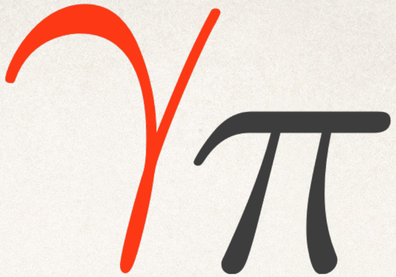

A **Python** package for
gamma-ray astronomy

Gammapy: current status and future plans

Atreyee Sinha

on behalf of the Gammapy dev team

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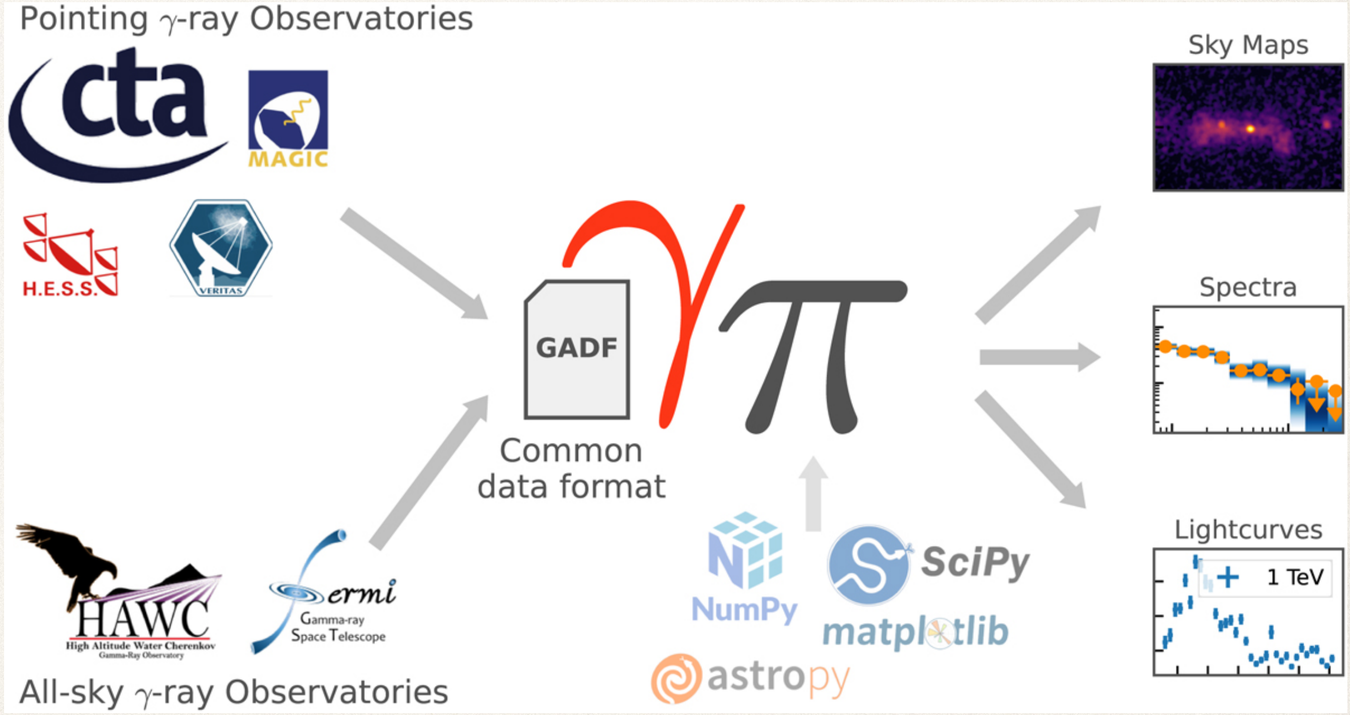
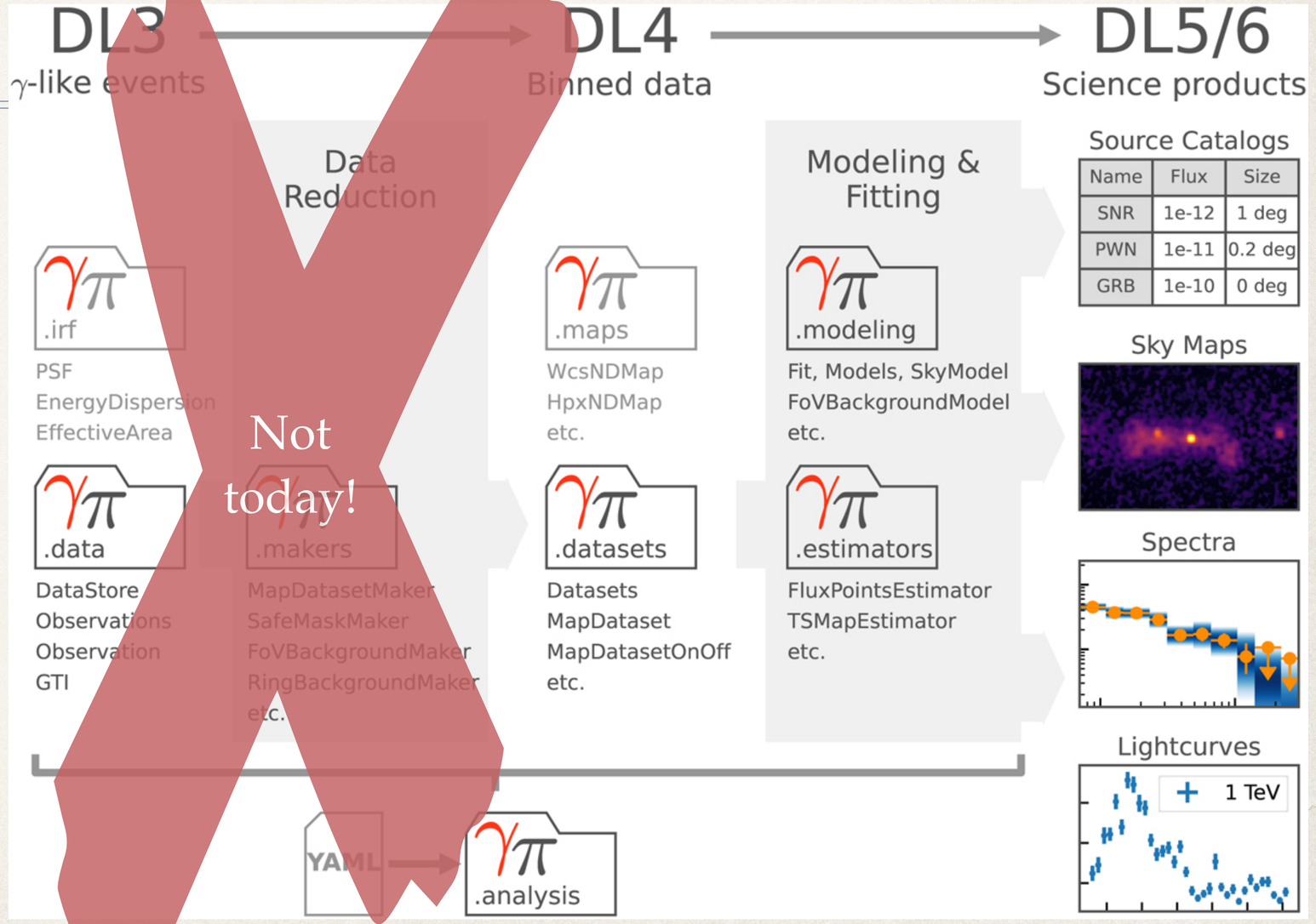
Gammapy: high level analysis tool

- 2013: Started as an open source python package for Gamma-ray astronomy
- 2021: Library for the CTAO science tools
  - Open IACT observatory
- Adopted by H.E.S.S., MAGIC, VERITAS, HAWC, LST1, ASTRI, SWGO
- Supports Fermi-LAT analysis
- Data to be serialised according to the GADF/VODF formats



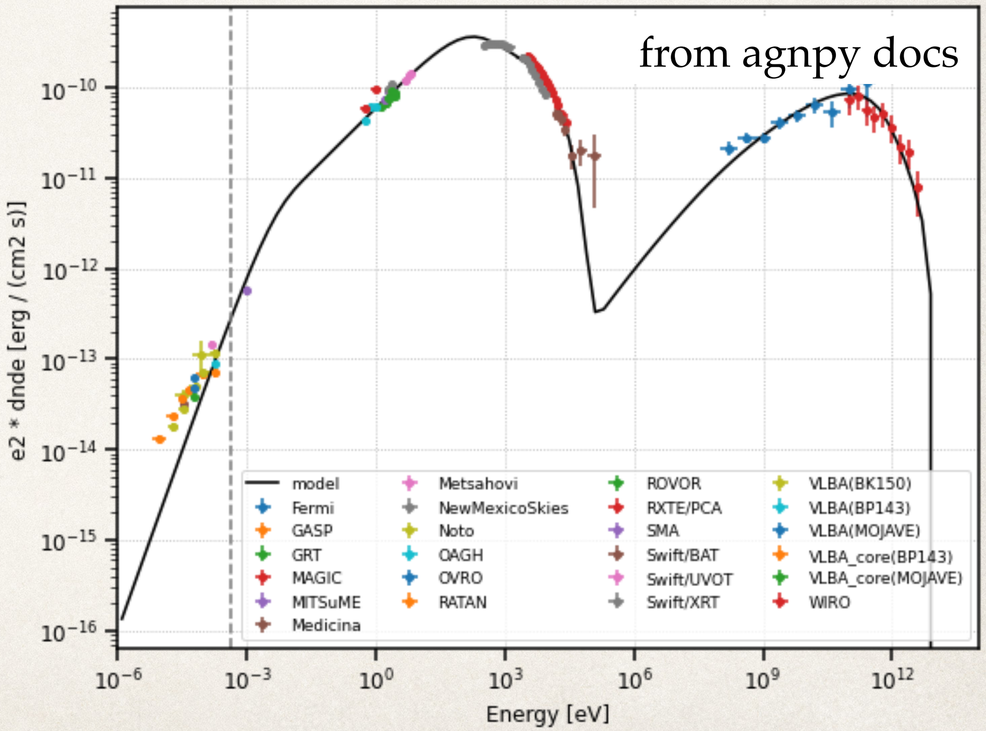
Functionalities

- Data handling from multiple instruments
- IRF access and manipulation
- Background estimation (ring, reflected, FoV…)
- Joint likelihood from same or different instruments
- Imaging (flux, ts maps, …)
- Spectral analysis
- Temporal analysis
- Parameter estimation
- Observation simulations
- High level interface
- Common catalogs



Common multi-wavelength approach

- Extract flux points from individual instruments
  - Different frameworks
  - Usually considering simplistic models (eg: Power law)
- Fit (or plot) physical models on top
  - Systematics (if any) added in quadrature
  - Gaussian errors assumed



Solution: Fit directly on the counts

Forward folding directly with emission models

3ML: Wrappers around each native tool to obtain the likelihood functionality.

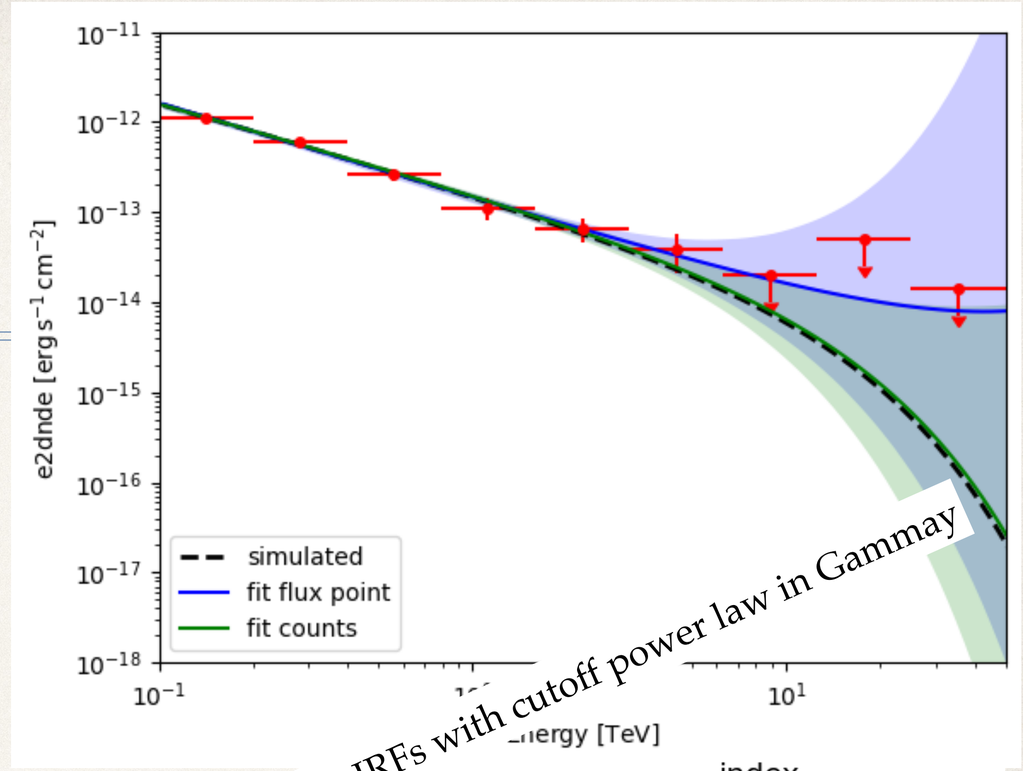
- ✓ Uses native tools
- ◉ All tools need to ‘coexist’ in the same environment

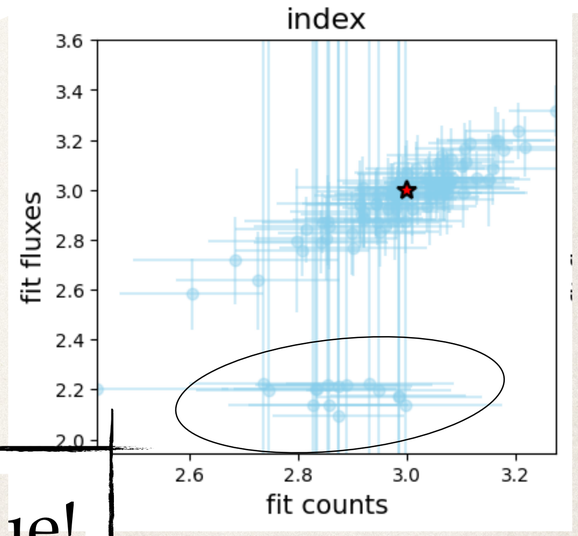
Gammapy: Convert the data and instrument description to a common format.

- ✓ Common likelihood code
- ✓ Handling of inter-instrument effects
- ◉ Need to convert the data and the instrument responses into common format

Not ideal

1. Fitting flux points may be biased
   - Lose underlying features depending on extraction type
2. Unclear Handling of upper limits
   - Upper limits depend on underlying model assumption
3. X-rays: xspec is NOT designed to produce flux points - "hacks" used
4. Ignores flux points correlations
   - Specially important if Flux points were obtained through unfolding
5. Statistical assumption: Gaussian statistics



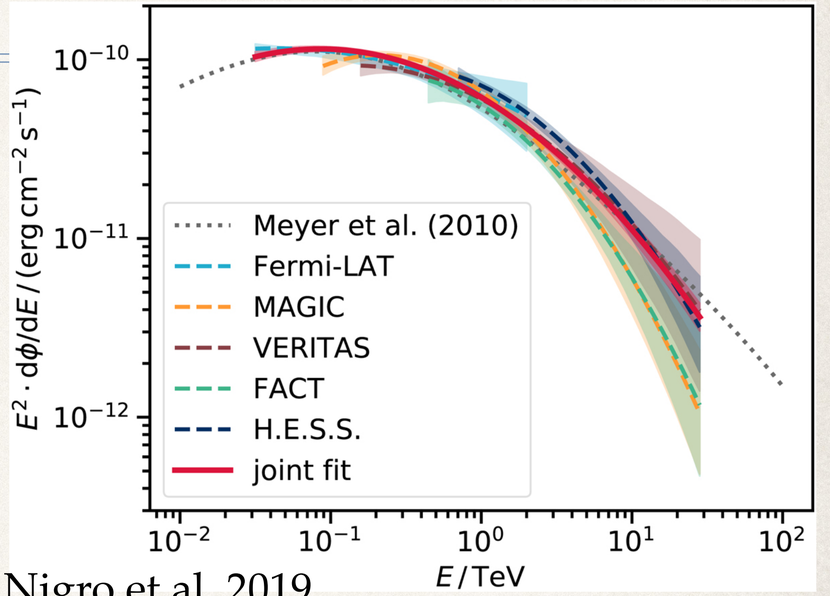


Reconstructed parameters may differ from true value!

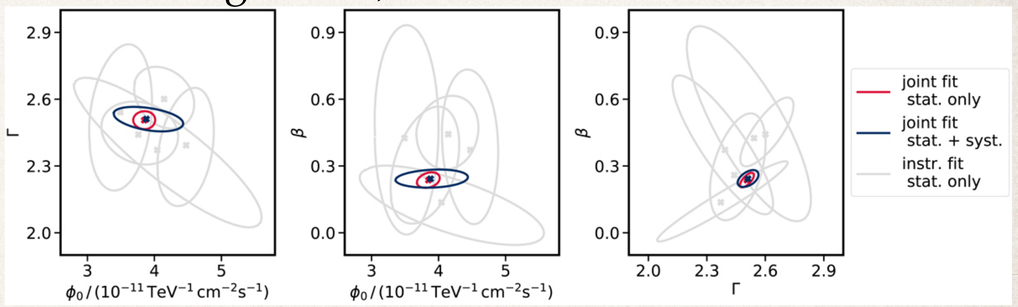
Joint likelihood for Gamma-ray instruments

- Simultaneous fitting from various instruments at the counts level
  - ✓ Different types of **models** and **likelihoods** for **different datasets**, eg
    - Fermi-LAT: Multiple sources in the FoV; cash likelihood
    - IACT: src model+ absorption, on-off background, wstat likelihood
    - Also allows to use precomputed flux points; chi2 stat
  - ✓ Efficient book-keeping between different models and datasets
  - ✓ Systematics included as nuisance parameters in likelihood

```
FIT_STATISTICS_REGISTRY = {
    "cash": CashFitStatistic,
    "wstat": WStatFitStatistic,
    "chi2": Chi2FitStatistic,
    "distrib": Chi2AsymmetricErrorFitStatistic,
    "profile": ProfileFitStatistic,
    "cash_weighted": WeightedCashFitStatistic,
}
```



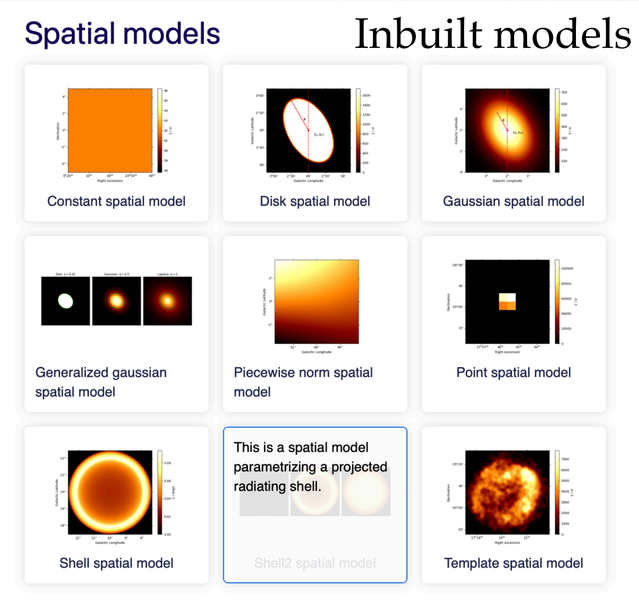
Nigro et al, 2019



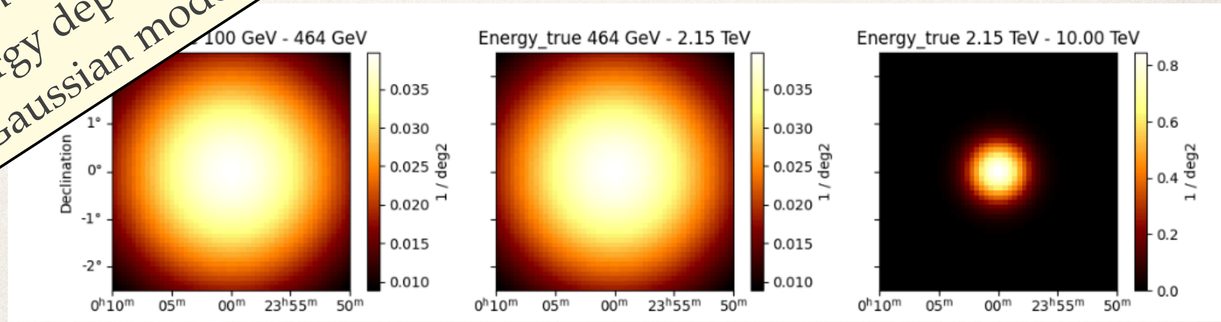
Support for user contributed models

- Inbuilt support for common analytical model definitions
- Easy to incorporate your own models
  - As a `Custom model`
    - Analytic models
  - As a `TemplateModel`
    - Precomputed n-dim grid + interpolation
    - Useful for computationally heavy models (eg: hadronic models)
- Interoperability with physical models
  - Dark matter models (COSMIXS, PPPC4)
  - Blazar models (JetSET, Agnpy)
  - Hadronic models (Naima, GAMERA)

$$f_{Src} = f_{Spectral}(E) \cdot f_{Spatial}(E, l, b) \cdot f_{Temporal}(t)$$



An analytic energy dependent Gaussian model



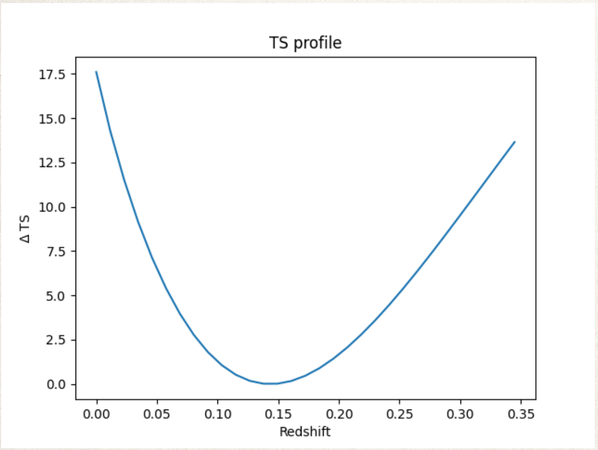
Inbuilt support for EBL absorption

- EBL models can be multiplied with spectral models to account for the absorption
- Redshift and absorption scale are model parameters
  - You can fit these values directly!

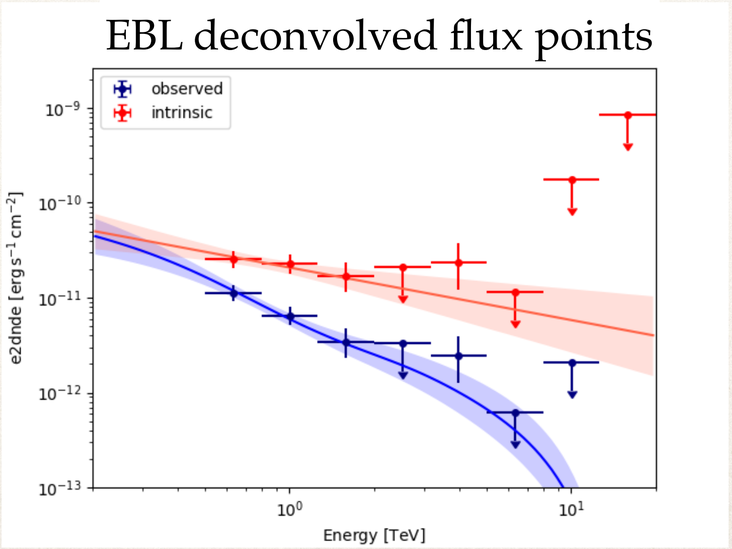
$$\exp\left(-\alpha \times \tau(E, z)\right)$$

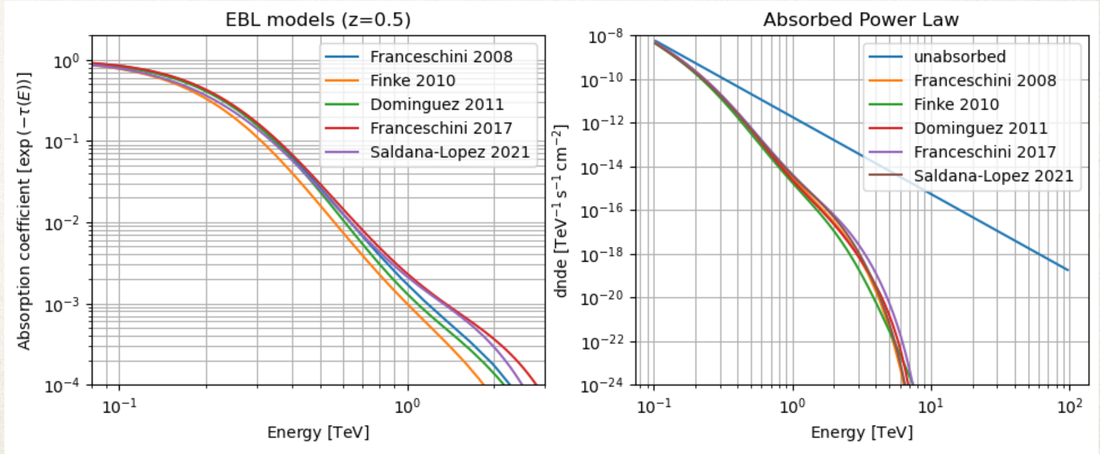
Scalable norm

Predicted optical depth



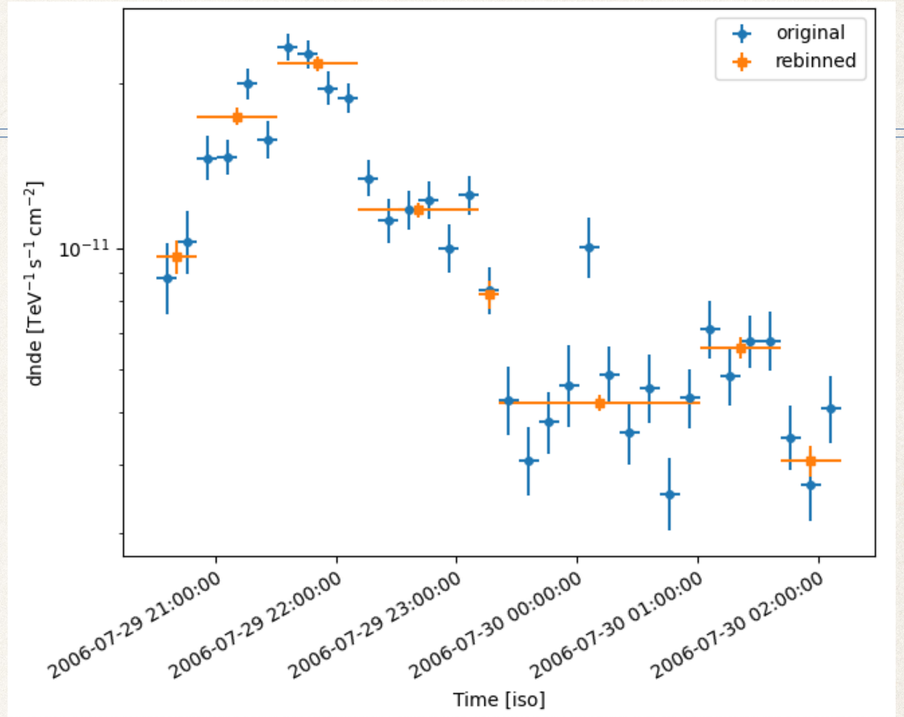
Likelihood profile of redshift

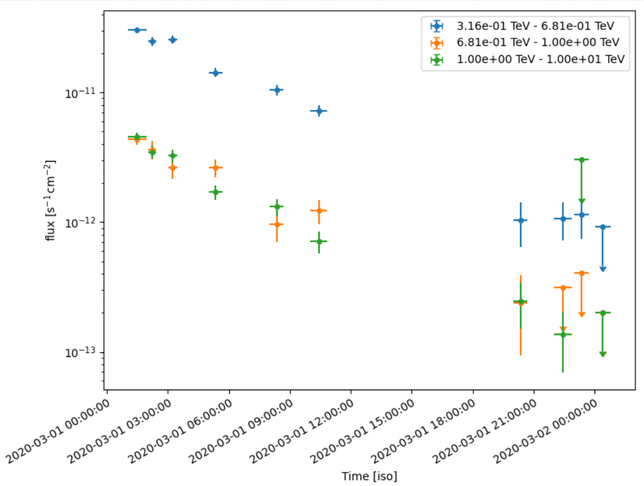




Temporal analysis

- Creation of lightcurves
  - Rebin lightcurves on the fly using likelihood profiles
- Simulation and fitting of light curves
  - Timmer & König and Emmanoulopoulos algorithms
  - Fitting flares with temporal models
- Inbuilt variability estimation tools





Simultaneous

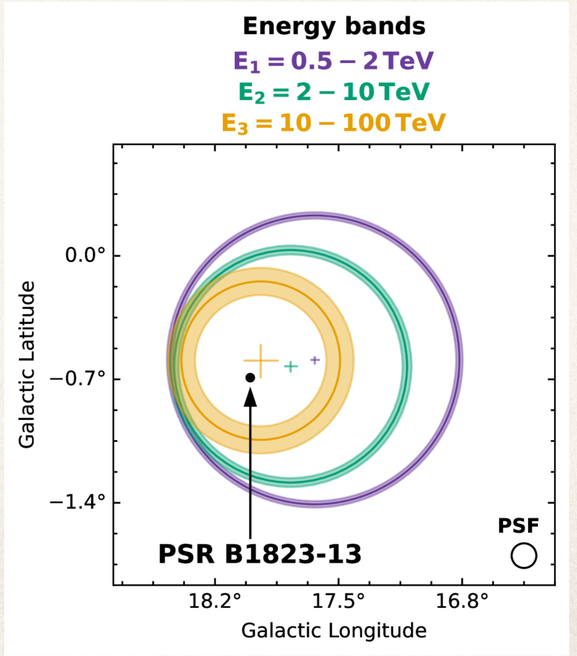
Spectro-temporal fitting

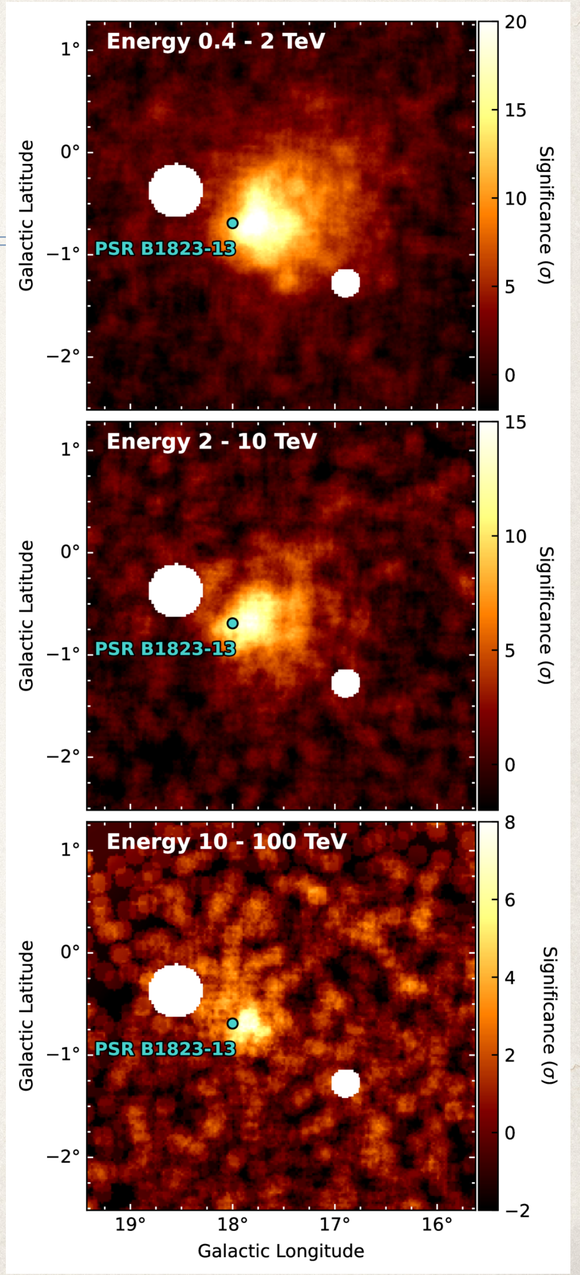
name	value	unit	error	frozen
---	---	---	---	---
index	2.9558E+00		3.131E-02	False
amplitude	1.0292E-11	cm-2 s-1 TeV-1	3.541E-13	False
reference	1E+00	TeV	0E+00	True
t0	5.8447E+00	h	2.002E-01	False
t_ref	5.8909E+04	d	0E+00	True

Energy dependent morphology

- Estimators to compute flux and significance maps in different energies
- Estimator to quantify if source morphology changes with energy

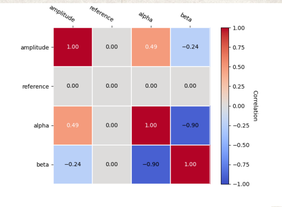
Feijen et al, 2025

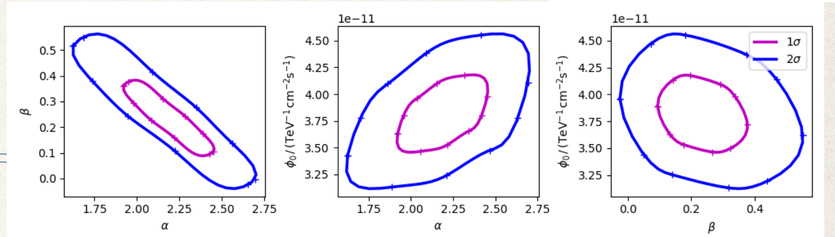


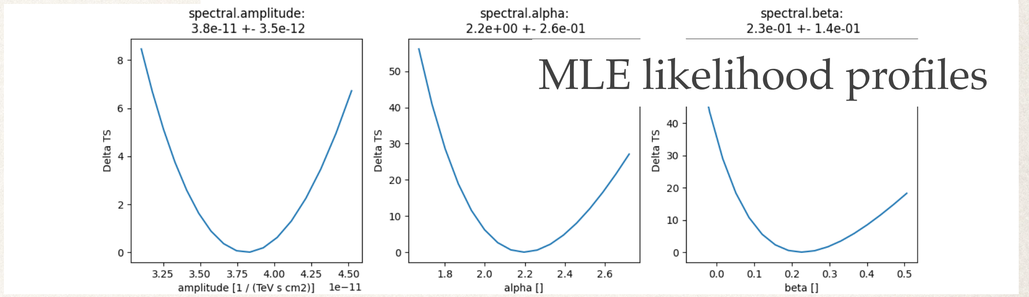


Obtaining “best” parameters

- Gammapy offers several statistical methods to *estimate* ‘best’ parameters from the data:
  - ***Maximum likelihood estimation (MLE):***
    - Frequentist inference of parameters from sample data
    - Hypothesis testing, Confidence intervals…
    - Prior distributions of parameters are uniform in the region of interest
  - ***Maximum A Posteriori estimation (MAP):***
    - Incorporating a *Prior* density over the quantities one wants to estimate
    - Maximise the a posteriori likelihood
  - ***Bayesian inference***
    - Inference of the best a posteriori parameters
    - Not associated to the “best model” in the Frequentist sense, but rather to the most probable given a set of parameters’ priors.
    - Very powerful in case of
      - non-Gaussian degeneracies
      - larger number of parameters,
      - map likelihood landscapes with multiple solutions
    - Can be more computationally intensive

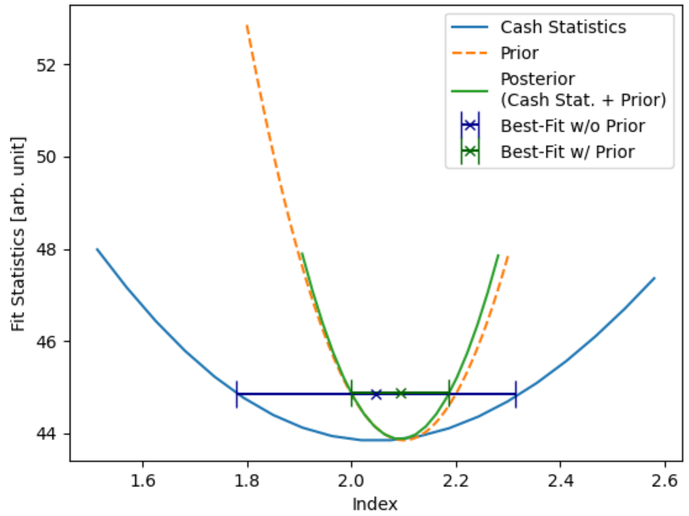




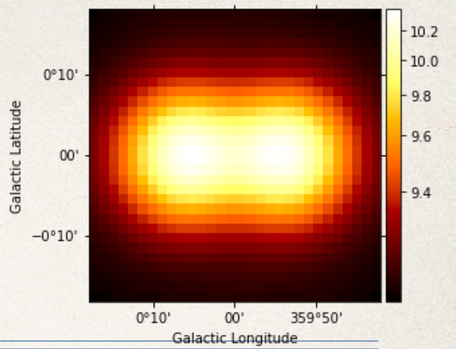


MLE likelihood profiles

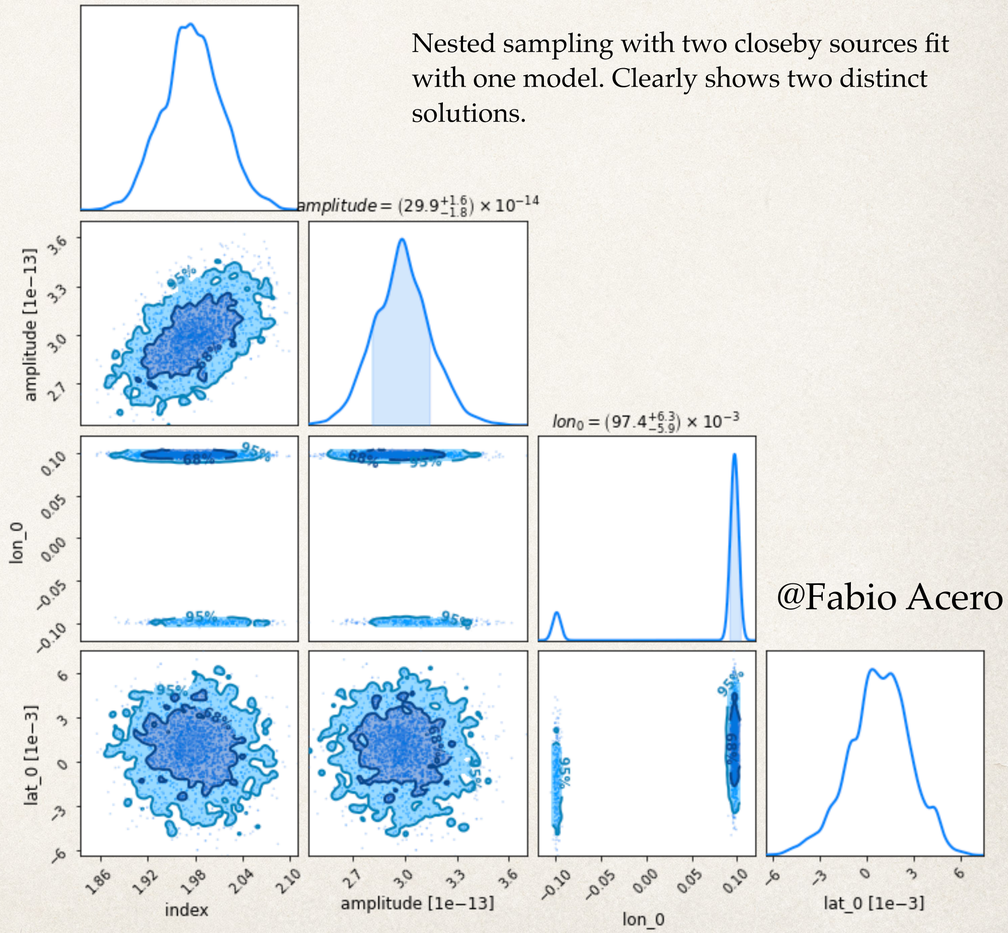
A Gaussian prior for MAP



Bayesian analysis



- Support for Bayesian analysis with Nested Sampling
  - ✓ No initial points
  - ✓ No burn-in period (eg: as in MCMC)
  - ✓ No issues with multi-modal distributions
  - ✓ Obtain the full posterior distribution
  - ✓ Calculates the Bayesian evidence Z: compare non-nested models
  - Need to define priors
  - Slower



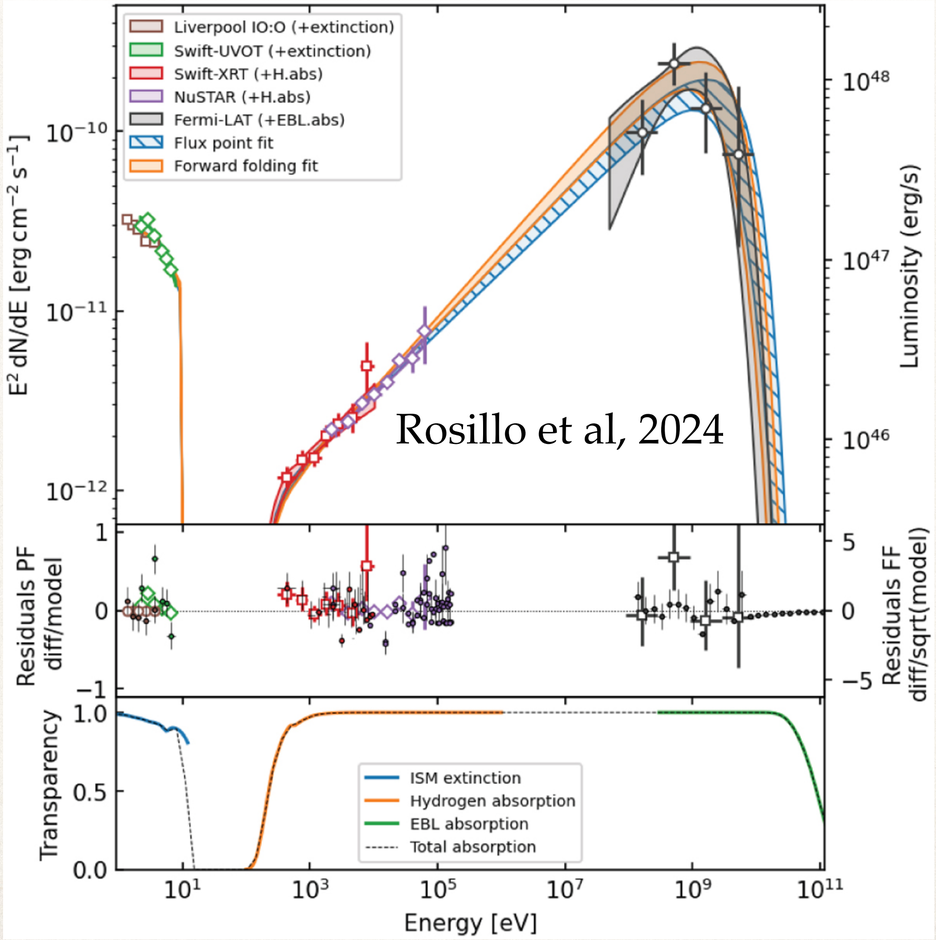
Nested sampling with two closeby sources fit with one model. Clearly shows two distinct solutions.

@Fabio Acero

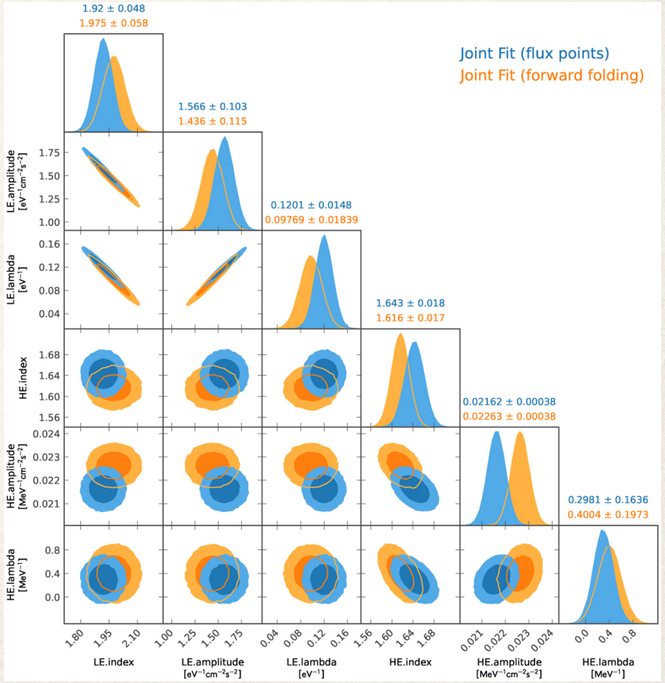
Beyond gamma-ray analysis: multiwavelength

https://github.com/gammapy/gammapy-mwl

- Extension to X-rays and Optical/UV
- Multi-instrument, multi-wavelength forward folding fit for OP 313 over 10 decades in energy
  - Multiple sources in LAT + diffuse components
  - Instrumental background in NuSTAR
  - Absorption componets: EBL, hydrogen, reddening



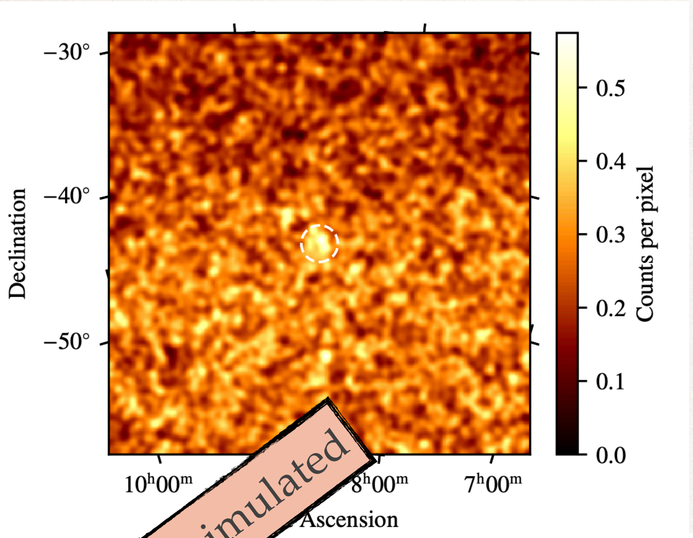
Corner plot from cov matrix



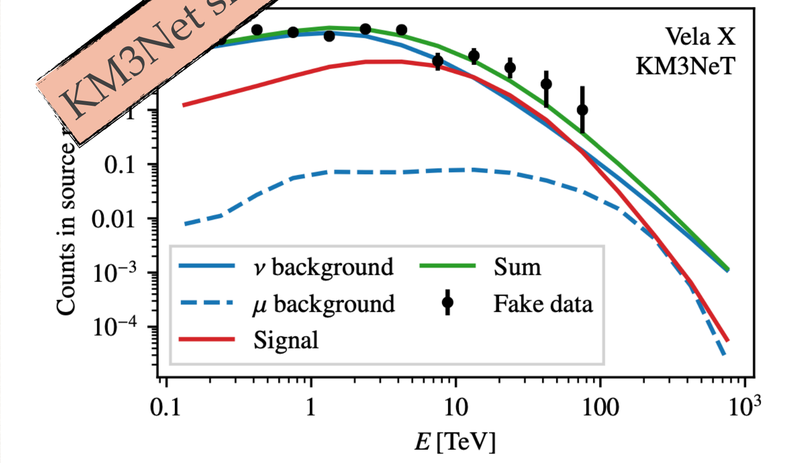
Beyond EM: Multimessenger

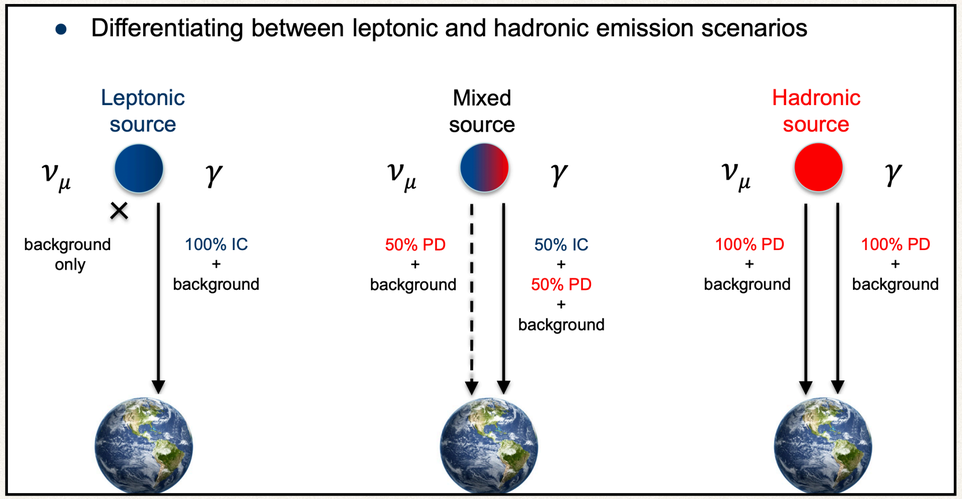
Ubenhaun et al, 2024

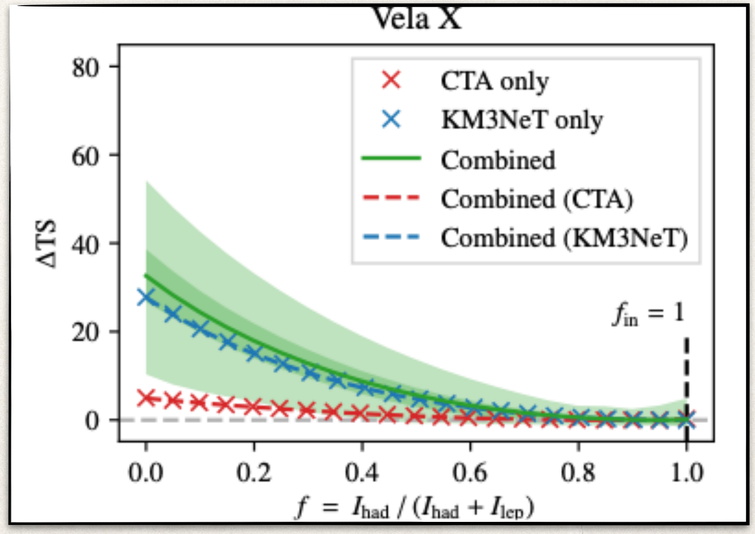
Prototype joint KM3NET and CTAO analysis

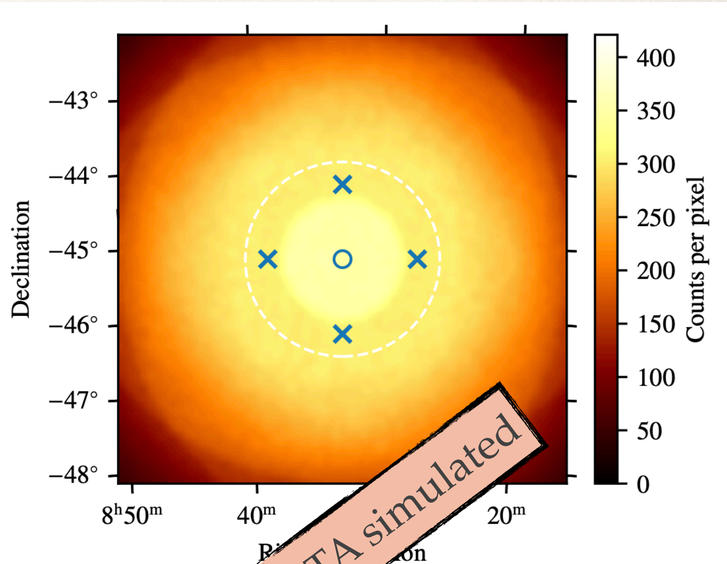


KM3Net simulated

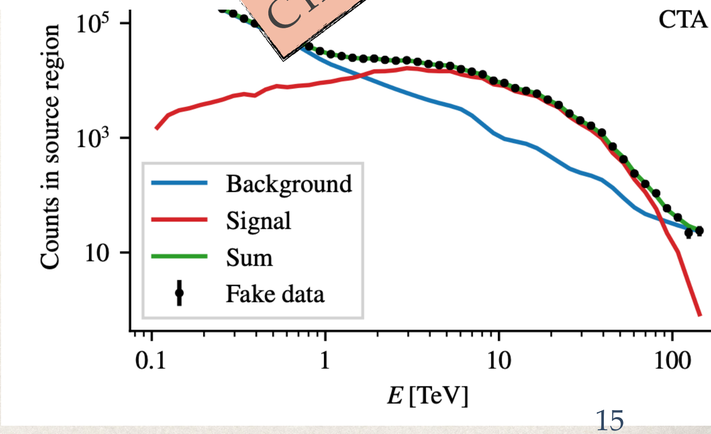






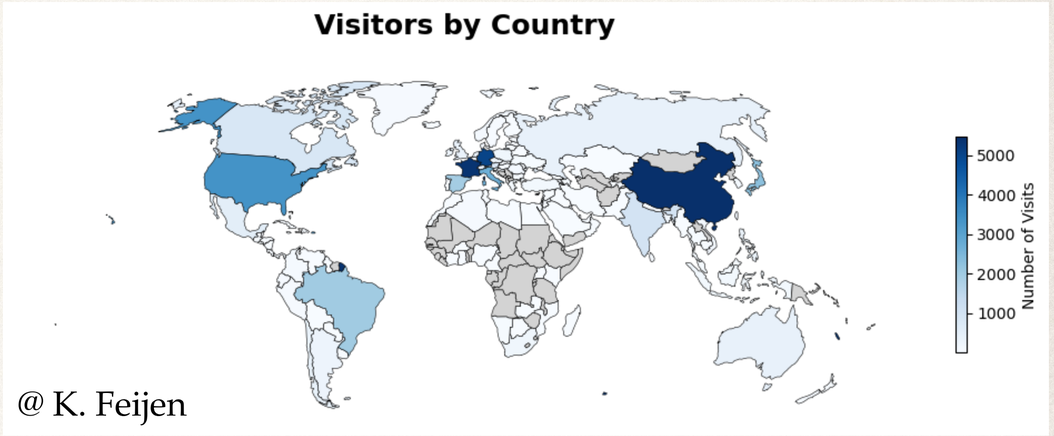


CTA simulated

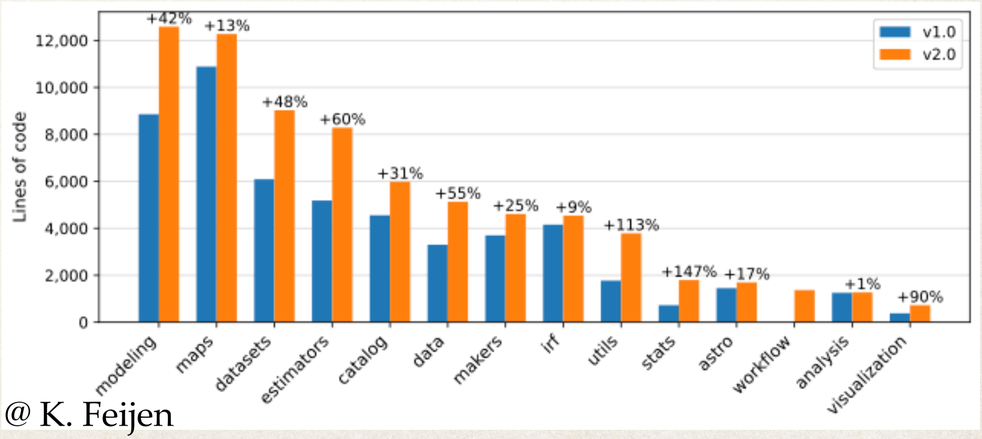


Current status

- Releases:
  - LTS 2.0: released 26 August, 2025
    - Bug fix 2.0.1: released 16th Dec, 2025
  - Feature release 2.1: Expected March, 2025
- Regular user calls:
  - https://github.com/gammapy/gammapy-meetings/tree/master/user-meetings
  - Get in touch with your usage!



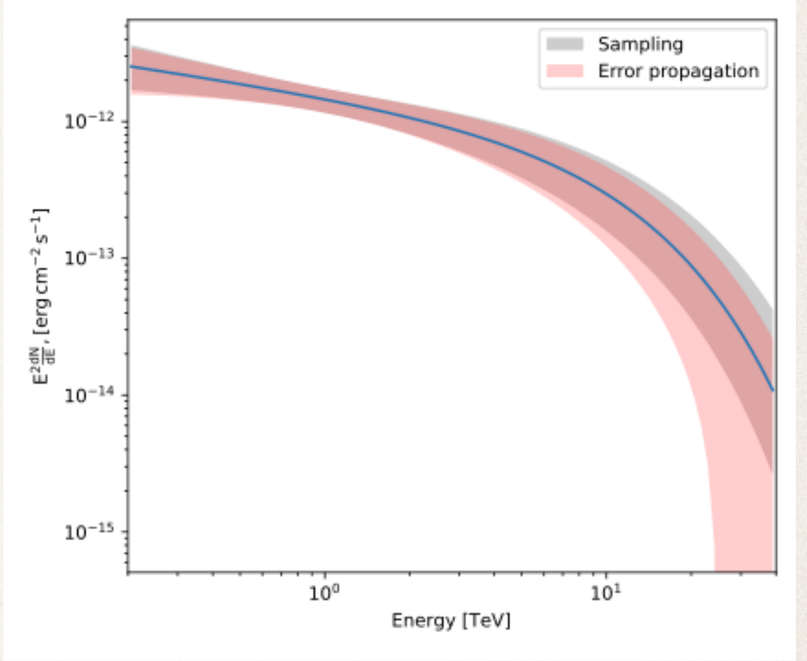
@ K. Feijen



@ K. Feijen

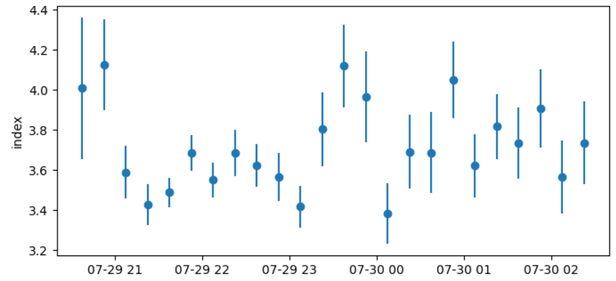
Change in the butterfly plot

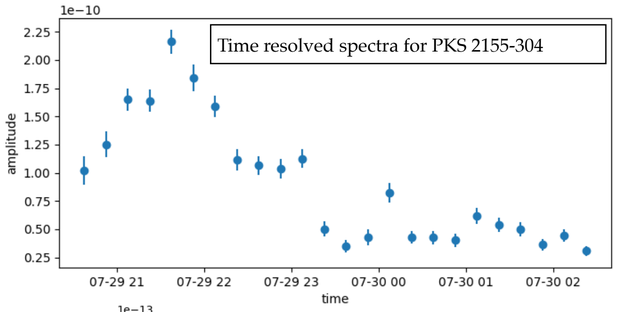
- Till version 1.3: Computation of flux errors performed with regular error propagation
  - Linear combination of multi-normal random variables
  - Problems far away from the decorrelation energy
- ➡ Version 2.x: Get uncertainty band by computing the envelope of flux for a Monte Carlo sample of the multi-normal variables
  - ➡ For user contributed models: Please try to vectorise your evaluations!

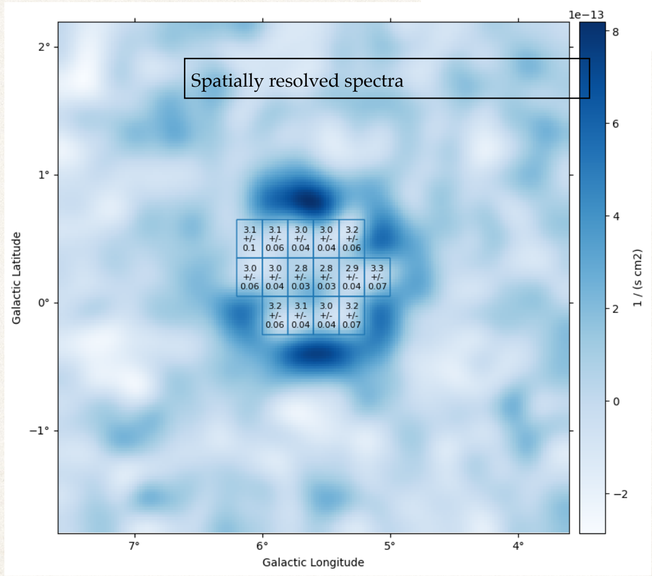


Future plans

1. Improve Bayesian analysis framework
2. Support for unbinned analysis
3. Nuanced upper limit calculations
4. Support for unfolding
5. Time/spatially resolved spectroscopy
6. Improvement in `gammapy.astro` (dark matter, etc)
7. Handling systematic errors:
   - Partly supported with the priors







Comments, suggestions and contributions welcome!

Join/Contact Us!

- Install Gammapy:
  - conda install -c conda-forge gammapy
  - New releases:
    - LTS: 2 yrs; major release: 6months; bug fixes: as required - released on Zenodo, PyPI, Conda
    - Latest dev version on GitHub
- Docs:
  - https://docs.gammapy.org
- Issues?
  - Slack: gammapy.slack.com (quick questions, immediate help)
  - GitHub issues: https://github.com/gammapy/gammapy/issues (feature requests & bug reports)

Thank you!