Search for Gravitational Waves associated with Gamma Ray Bursts during the LIGO-Virgo Run O3b

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Gamma Ray Bursts

- Intense and highly variable flashes of γ-rays (prompt emission)
- The duration T_{90} defines their class: short (≤ 2 s) or long (> 2 s)
- Followed by long-lasting (afterglow) emission from radio to γ-rays
- Long GRBs associated with the core collapse of massive stars
- Short GRBs associated with Compact Binary Coalescences (CBCs) with at least one Neutron Star (NS), as proved by event GW170817/GRB 170817A
- Believed to be powered by ultra-relativistic jets produced by rapid accretion onto a central Black Hole (BH)

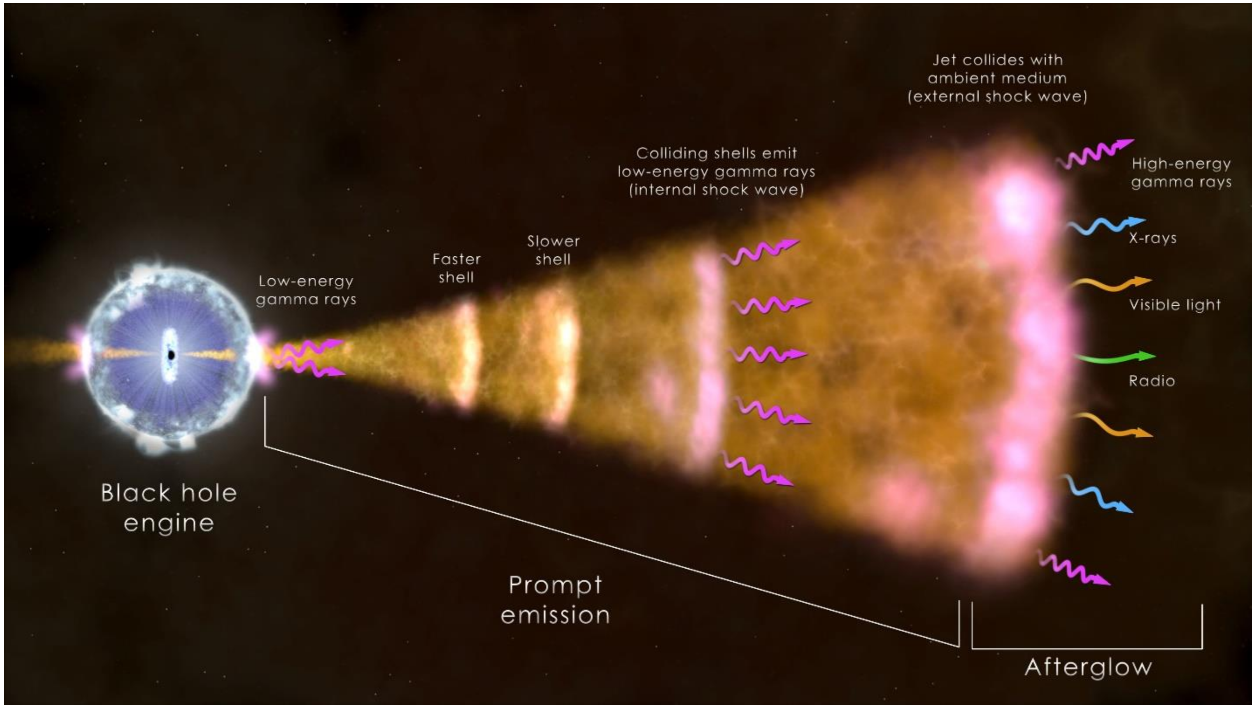


Image: NASA Goddard Space Flight Center

Targeted Search for GWs from GRBs

- **Aims at finding Gravitational Wave (GW) signals in coincidence with GRBs**
- **Benefits from the sky localisation of the source given by the GRB detection, improving its sensitivity**
- **Achieves high sensitivity thanks to a detailed knowledge of the signal morphology**
- **Carried out with two different analyses: modelled search for CBCs and search for generic GW transients**

LIGO-Virgo-KAGRA Collaboration, ApJ 928 (2022) 186

Sample of GRBs during LIGO-Virgo Run O3b

108 GRBs detected by the Swift and Fermi satellites between 2019 November 1 15:00 UTC and 2020 March 27 17:00 UTC (second part of the third LIGO-Virgo Observing Run, O3b)

GRBs are separated in three classes:

- Short, when $T_{90} + |\delta T_{90}| < 2$ s
- Long, when $T_{90} - |\delta T_{90}| > 4$ s
- Ambiguous, for all the others

Following this classification, we obtain:

- 7 short GRBs
- 89 long GRBs
- 12 ambiguous GRBs

The redshift is known only for GRB 191221B (z = 1.148) and GRB 200205B (z = 1.465)

Modelled Search for CBCs

- **This analysis is carried out by a coherent matched filtering pipeline, PyGRB (Harry & Fairhurst 2011; Williamson et al. 2014)**
- **Only 17 short and ambiguous GRBs with a minimum amount of data in at least one GW interferometer around the trigger time are analysed**
- **The on-source window is defined as [-5, +1] s around the GRB trigger time, based on the assumption that a GW may precede the prompt GRB emission by several seconds (as confirmed by GW170817/GRB 170817A)**
- **The analysis requires a bank of template waveforms to carry out the matched filtering for Binary Neutron Star (BNS) and NSBH coalescences. In this bank NS masses are within [1.0, 2.8]$M_\odot$ and BH masses within [2.8, 25]$M_\odot$**

Outline of the Modelled Search for CBCs

- 6 s off-source windows surrounding (~ 90 minutes) the GRB trigger time are used to estimate the background
- A search grid is based on the best GRB localisation determined by Fermi or Swift satellite
- For each time and template a coherent Signal-to-Noise Ratio (SNR) is computed, a candidate event is recorded if this SNR > threshold, and then the SNR is reweighted according to how well the template matches the identified signal
- The significance (p-value) of any candidate event is ranked against the background using the off-source windows
- In order to improve the ranking statistic, the amount of off-source data is artificially increased with time slides
- By injecting signals in the off-source data and attempting to recover them, the 90% exclusion distance is calculated

Search for Generic GW Transients

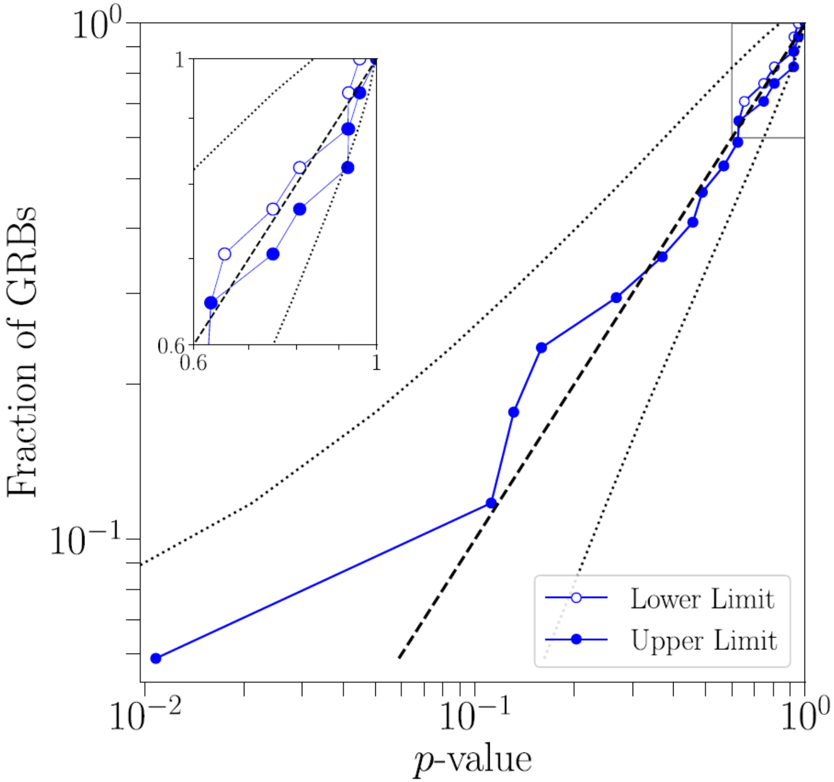
- This analysis is carried out by the X-Pipeline (Sutton et al. 2010; Was et al. 2012), which searches for excess power coherent across the GW detector network and consistent with the GRB localisation and time. New procedure to treat glitches.
- 86 GRBs (of any class) with a minimum amount of data in at least two GW interferometers around the trigger time are analysed
- The on-source window is defined as [-600, +60] s around the GRB trigger time (or [-600, T_{90}] s if $T_{90} > 60$ s), covering the possible time delay between GW emission from a GRB progenitor and any prompt GRB emission
- Simulated waveforms are chosen to search for three distinct sets of signals: BNS and NSBH inspiral, stellar collapse (represented by a Circular Sine-Gaussian (CSG)), Accretion Disk Instability (ADI)

Outline of the Search for Generic GW Transients

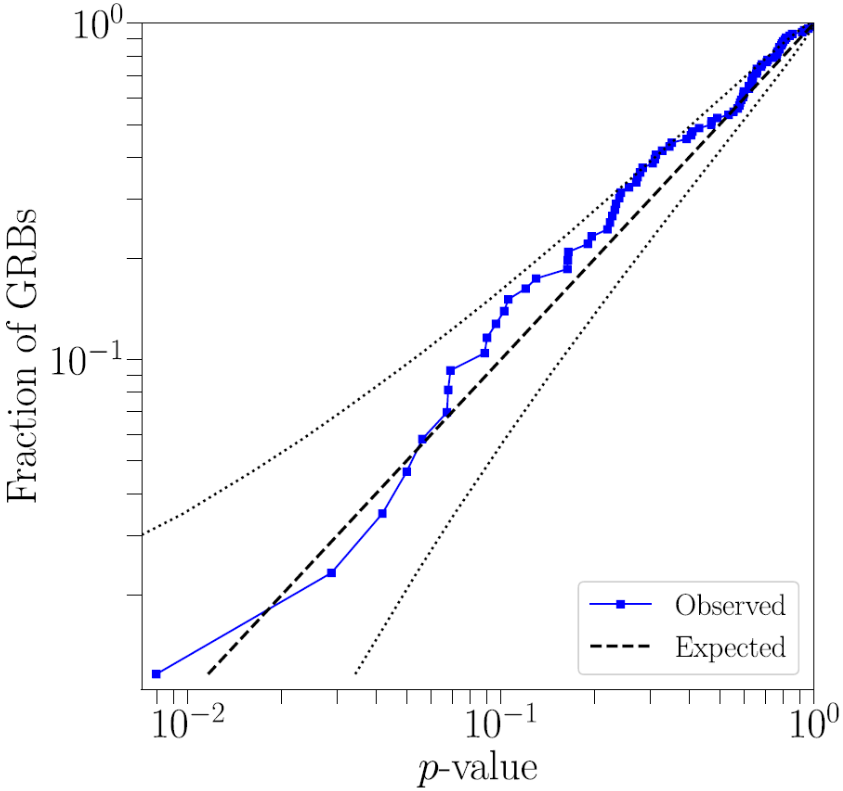
- 660 s off-source windows in at least ~ 90 minutes surrounding the GRB trigger time are used to estimate the background
- A search grid is based on the best GRB localisation determined by Fermi or Swift satellite
- Time-frequency maps are produced for the GW data coherently combined between the interferometers, giving the temporal evolution of the signal spectral properties, in order to search for clusters of pixels with excess energy (events)
- Each event is ranked according to a detection statistic based on energy, and the event with the largest ranking statistic is the best candidate, with a significance (p-value) given by the probability of its production by the background alone
- As with the modelled search, by injecting signals in the off-source data, the 90% exclusion distance is calculated

Resulting Significances

17 GRBs with modelled search (some events without p-value)



86 GRBs with generic search (p-value always found)



Cumulative distributions of p-values for the loudest on-source events found during O3b. If no trigger is identified in the on-source window, lower and upper limits are determined. The dashed line indicates a uniform distribution expected under a no-signal hypothesis, while the dotted lines give the corresponding 90% band.

Most Significant Events

Modelled Search

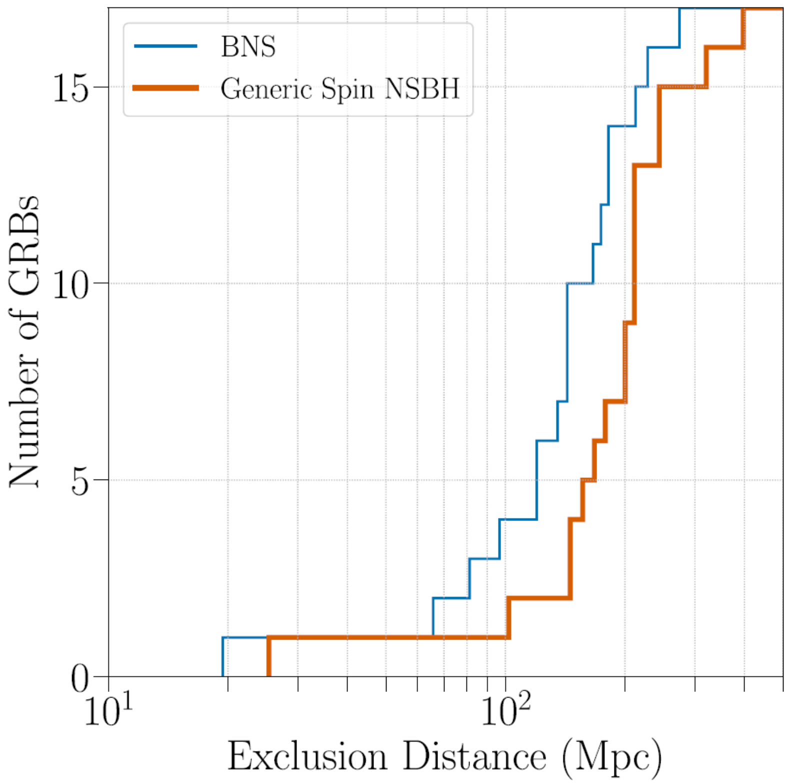
GRB 200129A has a p-value of 1.08×10^{-2}, however further investigation of this event pointed out a period of excess noise in one of the GW interferometers ~20 s before the GRB trigger time. After cleaning the data, the candidate event is no longer significant with respect to the background, suggesting that much of its power is caused by noise and not by a GW.

Generic Search

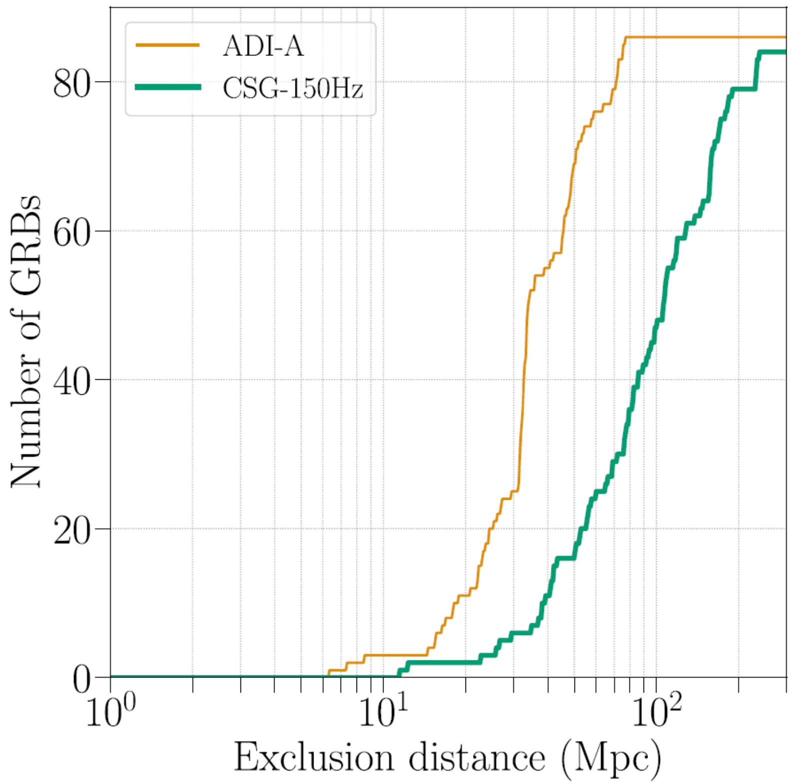
GRB 200224B has a p-value of 7.95×10^{-3}, however this very small value is not unexpected given the high number of GRBs analysed.

Resulting Exclusion Distances

17 GRBs with modelled search



86 GRBs with generic search



Cumulative histograms of the 90% exclusion distances during O3b for some CBCs and generic transient signals. For a given GRB and signal model, this is the distance within which 90% of the signals injected into off-source data are successfully recovered with a significance greater than the loudest on-source trigger.

Median Exclusion Distances

Modeled Search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins
D_{90} (Mpc)	149	207	257

Generic Transient Search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} (Mpc)	166	126	92	42

Generic Transient Search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} (Mpc)	34	140	54	22	52

Median 90% exclusion distances (D_{90}) for both the modelled and generic transient signals during O3b. For the modelled search, the values for all three considered signal types are given, while for the generic search only the results obtained with different CSG models, depending on the central frequency, and different families of ADI models are given.

Conclusions

- Follow-up of Fermi and Swift GRBs during the second part of the third LIGO-Virgo Observing Run (O3b)
- Targeted search carried out using GRB trigger times and sky localisations for possible associations with GWs
- Short and ambiguous GRBs analysed with a template-based search for BNS and NSBH waveforms
- All GRBs analysed with a generic transient search for GW signals
- No significant GW candidate found in coincidence with the GRBs analysed
- Different emission models used to put a lower limit on the distances of the GRB progenitors
- The median 90% exclusion distances obtained with the modelled search are 10%–30% larger than those obtained in the first part of the third LIGO-Virgo Observing Run (O3a)
- The median 90% exclusion distances obtained with the generic transient search are on average about 50% larger than those obtained in O3a (also thanks to the new procedure to treat glitches)
- Null result consistent with the detection rate of 0.07–1.8 yr^{-1} predicted for O3