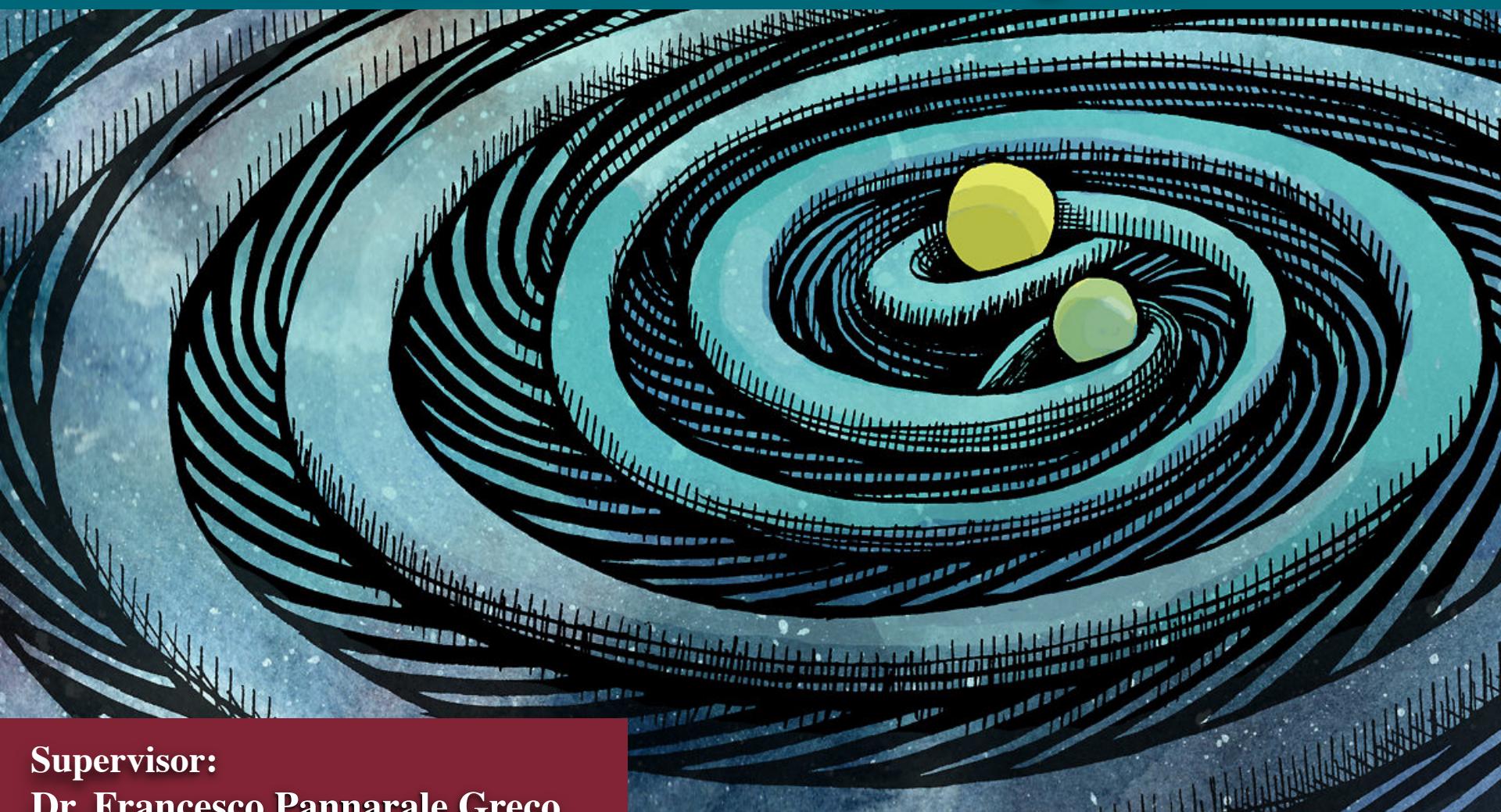


# Coherent and Coincident Analyses of LIGO-Virgo Data from the Third Observing Run



Supervisor:

**Dr. Francesco Pannarale Greco**

Candidate:

**Giada Caneva Santoro**



**SAPIENZA**  
UNIVERSITÀ DI ROMA

# GRAVITY: FROM APPLES TO RIPPLES

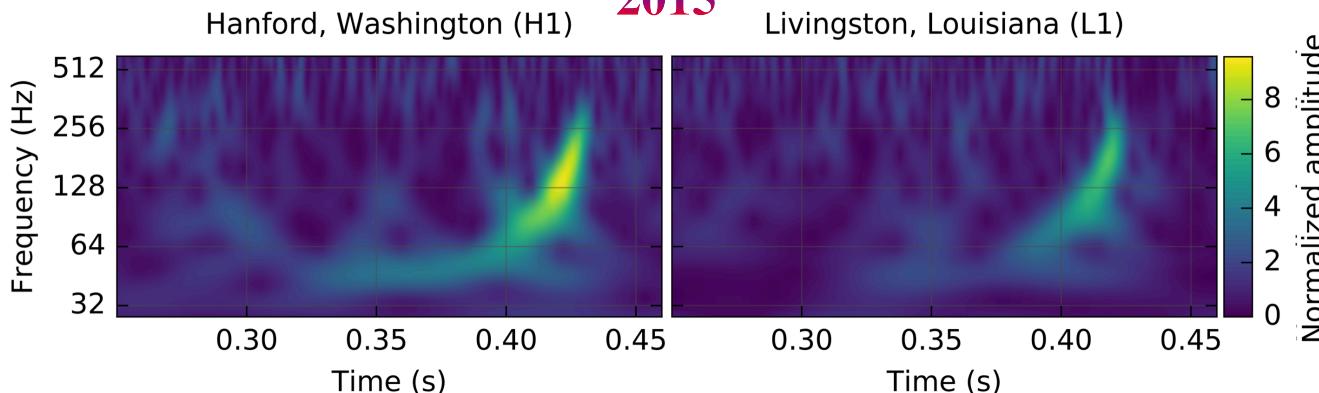
1.4 billion light years ago



1916



2015

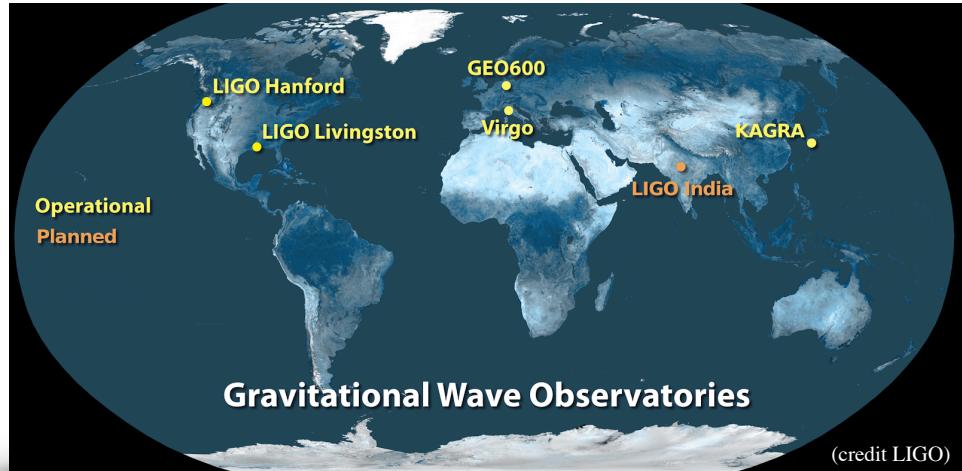


GW150914: Abbott et al. (2016) Phys. Rev. Lett. 116, 061102

# GRAVITATIONAL WAVE DETECTION

Network of detector required.

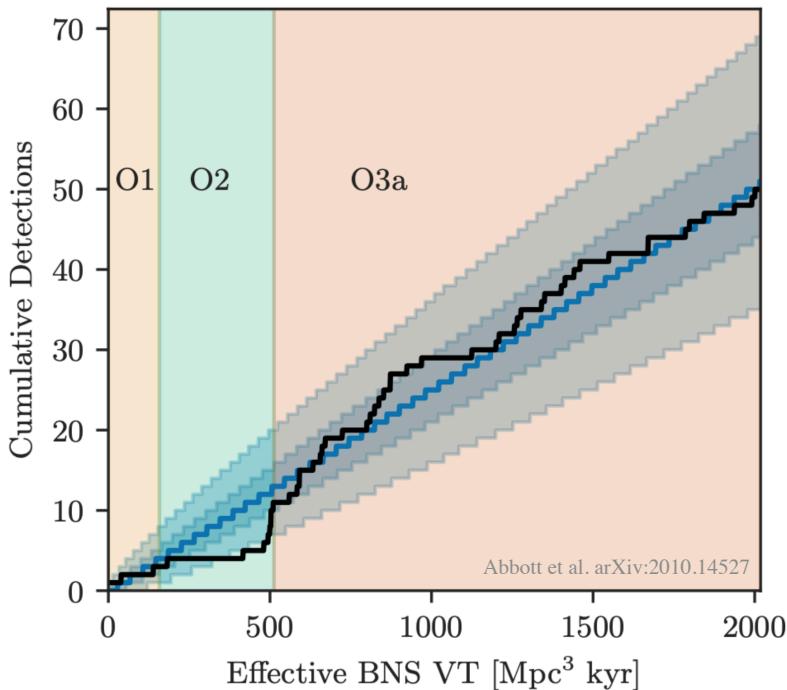
- ★ COINCIDENCE OF DETECTIONS:  
confidence that signal is from  
extraterrestrial sources, rather than from  
noise.



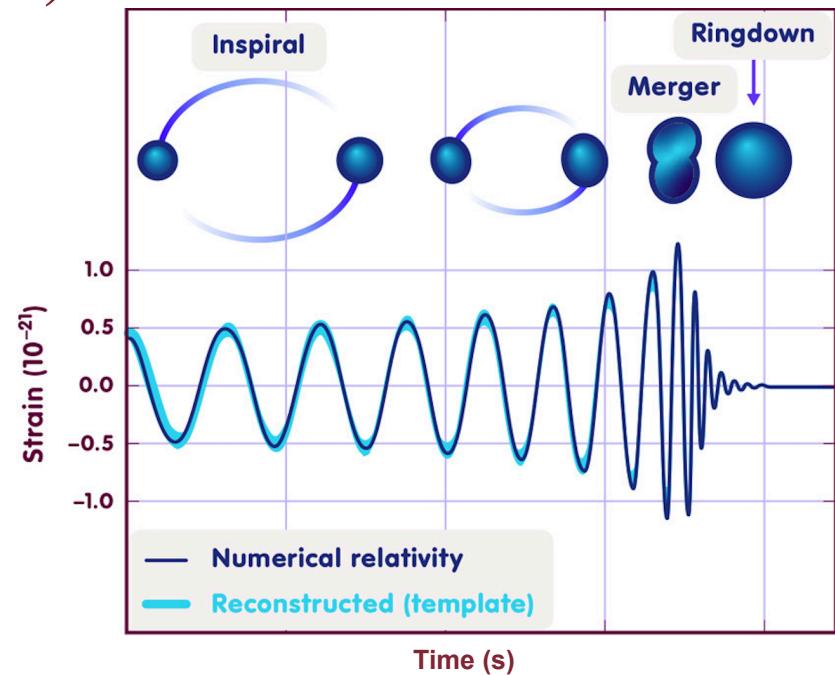
- ★ More detectors may provide a larger signal-to-noise ratio, which decreases the sky localisation area.
- ★ More detectors provide a higher duty cycle.
- ★ SKY LOCALISATION: triangulation techniques based on the time delay in more than two detectors.

→ **Enables Multi Messenger Astronomy**

# COMPACT BINARY COALESCENCE (CBC)



**O1:** September 12, 2015 - January 19, 2016  
**O2:** November 30, 2016 - August 25, 2017  
**O3a:** April 1, 2019 - 30 September, 2019



**BBH:** binary black hole.  
**BNS:** binary neutron star.  
**NSBH:** neutron star-black hole.

# CBC SEARCHES

- **ONLINE**: detect and report events with sub-minute latencies.
- **OFFLINE**: data calibration and data quality to produce a more sensitive search.

## PyCBC

- All-sky coincident search
- Targets all kinds of CBCs
- Background analysis of a chunk of O3b data  
(yet to be published by LVC)

## PyGRB

- Targeted coherent search
- Follow-up to EM transient (GRBs)
- Analysis of three GRBs (from Swift & Fermi) in O3a data published in a **LIGO-Virgo paper**  
[arXiv:2010.14550](https://arxiv.org/abs/2010.14550) submitted to *Astrophysical Journal*.

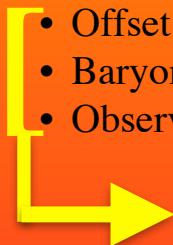
Both publicly available at <https://github.com/gwastro/pycbc>

# GAMMA RAY BURSTS

Farthest and brightest explosions in the Universe (1 keV–10 MeV).

## Short Gamma Ray Burst ( $T_{90} < 2\text{ s}$ )

- More highly-energetic (hard) gamma rays
- Fainter afterglow
- Offset relative to their host galaxy center
- Baryon-poor environments
- Observation in all type of host galaxies

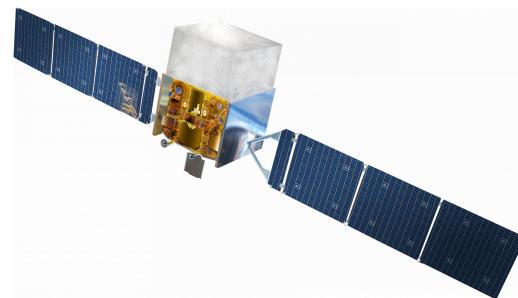


MERGER PROGENITOR  
HYPOTHESIS (Late '80s)  
Recently (2017) confirmed.

## The Neil Gehrels *Swift* Observatory



## The Fermi Gamma-ray Space Telescope



## Long Gamma Ray Burst ( $T_{90} > 2\text{ s}$ )

- Observed only in star-forming galaxies
- Direct associations of LGRBs with core-collapse supernovae

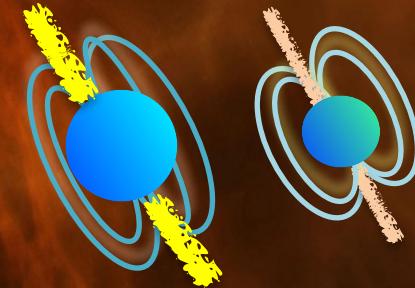
# SHORT GAMMA RAY BURSTS

Necessary condition for SGRB ignition: presence of NS.

PROGENITOR  
CANDIDATES

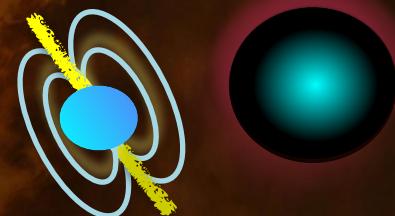
**Binary Neutron Stars**  
Confirmed by the joint detection of  
**GW170817 and GRB 170817A!**

[Abbott *et al* 2017 *ApJL* 848 L13]



**Neutron Star-Black Hole**

- Not confirmed by observation yet.
- Not all systems are “bright”.



# SHORT GAMMA RAY BURSTS

NSBH MERGER SCENARIO

plunge

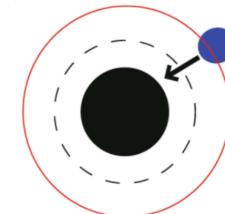
*tidal disruption*

Baryonic Remnant Mass  
( $M_{\text{rem}}$ )

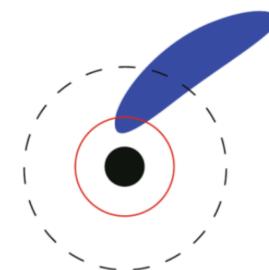
- Indicator of potential GRB source.
- Estimation through models fitted to numerical simulations.
- Dependence on binary parameters (masses, spins, NS equation of state).

EM  
BRIGHT<sup>1</sup>

$$d_{\text{tid}} \lesssim R_{\text{ISCO}}$$



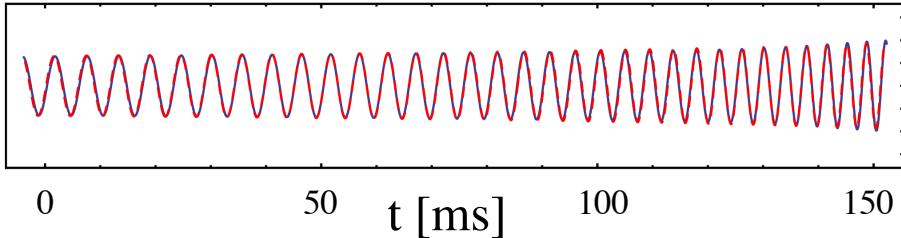
$$d_{\text{tid}} \gtrsim R_{\text{ISCO}}$$



1. Pannarale F. and Ohme F. *Astrophys.J.Lett.* 791 (2014) L7  
Figures adapted from Kyutoku et al. *Phys.Rev.D* 84 (2011) 064018

# EM-BRIGHT TEMPLATE BANK

$$(1.35 + 5)M_{\odot}, \chi = 0.3$$
$$(2.4 + 2.6)M_{\odot}, \chi = 0.08$$



PyGRB filters the data with templates drawn from a bank that targets potentially EM-Bright CBCs.

**GOAL:** build effectual template banks with a computationally reasonable number of templates.

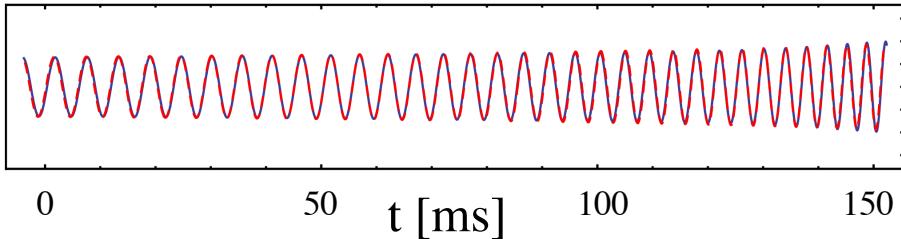
Template proposal is accepted and added to the bank if

Match < 0.97, i.e., accept a maximum signal loss of 10%

- BNS ( $M_1, M_2 < 2.8 M_{\odot}$ )  
or
- NSBH with  $M_{\text{rem}} > 0$

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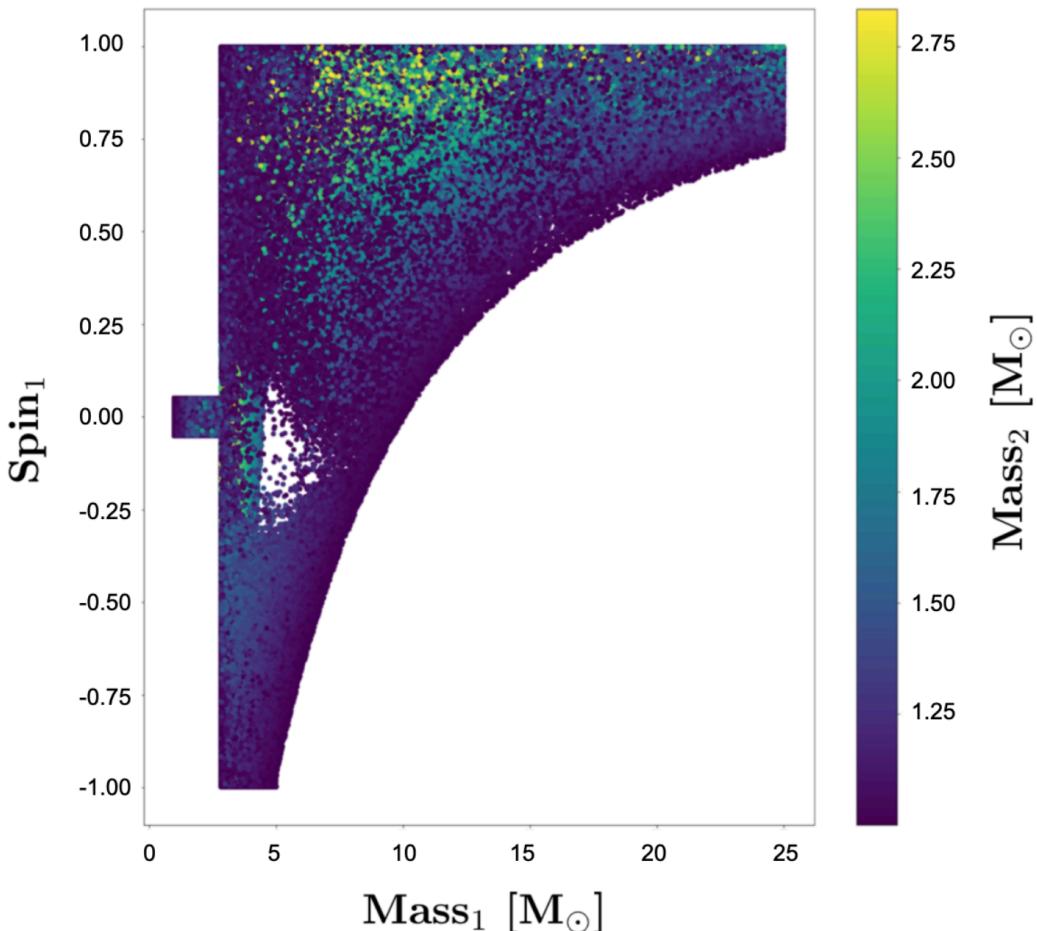
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- BNS ( $M_1, M_2 < 2.8 M_{\odot}$ )  
or
- NSBH with  $M_{\text{rem}} > 0$

★ I IMPLEMENTED A NEW  $M_{\text{rem}}$  MODEL AND BUILT AND VALIDATED THE BANK TO PROCESS ALL SHORT GRBs IN O3a.

LIGO-Virgo paper: [arXiv:2010.14550](https://arxiv.org/abs/2010.14550)

# EM-BRIGHT TEMPLATE BANK



## BANK PARAMETER SPACE

$\text{Mass}_1$  = BH or NS mass ( $> \text{Mass}_2$ ).

$\text{Mass}_2$  = NS mass.

$\text{Spin}_1$  = dimensionless spin parameter.

## BANK EFFECTUALNESS TESTS

Recovery of 10,000 + 10,000 BNS and NSBH simulated signals.

## EFFECTIVE FITTING FACTOR

$$\text{FF}_{\text{eff}} = 0.99$$

(6% signal loss)

# THE PyGRB PIPELINE

## TARGETED

- Sky location and time of an observed SGRBs are known.
- GW detector sensitivities.

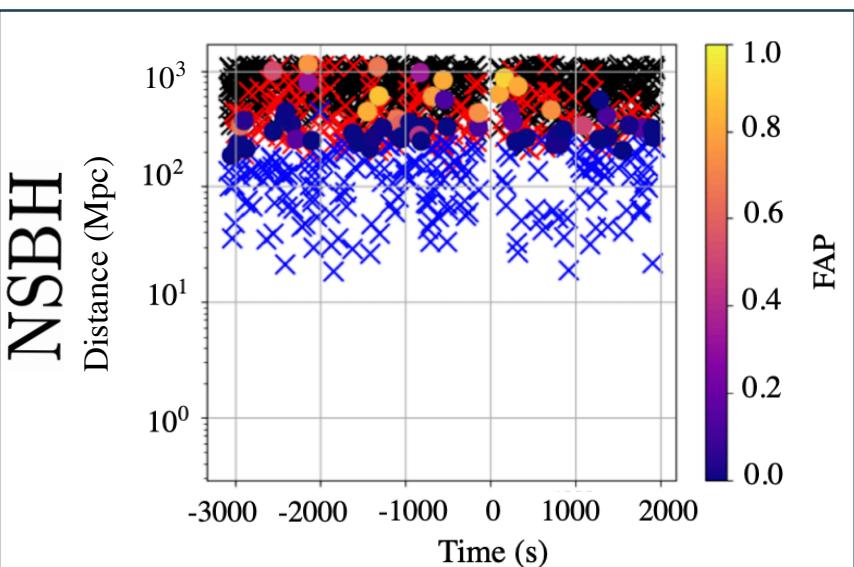
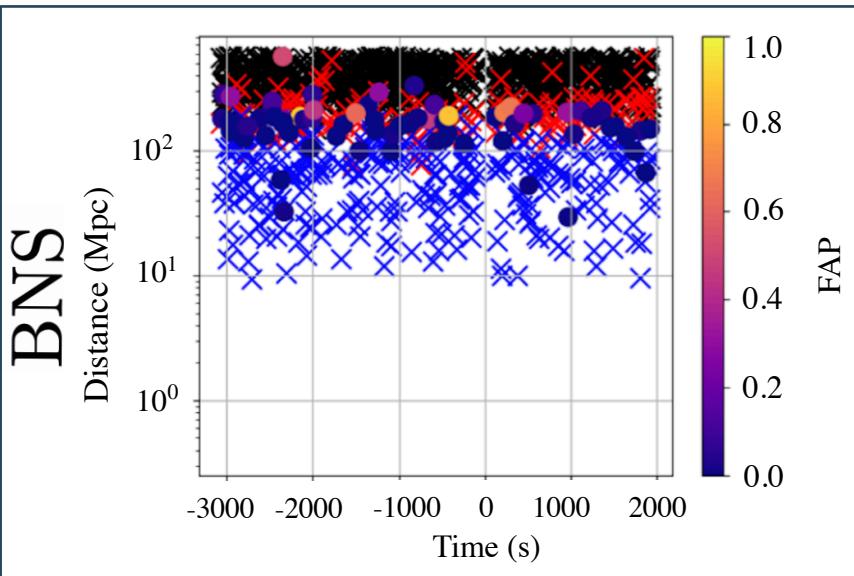
## COHERENT

- Data from all detectors combined and then processed.
- Single statistic for full network.

## GW SEARCH TRIGGERED BY SGRBs

- “On-source”: 6s around the GRB time; potentially contains a GW signal so it is filtered against template bank to determine the *foreground* loudest trigger.
- “Off-source”: surrounding 90 mins of data, artificially extended and decorrelated with time slides; it is divided in 6s off-source trials and filtered to produce the list of loudest *background* triggers.
- Comparison between on-source and off-source results yields a false alarm probability (FAP).
- If the loudest on-source trigger is not significant, lower bound on source distance is set via recovery of simulated GW signals added to the detector data

# Bird's eye view of a PyGRB analysis



## CLOSED BOX

- Check detection statistic distribution
- Check consistency tests (chi-squared) results.
- Check injection sets results.

## RESULTS DISCUSSION

At least three LIGO-Virgo Collaboration internal calls are needed to assess the quality of the background results and unblind the foreground.

## OPEN BOX

- Check FAP
  - The on-source trigger becomes a candidate if  $\text{FAP} \leq 10^{-4}$ .
  - Otherwise exclusion distances from injection campaign are reported.

# ANALYSIS RESULTS

GRB	FAP	BNS	Generic NSBH	Aligned NSBH
		$D_{90}$ (Mpc)	$D_{90}$ (Mpc)	$D_{90}$ (Mpc)
190425089	0.075	204	247	440
190627A	0.481	115	139	211
190728271	0.513	160	204	272

- These are three of the 32 results from the modelled search, while the unmodelled search analysed 105 GRBs, reported in the LIGO-Virgo paper: [arXiv:2010.14550](https://arxiv.org/abs/2010.14550).
- The sensitivity and number of operating detectors impact the recovered 90% confidence exclusion distances.
- NSBH binaries are more massive than BNS and thus can be detected at further distances.
- Precession in NSBH systems lowers the detection distance.
- No significant evidence for a population of sub-threshold GW signal from weighted binomial test on exclusion distances.

# CONCLUSIONS

Gravitational wave detections allow us to directly investigate previously unobservable phenomena and to probe known phenomena in a new way.

Combined efforts from the gravitational and electromagnetic communities broaden our knowledge of the Universe.

## MY CONTRIBUTION

- ★ Construction and validation of an updated EM-bright template bank used by the LVC to look for GW signals in coincidence with short GRBs during O3a.
- ★ Targeted analyses for GWs associated to three GRBs included in the LVC paper [arXiv:2010.14550](https://arxiv.org/abs/2010.14550).
- ★ Contribution to the O3b all-sky analysis.



# BACK UP SLIDES

# Post-merger remnant mass

## OLD MODEL

$$\frac{M_{\text{rem}}^{\text{model}}}{M_{\text{NS}}^b} = \alpha(3q)^{1/3}(1 - 2C_{\text{NS}}) - \beta \frac{R_{\text{ISCO}}}{R_{\text{NS}}}$$

Model properties:

- BH spins aligned with L.
- Non-precessing, low-eccentricity NSBH mergers.
- Remnants below  $\sim 20 - 25\%$  of the  $M_{\text{NS}}$ .

Model range of validity:

- $M_{\text{BH}} = 3 - 7 M_{\text{NS}}$ .
- $R_{\text{NS}} = 11 - 16 \text{ km}$
- $a_{\text{BH}} / M_{\text{BH}} = 0 - 0.9$ .

**It overestimates  $M_{\text{rem}}$  for near equal mass binaries!!**

**Unexplored parameter space:** high mass ratios, high BH spin magnitudes, and (moderately) spinning NSs.

## NEW MODEL

$$\frac{M_{\text{rem}}^{\text{model}}}{M_{\text{NS}}^b} = \left[ \max \left( \alpha \frac{1 - 2C_{\text{NS}}}{\eta^{1/3}} - \beta \frac{R_{\text{ISCO}} C_{\text{NS}}}{\eta M_{\text{BH}}} + \gamma, 0 \right) \right]^{\delta}$$

- More coverage of parameter space including comparable masses and high BH spins.
- Remnant mass is significantly lower for nearly equal-mass NSBH mergers and higher for large BH spins than previously predicted.
- Better differentiating NSNS from low-mass NSBH mergers.

