

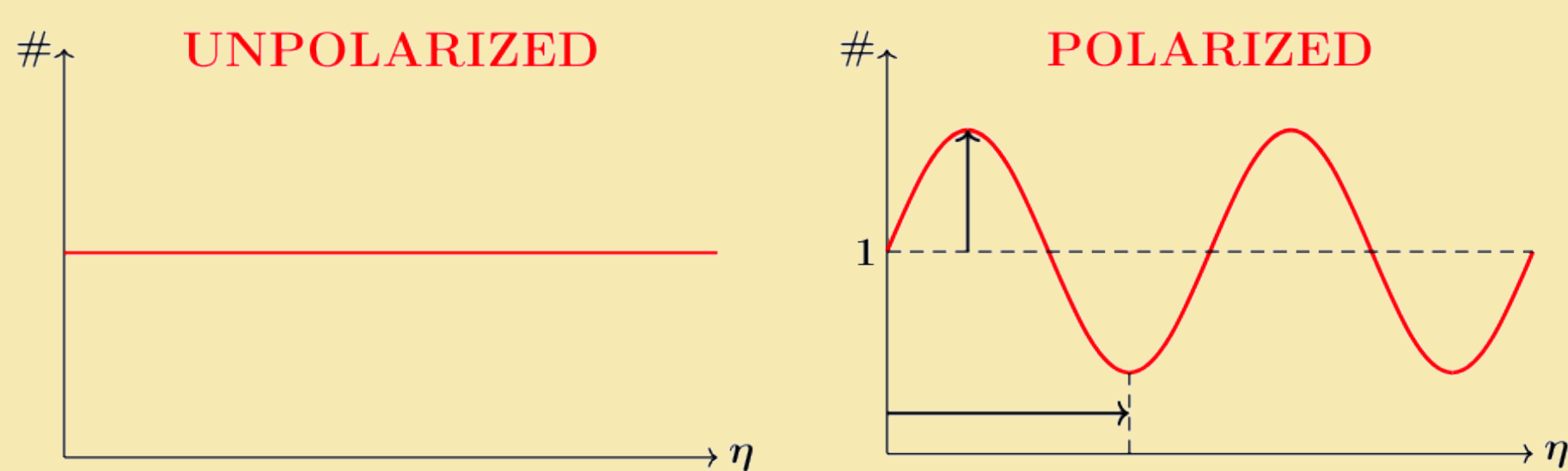
# PolPy: A 3ML-based universal tool for X-/γ-ray polarimetry using common data format standards

## Abstract

Over the past few years, X-/gamma-ray polarimetry has witnessed a boom with great results from missions like POLAR, AstroSat/CZTI, or IXPE. Furthermore, the numerous missions in the pipeline (e.g. POLAR-2, COSI, LEAP, Daksha, eXTP, CATCH, etc.) that are dedicated or are capable of measuring X-/gamma-ray polarisation indicate a coming-of-age of the field. Moreover, neither joint analysis or cross calibration have been possible up to now for polarimetry. Hence, going forward it is important to set standards for effective use of the data generated by current and future missions. We present a universal tool based on the Multi-Mission Maximum Likelihood (3ML) analysis framework [1] that can be used for multi-instrument spectro-polarimetric analysis of data from current and future space-based X-/gamma-ray missions using common data format standards. We have defined the standards in consultation with several mission teams, and they are based on the well-established OGIP standards for spectroscopy. The tool is instrument-agnostic and hence can be easily used for cross-instrument joint analysis if the data and response standards are followed. The common data and response standards that have been developed for X-/gamma-ray polarimetry as well as the analysis tool are presented here.

## High-energy Polarimetric Data Analysis

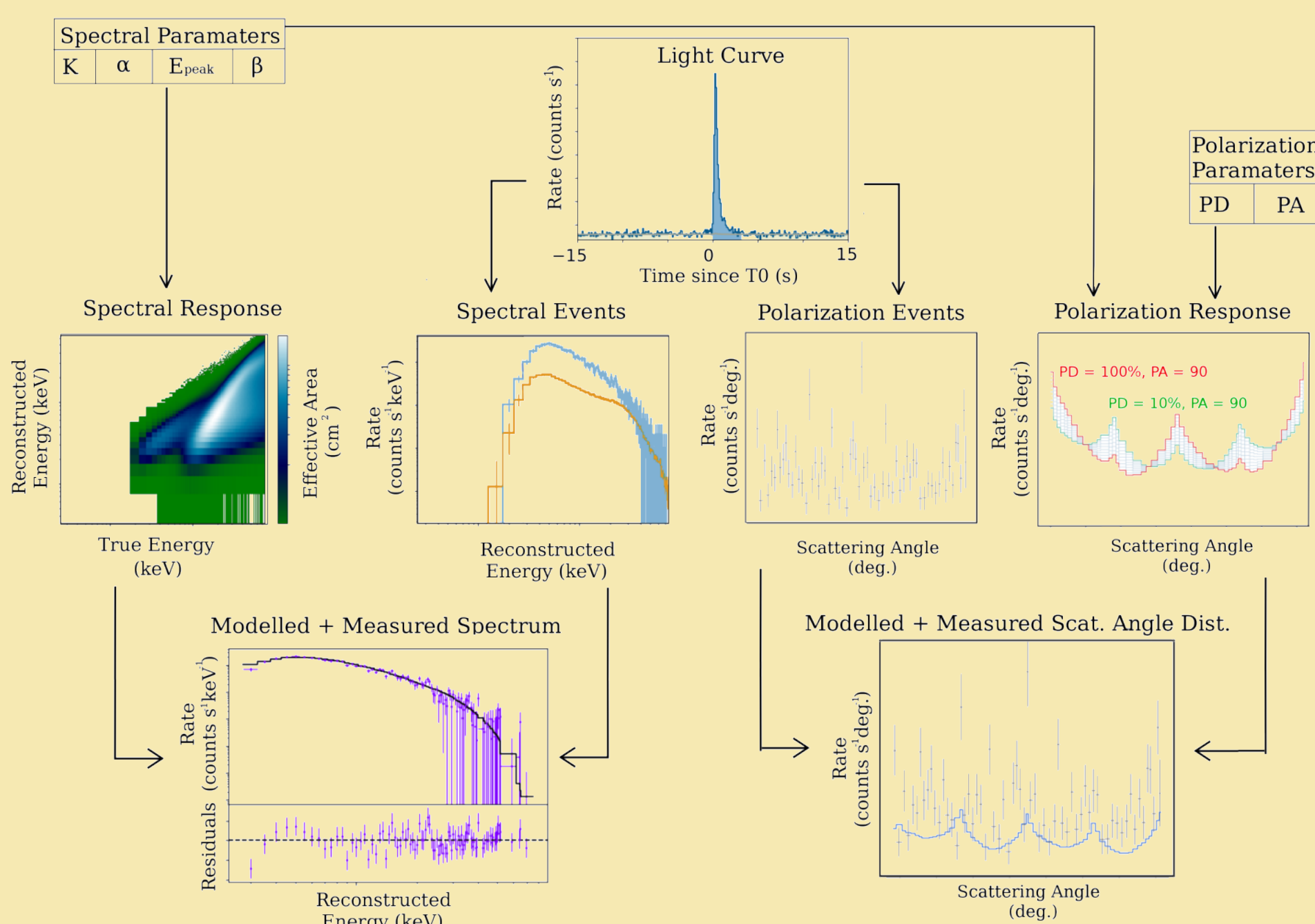
- ▶ Fitting measured and response modulation with a sinusoidal
- ▶ **Forward folding through polarization response in the PA-PD space**
- ▶ Fit in the Stokes (I,Q,U) space



**Figure 1:** Expected angular modulation from an unpolarized (left, no modulation) and a polarized (right, sinusoidal modulation) source

## POLAR Catalog Analysis with 3ML

- ▶ POLAR was a dedicated GRB Compton polarimeter operated for 6 months starting September 2016 on the Tiangong-2 space lab.
- ▶ It detected 55 GRBs, the 14 brightest have been analyzed for polarization using joint spectral fitting with Fermi-GBM and Swift-BAT data when available [2]. This joint analysis was performed using the 3ML [1] multi-mission analysis framework, the forward folding analysis flow if shown in Figure 2.
- ▶ POLAR reported low level of polarization for the 14 analysed GRBs [2], as well as a hint for temporal evolution of the polarization parameters for the two brightest FRED-like GRBs that had the required statistics to perform such analysis [3]. No significant energy dependence of polarization was found as the data is very limited by statistics [4].



**Figure 2:** Scheme of the POLAR catalog analysis method. Taken from [2].

## PolPy: Standardized Response and Data Format

- ▶ Developing a 3ML analysis plugin based on **polarp** which was used for the POLAR analysis [2, 3]
- ▶ It will allow joint spectro-polarimetric analysis with data from multiple instruments, particularly relevant for polarimetry as it is a statistically-hungry measurement
- ▶ We defined a common data and response format based on the OGIP standard for spectral data, as shown in Figure 3

|   |                      |        |                   |        |       |       |
|---|----------------------|--------|-------------------|--------|-------|-------|
| 0 | Primary              | Image  | 0                 | Header | Image | Table |
| 1 | INEBOUNDS            | Binary | 2 cols X 150 rows | Header | Hist  | Plot  |
| 2 | INPAVALS             | Binary | 1 cols X 61 rows  | Header | Hist  | Plot  |
| 3 | SABOUNDS             | Binary | 3 cols X 360 rows | Header | Hist  | Plot  |
| 4 | SPECRESP POLMATRIX   | Image  | 150 X 61 X 360    | Header | Image | Table |
| 5 | SPECRESP UNPOLMATRIX | Image  | 150 X 360         | Header | Image | Table |

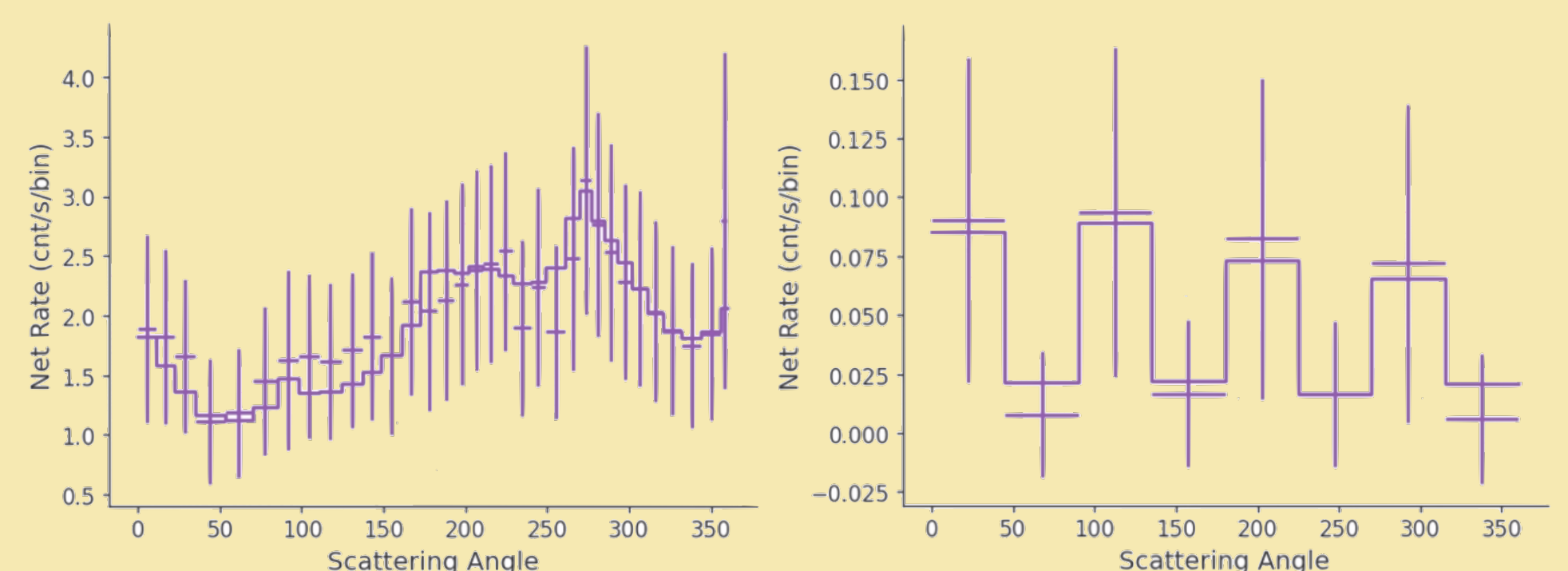
  

|        |                    |              |                      |              |
|--------|--------------------|--------------|----------------------|--------------|
| 0      | Primary            | Image        | 0                    | Header       |
| 1      | POLEVENTS          | Binary       | 4 cols X 485242 rows | Header       |
| TIME   | ENERGY             | SA           | DEADFRAC             |              |
| D      | E                  | E            | E                    |              |
| sec    | keV                | deg          |                      |              |
| Invert | Modify             | Modify       | Modify               | Modify       |
| 1      | 1.484431069501E+09 | 5.300000E+01 | -1.000000E+00        | 6.890131E-02 |
| Z      | 1.484431069503E+09 | 1.641000E+02 | -1.000000E+00        | 3.984013E-03 |

**Figure 3:** Standard polarization response (top) and data (bottom center) formats developed based on the OGIP spectral format. QR codes to documents describing the data format (bottom left) as well as the coordinate frame and PA transformation definitions (bottom right) are also provided.

## PolPy: Code Development and Testing through Joint POLAR-Astrosat/CZTI GRB Analysis

The **open source PolPy pipeline** [5] is being tested by jointly analysing two GRBs that were both observed by POLAR and Astrosat/CZTI, namely GRB161218B and GRB170202B, and for which past independent analysis gave inconsistent results. The POLAR data are publicly accessible here: <https://www.astro.unige.ch/polar/grb-light-curves>. Work in progress, stay tuned! Preliminary results for GRB161218B are shown below.



**Figure 4:** POLAR (left) and Astrosat/CZTI (right) modulation curve for GRB161218B

|                  | PD [%]                           | PA [°]                             |
|------------------|----------------------------------|------------------------------------|
| POLAR catalog    | 13 <sup>+28</sup> <sub>-13</sub> | 68 <sup>+36</sup> <sub>-54</sub>   |
| Joint POLAR+CZTI | 12 <sup>+20</sup> <sub>-7</sub>  | 161 <sup>+20</sup> <sub>-130</sub> |

**Table 1:** Polarization results obtained with POLAR compared to the joint fit with CZTI

## Take-home Messages

- ▶ High-energy polarimetry is a rapidly growing field, and as more missions will be sent a standardized response and data format as well as a common analysis tool will allow joint spectro-polarimetric analysis with several instruments
- ▶ We defined a standard polarization format based on OGIP and developed a publicly available analysis framework [5]
- ▶ The code is still under active development, contributions are welcome!

## References

- [1] Vianello G., et al., *arXiv:1507.08343* (2015)
- [2] Kole M., et al., *A&A* 644, A124 (2020)
- [3] Burgess J.M., Kole M., et al., *A&A* 627, A105 (2019)
- [4] De Angelis N., *PhD thesis Sc. 5785, UniGe* (2023)
- [5] PolPy code – <https://github.com/threeML/polpy>

