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

VHE data analysis using Open Source Packages workshop

Feb 2th 2022

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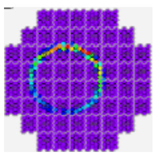
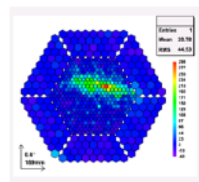
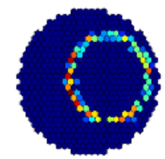
VHE analysis: formats and tools

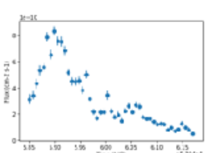
- All VHE gamma-ray instruments have their own proprietary formats and tools making joint analyses impossible

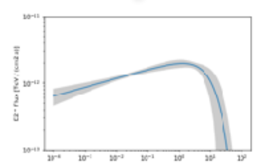


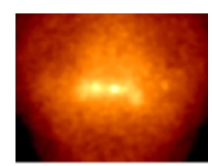




Raw data







High level science products

How to compare:

- instrument-based assumptions on physical spectrum?
- inter-instrument systematics effects?
- treatment of low statistics?

VHE analysis: formats and tools

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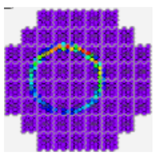
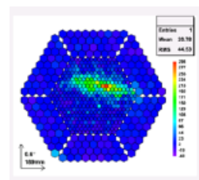
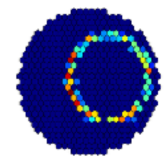
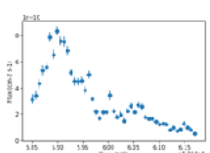
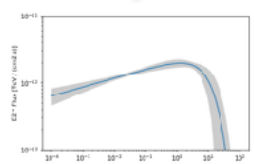
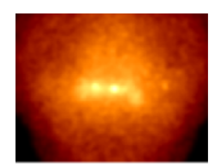




Raw data

VHE analysis needs common open *data formats* and common open *tools*

High level science products

How to compare:

- instrument-based assumptions on physical spectrum?
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- treatment of low statistics?

The data flow

Separating instrument specific data treatment from common use cases and methods

Reconstruction pipeline
(instrument specific)

Science Tools (general users)

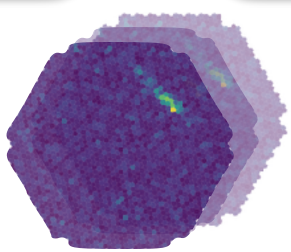
DL 0-1
raw - calibrated

DL 2
reconstructed

DL 3
filtered γ-like events

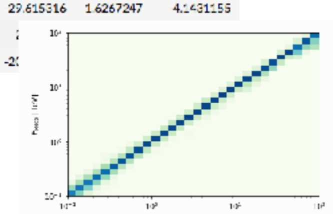
DL 4
science

DL 5
high-level

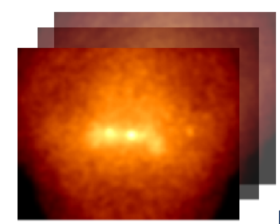


camera data

ENERGY	RA	DEC	L	B
MeV	deg	deg	deg	deg
float32	float32	float32	float32	float32
12186.642	260.45935	-33.553337	353.36273	1.7538676
25196.598	261.37506	-34.395004	353.09607	0.6520652
15621.498	259.56973	-33.409416	353.05673	2.4450684
12816.32	279.95883	-25.340391	6.45856	-4.0548873
18988.387	260.8568	-36.355804	351.23734	-0.101912394
11610.23	266.15518	-26.224436	2.1986027	1.6034819
13960.802	271.44742	-29.615316	1.6267247	4.1431155
10477.372	266.3981	[illegible]		
13030.88	271.70128	[illegible]		



γ-like event lists
IRFs



maps,
spectra,
light curves

The gammapy concept

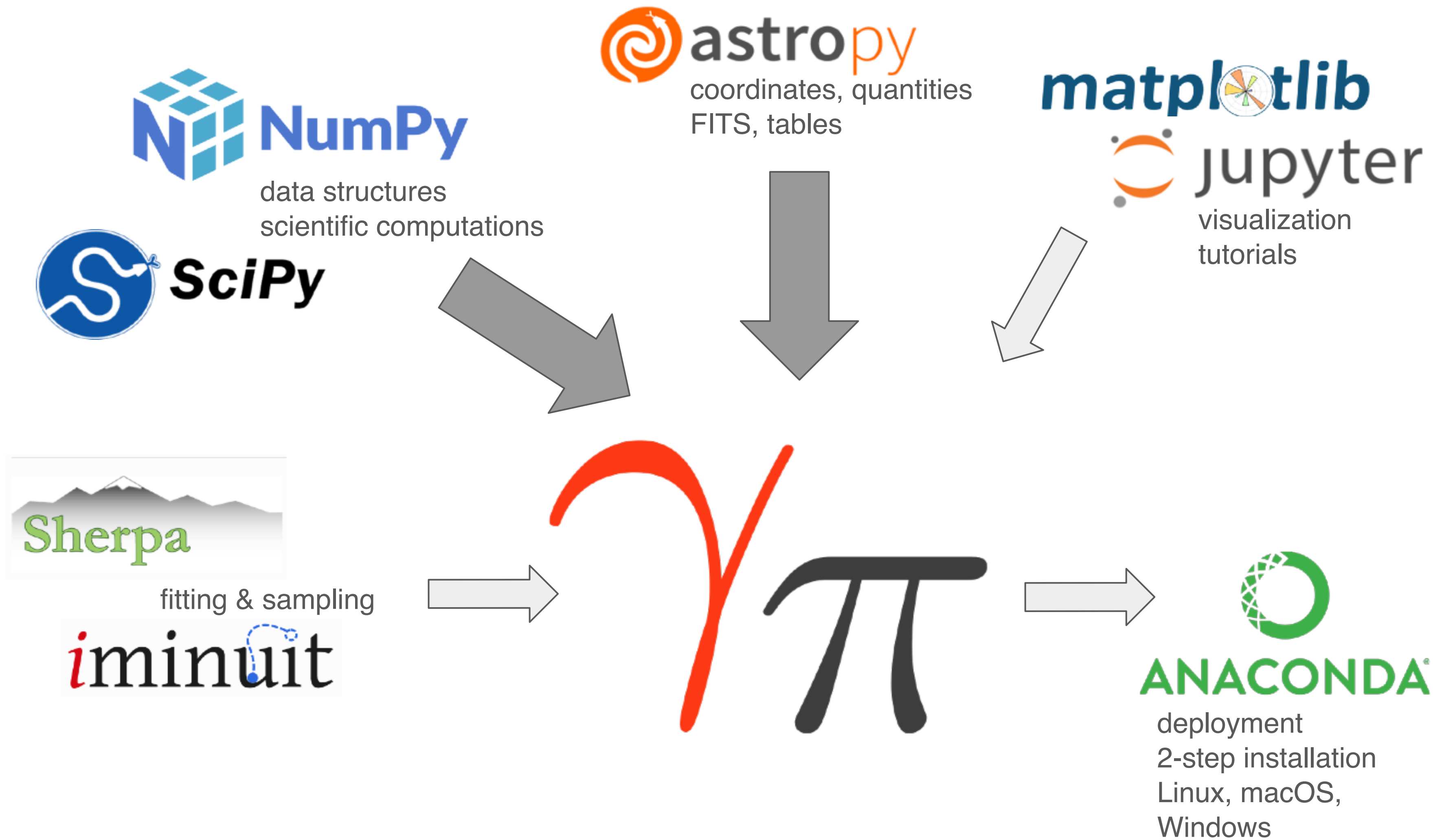
A python package for high-level γ-ray astronomy based on common data formats

A flexible, open-source, community driven, python library

+

The library for CTA science tools

Gammapy in the Python ecosystem



Getting the software

- **Recommended gammapy installation**

```
curl -O https://gammapy.org/download/install/gammapy-0.19-
environment.yml
conda env create -f gammapy-0.19-environment.yml
conda activate gammapy-0.19
```

- **Download tutorials & associated data**

```
gammapy download notebooks --release 0.19
gammapy download datasets
export GAMMAPY_DATA=$PWD/gammapy-datasets
```

Note: mamba might prove a better/faster package manager

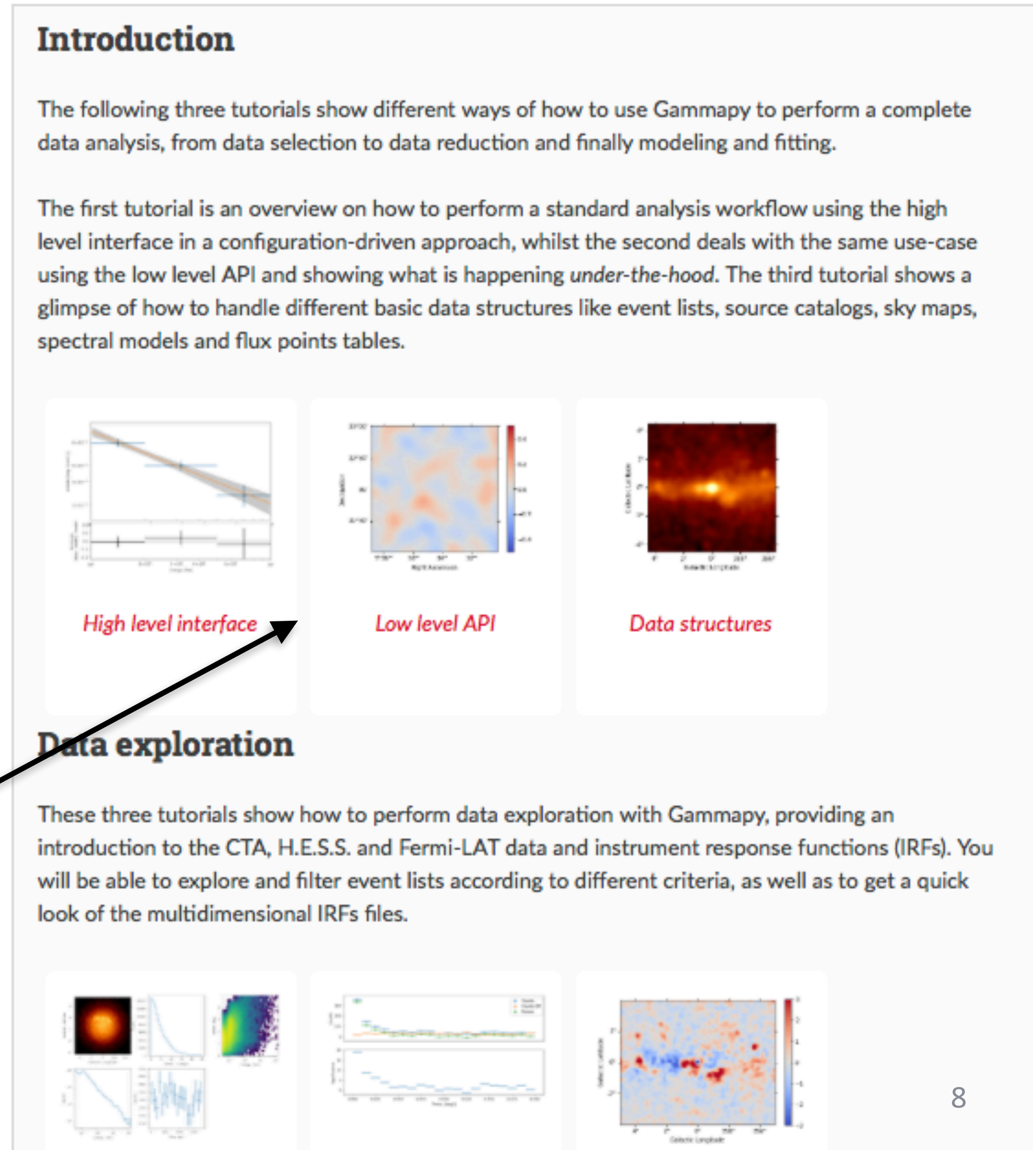
See: https://docs.gammapy.org/0.19/install/index.html

Getting started: documentation

See docs.gammapy.org

Tutorials to learn simple data analysis recipes

- spectral analysis
- lightcurve extraction
- 3D fitting
- simulation



Introduction

The following three tutorials show different ways of how to use Gammapy to perform a complete data analysis, from data selection to data reduction and finally modeling and fitting.

The first tutorial is an overview on how to perform a standard analysis workflow using the high level interface in a configuration-driven approach, whilst the second deals with the same use-case using the low level API and showing what is happening *under-the-hood*. The third tutorial shows a glimpse of how to handle different basic data structures like event lists, source catalogs, sky maps, spectral models and flux points tables.

High level interface *Low level API* *Data structures*

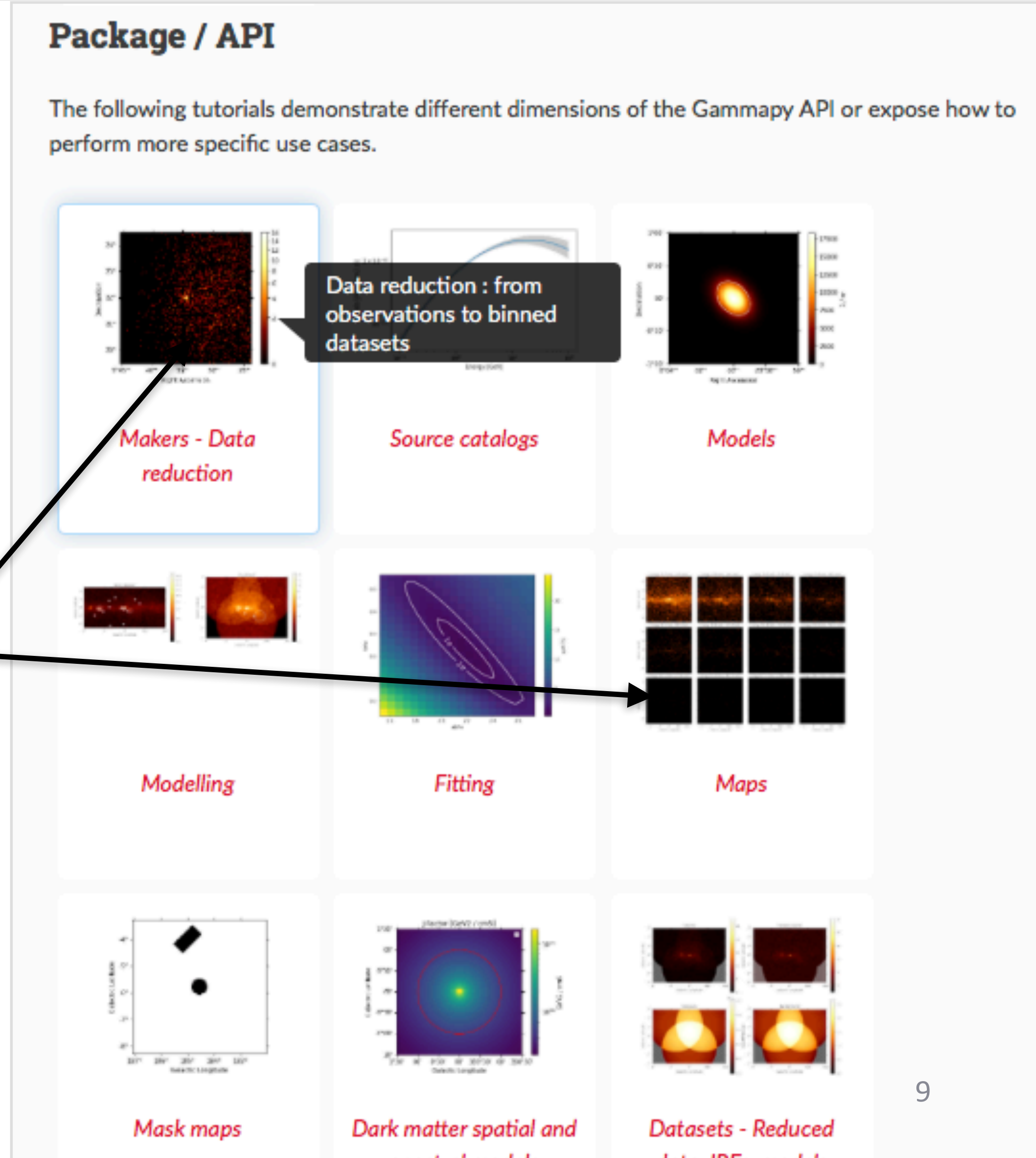
Data exploration

These three tutorials show how to perform data exploration with Gammapy, providing an introduction to the CTA, H.E.S.S. and Fermi-LAT data and instrument response functions (IRFs). You will be able to explore and filter event lists according to different criteria, as well as to get a quick look of the multidimensional IRFs files.

Getting started: documentation

Learn how to use the general API

- go beyond tutorials use cases
- exploit Gammapy flexibility



Getting help

- Where/How to interact with dev team and experienced users, provide feedback, get help:

  - gammapy.slack.
    - In particular: #help channel

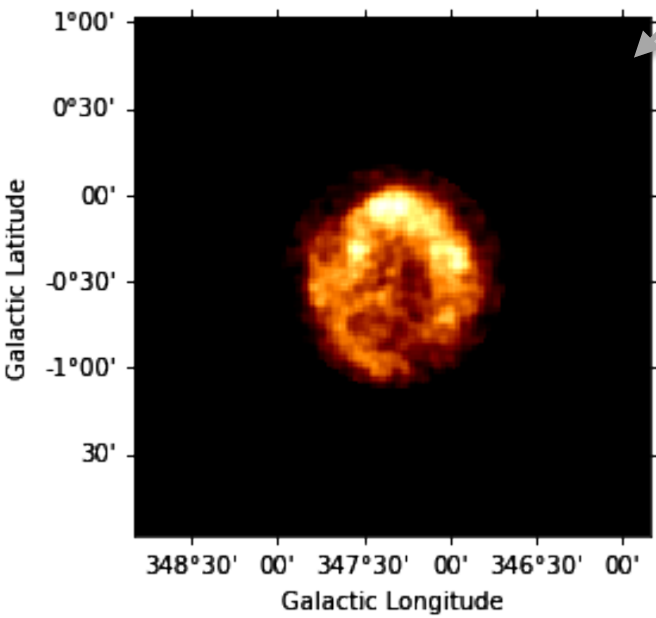
  - [GitHub discussions]
    - help category

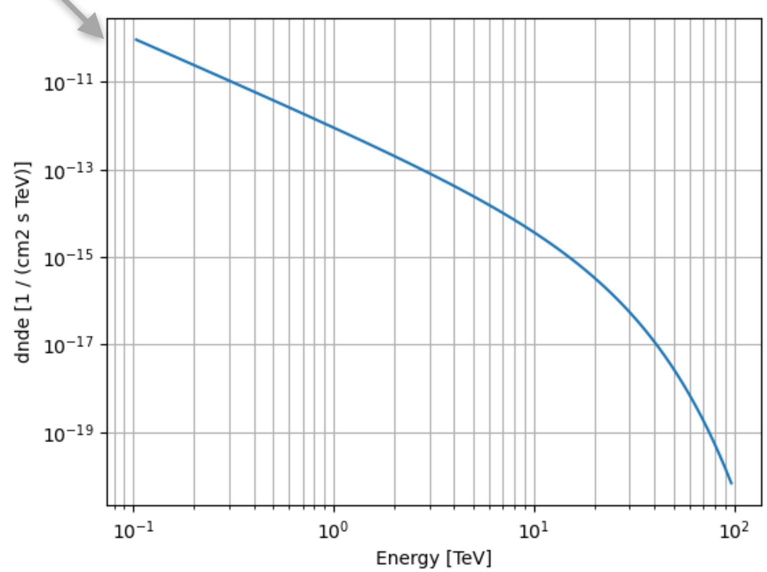
  - [GitHub issues] to report bugs or feature requests

Modeling the expected number of detected photons

- Assume a source *S* emits gamma-ray photons.
- Its emission is represented by sky model $\Phi(p_t, E_t)$ with p_t the photon position in the sky and E_t its energy
- We want to determine the model parameters that best reproduce the measured data.

$$\Phi(p_t, E_t)$$





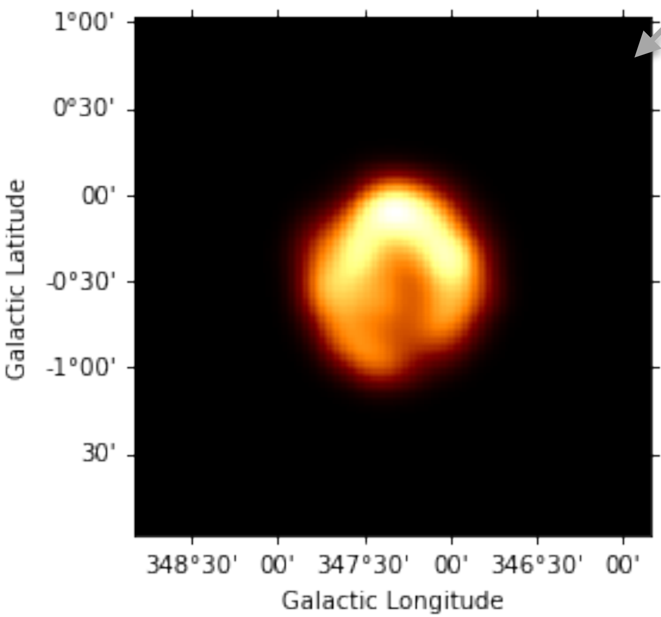
Modeling the expected number of detected photons

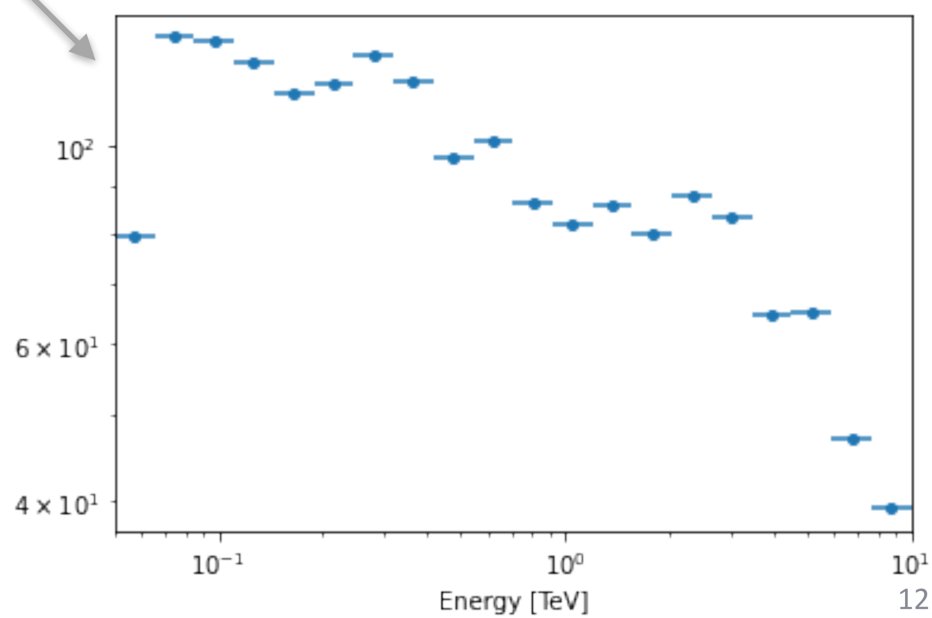
- The number of observed photons from source *S* is

$$N(p,E)dpdE = t_{obs}\int_{E_t} dE_t \int_{p_t} dp_t\ R(p,E\,|\,p_t,E_t) \times\ \Phi(p_t,E_t)$$

where $R(p,E\,|\,p_t,E_t)$ is the instrument response

$N(p,E)$





The Instrument Response Functions (IRFs)

- We assume that the instrument response can be simplified as the product of:

$$R(p, E \,|\, p_t, E_t) = A_{\text{eff}}(p_t, E_t) \times PSF(p \,|\, p_t, E_t) \times E_{\text{disp}}(E \,|\, p_t, E_t)$$

with :

- $A_{\text{eff}}(p_t, E_t)$ the effective collection area in m^2
- $PSF(p \,|\, p_t, E_t)$ the point spread function in sr^{-1}. It is the density function of the probability to detect a photon emitted at p_true at position p.
- $E_{\text{disp}}(E \,|\, p_t, E_t)$ the energy dispersion in TeV^{-1}. Probability to detect photon emitted at True at energy E.

The Instrument Response Functions (IRFs)

- Measured events do not only contain genuine photons but also residual charged cosmic-ray background:

$$N(p,E) = \sum_S N_S(p,E) + N_{bkg}(p,E)$$

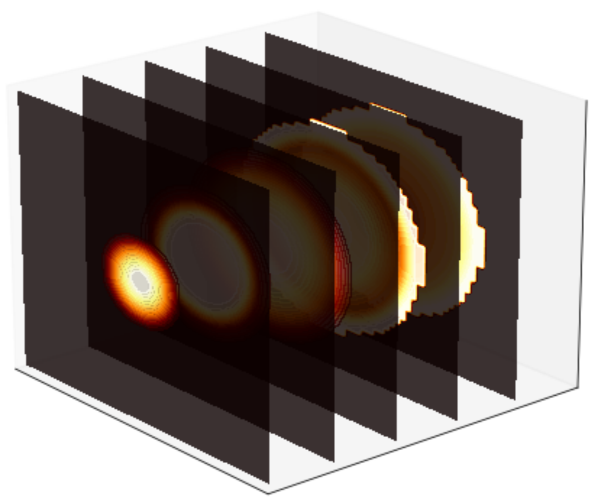
with :

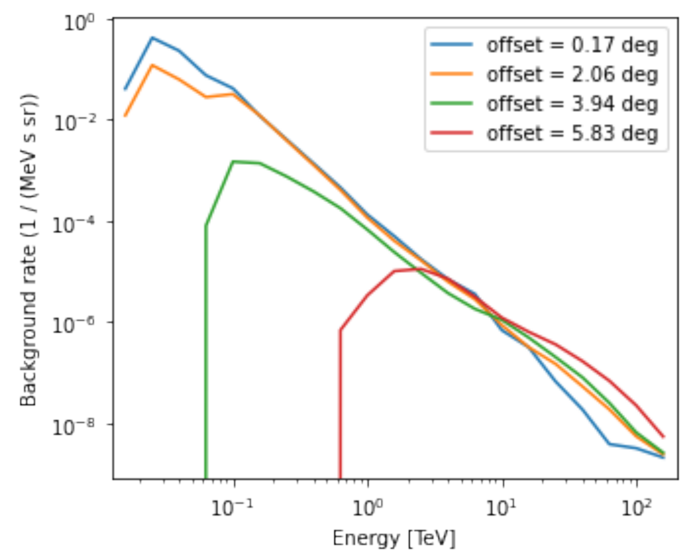
- $N_S(p,E)$ the number of predicted photons from source S
- $N_{bkg}(p,E)$ the number of background events

- The residual CR background must be modeled along the sky model:
  - can be estimated from OFF data
  - can be described by a model $N_{\rm bkg}(p,E) = BKG(p,E) \times t_{\rm obs}$

The background model IRF

- $BKG(p, E)$ is the 3D background model in $s^{-1}sr^{-1}TeV^{-1}$
- The model can be built from simulations of atmospheric showers or from a large set of empty field observations taken in similar conditions. ***It is subject to non-negligible uncertainties***.
- Note that the background is highly sensitive to observing conditions such as zenith angle, optical efficiency of the system, atmospheric transparency etc.

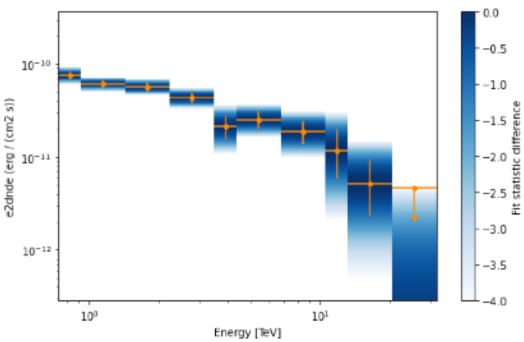




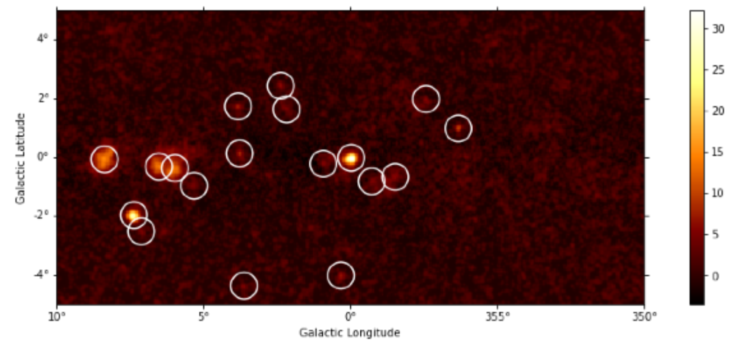
Exploring DL3 with gammapy

- The g.a.d.f. v0.2 format relies on several FITS HDUs:
  - EVENTS: table of gamma-like events measured parameters
  - GTI: Interval of time associated to events
  - POINTING: Telescope pointing info
  - AEFF : Effective area table (true energy, FoV offset)
  - EDISP : Energy dispersion (true energy, FoV offset)
  - PSF: isotropic PSF (true energy, FoV offset)
  - BACKGROUND: (energy, FoV lon, FoV lat)
- A general HDU table connects everything
- See data exploration tutorial

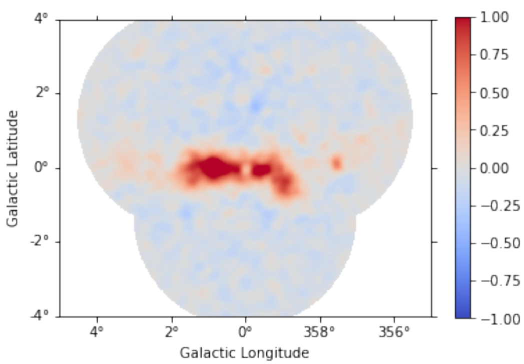
Typical analysis use cases



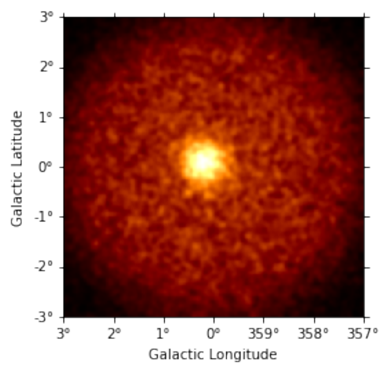
[1D spectral analysis]



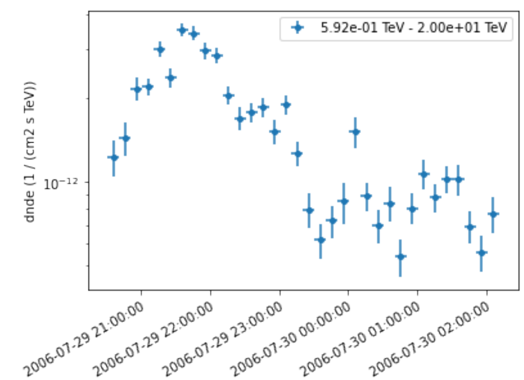
[Source detection]



[3D analysis]



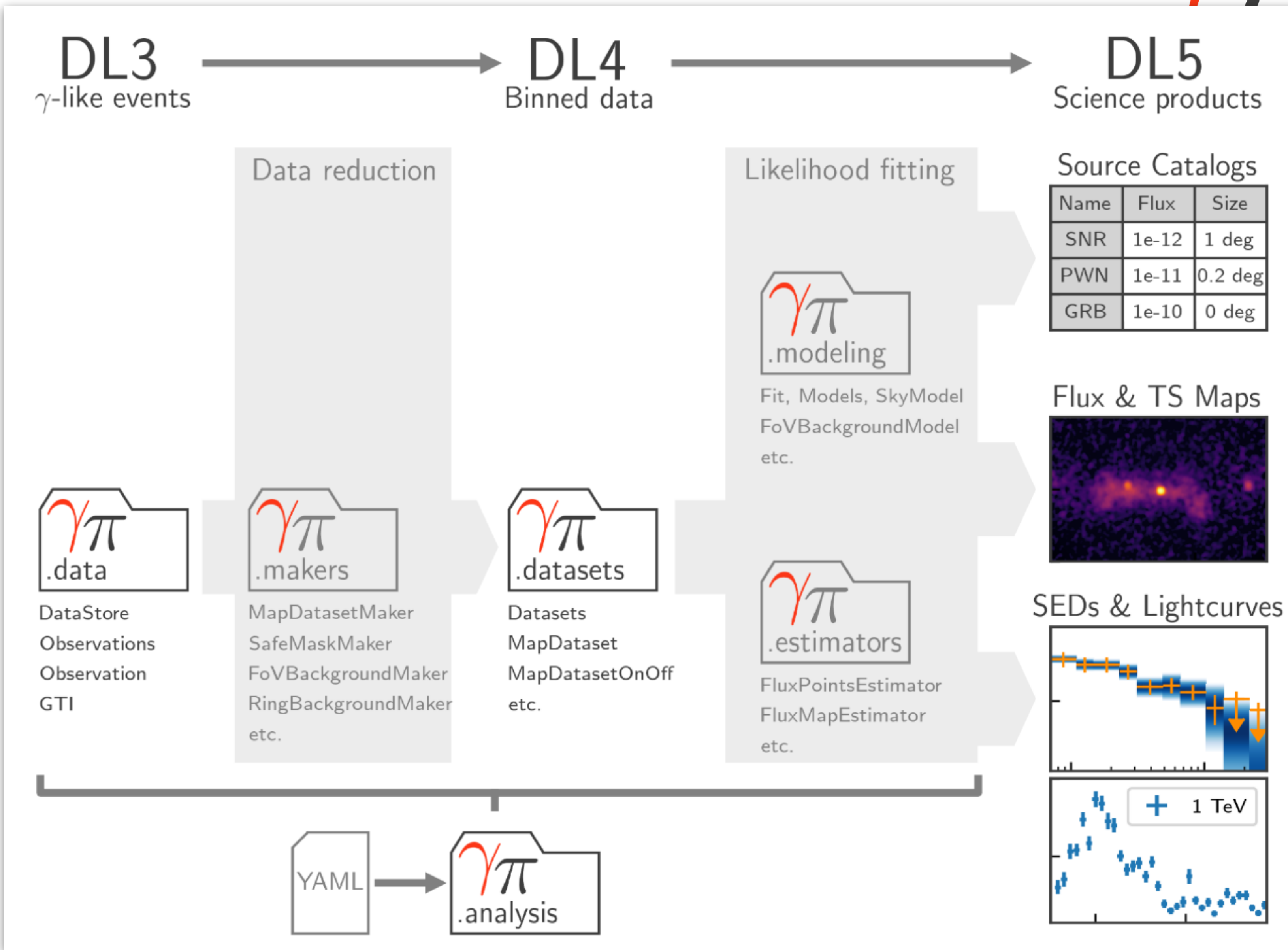
[observation simulation]



[light-curve extraction]

All analysis types follow the same workflow and the same API

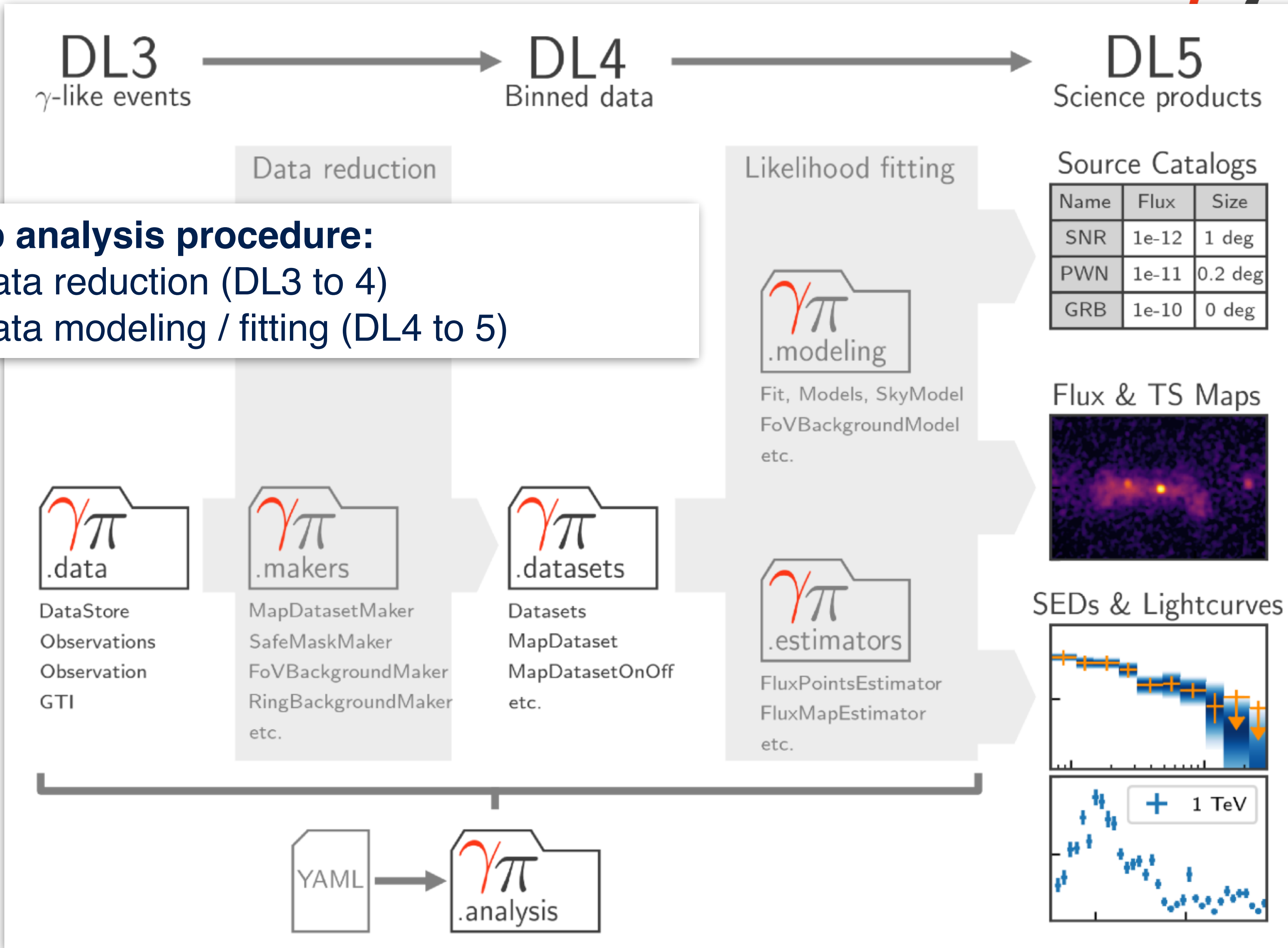
Data workflow and package structure



Data workflow and package structure

2-step analysis procedure:

- data reduction (DL3 to 4)
- data modeling / fitting (DL4 to 5)

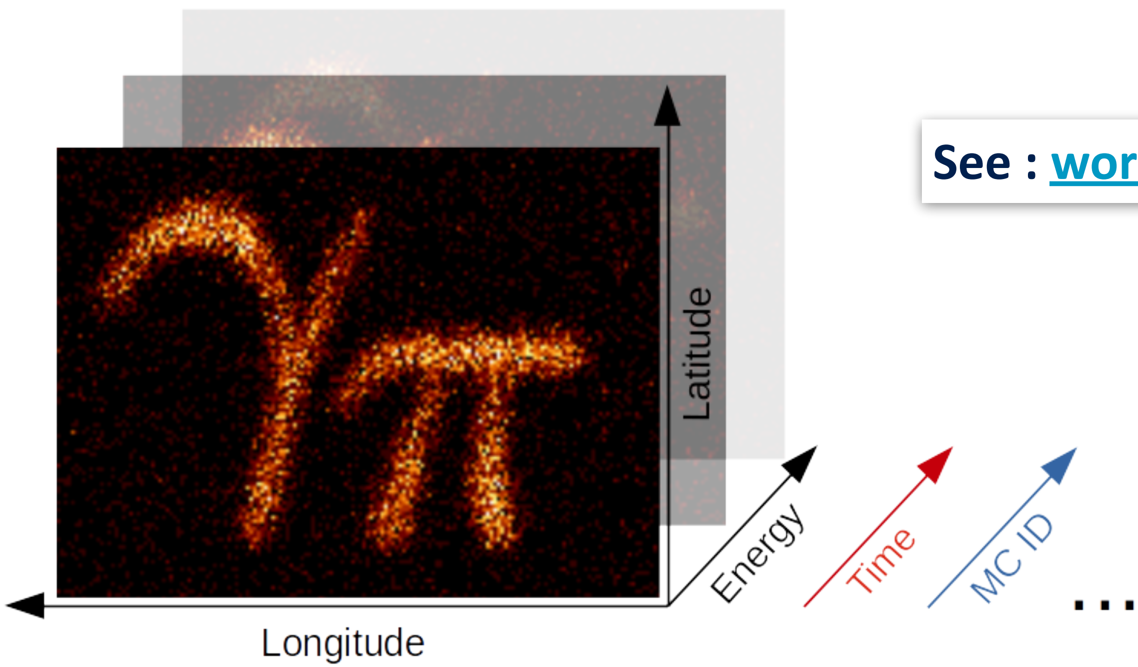


Data reduction

1. Select and retrieve relevant observations from the data store
2. Define the reduced dataset geometry
   - Is the analysis 1D (spectral only) or 3D?
   - Define target binning and projection
3. Initialize the data reduction methods (makers)
   - Data and IRF projection
   - Background estimation
   - Safe Mask determination
4. Loop over selected observations
   - Apply makers to produce reduced datasets
   - Optionally combine them (stacking)

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



See : working with maps

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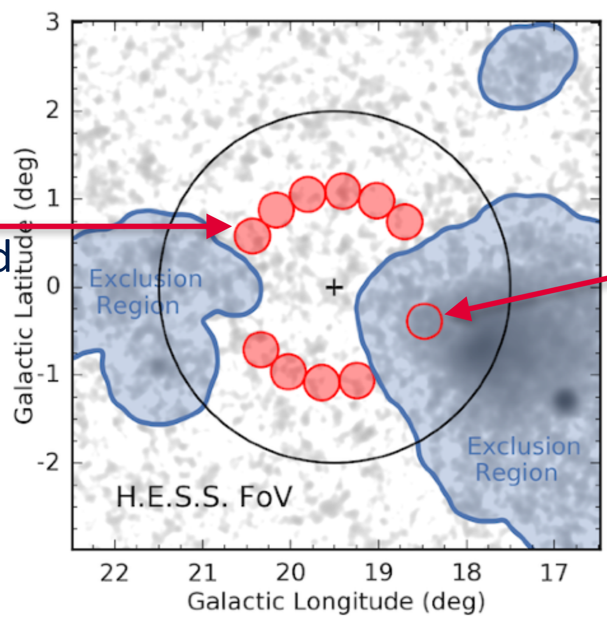
Estimating the background from the data

- To reduce systematic uncertainties, $BKG(p, E)$ is usually corrected on the observed data themselves.
  - Field of View (FoV) background estimation
    - $BKG(p, E)$ is normalized in regions of the observed FoV assumed to be deprived of gamma-ray signal

Measuring the background from the data

- To further reduce systematics, 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 background

OFF regions
containing only background



ON region
containing signal and background

Data reduction

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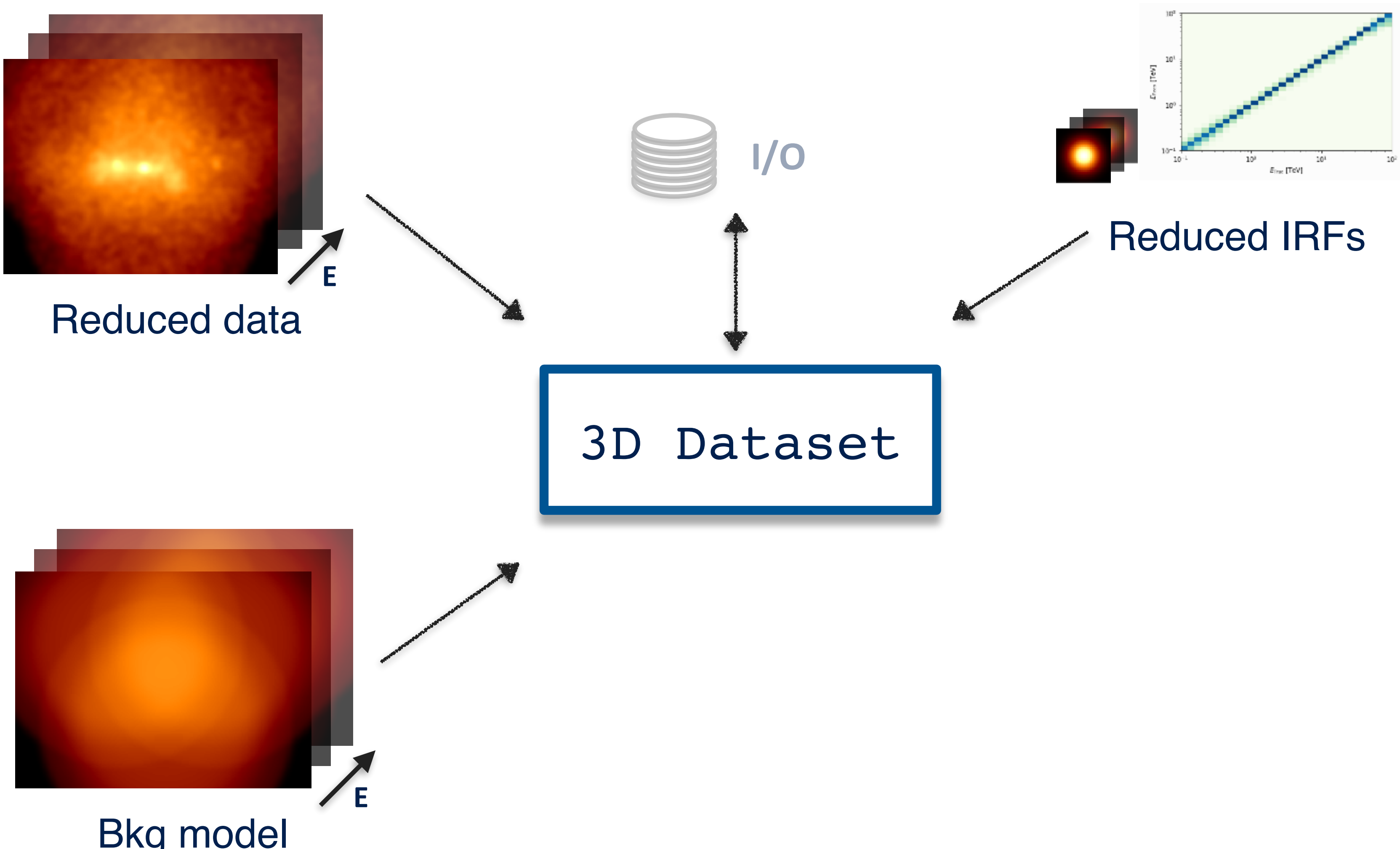
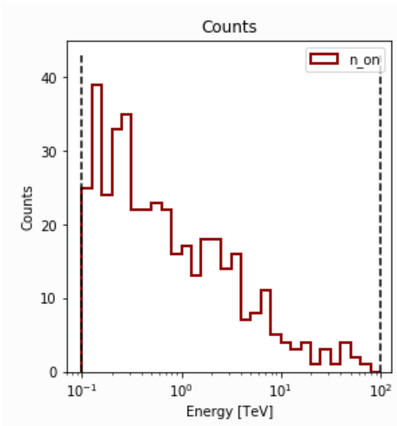
DL4 structures: Datasets



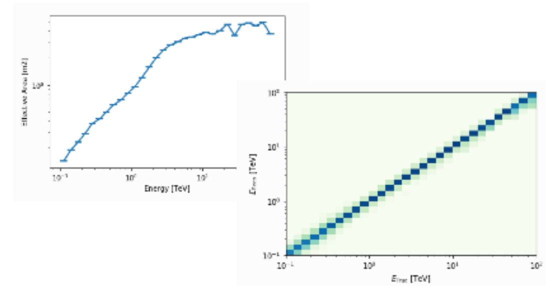
see: [Dataset API tutorial]

DL4 structures: Datasets



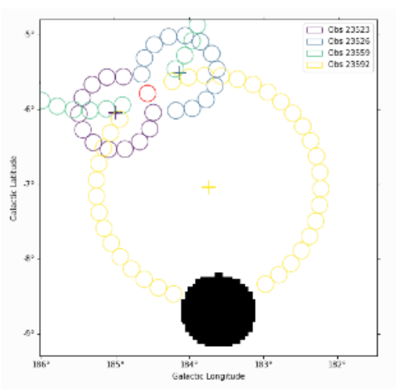
Reduced data

I/O



Reduced IRFs

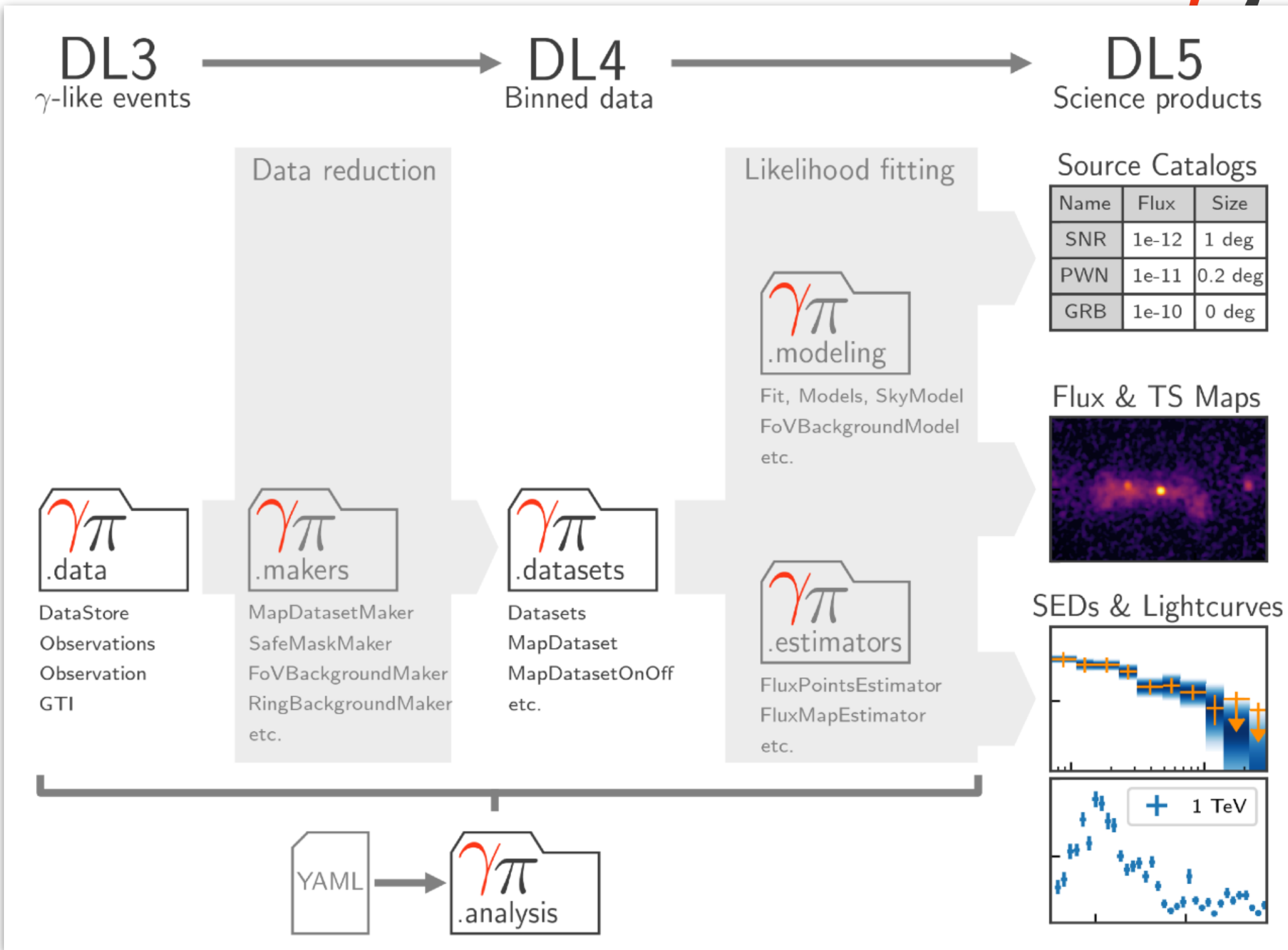
1D Dataset



Bkg data or model

see: Dataset API tutorial

Data workflow and package structure



Modeling and fitting

- For modeling and fitting, Gammapy relies on ***forward-folding***:
  - the number of measured counts N is compared to the total predicted number of counts N_{pred}

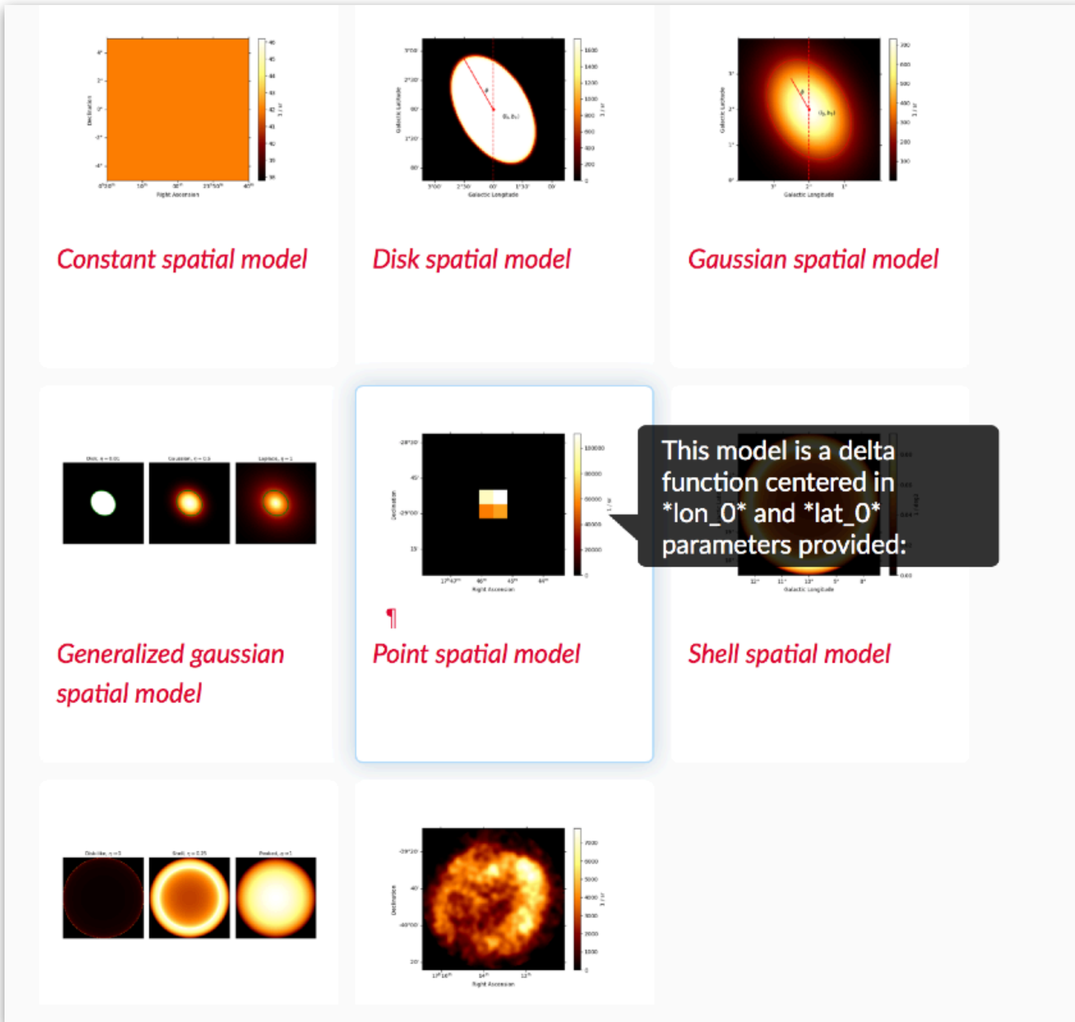
$$N_{\mathrm{pred}}(p, E) = \sum_{S} N_S(p, E) + N_{\mathrm{bkg}}(p, E)$$

- Model parameter estimation is performed through maximum likelihood technique.
  - [Cash statistics]() is used for counts data with a known background

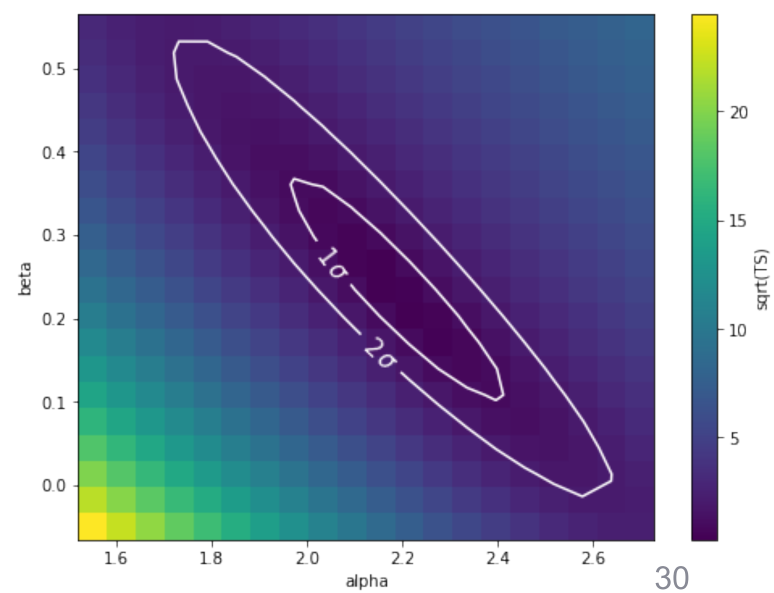
$$TS = -2 \log L = 2 \sum \left(N \log N_{\mathrm{pred}} - N_{\mathrm{pred}} \right)$$

  - [Wstat statistics]() is used for counts data with a measured background

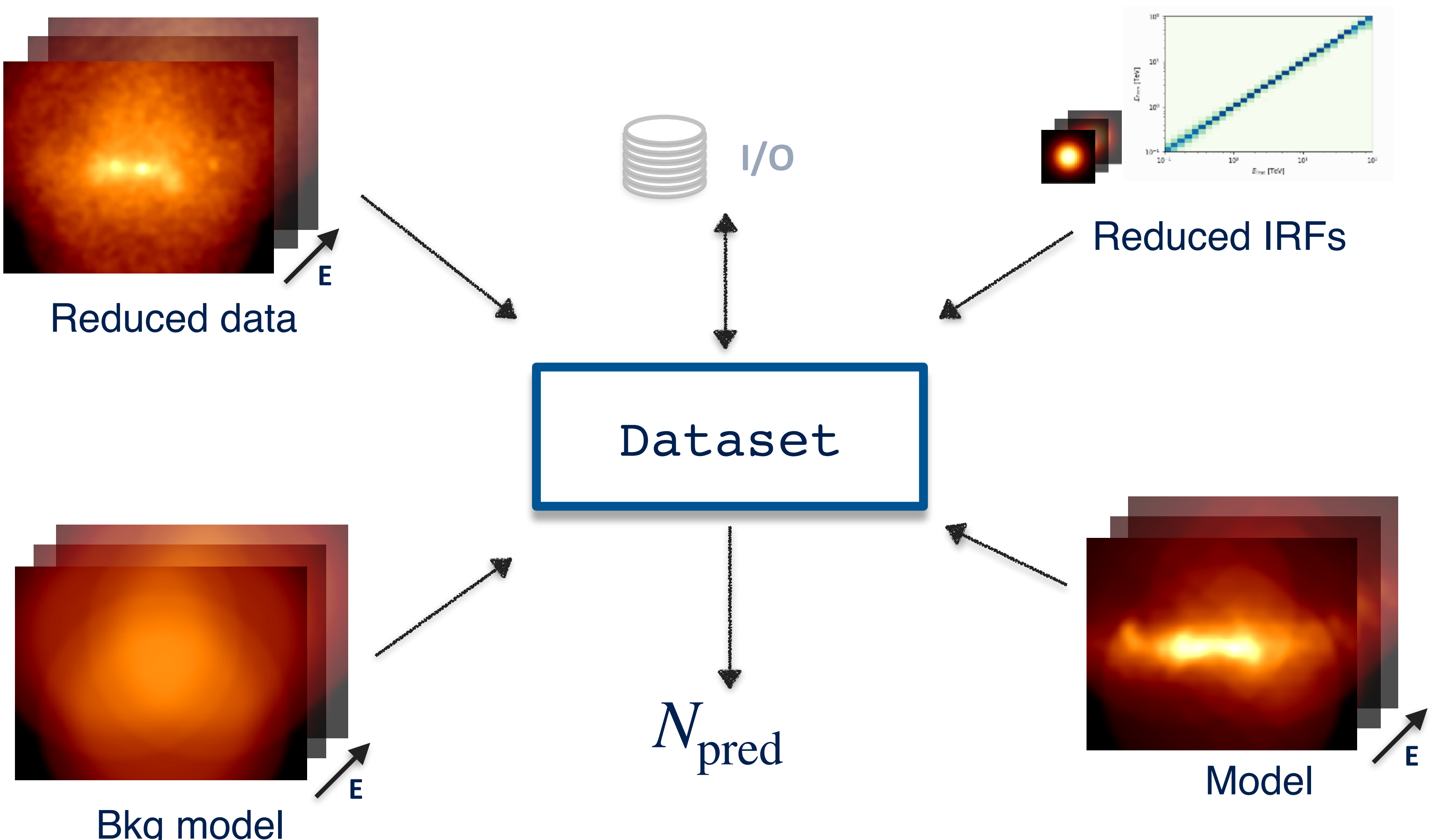
Datasets modeling and fitting



A library of models and a Fitting interface

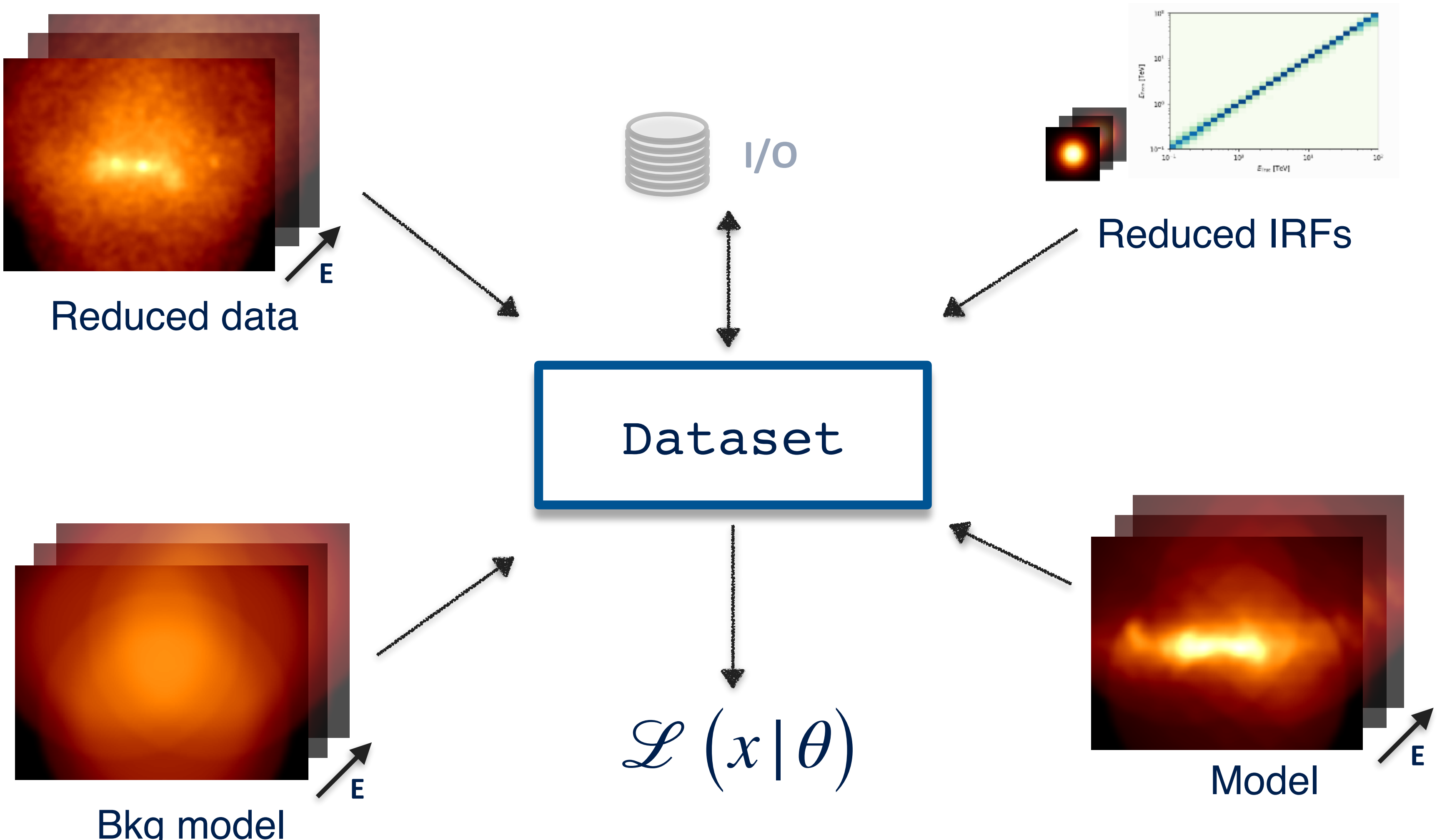


Datasets modeling and fitting



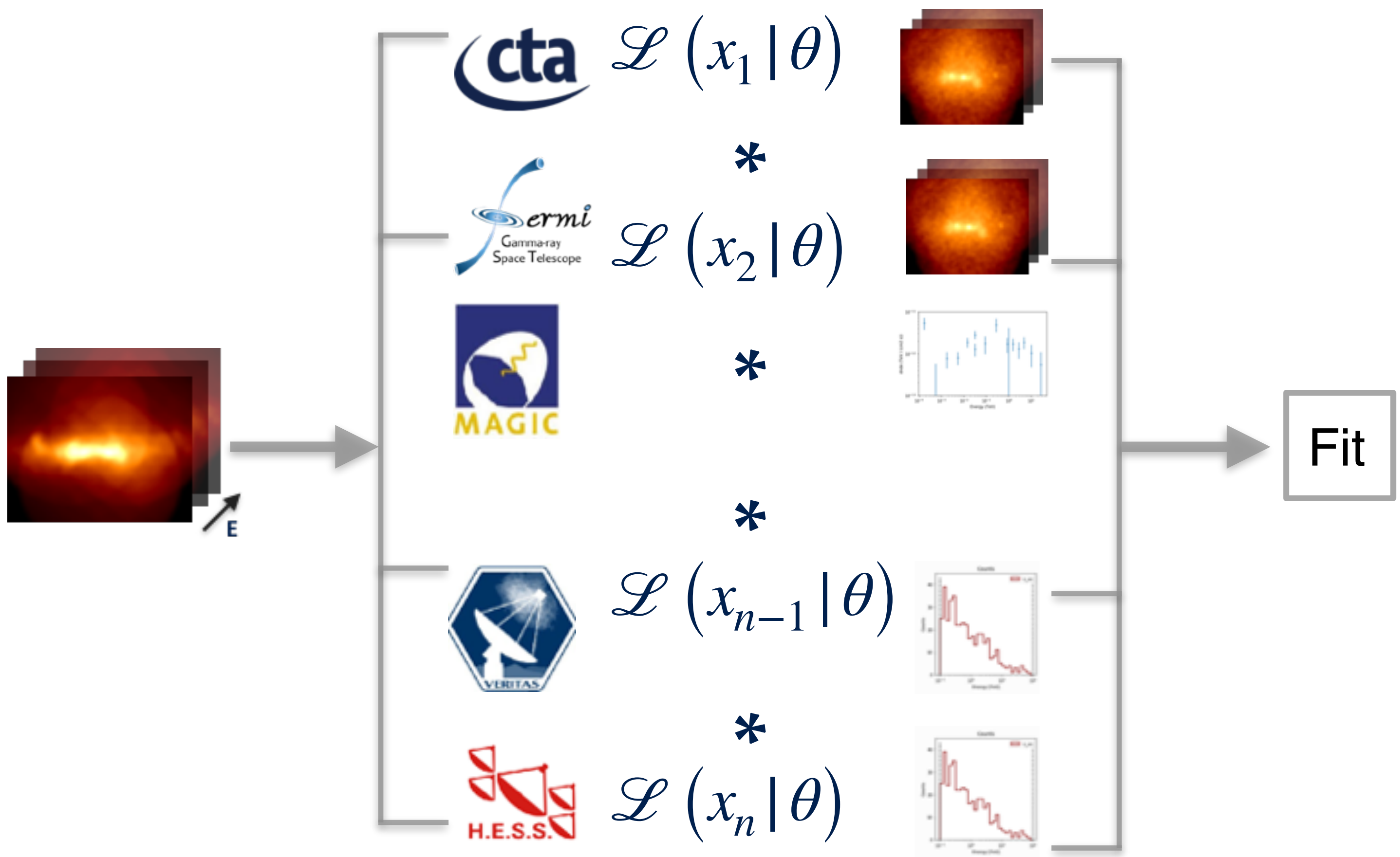
see:[Dataset simulation tutorial]

Datasets modeling and fitting



see: [Dataset fitting tutorial]

Multi-instrument modeling and fitting

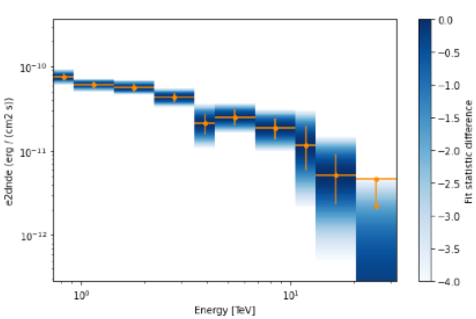


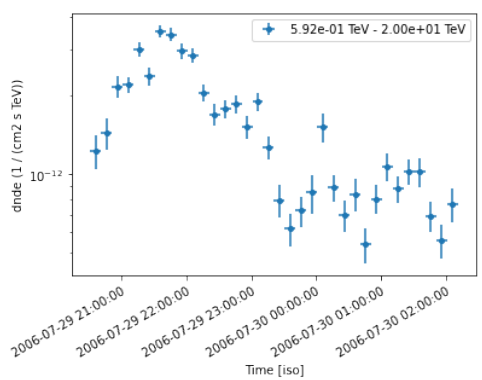
Gammapy Dataset structure allows heterogeneous data modeling and fitting:

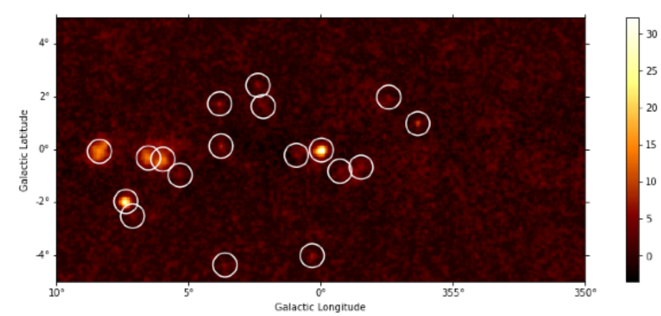
- See [joint fit tutorial]

DL5 products: 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







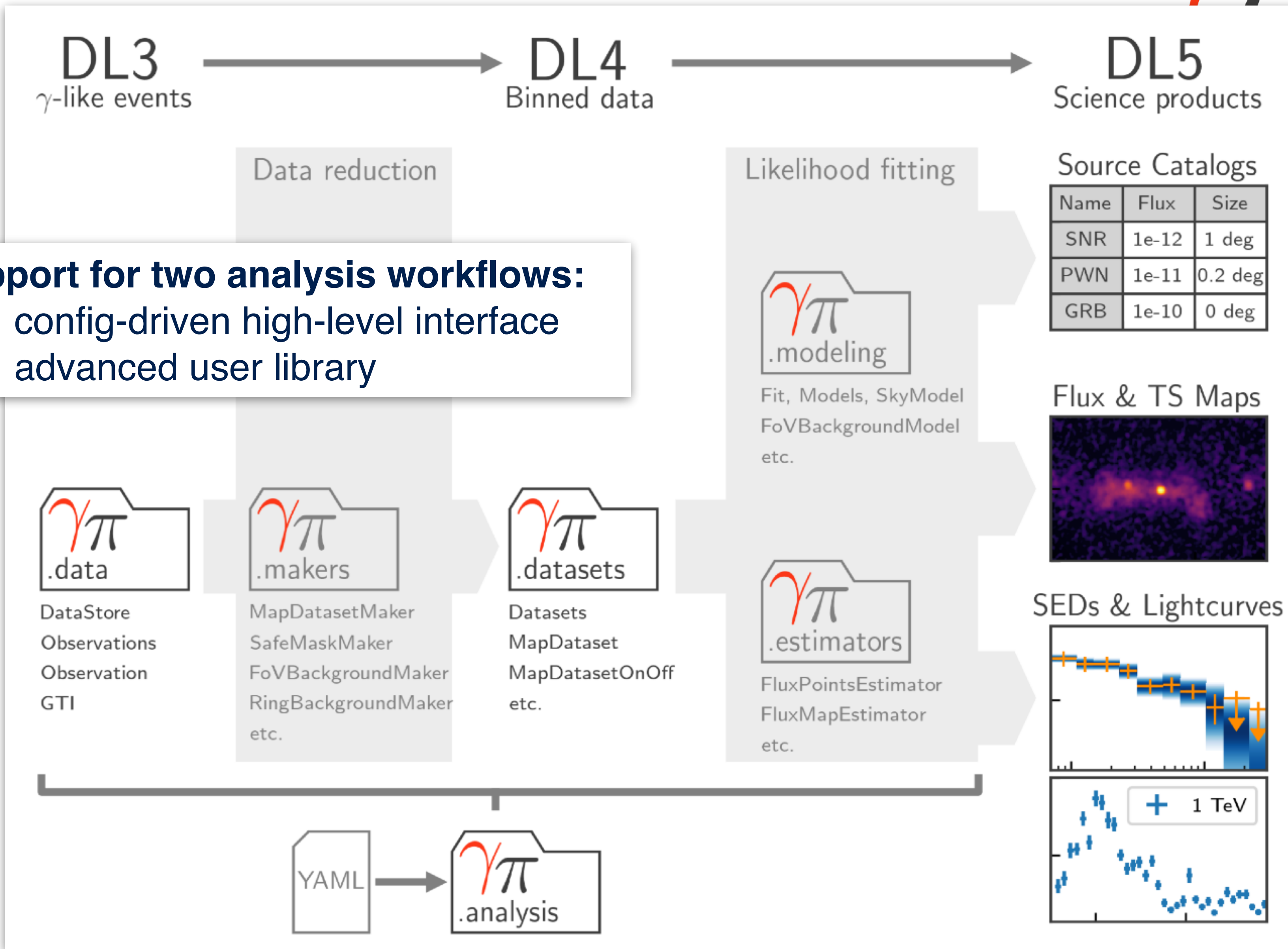
Estimating statistical significance

- Estimate whether H_1 is statistically preferred over the reference H_0
- It is possible to compare the two *nested models* (i.e. H_0 is a subset of H_1) with the maximum likelihood ratio test
  - $\Delta TS = TS_1 - TS_0$ follows asymptotically a χ^2 with n degrees of freedom
    - allows to determine p-value of e.g. a source component
  - with 1 degree of freedom $\sqrt{\Delta TS}$ gives a statistical significance as a number of « gaussian sigma »

Data workflow and package structure

support for two analysis workflows:

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



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()
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models = Models.read(f"{estimate}/models.yaml")
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Select observations

Define target Dataset geometry

Define data reduction methods

Define Fit configuration

Define high level estimators config.

See High Level Interface tutorial

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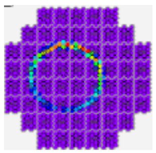
See [High Level Interface tutorial]

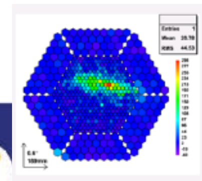
Questions & Comments

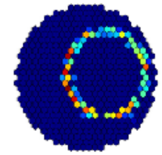
- Where/How to interact with dev team and experienced users, provide feedback, get help:
  - gammapy.slack.
    - In particular: #help channel
  - [GitHub discussions]
    - help category
  - [GitHub issues] to report bugs or feature requests

Thank you!

An example of joint analysis



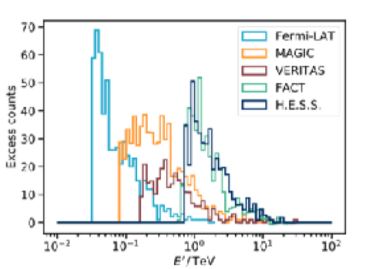


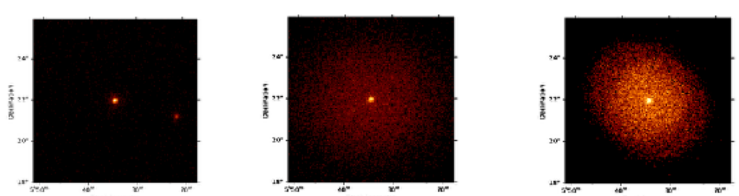


Raw data

Dataset	T_{obs}	E_{min} (TeV)	E_{max} (TeV)	N_{on}	N_{bkg}	R_{on} (deg)
Fermi-LAT	~7 yr	0.03	2	578	1.2	0.30
MAGIC	0.66 h	0.08	30	784	129.9	0.14
VERITAS	0.67 h	0.16	30	289	13.7	0.10
FACT	10.33 h	0.45	30	691	272.8	0.17
H.E.S.S.	1.87 h	0.71	30	459	27.5	0.11

DL3 gadf

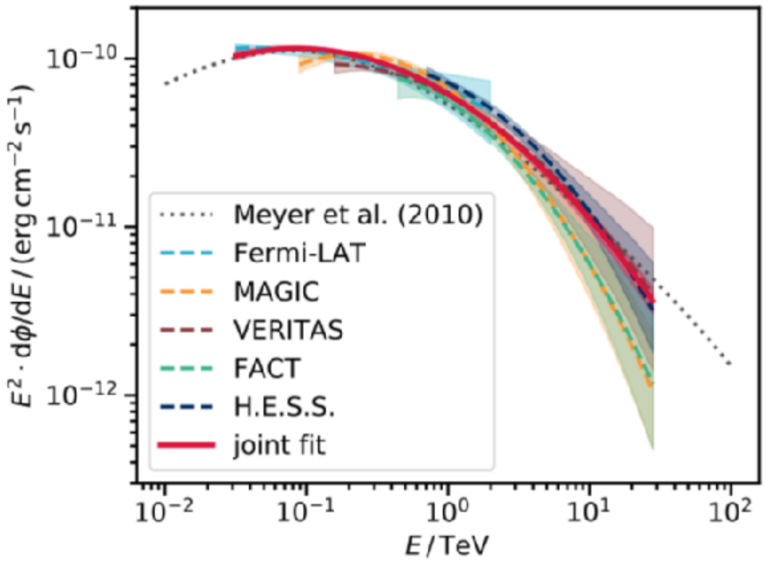


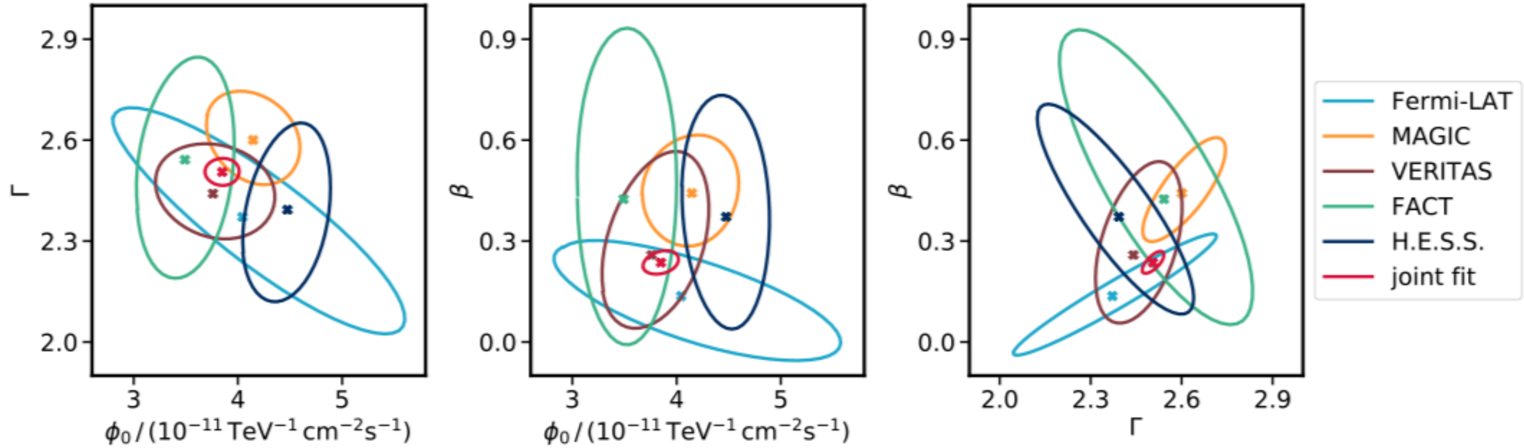


High level
science products

An example of joint analysis

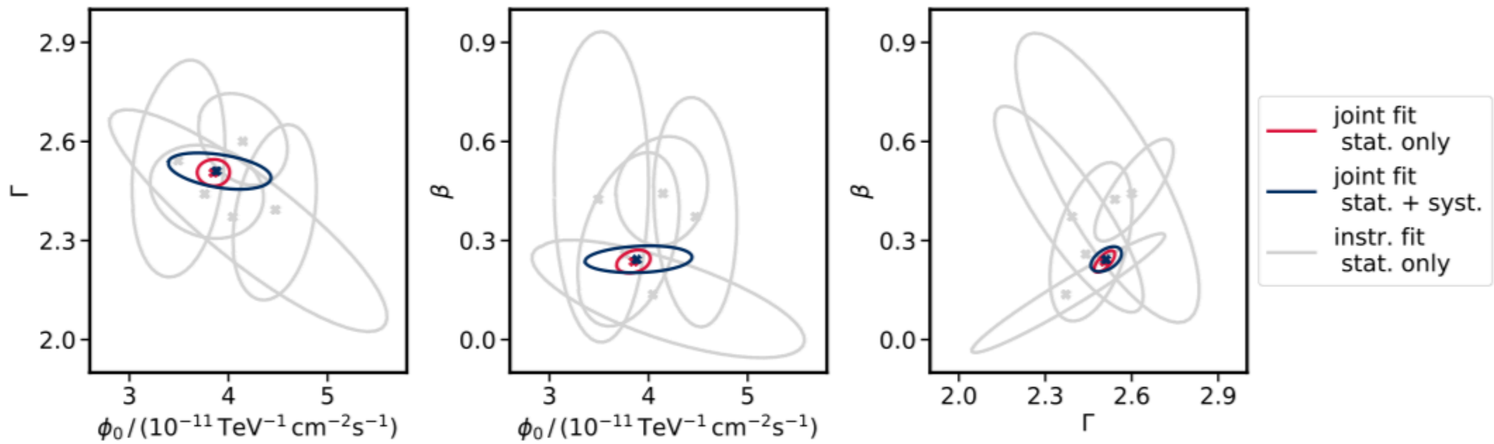
- joint point-like analysis
- log-parabola fit using ON-OFF likelihood





An example of joint analysis

- Can perform inter-calibration studies to evaluate systematics:
  - e.g. uncertainties on energy scale



- Can perform spectral fits on the parent particle population