The LIGO-Virgo O3 run: science results and multi-messenger investigations

R. Poggiani* on behalf of the LVK Collaboration

Department of Physics "E. Fermi", University of Pisa, and INFN-Sezione di Pisa, Pisa, Italy

rosa.poggiani@unipi.it

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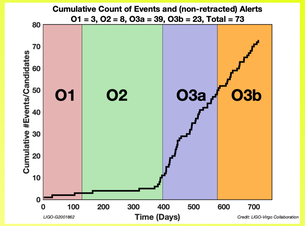
The third observation run (O3) of Advanced LIGO and Advanced Virgo started in April 2019 and ended in March 2020. The science results of the O3 run are summarized here, with a focus on the GWTC-2, GWTC-2.1, GWTC-3 catalogs of compact binary mergers and several exceptional events, including the first detected neutron star-black hole (NSBH) mergers. Multi-messenger investigations have been performed searching for EM and neutrino counterparts in coincidence with gravitational mergers, without any confirmed detection.

O3 run (April 2019-March 2020)

Public alerts

3 event catalogs

Exceptional events:
- GW190412: asymmetric BBH merger
- GW190425: second BNS merger
- GW190521: first IMBH observation
- GW190814: NS or BH secondary
- GW200105, GW200115: first NSBH mergers



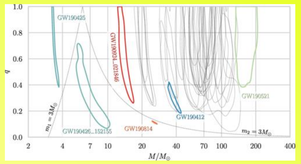
Gravitational-Wave Transient Catalog-2 (GWTC-2)

LVK, PRX 11 (2021) 021053

39 candidates in O3a (FAR<2/yr)

Total mass range 14-150 $M_\odot$

11 events with positive inspiral spin



GWTC-2.1: Deep Extended Catalog

LVK, arXiv: 2108.01045

Deeper list (improved calibration and noise subtraction), some new events

Gravitational-Wave Transient Catalog-3 (GWTC-3)

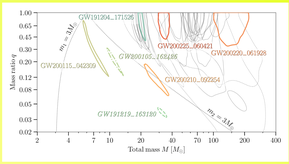
LVK, arXiv: 2111.03606

35 candidates in O3b (p_{astro} > 0.5)

32 BBH + 3 NSBH

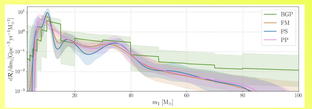
Total mass range 16.8-141 $M_\odot$

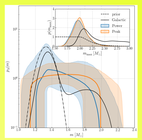
Two events with negative inspiral spin



GWTC-3 investigations

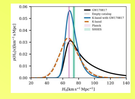
Population properties of black hole and neutron stars (LVK, arXiv:2111.03634)





Tests of General Relativity (LVK, arXiv:2112.06861), no deviations

Cosmic expansion (LVK, arXiv:2111.03604): $H_0 = 68^{+13}_{-7}$ km s^{-1} Mpc^{-1}



O3 run: low latency system

Candidates cataloged in Gravitational Candidate Event Database (GraceDB)

Alerts processed by GWCelery + human vetting

FAR threshold for GCN alerts:
- Compact Binary Coalescences (CBC): 1 per 2 months
- Bursts: 1 per year

O3a: 39 alerts total, 32 not retracted, median distribution time 7.3^{+56}_{-2} min

O3b: 39 alerts total, 23 not retracted, median distribution time 5.8^{+377}_{-3} min

O3 run: follow-up investigations

About one hundred ground and space based multi-messenger instruments: very high energy gamma-ray instruments, space-based X-ray and gamma-ray instruments, visible and infrared observatories, radio telescopes, neutrino observatories (summary in LVK, arXiv: 2111.03606)

~1500 related GCN circulars (44% all GCN circulars), > 150 papers/GCN notices

Combination of prompt and archival searches, wide-field searches, targeted searches

Majority of searches found no counterpart
- Neutrinos: 1 MeV-1 PeV
- X-rays/gamma-rays: <1 TeV: GW190425 possible EM counterpart
- Optical/infrared: observations of several candidates and targeted observations
- Radio: generally targeting events containing NS

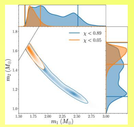
Additional searches after alerts, see GW190521

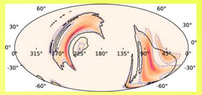
O3 exceptional events: GW190425

BNS merger, mass of both components < 3 $M_\odot$, total mass 3.4 $M_\odot$, larger than for known BNS

NS presence triggered > 100 GCN circulars

Poor sky localization, ~ 8000 deg^2 Luminosity distance ~ 160 Mpc





LVK, ApJL 892 (2020) L3

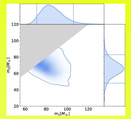
Possible EM counterpart: weak GRB190425 (two pulses at ~0.5s, ~5.9s after merger) detected by INTEGRAL SPI-ACS (AstL 45 (2019) 710)

O3 exceptional events: GW190521

First detection of an intermediate mass black hole (IMBH), mass ~150 $M_\odot$

Sky localization, ~ 800 deg^2

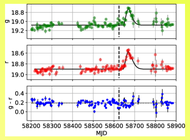
LVK, PRL 125 (202) 101102



Eccentric BBH? (Romero-Shaw+ 2020, Gayathri+ 2022, Gamba+ 2021, Iglesias+ 2022)

Multimode ringdown spectrum (Capano+2021)

Possible EM counterpart: transient ZTF19abanrhr observed ~34 days after merger associated with AGN J124942.3+344929 (Graham+ 2020); Multi-messenger significance of association (Ashton+ 2021, De Paolis+ 2020, Palmese+ 2021, Chen+ 2022)

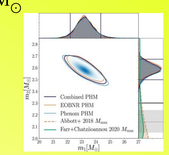


O3 exceptional events: GW190814

Component masses in ranges 22.2-24.3 $M_\odot$, 2.50-2.67 $M_\odot$

Extreme mass ratio, high multipole emission

Secondary component:
heaviest NS or lightest BH in compact binary?



ApJL 896 (2020) L44

No EM counterpart

O3 exceptional events: GW200105, GW200115

First detection of neutron star-black hole mergers during O3b

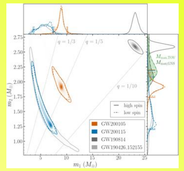
No EM counterpart observed

GW200105

Component masses: $8.9^{+1.2}_{-1.5}$ $M_\odot$, $1.9^{+0.2}_{-0.3}$ $M_\odot$

GW200115

Component masses: $5.7^{+1.8}_{-2.1}$ $M_\odot$, $1.5^{+0.6}_{-0.3}$ $M_\odot$



ApJL 915 (2021) L5

Other multi-messenger investigations during O3

Targeted unmodeled searches for GW transients associated with Fermi and Swift GRBs, minimum coincident data from two IFOs at least around the GRB time, no signal found
- O3a: 105 GRBs, 32 GRBs targeted for BNS mergers (LVK, ApJ 915 (2021) 86)
- O3b: 86 GRBs, 15 GRBs targeted for mergers with at least one NS (LVK, arXiv:2111.03608)

Search for GW transients associated to Fast Radio Bursts (FRBs) detected by the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst Project (CHIME/FRB), no evidence of gravitational association found (arXiv:2203.12038)
- O3a: 22 and 40 FRBs looking for CBC with at least one NS component and for generic GW transients

Search for GW transients associated magnetar bursts, upper limits (arXiv:2210.10931)
- O3: 13 bursts from SGR 1935+2154 and Swift J1818.0-1607 and 3 Fermi-GBM bursts

O3 run and follow-up

Optical and infrared photometric and spectroscopic observations: several collaborations searched counterparts for a large fraction of events
- Lack of KN counterparts constraining KN luminosity function (Kasliwal+ 2020)
- KN candidates lacking classification information, brighter than GW170817 KN (Rastinejead+ 2022)

X-ray and gamma ray observations: ground and space based observatories covering energies from keV to TeV
- No Swift counterparts to coincident GW and neutrino events (Keivani+ 2021)
- No GRB precursors with modulation associated to mergers in Fermi-GBM data (Stachie+ 2022)
- But: optical/IR KN, QPO detected in GRB 211211A (Mei+ 2022, Rastinejead+ 2022, Xiao+ 2022, Zhang+ 2022)