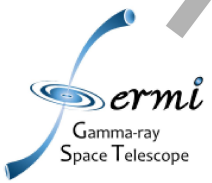
A **Python** package for
gamma-ray astronomy

Gammapy overview

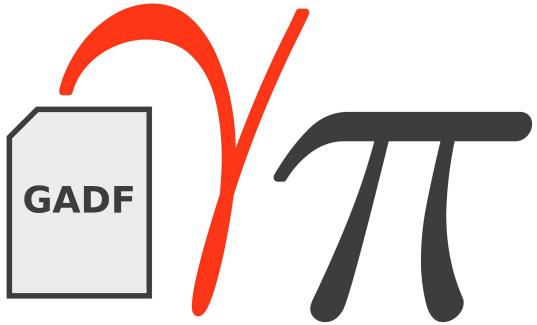
Gammapy hands-on session
CTA meeting, Granada
April 27th 2023

Gammapy overview

Pointing γ-ray Observatories

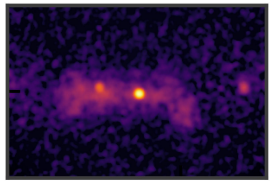


All-sky γ-ray Observatories

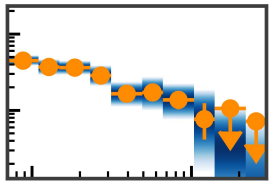


Common
data format

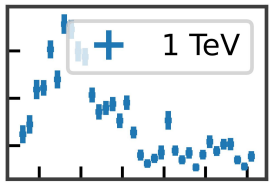
Sky maps



Spectra

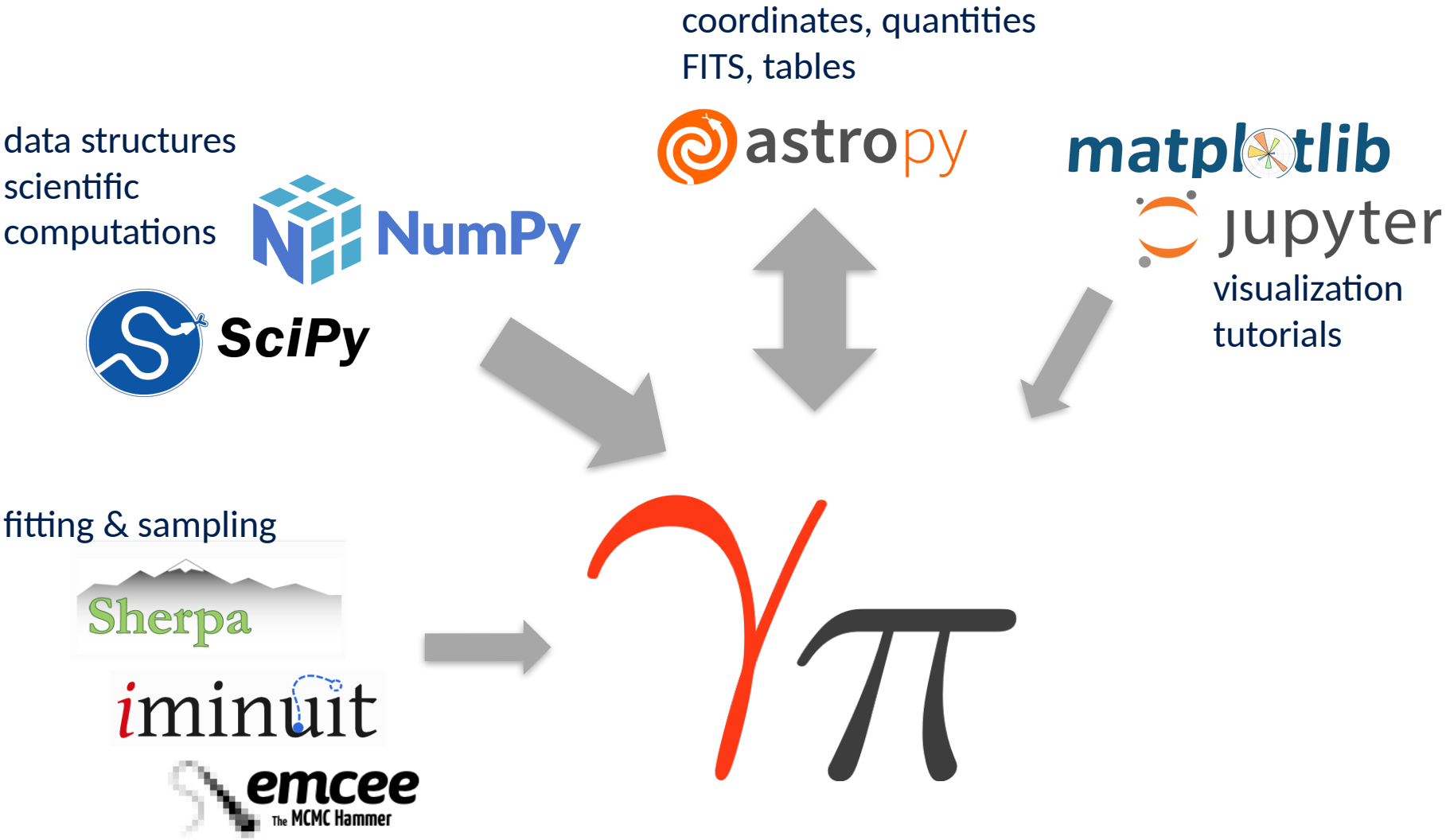


Lightcurves

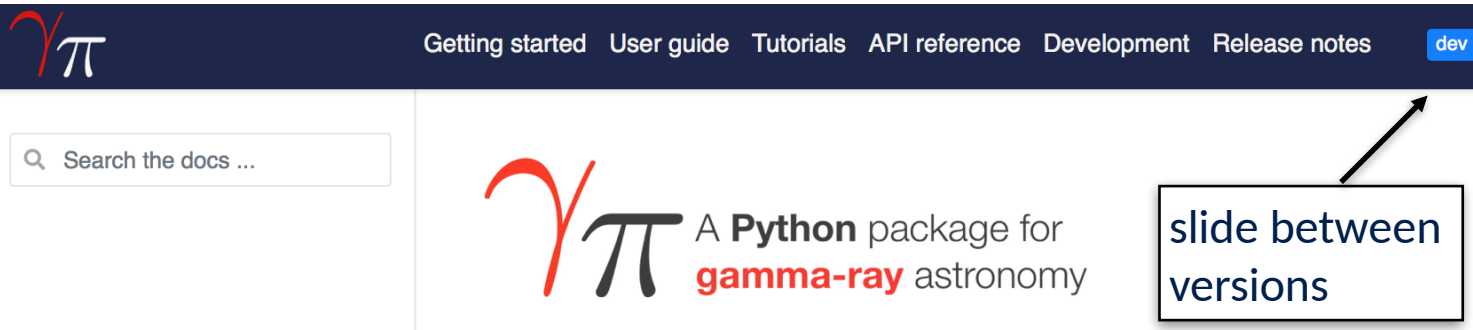


V1.0.1 released on March 14th

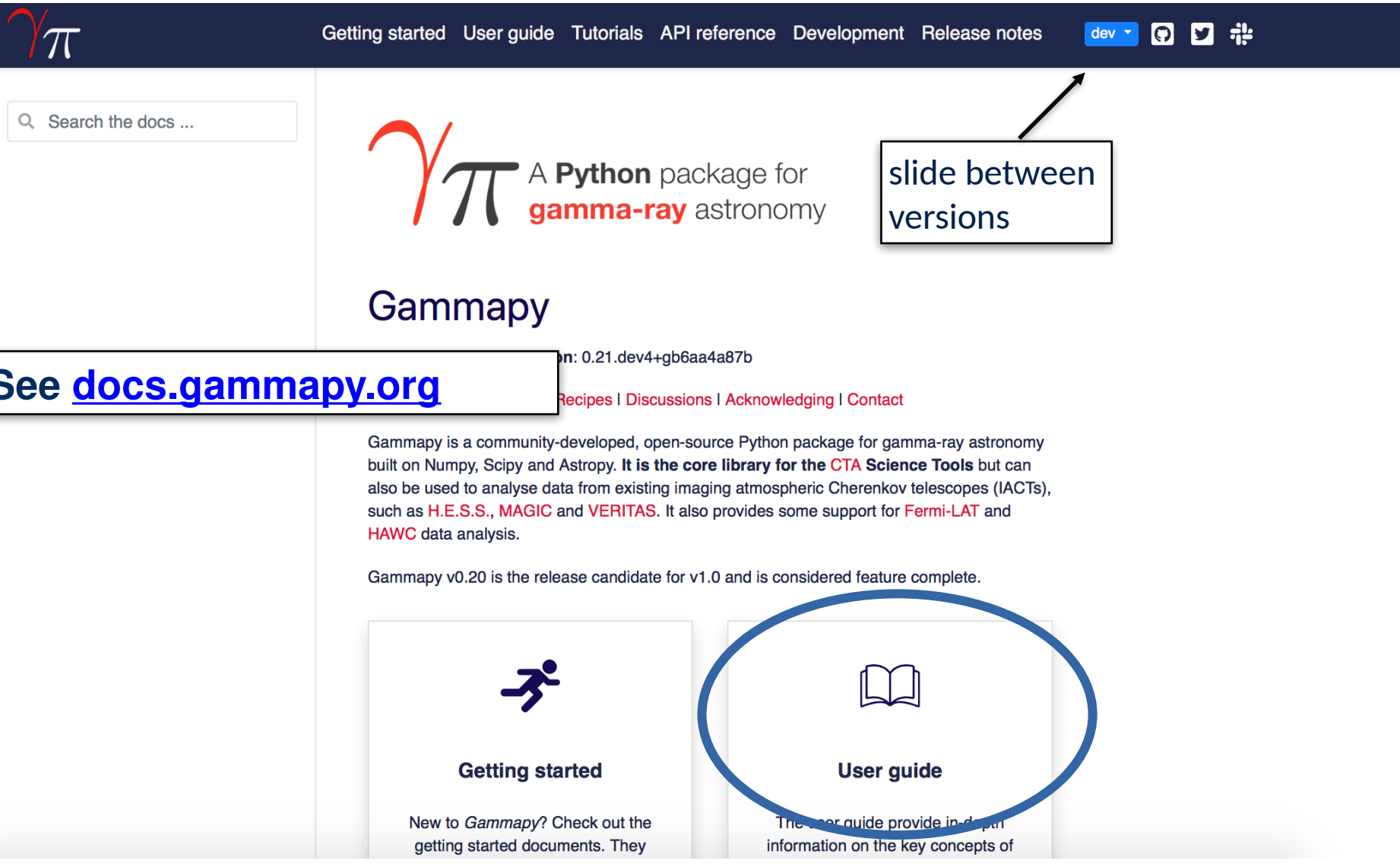
Gammapy dependencies



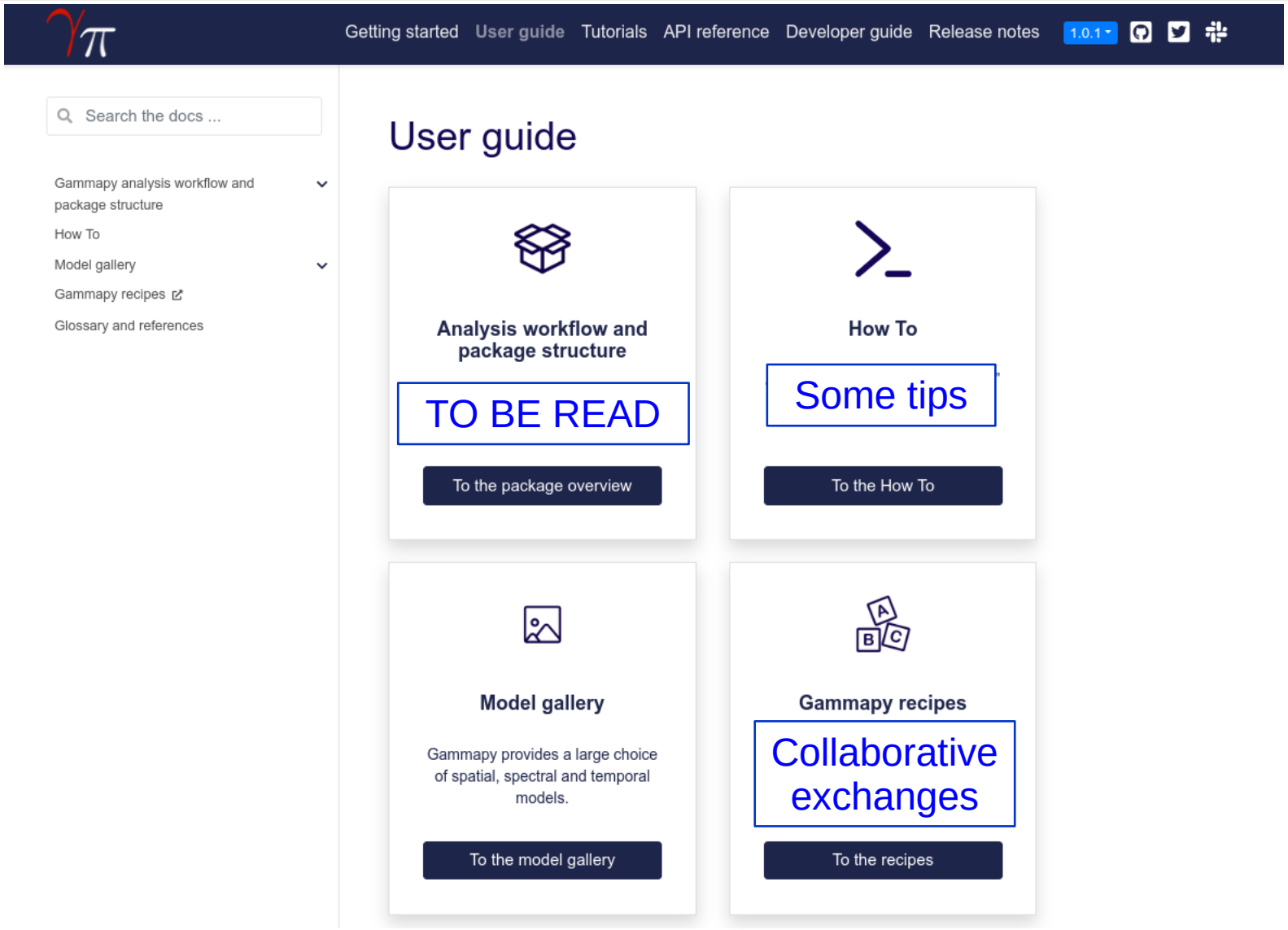
Getting started: documentation



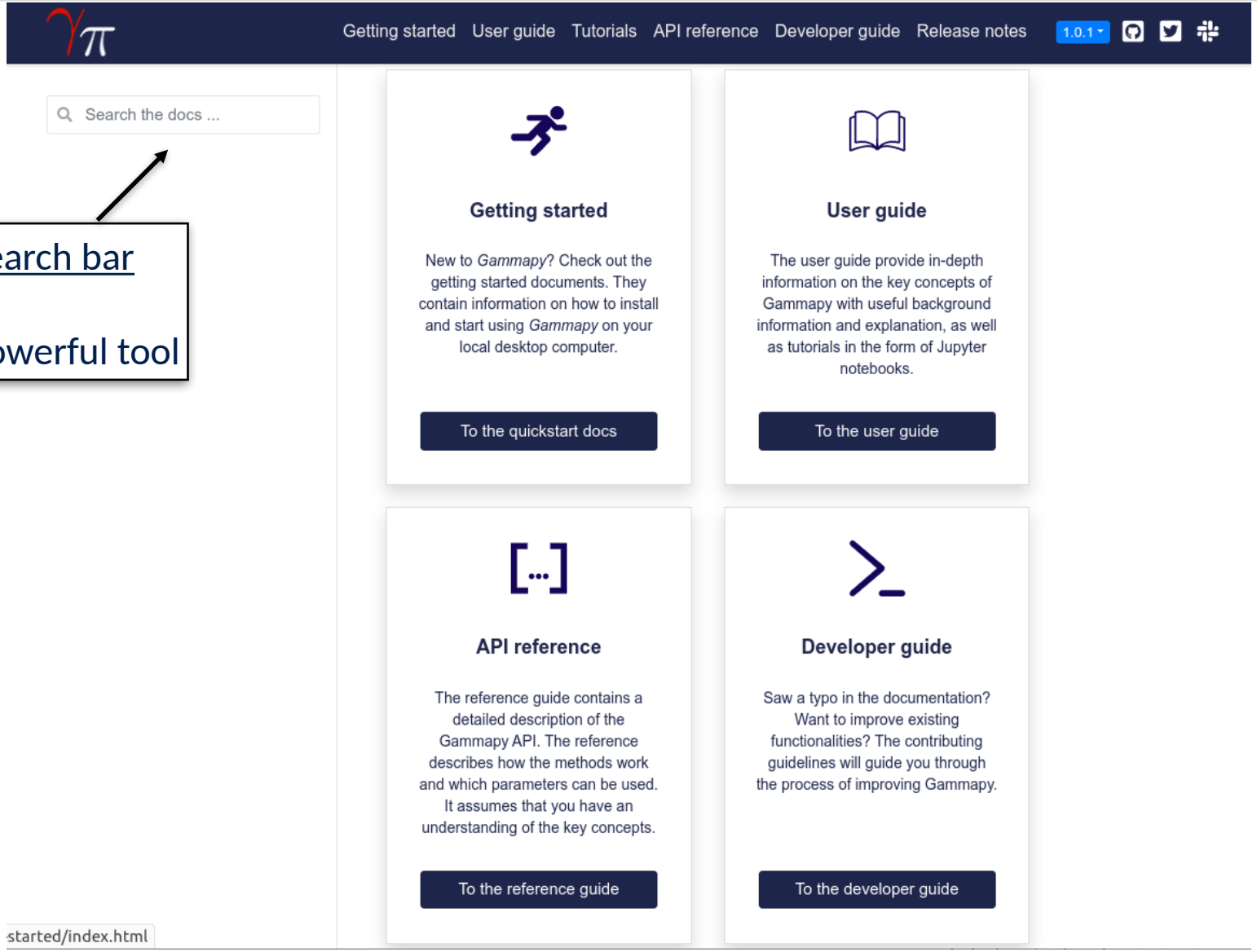
Getting started: documentation



Getting started: documentation



Getting started: documentation

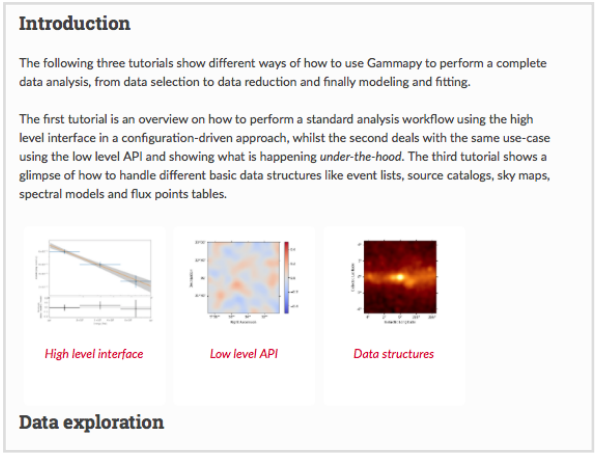


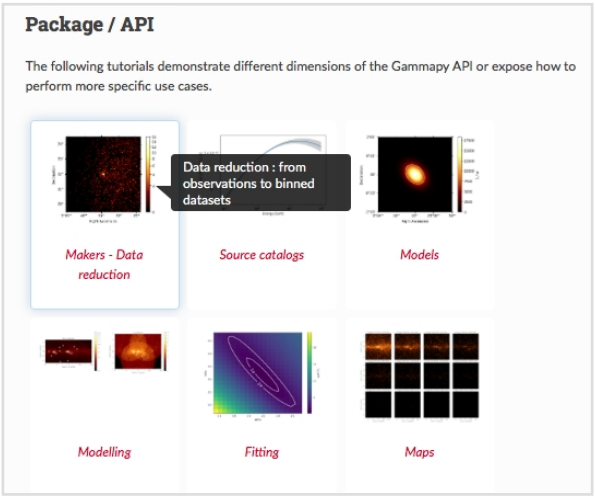
Search bar

Powerful tool

Getting started: documentation

- Learning with examples: the Tutorials
  - Data exploration
  - Analysis examples
  - API description



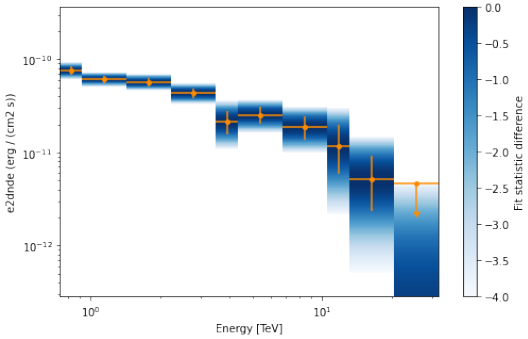


- More in depth: the API description

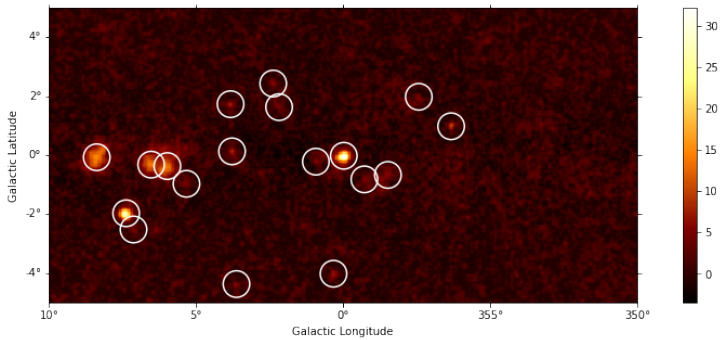
Getting help

- Where/How to interact with dev team and experienced users, provide feedback, get help:
  - gammapy.slack
    - In particular: #help channel
  - GitHub discussions
    - help category
  - GitHub issues to report bugs or feature requests

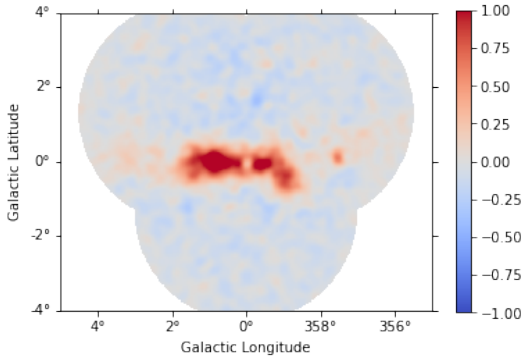
Typical analysis use cases



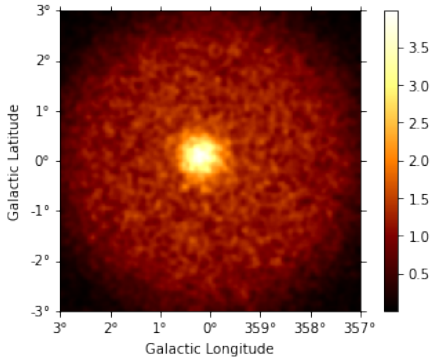
1D spectral analysis



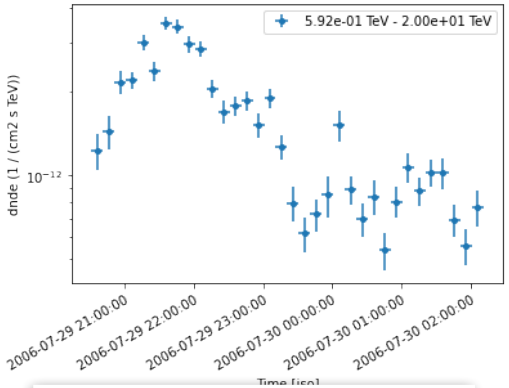
Source detection



3D analysis



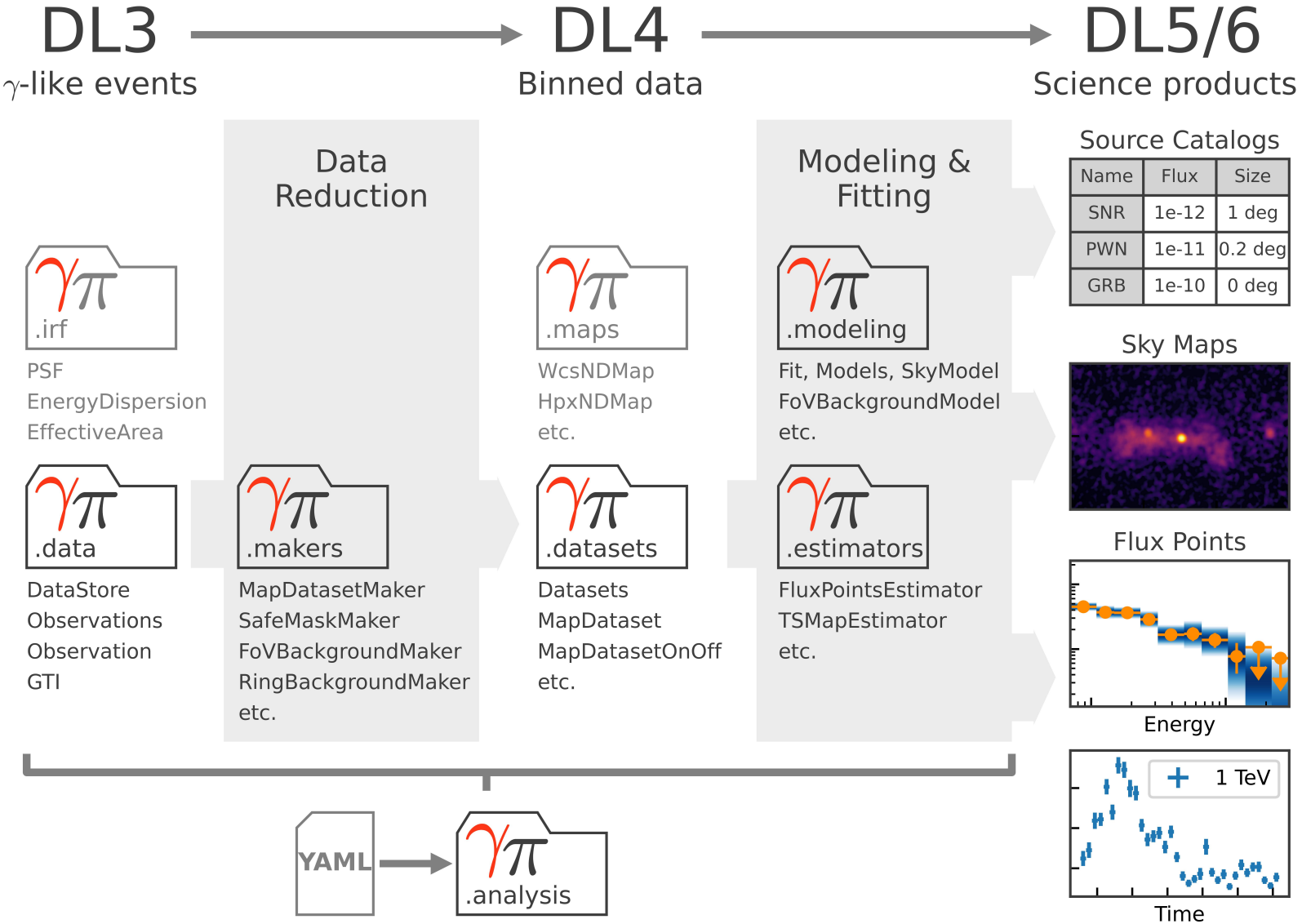
Observation simulation



Light-curve extraction

All analysis types follow the same workflow and the same API

Data workflow and package structure



Data workflow and package structure

DL3 → DL4 → DL5/6

γ-like events → Binned data → Science products

2-step analysis procedure:

- data reduction (DL3 to DL4)
- data modeling / fitting (DL4 to DL5)

.irf
PSF
EnergyDispersion
EffectiveArea

.maps
WcsNDMap
HpxNDMap
etc.

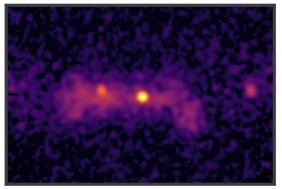
Modeling & Fitting

.modeling
Fit, Models, SkyModel
FoVBackgroundModel
etc.

Source Catalogs

Name	Flux	Size
SNR	1e-12	1 deg
PWN	1e-11	0.2 deg
GRB	1e-10	0 deg

Sky Maps



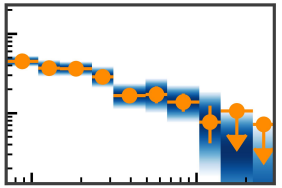
.data
DataStore
Observations
Observation
GTI

.makers
MapDatasetMaker
SafeMaskMaker
FoVBackgroundMaker
RingBackgroundMaker
etc.

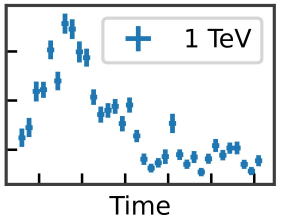
.datasets
Datasets
MapDataset
MapDatasetOnOff
etc.

.estimators
FluxPointsEstimator
TSMapEstimator
etc.

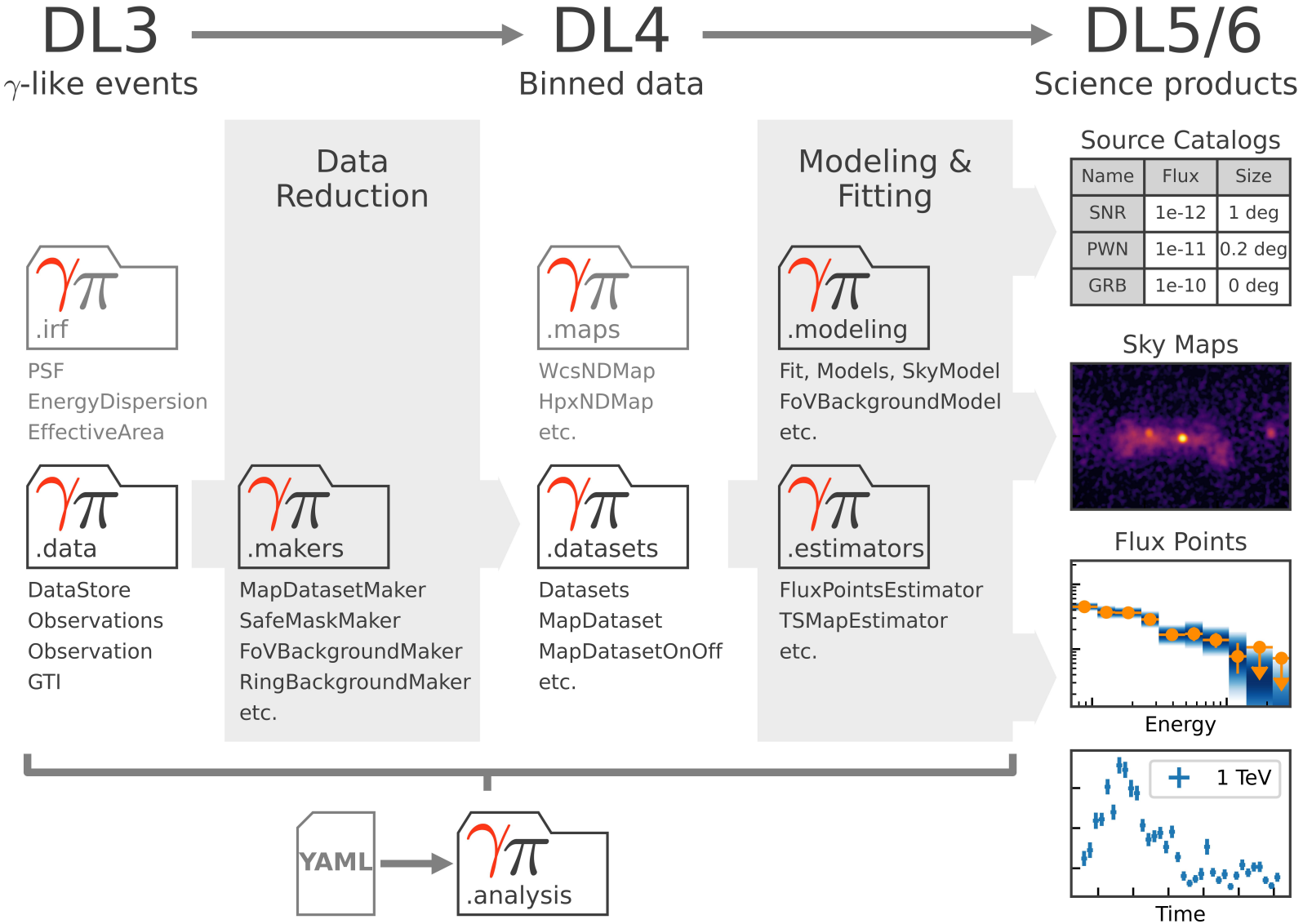
Flux Points



YAML → .analysis



Data workflow and package structure



The basic analysis steps

DL3 to DL4

1. Select and retrive observations
   - `Datastore` → list of `Observation`

See the backup slides...

DL4 to DL5

The basic analysis steps

DL3 to DL4

1. Select and retrive observations
2. Define the reduced dataset geometry
   - Is the analysis 1D or 3D?
   - Define target binning and projection

See the backup slides...

DL4 to DL5

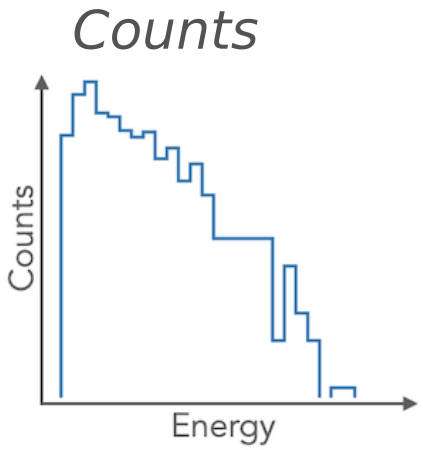
The basic analysis steps

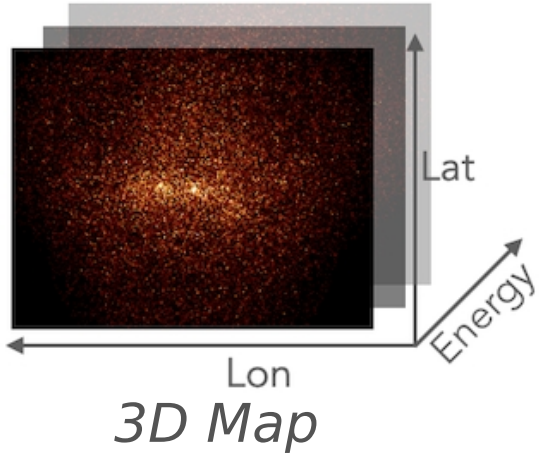
DL3 to DL4

1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
   - Data and IRF projection
   - Safe Mask determination
   - Background estimation

DL4 to DL5

Data and IRF reprojection





SpectrumDatasetMaker

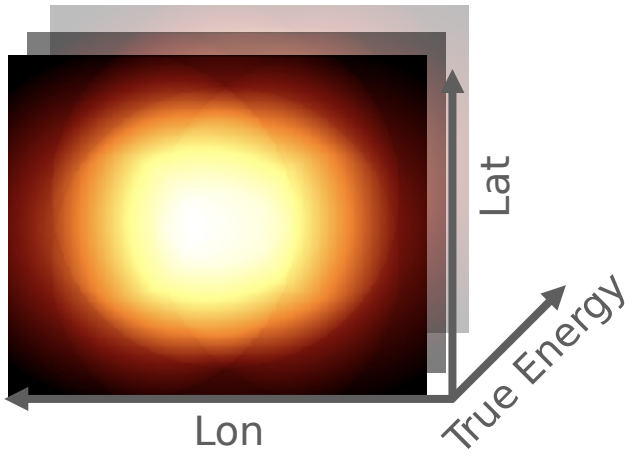
MapDatasetMaker

```
empty = MapDataset.create(
    geom,
    energy_axis_true=energy_axis_true,
    migra_axis=migra_axis,
    name="my-dataset",
)
maker = MapDatasetMaker(selection=["exposure", "background", "psf", "edisp"])
dataset = maker.run(empty, observation)
```

Reduced IRFs

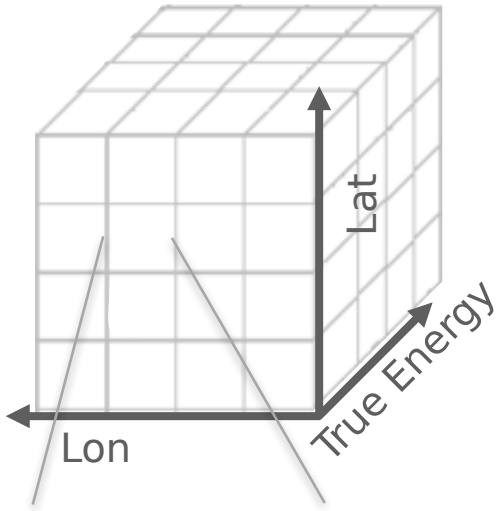
- DL3 IRFs are reprojected by the DatasetMaker on the target geometry

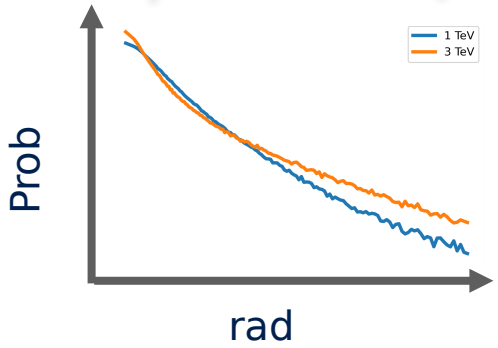
Exposure



PSF

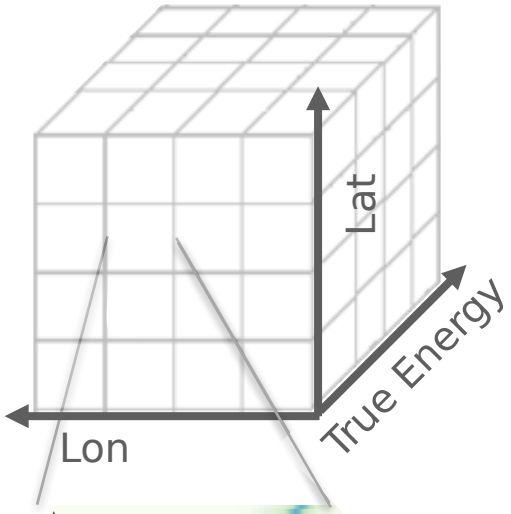
4th Dimension: rad

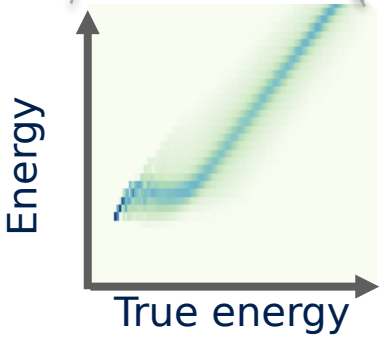




EDisp

4th Dimension: Energy





PSFMap /
EDispKernelMap

The basic analysis steps

DL3 to DL4

1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
   - Data and IRF projection
   - Safe Mask determination
   - Background estimation

DL4 to DL5

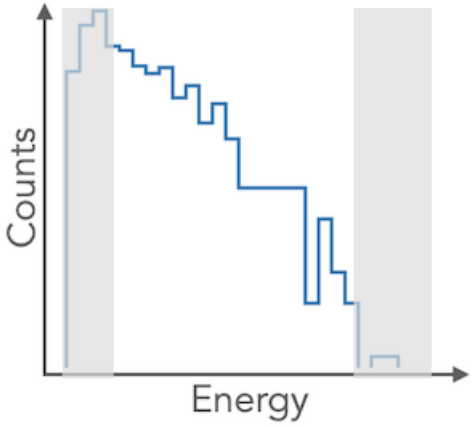
SafeMask concept

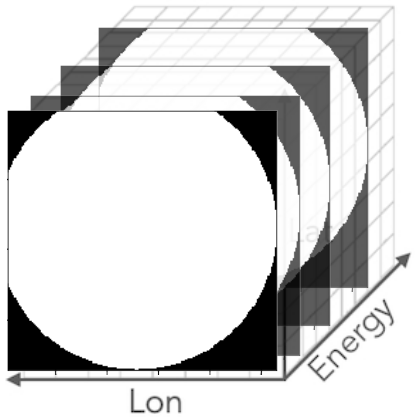
It allows to restrict the analysis bins because of any of these reasons:

- restriction the phase space (statistics, sources)
- validity range of the IRFs (systematics)
- scaling of the bkg model to the data

SafeMaskMaker

Safe Mask





The basic analysis steps

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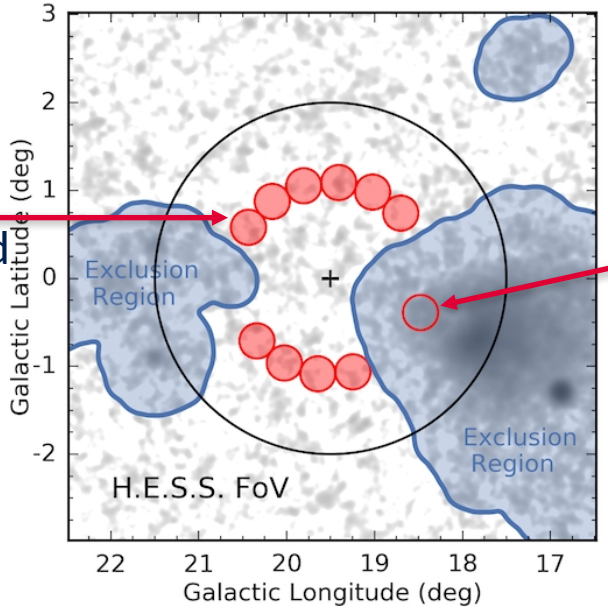
DL4 to DL5

Correcting background from data

- To further reduce systematics or for the 1D analysis (spectrum), the background is sometimes measured directly in the data, e.g. in regions of the FoV where the background is assumed to be identical
  - Common approach used for 1D spectral analysis
  - e.g. reflected regions or wobble regions background

OFF regions
containing only background



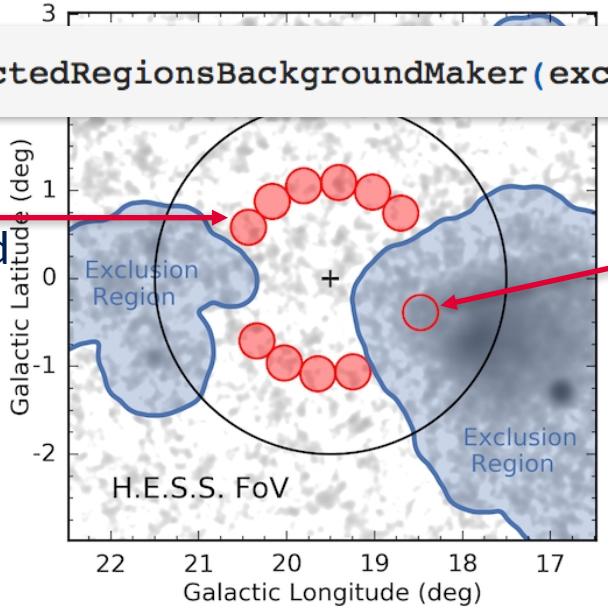
ON region
containing signal and background

Correcting background from data

- To further reduce systematics or for the 1D analysis (spectrum), the background is sometimes measured directly in the data, e.g. in regions of the FoV where the background is assumed to be identical
  - Common approach used for 1D spectral analysis
  - e.g. reflected regions or wobble regions background

```
bkg_maker = ReflectedRegionsBackgroundMaker(exclusion_mask=exclusion_mask)
```

OFF regions
containing only background

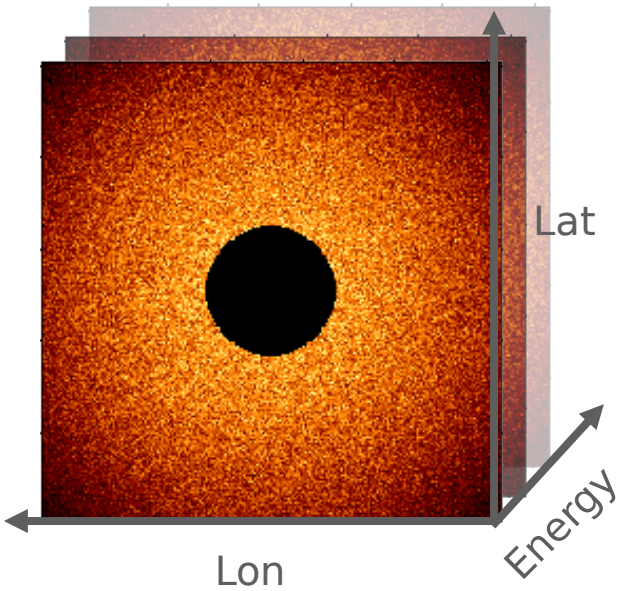


ON region
containing signal and background

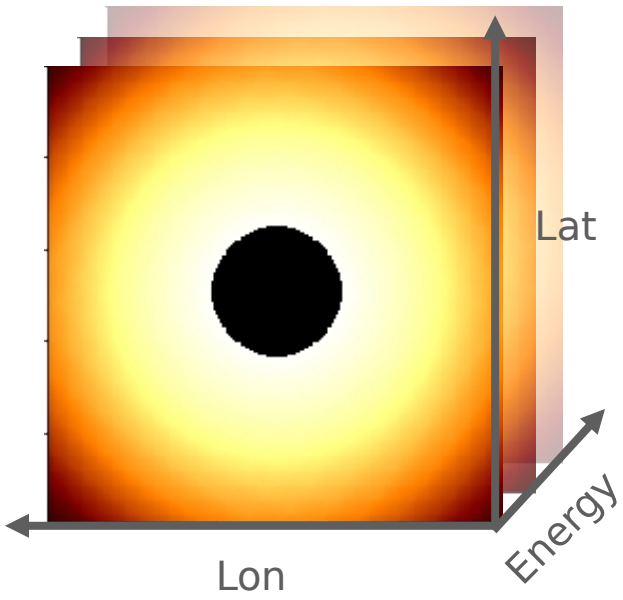
Correcting background from data

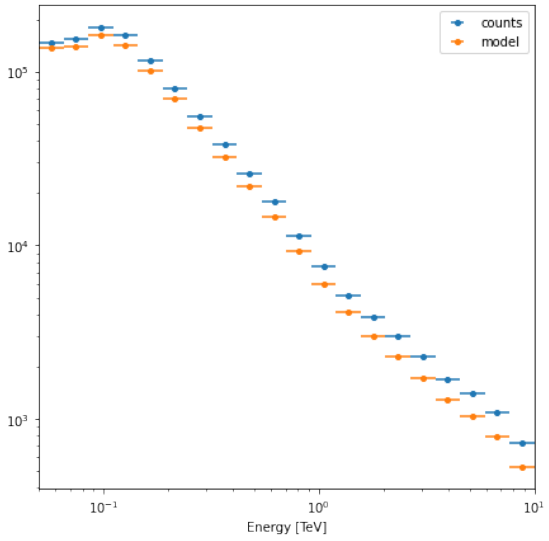
- *BKG(p, E)* is usually corrected on the observed data themselves.
  - Field of View (FoV) background estimation
    - *BKG(p, E)* is normalized in regions devoid of signal

Counts



Background template

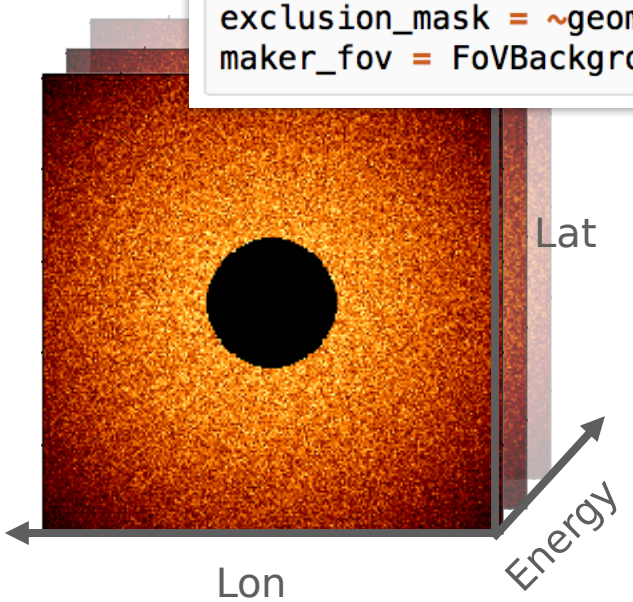


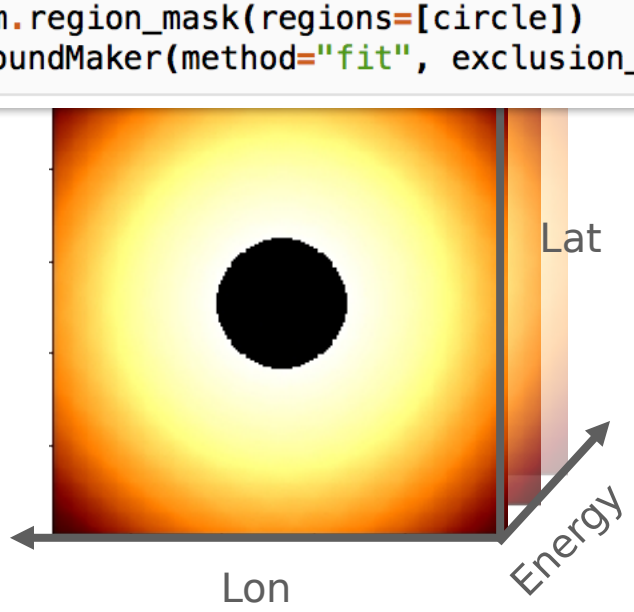


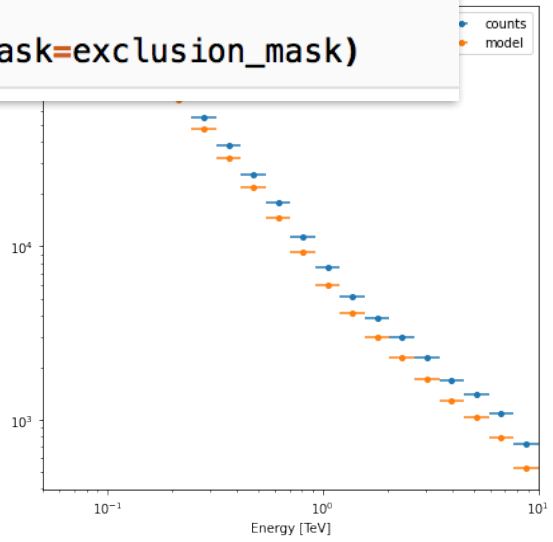
Correcting background from data

- *BKG(p, E)* is usually corrected on the observed data themselves.
  - Field of View (FoV) background estimation
    - *BKG(p, E)* is normalized in regions devoid of signal

```
circle = CircleSkyRegion(
    center=SkyCoord("83.63 deg", "22.14 deg"), radius=0.2 * u.deg
)
exclusion_mask = ~geom.region_mask(regions=[circle])
maker_fov = FoVBackgroundMaker(method="fit", exclusion_mask=exclusion_mask)
```







The basic analysis steps

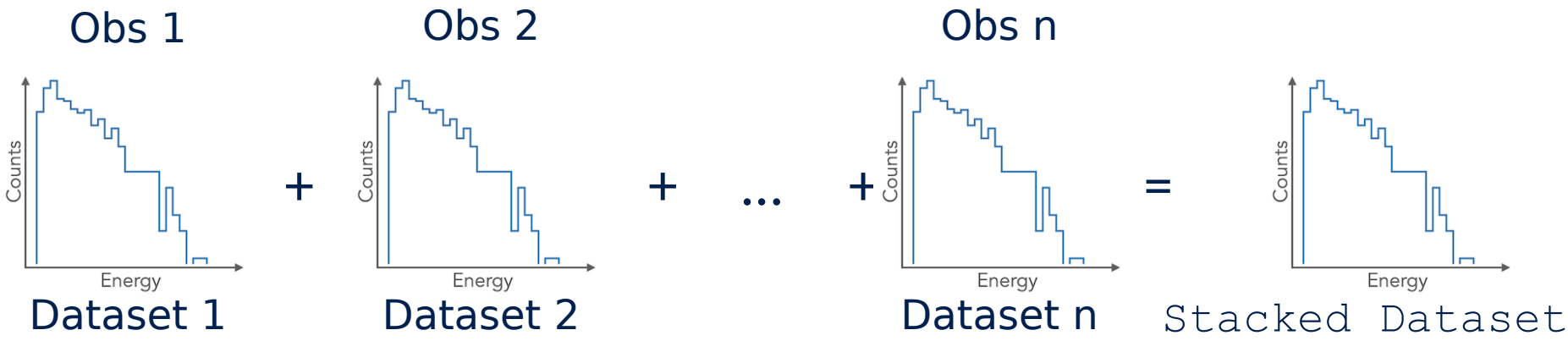
DL3 to DL4

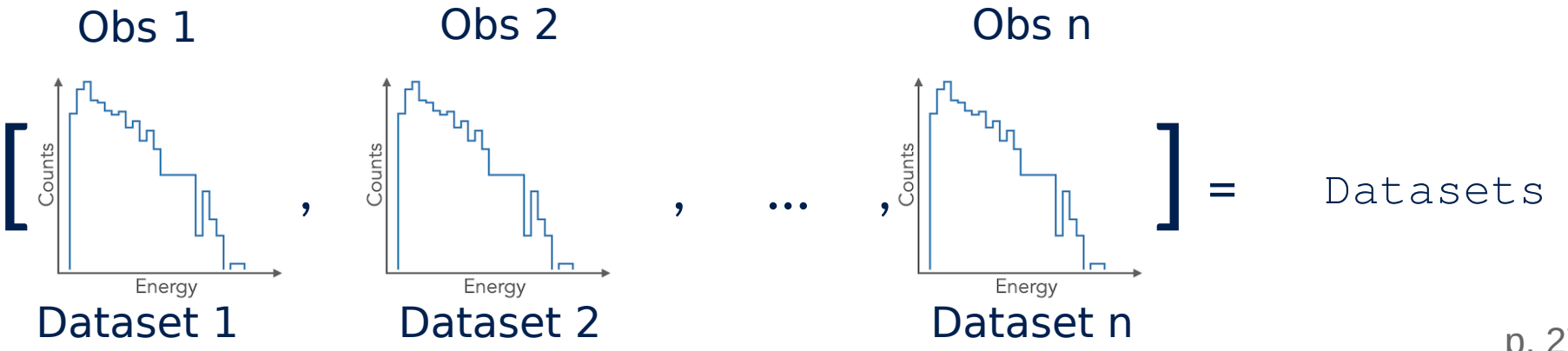
1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
4. Loop over selected observations
   - Apply makers to produce reduced datasets
   - Combine them for stacked or joint analysis

DL4 to DL5

Loop over observations

- Apply makers to produce reduced datasets
- Combine them for stacked or joint analysis





The basic analysis steps: overview of the Data Reduction

DL3 to DL4

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   - Define target binning and projection
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4. Loop over selected observations
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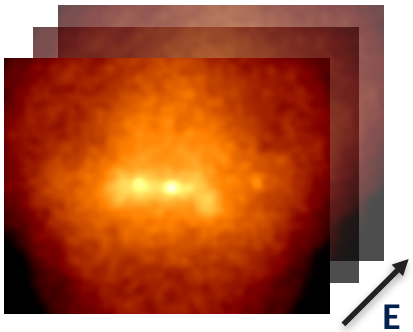
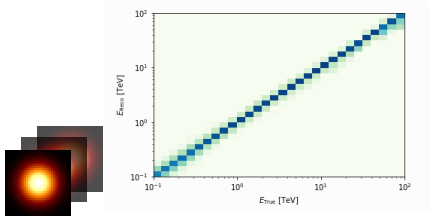
   - Combine them for stacked or joint analysis

DL4 structures: Datasets



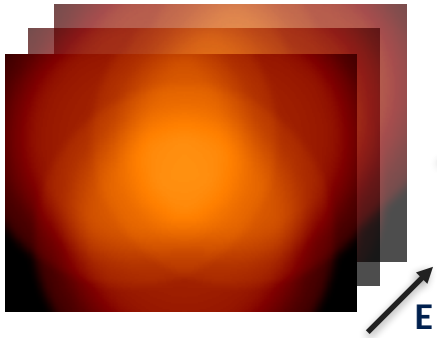
Reduced data

I/O



Reduced IRFs

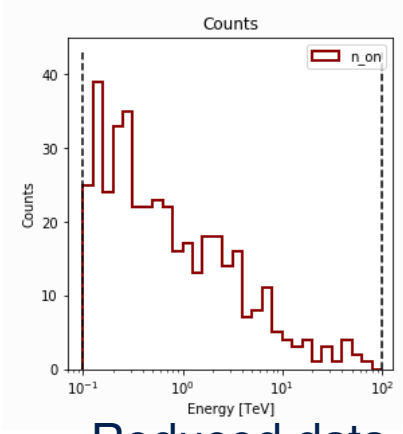
`MapDataset`



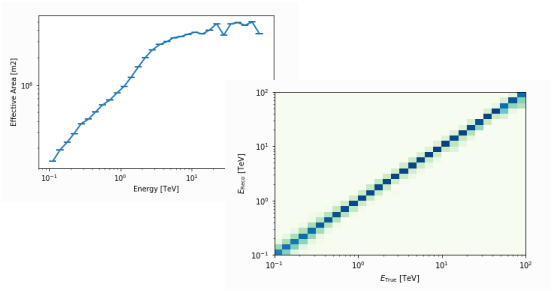
Bkg model

see: Dataset API tutorial

DL4 structures: Datasets



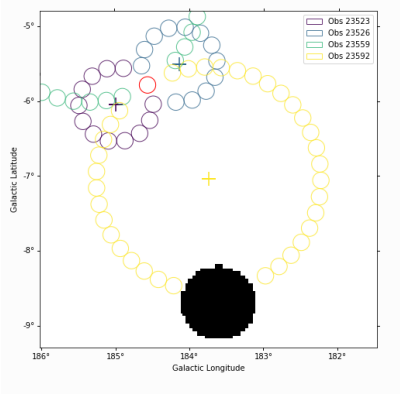
Reduced data



Reduced IRFs

I/O

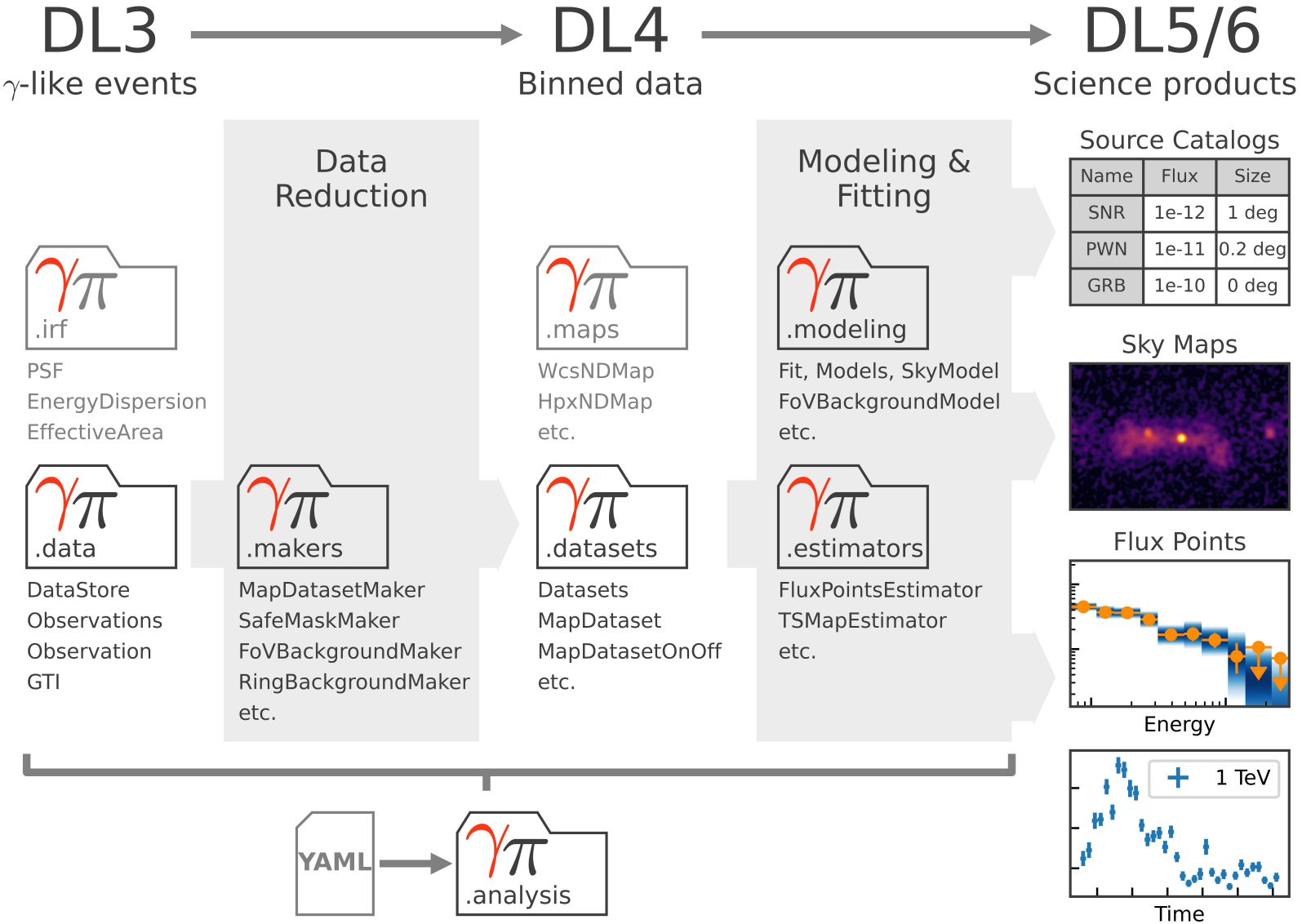
SpectrumDataset



Bkg data or model

see: Dataset API tutorial

Data workflow and package structure



DL4 to DL5: Modeling and fitting

- For modeling and fitting, Gammapy relies on ***forward-folding***:
  - Measured counts is compared to predicted counts

- Model parameter estimation is performed through maximum likelihood technique:
  - Cash statistics is used for counts data with a known background
  - Wstat statistics is used for counts data with a measured background

The basic analysis steps

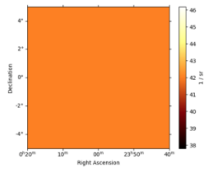
DL3 to DL4

1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
4. Loop over selected observations

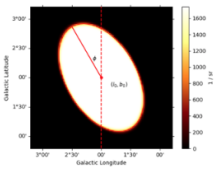
DL4 to DL5

1. Modeling
   - Define your model(s)
     - For the 3D analysis, add a final `FoVBackgroundModel`
   - Associate them/it to the correct dataset (or several)

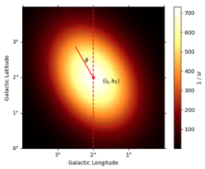
Datasets modeling and fitting



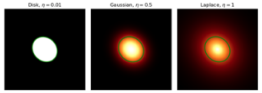
Constant spatial model



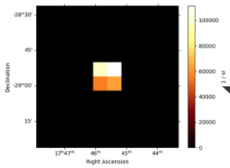
Disk spatial model



Gaussian spatial model



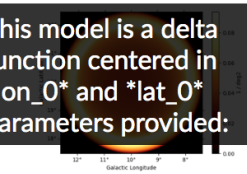
Generalized gaussian spatial model



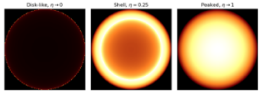
This model is a delta function centered in *lon_0* and *lat_0* parameters provided:

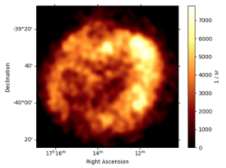
¶

Point spatial model

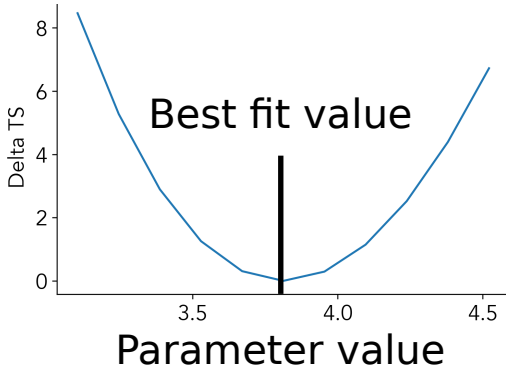


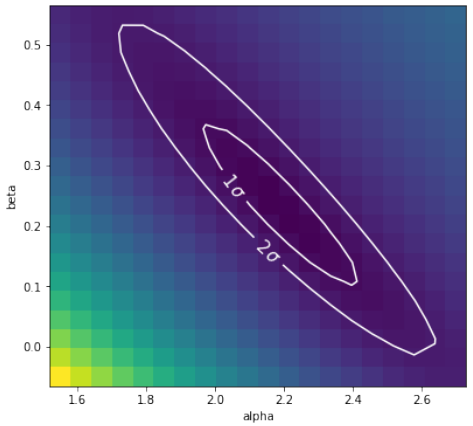
Shell spatial model



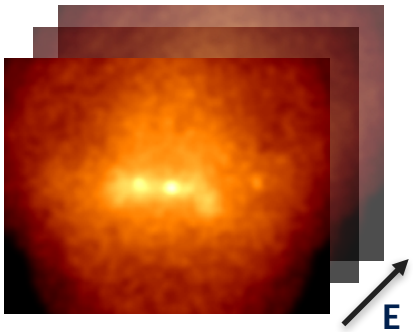


A library of models and a [Fitting] interface



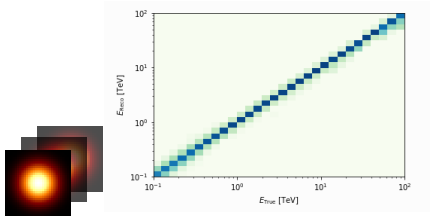


Datasets modeling and fitting



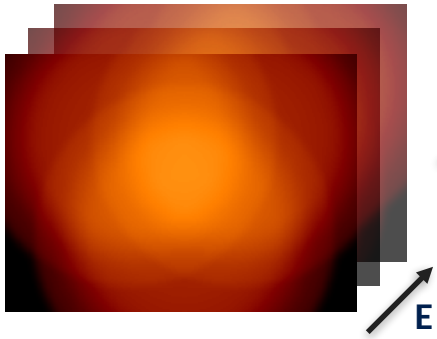
Reduced data

I/O



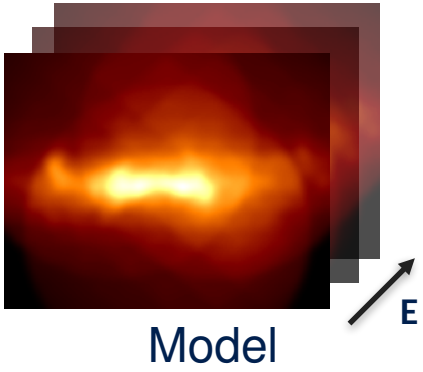
Reduced IRFs

Dataset



Bkg model

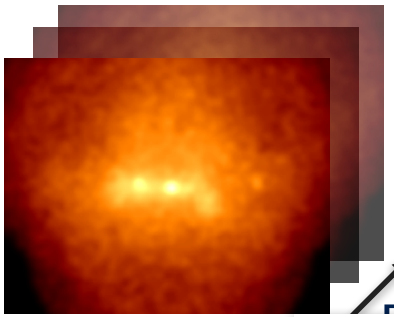
N_{pred}



Model

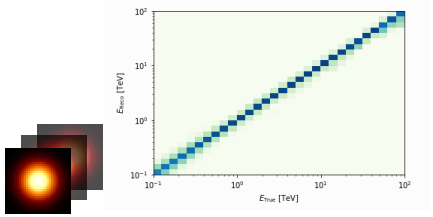
see:Dataset simulation tutorial

Datasets modeling and fitting



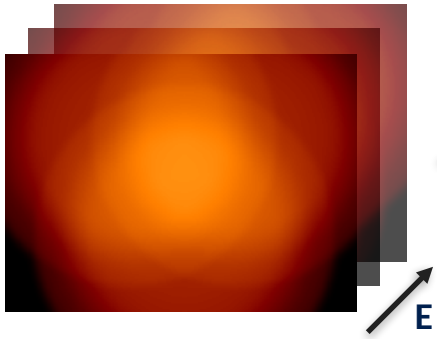
Reduced d

I/O



Reduced IRFs

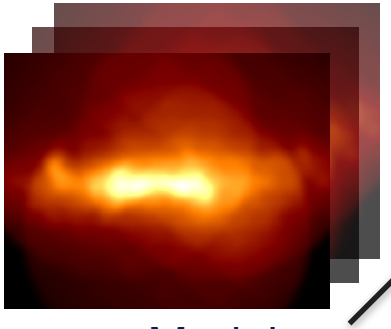
```
# Add the model on the dataset and Poission fluctuate
dataset.models = models
dataset.fake()
# Do a print on the dataset - there is now a counts maps
print(dataset)
```



E

Bkg model

N_{pred}

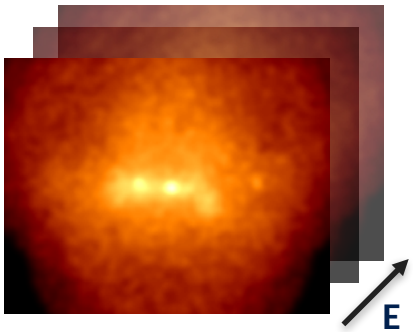


E

Model

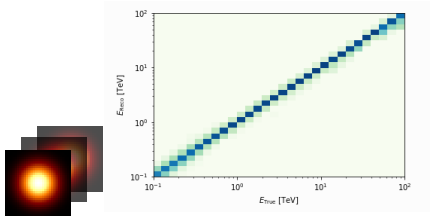
see:Dataset simulation tutorial

Datasets modeling and fitting



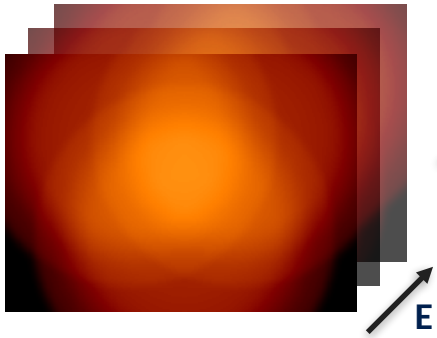
Reduced data

I/O



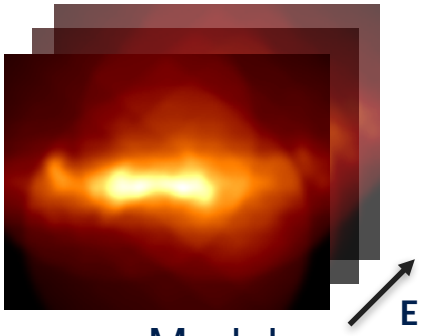
Reduced IRFs

Dataset



Bkg model

$\mathcal{L}(x \mid \theta)$



Model

see: Dataset fitting tutorial

The basic analysis steps

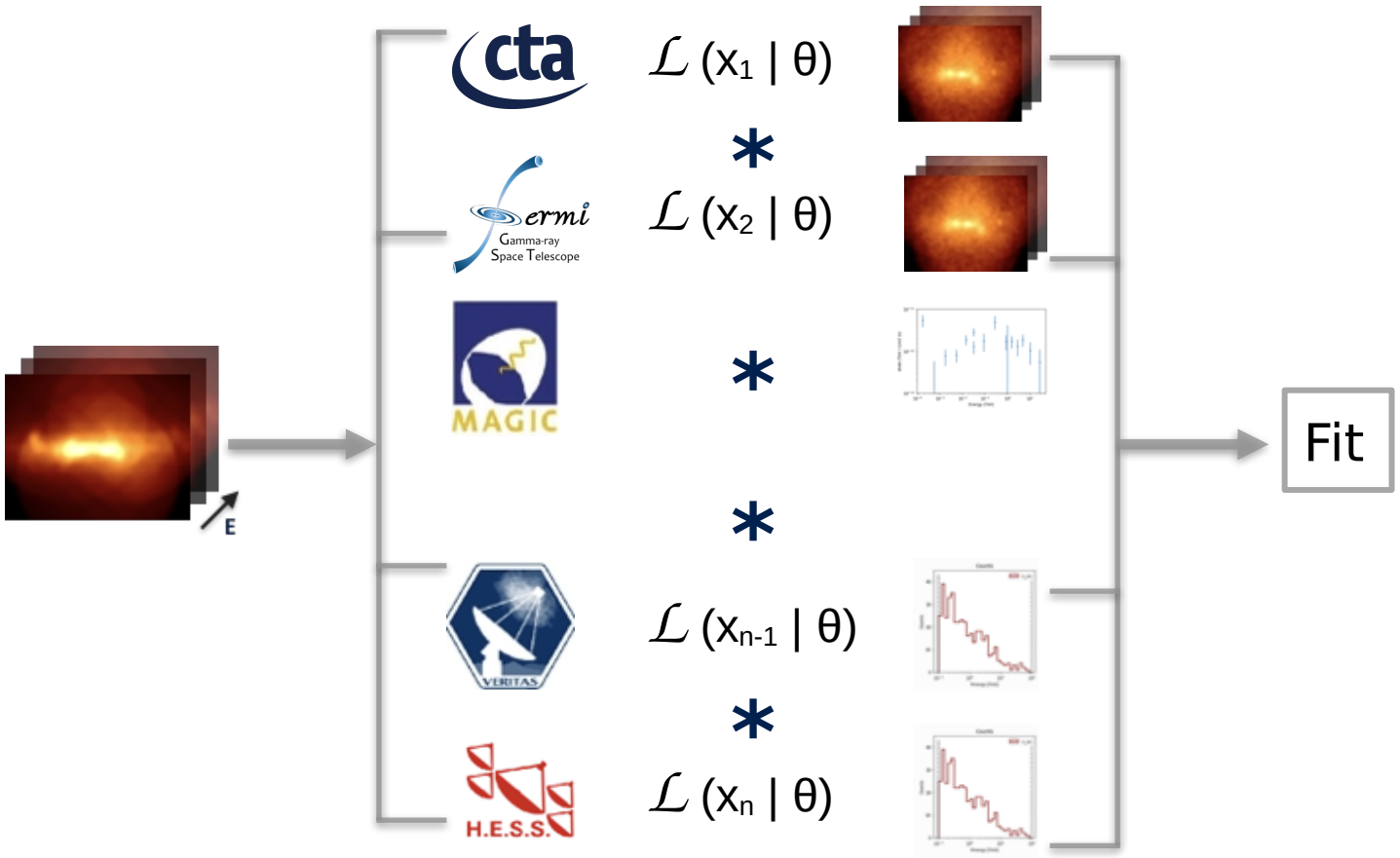
DL3 to DL4

1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
4. Loop over selected observations

DL4 to DL5

1. Modeling
2. Do the fit
   - Choose your minimization parameters (optional)
   - Make the control plots, compute significance

DL4 to DL5 : Joint fitting



Gammapy Dataset structure allows heterogeneous data modeling and fitting:

- See joint fit tutorial

The basic analysis steps

DL3 to DL4

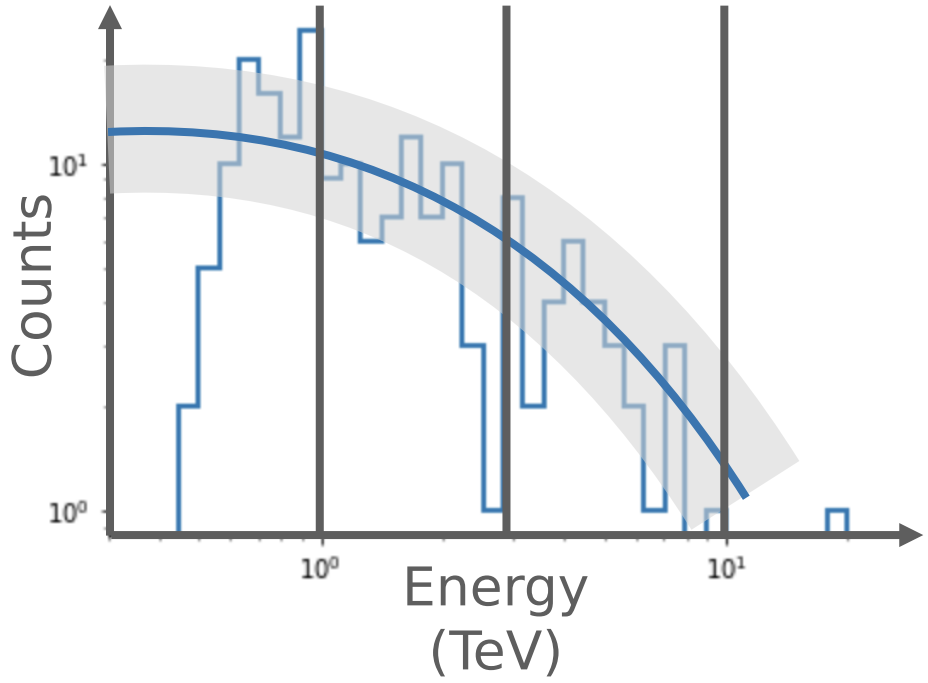
1. Select and retrive observations
2. Define the reduced dataset geometry
3. Initialize the data reduction methods (makers)
4. Loop over selected observations

DL4 to DL5

1. Modeling
2. Do the fit
3. Run the DL5 estimators (estimators)
   - Initialisation of the geometry
   - Creation of the estimator(s)
   - Run them of the dataset(s)

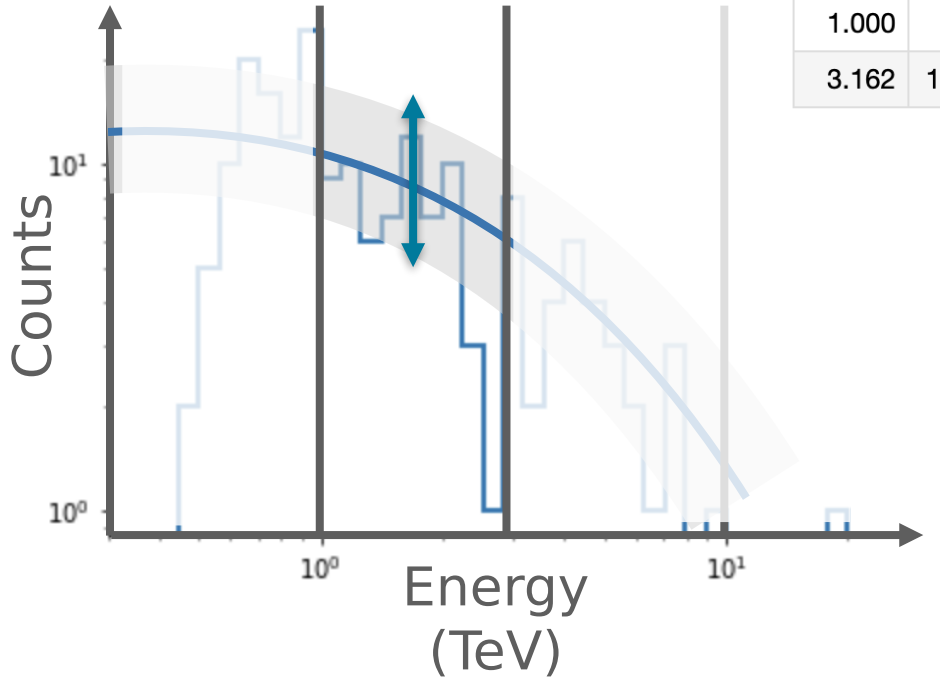
DL4 to DL5: estimating fluxes

- Gammapy provides a set of estimator objects which create DL5 data products based on a model assigned to one or more datasets.



DL4 to DL5: estimating fluxes

- Gammapy provides a set of estimator objects which create DL5 data products based on a model assigned to one or more datasets.



e_min	e_max	ref_flux	ref_eflux	norm	norm_err	norm_ul
TeV	TeV	1 / (cm2 s)	TeV / (cm2 s)			
float64	float64	float64	float64	float64	float64	float64
0.300	1.000	1.699e-10	8.184e-11	nan	nan	nan
1.000	3.162	2.433e-11	3.845e-11	1.032	0.058	1.152
3.162	10.000	3.847e-12	1.923e-11	0.879	0.103	1.099

FluxPointsEstimator
LightCurveEstimator
TSMapEstimator
ExcessMapEstimator

The basic analysis steps: Overview of the modeling and fitting

DL4 to DL5

1. Modeling
   - Define your model(s)
     - For the 3D analysis, add a final `FoVBackgroundModel`
   - Associate them/it to the correct dataset (or several)
2. Do the fit
   - Choose your minimization parameters (optional)
   - Make the control plots, compute significance
3. Run the DL5 estimators (estimators)
   - Initialization of the geometry
   - Creation of the estimator(s)
   - Run it/them on dataset(s)

Data workflow and package structure

DL3
γ-like events

DL4
Binned data

DL5/6
Science products

Data Reduction

Modeling & Fitting

support for two analysis workflows:

- config-driven high-level interface
- advanced user library

.data
DataStore
Observations
Observation
GTI

.makers
MapDatasetMaker
SafeMaskMaker
FoVBackgroundMaker
RingBackgroundMaker
etc.

.datasets
Datasets
MapDataset
MapDatasetOnOff
etc.

.modeling
Fit, Models, SkyModel
FoVBackgroundModel
etc.

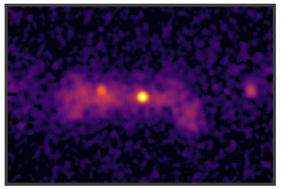
.estimators
FluxPointsEstimator
TSMapEstimator
etc.

YAML → .analysis

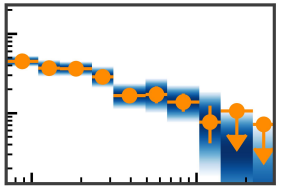
Source Catalogs

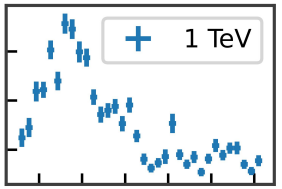
Name	Flux	Size
SNR	1e-12	1 deg
PWN	1e-11	0.2 deg
GRB	1e-10	0 deg

Sky Maps



Flux Points





Tutorials

We have prepared two specific analysis tutorials:

Spectral analysis of PKS 2155-304 – together

A full 1D (spectral) analysis from A to Z for a point-like extra-Galactic source.

3D analysis of MSH 15-52 – alone with our help

A full 3D analysis from A to Z for an extended Galactic source.

You can retrieve them with:

```
git clone https://github.com/bkhelifi/CTAO-CTAC_Meeting_Granada_2023.git
```

You can try to execute the tutorials along or simply follow.

Backup slides

Getting the software

- **Recommended gammapy installation**

```
curl -O https://gammapy.org/download/install/gammapy-1.0.1-environment.yml
conda env create -f gammapy-1.0.1-environment.yml
conda activate gammapy-1.0.1
```

- **Download tutorials & associated data**

```
gammapy download notebooks
gammapy download datasets
export GAMMAPY_DATA=$PWD/gammapy-datasets/1.0.1
```

Note: mamba might prove a better/faster package manager

See: https://docs.gammapy.org/1.0.1/getting-started/index.html#quickstart-setup

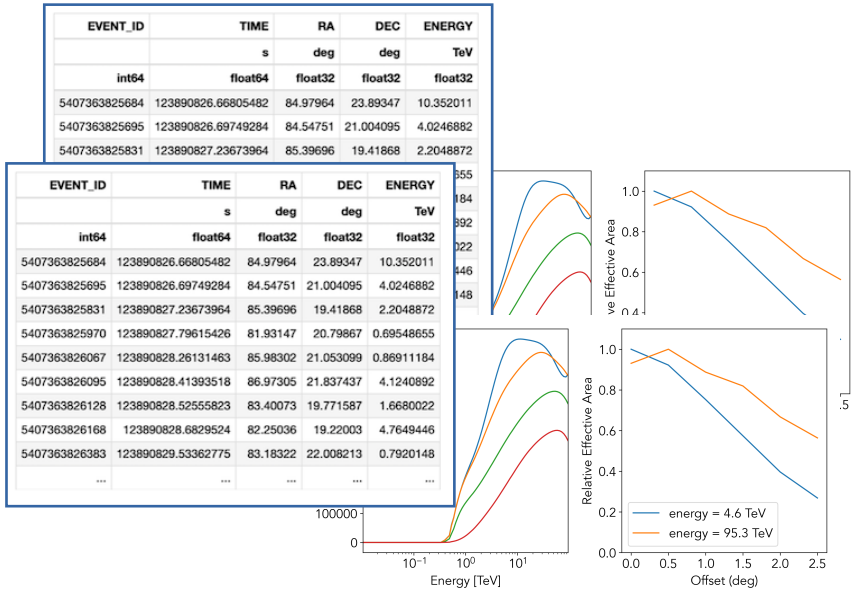
DL3 to DL4: data reduction

DL3

γ-like events

1. Select and retrieve relevant observations

EVENT_ID	TIME	RA	DEC	ENERGY
	s	deg	deg	TeV
int64	float64	float32	float32	float32
5407363825684	123890826.66805482	84.97964	23.89347	10.352011
5407363825695	123890826.69749284	84.54751	21.004095	4.0246882
5407363825831	123890827.23673964	85.39696	19.41868	2.2048872
5407363825970	123890827.79615426	81.93147	20.79867	0.69548655
5407363826067	123890828.26131463	85.98302	21.053099	0.86911184
5407363826095	123890828.41393518	86.97305	21.837437	4.1240892
5407363826128	123890828.52555823	83.40073	19.771587	1.6680022
5407363826168	123890828.6829524	82.25036	19.22003	4.7649446
5407363826383	123890829.53362775	83.18322	22.008213	0.7920148
...	...	...	...	...



DataStore

Observation / Observations

DL3 to DL4: data reduction

DL3

γ-like events

1. Select and retrieve relevant observations

```
datastore = DataStore.from_dir("$GAMMAPY_DATA/hess-dl3-dr1/")
obs_ids = [23523, 23526, 23559, 23592]
observations = datastore.get_observations(obs_ids)
```

EVENT_ID	TIME	RA	DEC	ENERGY
	s	deg	deg	TeV
int64	float64	float32	float32	float32
5407363825684	123890826.66805482	84.97964	23.89347	10.352011
5407363825695	123890826.69749284	84.54751	21.004095	4.0246882
5407363825831	123890827.23673964	85.39696	19.41868	2.2048872
5407363825970	123890827.79615426	81.93147	20.79867	0.69548655
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5407363826095	123890828.41393518	86.97305	21.837437	4.1240892
5407363826128	123890828.52555823	83.40073	19.771587	1.6680022
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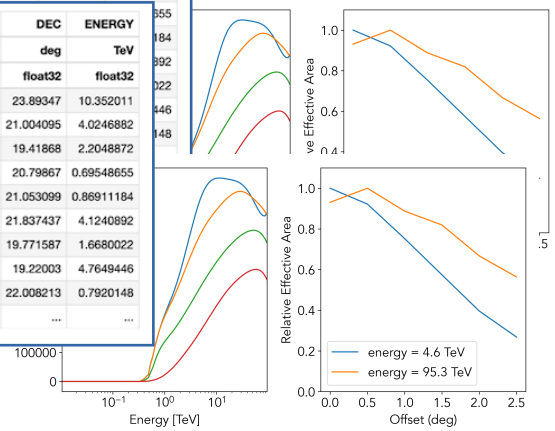
5407363826383	123890829.53362775	83.18322	22.008213	0.7920148
...	...	...	...	...



DataStore

Observation / Observations

DL3 to DL4: data reduction

DL3

γ-like events

1. Select and retrieve relevant observations

```
# Create an in-memory observation
location = observatory_locations["cta_south"]
obs = Observation.create(
    pointing=pointing, livetime=livetime, irfs=irfs, location=location
)
```

EVENT_ID	TIME	RA	DEC	ENERGY
	s	deg	deg	TeV
int64	float64	float32	float32	float32
5407363825684	123890826.66805482	84.97964	23.89347	10.352011
5407363825695	123890826.69749284	84.54751	21.004095	4.0246882
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5407363826128	123890828.52555823	83.40073	19.771587	1.6680022
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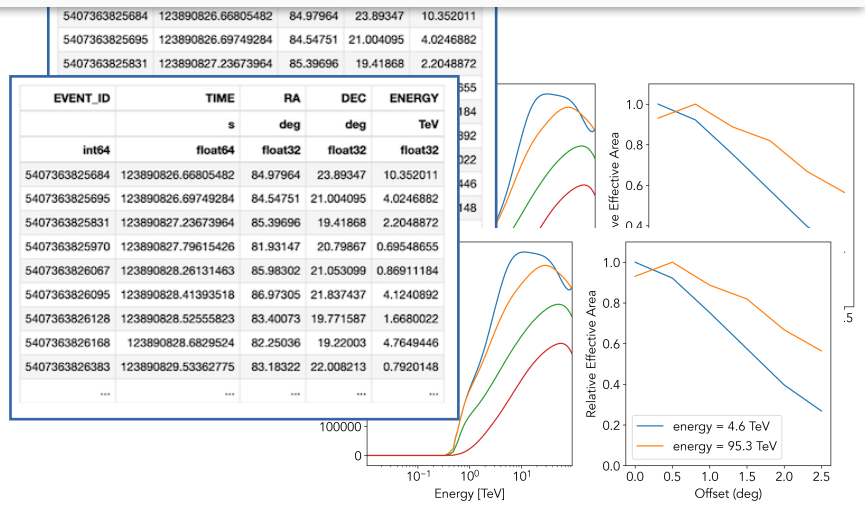
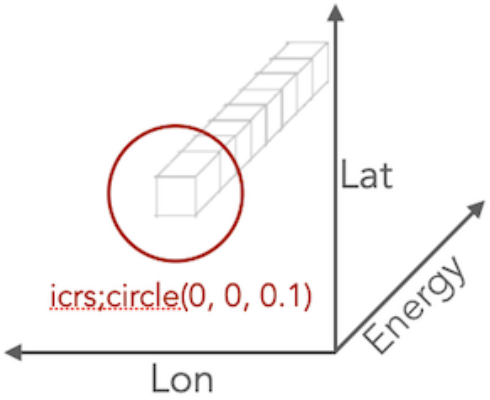
5407363826383	123890829.53362775	83.18322	22.008213	0.7920148
...	...	...	...	...



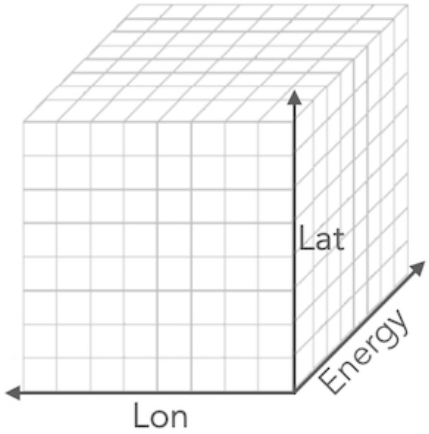
DataStore

Observation / Observations

DL3 to DL4: data reduction



region & energy



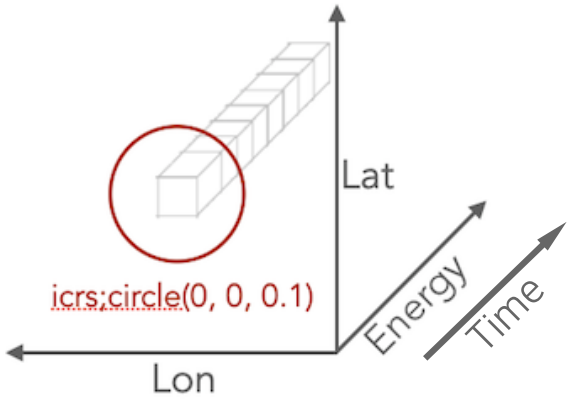
WCS & energy

1. Select and retrieve relevant observations

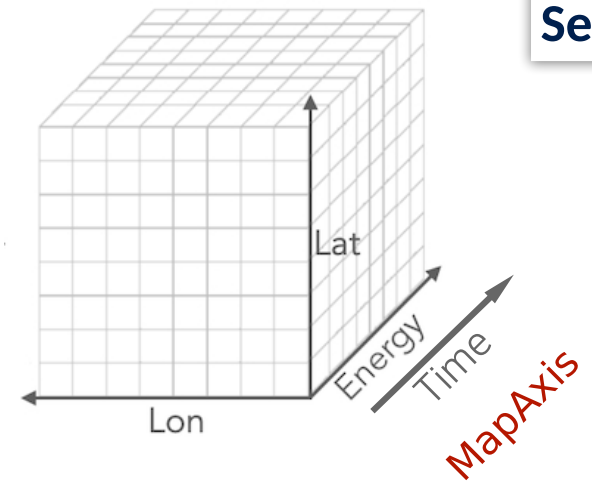
2. Define the reduced dataset geometry
   - Is the analysis 1D (spectral only) or 3D?
   - Define target binning and projection

Geometry : multidimensional maps

- Gammapy maps represent data on the sky with non-spatial dimensions (in particular energy)
  - World Coord. System (WCS) for 3D analyses (lon, lat, E)
  - Region geometry for 1D analysis



RegionGeom / RegionNDMap



WcsGeom / WcsNDMap

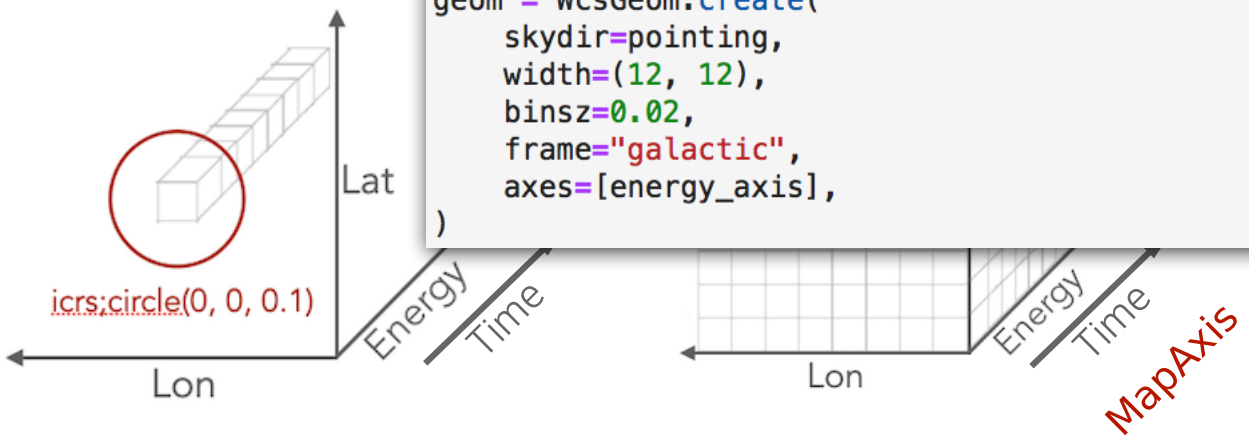
See : working with maps

Geometry : multidimensional maps

- Gammapy maps represent data on the sky with non-spatial dimensions (in particular energy)
  - World Coord. System (WCS) for 3D analyses (lon, lat, E)
  - Region geometry for 1D analysis

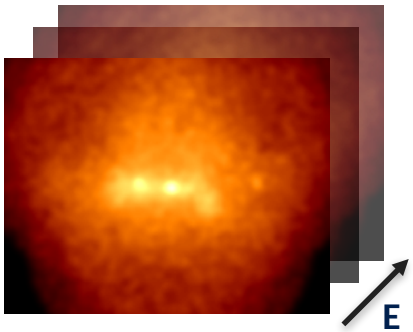
```
energy_axis = MapAxis.from_energy_bounds(
    "0.02 TeV", "100 TeV", nbin=10, per_decade=True
)

geom = WcsGeom.create(
    skydir=pointing,
    width=(12, 12),
    binsz=0.02,
    frame="galactic",
    axes=[energy_axis],
)
```

king with maps



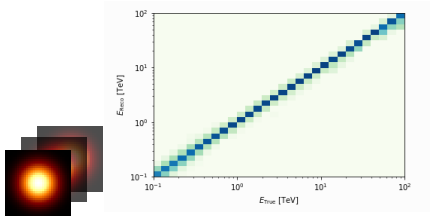
RegionGeom / RegionNDMap WcsGeom / WcsNDMap

Datasets modeling and fitting



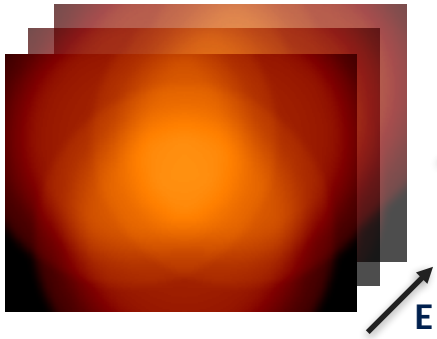
Reduced data

I/O



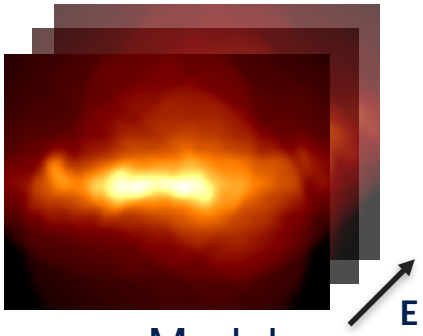
Reduced IRFs

```
fit = Fit(optimize_opts={"print_level": 1})
result = fit.run(datasets=[dataset])
```



Bkg model

$\mathcal{L}(x \mid \theta)$

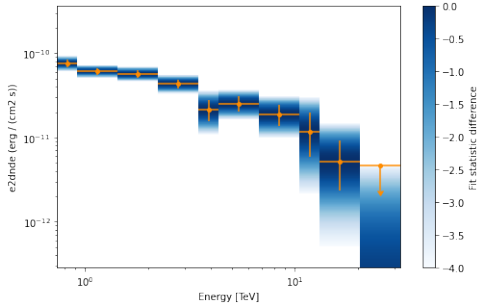


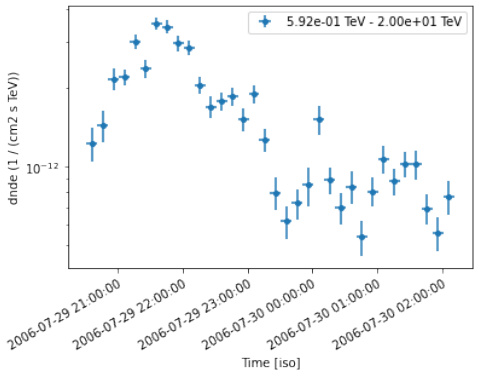
Model

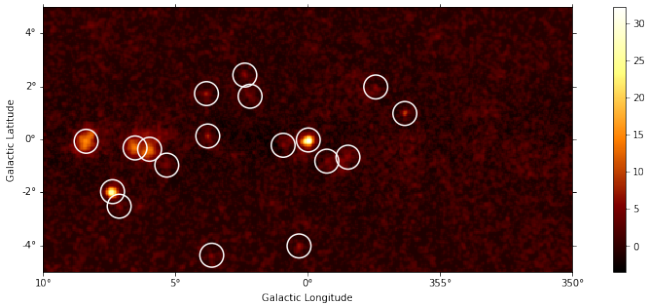
see: Dataset fitting tutorial

DL4 to DL5: estimating fluxes

- Gammapy provides a set of estimator objects which create DL5 data products based on a model assigned to one or more datasets.
  - Once a proper model is determined
  - In predefined energy intervals, estimators compute:
    - fluxes errors and associated significance
    - fit statistic scan etc.
  - They can produce flux points, light curves, flux maps







Config-file driven analysis

The YAML configuration file

```yaml
general:
    log: {level: info, filename: null, filemode: null, format: null, datefmt: null}
    outdir: .
observations:
    datastore: $GAMMAPY_DATA/hess-dl3-dr1
    obs_ids: []
    obs_file: null
    obs_cone: {frame: icrs, lon: 83.633 deg, lat: 22.014 deg, radius: 5.0 deg}
    obs_time: {start: null, stop: null}
    required_irf: [aeff, edisp, bkg]
datasets:
    type: 1d
    stack: true
    geom:
        axes:
            energy: {min: 0.2 TeV, max: 30.0 TeV, nbins: 15}
            energy_true: {min: 0.1 TeV, max: 60.0 TeV, nbins: 30}
    map_selection: [counts, exposure, edisp]
    background:
        method: reflected
        exclusion: null
    safe_mask:
        methods: [aeff-default, aeff-max]
        parameters: {aeff_percent: 10}
    on_region: {frame: icrs, lon: 83.63 deg, lat: 22.01 deg, radius: 0.11 deg}
    containment_correction: true
fit:
    fit_range: {min: 0.6 TeV, max: 20.0 TeV}
flux_points:
    energy: {min: 0.4 TeV, max: 20.0 TeV, nbins: 10}
    source: Crab
    parameters: {selection_optional: all}
```

```python
config = AnalysisConfig.read(f"{estimate}/config.yaml")
analysis = Analysis(config)
analysis.get_observations()
analysis.get_datasets()

models = Models.read(f"{estimate}/models.yaml")
analysis.set_models(models)
analysis.run_fit()
```

Select observations

Define target Dataset geometry

Define data reduction methods

Define Fit configuration

Define high level estimators config.

See High Level Interface tutorial