Data analysis for the Cherenkov Telescope Array using Gammapy

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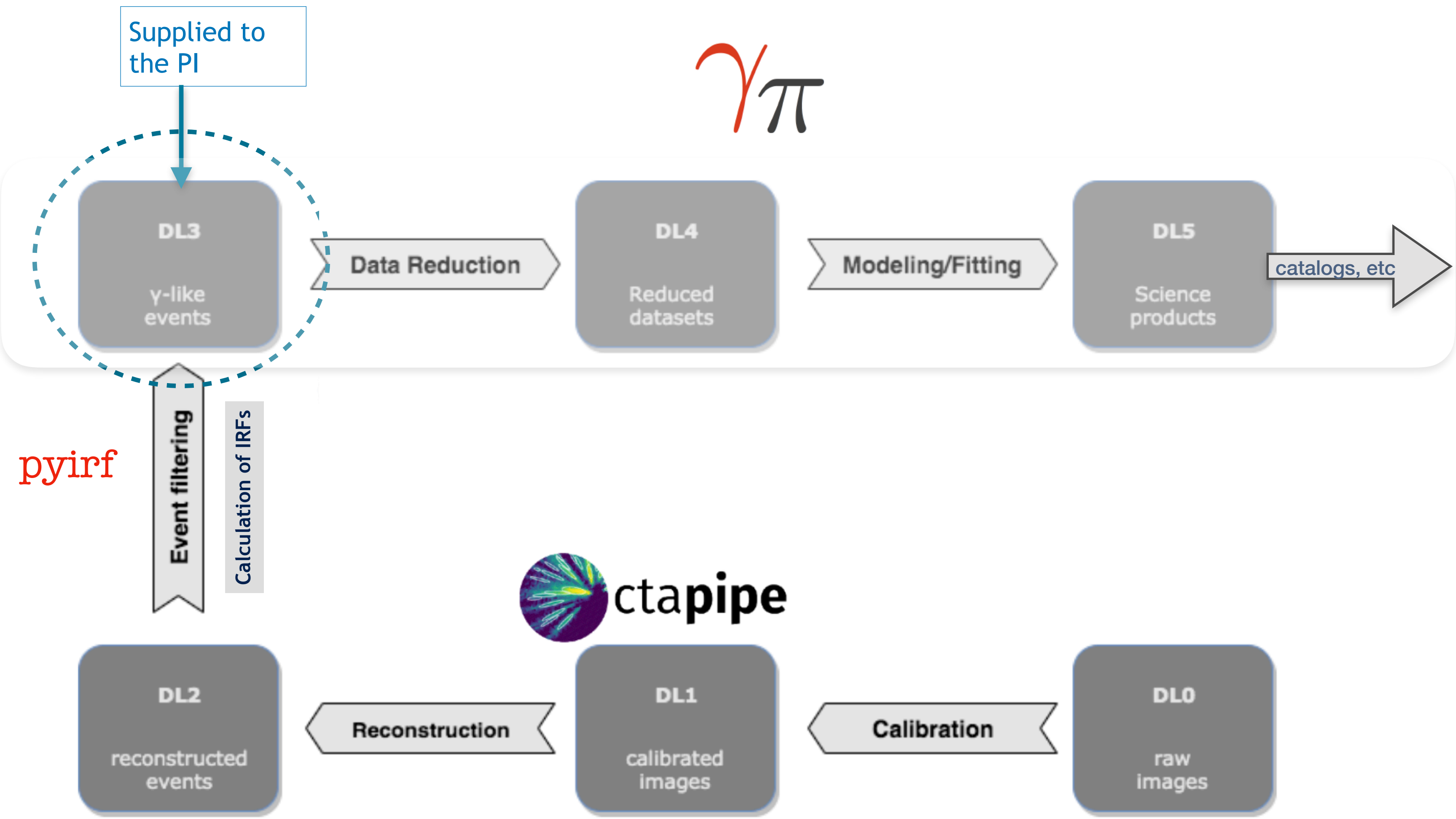
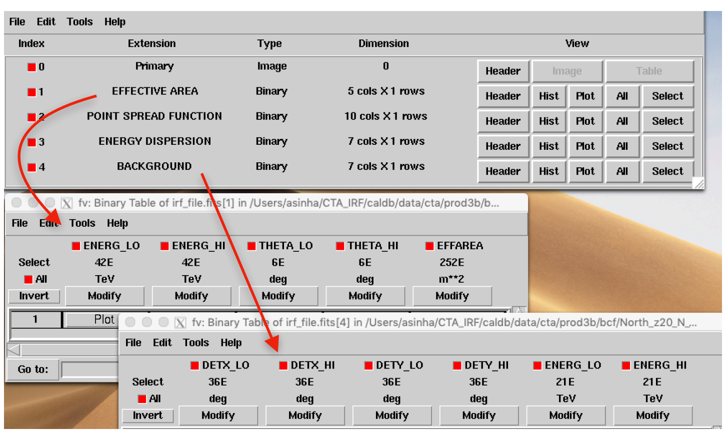
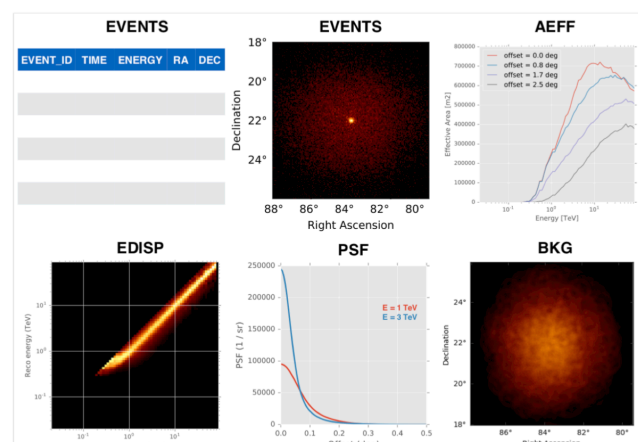
CTA data levels



DL3 format: γ-like events and IRFs

- Common data format for gamma-ray data
- Community effort in the Gamma Astro Data Formats (GADF): https://gamma-astro-data-formats.readthedocs.io/en/v0.2/ : Will evolve once CTA specifications are defined
- Started for IACTs, also adaptable for Fermi, HAWC…
- Based on FITS standards, follow FITS conventions for time and co-ordinates
- Information stored in binary tables in specific Header Data Unit (HDU)





Deil et al, 2017

Response: IRFs in DL3 format

- IRFs meant to perform model forward-folding:
  - compute predicted number of counts in detector

$$N(p, E)\mathrm{d}p\mathrm{d}E = t_{\mathrm{obs}} \int_{E_{\mathrm{true}}} \mathrm{d}E_{\mathrm{true}} \int_{p_{\mathrm{true}}} \mathrm{d}p_{\mathrm{true}}\, R(p, E|p_{\mathrm{true}}, E_{\mathrm{true}}) \times \Phi(p_{\mathrm{true}}, E_{\mathrm{true}})$$

- Hypothesis: response can be factored:

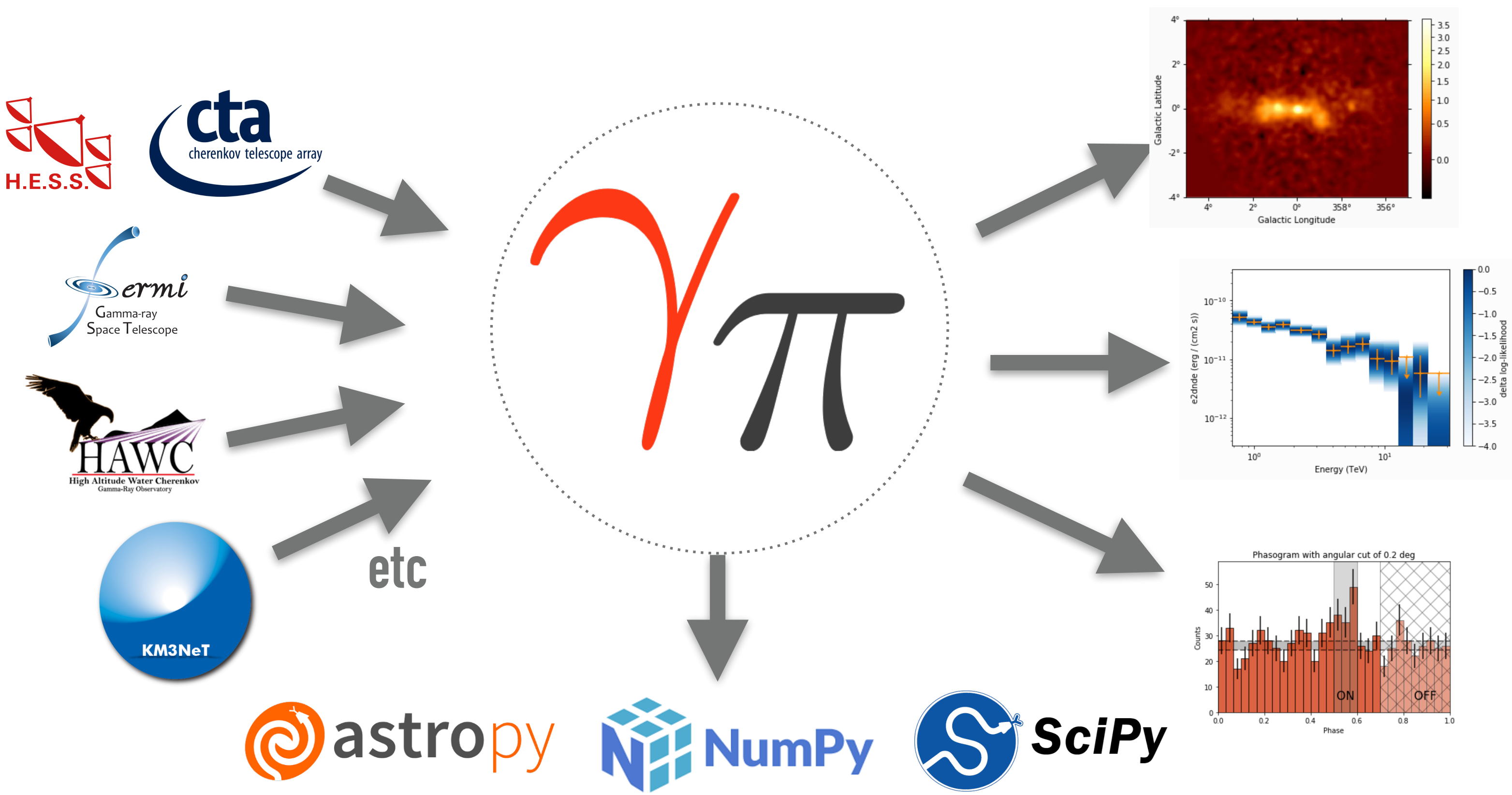
$$R(p, E|p_{\mathrm{true}}, E_{\mathrm{true}}) = A_{\mathrm{eff}}(p_{\mathrm{true}}, E_{\mathrm{true}}) \times PSF(p|p_{\mathrm{true}}, E_{\mathrm{true}}) \times E_{\mathrm{disp}}(E|p_{\mathrm{true}}, E_{\mathrm{true}}),$$

- All IRFs are functions of true photon energy (except background)

What is shipped at DL3 level

- EVENTS HDU: event parameters (reco energy, arrival time, arrival direction, etc)
- GTI HDU: Interval of time validity of IRF response associated to events
- POINTING HDU: Pointing direction of telescope at different time stamps
- 4 main IRF components:
  - AEFF: response over the FoV, validity thresholds can be exported to header keywords
  - EDISP: pdf of migration E_reco/E_true as a fn of E_true and FoV position
  - PSF: isotropic PSF with radially symmetric response over the FoV
  - BACKGROUND: differential background flux brightness as function of reconstructed energy and FoV co-ordinates.
- HDU Index table for connecting relevant HDUs
- Observation Index Table providing meta data about each observation run (eg: livetime, #event, pointing position, etc)

Gammapy



H.E.S.S.
cta
cherenkov telescope array
Fermi
Gamma-ray
Space Telescope
HAWC
High Altitude Water Cherenkov
KM3NeT
etc
Galactic Latitude
Galactic Longitude
e2dnde (erg / (cm2 s))
Energy (TeV)
delta log-likelihood
Phasogram with angular cut of 0.2 deg
Counts
Phase
ON
OFF
astropy
NumPy
SciPy

Gammapy

- Official science tools for the CTA
- Plus, a generalised toolkit for gamma ray astronomy
  - Official s/w within HESS
  - Being used within VERITAS, MAGIC, HAWC, KM3NET, etc…
  - `gammapy.maps`: Official dependency within Fermipy
  - Gammapy modelling and fitting framework used within agnpy

Installation and set-up

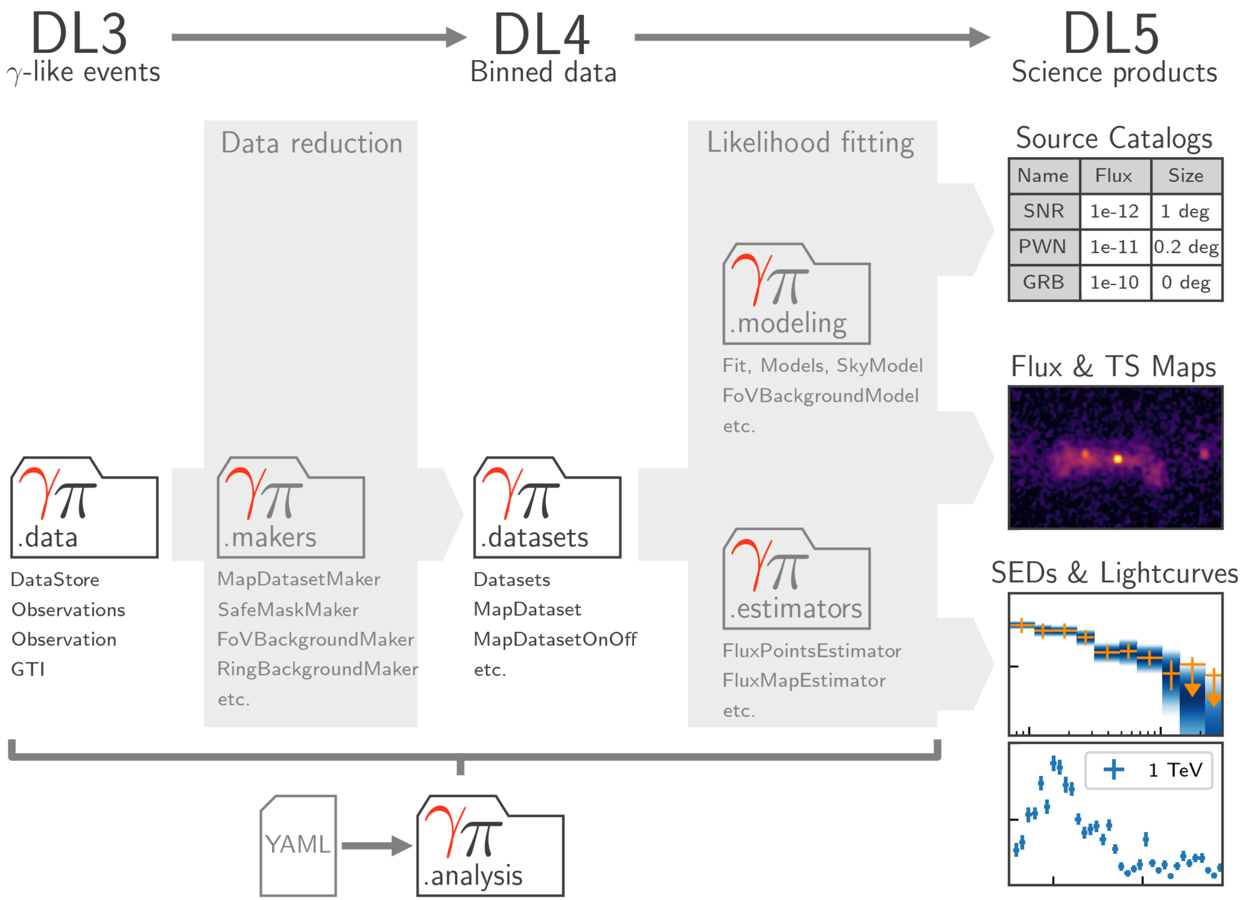
- Installation:
  - $ curl -O https://gammapy.org/download/install/gammapy-0.18.2-environment.yml
  - $ conda env create -f gammapy-0.18.2-environment.yml
  - $ conda activate gammapy-0.18.2

- Download tutorials:
  - $ gammapy download tutorials
  - $ cd gammapy-tutorials
  - $ export GAMMAPY_DATA=$PWD/datasets

Please finish the installation now if not already done!!!

Analysis flow in Gammapy

➤ Gammapy is sructured into sub-package, mostly based **by API and data level.** The core functionality for a typical analysis workflow is distributed as:



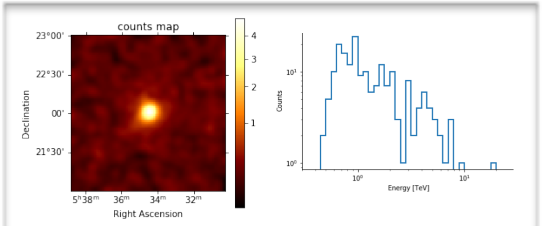
Data analysis for CTA

Event list
DL3

EVENT_ID	TIME	RA	DEC	ENERGY	DETX	DETY	MC_ID
	s	deg	deg	TeV	deg	deg	
uint32	float64	float32	float32	float32	float32	float32	int32
1	664502403.0454683	-92.63541	-30.514854	0.03902182	-0.9077294	-0.2727693	2
2	664502405.2579999	-92.64103	-28.262728	0.030796371	1.3443842	-0.2838398	2
3	664502408.8205513	-93.20372	-28.599625	0.04009629	1.0049409	-0.7769775	2
4	664502409.0143764	-94.03383	-29.269627	0.039580025	0.32684833	-1.496021	2
5	664502414.8090746	-93.330505	-30.319725	0.03035851	-0.716062	-0.8733348	2

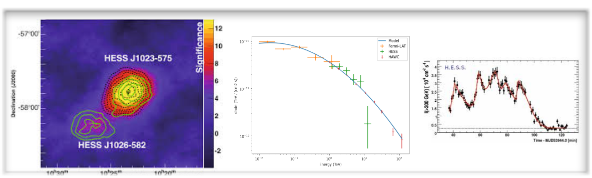
Data reduction

Binned
histograms
DL4



Data fitting

Flux/
Spectra/
lightcurves
DL5



- CTA data will be <u>background</u> dominated
- Background rejection is fundamental.
- Remaining irreducible background is still very high- statistical background
- Statistical background (<1%) subtraction - different techniques

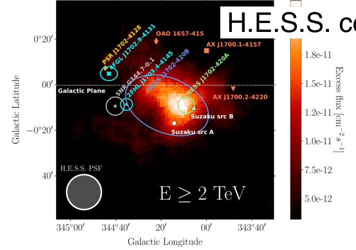
A few typical (non-exhaustive) analysis cases, and their implementation in Gammapy

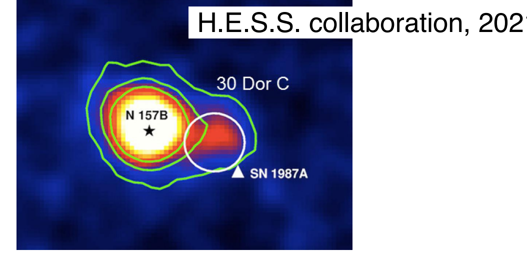
https://docs.gammapy.org/0.18.2/tutorials/index.html

Intro and IRF handling

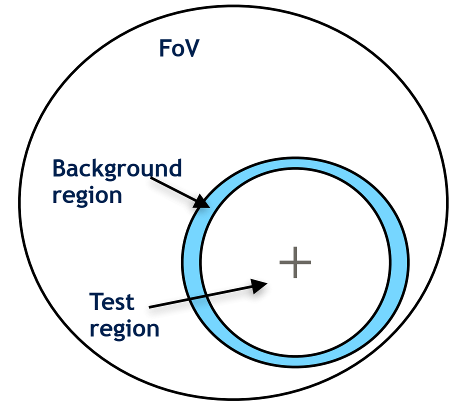
- Getting used to gammapy:
  - Navigating gammapy docs: https://docs.gammapy.org/0.18.2/
  - Filing issues on GitHub: https://github.com/gammapy/gammapy/issues
- IRF handling:
  - Notebook: cta.ipynb
  - Aim: To visualise CTA IRFs
    - At the DL3 table - table IRFs

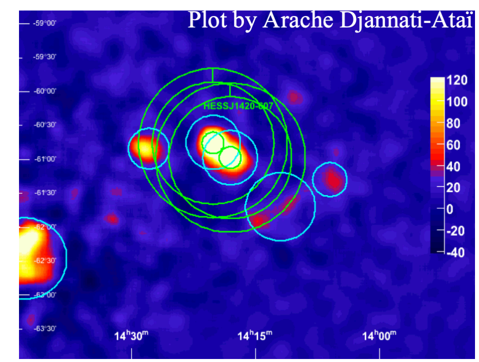
Sky images





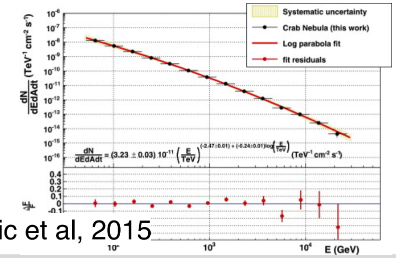
- Notebook: image.ipynb
- AIM: To make a significance maps of an extended source
- Background subtraction: Using the Ring background
  - Background estimated from annular regions around each region
  - Radial dependency correction
  - No energy dependance of acceptance - cannot be used for spectral analysis
- **On-off measurement:** background is estimated from real off counts, subtracted out during analysis, uses **WSTAT** count statistics





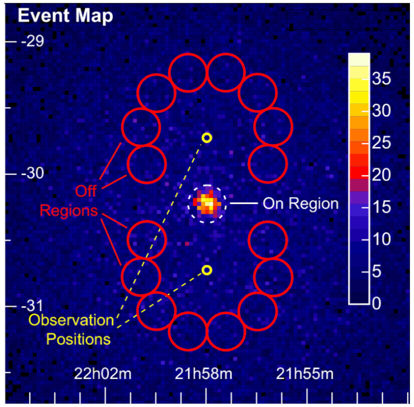
https://docs.gammapy.org/0.18.2/tutorials/ring_background.html

1D spectral analysis



Aleksic et al, 2015

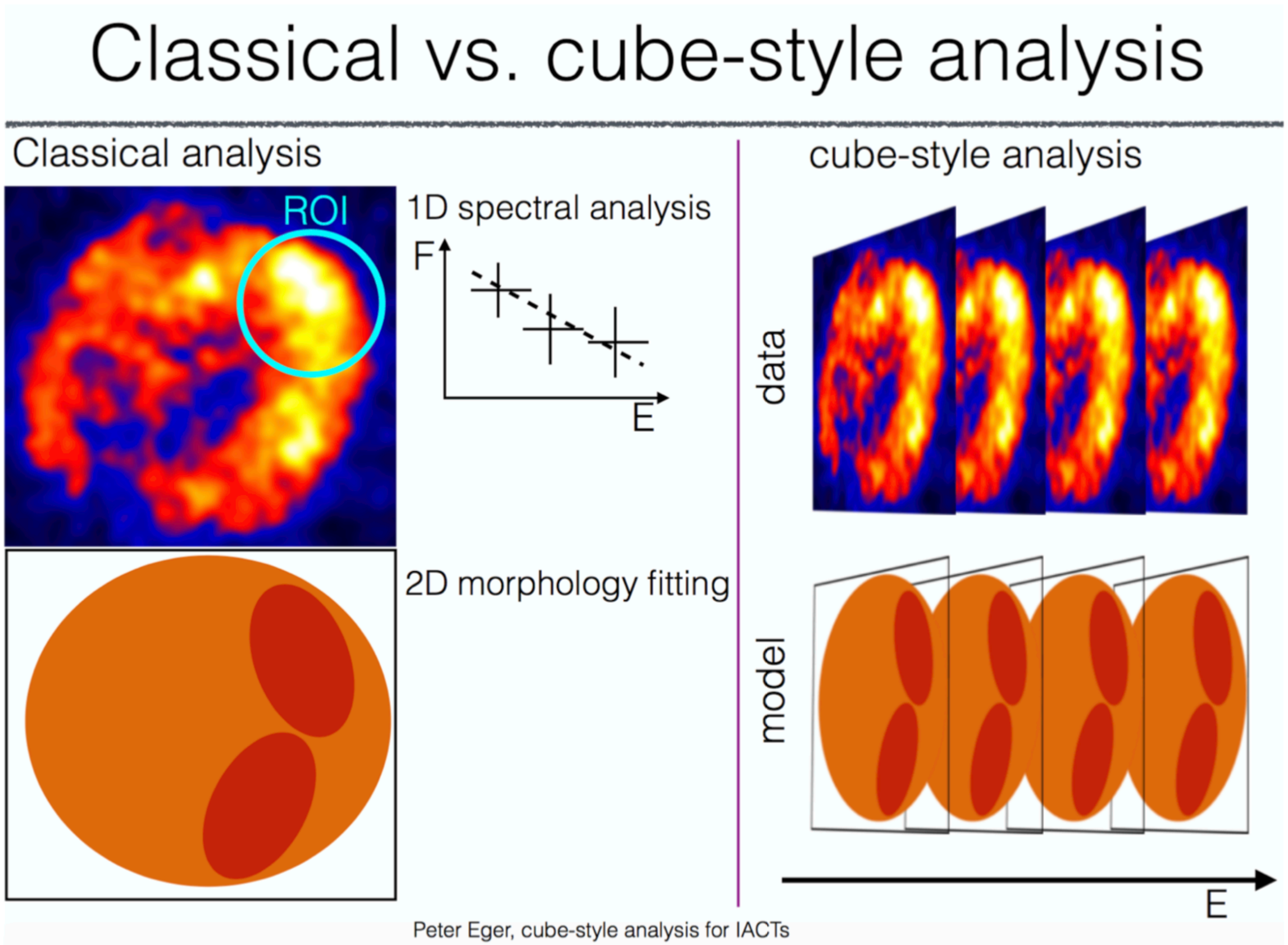
- Notebook: spectrum.ipynb
- AIM: To fit a 1D spectral model to a point source
- Background subtraction: Using the Reflected regions background
  - Developed initially by Whipple and HEGRA
  - Works for Wobble observations - pointing position offset from source
  - Background estimated from opposite region in field of view
  - Assumes an azimuthal symmetry of acceptance.
  - Cannot be used to make maps
- **On-off measurement**: background is estimated from real off counts, subtracted out during analysis, uses **WSTAT** count statistics



Berge et al, 2006

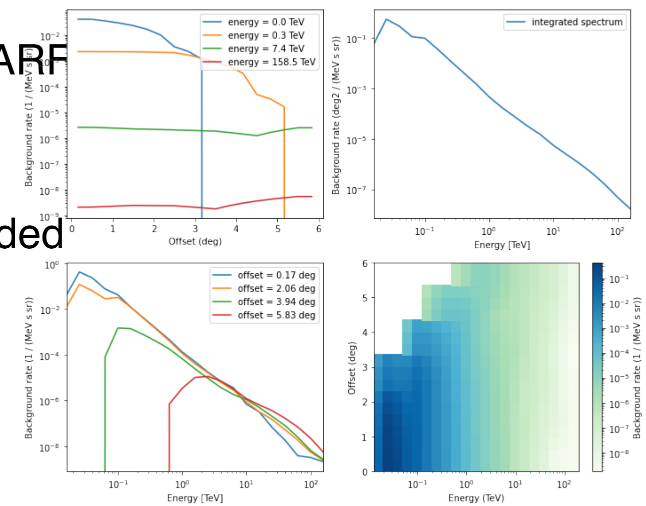
https://docs.gammapy.org/0.18.2/tutorials/spectrum_analysis.html

3D likelihood analysis



3D analysis

- Notebook: 3D.ipynb
- AIM: To simultaneously fit spectra and morphology
- Why:
  - Full ***multi-dimensional instrument response*** (PSF, ARF EDISP) correctly taken into account
  - ***Sensitivity gain*** for point-like and extended sources
  - ***Separation of multiple source components*** in crowded regions
- Successful implementation by Fermi-LAT
- Background subtraction: Using FoV background models
  - Background Models constructed a-priori either from simulations (eg: run-wise simulations) or data (eg: dedicated off runs/extra-galactic runs)
  - Control of systematics is difficult
- **Background model is fit to the data** - uses **CASH** count statistics



https://docs.gammapy.org/0.18.2/tutorials/analysis_3d.html

https://docs.gammapy.org/0.18.2/tutorials/cta_data_analysis.html

Simulations

- Probably the most useful case at present!
- Event Sampling:
  - Simulate a complete event list - unbinned simulation
  - Most realistic
- Binned simulation:
  - Simulate a reduced dataset.
  - Usually suffices for most cases
  - Notebook: simulate_3d.ipynb

https://docs.gammapy.org/0.18.2/tutorials/spectrum_simulation.html

https://docs.gammapy.org/0.18.2/tutorials/event_sampling.html

https://docs.gammapy.org/0.18.2/tutorials/simulate_3d.html

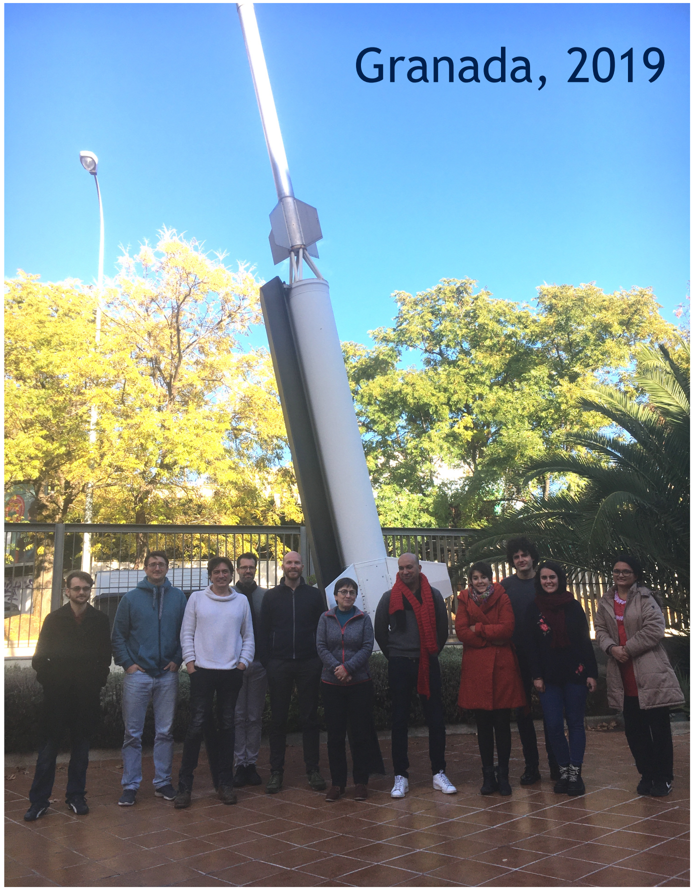
Other cases not covered today

Find these (and more!) on https://docs.gammapy.org/0.18.2/tutorials/

- Event sampling - full simulations
- Making lightcurves
  - Can be extracted in large time bins (over multiple observations, eg: weekly blazar light curves) or very short durations (eg: blazar flares, GRBs etc)
  - Possible through both 1D and 3D analysis
  - Use temporal models for modelling and fitting
- Use of the high level analysis
  - Automatic analysis using config driven yaml files
  - Quick and easy data reduction/fitting for standard use cases
- FluxPoint fitting
  - Combining multi instrument and multi wavelength data
    - eg: fluxes taken from published papers
    - No IRF convolution
    - Possible to do joint analysis between flux points, spectra and cubes
      - eg: 3D cubes from Fermi-LAT, flux points from H.E.S.S. and spectra from CTA
- Sensitivity estimation, dark matter analysis, pulsar analysis, …

Questions/Comments

- Contact us:
  - ➤ **Slack:** gammapy.slack.com (quick questions, immediate help)
  - ➤ **Github issues**: https://github.com/gammapy/gammapy/issues (feature requests & bug reports)
  - ➤ Gammapy **mailing list** gammapy@googlegroups.com
- Regular Gammapy user calls, announced on the CTA mailing list



Thank you !