

¹ Sensipy: simulate gamma-ray observations of transient astrophysical sources

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¹¹ Summary

¹² We present sensipy, an open-source Python toolkit for simulating observations of transient ¹³ astrophysical sources, particularly in the high-energy (HE, keV-GeV) and very-high-energy (VHE, ¹⁴ GeV-TeV) gamma-ray sky. The most explosive events in our universe are often short-lived, ¹⁵ emitting the bulk of their energy in a relatively small time window. Due to their often rapidly ¹⁶ fading emission profiles, understanding how and when to observe these sources is crucial to ¹⁷ both test theoretical predictions and efficiently optimize telescope time for detection.

¹⁸ The information extracted from the tools included in sensipy can be used to help astronomers ¹⁹ understand the detectability of theoretical models, justify the feasibility of proposed observations, ²⁰ estimate detection rates (events/year) for various classes of sources, and provide scheduling in ²¹ realtime during gamma-ray and multi-messenger observational campaigns.

Statement of need

²³ The need for a toolkit like sensipy became clear when we were attempting to estimate the ²⁴ detectability of VHE counterparts to GW signals of binary neutron star mergers (BNS). While ²⁵ there is no observational evidence yet for such emission from BNS mergers, the upcoming ²⁶ Cherenkov Telescope Array Observatory (CTAO) will provide among the best opportunities to ²⁷ follow up these events in the VHE-regime. While this toolkit began development with the ²⁸ aim to optimize a strategy for such joint detections with CTAO, the usefulness of the package ²⁹ became apparent and can be applied not just to BNS mergers, but also to GRBs, AGN flares, ³⁰ novae, supernovae, and more.

³¹ Between GW, neutrino, optical, high-energy gamma-ray experiments, thousands of low-latency ³² alerts are sent out to the greater community each year. However, very few of these events ³³ actually result in detections in the VHE gamma-ray regime. This is due to many factors, ³⁴ including the relative rarity of events, rapid decay of fluxes, delay in telescope repointing, ³⁵ uncertainty regions of alerts, and observatory duty cycles. In the face of these challenges, ³⁶ sensipy aims to help answer the following questions for gamma-ray astronomers interested in ³⁷ transient astrophysics:

- ³⁸ ▪ Given a theoretical emission model, what are the detection possibilities with a give ³⁹ instrument?
- ⁴⁰ ▪ How much observing time is needed to detect a source given How much time after the ⁴¹ onset of a given event does the source become undetectable for a specific observatory?

44 Functionality

- 45 The two main inputs to any sensipy pipeline are:

- 46 ■ an instrument response function (IRF), which describes how a telescope performs under
47 specific observing conditions, provided in a Data formats for gamma-ray astronomy
48 (DFGA) compatible FITS file
49 ■ intrinsic time-dependent emission spectra for a source, which can be provided in either a
50 FITS or CSV format.

Given these inputs, sensipy toolkit builds upon the primitives provided by numpy, scipy, astropy, and gammipy to provide the following main functionalities. In addition, mock datasets are included with the code with working code examples based on the sample data, and batteries are included for accessing CTAO IRFs.

55 Sensitivity Curve Calculation with `sensipy.sensitivity`

Sensitivity curves represent the minimum flux needed to detect a source at a given significance (usually 5σ) given an exposure time t_{exp} . Such curves are often used to compare the performances of different instruments, and sensipy can produce them in two flavors: integral and differential sensitivity curves. The sensitivity itself depends heavily on the rapidly-changing spectral shape of an event, which itself can be highly affected by distance due to the extragalactic background light (EBL). All of these factors are automatically into account by the Sensitivity module of sensipy:

[Plot of differential and integral sensitivity curves for CTAO calculated with sensipy]

64 Simulating Observations with `sensipy.source`

Given that the user has already calculated the sensitivity curve for a specific event, sensipy can determine if the source is actually detectable given a starting time. In the positive case, the exposure time necessary for detection is also provided. This answers the fundamental question: if we begin observations with a latency of X min after an alert, what observation time is required in order to eke out a detection?

70 Working with large catalogs with sensipy.detectability

71 sensipy can further be used to estimate the overall detectability of entire classes of objects,
72 given a catalog or survey of simulated events under various conditions. By performing and
73 collating a large number of observation simulations for various events and latencies t_L , the
74 toolkit can help produce visualizations which describe the optimal observing conditions for
75 such events.

⁷⁶ [Two example heatmap plots calculated with sensipy]

77 Realtime applications with sensipy.followup

Tables of observation times for an entire class of objects can also be used as lookup tables (LUTs) during telescope observations in order to plan observation campaigns. For example, imagine the following pipeline:

- 81 ■ a catalog of simulated spectra is processed with the above pipeline under various
82 observation conditions, and a LUT is created

- 83 ▪ a transient alert arrives during normal telescope operation and telescopes start observing
- 84 the event position with a latency of t_L
- 85 ▪ the LUT can be filtered and interpolated in realtime in order to quickly calculate an
- 86 informed estimate on the exposure time needed for a detection

87 Such pipelines based on sensipy modules are already being internally evaluated within the
88 MAGIC, Large-Size Telescope (LST), and CTAO collaborations for followup of both GW and
89 GRB alerts.

90 **GW scheduling**

91 In addition, the functions included in sensipy.followup may be used in tandem with scheduling
92 software like tilepy for poorly-localized events. In such cases, these scheduling tools create
93 an optimized list of telescope pointings on the sky, while sensipy is used to simultaneously to
94 optimize the exposure time needed at each new pointing. It is in this context that members of
95 CTAO collaboration began development of sensipy.

96 [Show example of a GW pointing scheduling for a well-localized event, if possible overlay
97 pointing durations on top of each pointing]

98 **Citations**

99 Citations to entries in paper.bib should be in [rMarkdown](#) format.

100 If you want to cite a software repository URL (e.g. something on GitHub without a preferred
101 citation) then you can do it with the example BibTeX entry below.

102 For a quick reference, the following citation commands can be used:

- `@author:2001` -> "Author et al. (2001)"
- `[@author:2001]` -> "(Author et al., 2001)"
- `[@author1:2001; @author2:2001]` -> "(Author1 et al., 2001; Author2 et al., 2002)"

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105 **Statement on AI**

106 Let's say how we did not use generative AI to assist in the writing of this manuscript.

107 **References**