

# Perfect is the enemy of good enough: predicting electromagnetic counterparts using low-latency, gravitational-wave data products

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## ABSTRACT

Searches for gravitational-wave counterparts have been going in earnest since GW170817 and the discovery of AT2017gfo. Since then, the lack of detection of other optical counterparts connected to binary neutron star or black hole - neutron star candidates has highlighted the need for a better discrimination criterion to support this effort. At the moment, the low-latency gravitational-wave alerts contain preliminary information about the binary properties and, hence, on whether a detected binary might have an electromagnetic counterpart. The current alert method is a classifier that estimates the probability that there is a debris disk outside the black hole created during the merger as well as the probability of a signal being a binary neutron star, a black hole - neutron star, a binary black hole or of terrestrial origin. In this work, we expand upon this approach to predict both the ejecta properties and provide contours of potential lightcurves for these events in order to improve follow-up observation strategy. To validate the method, we test our approach on real events from the second and third Advanced LIGO-Virgo observing runs.

**Key words:** gravitational waves – methods: statistical

## 1 INTRODUCTION

The search for, detection, and the characterization of the kilonova AT2017gfo (Coulter et al. 2017; Smartt et al. 2017; Abbott et al. 2017c), associated with the binary neutron star (BNS) merger GW170817 (Abbott et al. 2017a) and the short gamma-ray burst GRB170817A (Goldstein et al. 2017; Savchenko et al. 2017; Abbott et al. 2017d), has spurred on the search for more of these objects. These kilonovae are expected to be produced in many of the mergers of compact objects involving at least one neutron star (with another neutron star or black hole as companion). Powered

by the neutron-rich outflows undergoing the radioactive decay of r-process elements (Lattimer & Schramm 1974; Li & Paczynski 1998; Metzger et al. 2010; Kasen et al. 2017), these ultra-violet/optical/infrared transients produce emissions approximately isotropically<sup>1</sup> and therefore are visible from nearly all directions. The properties of the kilonova, including the lightcurves and spectra, depend on the parameters of the original binary, including the masses (typically characterized by the chirp mass and mass ratio), spin an-

<sup>1</sup> We emphasize that despite the approximately isotropic nature of the kilonovae, an angular dependence exists as pointed out in, e.g., (Perego et al. 2017; Kawaguchi et al. 2019; Heinzel et al. 2020).

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gular momentum, and the equation of state describing the neutron stars' interior (Bauswein et al. 2013a; Piran et al. 2013; Abbott et al. 2017a; Bauswein et al. 2017; Dietrich & Ujevic 2017; Radice et al. 2018b). The association between lightcurves and binary parameters has been used to place constraints on the character of the progenitor systems and quantity of matter expelled, e.g., (Kasen et al. 2017; Coughlin et al. 2017; Smartt et al. 2017; Perego et al. 2017; Hinderer et al. 2019; Kawaguchi et al. 2019; Bulla 2019; Coughlin & Dietrich 2019; Nicholl et al. 2021; Raaijmakers et al. 2021).

Searches for these counterparts are difficult for a variety of reasons, the most important one is the large sky localizations spanning  $\approx 100 - 10,000 \text{ deg}^2$  (Röver et al. 2007; Fairhurst 2009; Fairhurst 2011; Grover et al. 2014; Wen & Chen 2010; Sidery et al. 2014; Singer et al. 2014; Berry et al. 2015; Essick et al. 2015; Cornish & Littenberg 2015; Klimentko et al. 2016). Due to the size of the localizations, wide-field survey telescopes such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS; (Morgan et al. 2012)), Asteroid Terrestrial-impact Last Alert System (ATLAS; (Tonry et al. 2018)), the Zwicky Transient Facility (ZTF; (Bellm et al. 2018; Graham et al. 2019; Dekany et al. 2020; Masci et al. 2018)), telescope networks such as the Gravitational-Wave Optical Transient Observer (GOTO-4) (Gompertz et al. 2020), GRANDMA (Antier et al. 2020b; Antier et al. 2020a) and future facilities such as BlackGEM (Bloemen et al. 2015) and the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST; (Ivezic et al. 2019)), can most efficiently cover the extended regions.

Given limited telescope time, prioritization of gravitational-wave (GW) event candidates for follow-up is essential. This can include considerations such as the false alarm rate of the event, the time of the merger (and therefore its relation to observability (Chen et al. 2017)) and properties of the merger itself. In particular, one quantity of interest is the apparent magnitude of the lightcurve in bands of a particular telescope during its observability window. This would limit observations to those objects that could be feasibly detected given the available telescope time and would help prioritizing between exposure time and sky coverage. An observation strategy, based on the idea of using low-latency GW products to predict electromagnetic (EM) properties, was first introduced in (Salafia et al. 2017).

A number of previous studies tried to address the question of which compact binary merger should be the target of EM observations, e.g., Pannarale & Ohme (2014) were one of the first who used the remnant matter outside the final black hole as a proxy for the likelihood of potential EM counterparts. In addition, based on general-relativistic numerical simulations, empirical fitting formulas have also been derived for the ejected material and for the disk mass for BNS systems (Dietrich & Ujevic 2017; Radice et al. 2018a; Coughlin et al. 2018a; Dietrich et al. 2020; Nedora et al. 2020) and black hole-neutron star (BHNS) systems (Foucart 2012; Kawaguchi et al. 2016; Foucart et al. 2018; Krüger & Foucart 2020).

Rapid analysis of the GW data in the era of the advanced detectors is done by online low-latency pipelines. Traditionally there are two types of pipelines: one category targeting modeled signals and the other category tracking

unmodeled events, both signals being General Relativity predictions. Thereby the pipelines of the first type search for well-modeled predicted signals (Dal Canton et al. 2014; Cannon et al. 2020; Aubin et al. 2020; Hooper et al. 2012), whereas the other type of pipelines searches for an excess of power in the data (Klimentko et al. 2008; Lynch et al. 2017; Cornish et al. 2021; Sutton et al. 2010). For the present study, we will use the templates which came out at the end of an analysis realised by the multi-band template analysis (MBTA) pipeline (Aubin et al. 2020), which searches for modeled binary mergers.

The realtime public data products (Abbott et al. 2018b) to aid the EM/neutrino follow-up of binary merger candidates include 3D sky localization (Singer & Price 2016; Singer et al. 2016), the probability that the candidate is an astrophysical event (Kapadia et al. 2020), the probability of having at least one neutron star – characterized by the probability of having one companion with mass below  $3M_{\odot}$  – and the probability of having remnant matter from the merger (Chatterjee et al. 2020) – based on the disk mass prediction of Foucart et al. (2018). Overall, while extremely useful, it requires that all compact objects with masses below  $3M_{\odot}$  to be neutron stars, and there are some shortcomings to this analysis, e.g., not all BNS mergers will have a detectable EM counterpart, (e.g. Coughlin et al. 2020b,c; Bauswein et al. 2020). A source classifier based on the template chirp mass was equally discussed in Dal Canton et al. (2020).

One issue to overcome, in addition to the statistical uncertainties, is the systematic errors in the low-latency template based analysis. These searches use discrete template banks of waveforms to perform matched filtering on the data. For the online searches, which are what we will be concerned here, the templates are characterized by masses,  $m_1$  and  $m_2$ , and the dimensionless aligned/anti-aligned spins of the binary elements along the orbital angular momentum of the binary,  $s_1$  and  $s_2$ . These pipelines report the best matching templates based on a detection statistic, giving a point estimate of these four quantities. The downside to this is clear: while quantities like the *chirp mass*  $m_{\text{chirp}}$  of systems are well measured, mass ratio and spin tend to be poorly constrained by this point estimate (Biscoveanu et al. 2019).

Additional, important supra-nuclear matter equation of state dependent information not provided by the low-latency pipelines are estimates of the maximum mass, compactness and/or tidal deformability of neutron stars. The maximum mass informs the classification of events as BNS, neutron star - black hole (NSBH), or binary black hole (BBH) (Essick & Landry 2020).

The presence or absence of an EM counterpart to a compact binary coalescence is determined by the amount of unbound baryonic material. The amount of ejecta, or even whether there is measurable ejecta, is directly linked either to the compactness of the neutron star(s) or to their tidal deformability  $\Lambda$  in the combination

$$\tilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12m_2)m_1^4\Lambda_1 + (m_2 + 12m_1)m_2^4\Lambda_2}{(m_1 + m_2)^5}. \quad (1)$$

In general, the larger the tidal deformability, the less compact the stars and the higher the probability of gravitationally unbound material producing bright kilonovae.

In order to create a prior for the compactness  $C$  and maximum neutron-star mass, a choice of the neutron star

equation of state is necessary. The equations of state employed in this work are a zero temperature relation between pressure and the rest-mass energy density governing a fluid of baryons at supra-nuclear densities. Given an equation of state, there is a one-to-one correspondence between mass and tidal deformability, if the neutron star is completely made up of hadrons. Indeed, in the case of hybrid stars, hypothetical objects where deconfined quarks might exist (Alford et al. 2013; Han et al. 2019; Lindblom 1998), the situation is different. Hybrid equations of state can support twin stars, neutron stars with the same mass but different central densities: the lower-density star’s core is hadronic, while the higher-density star’s is quark-like (Essick et al. 2020a; Chatziioannou & Han 2020; Pang et al. 2020). For this study we consider only the case of hadron stars. Moreover, the supra-nuclear matter equation of state is important for the determination of a maximum neutron star mass. Effectively a soft (stiff) equation of state means more (less) compact neutron stars corresponding to lower (higher) maximum mass. Unfortunately the supra-nuclear matter equation of state is not known exactly despite progress by different methods: simultaneous measurement of neutron star mass and radius, e.g., (Miller et al. 2019; Lattimer & Prakash 2001; Miller et al. 2019; Raaijmakers et al. 2020; Riley et al. 2019; Bogdanov et al. 2019); combination of gravitational tidal effect and EM data, e.g., (Radice & Dai 2018; Dietrich et al. 2020; Landry et al. 2020; Breschi et al. 2021); or by a combination of nuclear physics and multi-messenger astronomy observations, e.g., (Capano et al. 2020; Dietrich et al. 2020; Essick et al. 2020b).

As stated above, the mass ejecta is a key ingredient in the derivation of kilonova lightcurves. However, numerical simulations relying on General Relativity are required to estimate this quantity. Despite the existence of such calculations (e.g., Goriely et al. 2011; Rosswog et al. 2014; Grossman et al. 2014; Tanaka & Hotokezaka 2013; Dietrich et al. 2018; Radice et al. 2018a; Bovard et al. 2017; Shibata et al. 2017; Foucart et al. 2019), they are computationally expensive, and cannot be performed directly in the minutes following a GW alert. For this reason, groups have proposed fits for the ejecta mass based on numerical-relativity simulations for both BNS mergers, e.g., Dietrich & Ujevic (2017); Radice et al. (2018a); Coughlin et al. (2018a); Dietrich et al. (2020); Nedora et al. (2020), and NSBH mergers, e.g., Foucart (2012); Kawaguchi et al. (2016); Foucart et al. (2018); Krüger & Foucart (2020). The present paper aims to put together such existing tools as well as parametrized kilonova lightcurve models (Kasen et al. 2017; Bulla 2019) in order to predict EM counterparts based on only low-latency GW pipeline signal-to-noise distributions over the template bank.

The remainder of the paper is structured as follows: In Section 2, we discuss the GW low-latency analysis and the current parameters released to aid observers. Section 3 presents how we convert component binary parameters to mass ejecta and we discuss the two models that we employ in the computation of kilonova lightcurves in Section 4. We validate our method on GW events from recent LIGO-Virgo Observing Runs in Section 5. We summarize the performance of this tool and suggest improvements for future work in Section 6.

## 2 ADDRESSING THE POINT ESTIMATE UNCERTAINTIES

MBTA (Aubin et al. 2020) is a modeled search pipeline based on matched filtering, which compares the inspiral waveforms from a “bank” of the templates to the data. Templates are distributed across the parameter space such that any point has a good match with at least one of the templates of the bank, the minimal match value being typically 97% (for GW170817 we used here 99%). The template bank is therefore a rather uniform sampling of the parameter space. This template bank is applied separately to each detector; coincident triggers are those that share the same template parameters and have time delays consistent with astrophysical sources.

MBTA splits this analysis in two or more frequency bands, i.e., instead of comparing all the frequency components of the data to those of the template, the frequency band of the detector data and templates are split into multiple bands.<sup>2</sup> The matched filter is computed within each band, and the signal-to-noise ratio corresponding to the different bands are combined to assign an overall statistical significance to the template. This procedure reduces the computational cost such that the pipeline is able to analyze the LIGO-Virgo data with a sub-minute latency using modest computing resources (about 150 cores). It is worth mentioning the analysis pursued in this work should apply equally well to all low-latency pipelines.

### 2.1 Template uncertainties

As mentioned previously, during observing runs O2 and O3, the low-latency alerts released by the LVC consisted of the binary parameters of the template with the highest statistical significance. In Table 1, these parameters are displayed for GW170817, GW190425, and GW190814. The reason we focus on these events is that they are the unambiguously confirmed binary systems which have a non-negligible probability to possess at least one neutron star. However, for the present work, we consider not only the “best” template, with corresponding  $\text{SNR}_{\text{max}}$ , but all templates with signal-to-noise ratio,  $\text{SNR} > \text{SNR}_{\text{max}} - 3$ ,  $\text{SNR}_{\text{max}}$  is the signal-to-noise ratio of the “best” template. The motivation for this choice is the desire to realize a rapid parameter estimation based on these neighbourhood templates which are within three standard deviations of the best template and therefore capture 99.7% of the parameters information.

### 2.2 Using multiple templates

For one event, MBTA provides the list of templates that have been triggered, with their SNR. For each of them, a weight,  $w$ , is given to capture the probability that this template is the most likely to describe the event. It is based on the SNR of the template  $i$  relative to the maximum SNR:  $\text{dSNR} = \text{SNR}_{\text{max}} - \text{SNR}_i$ , that is the number of standard deviations for this template compared to the best template. The

<sup>2</sup> Other pipelines also perform multi-band analyses, an example being Sachdev et al. (2019).

**Table 1.** The MBTA preferred templates that maximize the signal-to-noise ratio for GW170817, GW190425, and GW190814. We include the name of the event, the mass of the more massive compact object,  $m_1$ , the mass of the lighter compact object,  $m_2$ , the chirp mass  $m_{\text{chirp}}$ , the mass ratio  $q$ , the projection of the heavier binary component’s spin in the direction of the orbital angular momentum  $s_1$ , the projection of the lighter binary component’s spin in the direction of the orbital angular momentum  $s_2$ .

Event	$m_1$ ( $M_\odot$ )	$m_2$ ( $M_\odot$ )	$m_{\text{chirp}}$ ( $M_\odot$ )	$q$	$s_1$	$s_2$	$\chi_{\text{eff}}$
GW170817	1.674	1.139	1.198	0.680	0.040	0.000	0.024
GW190425	2.269	1.305	1.487	0.575	0.080	-0.010	0.047
GW190814	36.881	2.093	6.522	0.057	0.340	0.960	0.373

weights are computed by sorting the templates by increasing dSNR, and then getting the difference of the error function with the following template:  $w_i = \text{erf}(\text{dSNR}_{i+1}/\sqrt{2}) - \text{erf}(\text{dSNR}_i/\sqrt{2})$ . Before being used, the weights are smoothed by averaging them with their two adjacent templates in dSNR. With this procedure, the sum of all weights is one. We will use the weights as the “significance” measure for a given template.

The input data is represented by a list of templates, which is a 5-tuple  $(m_1, m_2, s_1, s_2, w)$ , where  $m_1, m_2$  ( $m_1 \geq m_2$ ) are the masses of the binary components,  $s_1, s_2$  are the projections of the spins onto the direction of the orbital angular momentum, and  $w$  is the normalized weight. In Table 2 we list the median, lower and upper limits for the binary parameters obtained by this procedure. The corresponding values obtained by the more expensive offline parameter estimation method (Veitch et al. 2015) (hereafter PE) are also presented. One can observe that there is a very good similarity (at most a few percent deviation) between PE and our method for  $m_{\text{chirp}}$ . On the other hand the mass ratio and effective spin distributions can be very different (more than 100% in the case of GW190814). One could imagine different ways to address the problem of these latter distributions. A possibility might be to consider a population prior based on the already detected binary compact merger events as suggested in, e.g., Essick & Landry (2020); Fishbach et al. (2020b,a); Mandel (2010); Abbott et al. (2020a), however this procedure might introduce additional biases if yet unobserved populations of compact binaries exist.

In the following, the intrinsic masses and spins estimated here will be used for the computation of the mass and the velocity of ejecta in Section 3. It is worth mentioning that over the past years several rapid parameter estimation efforts have been realized, e.g., (Pankow et al. 2015; Lange et al. 2018; Smith et al. 2020).

### 3 DYNAMICAL AND DISK WIND EJECTA FROM TEMPLATES

Two important features of a kilonova lightcurve are the overall luminosity and the relative colors in the photometric bands. The former is related to the amount of matter as well as the object’s distance, while the latter is related to its composition, such as the lanthanide fraction, and viewing angle to the binary. The mass of the unbound material ejected from the system is a key parameter for the computation of kilonova lightcurves. The ejecta mass and further ejecta properties depend on both the nature of the binary – a BNS, NSBH, or BBH – and the supra-nuclear equation of state describing the neutron star material.

#### 3.1 Equation of state of neutron star

Low latency / near real-time GW searches do not provide information concerning the compactness of the compact objects. But, for a fixed equation of state that does not support twin stars, fixing the mass of a neutron star fixes the baryonic mass  $m^{\text{bar}}$ . Equally, it fixes the radius  $R$  and also the compactness by means of the relation  $C = \frac{Gm}{Rc^2}$ , where  $G$ ,  $m$ , and  $c$  are the gravitational constant, the mass of the compact object, and the speed of light in vacuum. In the literature, there are several equation of state candidates. One possibility is to assume a popular one, e.g. Douchin & Haensel (2001), or to sample a number of equations of state simultaneously, e.g., Landry & Essick (2019); Capano et al. (2020); Dietrich et al. (2020). We do the latter using the 4-parameter spectral representation of the equation of state presented in Abbott et al. (2018a).

For every  $(m_1, m_2)$ , we sample independently the compactness for each component. To do so, we marginalize over the 2396 GW170817-like equations of state presented in Abbott et al. (2018a). For each equation of state, the compactnesses  $C_1 = C(m_1)$  and  $C_2 = C(m_2)$ , as well as the baryonic mass of the lighter object  $m_2^{\text{bar}} = m^{\text{bar}}(m_2)$  are calculated, and a maximum neutron star mass is prescribed. For each sample, if one of the components has a mass higher than this threshold (defined by the equation-of-state dependent maximum neutron star mass), it is considered to be a black hole.<sup>3</sup> This allows us to put each sample in one of the three categories: BNS, NSBH, and BBH. This marginalization procedure yields a list of 7-tuples  $(q, m_{\text{chirp}}, \chi_{\text{eff}}, C_1, C_2, m_2^{\text{bar}}, f)$ , where  $f \in \{0, 1, 2\}$  stands for the type of binary: BNS ( $f = 0$ ) or NSBH ( $f = 1$ ) or BBH ( $f = 2$ ). The size of this list of samples is equal to the number of initial MBTA templates times 2396 (the number of equations of states). For those samples consistent with being BBHs, we assume that there are no ejecta. For the BNS and NSBH cases, we calculate the ejecta mass and velocity as described in the following.

#### 3.2 Ejecta parameters: BNS

In general, there are (at least) two ejecta mass components contributing to the kilonova: the dynamical ejecta and the disk mass. We follow Dietrich et al. (2020) and use the formula  $m_{\text{ej}} = M_{\text{ej}}^{\text{dyn}} + \zeta M_{\text{disk}}$  to represent the ejecta proportions. Here,  $M_{\text{ej}}^{\text{dyn}}$  stands for the mass of the dynamical ejecta, and  $M_{\text{disk}}$  stands for the disk mass. From the disk a fraction of matter ( $\zeta$ ) will become unbound through disk winds

<sup>3</sup> Note that spinning NSs can support  $\sim 20\%$  more mass (Breu & Rezzolla 2016), but we neglect this as all known Galactic NS have relatively low spins.

**Table 2.** The median, the upper limits (90th percentile) and the lower limits (10th percentile) for GW170817, GW190425 and GW190814 parameters for the chirp mass  $m_{\text{chirp}}$ , the mass ratio  $q$ , and the effective spin  $\chi_{\text{eff}}$ . These quantities are obtained from the set of templates generated as explained in Section 2.2. The same quantities obtained from offline PE posteriors are also illustrated for comparison. A missing  $m_{\text{chirp}}$  upper/lower limit means that the deviation from the median value is less than  $0.001M_{\odot}$ . The waveforms used for the generation of PE posteriors for GW170817, GW190425, and respectively GW190814 are *IMRPhenomPv2\_NRTidal*, (Dietrich et al. 2017, 2019), *TaylorF2* (Blanchet 2014; Sathyaprakash & Dhurandhar 1991; Vines et al. 2011), and respectively *SEOBNRv4\_ROM\_NRTidalv2\_NSBH* (Matas et al. 2020).

Event	MBTA			PE		
	$m_{\text{chirp}}$ ( $M_{\odot}$ )	$q$	$\chi_{\text{eff}}$	$m_{\text{chirp}}$ ( $M_{\odot}$ )	$q$	$\chi_{\text{eff}}$
GW170817	1.198 $_{-0.001}$	0.756 $^{+0.068}_{-0.157}$	0.029 $^{+0.017}_{-0.018}$	1.198	0.853 $^{+0.117}_{-0.139}$	0.003 $^{+0.014}_{-0.007}$
GW190425	1.487 $^{+0.001}_{-0.002}$	0.784 $^{+0.121}_{-0.229}$	0.026 $^{+0.024}_{-0.056}$	1.487	0.898 $^{+0.082}_{-0.127}$	0.011 $^{+0.011}_{-0.009}$
GW190814	6.474 $^{+0.125}_{-0.134}$	0.058 $^{+0.178}_{-0.008}$	0.321 $^{+0.094}_{-0.817}$	6.409 $^{+0.040}_{-0.026}$	0.109 $^{+0.017}_{-0.026}$	0.008 $^{+0.153}_{-0.088}$

caused by several physical phenomena, e.g., neutrino radiation, magnetic-driven winds, or the redistribution of angular momentum. We assume, based on numerical-relativity simulations, that  $\zeta = 0.15$  of the entire disk mass gets gravitationally unbound and ejected from the system, e.g., (Fernández et al. 2015; Siegel & Metzger 2018; Fernández et al. 2019; Christie et al. 2019).

To estimate the dynamical ejecta, we use the fitting formula from Coughlin et al. (2019a):

$$\log_{10} M_{\text{ej}}^{\text{dyn}}(M_{\odot}) = \left[ a \frac{(1-2C_1)m_1}{C_1} + b m_2 \left( \frac{m_1}{m_2} \right)^n + \frac{d}{2} \right] + [1 \leftrightarrow 2],$$

where  $m_1$  and  $C_1$  (respectively  $m_2$  and  $C_2$ ) are the mass and the compactness of the heavier (respectively lighter) binary component, and  $a = -0.0719$ ,  $b = 0.2116$ ,  $d = -2.42$ ,  $n = -2.905$  are fitting coefficients. To estimate the disk mass, we use the fitting formula from Dietrich et al. (2020):

$$\log_{10} M_{\text{disk}}(M_{\odot}) = \max \left( -3, a \left( 1 + b \tanh \left( \frac{c - (m_1 + m_2)/M_{\text{thresh}}}{d} \right) \right) \right),$$

the floor value of  $10^{-3}M_{\odot}$  is added as it is difficult to resolve smaller masses in numerical relativity (see, e.g., Dietrich & Ujevic (2017); Radice et al. (2018a)). Here,  $M_{\text{thresh}}$  is the minimum total mass such that the prompt collapse occurs after the coalescence of the two neutron stars; this expression is calculated as in Bauswein et al. (2013b). While the parameters  $c = 70.953$  and  $d = 0.0417$  are fixed, the parameters  $a$  and  $b$  are not constant but mass ratio dependent; cf. Dietrich et al. (2020) for a detailed discussion.

For comparison, in Nedora et al. (2020), the disk and dynamical masses are calculated by means of a formula using mass ratio and the tidal deformability  $\tilde{\Lambda}$ . An illustration of the ejecta dependence on the binary component masses, as well as a comparison to the predictions of this latter model, is illustrated in Figure 1. This demonstrates broad qualitative consistency, but differences of  $\sim 100\%$  between different predictions are common. This is mainly due to different sets of numerical-relativity simulations that are used for the calibration and different functional forms for the phenomenological fits. In addition, one has to point out that while the numerical-relativity simulations provide a description of the merger and postmerger dynamics and are capable of predicting (to some extent) the amount of ejecta, the individual predictions are usually connected to large uncertainties due to, among others, (i) the absence of an accurate microphysical modelling of the fluid as well as the inclusion of magnetic fields, (ii) the complications during the simula-

tion of the relativistic fluids, when shocks and discontinuities form, (iii) inaccuracies during the simulation of the expanding and decompressing ejected material, and (iv) a limited set of numerical simulation that do not cover the entire BNS parameter space. Nonetheless, some relations between the binary parameters and the amount of ejecta are noticeable and we find that lower compactness and/or smaller individual masses produce in general more ejecta.

We also compute the velocity of the ejecta. Following Coughlin et al. (2019a), we use  $v_{\text{ej}} = \left[ a(1+c) C_1 \frac{m_1}{m_2} + \frac{b}{2} \right] + [1 \leftrightarrow 2]$ , where fit coefficients are  $a = -0.3090$ ,  $b = 0.657$  and  $c = -1.879$ . The result in this formula is expressed in units of the speed of light.

### 3.3 Ejecta parameters: NSBH

Similar to the BNS merger case, we assume that NSBH ejecta have (at least) two components: the dynamical ejecta and disk wind ejecta. In a NSBH system, the only baryonic matter responsible for any EM signature is the one contained in the neutron star, i.e.,  $m_2^{\text{bar}}$ . As in the BNS case, we assume that 15% of the disk mass becomes gravitationally unbound over time, where the disk mass is estimated according to Foucart et al. (2018) as

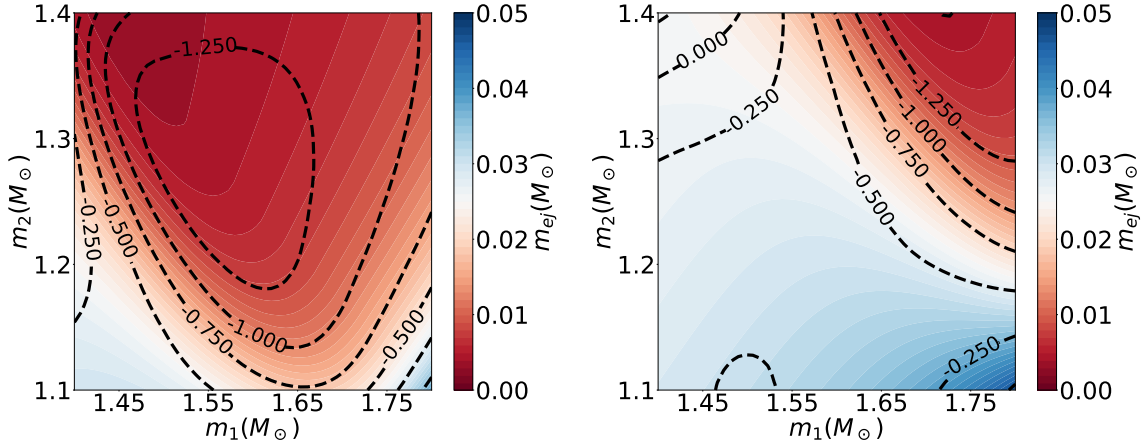
$$M_{\text{disk}}(M_{\odot}) = m_2^{\text{bar}} \max \left( 0, \alpha \frac{1-2C_2}{\eta^{1/3}} - \beta r_{\text{ISCO}} \frac{C_2}{\eta} + \gamma \right)^{\delta},$$

with  $m_2^{\text{bar}}$ ,  $C_2$ ,  $\eta = \frac{m_1 m_2}{m_1 + m_2}$ , and  $r_{\text{ISCO}}$  being the baryonic mass of the neutron star, the compactness of the neutron star, the reduced mass, and the innermost stable circular orbit. The coefficients are  $\alpha = 0.4064$ ,  $\beta = 0.1388$ ,  $\gamma = 0.2551$ , and  $\delta = 1.7612$ . The mass of the dynamical ejecta is calculated from Krüger & Foucart (2020)

$$M^{\text{dyn}}(M_{\odot}) = m_2^{\text{bar}} \left( a_1 \left( \frac{m_1}{m_2} \right)^{n_1} \frac{1-2C_2}{C_2} - a_2 \left( \frac{m_1}{m_2} \right)^{n_2} \frac{r_{\text{ISCO}}}{m_1} + a_4 \right).$$

In this formula,  $m_1$  is the mass of the black hole and the fitting coefficients are  $a_1 = 0.007116$ ,  $a_2 = 0.001436$ ,  $a_4 = -0.02762$ ,  $n_1 = 0.8636$  and  $n_2 = 1.6840$ .

The dependence of mass ejected with the various parameters is illustrated in Figure 2. One can easily observe that the higher the effective spin, the higher the mass ejecta. At very high inverse mass ratios, for a constant  $m_2$ , the neutron star is swallowed by the black hole before being dis-



**Figure 1.** In color we show the predicted mass ejecta obtained by our model for BNS mergers with different binary component masses. The level lines show the relative difference which exists between our model and the one from (Nedora et al. 2020). The quantity illustrated by those lines is  $2(m_{\text{ej}} - m_{\text{ej}}^{\text{NEA}})/(m_{\text{ej}} + m_{\text{ej}}^{\text{NEA}})$ , where  $m_{\text{ej}}^{\text{NEA}}$  is the predicted mass ejecta computed by the model in (Nedora et al. 2020). Each side (left and right) corresponds to an equation of state. The right plot correspond to less compact objects.

rupted; cf. Shibata & Taniguchi (2011); Foucart (2020) and references therein for a detailed description.

We also compute the velocity of the ejecta. Following Kawaguchi et al. (2016):  $v_{\text{ej}} = \alpha \frac{m_1}{m_2} + \beta$  with  $\alpha = 0.01533$  and  $\beta = 0.1907$ . The result in this formula is expressed in units of the speed of light.

#### 4 LIGHTCURVES

Once the calculations presented in the previous section are done we have 2396 times  $n_{\text{templates}}$  ( $m_{\text{ej}}, v_{\text{ej}}$ ) tuples, where  $n_{\text{templates}}$  stands for the number of MBTA templates. This set is downsampled to a set of size 1,000 for computational cost reasons. The value 1,000 is justified by the similarity between the  $m_{\text{ej}}$  distributions of the initial and the downsampled set. Such a size of the downsampled set allows an overlap higher than 80% between the initial and the new mass ejecta distributions in the case of GW170817 and GW190425. We now use lightcurve models to translate the ejecta properties into observed lightcurves. We use the lightcurve models proposed in Kasen et al. (2017) (hereafter *Model I*) and Bulla (2019) (hereafter *Model II*). These are radiative transfer simulations predicting lightcurves and spectra, based on the wavelength-dependent emissivity, and opacity taking place at the atomic scale. In particular, we use the surrogate technique first presented in Coughlin et al. (2018b) to create a grid of lightcurves in the photometric bands  $u$ ,  $g$ ,  $r$ ,  $i$ ,  $z$ ,  $y$ ,  $J$ ,  $H$ , and  $K$  for a set of model parameters. Using Gaussian Process Regression, one can predict the lightcurve for any input parameters. A common parameter for the two models is the total ejecta mass, i.e., the sum of the dynamical and wind ejecta. That is equivalent to saying that we use the 1-component ejecta model presented in Coughlin et al. (2018b), i.e., the EM signal luminosity is calculated at once for the entire ejected matter. This is contrary to the case of 2-component model where the brightness due to disk winds and dynamical ejecta are calculated separately and added up a posteriori. Therefore the statistical errors regarding the 2-

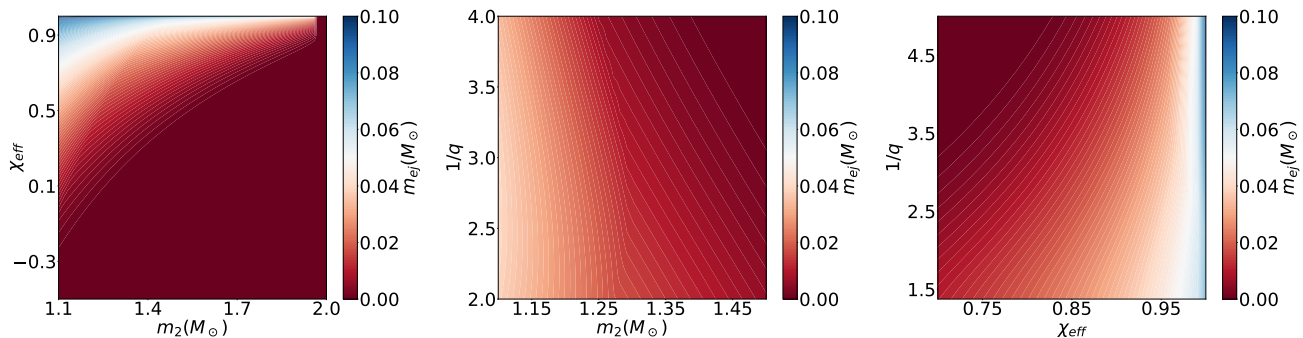
component model are already large enough that this choice does not make a difference; cf. e.g. (Kawaguchi et al. 2019; Heinzel et al. 2020) for a discussion about uncertainties and viewing angle dependencies of the kilonova signal. In addition, for *Model II* we use the grid first presented in Coughlin et al. (2020a), but extended to better cover the lower- and upper-mass end (it goes from  $10^{-6}M_{\odot}$  to  $1M_{\odot}$ ). This upgrade will be made publicly available.<sup>4</sup> It is noteworthy to mention that for all the lightcurves presented in this section, two extra magnitude errors have been added, i.e. the upper (lower) magnitude limits have been raised (lowered) by 1, in order to be robust against twice the errors in thermalization rate and/or ejecta geometry.

##### 4.1 *Model I* lightcurve model

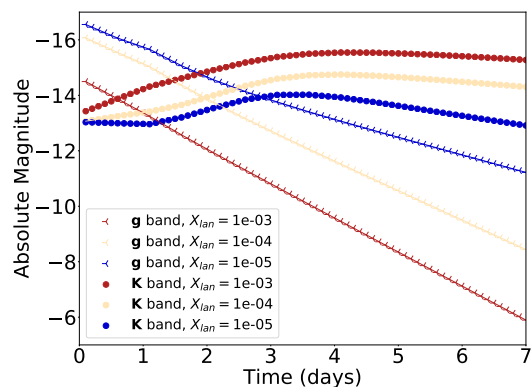
*Model I* presented in Kasen et al. (2017) solves the relativistic radiation transport Boltzmann equation governing the interior of a radioactive plasma. In this way, both the thermal and spectral-lines radiation determine the final wavelength-dependent luminosity and timescale of the lightcurve. *Model I* lightcurve is a function of  $m_{\text{ej}}, v_{\text{ej}}$  and  $X_{\text{lan}}$ , where  $m_{\text{ej}}$  is the ejected mass,  $v_{\text{ej}}$  is the velocity of the ejecta, and  $X_{\text{lan}}$  is the lanthanide fraction. The effects of the first two parameters are simple and intuitive: the higher the amount of ejecta, the brighter and longer-lasting is the electromagnetic signal; meanwhile the higher the speed of the ejecta; the brighter and shorter (the ejecta is expanding faster) is the kilonova. The latter parameter  $X_{\text{lan}}$  expresses the composition of the ejecta and controls the opacity at the atomic scale. Therefore, for ejecta containing heavier elements, the density of spectral lines is larger. This aspect will imply a higher opacity and with that a fading of the brightness on larger timescales.

We compute  $m_{\text{ej}}$  and  $v_{\text{ej}}$  as described in Section 3;  $X_{\text{lan}}$ , on the other hand, requires further assumptions. In general,

<sup>4</sup> [https://github.com/mbulla/kilonova\\_models](https://github.com/mbulla/kilonova_models)



**Figure 2.** Amount of ejected mass (in color axis) for NSBH mergers with different binary characteristics.  $\chi_{\text{eff}}$  versus  $m_2$ , keeping  $1/q = m_1/m_2 = 2$  (left panel); inverse mass ratio  $1/q$  versus neutron star mass  $m_2$ , keeping  $\chi_{\text{eff}} = 0.6$  (middle panel); and  $1/q$  versus  $\chi_{\text{eff}}$  at constant  $m_2 = 1.6M_{\odot}$  (right panel). These simulations use the same equation of state.



**Figure 3.** Absolute magnitude versus time for kilonovae with different lanthanide percentage  $X_{\text{lan}}$ , as predicted by *Model I*. For all the lightcurves the values of mass ejecta and velocity of ejecta are set to  $m_{\text{ej}} = 0.05M_{\odot}$  and  $v_{\text{ej}} = 0.15c$ . The plot corresponds to the ‘g’ and ‘K’ photometric bands. The x axis origin corresponds to the merger time.

a larger  $X_{\text{lan}}$  yield redder lightcurves. In Figure 3, there is an example of the dependence of lightcurve with lanthanide fraction. One can observe that an uncertainty in  $X_{\text{lan}}$  of 3 orders of magnitude leads to an uncertainty in the ‘g’ band of more than 2 (respectively 5) magnitudes at the end of the first (seventh) day .

#### 4.2 *Model II* lightcurve model

*Model II* (Bulla 2019; Coughlin et al. 2020a) is also based on Monte-Carlo radiative transfer simulations. Unlike *Model I*, which is 1D and has geometry-independent parameters, *Model II* is 2D, i.e., axisymmetric, and the ejecta are considered to have two components with different compositions and whose locations are determined with respect to the geometry of the binary. Therefore, the EM signal depends on the position of the external observer, i.e., the viewing angle. In this model, one component is lanthanide-rich and is situated around the plane of the merger, whereas a second component is lanthanide-free and positioned at higher latitudes. The interplay between the two components is captured by

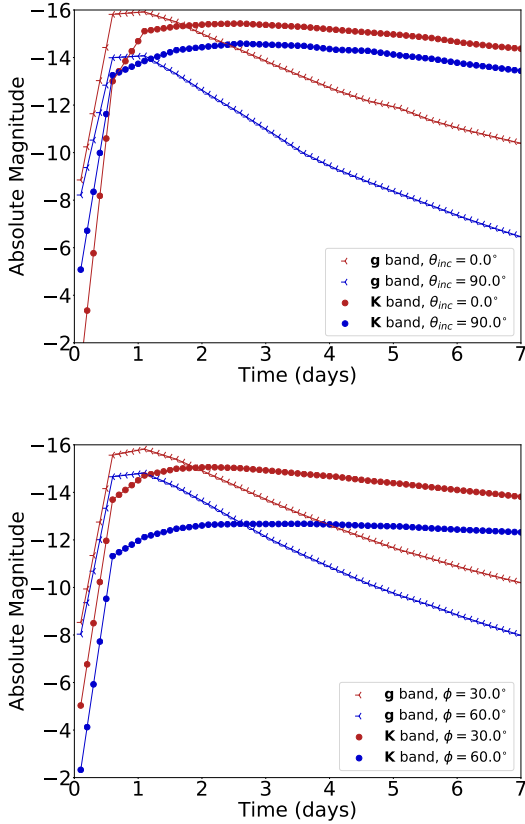
the half opening angle of the lanthanide-rich component,  $\Phi$ , while the position of the observer is controlled by the viewing angle  $\theta_{\text{inc}}$ .

The two models differ in their considerations of ejecta opacities. While in *Model I* the lanthanide fraction can take whatever value and the opacities are calculated correspondingly, in *Model II* the composition of the two ejecta components are fixed and for simplicity we assume just two different compositions and corresponding opacities (one for each component, see (Bulla 2019)).

*Model II* depends on the following parameters:  $m_{\text{ej}}$ ,  $\theta_{\text{inc}}$ , and  $\phi$ , where  $m_{\text{ej}}$  is as above the total mass of the ejecta. Because MBTA samples do not provide  $\theta_{\text{inc}}$  for O2 and O3, and there is no imprint of  $\Phi$  in the GW signal, some additional assumptions are necessary. For illustration purposes, Figure 4 shows the dependence of the EM lightcurves for different prior choices, where an increase in the opening angle reddens the lightcurve, whereas an increase in the inclination angle will lower the luminosity and redden the signal.

## 5 DEMONSTRATION ON REAL EXAMPLES

In this section, we demonstrate the output of our tool on the following O2/O3a LIGO-Virgo GW events: GW170817 (Abbott et al. 2017b), GW190425 (Abbott et al. 2020b), and GW190814 (Abbott et al. 2020c). GW170817 and GW190425 are BNSs, while GW190814 is either a NSBH or a BBH; cf. the discussion in e.g. (Abbott et al. 2020c; Essick & Landry 2020; Most et al. 2020; Tews et al. 2020; Tan et al. 2020). It is worth mentioning that more than 98% of the time needed for the code to run is used in the equation of state marginalization (presented in Section 3) and lightcurve generation (presented in Section 4) processes. More precisely with a single *E5-2698 v4* processor, we need on average 6.204s for the equation of state marginalization and 0.198s (respectively 0.471s) for the computation of a *Model I* (respectively *Model II*) lightcurve, if only one core is used. In this case the total necessary time to convert the input low-latency data into kilonova lightcurves is around  $198s + 6.204s \times n_{\text{templates}}$  (respectively  $471s + 6.204s \times n_{\text{templates}}$ ) when *Model I* (respectively *Model II*) is used. In the preceding expression  $n_{\text{templates}}$  is the number of input MBTA templates, which typically is  $O(10)$ . We note, though, that



**Figure 4.** Absolute magnitude versus time for kilonovae with different inclination angles  $\theta_{inc}$  (top) and opening angles  $\phi$  (bottom) as expected in 'g' and 'K' photometric passband and as predicted by *Model II*. For the top plot, we set  $m_{ej} = 0.05M_{\odot}$  and  $\phi = 45^{\circ}$ , while for the bottom plot we set  $m_{ej} = 0.05M_{\odot}$  and  $\theta_{inc} = 45^{\circ}$ . On both sides, the x axis origin corresponds to the merger time.

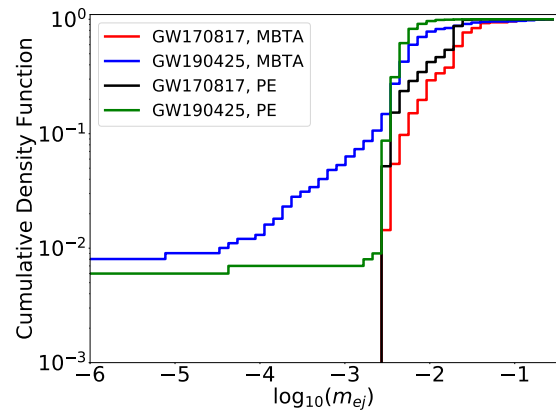
this computation is easily parallelizable and latency could be reduced. For example, when the same processor is used with 8 cores, the times required for the equation of state marginalization, *Model I* and *Model II* lightcurve computations become 0.975s, 0.059s and 0.249s which means that the overall code is executed in around  $59s + 0.975s \times n_{templates}$  (respectively  $249s + 0.975s \times n_{templates}$ ) if *Model I* (respectively *Model II*) is employed.

### 5.1 Comparison of ejecta mass and *HasEjecta*

As stated above, each binary system sample has a value for the ejecta mass  $m_{ej}$ . To estimate the fraction of samples with potentially detectable ejecta, we define *HasEjecta*, the percentage of samples having  $m_{ej} > 3 \times 10^{-4}M_{\odot}$ . The value of this threshold is argued by the fact that  $1.5 \times 10^{-4}M_{\odot}$  is the minimum mass ejecta for a BNS (based on the disk wind mass fit), and as a consequence we consider that a configuration produces noticeable ejecta when the total ejecta is at least twice as large as this default value. The definition of *HasEjecta* is similar to that of *HasRemnant* (Chatterjee et al. 2020), a low-latency data based product provided by the LVC. In Table 3, we compare *HasRemnant* and *HasEjecta* calculated in two ways: (i) the MBTA samples de-

**Table 3.** Values of *HasRemnant* (second column) and *HasEjecta*, based on both MBTA (third column) and PE (fourth column) samples, for the O2/O3a compact binary coalescence events: GW170817, GW190425 and GW190814. The values of *HasRemnant* for GW190425 and GW190814 triggers are taken from (LIGO Scientific Collaboration & Virgo Collaboration 2019a) and (LIGO Scientific Collaboration & Virgo Collaboration 2019b). Given the fact that *HasRemnant* has been introduced at the beginning of O3, for the GW170817 *HasRemnant* we had to assume the same value as for *EM-Bright* reported in (B. P. Abbott et al. 2019). Regarding the PE results, the waveforms used for GW170817, GW190425, and respectively GW190814 are *IMRPhenomPv2\_NRTidal*, (Dietrich et al. 2017, 2019), *TaylorF2* (Blanchet 2014; Sathyaprakash & Dhurandhar 1991; Vines et al. 2011), and respectively *SEOBNRv4\_ROM\_NRTidal* (Matas et al. 2020).

Event	HasRemnant	MBTA HasEjecta	PE HasEjecta
GW170817	100%	100%	100%
GW190425	> 99%	98%	>99%
GW190814	< 1%	0%	0%



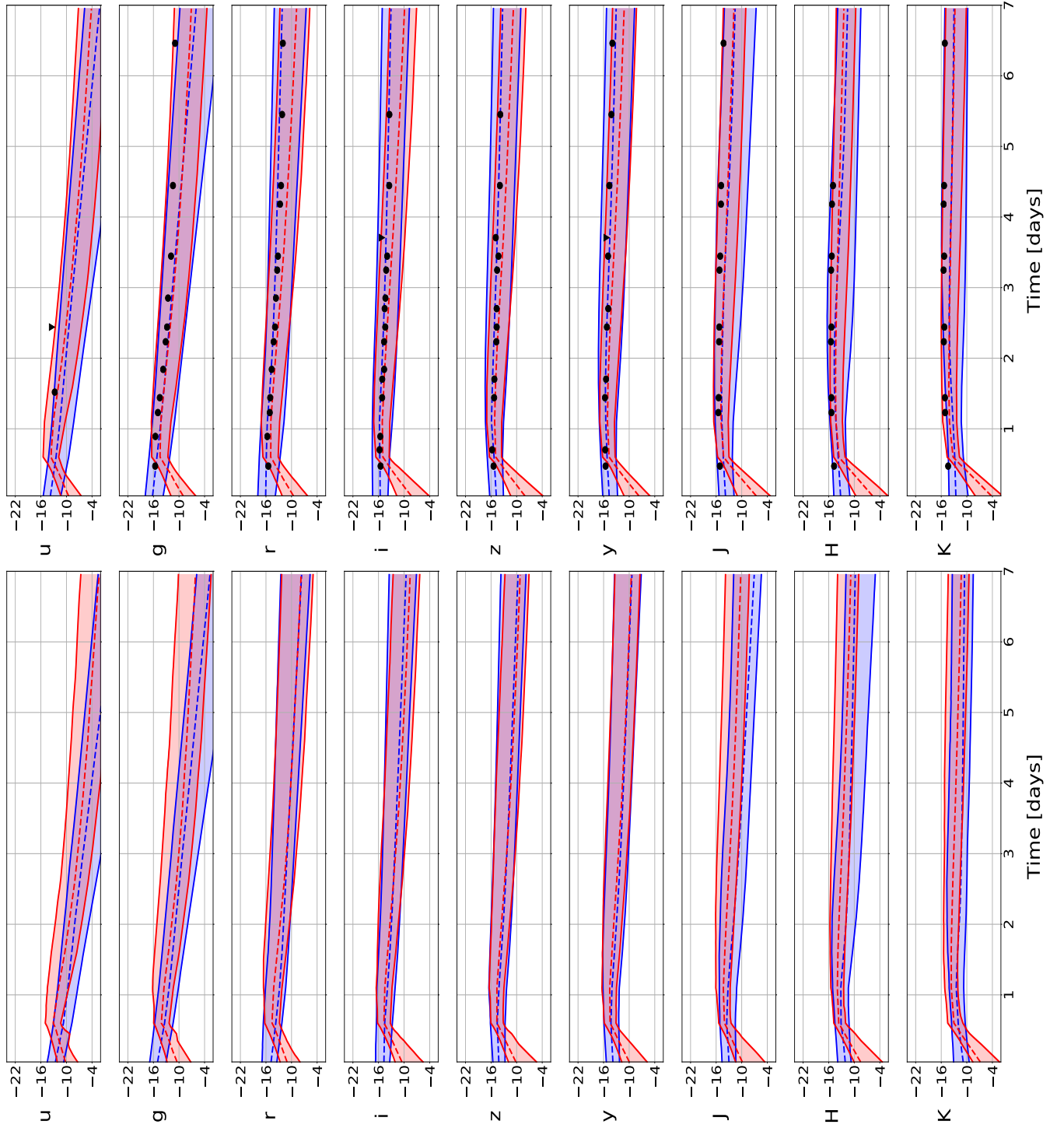
**Figure 5.** Cumulative distribution function of the ejected mass  $m_{ej}$  for the following GW triggers: GW170817, GW190425. There are both the low-latency results (the input data is represented by the MBTA weighted templates) and the PE results (the input data is represented by the offline PE (Veitch et al. 2015) posteriors).

scribed in Section 2, and (ii) sampling the waveform model posteriors of PE results. From this table, the three quantities give consistent results. From the list of three events mentioned at the beginning of this section, only two of them (GW170817 and GW190425) have non-negligible *HasEjecta*. Therefore in Figure 5 there is an illustration of mass ejecta  $m_{ej}$  distribution for GW170817 and GW190425. This figure suggests that the low-latency based method presented in this paper reproduces fairly well the predictions one could get by means of the offline PE posteriors, however, further studies of other events are required for a final conclusion.

### 5.2 Lightcurve predictions

In Figure 6, we illustrate the corresponding lightcurves employing both *Model I* and *Model II*. Regarding *Model I*, we set the lanthanide fraction for this analysis to  $X_{lan} = 10^{-4}$  (consistent with the results presented in Coughlin et al. (2018b)), while concerning *Model II*, we use a uniform prior



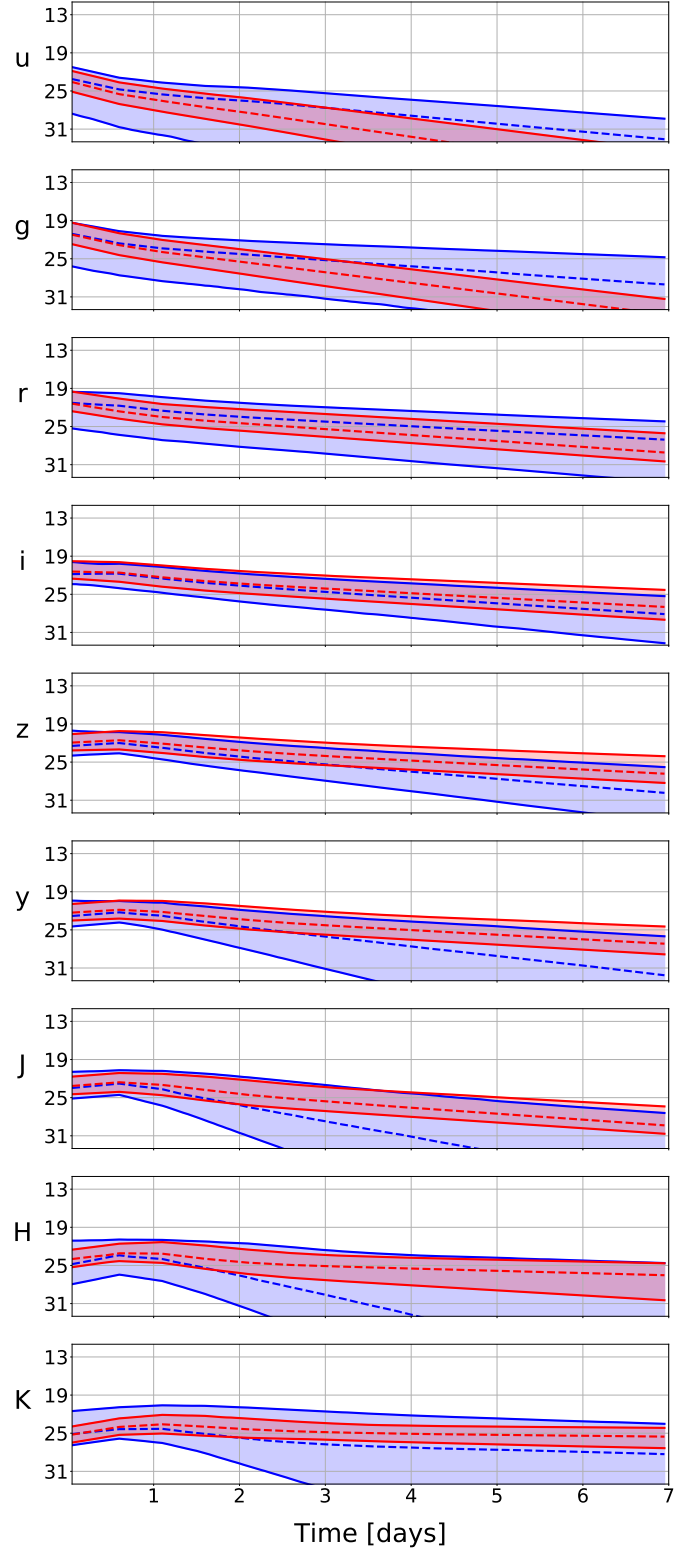


**Figure 6.** Kilonova lightcurves (absolute magnitude versus time) predicted by *Model I* (in blue) and *Model II* (in red) for  $u, g, r, i, z, y, J, H, K$  photometric bands. The predicted lightcurve for GW170817 (top) and for GW190425 (bottom). For each filter there are three curves plotted: the upper solid line, the middle dashed line and respectively the lower solid line represent the 90th, 50th and respectively the 10th percentiles. In the case of GW170817 the circle and triangle symbols in black illustrate the measured optical points of AT2017gfo. The circle symbols are measure points with finite uncertainty, while triangle symbols are upper limits. The prior  $X_{\text{lan}} = 10^{-4}$  (respectively  $\Phi = 45^\circ$  and  $\cos\theta_{\text{mc}}$  uniform in  $[0,1]$ ) is used for *Model I* (respectively *Model II*).

in  $\cos\theta_{\text{inc}}$ , for the inclination angle  $\theta_{\text{inc}}$ , and we fix  $\Phi = 45^\circ$  (consistent with the results presented in (Dietrich et al. 2020)). A significant difference between the two models, clearly highlighted by Figure 6, concerns the first half day following the kilonova. *Model I* lightcurves present a small (negative for the lower wavelengths and positive for the higher wavelengths) slope, while *Model II* has a more pronounced raising shape.

One can observe a good agreement between the real data and our predictions in the case of GW170817. Almost all the observational points are included in between the upper and lower limits in the case of *Model I*, whereas the predictions from *Model II* are missing a few more points in the first half day. Nevertheless the agreement could be strengthened by choosing other parameters ( $X_{\text{lan}}$ ,  $\theta_{\text{inc}}$ ,  $\Phi$ ), which are not constrained by the GW data and/or our compact objects understanding. Also, this suggests that the uncertainty presented here could be significantly underestimated because we fixed these parameters. The *Model I* predictions for GW190425 show that it is less bright than GW170817. Indeed, predictions for GW190425 are at least 1 magnitude higher (i.e., dimmer) in almost all photometric bands after only 1 hour, and at least 3 magnitude higher after 3 days. This fact corroborated with the broad skymap localization (LIGO Scientific Collaboration & Virgo Collaboration 2019a) could explain the non-detection of an EM counterpart for GW190425.

In order to convert absolute magnitude in apparent magnitude, we use the distance in the form of the distance modulus:  $m - M = 5 \log_{10} d_L - 5$ , where  $m, M, d_L$  are the apparent magnitude, the absolute magnitude, and the luminosity distance expressed in units of pc. Here, we will use LIGO-Virgo-Kagra based low-latency products which contain the required distance information. One of the data released in low-latency is the Bayestar skymap (Singer & Price 2016); this skymap provides an array of sky coordinates, each of them being assigned with a localization probability, a luminosity distance and a distance uncertainty. From this skymap a mean distance is calculated. It is worth mentioning that the luminosity distance uncertainty is not taken into account for the calculation of the lightcurve contours. For example the Bayestar distance relative error for GW170817, GW190425, and GW190814 is less than 0.3 which translates to an uncertainty on the apparent magnitude of less than 0.7 magnitudes. Nonetheless, this value is not negligible, as it represents  $\sim 20\%$  of the total error budget. This suggests that the uncertainty stated here is underestimated. In Figure 7 there is an example of contours representing the evolution of the apparent magnitude with time. This figure shows again that the lack of information concerning the chemical composition of the ejecta is responsible of a large uncertainty. Also this figure emphasizes that whatever the lanthanide fraction  $X_{\text{lan}} \in [10^{-9}, 10^{-1}]$ , the output for GW190425 predicts a kilonova with apparent magnitude higher than 21.2 (respectively 20.2) in  $g$  (respectively  $r$ ) photometric band after only one day, which is in agreement with the ZTF observational data based upper limits presented in Coughlin et al. (2019b).



**Figure 7.** Apparent magnitude versus time based on the offline PE posteriors and LALInference (Veitch et al. 2015) skymap. The presented event is GW190425 and the lightcurves in blue (respectively red) are predicted by *Model I* with prior  $\log_{10} X_{\text{lan}}$  uniform in  $[-9, -1]$  (respectively  $X_{\text{lan}} = 10^{-4}$ ).

## 6 CONCLUSION

In this paper, we present a tool aimed to predict kilonova lightcurves based on the low-latency data products. We propose a way to take advantage of the multiple templates around the preferred event found by the low-latency pipelines and show how to predict mass ejecta from preliminary estimated of the binary parameters. We demonstrate the procedure on GW candidates, computing the ejecta probability (*HasEjecta*) reported by our tool and comparing to the value of *HasRemnant* currently released by the LIGO-Virgo-Kagra Collaborations. We then propose two ways to convert mass ejecta and other parameters such as ejecta velocity, lanthanide fraction, binary inclination angle and half opening angle of the lanthanide-rich ejecta component into kilonova lightcurves. We compare our predicted lightcurve with the only kilonova counterpart observed to date, i.e., AT2017gfo, showing consistency with those results. Finally, we suggest how to convert absolute magnitude to apparent magnitude by means of Bayestar skymap. This method can be used during the next observing run O4 as a utility to better inform the EM community concerning the characteristics of the kilonova signal they are trying to catch.

Improvements to the tool can be envisaged. A better treatment of the input low-latency data of LIGO-Virgo-Kagra could be considered, in particular, the availability of low-latency parameter estimation results might be of importance, since the uncertainties on the individual mass are non-negligible and only the chirp mass is quite well measured. On the other hand, the mass ratio for the existing binary population in the Universe considerably improved during the last years. As a consequence, one way to reduce errors could be to consider only the chirp mass from templates (Margalit & Metzger 2019), but use the mass ratio based on the observed binary population (e.g., Mandel 2010; Abbott et al. 2020a; Essick & Landry 2020; Fishbach et al. 2020b,a). Equally, one could provide lightcurve estimates conditioned on the direction to the source, which will probably be what an EM observer would want. Such a development should be easily implementable given the format of the actual Bayestar and LALInference skymaps. Likewise, more counterparts to binary compact mergers in the next years will improve our understanding of the equation of state of supra-nuclear-dense matter and potentially of the ejecta composition and geometry of the different ejecta components. Thereafter, priors like the lanthanide fraction and/or the half-opening angle of some ejecta component, needed for the computation of lightcurve made by the surrogates, could be addressed more accurately.

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