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

Tesi di laurea magistrale in Fisica

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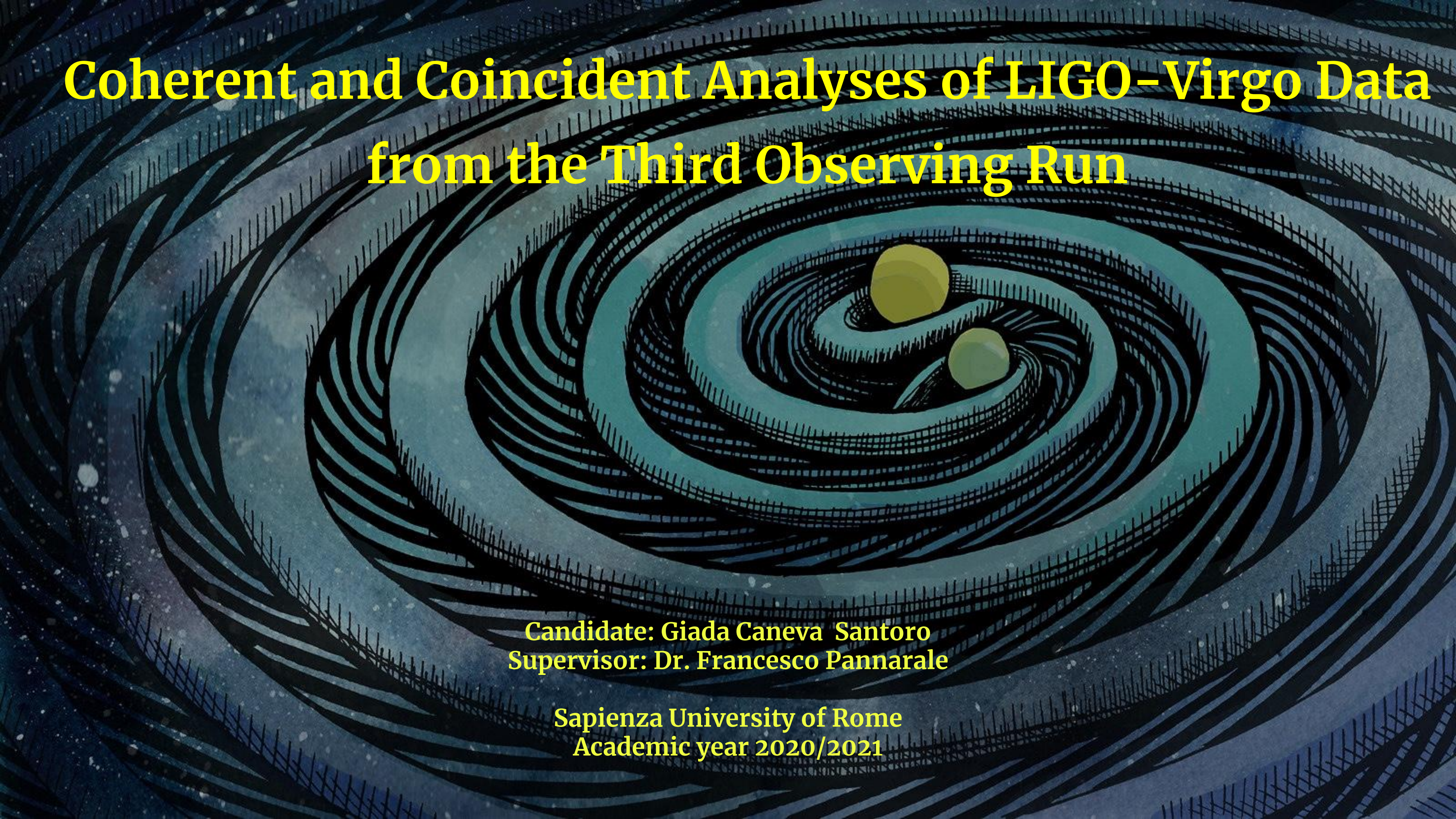
Anno Accademico 2020/2021



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Supervisor: Dr. Francesco Pannarale

Sapienza University of Rome
Academic year 2020/2021

GRAVITY: FROM APPLES TO RIPPLES

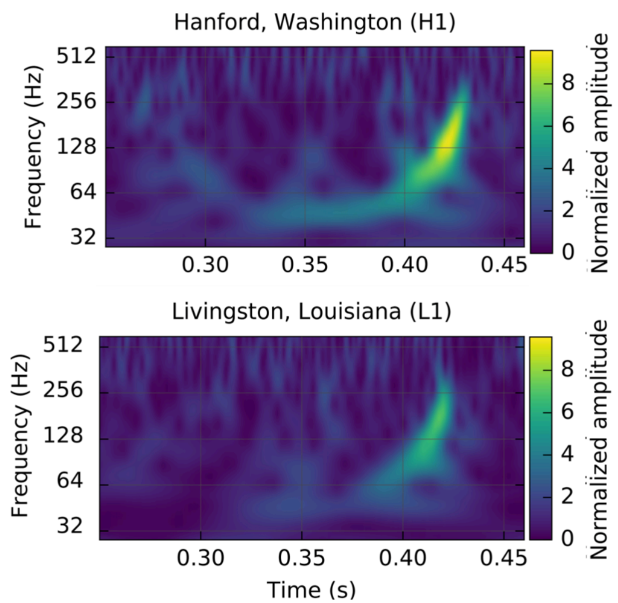
Einstein Field Equations

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

Linearised Field Equations

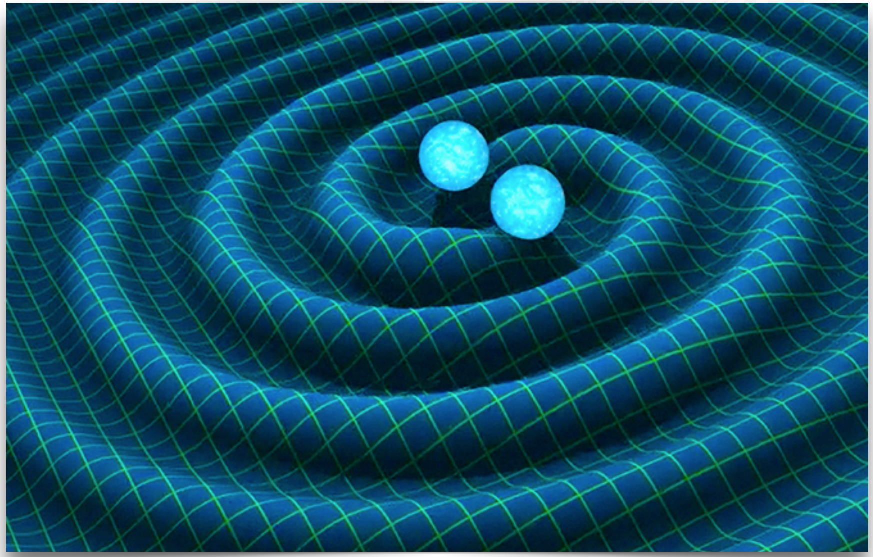
$$\Box \bar{h}_{\mu\nu} = 0$$

GW1590914



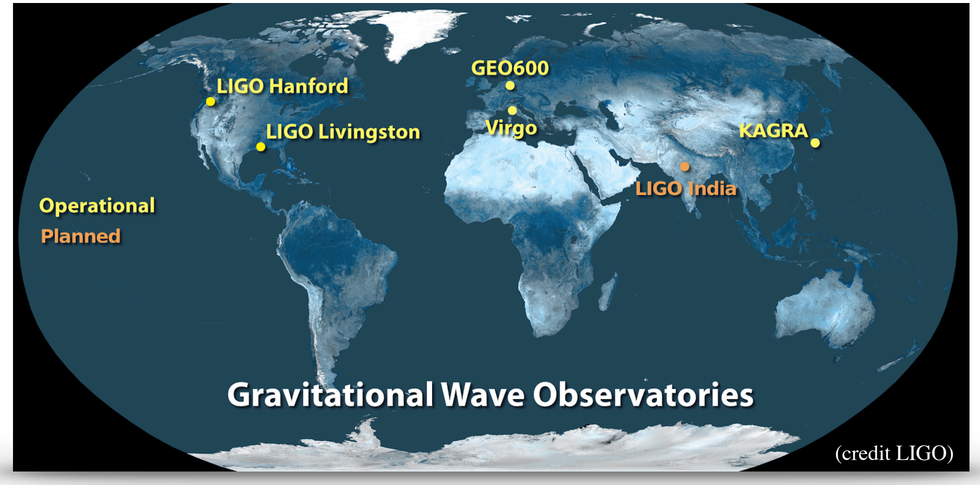
Abbott et al. (2016) Phys. Rev. Lett. 116, 061102

GRAVITATIONAL WAVES



GRAVITATIONAL WAVE DETECTION

Network of detector required.

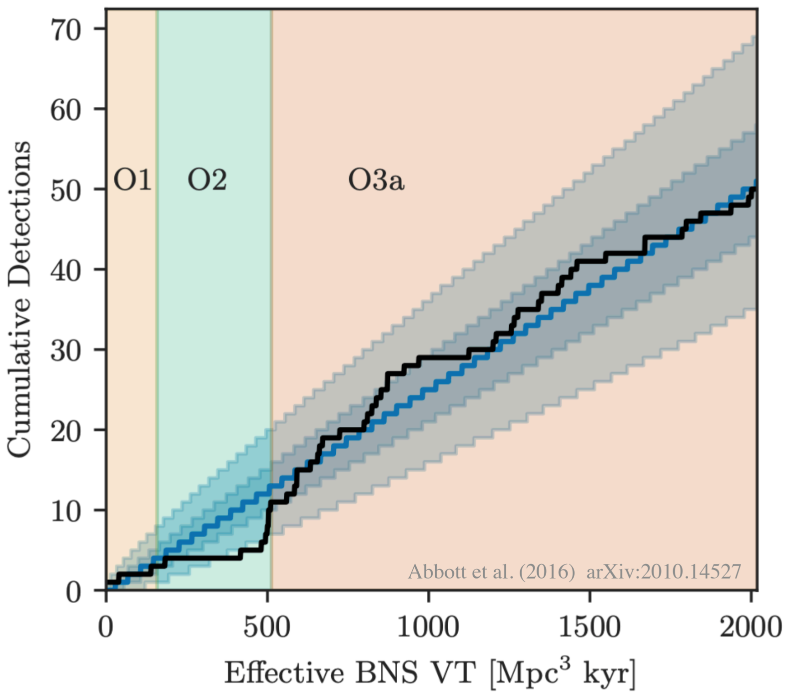


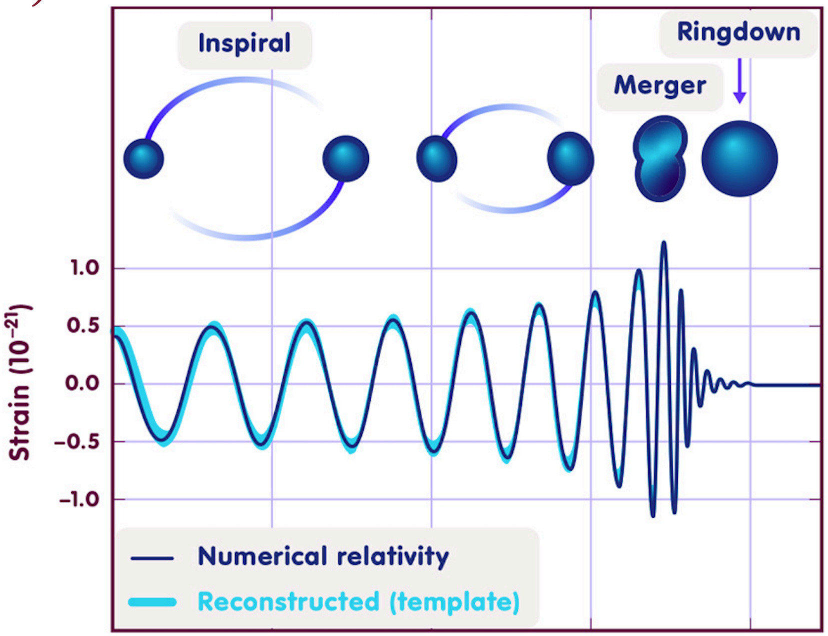
- COINCIDENCE OF DETECTIONS: confidence that signal is from extraterrestrial sources, rather than from noise.
- SKY LOCALISATION: triangulation techniques based on the time delay in more than two detectors.

Enables Multi Messenger Astronomy

- Smaller sky localisation, larger signal-to-noise ratio.
- More IFOs, more 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 kind of CBC
- 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).

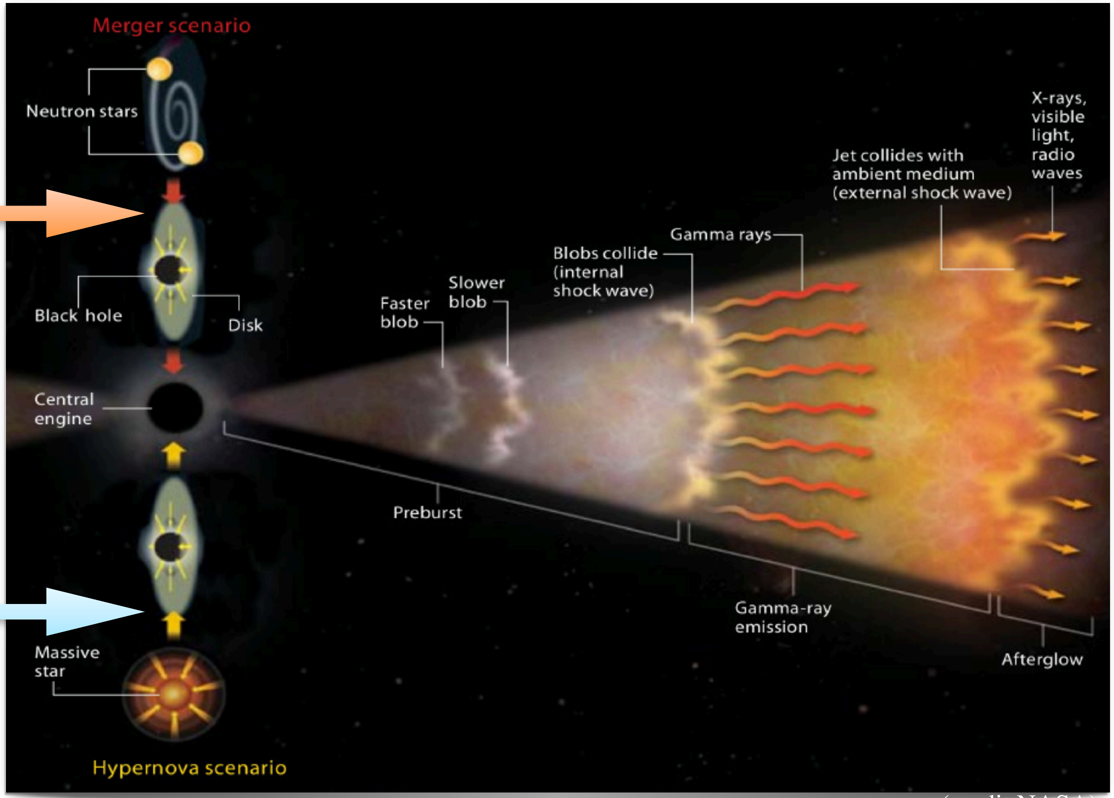
Short Gamma Ray Burst ($T_{90} < 2s$)

- 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.

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

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



(credit NASA)

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

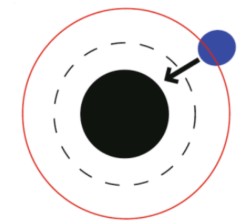
- Not confirmed by observation yet.
- Not all systems are "bright"

SHORT GAMMA RAY BURSTS

NSBH MERGER SCENARIO

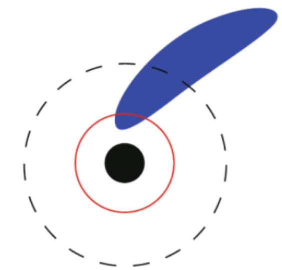
plunge

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



tidal disruption

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



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

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

Template proposal is accepted and added to the bank if

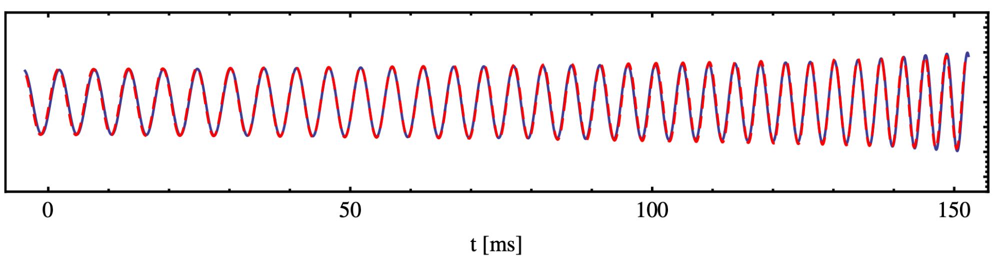
- BNS ($M_1, M_2 < 2.8\ M_\odot$)

or

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

Minimum Match: 0.97
=
Max Signal loss: 10%

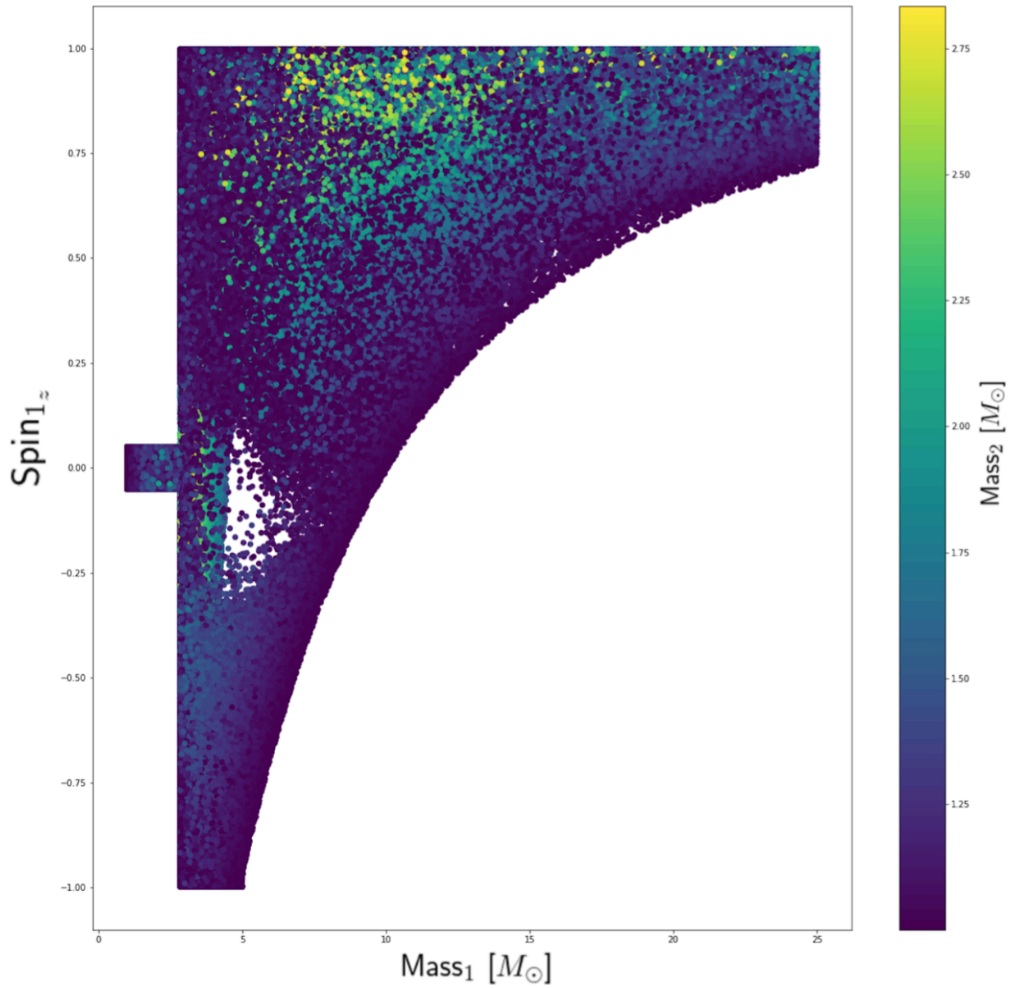
$$(1.35 + 5)M_\odot, \chi = 0.3$$
$$(2.4 + 2.6)M_\odot, \chi = 0.08$$



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" : filtered against template bank; list of trigger is produced.**
- **"off-source" : *background* with time slides, divided in *off-source trials*, analysed and list of loudest trigger is produced.**
- **Comparison between on-source and off-source results.**
- **FAP is computed.**

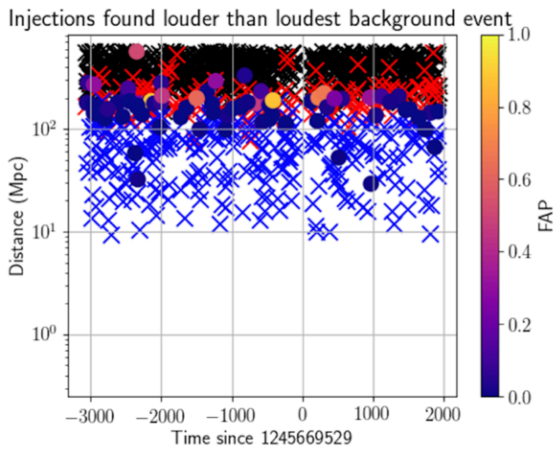
- ***on-source* data:** 5s before and 1s after GRB; potentially contains GW signal.
- ***off-source* data:** contains no GW signal.

Analysis efficiency: re-perform analysis on data stream + injection sets.

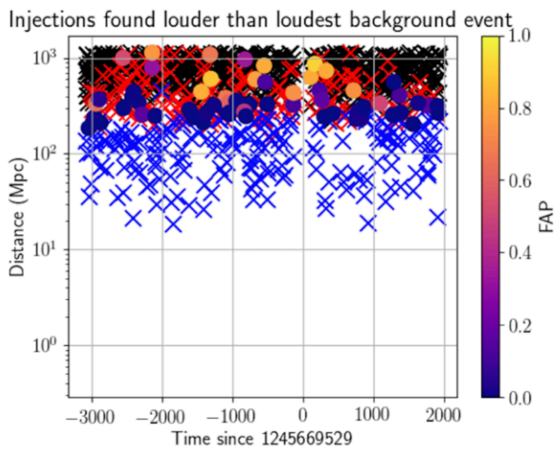
If no GW signal is present, lower bound on distance is set.

THE PyGRB ANALYSIS

BNS



NSBH



CLOSED BOX

- Check loudest trigger's re-weighted SNR.
- Check consistency tests (chi-squared) results.
- Check injection sets results.

RESULTS DISCUSSION

Three LVC calls to assess the quality of the results and decide whether to open the box or further background investigations are needed.

OPEN BOX

- Check FAP
  - Detection is claimed if ≥ 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 lower the detection distance.**
- **The sensitivity and number of operating IFOs affect the recovered 90% confidence exclusion distances.**

BACK UP SLIDES

Post-merger remnant mass

OLD MODEL

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

<u>Model properties:</u>

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

<u>Model range of validity:</u>

- 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.