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

Tesi di laurea magistrale in Fisica

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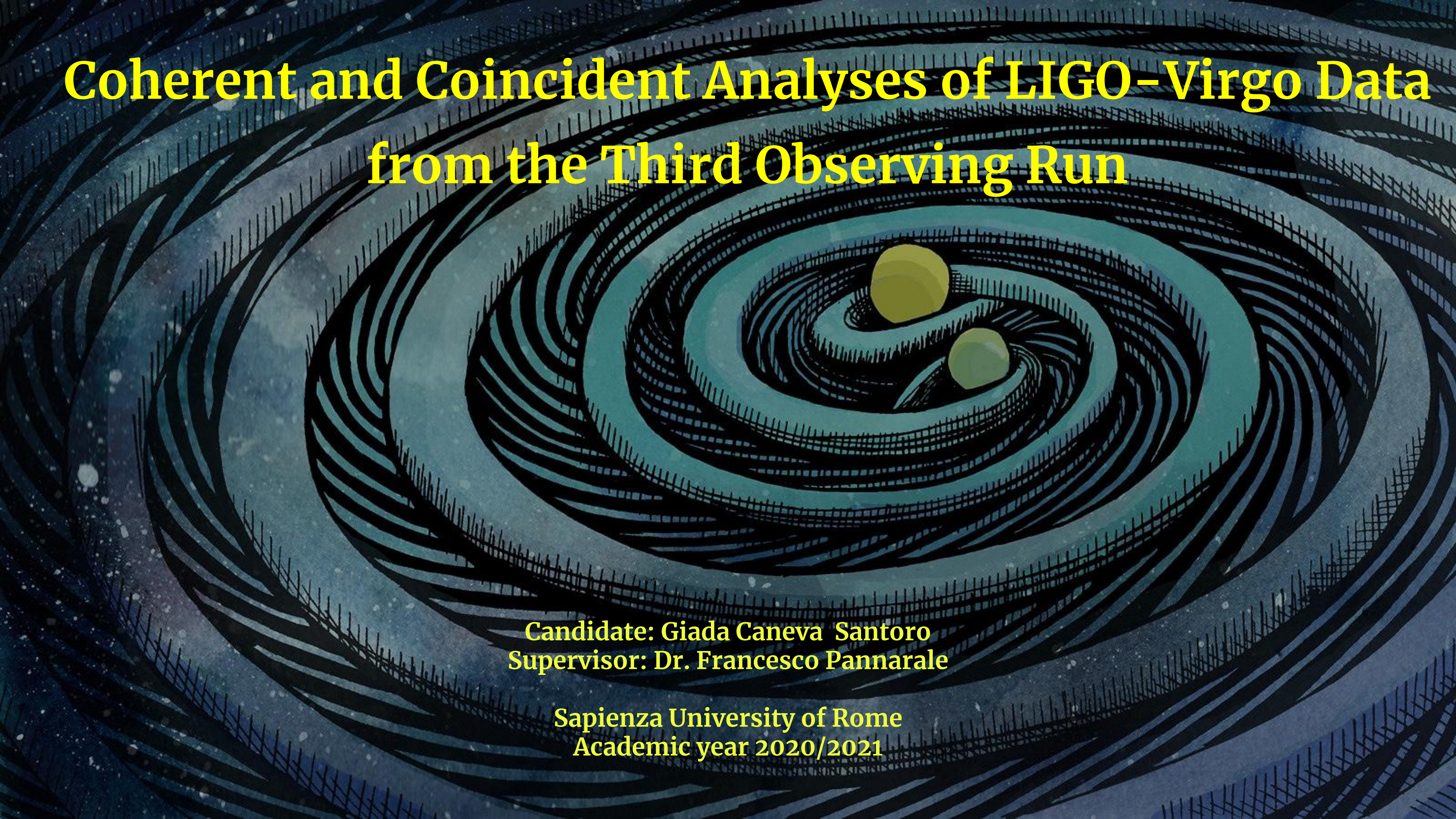

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Sapienza University of Rome

Academic year 2020/2021

GRAVITY: FROM APPLES TO RIPPLES

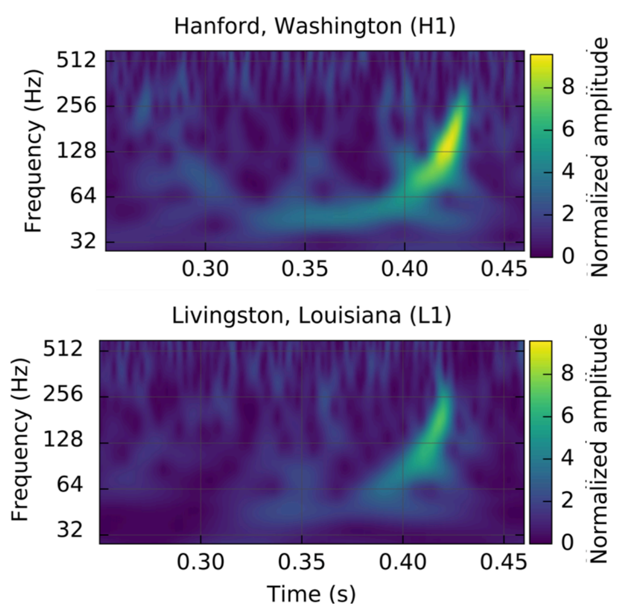
Einstein Field Equations

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Linearised Field Equations

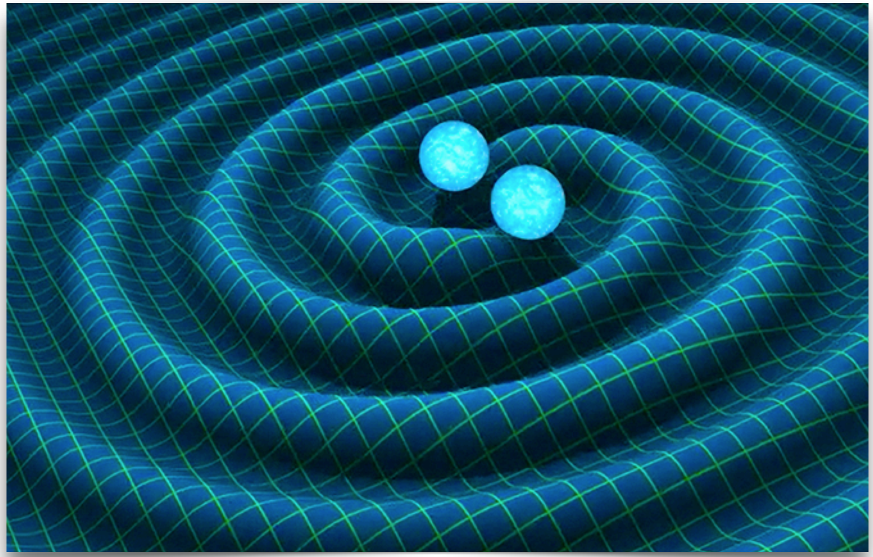
$$\Box \bar{h}_{\mu\nu} = 0$$

GW1590914



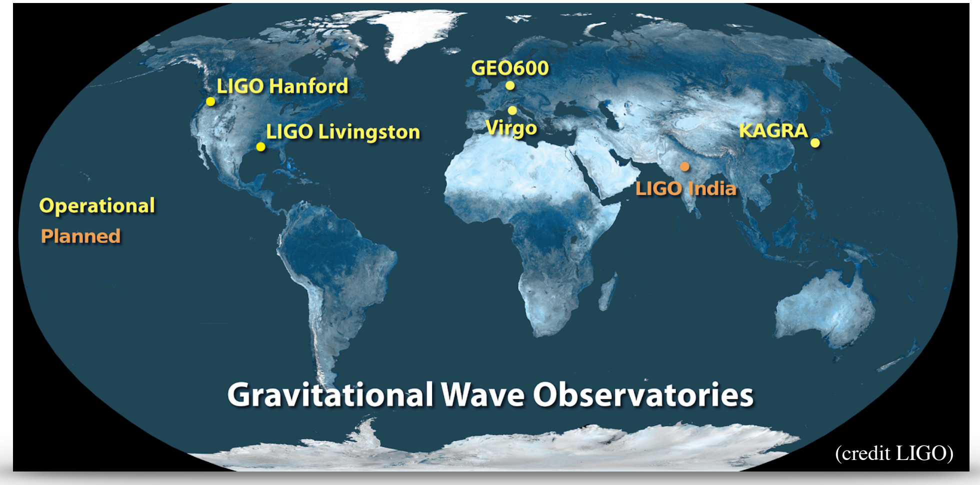
Abbott et al. (2016) Phys. Rev. Lett. 116, 061102

GRAVITATIONAL WAVES



GRAVITATIONAL WAVE DETECTION

Network of detector required.



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

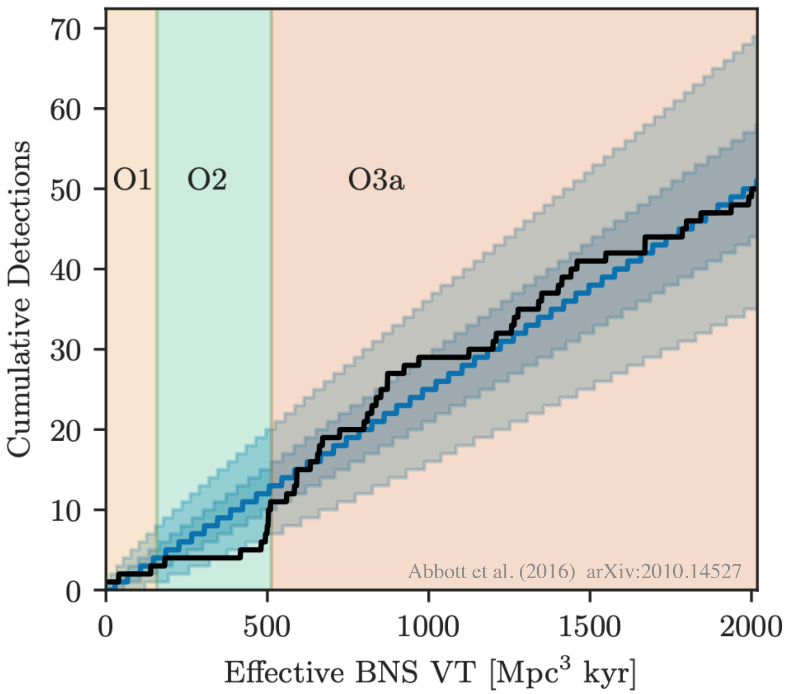
- **SKY LOCALISATION:** triangulation techniques based on the time delay in more than two detectors.

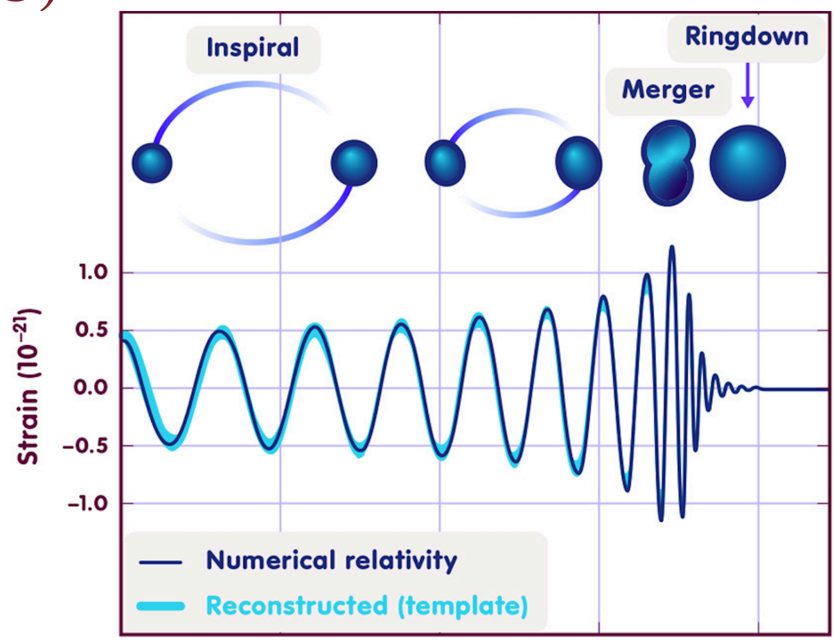
Enables Multi Messenger Astronomy

- More detectors may provide a larger signal-to-noise ratio, which decreases the sky localisation area.

- More detectors provide a higher duty cycle.

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 in O3a data published in arXiv:2010.14550

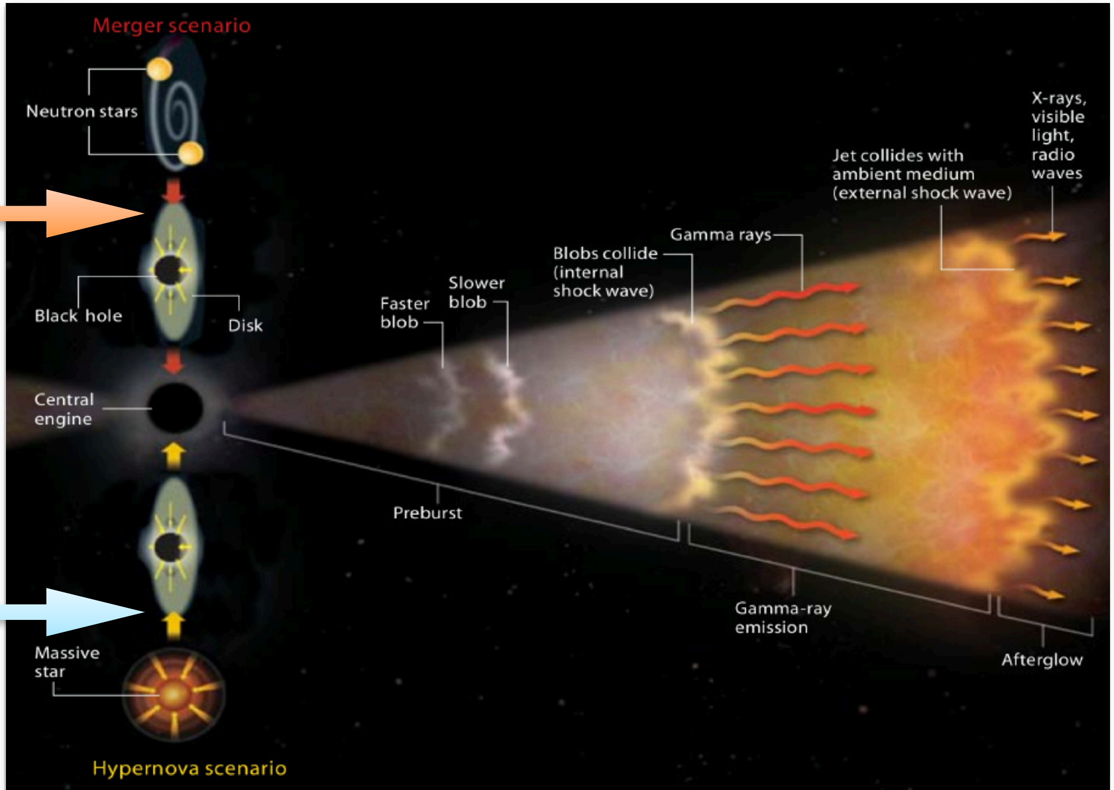
GAMMA RAY BURSTS

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

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

- 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.



(credit NASA)

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

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

SHORT GAMMA RAY BURSTS

Necessary condition for SGRB ignition: <u>presence of NS</u>.

PROGENITOR CANDIDATES

BNS

Confirmed by the joint detection of

GW170817 and GRB 170817A!

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

NSBH

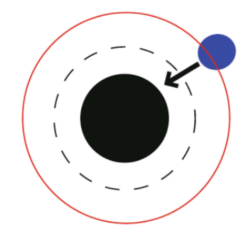
- Not confirmed by observation yet.
- Not all systems are “bright”

SHORT GAMMA RAY BURSTS

NSBH MERGER SCENARIO

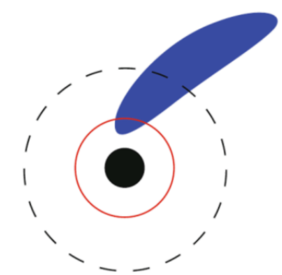
plunge

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



tidal disruption

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



EM BRIGHT[1]

Baryonic Remnant Mass (M_{rem})

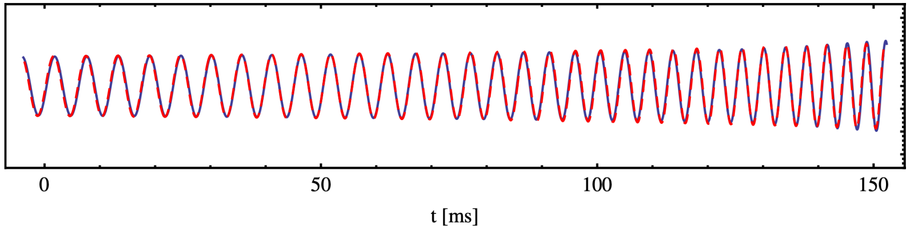
- Indicator of potential GRB source.
- Estimation through models fitted to numerical simulations.
- Dependence on binary parameters (masses, spins, NS equation of state).

1. Astrophys.J.Lett. 791 (2014) L7

Figures adapted from *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

- BNS ($M_1, M_2 < 2.8\ M_\odot$)

or

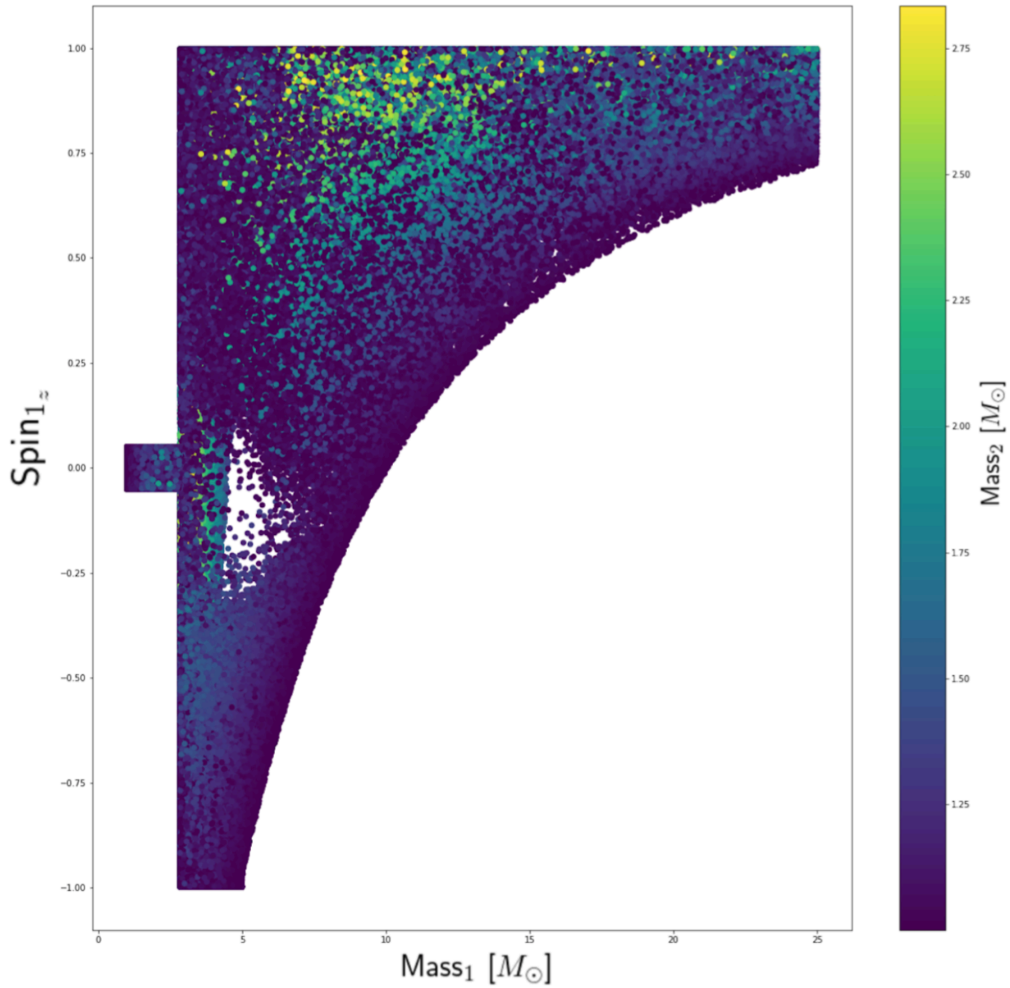
- NSBH with $\boxed{M_{rem} > 0}$

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

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

arXiv:2010.14550

EM-BRIGHT TEMPLATE BANK



BANK PARAMETER SPACE

M_1 = BH mass

M_2 = NS mass

S_1 = BH spin

BANK EFFECTUALNESS TESTS

Recovery of 10,000 injections for BNS and NSBH sets

EFFECTIVE FITTING FACTOR

$\mathbf{FF_{eff} = 99\%}$

(6% signal loss)

THE PyGRB PIPELINE

TARGETED COHERENT GW SEARCH TRIGGERED BY SGRBs

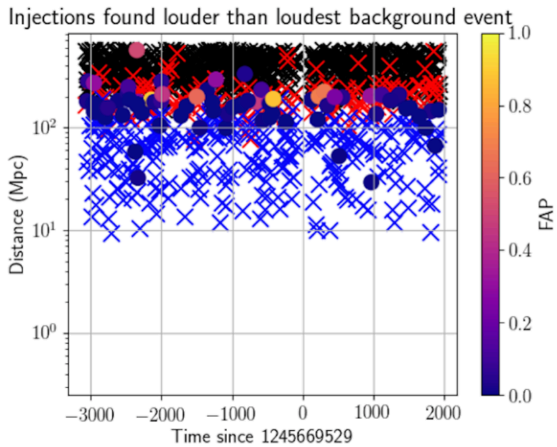
- Sky location and time of an observed SGRBs are known.
- GW detector sensitivities.

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

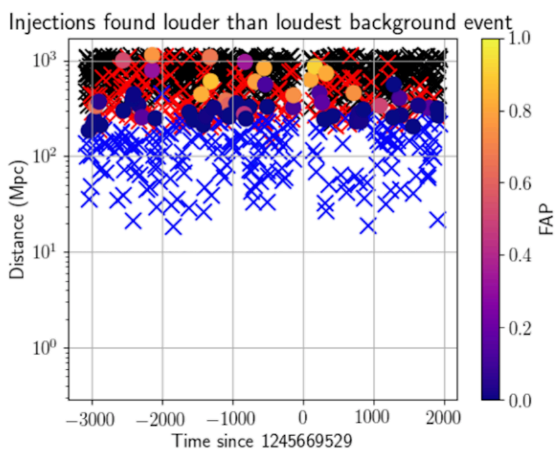
- "on-source": [-5s, +1s) around the GRB time; potentially contains a GW signal so it is filtered against template bank to determine the *foreground* loudest trigger.
- "off-source": surrounding 90 mins of data, artificially extended and decorrelated with time slides; it is divided in 6s off-source trials 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

BNS



NSBH



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 $\geq 10^{-4}$
  - Otherwise exclusion distances from injection campaign are reported

ANALYSIS RESULTS

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

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

BACK UP SLIDES

Post-merger remnant mass

OLD MODEL

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

Model properties:

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

Model range of validity:

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

It overestimates M_{rem} for near equal mass binaries!!

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

NEW MODEL

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

- 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.