Constraining binary neutron star merger times from kilonova observations

L. E. H. Datrier, M. Hendry, G. Woan

Introduction

The detection of the **binary neutron star merger** (BNS) GW170817 and its electromagnetic (EM) counterparts marked the **first joint gravitational wave-electromagnetic observations**. The use of gravitational wave triggers is the most promising strategy for detecting more **kilonovae** (KNe), the faint optical transient associated with binary neutron star and neutron star-black hole (NSBH) mergers. However, new generations of optical telescopes like the **LSST** are expected to make serendipitous observations of kilonovae. We use KN models interpolated through Gaussian process regression to constrain kilonova parameters from incomplete light curves. We focus on recovering the merger time of the BNS, and consider the prospects for **EM-triggered gravitational wave searches**.

Gaussian Processes

A Gaussian process is defined as a collection of random variables, any finite number of which have a joint Gaussian distribution. Gaussian processes are used to infer directly in function space, by describing a distribution over functions.

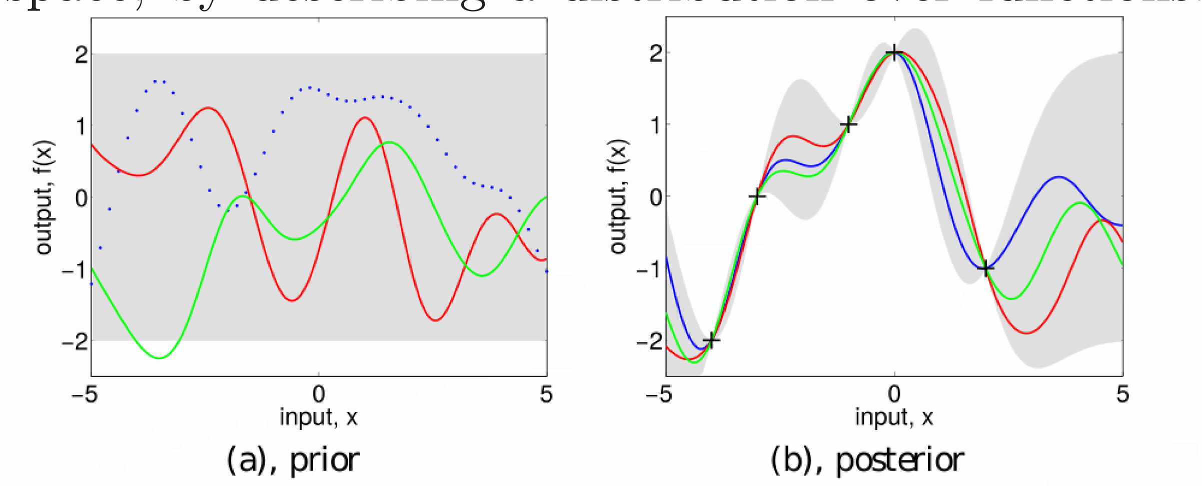

Figure 3: Functions drawn from GP prior (a) and posterior (b) i.e. prior conditioned by 5 noiseless data points.[5]

Kilonovae

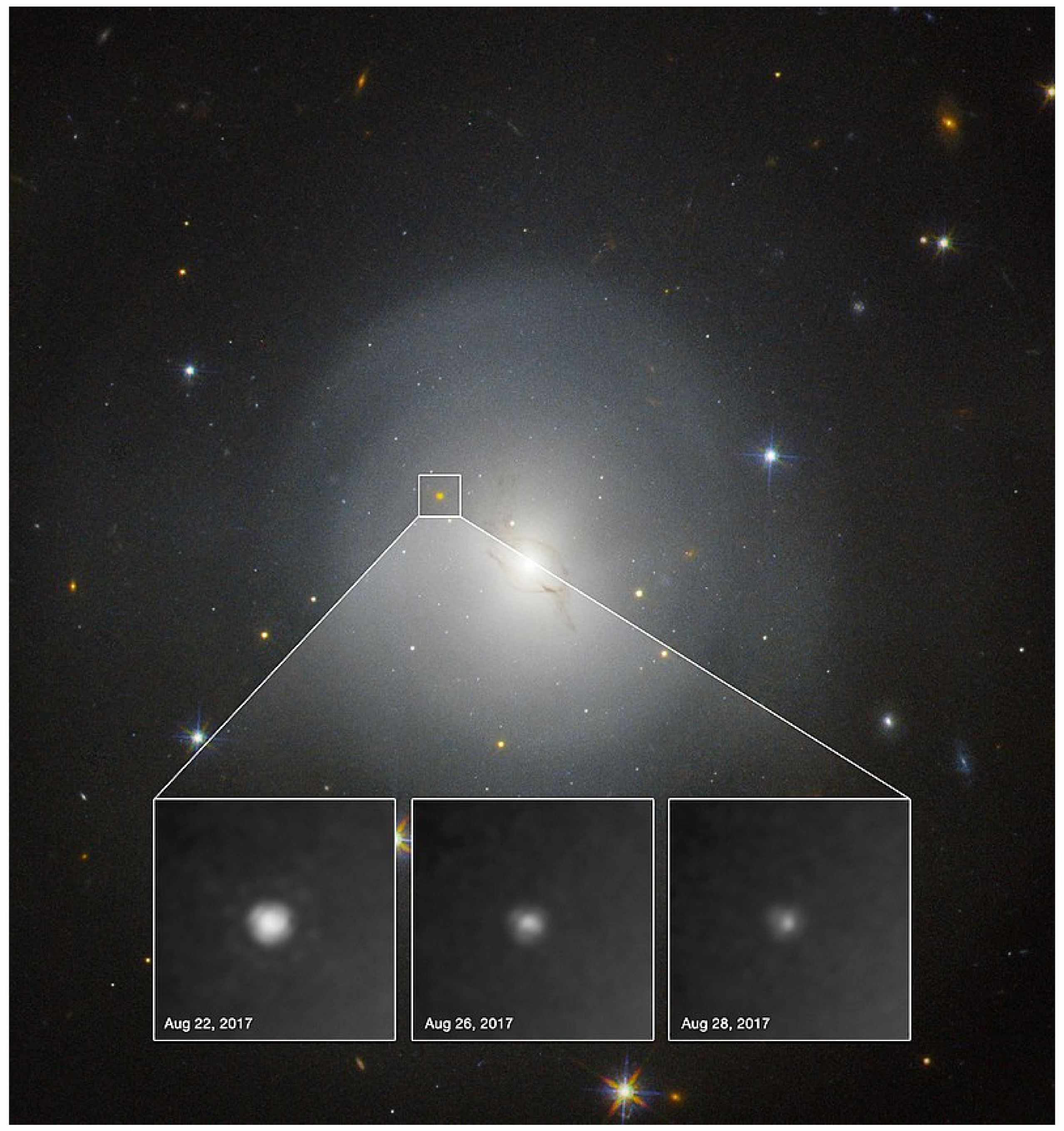

Figure 4: Observations of the KN associated with GW170817 by Hubble. (NASA/ESA)

Kilonovae are the faint, mostly isotropically emitting, long-lived optical and infrared transients associated with the merger of two neutron stars (BNS) or of a neutron star with a black hole (NSBH).

- Promising candidates for the electromagnetic follow-up of gravitational wave observations of BNS and NSBH.
- New generations of telescopes will unveil populations of kilonovae both with and without GW triggers.

The ejected neutron-rich matter in kilonovae undergoes rapid neutron capture (**r-process**) nucleosynthesis. This process enriches the universe with heavy elements such as gold and platinum.

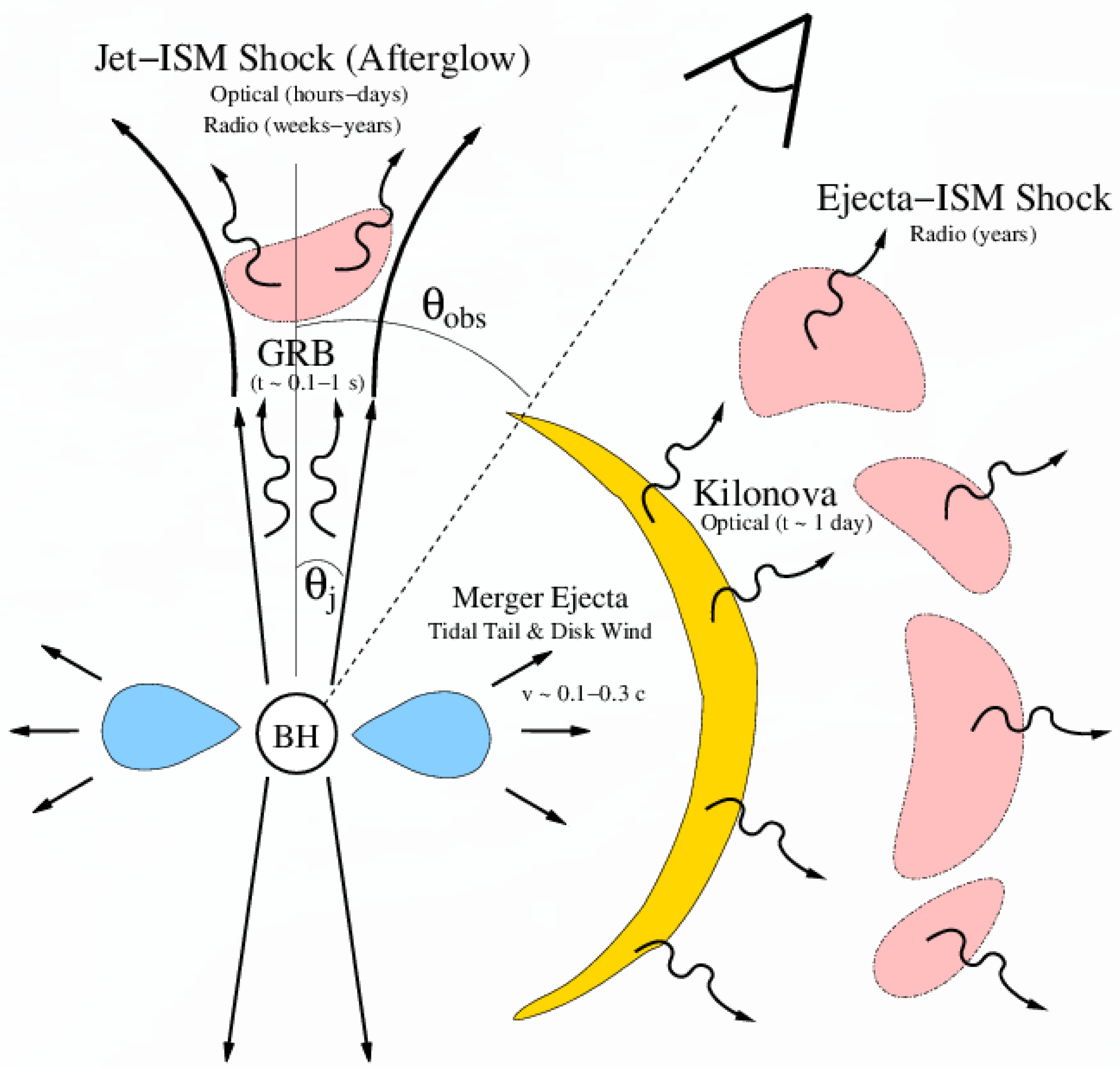

Figure 5: Schematic view of the counterparts associated with BNS[4]

EM triggered GW searches

Up to **200** kilonovae detected by LSST could be generated by BNS mergers associated with sub-threshold gravitational wave signals.[6] While strategies are in place for the electromagnetic follow-up of gravitational wave triggers, optimising searches for the serendipitous discovery of kilonovae could lead to more prospects for multi-messenger astronomy.

GW170817

Gravitational waves from two neutron stars coalescing were detected for the first time on 17th August 2017. These observations were followed by a kilonova (AT 2017gfo) and a short GRB.

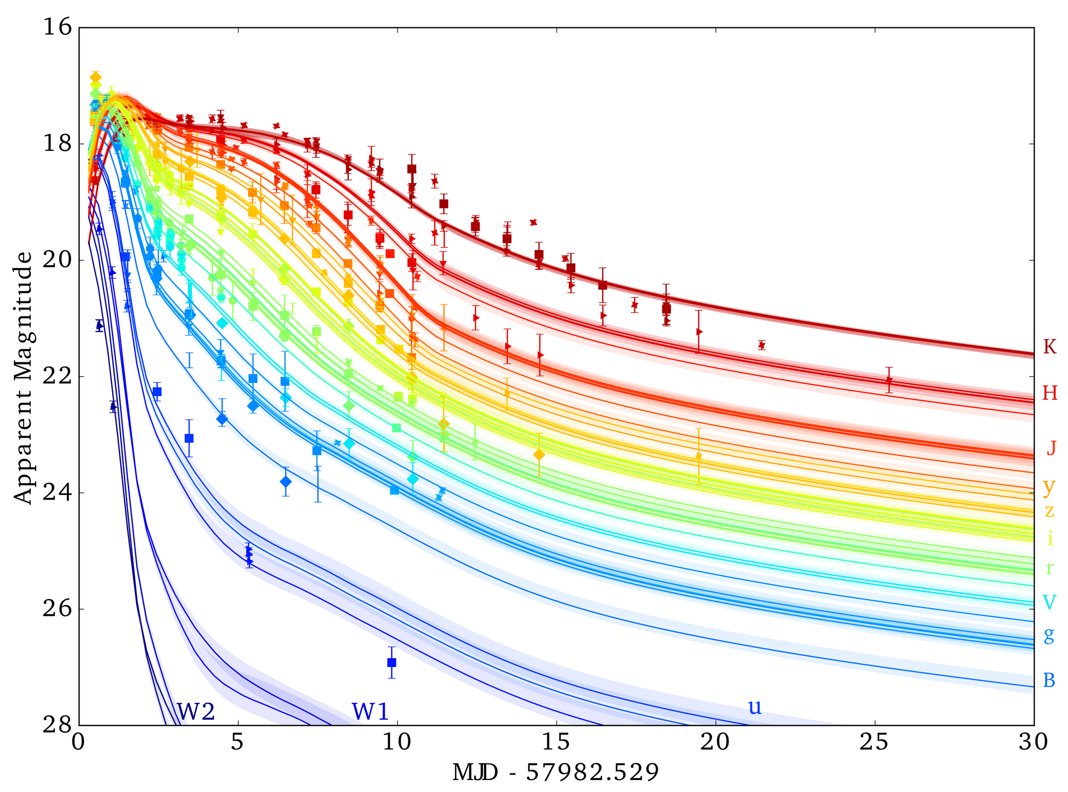

Figure 2: Complete UVOIR curves of AT 2017gfo.[1]

Kilonova models

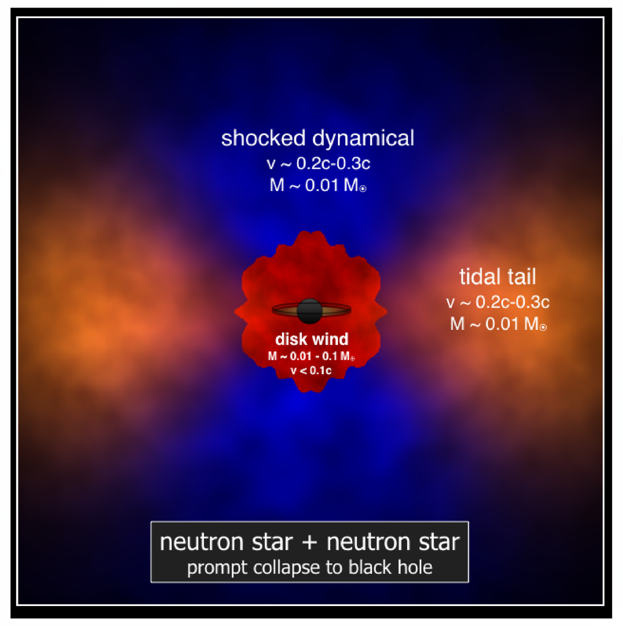

Figure 1: The tidal and dynamical components of the kilonova ejecta.[2]

Models of kilonova light curves are obtained from time-resolved spectra by Kasen (2017).[2]Each kilonova is made up of a tidal and a dynamical component. These models are the result of computationally expensive radiative transfer simulations, and are therefore available for only a discrete set of ejecta parameters. We use Gaussian Process regression to extend the models.

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Results

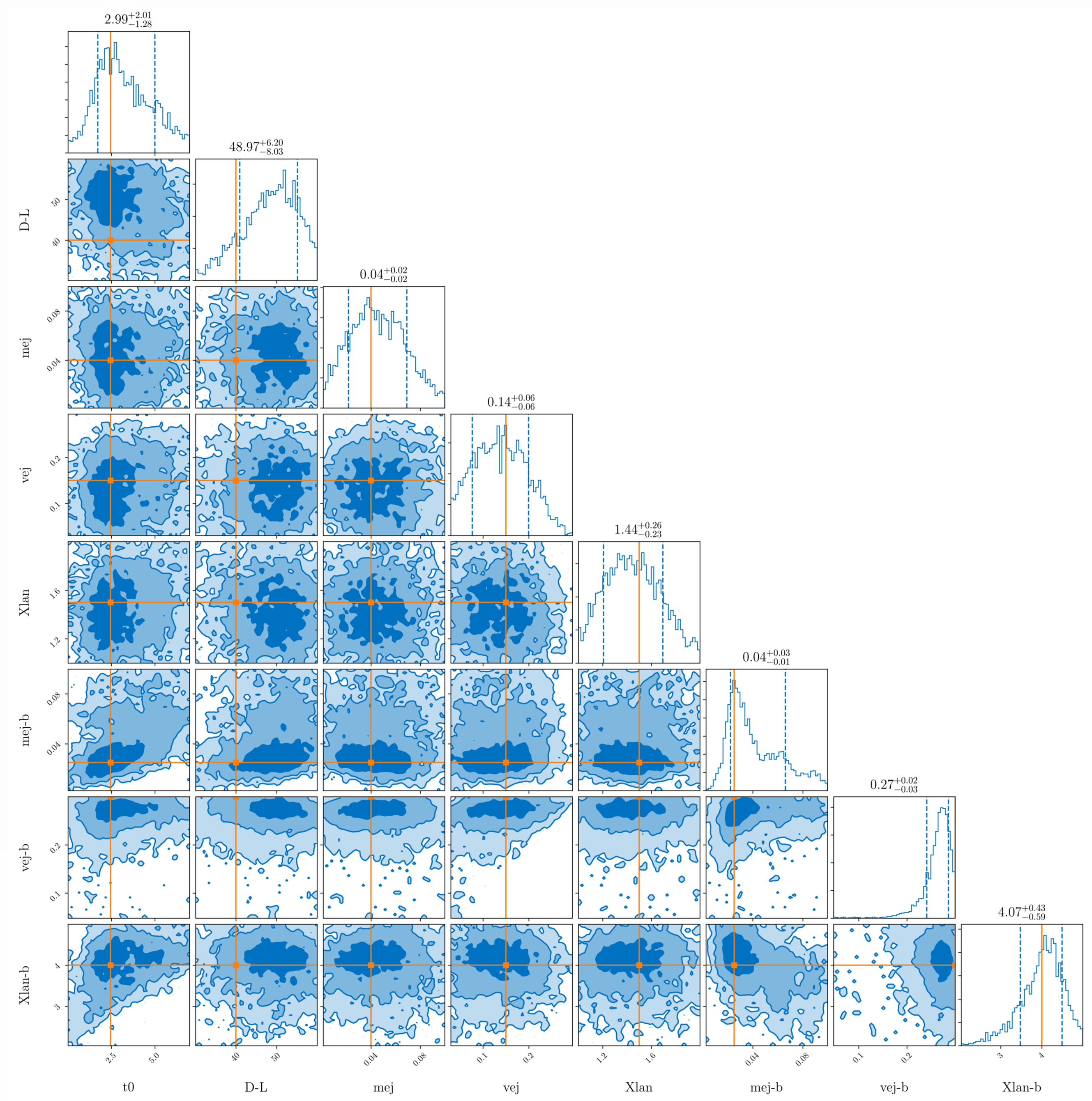

Figure 1: Parameter estimation on AT 2017 gfo DECam data, observations starting 3 days post-merger, g,r,i bands

We run a full parameter estimation on kilonova light curves, both simulated and real. The kilonovae are made up of two components (tidal and dynamical), each with three parameters:

- Lanthanide fraction X_{lan}
- Mass of ejecta m_{ej}
- Vvelocity of ejecta v_k.

The merger time t_0 and luminosity distance d_L are also allowed to vary. We use wide, flat priors for all parameters.

Figure 1 and **Figure 2** show the results of the full parameter estimation on g, r, i observations of AT 2017 gfo. In **Figure 1**, observations start 3 days after the merger, while in **Figure 2**, observations start 1.2 days after the merger.

Figure 3 shows results for a simulated kilonova light curve, with a fixed luminosity distance d_L, for nightly g, r, i observations starting 2 days after the merger.

In all cases, the merger time is accurately recovered, along with most of the ejecta parameters. Fixing the luminosity distance d_L removes some degeneracies in the ejecta parameters. As expected, constraints on the merger time are tighter for earlier observation starting times. With a fixed luminosity distance, the merger time can be recovered to within **half a day** for observations starting 2 days post-merger.

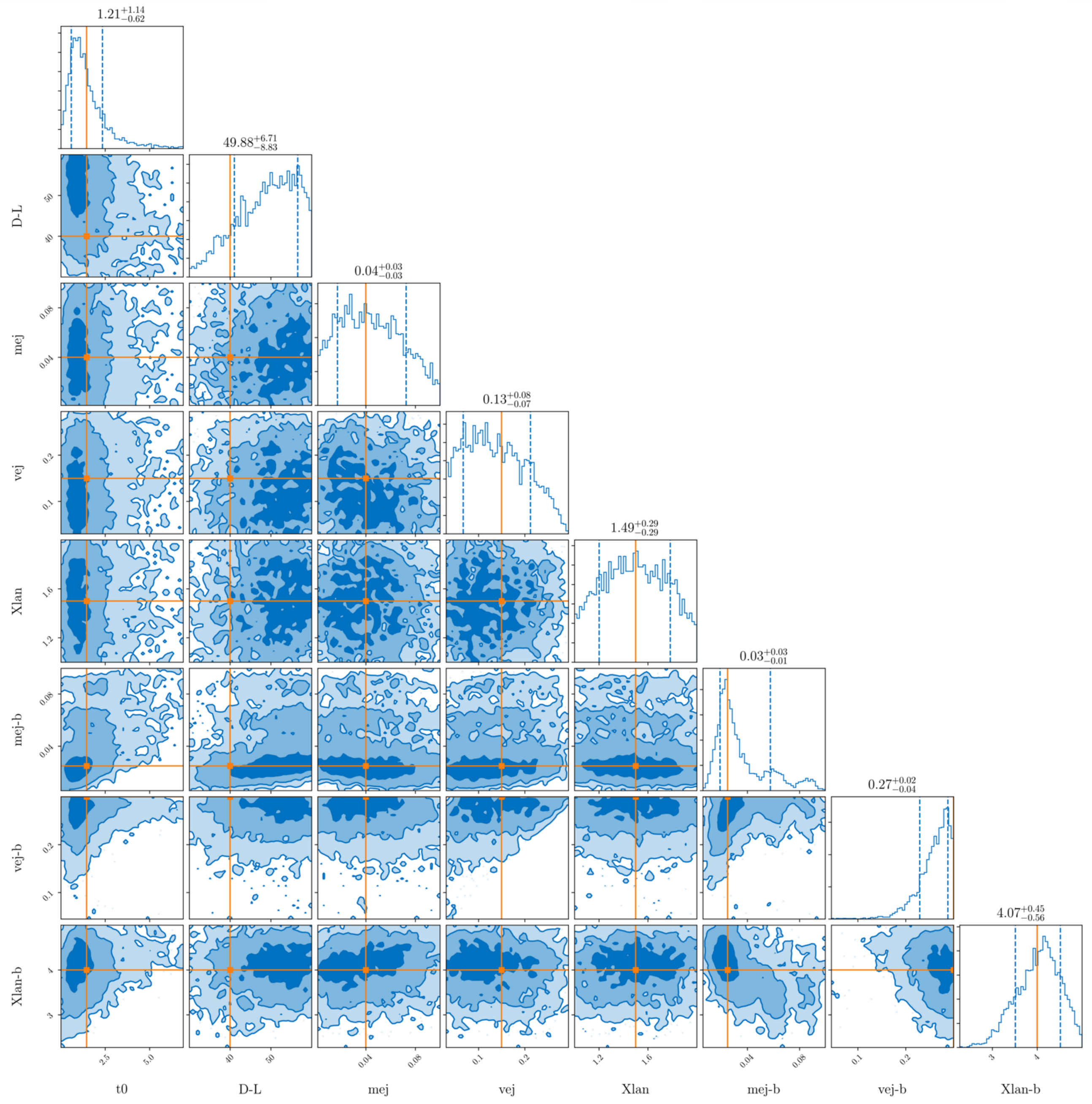

Figure 2: Parameter estimation on simulated AT 2017 gfo DECam data, observations starting 1.2 days post-merger, g,r,i bands

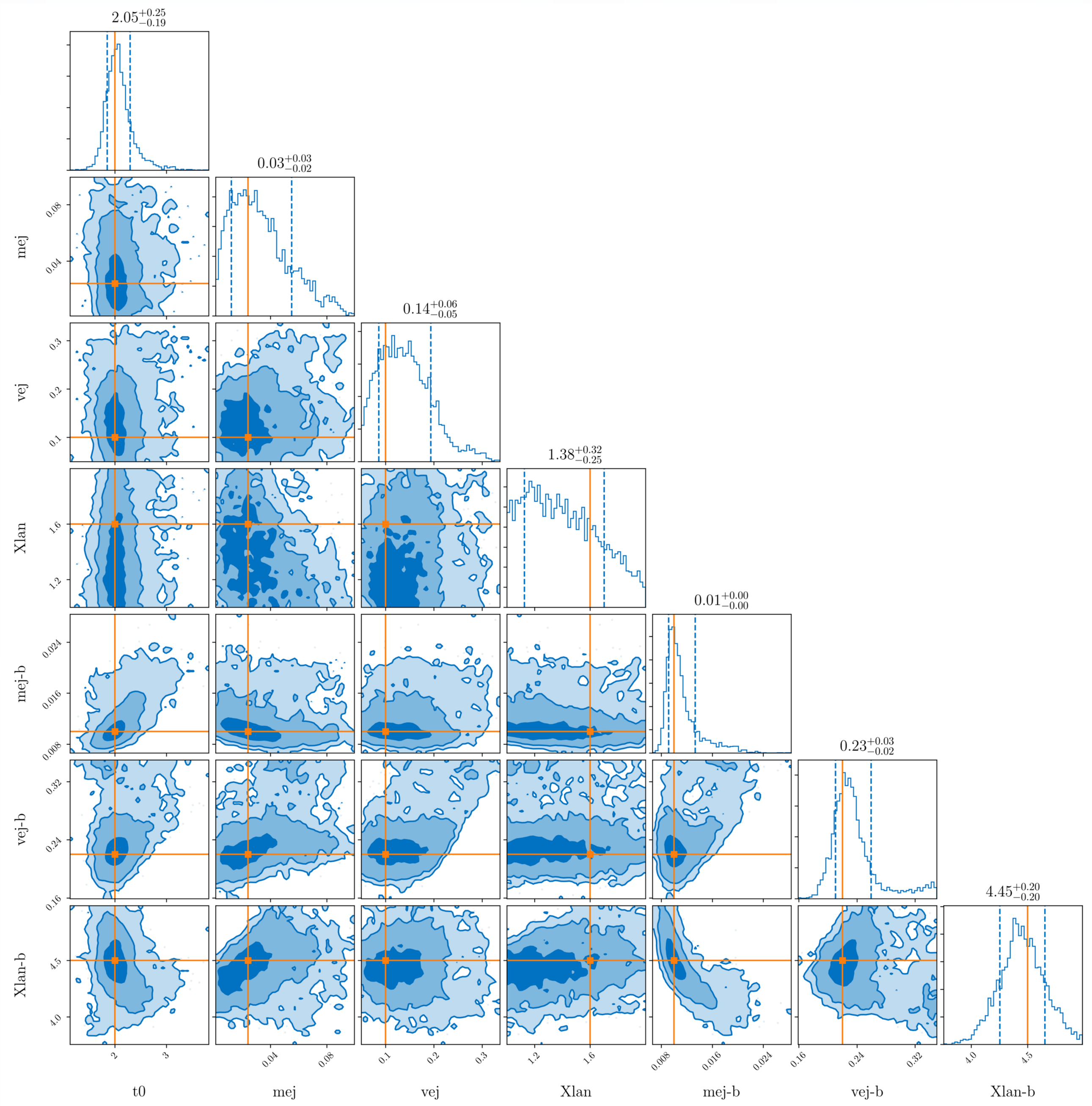

Figure 3: Parameter estimation on simulated KN, observations starting 2 days post-merger, fixed d_L, g,r,i bands

Discussion

Using incomplete kilonova light curves, **we can accurately recover the merger time of BNS to within one to three days**, depending on when observations of the transient start. All ejecta parameters are also recovered, with the largest source of degeneracy coming from the luminosity distance. This however can be fixed with host galaxy identification. The recovery of the merger time from kilonova light curves only is a promising prospect for confirming sub-threshold or single detector gravitational wave events.

References

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