Gammapy Paper Proposal

Oct 1, 2018 @ Gammapy meeting, Madrid
Christoph Deil

Proposal

- **Suggest we write a paper on Gammapy now**

  - Many developments have converged in v0.8, we have developed a lot
  - Many people worked on Gammapy for years and need academic credit
  - Method and science papers are starting to use Gammapy,
  good to create a reference and gather citation count on that
  - A paper can’t hurt in CTA ST selection and adoption e.g. in HESS or by others

- Alternative: continue work on Gammapy,
  write a paper later, e.g. on Gammapy v1.0 in late 2019 or in 2020

- Note that a short Gammapy paper now doesn’t limit options for future papers much. There should be other papers describing the package design, analysis algorithms, performance, science validation, …

Proposal

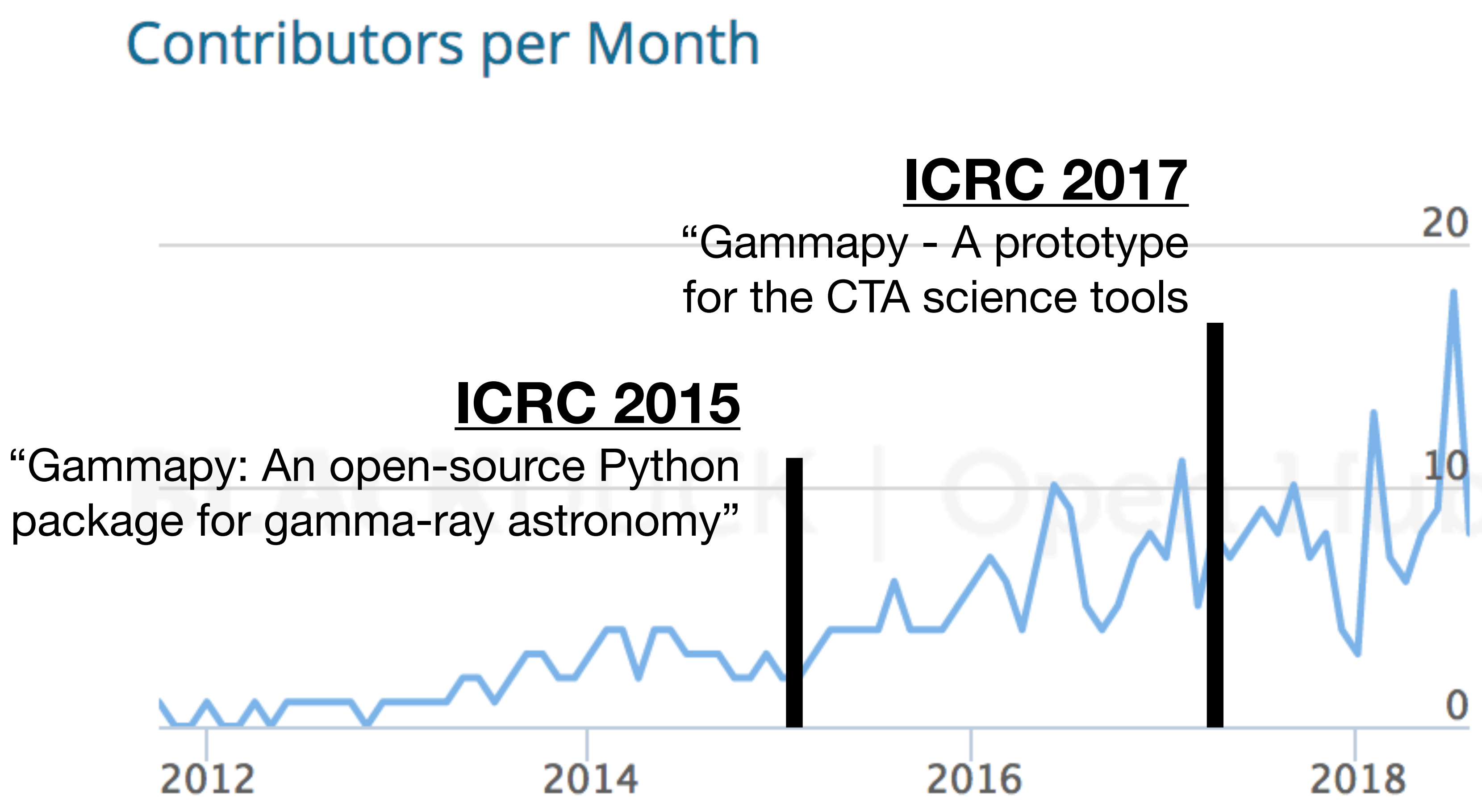
- Suggest we write a paper on Gammapy now
- Basis: **v0.9**, basically what we have already
- Length: relatively short, maybe **6-8 pages** total?
- Timescale: write October, review November, **submit December**
- Content: **short and simple**; see later slides
- Journal: target **A&A**
- Co-authors: invite everyone that contributed to Gammapy
- Workflow: few people write, everyone discusses and reviews

Start with a discussion session later this week about key message and content of the paper.

Background

Before presenting a first proposal for the Gammapy paper,
let’s look at what we have written so far and what others did.

Two Gammapy proceedings

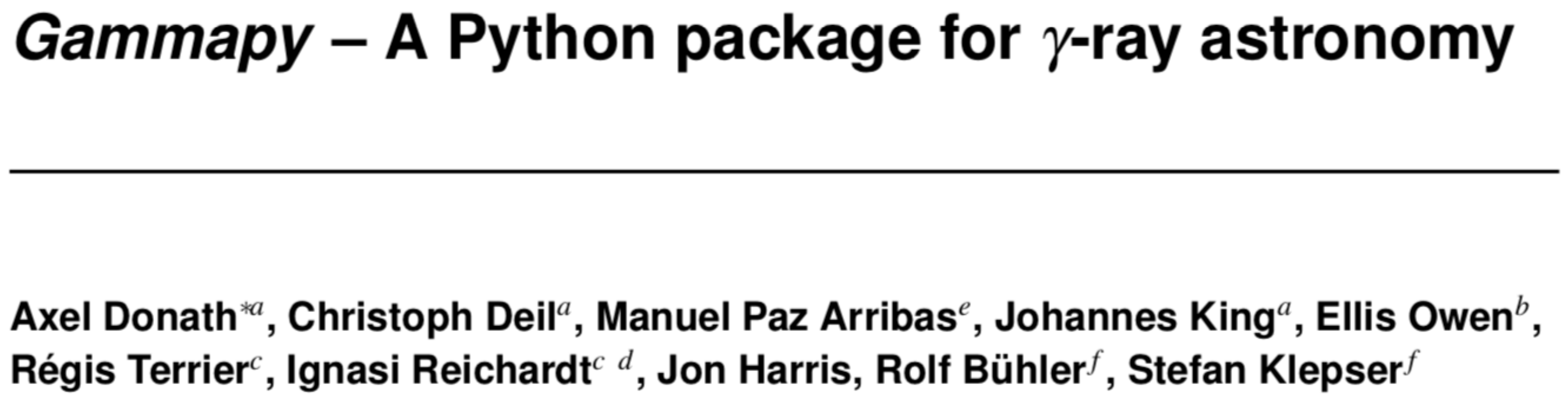


+ a few more posters advertising Gammapy, and posters / papers using Gammapy

Gammapy proceeding ICRC 2015

Donath et al. (10 co-authors)
8 pages, 5 figures, 6 citations
1 command line and
1 code example
Describes Gammapy v0.3

1. Introduction
2. Gammapy stack
3. Development workflow,
4. Gammapy toolbox
5. Usage examples,
6. Planned functionality
7. Summary



***Gammapy* – A Python package for γ-ray astronomy**

Axel Donath[*a], **Christoph Deil**[a], **Manuel Paz Arribas**[e], **Johannes King**[a], **Ellis Owen**[b], **Régis Terrier**[c], **Ignasi Reichardt**[c d], **Jon Harris**, **Rolf Bühler**[f], **Stefan Klepser**[f]

PROCEEDINGS OF SCIENCE

Gammapy – A Python package for γ-ray astronomy

Axel Donath[*a], **Christoph Deil**[a], **Manuel Paz Arribas**[e], **Johannes King**[a], **Ellis Owen**[b], **Régis Terrier**[c], **Ignasi Reichardt**[c d], **Jon Harris, Rolf Bühler**[f], **Stefan Klepser**[f]
[a]*MPIK, Heidelberg, Germany*
[b]*UCL-MSSL, Dorking, United Kingdom*
[c]*APC, University of Paris 7, France*
[d]*INFN, Padova, Italy*
[e]*Humboldt University, Berlin, Germany*
[f]*DESY, Zeuthen, Germany*
E-mail: `Axel.Donath@mpi-hd.mpg.de`, `Christoph.Deil@mpi-hd.mpg.de`

In the past decade imaging atmospheric Cherenkov telescope arrays such as H.E.S.S., MAGIC, VERITAS, as well as the *Fermi*-LAT space telescope have provided high quality images and spectra of the γ-ray universe. Currently the γ-ray community is preparing to build the next-generation Cherenkov Telecope Array (CTA), which will be operated as an open observatory.
Gammapy v0.3 (available at https://github.com/gammapy/gammapy under the open-source BSD license) is a new in-development Astropy affiliated package for high-level analysis and simulation of astronomical γ-ray data. It is built on the scientific Python stack (Numpy, Scipy, matplotlib and scikit-image) and makes use of other open-source astronomy packages such as Astropy, Sherpa and Naima to provide a flexible set of tools for γ-ray astronomers.
We present an overview of the *Gammapy* scope, development workflow, status, structure, features, application examples and goals. We would like *Gammapy* to become a community-developed project and a place of collaboration between scientists interested in γ-ray astronomy with Python. Contributions welcome!

*The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands*

*Speaker.

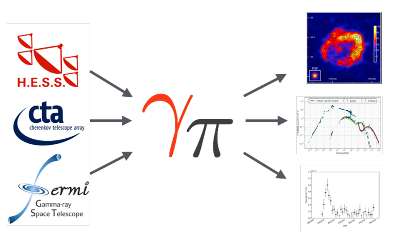


Figure 1: Gammapy is a Python package for high-level γ-ray data analysis. Using event lists, exposures and point spread functions as input you can use it to generate science results such as images, spectra, light curves or source catalogs. So far it has been used to simulate and analyse H.E.S.S., CTA and *Fermi*-LAT data, hopefully it will also be applied to e.g. VERITAS, MAGIC or HAWC data in the future.

1. Introduction

1.1 What is *Gammapy* ?

Gammapy is an open-source Python package for γ-ray astronomy. Originally *Gammapy* started as a place to share morphology fitting Python scripts for the work on the H.E.S.S. Galactic plane survey [1] two years ago. Since that time *Gammapy* has grown steadily: functionality as well as development infrastructure has been improved and it has been accepted as an in-development Astropy-affiliated package. Now, in this proceeding, we would like to introduce *Gammapy* to the community and present our vision of *Gammapy* as a future community-developed, general purpose analysis toolbox for γ-ray astronomers.

The general concept of *Gammapy* is illustrated in Figure 1. Based on pre-processed input data (e.g. event lists) provided by instruments such as H.E.S.S., *Fermi* or CTA, *Gammapy* offers the high-level analysis tools to generate science results such as images, spectra, light curves and source catalogs. By using common data structures and restriction to binned analysis techniques, all input data can be treated the same way, independent of the instrument. Research already making use of *Gammapy* is presented in [1, 2, 3].

1.2 How to get *Gammapy*

Recently *Gammapy* version 0.3 was released. It is available via the Python package index [1] or using package manager tools like pip and conda. *Gammapy* works on Linux and Mac (Windows most likely as well, but this has not been tested yet) and is compatible with Python 2.7 and Python

[1]https://pypi.python.org/pypi/gammapy/

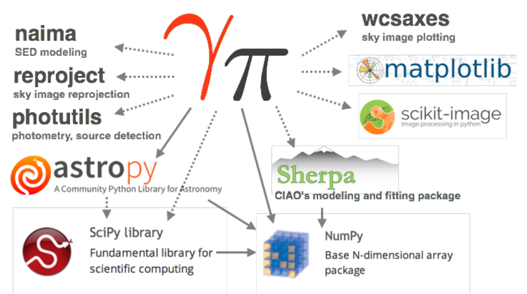

naima
SED modeling
reproject
sky image reprojection
photutils
photometry, source detection
astropy
A Community Python Library for Astronomy
wcsaxes
sky image plotting
matplotlib
scikit-image
Sherpa
CIAO's modeling and fitting package
SciPy library
Fundamental library for scientific computing
NumPy
Base N-dimensional array package

Figure 2: The Gammapy stack. Required dependencies Numpy and Astropy are illustrated with solid arrows, optional dependencies (the rest) with dashed arrows.

3.3 or later. Further details on requirements and installation are available online [2]. The latest documentation is available on *Read the Docs* [3], including tutorials, code and analysis examples. We have also set up a mailing list for user support and discussion [4].

2. The *Gammapy* stack

Gammapy is primarily built on the scientific Python stack. We employ Numpy and Astropy [4] as main dependencies and integrate other packages as optional dependencies where necessary. The current dependency structure is illustrated in Figure 2. Numpy provides the low level data structures and the framework for numerical/array computations. Astropy is used for higher level data structures like tables (Table) and n-dimensional data objects (NDData), for I/O, coordinates and WCS transformations, and handling of physical quantities with units. Scipy is used for advanced numerical and data processing algorithms. For specific image processing routines we additionally use scikit-image.

To allow morphology and spectral fitting of TeV sources with *Gammapy* we use the established X-ray modelling and fitting package Sherpa [5]. Sherpa allows interactive and scripted fitting of data sets with various spectral, light curve and morphology models taking instrument response functions into account. Additionally, it is possible to determine confidence levels on best-fit model parameters, compute likelihood profiles and goodness of fit measures. Sherpa recently also became an open-source project which makes it possible for users and external developers to contribute missing functionality or fix issues themselves in future.

[2]https://gammapy.readthedocs.org/en/latest/install.html
[3]https://gammapy.readthedocs.org/en/latest
[4]https://groups.google.com/forum/#!forum/gammapy

Modelling and fitting of non-thermal radiation processes to spectral energy distributions (SEDs) is provided with the Naima package. It uses Markov-Chain Monte Carlo emcee sampling to find best-fit model parameters of physical radiation models and thus determine the radiation mechanism that leads to the observed emission. The radiative models available in Naima can be called as source models in the *Gammapy* environment and be used, for example, to simulate spectra for source population studies.

Data visualizing and plotting of sky images is done with matplotlib and the astropy-affiliated package wcsaxes. Further astropy-affilated packages we allow as optional dependencies are photutils and reproject. Photutils is used for source detection and photometry and reproject for re-projection of sky images.

While this is a large number of dependencies, most of them are optional and only needed for small specific tasks so we do not see this as a strong disadvantage. Optional packages can be easily installed using package managing tools like *pip* or *conda*. By re-using other packages' functionality which would be complex to re-implement, new tools and techniques can be easily integrated into *Gammapy* to help obtain scientific results more quickly with a minimal coding effort.

3. Development workflow

Gammapy uses all the standard tools of modern community-driven open-source software development. The code repository is hosted on *GitHub* [5], which allows for convenient and public interaction of developers, contributors and users via the *GitHub* interface. This includes, for instance, *feature requests* for missing functionality, *issues* for bugs or questions and *pull requests* for code contributions. The code base is continuously built and tested in different virtual environments using the *continuous integration* service Travis CI. This helps to maintain high coding standards and compatibility with different versions of Numpy and Astropy.

The documentation of *Gammapy* is generated using Sphinx. An online version of the latest documentation is built automatically and is available on *Read the Docs* [6]. In addition to the main code repository we maintain gammapy-extra. This repository contains prepared catalog and map data and IPython notebooks with more extensive analysis examples and tutorials.

4. The *Gammapy* toolbox

4.1 Sub-packages

The *Gammapy* code base is structured into several sub-packages where each of the packages bundle corresponding functionality in a namespace. This follows the concept of other Python packages such as Astropy and Scipy. The following list gives a rough overview of the different sub-packages with a short description:

- **`gammapy.astro`** – Galactic population and emission models of TeV sources
- **`gammapy.background`** – Background estimation and modeling

[5]https://github.com/gammapy/gammapy
[6]https://gammapy.readthedocs.org/en/latest

- **`gammapy.catalog`** – γ-ray source catalog access and processing
- **`gammapy.datasets`** – Easy access to bundled and remote datasets
- **`gammapy.detect`** – Source detection tools and algorithms
- **`gammapy.hspec`** – Interface to spectral fitting with Sherpa
- **`gammapy.image`** – Image processing and analysis tools
- **`gammapy.irf`** – Instrument response function (IRF) access and handling
- **`gammapy.morphology`** – Morphology models and tools
- **`gammapy.obs`** – Observation handling
- **`gammapy.spectrum`** – Spectrum models and tools
- **`gammapy.stats`** – Statistical functions
- **`gammapy.time`** – Handling of time series and γ-ray lightcurves
- **`gammapy.utils`** – Utility functions and classes (in sub-modules)

There are some cases (e.g. **`gammapy.spectrum.models`** and several sub-modules of **`gammapy.utils`**) where the end-user functionality is exposed one level further down in the hierarchy. This is because putting everything into the top-level **`gammapy.spectrum`** or **`gammapy.utils`** namespace would lead to an unstructured collection of functions and classes. A large part of *Gammapy* 's functionality uses an object-oriented API. Functions are only used where it leads to an improved or more intuitve user interface.

4.2 Command-line tools

Gammapy includes various ready to use command-line tools which provide a familiar interface to data processing for many astronomers. A complete overview of all available tools can be found online [7]. When *Gammapy* is installed the user can simply type `gammapy-` on the command-line and use tab completion to see the list of tools, as all *Gammapy* tools start with the same `gammapy-` prefix. Specific information on single command-line tools and a description of available parameters is shown when calling the corresponding tool with the standard `-h` or `--help` option.

5. Usage examples

The *Gammapy* package should be considered as a toolbox out of which powerful analysis scripts can be composed easily by astronomers, even if they have very little programming experience. In the following section we present a selection of code examples demonstrating how to set up complex analysis steps with just a few lines of code.

5.1 Morphology fitting command-line tool

Gammapy includes a simple to use command-line script `gammapy-sherpa-like` to perform a Poisson maximum likelihood morphology fitting using FITS files as input. The input counts, exposure and background maps can be specified by the corresponding parameters `--counts`, `--exposure` and `--background`. The source model is defined in a JSON file and should be passed using the `--sources` option. The model parameters for a multi-Gaussian point spread function (PSF) can be specified in JSON format using the `--psf` option.

[7]https://gammapy.readthedocs.org/en/v0.3/scripts/index.html

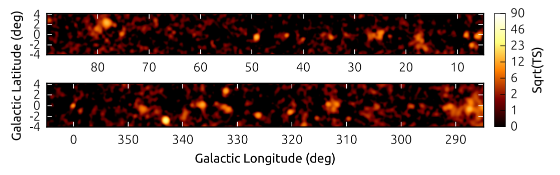


Figure 3: *Fermi* survey TS map.

```
$ gammapy-sherpa-like --counts counts.fits --exposure exposure.fits
 --background background.fits --psf psf.json --sources sources.json
  result.json
```

Fit results and additional information are stored in `result.json`.

5.2 Test statistics maps

The **`gammapy.detect`** module includes a high performance `compute_ts_map` function to compute test statistic (TS) maps for γ-ray survey data. The implementation is based on the method described in [6]. As input data, the user provides counts, background and exposure maps. The following code example demonstrates the computation of a TS map for prepared *Fermi* survey data, which is provided in gammapy-extra. The resulting TS map is shown in Figure 3.

```python
from astropy.io import fits
from astropy.convolution import Gaussian2DKernel
from gammapy.detect import compute_ts_map
hdu_list = fits.open('all.fits.gz')
kernel = Gaussian2DKernel(2.5)
result = compute_ts_map(hdu_list['On'].data,
                        hdu_list['Background'].data,
                        hdu_list['ExpGammaMap'].data, kernel)
result.write('ts_map.fits')
```

5.3 Galactic population models

Gammapy also offers functionality for modeling and simulation. The **`gammapy.astro`** sub-package provides tools to simulate Galactic TeV source populations and source characteristics, which is useful in the context of surveys and population studies. Figure 4 illustrates a source population simulated with *Gammapy* and the different radial distribution models the user can choose from.

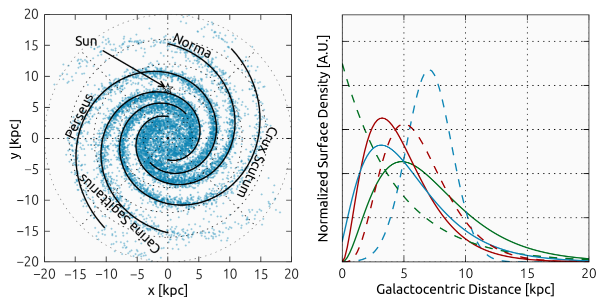


Figure 4: Galactic source population simulated using *Gammapy* , assuming a radial distribution of sources after [7] and the spiral-arm model of [8].

6. Planned functionality

Gammapy already includes key analysis features like morphology and spectrum fitting but both are currently limited to either 2D image-based data or 1D spectral data. As a major next step we plan to support joint likelihood fitting of datasets, as illustrated in Figure 5. Events are binned into longitude, latitude and energy cubes and fitted simultaniously with spectral and spatial models taking energy-dependent background, exposure and point spread function (PSF) into account.

Support for un-binned analyses is not planned.

7. Summary

Gammapy 0.3 is still alpha quality software. It is a package where standard γ-ray analyses are available on the one hand while, on the other hand, integration and prototyping of new methods is easily possible. So far it only contains limited functionality but the setup of documentation, testing and deployment is already very advanced. It's scope will continously grow and we hope that many users and developers show interest in open and reproducible γ-ray astronomy with Python. As long-term goal we would like *Gammapy* to turn into a fully community-developed package. So all contributions to *Gammapy* are welcome! If you don't know how to turn your scripts into production-quality, reusable code, please get in touch with us (e.g. using the mailing list) and we will help you get there!

For further information on how *Gammapy* and other tools are being used for H.E.S.S. data analysis, we encourage you to look at [9].

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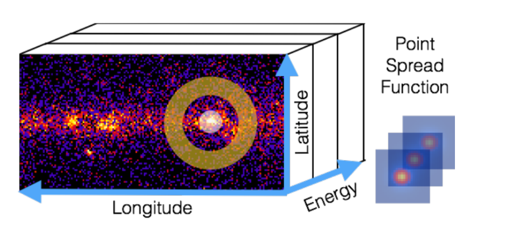

Figure 5: Gammapy data model illustration. Binned analysis of lon-lat-energy cube data is supported via joint likelihood analysis of one image per energy bin. On-off-region based spectral analysis is supported as well.

References

[1] C. Deil et al. for the H.E.S.S. collaboration, *The H.E.S.S. Galactic plane survey*, in *these proceedings*, 2015.

[2] E. Owen, C. Deil, A. Donath, and R. Terrier, *The gamma-ray Milky Way above 10 GeV: Distinguishing Sources from Diffuse Emission*, *PoS(SciNeGHE2014)* **34** (June, 2015) [`arXiv:1506.0231`].

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[4] Astropy Collaboration, T. P. Robitaille, E. J. Tollerud, and P. Greenfield et al., *Astropy: A community Python package for astronomy*, *AAP* **558** (Oct., 2013) A33.

[5] B. Refsdal et al., *Sherpa: 1d/2d modeling and fitting in python*, in *Proceedings of the 8th Python in Science Conference*, (Pasadena, CA USA), pp. 51 – 57, 2009.

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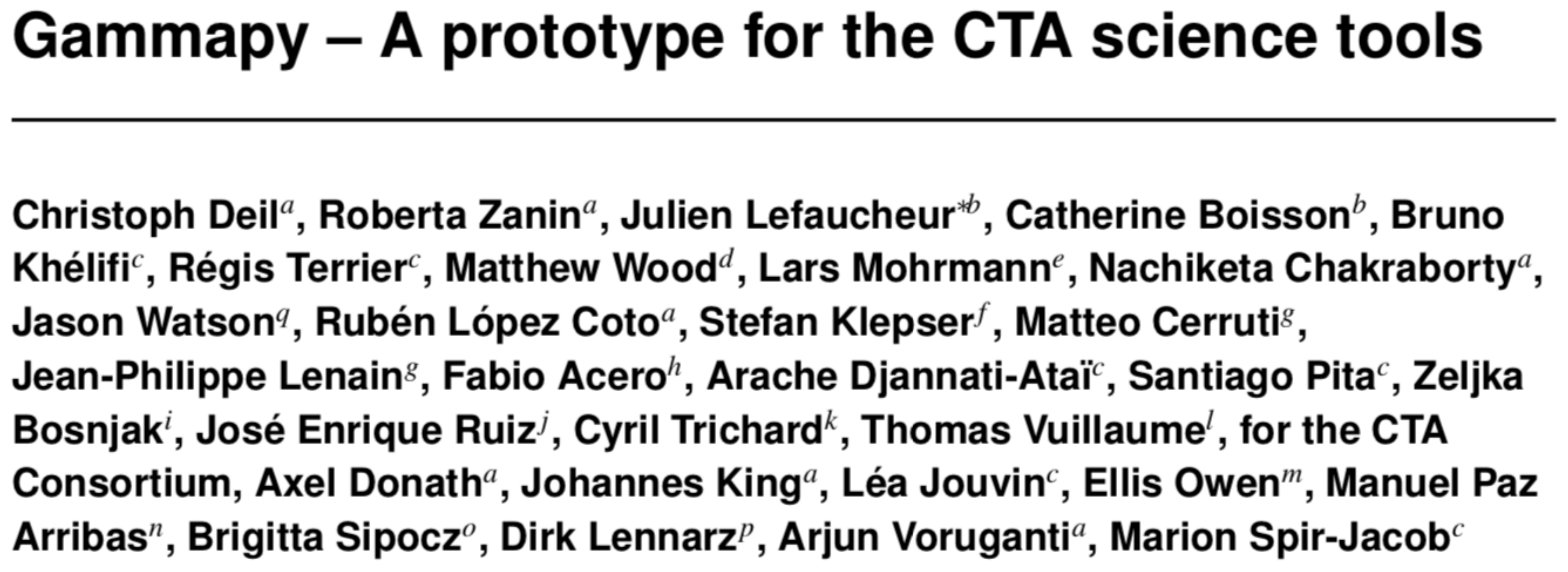
[8] J. P. Vallée, *New Velocimetry and Revised Cartography of the Spiral Arms in the Milky Way - A Consistent Symbiosis*, *aj* **135** (Apr., 2008) 1301–1310.

[9] C. Deil et al. for the H.E.S.S. collaboration, *H.E.S.S. data analysis with open source science tools*, in *these proceedings*, 2015.

Gammapy proceeding ICRC 2017

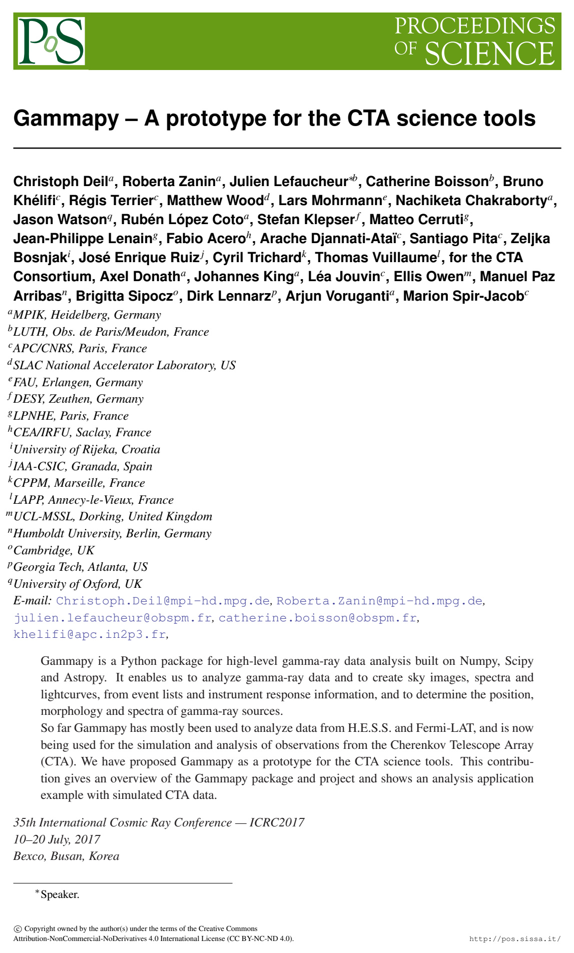
Deil et al. (30 co-authors)
for the CTA Consortium
8 pages, 2 figures, 3 citations
1 code example (as figure)

1. Introduction
2. Context
3. Gammapy package
4. Gammapy project
5. Conclusions
6. Acknowledgements



Gammapy – A prototype for the CTA science tools

Christoph Deil[a], Roberta Zanin[a], Julien Lefaucheur[*b], Catherine Boisson[b], Bruno Khélifi[c], Régis Terrier[c], Matthew Wood[d], Lars Mohrmann[e], Nachiketa Chakraborty[a], Jason Watson[q], Rubén López Coto[a], Stefan Klepser[f], Matteo Cerruti[g], Jean-Philippe Lenain[g], Fabio Acero[h], Arache Djannati-Ataï[c], Santiago Pita[c], Zeljka Bosnjak[i], José Enrique Ruiz[j], Cyril Trichard[k], Thomas Vuillaume[l], for the CTA Consortium, Axel Donath[a], Johannes King[a], Léa Jouvin[c], Ellis Owen[m], Manuel Paz Arribas[n], Brigitta Sipocz[o], Dirk Lennarz[p], Arjun Voruganti[a], Marion Spir-Jacob[c]



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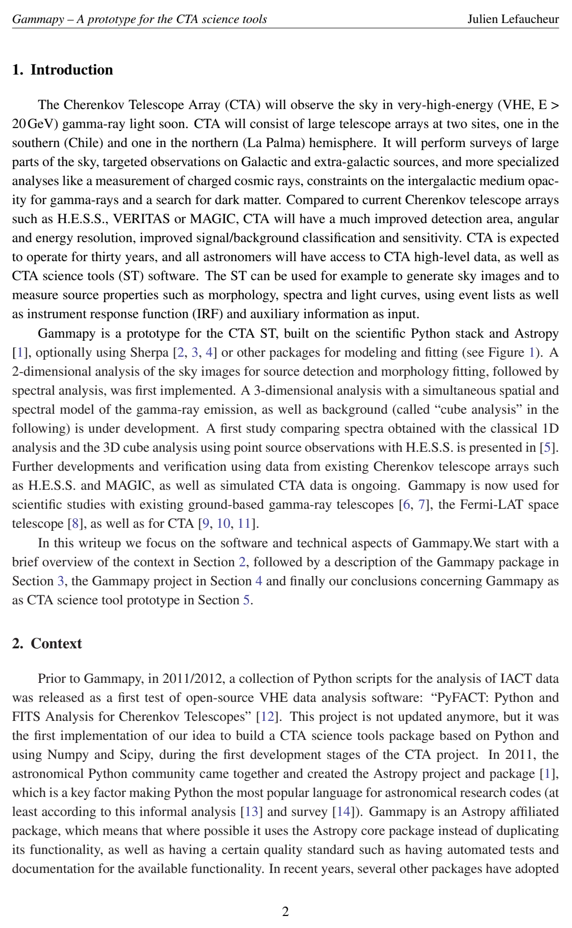
[a]*MPIK, Heidelberg, Germany*
[b]*LUTH, Obs. de Paris/Meudon, France*
[c]*APC/CNRS, Paris, France*
[d]*SLAC National Accelerator Laboratory, US*
[e]*FAU, Erlangen, Germany*
[f]*DESY, Zeuthen, Germany*
[g]*LPNHE, Paris, France*
[h]*CEA/IRFU, Saclay, France*
[i]*University of Rijeka, Croatia*
[j]*IAA-CSIC, Granada, Spain*
[k]*CPPM, Marseille, France*
[l]*LAPP, Annecy-le-Vieux, France*
[m]*UCL-MSSL, Dorking, United Kingdom*
[n]*Humboldt University, Berlin, Germany*
[o]*Cambridge, UK*
[p]*Georgia Tech, Atlanta, US*
[q]*University of Oxford, UK*
E-mail: Christoph.Deil@mpi-hd.mpg.de, Roberta.Zanin@mpi-hd.mpg.de, julien.lefaucheur@obspm.fr, catherine.boisson@obspm.fr, khelifi@apc.in2p3.fr,

Gammapy is a Python package for high-level gamma-ray data analysis built on Numpy, Scipy and Astropy. It enables us to analyze gamma-ray data and to create sky images, spectra and lightcurves, from event lists and instrument response information, and to determine the position, morphology and spectra of gamma-ray sources.
So far Gammapy has mostly been used to analyze data from H.E.S.S. and Fermi-LAT, and is now being used for the simulation and analysis of observations from the Cherenkov Telescope Array (CTA). We have proposed Gammapy as a prototype for the CTA science tools. This contribution gives an overview of the Gammapy package and project and shows an analysis application example with simulated CTA data.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

*Speaker.



1. Introduction

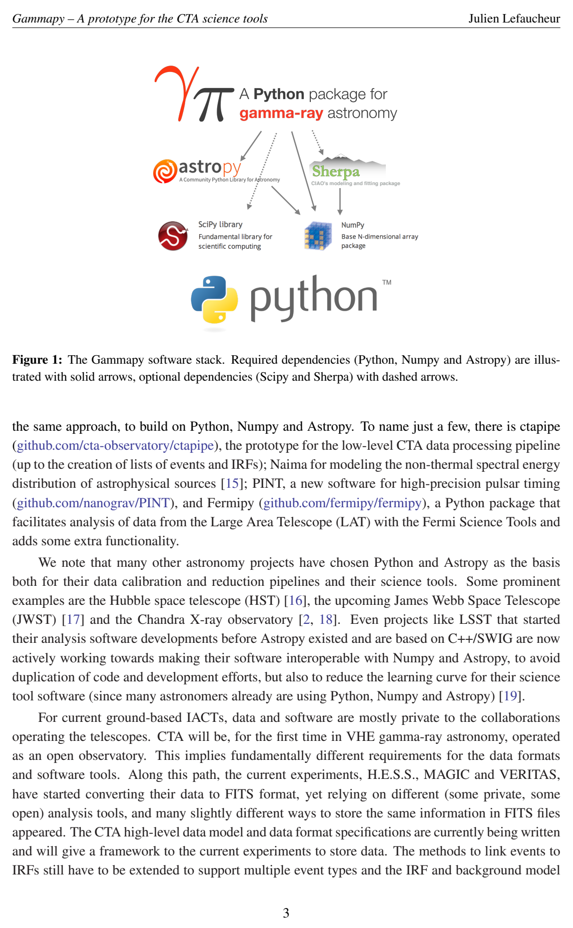
The Cherenkov Telescope Array (CTA) will observe the sky in very-high-energy (VHE, E > 20 GeV) gamma-ray light soon. CTA will consist of large telescope arrays at two sites, one in the southern (Chile) and one in the northern (La Palma) hemisphere. It will perform surveys of large parts of the sky, targeted observations on Galactic and extra-galactic sources, and more specialized analyses like a measurement of charged cosmic rays, constraints on the intergalactic medium opacity for gamma-rays and a search for dark matter. Compared to current Cherenkov telescope arrays such as H.E.S.S., VERITAS or MAGIC, CTA will have a much improved detection area, angular and energy resolution, improved signal/background classification and sensitivity. CTA is expected to operate for thirty years, and all astronomers will have access to CTA high-level data, as well as CTA science tools (ST) software. The ST can be used for example to generate sky images and to measure source properties such as morphology, spectra and light curves, using event lists as well as instrument response function (IRF) and auxiliary information as input.

Gammapy is a prototype for the CTA ST, built on the scientific Python stack and Astropy [1], optionally using Sherpa [2, 3, 4] or other packages for modeling and fitting (see Figure 1). A 2-dimensional analysis of the sky images for source detection and morphology fitting, followed by spectral analysis, was first implemented. A 3-dimensional analysis with a simultaneous spatial and spectral model of the gamma-ray emission, as well as background (called "cube analysis" in the following) is under development. A first study comparing spectra obtained with the classical 1D analysis and the 3D cube analysis using point source observations with H.E.S.S. is presented in [5]. Further developments and verification using data from existing Cherenkov telescope arrays such as H.E.S.S. and MAGIC, as well as simulated CTA data is ongoing. Gammapy is now used for scientific studies with existing ground-based gamma-ray telescopes [6, 7], the Fermi-LAT space telescope [8], as well as for CTA [9, 10, 11].

In this writeup we focus on the software and technical aspects of Gammapy.We start with a brief overview of the context in Section 2, followed by a description of the Gammapy package in Section 3, the Gammapy project in Section 4 and finally our conclusions concerning Gammapy as as CTA science tool prototype in Section 5.

2. Context

Prior to Gammapy, in 2011/2012, a collection of Python scripts for the analysis of IACT data was released as a first test of open-source VHE data analysis software: "PyFACT: Python and FITS Analysis for Cherenkov Telescopes" [12]. This project is not updated anymore, but it was the first implementation of our idea to build a CTA science tools package based on Python and using Numpy and Scipy, during the first development stages of the CTA project. In 2011, the astronomical Python community came together and created the Astropy project and package [1], which is a key factor making Python the most popular language for astronomical research codes (at least according to this informal analysis [13] and survey [14]). Gammapy is an Astropy affiliated package, which means that where possible it uses the Astropy core package instead of duplicating its functionality, as well as having a certain quality standard such as having automated tests and documentation for the available functionality. In recent years, several other packages have adopted



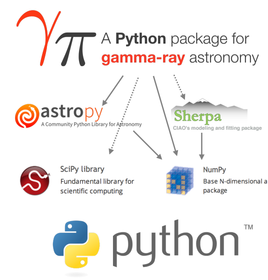
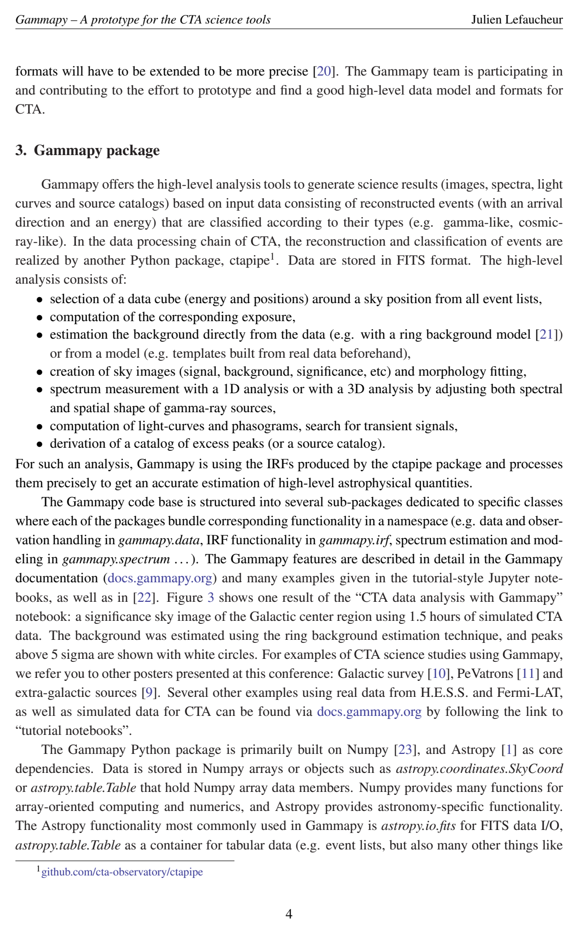

A Python package for gamma-ray astronomy
astropy
A Community Python Library for Astronomy
Sherpa
CIAO's modeling and fitting package
SciPy library
Fundamental library for scientific computing
NumPy
Base N-dimensional array package
python ™

Figure 1: The Gammapy software stack. Required dependencies (Python, Numpy and Astropy) are illustrated with solid arrows, optional dependencies (Scipy and Sherpa) with dashed arrows.

the same approach, to build on Python, Numpy and Astropy. To name just a few, there is ctapipe (github.com/cta-observatory/ctapipe), the prototype for the low-level CTA data processing pipeline (up to the creation of lists of events and IRFs); Naima for modeling the non-thermal spectral energy distribution of astrophysical sources [15]; PINT, a new software for high-precision pulsar timing (github.com/nanograv/PINT), and Fermipy (github.com/fermipy/fermipy), a Python package that facilitates analysis of data from the Large Area Telescope (LAT) with the Fermi Science Tools and adds some extra functionality.

We note that many other astronomy projects have chosen Python and Astropy as the basis both for their data calibration and reduction pipelines and their science tools. Some prominent examples are the Hubble space telescope (HST) [16], the upcoming James Webb Space Telescope (JWST) [17] and the Chandra X-ray observatory [2, 18]. Even projects like LSST that started their analysis software developments before Astropy existed and are based on C++/SWIG are now actively working towards making their software interoperable with Numpy and Astropy, to avoid duplication of code and development efforts, but also to reduce the learning curve for their science tool software (since many astronomers already are using Python, Numpy and Astropy) [19].

For current ground-based IACTs, data and software are mostly private to the collaborations operating the telescopes. CTA will be, for the first time in VHE gamma-ray astronomy, operated as an open observatory. This implies fundamentally different requirements for the data formats and software tools. Along this path, the current experiments, H.E.S.S., MAGIC and VERITAS, have started converting their data to FITS format, yet relying on different (some private, some open) analysis tools, and many slightly different ways to store the same information in FITS files appeared. The CTA high-level data model and data format specifications are currently being written and will give a framework to the current experiments to store data. The methods to link events to IRFs still have to be extended to support multiple event types and the IRF and background model



formats will have to be extended to be more precise [20]. The Gammapy team is participating in and contributing to the effort to prototype and find a good high-level data model and formats for CTA.

3. Gammapy package

Gammapy offers the high-level analysis tools to generate science results (images, spectra, light curves and source catalogs) based on input data consisting of reconstructed events (with an arrival direction and an energy) that are classified according to their types (e.g. gamma-like, cosmic-ray-like). In the data processing chain of CTA, the reconstruction and classification of events are realized by another Python package, ctapipe[1]. Data are stored in FITS format. The high-level analysis consists of:

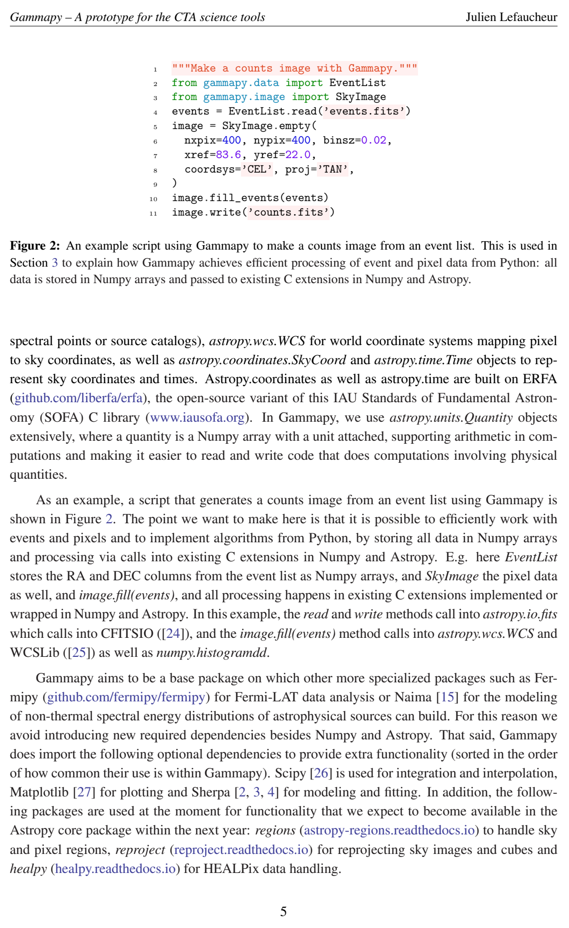
- selection of a data cube (energy and positions) around a sky position from all event lists,
- computation of the corresponding exposure,
- estimation the background directly from the data (e.g. with a ring background model [21]) or from a model (e.g. templates built from real data beforehand),
- creation of sky images (signal, background, significance, etc) and morphology fitting,
- spectrum measurement with a 1D analysis or with a 3D analysis by adjusting both spectral and spatial shape of gamma-ray sources,
- computation of light-curves and phasograms, search for transient signals,
- derivation of a catalog of excess peaks (or a source catalog).

For such an analysis, Gammapy is using the IRFs produced by the ctapipe package and processes them precisely to get an accurate estimation of high-level astrophysical quantities.

The Gammapy code base is structured into several sub-packages dedicated to specific classes where each of the packages bundle corresponding functionality in a namespace (e.g. data and observation handling in *gammapy.data*, IRF functionality in *gammapy.irf*, spectrum estimation and modeling in *gammapy.spectrum* . . .). The Gammapy features are described in detail in the Gammapy documentation (docs.gammapy.org) and many examples given in the tutorial-style Jupyter notebooks, as well as in [22]. Figure 3 shows one result of the "CTA data analysis with Gammapy" notebook: a significance sky image of the Galactic center region using 1.5 hours of simulated CTA data. The background was estimated using the ring background estimation technique, and peaks above 5 sigma are shown with white circles. For examples of CTA science studies using Gammapy, we refer you to other posters presented at this conference: Galactic survey [10], PeVatrons [11] and extra-galactic sources [9]. Several other examples using real data from H.E.S.S. and Fermi-LAT, as well as simulated data for CTA can be found via docs.gammapy.org by following the link to "tutorial notebooks".

The Gammapy Python package is primarily built on Numpy [23], and Astropy [1] as core dependencies. Data is stored in Numpy arrays or objects such as *astropy.coordinates.SkyCoord* or *astropy.table.Table* that hold Numpy array data members. Numpy provides many functions for array-oriented computing and numerics, and Astropy provides astronomy-specific functionality. The Astropy functionality most commonly used in Gammapy is *astropy.io.fits* for FITS data I/O, *astropy.table.Table* as a container for tabular data (e.g. event lists, but also many other things like

[1]github.com/cta-observatory/ctapipe



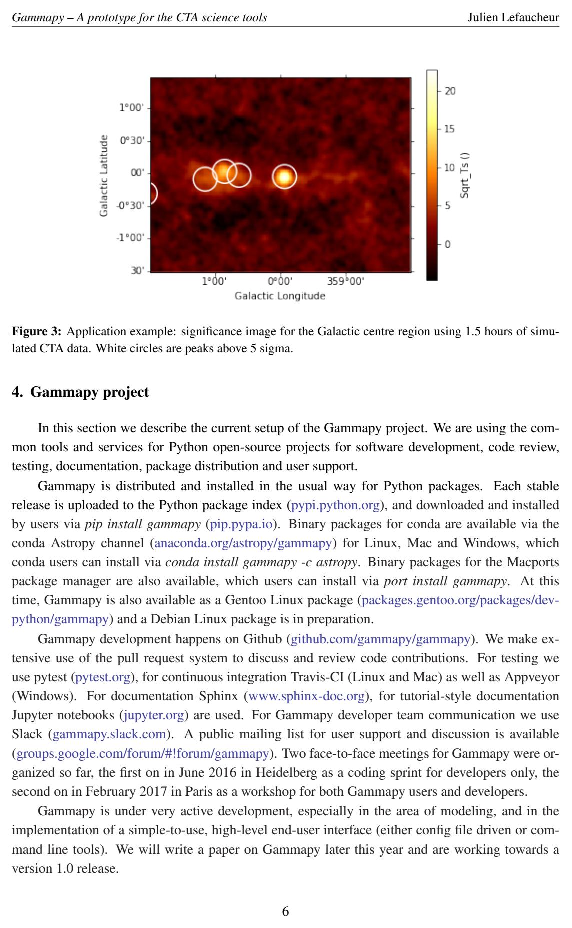
```
"""Make a counts image with Gammapy."""
from gammapy.data import EventList
from gammapy.image import SkyImage
events = EventList.read('events.fits')
image = SkyImage.empty(
  nxpix=400, nypix=400, binsz=0.02,
  xref=83.6, yref=22.0,
  coordsys='CEL', proj='TAN',
)
image.fill_events(events)
image.write('counts.fits')
```

Figure 2: An example script using Gammapy to make a counts image from an event list. This is used in Section 3 to explain how Gammapy achieves efficient processing of event and pixel data from Python: all data is stored in Numpy arrays and passed to existing C extensions in Numpy and Astropy.

spectral points or source catalogs), *astropy.wcs.WCS* for world coordinate systems mapping pixel to sky coordinates, as well as *astropy.coordinates.SkyCoord* and *astropy.time.Time* objects to represent sky coordinates and times. Astropy.coordinates as well as astropy.time are built on ERFA (github.com/liberfa/erfa), the open-source variant of this IAU Standards of Fundamental Astronomy (SOFA) C library (www.iausofa.org). In Gammapy, we use *astropy.units.Quantity* objects extensively, where a quantity is a Numpy array with a unit attached, supporting arithmetic in computations and making it easier to read and write code that does computations involving physical quantities.

As an example, a script that generates a counts image from an event list using Gammapy is shown in Figure 2. The point we want to make here is that it is possible to efficiently work with events and pixels and to implement algorithms from Python, by storing all data in Numpy arrays and processing via calls into existing C extensions in Numpy and Astropy. E.g. here *EventList* stores the RA and DEC columns from the event list as Numpy arrays, and *SkyImage* the pixel data as well, and *image.fill(events)*, and all processing happens in existing C extensions implemented or wrapped in Numpy and Astropy. In this example, the *read* and *write* methods call into *astropy.io.fits* which calls into CFITSIO ([24]), and the *image.fill(events)* method calls into *astropy.wcs.WCS* and WCSLib ([25]) as well as *numpy.histogramdd*.

Gammapy aims to be a base package on which other more specialized packages such as Fermipy (github.com/fermipy/fermipy) for Fermi-LAT data analysis or Naima [15] for the modeling of non-thermal spectral energy distributions of astrophysical sources can build. For this reason we avoid introducing new required dependencies besides Numpy and Astropy. That said, Gammapy does import the following optional dependencies to provide extra functionality (sorted in the order of how common their use is within Gammapy). Scipy [26] is used for integration and interpolation, Matplotlib [27] for plotting and Sherpa [2, 3, 4] for modeling and fitting. In addition, the following packages are used at the moment for functionality that we expect to become available in the Astropy core package within the next year: *regions* (astropy-regions.readthedocs.io) to handle sky and pixel regions, *reproject* (reproject.readthedocs.io) for reprojecting sky images and cubes and *healpy* (healpy.readthedocs.io) for HEALPix data handling.



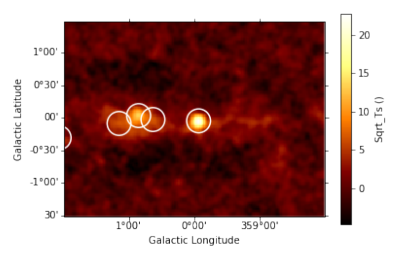


Figure 3: Application example: significance image for the Galactic centre region using 1.5 hours of simulated CTA data. White circles are peaks above 5 sigma.

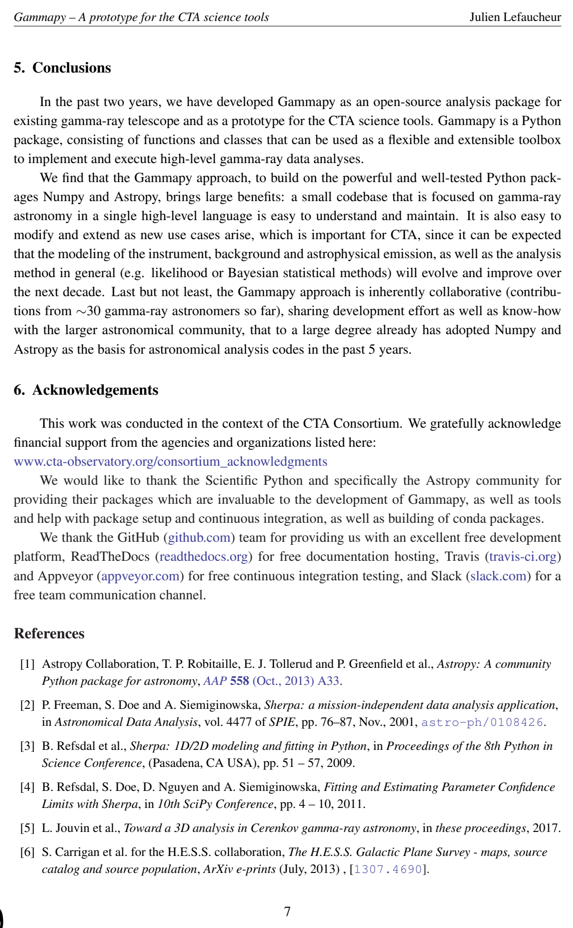
4. Gammapy project

In this section we describe the current setup of the Gammapy project. We are using the common tools and services for Python open-source projects for software development, code review, testing, documentation, package distribution and user support.

Gammapy is distributed and installed in the usual way for Python packages. Each stable release is uploaded to the Python package index (pypi.python.org), and downloaded and installed by users via *pip install gammapy* (pip.pypa.io). Binary packages for conda are available via the conda Astropy channel (anaconda.org/astropy/gammapy) for Linux, Mac and Windows, which conda users can install via *conda install gammapy -c astropy*. Binary packages for the Macports package manager are also available, which users can install via *port install gammapy*. At this time, Gammapy is also available as a Gentoo Linux package (packages.gentoo.org/packages/dev-python/gammapy) and a Debian Linux package is in preparation.

Gammapy development happens on Github (github.com/gammapy/gammapy). We make extensive use of the pull request system to discuss and review code contributions. For testing we use pytest (pytest.org), for continuous integration Travis-CI (Linux and Mac) as well as Appveyor (Windows). For documentation Sphinx (www.sphinx-doc.org), for tutorial-style documentation Jupyter notebooks (jupyter.org) are used. For Gammapy developer team communication we use Slack (gammapy.slack.com). A public mailing list for user support and discussion is available (groups.google.com/forum/#!forum/gammapy). Two face-to-face meetings for Gammapy were organized so far, the first on in June 2016 in Heidelberg as a coding sprint for developers only, the second on in February 2017 in Paris as a workshop for both Gammapy users and developers.

Gammapy is under very active development, especially in the area of modeling, and in the implementation of a simple-to-use, high-level end-user interface (either config file driven or command line tools). We will write a paper on Gammapy later this year and are working towards a version 1.0 release.



5. Conclusions

In the past two years, we have developed Gammapy as an open-source analysis package for existing gamma-ray telescope and as a prototype for the CTA science tools. Gammapy is a Python package, consisting of functions and classes that can be used as a flexible and extensible toolbox to implement and execute high-level gamma-ray data analyses.

We find that the Gammapy approach, to build on the powerful and well-tested Python packages Numpy and Astropy, brings large benefits: a small codebase that is focused on gamma-ray astronomy in a single high-level language is easy to understand and maintain. It is also easy to modify and extend as new use cases arise, which is important for CTA, since it can be expected that the modeling of the instrument, background and astrophysical emission, as well as the analysis method in general (e.g. likelihood or Bayesian statistical methods) will evolve and improve over the next decade. Last but not least, the Gammapy approach is inherently collaborative (contributions from $\sim$30 gamma-ray astronomers so far), sharing development effort as well as know-how with the larger astronomical community, that to a large degree already has adopted Numpy and Astropy as the basis for astronomical analysis codes in the past 5 years.

6. Acknowledgements

This work was conducted in the context of the CTA Consortium. We gratefully acknowledge financial support from the agencies and organizations listed here:
www.cta-observatory.org/consortium_acknowledgments
We would like to thank the Scientific Python and specifically the Astropy community for providing their packages which are invaluable to the development of Gammapy, as well as tools and help with package setup and continuous integration, as well as building of conda packages.
We thank the GitHub (github.com) team for providing us with an excellent free development platform, ReadTheDocs (readthedocs.org) for free documentation hosting, Travis (travis-ci.org) and Appveyor (appveyor.com) for free continuous integration testing, and Slack (slack.com) for a free team communication channel.

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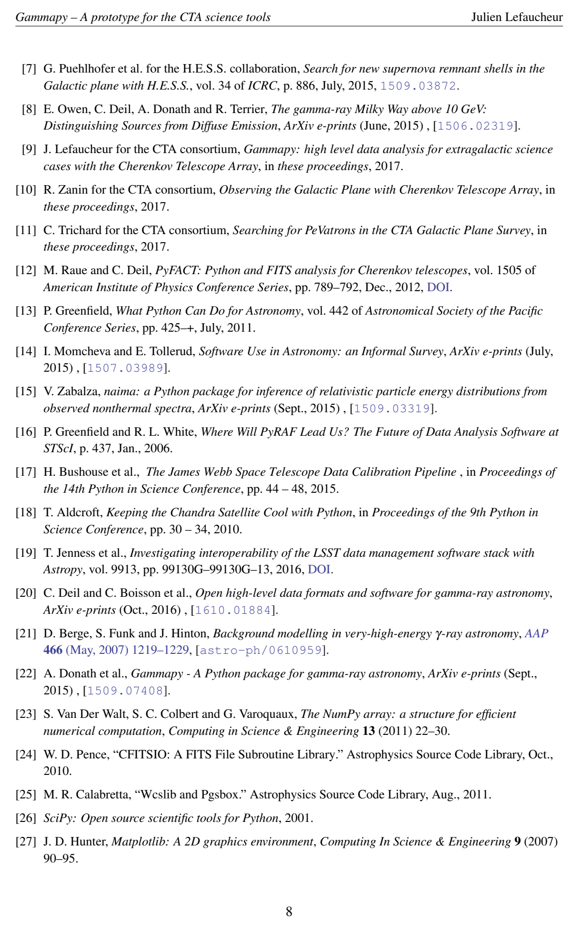

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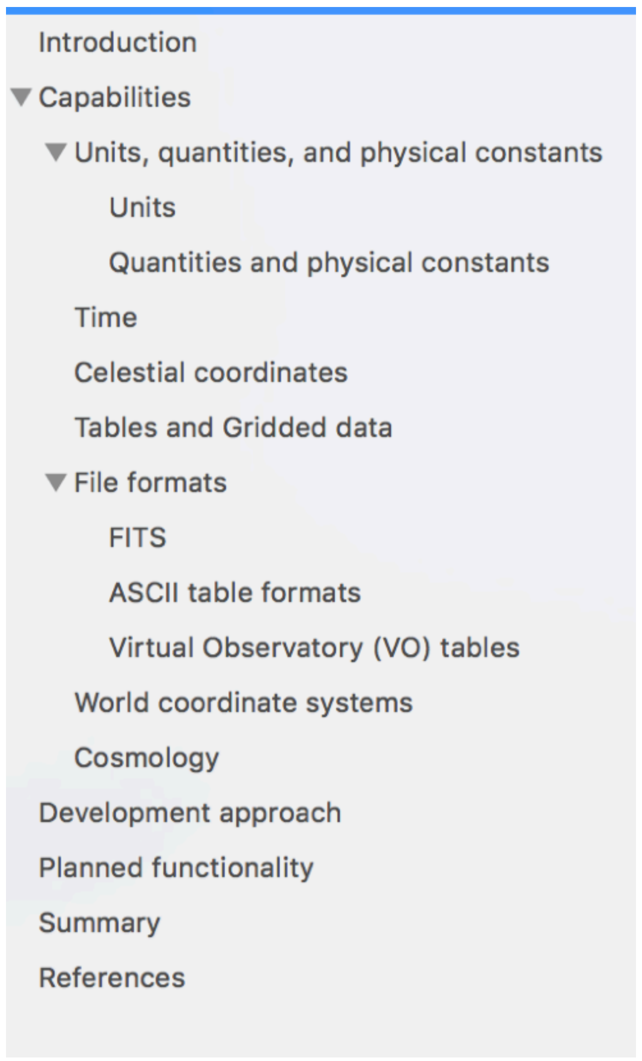
Other papers

- We can look at a few other similar papers as examples.
- Astropy: 2013A&A...558A..33A and 2018arXiv180102634P
- Sunpy: Python for Solar Physics
- Gammalib & ctools
- scikit-image
- Know of other good examples we should look at?

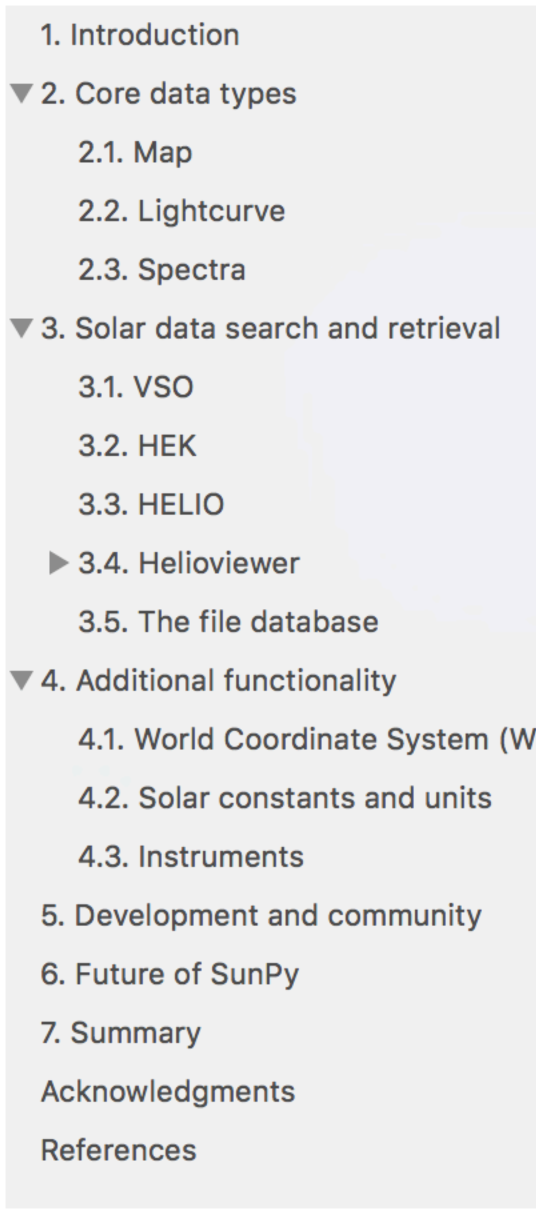
Other papers

Astropy v0.2



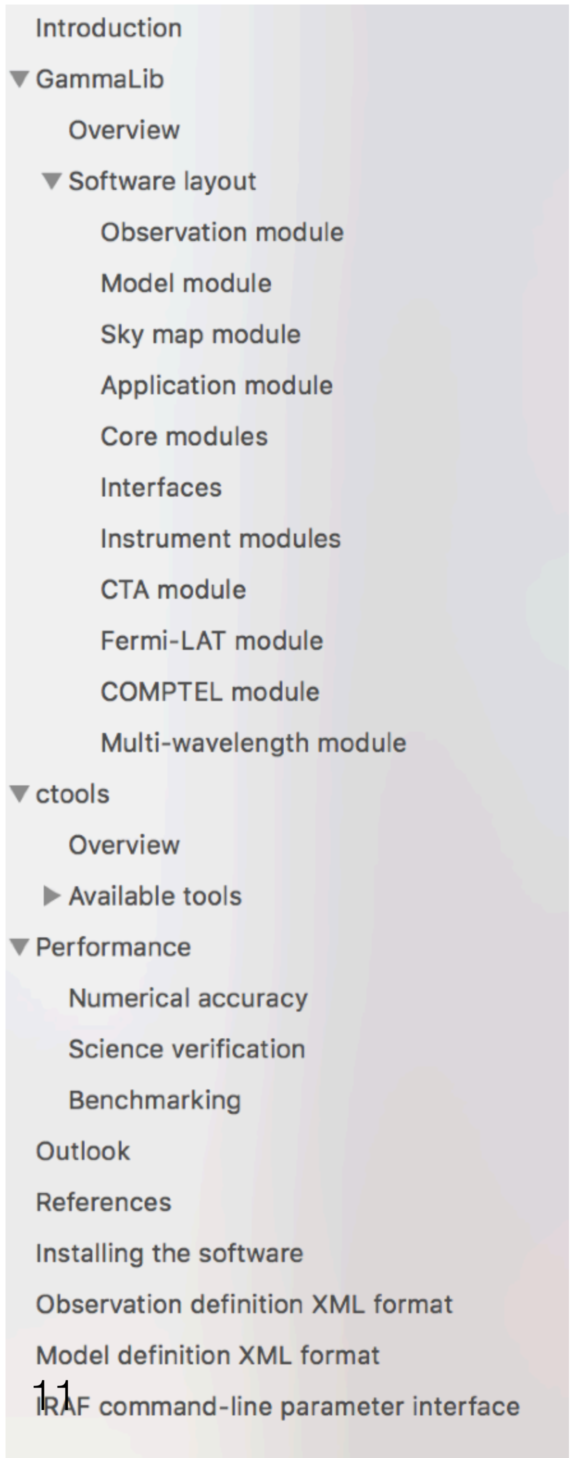
- Introduction
- Capabilities
  - Units, quantities, and physical constants
    - Units
    - Quantities and physical constants
  - Time
  - Celestial coordinates
  - Tables and Gridded data
  - File formats
    - FITS
    - ASCII table formats
    - Virtual Observatory (VO) tables
  - World coordinate systems
  - Cosmology
- Development approach
- Planned functionality
- Summary
- References

Sunpy



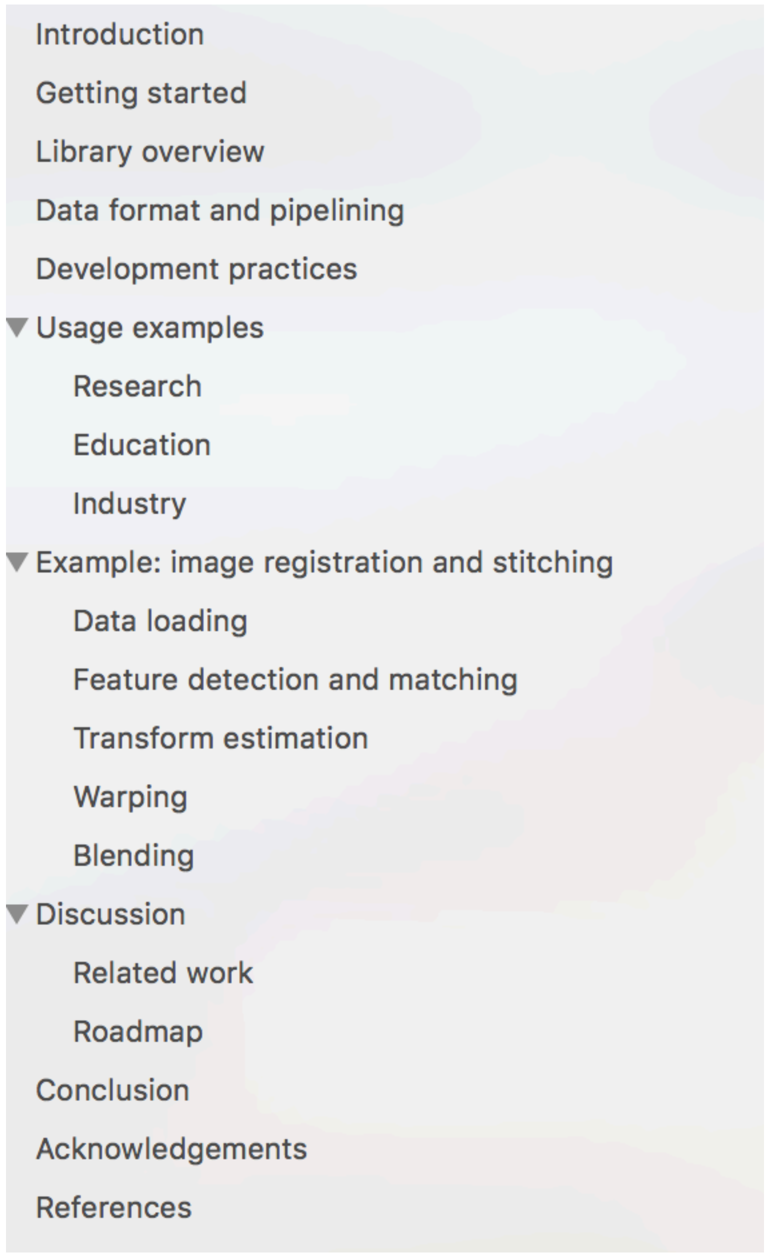
- 1. Introduction
- 2. Core data types
  - 2.1. Map
  - 2.2. Lightcurve
  - 2.3. Spectra
- 3. Solar data search and retrieval
  - 3.1. VSO
  - 3.2. HEK
  - 3.3. HELIO
  - 3.4. Helioviewer
  - 3.5. The file database
- 4. Additional functionality
  - 4.1. World Coordinate System (W
  - 4.2. Solar constants and units
  - 4.3. Instruments
- 5. Development and community
- 6. Future of SunPy
- 7. Summary
- Acknowledgments
- References

Gammalib/ctools



- Introduction
- GammaLib
  - Overview
  - Software layout
    - Observation module
    - Model module
    - Sky map module
    - Application module
    - Core modules
    - Interfaces
    - Instrument modules
    - CTA module
    - Fermi-LAT module
    - COMPTEL module
    - Multi-wavelength module
- ctools
  - Overview
  - Available tools
- Performance
  - Numerical accuracy
  - Science verification
  - Benchmarking
- Outlook
- References
- Installing the software
- Observation definition XML format
- Model definition XML format
- IRAF command-line parameter interface

scikit-image



- Introduction
- Getting started
- Library overview
- Data format and pipelining
- Development practices
- Usage examples
  - Research
  - Education
  - Industry
- Example: image registration and stitching
  - Data loading
  - Feature detection and matching
  - Transform estimation
  - Warping
  - Blending
- Discussion
  - Related work
  - Roadmap
- Conclusion
- Acknowledgements
- References

Gammapy Paper Proposal

This is a first proposal,
to be discussed in a session later this week.

Title

- Suggestion:
  Gammapy: A Python package for gamma-ray astronomy

  Possible alternative:
  Gammapy: A prototype for the CTA science tools

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

Gammapy is an open-source Python package for gamma-ray astronomy built on Numpy and Astropy. It is a prototype for the Cherenkov Telescope Array (CTA) science tools, and can also be used to analyse data from existing gamma-ray telescopes.

Content

- Similar and parts re-used from the two proceedings.
- Possible outline:
  1. Introduction
  2. Gammapy project
  3. Gammapy package
  4. Application examples
  5. Conclusions
- Project and package order could be flipped. There could be a “Future of Gammapy” or “Planned developments” at the end. Or just mention it at the end of sections 2 and 3.

Application examples

- Probably should do at least one or two application examples, to have an image, spectrum and lightcurve plot.
- To be discussed: some first thoughts:
  - CTA DC-1 three runs on GC for image and spectrum (what we now use in all tutorials, already used for ICRC 2017 proceeding)
  - Could also simulate some CTA data ourselves (binned maps) using public prod 3 IRFs, to highlight that one can do CTA simulations with Gammapy.
  - Fermi-LAT: also GC above 10 GeV, as in tutorial, combine with CTA?
  - HESS: maybe the PKS light curve? Or nothing, just refer to HESS validation paper?
  - Other ideas?

Code examples

Would like to have at least one Events & Maps code example.
Could have others for map analysis or modelling. Useful?

```python
"""Make a counts image with Gammapy."""
from gammapy.data import EventList
from gammapy.image import SkyImage
events = EventList.read('events.fits')
image = SkyImage.empty(
  nxpix=400, nypix=400, binsz=0.02,
  xref=83.6, yref=22.0,
  coordsys='CEL', proj='TAN',
)
image.fill_events(events)
image.write('counts.fits')
```

```python
from gammapy.image.models import SkyGaussian
from gammapy.spectrum.models import PowerLaw
from gammapy.cube.models import SkyModel

spatial_model = SkyGaussian(
  lon_0="0.2 deg",
  lat_0="0.1 deg",
  sigma="0.3 deg",
)
spectral_model = PowerLaw(
    index=3,
    amplitude="1e-11 cm-2 s-1 TeV-1",
    reference="1 TeV",
)
sky_model = SkyModel(
    spatial_model,
    spectral_model,
)
print(sky_model)
```

```
curl -O http://gammapy.org/download/install/gammapy-0.8-environment.yml
conda env create -f gammapy-0.8-environment.yml
conda activate gammapy-0.8
```

Authorship

- Anyone who contributed is welcome to co-author.
  We don't cut off at a given contribution level.
- Note that some people contributed significantly to the Gammapy project without making a git commit.
  E.g. hosting a Gammapy meeting or mentoring.
- I will invite the people at http://gammapy.org/team.html to co-author in a few weeks. If someone is missing let me know.
- You have to reply! Don't be shy, the more the merrier!
  (We can't automatically add people to co-author without explicit consent.)
- Then lead developers and project managers will make a proposal for author list order, final decision by Gammapy CC.

Authorship

- Suggest to **not** put “Gammapy community” or “Gammapy collaboration” at the start of the author list.
  (Astropy and Sunpy did that, we didn’t for Gammapy proceedings)

- **No** “for the CTA consortium” at the end. Even if we use a CTA DC-1 analysis example and it becomes a CTA category 2 paper.
  (even if we decide that CTA appears in the title)

- As email contact, suggest to put CC: gammapy-cta-l@in2p3.fr
  Alternative: mailing list: gammapy@googlegroups.com
  Sunpy put sunpy@googlegroups.com
  Astropy put coordinators@astropy.org

Thoughts?