Prospects for multi-messenger detections of BNS mergers in O4

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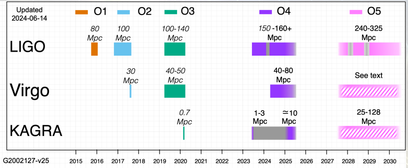
Introduction

- Joint observation of GW170817 and GRB 170817A during the second LIGO-Virgo-KAGRA (LVK) observing run:
  - BNS mergers are progenitors of at least a fraction of short GRBs (Abbott et al. 2017)
  - some basic properties of short GRB jets were inferred (see, e.g., Ghirlanda et al. 2019)
- Another BNS detected during the third LVK observing run (GW190425), but no EM counterpart has been found (Abbott et al. 2020)

- The fourth LIGO-Virgo-KAGRA (O4) is currently ongoing
- $\sim$ 11 months of data taking so far; O4 will run until June 9, 2025



How many GW and multi-messenger detection of BNS mergers do we expect in O4?

The BNS population

We generated a sample of synthetic BNSs populating the local Universe up to z=0.11

- MOBSE population-synthesis code
  (Mapelli et al. 2017, Giacobbo et al. 2018)
- 3 sets of simulations corresponding to 3 different choices of the common-envelope parameter α=1, 3 and 7 (model A1, A3 and A7)

  ⇒ Catalogs of BNS masses and delay times
- These quantities were fed to the code COSMO$\mathcal{R}$ATE (Santoliquido et al. 2021)

  ⇒ Catalogs of BNS systems merging within an Hubble time, with their redshift

We gave these BNS systems:

- Isotropic and homogeneous distribution in space
- Random inclination of the orbital plane with respect to the line of sight (θ_j)

The GW simulations

- GW signal: TaylorT4 waveforms
- Gaussian and stationary noise
- GW network: Advanced LIGO (aLIGO), Advanced Virgo (AdV) and KAGRA
- Sensitivity curves from `https://dcc.ligo.org/LIGO-T2000012/public`;
  BNS range: 190 Mpc (aLIGO); 120 Mpc (AdV); 80 Mpc (KAGRA)
- GW detection - two scenarios:

case a

- *at least 2 detectors;*
- *combined SNR > 12*

(see, e.g., Abbott et al. 2020)

case b

- *at least 1 detector;*
- *combined SNR > 8*

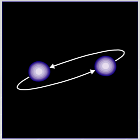
(see, e.g., Petrov et al. 2022)

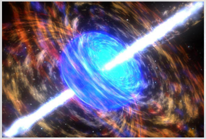
- Independent interferometer duty cycle: 70 %
- GW sky localization with BAYESTAR

Matched filter pipeline and sky localization: `ligo.skymap` package
`https://lscsoft.docs.ligo.org/ligo.skymap/`

The short GRB emission

- We assumed that all BNS mergers are associated with a short GRB (S-GRB)





- We considered both the GRB prompt emission and afterglow emission

- We considered two cases:
  - uniform jet;
  - structured jet

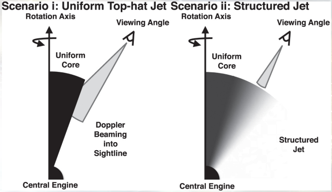


Image from Abbott et al. 2017, ApJL, 848, 13

- We considered different EM facilities: *Swift*, **SVOM**, INTEGRAL and *Fermi*

The GRB prompt emission

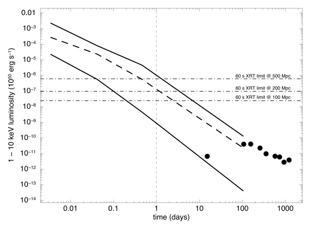
- **Uniform jet** with θ_c=5°, 10°
  - ◇ On-axis S-GRBs ($\theta_j < \theta_c$);
  - ◇ The S-GRB prompt emission is described by: $E_{\rm pk}$, $L_{\rm iso}$, θ_j, z:
    - $E_{\rm pk}$ from a broken power law distribution (model "a", Ghirlanda et al. 2016);
    - $L_{\rm iso}$ assuming $E_{\rm pk}$-$L_{\rm iso}$ (Yonetoku) correlation;
    - θ_j and z same as BNS merger.
  - ◇ Spectrum: Band function $S(E_{\rm pk},\alpha,\beta)$ with α=-0.6, β=-2.5, normalised to $L_{\rm iso}$
  - ◇ The photon peak flux ($P_{\rm pk}$) is calculated in the characteristic energy band for different instruments
  - ◇ $P_{\rm pk}$ is then compared with the detector sensitivity

- **Structured jet** with θ_c=5° and a power-law/gaussian angular distribution of the radiated luminosity and the Lorentz factor
  - ◇ On-axis plus moderately off-axis (5° $< \theta_j <$ 35°) S-GRBs
  - ◇ Same procedure as for GRBs with uniform jet, but using the $L_{\rm iso}(\theta_j)$ and $E_{\rm pk}(\theta_j)$ as seen by an observer at θ_j

The GRB X-ray afterglow emission

- Observational strategy put in place by *Swift*/XRT during O3 as a reference (Evans et al. 2016)

- Sample of on-axis S-GRBs presented in D'Avanzo et al. 2014 as a reference
    - For each S-GRB we estimated the X-ray luminosity
    - We compared the X-ray light curves with the limiting luminosity that can be reached by *Swift*/XRT at different distances



- We convolved the rates of the observable BNS mergers with the probability that the X-ray luminosity is above the *Swift*/XRT flux limit

Results - I

GWs + GRB (prompt emission), case a

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	1	0.0006 (0.0023)	0.014-0.020	0.003 (0.013)	0.070-0.11	0.0001 (0.0004)	0.0024-0.0035	0.0005 (0.0019)	0.013-0.017
A3	258	5	0.003 (0.01)	0.07-0.10	0.017 (0.068)	0.35-0.54	0.0005 (0.002)	0.01-0.02	0.002 (0.01)	0.06-0.08
A7	765	13	0.008 (0.031)	0.18-0.26	0.045 (0.18)	0.91-1.42	0.001 (0.005)	0.031-0.046	0.006 (0.025)	0.17-0.22

GWs + GRB (prompt emission), case b

model	$\mathcal{R}(0)$	GW	GW+EM (prompt)							
			Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
			uniform	structured	uniform	structured	uniform	structured	uniform	structured
	$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	31	5	0.002 (0.01)	0.05-0.08	0.014 (0.06)	0.27-0.46	0.0005 (0.002)	0.009-0.014	0.002 (0.008)	0.05-0.07
A3	258	22	0.01 (0.04)	0.24-0.37	0.06 (0.26)	1.17-2.00	0.002 (0.008)	0.04-0.06	0.009 (0.04)	0.22-0.32
A7	765	61	0.03 (0.12)	0.67-1.05	0.18 (0.74)	3.28-5.65	0.006 (0.02)	0.11-0.18	0.02 (0.10)	0.63-0.90

- GW detection rate between 1 and 13 (5 and 61) yr^{-1} for case a (case b)
- Maximum joint GW+EM detection rate with *Fermi*/GBM, structured jet
- **Swift/BAT and SVOM/ECLAIRs have similar performances**: working together they will almost double the possibilities to catch the S-GRB prompt emission

Results - II

GWs + GRB (X-ray afterglow emission, $\theta_j < 5^\circ$)

	Model	case a			case b		
		$<$ 100 Mpc yr^{-1}	100-200 Mpc yr^{-1}	200-500 Mpc yr^{-1}	$<$ 100 Mpc yr^{-1}	100-200 Mpc yr^{-1}	200-500 Mpc yr^{-1}
1^{st} day, 60 s	A1	0.0015-0.0026	0.0007-0.0014	0.0002-0.0006	0.005-0.008	0.002-0.004	0.0007-0.0024
	A3	0.007-0.012	0.003-0.007	0.001-0.003	0.019-0.032	0.010-0.019	0.004-0.013
	A7	0.021-0.035	0.009-0.017	0.002-0.006	0.098-0.059	0.025-0.050	0.008-0.028
1^{st}-3^{rd} day, 500 s	A1	0.0014-0.0017	0.0006-0.0009	0.0002-0.0003	0.004-0.005	0.0018-0.0025	0.0006-0.0012
	A3	0.007-0.010	0.003-0.004	0.0008-0.002	0.018-0.021	0.009-0.011	0.003-0.006
	A7	0.019-0.023	0.008-0.010	0.001-0.003	0.054-0.064	0.022-0.030	0.007-0.014

- The rates of joint GW and GRB afterglow detections are $<< 1$ yr^{-1}
- If we consider BNS mergers with $\theta_j < 10^\circ$, the rates rise up to a factor $\sim$ 4, but they remain very low
- Under the assumption of a structured jet, the discovery of X-ray counterparts of BNS mergers with $\theta_j > 10^\circ$ is highly unlikely

Conclusions

- Depending on the population model considered and on the assumed GW SNR thresholds, the expected number* of BNS merger detections is between 1 and 61 per year

  → Comparison with O4 observations would allow us to put constraints on population synthesis models

- Expected rate* of multimessenger detections higher when considering Fermi/GBM

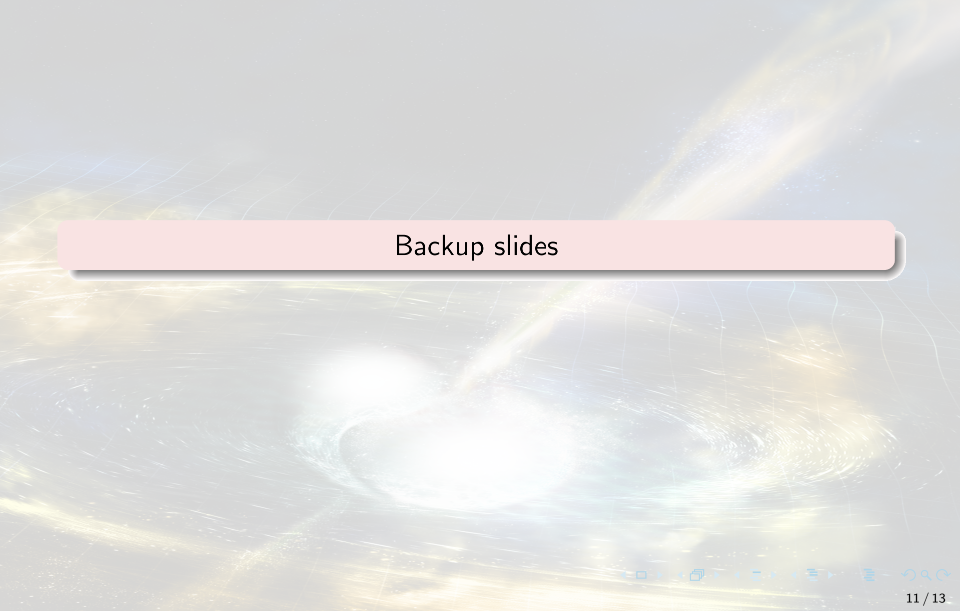
  → Fermi/GBM represents a very efficient detector of counterparts to GWs

- Probability to detect an X-ray counterpart is very low, mainly because only on-axis sources can be detected

- SVOM could play an important role for the discovery of S-GRB associated with BNS mergers

*NB: rates have been obtained assuming GW detector sensitivities higher than the current ones

Backup



Backup slides

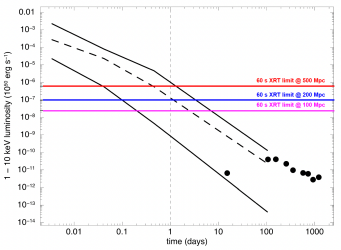
Results - gaussian jet

Model	GW+EM (prompt)							
	Swift/BAT		Fermi/GBM		INTEGRAL/IBIS		SVOM/ECLAIRs	
	case a	case b	case a	case b	case a	case b	case a	case b
	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}	yr^{-1}
A1	0.015	0.06	0.073	0.28	0.0025	0.01	0.013	0.05
A3	0.017	0.25	0.37	1.24	0.010	0.04	0.07	0.24
A7	0.19	0.71	0.96	3.44	0.032	0.12	0.17	0.66

Results - afterglow

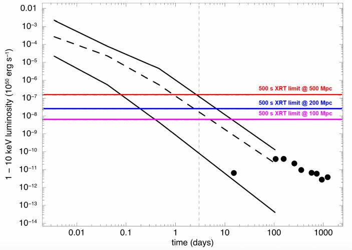
X-ray afterglow emission

60 s exposure



~ 60 % (50 %; 30 %) of on-axis S-GRBs at 100 Mpc (200 Mpc; 500 Mpc) would be detectable by *Swift*/XRT 1 day after the merger, with an exposure of 60 s

500 s exposure



~ 55 % (45 %; 25 %) of on-axis S-GRBs at 100 Mpc (200 Mpc; 500 Mpc) would be detectable by *Swift*/XRT 3 days after the merger, with an exposure of 500 s