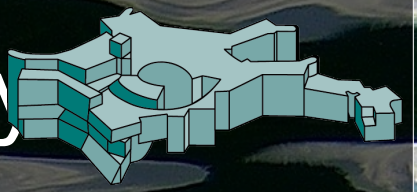
# Gamma-ray analysis with $D^3PO$

Andy Strong
MPE Garching
Torsten Enßlin, Niels Oppermann,
Marco Selig, Valentina Vacca
(MPA Garching)

Gamma2016 Conference

Heidelberg, July 2016

# Information Field Theory



**Torsten Enßlin**
**MPI for Astrophysics**
**Ludwig Maximilian University**
**Munich**

**THANKS!**

## Motivation

Imaging and spectral analysis of gamma-ray data

Diffuse & point sources

„Model-free“ (use image statistical properties only)

One-shot, self-consistent :

all sources and diffuse simultaneously

Sources can be as weak as desired (unresolved populations)

Formal, objective – no manual intervention.

# Bayes Theorem

$s = \text{signal}$

$d = \text{data}$

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

Prob (signal | data) ~ Prob(data | signal) X Prob( signal )

# Bayes Theorem

$s = \text{signal}$

$d = \text{data}$

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

Prob (signal | data) ~ Prob(data | signal) X Prob( signal )

# Inference problem as a statistical field theory

$$s = \text{signal}$$

$$d = \text{data}$$

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

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

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

Maximise P → maximize -H → minimize H

In words: *minimize information energy of field*.

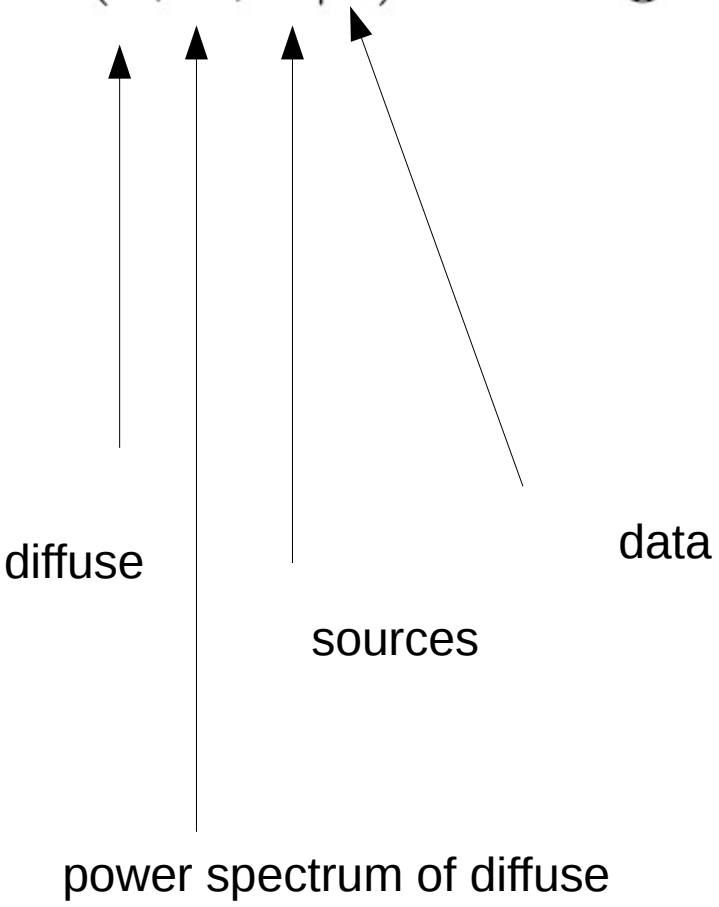
It is a mathematical equivalence.

Selig & Enßlin (2014)
arXiv: 1311.1888

Hamiltonian

log-posterior

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



Selig & Enßlin (2014)
arXiv: 1311.1888

Hamiltonian

log-posterior

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

Poisson log-likelihood

$$= H_0 + \mathbf{1}^\dagger \boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right) - \boldsymbol{d}^\dagger \log\left(\boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right)\right)$$

+ .....

instrument response function

data

Selig & Enßlin (2014)
arXiv: 1311.1888

Hamiltonian

log-posterior

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

Poisson log-likelihood

$$= H_0 + \mathbf{1}^\dagger \boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right) - \boldsymbol{d}^\dagger \log\left(\boldsymbol{R}\left(\mathrm{e}^{\boldsymbol{s}} + \mathrm{e}^{\boldsymbol{u}}\right)\right)$$

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

Prior for diffuse

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

$$+ (\boldsymbol{\beta}-\mathbf{1})^\dagger \boldsymbol{u} + \boldsymbol{\eta}^\dagger \mathrm{e}^{-\boldsymbol{u}}$$

Prior for sources

5 parameters in prior:

3 for  diffuse

2 for  point sources

Diffuse: **Gaussian random field in log flux**, with 2-point correlation function specified through an **unknown power spectrum** controled by 3 hyperparameters

Point sources: present **in each pixel, uncorrelated**, dN/dS = power law with lower flux cutoff

# IFT Dictionary

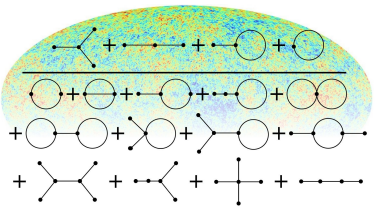
**Translation:**

field inference problem → statistical field theory

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

**Dictionary:**

| | | |
|---|---|---|
| log joint PDF | = | negative Hamiltonian |
| evidence | = | partition function Z |
| Wiener variance | = | information propagator |
| noise weighted data | → | information source |
| inference algorithms | ← | Feynman diagrams |
| maximum a Posteriori | = | classical solution |
| uncertainty corrections | = | loop correction |
| Shannon information | = | negative entropy |

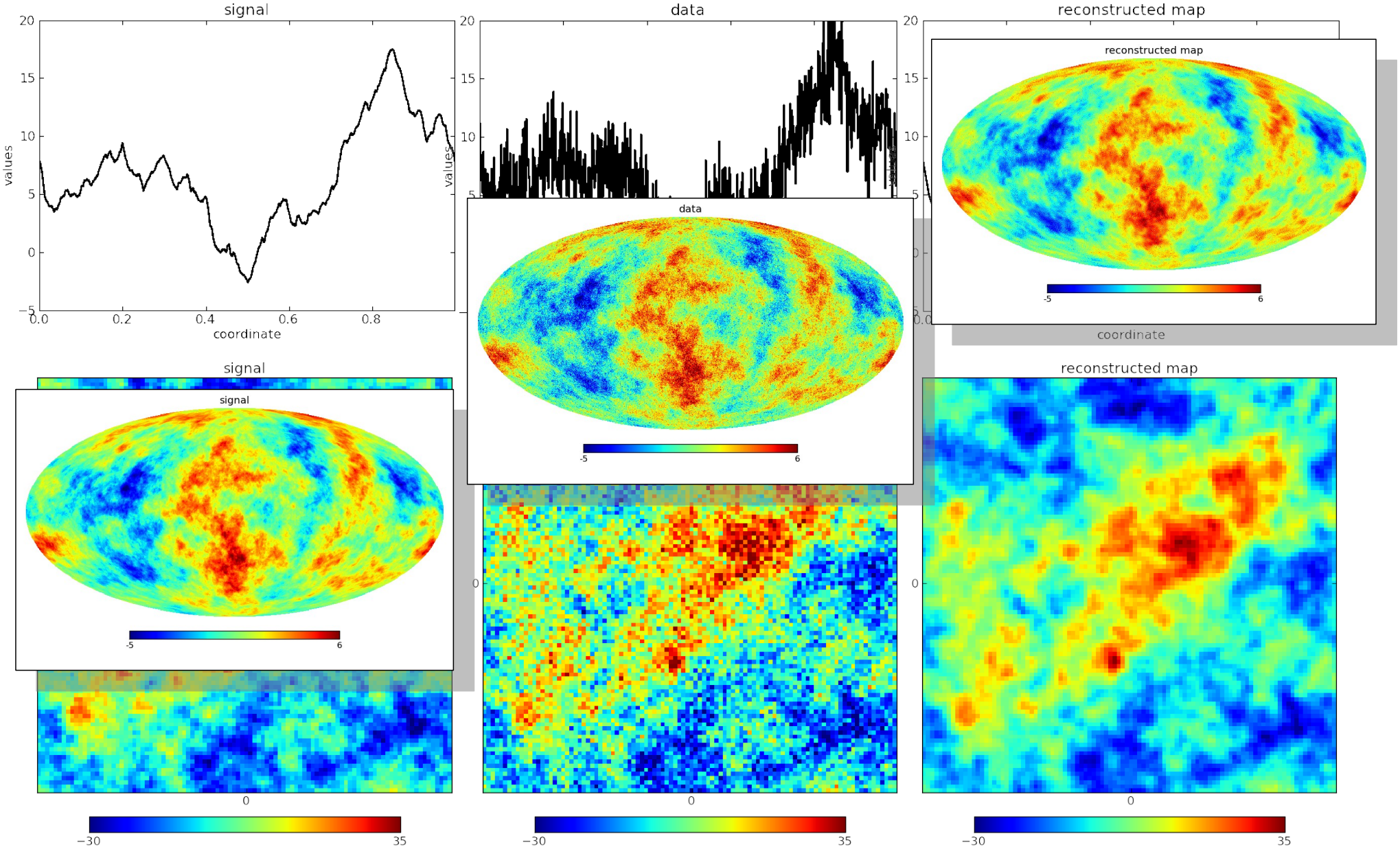


Use QFT methods to do the formal analysis

# NIFTy - **N**umerical **I**nformation **F**ield **T**heor**y**

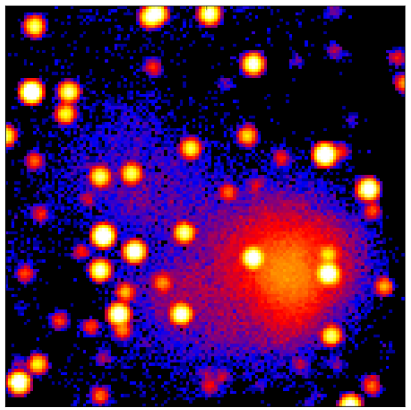
Selig et al. (arXIv:1301.4499)

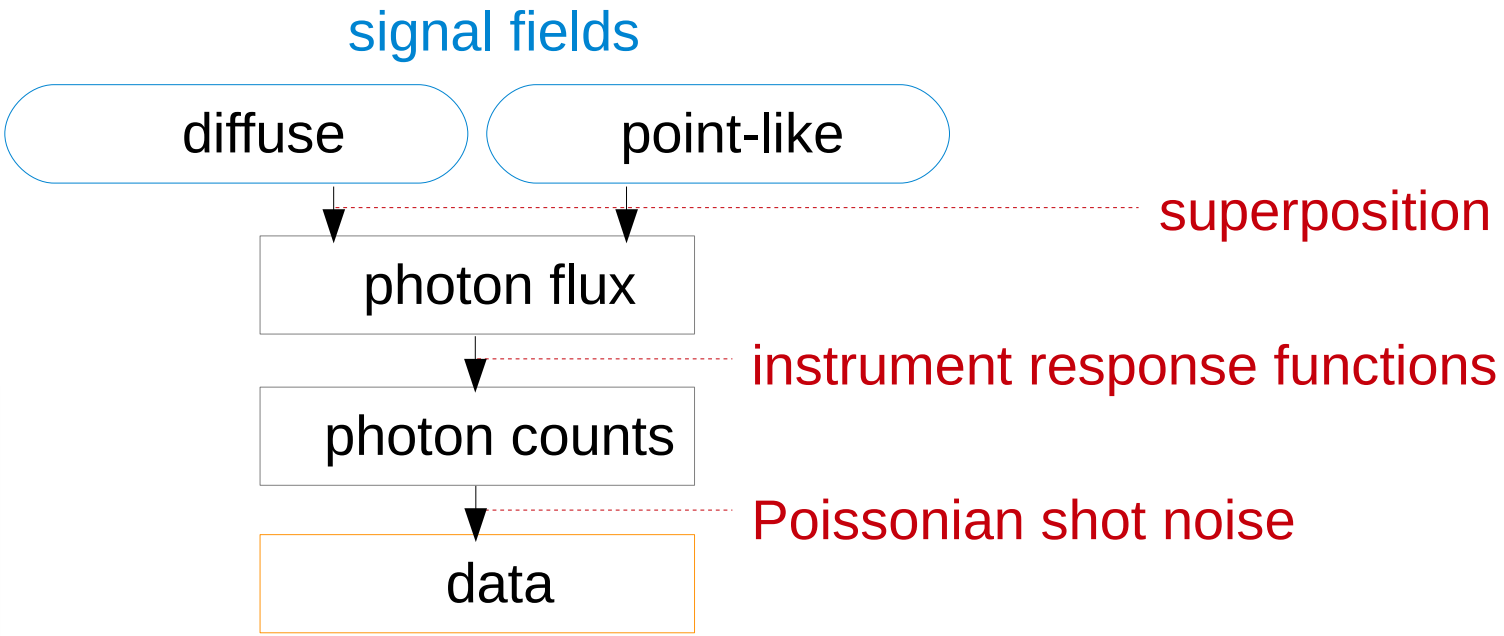
Code & Docu @ http://www.mpa-garching.mpg.de/ift/nifty/



# D³PO – challenges

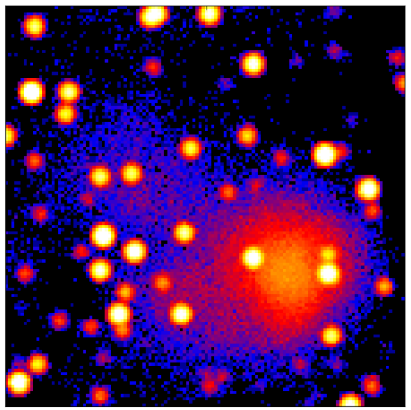
Selig & Enßlin (2014)
arXiv: 1311.1888

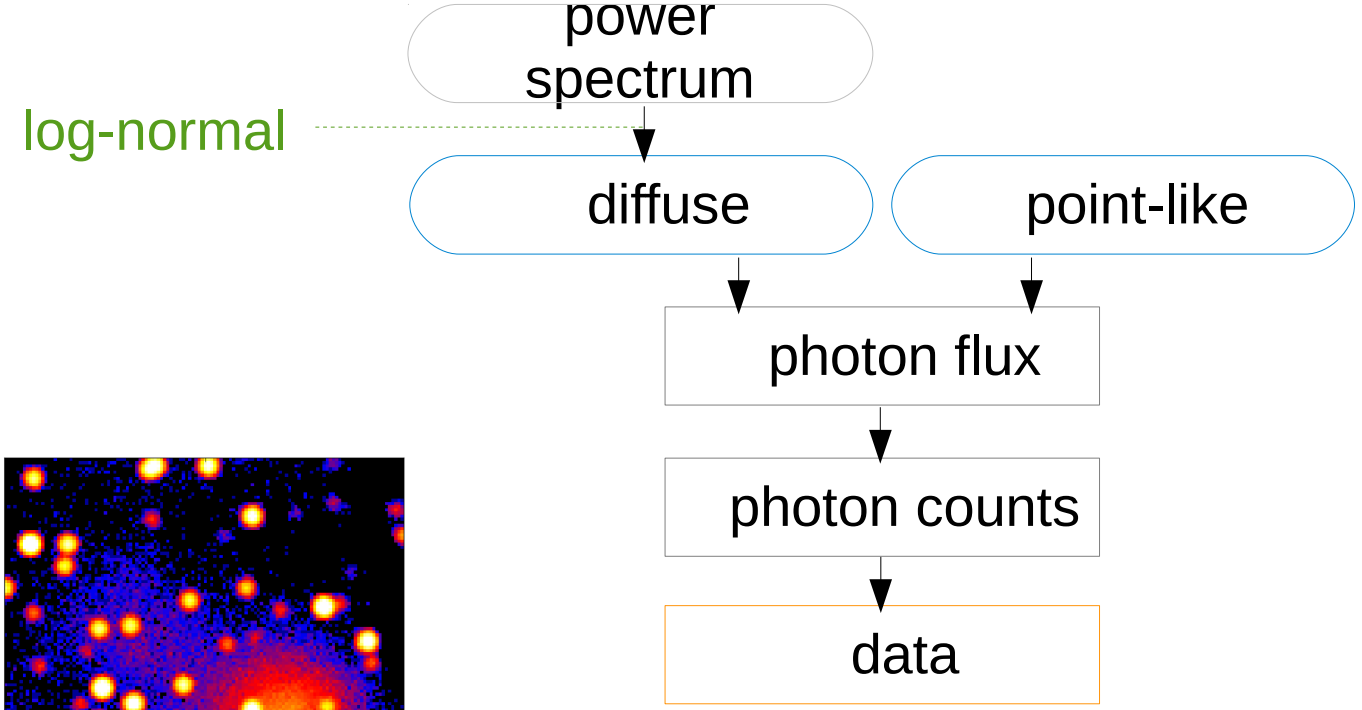




# D³PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888

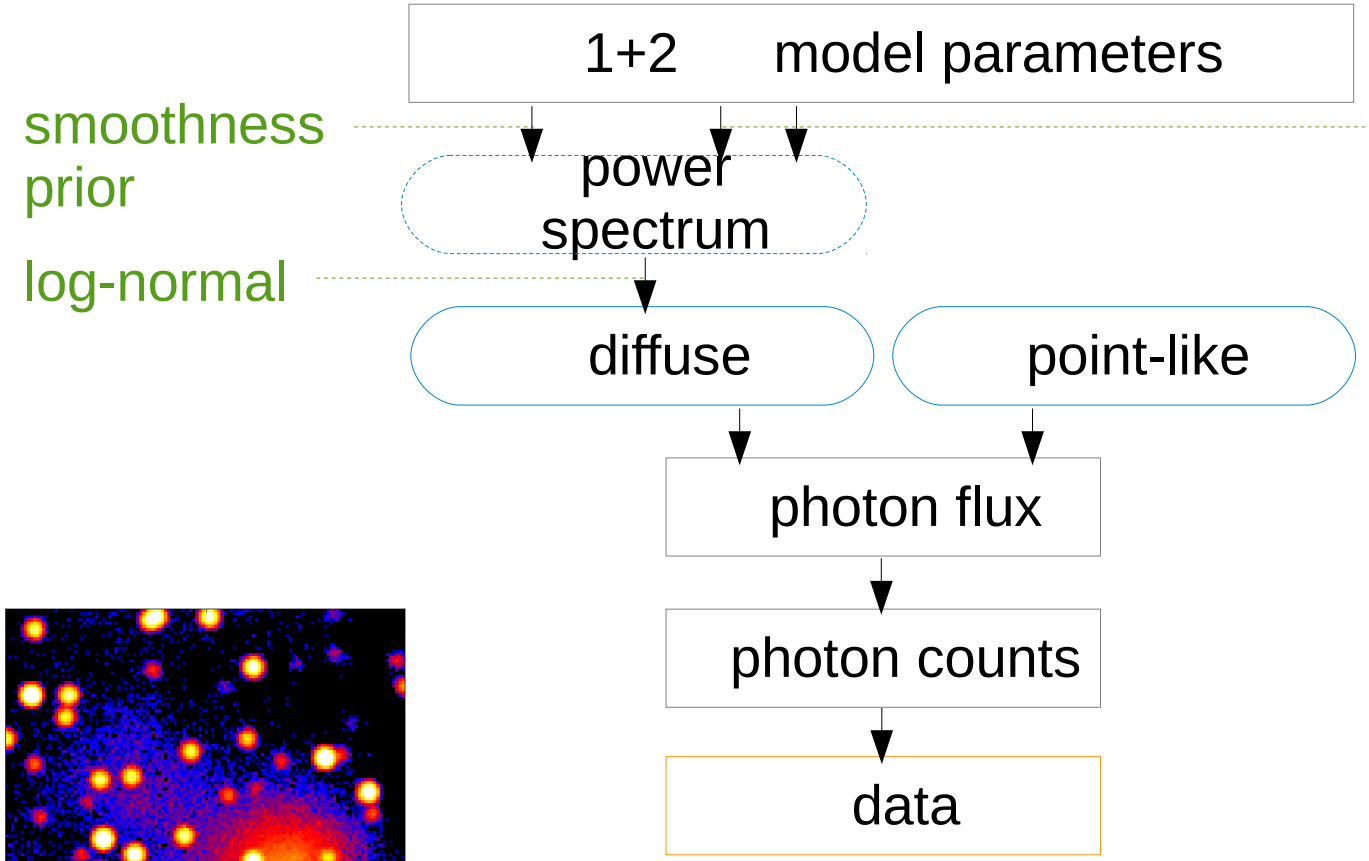


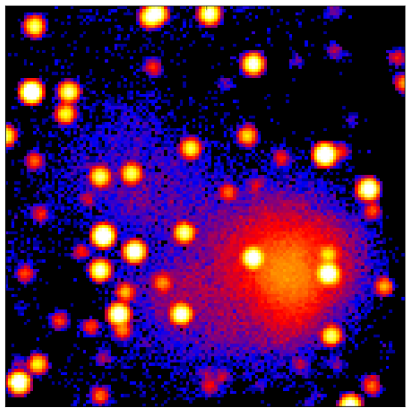



likelihood

# $D^3PO$ – challenges & assumptions

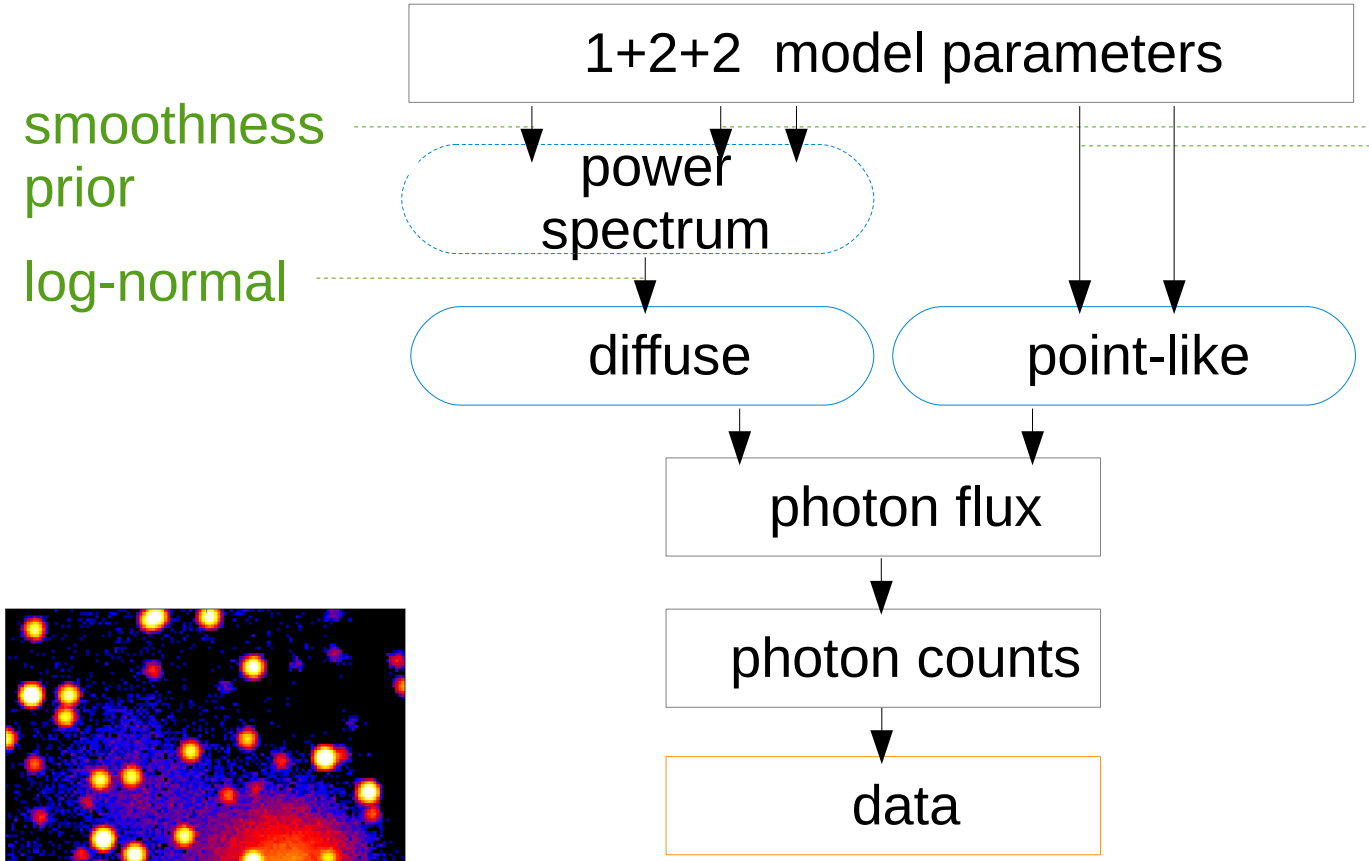
Selig & Enßlin (2014)
arXiv: 1311.1888

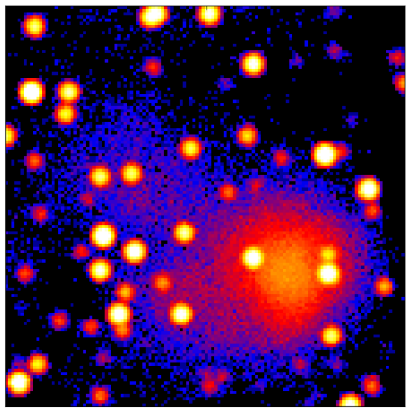


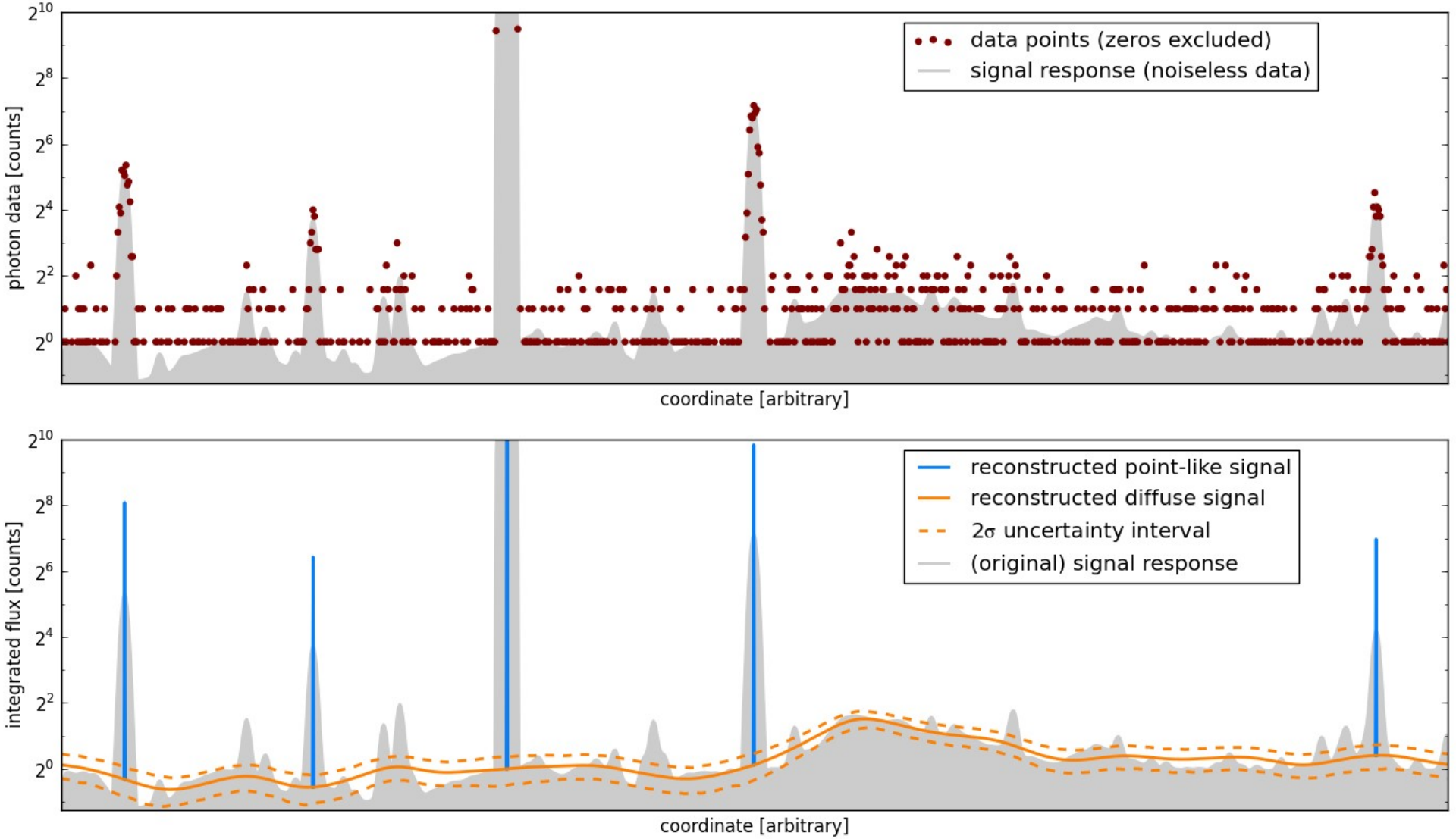
# D³PO – challenges & assumptions

Selig & Enßlin (2014)
arXiv: 1311.1888



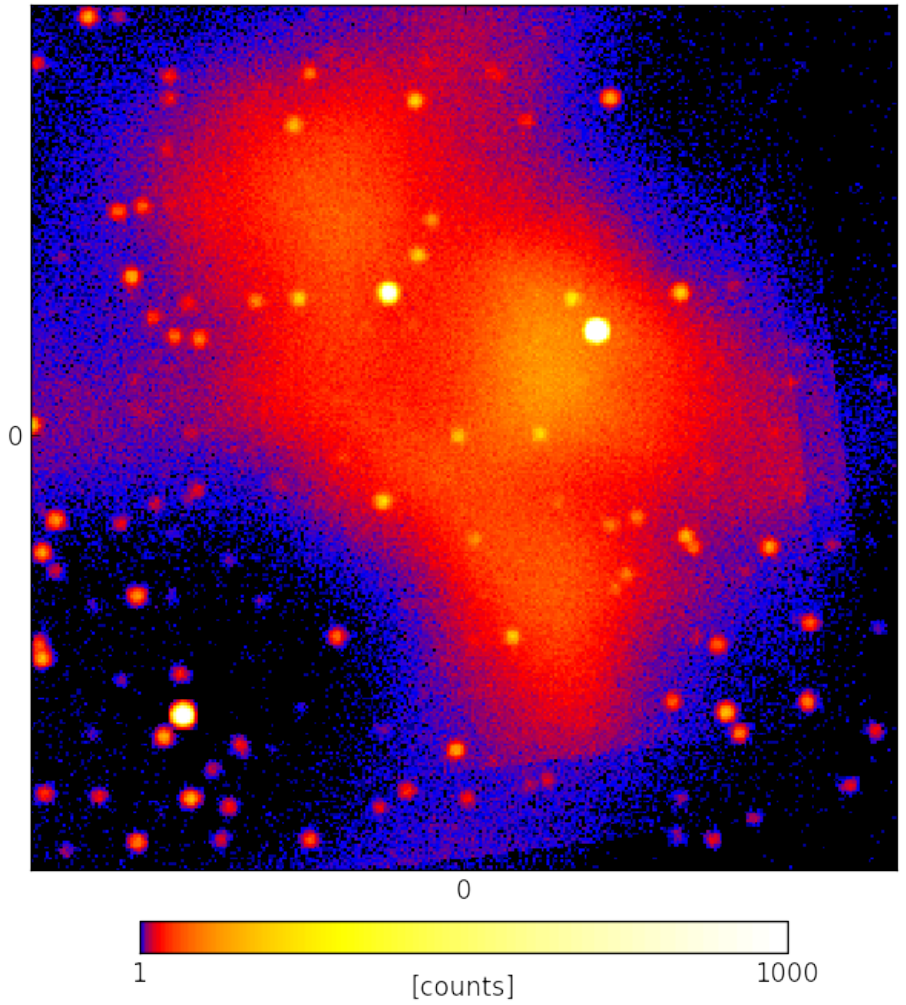



# **D$^3$PO** – 1D scenario

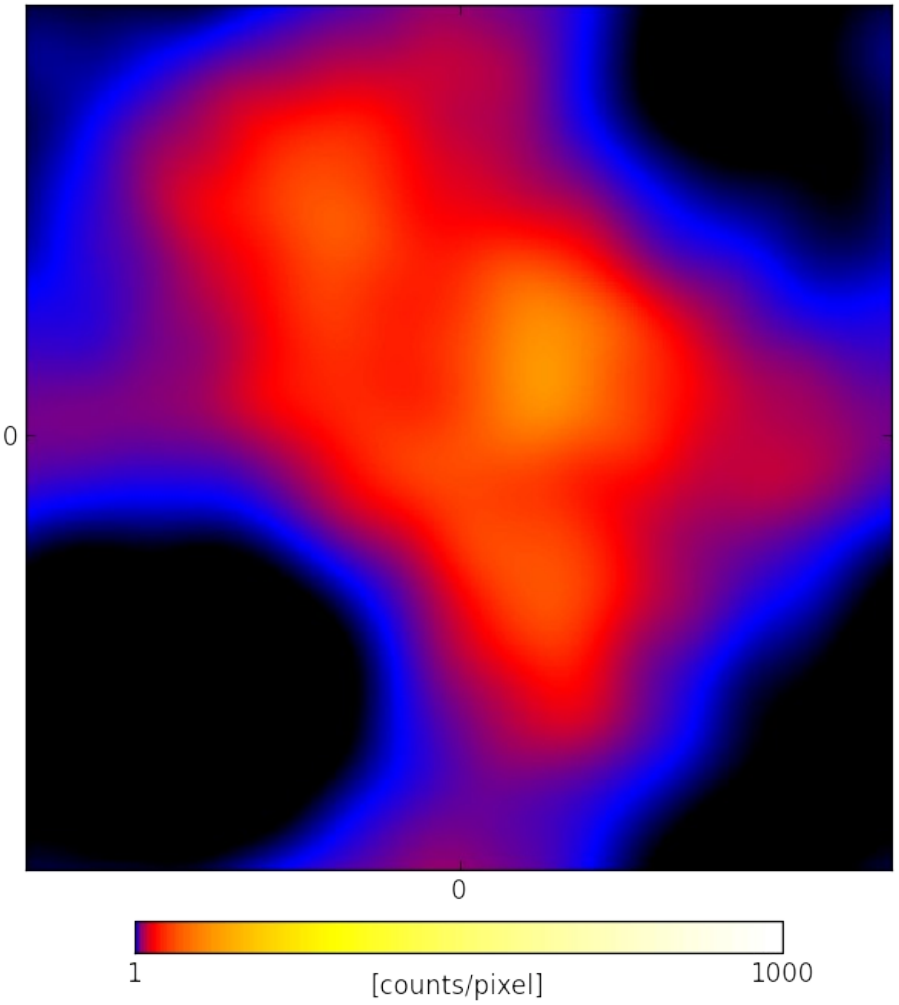


# **D$^3$PO** – 2D scenario

noisy log-data

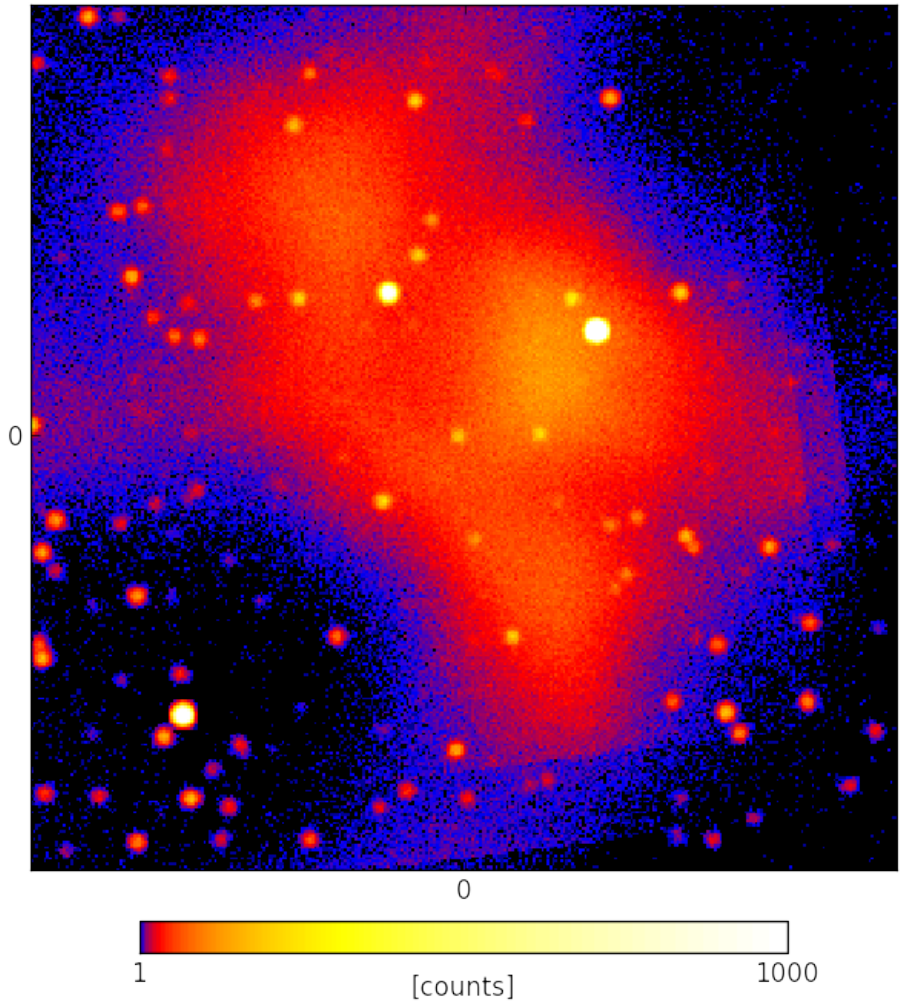



diffuse photon flux

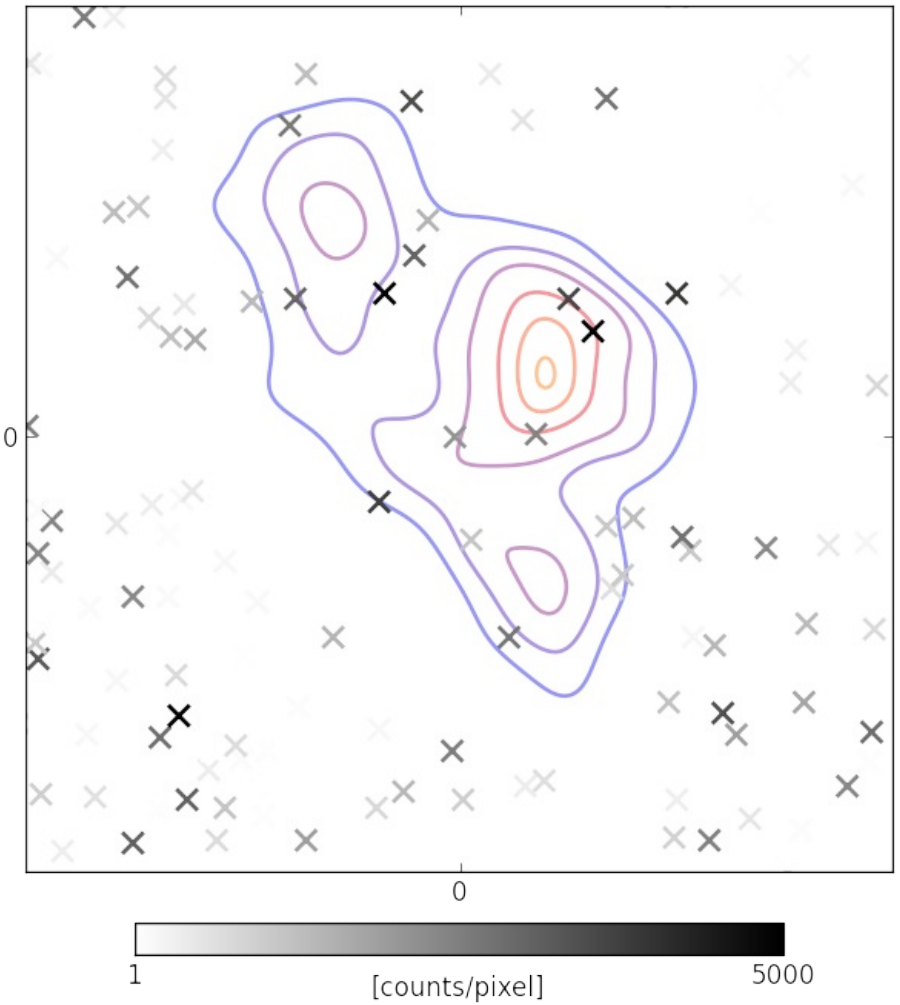


# **D$^3$PO** – 2D scenario

noisy log-data



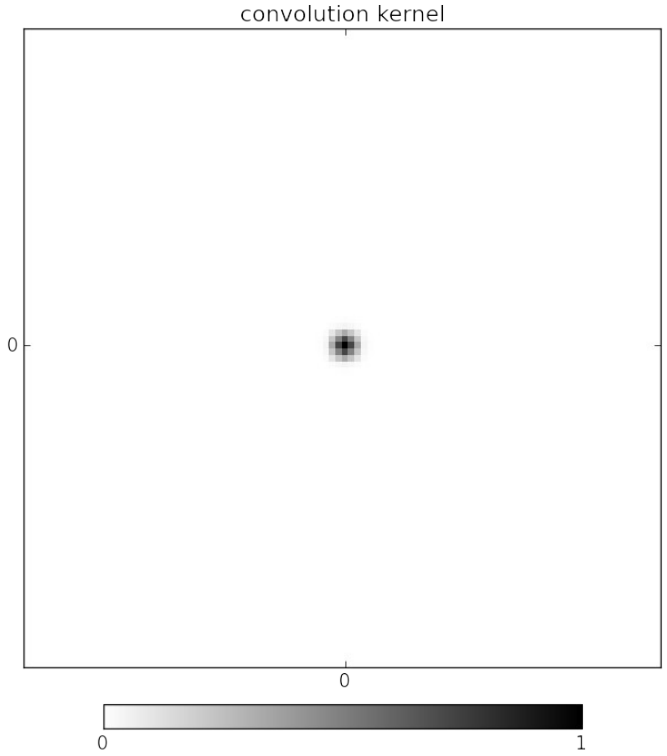

point-like photon flux

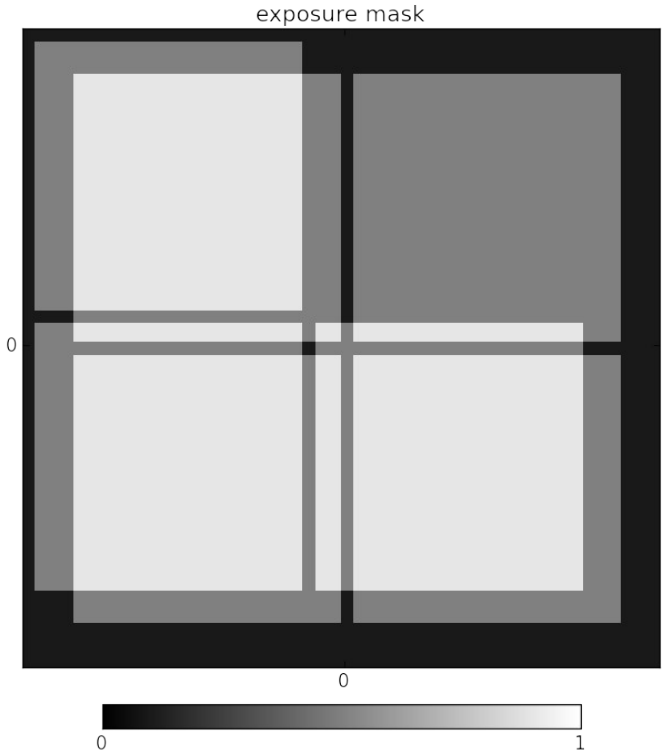


# D3PO a guided demo

## The Response operator

$$\lambda = \boldsymbol{R}\left(\mathrm{e}^{s} + \mathrm{e}^{u}\right)$$

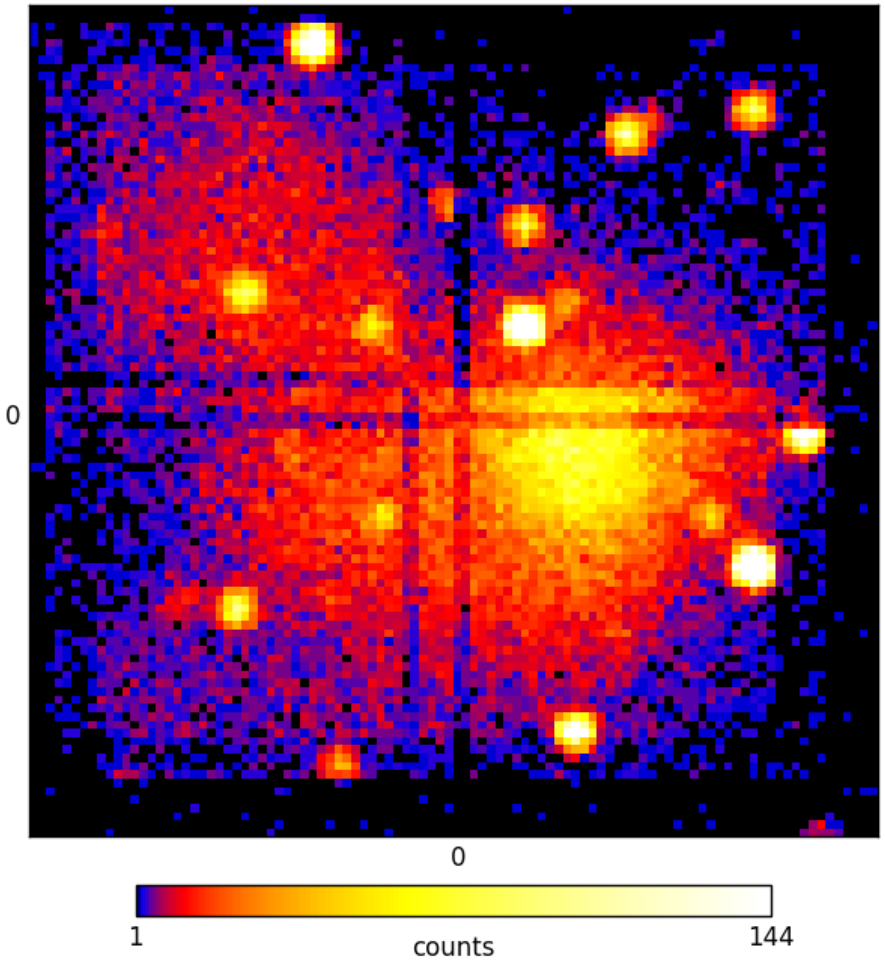


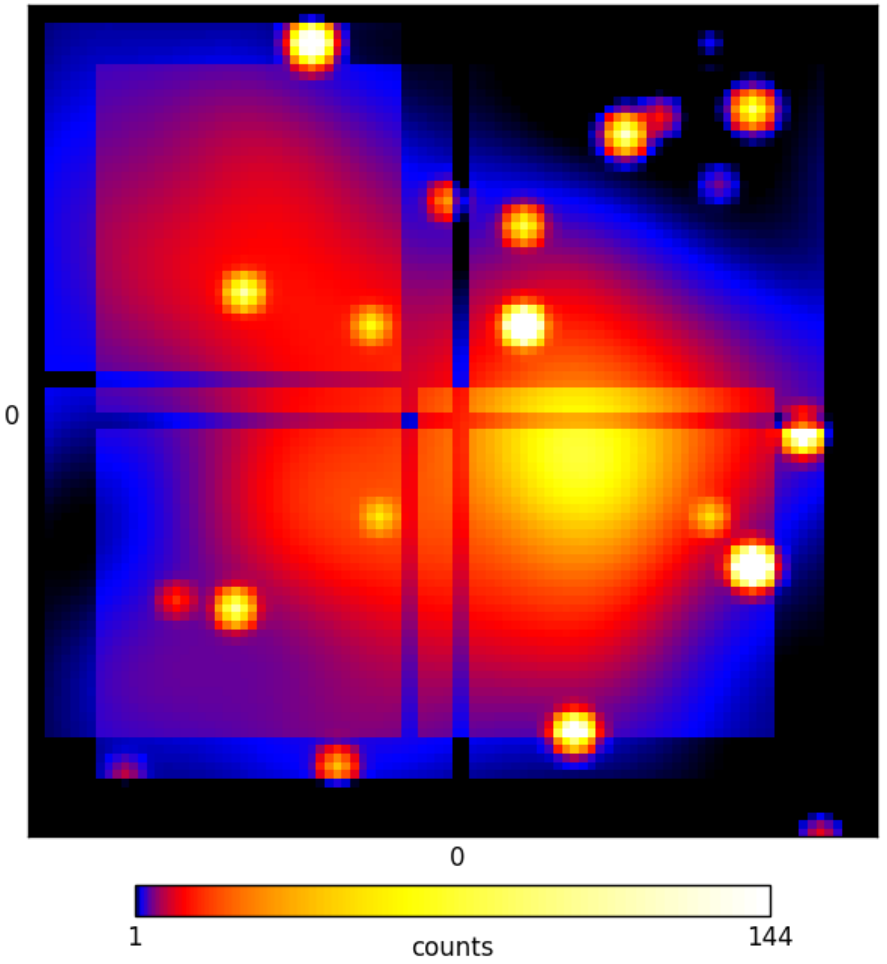
# D3PO a guided demo

## D1PO

raw input data



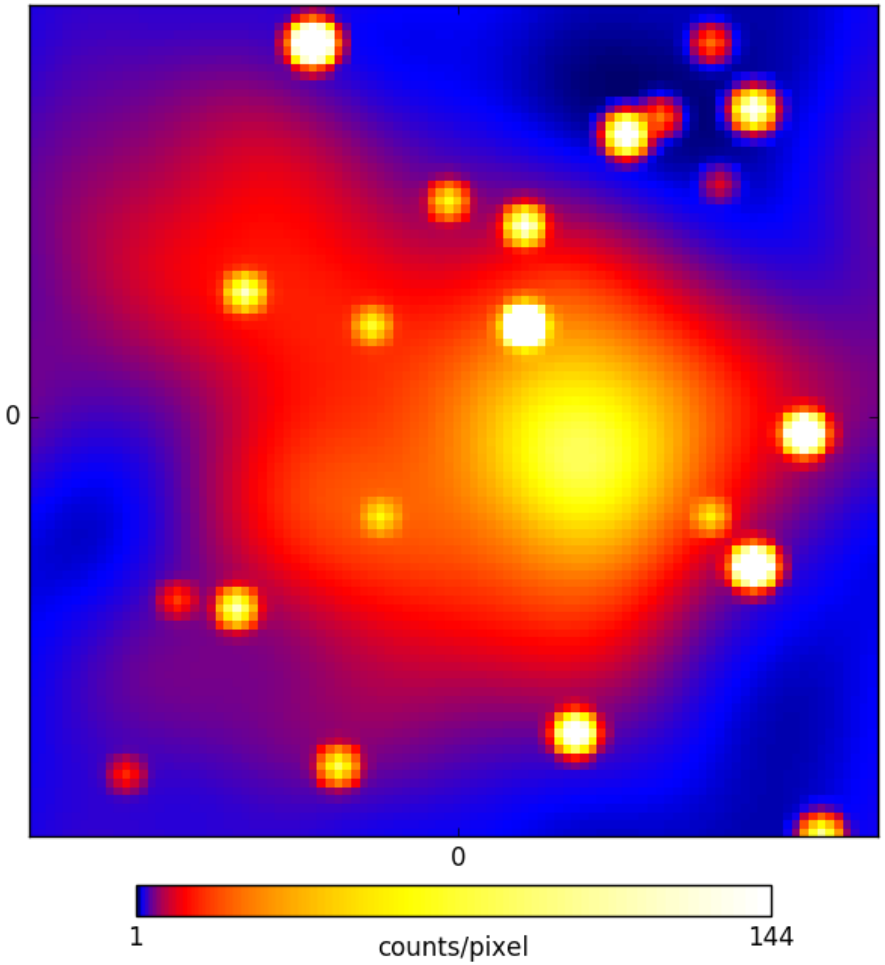

denoised observations



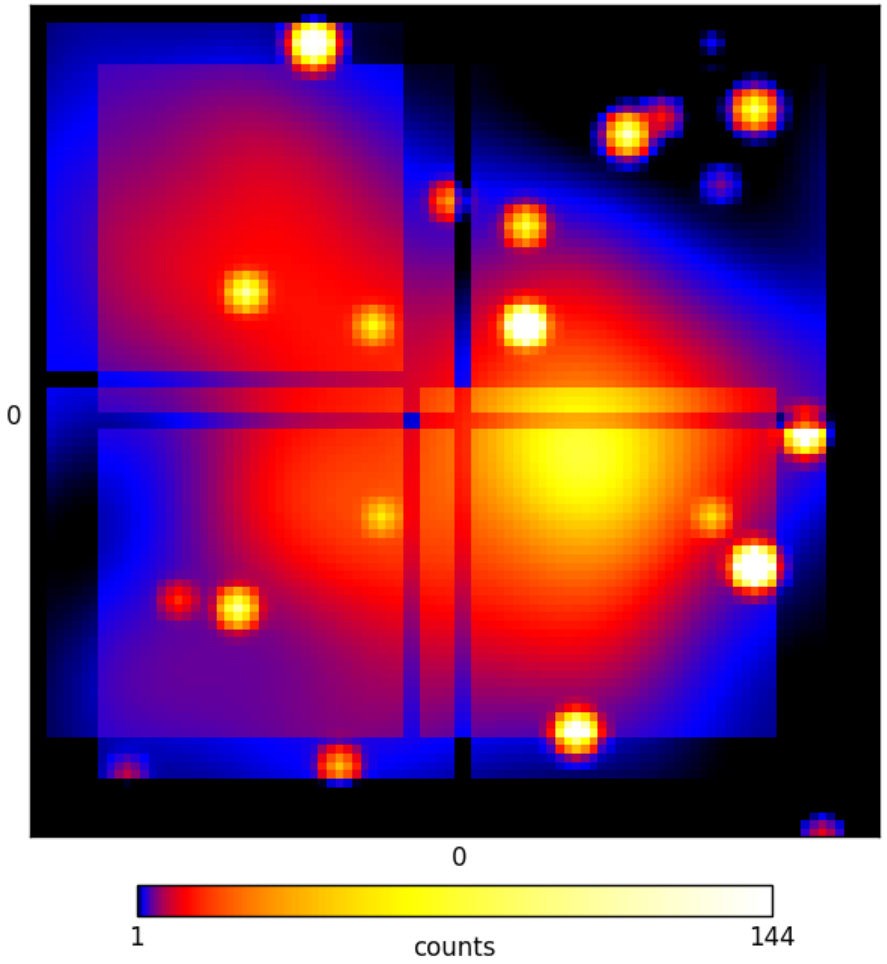
# D3PO a guided demo

## D2PO

demasked flux




denoised observations

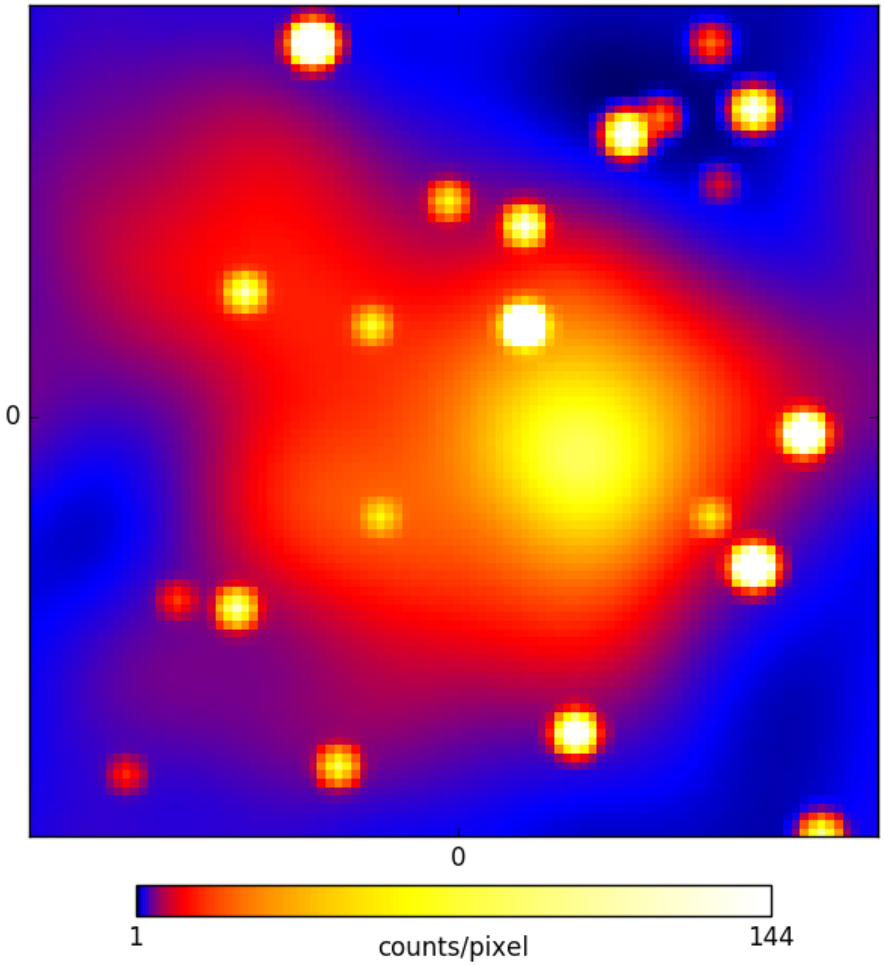


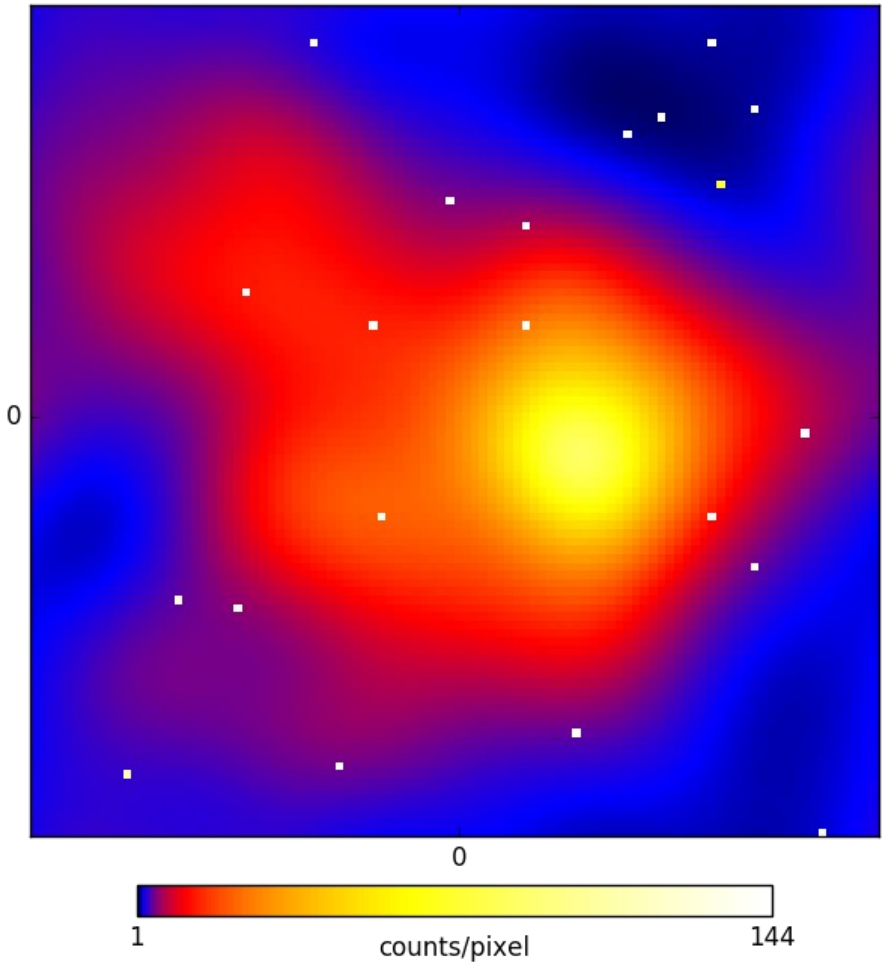
# D3PO a guided demo

## D2PO

demasked flux

deconvolved flux

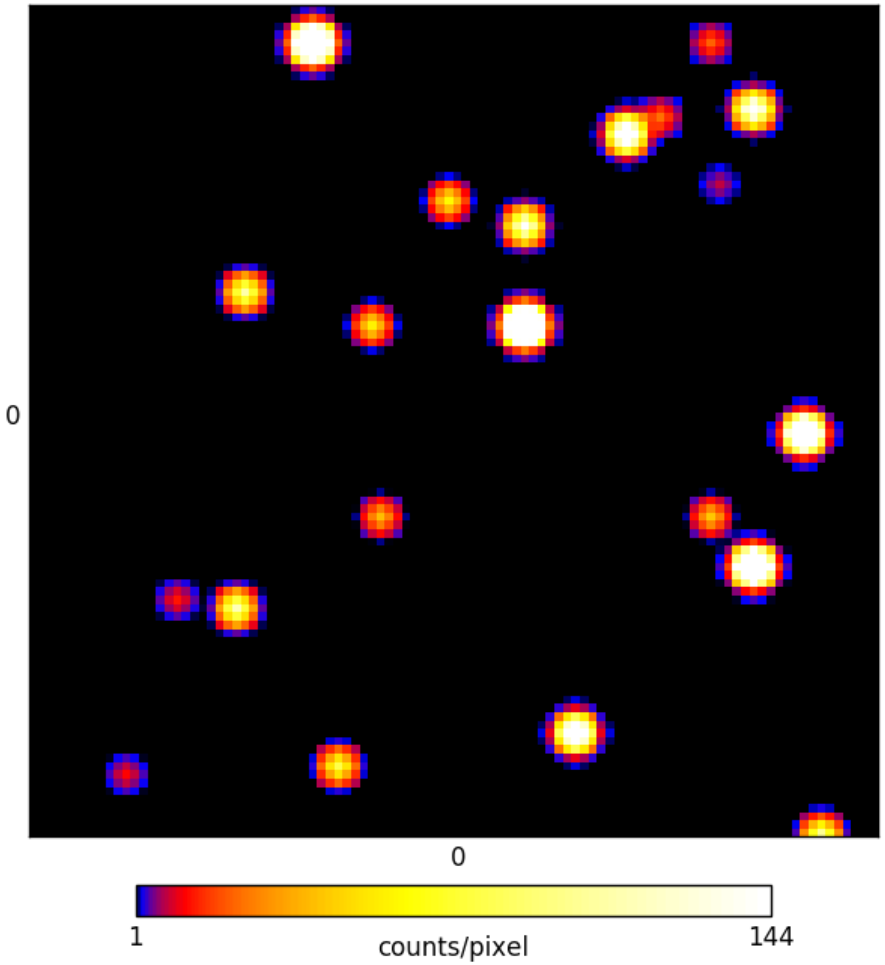


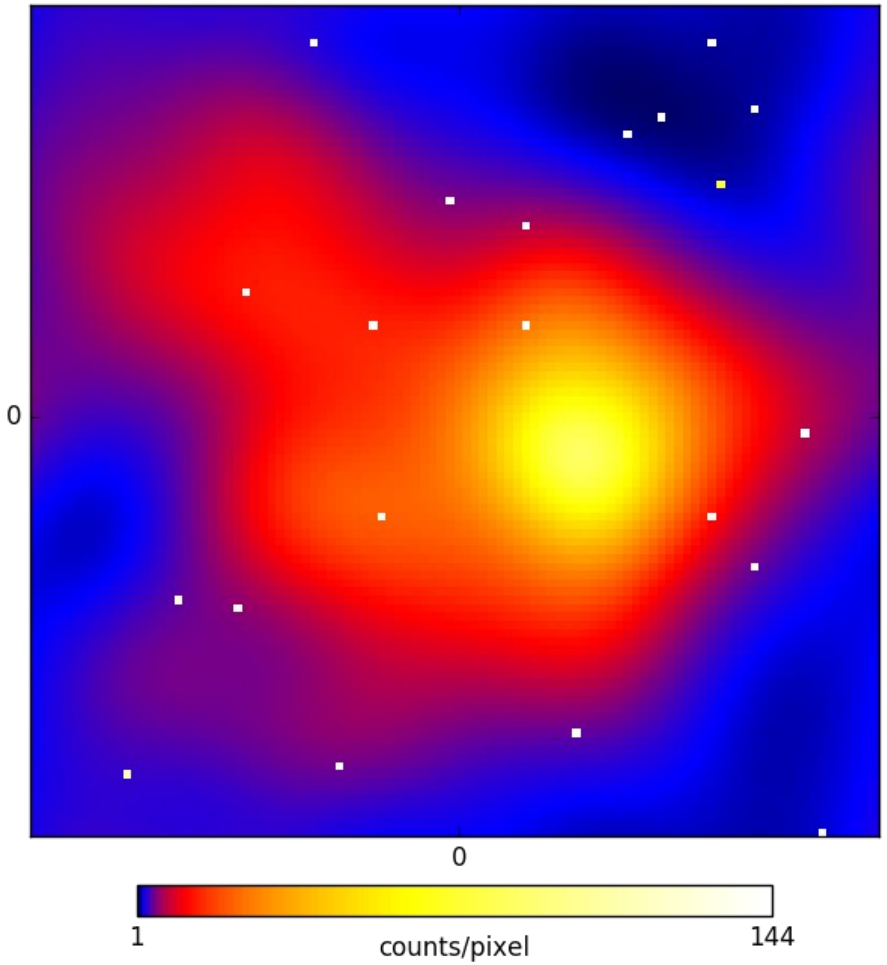
# D3PO a guided demo

## D2PO

reconvolved point sources



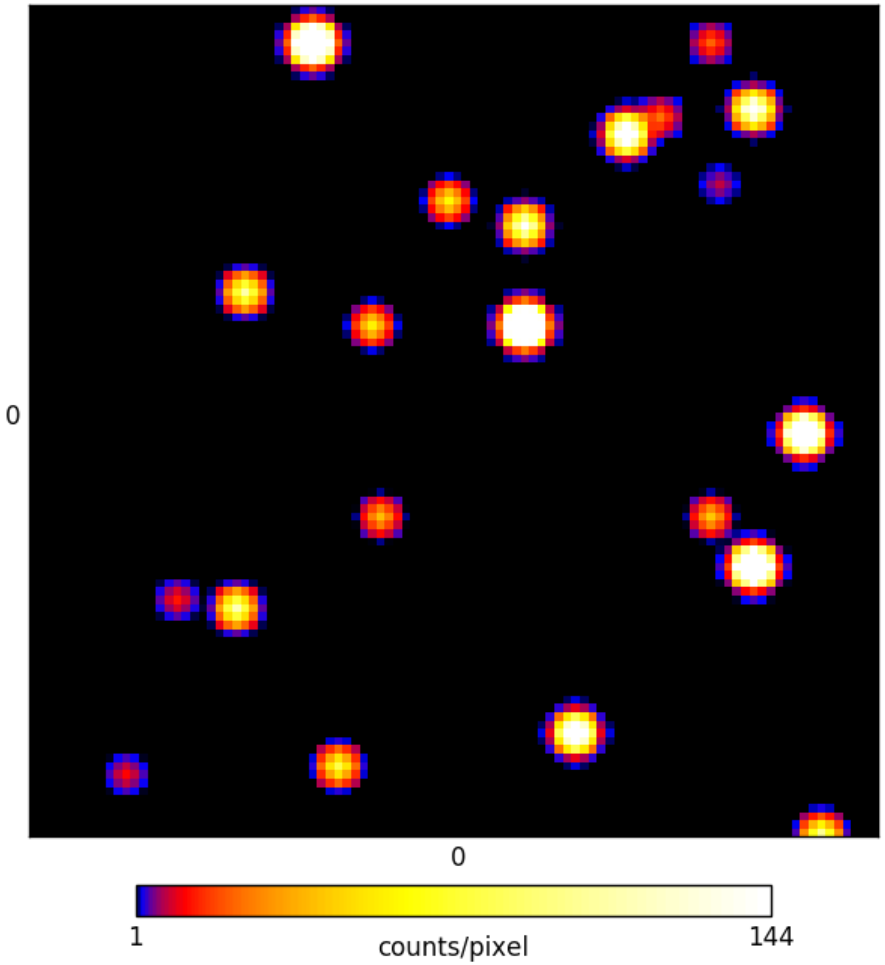

deconvolved flux



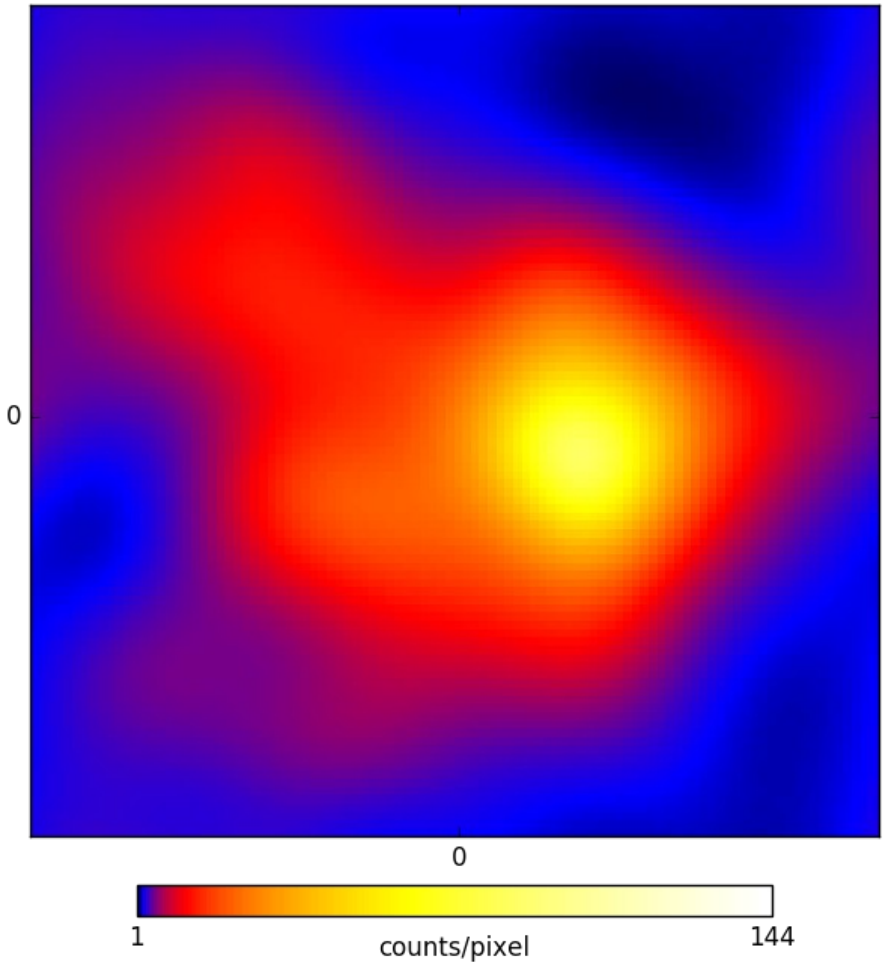
# D3PO a guided demo

## D3PO

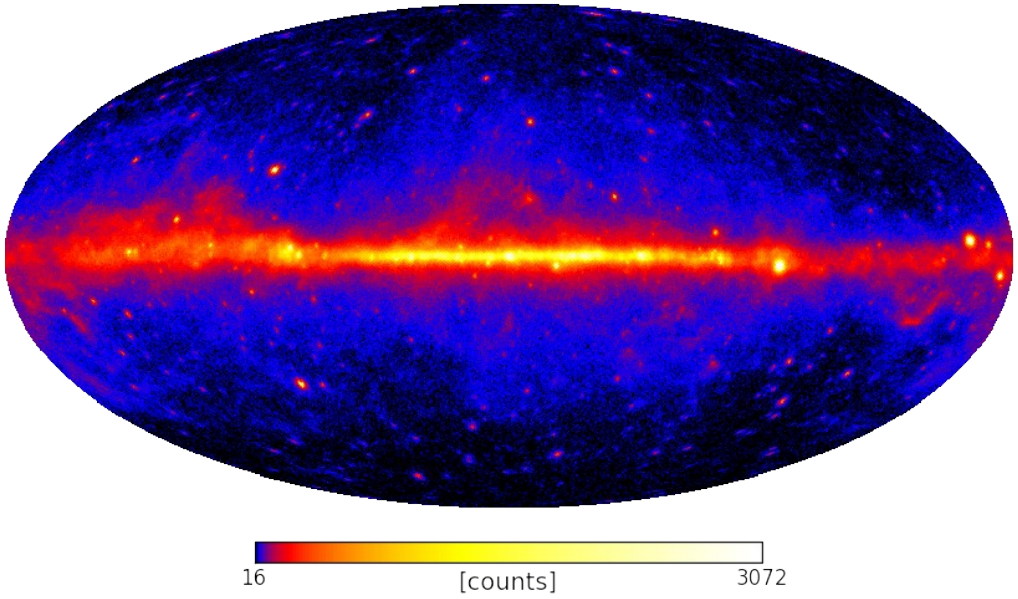
reconvolved point sources

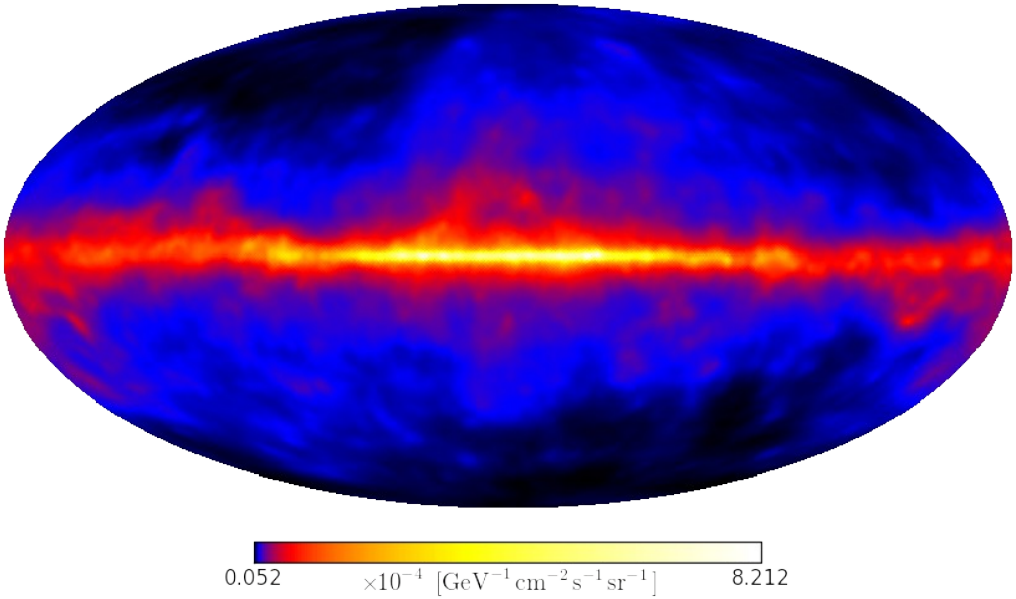



diffuse flux

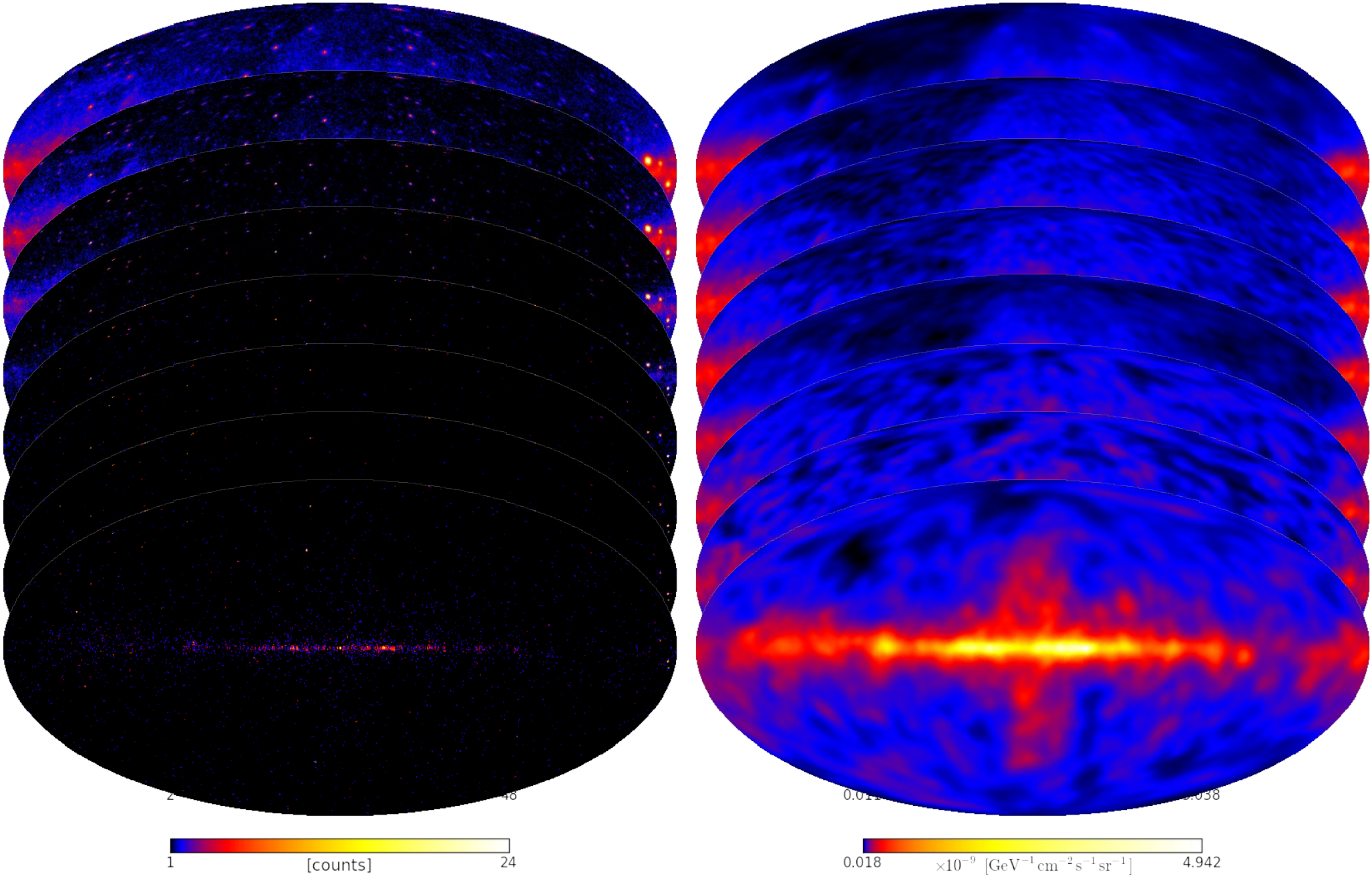


γ-ray sky

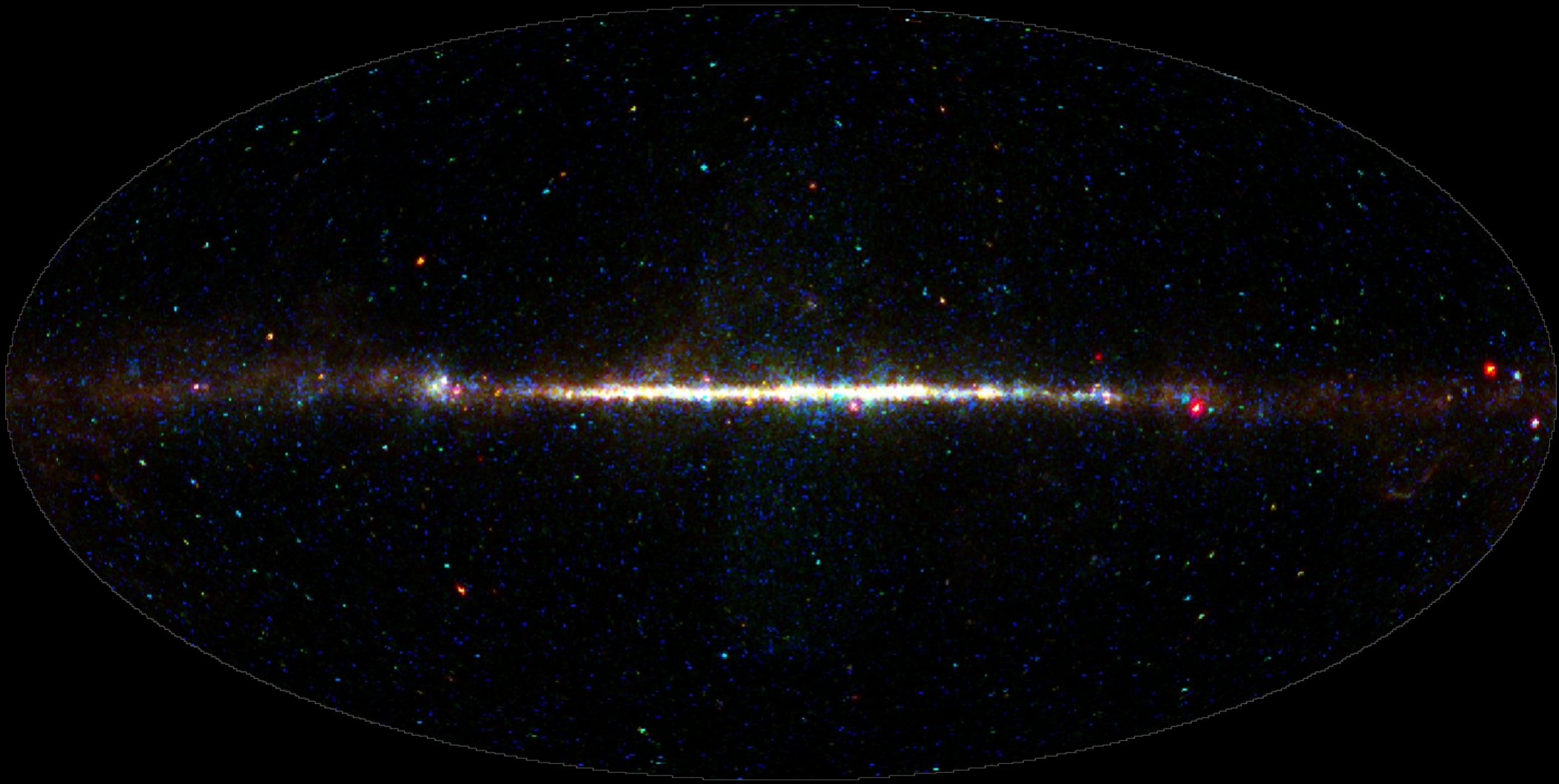


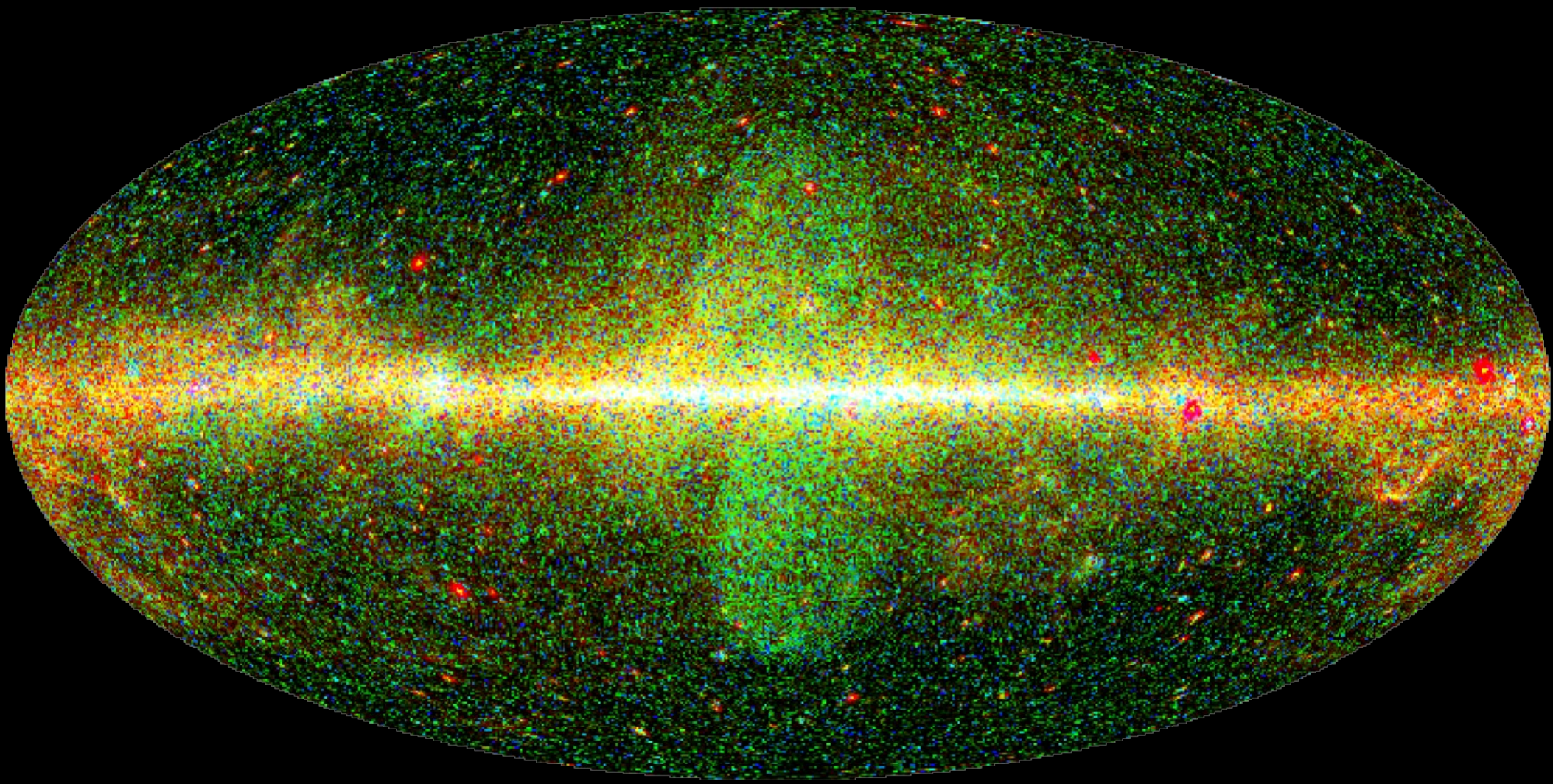

$\sim 0.9\,\mathrm{GeV}$



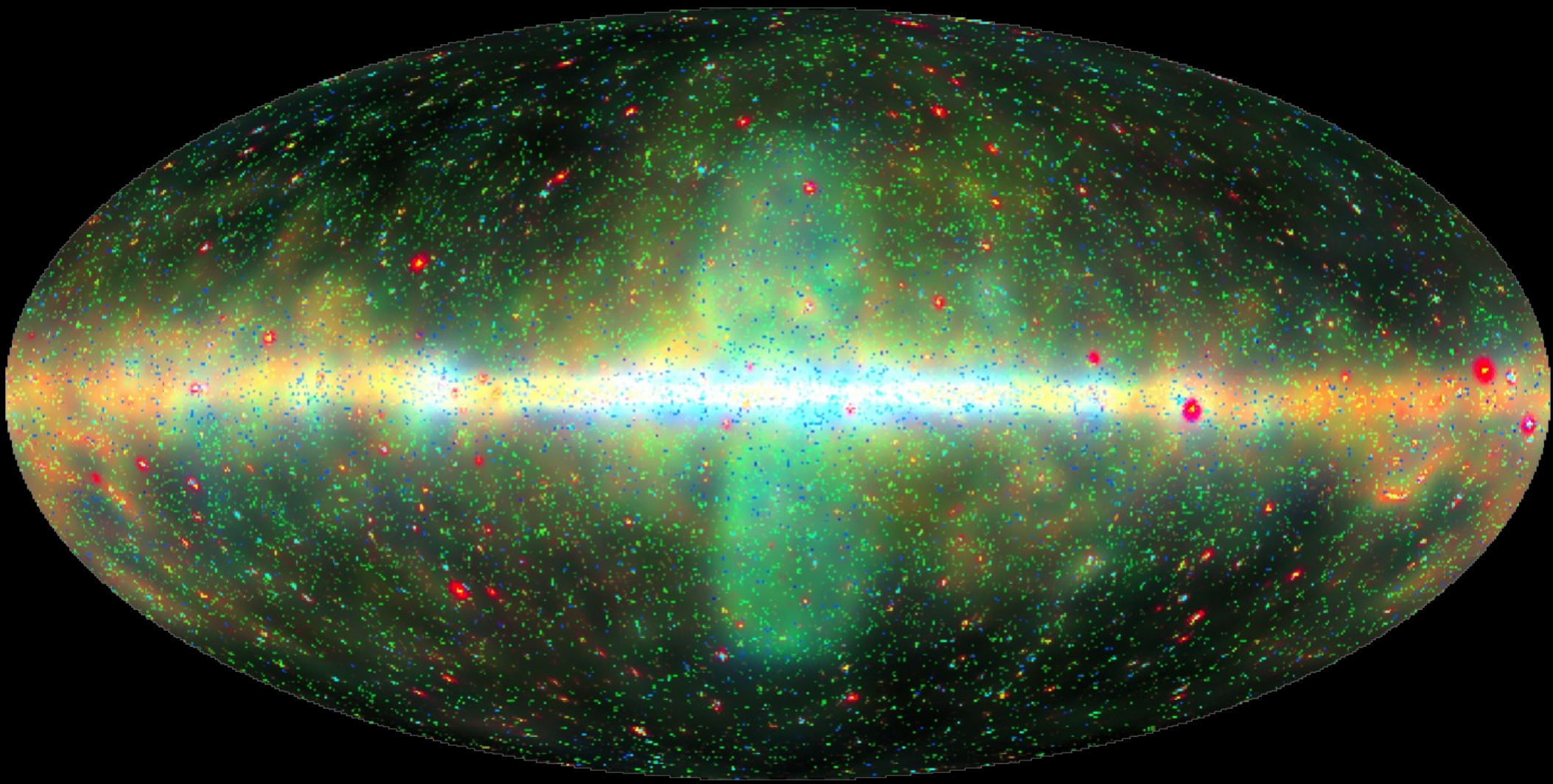

$\sim 108.6\,\mathrm{GeV}$



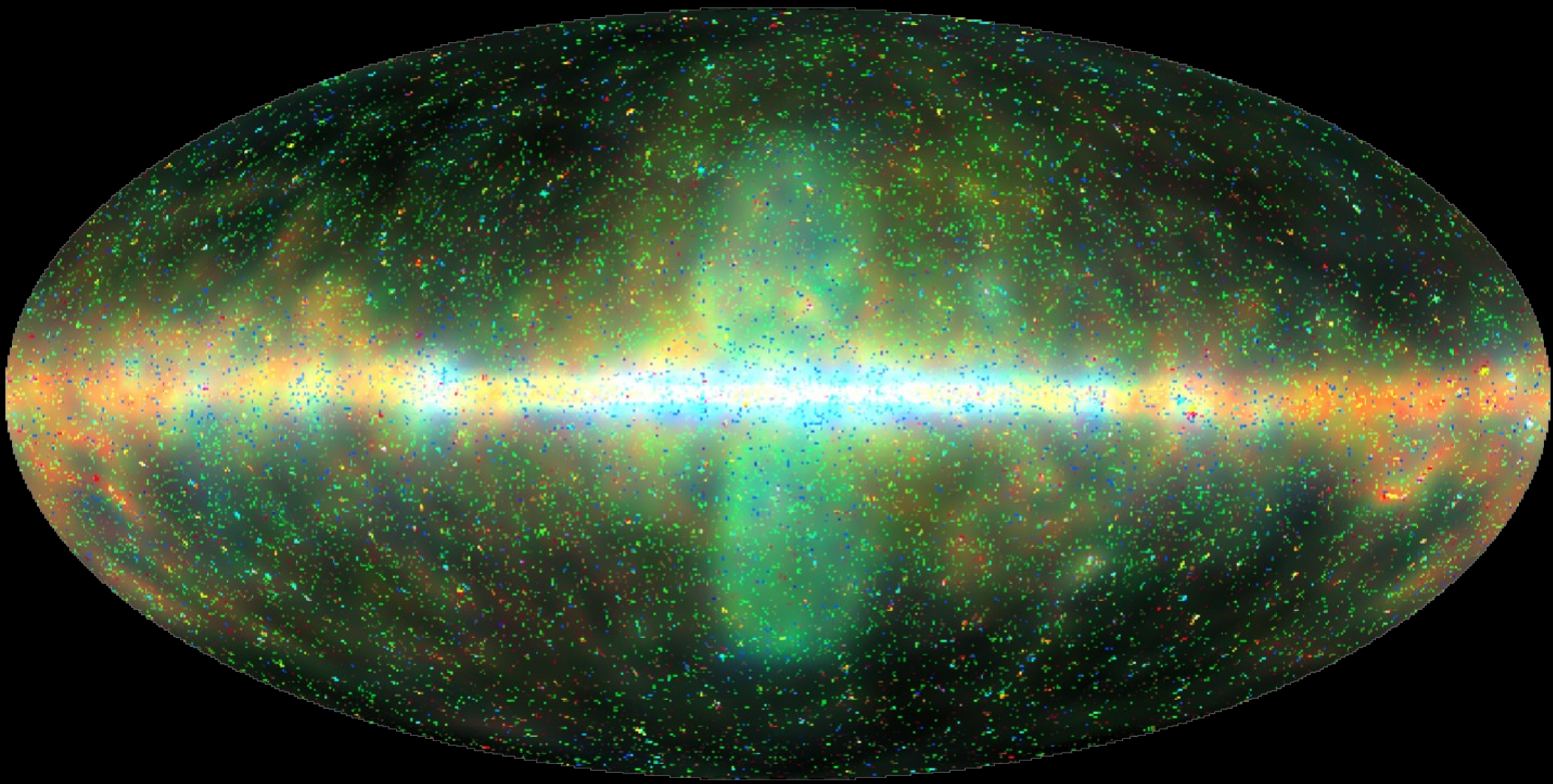
data



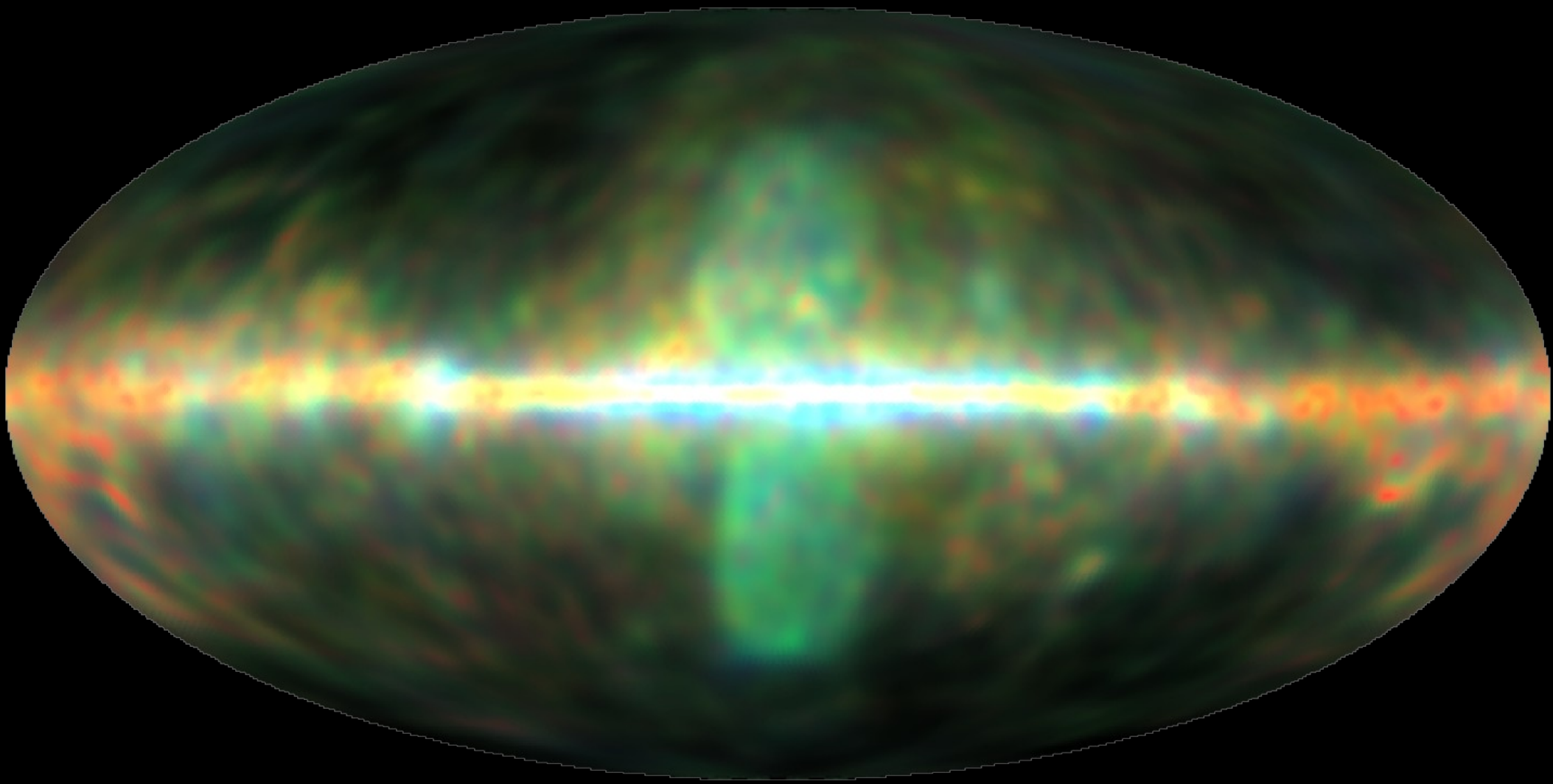
log-data



log-data … denoised

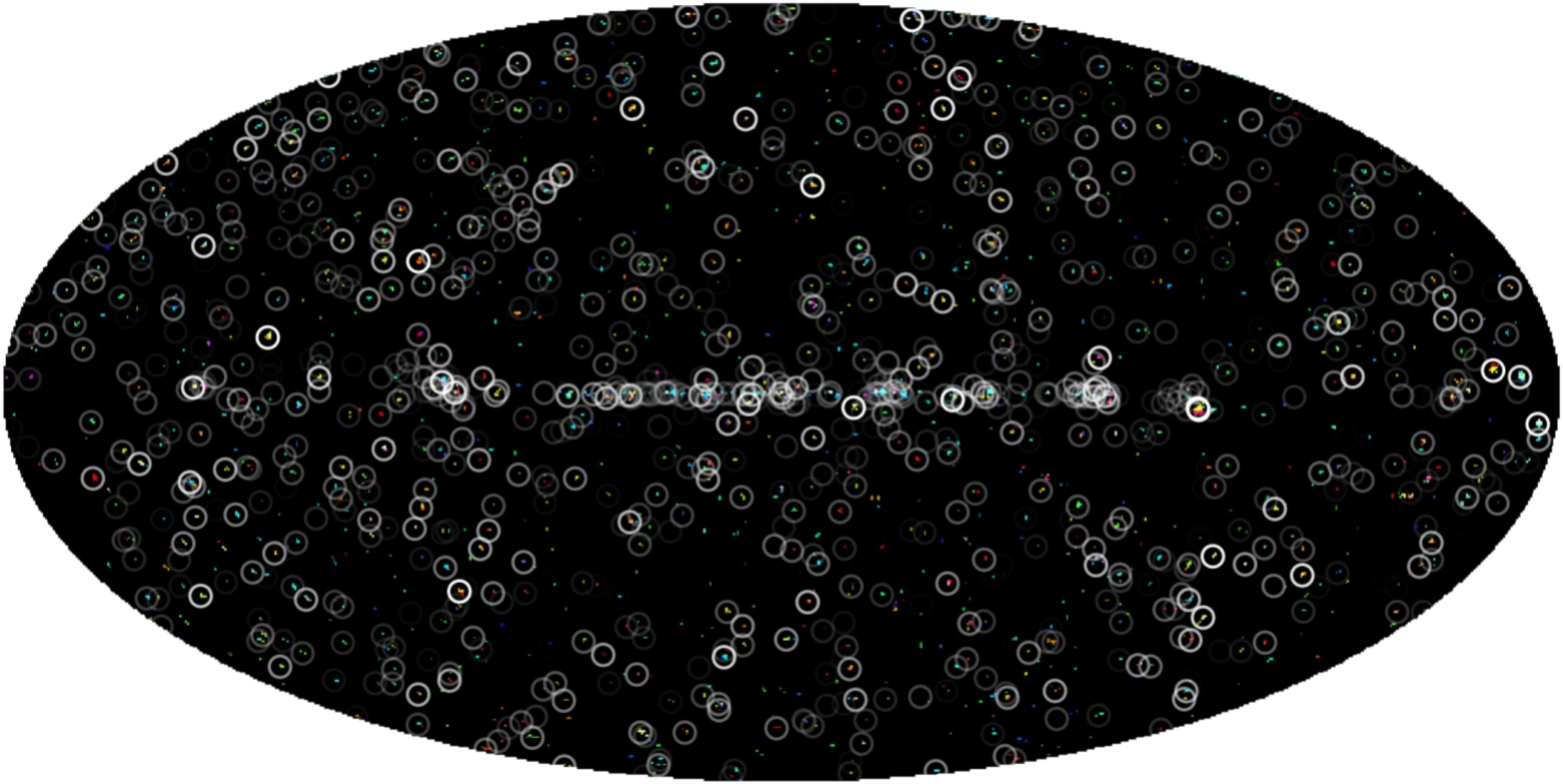


log-data … denoised … deconvolved



log-data … denoised … deconvolved … decomposed

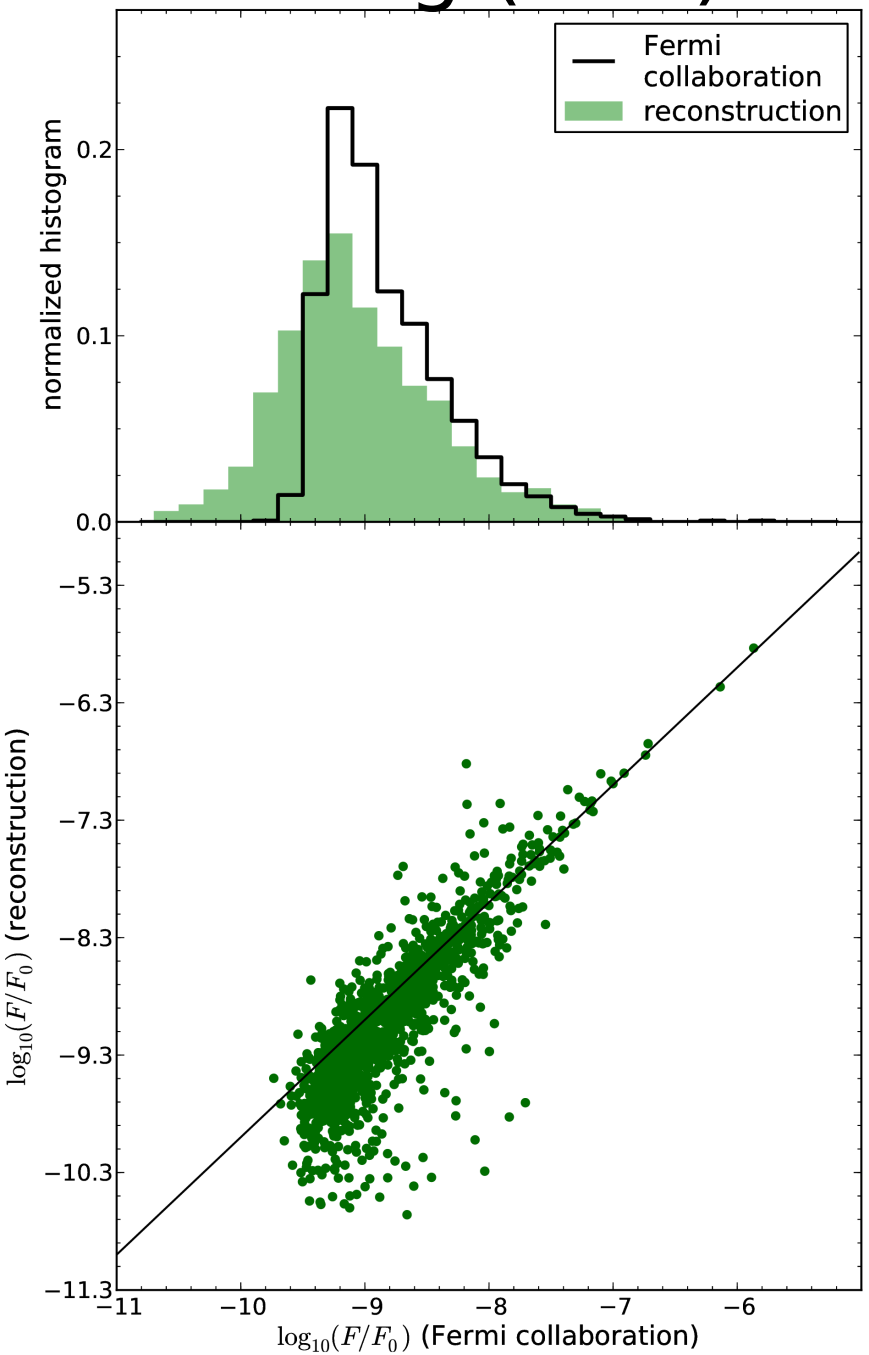
# First D³PO Fermi Point Source Candidates Catalog (1DF)



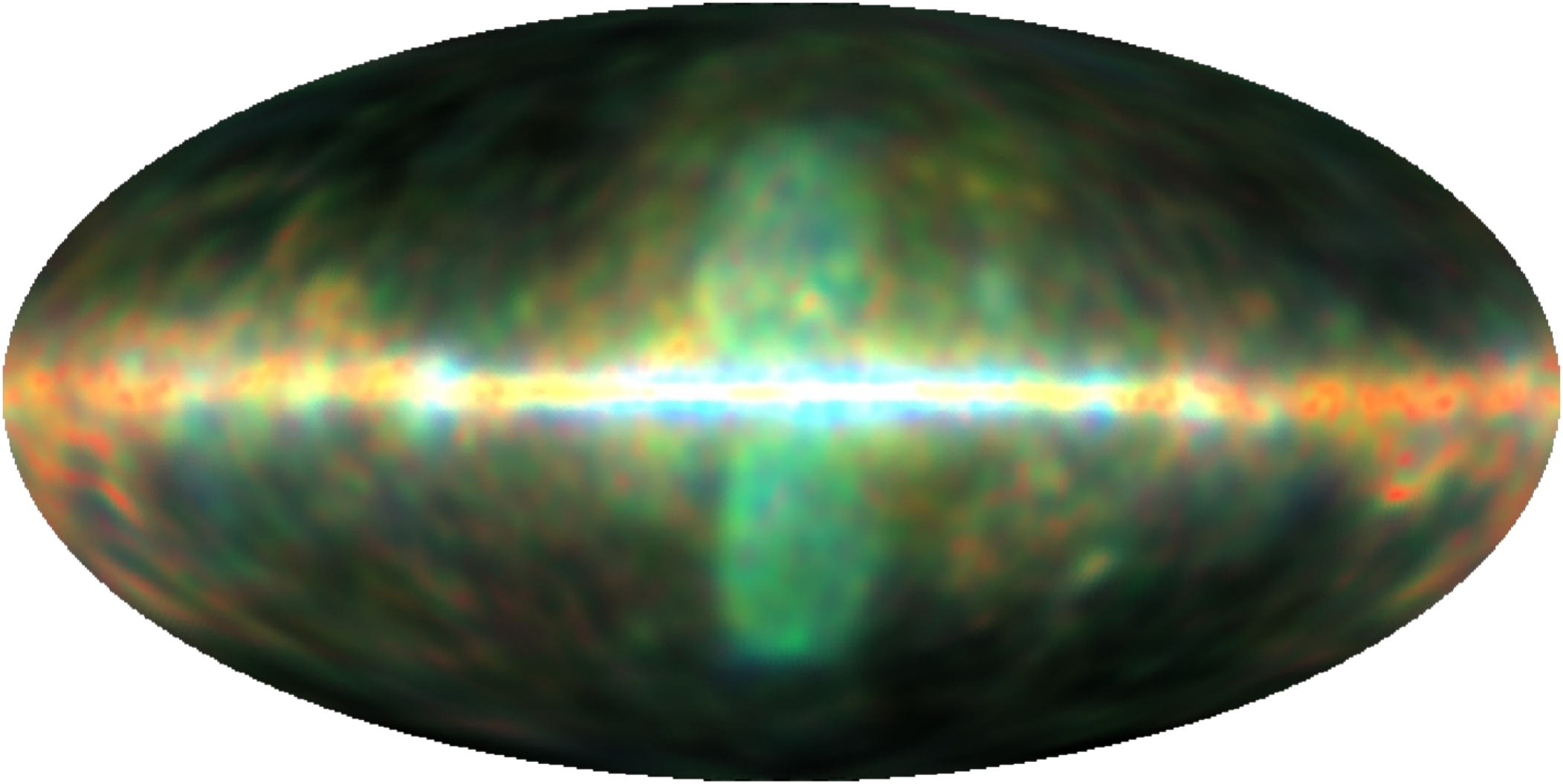
catalog with 3106 candidates, 1897 of them known in 3FGL

# First D³PO Fermi Point Source Candidates Catalog (1DF)

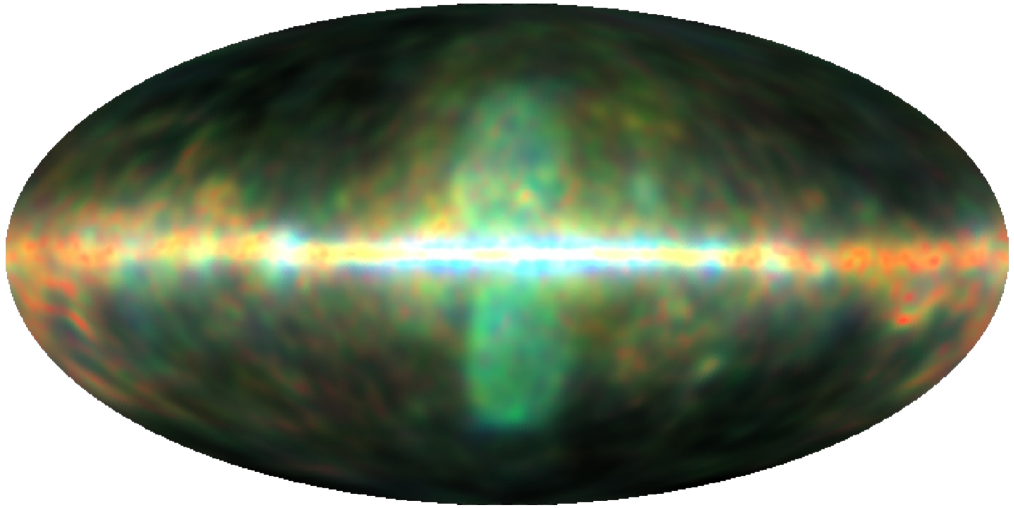
Total flux above 0.6 GeV



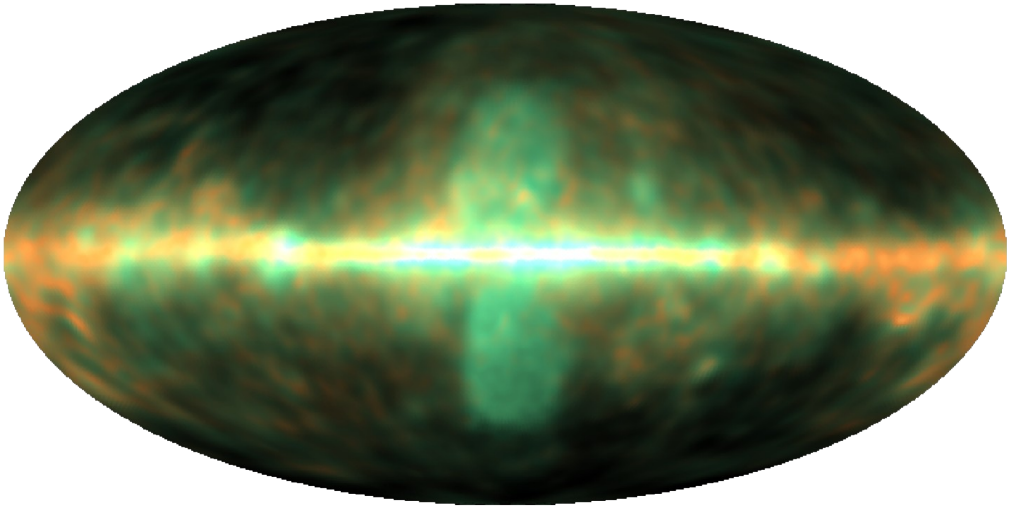
# Diffuse gamma-ray sky



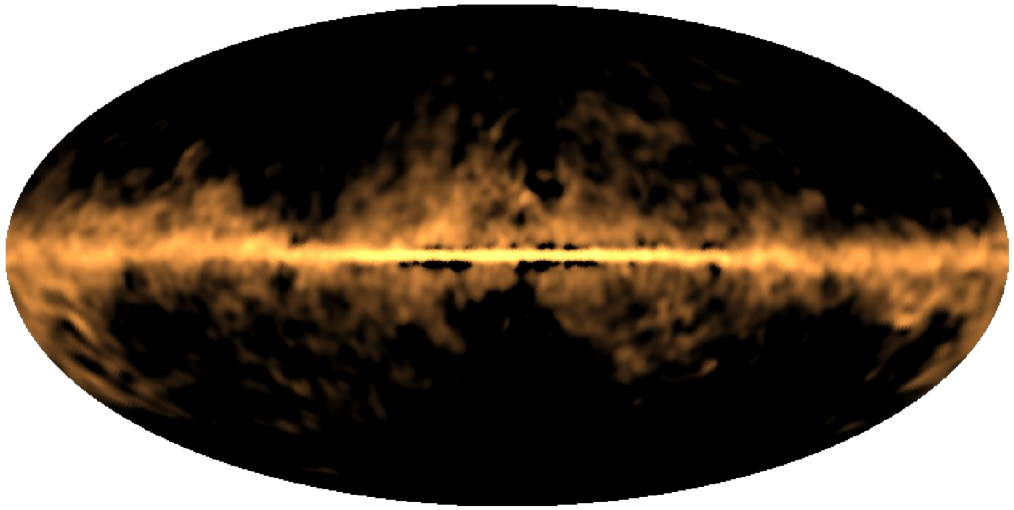
diffuse flux



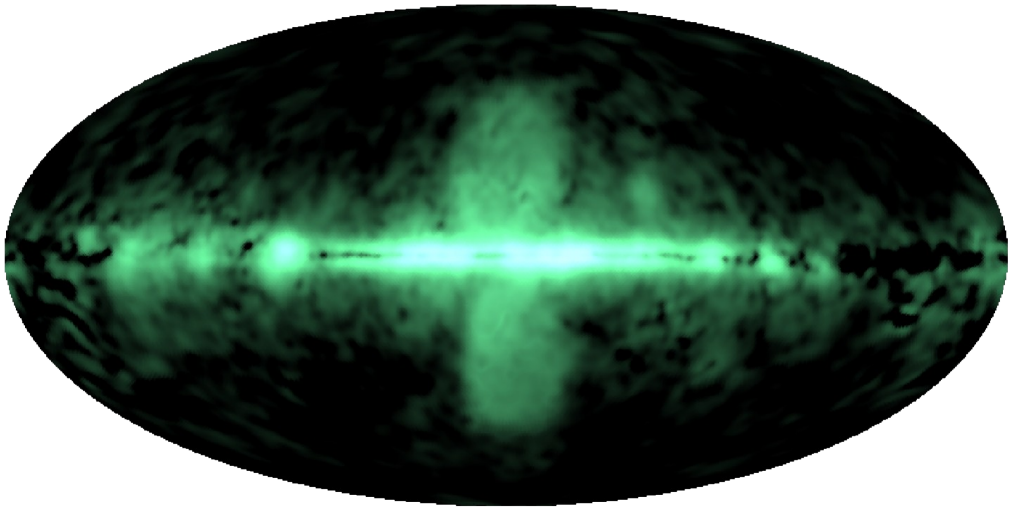
superposition

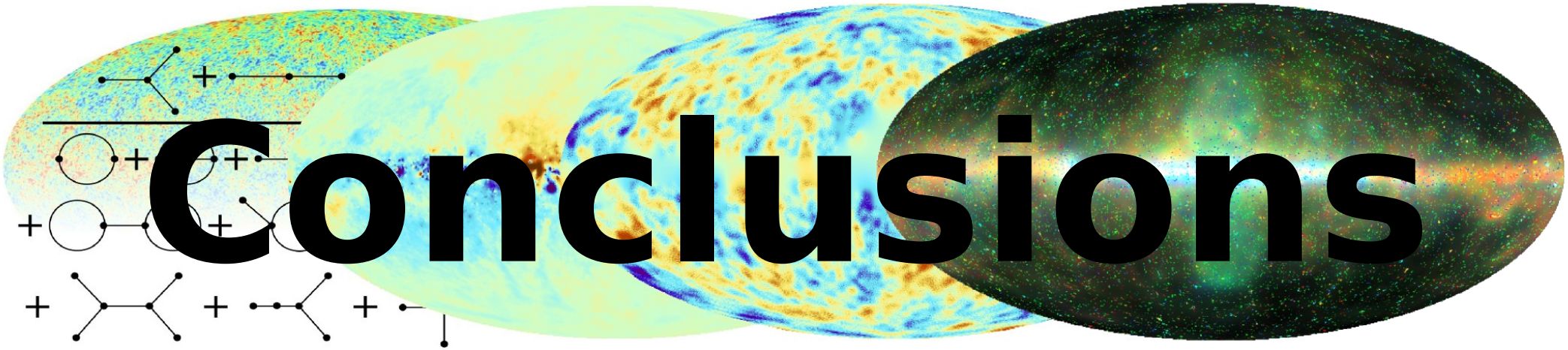


“cloud”-like



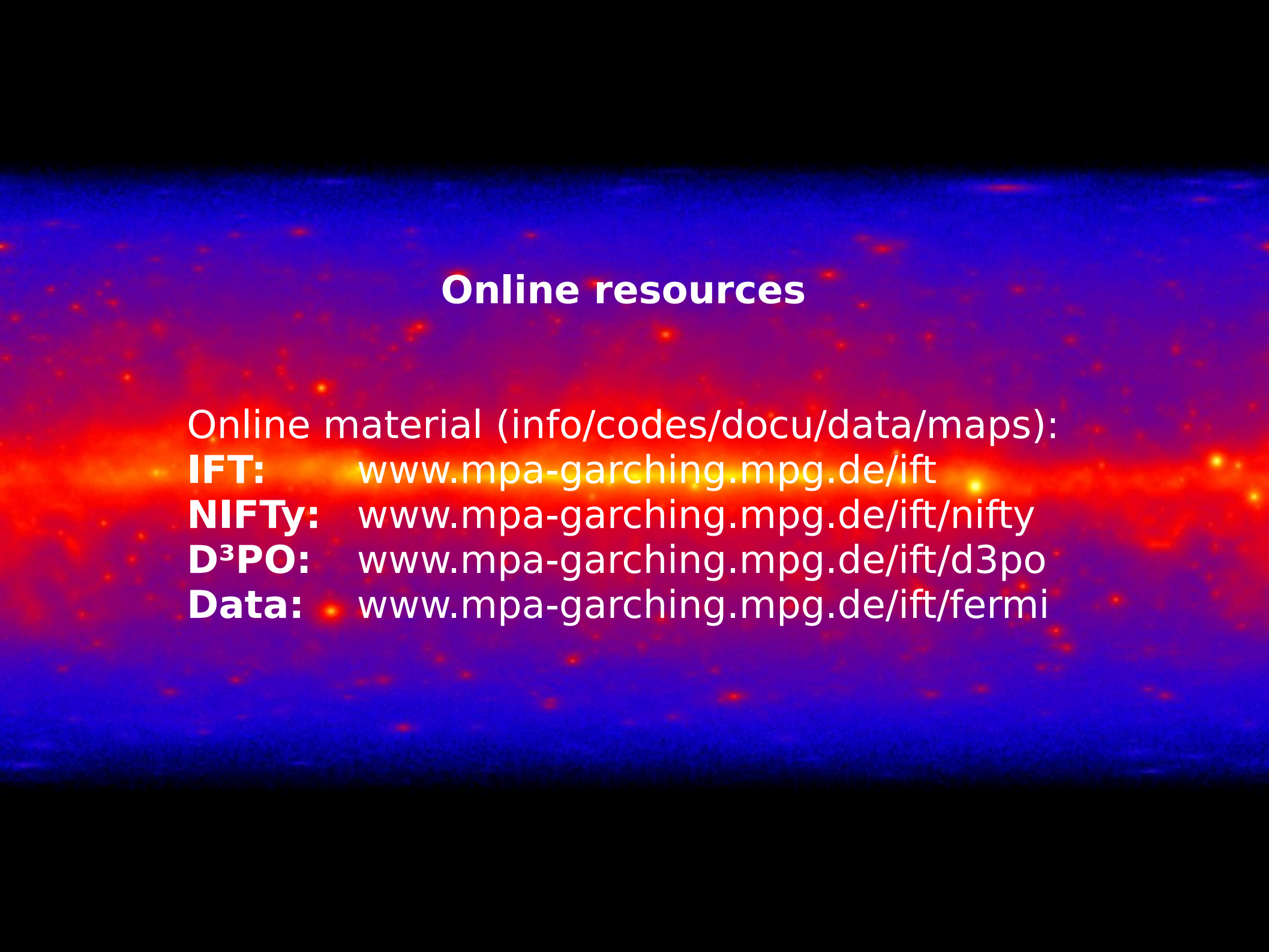
“bubble”-like





# Conclusions

- **Information field theory**
- **Methods from QFT** can be used
- **Numerical IFT** in coordinate free way via **NIFTy**
- **Applications** so far: radio interferometry, Galactic tomography, Faraday studies, CMB studies, cosmography, gamma rays



## Online resources

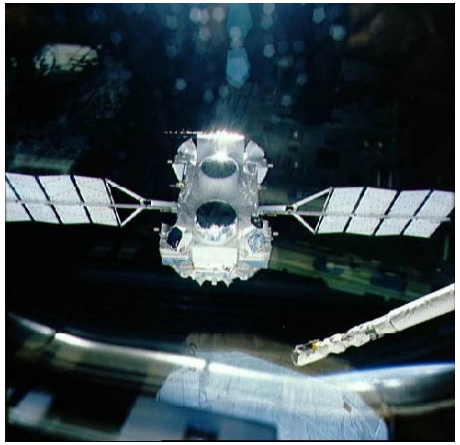
Online material (info/codes/docu/data/maps):

**IFT:** www.mpa-garching.mpg.de/ift

**NIFTy:** www.mpa-garching.mpg.de/ift/nifty

**D³PO:** www.mpa-garching.mpg.de/ift/d3po

**Data:** www.mpa-garching.mpg.de/ift/fermi

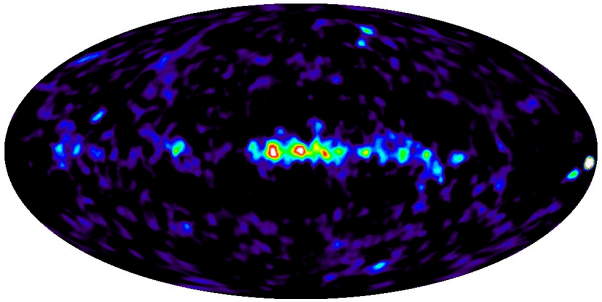


Advert.

Not just Fermi !

Also **COMPTEL**

MeV energies



New skymaps

See Poster 6-2  'COMPTEL Reloaded'