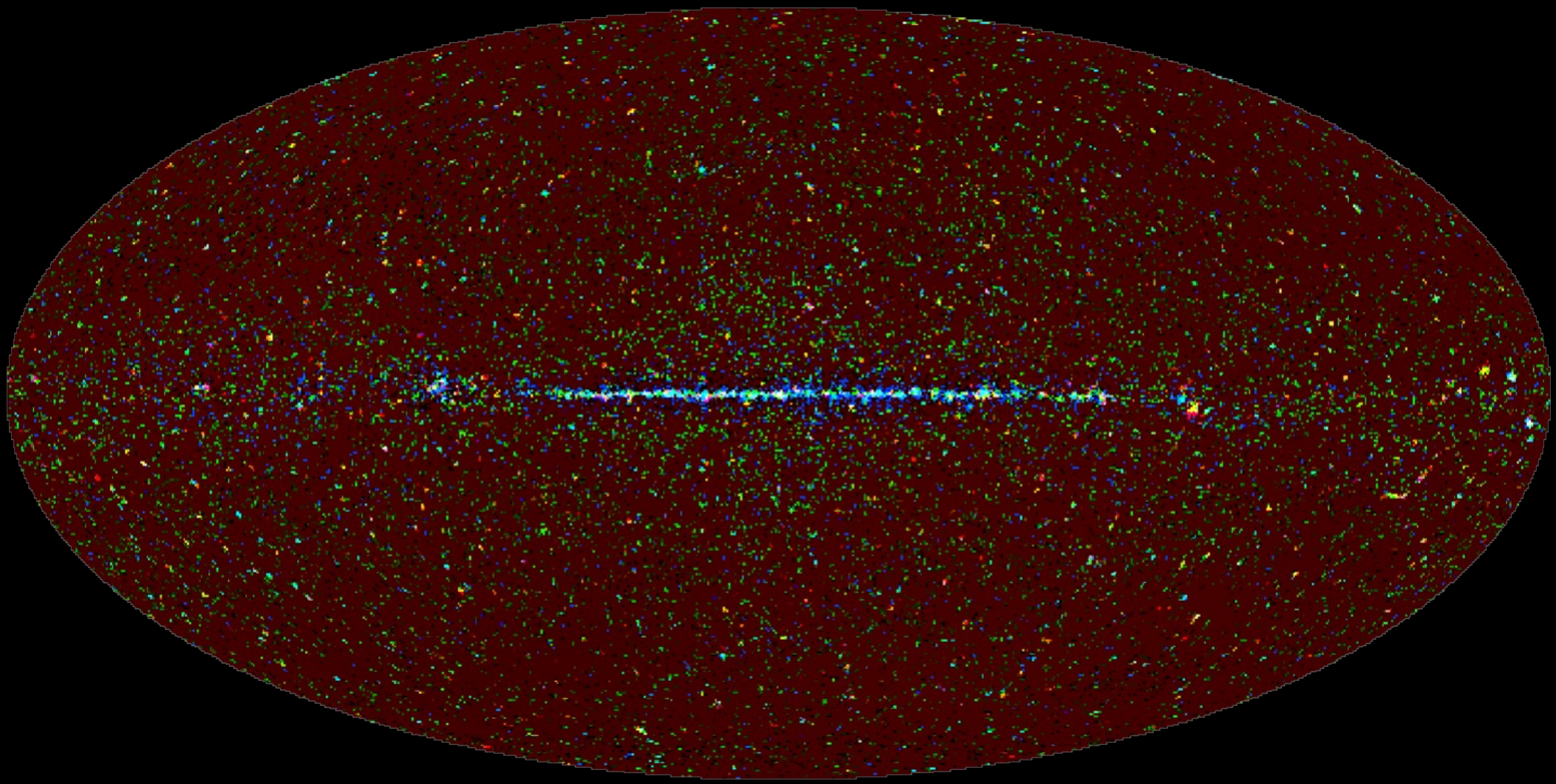


log-data … denoised … deconvolved



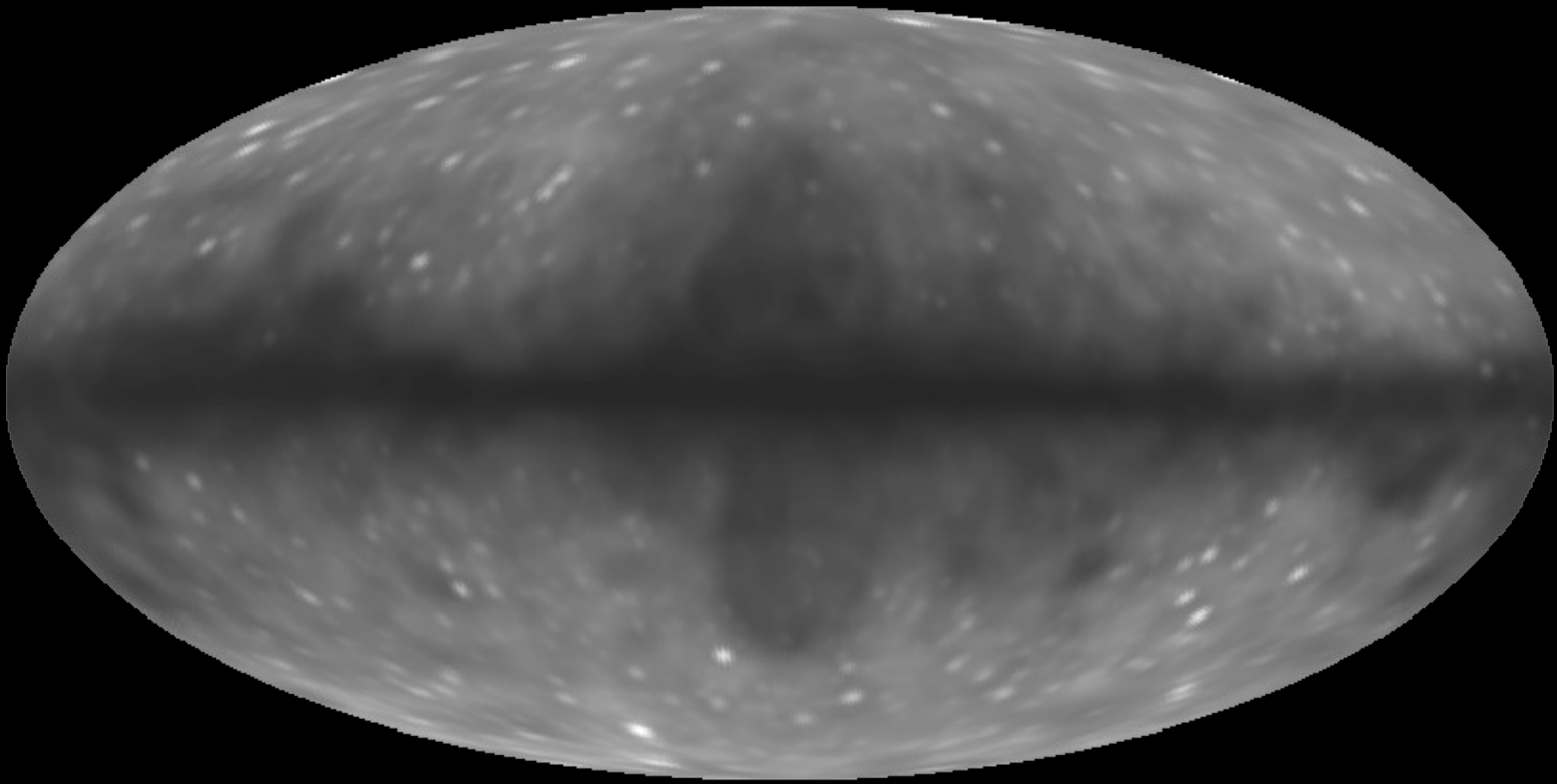
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)



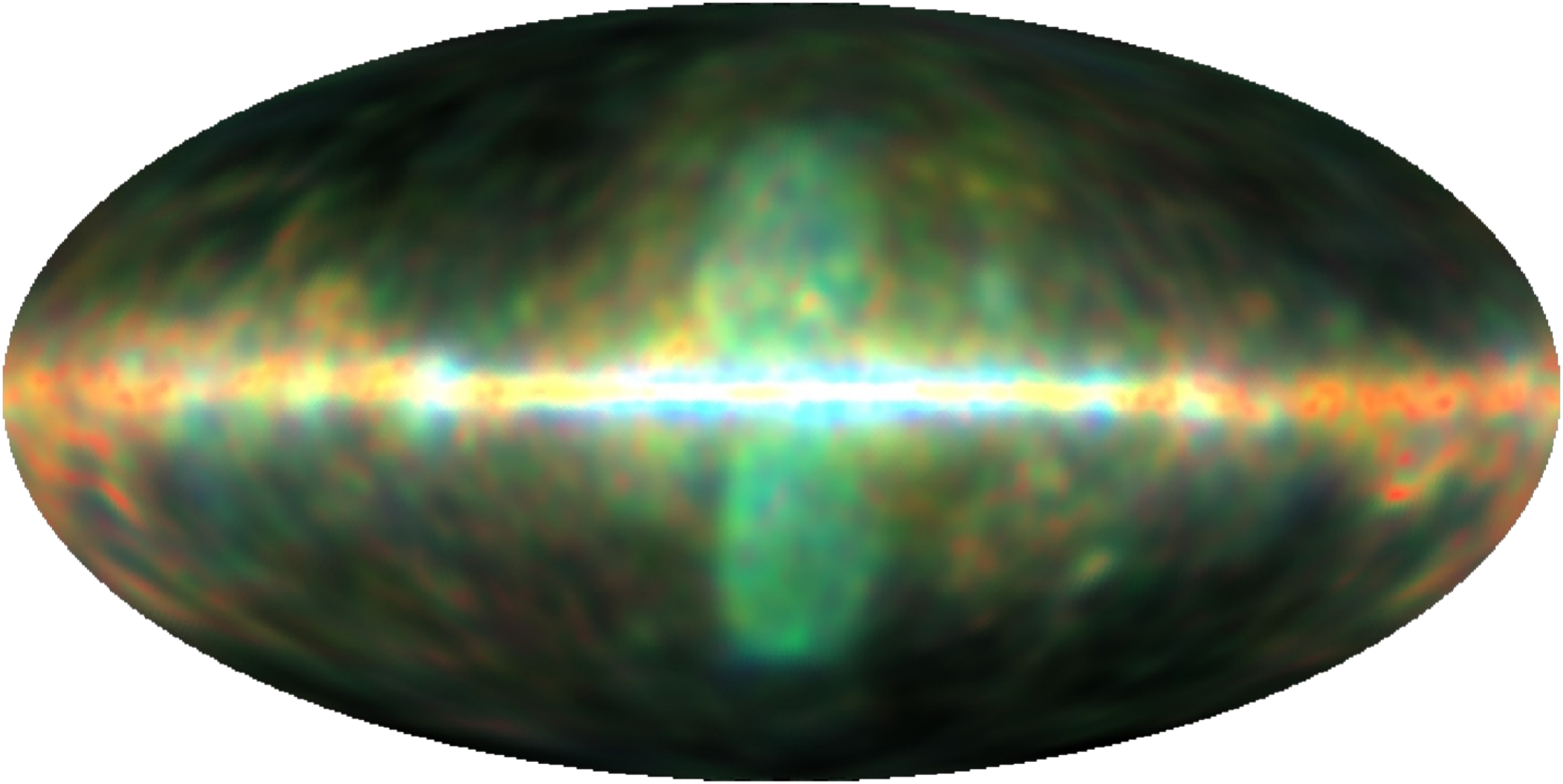
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)

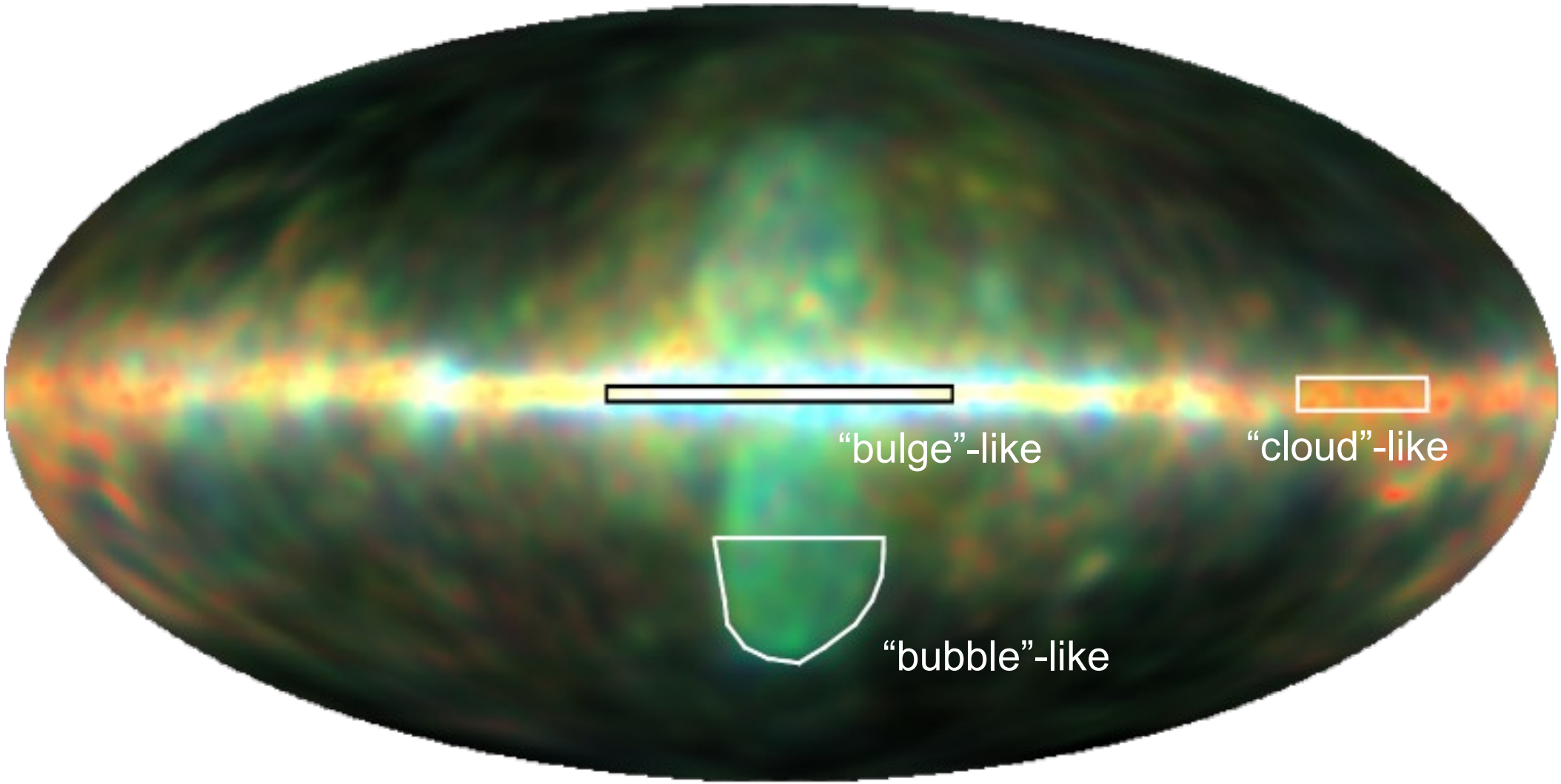


relative uncertainty of diffuse emission

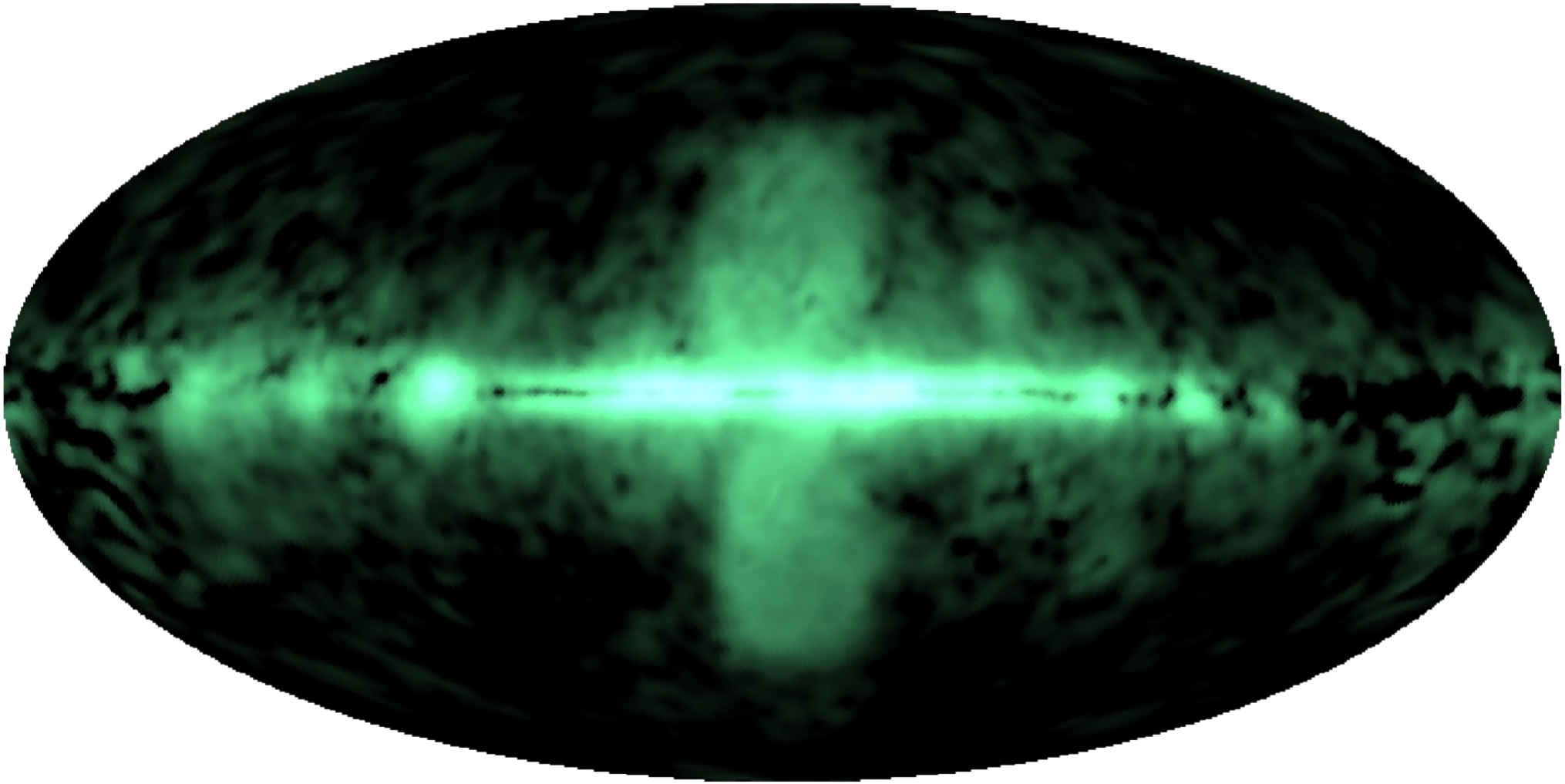
Diffuse gamma-ray sky



Diffuse gamma-ray sky

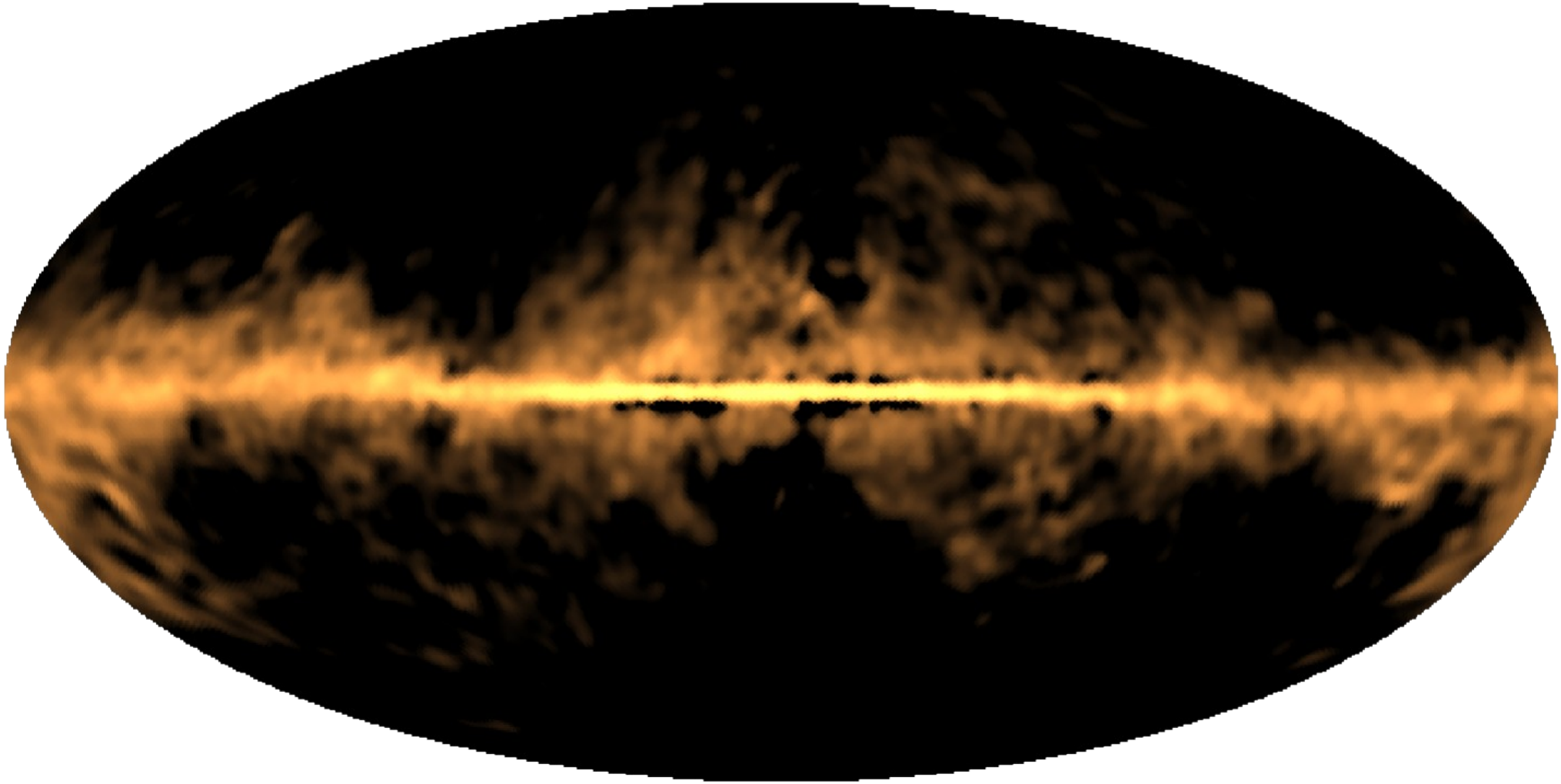


bubble-like

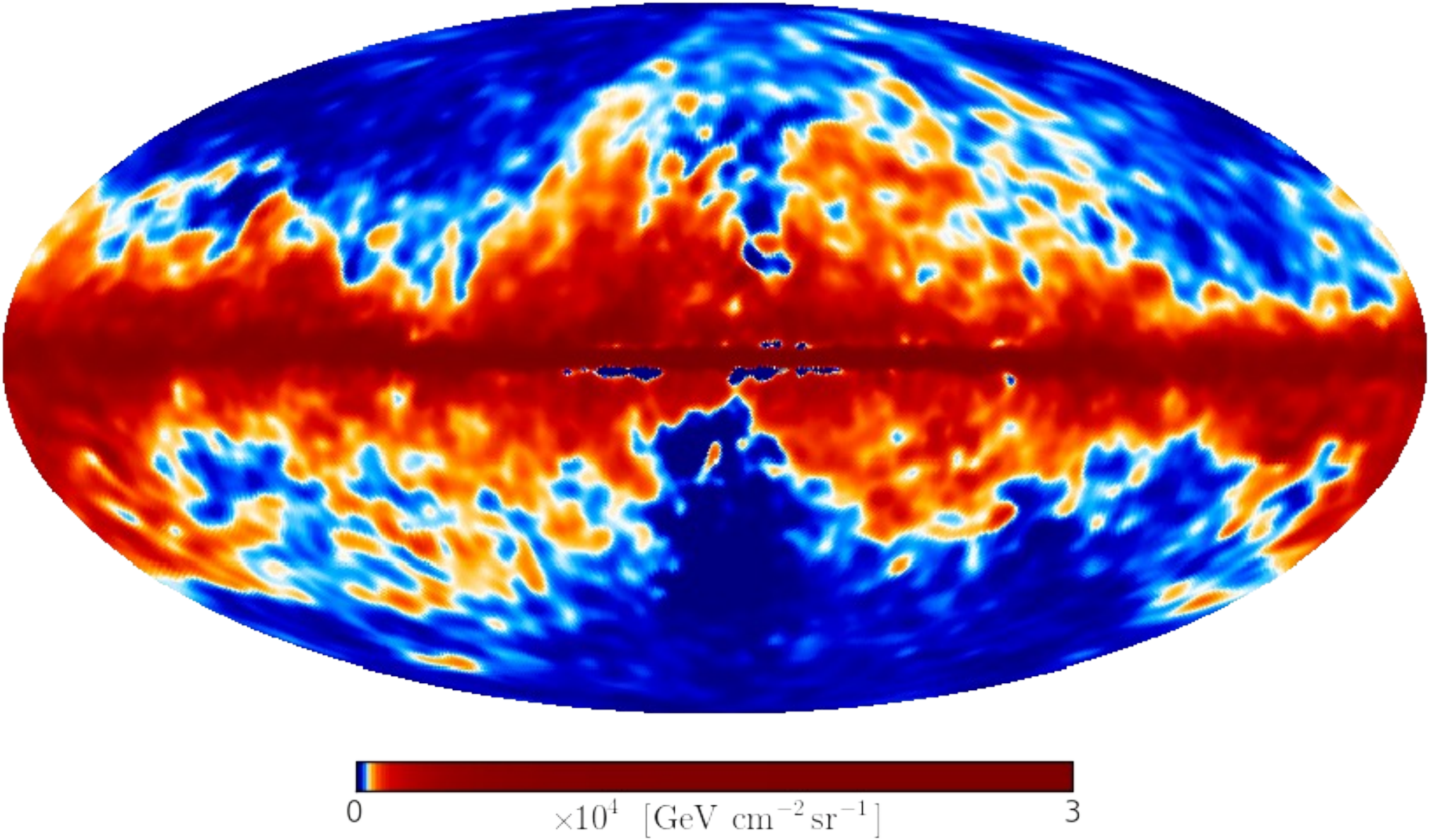


Photon spectral index: **2.4** – Inverse Compton?

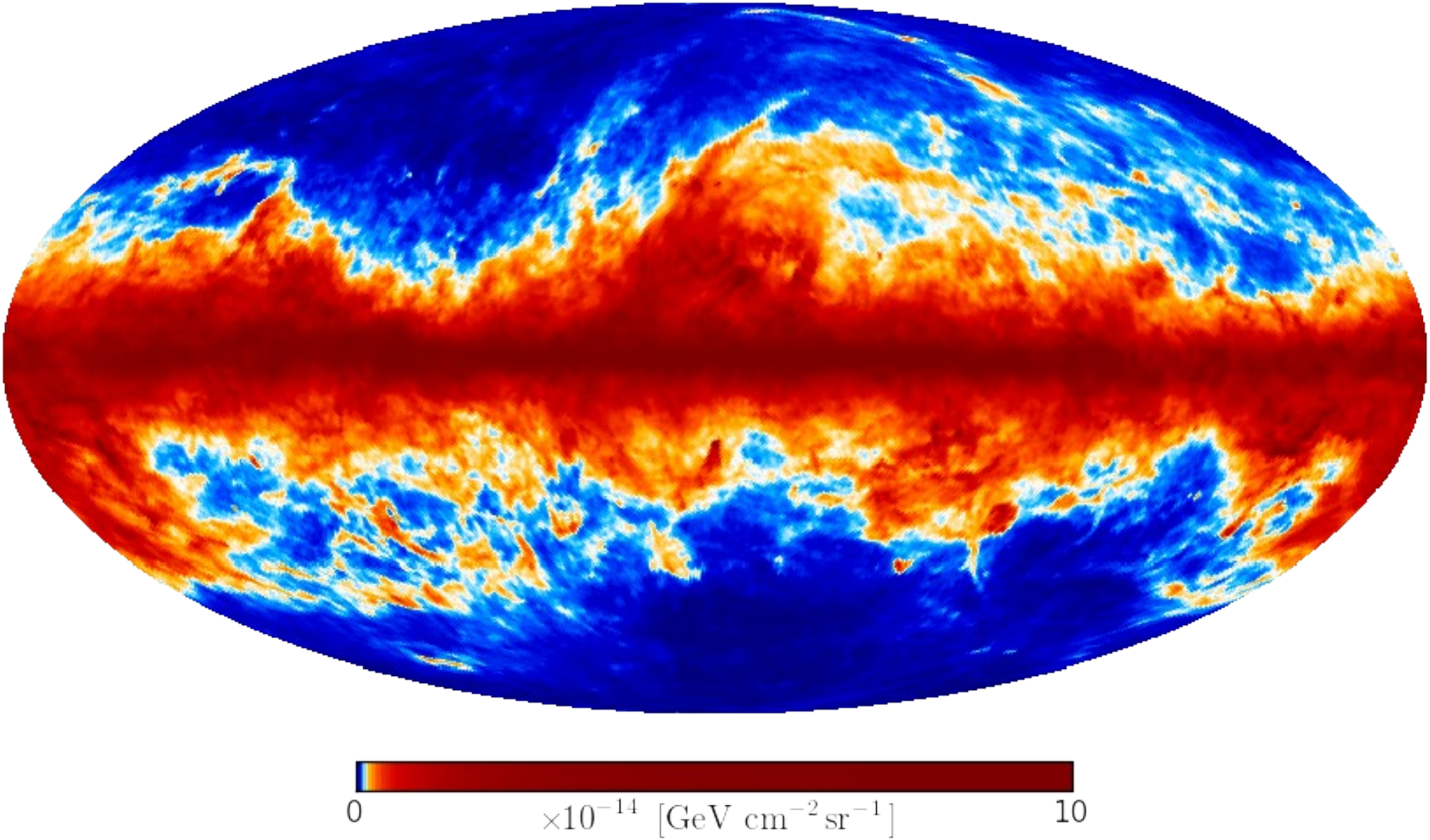
“cloud”-like



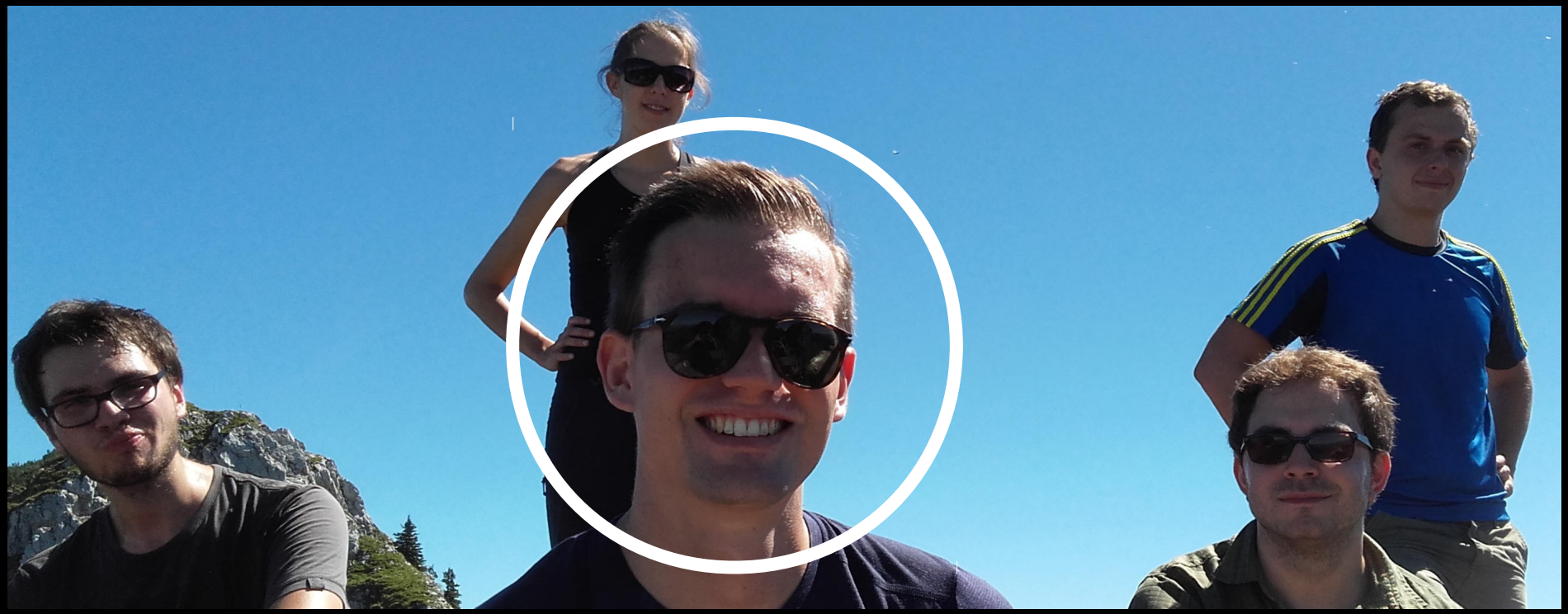
“cloud”-like



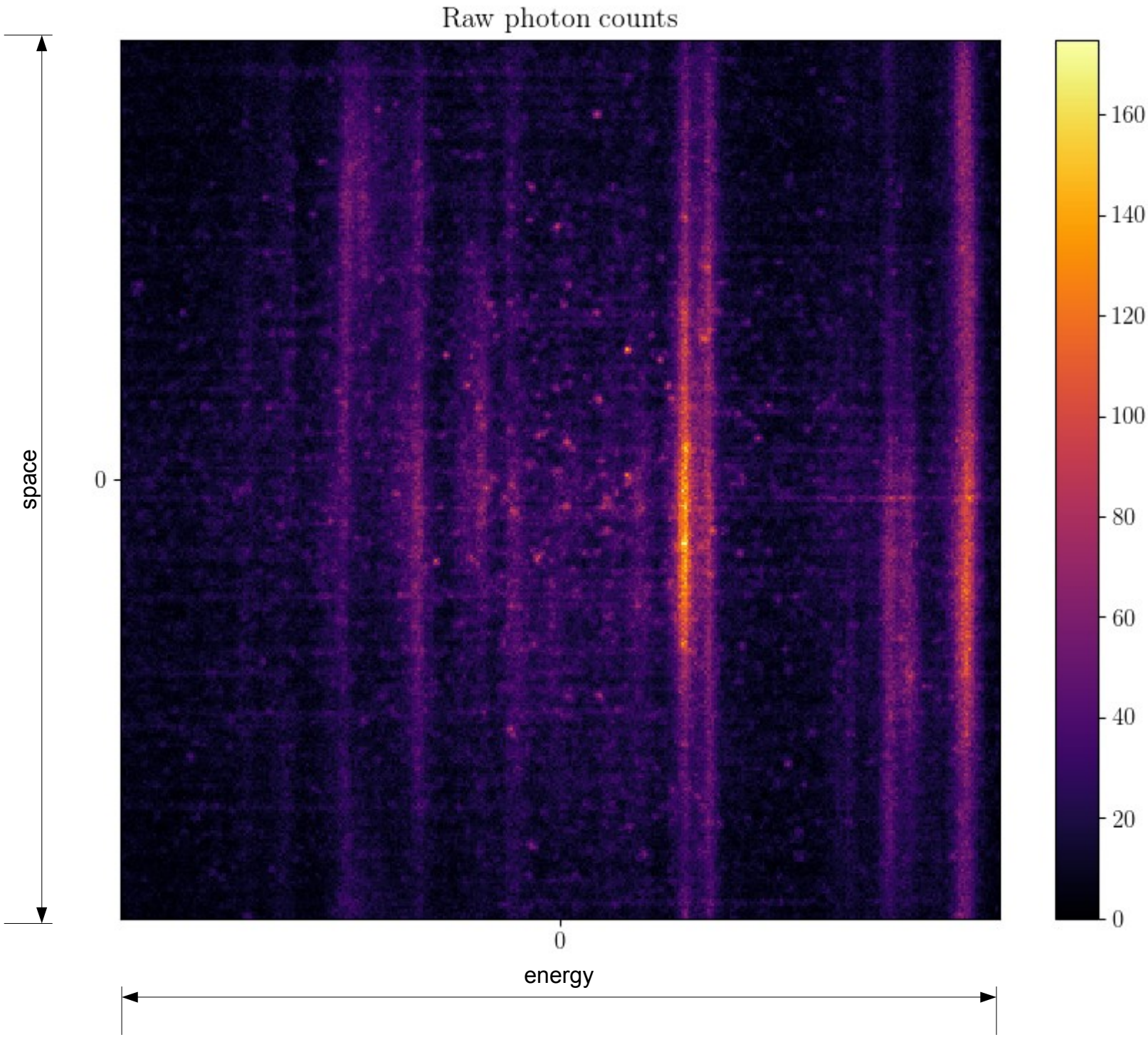
Planck dust map

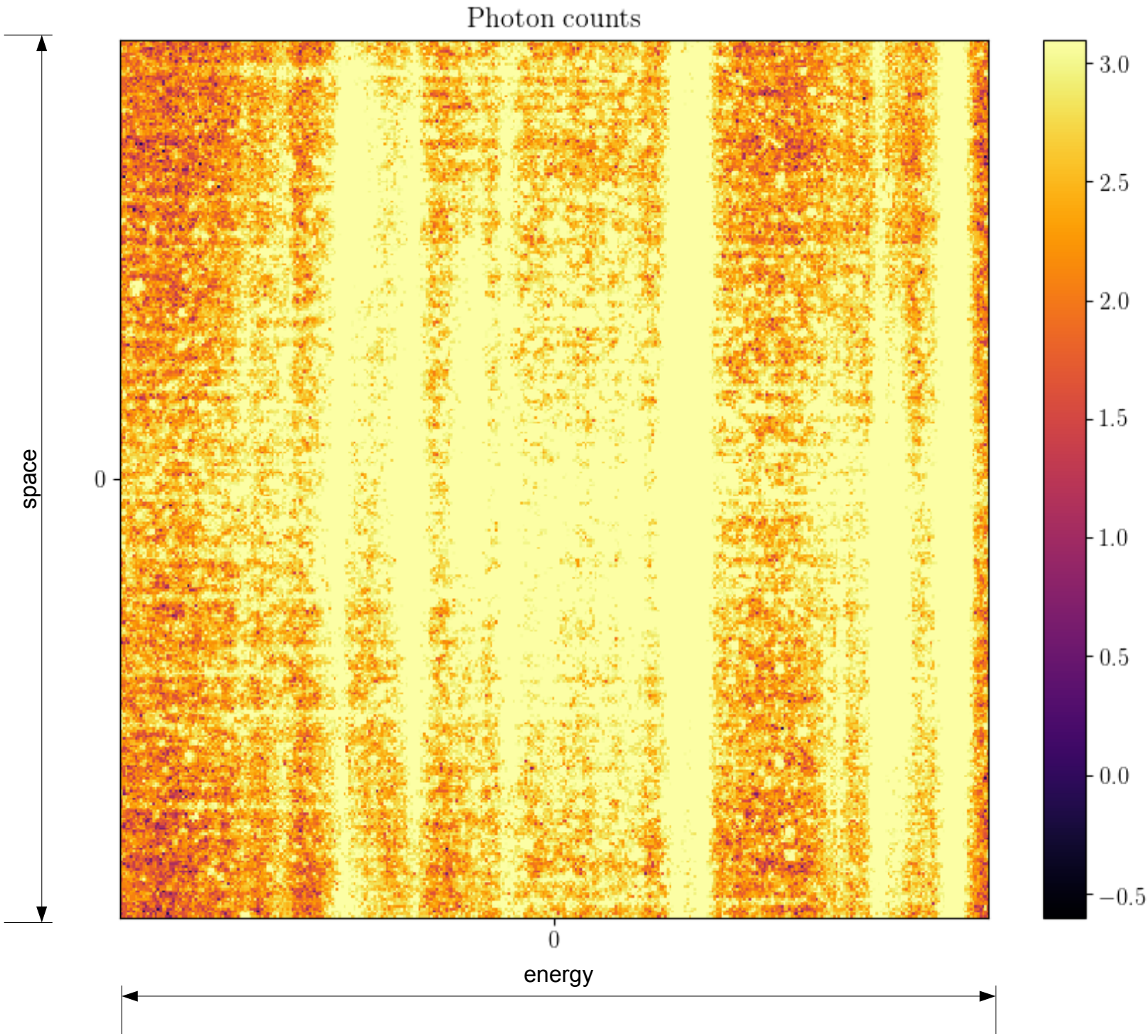


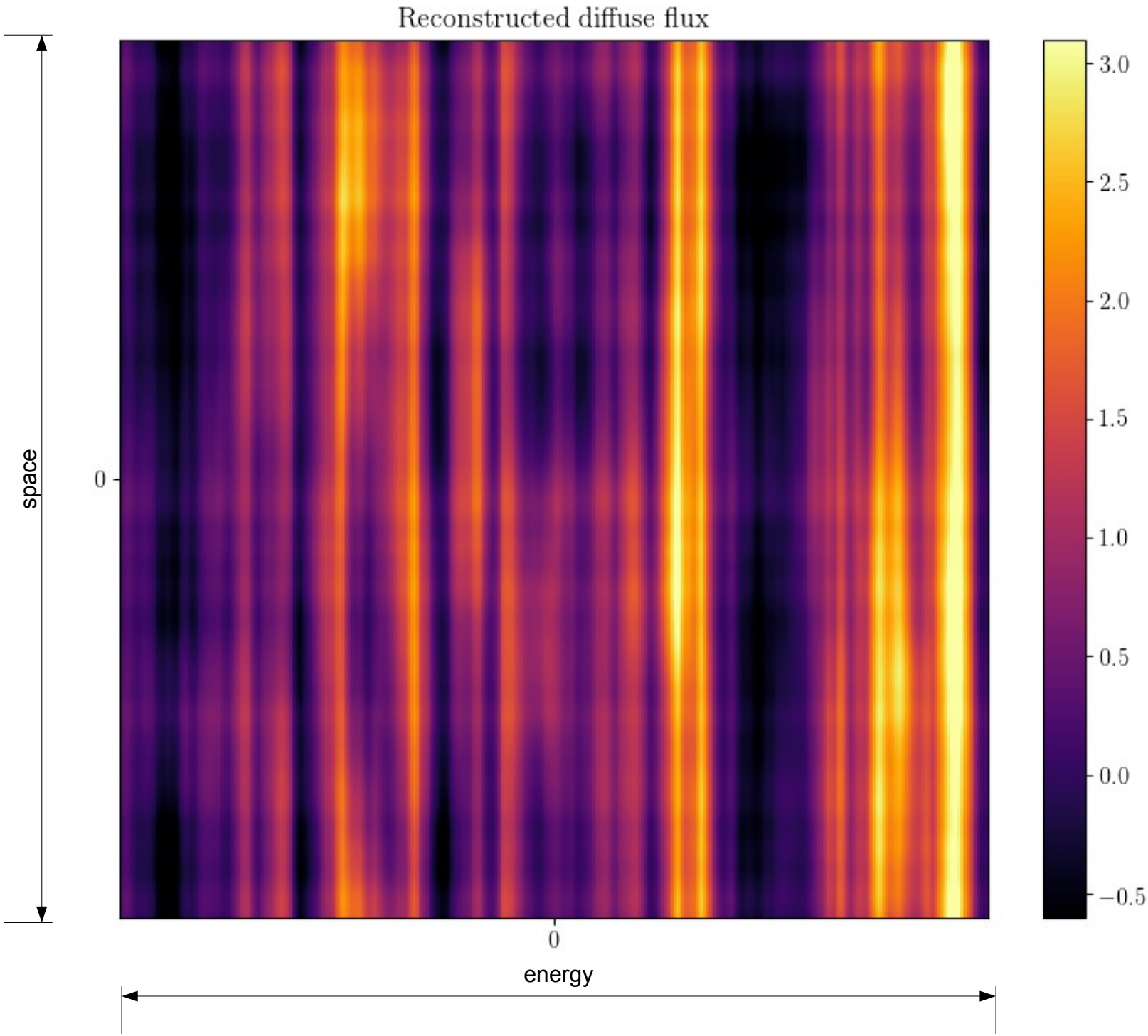
Glimpses into the future

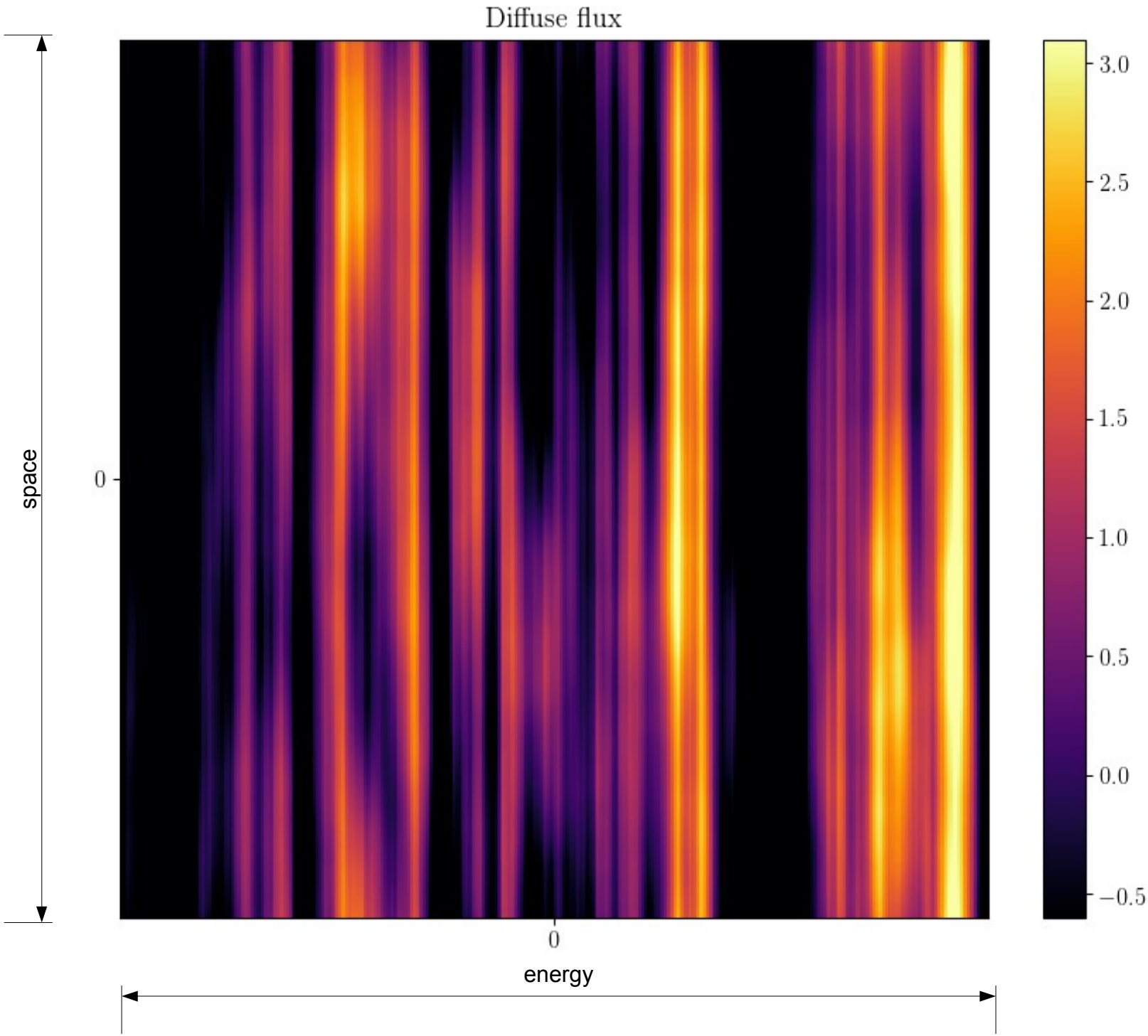


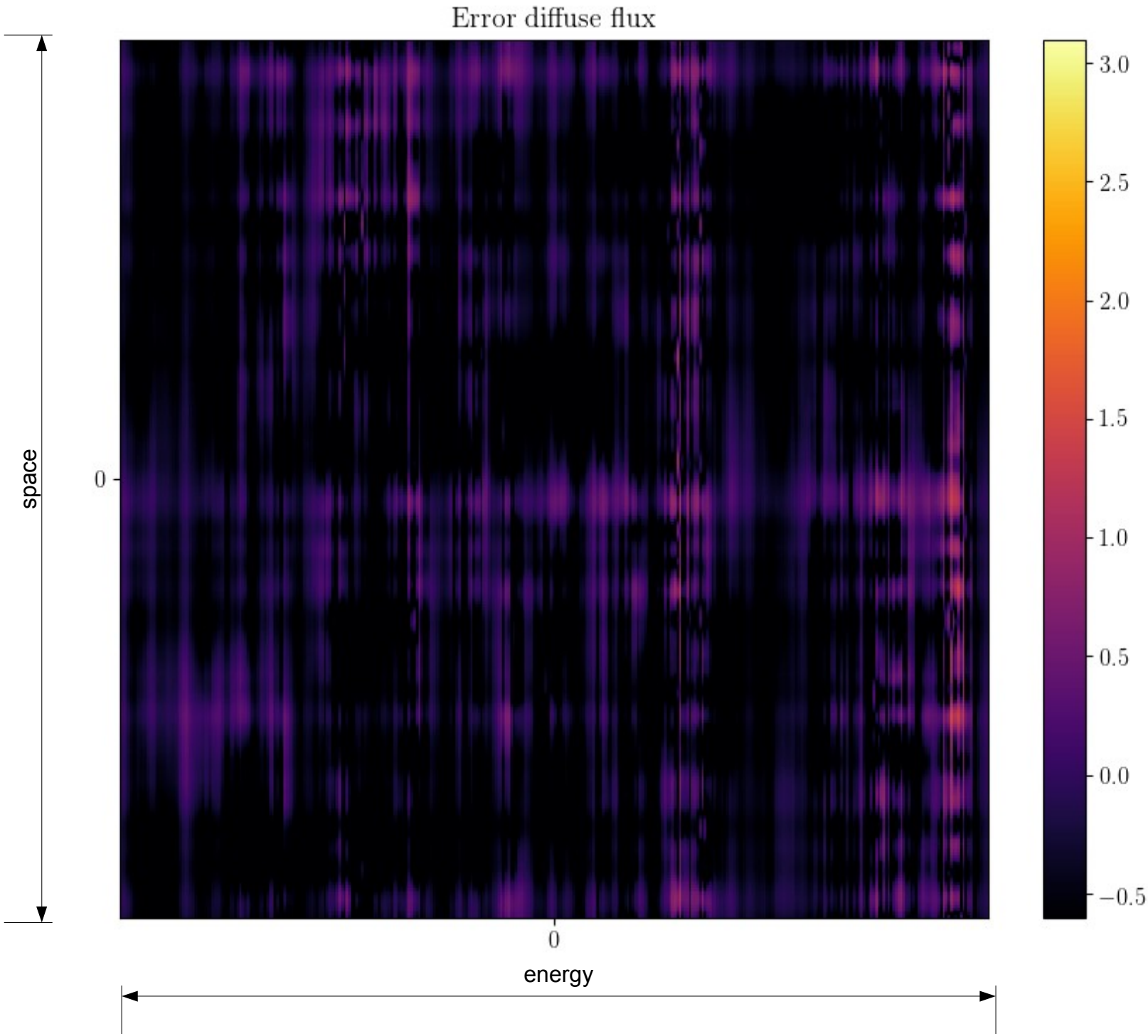
Daniel Pumpe: D^4PO

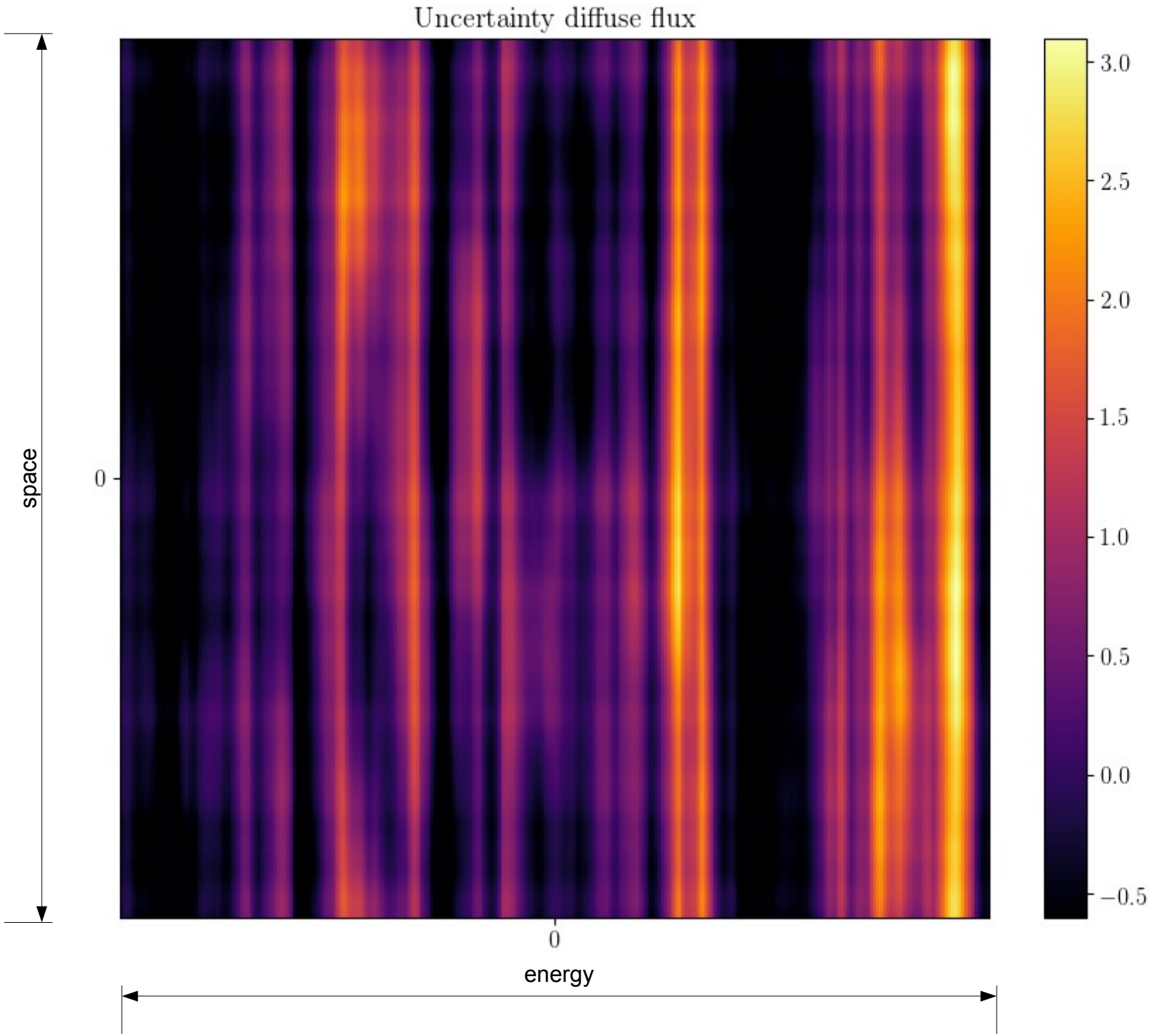

Raw photon counts
space
0
0
energy
160
140
120
100
80
60
40
20
0

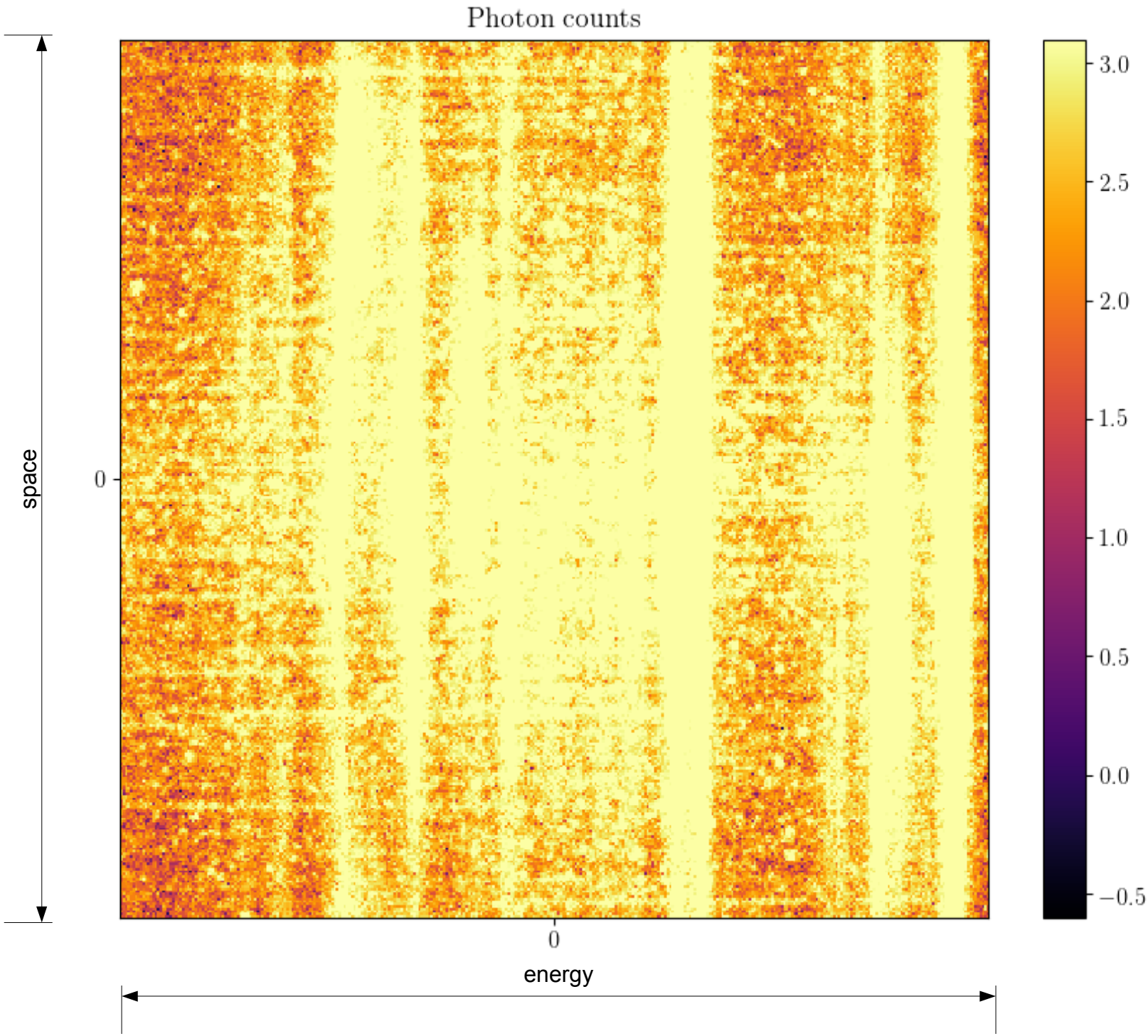

Photon counts
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

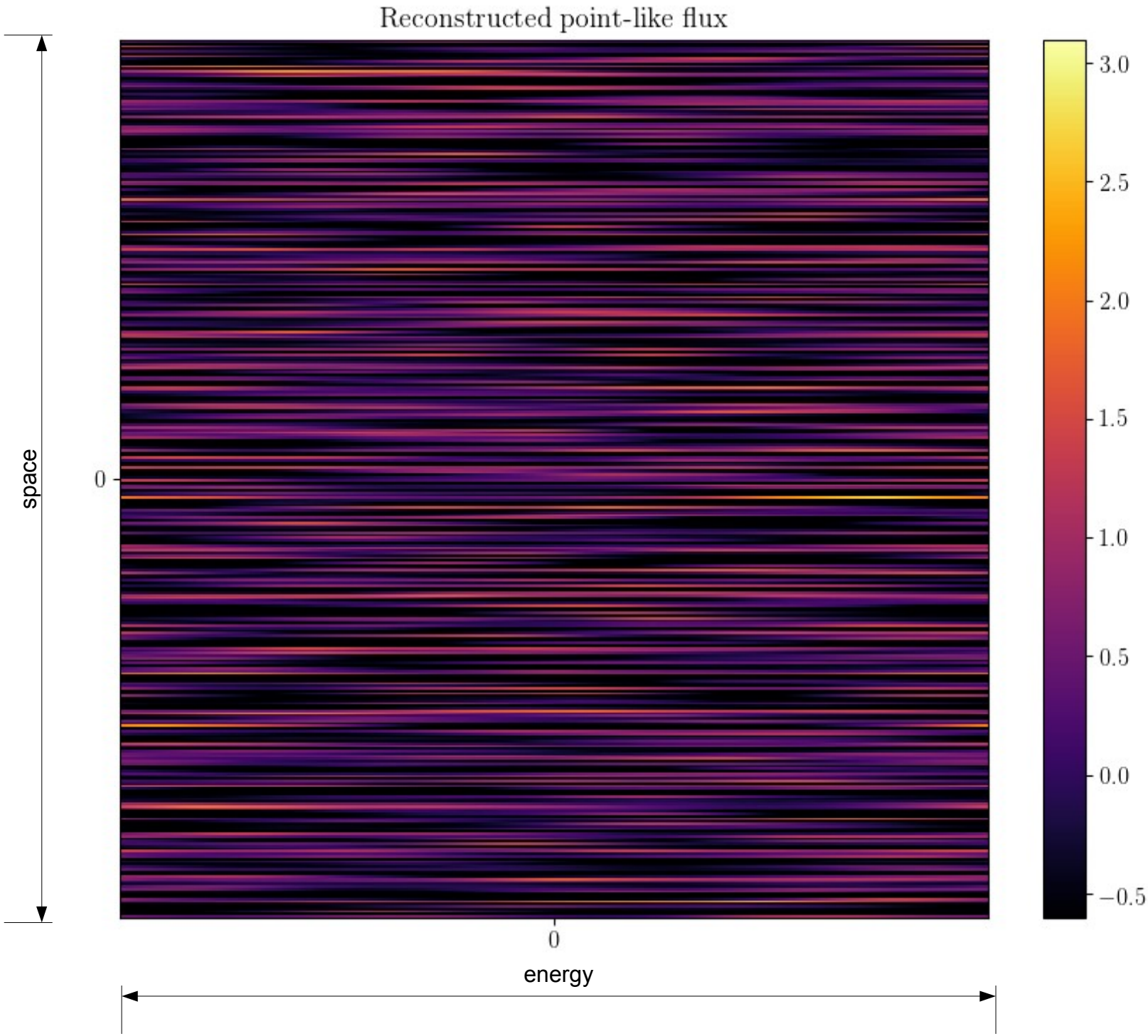

Reconstructed diffuse flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

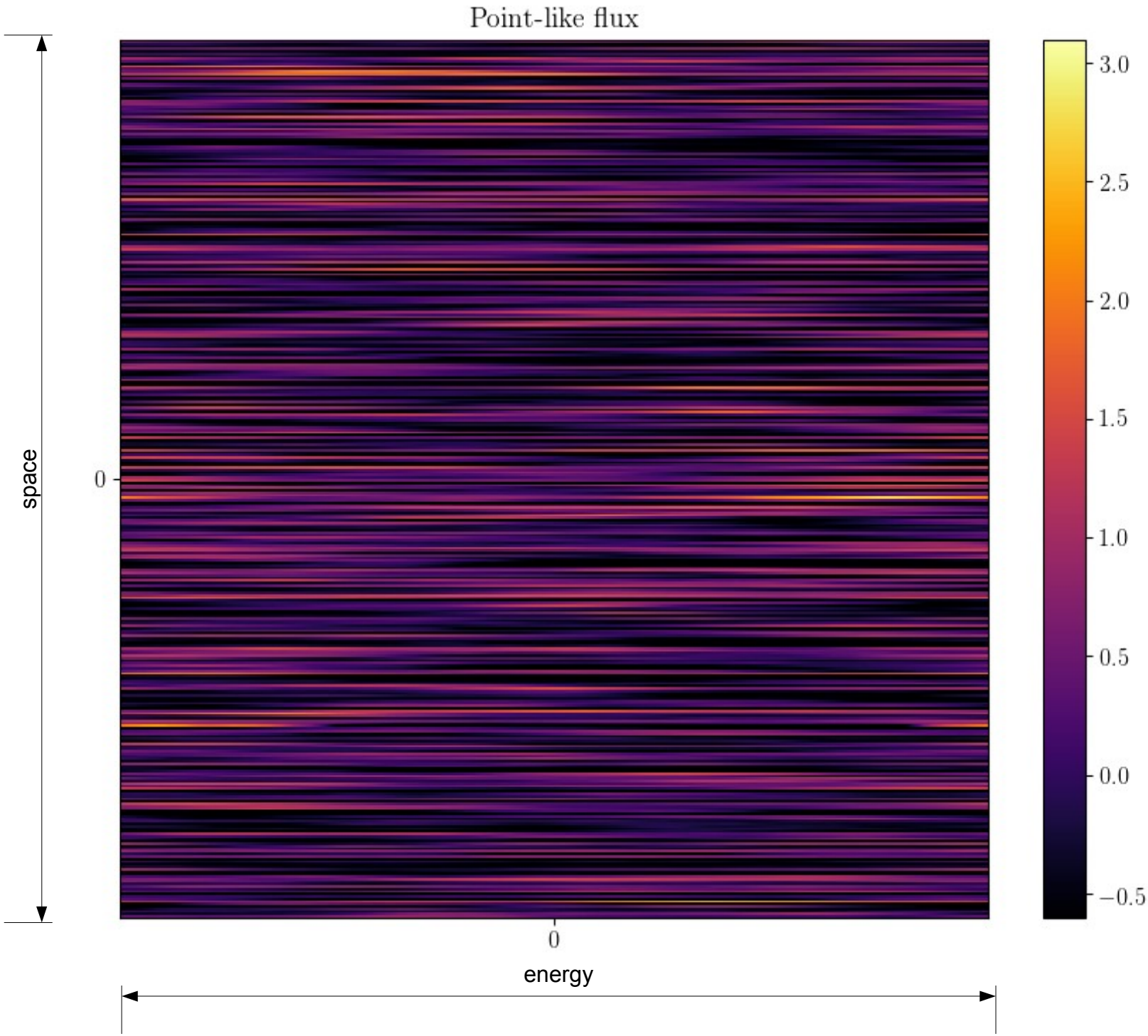

Diffuse flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

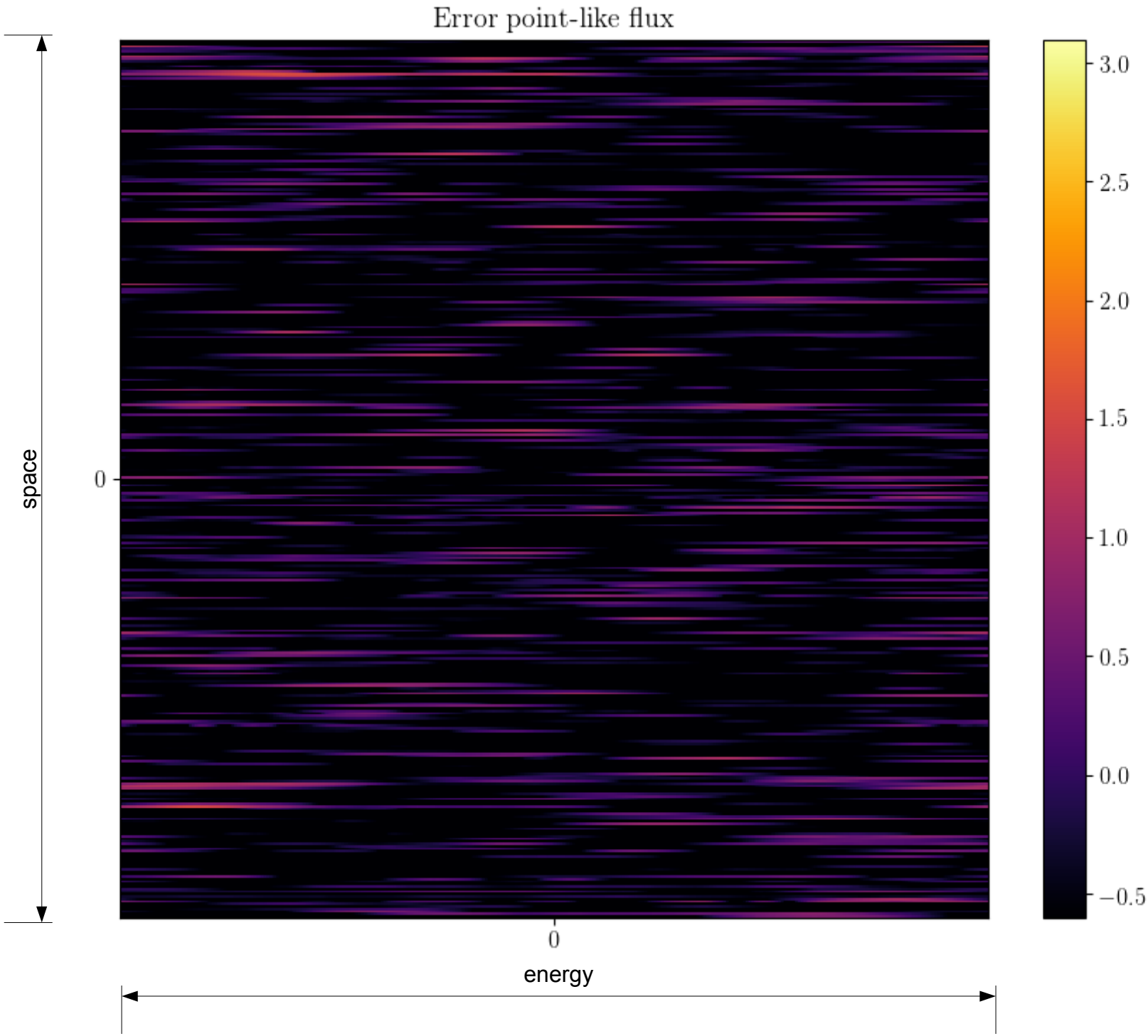

Error diffuse flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

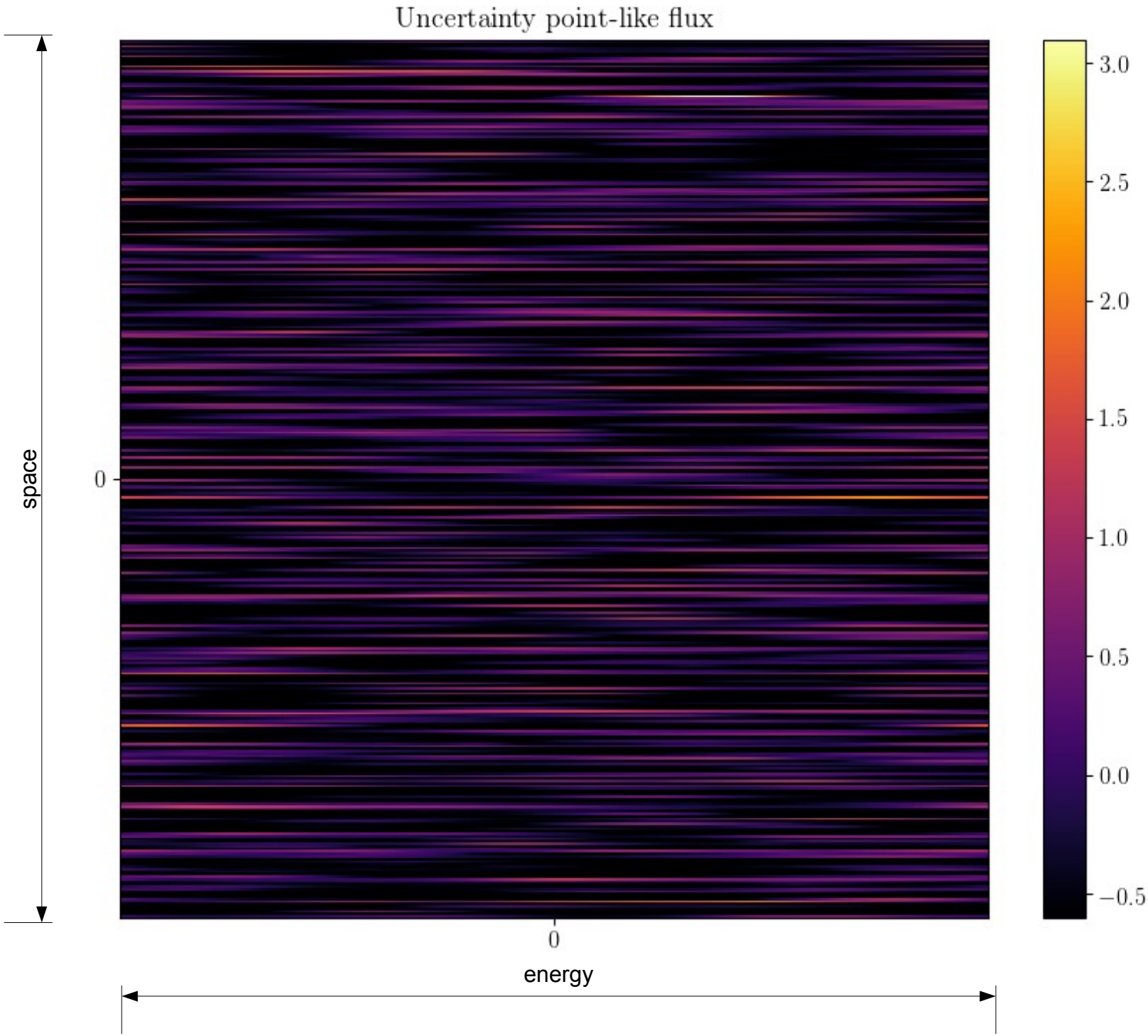

Uncertainty diffuse flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

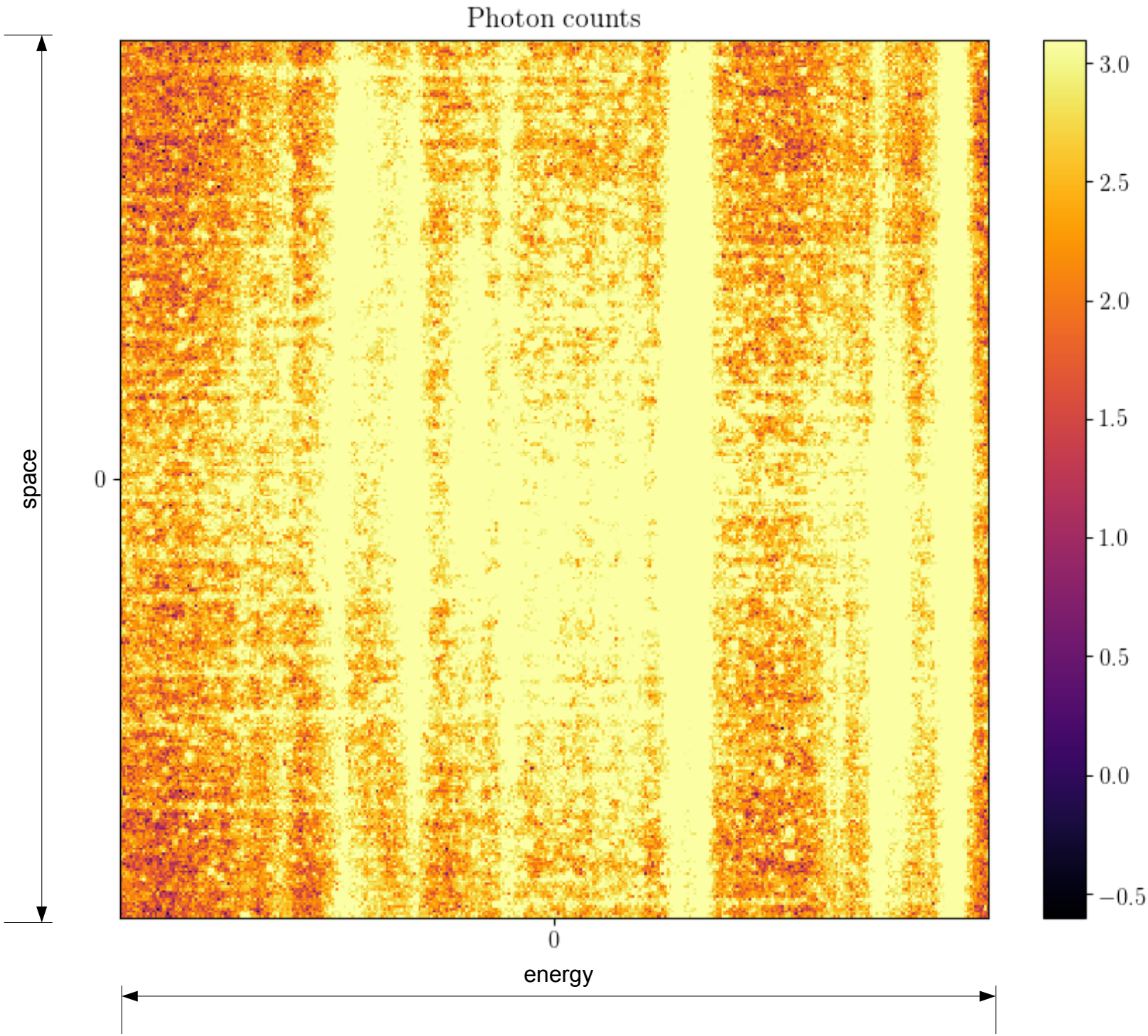

Photon counts
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

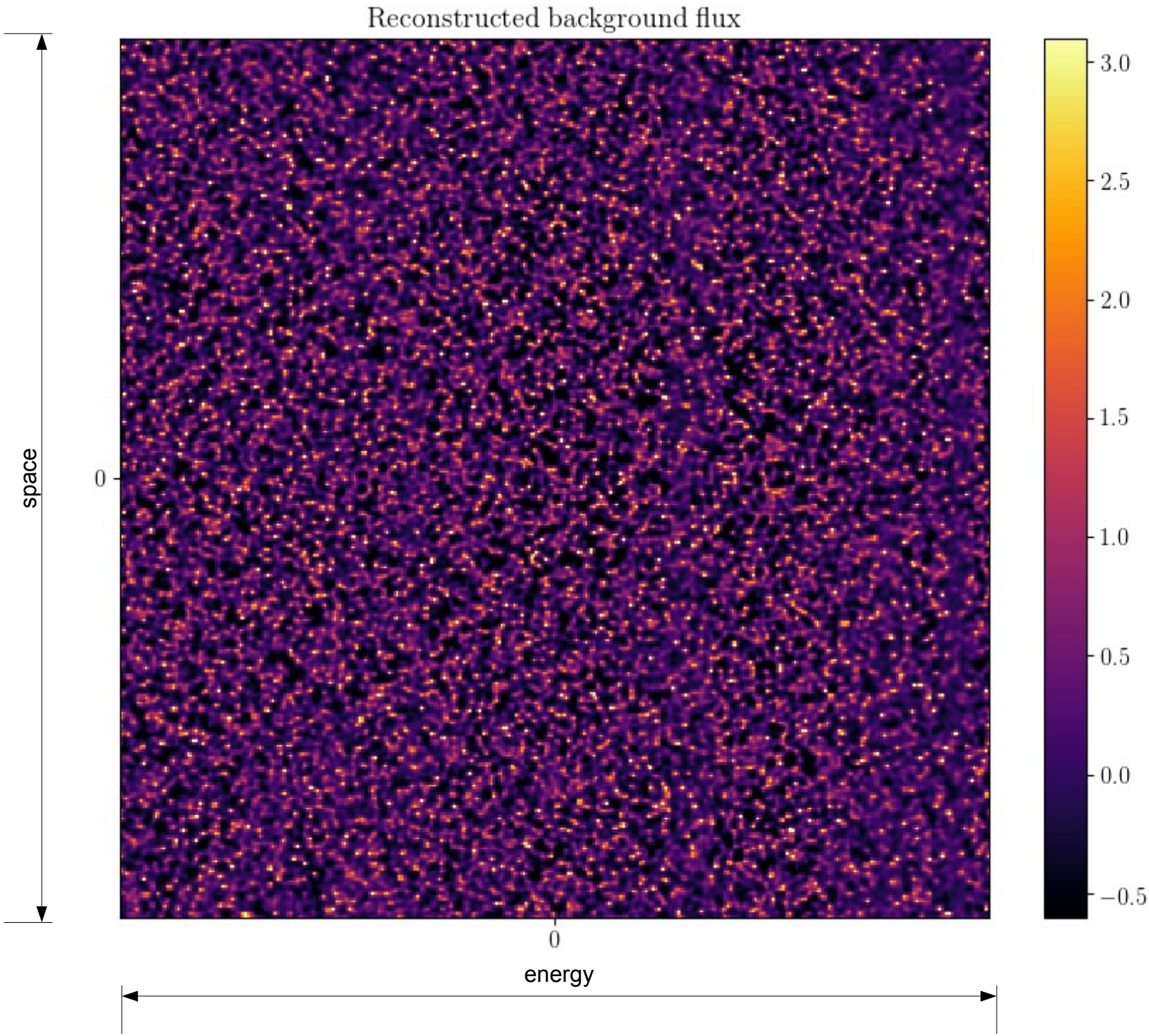

Reconstructed point-like flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

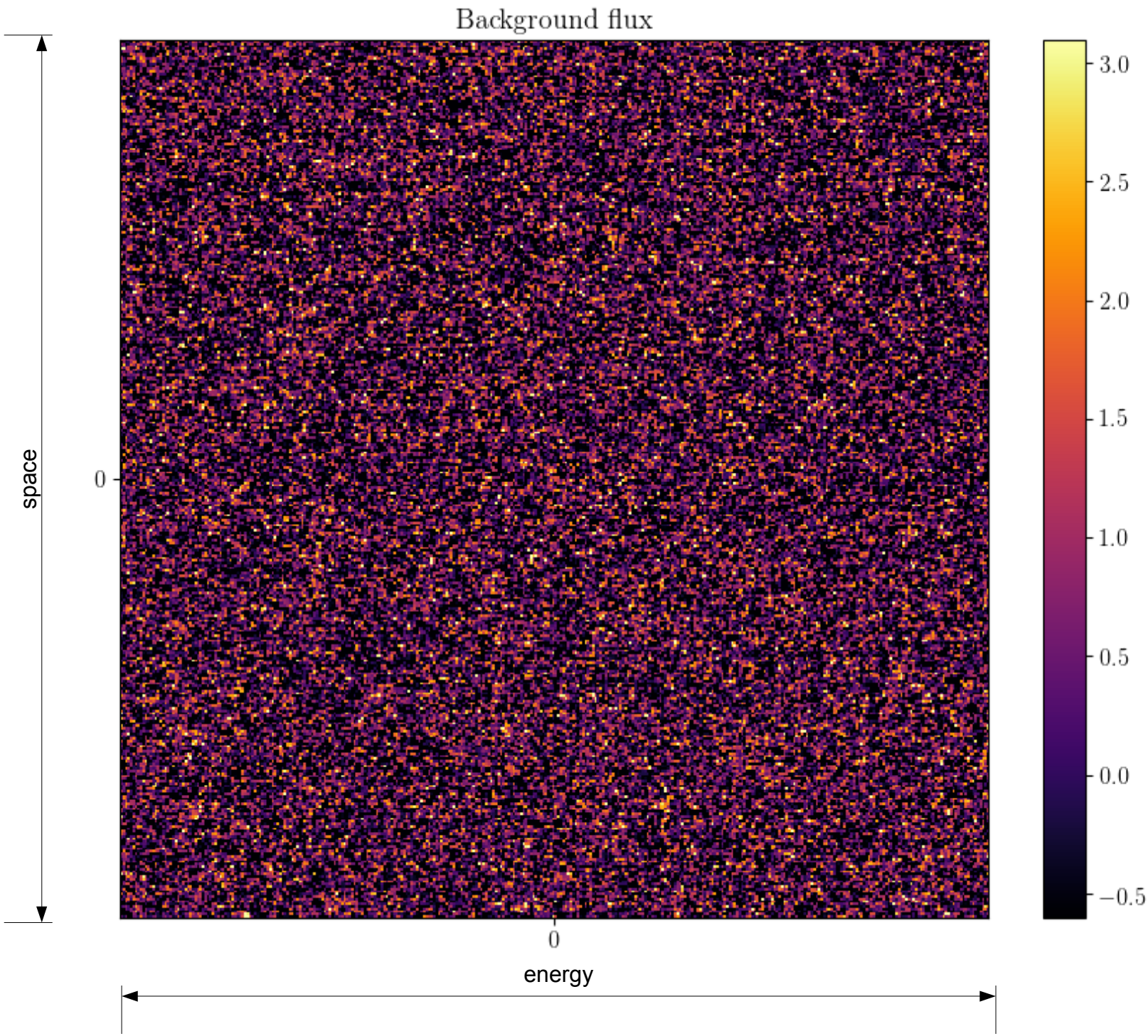

Point-like flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

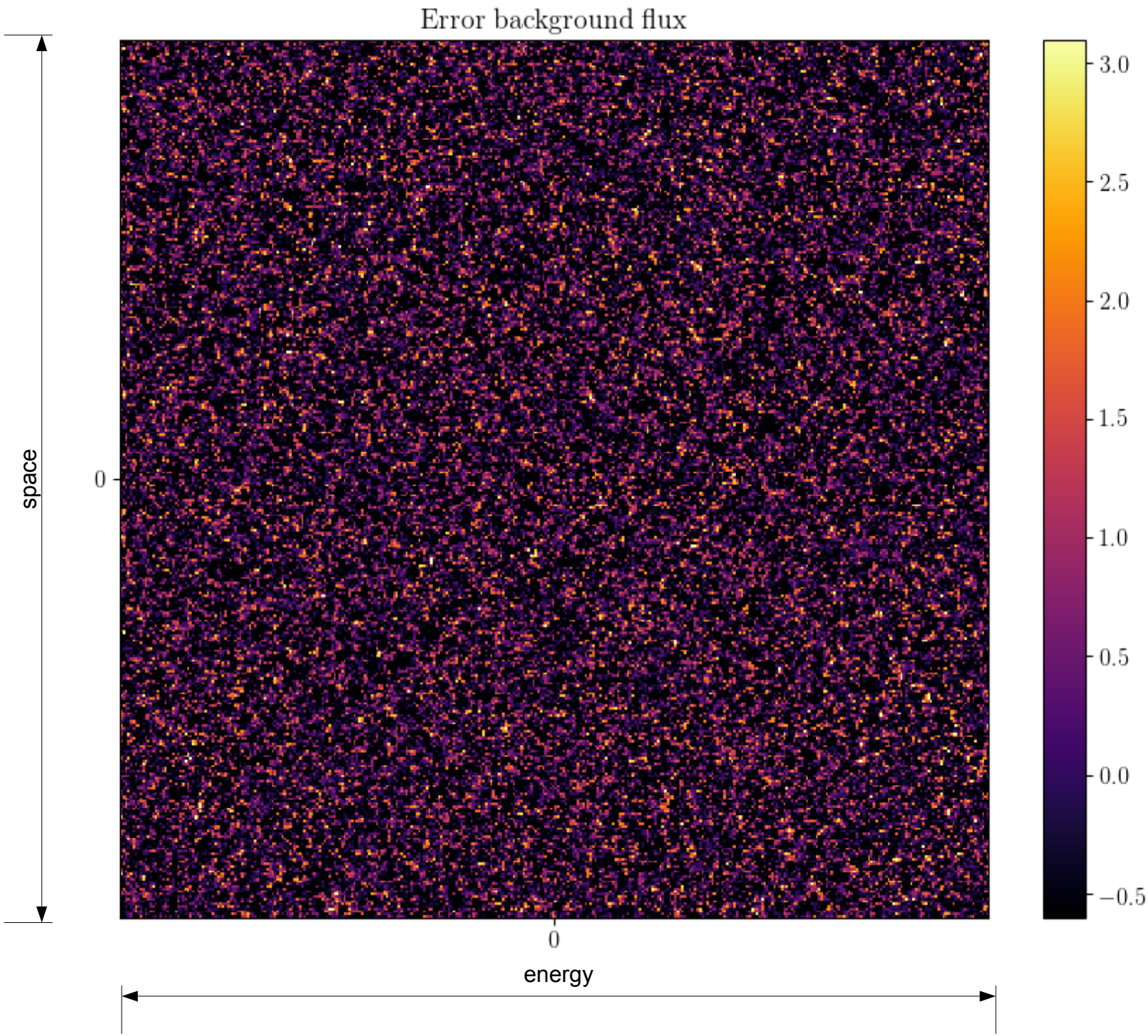

Error point-like flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

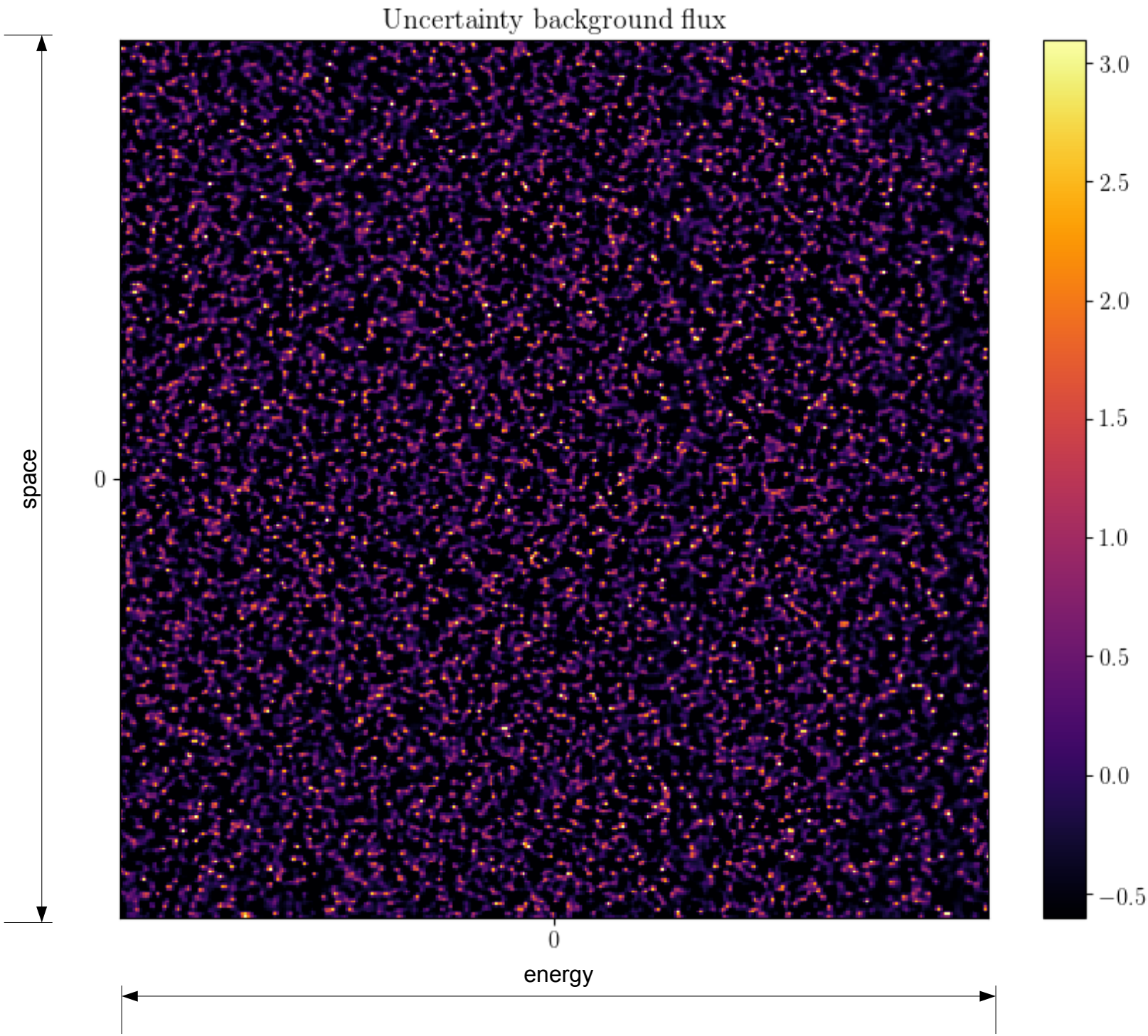

Uncertainty point-like flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

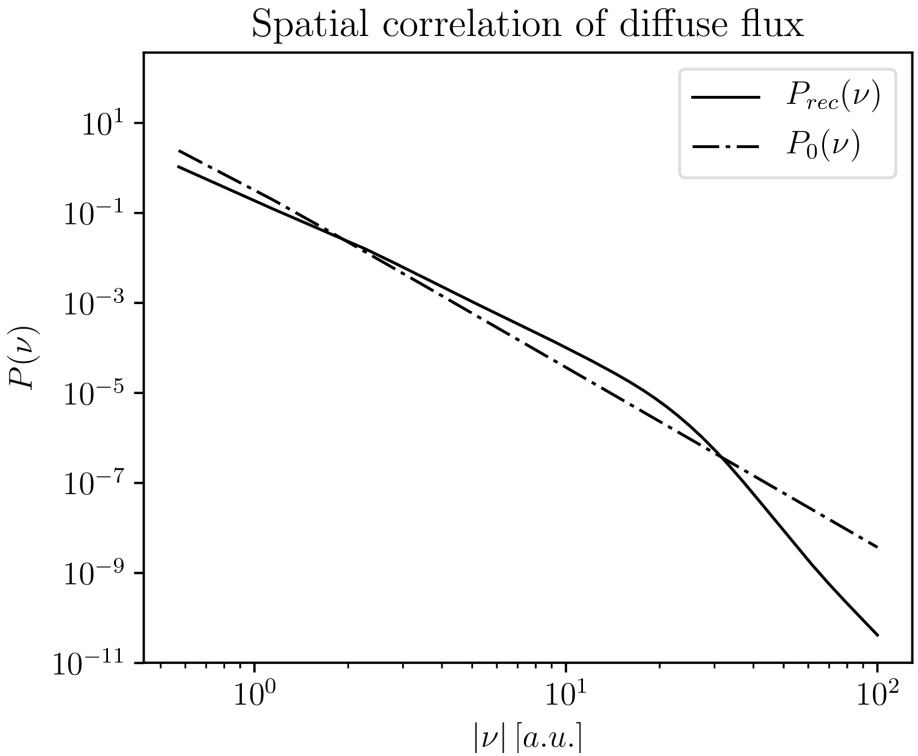

Photon counts
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

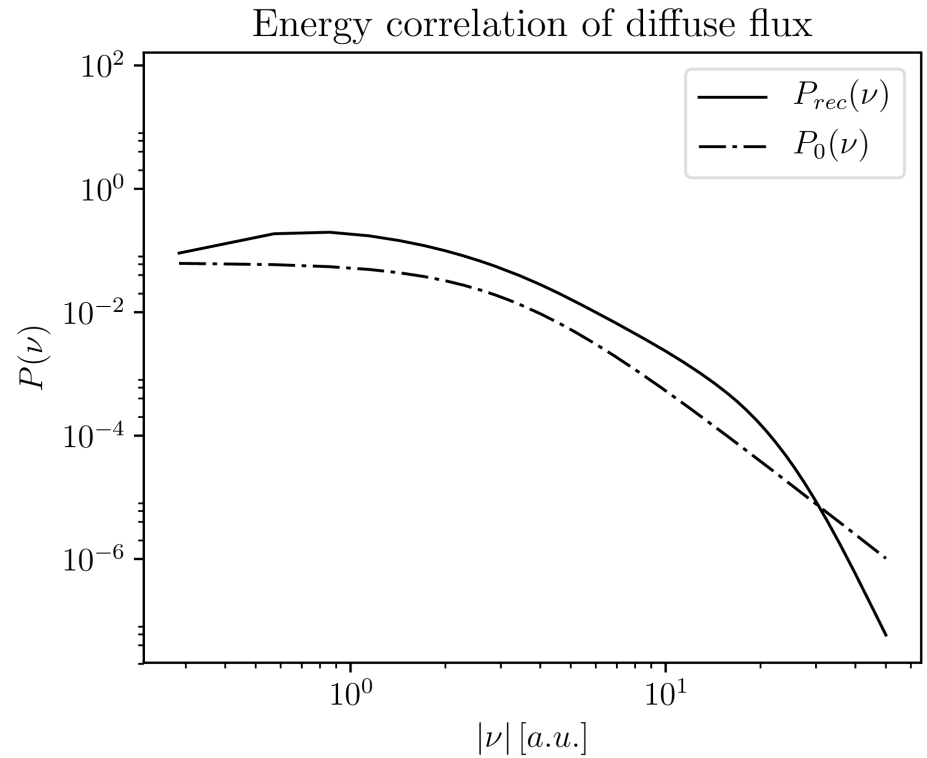

Reconstructed background flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

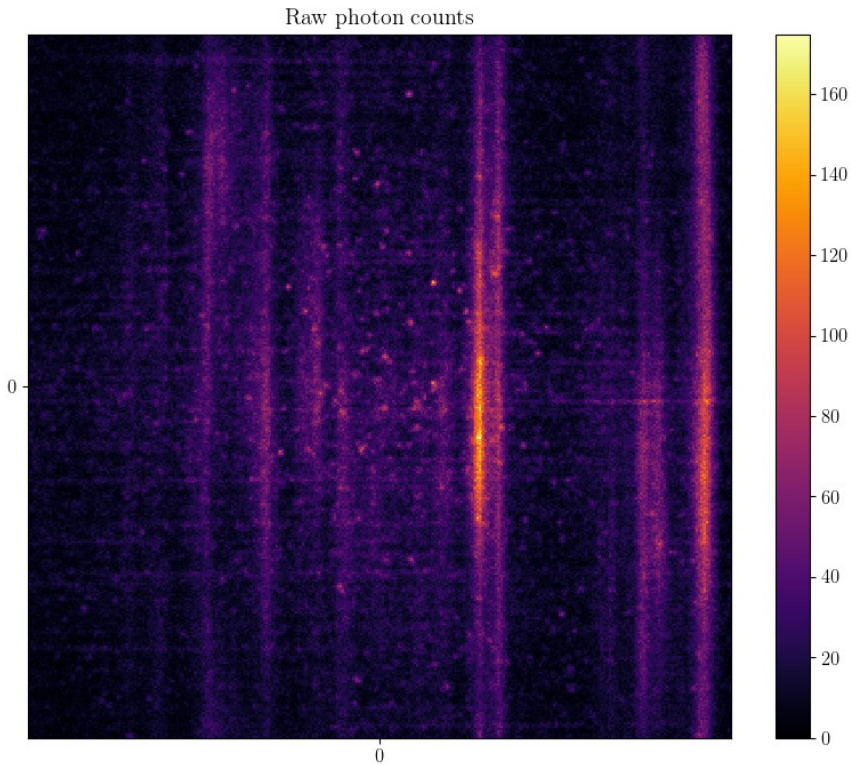

Background flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5

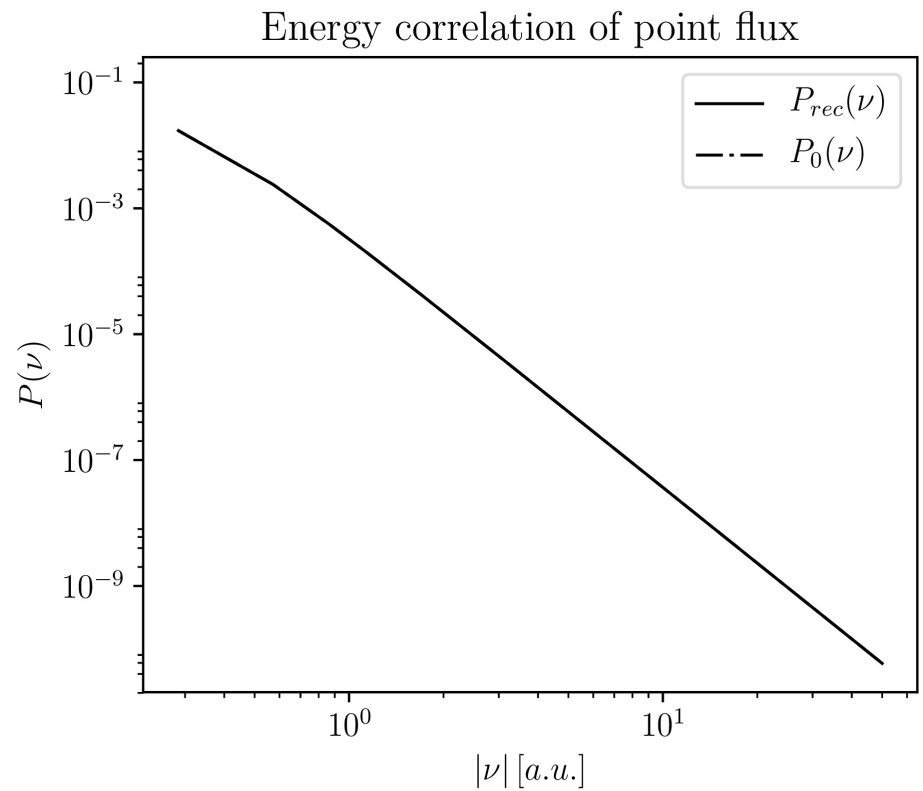

Error background flux
space
0
0
energy
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−0.5


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


Spatial correlation of diffuse flux
$P_{rec}(\nu)$
$P_0(\nu)$
$P(\nu)$
$|\nu|$ [a.u.]

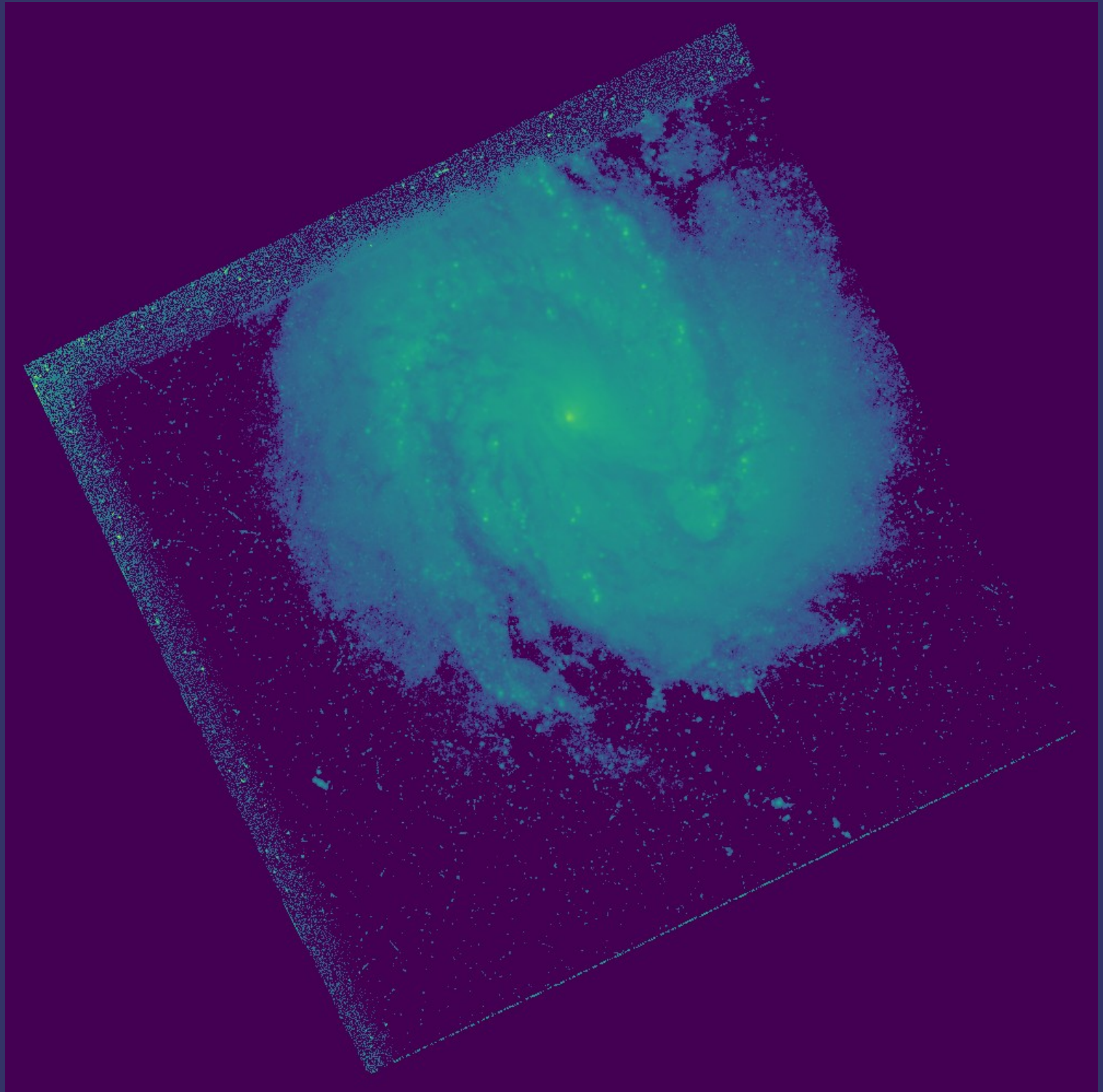

Energy correlation of diffuse flux
$P_{rec}(\nu)$
$P_0(\nu)$
$P(\nu)$
$|\nu|$ [a.u.]

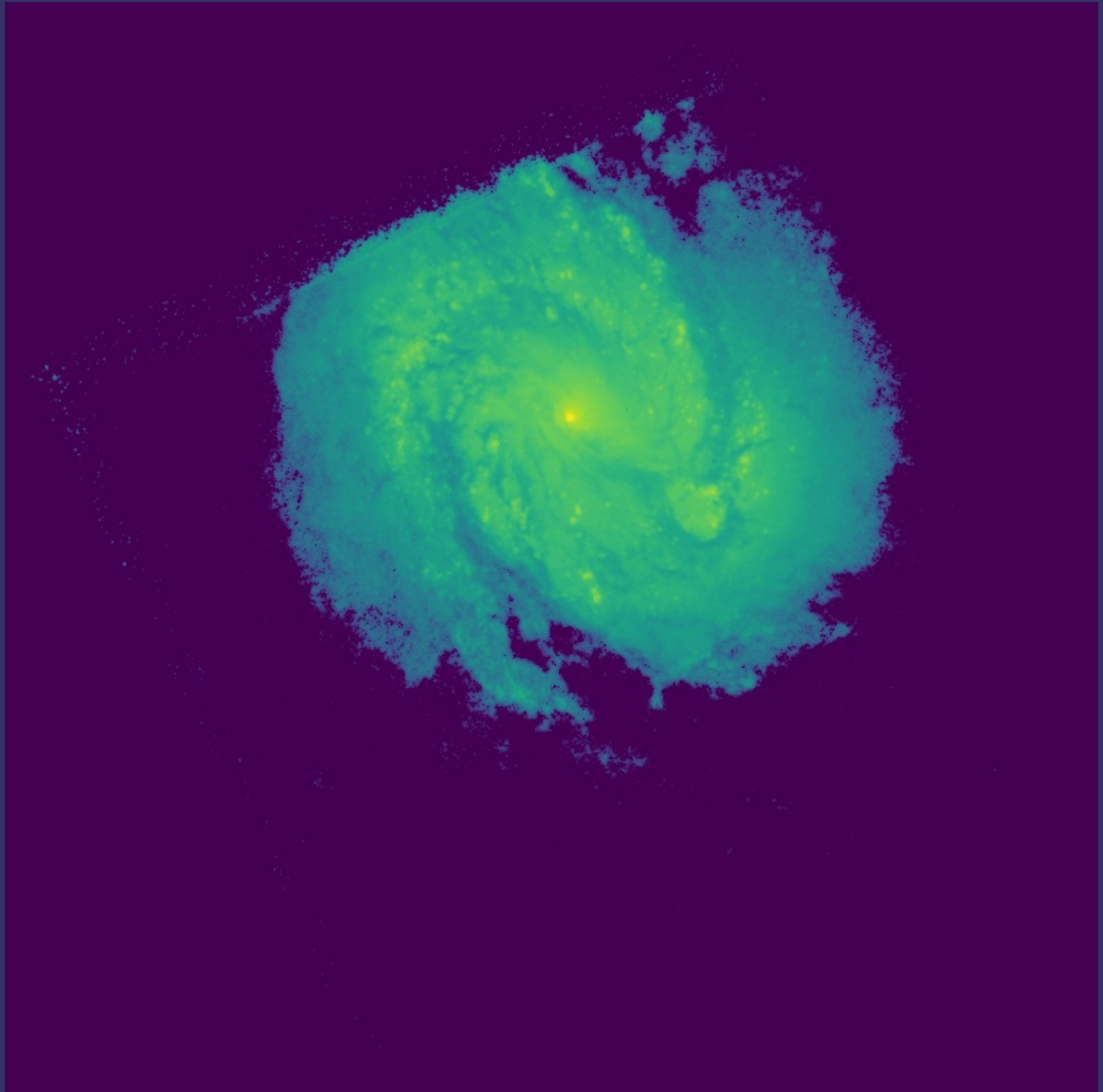

Raw photon counts

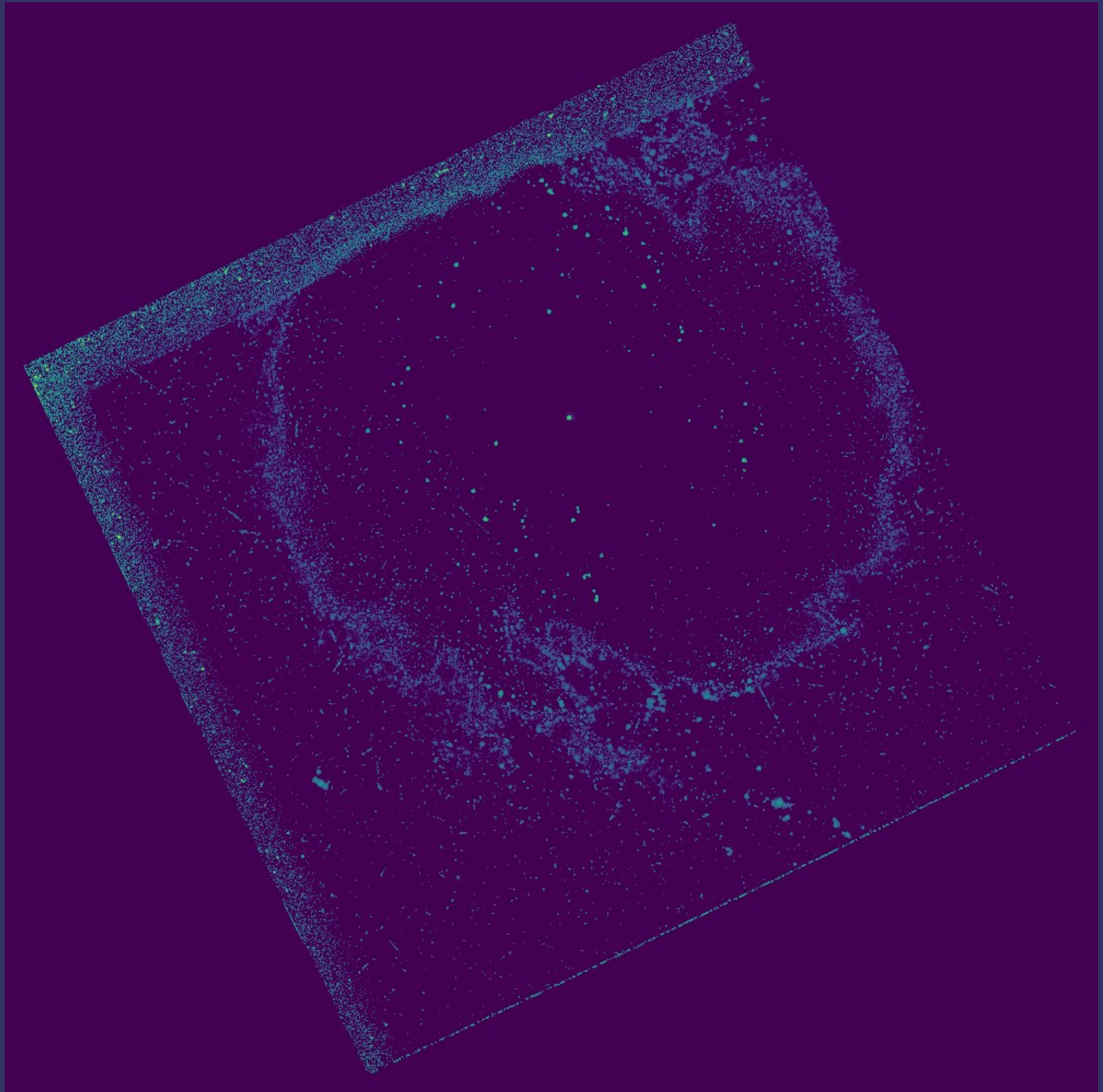

Energy correlation of point flux
$P_{rec}(\nu)$
$P_0(\nu)$
$P(\nu)$
$|\nu|$ [a.u.]

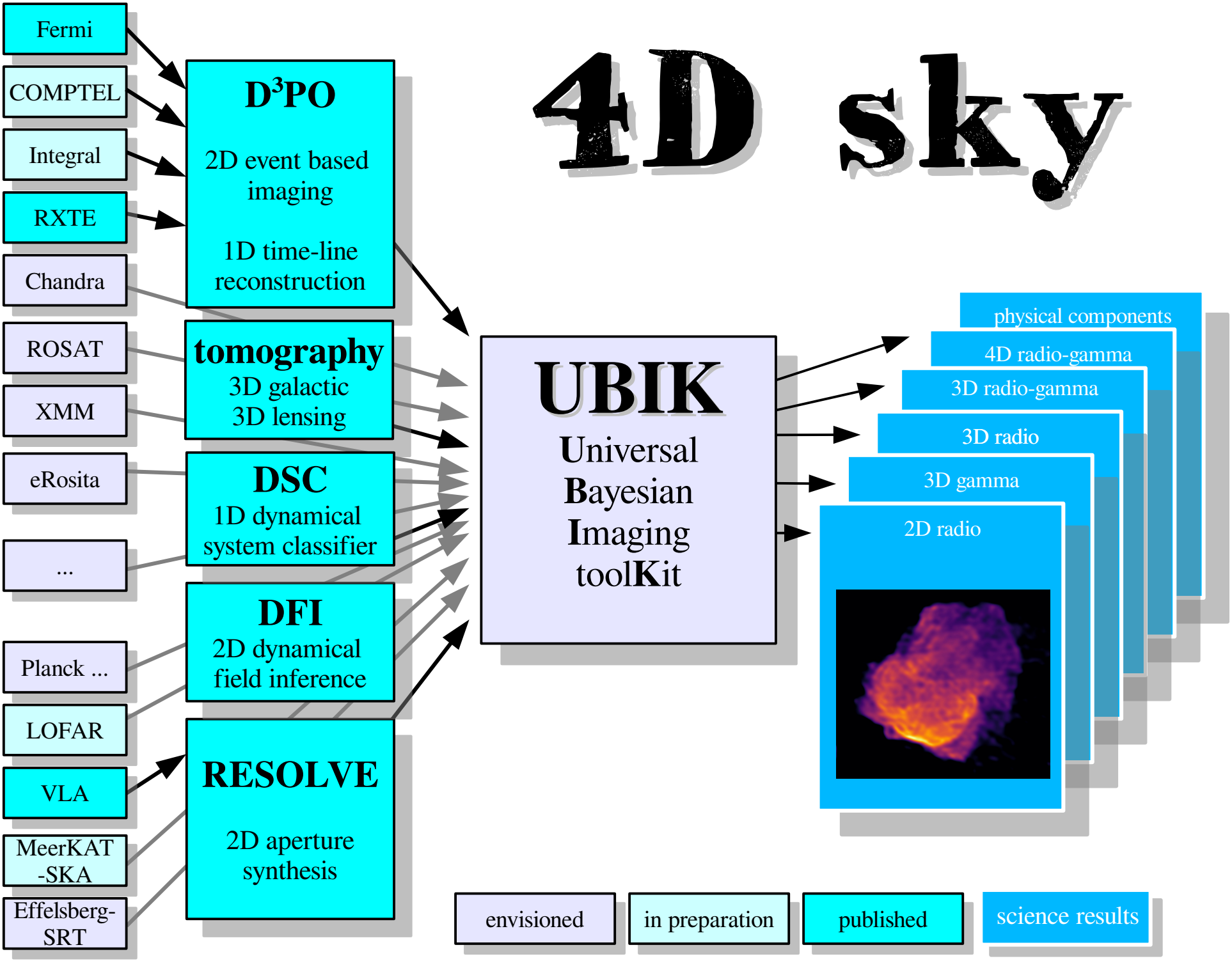
Glimpses into the future

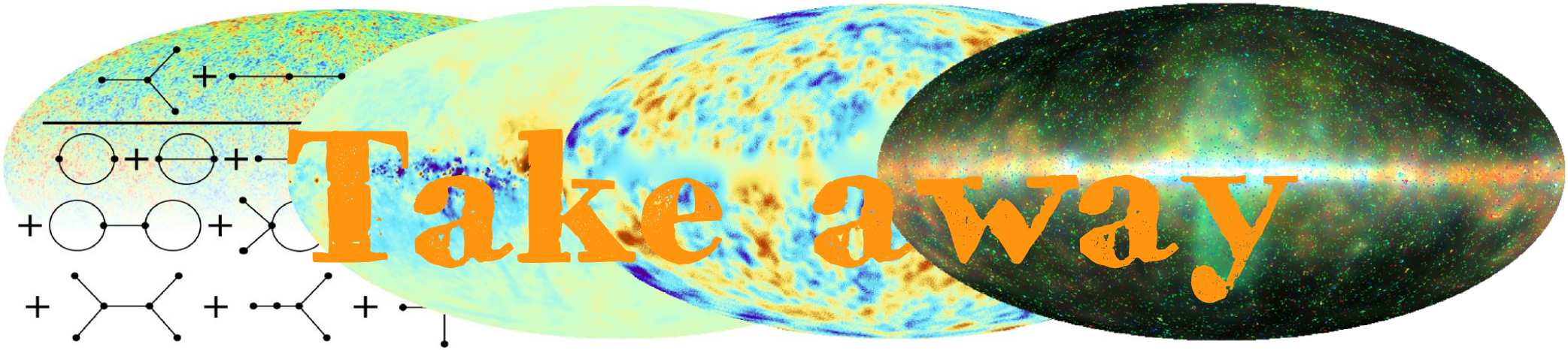
Jakob Knollmüller








4D sky
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

IFT	-	information field theory
NIFTy	-	nummerical IFT
D^3PO	-	photon/event imaging
RESOLVE	-	interferometric imaging
UBIK	-	universal imaging
4D sky	-	multi-instrument & -dimension spatio-spectral-temporal imaging

Online material (info/codes/docu/data/maps):
IFT: www.mpa-garching.mpg.de/ift

lecture: wwwmpa.mpa-garching.mpg.de/~ensslin/lectures