Friedrich-Alexander-Universität
Erlangen-Nürnberg

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Erlangen Centre for Astroparticle Physics

FAU

eROSITA data analysis with Gammapy

Gammapy user call 15th May 2025

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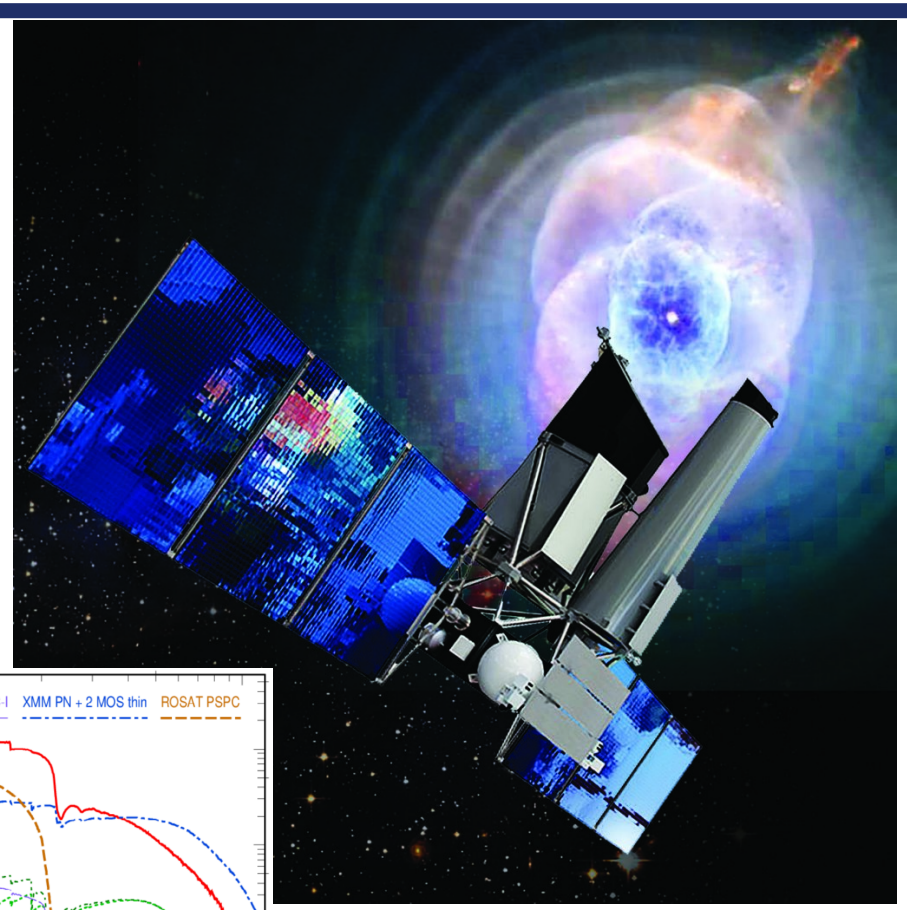
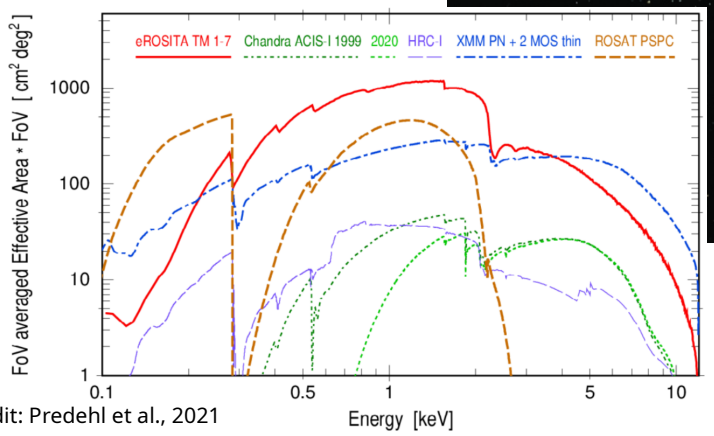
eROSITA

X-ray Telescope

- **e**xtended **RO**entgen **S**urvey with an **I**maging **T**elescope **A**rray
- Energy range: ~0.2-10 keV
- Launched on 13th July 2019
- Four complete all-sky surveys eRASS1-4
- DR1 containing eRASS1 available since 31st January 2024
  → Raw data and data products



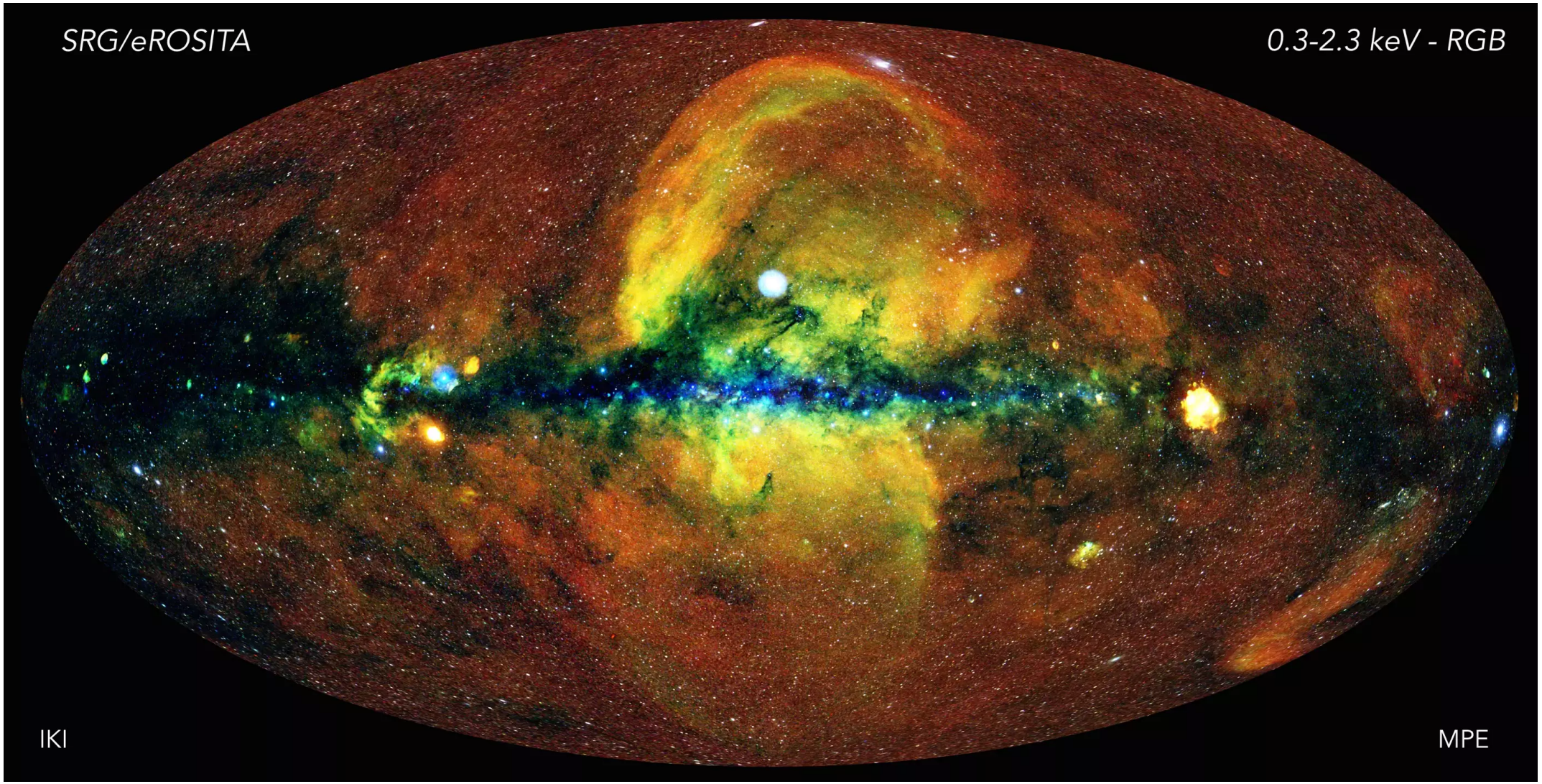
Credit: Roscosmos/DLR/SRG/Lavochkin



Credit: Predehl et al., 2021

eROSITA

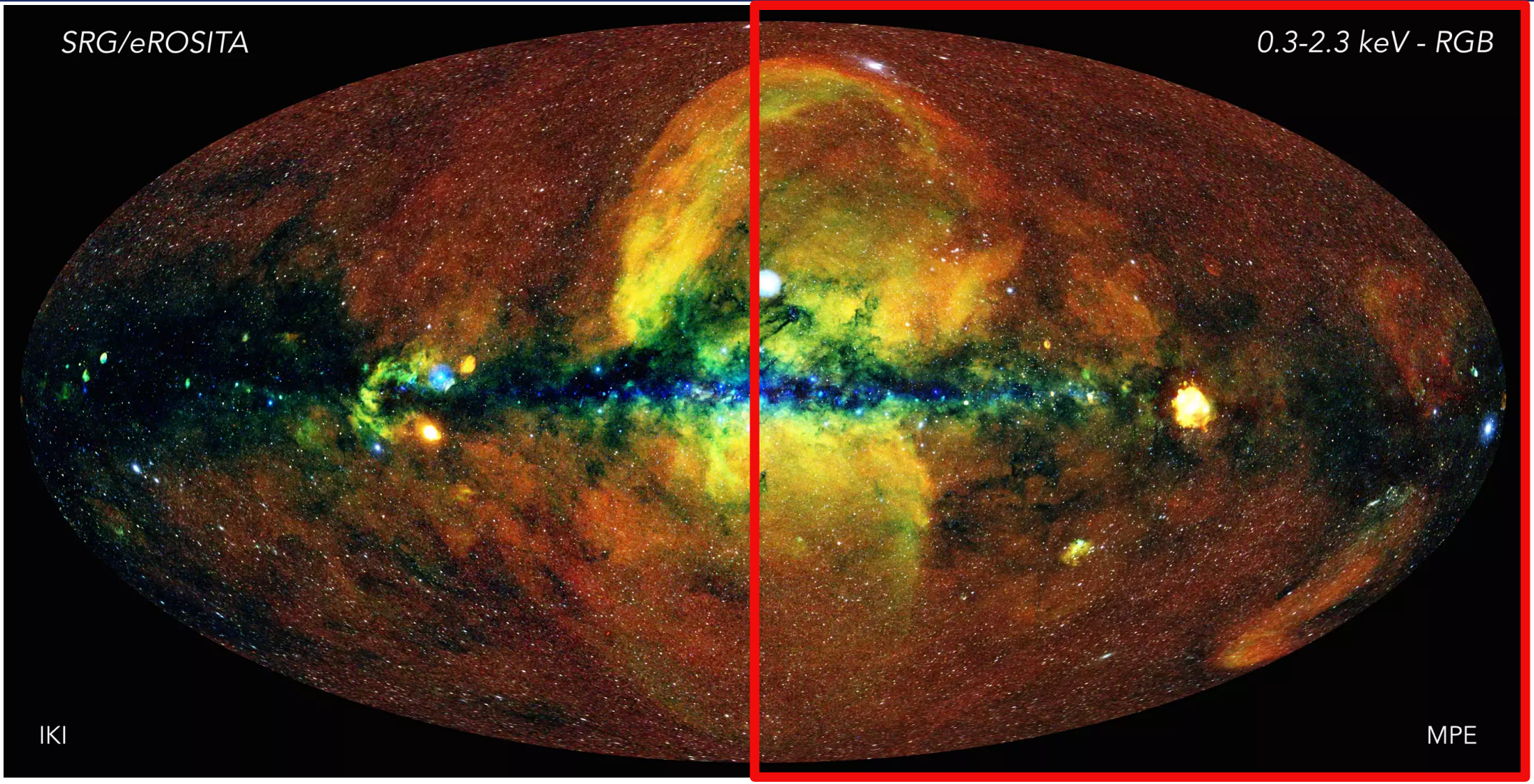
eRASS1 all-sky survey: DR1 available since 31st January 2024



Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)

eROSITA

eRASS1 all-sky survey: DR1 available since 31st January 2024



Credit: Jeremy Sanders, Hermann Brunner and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI)

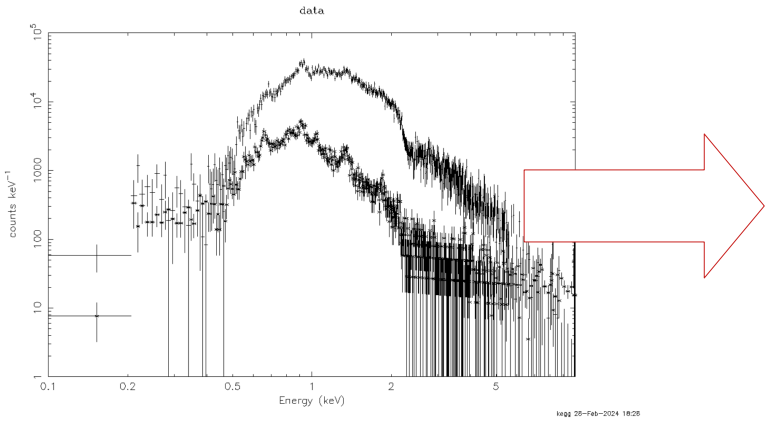
1D eROSITA spectra in Gammapy

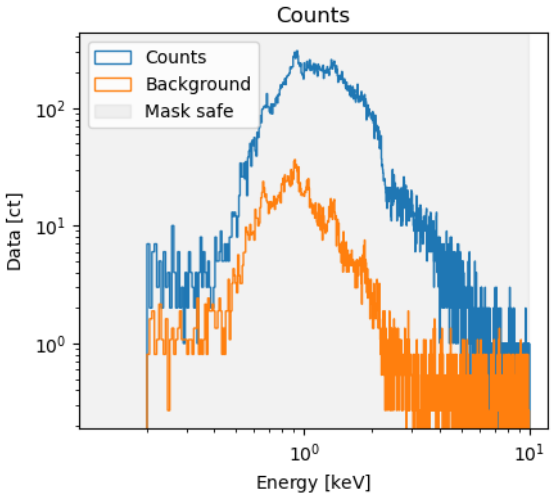
- OGIP spectrum Reader available : **OGIPDatasetReader**

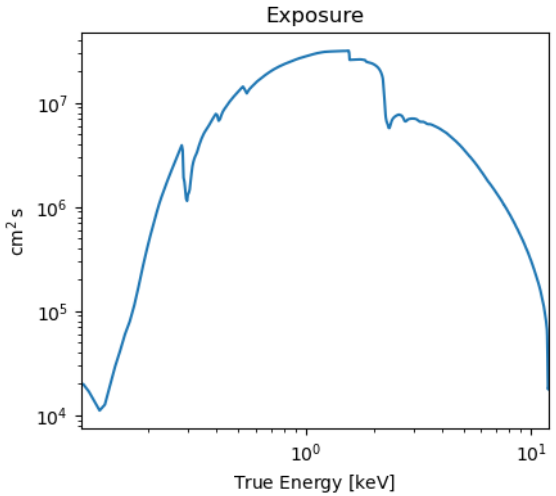
  → Tests: problems with eROSITA spectra and IRF file formats (→ gammapy-mwl)

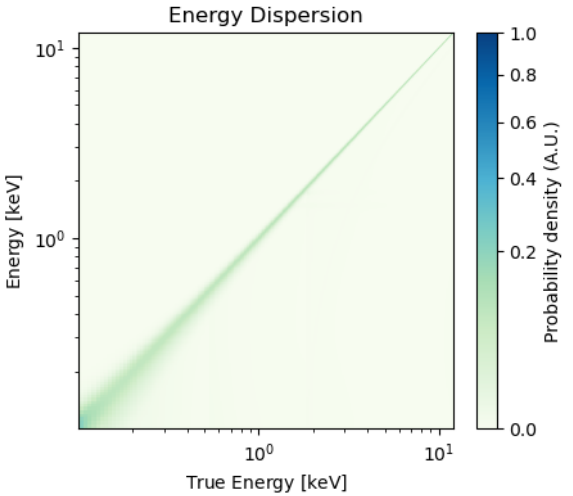
- Adjustments to the files → developed an **OGIPconverter** function

→ 1D eROSITA spectra: success!









3D analysis in Gammapy

What is needed?

Files
- **Eventfile**

IRFs
- **E**nergy**Disp**ersion
- **Exposure (eff**ective **A**rea)
- **P**oint **S**pread **F**unction
- Background

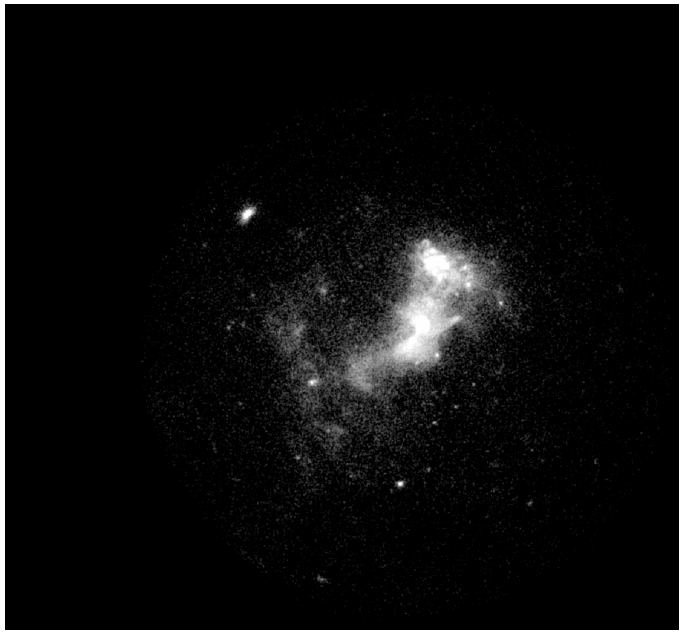
Models
- X-ray models

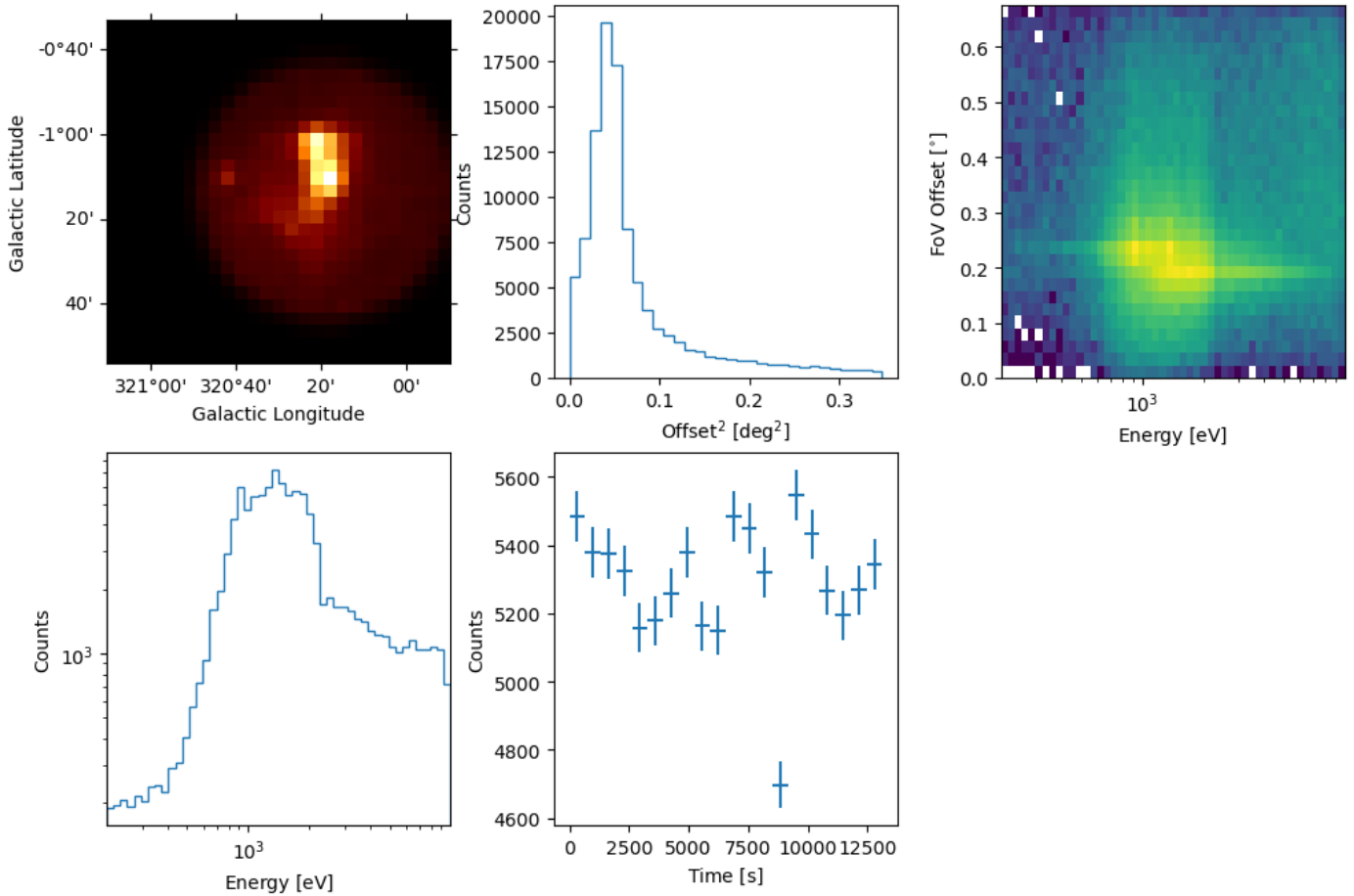
3D analysis in Gammapy

Eventfiles

→ Small adjustments (e.g. keyword changes) necessary → developed an **Evtfile_converter** function

→ Read in as **EventList** with accompanying **GTI**





3D analysis in Gammapy

What is needed?

Files
- **Eventfile** ✓

IRFs
- **E**nergy**Disp**ersion
- **Exposure (eff**ective **A**rea)
- **P**oint **S**pread **F**unction
- Background

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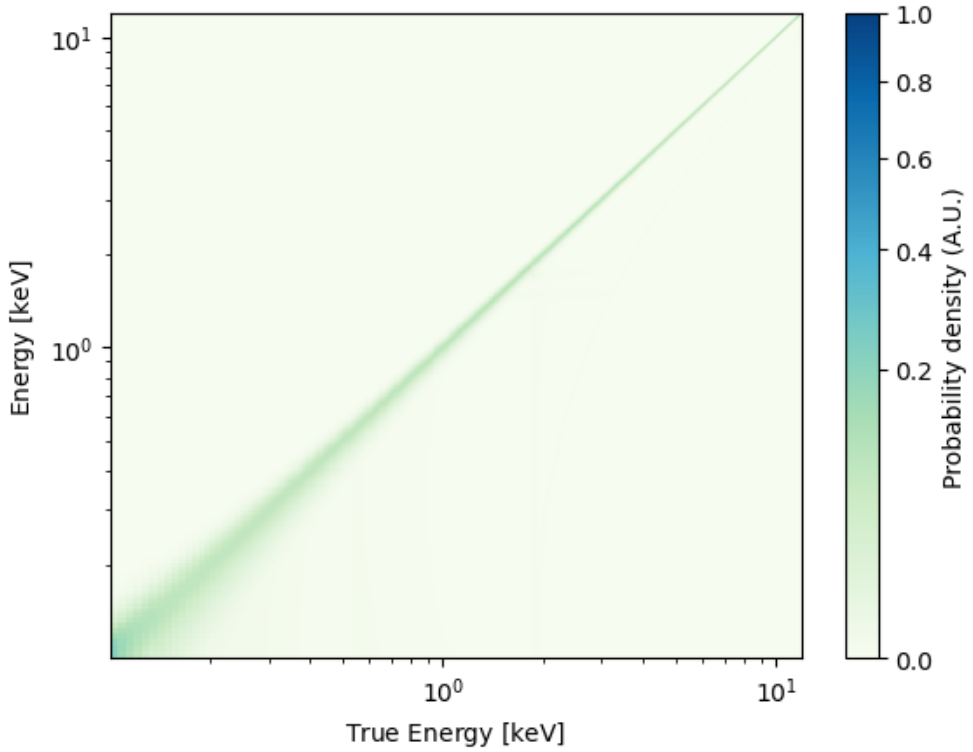
3D analysis in Gammapy

Edisp/eROSITA RMF

- RMF: **R**edistribution **M**atrix **F**ile
- Constant RMF for all data
- Read in as **EdispKernel** using **RMFconverter**

  → Could be removed with small change in Gammapy source code



3D analysis in Gammapy

What is needed?

Files

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IRFs

- **E**nergy**Disp**ersion ✓
- **Exposure (eff**ective **A**rea)
- **P**oint **S**pread **F**unction
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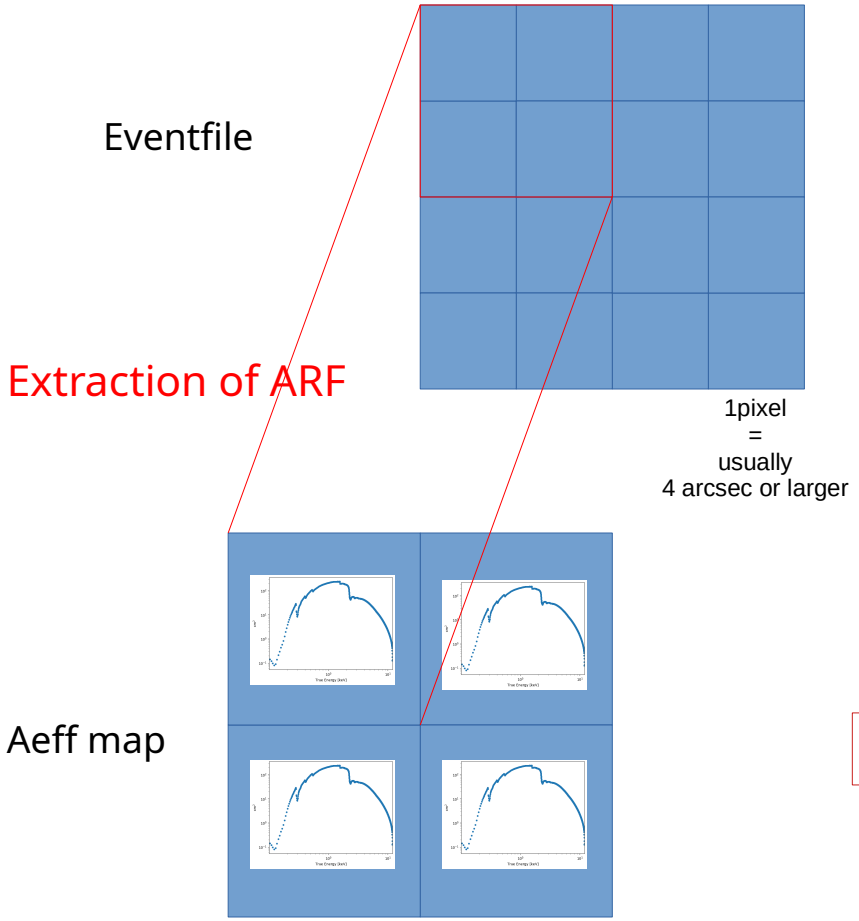
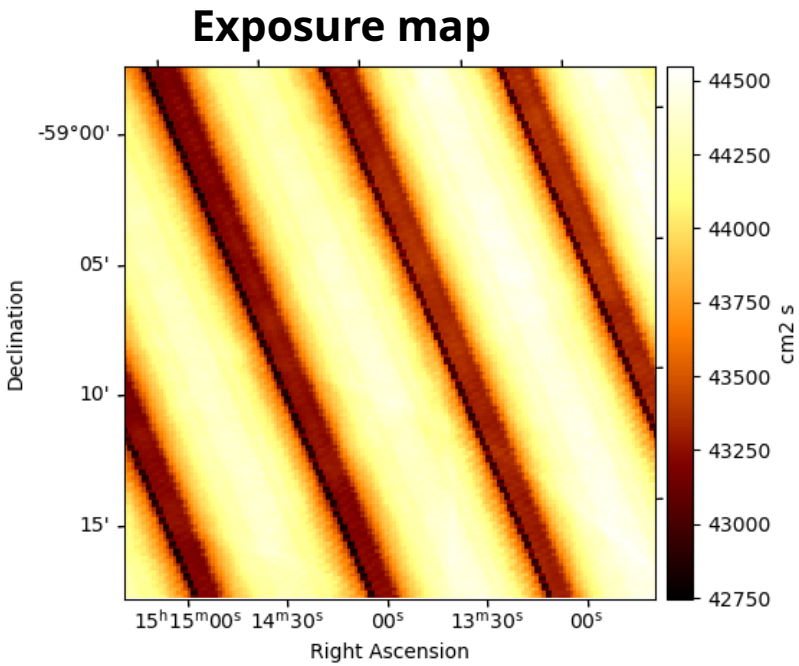
3D analysis in Gammapy

ARF 3D map



- X-rays: ARF, 1D Aeff file
- ARF extraction over 4 pixels (or more)
- 3D map of Aeff
- Multiplied with exposure time map:
  → Read in as WcsNDMap

→ eROSITA scans causes stripes - DR1



3D analysis in Gammapy

What is needed?

Files

- **Eventfile** ✓

IRFs

- **E**nergy**Disp**ersion ✓
- **Exposure (eff**ective **A**rea) ✓
- **P**oint **S**pread **F**unction
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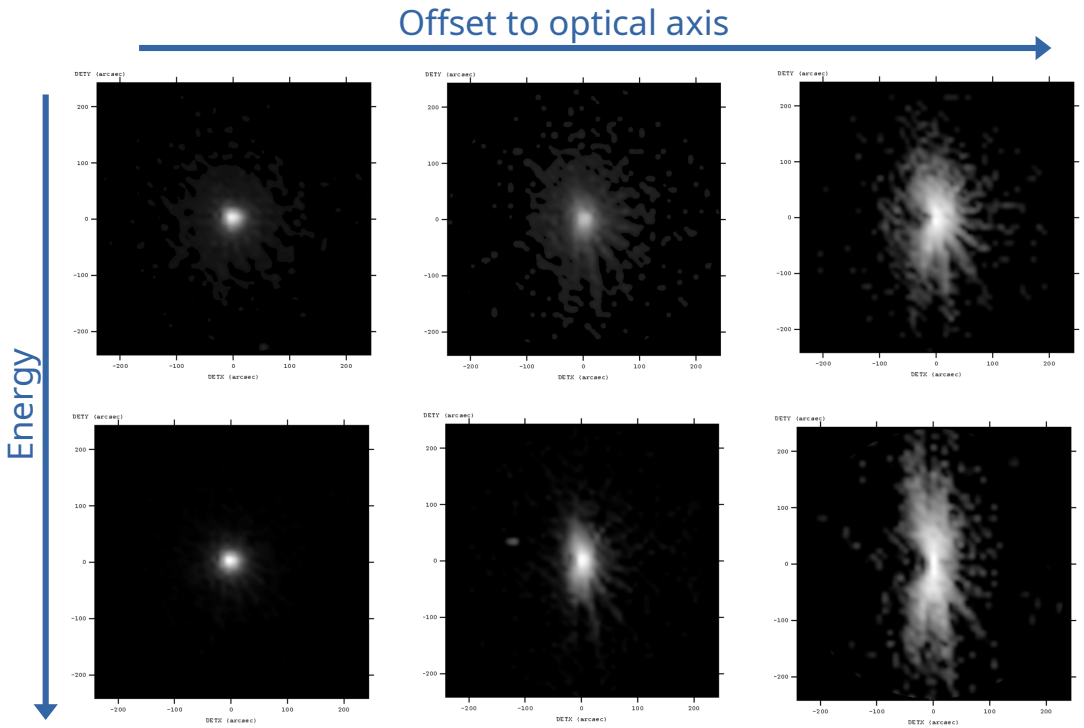
3D analysis in Gammapy

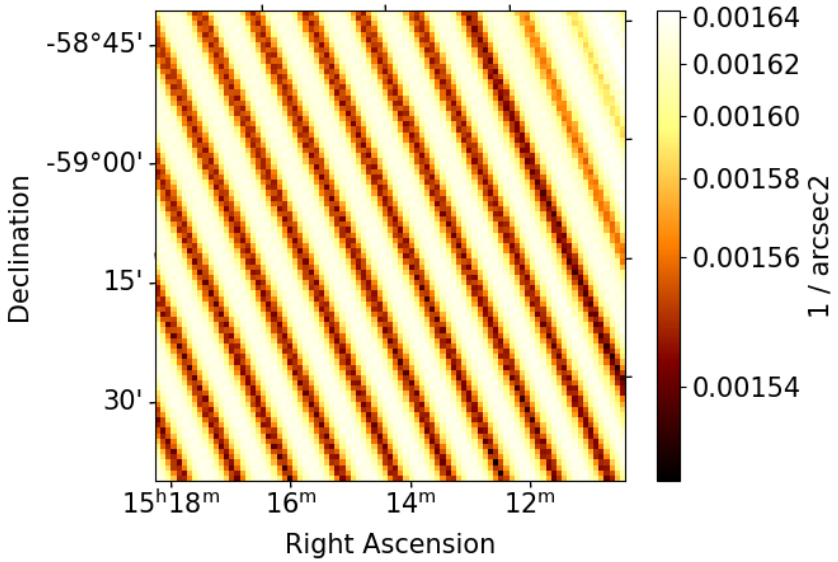
eROSITA PSF



Solution for POINTING mode data (some EDR eROSITA data)

- Radial averaging over images

  → Read into Gammapy as **PSFTable**



Solution for SURVEY mode data (DR1 eROSITA data)

- Manual mixing of radially averaged PSFs using data on eROSITA pointing direction (+ weighting with effective area)
- Read into Gammapy as **PSFMap**

3D analysis in Gammapy

What is needed?

Files

- **Eventfile** ✓

IRFs

- **E**nergy**Disp**ersion ✓
- **Exposure (eff**ective **A**rea) ✓
- **P**oint **S**pread **F**unction ✓
- Background

Models

- X-ray models

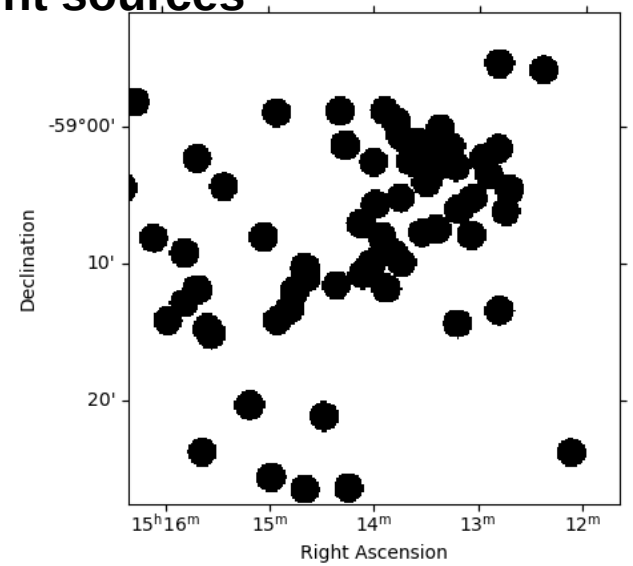
3D analysis in Gammapy

Background

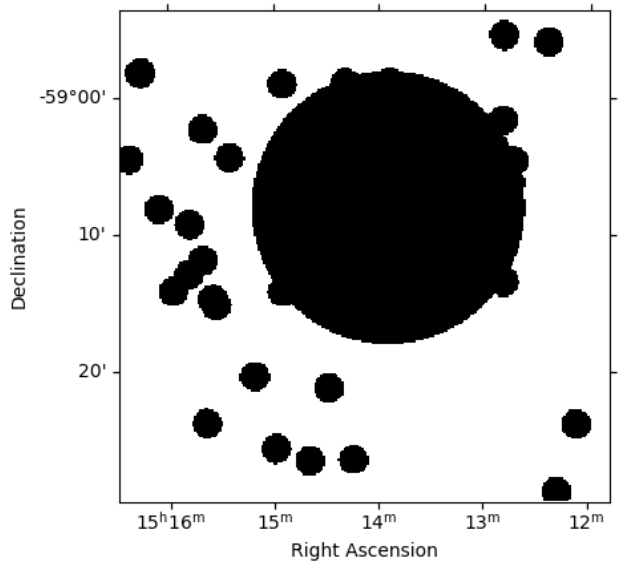
- Eventually: background fitting
- Now: background subtraction → filter region of catalog point sources with mask

→ ON/OFF background using an average spectrum of a background region,
functionally equivalent to X-ray background subtraction

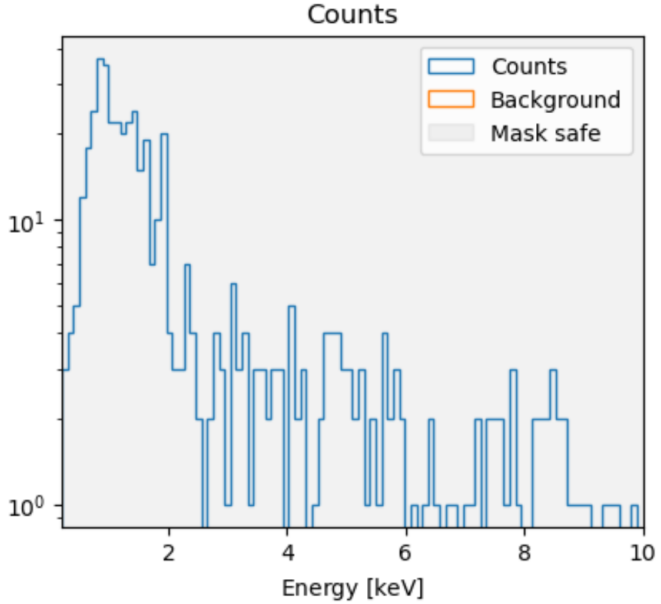
Exclude eROSITA catalog point sources



Widely exclude source region



Extract background spectrum



3D analysis in Gammapy

What is needed?

Files

- **Eventfile** ✓

IRFs

- **E**nergy**Disp**ersion ✓
- **Exposure (eff**ective **A**rea) ✓
- **P**oint **S**pread **F**unction ✓
- Background ✓

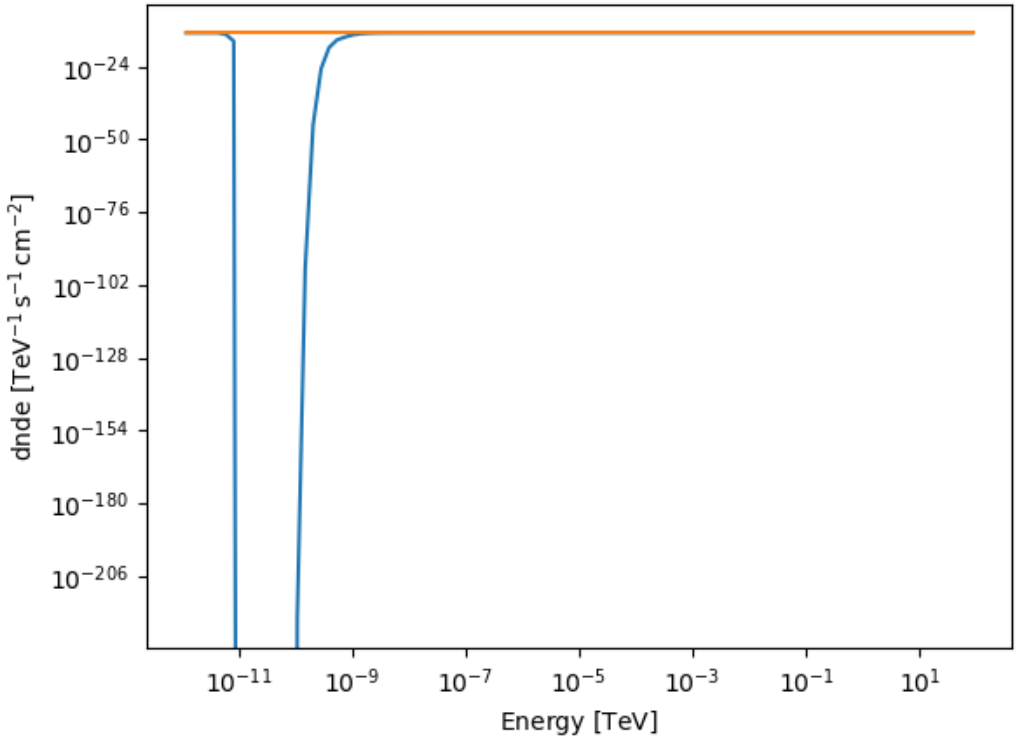
Models

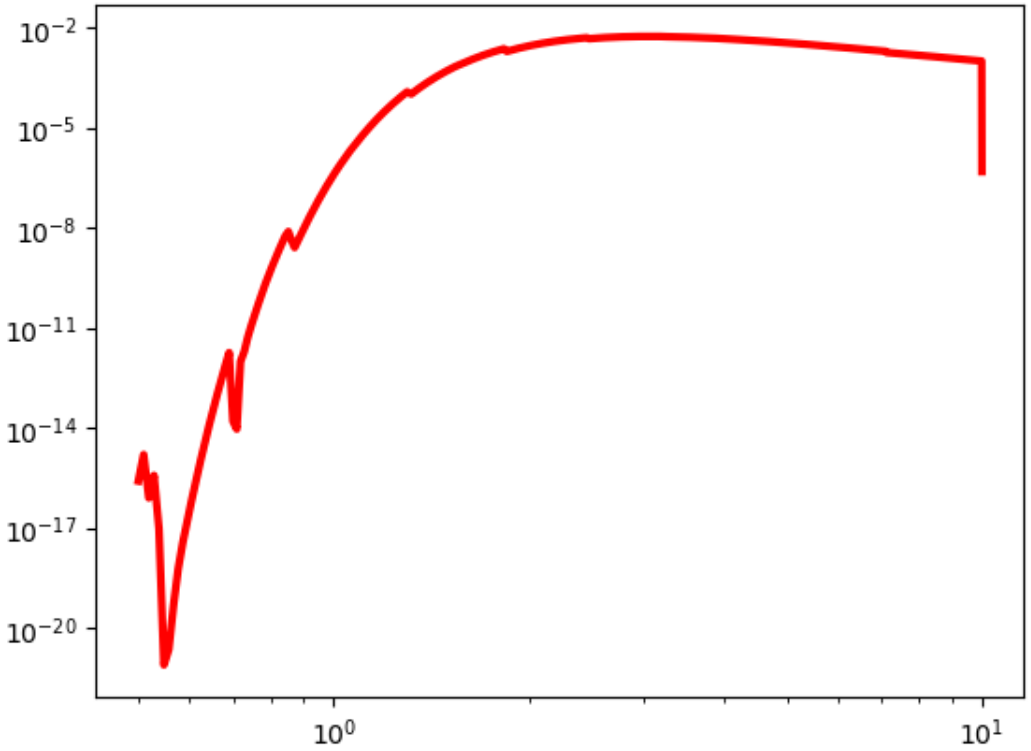
- X-ray models

3D analysis in Gammapy

X-ray models

→ Successful integration of Xspec models into gammapy via sherpa wrapper by Luca Giunti
(→ https://github.com/luca-giunti/gammapyXray) (with slight modifications)





3D analysis in Gammapy

What is needed?

Files

- **Eventfile** ✓

IRFs

- **E**nergy**Disp**ersion ✓
- **Exposure (eff**ective **A**rea) ✓
- **P**oint **S**pread **F**unction ✓
- Background ✓

Models

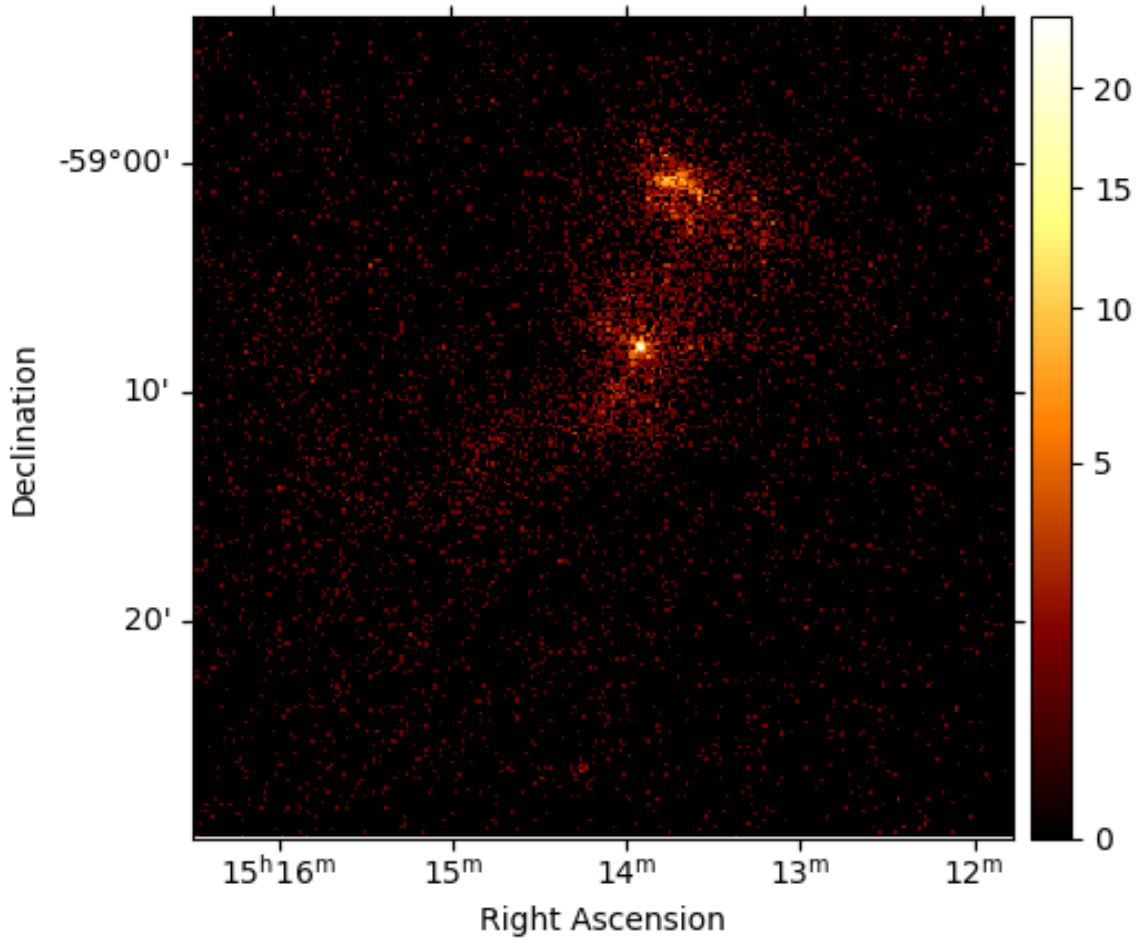
- X-ray models ✓

eROSITA datasets in Gammapy

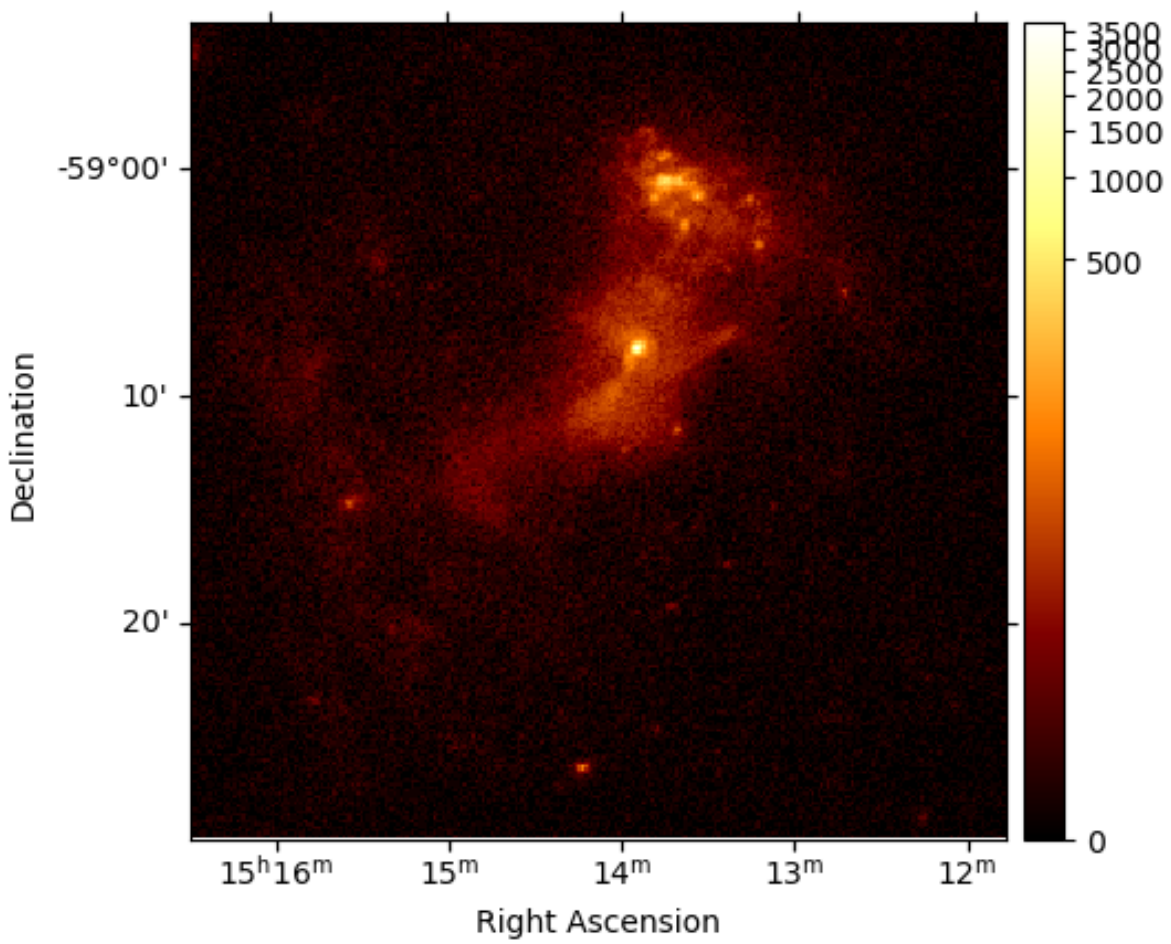
→ Bring all maps together in a **MapDatasetOnOff**

Example: application to PWN MSH 15-52

DR1 stacked dataset:



EDR stacked dataset:



eROSITA data in Gammapy

Automatization

- Automatization of producing and reading data with custom class **eROdata**

  → only a few commands necessary to create and save eROSITA datasets in Gammapy

- Functional but still being improved!

```
data=eROdata(path+"evtfiles.txt",path+"region.reg",path,tms=[1,2,3,4,6],dr1=True)

data.eSASS_data_products()
data.arf_q_cmd(2)
data.psf_map_cmd(20)
data.convert_files(add_pointing=True)
data.load_data(wid=1.0*u.deg)
```

```
data2=eROdata(path+"evtfiles.txt",path+"region.reg",path,tms=[1,2,3,4,6],dr1=True)

data2.find_data_products()
data2.load_data()
```

```
data.background_spectrum(data2,on_off=True,exp=True,ext_mask=path+"mask_backgr.fits")
```

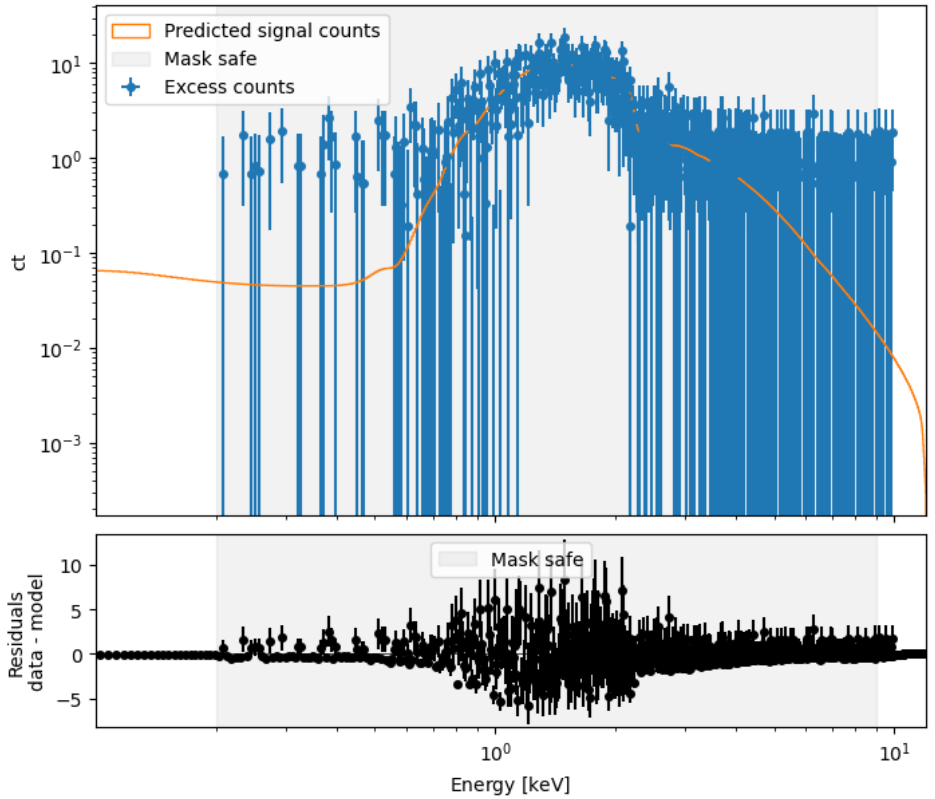
```
data.stack()
data.wstat_rebin(5)
```

```
data.write_to_files(tms=[1,2,3,4,6], stacked=True, filename=path+"dataset.fits.gz")
```

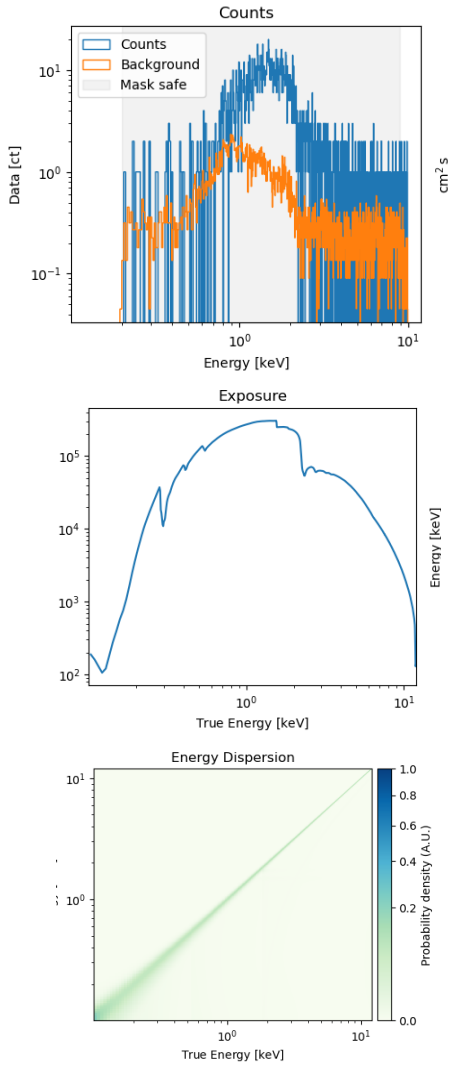
eROSITA data in Gammapy

OGIP spectra validation (preliminary)

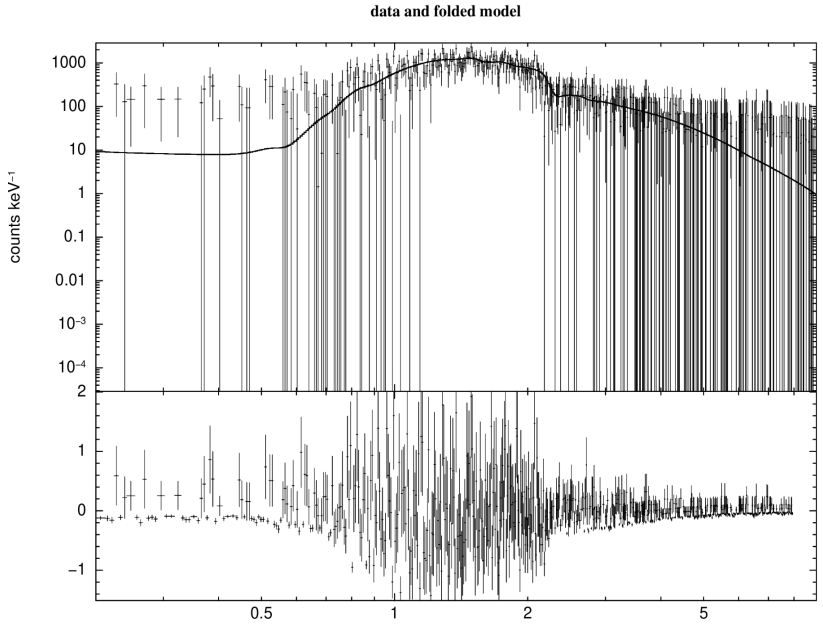
DR1 stacked (820) OGIP spectrum:



- PhoInd: 2.05 +/- 0.08
- Norm: 0.022 +/- 0.001



- Read OGIP spectrum into Gammapy
- Compare against OGIP spectrum in PyXspec

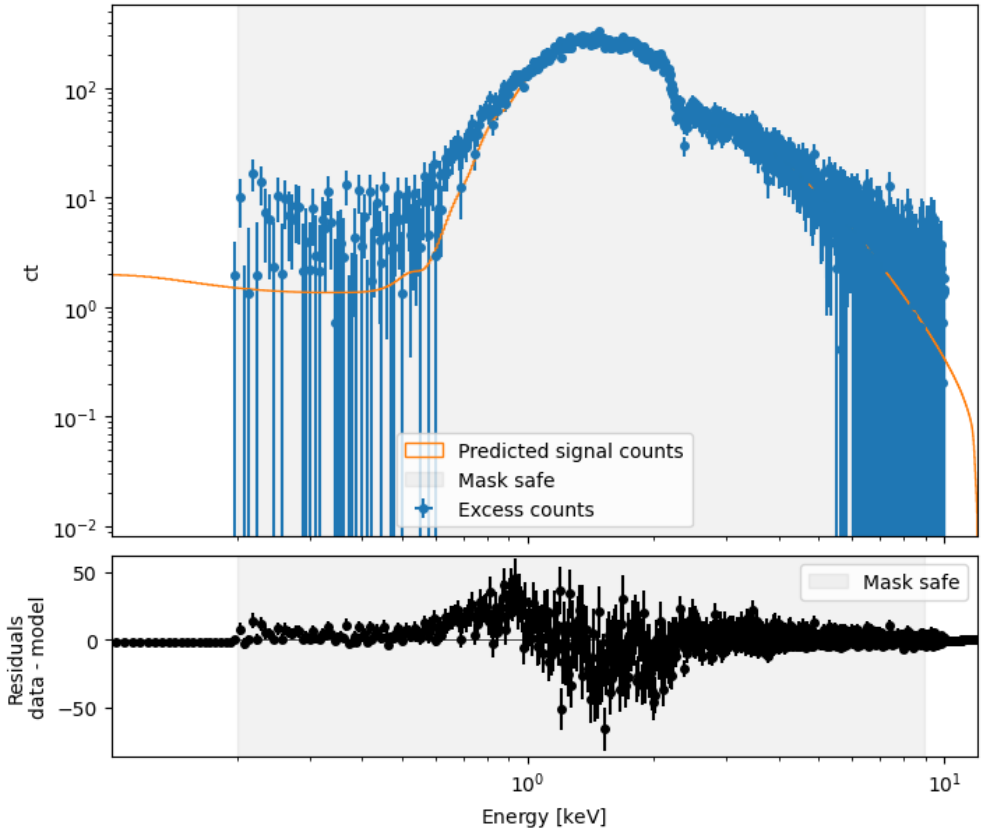


- PhoInd: 2.06 +/- 0.08
- Norm: 0.022 +/- 0.001

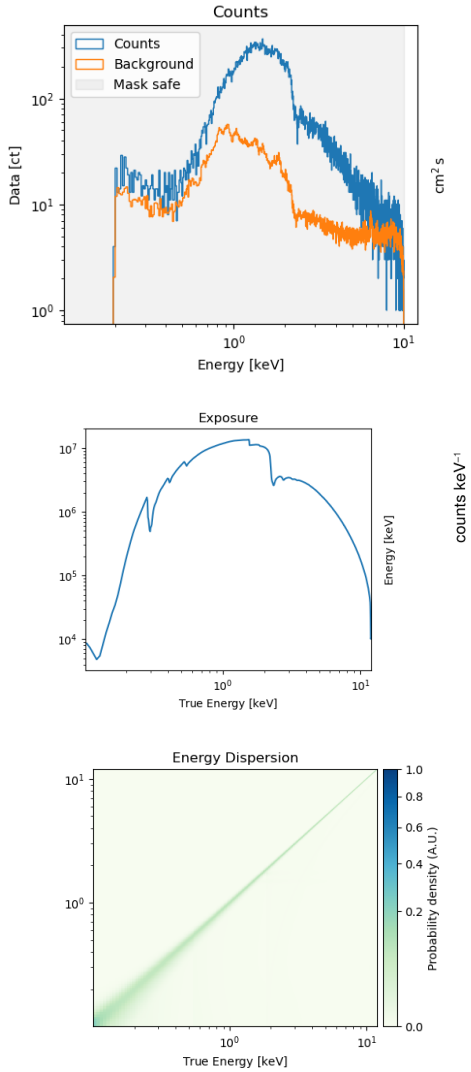
eROSITA data in Gammapy

OGIP spectra validation (preliminary)

EDR stacked (820) OGIP spectrum:

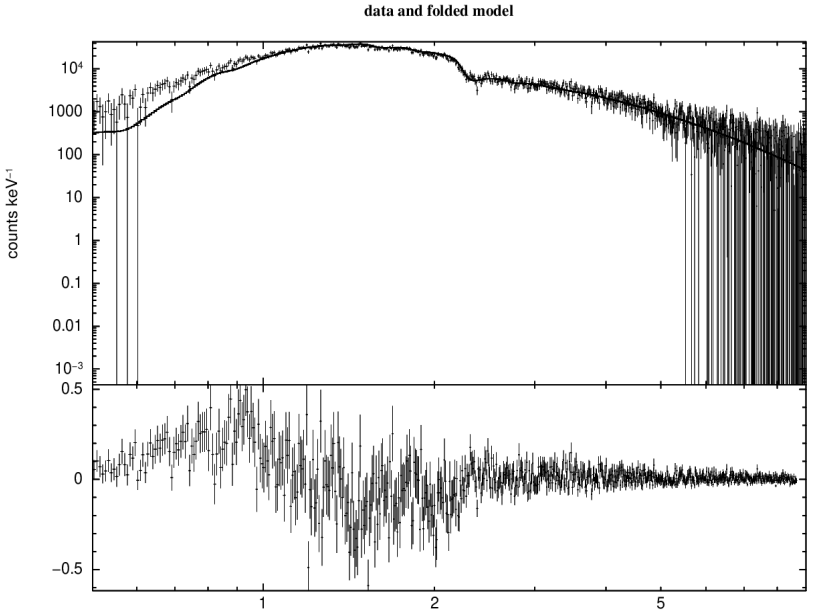


- PhoInd: 2.13 +/- 0.01
- Norm: 0.0153 +/- 0.0001



Read OGIP spectrum into Gammapy

Compare against OGIP spectrum in PyXspec

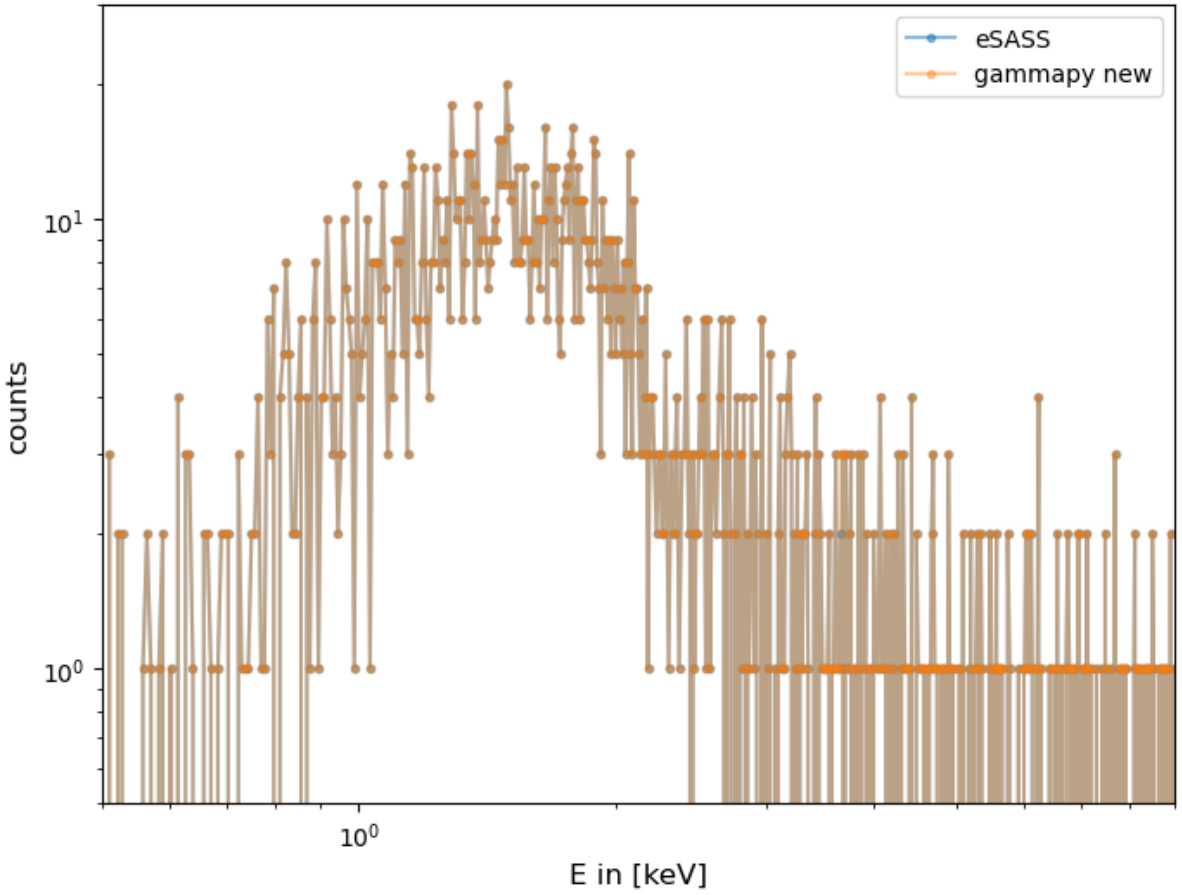


- PhoInd: 2.13 +/- 0.01
- Norm: 0.0153 +/- 0.0001

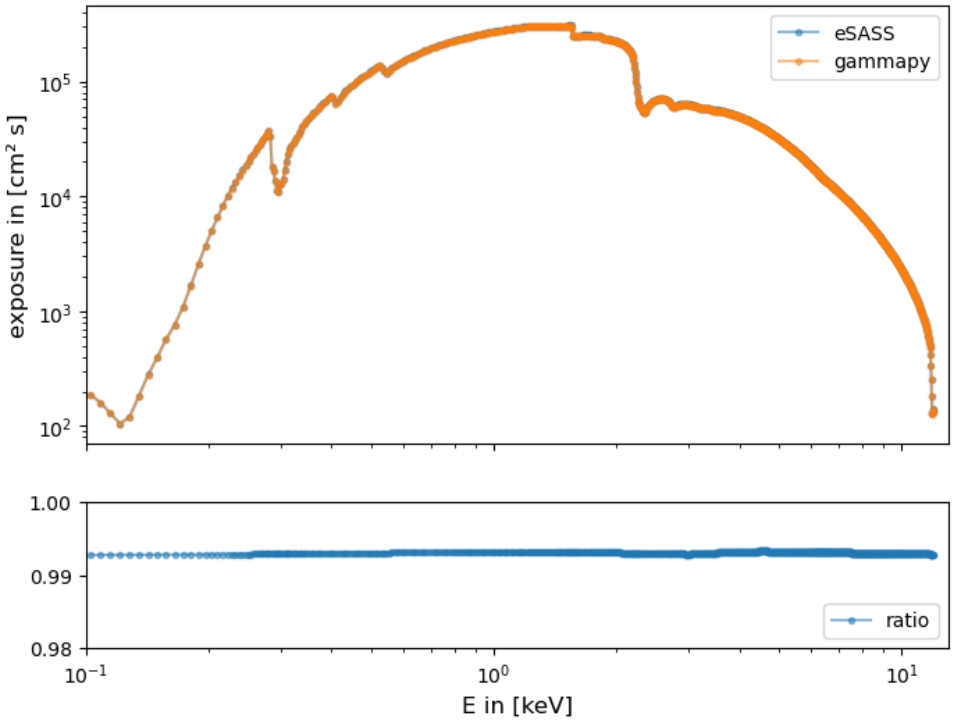
eROSITA data in Gammapy

3D dataset validation (preliminary)

DR1 stacked dataset:



- Extract spectrum from MapDatasetOnOff
- Compare against spectrum extracted with native software eSASS

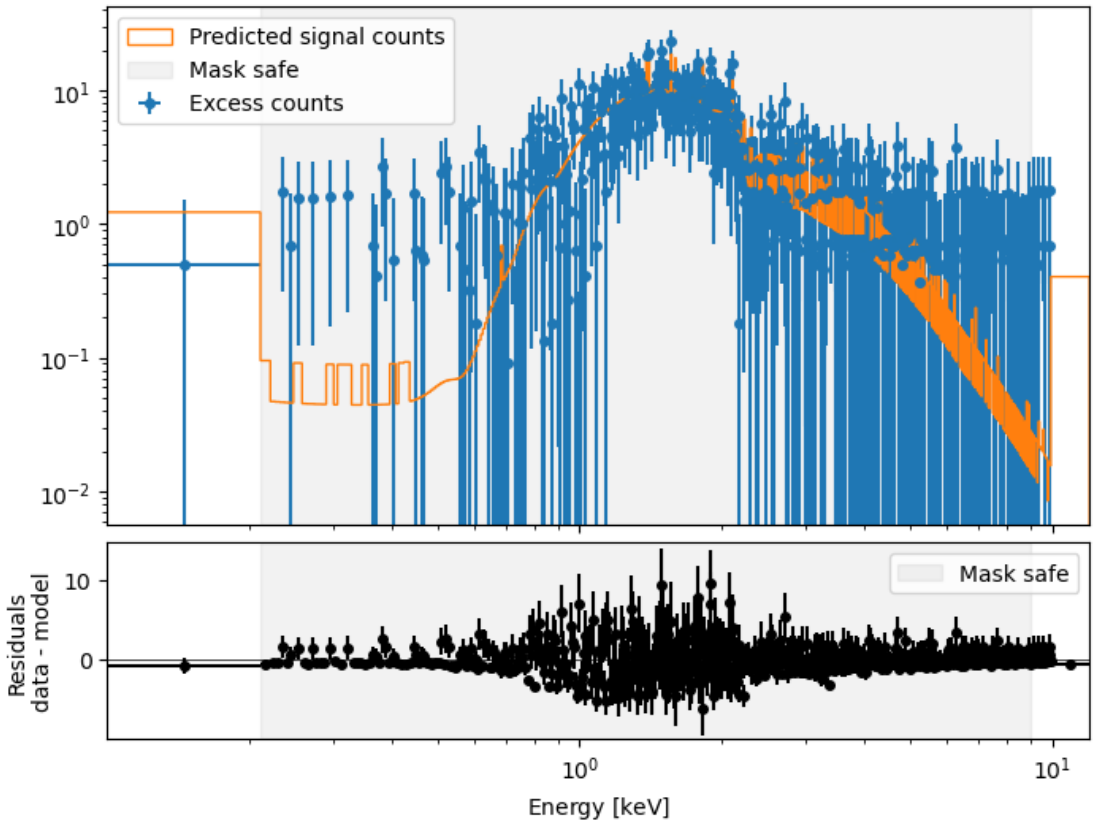


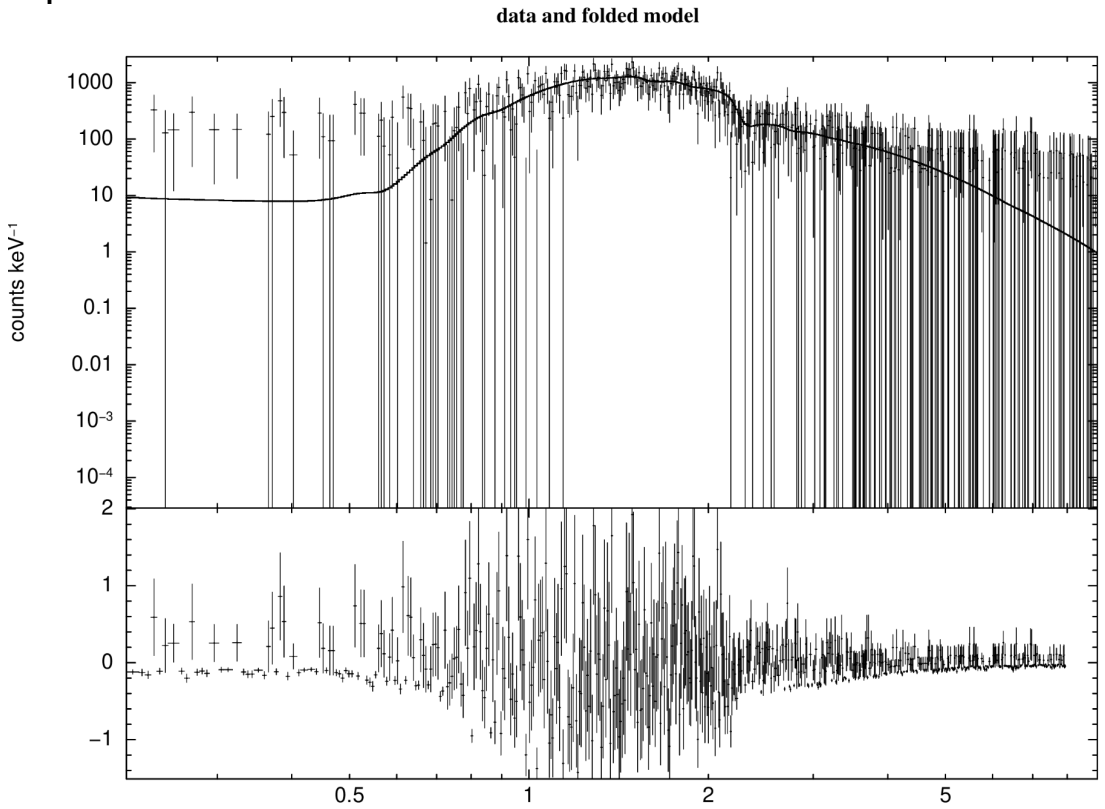
eROSITA data in Gammapy

3D dataset validation (preliminary)

DR1 stacked dataset:

- Compare Gammapy and PyXspec fit





- PhoInd: 2.07 +/- 0.08
- Norm: 0.022 +/- 0.001

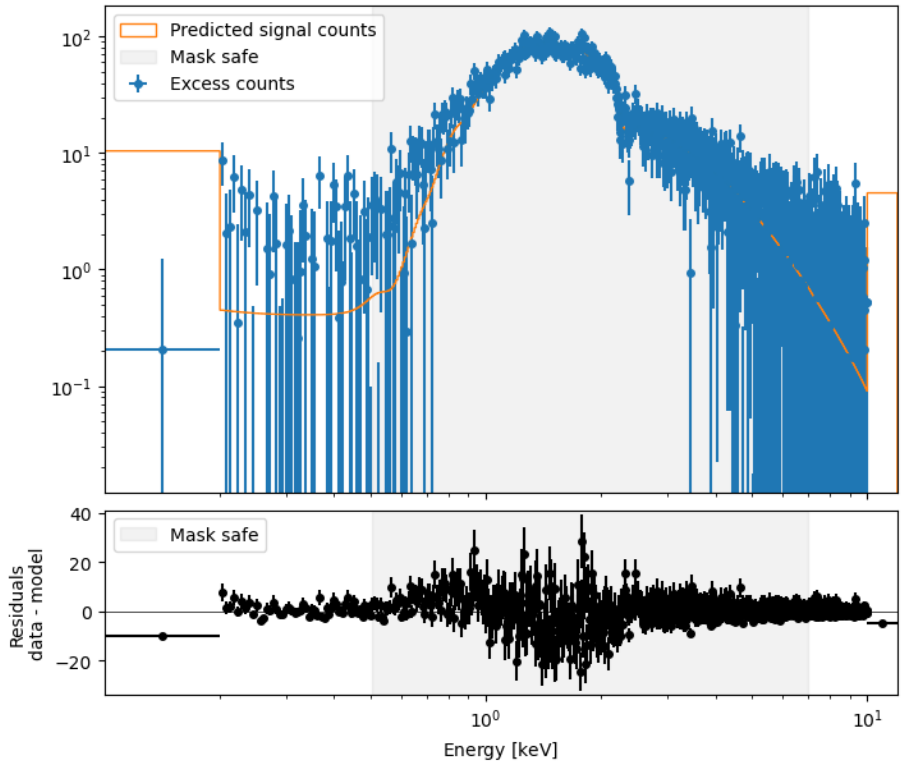
- PhoInd: 2.06 +/- 0.08
- Norm: 0.022 +/- 0.001

eROSITA data in Gammapy

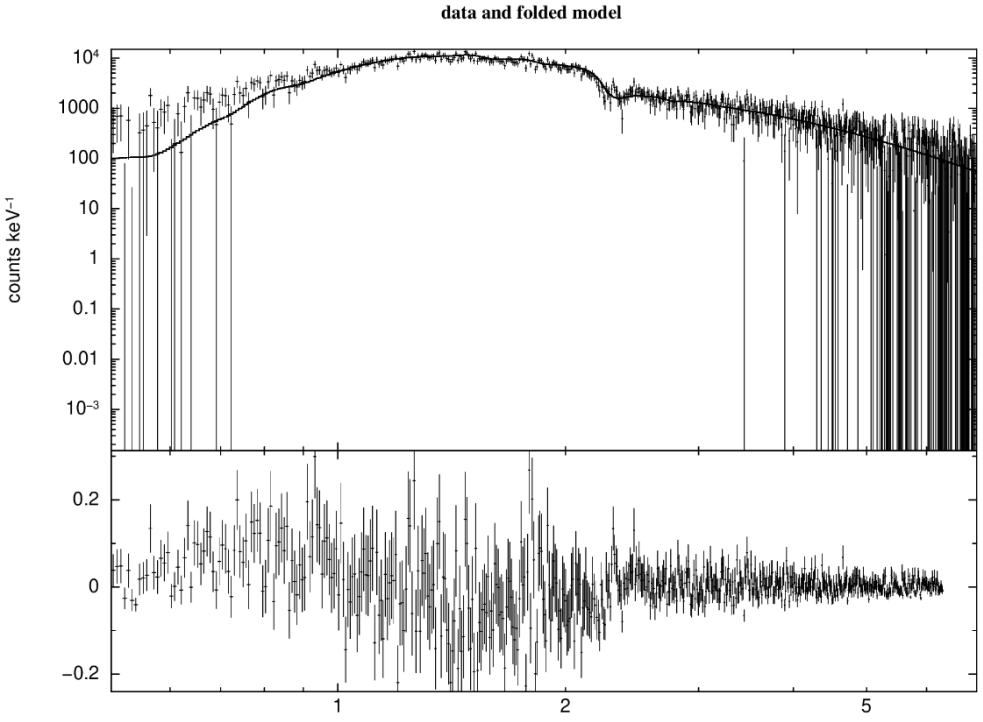
3D dataset validation (preliminary)

EDR TM1 dataset:

- Compare Gammapy and PyXspec fit



- PhoInd: 2.15 +/- 0.03
- Norm: 0.0157 +/- 0.0003



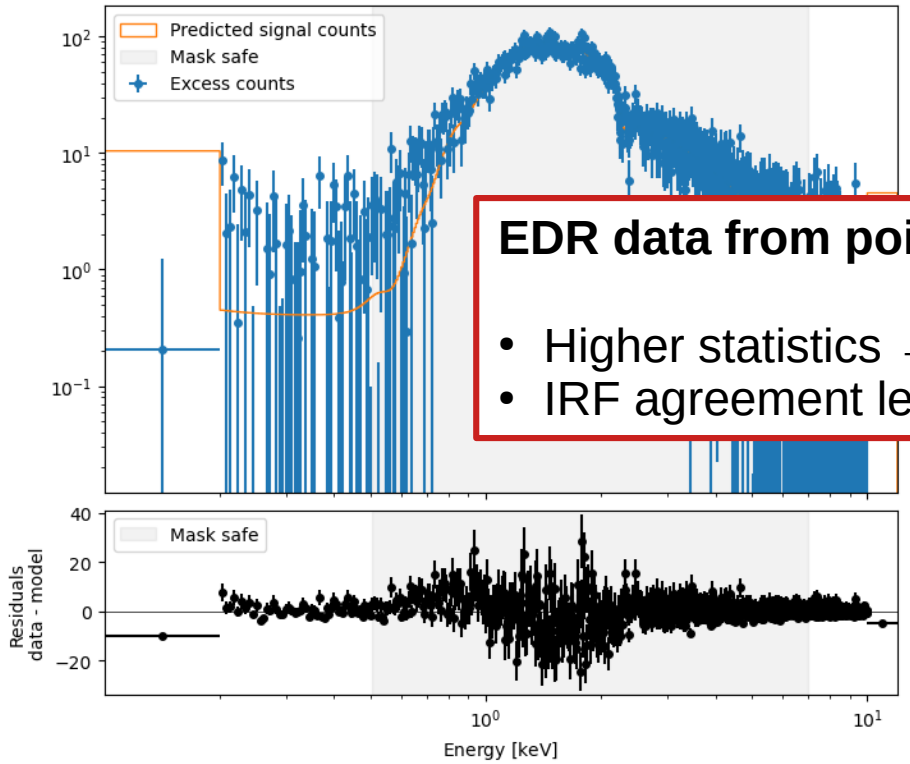
- PhoInd: 2.18 +/- 0.03
- Norm: 0.0159 +/- 0.0003

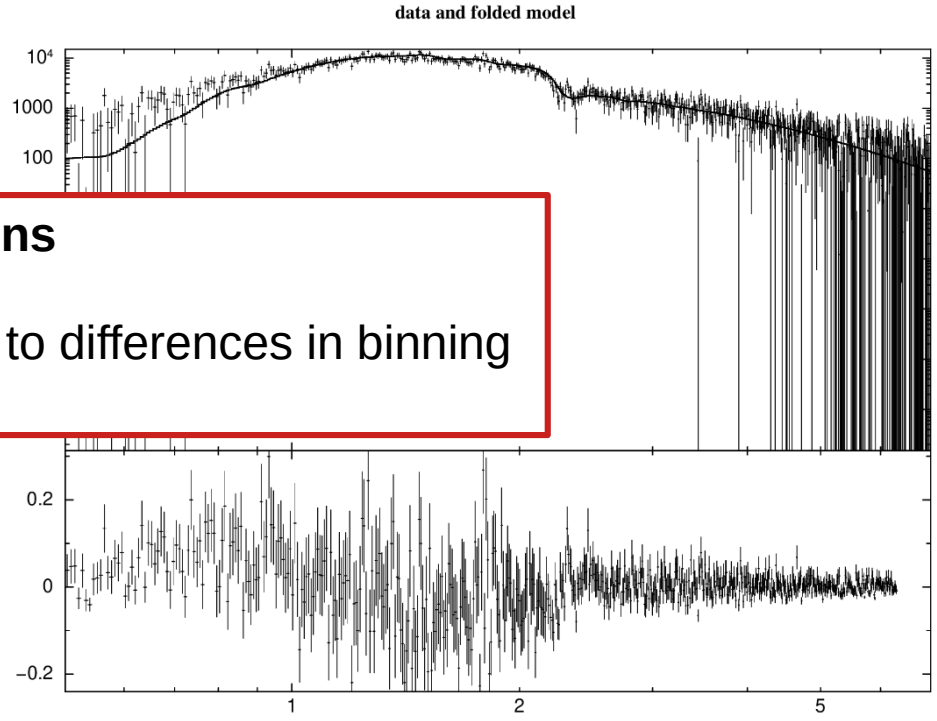
eROSITA data in Gammapy

3D dataset validation (preliminary)

EDR TM1 dataset:

- Compare Gammapy and PyXspec fit





EDR data from pointed observations

- Higher statistics → more sensitive to differences in binning
- IRF agreement less “good”

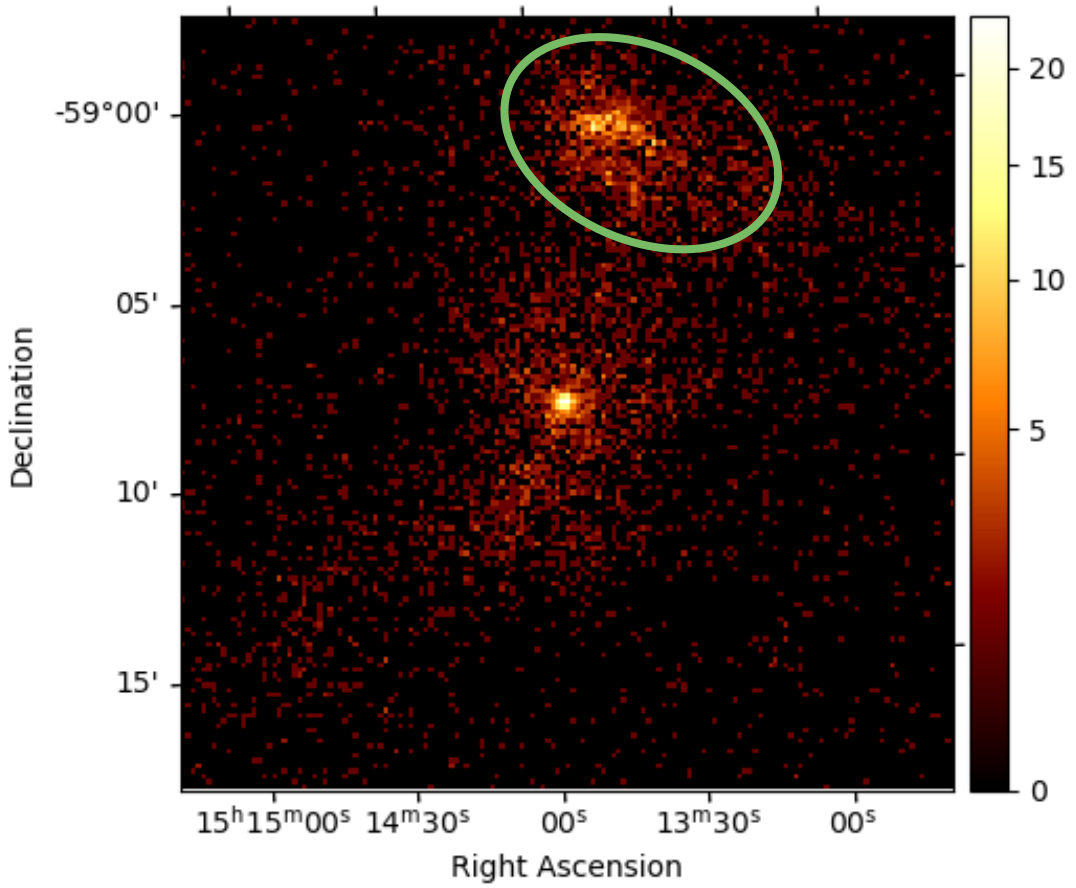
- PhoInd: 2.15 +/- 0.03
- Norm: 0.0157 +/- 0.0003

- PhoInd: 2.18 +/- 0.03
- Norm: 0.0159 +/- 0.0003

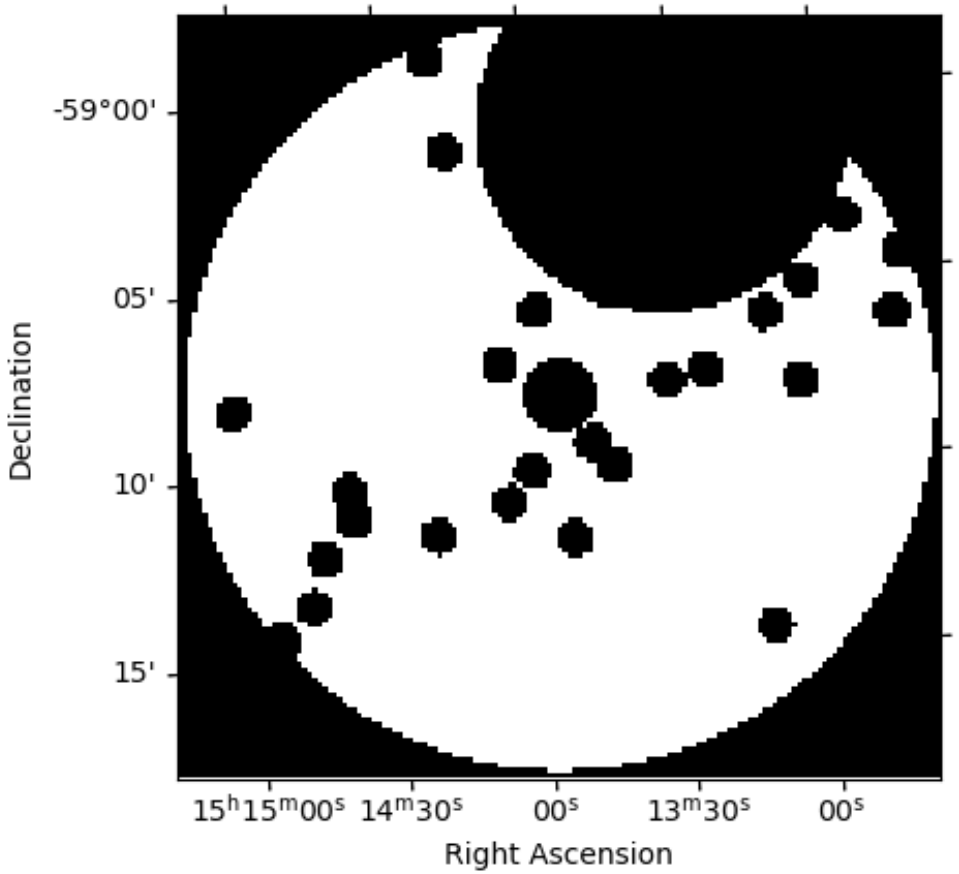
3D analysis in Gammapy

Sources

DR1 stacked dataset:



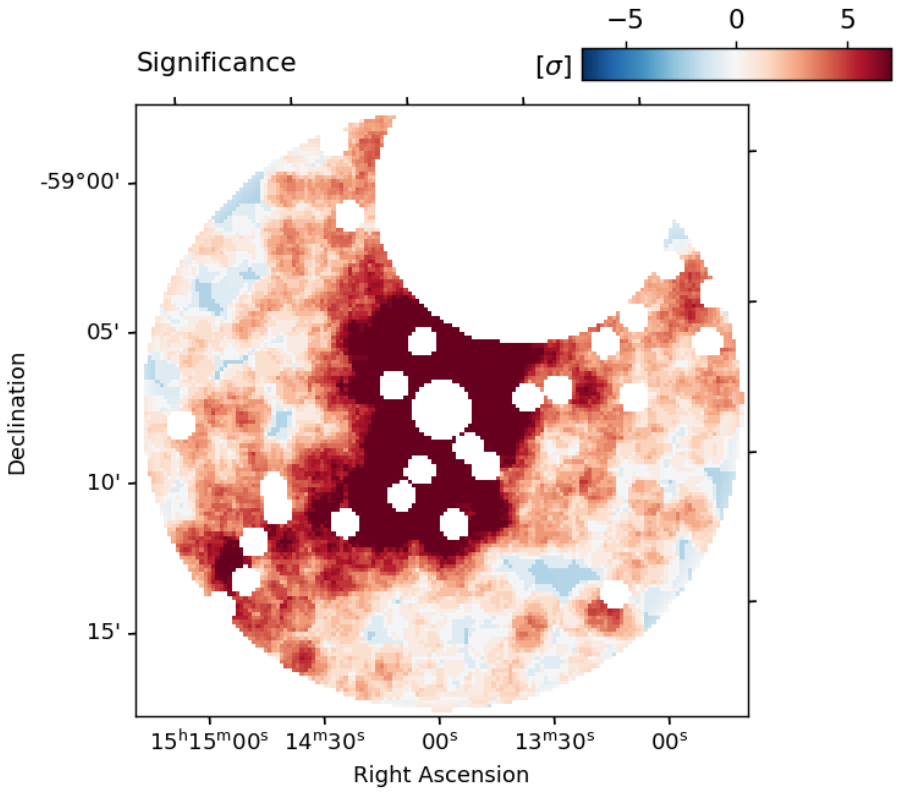
Mask:



3D fit of eROSITA data in Gammapy

DR1 data

Before fitting:



Model:

Spectral:

→ Absorbed powerlaw

`TBabs*powerlaw`

Spatial:

→ 2D Gaussian: $\phi(\mathrm{lon}, \mathrm{lat}) = \frac{1}{2\pi\sigma_{eff}^2}\left(-\frac{1}{2}\frac{\theta^2}{\sigma_{eff}^2}\right)$

with: $\sigma_{eff}(\mathrm{lon}, \mathrm{lat}) = \sqrt{(\sigma_M \sin(\Delta\phi))^2 + (\sigma_m \cos(\Delta\phi))^2}$

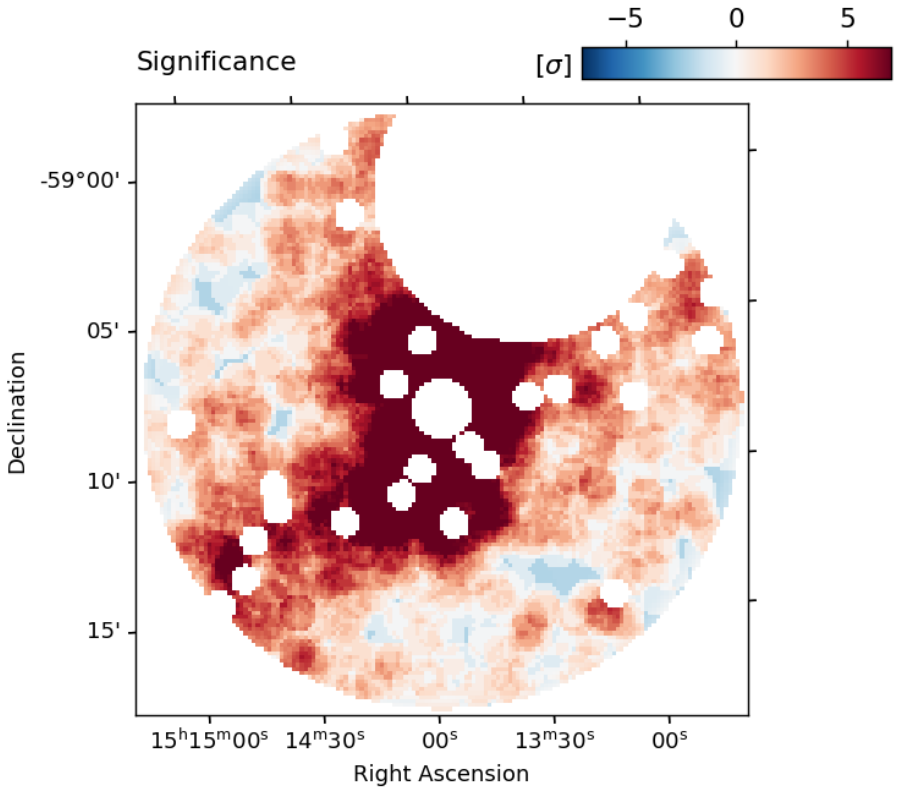
Results:

nH (frozen)	1.360		
PhoIndex	2.027	+/-	0.07
norm	0.042	+/-	0.004
lon_0	228.448	+/-	0.01 deg
lat_0	-59.106	+/-	0.01 deg
sigma	5.591	+/-	0.34 arcmin
e	0.894	+/-	0.01
phi	-38.653	+/-	1.72 deg

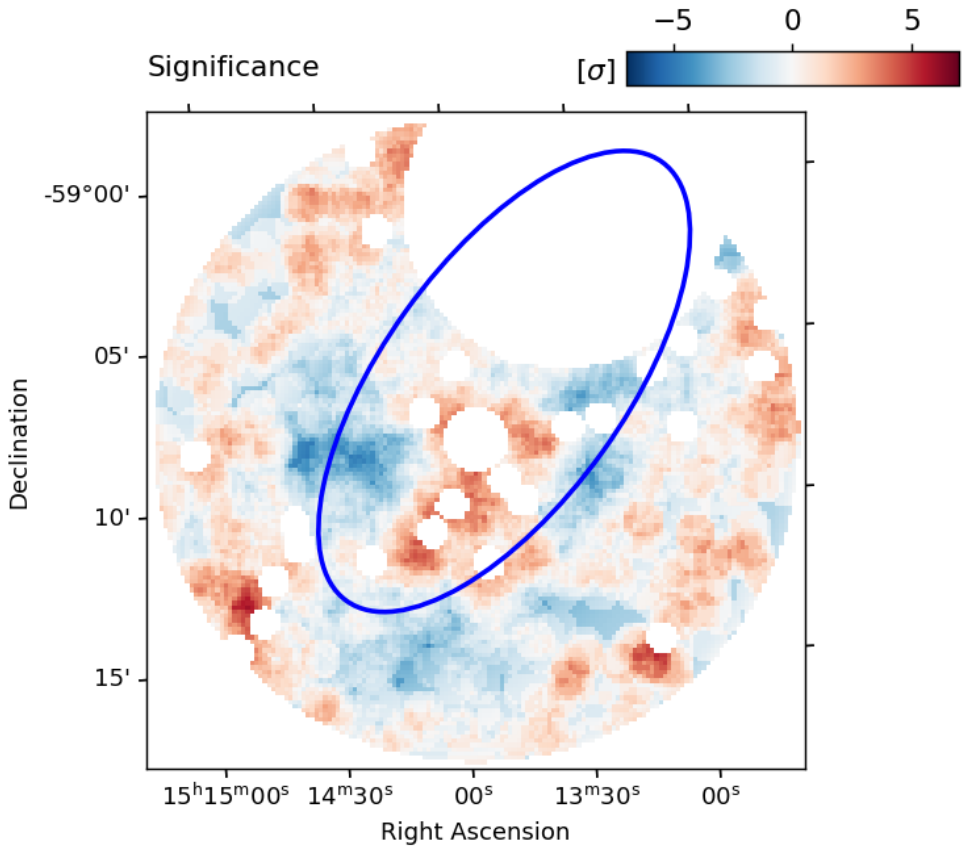
3D fit of eROSITA data in Gammapy

DR1 data

Before fitting:

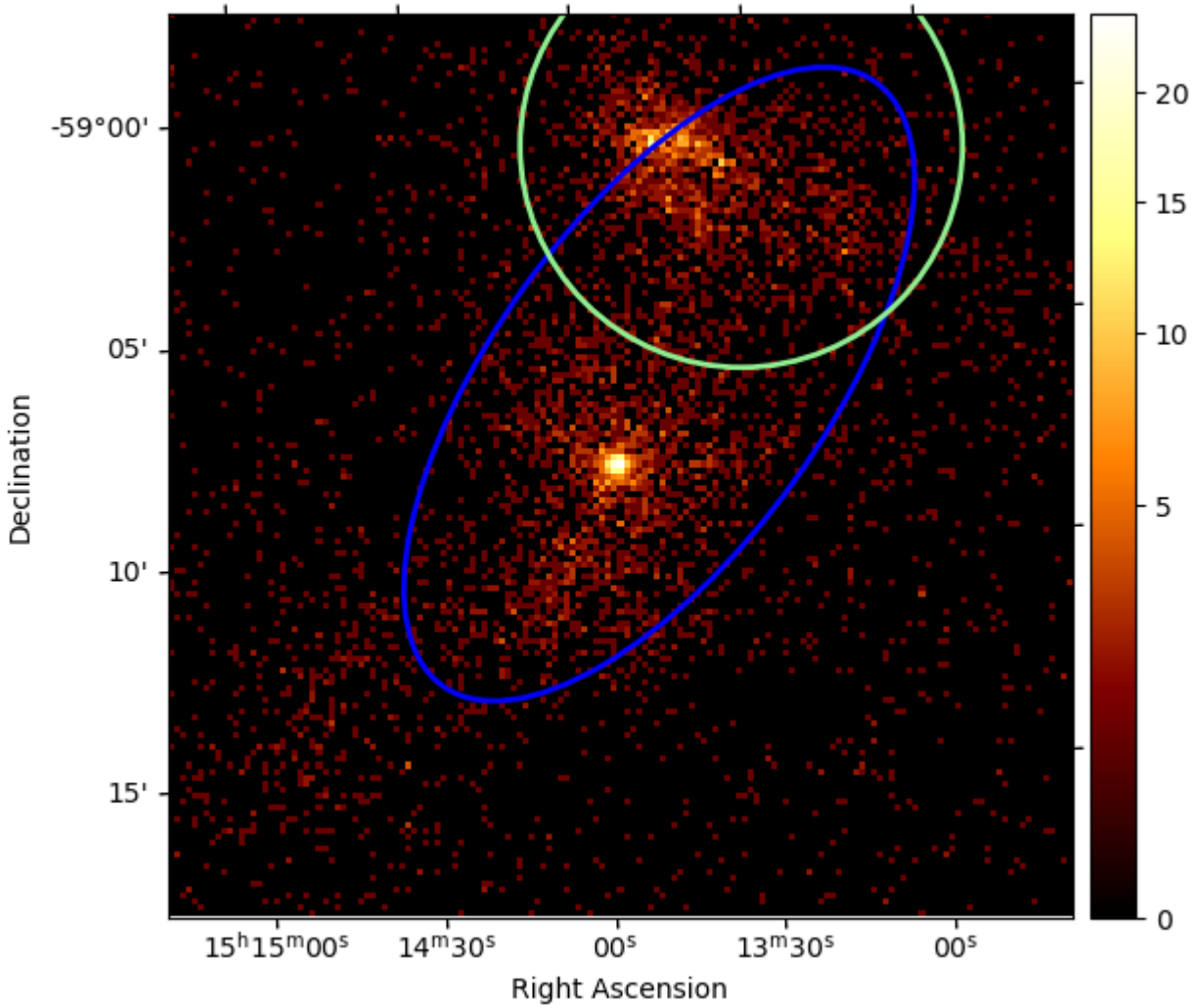


After fitting:



3D fit of eROSITA data in Gammapy

DR1 data



Spatial parameters:

lon_0	228.448	+/- 0.01 deg
lat_0	-59.106	+/- 0.01 deg
sigma	5.591	+/- 0.34 arcmin
e	0.894	+/- 0.01
phi	-38.653	+/- 1.72 deg

Joint fit of eROSITA, H.E.S.S., and Fermi data in Gammapy

Shared 3D model:

Spectral Model:
Two ExpCutoffPL models, multiplied with nH absorption: $\phi_{1,2}(E) = \phi_{0_{1,2}} \cdot \left(\frac{E}{E_{0_{1,2}}}\right)^{-\Gamma_{1,2}} \exp\left(-(\lambda_{1,2}E)^{\alpha_{1,2}}\right)$

→ $\phi_{\text{total}} = \text{TBabs} \cdot (\phi_1(E) + \phi_2(E))$

Spatial Model:
2D Gaussian → for both eROSITA and H.E.S.S. data

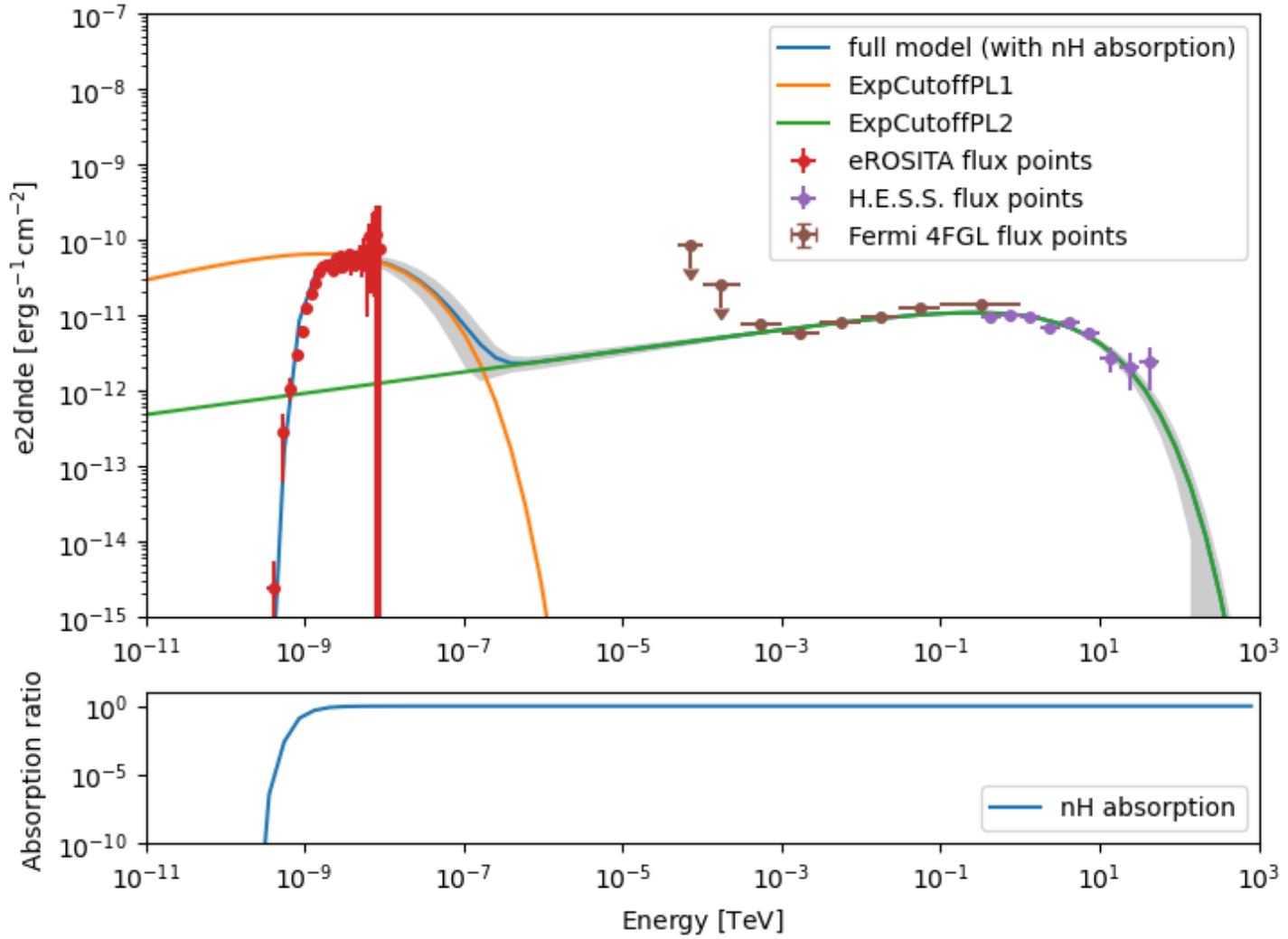
→ $\phi(\text{lon}, \text{lat}) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{1}{2}\frac{\theta^2}{\sigma^2}\right)$

$\sigma_{eff}(\text{lon}, \text{lat}) = \sqrt{(\sigma_M \sin(\Delta\phi))^2 + (\sigma_m \cos(\Delta\phi))^2}$

→ Preliminary: Work in progress

Joint fit of eROSITA, H.E.S.S., and Fermi data in Gammapy

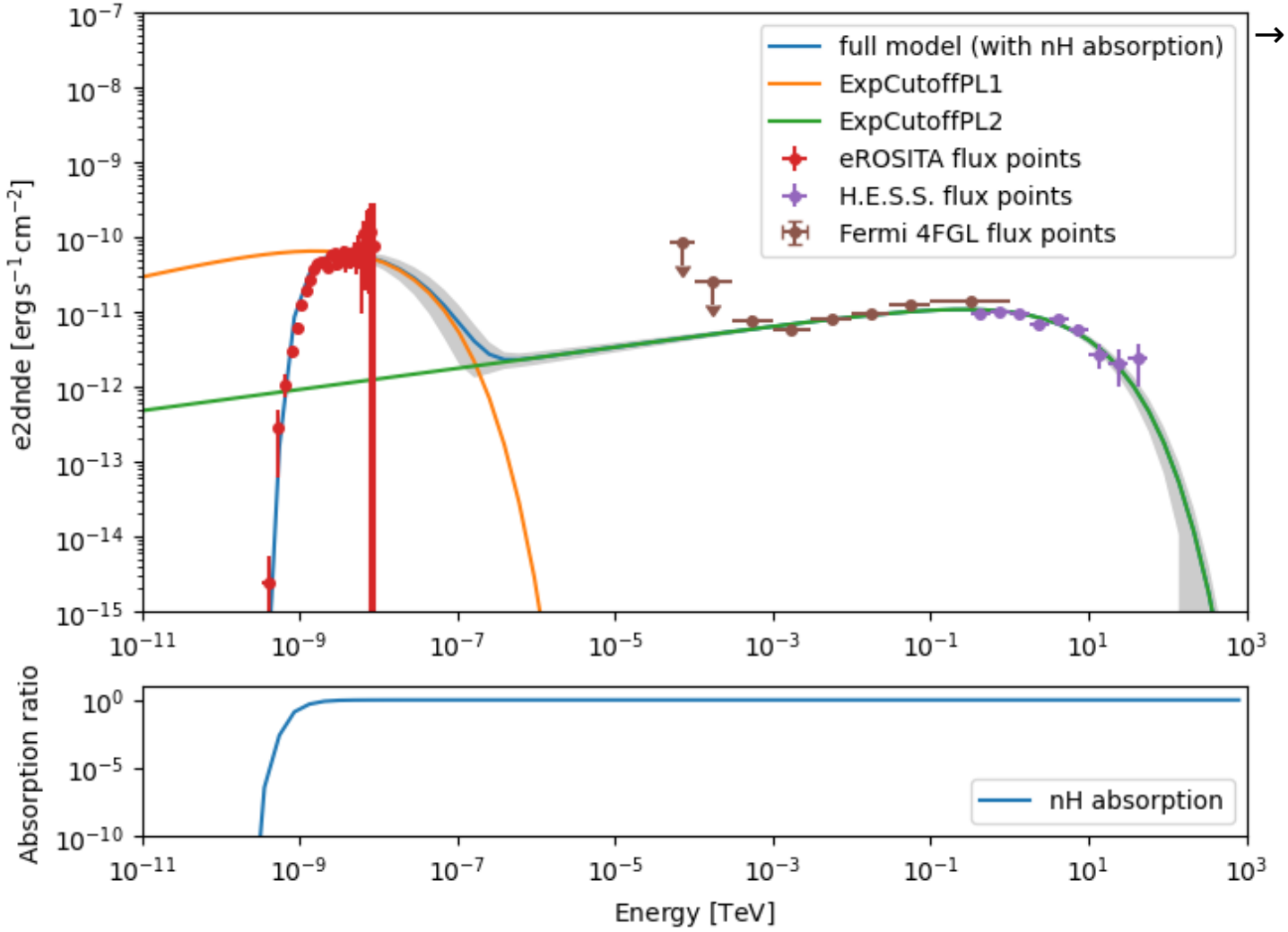
eROSITA, H.E.S.S., and Fermi data



→ Preliminary: Work in progress

Joint fit of eROSITA, H.E.S.S., and Fermi data in Gammapy

eROSITA, H.E.S.S., and Fermi data



→ Function: $\phi_{\text{total}} = \text{TBabs} \cdot (\phi_1(E) + \phi_2(E))$

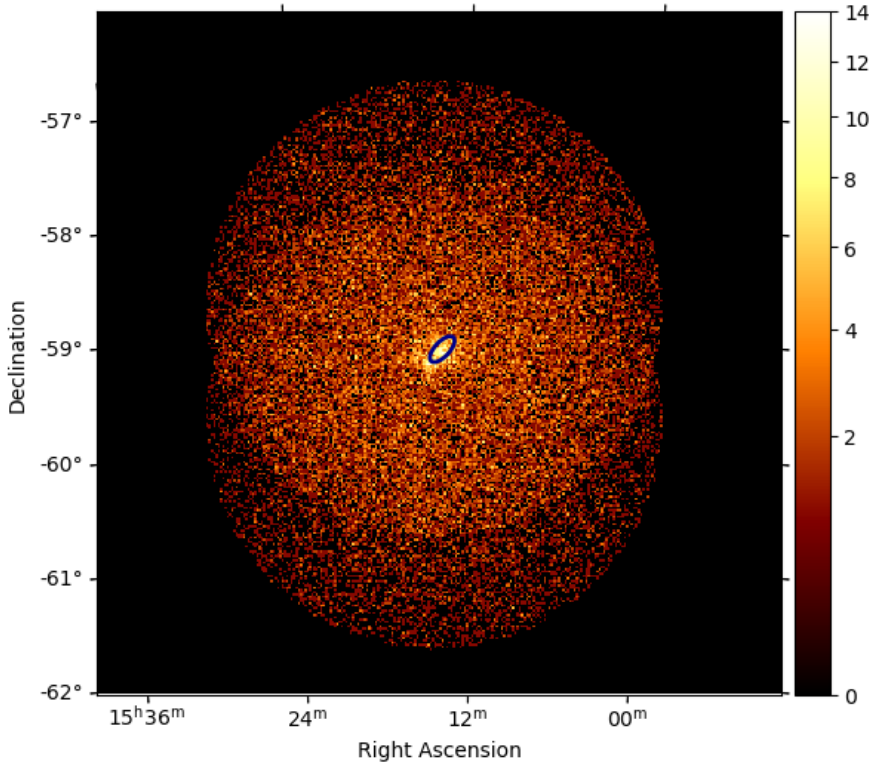
$$\phi_{1,2}(E) = \phi_{0_{1,2}} \cdot \left(\frac{E}{E_{0_{1,2}}}\right)^{-\Gamma_{1,2}} \exp\left(-(\lambda_{1,2}E)^{\alpha_{1,2}}\right)$$

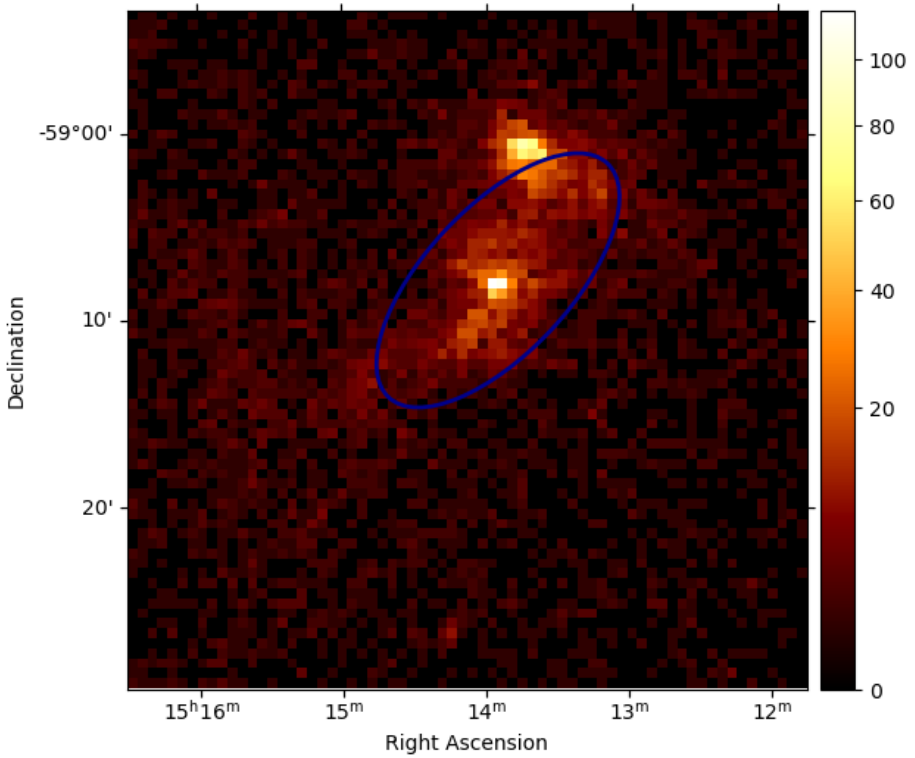
Results: → Preliminary: Work in progress

nH	1.283	+/-	0.09
index 1	1.752	+/-	0.15
amplitude 1	5.96e-02	+/-	1.1e-02 1 / (keV s cm2)
reference (frozen) 1	1.000 keV		
lambda_ 1	0.155	+/-	0.10 (1 / keV)
alpha (frozen) 1	0.500		
index 2	1.859	+/-	0.02
amplitude 2	1.08e-11	+/-	1.3e-12 1 / (TeV s cm2)
reference (frozen) 2	1.000 TeV		
lambda_ 2	0.300	+/-	0.09 (1 / TeV)
alpha (frozen) 2	0.500		
lon_0	228.480	+/-	0.005 deg
lat_0	-59.132	+/-	0.003 deg
sigma	5.698	+/-	0.21 arcmin
e	0.891	+/-	0.01
phi	137.077	+/-	1.42 deg

Joint fit of eROSITA, H.E.S.S., and Fermi data in Gammapy

eROSITA, H.E.S.S., and Fermi data



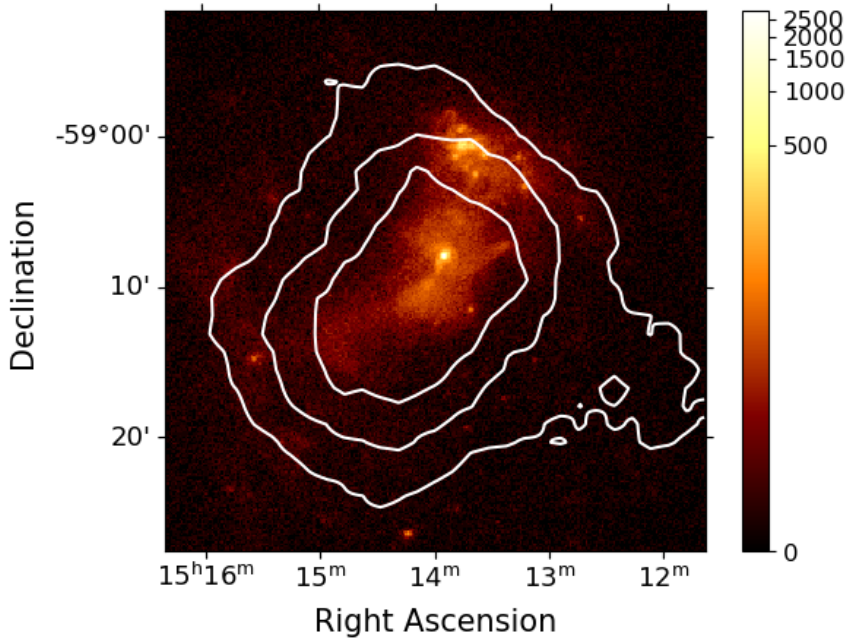


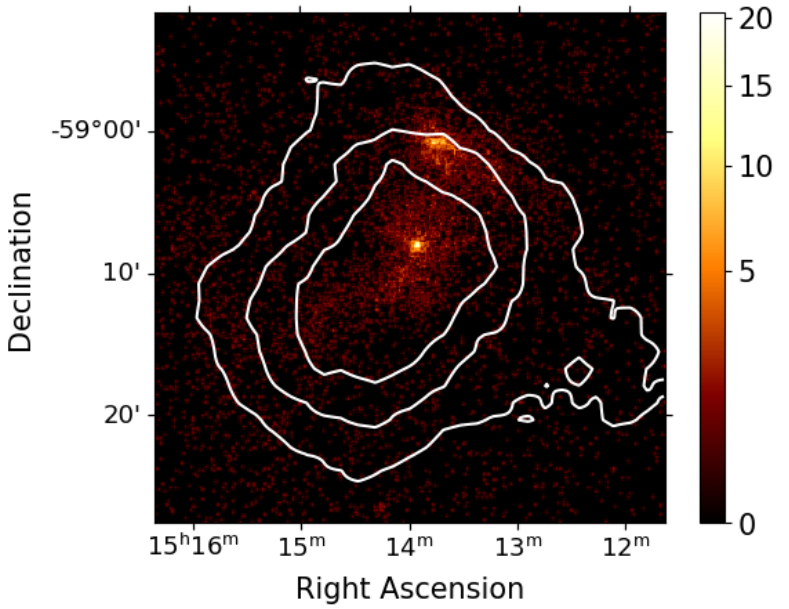
→ Preliminary: Work in progress

Outlook

Next steps

- Validation paper in preparation
- Find multicomponent model to approximate X-ray morphology
- Conclude validation with MSH 15-52
- Continue joint source analysis of MSH 15-52





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Thanks for listening!

Any questions?