

Sensipy: simulate gamma-ray observations of transient astrophysical sources

Jarred G. Green^{1,2}, Barbara Patricelli^{3,4}, Antonio Stamerra^{4,5}, and Monica Seglar-Arroyo⁶

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

DOI: 10.xxxxx/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Published: unpublished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).

Summary

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

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

Statement of need

The need for a toolkit like *sensipy* became clear while attempting to estimate the detectability of VHE counterparts to gravitational wave (GW) signals from binary neutron star mergers (BNS) with the upcoming Cherenkov Telescope Array Observatory (CTAO) (Green et al., 2024; Patricelli et al., 2022). During development, it became apparent that the included tools could be applied not only to VHE counterparts of BNS mergers, but also to other transient sources like gamma-ray bursts (GRBs), active galactic nuclei flares, novae, supernovae, and more.

Between GW, neutrino, optical, and space-based gamma-ray experiments, thousands of low-latency alerts are sent out to the greater community each year (Abac et al., 2025; Abbasi et al., 2023; Kienlin et al., 2020). However, very few of these events actually result in detections in the VHE gamma-ray regime. This is due to many factors, including the rapid decay of fluxes, delay in telescope repointing, uncertainty on the sky localization of the source, and observatory duty cycles. In the face of these challenges, *sensipy* aims to help answer the following questions for gamma-ray astronomers interested in optimizing their follow-up campaigns:

- Given a theoretical emission model, what are the detection possibilities with a given instrument?
- How much observing time is needed to detect a source given a delay in starting observations?

- 42 ■ At what significance level is a source detectable given a certain observation time?
- 43 ■ How long does a source remain detectable after the onset of emission?
- 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, the sensipy toolkit builds upon primitives provided by astropy and
55 gammapy to provide the following main functionalities (Donath et al., 2023; The Astropy
56 and Price-Whelan Collaboration et al., 2022). In addition, mock datasets are provided with
57 working code examples, and batteries are included for easy access to publicly-available IRFs,
58 eg (Cherenkov Telescope Array Observatory and Consortium, 2021).

59 Sensitivity Curve Calculation with sensipy.sensitivity

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

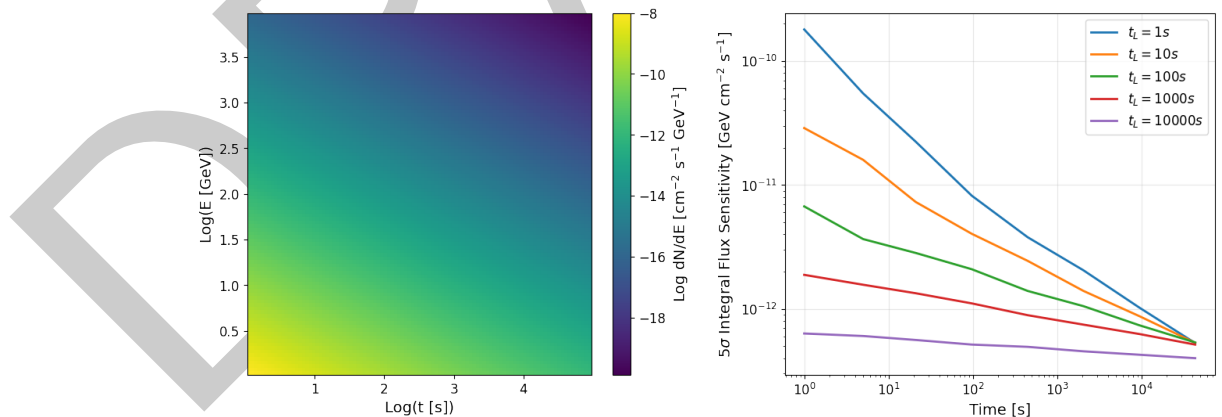


Figure 1: A 2-D representation of the intrinsic time-dependent VHE gamma-ray flux for an example transient event (left) and the corresponding integral flux sensitivity of CTAO for a source with this spectrum (right). The sensitivity curves are calculated for different latencies (t_L) after the event onset.

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 In addition, the class can also determine the inverse: given an observation time, at what
70 significance can a source be detected. Given that the user has already calculated the sensitivity

71 curve for an event, `sensipy` can determine if the source is actually detectable, given t_L . When
72 detectable, the exposure time necessary for detection is also calculated.

73 Working with large catalogs with `sensipy.detectability`

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

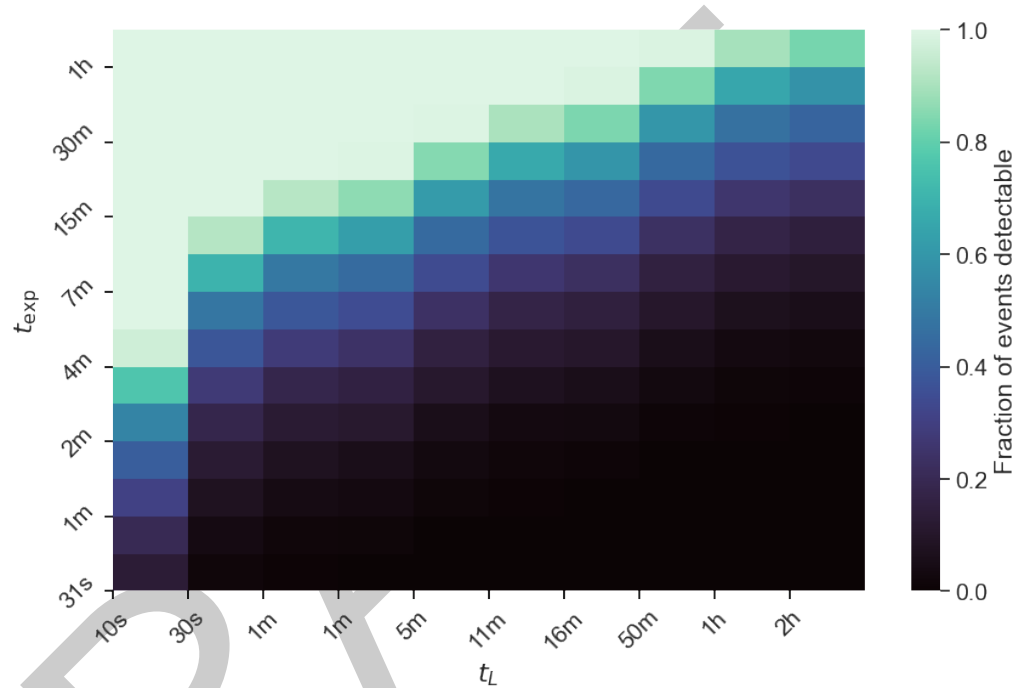


Figure 2: Detectability heatmap produced with `sensipy`. Given a large catalog of transient events, this heatmap shows what fraction are potentially detectable given a specific observation time t_{exp} and latency t_L since the event onset.

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 follow-up of both GW and
90 GRB alerts (eg, [Green et al., 2024](#); [Patricelli et al., 2022](#)).

91 Follow-ups of poorly localized events

92 In addition, the functions included in `sensipy.followup` may be used in tandem with scheduling
93 software like `tilepy` for the realtime follow-up of poorly-localized events, including GRB, GW,
94 and neutrino alerts (Seglar-Arroyo et al., 2024). These scheduling tools create an optimized
95 list of telescope pointings on the sky, while `sensipy` is used simultaneously to optimize the
96 exposure time needed at each new pointing.

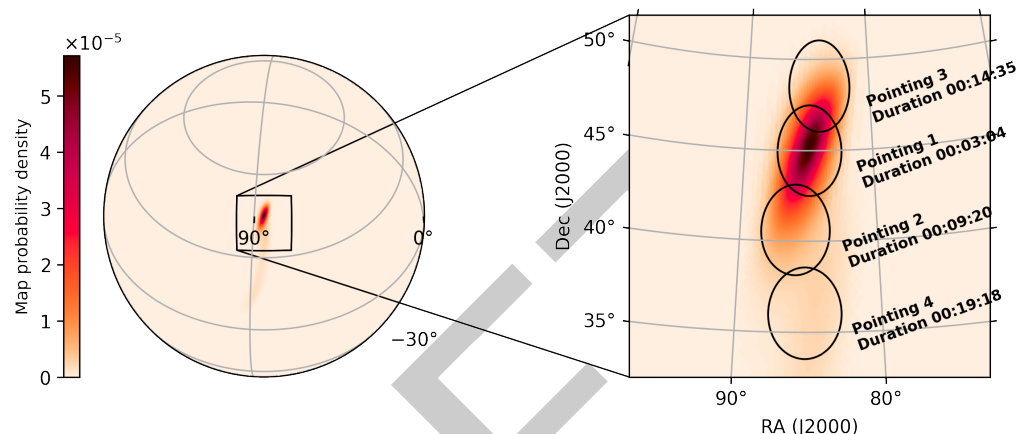


Figure 3: A follow-up coverage map for an example GW event (S250704ab). The ordering of pointings is calculated by `tilepy` and the optimal observing time at each pointing by `sensipy`.

97 AI usage disclosure

98 AI tools (GitHub Copilot, Grammarly) were used to proofread documentation and pull requests.
99 These AI-assisted suggestions were carefully reviewed and approved by the authors of this
100 manuscript. AI tools were not used in the writing of this manuscript in any capacity.

101 References

- 102 Abac, A. G., Abouelfettouh, I., Acernese, F., Ackley, K., Adhicary, S., Adhikari, D., Adhikari,
103 N., Adhikari, R. X., Adkins, V. K., Afroz, S., Agarwal, D., Agathos, M., Aghaei Abchouyeh,
104 M., Aguiar, O. D., Ahmadzadeh, S., Aiello, L., Ain, A., Ajith, P., Akcay, S., ... Bulashenko,
105 O. (2025). GWTC-4.0: An introduction to version 4.0 of the gravitational-wave transient
106 catalog. *The Astrophysical Journal*, 995, L18. <https://doi.org/10.3847/2041-8213/ae0c06>
- 107 Abbasi, R., Ackermann, M., Adams, J., Agarwalla, S. K., Aguilar, J. A., Ahlers, M., Alameddine,
108 J. M., Amin, N. M., Andeen, K., Anton, G., Argüelles, C., Ashida, Y., Athanasiadou, S.,
109 Axani, S. N., Bai, X., Balagopal V, A., Baricevic, M., Barwick, S. W., Basu, V., ... Zhelnin,
110 P. (2023). IceCat-1: The IceCube event catalog of alert tracks. *The Astrophysical Journal*
111 *Supplement Series*, 269(1), 25. <https://doi.org/10.3847/1538-4365/acfa95>
- 112 Cherenkov Telescope Array Observatory and Consortium. (2021). *CTAO instrument response*
113 *functions - prod5 version v0.1*. Zenodo. <https://doi.org/10.5281/zenodo.5499840>
- 114 Donath, A., Terrier, R., Remy, Q., Sinha, A., Nigro, C., Pintore, F., Khélifi, B., Olivera-Nieto,
115 L., Ruiz, J. E., Brügge, K., Linhoff, M., Contreras, J. L., Acero, F., Aguasca-Cabot, A.,
116 Berge, D., Bhattacharjee, P., Buchner, J., Boisson, C., Fidalgo, D. C., ... Zanin, R. (2023).
117 Gammapy: A python package for gamma-ray astronomy | astronomy & astrophysics
118 (a&a). *Astronomy & Astrophysics*, 678, A157. [https://www.aanda.org/component/](https://www.aanda.org/component/article?access=doi&doi=10.1051/0004-6361/202346488)
119 [article?access=doi&doi=10.1051/0004-6361/202346488](https://www.aanda.org/component/article?access=doi&doi=10.1051/0004-6361/202346488)

- 120 Green, J. G., Carosi, A., Nava, L., Patricelli, B., Schussler, F., Seglar-Arroyo, M., Stamerra,
121 A., Abe, K., Abe, S., Acharyya, A., Adam, R., Aguasca-Cabot, A., Agudo, I., Alfaro,
122 J., Alvarez-Crespo, N., Alves Batista, R., Amans, J.-P., Amato, E., Ambrosino, F., ...
123 Zuriaga-Puig, J. (2024). *Chasing gravitational waves with the cherenkov telescope array*.
124 <https://doi.org/10.22323/1.444.1534>
- 125 Kienlin, A. von, Meegan, C. A., Paciesas, W. S., Bhat, P. N., Bissaldi, E., Briggs, M. S., Burns,
126 E., Cleveland, W. H., Gibby, M. H., Giles, M. M., Goldstein, A., Hamburg, R., Hui, C. M.,
127 Kocevski, D., Mailyan, B., Malacaria, C., Poolakkil, S., Preece, R. D., Roberts, O. J., ...
128 Wilson-Hodge, C. A. (2020). The fourth fermi-GBM gamma-ray burst catalog: A decade of
129 data. *The Astrophysical Journal*, 893(1), 46. <https://doi.org/10.3847/1538-4357/ab7a18>
- 130 Patricelli, B., Carosi, A., Nava, L., Seglar-Arroyo, M., Schussler, F., Stamerra, A., Adelfio, A.,
131 Ashkar, H., Bulgarelli, A., Di Girolamo, T., Di Piano, A., Gasparetto, T., Green, J. G.,
132 Longo, F., Agudo, I., Berti, A., Bissaldi, E., Cella, G., Circiello, A., ... Vergani, S. (2022).
133 *Searching for very-high-energy electromagnetic counterparts to gravitational-wave events*
134 *with the cherenkov telescope array*. <https://doi.org/10.22323/1.395.0998>
- 135 Seglar-Arroyo, M., Ashkar, H., Bony de Lavergne, M. de, & Schüssler, F. (2024). Cross
136 observatory coordination with tilepy: A novel tool for observations of multimessenger
137 transient events. *The Astrophysical Journal Supplement Series*, 274, 1. <https://doi.org/10.3847/1538-4365/ad5bde>
- 139 The Astropy and Price-Whelan Collaboration, A. M., Lim, P. L., Earl, N., Starkman, N.,
140 Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A.,
141 Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson,
142 W., Kerkwijk, M. H. van, ... Contributors, A. P. (2022). The astropy project: Sustaining and
143 growing a community-oriented open-source project and the latest major release (v5.0) of
144 the core package*. *The Astrophysical Journal*, 935(2), 167. <https://doi.org/10.3847/1538-4357/ac7c74>