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REDBACK: a Bayesian inference software package for electromagnetic transients

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ABSTRACT

Fulfilling the rich promise of rapid advances in time-domain astronomy is only possible through confronting our observations with physical models and extracting the parameters that best describe what we see. Here, we introduce REDBACK; a Bayesian inference software package for electromagnetic transients. REDBACK provides an object-orientated PYTHON interface to over 12 different samplers and over 100 different models for kilonovae, supernovae, gamma-ray burst afterglows, tidal disruption events, engine-driven transients among other explosive transients. The models range in complexity from simple analytical and semi-analytical models to surrogates built upon numerical simulations accelerated via machine learning. REDBACK also provides a simple interface for downloading and processing data from various catalogues such as *Swift* and FINK. The software can also serve as an engine to simulate transients for telescopes such as the Zwicky Transient Facility and Vera Rubin with realistic cadences, limiting magnitudes, and sky coverage or a hypothetical user-constructed survey or a generic transient for target-of-opportunity observations with different telescopes. As a demonstration of its capabilities, we show how REDBACK can be used to jointly fit the spectrum and photometry of a kilonova, enabling a more powerful, holistic probe into the properties of a transient. We also showcase general examples of how REDBACK can be used as a tool to simulate transients for realistic surveys, fit models to real, simulated, or private data, multimessenger inference with gravitational waves, and serve as an end-to-end software toolkit for parameter estimation and interpreting the nature of electromagnetic transients.

Key words: software: data analysis – black hole–neutron star mergers – gamma-ray bursts – neutron star mergers – transients: supernovae – transients: tidal disruption events.

1 INTRODUCTION

Rapid advances in electromagnetic telescope sensitivity and survey capabilities are revolutionizing transient astronomy. However, to realize the full promise of the rich and large photometric and spectroscopic data sets, we need a robust toolkit for simulating what we expect to see, building and exploring our models and fitting the observations. Such advancements can enable us to ultimately learn the physics that drives these transients, optimize our survey strategies and instruments, and gain insights into the lives and afterlives of stars and the evolution of our Universe. Such a tool must also be modular and open-source, easily adaptable to an individual user's needs and efficiently maintained and upgraded.

Several iterations of open-source software have served important roles in improving our understanding of transients. For example, MOSFIT (Guillochon et al. 2018), a modular package that has been used for parameter estimation of several electromagnetic transients such as tidal disruption events (Mockler, Guillochon & Ramirez-Ruiz 2019), superluminous supernovae (Nicholl, Guillochon & Berger 2017), and kilonovae (Villar et al. 2017b). The SNCOSMO (Barbary et al. 2022), and SNANA (Kessler et al. 2009) software suites that are readily used to fit Type Ia supernovae to enable cosmological analyses (e.g. Vincenzi et al. 2024) or study the detectable rates of supernovae

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for different survey designs (e.g. Bom et al. 2024). 3ML (Vianello et al. 2015), which provides a cohesive framework utilizing existing instrument-specific software to best capture how the data is generated and perform detailed modelling of gamma-ray bursts (GRBs) across data from multiple instruments (e.g. Klinger et al. 2024). `Haffet` (Yang & Sollerman 2023), which enables data-driven reconstruction of supernova bolometric luminosity from multiband photometry enabling a more direct probe to study the explosion properties (e.g. Dong et al. 2023). NMMA (Pang et al. 2023), that provides machine-learning based 'surrogates'to radiative transfer simulations of kilonovae, enabling inference with kilonova models that include the most physics. The NMMA package also provides an interface for jointly analysing electromagnetic and gravitational-wave data such as for the first gravitational-wave observation of a binary neutron star (BNS) merger, GW170817 (Abbott et al. 2017b), enabling strong constraints on the behaviour of nuclear matter (Koehn et al. 2024).

Although these software packages have driven significant progress in electromagnetic transient astronomy, several limitations must be addressed to take full advantage of the currently available and forthcoming electromagnetic data. For example, models for explosive transients are under constant development and often make several underlying assumptions. However, these packages above are limited to a small library of implemented models and inflexible interfaces to change or add new models. This prevents detailed studies into modelling systematics or the use of the best models for any given transient. To truly leverage the data and maximally extract insights into these transients, open-source packages must come equipped with a large variety of built-in models and are routinely updated to capture the best theory has to offer. Ideally, such packages also provide a simplified interface to enable end users to drop-in replacements or modify features for inbuilt models or with minimal interaction with the source code. The last point is pertinent as this could help remove the burden on development teams to keep pace and implement developments from transient modelling, particularly in the scenario where key developers leave the field, as has been the case of some of the above packages.

Similarly, there are constant improvements to Bayesian inference techniques that are not captured by several of these packages above as they typically use at most one sampling package such as EMCEE (Foreman-Mackey 2015). It is worth noting that some of these packages are also not Bayesian, failing to provide robust estimation of the uncertainty in estimating parameters from any fit. The lack of multiple implemented packages prevents cross-sampler validation (a valuable tool to determine if results are robust) or leveraging the benefits of different samplers, such as evidence calculation for Bayesian model selection. Other sampling algorithms can also be better tuned for specific transient problems (dramatically improving sampling wall-clock time), allowing for the use of the best tools for the task at hand. Similarly, there are also several practical benefits to having access to multiple different sampling algorithms, such as a better ability to capture multimodal posterior distributions or parallelization.

A critical validation step in any inference workflow is to test how models perform across the parameter space and tests with complete end-to-end analyses, that is, from simulation to fitting workflow. While the above packages have been tested in various ways, they do not all provide a cohesive framework to both simulate model outputs (for a variety of different formats such as flux density or magnitudes or bolometric luminosity) and realistic observations (for real surveys or target-of-opportunity, ToO, observations) and fit them. This is a limitation of many of these packages, as we can only truly determine bias in parameter estimation by performing simulations with the same tools we use to fit and control the data generation process. Properly capturing the data-generation process is also instrumental for accurate transient analyses. The bulk of the above packages can only work with the simple assumption of a Gaussian likelihood (i.e. the noise distribution is Gaussian around the true input model). This simple noise assumption is known to be incorrect for the majority of current and projected future observations and will undoubtedly cause problems as we continue to observe each transient more frequently and with higher fidelity.

Higher fidelity and more extensive observations of transients also open up another challenge to maximally leverage our data: astronomical events are now readily observed in multiple ways. An example already described above was the multimessenger gravitational-wave discovery of the BNS merger GW170817 (Abbott et al. 2017b), which had an afterglow observed across the electromagnetic spectrum (Hallinan et al. 2017; Alexander et al. 2018; Fong et al. 2019; Lamb et al. 2019a), a kilonova from near-infrared to ultraviolet (UV, Pian et al. 2017; Smartt et al. 2017; Villar et al. 2017b), very-long baseline interferometry (VLBI, Mooley et al. 2018), and gravitational-wave data (Abbott et al. 2017a). While packages such as NMMA can perform a joint analysis of the gravitational wave and electromagnetic photometry, they fail to include the spectrum or VLBI data. Although these constraints could be folded through after the photometric and gravitational-wave analysis, you then lose the significant benefits offered by the full Bayesian framework (Gianfagna et al. 2023; Ryan et al. 2023). The opportunity to jointly fit the spectrum and photometry also provides a holistic look into the properties of the transient, where the photometric and spectroscopic analyses can often tell a contradictory story. Moreover, a flexible framework for combining datasets could also enable Bayesian hierarchical modelling, a powerful technique to uncover the properties of a population.

Here, we introduce REDBACK, an open-source, end-to-end Bayesian Inference software package for simulating and fitting electromagnetic transients. REDBACK provides an object-orientated PYTHON interface to over 12 sampling software and over 100 models for several different electromagnetic transients. Furthermore, REDBACK provides a simplified interface to download data for multiple transients from various catalogues, handling processing to a homogeneous format, removing the burden from end users to fully understand the peculiarities of different data sources. For all models implemented in REDBACK or user-provided models, end users of REDBACK can simulate transients for actual surveys such as the Large Synoptic Survey of Space and Time (LSST, Ivezić et al. 2019) and Zwicky Transient Facility (ZTF, Bellm et al. 2019), or a custom survey, alongside ToO observations for any collection of observatories/telescopes. Users can fit this simulated, private, or publicly available data through Bayesian inference alongside combinations of different data types such as VLBI data, gravitational-wave data, and a transient spectrum and photometry. REDBACK is also built on modern PYTHON, with many adopted practices to aid continual development, continuous integration, and an extensive library of unit tests and examples which ensure that the primary features of REDBACK remain stable through future development.

REDBACK provides several advantages over other software packages and mitigates the aforementioned issues:

(i) An extensive library of inbuilt models and a simple interface for users to add their own. Several models implemented in REDBACK are direct improvements to previous models or model transients one can not model in other packages.

(ii) An engine to simulate realistic transients for surveys and ToO observations and perform inference, that is, a tool to validate an entire inference workflow or optimize surveys.

(iii) A tool to access and process photometric data alongside auxiliary data such as sky position from many publicly available catalogues and brokers.

(iv) A modular and flexible interface, users can swap likelihoods, models, and plotting without ever modifying the source code. Alternatively, change how existing aspects of REDBACK function by passing their own function to existing functional modules.

(v) Simplified interface (replace a string) to over 12 different open-source samplers, enabling cross-sampler validation or use of samplers better tuned for transient inference or have additional capabilities such as multiprocessing.

(vi) Modern PYTHON software development practices, including continuous integration and unit-testing to ensure core software features remain functional, even if core developers leave the field.

This paper is intended to describe the capabilities and mark the version 1.0 release of REDBACK. REDBACK is installable via `pip` and available at https://github.com/nikhil-sarin/redback. We note that REDBACK has been open-source and distributed under the GPL licence since 2022 March. Earlier versions of REDBACK have already been used in previous publications, which we refer the interested reader to see some of the use cases for REDBACK (Sarin, Lasky & Ashton 2020a, b; Sarin et al. 2021, 2022a, b; Sarin & Lasky 2022; Levan et al. 2024; Schulze et al. 2024; Omand & Sarin 2024; Rosswog et al. 2024; Sarin & Metzger 2024).

This paper is structured as follows: in Section 2, we describe the design objectives of REDBACK, how the different parts of the software interact, and the three typical workflows we expect REDBACK to be used for. In Section 3, we describe the different functional modules in REDBACK and how they are used in various workflows. In Section 4, we showcase a new scientific analysis enabled by REDBACK; the joint fitting of the spectrum and photometry of a kilonova. In Section 5, we briefly describe features in REDBACK that will be added in future releases and conclude in Section 6. In the appendix, we showcase the general interface with detailed code snippets of how to use REDBACK, alongside more detailed examples. In particular, in Appendix A, we show how to download and process data, set up the inference workflow, several plotting methods and simulate transients. This basic interface is followed by more detailed examples in Appendices B and C where we demonstrate the different capabilities of REDBACK. In particular, we first show how REDBACK can be used to jointly analyse a multimessenger BNS signal with X-ray and gravitational-wave data and then to fit different types of real electromagnetic transients.

2 DESIGN AND IMPLEMENTATION

A core design objective for REDBACK is to be truly modular, with the flexibility to adapt to the different requirements/preferences of end users and for users to use different parts of the software without requiring additional overhead or modifying the source code.

Second, REDBACK must be flexible to both serve as a workhorse in expert workflows in transient astronomy and as an accessible tool for newcomers to the field. In particular, while advanced users can be expected to modify or interact more directly with various aspects of the REDBACK software, novice users must be able to use all aspects of REDBACK from data collection, simulation, and fitting with just a few lines of code.

Third, where possible, we also aim to leverage other open-source software to reduce the burden on core developers of REDBACK and better keep pace with developments in other areas. For example, we are tightly integrated with the BILBY framework for sampling. This provides a simplified interface for end users to multiple open-source samplers and access to a large and active development team that maintains BILBY and different sampling packages.

To address these design objects, all primary functional modules of REDBACK are built as PYTHON classes or functions. These functional modules can be readily modified by end users via keyword arguments or replaced entirely within a workflow with other functional modules implemented in REDBACK or something the user provides. This modularity extends to primary modules described below and to more practical features such as plotting or where REDBACK outputs are stored.

This modular interface addresses some critical limitations with previous packages described in the introduction. For example, all REDBACK models are implemented as callable PYTHON functions. These models also have minimal dependencies and do not depend on other aspects of the software, enabling users to evaluate a model as they would with any other PYTHON function. Moreover, all models in REDBACK can produce different outputs, for example, bolometric luminosity, a spectrum, a flux, a magnitude, a flux density, or auxiliary information such as the photospheric velocity. For many REDBACK models, users can also change critical assumptions of the model, such as the spectral energy distribution (SED), by passing in a different keyword argument. This allows end users to generate model outputs for any arbitrary input, better understand the effects of different parameters, or change modelling assumptions without modifying the source code. It also facilitates holistic studies by fully considering various observations, for example, spectrum and photometry. End users can also replace a model with their own PYTHON function, keeping intact all of the other functionality of REDBACK, making it significantly easier to use new and improved models with REDBACK.

Advanced users can also change the likelihood, that is, their assumptions about the data-generating process or the prior distribution on model parameters with different implementations in REDBACK or their implementation, again, without needing to change the source code. This enables advanced users to adapt their fitting or simulation workflows for more sophisticated analyses. At the same time, such choices are made by default for novice users, who can perform such tasks with minimal domain expertise. Moreover, different sampling algorithms and software packages can be used with minimal effort by simply changing the string referring to a sampler. This addresses the limitations of previous packages with inflexible interfaces for users to change assumptions about how the data are processed or generated and leverage the best samplers for the respective task.

In Fig. 1, we show the different functional modules of REDBACK, implemented as either a PYTHON subpackage, a PYTHON module, a PYTHON class or as a PYTHON function and how they interact for the three most common workflows we expect this software to be used for.

A: Fitting a real transient. We anticipate that one of the most common use cases for REDBACK will be fitting data of a real astrophysical transient. This workflow typically involves getting data from one of the catalogues using the `get_data` subpackage in REDBACK, or users can provide private data. The user will then use this data to create a specific `Transient` class object from the transient subpackage, which loads the data in a homogeneous format and can be used for plotting the data or additional processing,

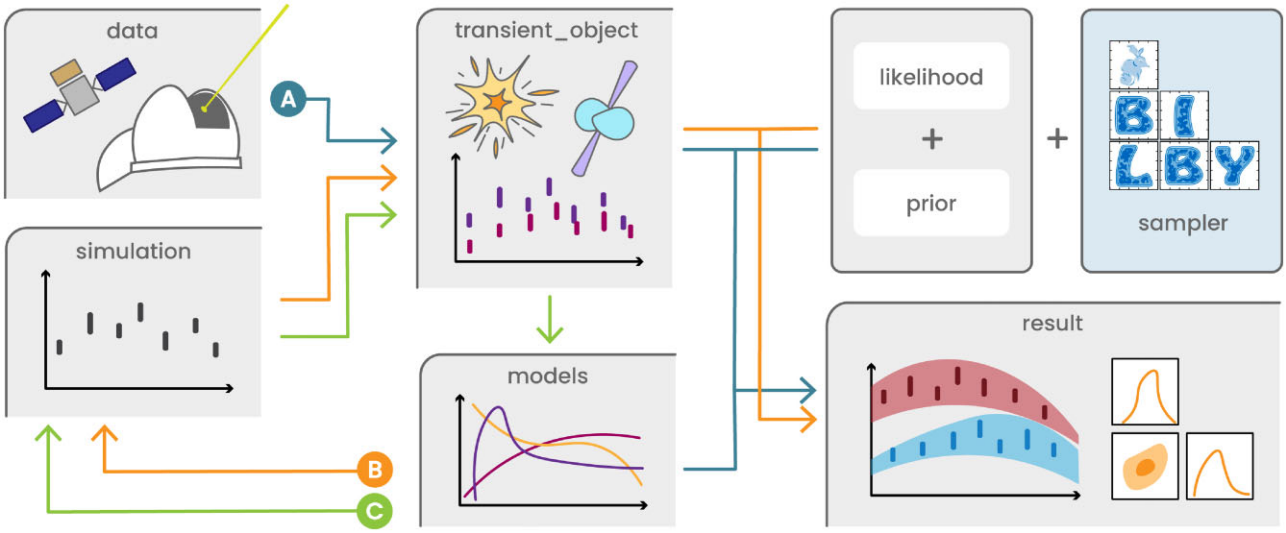

Figure 1. Flowchart showcasing the different subpackages, modules, and classes of REDBACK and how they interact for different workflows.

such as converting flux data to luminosity. The user then passes this `Transient` class object along with a string referring to a model from `transient_models` subpackage or their own PYTHON-wrapped model, an instance from the prior class, an instance of the likelihood class and a string referring to a sampler that is available in BILBY (Ashton et al. 2019; Romero-Shaw et al. 2020). This will perform fitting through Bayesian inference and obtain a `result` class object. The `result` object contains the posterior, and other properties such as the Bayesian evidence. This `result` class can also be used to make plots such as the fitted light curve, the corner plot, or the cumulative distribution function of all parameters, which are internally handled by a separate plotting module. We emphasize that for the novice user, choices like the likelihood, prior, sampler choice and plot aesthetics are made by default, but more advanced users can change these as they desire.

B: Fitting a simulated transient. Many users will also fit simulated data to verify the inference workflow or predict constraints from mock observations. In this workflow, the user would start with a model from `transient_models` or supply their own model. Then, use the `simulation` module to create synthetic data. After the creation of this simulated data, the workflow for fitting is the same as workflow A.

C: Simulating a transient or a population of transients. Users may also wish to create a population of transients, for example, to understand how many afterglows LSST will see in a year or to understand the selection effects of surveys. These workflows require choosing a model from `transient_models` or supplying a PYTHON-wrapped model and passing this to the `simulation` module alongside a `prior` object which describes the distribution of each parameter in the model that constitutes the population. Complex prior constraints can be placed on this population through the use of `prior_constraints` functional module.

The above briefly describes how different aspects in REDBACK interact for different workflows. We now give a general overview of the REDBACK software and describe each functional module's capabilities in detail and how it can be modified.

3 SOFTWARE PACKAGE OVERVIEW

REDBACK is built predominantly on a class structure and almost every aspect of the software exists as an independent PYTHON class. Here, we describe each of these different functional modules and their primary functionality. We stress that these modules are standalone and can be used independently to adapt to different needs and workflows, or modified via keyword arguments or replaced to provide additional functionality.

3.1 Data interface

REDBACK provides an interface to download and process data from multiple catalogues through the `get_data` subpackage. In particular, this includes the flux, flux density or the photon arrival time data for GRBs detected by the *Neil Gehrels Swift Observatory* available at Swift Data Centre (Evans et al. 2010), the magnitude or flux density data of transients from ZTF from `LASAIR` (Smith et al. 2019) or FINK (Möller et al. 2021) which in the future are expected to also host transient light curves from LSST (Ivezić et al. 2019), the archival GRB data from Burst and Transient Source Experiment (BATSE) (Fishman et al. 1994) and compilation of optical transient light curves available at the Open Access Catalog (OAC, Guillochon et al. 2017).

For each of the above catalogues, the `get_data` module provides a one line interface to download and process the data into a PANDAS data frame and save it as a human-readable file in an appropriate location to integrate with the rest of REDBACK. This module also attempts to find additional metadata such as the redshift of the transient, the GRB photon index, T90 among other properties and process the data to add additional attributes such as the integrated flux, flux density and their respective errors.

As the data are stored as human-readable file and readable as a PANDAS data frame, the user can easily add additional private data or verify and modify any erroneous data. The `get_data` can be used independently of all other parts of REDBACK and may be used to simply process a large quantity of transient data from public archives.

3.2 Transient classes

The primary unifying module of REDBACK are the `Transient` classes that are available through the `Transient` subpackage. These are separated into two main types, a generic transient class which is applicable for any type of transient and an optical transient class. These classes serve as parent classes for five other classes; `prompt`, `afterglow`, `kilonova`, `supernova`, and `tde` which provide a more seamless interface for the specific type of transient, any additional processing such as converting the flux data to a luminosity and modify some default behaviour, such as labels for plotting, where plots are saved etc. We note that the `afterglow` class is further split into a short and long GRB class but these are functionally equivalent and only differ in locations of metadata.

For all transient classes, we provide one-line class methods to load the data from different catalogues obtained via the `get_data` module, or from the `simulation` module (described in Section 3.4). The `Transient` objects can also be initialized independently of any class method by specifying the observed properties. In Appendix A2, we show how to initialize these `Transient` objects for different workflows.

All transient objects also have two important attributes; `data_mode` and `use_phase_model`. The former is an attribute which dictates what REDBACK assumes to be the mode of data for the transient, for example, `magnitude` for magnitude data, while the latter is a Boolean switch which dictates whether the transient has observed times in reference to a known start time (as usually the case for an afterglow) or is in Modified Julian Days (MJD) without a reference (as usually the case for most other transients). Again, these attributes affect choices such as the labels for plotting and where plots are saved but also in some cases the default likelihood used by REDBACK.

3.3 Models

While the most desirable method would be to confront observations with the best models that include the most physics (typically hydrodynamical and radiative transfer simulations), such models are not tractable for fitting given the demanding computational requirements of Bayesian inference (each model must be evaluated over a range of parameters at least $\mathcal{O}(10^4)$ times to fit a typical transient). To be tractable for inference, all models in REDBACK are either analytical, semi-analytical, or surrogates built with machine learning from numerical simulations. The latter are provided by another standalone software package `redback_surrogate` that is available independently but we consider as part of the REDBACK software stack. Here, we describe the models for various different transients available in REDBACK and how they can be modified.

To remain true to our driving aim of modularity, all models are callable PYTHON functions and can be called on an arbitrary set of values with minimal dependencies. These functions can all be easily modified through the use of dependency injection (described in Section 3.3.1) without needing modify the REDBACK source code or replaced entirely within the rest of the workflow with a user-provided model. Most REDBACK models can provide outputs in different formats, for example, luminosity, integrated flux, magnitude or flux density enabling them to be used to fit any type of data format. For magnitude and integrated flux data, REDBACK will integrate the spectrum and calculate the band pass magnitude/flux. This behaviour could be easily modified to use a flux density to magnitude conversion to further alleviate computational demands. We note that this behaviour is enabled by default for afterglow models where the effect of assuming a flux density to magnitude conversion as opposed to integrating a band pass is minimal.

3.3.1 User-defined models and dependency injections

As alluded to above, REDBACK is built on a flexible interface which allows the user to use their model with all other aspects of REDBACK. The only requirement is that the user-defined model is a PYTHON function with the first input being the time of observations and the output being the desired output, for example, `flux_density` if the user wants to fit `flux_density` data. Once written, this PYTHON function can be passed to different modules of REDBACK, either to simulate data or to fit some observations. This workflow also enables users to combine REDBACK models, replacing each of the individual models with their own model or a different REDBACK model.

Many REDBACK models use additional keyword arguments to dictate the precise physics of the model. Some keyword arguments are Boolean switches to turn on/off certain physics, but others require a more complex object. This pattern is often referred to as *dependency injection*, which allows us to build a more flexible interface. We implemented the dependency injection pattern to handle features such as the SED, or the conversion from inspiral parameters to kilonova parameters, photosphere, or the cosmology used to associate a redshift to a luminosity distance. By default, every model has these choices set internally but users can make changes to the model by simply using a different object as a keyword argument which could either be an instance of a REDBACK class or a class they write themselves. Through these model modifications and dependency injections, many REDBACK models can be extended and have their physics changed without ever modifying the source code, alleviating the burden on the end user to make a change to a model. However, as the interface is modular, a REDBACK model can also just be replaced entirely.

3.3.2 Specific transient models

Broad-band GRB afterglow. GRBs are typically followed by lower energy broad-band emission referred to as afterglow (e.g. Sari, Piran & Narayan 1998). The broad consensus is that the afterglow is a product of the relativistic jet interacting with the ambient interstellar medium, an interaction that produces synchrotron emission. However, there are several aspects of afterglow models that are ill-understood, such as the jet structure, that is, the distribution of energy as a function of angle, or the role of reverse shocks, or additional emission components, or energy injection.

REDBACK provides an interface to several different afterglow models. For example, the different jet-structure models implemented in `afterglowpy` (Ryan et al. 2020), and implementations of several other physical models described in the literature (Sari et al. 1998; Sari, Piran & Halpern 1999; Gottlieb, Nakar & Piran 2018; Lamb, Levan & Tanvir 2020; Lamb et al. 2021). For each of the models, users can make additional modifications to the physics such as the inclusion of jet spreading, inverse Compton emission, and energy injection or more specific settings such as the resolution of the integration scheme. For other models, users can choose the exact jet-structure profile, whether the interstellar medium is at a constant density or a wind-like medium etc., and whether the shock is refreshed. All these modifications are handled through additional optional keyword arguments in the PYTHON function which allows

the advanced users to make changes as they wish while more novice users can avoid having to make these decisions.

Alongside these physically motivated models we also include some purely phenomenological broken power-law models with different degrees of components. In total, REDBACK includes 21 physically motivated afterglow models in addition to the five phenomenological models, providing coverage of the different physical assumptions involved in afterglow modelling and to test the robustness of inferred models across different modelling assumptions.

Broad-band kilonova afterglow. Similar to a GRB afterglow, there also exists an expectation for synchrotron emission when the slower moving kilonova ejecta interacts with the ambient interstellar medium. However, unlike models for the GRB afterglow, where we are aided by decades of observations, there are currently no confident detections of a kilonova afterglow. Nevertheless, we provide an interface to several different kilonova afterglow models described previously in the literature (Nakar & Piran 2011; Sarin et al. 2022b) and make modifications to some of GRB afterglow models described above to be more suited for a kilonova afterglow (e.g. Gottlieb et al. 2018; Ryan et al. 2020). In the future, we will add kilonova afterglow models more representative of the ejecta distribution we see in numerical simulations (Kathirgamaraju, Giannios & Beniamini 2019; Nedora et al. 2021).

Kilonovae. The revolutionary observations of AT2017gfo (e.g. Abbott et al. 2017b, a; Arcavi et al. 2017; Kasen et al. 2017; Coulter et al. 2017; Villar et al. 2017a) provided definitive evidence of a thermal transient powered by *r*-process nucleosynthesis. However, despite the extensive observations and significant theoretical model development, many aspects of kilonovae remain uncertain. In REDBACK we provide implementations of 18 different kilonova models which range in complexity and implemented physics. Many aspects of these models such as the distribution of ejecta mass or the recipe to relate the BNS or neutron star black hole (NSBH) parameters to kilonova parameters can be changed through the use of dependency injection (described in Section 3.3.1).

The simplest kilonova model implemented in REDBACK is a one component kilonova model (Villar et al. 2017b). Although minimal in parameters and quick to evaluate and therefore fit to observations, this model has already been shown to be unsuccessful in explaining multiple aspects of kilonovae observations. To address the inability of such a simple model to explain observations, we also provide implementations of two- and three-component kilonova models following Villar et al. (2017b) and implementations of MOSFIT kilonova models (Cowperthwaite et al. 2017; Villar et al. 2017b). These models all effectively ignore the dynamics of the ejecta, assuming the entire ejecta component is moving at one velocity, an assumption that is likely incorrect. We therefore also provide models where the ejecta is distributed into shells which expand homologously, similar in spirit to the model presented in Metzger et al. (2010) and Metzger (2019). Alongside this, we also provide an interface to the heating-rate kilonova models (Korobkin et al. 2012; Hotokezaka & Nakar 2020; Dorsman et al. 2023), which allow the user to describe the velocity and opacity distribution themselves.

The above models all have parameters that describe the kilonova ejecta properties itself, that is, the mass and velocity of the ejecta. However, it has become increasingly common for kilonova models to be built upon the BNS or NSBH parameters which are then related to the ejecta parameters with a series of recipes from numerical relativity simulations. We provide several implementations of these models including models for BNS and NSBH, including, for example, the BNS model implemented in MOSFIT (Nicholl et al. 2021) which includes additional physics such as shock cooling to describe the early optical light curve (Piro & Kollmeier 2018), or implementations of models presented in Coughlin et al. (2019).

While the above models are all semi-analytical, we also provide three models that are machine-learning surrogates to numerical simulations. These surrogates are provided in the optional package `redback_surrogate` (described in more detail below), and are implementations of surrogates built in `KilonovaNet` (Lukošiute et al. 2022). In the future, we will continue to add more kilonovae models (Banerjee et al. 2020; Korobkin et al. 2021) and allow greater flexibility to existing models such as changing the calculation of the thermalization efficiency.

Supernovae. REDBACK contains many supernova models of varying levels of complexity. Most of the models have both a bolometric implementation and an implementation for multiband photometry. This setup allows the user to fit bolometric luminosity, magnitude, integrated flux, or flux density data. Similar to MOSFIT where physics such as the interaction process, photosphere, and SED can be swapped, REDBACK supernovae models can do the same since they are implemented using dependency injection. For all models, these aspects are chosen by default corresponding to the physics implemented but can be swapped without modifying the source code for a different module to capture different physics.

The simplest model, such the exponential-power-law model, is purely phenomenological and built upon no physics in terms of luminosity but assumes a diffusive photosphere with a temperature floor, and a blackbody SED. Other models are more physically motivated such as several variations of the Arnett (1980, 1982) model for ^{56}Ni-powered supernovae including a version which also incorporates shock cooling, a version that incorporates line absorption for modelling Type Ia supernovae, and a version which incorporates synchrotron emission for modelling Type Ic supernovae. Then there are models for circumstellar (CSM) interaction powered supernovae (Chatzopoulos et al. 2013; Villar et al. 2017a; Jiang, Jiang & Ashley Villar 2020) as well as a mix of CSM and ^{56}Ni power. We also include other models similar to those available in MOSFIT, such as the `basic magnetar`, `slsn`, and `magnetar + nickel` models (Nicholl et al. 2017; Guillochon et al. 2018), as well as new models which include non-vacuum dipole spin-down (Lasky et al. 2017) and ejecta acceleration from the pulsar wind nebula (Sarin et al. 2022b; Omand & Sarin 2024).

Again, through the use of dependency injection, these models can be easily modified to capture different physics. We also provide an interface to supernova models implemented in SNCOSMO (Barbary et al. 2022), which further amplifies the library of supernovae models available in REDBACK. In future releases, we will be adding surrogate models to hydrodynamical/radiative transfer simulations of interaction powered supernovae, among other models.

Engine-driven transients. Distinct from the magnetar-driven supernovae models described above, we also provide a general class of magnetar driven models. Such models aim to capture the emission that would be produced in a magnetar-driven kilonova or a magnetar-driven fast blue optical transient (Drout et al. 2014; Arcavi et al. 2016). Several different models are implemented such as those that capture the dynamical evolution of the nascent neutron star (Sarin et al. 2022b) or the dynamical evolution of the ejecta (Metzger & Piro 2014; Sarin et al. 2022b). We also include models with relativistic considerations (Yu, Zhang & Gao 2013; Sarin et al. 2022b), non-vacuum dipole spin (Lasky et al. 2017), and models with variation in their treatment of the thermalization efficiency or gamma-ray leakage (Wang et al. 2015; Sarin et al. 2022b). We also include an implementation of the trapped magnetar model that has been suggested as an explanation for the enigmatic fast X-ray transient,

CDF-S XT1 (Sun et al. 2019). In the future, we will add models to capture energy injection from fallback accretion onto a central black hole.

Millisecond magnetar. Ever since the launch of *Neil Gehrels Swift Observatory* (Gehrels et al. 2004), the origin of the X-ray afterglows of GRBs has been a long source of debate. In particular, features referred to as the internal and external plateaus are difficult (although not impossible) to explain within the standard picture of synchrotron emission from a jet interacting with the ambient medium. These plateaus are readily explained as the bare or processed spin-down from a highly magnetic, rapidly rotating newly born neutron star, that is, a millisecond magnetar.

In REDBACK, we provide several implementations of millisecond magnetar models, such as early models which assumed the neutron star only spun down through vacuum dipole radiation (Zhang & Mészáros 2001; Rowlinson et al. 2013), to extensions that included a variable braking index (Lasky et al. 2017). We also provide models which include a collapse time (Sarin et al. 2020a), to capture light curves when the neutron star undergoes a delayed collapse to a black hole. The above models all implicitly assume that the observed emission is a constant factor of the real spin-down power of the neutron star. In reality, it is difficult to assume that this factor will be constant in time and be the same for different environments/ejecta properties. To capture this behaviour, some other models have been developed which account for this changing efficiency by accounting for the radiative losses at the interface between the jet and interstellar medium (Dall'Osso et al. 2011; Sarin et al. 2020b), these models are also implemented in REDBACK. Similar to the extension in physics of how emission is generated, the assumption that a neutron star spins down with a constant braking index is also simplistic, we therefore include models where the braking index is a time-dependent value conditioned on the evolution of the angle between the spin and magnetic field axes (e.g. Şaşmaz Muş et al. 2019; Sarin et al. 2022b).

Tidal disruption events. Tidal disruption events occur when a star in a galactic nucleus approaches a supermassive black hole (SMBH) and is sufficiently close to be torn apart by tidal forces (Hills 1975). Many models for tidal disruption events exist which have different assumptions of how the optical/UV light curve is produced. For example, some models assume that the optical/UV light curve directly tracks the fallback rate (Guillochon & Ramirez-Ruiz 2013; Guillochon et al. 2017; Mockler et al. 2019), consistent with the light-curve decay slope of $L \propto t^{-5/3}$ expected for complete disruptions (e.g. Guillochon & Ramirez-Ruiz 2013). Other models assume that the disrupted material does not circularize rapidly and instead the light curve is powered by stream–stream collisions (Piran et al. 2015; Ryu et al. 2020, 2023). Recent numerical simulations have shown that disrupted material does indeed circularize rapidly (Steinberg & Stone 2024) but this need not lead to rapid feeding of the SMBH, instead the material forms a quasi-spherical pressure supported envelope rather than in an accretion disc (Metzger 2022).

Motivated by these different assumptions, in REDBACK, we provide two primary sets of models; the cooling envelope model described in Metzger (2022) and Sarin & Metzger (2024), which models the optical/UV emission from a cooling envelope and a more fallback rate inspired model similar to MOSFIT (Guillochon et al. 2018; Mockler et al. 2019). In future versions, we will add models that describe the light curve from stream–stream collisions and surrogates that directly emulate the light curve produced by radiative transfer simulations.

Shock-powered models. The emission produced via shocks is diverse and an important ingredient for many different transients, such as the early cooling that may occur in a supernova or kilonova ejecta (Piro & Kollmeier 2018), the shock powered emission when a blastwave interacts with the preceding material such as supernova explosions with CSM interaction (Margalit 2022; Margalit, Quataert & Ho 2022). Or the synchrotron emission produced in mildly relativistic blast waves with both thermal and non-thermal electrons (Margalit & Quataert 2021). In REDBACK, we provide an individual model for each of these processes, to be used independently or added onto any other REDBACK model.

Prompt gamma-ray burst. The mechanism that produces the high-energy gamma-ray emission in GRBs is unclear. However, the prompt emission light curves of GRBs are often analysed to look for signatures of periodicity (Hübner et al. 2022; Chirenti et al. 2023), lensing (Paynter, Webster & Thrane 2021), or to characterize the observations into different GRB subtypes. In REDBACK, we provide five models for GRB light curves to facilitate this research.

3.3.3 General purpose models

Generic models. While physical intuition is often the highest priority when performing inference, sometimes we require a model that is robust, flexible and will fit all our observations. Such models can often form the basis of more physically motivated models or just be used to directly gain insight into the population. In REDBACK, we provide several phenomenological models to address this aim, from models which mimic a Gaussian rise, to an exponential rise and power law decay, to broken power laws with one to six components. As these models have no physics, they are often orders of magnitude faster to evaluate and fit than the physical models described above, making them particularly practical as a way to screen transient candidates.

REDBACK surrogates. All of the models described above rely on an analytical or semi-analytical model prescription for the physics dictating the light curve. Although such models are incredibly useful for getting insight into different transient phenomena, they likely make simplified assumptions which may not be suitable to draw accurate inferences into observations. In an independent package, `redback_surrogate`, which has a direct interface to REDBACK, we provide a library of models which are machine learning surrogates to numerical simulations. At present these models are restricted to surrogates of kilonovae simulations (Kasen et al. 2017; Bulla 2019; Lukošiute et al. 2022). All models in `redback_surrogate` seamlessly integrate into REDBACK and can be used like any other model implemented in REDBACK. In future releases, we will provide surrogates for hydrodynamical/radiative transfer simulations of many different transients as well as an interface to build your surrogate from a grid of simulations.

Joint afterglow/kilonova/supernova. Observations of supernovae in afterglows (Zeh, Klose & Hartmann 2004; Greiner et al. 2015; Cano et al. 2017) and more recent infrared excesses consistent with a kilonova in some GRBs (Tanvir et al. 2013; Lamb et al. 2019b; Rastinejad et al. 2022; Levan et al. 2024) have motivated jointly fitting the broad-band afterglow alongside a kilonova or supernova component. In REDBACK, we provide three such joint models to enable joint fitting. In particular, a top-hat afterglow with an Arnett model, to jointly fit a wide variety of GRBs with supernovae, and two models for jointly fitting a kilonova, one using a two-component kilonova following Villar et al. (2017b) and another following the heating-rate model (Hotokezaka & Nakar 2020) with a simple top-hat afterglow.

We note that to keep a consistent data generation method, these models can only be fit in flux density, requiring the assumption that optical bandpass magnitudes are approximately equivalent to

the flux density at the bandpass effective wavelength. We further emphasize that these models are simply adding the prediction of the two emission processes and do not capture the complicated physics, for example, the interaction of the jet with the ejecta that may significantly alter the overall light curve (Klion et al. 2021; Nativi et al. 2021). We also note that while the above options are limited in variety, the choice is motivated by both the simplicity (less parameters to fit) and flexibility of the models. Users of REDBACK can replace each of the individual components with a different model implemented in REDBACK or their own model. We provide an additional, simple joint model interface that enables users to use any other REDBACK afterglow or kilonova/supernova model, only requiring the user to pass a string referring to the model they wish to use.

Gaussian process base model. While the large diversity of models in REDBACK offers a lot of opportunity that one model might explain observations sufficiently well. Transient phenomena is quite often too complicated, and often the data we observe has underlying processes, for example, periodicity, correlated noise or unmodelled physics that can not be captured analytically or not understood a priori. To provide even more flexibility and as a better estimate of uncertainty and fitting procedure in the presence of correlated noise, we provide a generic interface to Gaussian processes in REDBACK. In particular, every model in REDBACK can be used as a mean model for Gaussian process kernels implemented in `George` (Foreman-Mackey 2015) and `celerite` (Foreman-Mackey et al. 2017).

Phase and attenuation models. All REDBACK models are written with the assumption of no attenuation and that the transient time observations are since the transient started (i.e. that the time of the explosion is known). In practice, these assumptions are mostly incorrect. Therefore, we provide an interface which for all REDBACK models can make the time in reference to an unknown start time (which can be added as a parameter to sample) and/or add attenuation which can be added as a parameter to be estimated by sampling. The attenuation is handled through the EXTINCTION package (Barbary 2016). We note that REDBACK assumes all photometry has already been corrected for Milky Way extinction before creating a `Transient` object. However, if not, the user can do this through the EXTINCTION package alongside online resources to gather the Milky Way extinction along the line of sight of the transient.

Acknowledgement of models. Many of the models implemented in REDBACK are implementations of models that have been described previously in the literature or exist as an interface to another open-source package. To ensure these previous works are adequately acknowledged and facilitate development we provide a simple one line attribute to all models that will provide a reference to the NASA ADS page for the paper describing the model or the software that originally implemented this model.

3.4 Simulation

A key requirement for inference workflows is the ability to test pipelines on realistic synthetic data. To wit, we have created a simulation module in REDBACK to create light curves for transients that can be loaded in a transient object and used in inference. Specifically, we provide three classes.

(i) A generic simulation interface that can be used to create simulated data for any type of transient. In this module, the time, observed filters/frequencies are sampled randomly from user inputs and added to a user-specified noise level. This generic interface can be used for any REDBACK model and is appropriate for generating ToO style of observations rapidly.

(ii) A more detailed simulation interface specifically for optical transients to be used for producing light curves from real or user-generated surveys/telescopes. Specifically, here we use official table of pointings for ZTF and the Vera Rubin Observatory (provided in REDBACK), which describe the pointings of the telescope, the limiting magnitude, cadence of filters, and other properties. Users can also build a pointings table with minimal inputs and design their own survey or provide a table of pointings from an survey not implemented in REDBACK. This allows any REDBACK or user-provided model to be used to generate realistic survey light curves and not only validate their inference methodologies but also understand constraints from survey light curves or optimize survey design.

(iii) A full survey, here a user provides a rate, a survey duration and a REDBACK model and prior (described in detail below) and a full survey is generated with events drawn according to the rate, placed isotropically in the sky and uniformly in comoving volume. The detected/not-detected events are tracked and this can be used to understand the detectable fraction of events and how that is affected by the population properties of the transient and survey strategy.

We note that we assume a circular field of view for simulating real surveys in REDBACK. This is incorrect for surveys such as ZTF, which has a rectangular field of view and a circular field of view could underestimate the rate of transient detections if adopting a circular field of view. However, this approximation is likely not a concern, in ZTF, the fields are fixed to the same sky coordinates with no dithering, which provides uniformity and more accessible reduction and background subtraction. Nevertheless, the transients landing on the gaps between the CCD quadrants are consistently lost. This results in an ≈ 15 per cent loss of the effective area. In REDBACK, we approximate the 47 sq deg rectangular field of view of ZTF as a perfect inner circle of 36 sq deg, corresponding to a loss of ≈ 20 per cent, which is a reasonable approximation for most studies given significant uncertainties on rates and source properties. For, LSST, this is not a concern as the Rubin field of view can be well approximated as a circle. We will improve the treatment of different surveys' focal plane geometry in future releases. This `simulation` interface can also be used to optimize survey strategies and design for different transients or specific science goals.

3.5 Inference

The key aim of REDBACK is to enable Bayesian inference on electromagnetic transients. For inference, REDBACK leverages the interface to BILBY, which provides a wrapper to many open source sampling software. With this interface a user of REDBACK, simply needs to (1) specify an implemented sampler as a string (16 samplers are implemented at time of writing), (2) write a prior (or use the default for the model), (3) specify a likelihood (chosen by default unless specified), and then (4) fit a model. In this paper, we assume familiarity with Bayesian inference but we refer readers who are beginning in this field to Mackay (2003), Hogg, Bovy & Lang (2010), Ashton et al. (2019), and references therein.

3.5.1 Likelihoods

Likelihoods in REDBACK are chosen by default and apart from the exception of photon count data (which uses a Poisson likelihood), are by default, Gaussian. However, the modular interface means that users can change the likelihood used with one line of code

to another REDBACK-implemented likelihood (there are several to choose from) or write their own and use that instead. This flexibility enables REDBACK to be useful to both advanced users who wish to model the likelihood more accurately and users who simply wish to fit a transient.

3.5.2 Priors

To obtain a posterior in Bayesian inference, we require a prior. For all REDBACK implemented models, we provide a default prior, this prior is typically broad and uninformative. REDBACK priors are written in the same way as BILBY priors and are effectively a dictionary with keys corresponding to each prior. Many prior distributions are implemented but users can also implement their own which they either write mathematically or provide a grid of the prior that can be used to build an interpolant. REDBACK also provides access to conditional priors to write priors on parameters that depend on one another. Many astrophysical models also have constraints, for example in engine-driven models we always want to ensure that the energy in the ejecta does not exceed the energy budget of the engine or that our flux does not exceed a known upper-limit/non-detection. These conditions can be placed on any prior as a `Constraint`, which will ensure that any prior draw does not violate any constraints. All REDBACK priors can also be sampled from with one line of code to enable users to better understand the prior distributions.

3.5.3 Samplers

There are many advantages to being able to choose from a list of samplers (with no additional overhead beyond changing one line of code), for example, several samplers come with the ability to do parallel processing, which can dramatically improve run times. Some samplers also have the ability to resume from checkpoints and produce regular diagnostic plots that can be used to verify progress. There are also large differences in the algorithm of certain samplers, beyond the general distinction between nested sampling and Markov Chain Monte Carlo, with some algorithms better suited to one type of transient than another.

For REDBACK specifically, we use the DYNESTY (Speagle 2020) by default, but we regularly find that PYMULTINEST (Buchner et al. 2014) and NESTLE[1] give similar posteriors for significant shorter run times. However, the latter tend to be less robust at dealing with a complicated parameter space. A full sampler comparison is beyond the scope of this paper but we strongly encourage users to perform inference with multiple different samplers, both to gain a better understanding of the parameter space, what algorithms perform best and as a cross sampler validation to ensure that their results have converged.

3.6 Format of results

After a fit, REDBACK returns a homogeneous `result` object. This object is the same for any type of transient analysed. The object is also saved locally (in a machine-readable `json` file by default) either with a user-specified location/label or as a subfolder with the name of the model in a folder that is the name of the type of transient analysed (by default). The `result` object contains several attributes needed for diagnosis, such as a PANDAS data frame of the posterior values, alongside metrics (depending on the sampler) such as the Occam factor, the Bayesian evidence, the number of likelihood evaluations, the priors used in the analysis and additional metadata which includes a copy of the `Transient` object used in the fit. The `result` object also contains several methods, from convenience functions to obtain the credible intervals and latex strings for the constraints on all parameters, to plotting the corner or light curve and multiband light-curve plots with the data and the fit. The `result` file can also be shared and loaded in REDBACK to enable users to share their analysis or work across multiple machines. We note that the REDBACK `result` object inherits from the BILBY `result` object, inheriting additional useful methods and diagnostics such as the ability to importance sample or make a percentile–percentile (PP) plot (Cook, Gelman & Rubin 2006) to validate an inference workflow.

3.7 Plotting

In REDBACK, all plotting methods are implemented in a specific `plotting` module. However, we note that the access to these methods is through the `Transient` and `result` objects. In particular, we provide interfaces to plot the observations themselves, the fit to single or multiband photometry as random models drawn from the posterior or as a credible interval and a residual plot. The different REDBACK plotting functionality is demonstrated in Appendix C. To simplify modification of REDBACK plots, all plotting methods return the MATPLOTLIB axes, which can allow users to change things such as the axes labels/fontsize/scale/limits or plot something extra on the same plot. Furthermore, users can also pass their own MATPLOTLIB figure and axes to REDBACK, enabling multipanel light-curve plots or a customized size. The `plotting` module also uses dependency injection and keyword arguments for several settings which can be used to change many features of the different plots. Users can also replace the `plotting` module to be more specific to their needs or call the model themselves to plot what they would like.

3.8 Analysis

Separate from the main modules provided in REDBACK, we include an `analysis` module that can be used to set up the different workflows or make additional diagnostic plots for some models or calculate prior/posterior predictions for other properties. For example, here we provide a method to plot light curves generated by a user-provided set of parameters on top of the 'plot_multiband' or 'plot_data' generated plots to get a sense of the appropriate prior for fitting or build intuition about a model. Alongside this, we provide methods to plot the spectrum generated by REDBACK model, or additional posterior predictive plots such as of the evolution of the nascent neutron star. In the future, we will add more diagnostic analysis methods and encourage REDBACK users to contribute with typical diagnostic plots and calculations of their favourite transient.

3.9 Directory structure

By default, the REDBACK directory structure is set by the type of transient, the name of the transient and the model used in fitting. For example, if one downloads the data for the kilonova, AT2017gfo, this data will be saved to a folder called `kilonova` in the current working directory. If a user then loads this data and fits with a model called `redback`, then the `result` file alongside all plots and sampler-specific diagnostics will be saved to a folder within `kilonova` with the model name. This behaviour can be changed in two primary ways. (1) The user can specify an `outdir` and `label` when running the fit (see below) which will save the result to folder `outdir` with the `label` prepended to any output. (2) The user can

[1] http://kylebarbary.com/nestle/

change the `name` attribute of the `Transient` object. Which will change the label that is prepended to any output file but keep the default directory structure. We note that any `result` files generated by a non-default directory structure can simply be loaded up by specifying the path, while plotting locations can also be specified via the typical method of MATPLOTLIB.

4 JOINT ANALYSIS OF SPECTRUM AND PHOTOMETRY

With the software's design objectives and overview out of the way. We now turn towards a new application enabled by REDBACK. As we described in the introduction, it is becoming increasingly common for electromagnetic transients to have extensive spectroscopic and photometric observations. However, photometric analyses and spectroscopic analyses are often performed independently. Typically, the spectrum is often used primarily for the identification of a redshift and to identify the type of transient and later potentially specific emission lines. Meanwhile, the photometry is left for estimating the properties of the transient, such as the ejecta masses in supernovae and kilonovae or the black hole mass in tidal disruption events.

It is understandable that currently, analysis of the spectrum and photometry is performed separately, given the high computational cost of detailed spectral models and analytical/semi-analytical models that work on photometry but fail to capture the details of a spectrum. However, it is often the case that separate analyses of photometry and spectrum can provide contradictory information. For example, some supernovae observations where the photometry are often better described purely by ^{56}Ni decay while the spectrum has tell-tale signatures of interaction with CSM material. Each independently suggests different quantities of ejecta, making it difficult to understand the properties of supernovae explosions and can sometimes even change the interpretation of specific events (e.g. Schulze et al. 2024). Or the case of the kilonova, AT2017gfo, where the spectrum at 1.4 and 4.4 d is best described by electron fractions (Gillanders et al. 2022) inconsistent with those used to fit the photometry (Villar et al. 2017b). Such contradictions are likely down to modelling limitations. However, it is critical we understand which of the estimated properties are more robust, where our modelling could be improved and what the photometric and spectral observations are jointly telling us. Joint analysis can also provide significantly more powerful constraints by breaking degeneracies present in the independent analyses and thereby improving our estimation of the transient properties. This has important consequences as, ultimately, we aim to use the estimated parameters of the explosion to answer fundamental questions in physics and astrophysics.

We now describe how REDBACK can be used to jointly fit the spectrum and photometry of a kilonova. For the purposes of this demonstration, we choose a simplified simulated spectrum and photometry to ensure we can validate the entire process. This is a specific example of workflow B, described in Section 2. We simulate ToO observations of a hypothetical kilonova, AT2025ixp, observed by the Vera Rubin observatory through the REDBACK `simulation` module. In particular, we use the two-component kilonova model implemented in the `transient_models` subpackage following Villar et al. (2017b). We then evaluate the spectrum at 4.5 d from this model, by calling the model with an additional keyword argument to change the output format of the model. Assuming this model only captures continuum emission, we add an additional absorption and emission line at 8800 and 21 000 Å, respectively. Here, we model both spectral lines as a Gaussian, mimicking their Doppler broadening due to the high-velocity kilonova ejecta. We add Gaussian noise to the total spectrum (spectral lines and continuum emission) comparable to noise in the X-shooter spectrum of AT2017gfo (Pian et al. 2017; Smartt et al. 2017). With the data generated, we create an instance of the kilonova `Transient` object. We then independently fit the spectrum and photometry and jointly fit both together using the PYMULTINEST sampler (Buchner et al. 2014) through the REDBACK interface, specifying a Gaussian likelihood via the `likelihood` module and broad uninformative priors via the `prior` module.

In Fig. 2, we show the results from our analysis. In particular, in the left panel, we show the data in multiple LSST filters alongside the 95 per cent credible interval from our fit to the photometry. In the right panel, we show the simulated spectrum at 4.5 d (in black) alongside our fit, showing the continuum emission in blue and the full spectrum, including absorption and emission lines in red. In both cases, we see we can fit the observations well, correctly recovering the input.

In Fig. 3, we show the posterior distributions on multiple parameters of the two-component kilonova model from the independent spectrum and photometry fits and the joint fit. These posteriors highlight the power of joint analysis, while all analyses recover the true input (indicated by black lines), the joint spectrum and photometric fit do so with significantly more precision by breaking the degeneracy in the independent photometric and spectroscopic analyses. For example, the precision of the second ejecta component's mass and velocity improves from a precision of 29 per cent and 15 per cent, respectively, from the independent fit to the photometry to a precision of 8 per cent and 4 per cent. This boost to precision has several important consequences as kilonova properties have been previously shown to be useful for constraints on the behaviour of nuclear matter (Pang et al. 2023), constraints on the Hubble constant (Pérez-García et al. 2022), while offering better precision to ultimately understand how these explosions work.

The above example is a demonstration of one of the unique capabilities of REDBACK: a cohesive, single framework analysis of spectrum and photometry that is facilitated by the modular design of REDBACK. Specifically, REDBACK enables stitching together different functional modules for different problems. In particular, we can jointly, and independently fit both the spectrum and photometry by setting up the relevant functional modules in distinct ways. Similarly, we can simulate the two types of data in question, enabled by the design implementation of all models such that they can be evaluated for arbitrary inputs, times and return outputs in multiple formats, alongside the implementation of the `simulation` and `Transient` functional modules, where the former can be used to generate synthetic observations for distinct data types, while the latter has the required flexibility to handle such distinct data.

5 FUTURE DEVELOPMENT

As we continue to drive progress in transient astronomy, we develop newer and better models for transients and make improvements to how we treat the data. This paper marks version 1.0 release but REDBACK will be further developed to keep pace with the developments in modelling and treatment of data.

One of the primary aspects that will be improved are the models implemented in REDBACK. In particular, we are currently implementing models for interacting supernovae and fast-blue optical transients, from semi-analytical models of shocks produced by interacting shells (Margalit 2022), to surrogates of radiative transfer simulations (Khatami & Kasen 2023). We are also improving some of our models of afterglows for better treatment of reverse shocks and to make them more computationally efficient. We will soon implement model for *r*-process nucleosynthesis from collapsars (Barnes & Metzger 2022;

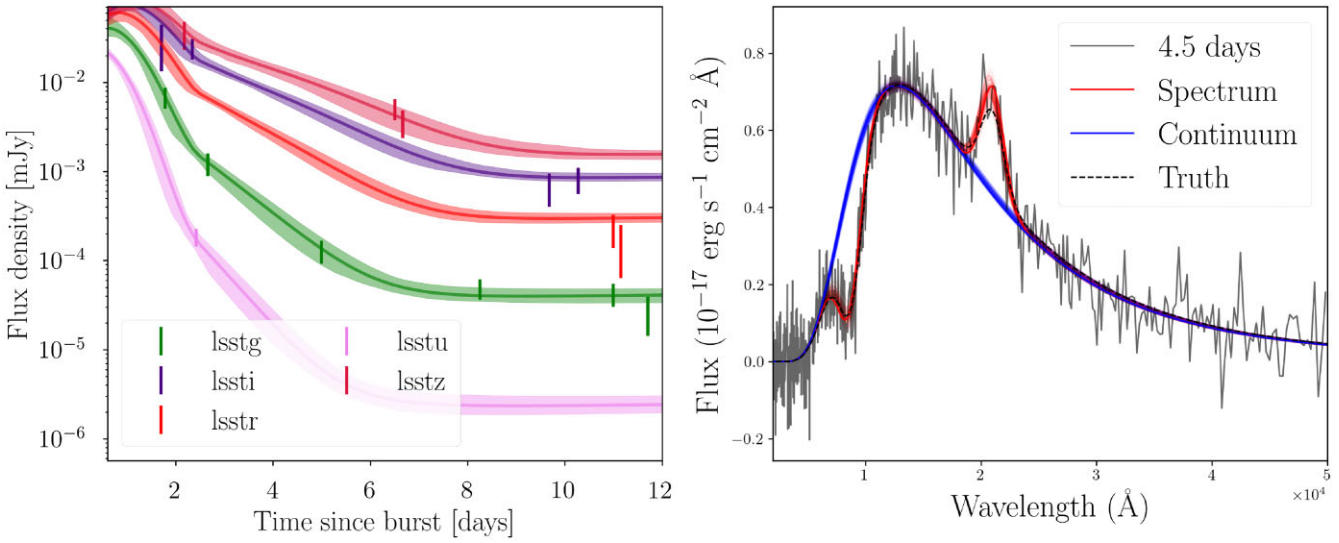

Figure 2. Simulated photometric data (left panel) with colours corresponding to different LSST filters and spectroscopic data (right panel) in black for a kilonova. In the left panel, the shaded band shows the 95 per cent credible interval fit to the photometry. On the right panel, we show the predicted continuum flux (in blue) and total spectrum (red) from 100 randomly drawn points from the posterior, alongside the true input in black dashed lines.

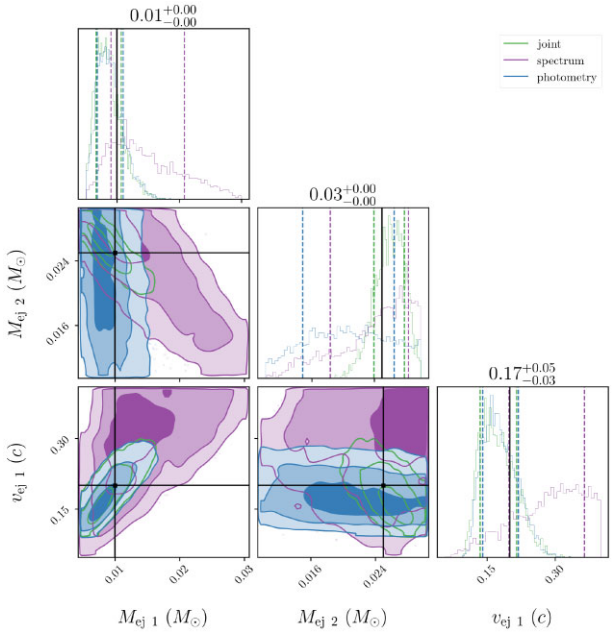

Figure 3. Posterior distribution on the component ejecta masses, $M_{ej,\,1}$ and $M_{ej,\,2}$, and bulk ejecta velocity of the first component, $v_{ej,\,1}$ for the joint fit and the photometry and spectrum independently.

Anand et al. 2024). On longer timescales, we will implement models with better spectral modelling, enabling joint fitting of the spectrum and photometry.

Alongside improvements and addition of models, we will further develop REDBACK for more practical purposes, for example, providing a generic interface in `redback_surrogate` to allow users to make their own surrogate from a grid of simulations and newer likelihoods that better describe the data generation process. We will also be further developing the `simulation` module to improve our treatment of focal plane geometry. On longer time-scales, we will add some GPU implementations of models to enable rapid inference and an application programming interface (API) to download and process data from the *Fermi* catalogue (e.g. von Kienlin et al. 2020).

6 CONCLUSION

Realizing the rich promise of the large transient data expected from new observing facilities such as the Vera Rubin Observatory and ULTRASAT (Shvartzvald et al. 2024) requires us to confront such data with models describing the different transient phenomena. This requires fast, reliable, open-source code that is both accessible to newcomers to the field and modular such that it can be adapted to be the powerhouse required by experts. Here, we have described REDBACK, a Bayesian inference software package for end-to-end for parameter estimation and interpretation of electromagnetic transients.

REDBACK is an engine for simulating realistic transients and inferring their properties enabling end-to-end analysis and validation of inference workflows. Furthermore, one can also use this software to understand how to optimize survey strategies/design or understand the selection function of different telescopes/surveys. REDBACK is also fully Bayesian, enabling the vast advantages of this statistical paradigm such as model selection, importance sampling, and Bayesian hierarchical modelling. We re-emphasize here that REDBACK is object-orientated, enabling users to input their own model, priors, and data without needing to edit the source code, and simply replace any functional module of REDBACK with their own code. The interface to BILBY also provides access to a large variety of samplers enabling validation across samplers and a simplistic interface for multimessenger analysis for joint events such as GW170817 (e.g. Radice et al. 2018; Coughlin et al. 2019; Gianfagna et al. 2023). These design objectives address many of the limitations of previous open-source packages for electromagnetic transients.

In this paper, we have described the overall design of REDBACK, a new scientific application where we jointly fit the spectrum and photometry of a kilonova. This holistic look at a complete transient data set offers the opportunity to both increase the precision of our constraints and confront contradictions that may emerge when

interpreting only one type of data. For the specific case of a kilonova, we show how joint fitting can dramatically improve the precision of the inferred ejecta masses, increasing the value of each event for constraints on the equation of state. Or also remove biases inadvertently caused by fixed opacities in photometric analyses that are inconsistent with the spectrum. In the appendix, we provide additional examples demonstrating the functionality and usability of the software in various applications and a general interface.

As discussed in Section 5, we will continue to further develop REDBACK, including the addition of newer models and additional functionality. REDBACK has already been used in previous publications such as inference on tidal disruption events (Sarin & Metzger 2024), analysis of SN 2018ibb (Schulze et al. 2024), magnetar-driven kilonovae and supernovae (Sarin et al. 2022b; Omand & Sarin 2024), GRB afterglows (Sarin et al. 2021, 2022a), and to infer joint GRB and kilonovae observations (Levan et al. 2024), demonstrating the flexibility of the software. A more comprehensive comparison of results for different transient catalogues is underway alongside interpretation for other transients.

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The REDBACK package makes use of the standard scientific PYTHON stack (Jones et al. 2001; McKinney 2010; Harris et al. 2020), MATPLOTLIB (Hunter 2007), and CORNER (Foreman-Mackey 2016), for the generation of figures, and ASTROPY (Robitaille et al. 2013; Price-Whelan et al. 2018; Astropy Collaboration 2022) for common astrophysics-specific operations. REDBACK makes use of BILBY (Ashton et al. 2019; Romero-Shaw et al. 2020) to provide an interface to different sampling algorithms and for evaluating prior distributions. REDBACK uses SNCOSMO (Barbary et al. 2022) for filter definitions and calculations of magnitude from SEDs, EXTINCTION (Barbary 2016) for extinction corrections. And REQUESTS and SELENIUM for downloading data from catalogues.

DATA AVAILABILITY

The software package along with example scripts for all analysis demonstrated in this manuscript alongside a plotting notebook to generate all the plots as well as other examples are available at https://github.com/nikhil-sarin/redback. The specific `result` objects for each of the analyses presented here are available at https://doi.org/10.5281/zenodo.8273145. REDBACK is available on PYPI. This paper uses v1.0 release of REDBACK with documentation at https://redback.readthedocs.io/en/latest/. The data for all transients is available at the OAC (Guillochon et al. 2017) gathered through the REDBACK `get_data` module or hosted at https://github.com/nikhil-sarin/redback.

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APPENDIX A: GENERAL INTERFACE

We now describe the general interface for REDBACK, for example how to download and load data, simulating a transient or calling a REDBACK model with a constrained prior. We note that these sections are not exhaustive demonstrations of the REDBACK API and merely show some demonstrative functionality. Full API documentation is provided at https://redback.readthedocs.io/en/latest/.

A1 Getting data

As mentioned in Section 3, REDBACK provides an API to download and process data from multiple catalogues. These data are saved as a human-readable file and returned as a PANDAS data frame. In particular,

```
import redback


# FINK
name = ''ZTF22abdjqlm''
data = redback.get_data.get_fink_data(transient=name, transient_type = ''supernova'')


# LASAIR
transient = ''ZTF20aamdsjv''
data = redback.get_data.get_lasair_data(transient=transient, transient_type = ''supernova'')


# Open Access Catalog
tde = ''PS18kh''
data = redback.get_data.get_tidal_disruption_event_data_from_open_transient_catalog_data(tde)


# BATSE
name = ''910505''
data = redback.get_data.get_prompt_data_from_batse(grb = name)


# SWIFT
GRB = ''070809''
data = redback.get_data.get_bat_xrt_afterglow_data_from_swift(grb=GRB, data_mode = ''flux'')
```

In all function calls, we specify the name of the transient we want to obtain the data for and use the relevant class method of the `get_data` module. For some of these methods we can also specify the type of transient or the type of data to ensure we get the data we want and that it is saved in the appropriate location. We note that REDBACK only processes the AB magnitude data for sources hosting multiband photometry. This is not a concern for FINK and LASAIR but may result in a loss compared to the OAC. However, the raw data file is also downloaded and users can reprocess the data as they wish.

A2 Creating transient objects

Once we have the data of a transient, there are many different ways to create a `Transient` object. For example, we provide simple class methods to load data that is downloaded from the OAC, FINK, and LASAIR.

```
supernova = redback.supernova.Supernova.from_open_access_catalogue(name=''ZTF22abdjqlm'',
data_mode = ''flux'')


sn = redback.transient.Supernova.from_lasair_data(name=''ZTF20aamdsjv'',
use_phase_model = True,
data_mode=''flux_density'', active_bands = np.array([''ztfr'']))
```

Here, the first line creates a `supernova` `Transient` object from data that was downloaded from FINK. We note that as FINK and OAC have the same data structure, the OAC method can be used for FINK data. Here, we have also specified the `data_mode` to be `flux`, which will create the transient object with the `flux` data mode. Similarly, the second line creates a supernova object but from LASAIR data. However unlike the FINK example, here we specify an active band, which sets all bands apart from the `ztfr` band to be inactive (not used in fitting), set the `data_mode` to be `flux_density` and set `use_phase_model = True`. The latter condition ensures that the time values we initialize are in MJD, to fit this data we therefore must also sample in the start time of the event.

We also provide simplified class methods for loading data from *Swift*, BATSE, and the `simulation` module. In particular,

```
kn_object = redback.transient.Kilonova.from_simulated_optical_data(name=''my_kilonova'',
data_mode = ''magnitude'')
```

Here, we have loaded the magnitude data for a kilonova; `my_kilonova` we generated using the `simulation` module. REDBACK `Transient` objects can also be constructed directly, for example, by loading in a data file and specifying the specific attributes directly. For example,

```
import pandas as pd


data = pd.read_csv(''example_data/grb_afterglow.csv'')
time_d = data[''time''].values
flux_density = data[''flux''].values
frequency = data[''frequency''].values
flux_density_err = data[''flux_err''].values
name = ''170817A''


afterglow = redback.transient.Afterglow(name=name, data_mode=''flux_density'', time = time_d,
 flux_density=flux_density, flux_density_err=flux_density_err, frequency = frequency)
```

This direct construction of a `Transient` object can be done for any other combination of attributes, enabling users to construct a `Transient` object in many different ways. We emphasize that we provide several other class methods than shown here and refer the reader to https://redback.readthedocs.io/en/latest/ for the full documentation.

A3 Calling a model

As alluded to in Section 3, all REDBACK models exist as PYTHON functions and can be called directly on an arbitrary time array and set of parameters. We also provide a convenient look up dictionary to find the function corresponding to a model as well as convenience functions to obtain the relevant citation for the model (for ease of reference and gather additional information about the model) and return an instance of the default `prior` for the model.

```
from redback.model_library import all_models_dict


model = ''one_component_kilonova_model''
priors = redback.priors.get_priors(model = model)
priors[''redshift''] = 1e-2
function = all_models_dict[model]
citation = function.citation


model_kwargs = dict(frequency=2e14, output_format = ''flux_density'')
time = np.linspace(0.1, 30, 50)
sample = priors.sample()
sample.update(model_kwargs)
fmjy = function(time, **sample)
```

Here, the first set of code creates the REDBACK prior object from a string referring to a model implemented in REDBACK, we also set the redshift of the prior to be a fixed value, and use a REDBACK dictionary to conveniently get the function corresponding to the model string. The function also has an attribute 'citation' that provides a reference for the model. The second set of code sets up some additional keywords required by the model such as the frequency we want to evaluate the model at and an output format. We then call the function on a random sample from the prior and arbitrary time array to obtain the flux density (in mJy) corresponding to the specific prior draw. This simple workflow can be readily changed to draw many more samples from the prior, add a constraint to the prior and draw from the constrained prior, or add/change keys in 'model_kwargs' to change the physics of the model or the output format.

A4 Simulating transient

While the interface described above can be used to simulate data, we also provide a more comprehensive `simulation` module (described in detail in Section 3). For example, generating a simulated light curve for a kilonova in ZTF can be done via,

```
import redback
from redback.simulate_transients import SimulateOpticalTransient


model_kwargs = {}
parameters = redback.priors.get_priors(model = ''one_component_kilonova_model'').sample()
parameters[''mej''] = 0.05
parameters[''t0_mjd_transient''] = 58288
parameters[''redshift''] = 0.005
```

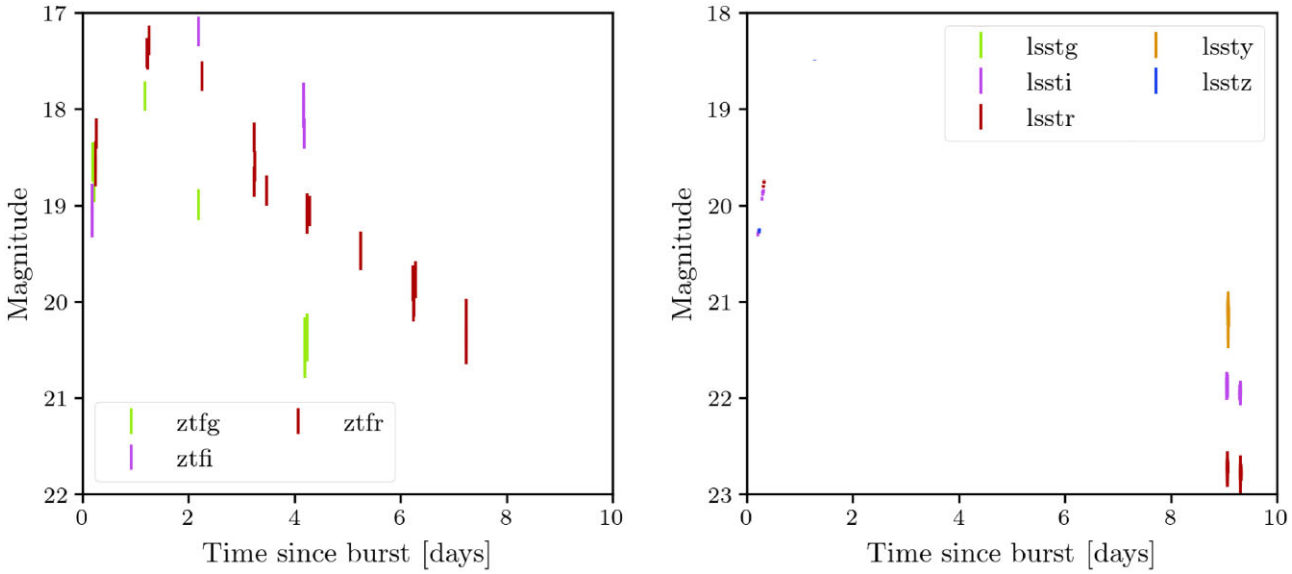

Figure A1. Simulated kilonova (one-component kilonova model) in (left) ZTF and (right) LSST. We emphasize that aesthetic features such as the colours of the data points, axes limits etc can all be modified by passing in relevant keyword arguments to the `plotting` methods.

```
parameters[''t0''] = parameters[''t0_mjd_transient'']
parameters[''temperature_floor''] = 3000
parameters[''kappa''] = 1
parameters[''vej''] = 0.2
parameters[''ra''] = 3.355395
parameters[''dec''] = 0.5820673


kn_sim = SimulateOpticalTransient.simulate_transient_in_ztf
(model = ''one_component_kilonova_model'',
  parameters=parameters, model_kwargs=model_kwargs, end_transient_time = 15.,
  snr_threshold=5., add_source_noise = True)
```

Here, the first set of code specifies the model we want to simulate with and the parameters of the simulated event. Then, we also place it in a part of a sky observable with ZTF (REDBACK will internally randomly place the source within the ZTF observable volume otherwise), then generate a light curve with the `simulation` module. As shown in Appendix A2, the simulated data can be easily saved and loaded in a single line of code to create a `Transient` object enabling inference. In Fig. A1, we show two representative simulated kilonovae in ZTF and the LSST Survey in the Vera Rubin Observatory, demonstrating through a simple example the benefits of the high cadence of surveys such as ZTF for fast transients such as kilonovae.

We note that this exact interface can also be used to generate survey light curves for the Nancy-Grace Roman Observatory or a user-generated survey and for any model implemented in REDBACK, and these examples are available at https://github.com/nikhil-sarin/redback. Furthermore REDBACK also offers the functionality to simulate transients more generically (in a manner more consistent with ToO observations) or simulate a full survey.

APPENDIX B: MULTIMESSENGER ANALYSIS

A key advantage of the interface with BILBY is to facilitate multimessenger gravitational-wave and electromagnetic transient analyses. Here, REDBACK provides the likelihood, model and/or simulated data for the electromagnetic transient and BILBY provides the same for the gravitational-wave data. Both likelihoods communicate together through the use of a `joint_likelihood` which combined with a full `prior`, can be used to perform joint multimessenger analyses.

We demonstrate this feature through the observation of a simulated BNS signal, GW231116, observed in O4 alongside a GRB afterglow detected in X-rays. We note that this workflow can be easily extended to also include an optical/radio afterglow and/or a kilonova. Furthermore, the joint likelihood interface can also be used to jointly fit any two data types, for example, a spectrum and photometry, both of which could be provided by REDBACK but we leave such examples from this paper for simplicity. This analysis has been performed for GW170817 by multiple groups (e.g. Gianfagna et al. 2023).

We start by setting up the data,

```
import bilby
import redback
from astropy.cosmology import Planck18 as cosmo
```

```
from redback.transient_models.afterglow_models import tophat
from bilby.core.prior import Uniform


source_redshift = 0.03
source_distance = cosmo.luminosity_distance(source_redshift).value


gw_injection_parameters = dict(mass_1=1.5, mass_2=1.3, chi_1=0.02, chi_2=0.02, lu-
minosity_distance=source_distance,theta_jn=0.43, psi=2.659, phase=1.3, geo-
cent_time = 1126259642.413,
 ra=1.375, dec=-1.2108, lambda_1=400, lambda_2=450, fiducial = 1)
```

For demonstrative purposes, we assume that the afterglow kinetic energy is some unknown fraction of the total rest mass energy of the binary, alongside the more conventional assumption that the jet is launched along the orbital angular momentum of the binary. These assumptions are not captured by any afterglow model implemented in REDBACK, so we create a new function, wrapping a simple `tophat` model already implemented in REDBACK.

```
def get_jet_energy(mass_1, mass_2, fudge):
 total_mass = (mass_1 + mass_2)
 return total_mass * fudge * 2e33 * 3e10**2


fudge_factor = 0.04
afterglow_energy = get_jet_energy(gw_injection_parameters[''mass_1''],
gw_injection_parameters
[''mass_2''],
fudge = fudge_factor)
grb_injection_parameters = dict(fudge = fudge_factor,
 theta_jn = gw_injection_parameters[''theta_jn''],
 redshift=source_redshift, loge0 = afterglow_energy,
 thc=0.1, logn0=-1, p=2.2, logepse=-1, logepsb=-2, ksin = 1,
 g0=50, mass_1 = gw_injection_parameters[''mass_1''],
 mass_2 = gw_injection_parameters[''mass_2''])


def grb_afterglow_model(time, redshift, theta_jn, mass_1, mass_2, fudge, thc, logn0, p,
 logepse, logepsb, ksin, g0, **kwargs):
 energy = get_jet_energy(mass_1, mass_2, fudge = fudge)
 energy = np.log10(energy)
 if ''loge0'' in kwargs.keys():
 kwargs.pop(''loge0'')
 return tophat(time=time, redshift=redshift, thv=theta_jn, loge0=energy, thc = thc,
 logn0=logn0, p=p, logepse=logepse, logepsb = logepsb,
 ksin=ksin, g0 = g0, **kwargs)
```

We can now simulate the electromagnetic data using this model following the method outlined in previous sections or by calling the model directly, and then create a REDBACK `Transient` class, alongside an instance of the likelihood. Furthermore, we can set up the gravitational-wave analysis, to reduce the computational cost we use the relative-binning approximation (Zackay, Dai & Venumadhav 2018; Krishna et al. 2023). We follow the standard BILBY relative-binning example for this aspect and do not outline the details here. We can also set up the electromagnetic aspect (i.e. the prior and likelihood) via

```
em_priors = bilby.core.prior.PriorDict()
em_priors[''redshift''] = source_redshift
em_priors[''thc''] = Uniform(0.01, 0.2, ''thc'',
latex_label = r''$\theta_{\mathrm{core}}$'')
em_priors[''logn0''] = Uniform(-4, 2, ''logn0'',
latex_label = r''$\log_{10} n_{\mathrm{ism}}$'')
em_priors[''p''] = Uniform(2,3, ''p'', latex_label = r''$p$'')
em_priors[''fudge''] = Uniform(0.01, 0.1, ''fudge'',
latex_label = r''$f_{\mathrm{fudge}}$'')
em_priors[''logepse''] = grb_injection_parameters[''logepse'']
em_priors[''logepsb''] = grb_injection_parameters[''logepsb'']
em_priors[''ksin''] = grb_injection_parameters[''ksin'']
em_priors[''g0''] = grb_injection_parameters[''g0'']
```

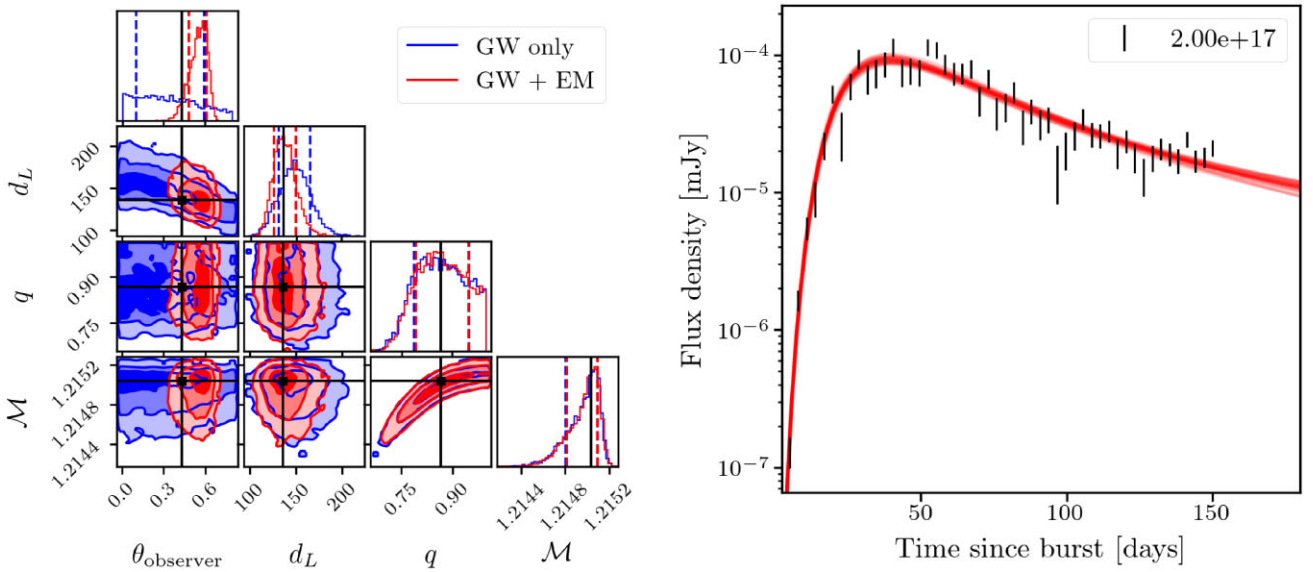

Figure B1. Left: corner plot showing the 1σ–3σ posterior on a subset of parameters with a gravitational-wave (GW) only analysis (blue) and a GW + Afterglow analysis (red), with black lines indicating the input values of the simulation. The right-hand panel shows the light-curve fit from the joint analysis.

```
em_likelihood = redback.likelihoods.GaussianLikelihood(x = sim_afterglow.time,
 y = sim_afterglow.flux_density,
 function = grb_afterglow_model,
 sigma=yerr, kwargs = afterglow_kwargs)
```

Here, we have first set up a prior on a series of parameters, while fixing some to the injected values to reduce the computational cost of the analysis, and then set up the electromagnetic likelihood, using the `Transient` object attributes.

Once, the electromagnetic and gravitational wave is set up (i.e. the individual likelihoods and priors), we can simply set up the joint analysis via,

```
joint_likelihood = bilby.core.likelihood.JointLikelihood(gw_likelihood, em_likelihood)
priors_emgw = em_priors.copy()
priors_emgw.update(gw_priors)
```

Here, the first line sets up a joint likelihood (the product of the two individual likelihoods) and the functional interface for the code to interact correctly. The second line does the same, setting up a `prior` object, automatically handling parameters that are shared.

Parameter estimation with the joint likelihood can then be performed via the BILBY interface,

```
result = bilby.run_sampler(joint_likelihood, priors=priors_emgw, label=''emgw'', out-
dir = ''joint'')
```

In Fig. B1, we show the constraints on various parameters provided by the above analysis, alongside constraints provided under the assumption that they are separate events. The orange lines indicate the true value of the simulation, indicating that the parameters are recovered correctly. In the right-hand panel, we show the fit to the simulated X-ray afterglow plotted via the `analysis` module. As expected, the primary benefit of including the afterglow is to break the distance–inclination angle degeneracy, clearly improving the estimate of distance and viewing angle for this hypothetical event.

APPENDIX C: EXAMPLES

We now go through a series of more general examples that demonstrate how REDBACK can be used to fit and infer properties of a variety of electromagnetic transients. We note that each of these examples are available as standalone scripts at https://github.com/nikhil-sarin/redback. To aid readability of these examples in this paper, we avoid code snippets that are identical to the snippets described above.

C1 Broad-band afterglow – GRB170817A

We first demonstrate how REDBACK can be used to fit private or simulated data by fitting the afterglow of GRB170817A (Hallinan et al. 2017; Abbott et al. 2017b; Alexander et al. 2018; Fong et al. 2019; Lamb et al. 2019a). We must first load the data file and create an `afterglow Transient` object via the method described in Appendix A2. After we have created the `Transient` object and have verified that the data looks correct (by plotting or by inspecting the `Transient` object), we are ready to fit. We know through many lines of evidence that GRB170817A was observed off-axis (e.g. Fong et al. 2019; Alexander et al. 2018) and the jet was likely structured (e.g. Lamb et al. 2019a; Fong et al. 2019). Furthermore, many previous analyses have already fit the

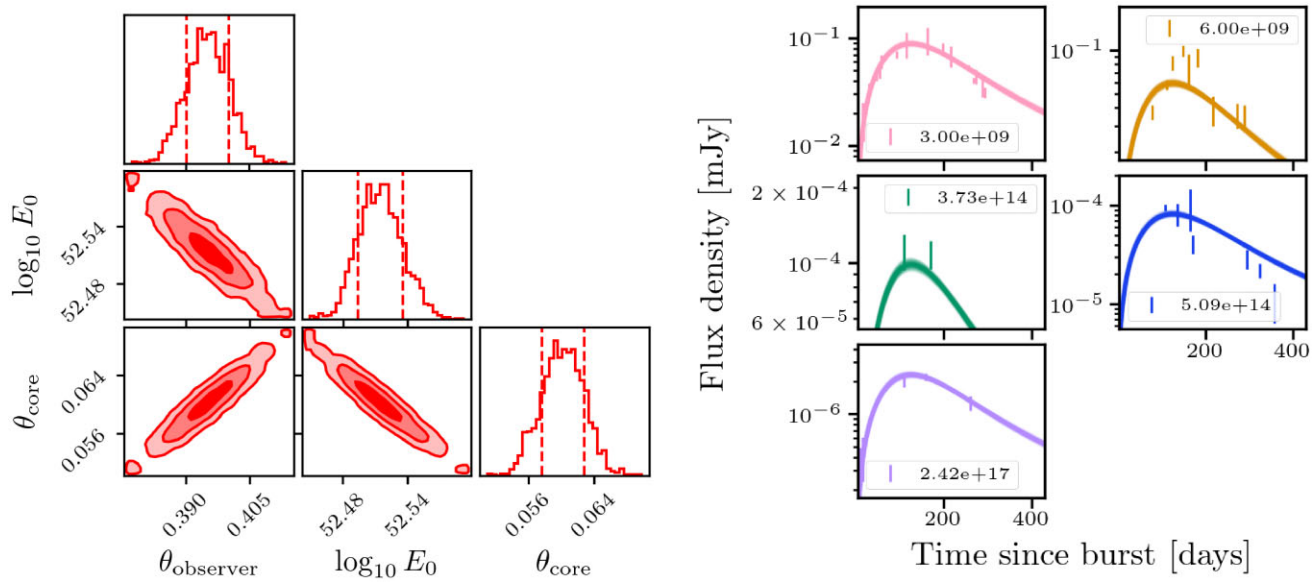

Figure C1. Left: posterior on the observers viewing angle, the isotropic equivalent energy of the afterglow and the opening angle of the relativistic jet from fitting the afterglow of GRB170817A with the different shading indicating the 1σ–3σ credible intervals. Right: data of the afterglow of GRB170817A at multiple frequencies along with the light curves from a 100 random draws from the posterior.

observations of GRB170817A to remarkable success. In particular, we can fit this data with a `gaussiancore` structured jet model from `afterglowpy`. As this model is already implemented in REDBACK, we simply need to specify this model as a string and load the associated prior.

```
model = ''gaussiancore''
priors = redback.priors.get_priors(model = model)
```

These lines construct a `prior` object using the default prior implemented in REDBACK for the `gaussiancore` model. To reduce inference wall time, we can also fix some of the parameters of the model with values consistent as those found by Ryan et al. (2020). This can be done via,

```
priors[''redshift''] = 1e-2
priors[''logn0''] = -2.6
priors[''p''] = 2.16
priors[''logepse''] = -1.25
priors[''logepsb''] = -3.8
priors[''ksin''] = 1.
```

We note that we could have instead set a narrow Gaussian prior around these values instead of fixing these parameters. With these few lines, we are now almost ready for inference. As mentioned in Section 3, several REDBACK models require additional keyword arguments; such as the frequencies at which each data point was was observed and the output format of the model (which must be the same as the data).

```
model_kwargs = dict(frequency=afterglow.filtered_frequencies,
output_format = ''flux_density'')
```

Here, we have set up a model dictionary which contains the frequency of the data points (this can be easily extracted from the `Transient` object via the `filtered_frequencies` attribute) and set the output format as flux density. We are now ready to fit via,

```
result = redback.fit_model(transient=afterglow, model=''gaussiancore'', sam-
pler = ''dynesty'',
 model_kwargs=model_kwargs, prior=priors, nlive=2000, resume = True)
```

Here we call the REDBACK `fit_model` function, which takes as input the `afterglow` object being fit, the name of the model, sampler, the prior, the model keyword arguments, and any other keyword arguments; and returns the REDBACK `result` object. Here, we have specified the sampler to be DYNESTY via a string, but this could be any other sampler implemented in BILBY. We also specify some sampler settings such as the number of live points and the option to resume from a previous run. When finished, this will return the REDBACK `result` object, which can be used to create a plot of the corner and a multiband light curve to verify the fit via,

```
result.plot_corner(parameters = [''thv'', ''loge0'', ''thc''])
result.plot_multiband_lightcurve(random_models = 100)
```

Here, in the first line we have also passed a list of the parameters we wish to show and in the second asked for 100 randomly sampled light curves from the posterior to be plotted. Note that several other arguments can be passed into these functions to change aesthetics or the type of information displayed. These two plots are shown in Fig. C1.

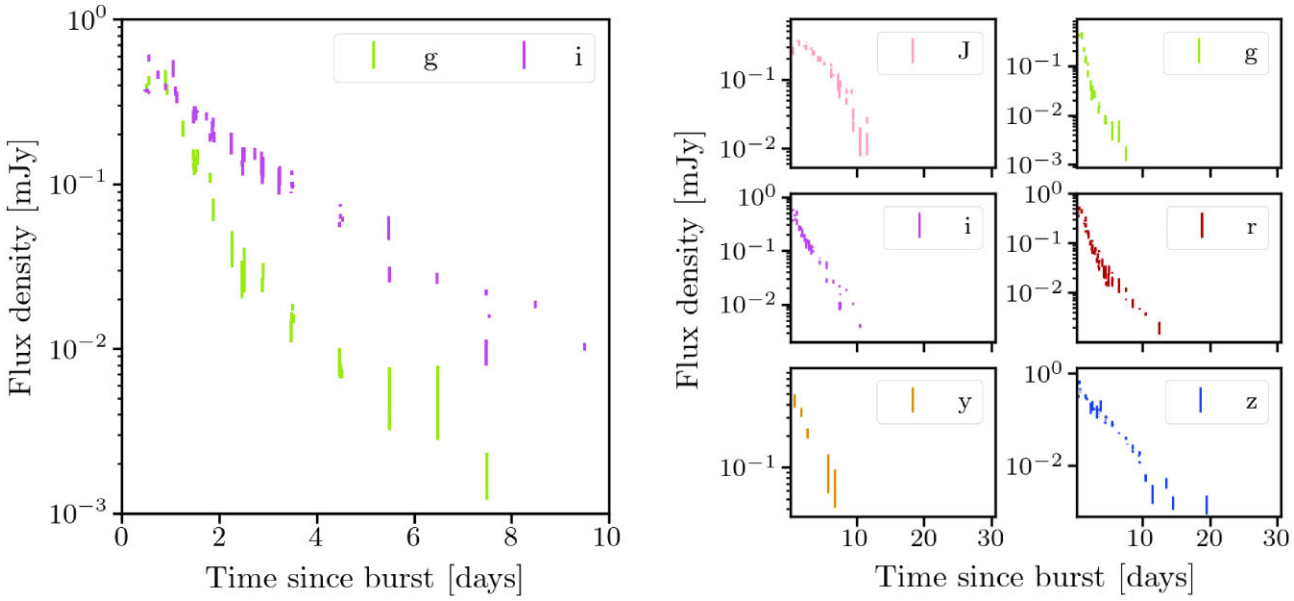

Figure C2. Left: data of AT2017gfo plotted through the `plot_data` method. Right: data of the AT2017gfo plotted through the `plot_multiband` method.

C2 Kilonova – AT2017gfo

We now demonstrate how REDBACK can be used to fit a kilonova, in particular the kilonova that accompanied GW170817, AT2017gfo (Abbott et al. 2017b; Villar et al. 2017b). For simplicity, we will fit a `one_component_kilonova_model` implemented within REDBACK to observations of AT2017gfo (Villar et al. 2017b). Such a model is known to not provide a great fit to the data so this is merely a demonstration of REDBACK functionality. As mentioned in Section 3, significantly more complex kilonovae models are available in REDBACK which have been previously shown to well explain the observations (e.g. Villar et al. 2017b; Bulla 2019; Nicholl et al. 2021).

The data of AT2017gfo is available at OAC (Guillochon et al. 2017), which can be obtained via the code shown in Appendix A1.

```
data = redback.get_data.get_kilonova_data_from_open_transient_catalog_data
(transient = ''at2017gfo'')
```

The above code calls the `get_data` module to obtain the data for AT2017gfo from the OAC. As mentioned above, this will return a PANDAS data frame while also saving the data to disc. Users can manipulate the data as they would any other PANDAS object. However, for our purpose it is more useful to use this data to create an `kilonova` object. This is done via

```
kilonova = redback.kilonova.Kilonova.from_open_access_catalogue(
 name=''at2017gfo'', data_mode=''flux_density'', active_bands = np.array(['g'', ''i'']))
```

Here we have created a `kilonova Transient` object, specifying the data mode to be flux density. We have also set the 'g' and 'i' bands as active, which will disable all other bands and only fit the active bands. This can be done to both reduce the computational time of inference but also for cases when the data or model are unreliable for specific filters. To ensure the data are correctly processed, we can plot the data via

```
kilonova.plot_data(show=True, save=False, plot_others=False,
band_colors={''g'':''green'', ''i'':''indigo''}, xlim_high = 10)
fig,~axes = plt.subplots(3, 2, sharex=True, sharey=True, figsize = (12, 8))
kilonova.plot_multiband(figure=fig,~axes=axes,
filters = [''g'', ''r'', ''i'', ''z'', ''y'', ''J''])
```

Here, the first line will plot all the data onto one figure, where we have also passed additional arguments such a dictionary of the colours for each band, whether to plot the inactive bands, to not save and to show the plot and the upper limit on the x-axis. Note that REDBACK returns the MATPLOTLIB axes so several other plotting related things can be changed by the user directly or by passing in an additional keyword argument. The second line, will make a plot with one band per axes and we have also specified the specific filters we wish to display. Note that this functionality allows us to show data for a filter or fits for a filter even if that filter was set as inactive. Both figures are shown in Fig. C2.

With the `Transient` object created and data verified through a plot, we are now ready to fit. As mentioned above, we will fit with the a one-component kilonova model. However, we will now also demonstrate how a user can fit the data with a different likelihood and sampler. We skip steps to load a prior and set up model keyword argument dictionary as they are identical to the afterglow example above.

```
prior[''sigma''] = Uniform(0.01, 0.0001, name=''sigma'', latex_label = ''$\sigma$'')
function = all_models_dict[model]
sampler = ''nestle''
```

Here, we first define a new prior on a parameter `sigma`, which is an additional parameter to be fit for, then use a convenience dictionary to get the REDBACK function for a one component kilonova model and specify the sampler to be used in inference as the NESTLE sampler. We note that `sigma` is the uncertainty in the typical Gaussian likelihood (i.e. σ), and if a user provides a prior but uses the standard (default) likelihood, this will overwrite the specific measured errors for a constant σ that is estimated by sampling. However, here, we wish to demonstrate the use

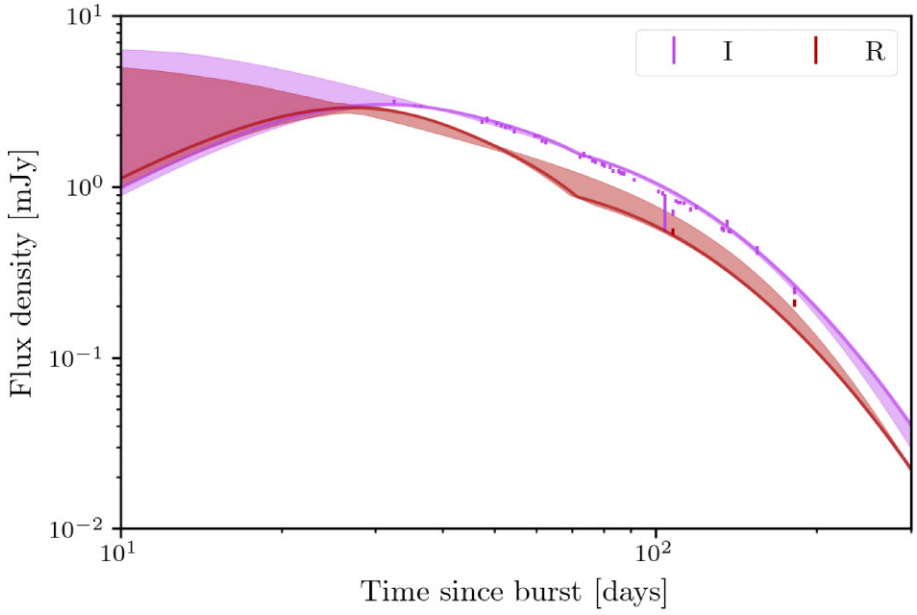

Figure C3. *R*- and *I*-band observations of SN1998bw alongside the 68 per cent credible interval from our fit.

of a custom likelihood (either something provided by the user or a different likelihood already implemented in REDBACK), we can do this using the processed attributes from the `Transient` object via,

```
likelihood = redback.likelihoods.GaussianLikelihoodQuadratureNoise
(x=kilonova.x[kilonova.filtered_indices], y=kilonova.y[kilonova.filtered_indices],
sigma_i=kilonova.y_err[kilonova.filtered_indices], function = function)
```

Here, we use a Gaussian likelihood with an additional noise source, σ added in quadrature (that is fitted for) to the measured y errors. This likelihood is already implemented in REDBACK, but a user could easily replace this likelihood with their own class. Then, users can use this likelihood in the fit via,

```
result = redback.fit_model(transient=kilonova, model=model, likelihood=likelihood, sam-
pler = sampler,
model_kwargs=model_kwargs, prior = priors)
```

With this simple change we can fundamentally change what we believe to be the data generation process and ensured that advanced users can easily change the likelihood and settings of the sampler, without ever digging into the REDBACK source code.

C3 Supernova – SN1998bw

REDBACK can also be used to fit supernovae. Here, we fit the `arnett` model (Arnett 1980, 1982) implemented within REDBACK to observations of SN1998bw (Galama et al. 1998). We can acquire the data for SN1998bw through the OAC and API shown above and create a `supernova` object.

After ensuring that the data are obtained correctly we can set up the fit in a few lines of code. As the `arnett` model is already implemented in REDBACK we can simply load up the default prior for this model via,

```
priors = redback.priors.get_priors(model = ''arnett'')
priors[''redshift''] = 0.0085
```

Here, we have also fixed the redshift to the known redshift of SN1998bw. We can now set up the fit in another two lines of code.

```
model_kwargs = dict(frequency=supernova.filtered_frequencies,
output_format = ''flux_density'')
result = redback.fit_model(transient=supernova, model=''arnett'', sampler=''dynesty'',
model_kwargs = model_kwargs,
prior=priors, nlive=500, clean=True, npool = 4)
```

Here, we have also specified `npool = 4` which will set up the DYNESTY sampler with multiprocessing over four cores to reduce the wall time of the analysis. We have also set the option `clean` to `True`, which ensures that REDBACK will restart this analysis from scratch and not resume from a previous analysis.

As with all other analysis, the fit returns a REDBACK `result` object, which we can use to obtain posteriors on various parameters, or for plotting. For example, we can plot the light curve with the fit shown as a 68 per cent credible interval (shown in Fig. C3) via,

```
ax = result.plot_lightcurve(uncertainty_mode=''credible_intervals'',
plot_others=False, show = False,
credible_interval_level = 0.68)
```

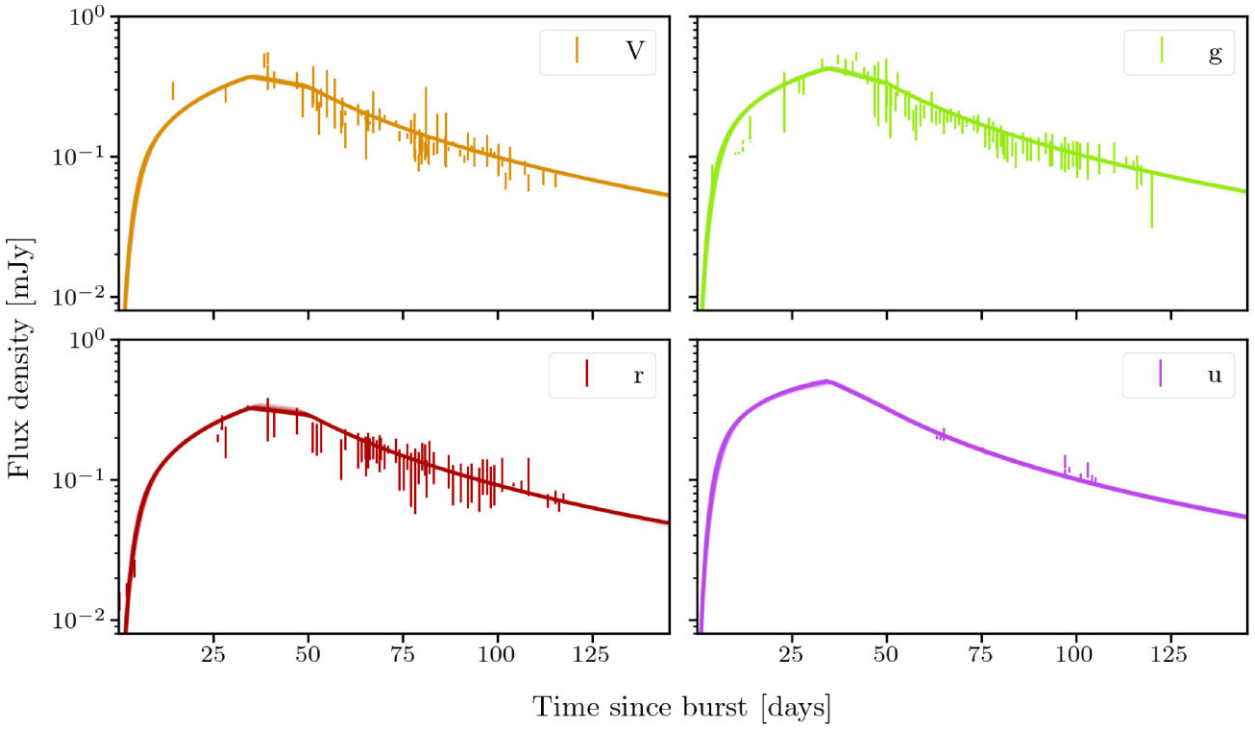

Figure C4. Multiband light curve of PS18bh along with the fitted light curve from a 100 random realizations randomly drawn from the prior.

```
ax.set_xscale(''log'')
ax.set_xlim(10, 300)
plt.show()
```

Here we have also returned the MATPLOTLIB axes and used this to modify the xscale and xlimits of the plot. The fit demonstrates the large uncertainty at early times where there are no observations in these bands.

C4 Tidal disruption events – PS18kh

Here, we fit the `tde_analytical` model implemented within REDBACK to multiband observations of, tidal disruption event, PS18kh (Holoien et al. 2019). We acquire the data from OAC and create a `tde Transient` object. We set only a subset of bands as active via,

```
tidal_disruption_event.active_bands = [''V'', ''g'', ''r'']
```

The rest of the code to fit is exactly like the afterglow example above. We can visualize our fit and make the predicted light curve (shown in Fig. C4) for multiple filters, including a filter that we did not fit, for example, the *u* band, via

```
result.plot_multiband_lightcurve(random_models=100, filters = [''V'', ''g'', ''r'', ''u''])
```

This is a useful verification exercise to understand which filters are driving the fit and whether the fits without a certain band are consistent with those observations.

C5 X-ray afterglow of GRB070809 – millisecond magnetars

We now use REDBACK on an integrated flux or luminosity data by fitting the X-ray afterglows of a GRB, by fitting the `evolving_magnetar` model (Şaşmaz Muş et al. 2019) to *Swift* observations of GRB070809, specifically the integrated flux obtained from *Swift*–XRT.

We acquire the Burst Alert Telescope (BAT) and X-ray Telescope (XRT) data of GRB070809 from *Swift* via the `get_data` module

```
redback.get_data.get_bat_xrt_afterglow_data_from_swift(grb=''070809'', data_mode = ''flux'')
```

We construct an `afterglow` class instance via

```
afterglow = redback.afterglow.SGRB.from_swift_grb(name=''070809'', data_mode = ''flux'',
 truncate=True, truncate_method = ''prompt_time_error'')
afterglow.analytical_flux_to_luminosity()
ax = afterglow.plot_data()
```

Here, we have specified to load the `flux` data for GRB070809 from *Swift*. This data typically also include BAT data from the prompt phase which we do not wish to fit here. We truncate this data using the `prompt_time_error` method.

The `evolving_magnetar` model works on luminosity data. We could have provided this data when creating the `afterglow` object but we also provide two convenience functions to generate this data, an analytical method which uses the GRBs photon index and a numerical method from SHERPA which uses the spectrum. All details necessary for either method are obtained internally by REDBACK from the *Swift* Data Centre. Here, we use the analytical method to convert the integrated flux data to a luminosity.

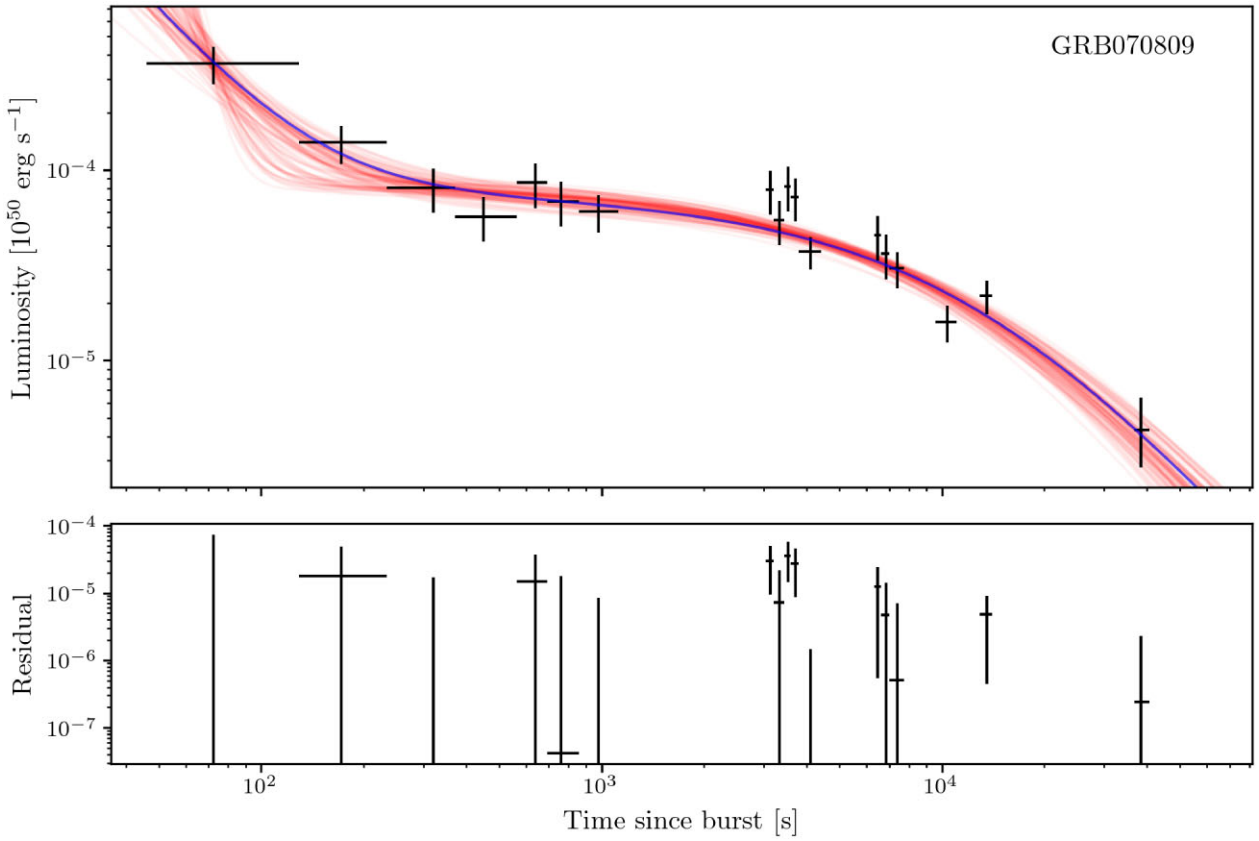

Figure C5. Residual plot obtained using `plot_residual` method of the `result` object. Here, the top panel shows the data in black with maximum likelihood and 100 randomly drawn light curves in blue and red, respectively, with the bottom panel showing the residual between the data and the maximum-likelihood model.

```
afterglow.analytical_flux_to_luminosity()
```

Note, that this will automatically change the `afterglow` objects data mode to luminosity. Beyond this point, the fitting workflow is identical to fitting any other transient, that is,

```
priors = redback.priors.get_priors(model = ''evolving_magnetar'')
result = redback.fit_model(model=''evolving_magnetar'', sampler=''dynesty'', nlive=200,
transient = afterglow,
 prior=priors, sample=''rslice'', resume = True)
```

The above code first constructs a `prior` object, using the default prior implemented in REDBACK for the `evolving_magnetar` model. This is followed by code calling `fit_model`. Note that here we do not need a dictionary for the model keywords as this model does not require any. We are again returned the REDBACK `result` object which can be used to plot a corner plot, the light curve or obtain any other diagnostic about the inference/posterior. For these data modes however, it can be especially informative to show a plot of the light curve with the residuals. This can be obtained using `plot_residual` method of the `result` object. This generates Fig. C5, where the top panel shows the data in black with maximum likelihood and random draws in blue and red, respectively, with the bottom panel showing the residual between the data and the maximum-likelihood model.

```
result.plot_residual()
```

C6 Phase and attenuation – SN2018ibb

In previous examples, we have ignored two important aspects of fitting transients; (1) we often do not know when the explosion occurred and (2) there is attenuation in the form of dust extinction from the host galaxy.

In this example, we show how to fit data while measuring the unknown explosion time and including extinction. We will also demonstrate how to fit in magnitudes and adding a new filter to REDBACK and SNCOSMO. We will do this by fitting a supernova, in particular, the UV-to-NIR light curve of the superluminous supernova SN 2018ibb (Schulze et al. 2024).

As previous examples, we can load the private data for SN 2018ibb and create a `Supernova Transient` object via

First, we read in the private data.

```
import pandas as pd
data = pd.read_csv(''SN2018ibb_photcat_Redback.ascii'', sep = '''')
sn=redback.transient.Supernova(name  =  ''SN2018ibb'',
```

```
  data_mode = ''magnitude'', time_mjd = data[''MJD''].values,
  magnitude = data[''MAG''].values, magnitude_err = data[''MAG_ERR''].values,
bands = data[''band''].values,
  use_phase_model = True)
```

In contrast to the previous examples, we fit the data in magnitude space. Furthermore, we set `use_phase_model = True` because we do not know the explosion date. We also specify time values in MJD instead of days since explosion. When fitting a model to such data, a user must then add a prior on the explosion time which will then be sampled over. We note that `use_phase_model = True`, will also change plotting labels to account for the change.

Before we can fit the magnitude data of SN 2018ibb, we must first ensure that all filters of the observations are available in REDBACK. We note that this is only a concern when fitting photometry in magnitudes or flux as this requires the full transmission curve of every filter rather than a reference wavelength. Some of the observations of SN 2018ibb were performed with the GROND camera mounted at the 2.2 m MPG telescope. The GROND filters (in our example `grond::i` and `grond::z`) are not part of SNCOSMO distribution that is used internally within REDBACK for filter definitions. After retrieving the filters, for instance, from the Spanish Virtual Observatory[2] (Rodrigo, Solano & Bayo 2012), we add them to SNCOSMO and by extension REDBACK, via

```
  from astropy.io import ascii
  import astropy.units as u
  import sncosmo


  filter_files = [
   ''/PATH/WHERE/YOU/STORED/FILTER_CURVES/GROND_I.dat'',
   ''/PATH/WHERE/YOU/STORED/FILTER_CURVES/GROND_Z.dat'',
  ]


  filter_names = [''grond::i'', ''grond::z'']


  for f, fname in zip(filter_names, filter_files):
   _data = ascii.read(fname)
   band = sncosmo.Bandpass(_data[''col1''], _data[''col2''], name=f, wave_unit = u.angstrom)
   sncosmo.register(band, f, force = True)
```

We can set up the rest of the inference workflow, first set up the model and the prior via

```
  model = ''t0_supernova_extinction''
  base_model = ''arnett''


  priors = redback.priors.get_priors(model = model)
  priors.update(redback.priors.get_priors(model = base_model))
```

Here, we choose the `t0_supernova_extinction` model, which has the explosion time and magnitude of extinction as a free parameter. This model itself does not contain any physics and must be specified an additional physical model. For simplicity, we use the physical `arnett` model as the base model. The last two lines of code just set up the prior object to include the parameters of both models.

We must now also set priors on the explosion time, the extinction magnitude and update the prior on the ejecta mass as SN 2018ibb requires an extraordinary amount of ejecta (Schulze et al. 2024).

```
  from bilby.core.prior import Uniform


  # Allow the explosion date to be up to 200 days before the first detection
  priors[''t0''] = Uniform(minimum = data[''MJD''].values.min()-200, maxi-
mum = data[''MJD''].values.min()-1, name = ''t0'', latex_label = r''$t_{\rm expl.}$'')


  priors[''mej''] = Uniform(minimum = 1, maximum = 260, name = ''mej'', la-
tex_label = r''$M_{\rm{ej}}~({\rm M}_{\odot})$'')

  # Extinction
  priors[''av''] = Uniform(minimum = 0, maximum = 1, name = ''av'',
latex_label = r''$A_V$ (mag)'')
```

With the model specified and prior set up, we can now fit via,

[2] http://svo2.cab.inta-csic.es/theory/fps/

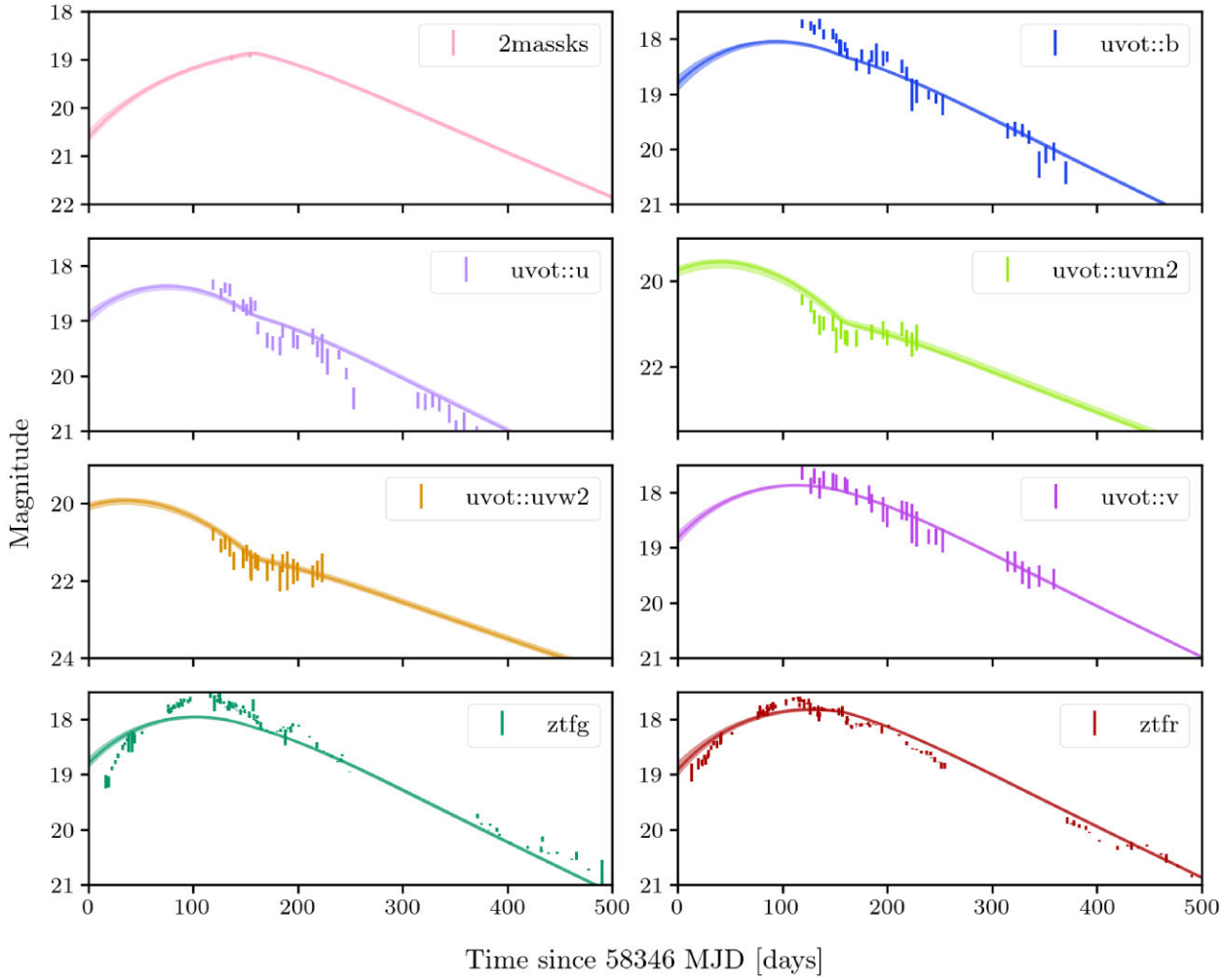

Figure C6. Multiband light curve of SN2018ibb along with the 68 per cent credible interval light-curve fit from the posterior.

```
model_kwargs = dict(bands = sn.filtered_sncosmo_bands, base_model = base_model, output_format = ''magnitude'')


result = redback.fit_model(transient = sn, model = model, model_kwargs = model_kwargs,
prior = priors, plot = True)
```

We note that as we are fitting with a base model and in magnitudes, there are some minor differences to the `model_kwargs`, namely that we must now specify a list of bands for the data points instead of frequency and must specify the base model. In the `fit_model` argument, we have also set `plot = True`, which will automatically generate the fitted light curve after inference finishes. In Fig. C6, we show the light-curve fit generated with the above code and the `result.plot_multiband_lightcurve()`.

This paper has been typeset from a TEX/LATEX file prepared by the author.