Information field theory for gamma ray astronomy

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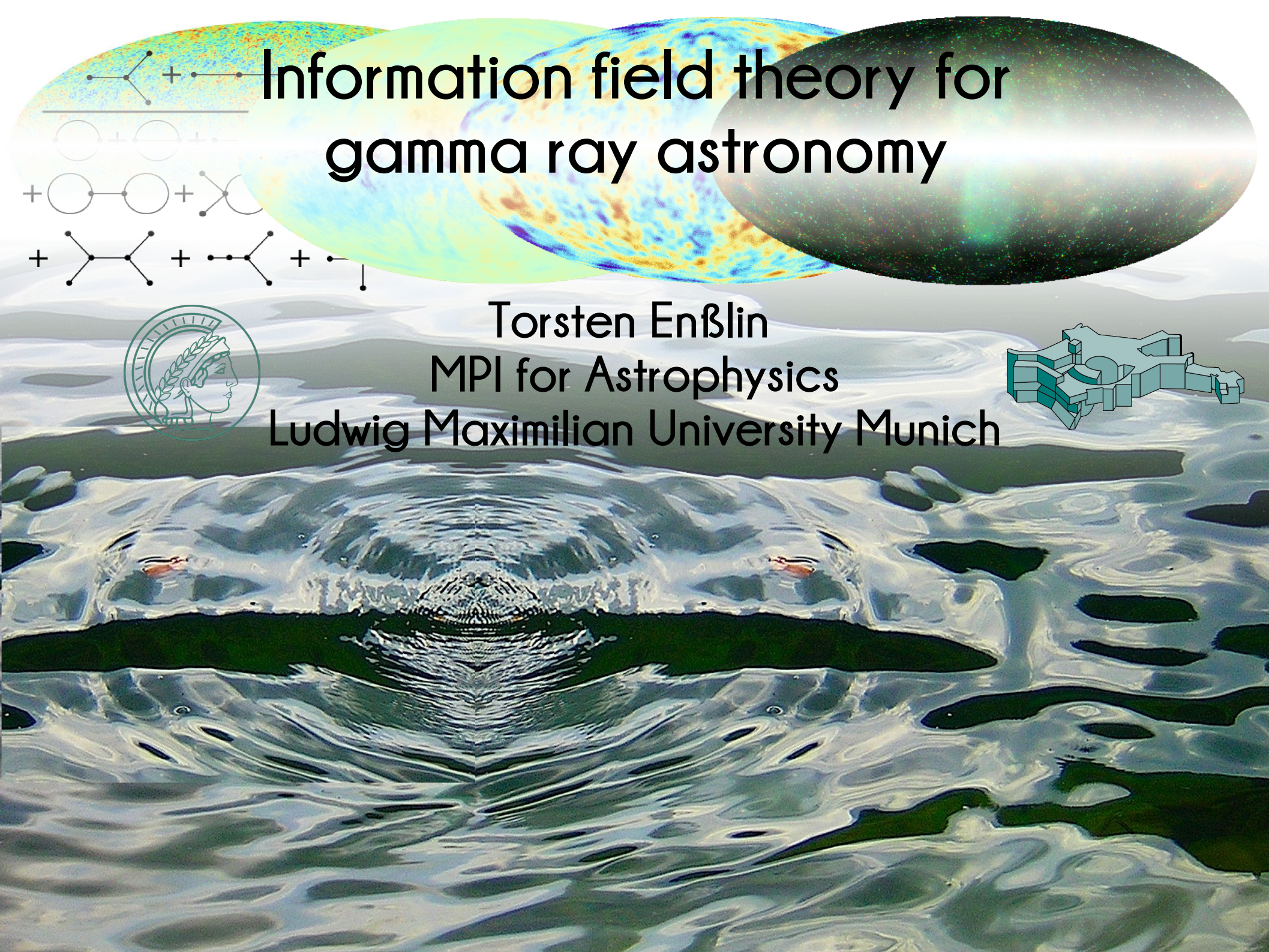


Information Field Theory

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

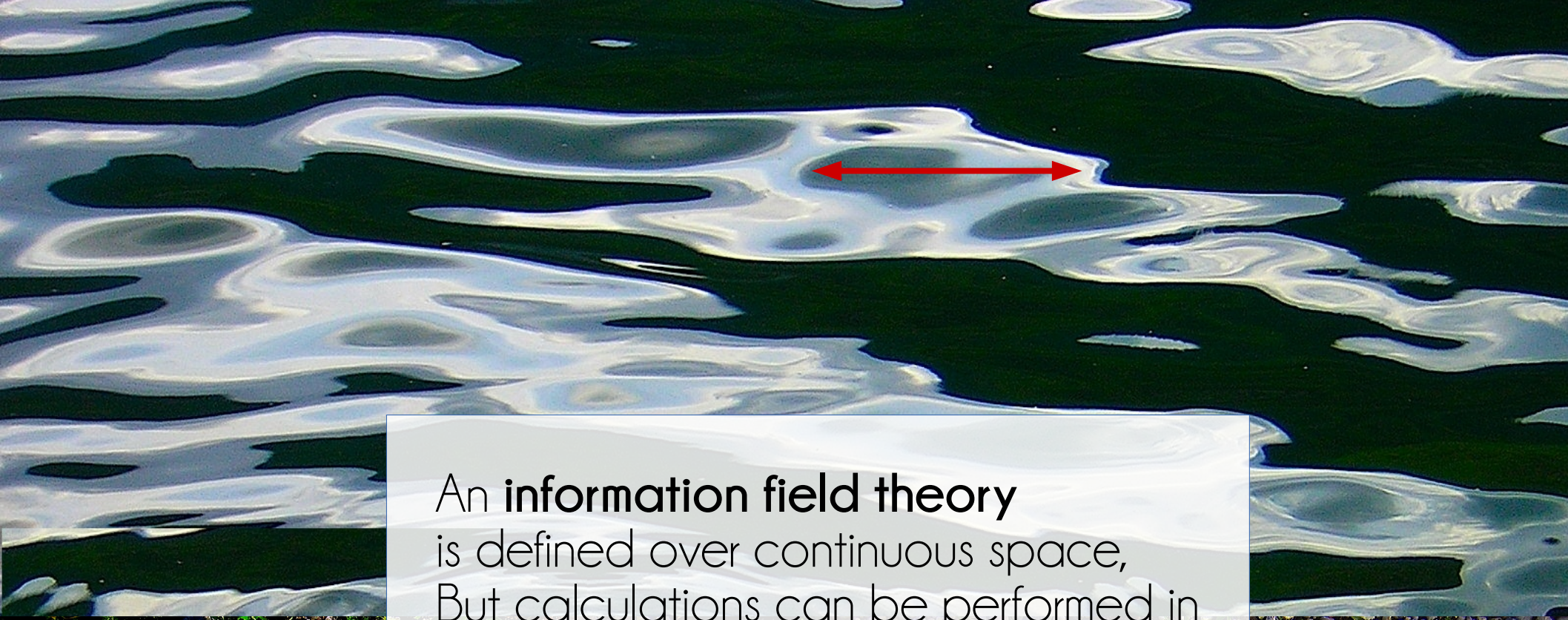
$$\mathcal{P}(s|d) = \frac{\mathcal{P}(d|s)\,\mathcal{P}(s)}{\mathcal{P}(d)}$$

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

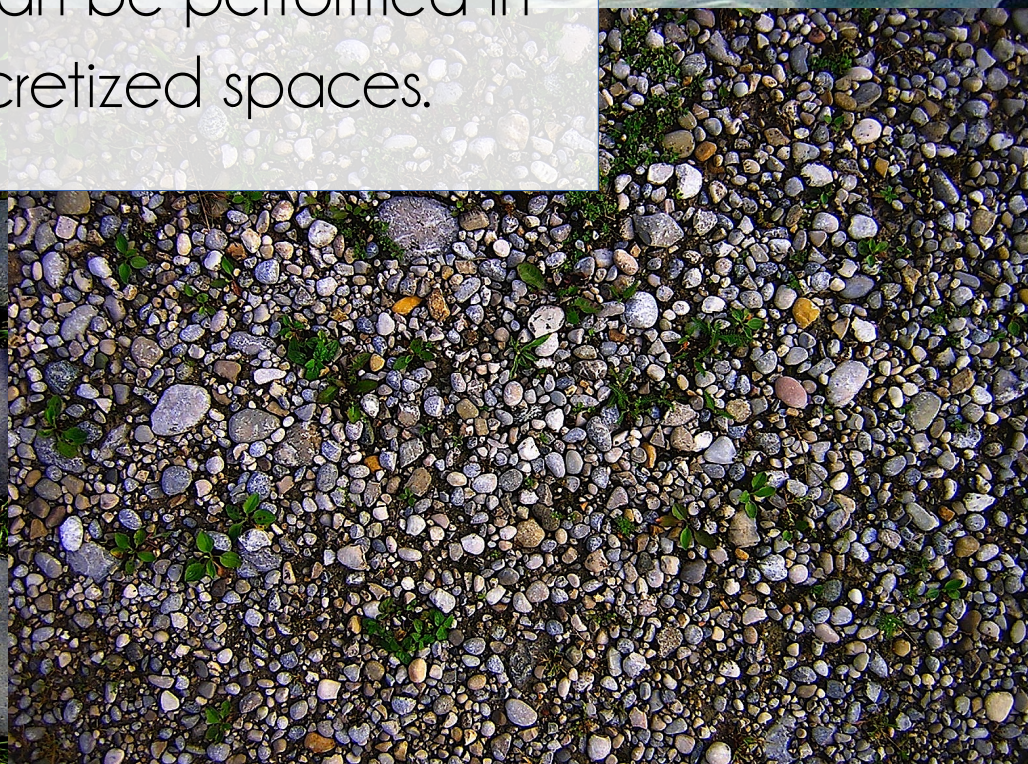
$$Z(d) = \int \mathcal{D}s\, \mathcal{P}(d,s)$$

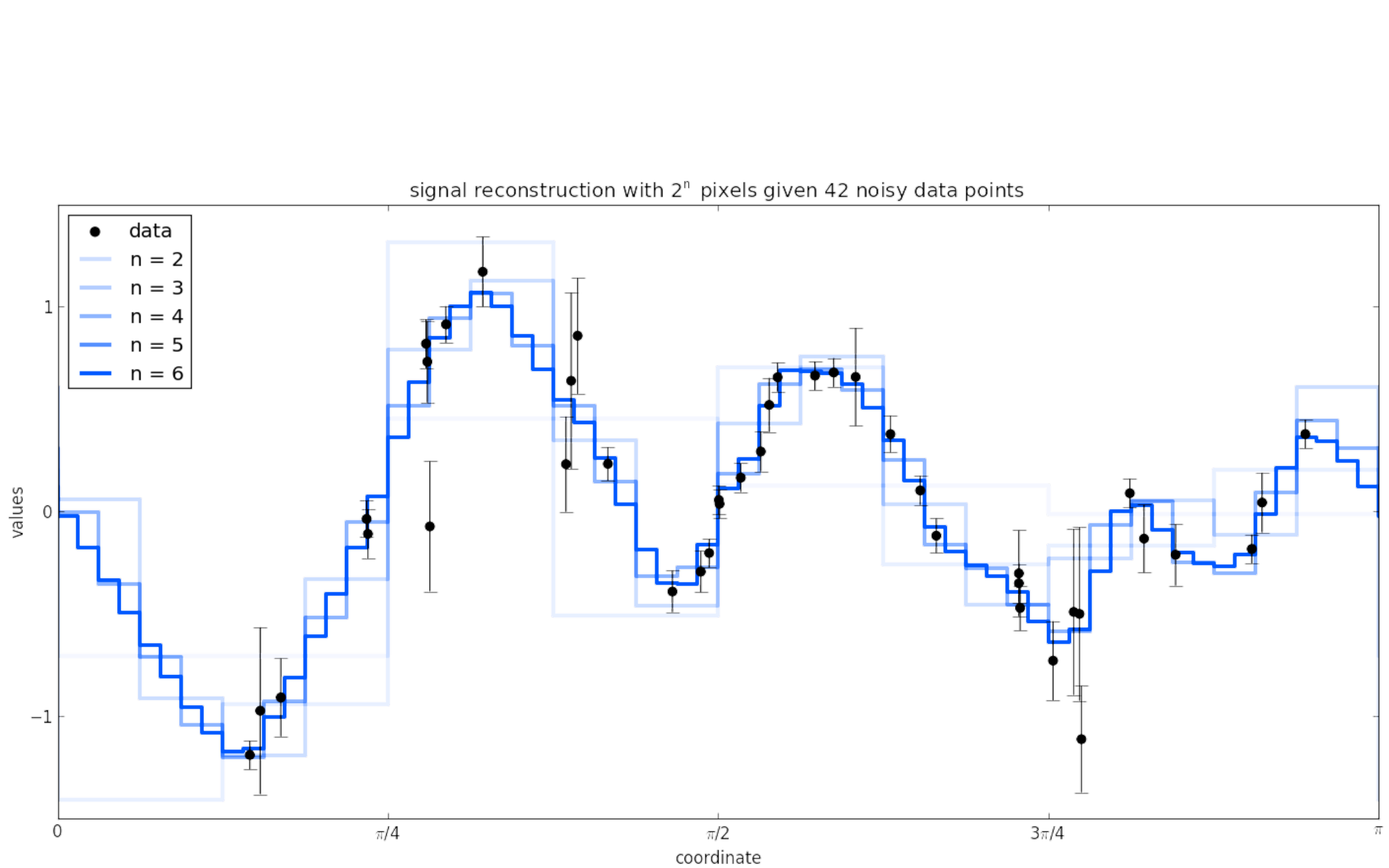
$$\langle s(x_1) \cdots s(x_n) \rangle_{P(s|d)} = \int \mathcal{D}s \, s(x_1) \cdots s(x_n) \, P(s|d)$$

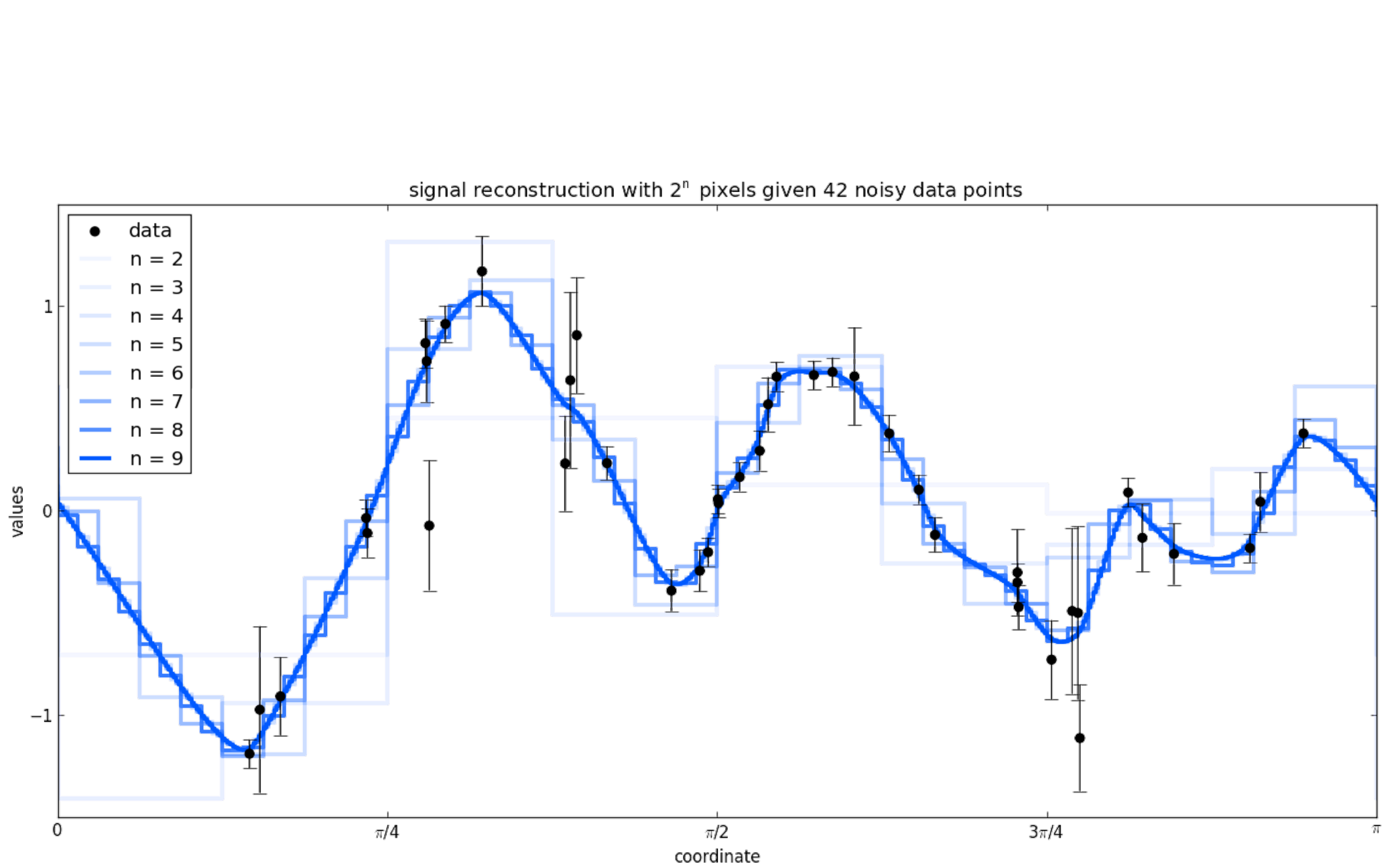
$$\int \mathcal{D}s = \prod_{i=1}^{N_{\text{pix}}} \int ds_i$$



An **information field theory**
is defined over continuous space,
But calculations can be performed in
sufficiently fine discretized spaces.



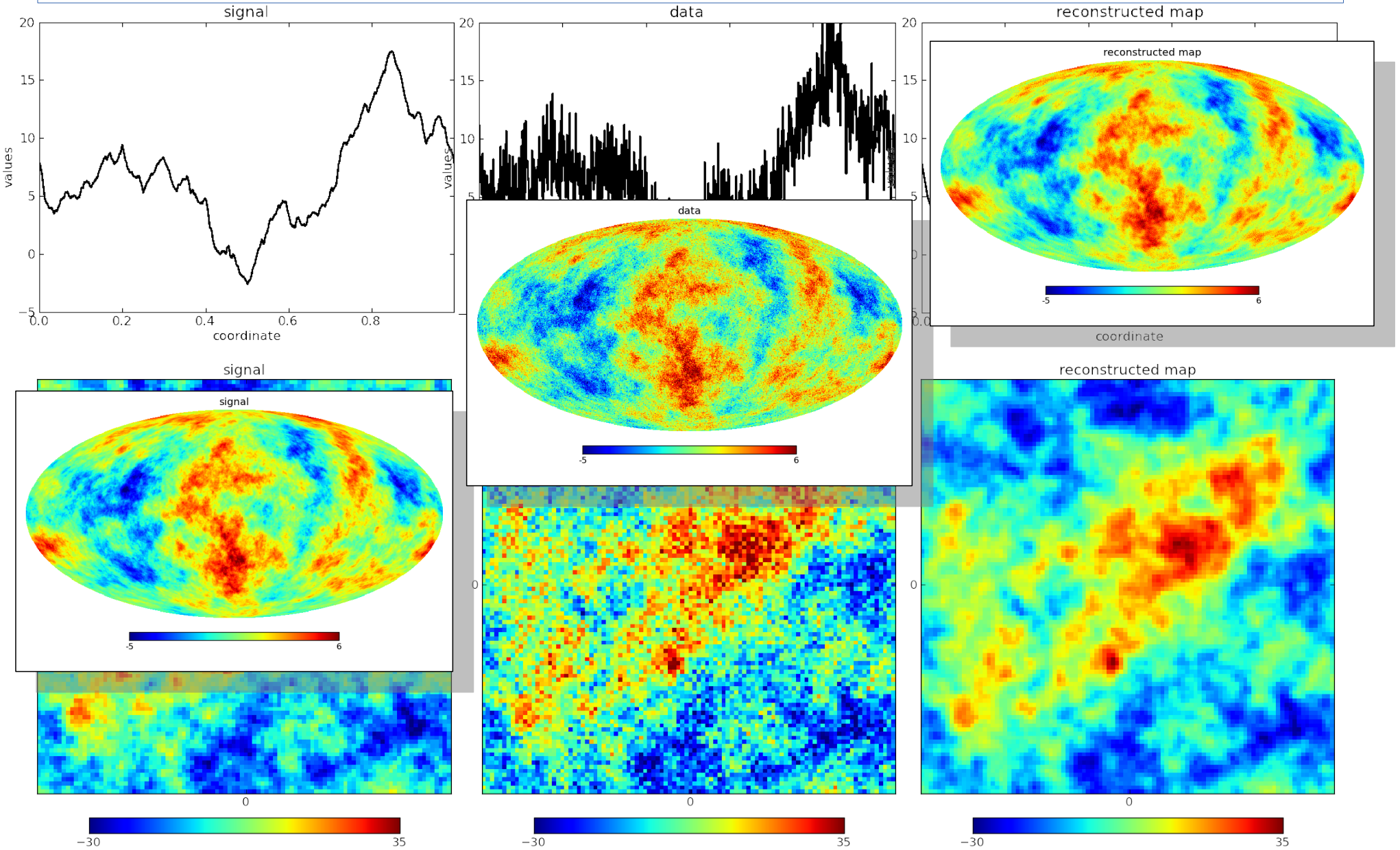

signal reconstruction with 2^n pixels given 42 noisy data points
data
n = 2
n = 3
n = 4
n = 5
n = 6
values
1
0
−1
0
π/4
π/2
3π/4
π
coordinate


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.)

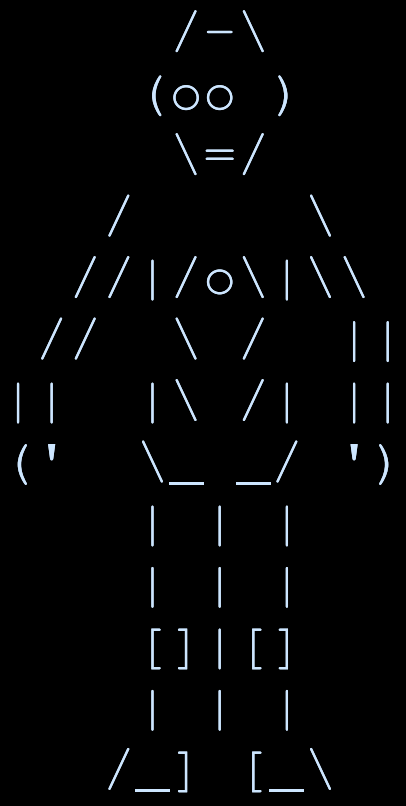
Code @ https://gitlab.mpcdf.mpg.de/ift/NIFTy



Denoising, Deconvolving, and Decomposing Photon Observations

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

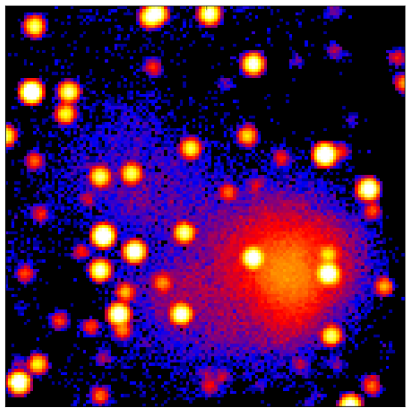
D³PO

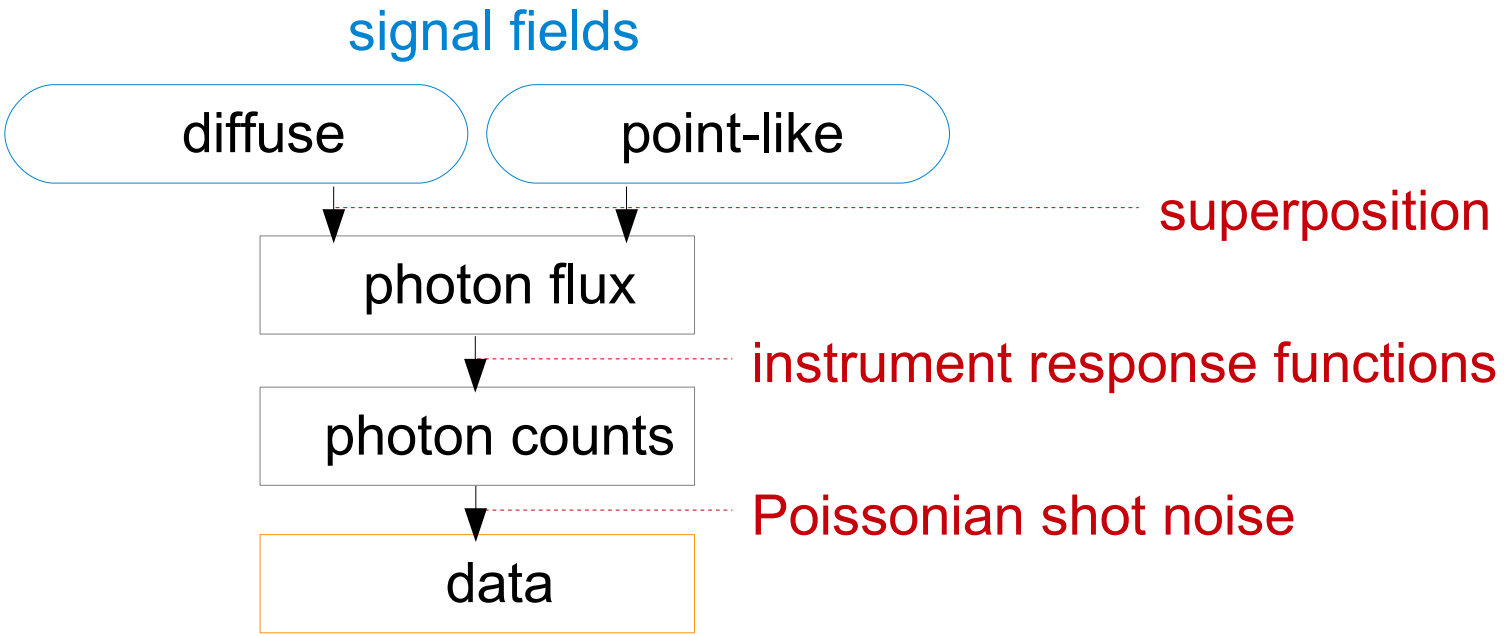


D³PO – challenges

Selig & Enßlin (2014)

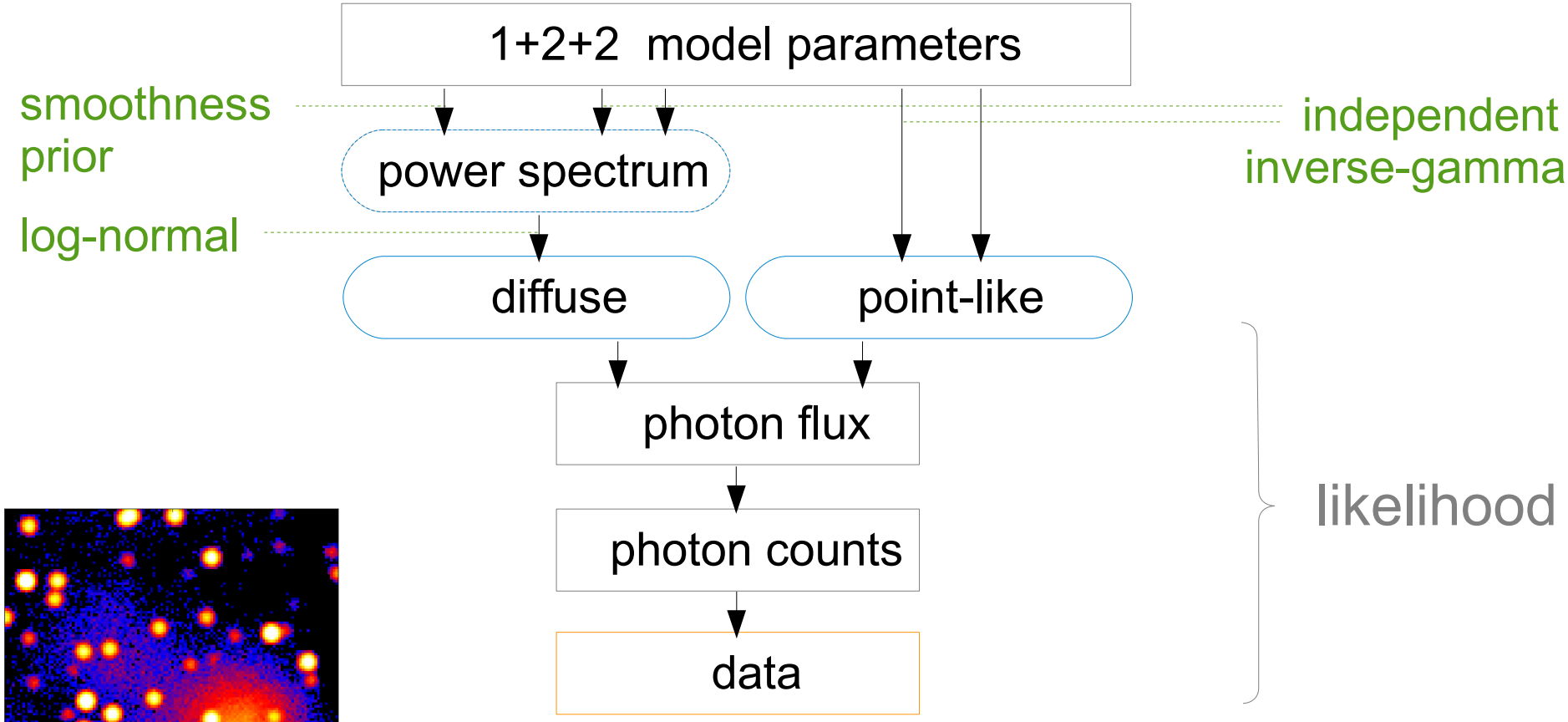
$$F(x) = F_0 \times \left[e^{s(x)} + e^{u(x)} \right]$$

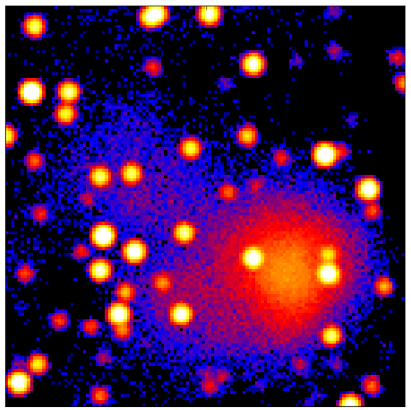




D^3PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888

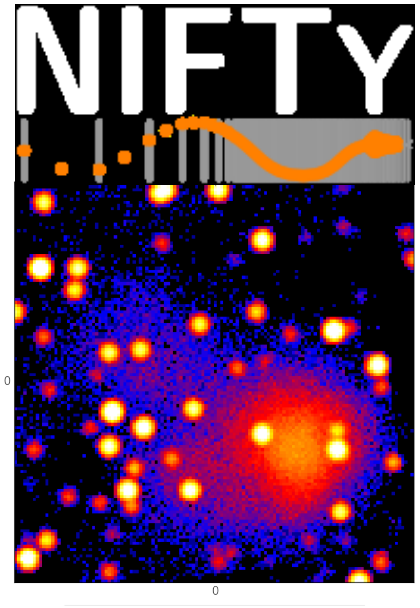




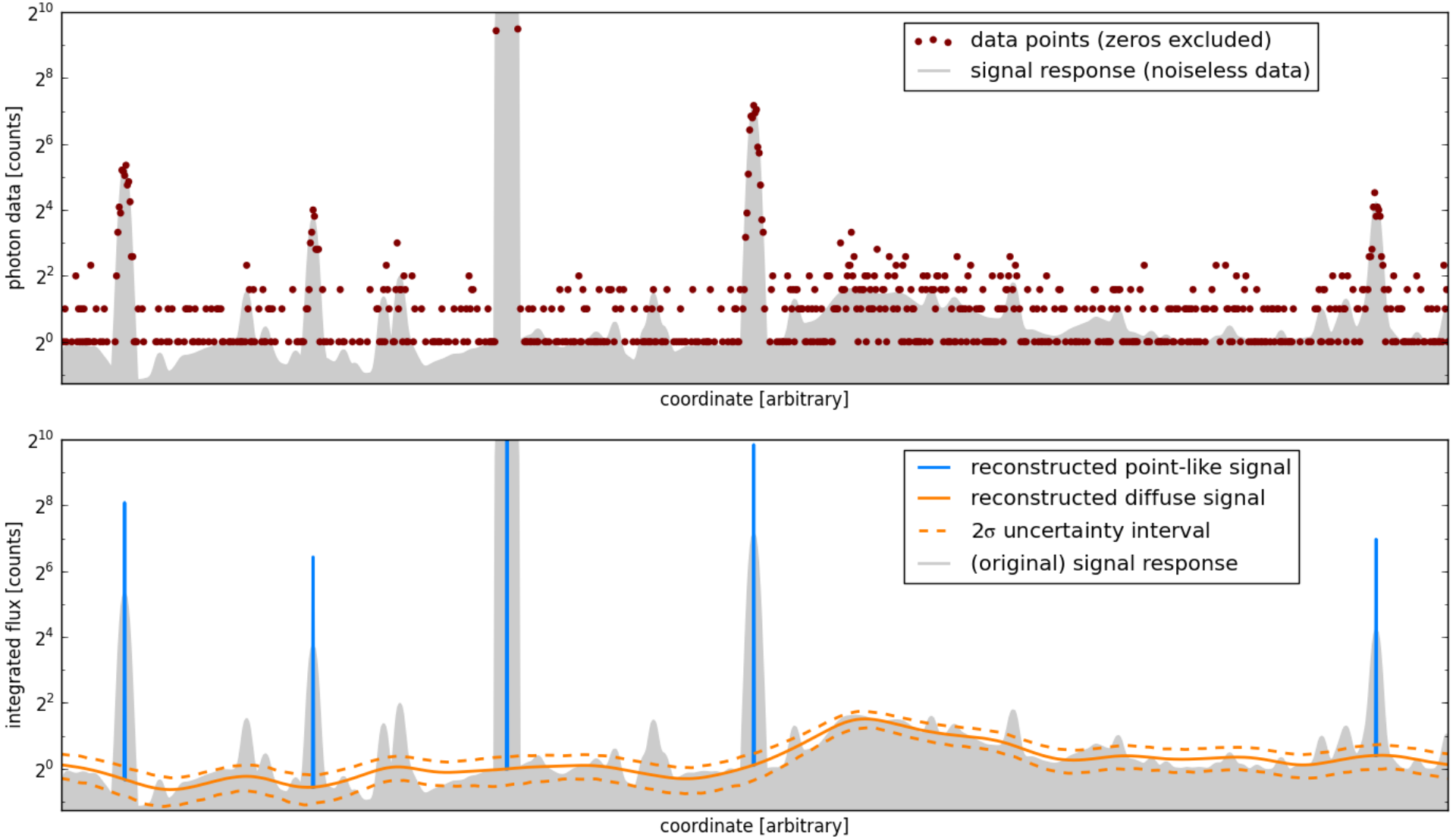
D³PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888

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



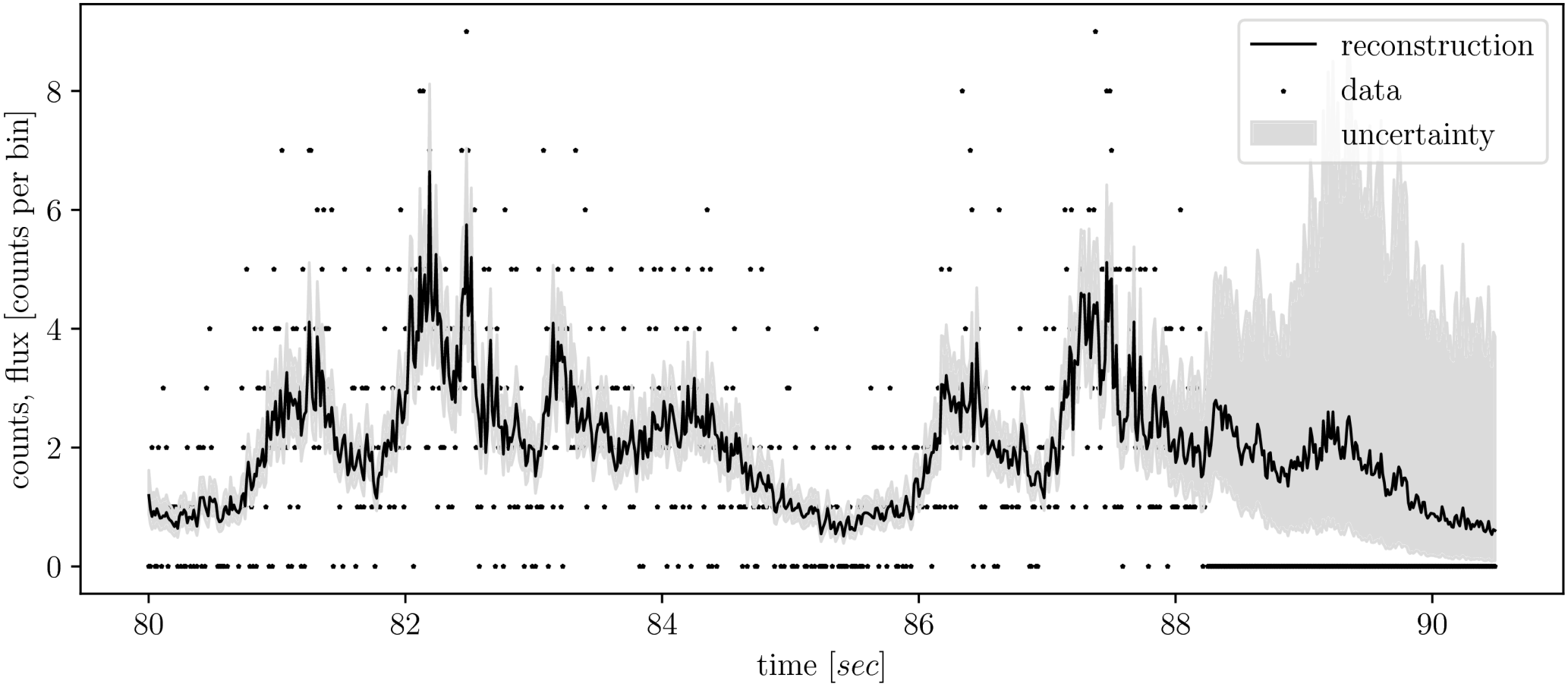
D³PO – 1D scenario



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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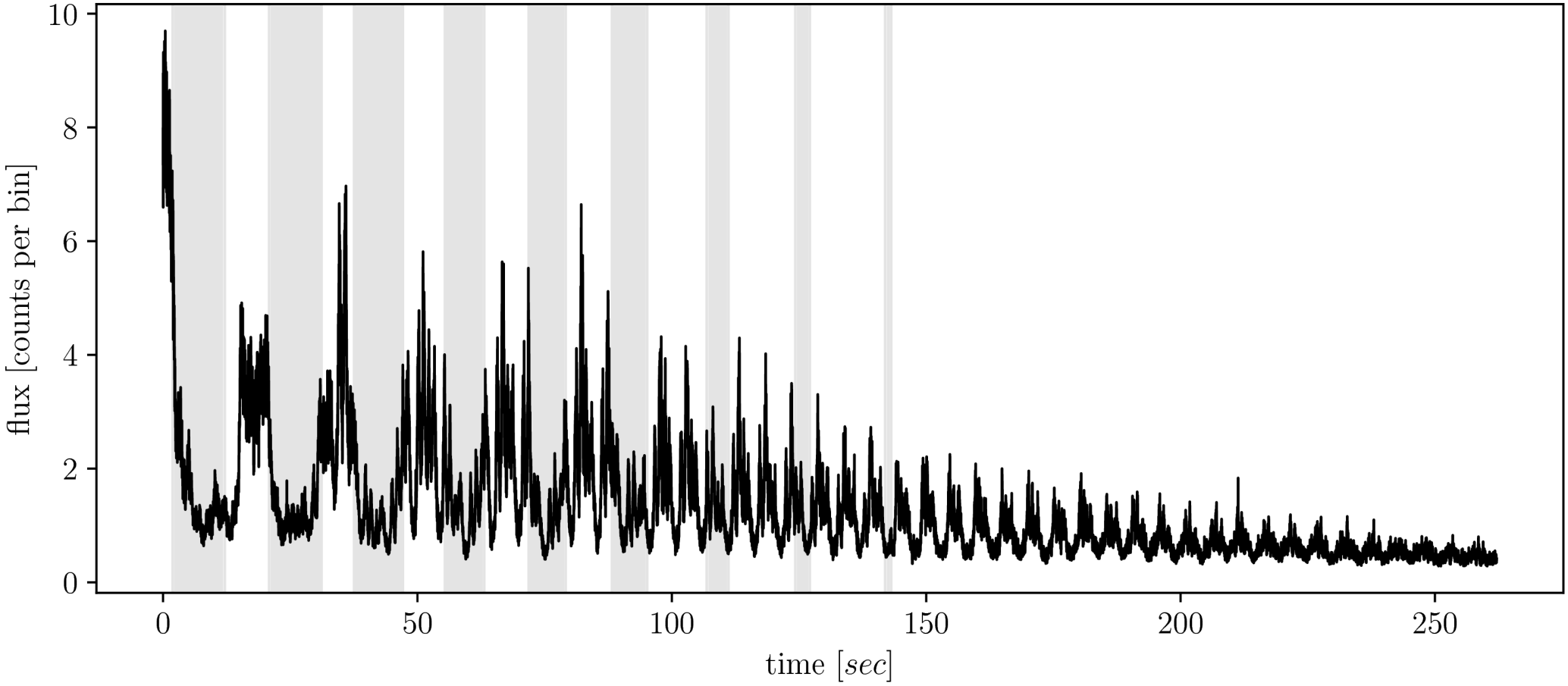

D³PO in 1D & QPOs

Magnetar flare SGR 1900+14

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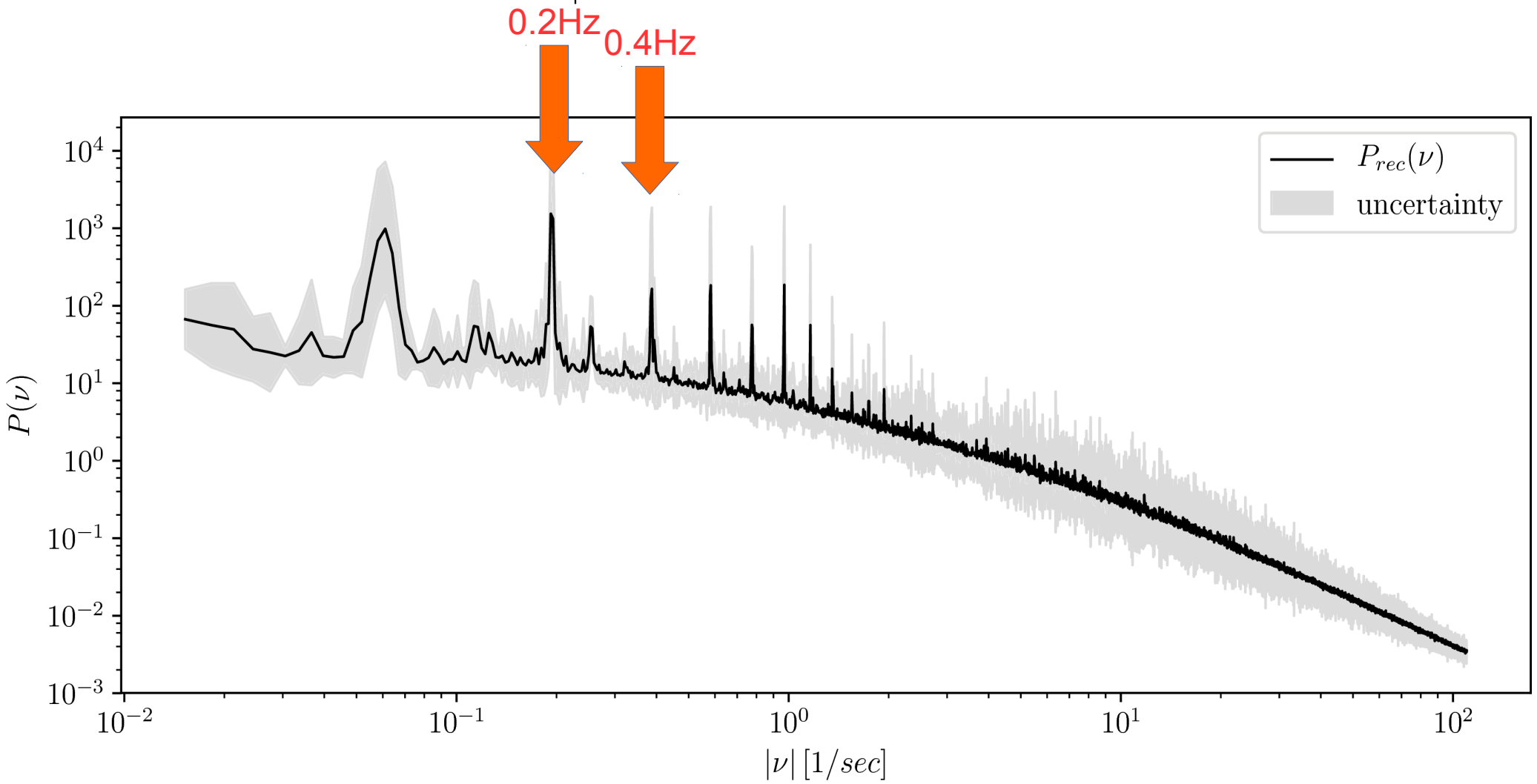
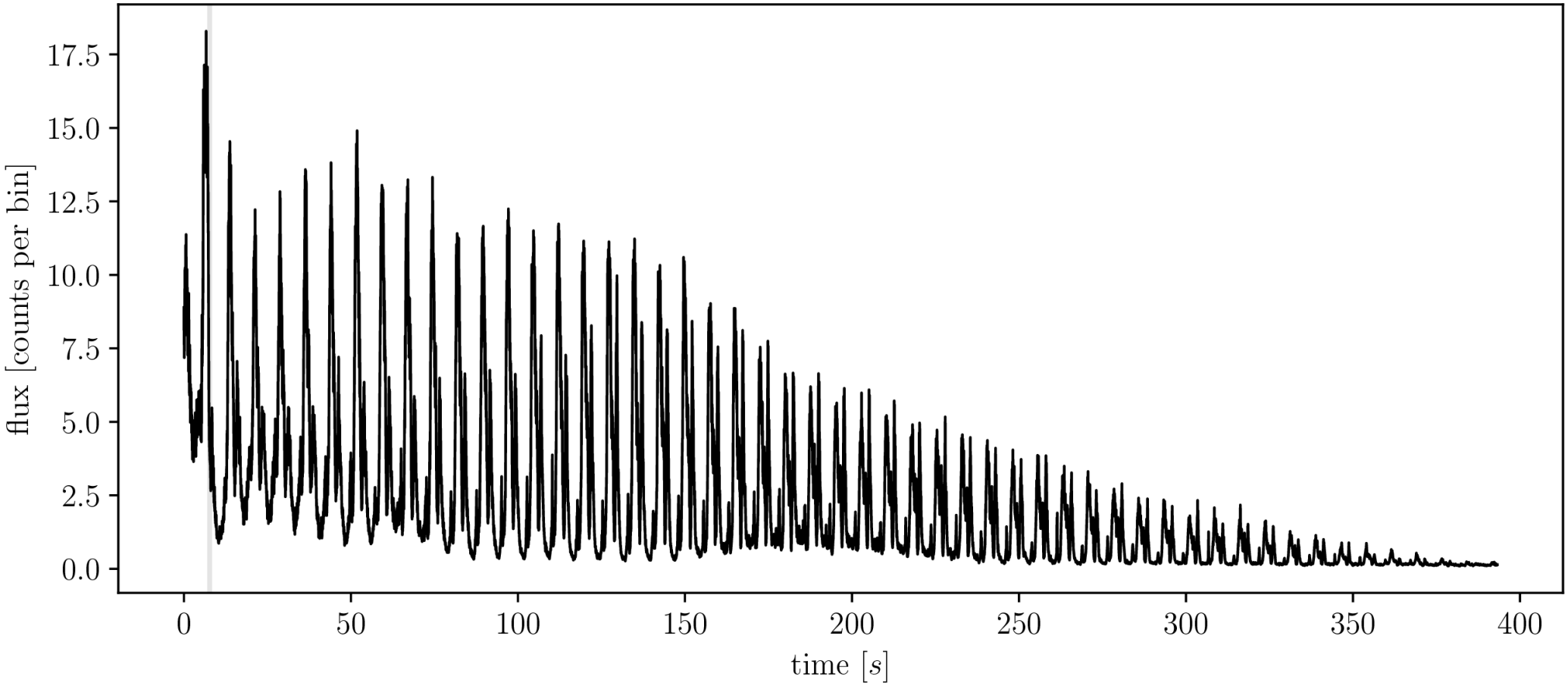


D³PO in 1D & QPOs

Magnetar flare SGR 1806+20

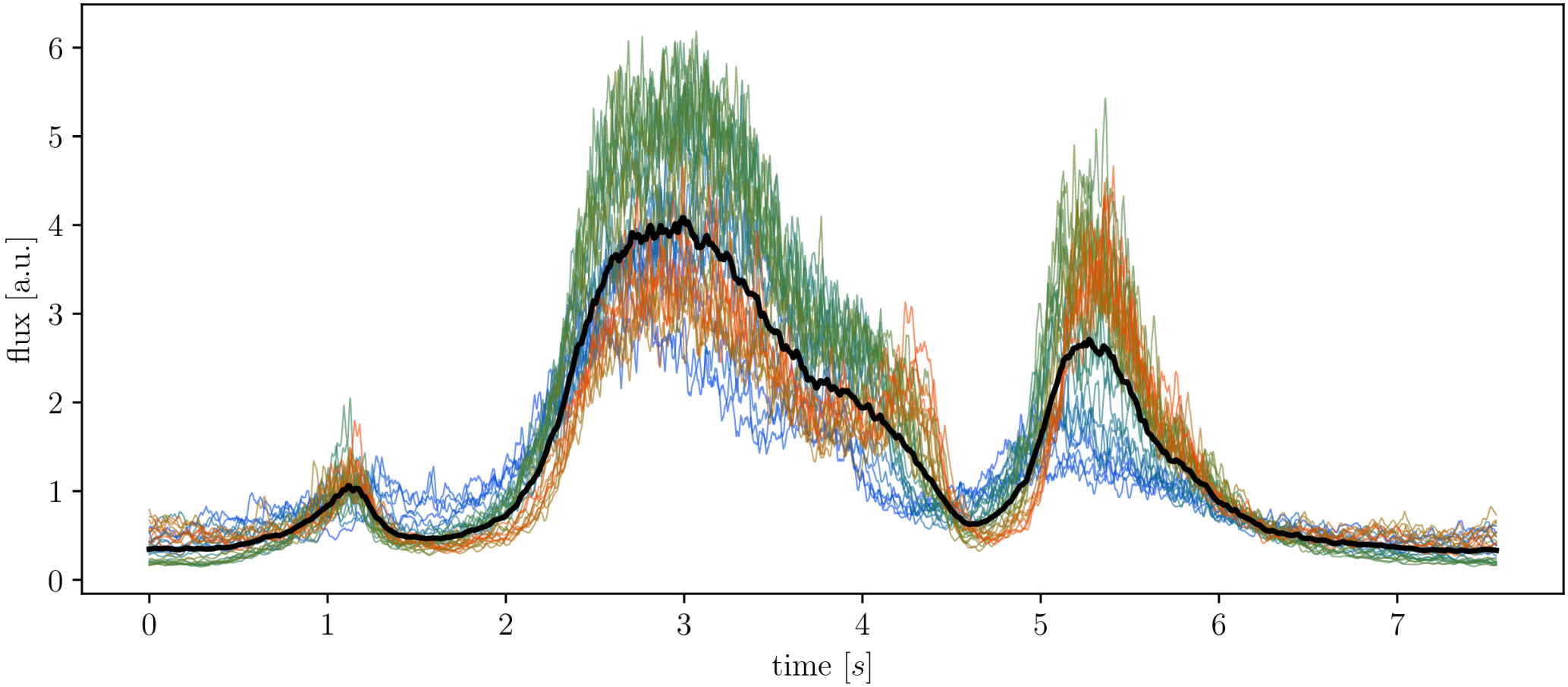
Pumpe et al. arXiv:1708.05702



D³PO in 1D & QPOs

Magnetar flare SGR 1806+20

Pumpe et al. arXiv:1708.05702



D³PO in 1D & QPOs

Magnetar flare SGR 1806+20

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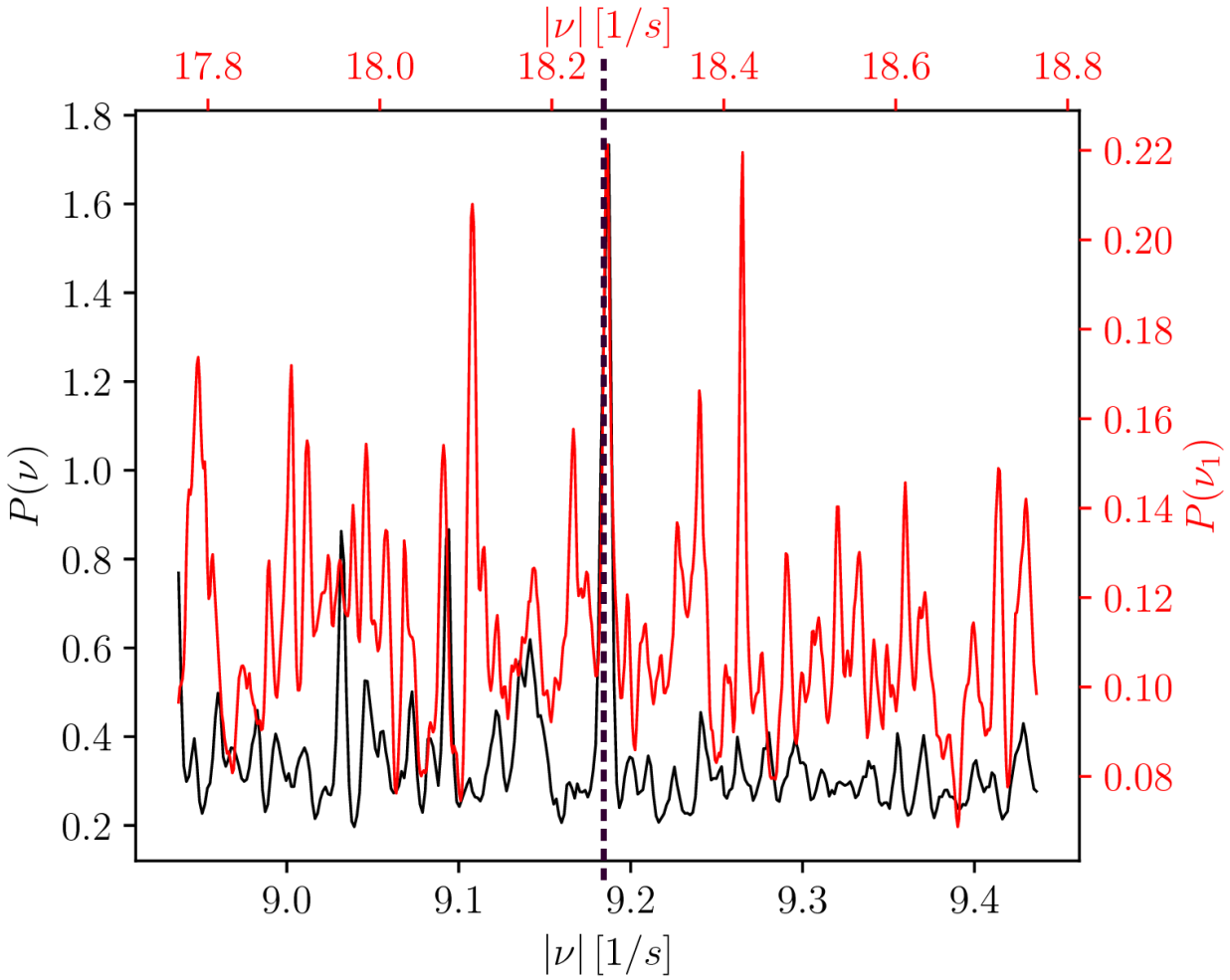
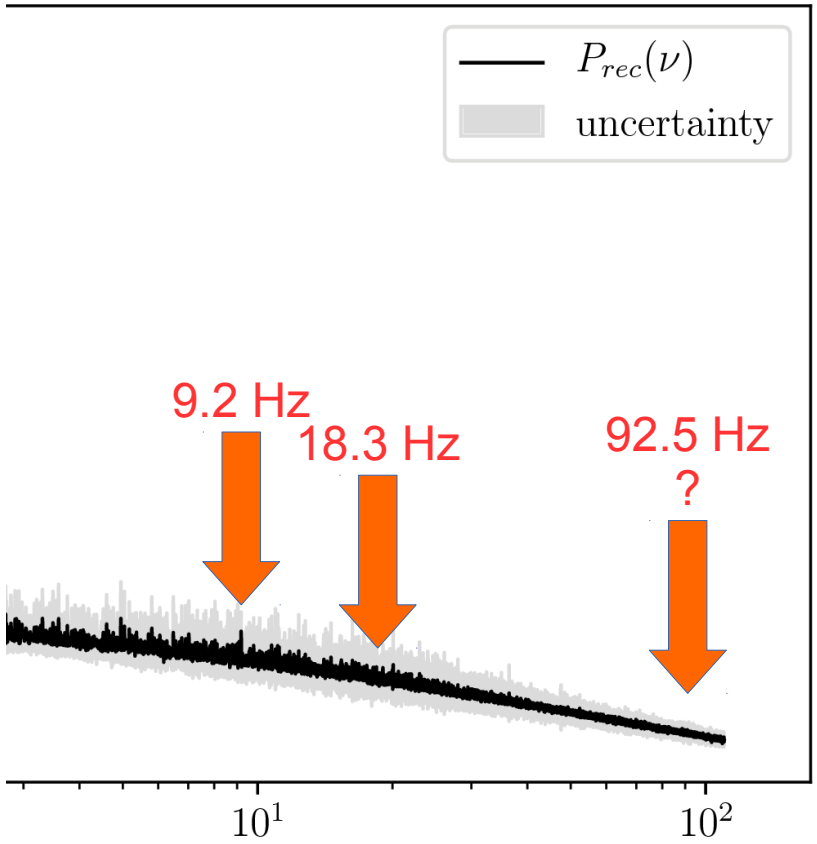
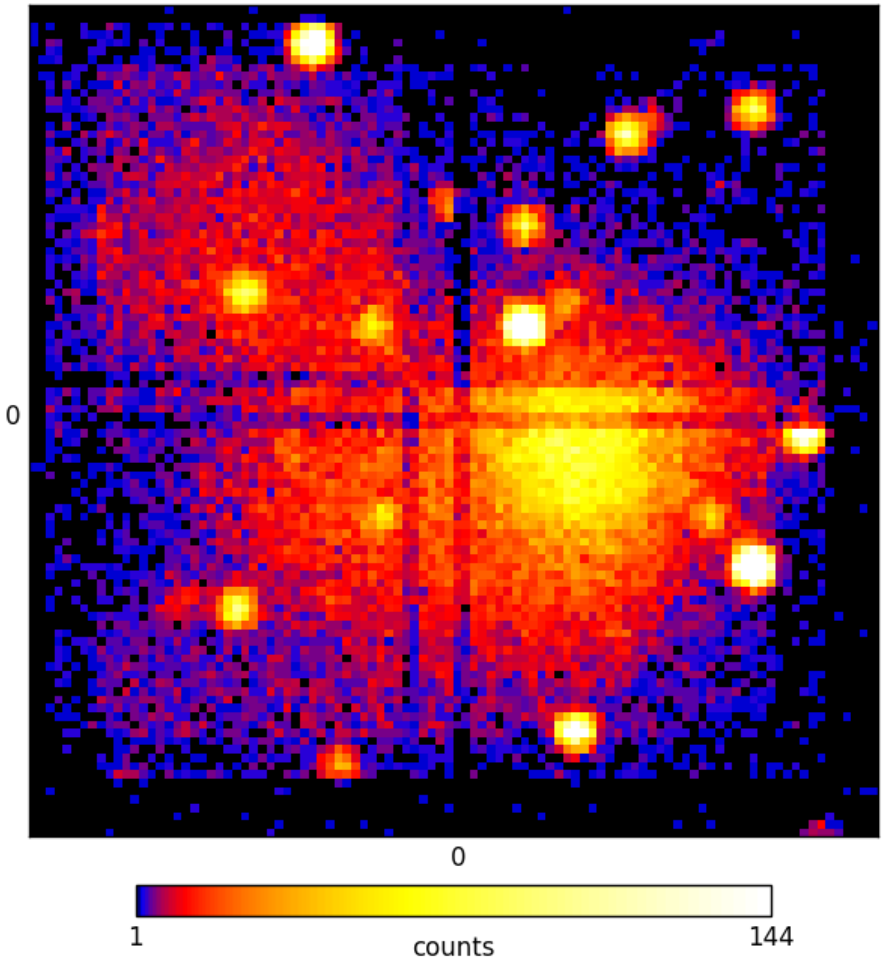




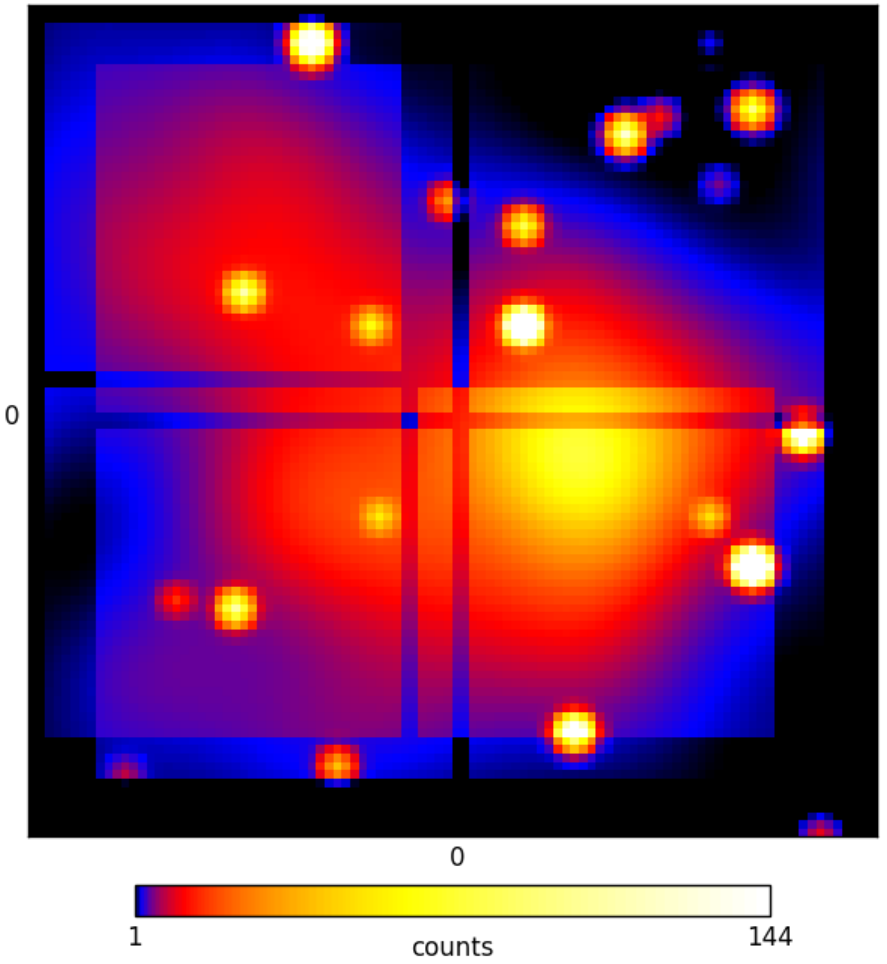
D3PO demo

D1PO

raw input data



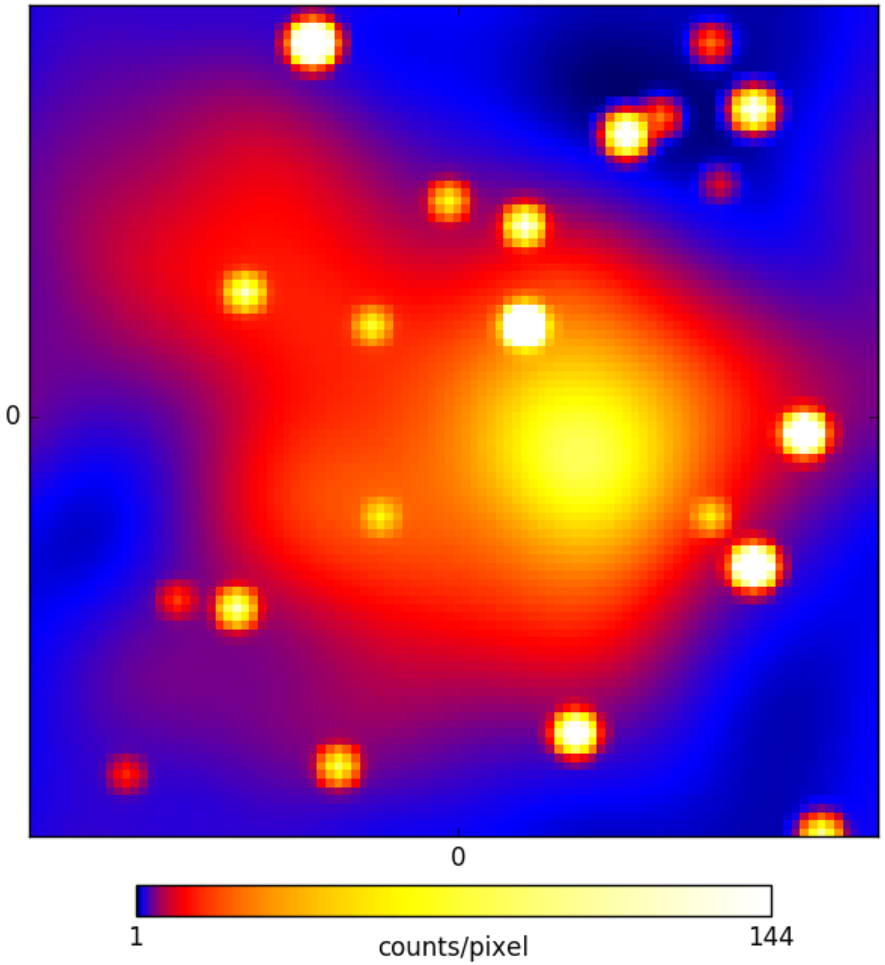
denoised observations



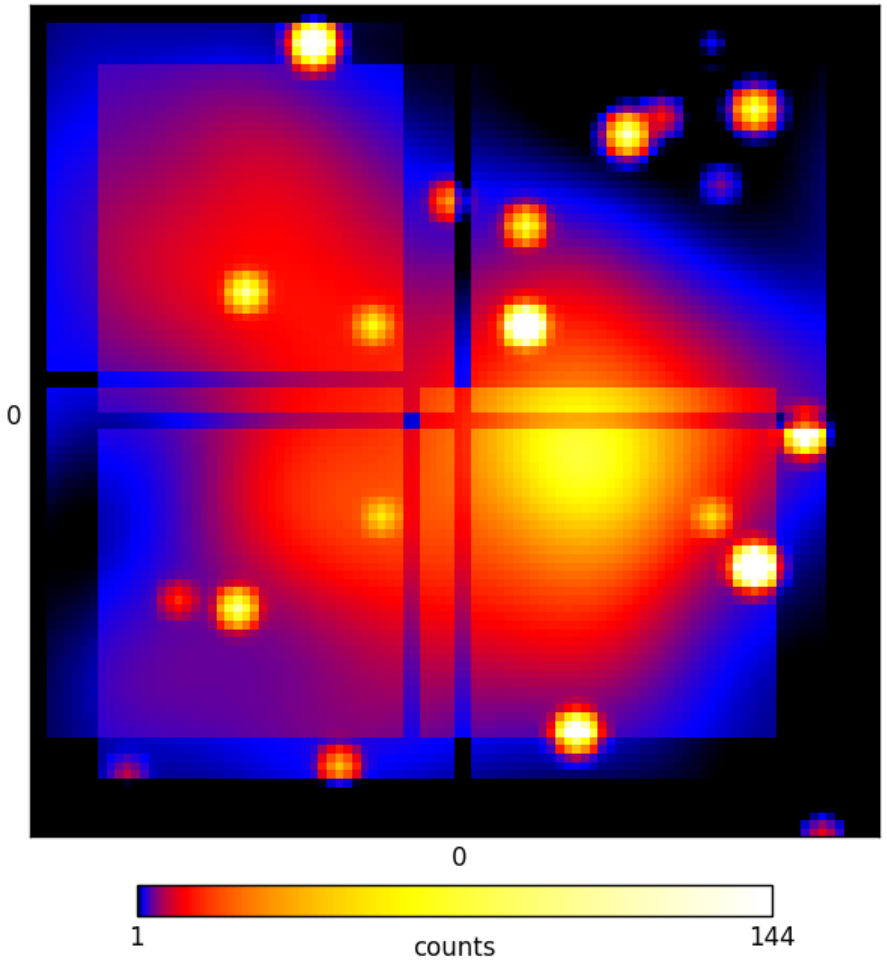
D3PO demo

D2PO

demasked flux



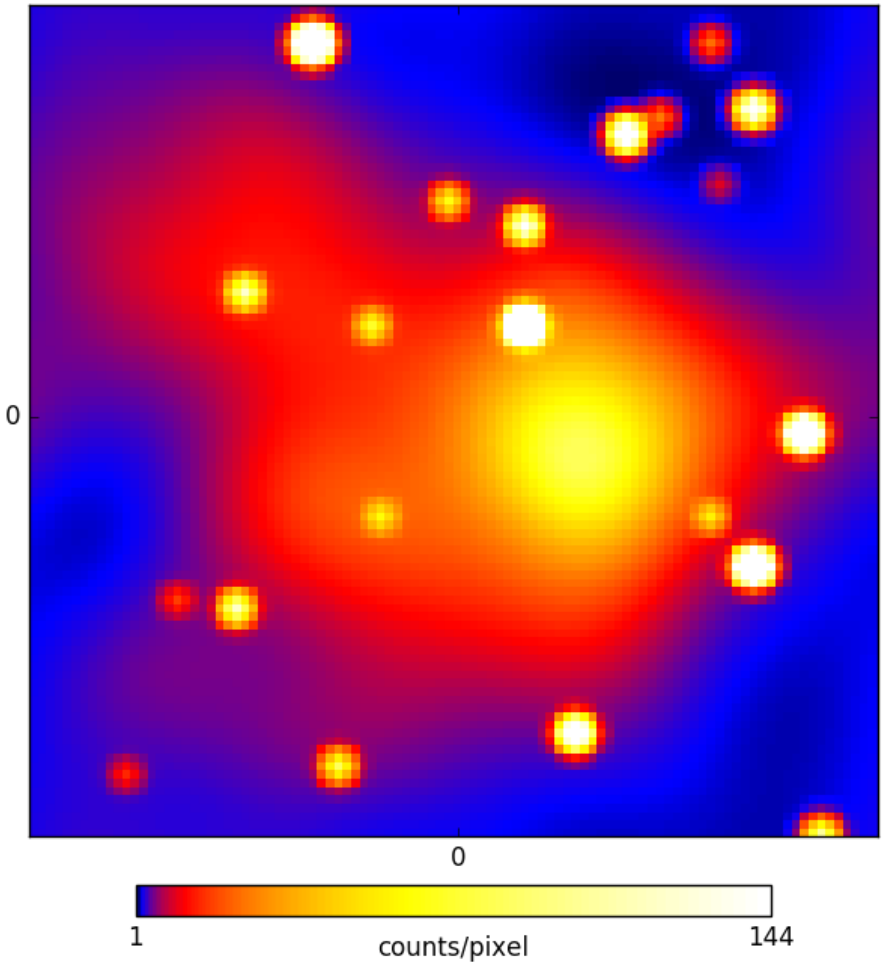
denoised observations



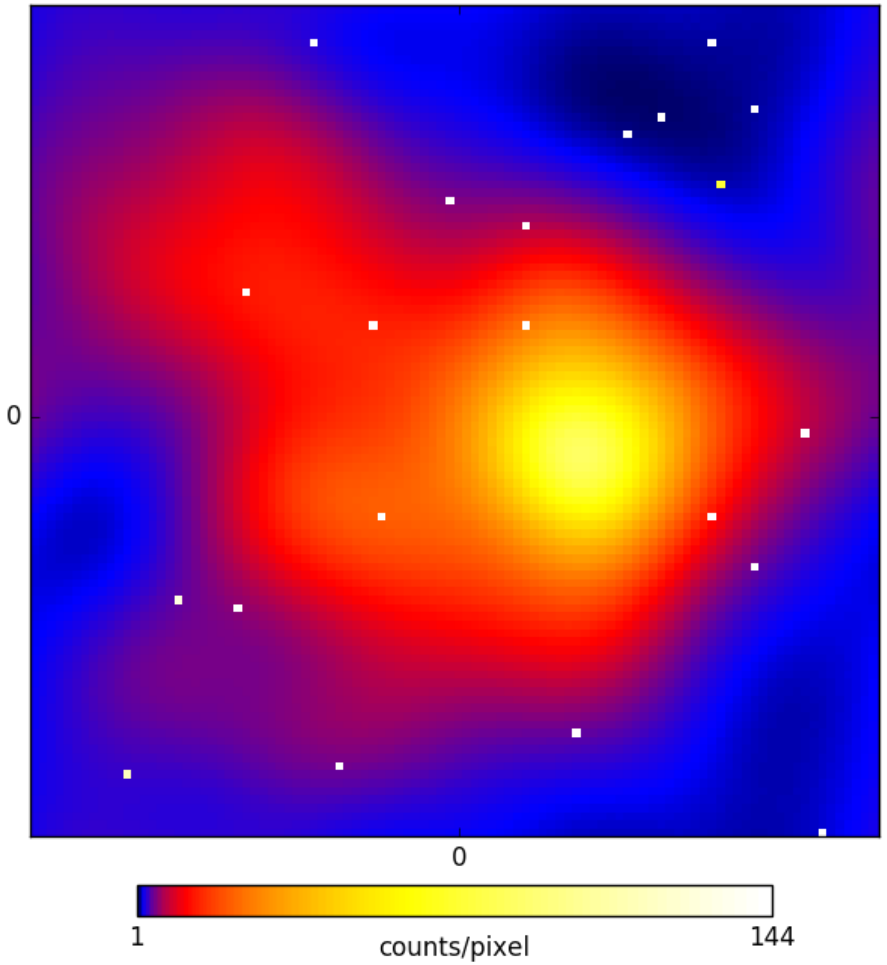
D3PO demo

D2PO

demasked flux



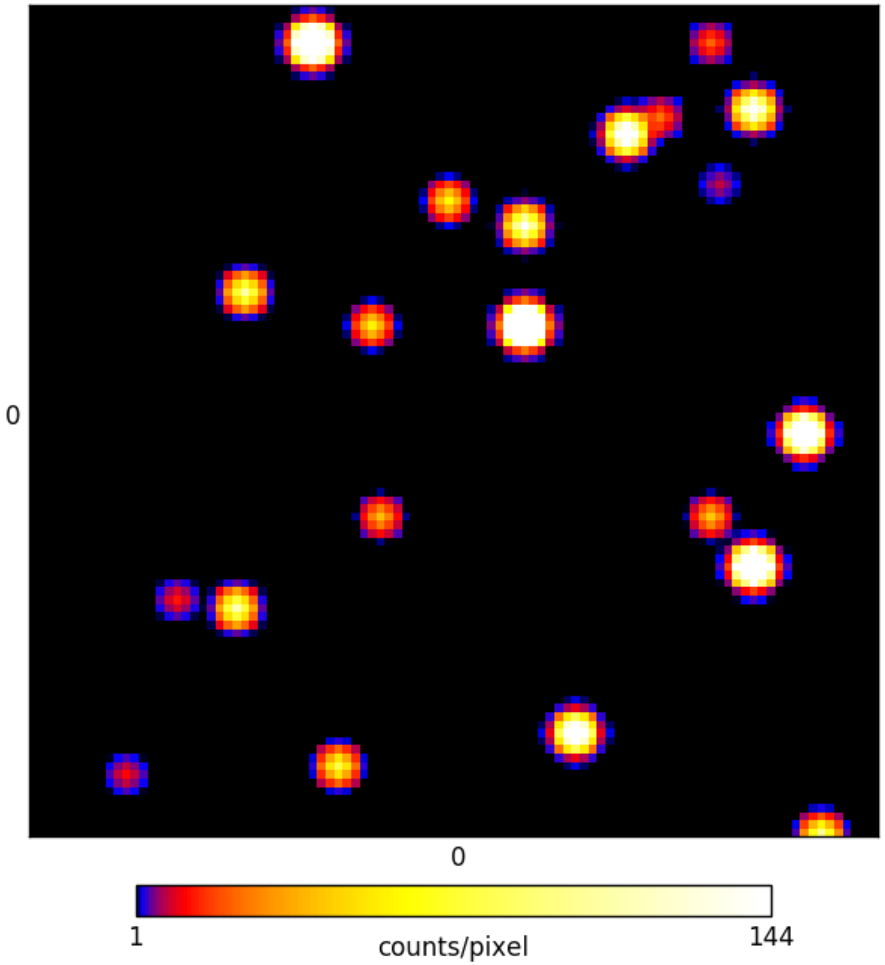
deconvolved flux



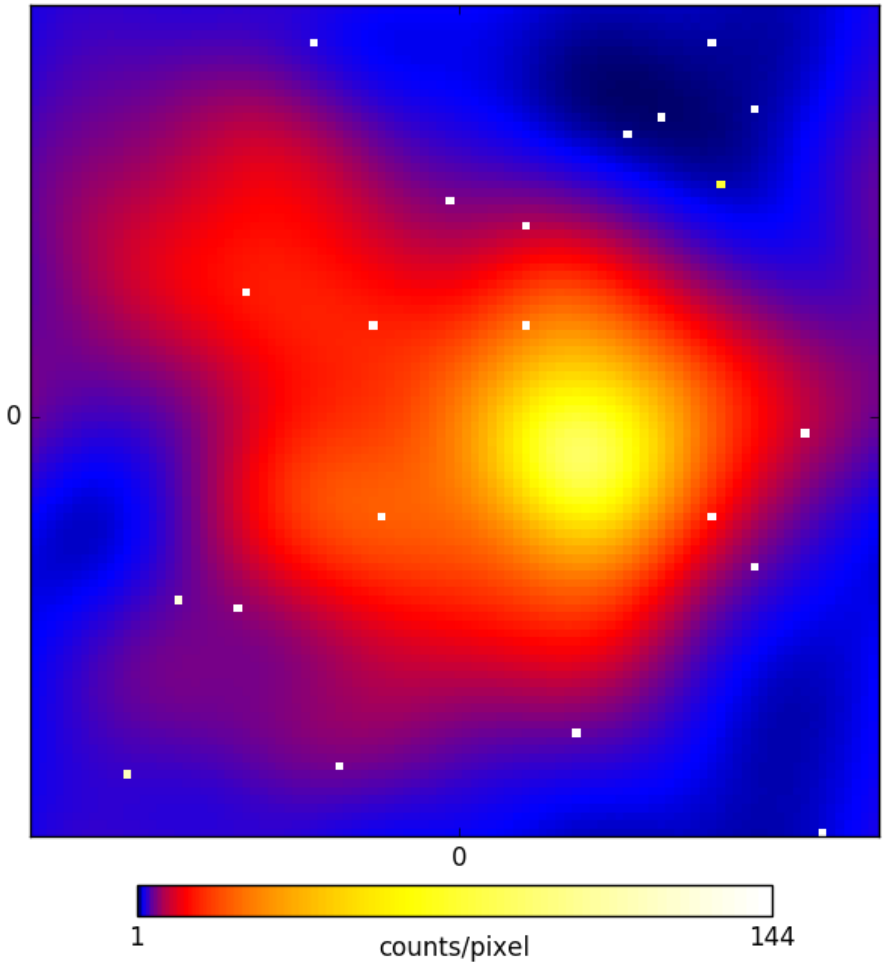
D3PO demo

D2PO

reconvolved point sources



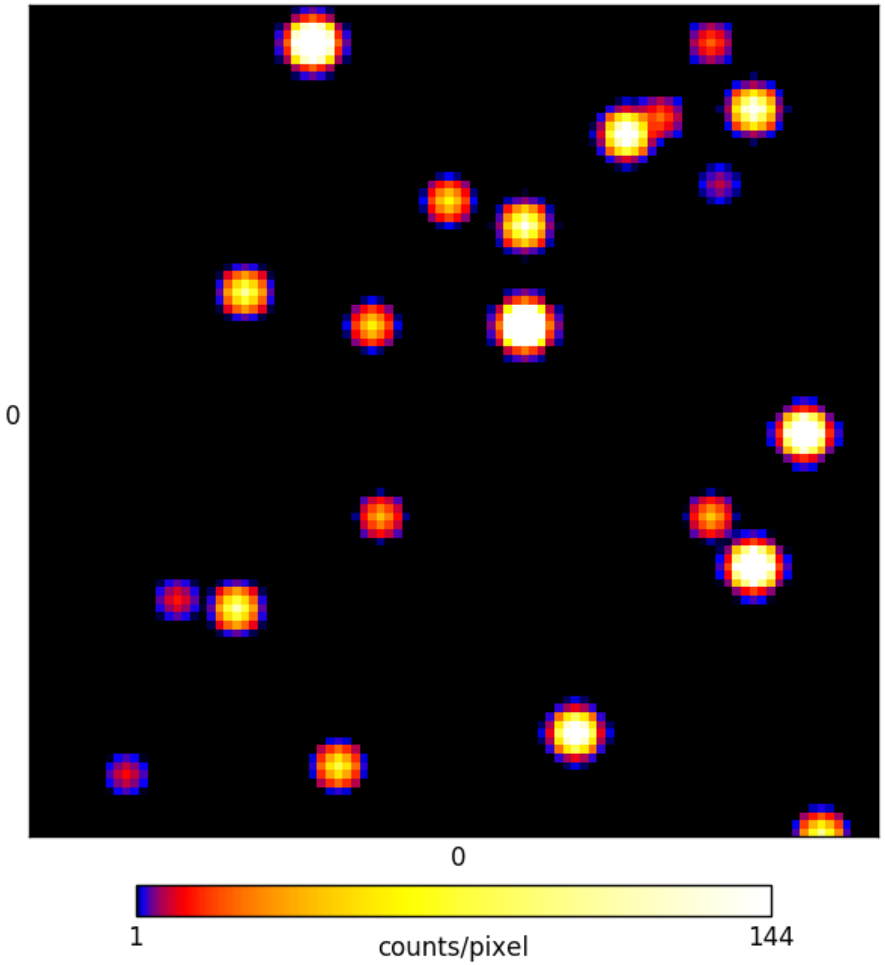
deconvolved flux



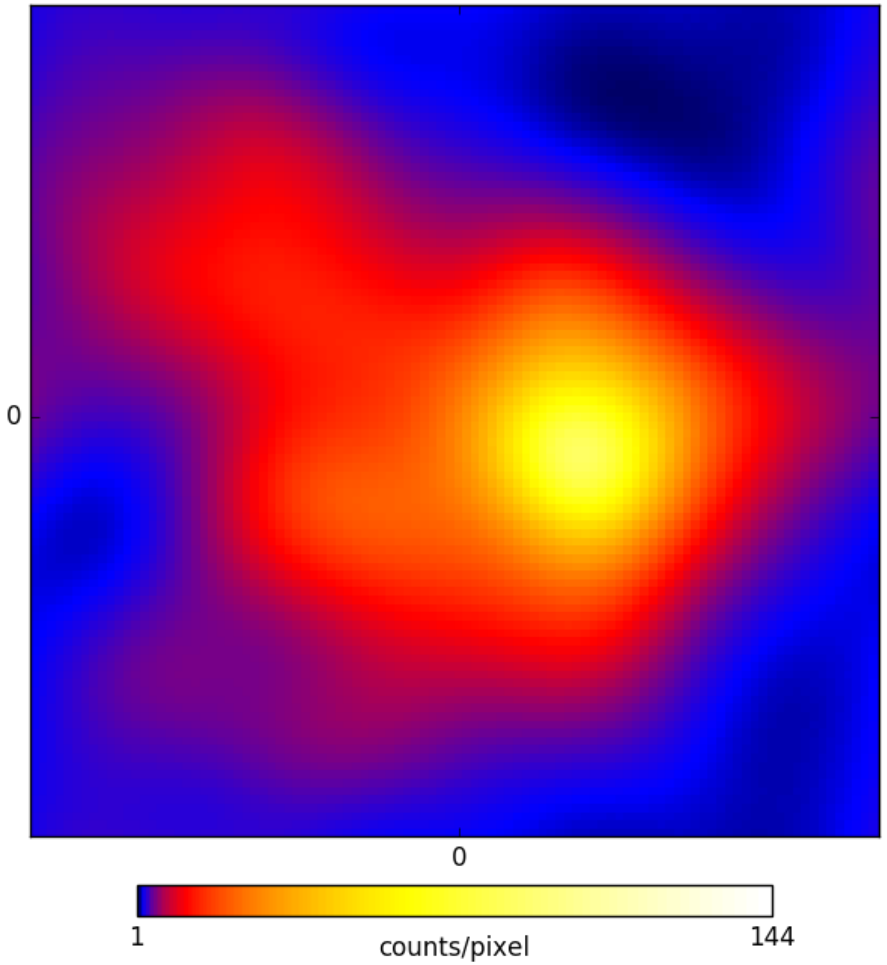
D3PO demo

D3PO

reconvolved point sources

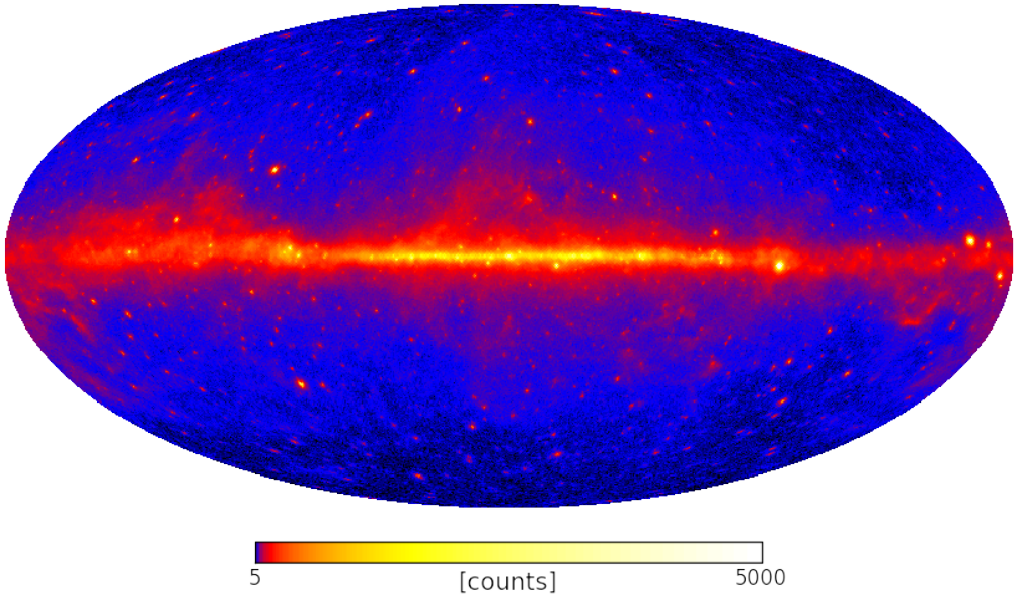


diffuse flux

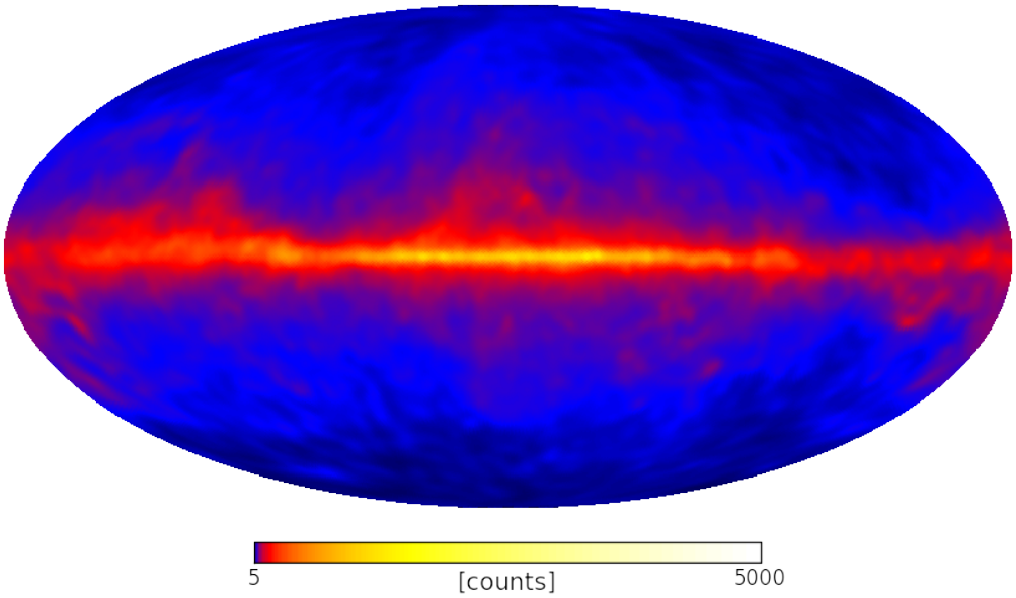


γ-ray sky

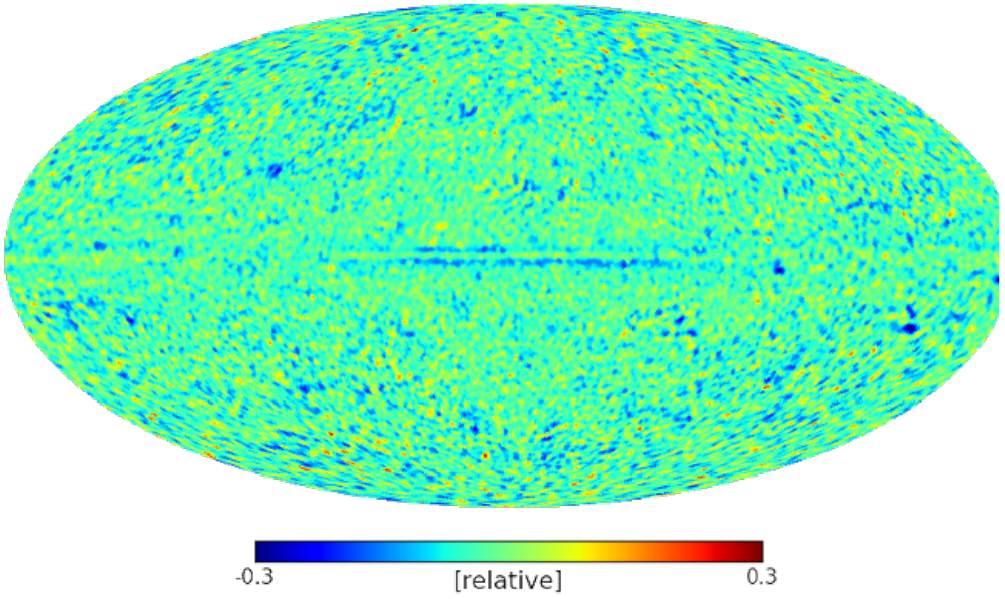
photon data



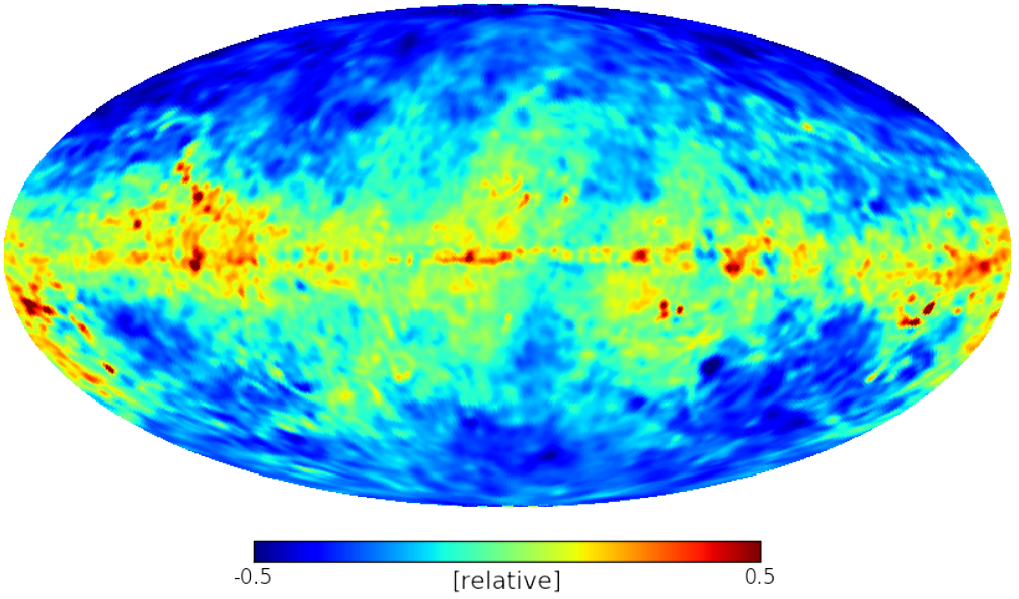
diffuse flux

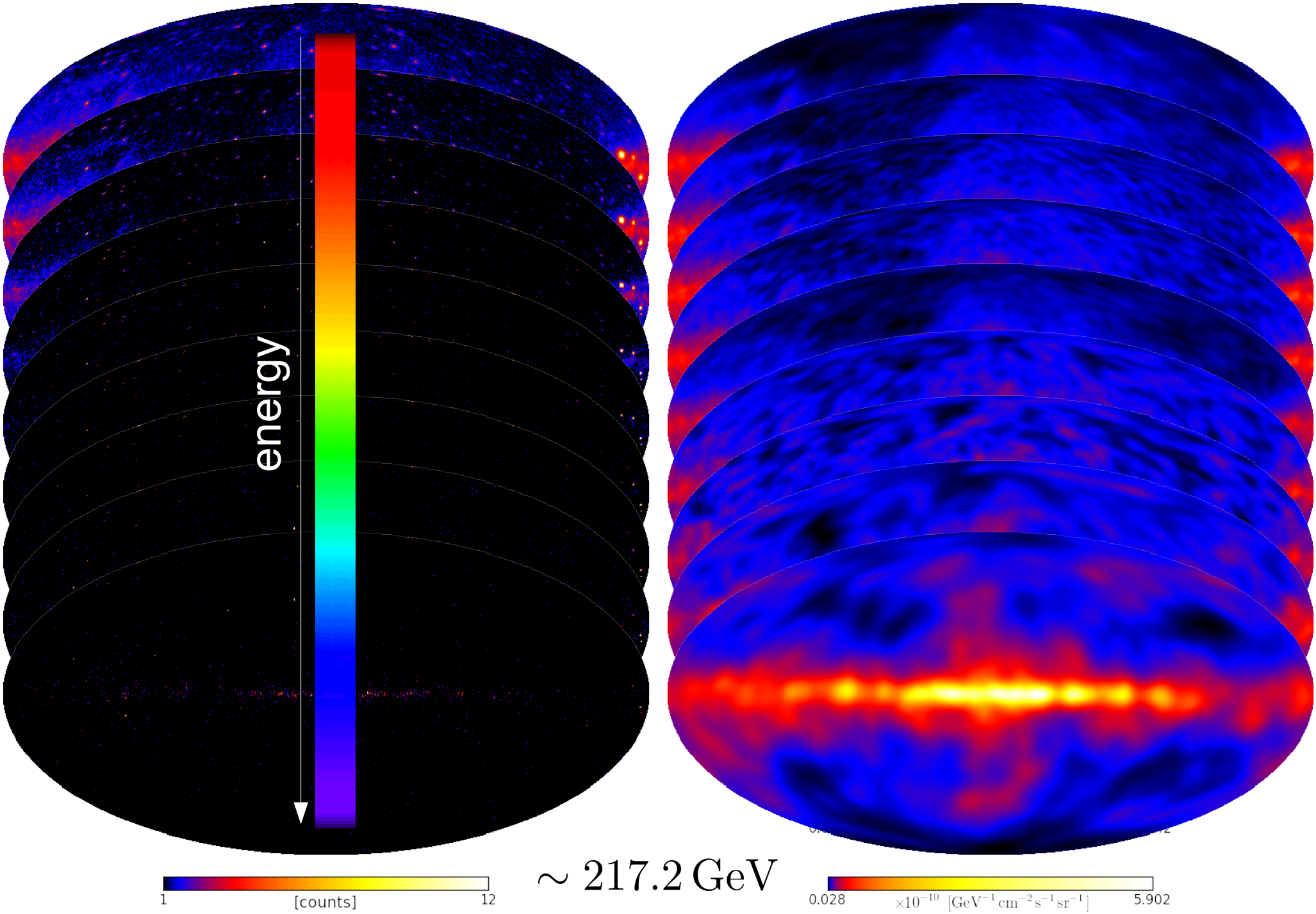


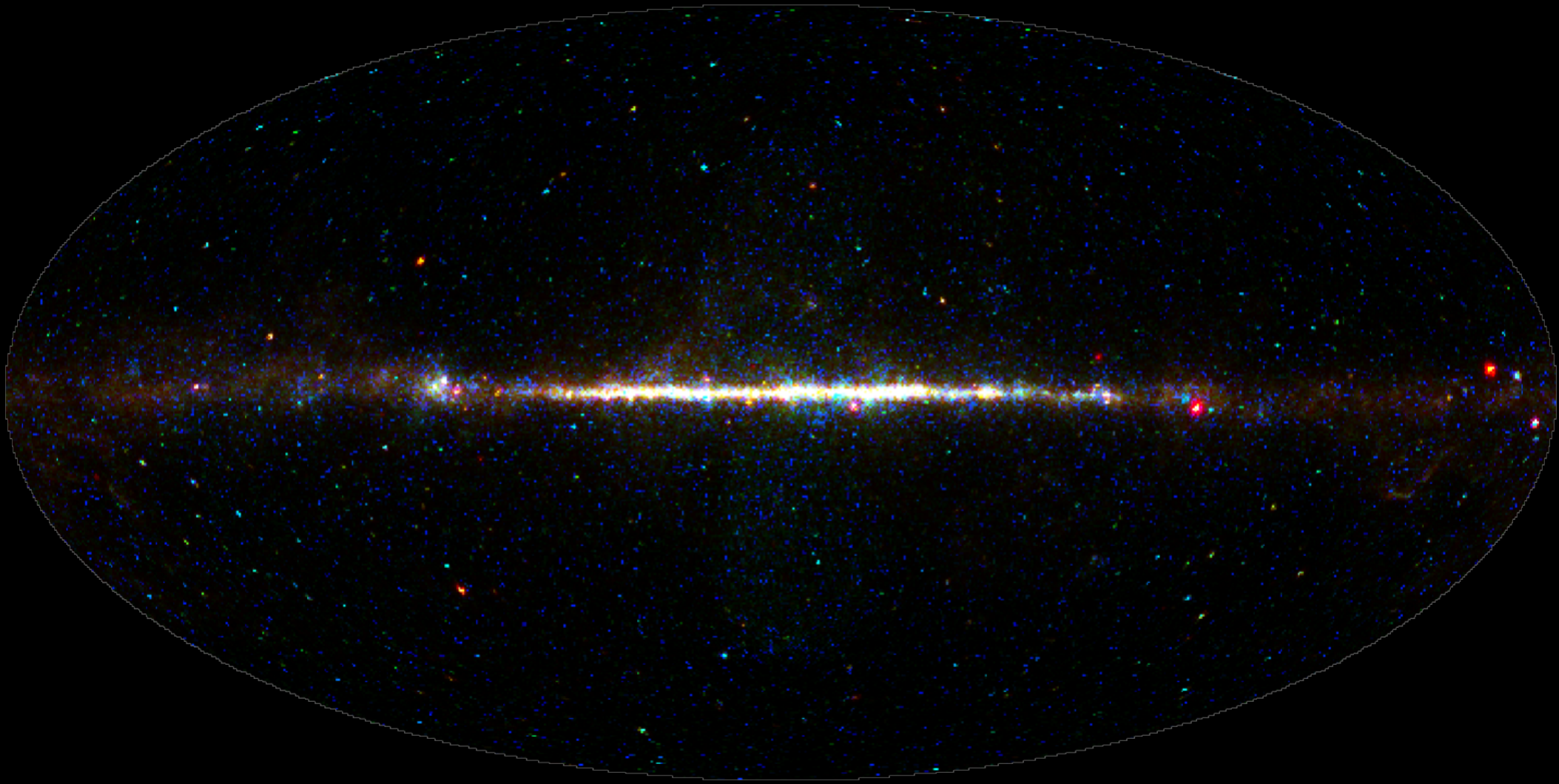
relative residuals



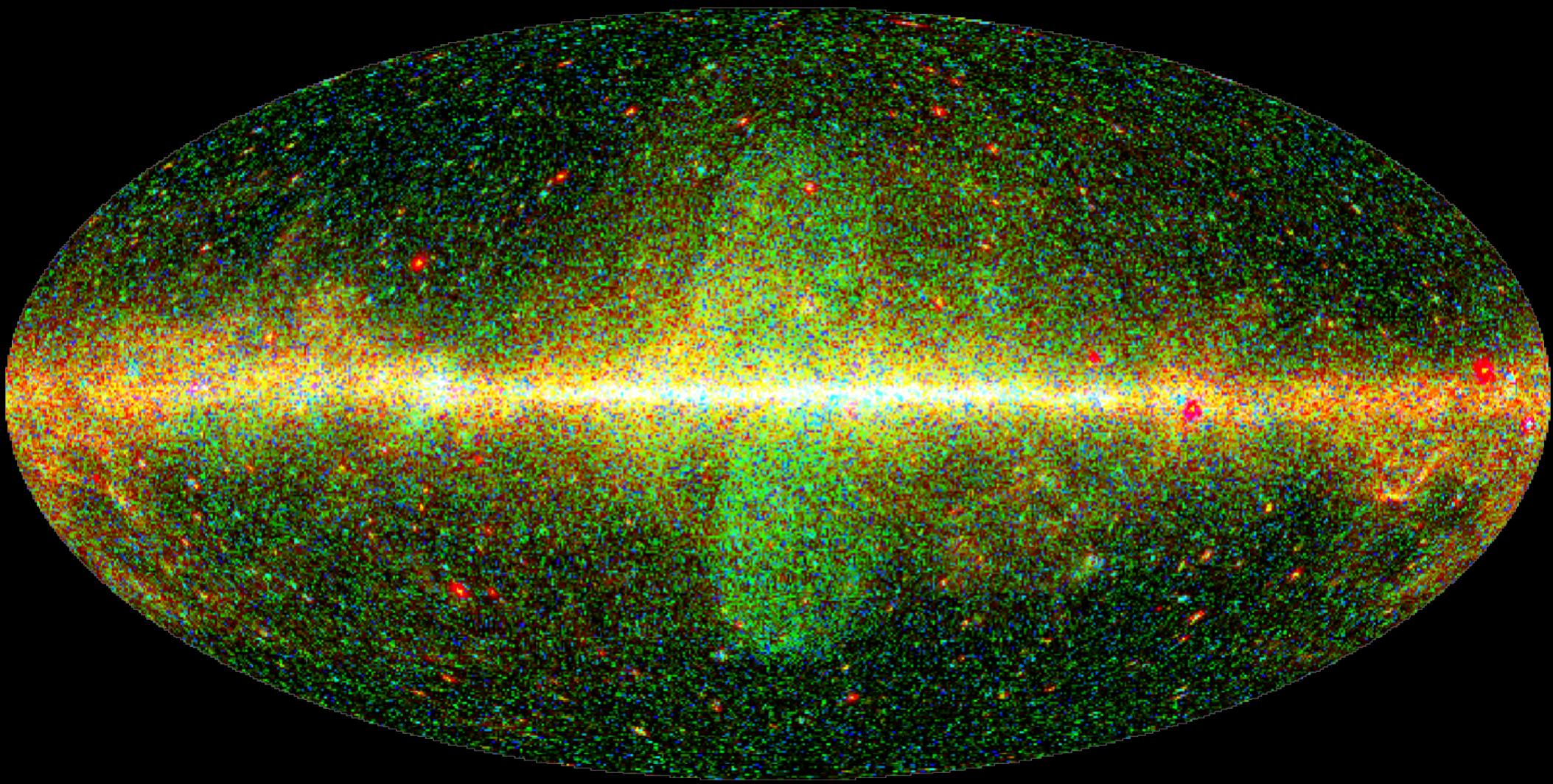
relative difference to Fermi map



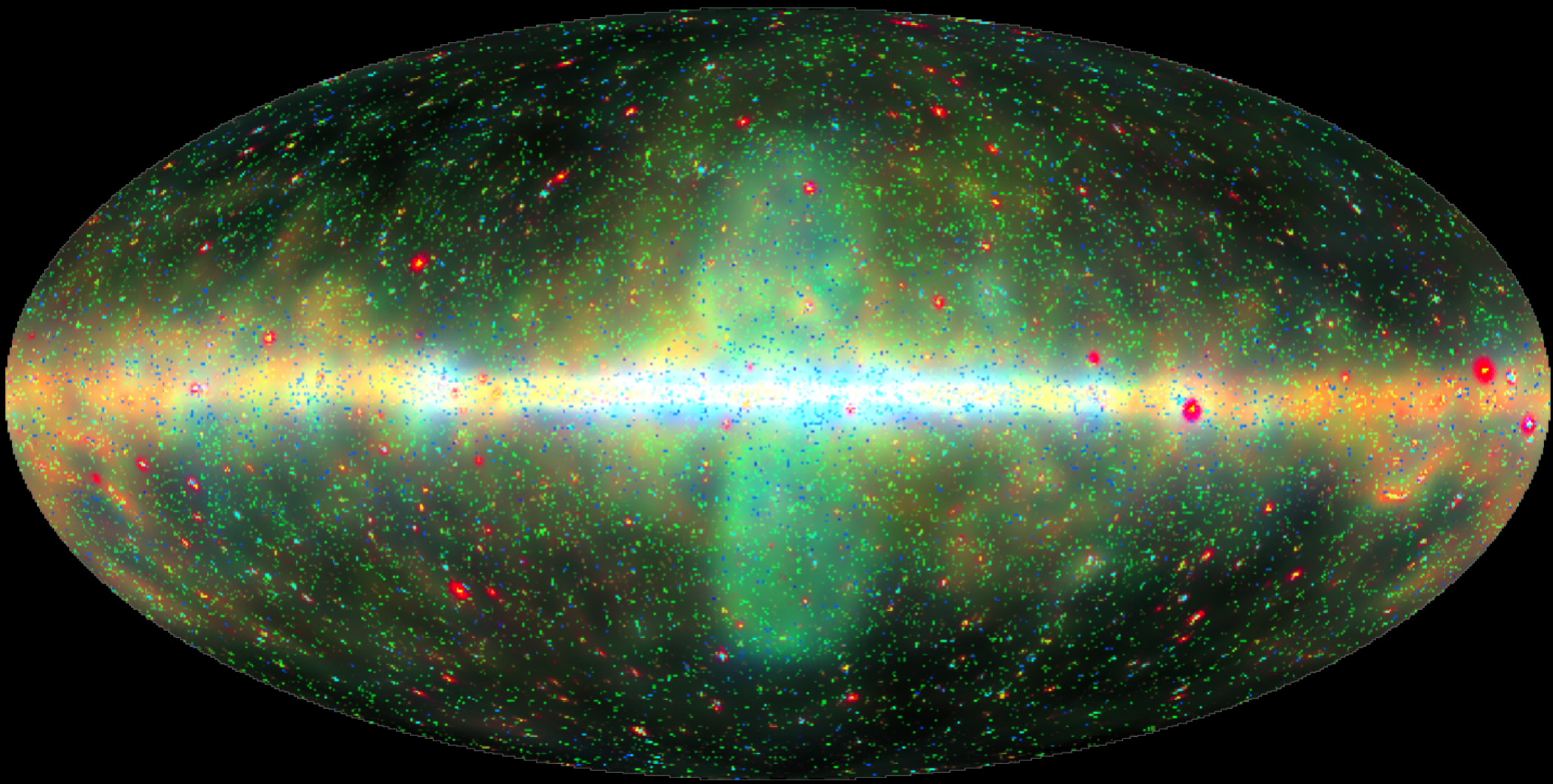

energy
1
[counts]
12
~ 217.2 GeV
0.028
$\times 10^{-10}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]
5.902



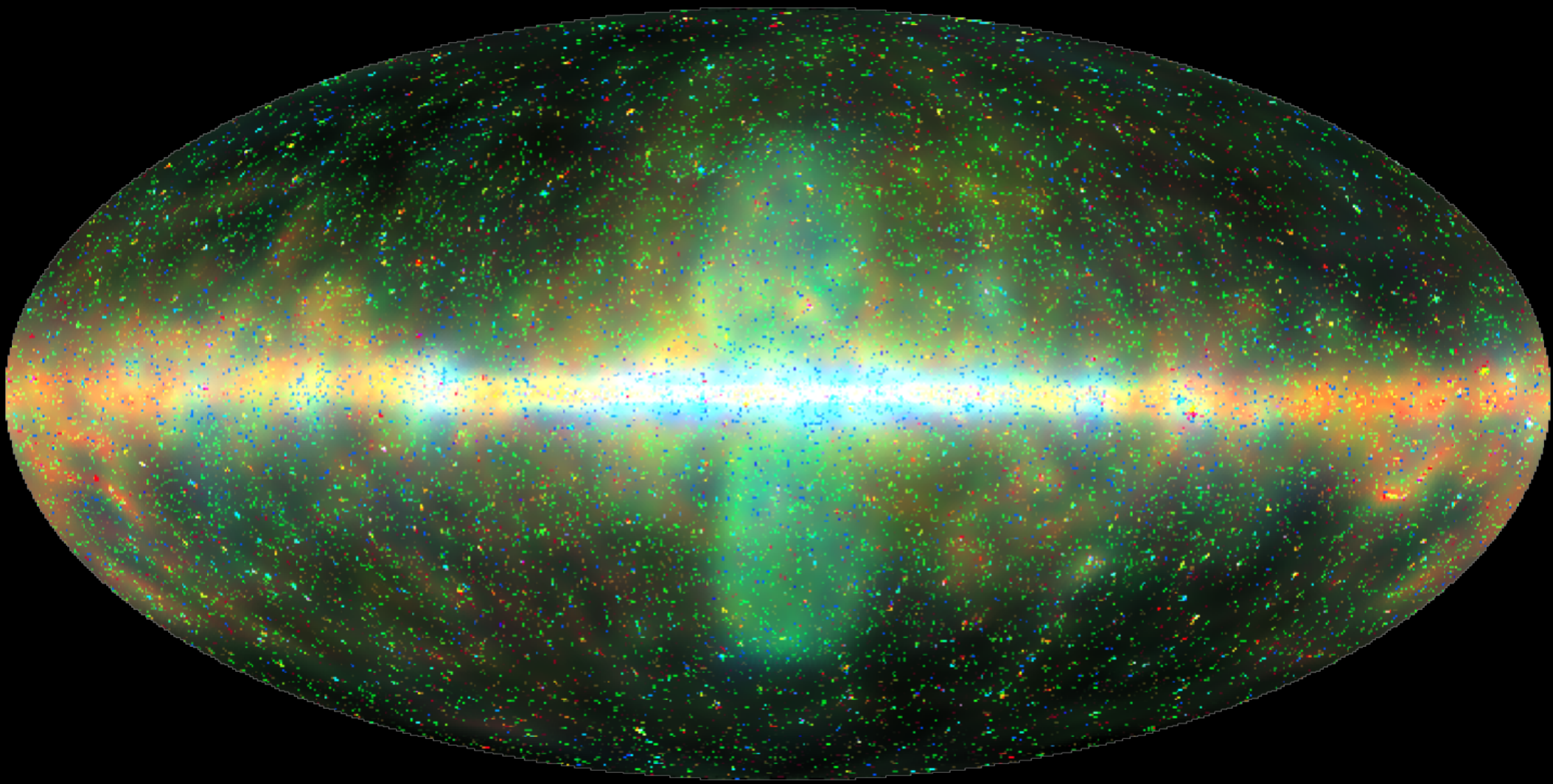
data



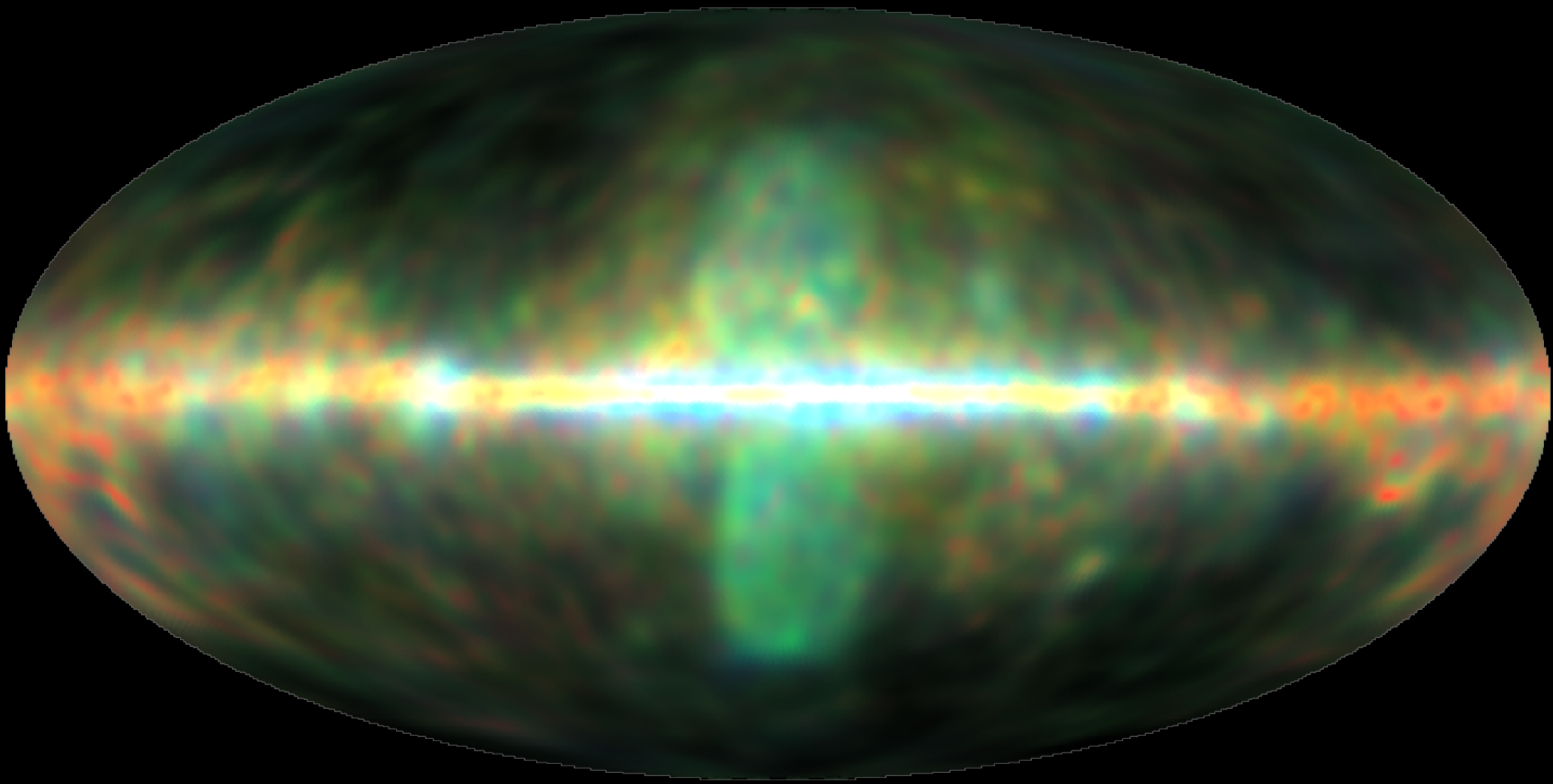
log-data



log-data … denoised

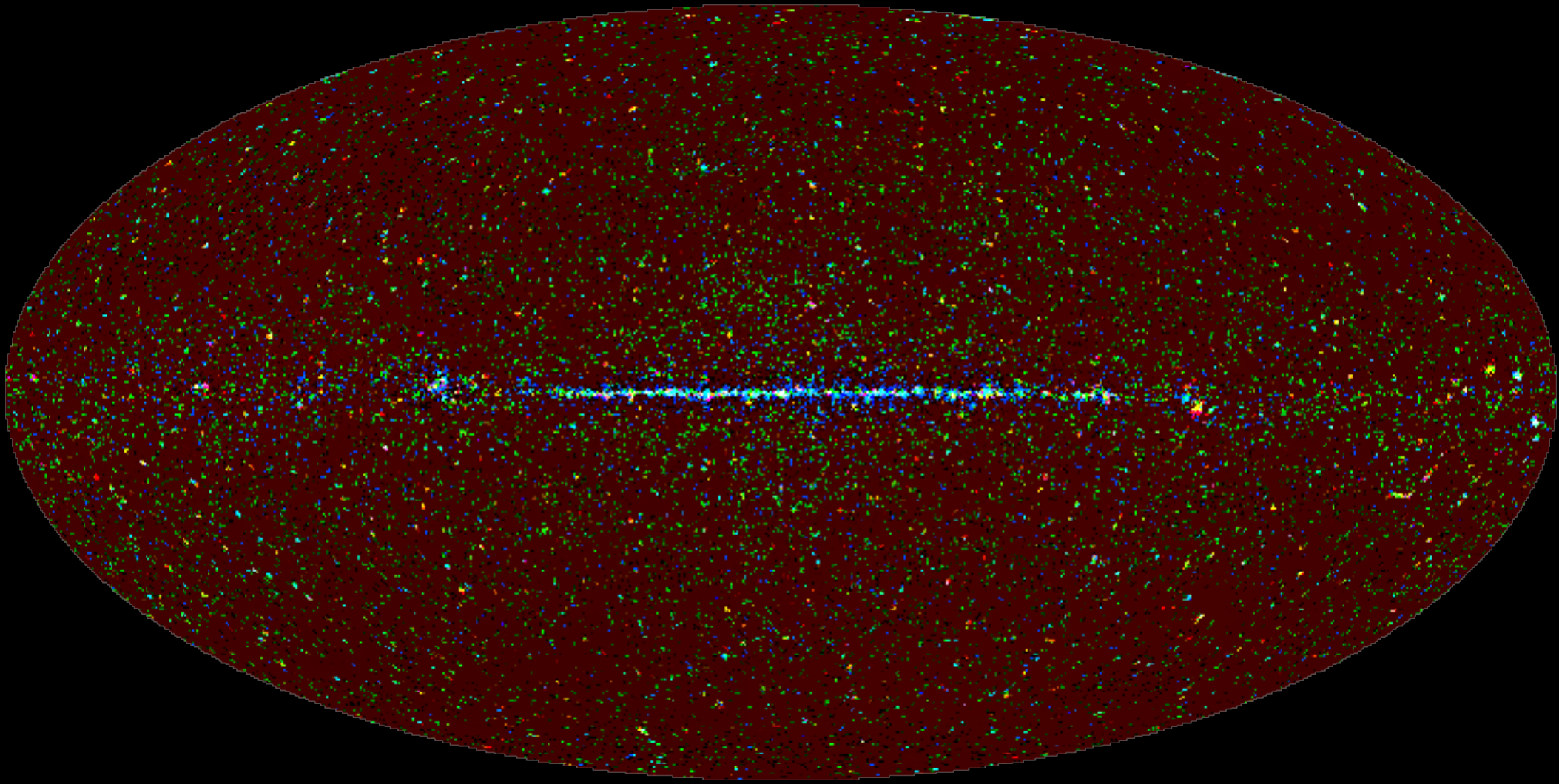


log-data … denoised … deconvolved



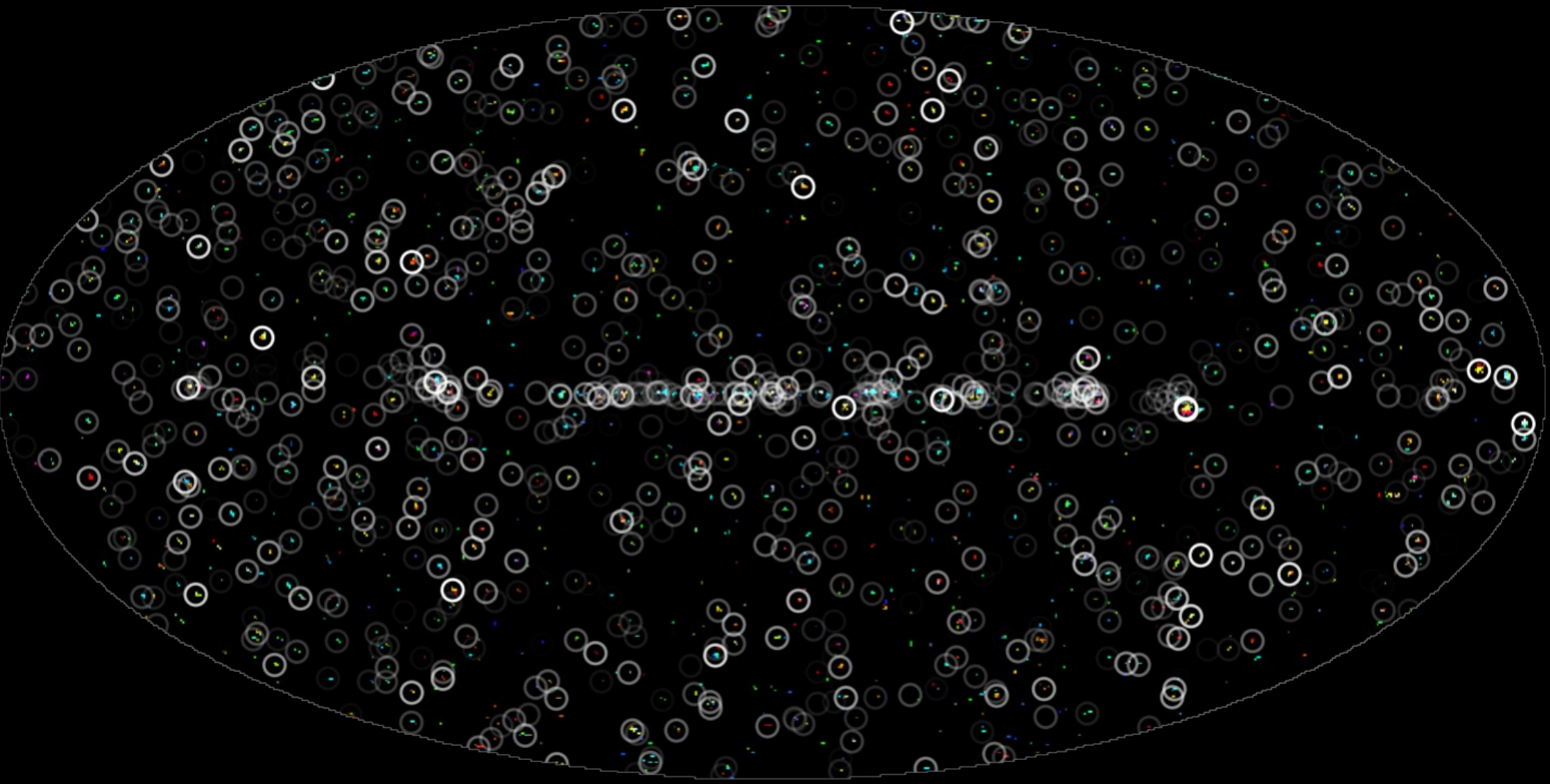
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)



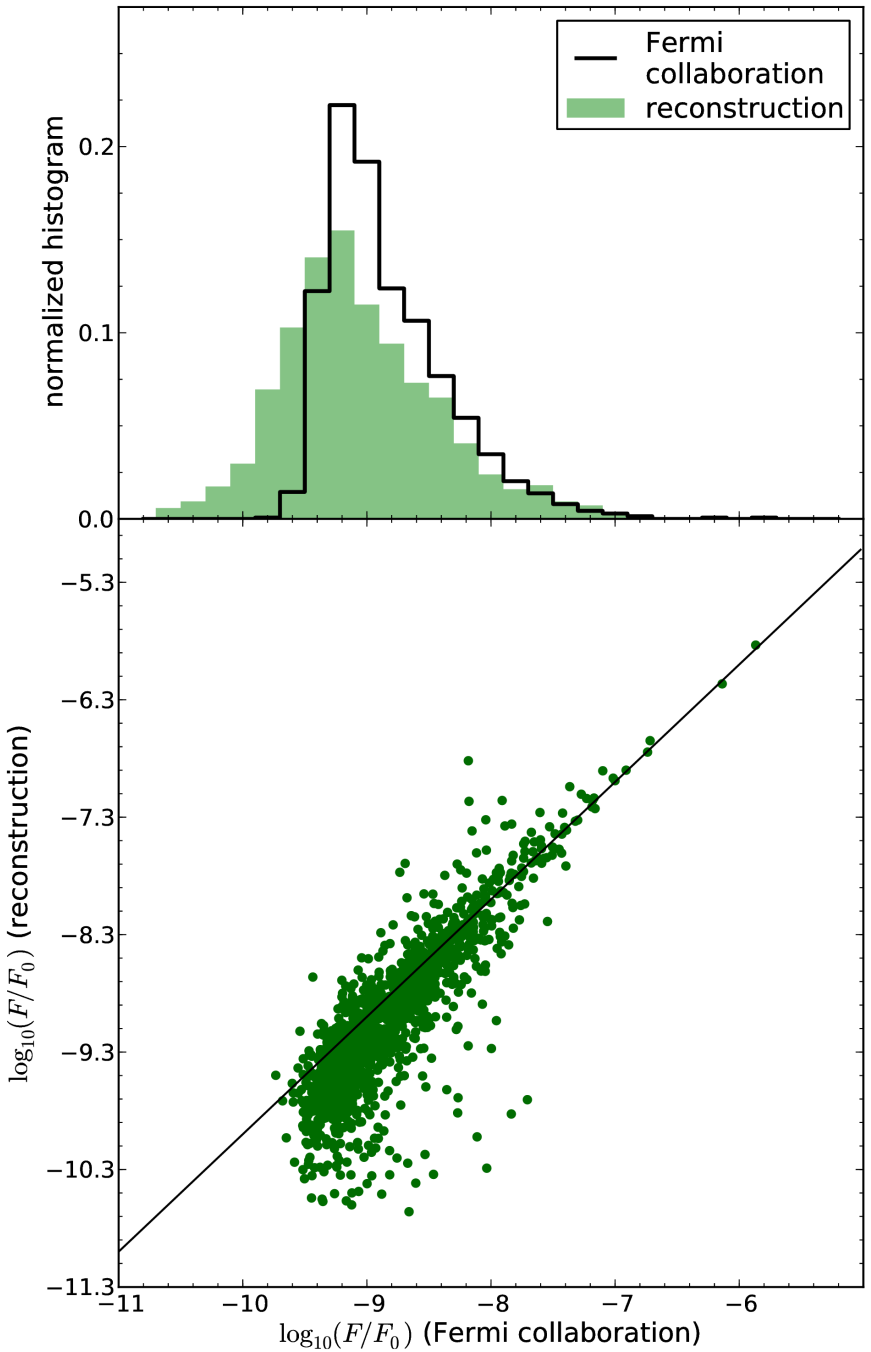
log-data … denoised … deconvolved … decomposed

Selig, Vacca, Oppermann, Enßlin (2015)

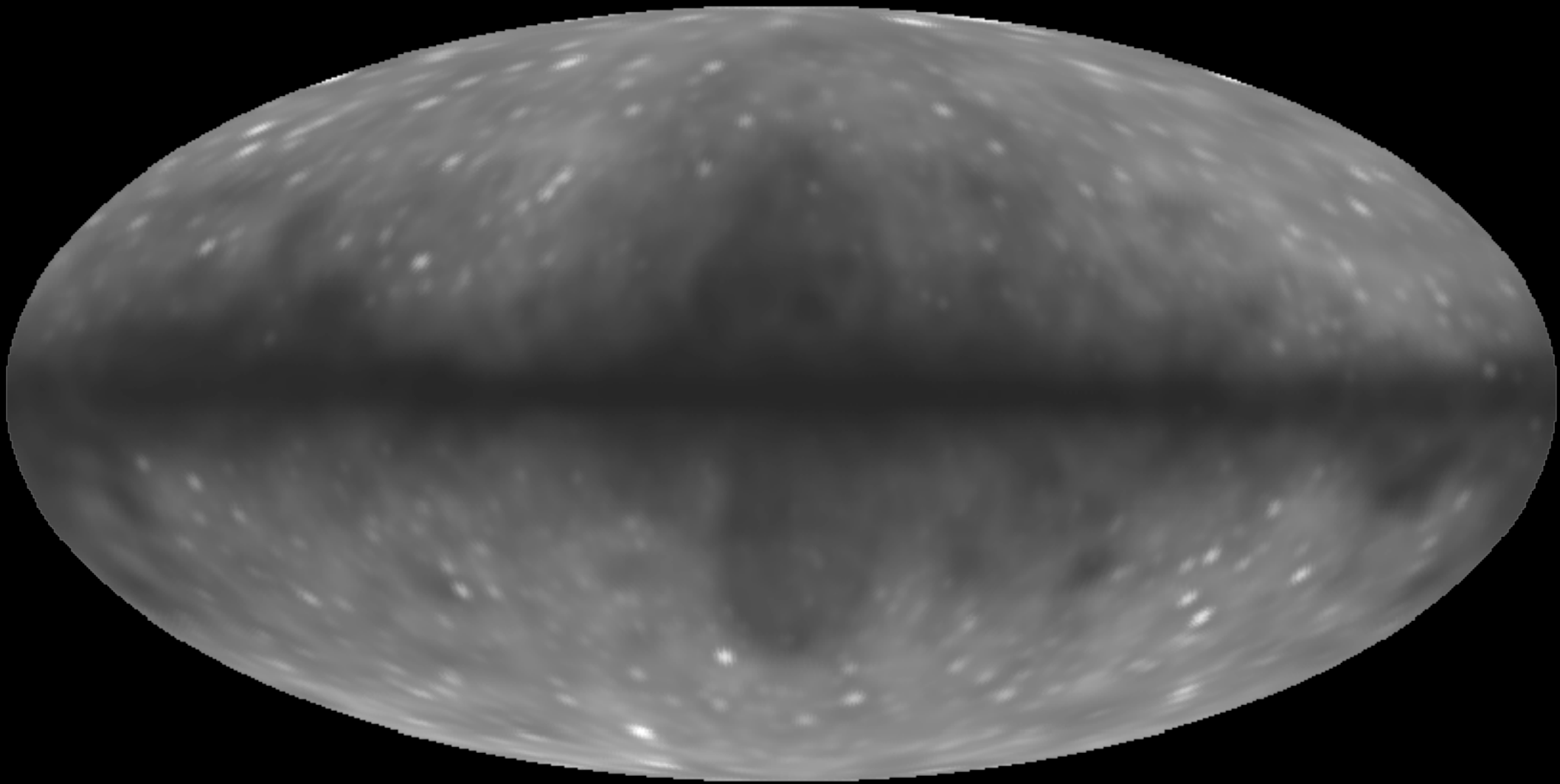


point sources

First D³PO Fermi Point Source Candidates Catalog (1DF)

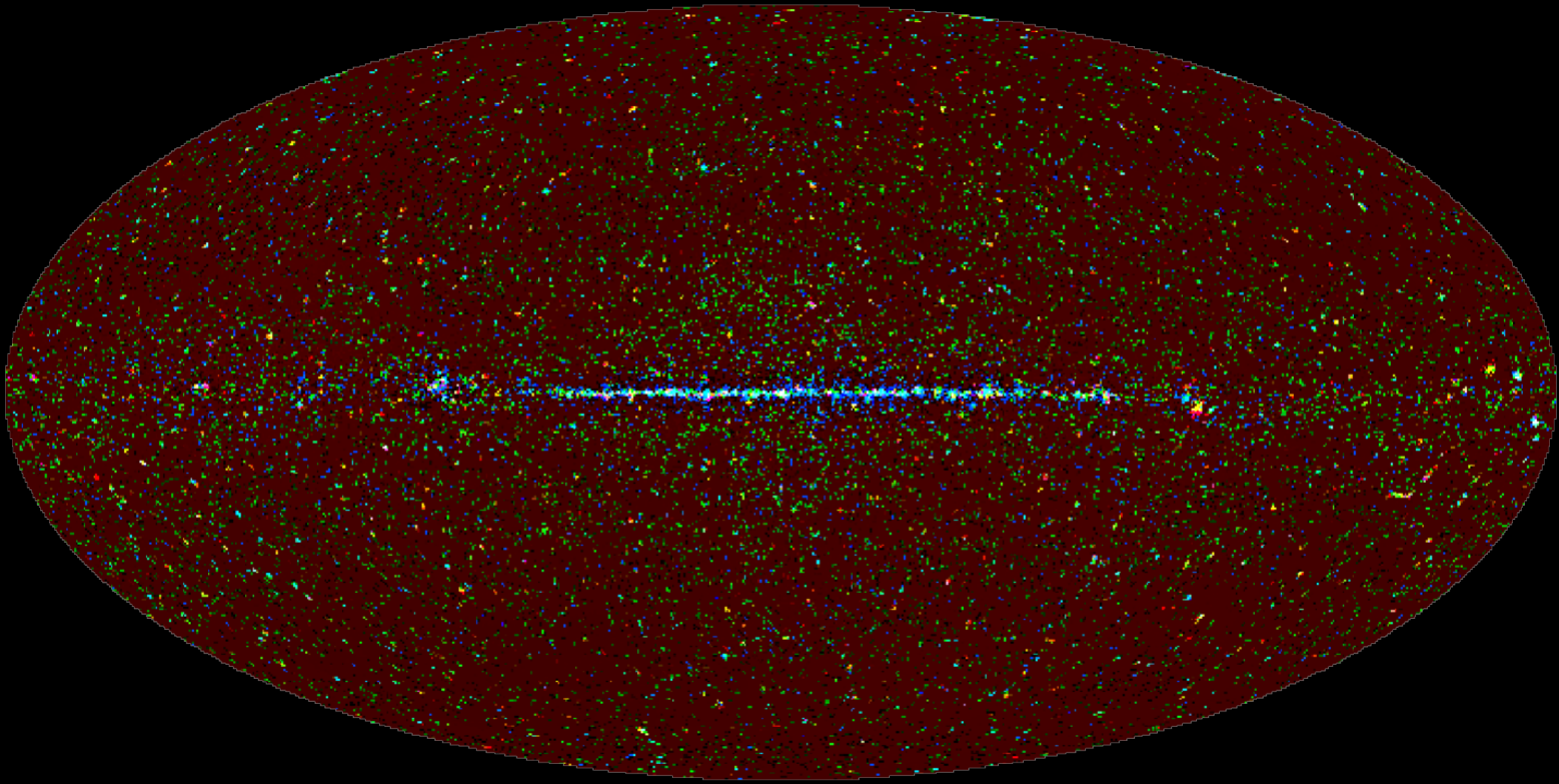


Selig, Vacca, Oppermann, Enßlin (2015)

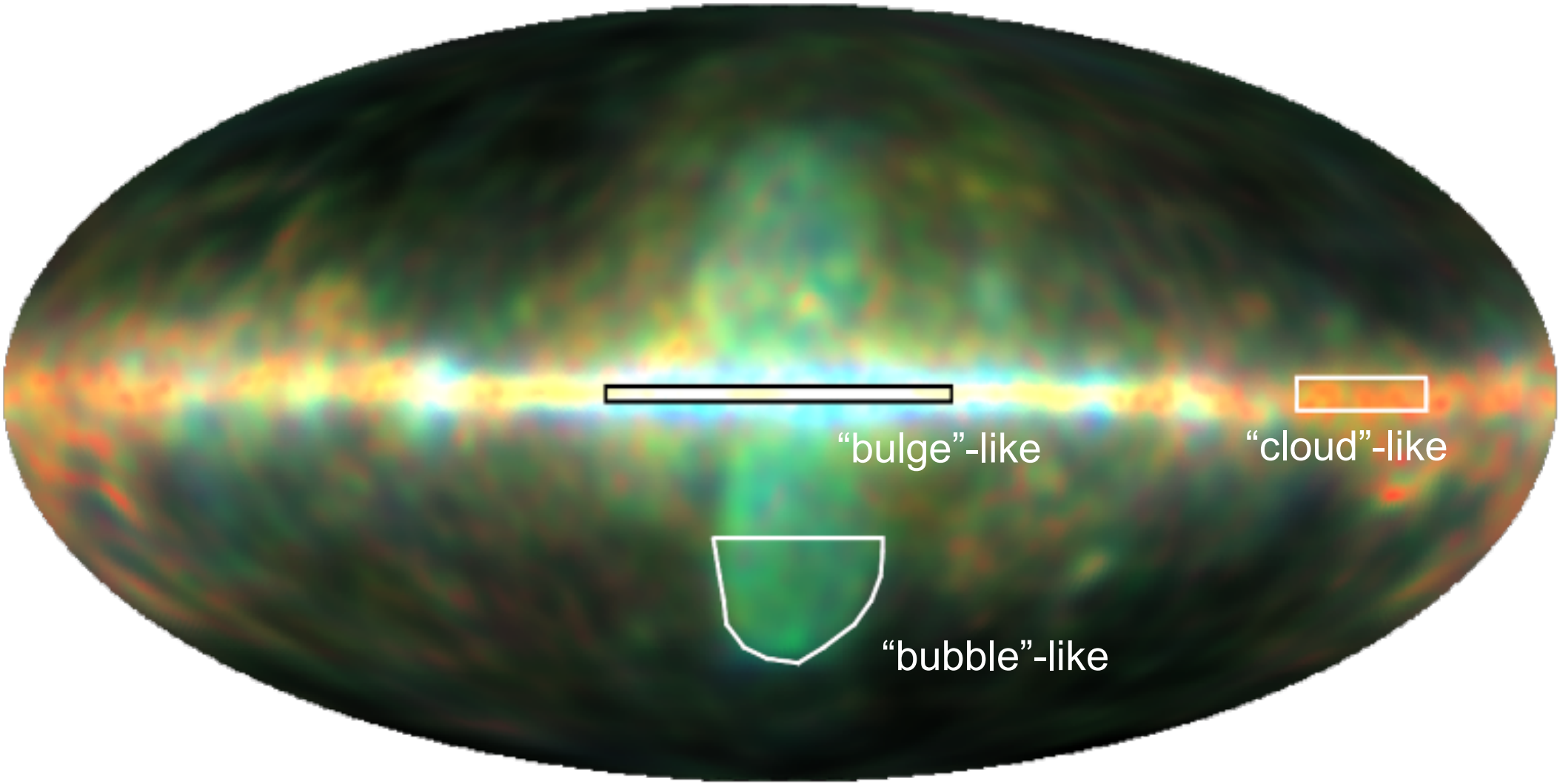


relative uncertainty of diffuse emission

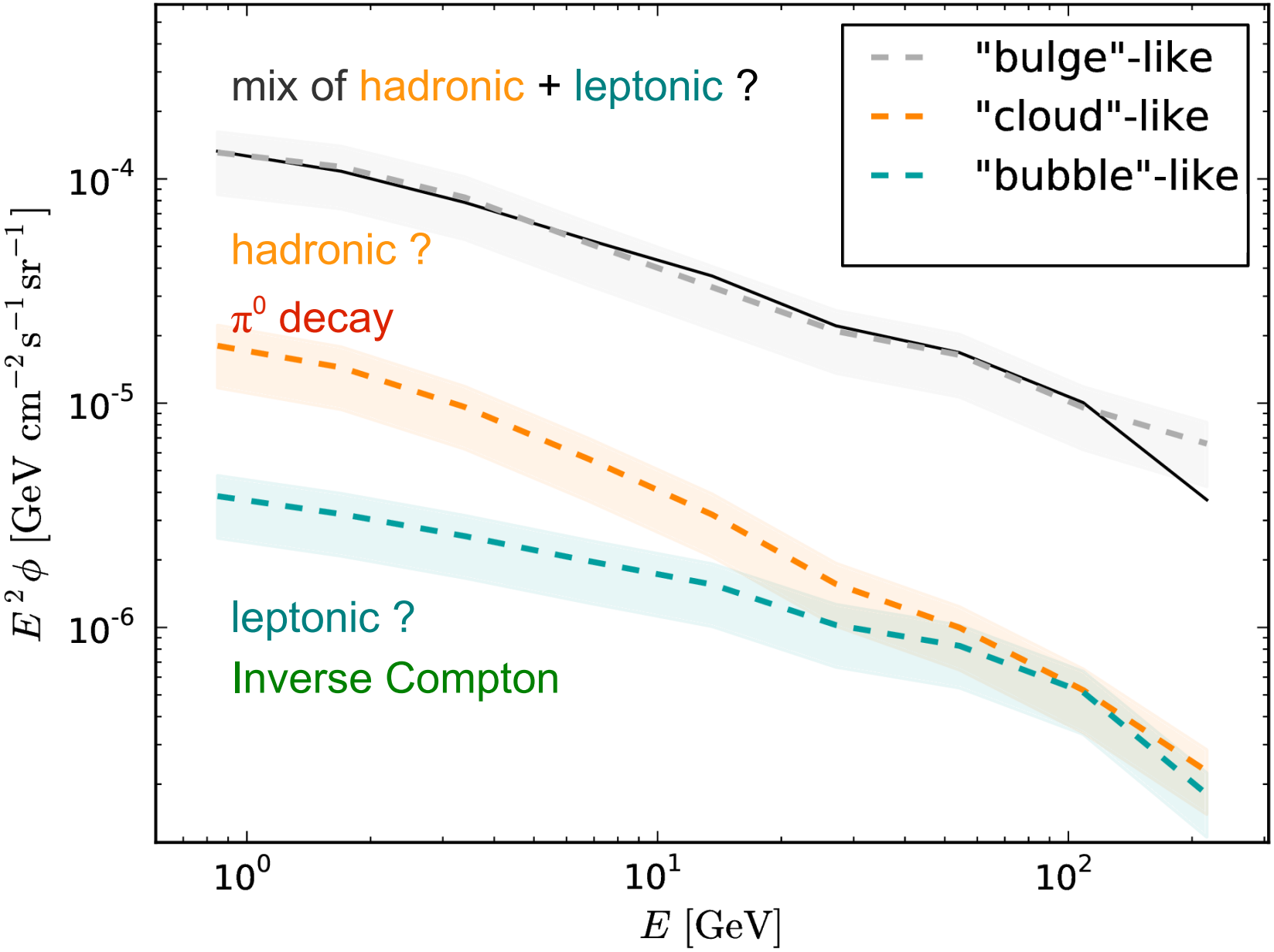
Selig, Vacca, Oppermann, Enßlin (2015)



Diffuse gamma-ray sky

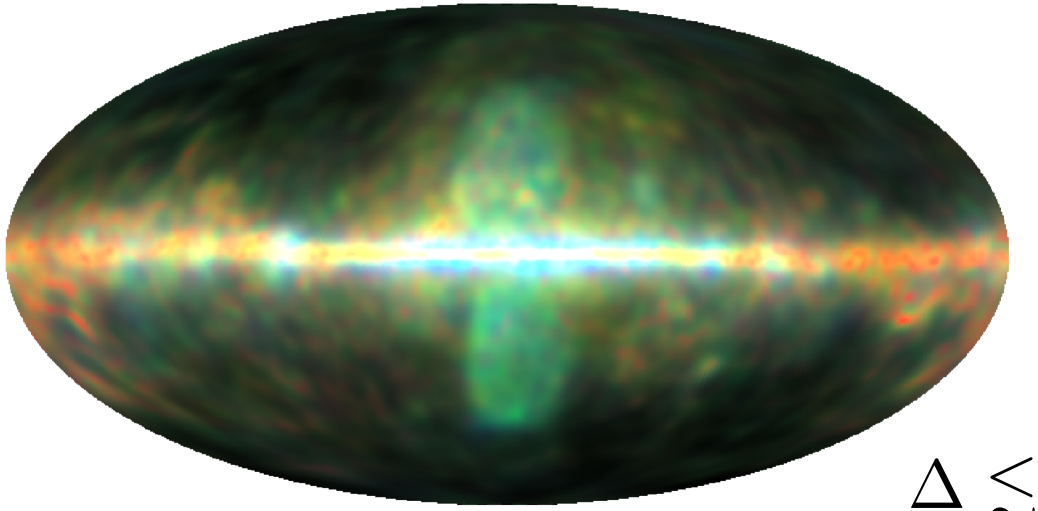


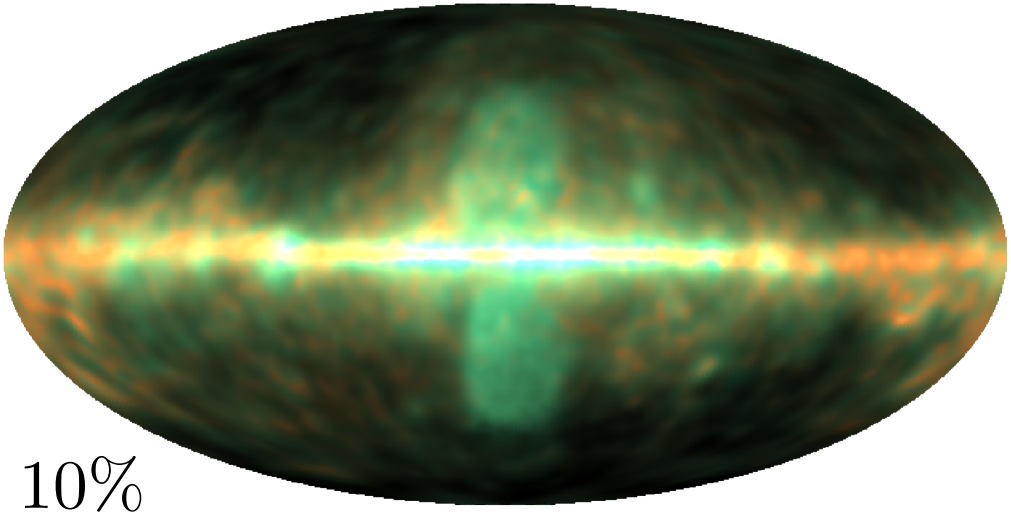
Spectra of diffuse components



diffuse flux

superposition

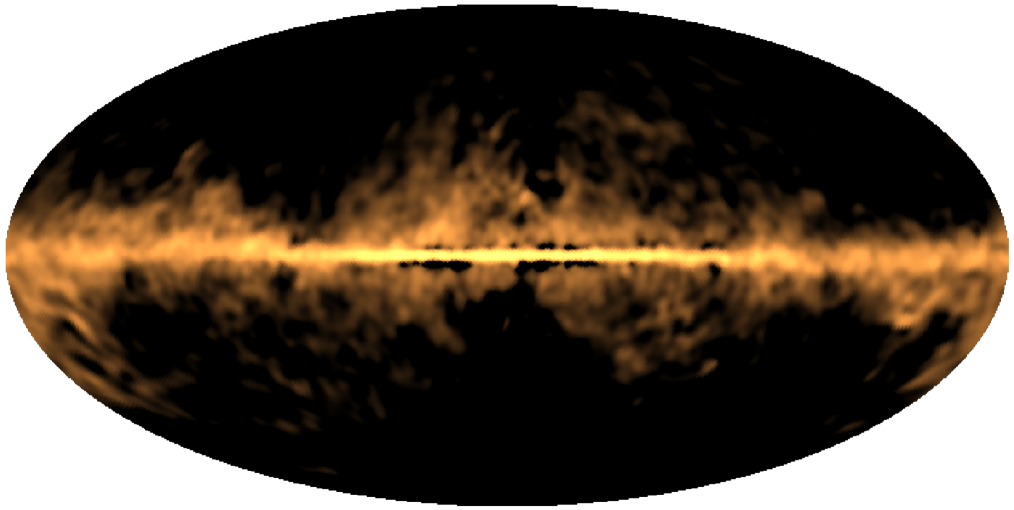


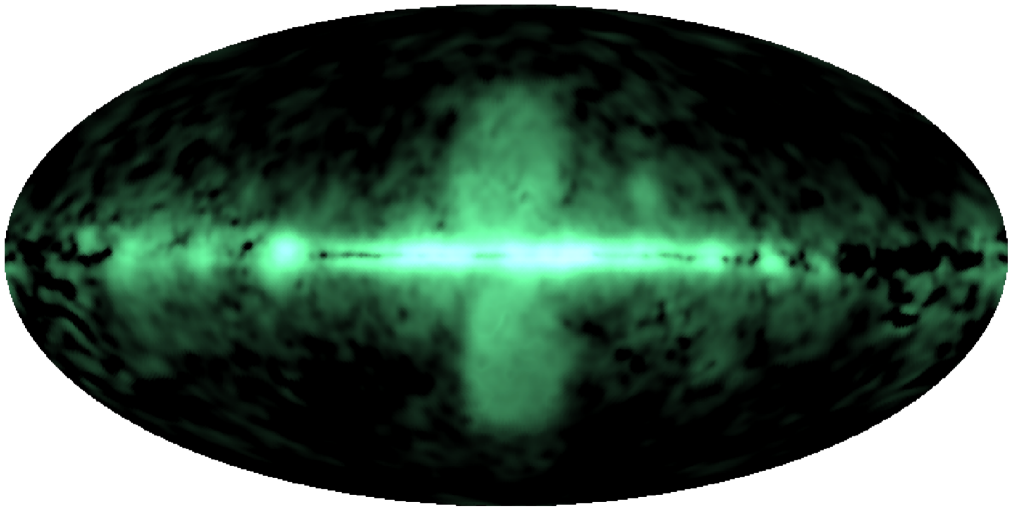


$\Delta \lesssim 10\%$

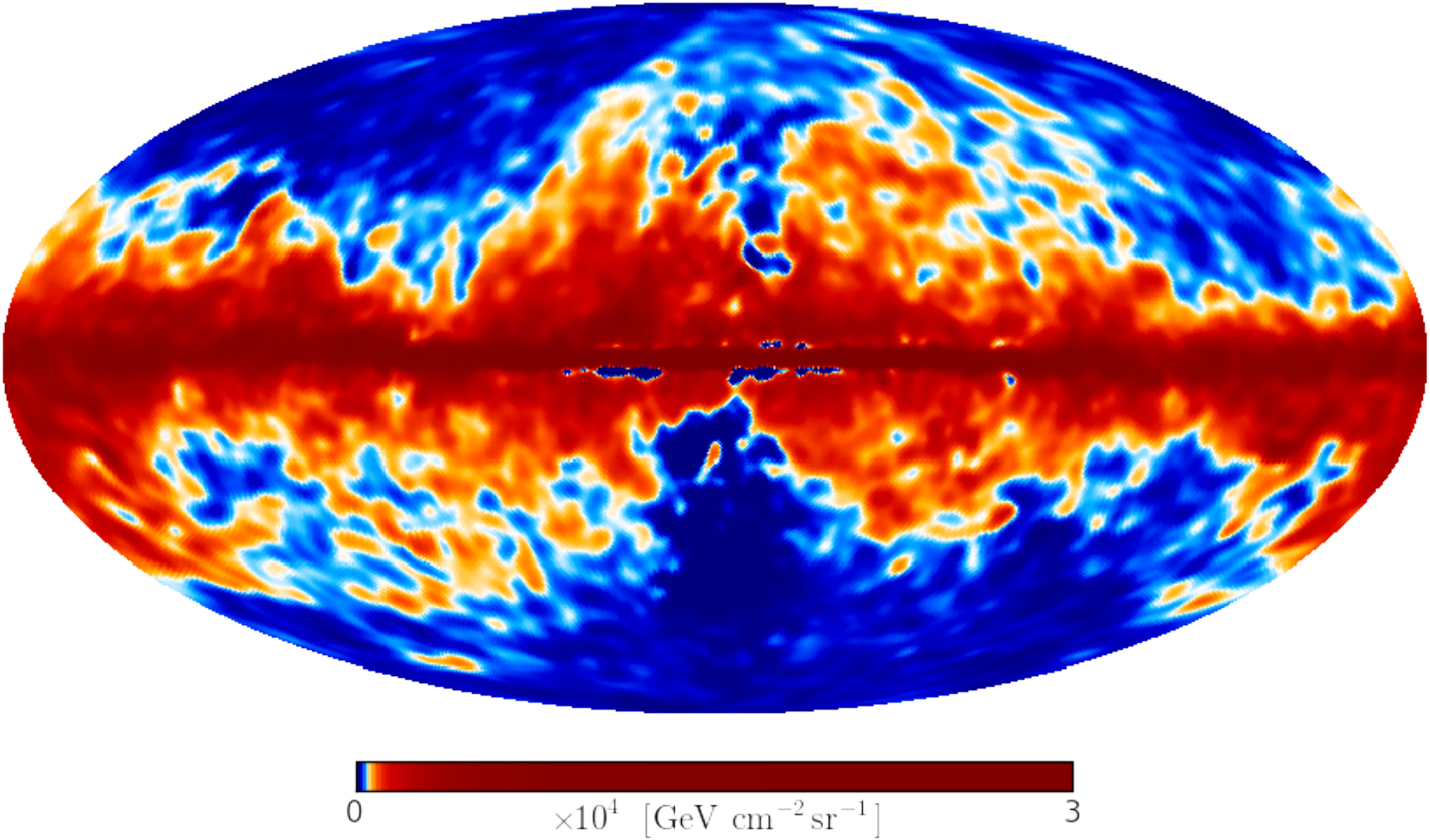
“cloud”-like

“bubble”-like

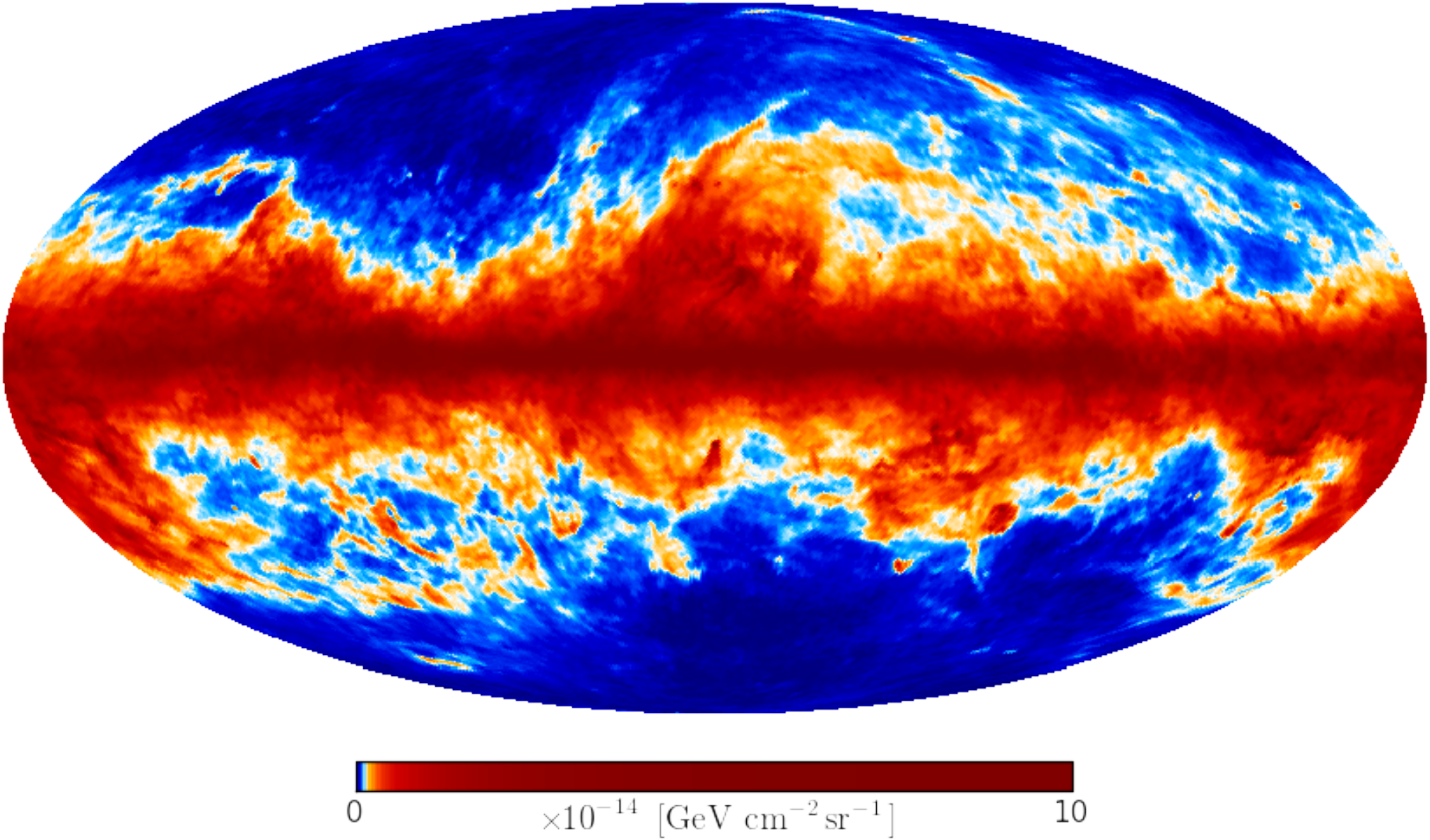




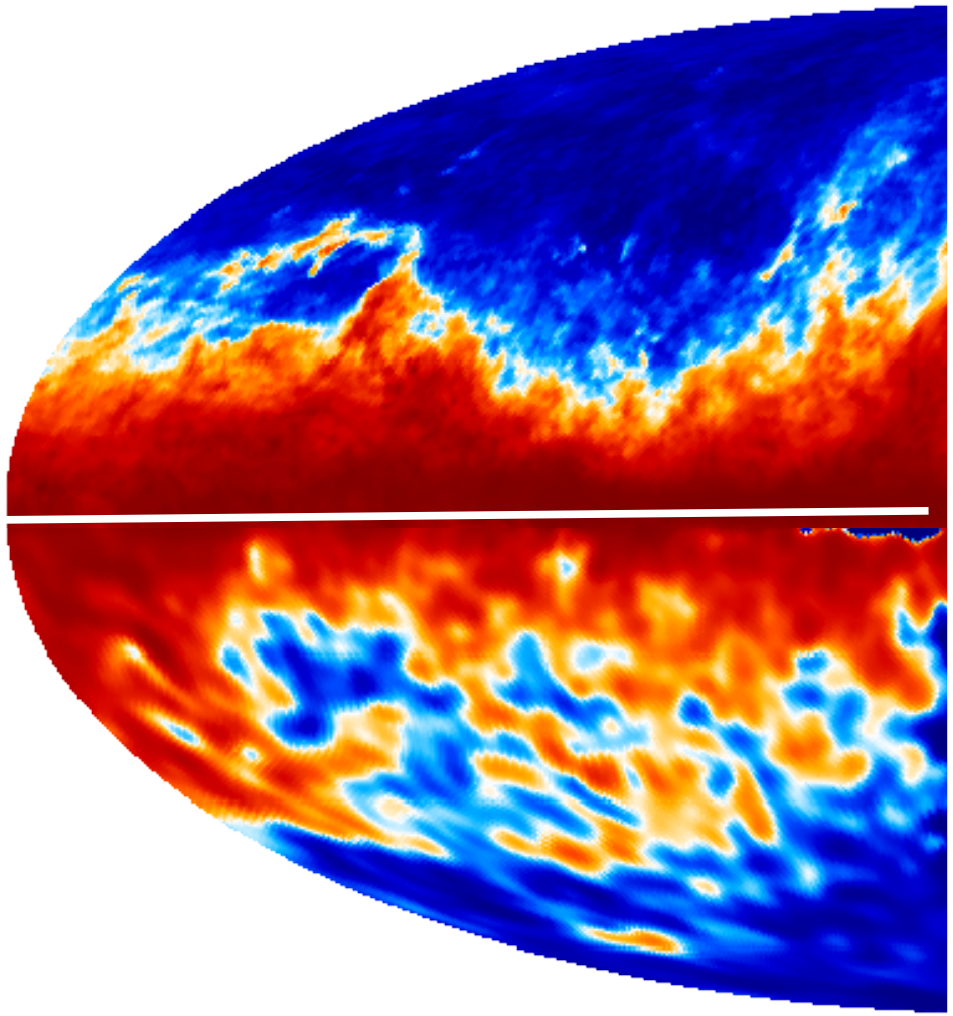
“cloud”-like

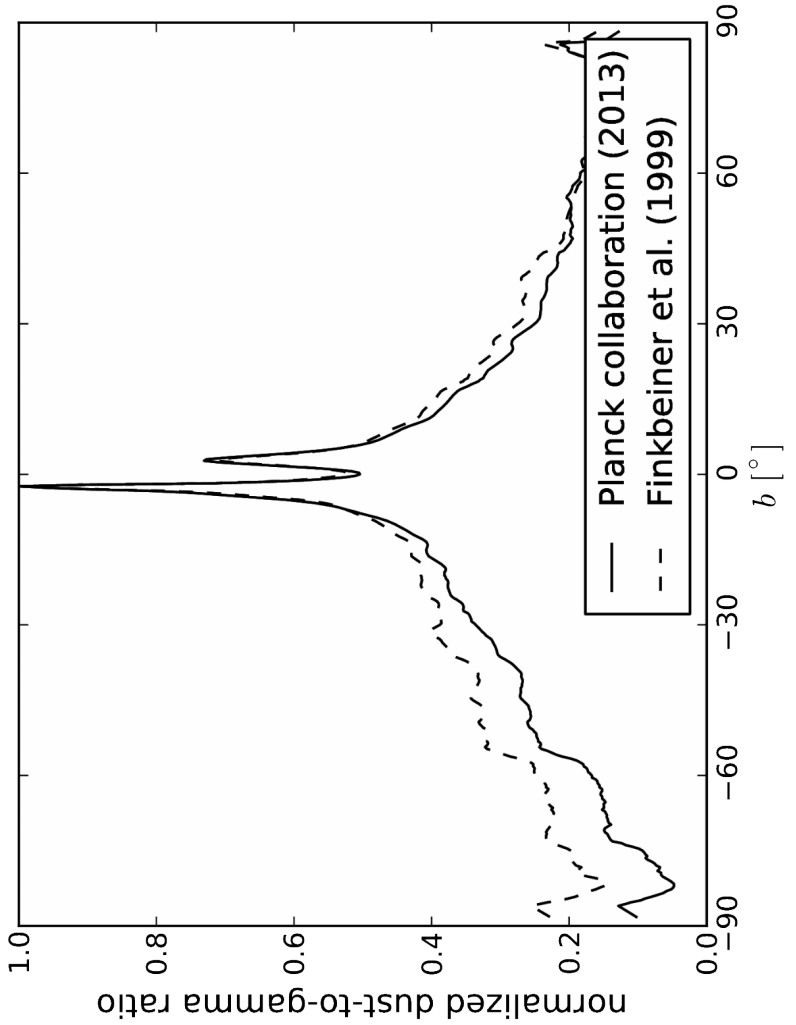


Planck dust map



dust profile / dust-like gamma profile



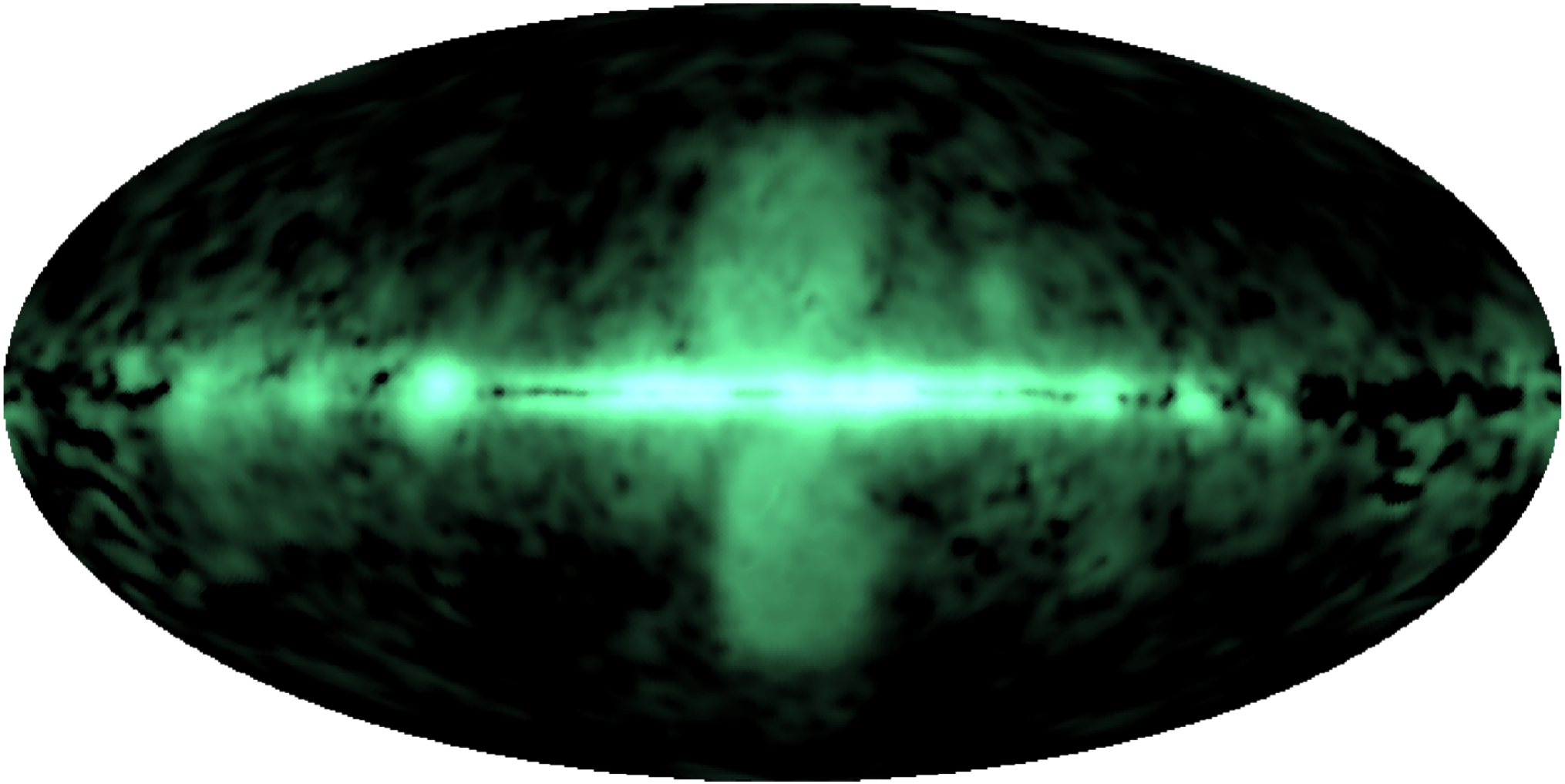


Dust profile is more narrow than gamma ray-profile. Indication for:

→ cosmic ray targets (gas) at higher latitude than starlight targets (dust)

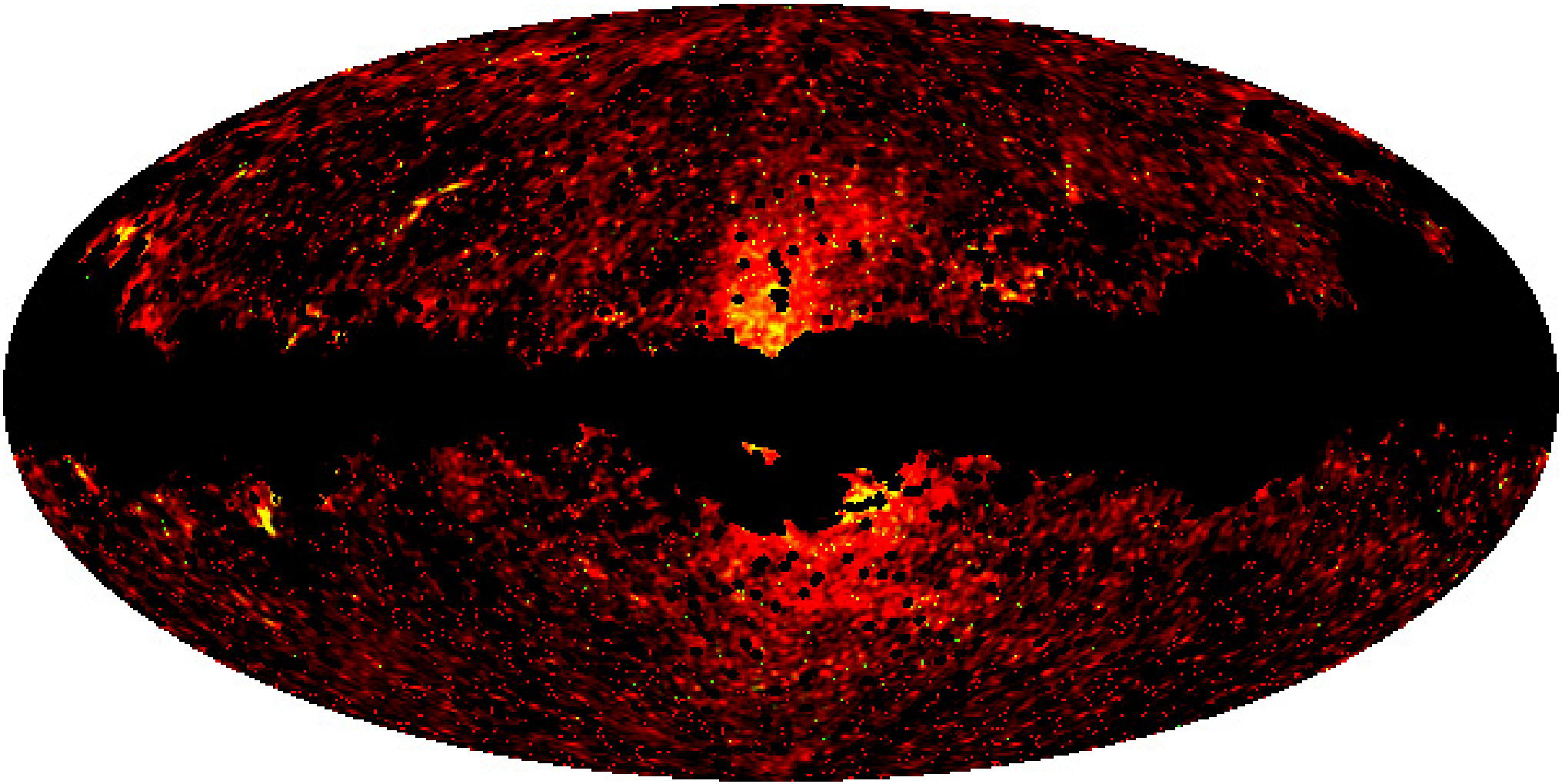
→ gravitational stratification of components of cold ISM phase

bubble-like



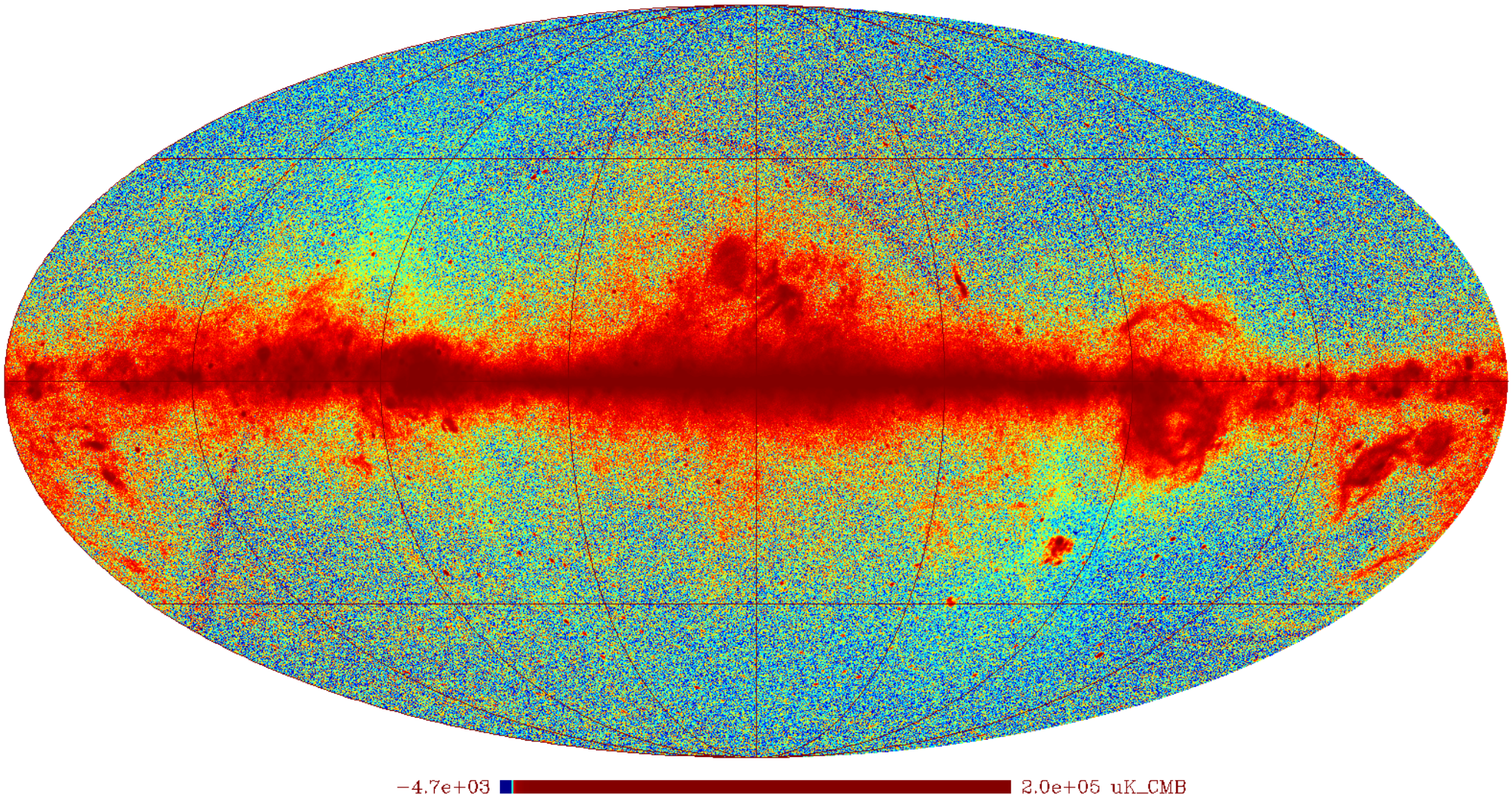
Photon spectral index: **2.4** – Inverse Compton?

Panck-haze @ 30GHz (Planck 2013)



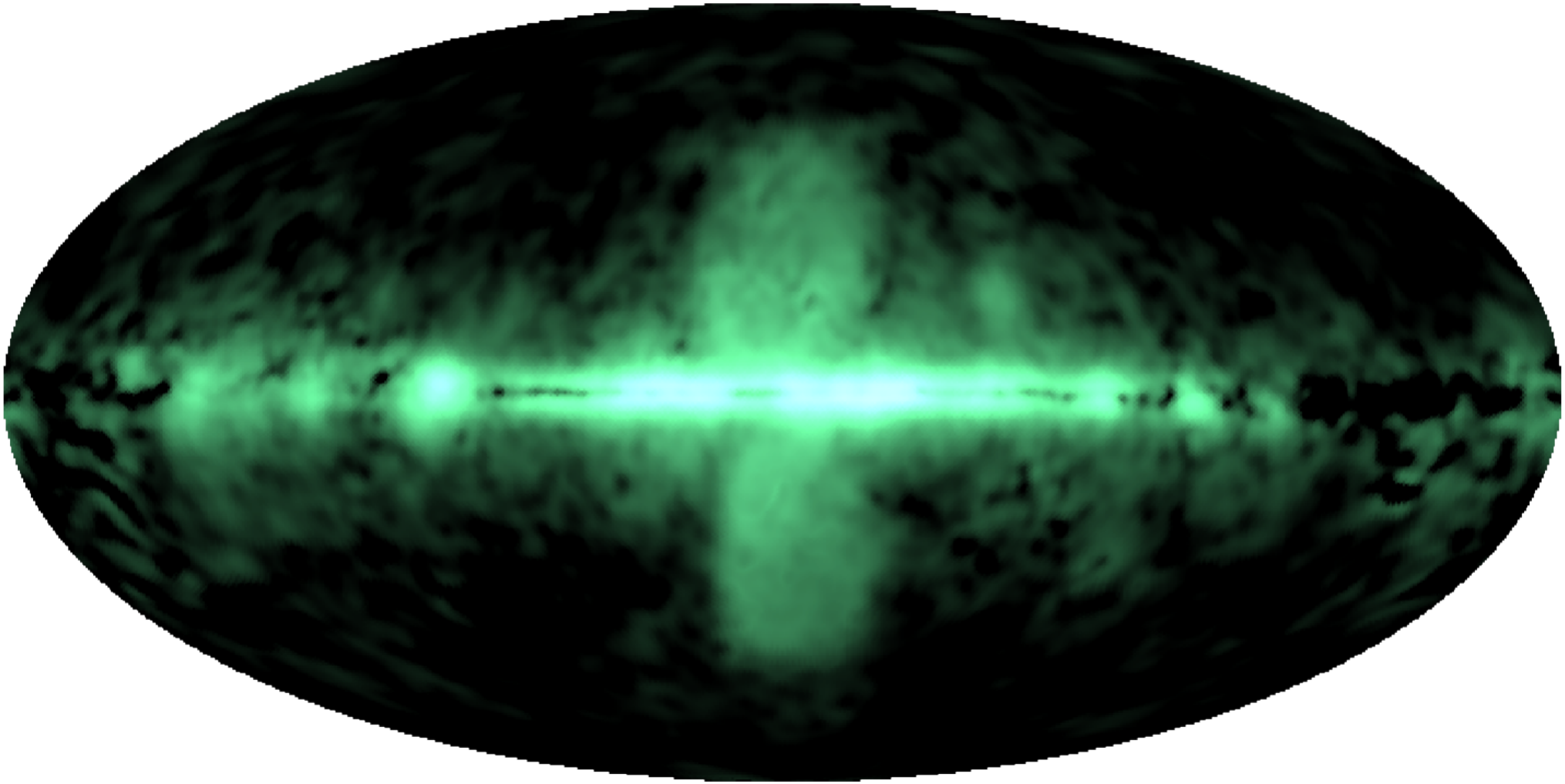
Photon spectral index: **2.56** – Synchrotron?

Planck 2013 low frequency component

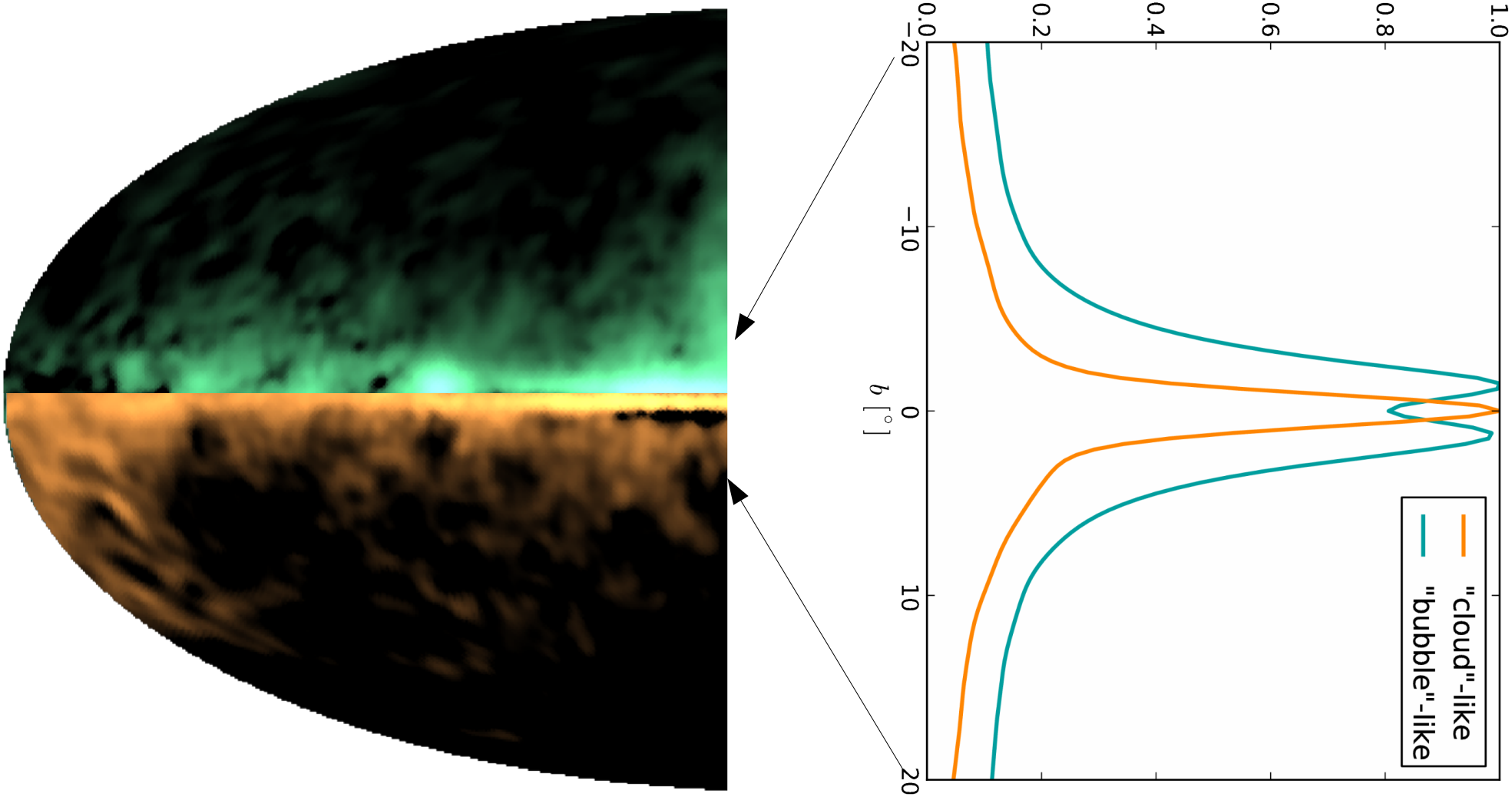


Free-free and synchrotron emission tracing hot ISM

“buble”-like = hot/dilute ISM



bubble-like & dust-like gamma profiles



Bubble-like component is wider than cloud-like one:

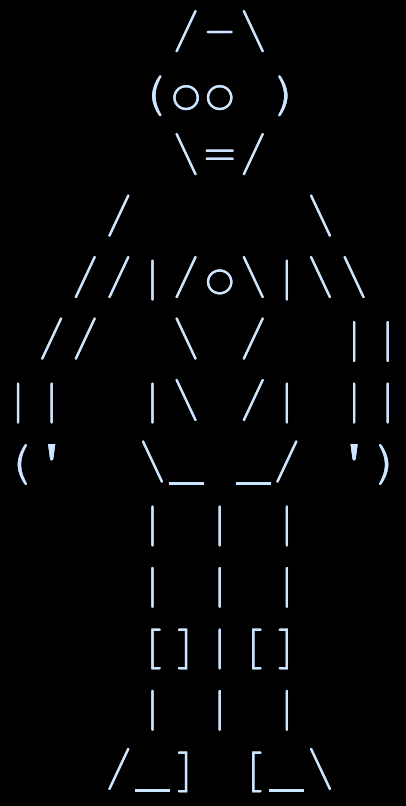
→ hotter phase of the ISM, which breaks out of disk?

→ Fermi-bubbles would just be normal hot ISM

Denoising, Deconvolving, and Decomposing Photon Observations

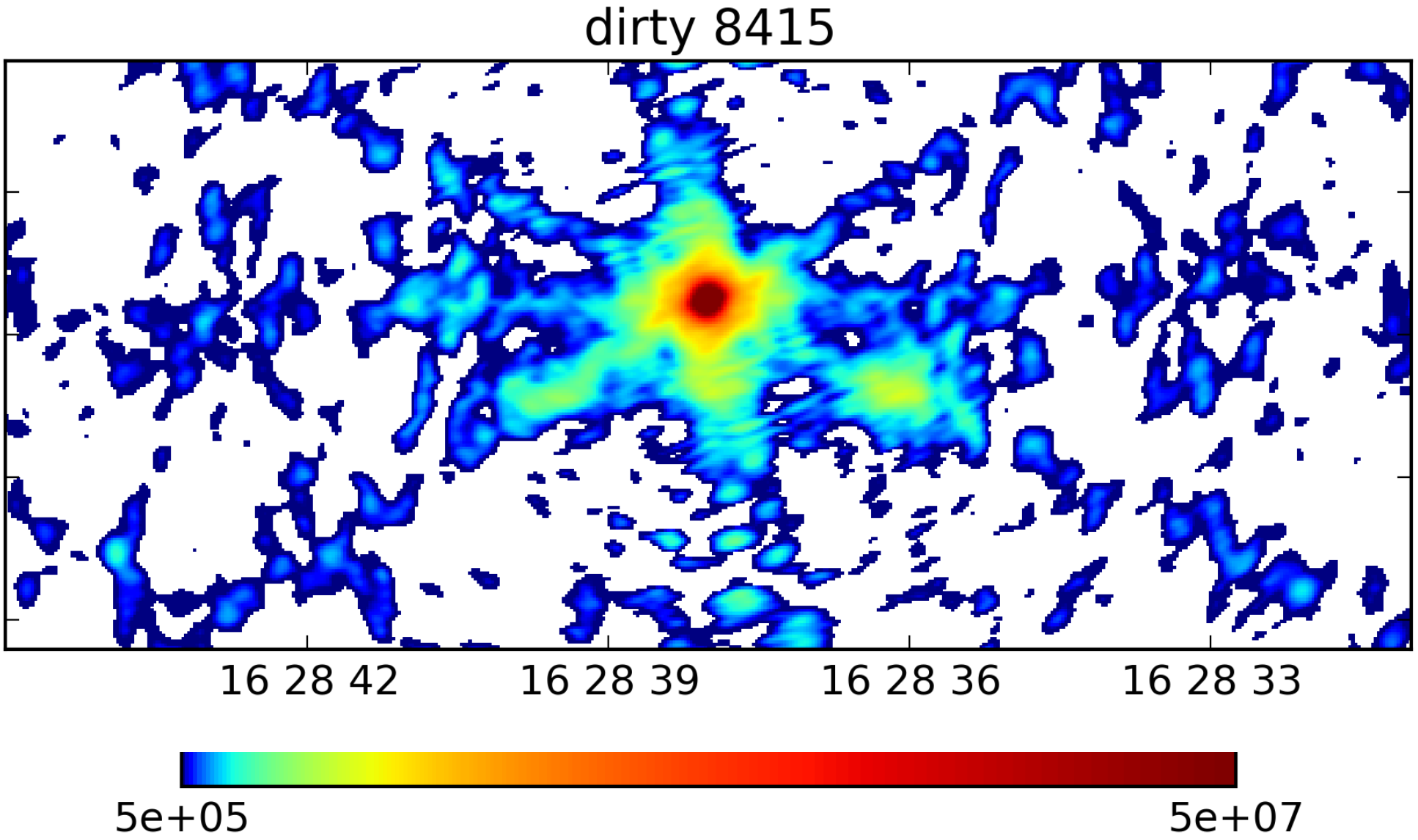
Selig et al. (2014)
www.mpa-garching.mpg.de/ift/d3po

D³PO

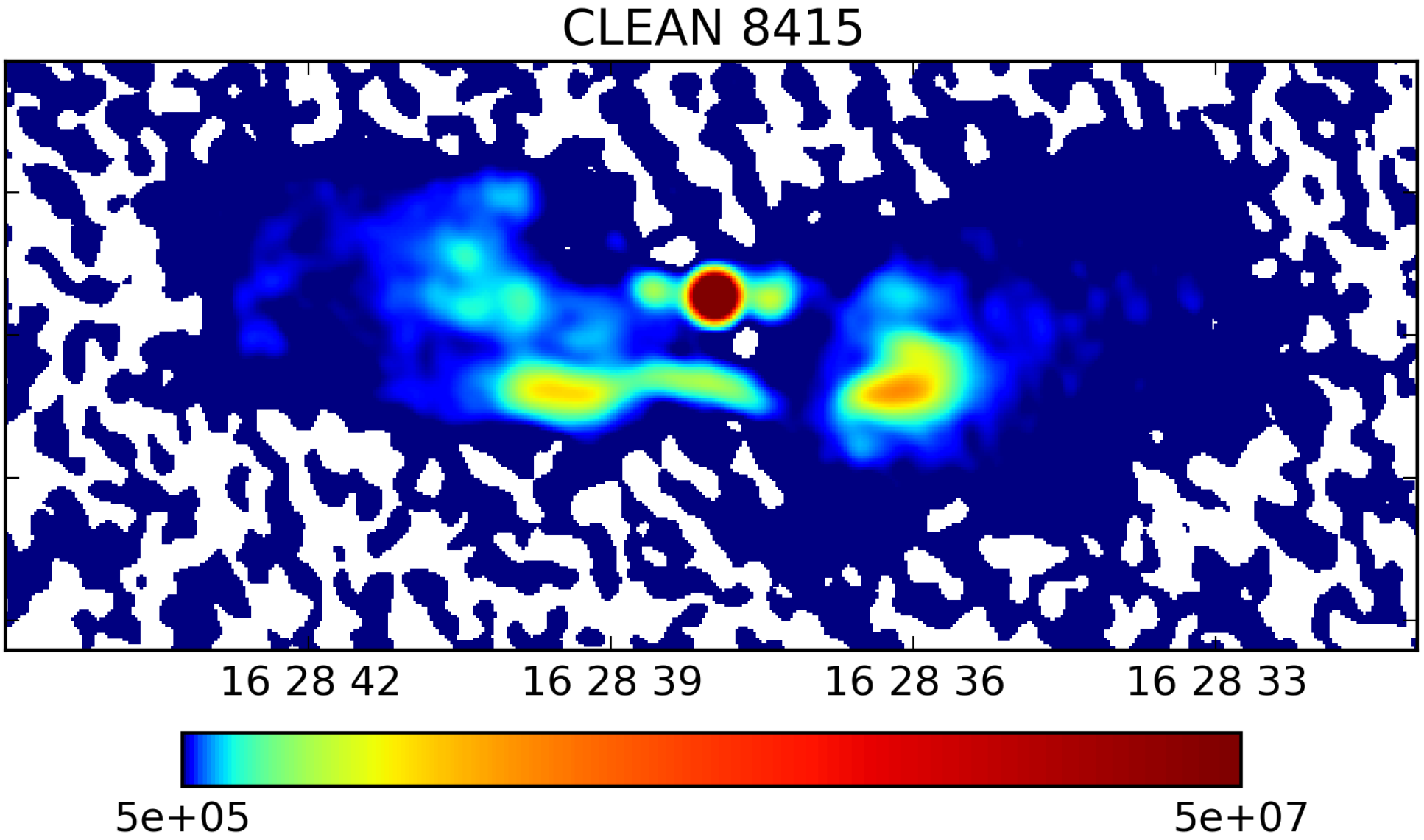



Extended VLA
LOFAR
RESOLVE
ALMA
APERTIF
SKA
Meerkat
ASKAP

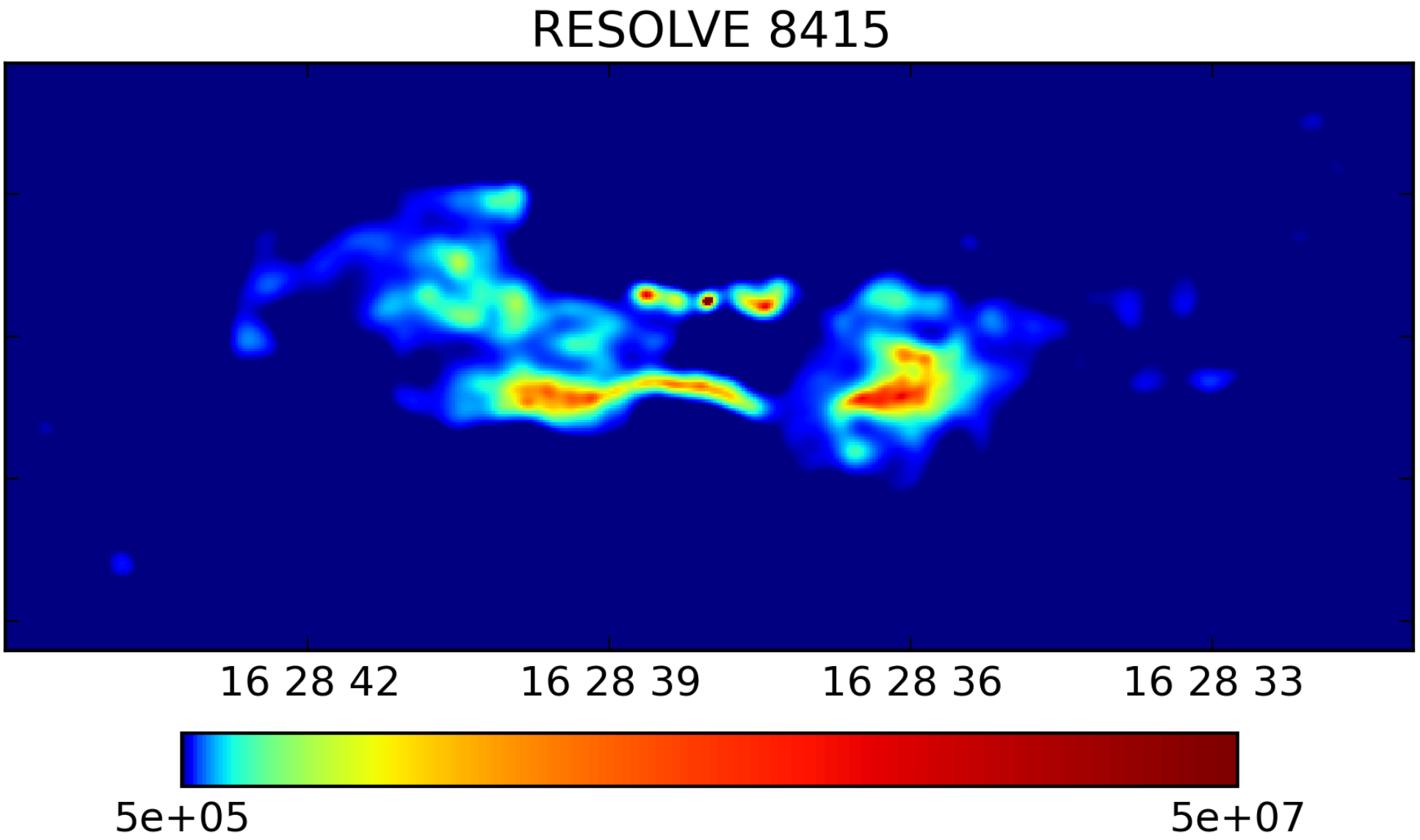
Abell 2219 @ 8415 MHz – data by Valentina Vacca

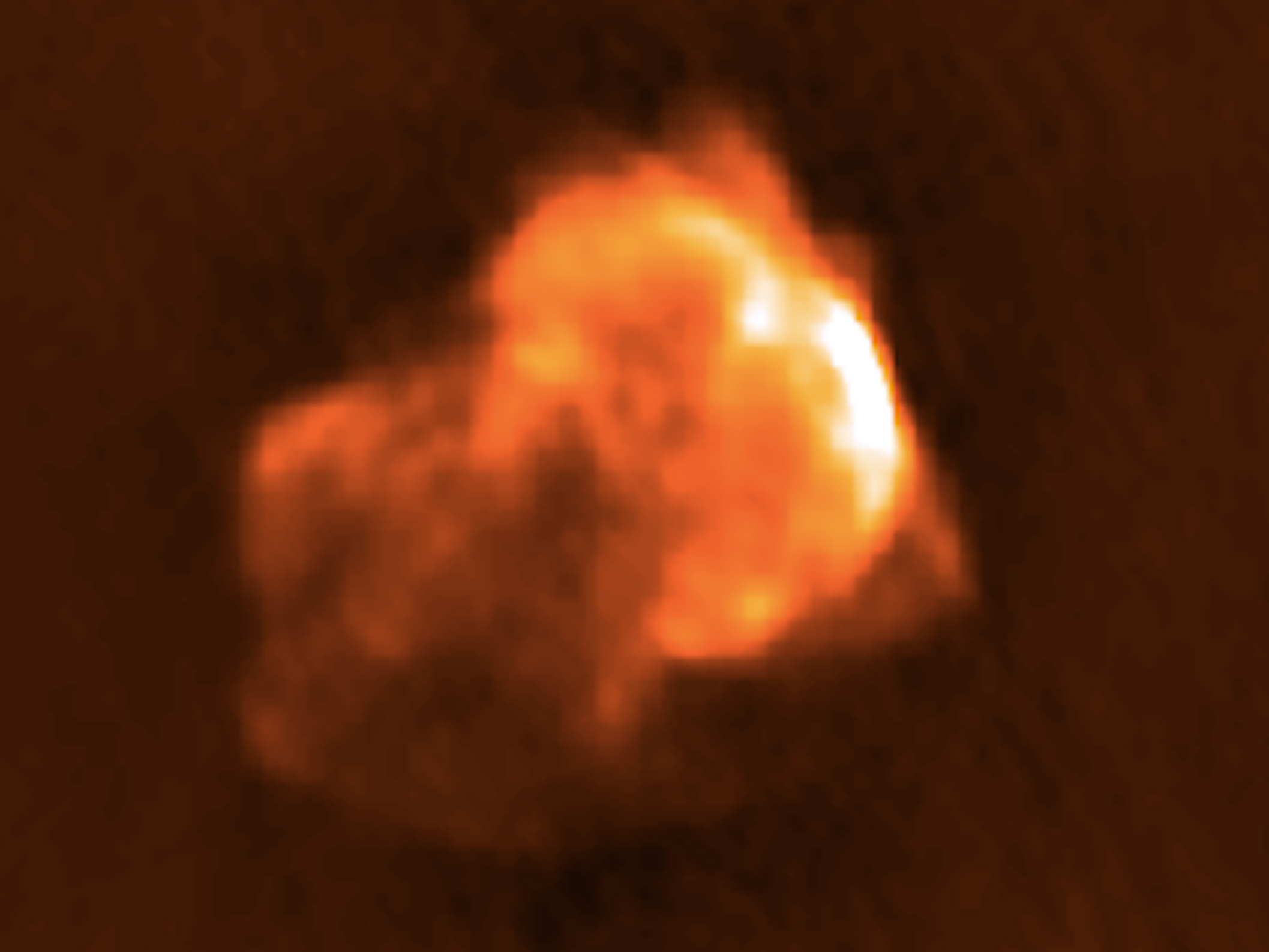


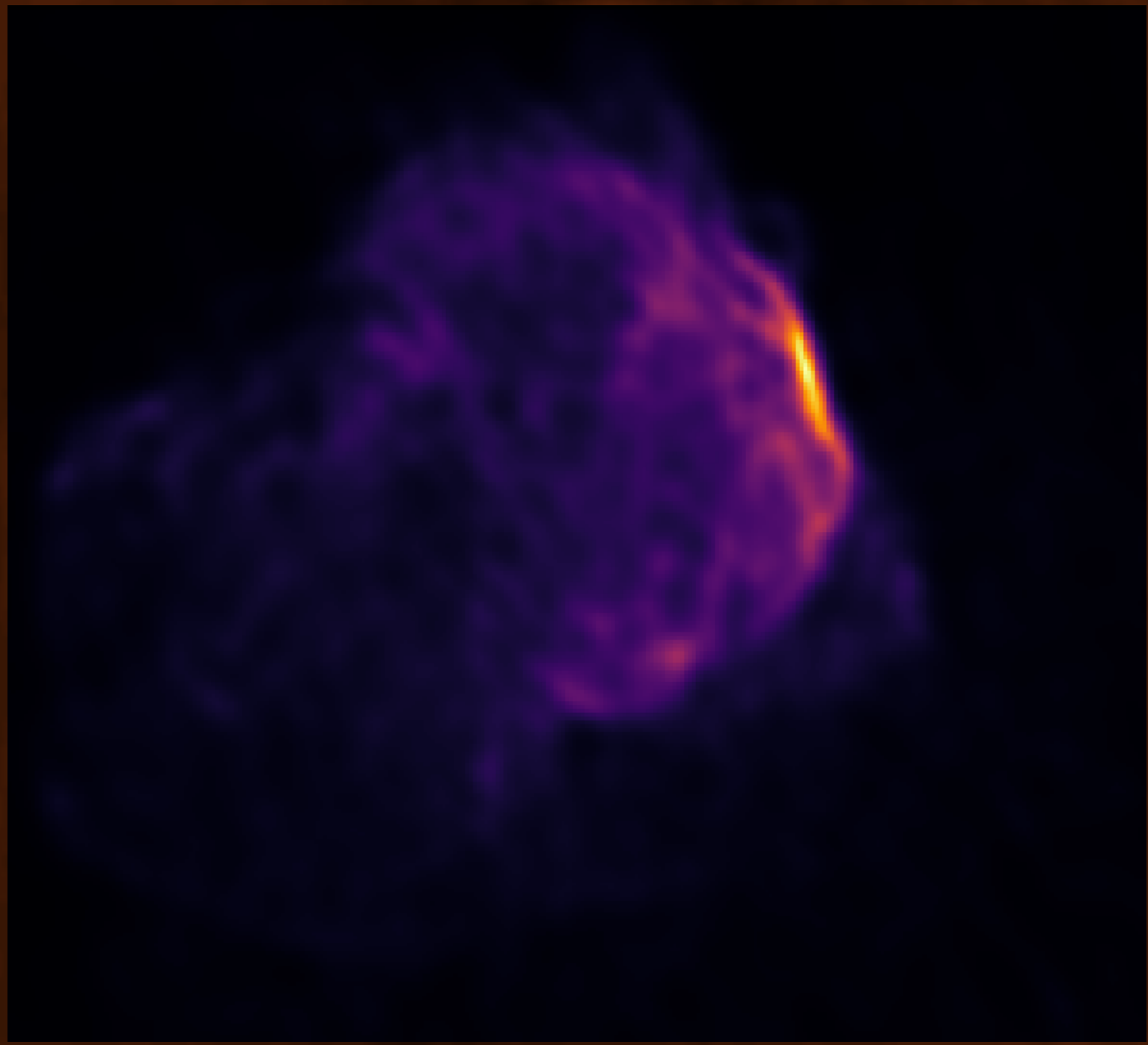
Abell 2219 @ 8415 MHz – CLEAN map by Valentina Vacca

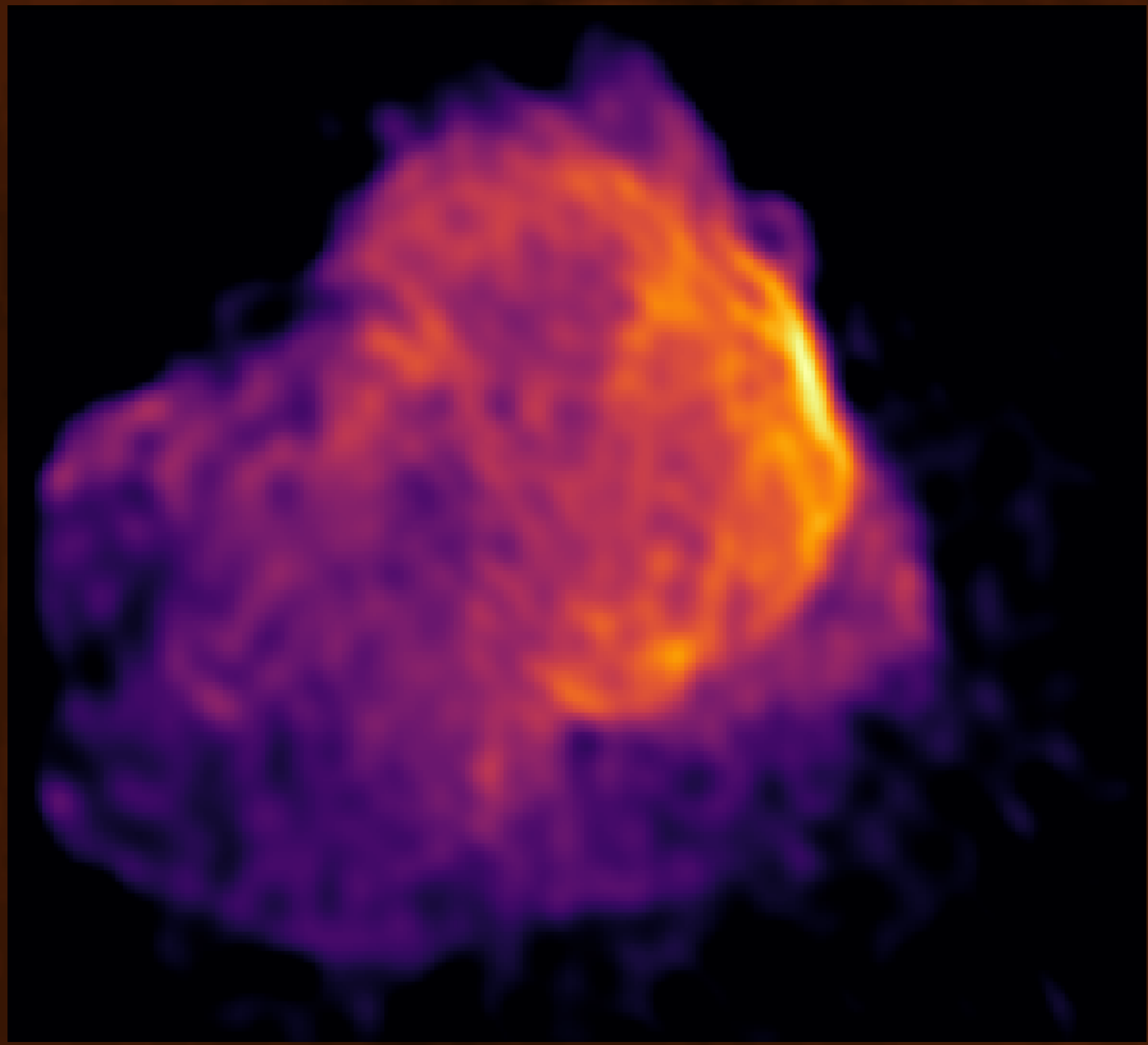


Abell 2219 @ 8415 MHz – **fast-RESOLVE** map by Maksim Greiner









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

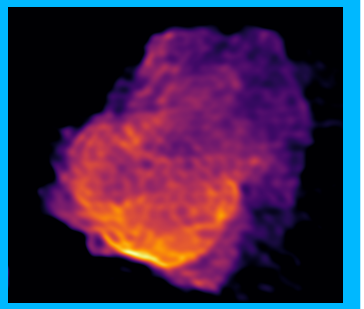
DSC
1D dynamical system classifier

DFI
2D dynamical field inference

RESOLVE
2D aperture synthesis

UBIK
Universal
Bayesian
Imaging
toolKit

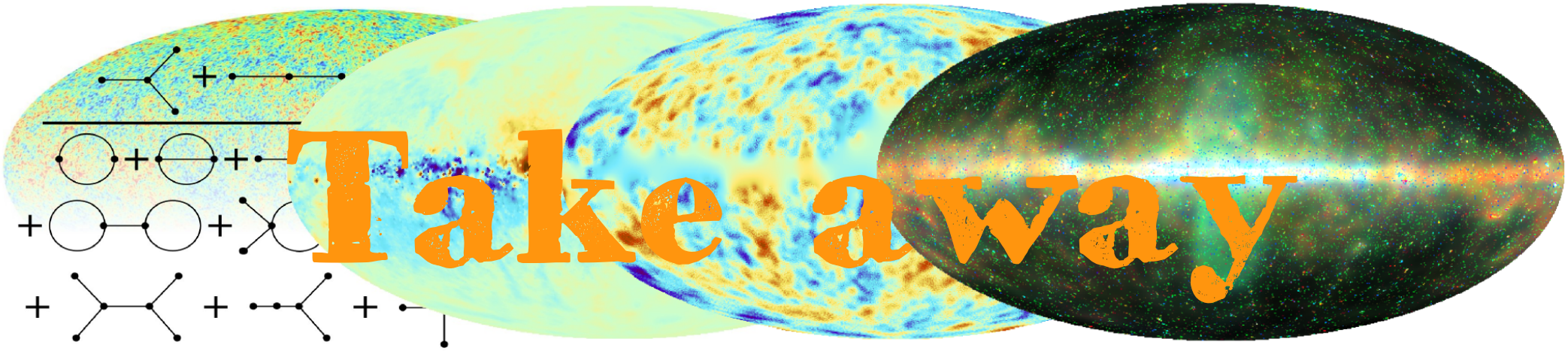
physical components
4D radio-gamma
3D radio-gamma
3D radio
3D gamma
2D radio



envisioned
in preparation
published
science results

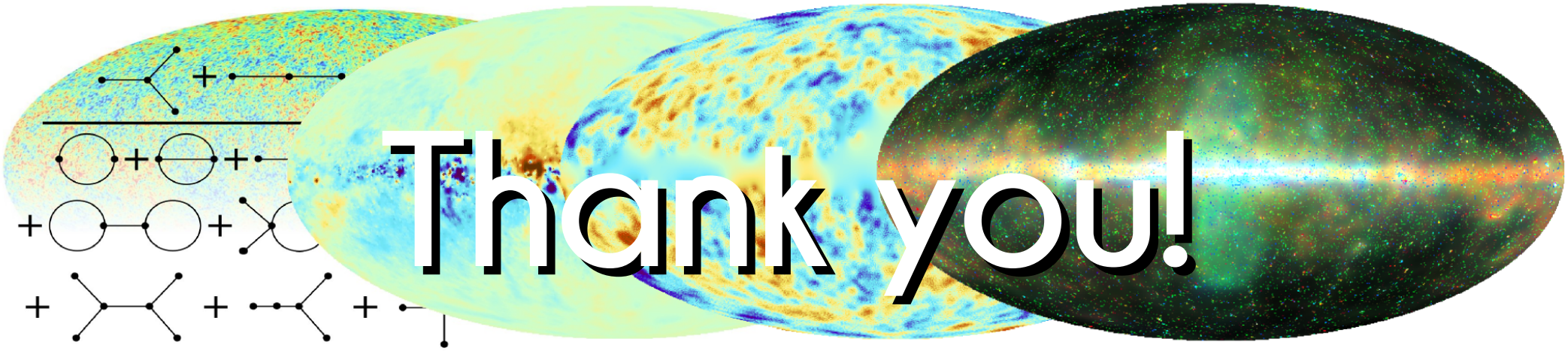
UBIK: reality support

Source:
https://martinacecilia.deviantart.com/art/Try-Ubik-New-and-powerful-204640851



Take away

IFT	–	**information field theory**
NIFTy	–	**nummerical IFT**
D³PO	–	**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