

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

³ **Jarred G. Green**  ^{1,2}, **Barbara Patricelli**  ^{3,4}, **Antonio Stamerra**  ^{3,5}, and ⁴ **Monica Seglar-Arroyo**  ⁶

⁵ 1 Max-Planck-Institut für Physik, Boltzmannstr. 8, 85748 Garching, Germany  ² Technische Universität München, 85748 Garching, Germany  ³ INAF - Osservatorio Astronomico di Roma, Via di Frascati 33, 00078, Monteporzio Catone, Italy  ⁴ University of Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy  ⁵ Cherenkov Telescope Array Observatory, Via Gobetti, 40129 Bologna, Italy  ⁶ Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona), Spain 

DOI: [10.xxxxxx/draft](https://doi.org/10.xxxxxx/draft)

Software

- [Review](#) 
- [Repository](#) 
- [Archive](#) 

Editor: [Open Journals](#) 

Reviewers:

- [@openjournals](#)

Submitted: 01 January 1970

Published: unpublished

License

Authors of papers retain copyright and release the work under a

Creative Commons Attribution 4.0 International License ([CC BY 4.0](#)).

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 often rapidly fading ¹⁶ emission profiles, understanding how and when to observe these sources is crucial to both test ¹⁷ theoretical predictions and efficiently optimize the available telescope time.

¹⁸ The information extracted from the tools included in sensipy can be used to help astronomers ¹⁹ investigate the detectability of sources considering different theoretical assumptions about their ²⁰ emission processes and mechanisms. This information can further help to justify the feasibility ²¹ of proposed observations, estimate detection rates (events/year) for various classes of sources, ²² and provide scheduling in realtime during gamma-ray and multi-messenger observational ²³ campaigns.

²⁴ Statement of need

²⁵ The need for a toolkit like sensipy became clear when we were attempting to estimate the ²⁶ detectability of VHE counterparts to GW signals from binary neutron star mergers (BNS) ²⁷ with the upcoming Cherenkov Telescope Array Observatory (CTAO). While this toolkit began ²⁸ development with the aim to optimize a strategy for such joint detections with CTAO, the ²⁹ usefulness of the package became apparent and can be applied not only to VHE counterparts ³⁰ of BNS mergers, but also to other transient sources like GRBs, AGN flares, novae, supernovae, ³¹ and more.

³² Between GW, neutrino, optical, and orbiting gamma-ray experiments, thousands of low-latency ³³ alerts are sent out to the greater community each year. However, very few of these events ³⁴ actually result in detections in the VHE gamma-ray regime. This is due to many factors, ³⁵ including the rapid decay of fluxes, delay in telescope repointing, uncertainty on the sky ³⁶ localization of the source, and observatory duty cycles. In the face of these challenges, sensipy ³⁷ aims to help answer the following questions for gamma-ray astronomers interested in optimizing ³⁸ their follow-up campaigns:

- ³⁹ ▪ Given a theoretical emission model, what are the detection possibilities with a given ⁴⁰ instrument?

- 41 ▪ How much observing time is needed to detect a source given you are delayed in starting
- 42 observations?
- 43 ▪ How much time after the onset of a given event does the source become undetectable?
- 44 ▪ How can intrinsic source properties (eg distance, flux), and observing conditions (eg
- 45 latency, telescope pointing) affect detectability?
- 46 ▪ How can these results for catalogs of simulated events inform follow-up strategies in
- 47 realtime?

48 **Functionality**

49 The two main inputs to any sensipy pipeline are:

- 50 ▪ an instrument response function (IRF), which describes how a telescope performs under
- 51 specific observing conditions
- 52 ▪ intrinsic time-dependent emission spectra for a source, which can be provided in either a
- 53 FITS or CSV format.

54 Given these inputs, sensipy toolkit builds upon the primitives provided by numpy, scipy,

55 astropy, and gammipy to provide the following main functionalities. In addition, mock datasets

56 are provided with working code examples, and batteries are included for easy access to

57 publicly-available IRFs.

58 **Sensitivity Curve Calculation with `sensipy.sensitivity`**

59 Sensitivity curves represent the minimum flux needed to detect a source at a given significance

60 (usually 5σ) given an exposure time t_{exp} . Such curves are often used to compare the

61 performances of different instruments, and sensipy can produce them in two flavors: integral

62 and differential sensitivity curves. The sensitivity itself depends heavily on the rapidly-changing

63 spectral shape of an event, which itself can be highly affected by distance due to the extragalactic

64 background light (EBL). All of these factors are automatically taken into account.

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

66 **Simulating Observations with `sensipy.source`**

67 This class addresses the fundamental question: if we begin observations with a latency of

68 $t_L = X$ min after an alert, what observation time is required in order to achieve a detection?

69 Given that the user has already calculated the sensitivity curve for an event, sensipy can

70 determine if the source is actually detectable, given T_L . When detectable, the exposure time

71 necessary for detection is also calculated.

72 **Working with large catalogs with `sensipy.detectability`**

73 sensipy can further estimate the overall detectability of entire classes of objects, given a

74 catalog or survey of simulated events under various conditions. By performing and collating a

75 large number of observation simulations for various events and latencies t_L , the toolkit can

76 help produce visualizations which describe the optimal observing conditions for such events.

77 [Two example heatmap plots calculated with sensipy]

78 **Realtime applications with `sensipy.followup`**

79 Tables of observation times can also be used as lookup tables (LUTs) during telescope

80 observations in order to plan observation campaigns. For example, the following workflow can

81 be implemented within sensipy:

- 82 1. a catalog of simulated spectra is processed with the above pipeline considering various
- 83 observation conditions, and a LUT is created
- 84 2. a transient alert arrives during normal telescope operation and telescopes begin observing
- 85 the event position with a latency of t_L
- 86 3. the LUT is filtered and interpolated in realtime in order to quickly calculate an informed
- 87 estimate on the exposure time needed for a detection

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

91 **GW scheduling**

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

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

99 **Citations**

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

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

103 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)"

104 **Acknowledgements**

105 We acknowledge contributions from some people

106 **Statement on AI**

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

108 **References**