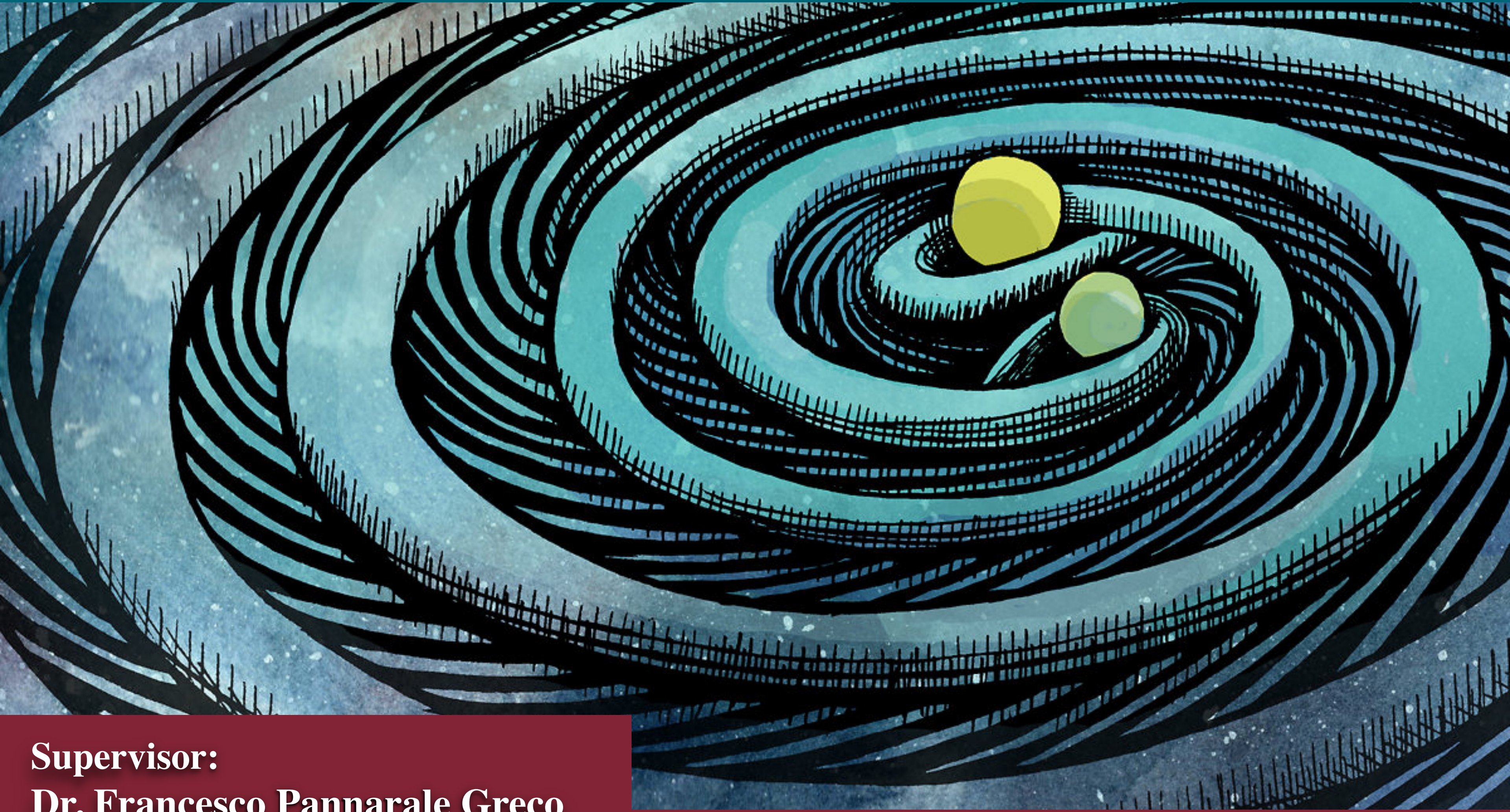
# Coherent and Coincident Analyses of LIGO-Virgo Data from the Third Observing Run



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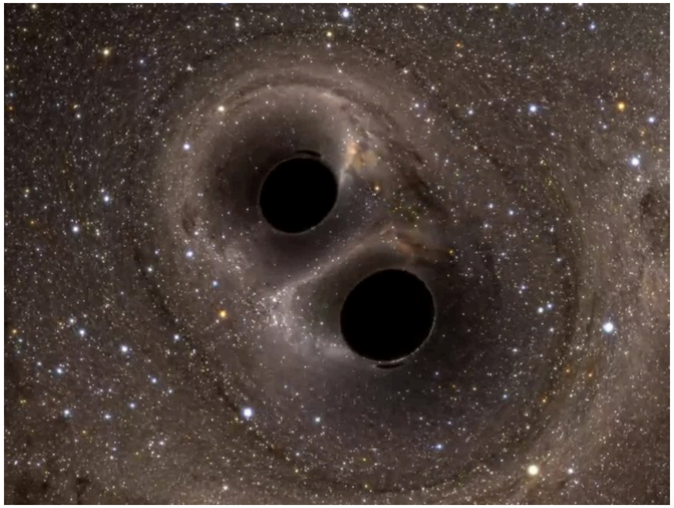
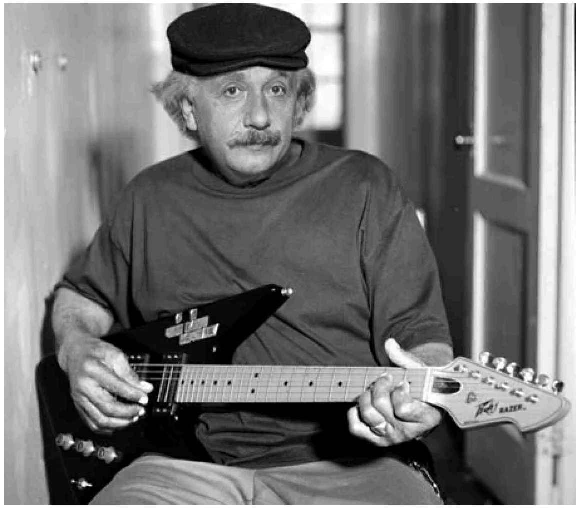
SAPIENZA
UNIVERSITÀ DI ROMA

# GRAVITY: FROM APPLES TO RIPPLES

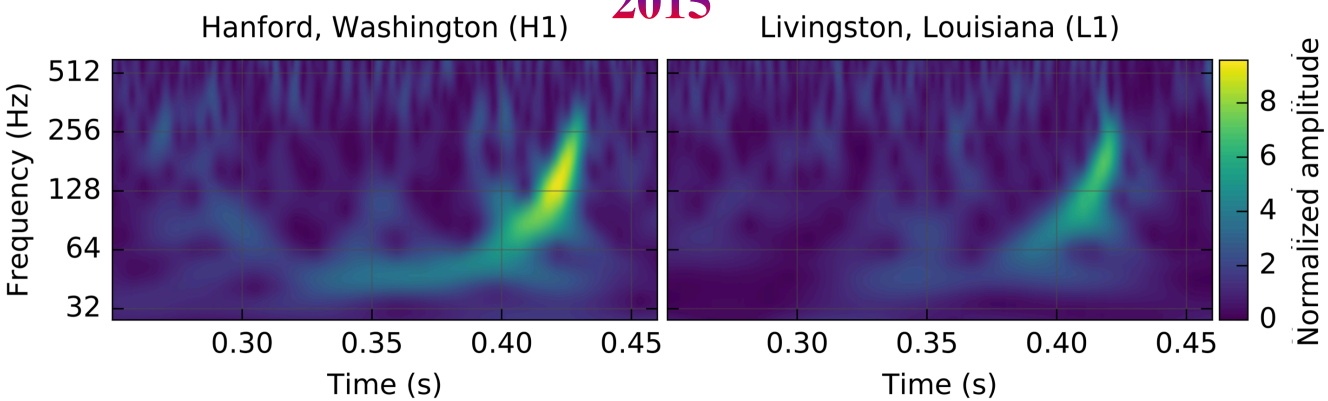
1.4 billion light years ago



1916



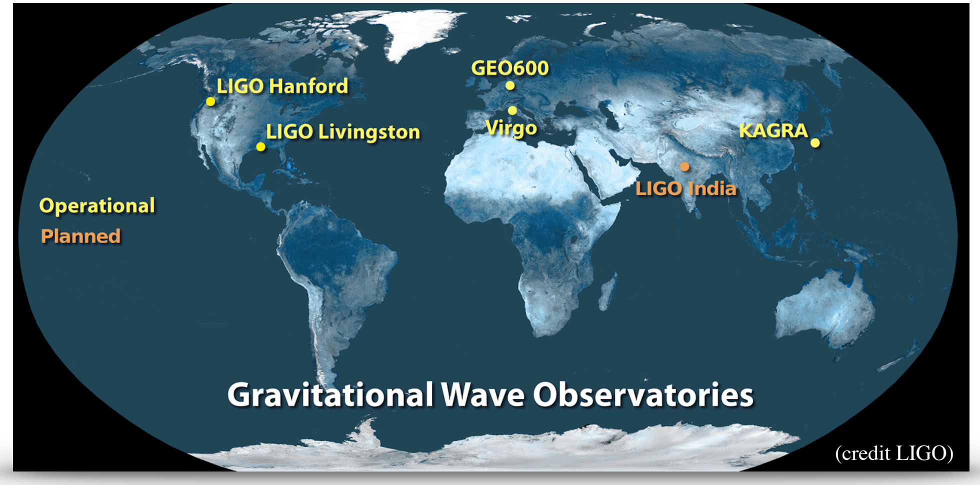
2015




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

# GRAVITATIONAL WAVE DETECTION

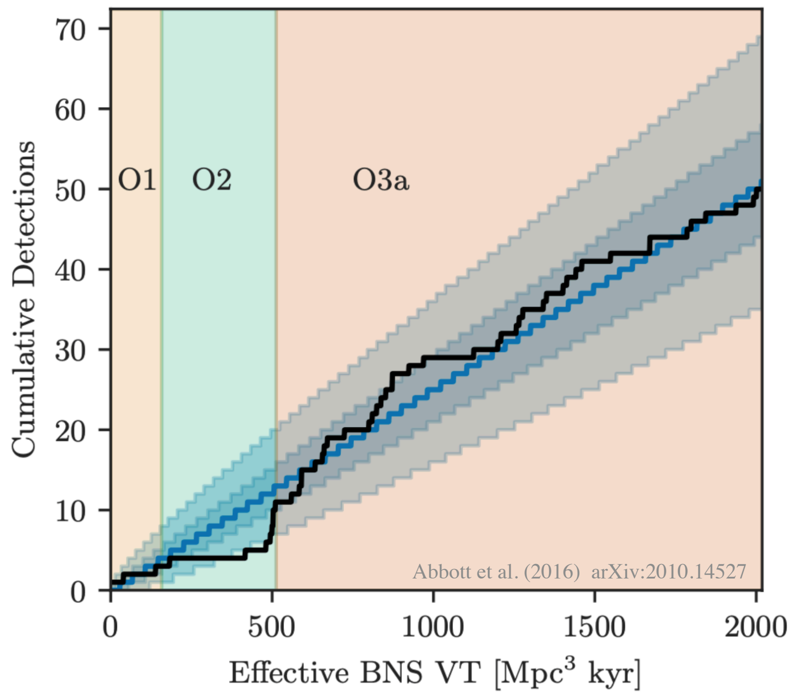
Network of detector required.

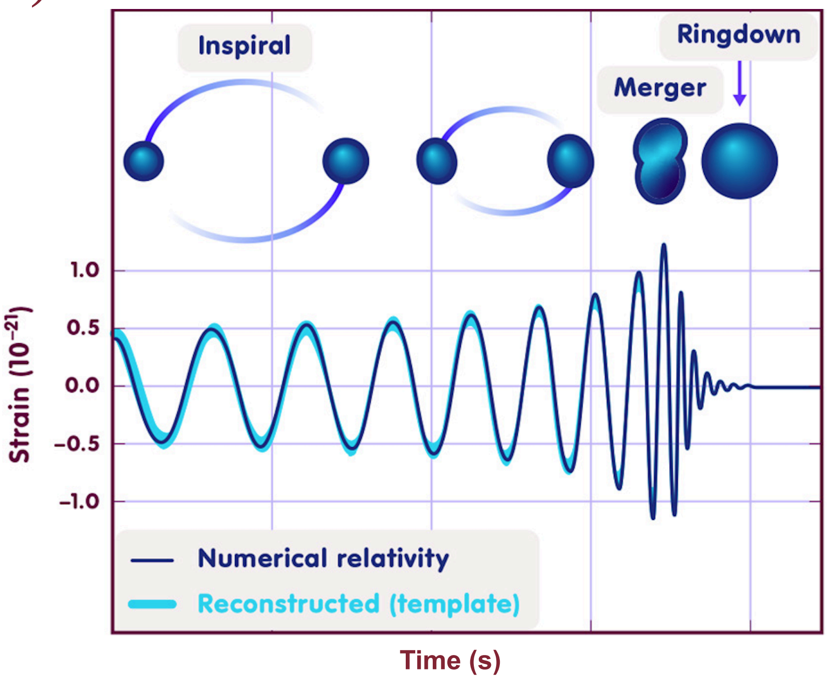



- COINCIDENCE OF DETECTIONS: confidence that signal is from extraterrestrial sources, rather than from noise.
- More detectors may provide a larger signal-to-noise ratio, which decreases the sky localisation area.
- More detectors provide a higher duty cycle (in a non-coincidence analysis).
- SKY LOCALISATION: 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 submitted to Astrophysical Journal.

# GAMMA RAY BURSTS

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

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

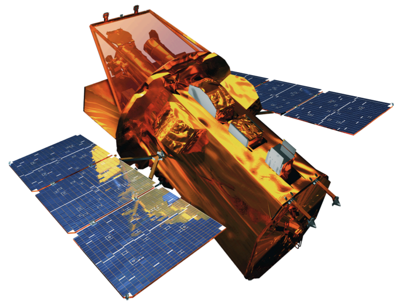
- More highly-energetic (hard) gamma rays
- Fainter afterglow
- Offset relative to their host galaxy center
- Baryon-poor environments
- Observation in all type of host galaxies

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

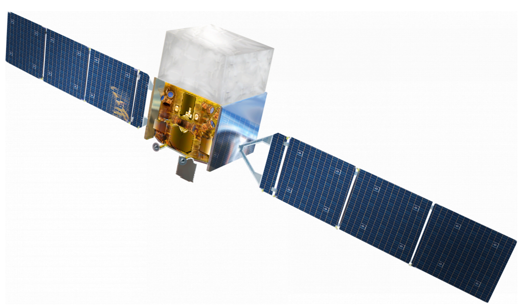
### Long Gamma Ray Burst ($T_{90} > 2s$)

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

**The Neil Gehrels *Swift* Observatory**



**The Fermi Gamma-ray Space Telescope**



# 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

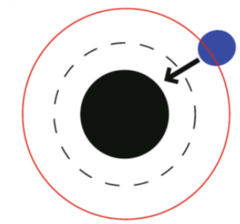
- **Not confirmed by observation yet.**
- **Not all systems are "bright".**

# SHORT GAMMA RAY BURSTS

**NSBH MERGER SCENARIO**

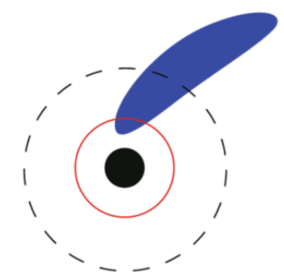
**plunge**

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



**tidal disruption**

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



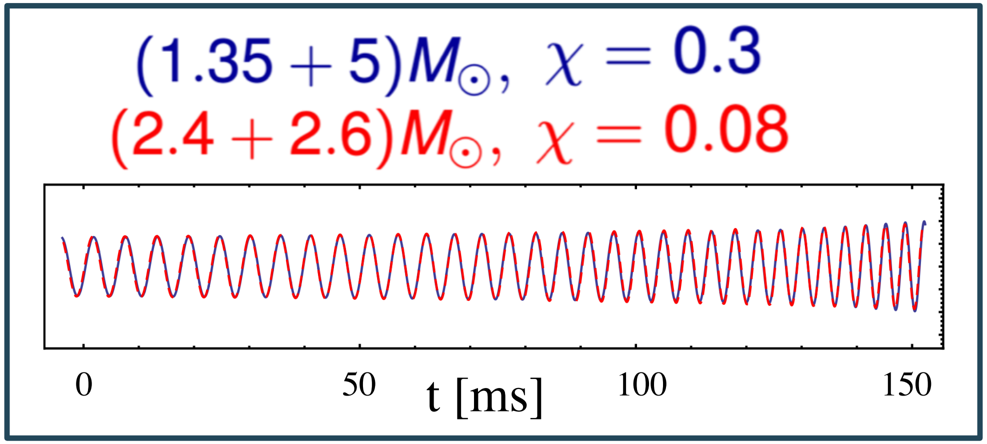
**EM BRIGHT**[1]

## Baryonic Remnant Mass ($M_{\mathrm{rem}}$)

- 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.**

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

Template proposal is accepted and added to the bank if

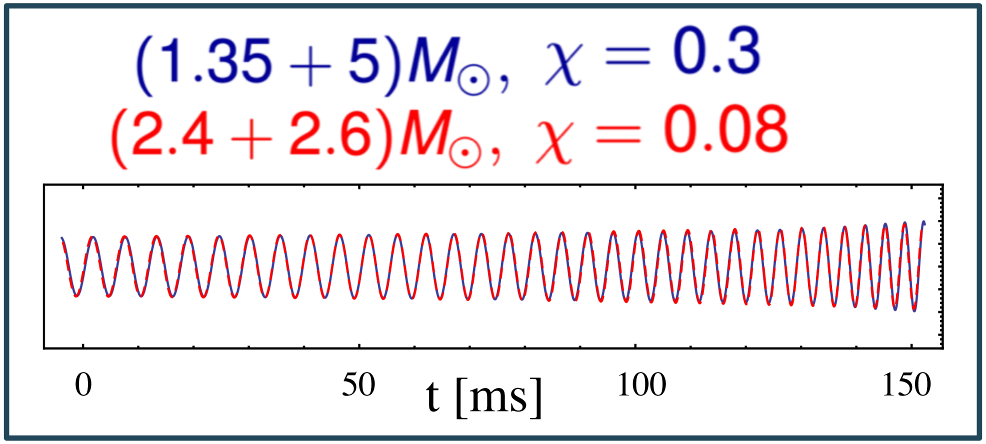
Match < 0.97, i.e., accept a maximum signal loss of 10%

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

or

- NSBH with $M_{rem}>0$

# EM-BRIGHT TEMPLATE BANK

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

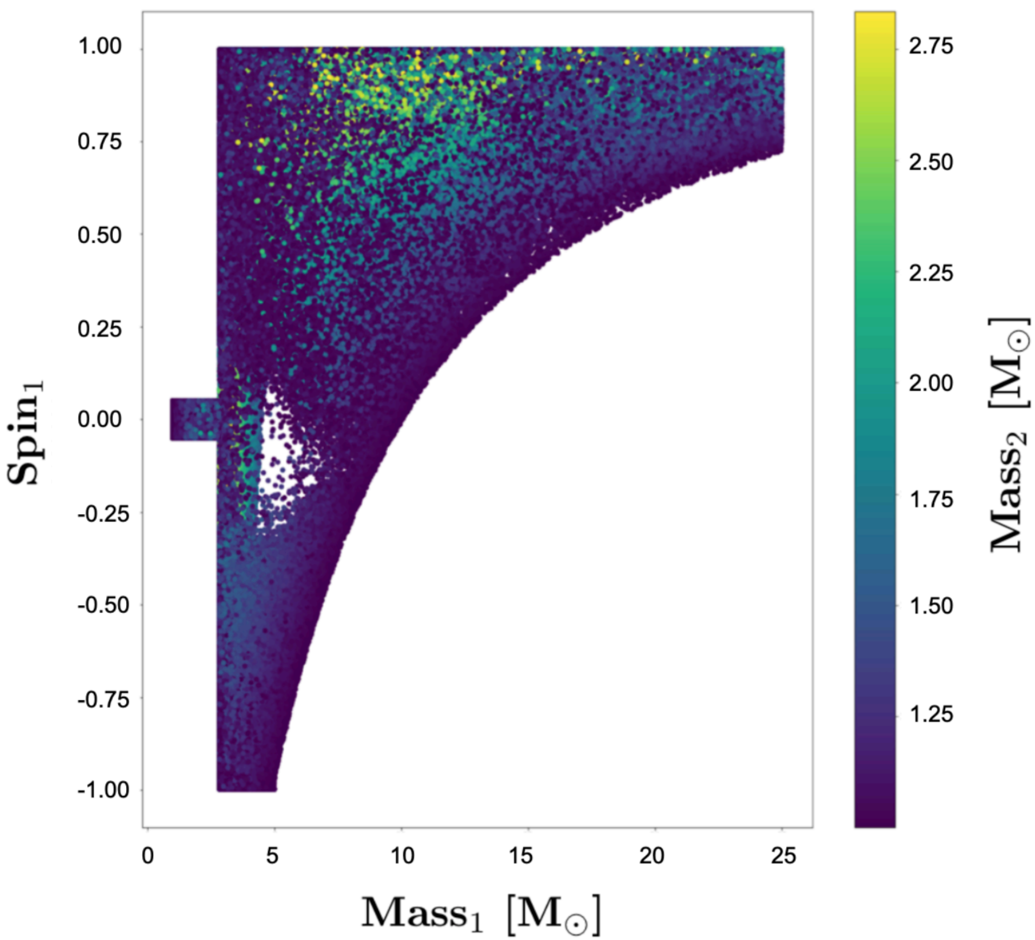
or

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

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

**LIGO-Virgo: 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**

**$FF_{eff}$ = 99%**

(6% signal loss)

# THE PyGRB PIPELINE

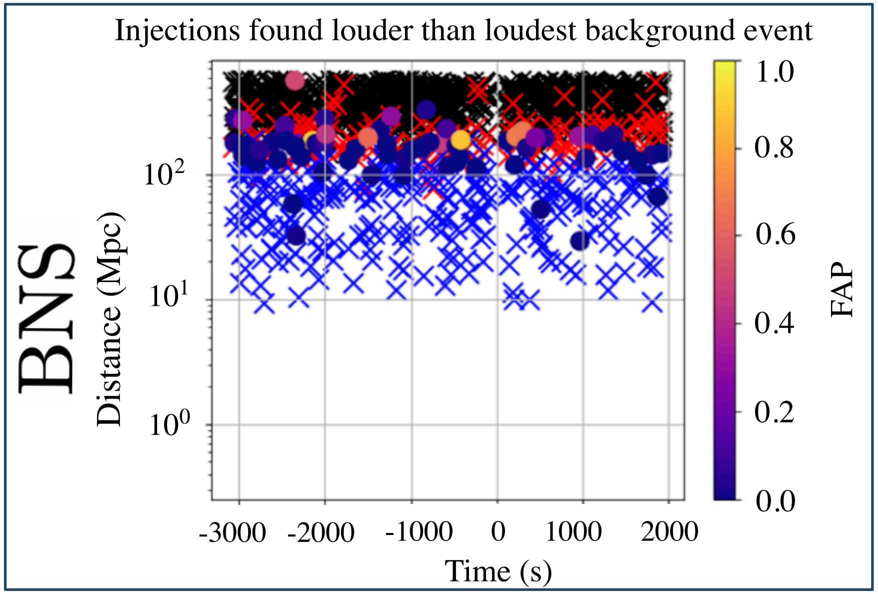
**TARGETED** **COHERENT** **GW SEARCH** **TRIGGERED BY SGRBs**

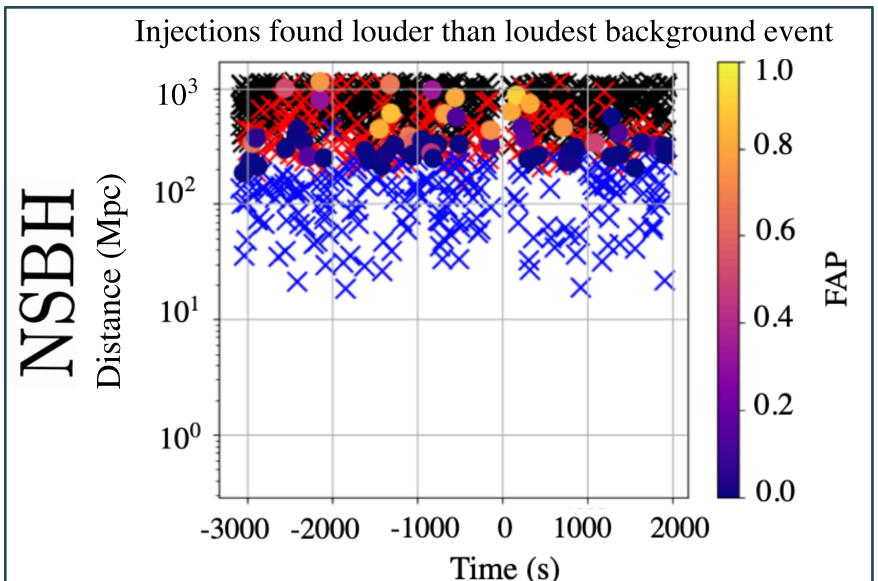
- Sky location and time of an observed SGRBs are known.
- GW detector sensitivities.

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

- "on-source": 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 ≥ $10^{-4}$**
  - **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 |

- **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.**
- **The sensitivity and number of operating detectors affect 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 allows to directly investigate previous unobservable phenomena.**

**Combined efforts from the gravitational and electromagnetic communities broadens 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 in the LVC paper.**

# 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.