Searching for gravitational-wave counterparts in TESS

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Introduction

- GW170817 and its counterpart ushered in the age of gravitational-wave (GW) multi-messenger astronomy, but LIGO-Virgo-KAGRA's (LVK) last observing run (O3) resulted in no confident multi-messenger detections
- The next run (O4) will begin in March 2023 with increased sensitivity and an enlarged network
- The Transiting Exoplanet Survey Satellite (TESS) has a 2300 deg^2 FOV, observed continuously for ~27 days (a "sector"); its bandpass is roughly flat from 600 to 1000 nm
- In this work we **search for counterparts in O3** and **simulate prospects** for observing kilonovae from binary neutron star (BNS) mergers in O4

Search in O3 data

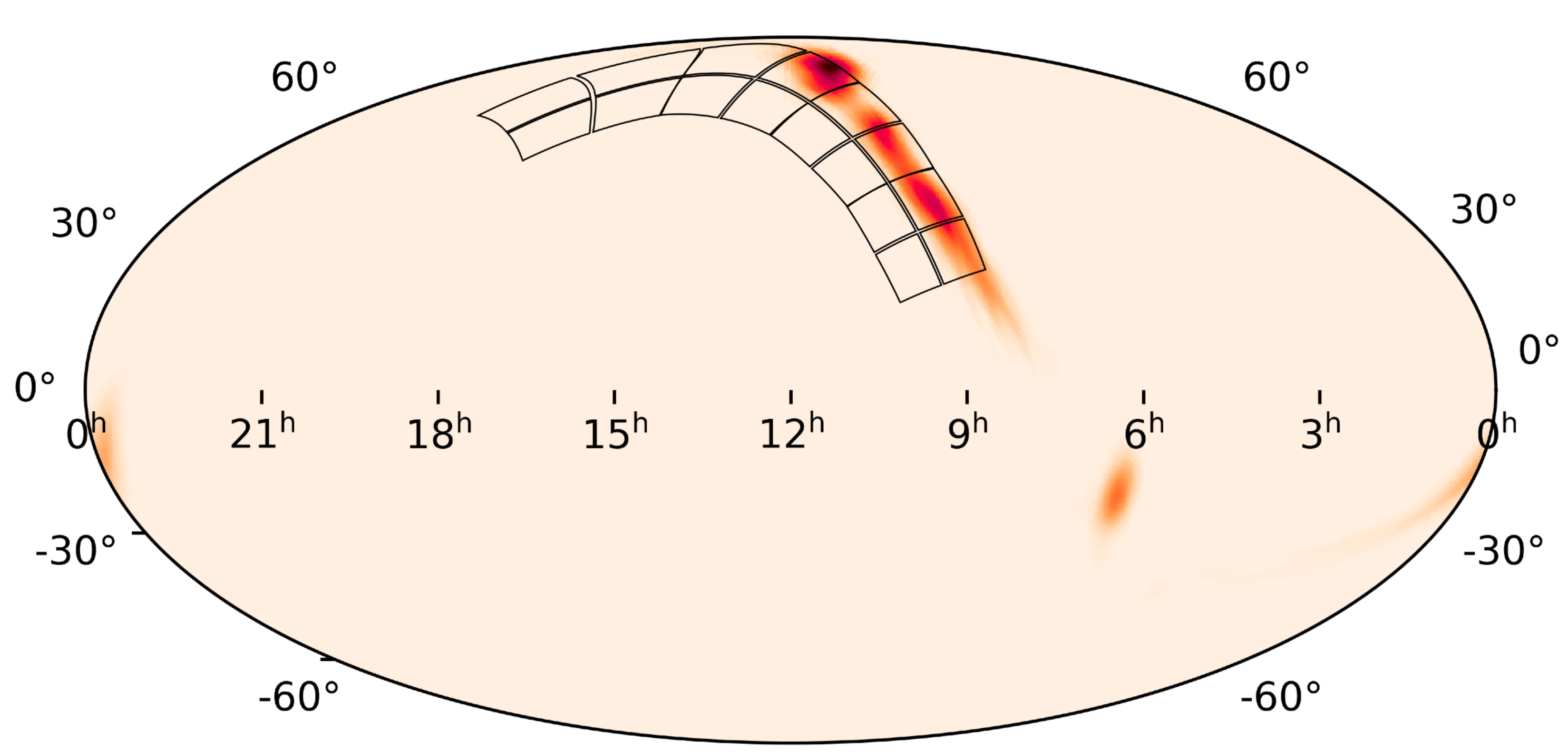

Fig. 1: The binary black hole merger GW200209_085452 during TESS sector 21, the best TESS-covered event in O3

- 75 GW events from O3 (71 BBH, 3 NSBH, 1 BNS) were released as part of the LVK's GWTC-2 and GWTC-3
- O3 lasted from April 2019 to March 2020 and overlapped with TESS sectors 10-23
- TESS full-frame images (FFIs) with 30 min integrations had 3-σ limiting magnitudes of 19.1 [1]
- We used the following search procedure:
  - Construct overlap with GW probability sky map and TESS sector (see Fig. 1 for an example)
  - Calculate probability enclosed in TESS (see Fig. 2 for the distribution of probabilities enclosed; **over a quarter of events have at least 5% probability enclosed in TESS**)
  - Search for TESS transient candidates in the overlapping region using a machine learning-based pipeline [2]
  - Inspect potential light curve matches (200-300 per GW event) for temporal and morphological consistency with the GW event
- **No counterparts were found,** but we are currently seeking to establish limits on EM emission from the mergers (including BBH)

Simulation for BNS in O4

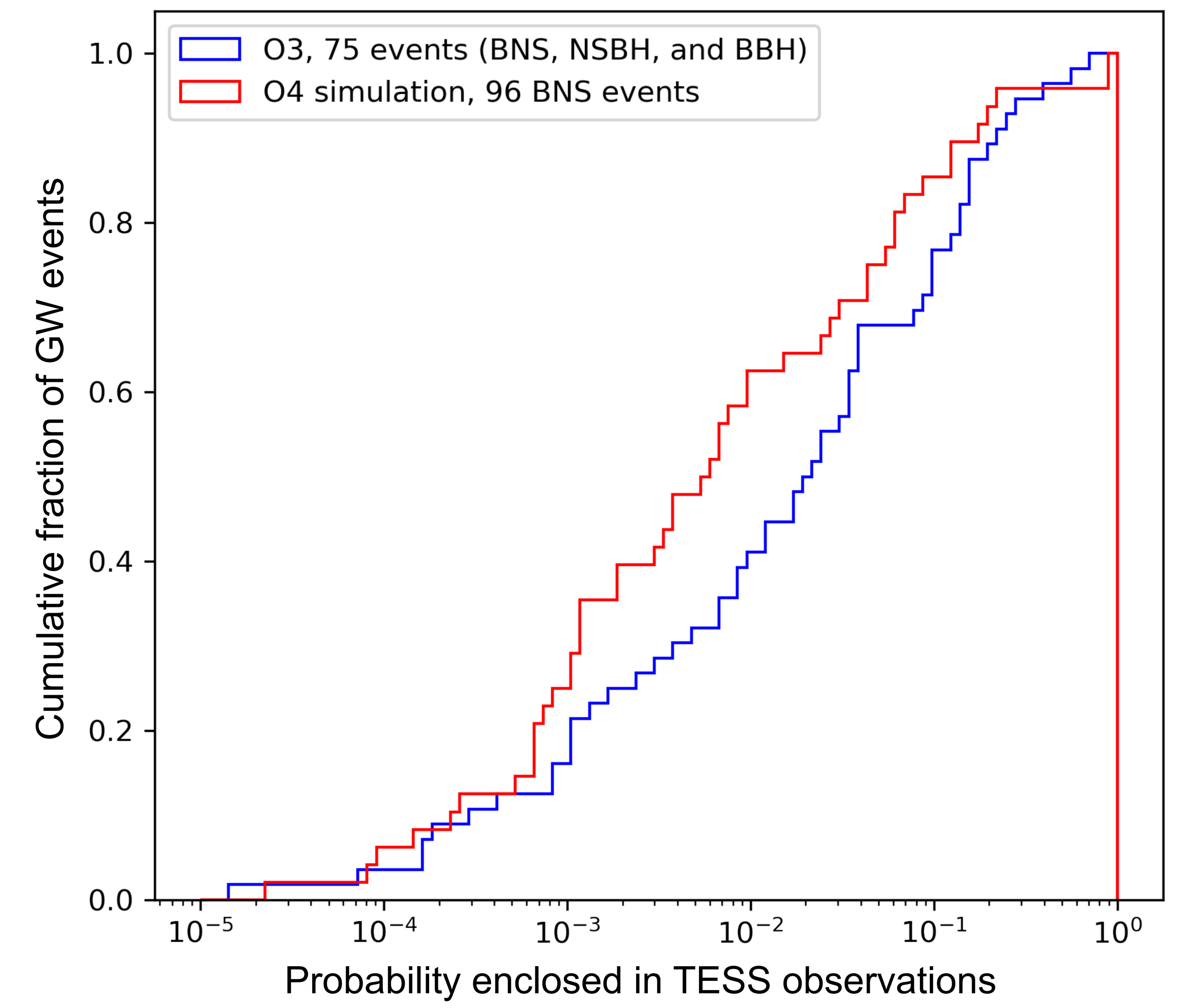

Fig. 2: Distribution of sky probabilities enclosed in concurrent TESS sectors for the 75 O3 GW events and for 96 simulated BNS events in O4

Gravitational Waves

- Realistic astrophysical BNS population simulated for O4 in [3]
  - We use the public data release including merger components, sky localizations, and detectability in the LVK detector networks
- Three astrophysical BNS rates chosen to span the current uncertainty in merger rates after O3 [4]: 50, 250, 1000 Gpc^{-3} yr^{-1}
- Repeat for 100 draws from population to obtain uncertainties

Kilonova light curves

- Simulate kilonova light curves using Kasen models [5], with dynamical ejecta mass and ejecta expansion velocity obtained from fits to BNS component masses [6]
- Lanthanide fraction X_{lan} remains as a free parameter; we choose $X_{lan} = \{10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}\}$ to allow for a broad range
  - GW170817 X_{lan} estimated to be between 10^{-2} and 10^{-3} [7]

BNS rate ($\mathrm{Gpc^{-3}yr^{-1}}$)	# found in GWs	# covered by TESS	# bright in TESS
50	2^{+2}_{-2}	0^{+0}_{-0}	0^{+0}_{-0}
250	8^{+4}_{-3}	0^{+1}_{-0}	0^{+0}_{-0}
1000	33^{+6}_{-9}	1^{+1}_{-1}	0^{+1}_{-0}

Table 1: Results from the simulation for BNS in O4. An event is *covered* if it is in the TESS FOV; it is *bright* if the peak of its light curve exceeds the 8-hour stacked TESS limiting magnitude of 20.5.

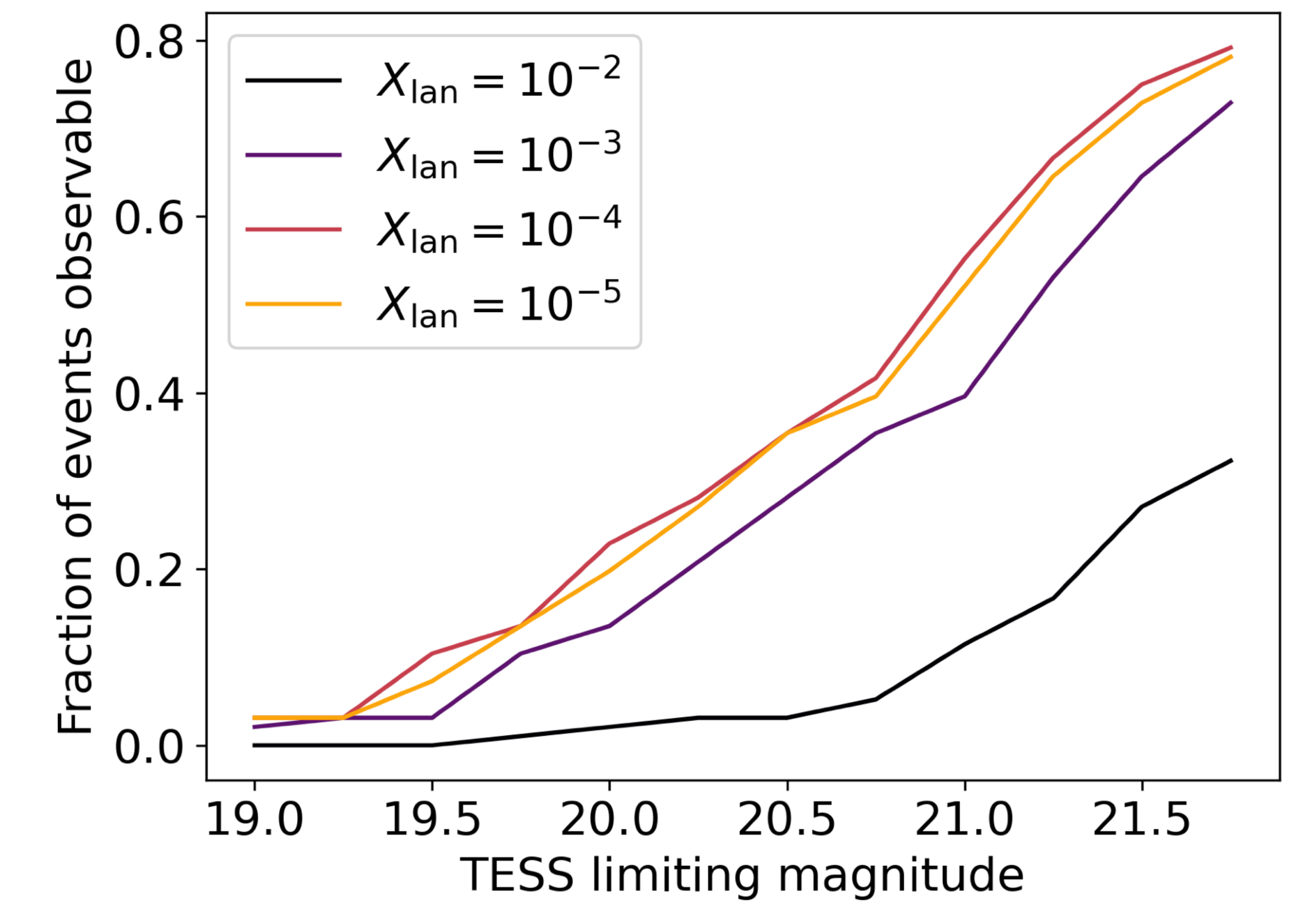

Fig. 3: Fraction of BNS events observable in TESS as a function of the limiting magnitude for various lanthanide fractions

- Results for the simulation are shown in Table 1
- Lower X_{lan} results in brighter light curves in TESS (see Fig. 3)
- The brightest kilonovae peak at almost 18th mag (see Fig. 4)
- Using an 8-hour stack of TESS images, a limiting magnitude of 20.5 is possible; fainter is possible but sacrifices temporal resolution

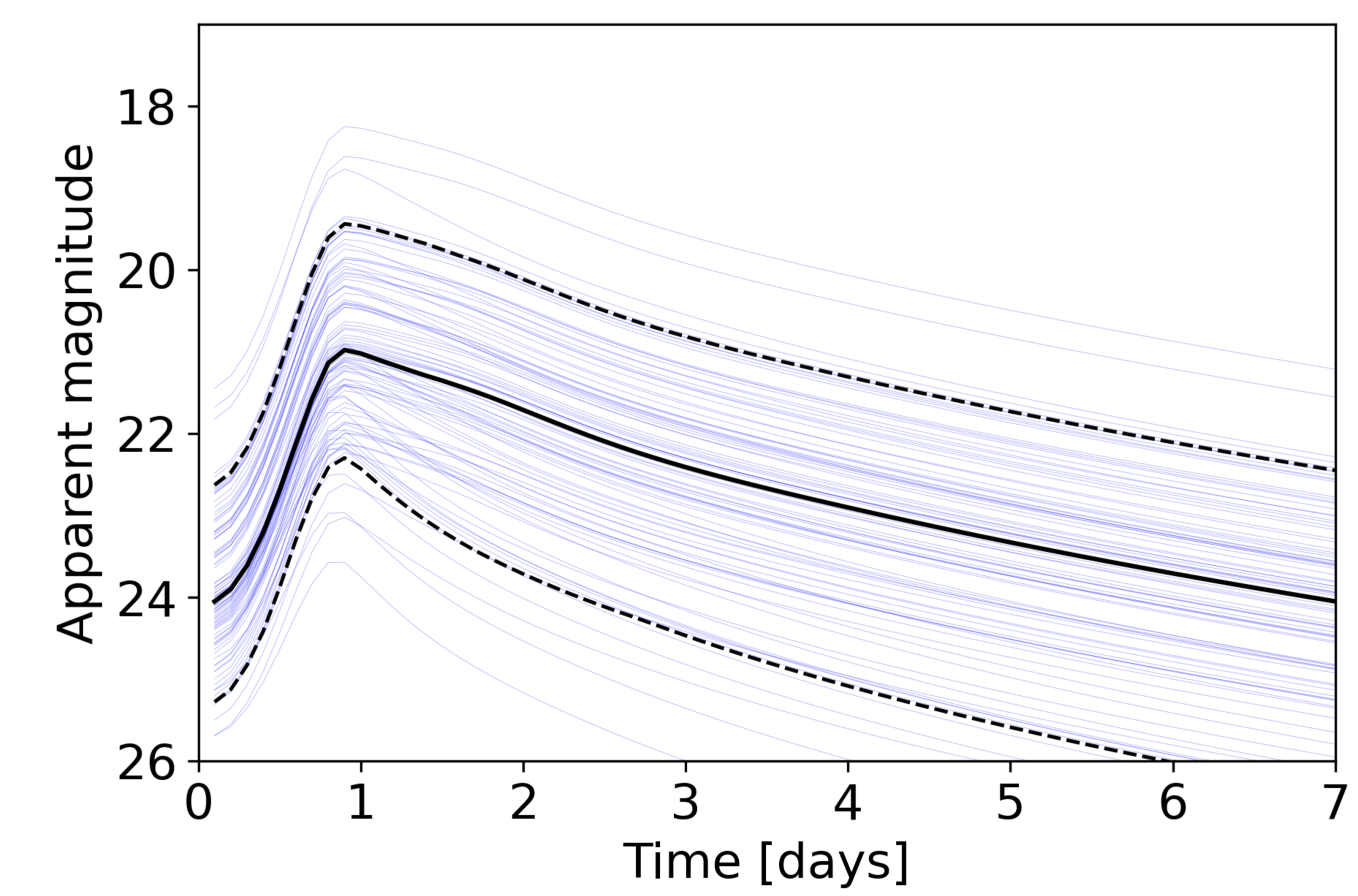

Fig. 4: All kilonova light curves found in TESS and detected in GWs for an X_{lan} of 10^{-5}. The solid black line is the median light curve and the dotted lines bound the 90% interval.

Conclusions and other use cases

- TESS could identify **up to one** BNS kilonova in O4 from GW triggers
  - Could also go the other way: TESS-identified kilonovae can trigger a search in GW data
- Minimal-cost search for BBH counterparts if covered by TESS
- Rapid exclusion of large areas of the skymap due to TESS's large FOV to preserve telescope time for other observers; potential TreasureMap [8] integration

References: [1] Fausnaugh+, RNAAS **4** 251 (2020) [2] Jayaraman+ in prep. [3] Frostig+, ApJ **926** 152 (2022) [4] arXiv:2111.03634 [5] Kasen+, Nature **551** 80 (2017) [6] Coughlin+, MNRAS **489** L91 (2019) [7] Ji+, ApJ **882** 40 (2019) [8] treasuremap.space