Astrophysical sources

Rosa Poggiani

Virgo-ET Pisa internal workshop, 22-23 May 2024

GWTC-3: member of PWT

Member of GWTC-4 scoping Team

Multi-messenger follow-up of events (all-sky short burst, O4 EM task force)

SN 2023ixf and close supernovae in O4 (distance < 30 Mpc)
SN 2023ixf: member of PWT

Review of software/pipelines/papers

Experience in IFO suspensions: seismic noise, thermal noise, UHV contamination
Cryogenic suspension for ET

Experience in observational optical astronomy, multi-frequency time series analysis

Cataclysmic variables as gravitational sources for LISA

Distance of astronomical objects

GWTC-3 Scope: O3b CBC events p-astro > 0.5

GWTC-3 Editorial Team: 12 members + 1 Review Coordinator + 76 reviewers

Open Project start date: April 1st, 2020

First call July 14th, 2020, more than 200 calls (two/week, ET members scattered in different continents)

LVK presentation: August 11th, 2021

First submission: November 10th, 2021

Referee report: April 5th, 2022

Final published version: December 4th, 2023

Citations as of May 21th, 2024: 1761

Includes summary of multi-messenger observations of candidates in O3, O3b

GWTC-3 Team (LIGO/Virgo)

Christopher Berry (chair; source properties)
Gareth Cabourn Davies (PyCBC; VT & p-astro)
Zoheyr Doctor (GWTC-2 liaison)
Rebecca Ewing (GstLAL; catalog-dev)
Frederique Marion (MBTA; searches)
Jess McIver (data quality)
Hannah Middleton (EPO; data release)
Edoardo Milotti (cWB; waveform reconstructions)
Rosa Poggiani (instruments; follow-up (proposed); waveform reconstructions)
Isobel Romero-Shaw (source properties)
Madeline Wade (paper manager; calibration)
Daniel Williams (PE management)
Aaron Zimmerman (review manager)

35 additional events (adding to 55 in GWTC-2.1), including 6 marginal events and 1048 subthreshold events

GWTC-3 paper structure

I) Introduction (paper outline)
   Appendix A: Low-latency alert system and multimessenger follow-up

II) Instruments (interferometer performances in O3b)
   Appendix B: Observatory evolution

III) Data
   Appendix C: Data-quality methods

IV) Candidate Identification (searches)
   Appendix D: Candidate identification methods

V) Source Properties (parameter estimation)
   Appendix E: Parameter-estimation methods
   Appendix F: Unconfirmed cWB-only candidates

VI) Waveform Consistency Tests

VII) Conclusion

	GWTC-1	GWTC-2	GWTC-3
Page length	49	52	89
Effective page length (no refs., no auth. list)	34	35	57
Main text length (without appendices)	28	27	32
Appendices page length	7	8	24
Number of references	264	306	695
References in appendices	35	19	279

GWTC-3 appendix A: low-latency alert system an multimessenger follow-up

Counterparts of events: frequent question at conferences

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

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

Multimessenger follow-up addressed in exceptional event papers, previously not in catalogs

Multimessenger follow-up is a measure of the impact of gravitational observations: ~100 observatories, ground and space based, covering gamma and X-rays, visible, infrared and radio domains, neutrinos over broad energy ranges

Systematic investigations of several candidates + targeted searches (mostly coalescences involving NS)

~1500 related GCN circulars (44% all GCN circulars)

> 150 papers and GCN notices

SID	Event	GCN	Follow-up publications
S191105e	GW191105_143521	[529]	[431, 433–436, 439, 441, 444, 447, 449, 451, 452, 455]
S191109d	GW191109_010717	[530]	[431, 433–436, 439, 441, 444, 447, 449, 451, 455]
S191110af		[531]	[456, 457]
S191110x		[532]	
S191117j		[533]	
S191120aj		[534]	
S191120at		[535]	
S191124be		[536]	
S191129u	GW191129_134029	[537]	[431, 433–436, 439, 444, 447, 449, 451, 455]
S191204r	GW191204_171526	[538]	[431, 433–436, 439, 441, 444, 447, 449, 451, 455]
S191205ah		[539]	[431, 436, 439, 441, 447, 450, 452, 464, 466]
S191212q		[540]	[433]
S191213g		[541]	[431, 433, 436, 439, 447, 450, 451, 456, 457, 464, 466, 472]
S191213ai		[542]	
S191215w	GW191215_223052	[543]	[431, 434–436, 439, 441, 444, 447, 449, 451, 455]
S191216ap	GW191216_213338	[544]	[431, 433–436, 439, 441, 444, 447, 449, 451, 452, 455–457, 500, 545]
S191220af		[546]	[462]
S191222n	GW191222_033537	[547]	[431, 433, 434, 436, 439, 444, 447, 449, 451, 455]

Concise summary of follow-up observations for O3a and O3b

No unambiguous detection of any counterpart, but reported potential associations GW190521/AGN J124942.3+344929 and GW190425/FRB 20190425

GWTC-4 scoping team

Outline the expected content of the GWTC-4 catalogue data release, define significant threshold for full treatment of events

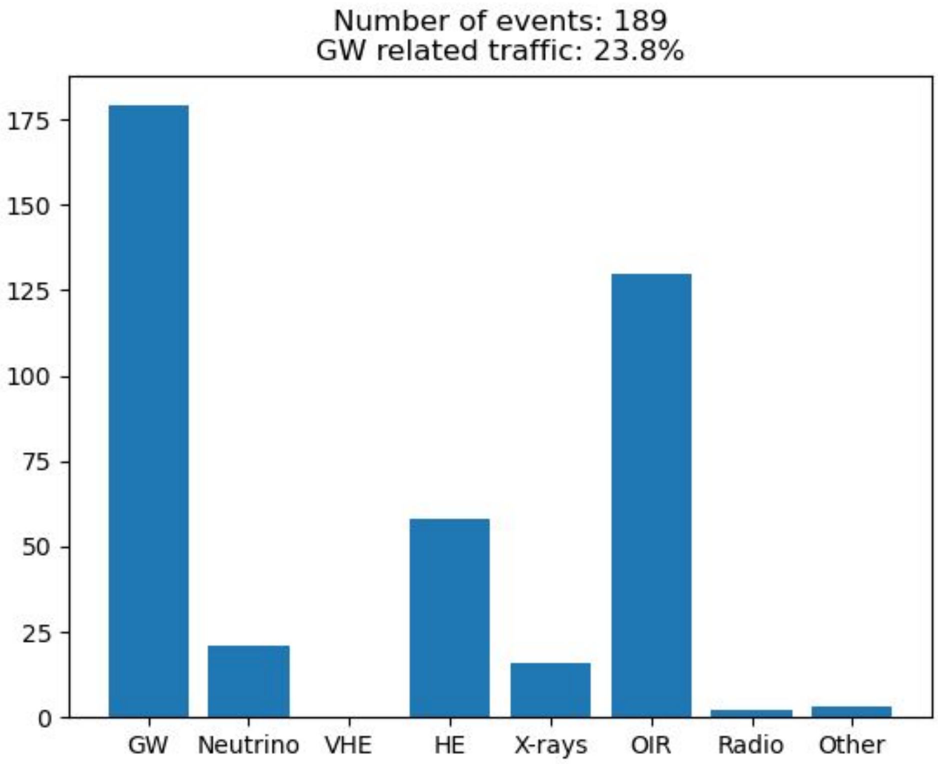
Estimate the resources and timeline for catalogue, identifying potential bottlenecks, potential risks
Recruit many reviewers in advance, analysis methods/code, analysis results to be reviewed in advance by a team other than the review catalog teams
Statements in the paper (tables, figures…) to be reviewed by the catalog review teams as well as data consistency

Consider any missing technology/resources needed to deliver the catalogue
Centralize data and metadata so that the same “repository” is the source of truth for all publications

Consider developing a lightweight catalog management system on top of tools to help enforce process

Suggestion to keep track of different interferometer configurations in Virgo Instrument Book/LIGO Instrument Book

Multi-messenger follow-up of O4a events



<u>End of O4a run update</u>

Statistics of events with GCN circulars

Relevant contribution to GCN traffic

Large number of OIR GCNs

Several X-ray, HE and neutrino GCNs

A few radio GCNs

No VHE GCNs

Tree with links to multi-messenger reports of events and end of O4a run summary:

https://dcc.ligo.org/LIGO-P2300191

Summary table of 24 O4a events with number of candidate EM/neutrino counterparts:

https://docs.google.com/spreadsheets/d/1zfVdscpoCMQZJKx0QpjjXi9o_knRWuc8i2AmeM_e0jw/edit#gid=0

Summary table of 100 O4a events with follow-up observations , but no detected counterpart:

https://docs.google.com/spreadsheets/d/15CjGN-BMTWMNdThXpaIWVUWoR58vzNZgkHEBx_dSPbg/edit#gid=0 https://docs.google.com/spreadsheets/d/1zfVdscpoCMQZJKx0QpjjXi9o_knRWuc8i2AmeM_e0jw/edit#gid=0

Candidate	Radio	Optical	X-rays	HE	Neutrino	Reference	Significant
S230518h	-	3+2	8	Delayed pulse in AGILE data	-	LIGO-P2300167	Y
S230521k	-	2+4+1	-	-	-	LIGO-P2300168	
S230522a	-	-	-	-	2	LIGO-P2300169	Y
S230527ch	-	2	-	-		LIGO-P2300170	
S230529ay	-	1	-	-	-	LIGO-P2300171	Y
S230615az	-	2+2+1	-	-	-	LIGO-P2300190	
S230619bd	-	-	-	1 (GBM-230619)	-	LIGO-P2300199	
S230619bg	-	-	-	-	1	LIGO-P2300209	
S230627c	-	4	-	-	-	LIGO-P2300210	Y
S230628aj	-	-	-	-	1	LIGO-P2300211	
S230701z	-	-	-	-	1	LIGO-P2300212	
S230726b	-	-	-	-	1	LIGO-P2300252	
S230812aj	-	-	-	-	2	LIGO-P2300308	
S230904n	-	-	-	-	1	LIGO-P2300309	Y
S230908b	-	-	-	-	1	LIGO-P2300310	
S230917af	-	-	2	-	-	LIGO-P2300323	
S230922g	-	13	-	-	-	LIGO-P2400019	Y
S231018cb	-	-	-	-	1	LIGO-P2300371	
S231025a	-	-	-	-	2	LIGO-P2300409	
S231029y	-	-	-	-	1	LIGO-P2300410	Y
S231106y	-	-	-	-	1	LIGO-P2300411	
S231119u	-	-	-	-	1	LIGO-P2300415	Y
S231205c	-	-	-	-	1	LIGO-P2300467	
S231215i	-	-	-	-	3	LIGO-P2300468	

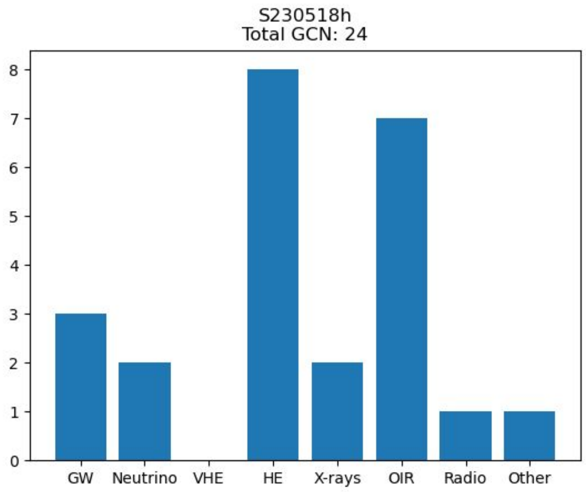
Events with candidate counterparts include both significant and not significant events

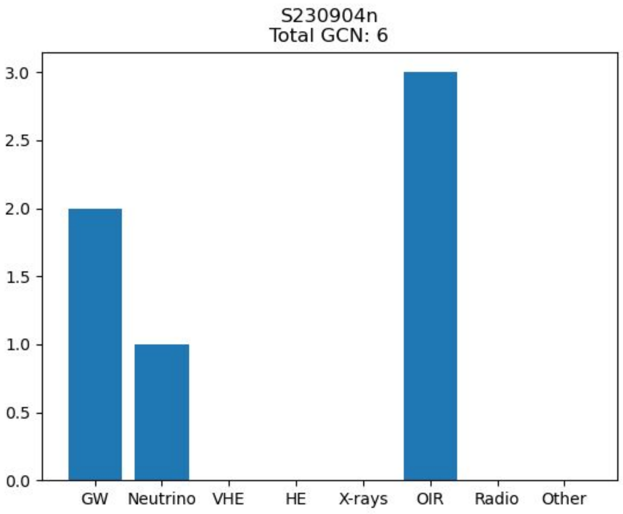
Excerpts of https://docs.google.com/spreadsheets/d/15CjGN-BMTWMNdThXpaIWVUWoR58vzNZgkHEBx_dSPbg/edit#gid=0

Candidate	Radio	Optical	X-rays	HE	Neutrino	Significant
S230522n	-	-	-	-	IceCube	
S230524b	-	MASTER	-	-	-	
S230528a	-	ZTF	-	-	-	
S230531f	-	MASTER	-	-	-	
S230601bf	-	MASTER	-	-	-	Y
S230602ap	-	MASTER, ZTF	-	-	-	
S230603aa	-	MASTER	-	-	-	
S230604z	-	MASTER	-	-	-	
S230605o	-	MASTER	-	-	-	Y
S230606d	-	MASTER	-	-	-	Y
S230606z	-	MASTER	-	-	-	
S230608q	-	MASTER	-	-	-	
S230608ah	-	MASTER	-	-	-	
S230608as	-	MASTER	-	-	-	Y
S230608aw	-	MASTER	-	-	-	
S230609a	-	MASTER	-	-	-	
S230609u	-	MASTER	-	-	-	Y
S230731an	-	-	AstroSAT, MAXI, Swift/BAT	-	-	Y
S230802aq	-	-	AstroSAT,INTEGRAL,MAXI	Fermi/GBM	-	Y
S230805q	-	-	Swift/BAT	-	-	
S230822bm	-	-	Swift/BAT	-	-	Y
S230825k	-	-	Swift/BAT	-	-	Y
S230914ak	-	-	Swift/BAT	-	-	Y
S230919bj	-	-	Swift/BAT	-	-	Y
S230920al	-	-	Swift/BAT	-	-	Y
S230924an	-	-	Swift/BAT	-	-	Y
S230928cb	-	-	Swift/BAT	-	-	Y
S230930al	-	-	Swift/BAT	-	-	Y
S231001aq	-	-	Swift/BAT	-	-	Y
S231005j	-	-	Swift/BAT	-	-	Y
S231014r	-	-	Swift/BAT	-	-	Y
S231020ba	-	-	MAXI	Fermi/GBM	-	Y
S231020bw	-	-	Swift/BAT	-	-	Y
S231021az	-	-	MAXI	-	-	

Events with follow-up include both significant and not significant events

Multi-messenger follow-up of O4a events

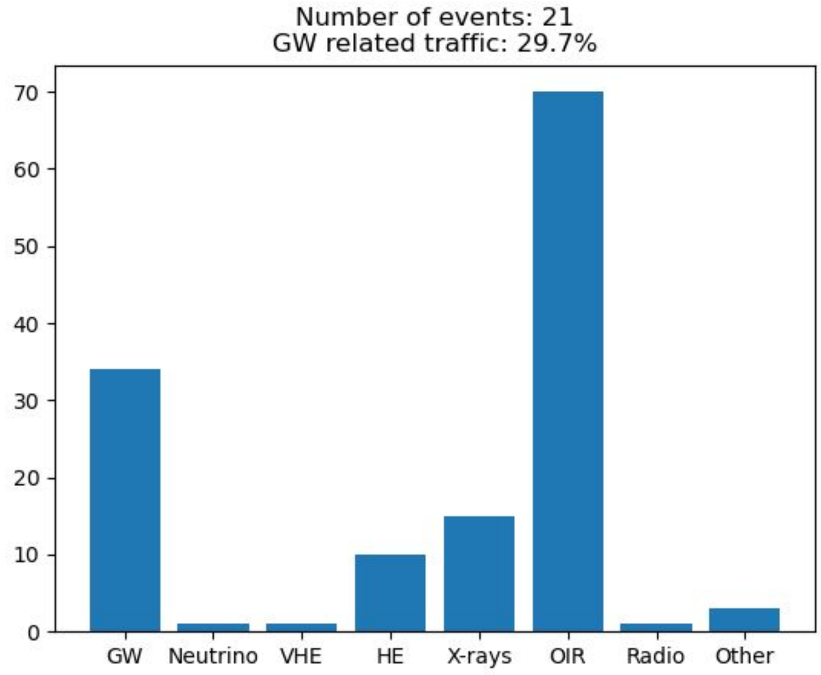




S230518h: several candidate counterparts, delayed pulse observed by AGILE

S230904n: O4 EM task force chat, report at https://dcc.ligo.org/P2300309

Multi-messenger follow-up of O4b events



<u>Update 22/05/2024</u>

Relevant contribution to GCN traffic

Large number of OIR GCNs

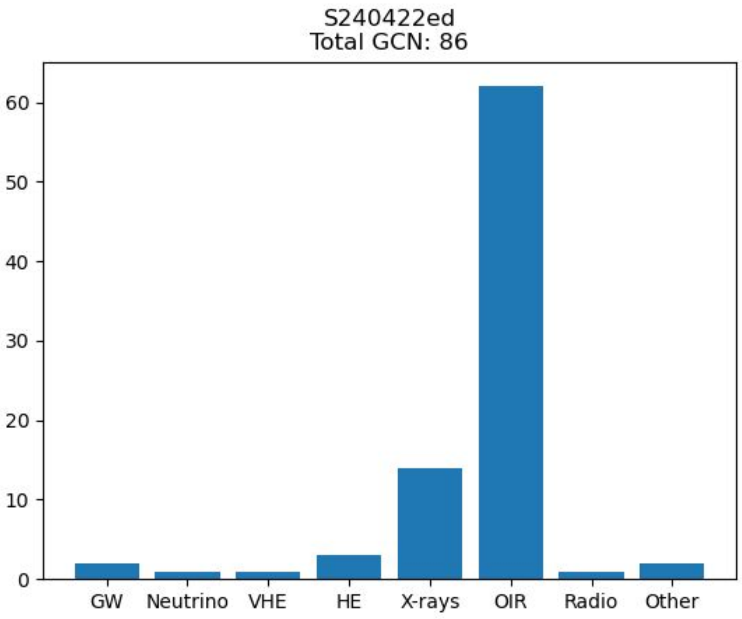
Several X-ray, HE and neutrino GCNs

Two radio GCNs

One VHE GCN (first in O4)

One neutrino GCN

Multi-messenger follow-up of O4b events



Several EM candidate counterparts detected, ~ 46 (preliminary):

- 41 optical counterparts
- 1 infrared counterpart
- 4 X-ray counterparts

Faint optical counterparts, magnitude in the range 19-21, generally a few photometric data points

Extensive X-ray follow-up for several candidates by Swift/XRT, eROSITA, EP-WXT, EP-FXT

Candidate counterpart vetting:

- large number of observations targeted to redshift estimation
- relevance of all-sky survey archives to search for photometric activity before merger

<u>No confirmed counterpart</u>

Candidate optical counterparts for several events, but spectroscopic observations to classify transients are sporadic, candidate counterparts generally faint and requiring large aperture instruments

Some X-ray and HE candidate counterparts, including one event with delayed HE pulse

One candidate VHE counterparts

Some events with neutrino candidate counterparts, as compared to O3

Supernovae

Sources of interest for burst searches, selection of objects with distances up to about 30 Mpc:

- Type II supernovae

- Type Ib supernovae

- Type Ic supernovae

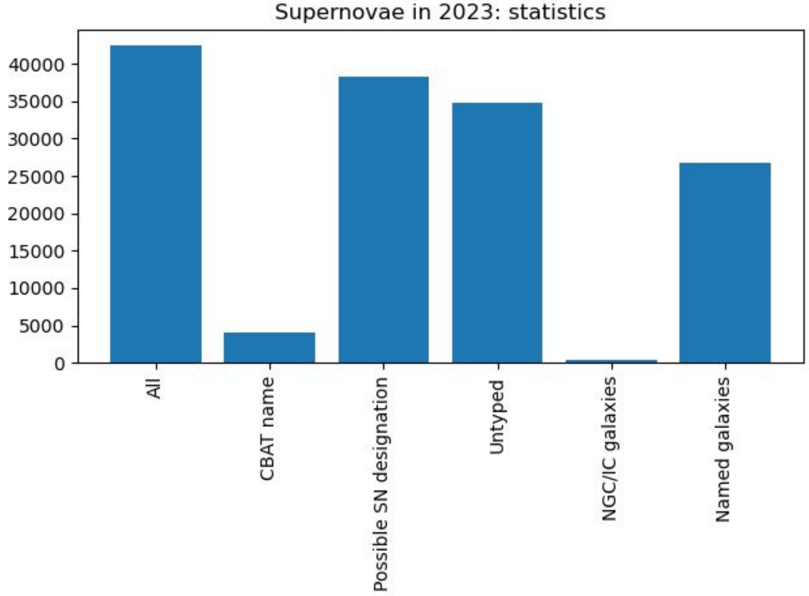
Relevant parameter: on-source window (OSW), time interval from t1 to t2 containing the core bounce and the following GW emission
t2 well approximated by first detection, t1 involving delay between collapse and shock breakout, whose time falls between t2 and latest pre-discovery observation, time delay depends on many properties of progenitor, including its mass

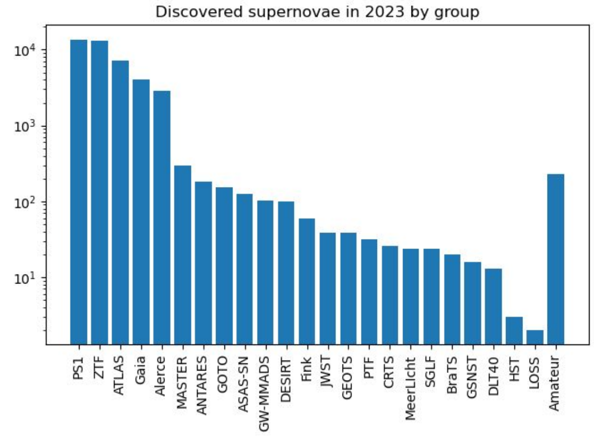
Core collapse supernovae:

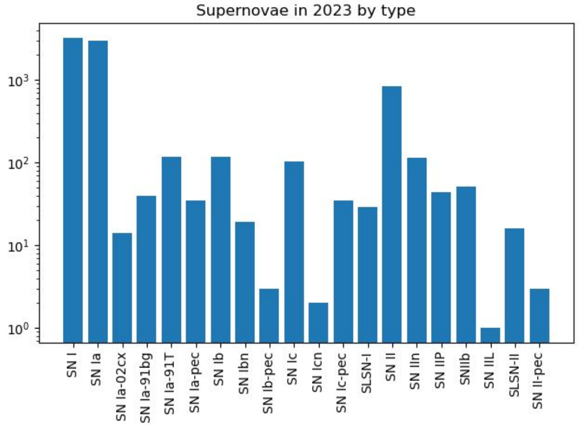
- OSW searches when early photometric evolution available
- often transition from quiescence to rise is not observed, all-sky searches

Statistics of 2023 supernovae

Data from https://www.rochesterastronomy.org/snimages/



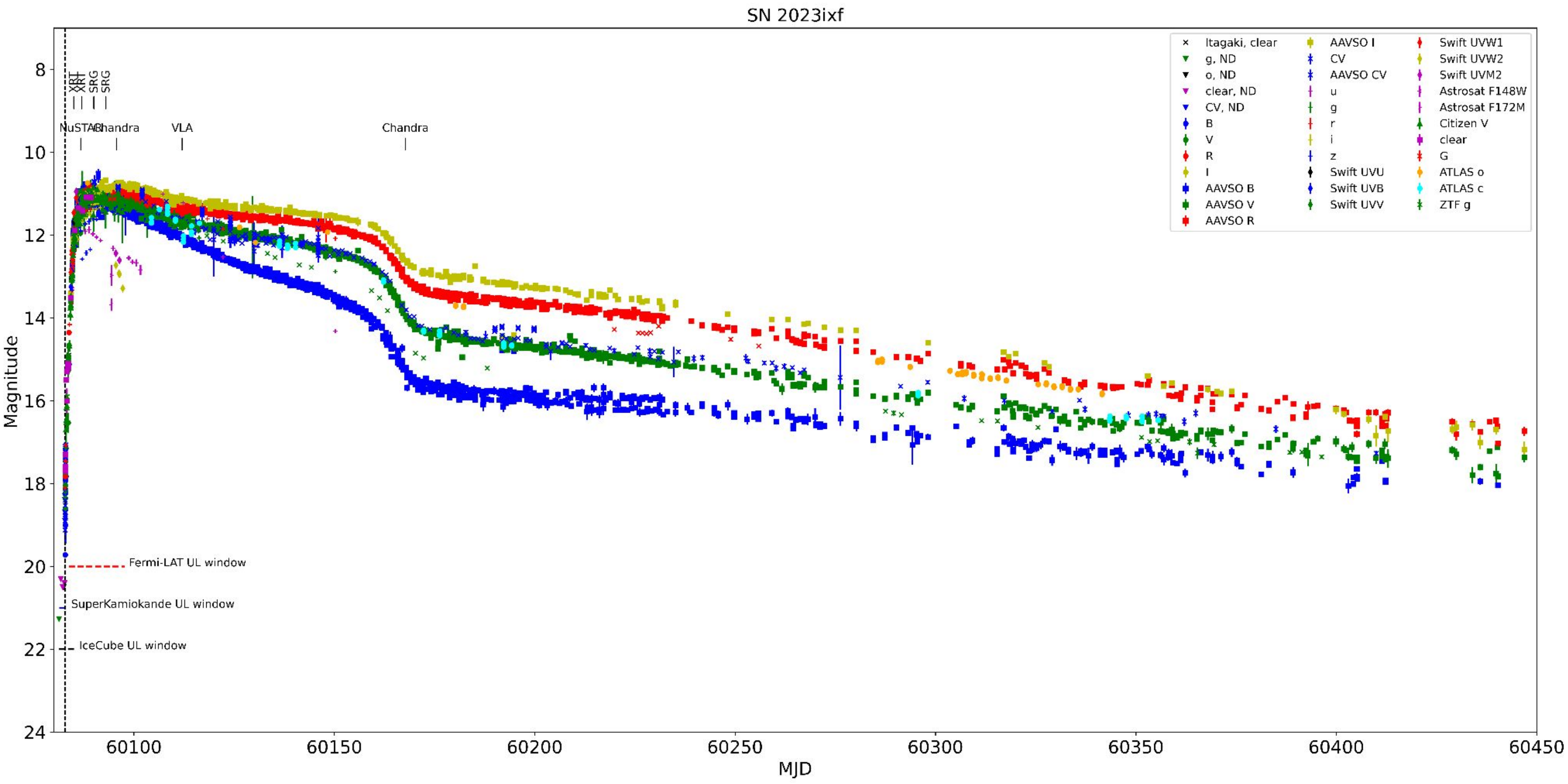




O4a close supernovae

Supernova	Type	Redshift (TNSAN)	NED Median distance (Mpc)	Host galaxy	Discovery date
SN 2023ixf	II	0.0008	6.7	M101	2023-05-19
SN 2023mut	IIb	0.0022	8.2	UGC 03174	2023-07-11
SN 2023hlf	II	0.0024	18.1	NGC 4414	2023-05-01
SN 2023ijd	II	0.007446	17.35	NGC 4568	2023-05-14
SN 2023mpz	II	0.005	-	GALEXASC J202049.64+092955.3	2023-07-09
AT2023gfo	II	0.006	25.95	NGC 4995	2023-04-20
SN 2023fyq	Ib-pec	0.008419	18.05	NGC 4388	2023-04-17
SN 2023rve	II	0.004	16	NGC 1097	2023-09-08
AT2023usp	II	0.006791	14.8	NGC 2848	2023-10-03
SN 2023zcu	II	0.006	26.55	NGC 2139	2023-12-08
SN 2023zdx	II	0.009	30.1	NGC 5630	2023-12-05
SN 2023abdg	II	0.006	27.65	NGC 7421	2023-12-24

SN 2023ixf



SN 2023ixf
Magnitude
MJD
8
10
12
14
16
18
20
22
24
60100
60150
60200
60250
60300
60350
60400
60450
XRT
XRT
SRG
SRG
NuSTAR
Chandra
VLA
Chandra
Fermi-LAT UL window
SuperKamiokande UL window
IceCube UL window
Itagaki, clear
g, ND
o, ND
clear, ND
CV, ND
B
V
R
I
AAVSO B
AAVSO V
AAVSO R
AAVSO I
CV
AAVSO CV
u
g
r
i
z
Swift UVU
Swift UVB
Swift UVV
Swift UVW1
Swift UVW2
Swift UVM2
Astrosat F148W
Astrosat F172M
Citizen V
clear
G
ATLAS o
ATLAS c
ZTF g

SN 2023ixf: progenitor

Progenitor: Red SuperGiant (RSG) with circumstellar medium (CSM)

CSM could have been produced by mass loss enhancement before explosion, but no pre-explosion outburst detected, only amplitude pulsations

Broad range of zero age main sequence (ZAMS) masses estimated using different methods, 8-20 $M_\odot$:

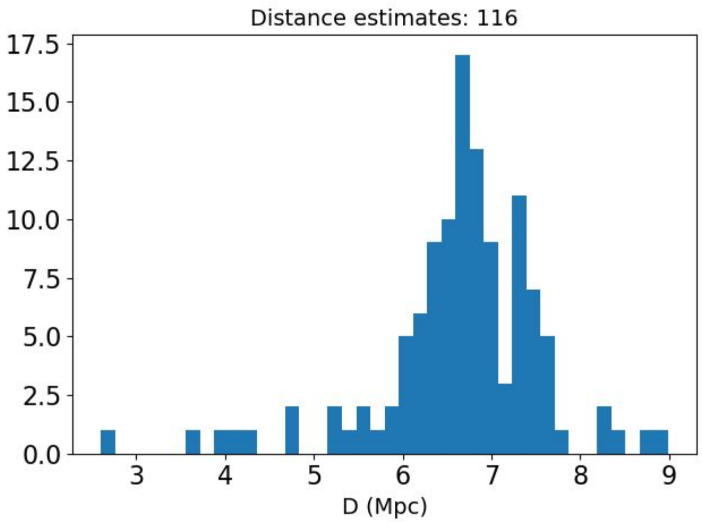
- Imaging
- Hydrodynamic modelling
- Comparison with stellar evolution models
- spectral energy distribution information
- Supernova environment
- Progenitor pulsations

End of OSW defined by first non upper limit observation. Shock-breakout time is within the interval between end of OSW and more recent pre-discovery observation. The unknown time delay between collapse and shock-breakout depends on progenitor properties, including mass (Barker+ 2021).

Large spread in mass estimations -> conservative OSW duration of 5 days

Distance to host galaxy M101

Distance estimates	Median distance (Mpc)
All methods	6.73
All methods w/o statistical	6.73



Method	# estimates	Median distance (Mpc)
Cepheids	39	6.95
PNLF	3	7.66
SN Ia	29	6.46
TRGB	18	6.77
SN II optical	29	7.4
Brightest Stars	4	6.475
Tully-Fisher	13	5.5
M stars	1	5.25
RSV Stars	1	7.59
S Doradus Stars	1	5.25
Statistical	1	6.95
HII region diameter	2	5.04
SNII radio	1	7.4

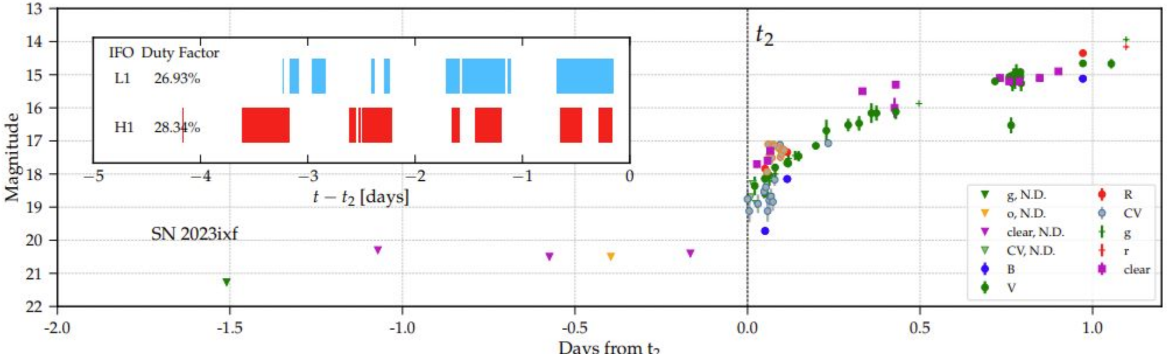
SN 2023ixf presently under circulation

Search for gravitational waves emitted from SN 2023ixf

LVK Collaboration

ABSTRACT

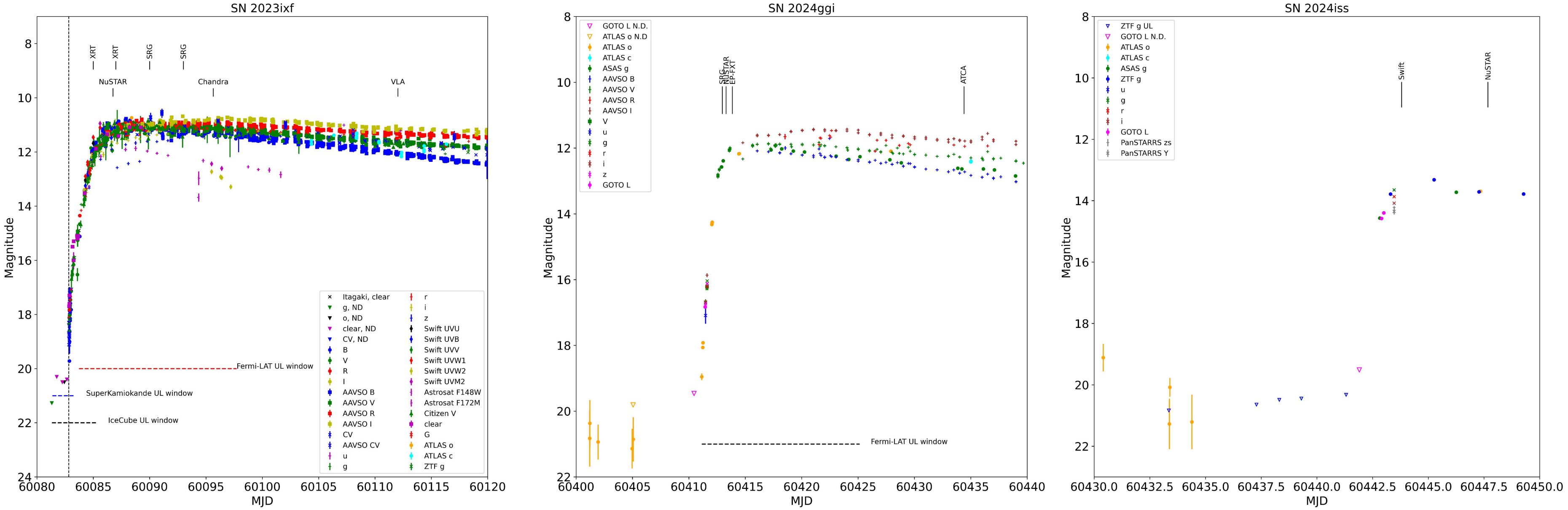
We present the results of a search for gravitational-wave transients associated with core-collapse supernova SN 2023ixf, which was observed in the galaxy Messier 101 during the 15th Engineering Run of Advanced LIGO-Virgo. No gravitational waves have been identified in double coincident gravitational-wave data covering only $\sim 14\,\%$ of the possible on-source window. We report the search detection efficiency for various possible gravitational-wave emission models. For most of the non-rotating neutrino-driven explosion models, a source in the Galaxy would be detectable. For more energetic magnetorotationally-driven explosions the search is sensitive to sources beyond the Large Magellanic Cloud. Furthermore, we derive constraints on the gravitational-wave emission mechanism of core-collapse supernovae across a broad frequency spectrum, ranging from 50 Hz to 2 kHz. Considering an ellipsoid model for a rotating proto-neutron star, our search is sensitive to gravitational-wave energy and luminosity as low as $10^{-5}\,M_\odot c^2$ and $2\times10^{-4}\,M_\odot c^2/s$ for a source emitting at 50 Hz. The constraint on the ellipticity of the proto-neutron star, obtained at frequencies above 1200 Hz, is as low as 1.04.



O4b close supernovae

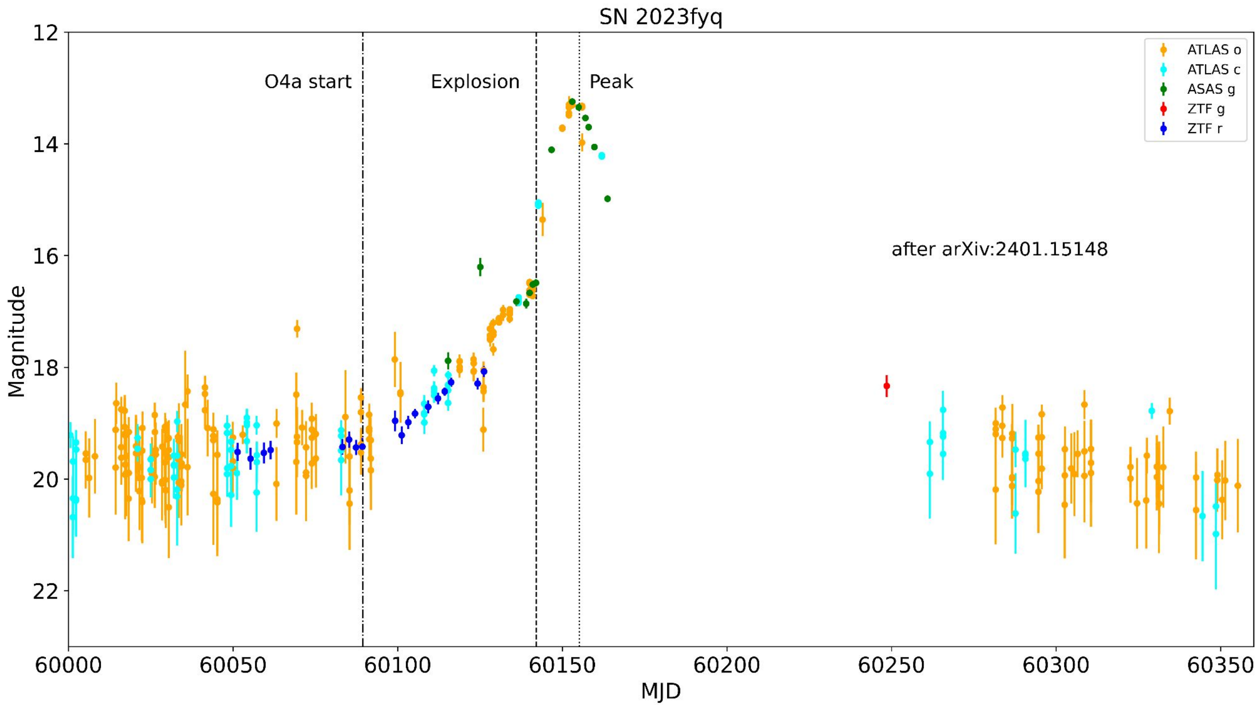
Supernova	Type	Redshift (TNSAN)	Host galaxy	Discovery date
SN 2024ehs	II	0.003776	NGC 3443	2024-03-15
SN 2024exw	II	0.007	UGC 7223	2023-04-10
SN 2024ggi	II	0.002435	NGC 3621	2024-04-11
SN 2024iss	II	0.00333	LEDA 1846725	2024-05-12

Photometric evolution of SN 2023ixf, SN 2024ggi, SN 2024iss



Similar photometric and spectroscopic evolution, RSG progenitor, interaction with CSM, larger for SN 2023ixf, SN 2024ggi

SN 2023fyq, type Ibn (= ZTF22abzzvln) (= ATLAS23rwh) (= PS23fnw) (= PSN J12254586+1239487)



arXiv:2401.15148: observations of progenitor in the previous 150 days before explosion as type Ibn supernova, flux showed an exponential rise prior to core-collapse. Asymmetric He-rich material present before and after explosion, surviving ejecta-CSM interaction. Progenitor highly unstable before core-collapse

Recent paper related PWT and reviewer activity

Rosa Poggiani	O3 isotropic stochastic (done)	result reviewer, data product reviewer
Rosa Poggiani	O3 directional stochastic (done)	result reviewer
Rosa Poggiani	O3 all-freq radiometer (done)	result reviewer
Rosa Poggiani	O3b Catalog (done)	PWT/editorial team member
Rosa Poggiani	O3 LVC-Swift sub-thresh GRB (active)	result reviewer
Rosa Poggiani	Search for GW emitted by SN2023ixf (active)	PWT/editorial team member
Rosa Poggiani	O3 LVC-GBM sub-thresh GRB (active)	result reviewer, data product reviewer

Member of Stochastic, LIGO-skymap review committees
PyGRB

Cryogenic suspensions for ET: material, components, technical solutions

- Behavior of materials at cryogenic temperatures cannot be extrapolated from room temperature properties
- Fundamental properties of materials: thermal conductivity, thermal expansion
- Thermometry
- Cabling
- Low temperature electronics
- Magnets
- Adhesives
- Actuators
- Creep at low temperatures
- Baffles
- Contamination