Latest results from LIGO-Virgo third observation run

PLANCK 2022 - Paris - May 31st

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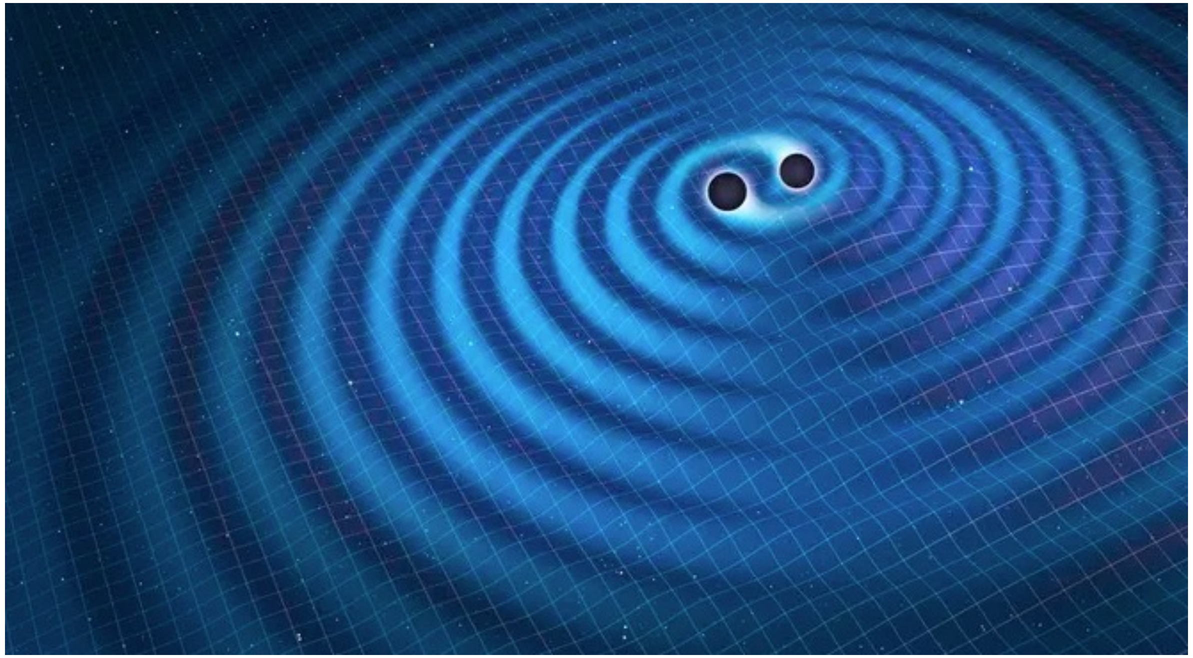
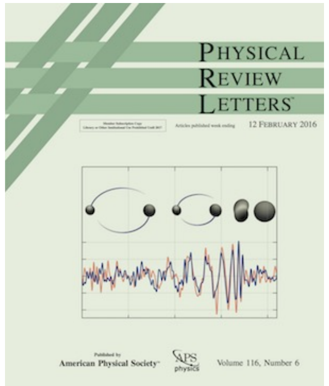
Outline

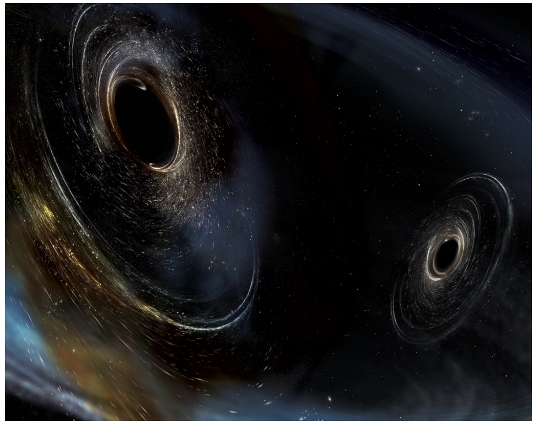
- Introduction to GW and terrestrial interferometers
- O3 data taking
- (many!) Results
    - CBC catalog(s)
    - NSBH discovery
    - Astrophysical populations
    - Tests of GR
    - Cosmology
    - O3 search for short (and long)-duration bursts
    - Lensing signature
    - Triggered searches (GRB/FRB O3a)
    - IMBH search
    - O3a sub-solar mass
    - A taste of non-transient analyses (CW, SGWB)
    - + many links..



Gravitational Waves

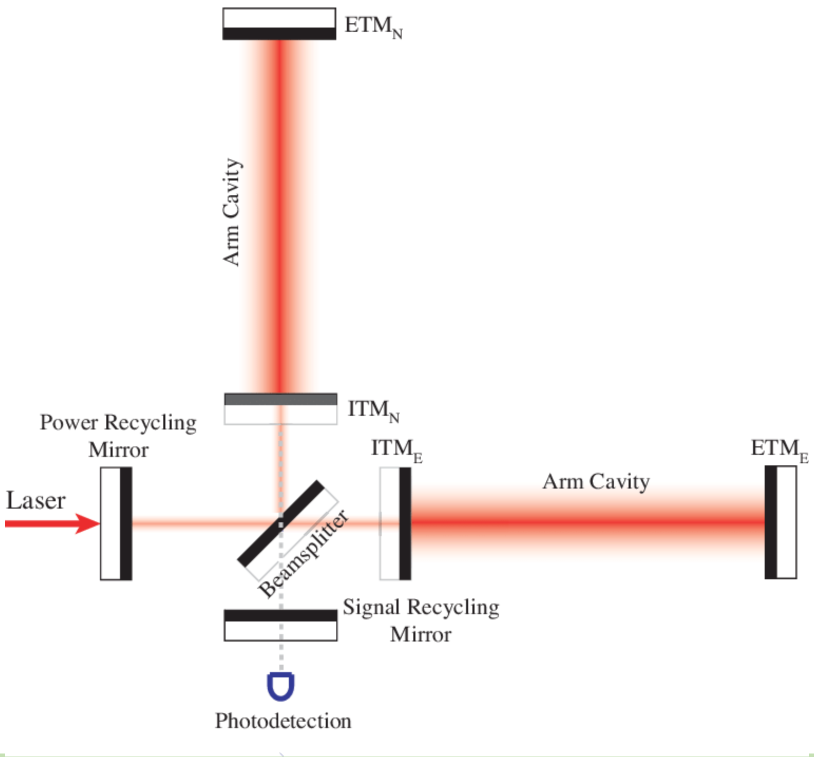
- Ripples in the spacetime metric generated by the acceleration of masses, propagating at the speed of light
- First direct observation 2015 (LIGO)
- Possible sources of detectable GW are some of the most violent events in the Universe involving massive and compact objects in relativistic regime
- Probe gravity in unprecedented conditions
- GW are a new messenger from the Universe, implications for
  - Astrophysics
  - Cosmology
  - Nuclear physics
  - …





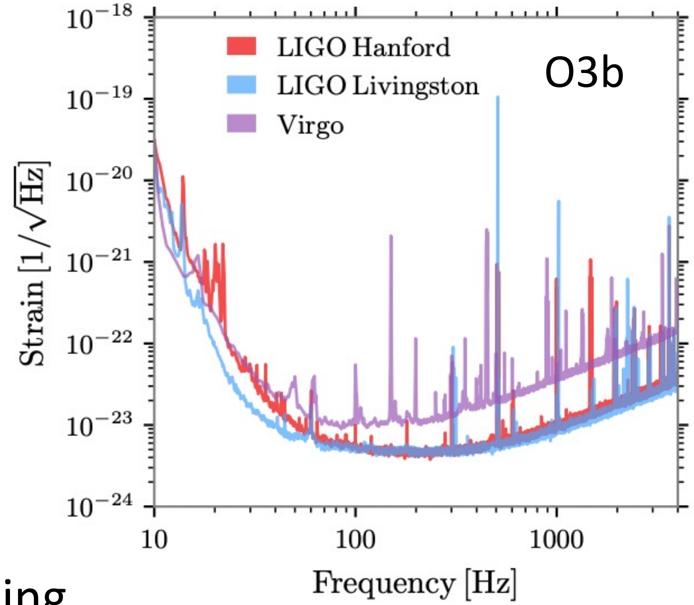
GW terrestrial detectors

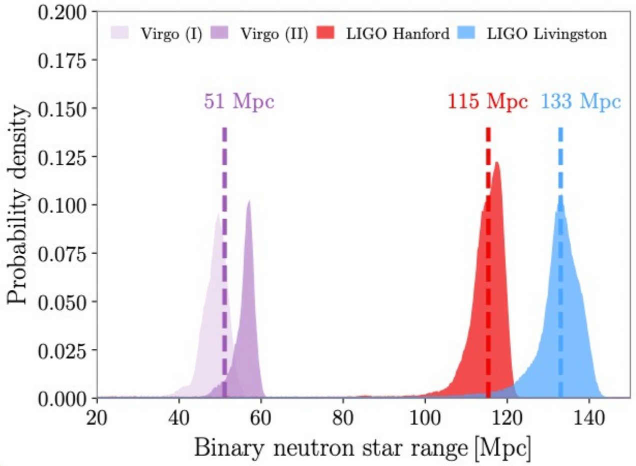
- Michelson interferometers with Fabry-Pérot cavities in the arms, operating on dark fringe
- Amplitude of gravitational waves $h \sim 10^{-22}$, $\delta L = hL$ → km-long arms
- Sensitive in the 10Hz – 10 KHz frequency band
- Sky localisation thanks to different positions and orientations



O3 data taking

- O3a : 1st April 2019 – 1st October 2019
- O3b : 1st November 2019 – 27th March 2020
- Duty cycle (O3b) ~76-79% for each detector, for an effective observation time during O3 of
  - 319 days – (at least) one detector
  - 264 days – (at least) two detectors
  - 156 days – three detectors
- Several detector improvements wrt previous data taking
- BNS range wrt O2 : x1.5-1.7
- A lot of work of detector characterization, noise understanding/subtraction, data quality optimization (LIGO, Virgo)
- April 2021 O3a data public release
- November 2021 O3b data public release

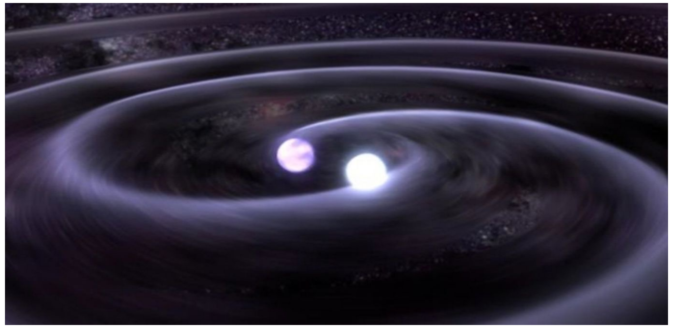




LIGO Virgo KAGRA physics program

Transient GW signals

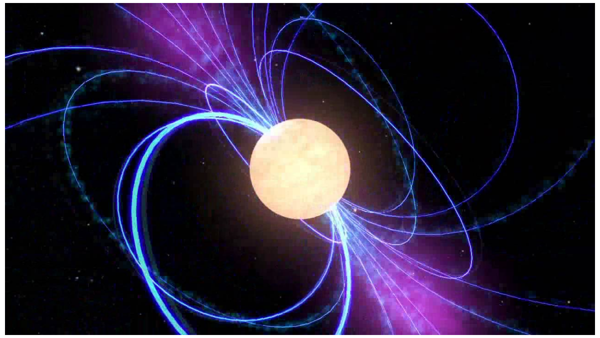
- Compact Binary Coalescences (CBC) – modelled



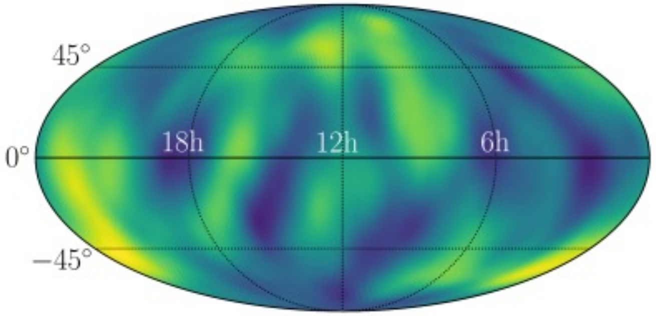
- Other "bursts", e.g. supernovae - unmodelled

Longer duration GW signals

- Continuous emission from rotating neutron stars

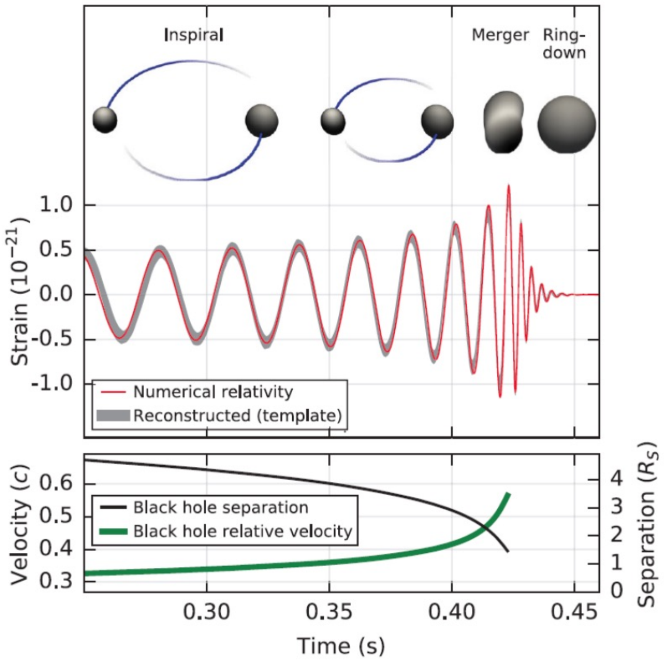


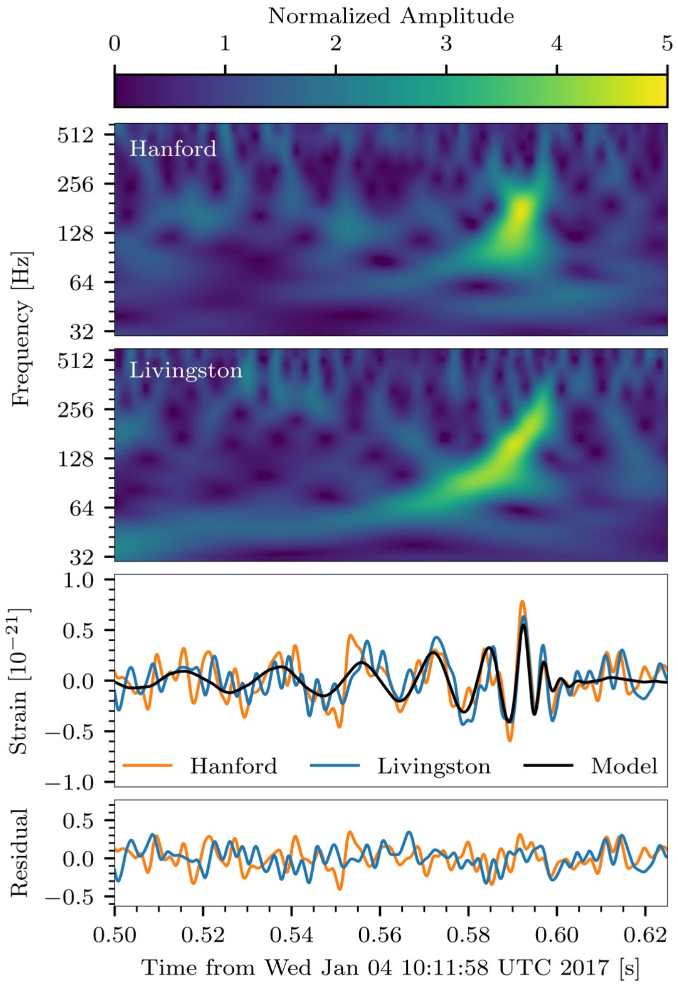
- Stochastic GW background



Compact Binary Coalescences (CBC)

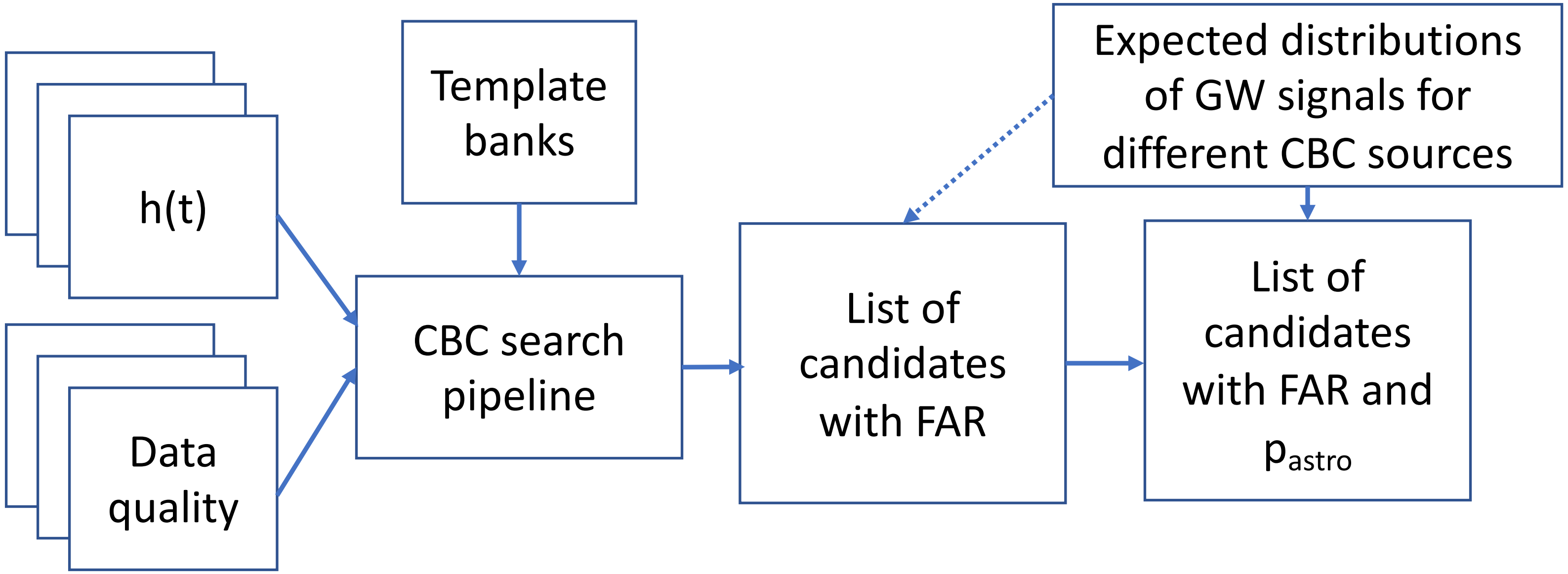
- Coalescences of compact objects : black holes or neutron stars (BBH, BNS, NSBH)
- Look for specific signal in large noise with matched filtering technique : cross-correlation of the data with a **known signal** waveform (weighted by noise)
- Provides a signal to noise ratio (and false alarm rate)
- Waveform assume GR, analytical in inspiral phase (PN), numerical relativity for merger, perturbation theory for ringdown
- Coalescences involving a NS can have an EM counterpart (only happened for GW170817 until now)
- CBC search analyses run **online** during data taking to issue alerts in case of interesting candidates
- Searches are then run **offline** with relaxed selection cuts, calibrated data, better noise subtraction, data-quality etc.

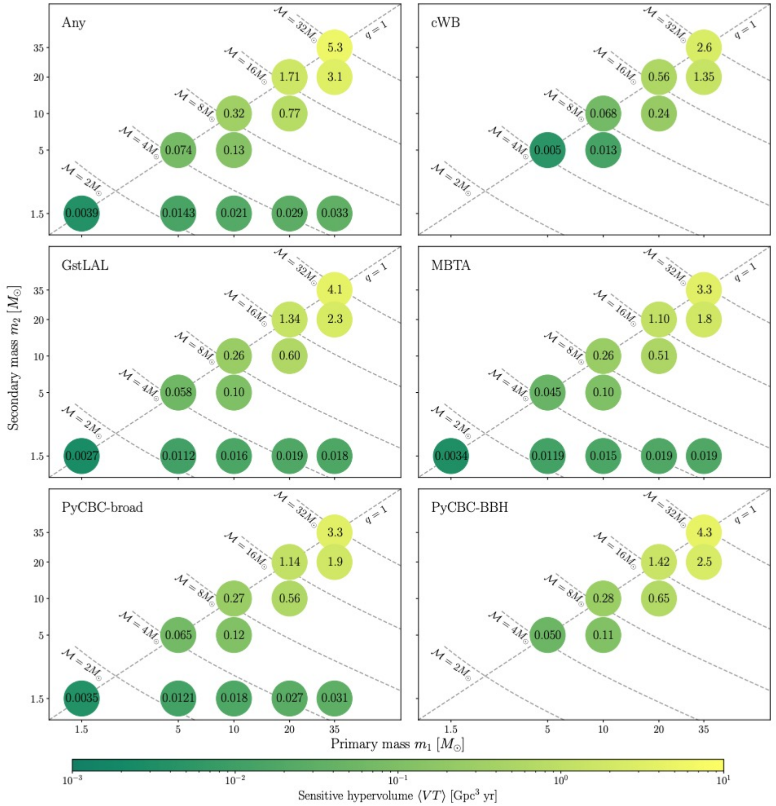




CBC searches

- Several analyses (pipelines) participate to the search :
  - Different strategies
  - Different parameter space
- Search sensitivity, estimated on simulation, shows their complementarity
- All use data from LIGO Hanford, LIGO Livingston, and Virgo





O3 LIGO-Virgo CBC catalogs

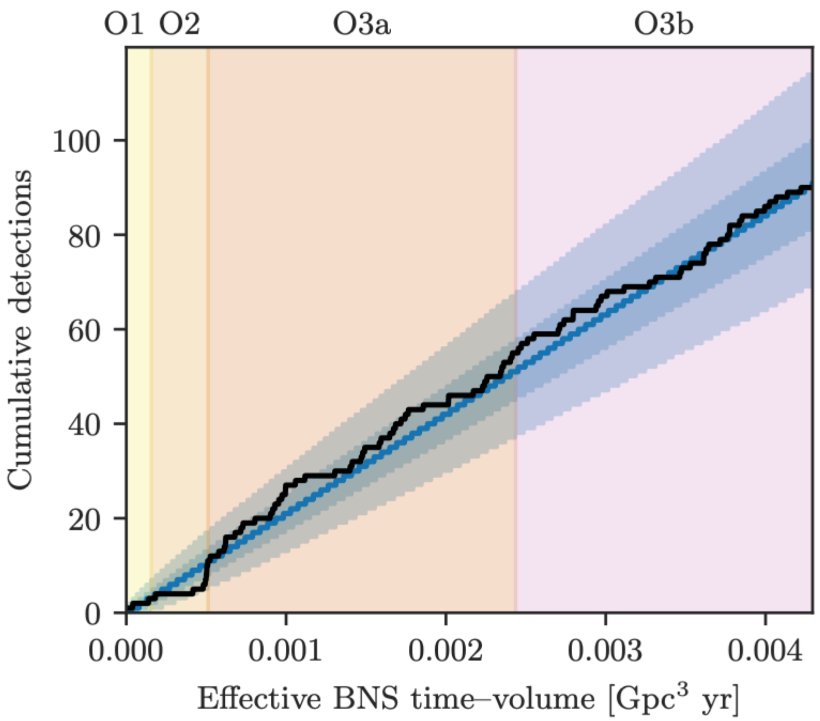
First half of O3 observation period (April - October 2019)

- GWTC-2 (Phys. Rev. X 11, 021053 (2021) arXiv)
  - Mixture of low-latency and offline calibrated data (improved noise subtraction)
  - 2 independent modelled searches, 1 minimally modelled
  - List of 39 candidates built based on the FAR
- GWTC-2.1 (arXiv) – superseding GWTC-2
  - Offline calibrated data, improved data quality. 3 modelled searches.
  - List of 44 candidates built based on p_{astro} + sub threshold candidates

Second half of O3 observation period (November 2019 – March 2020)

- GWTC-3 (arXiv)
  - 3 independent modelled searches, 1 minimally modelled
  - List of 35 additional candidates based on p_{astro}
  - Including first confident observations of NSBH

→90 confident candidates since the first observation !



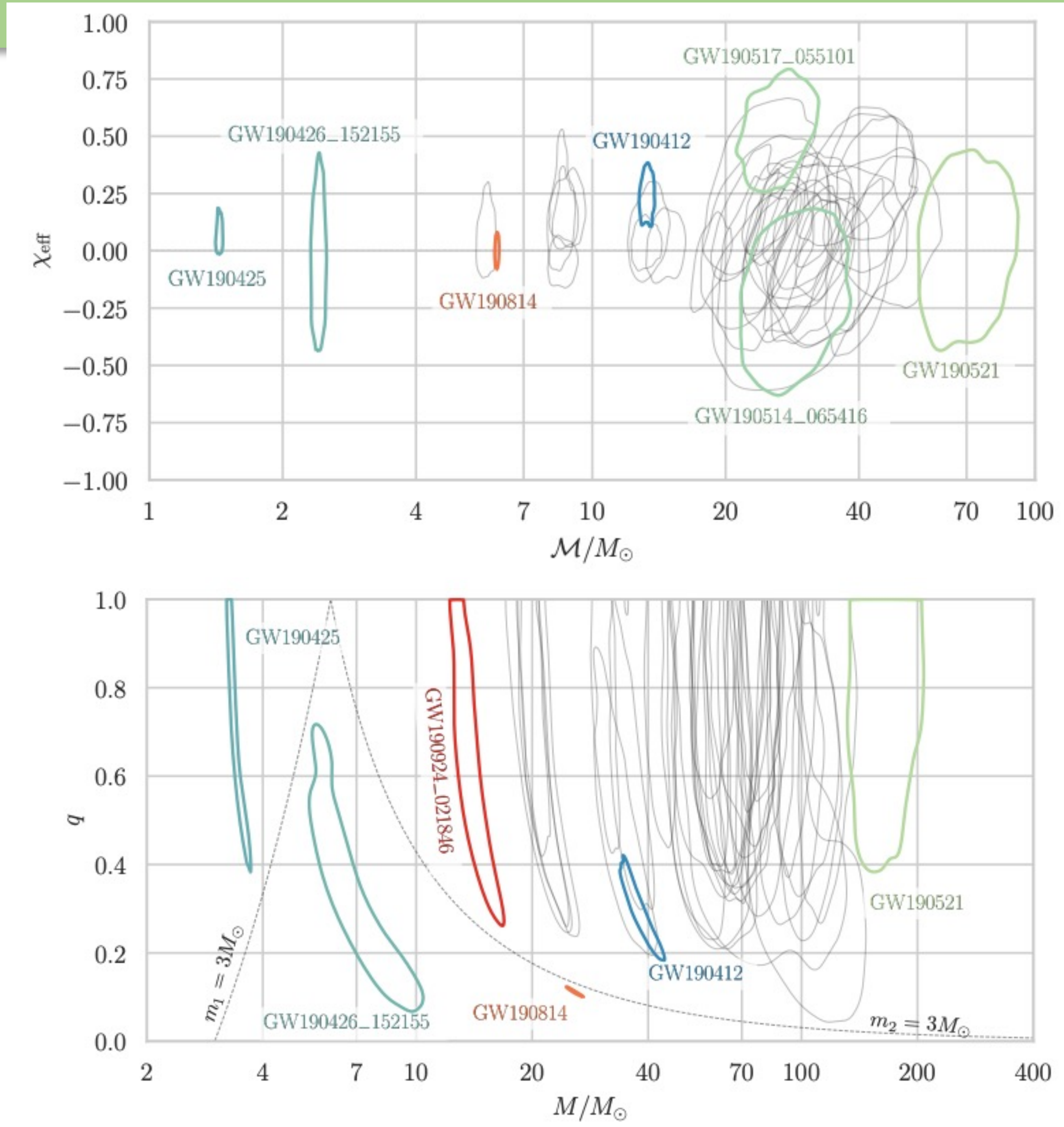
A CBC catalog anathomy

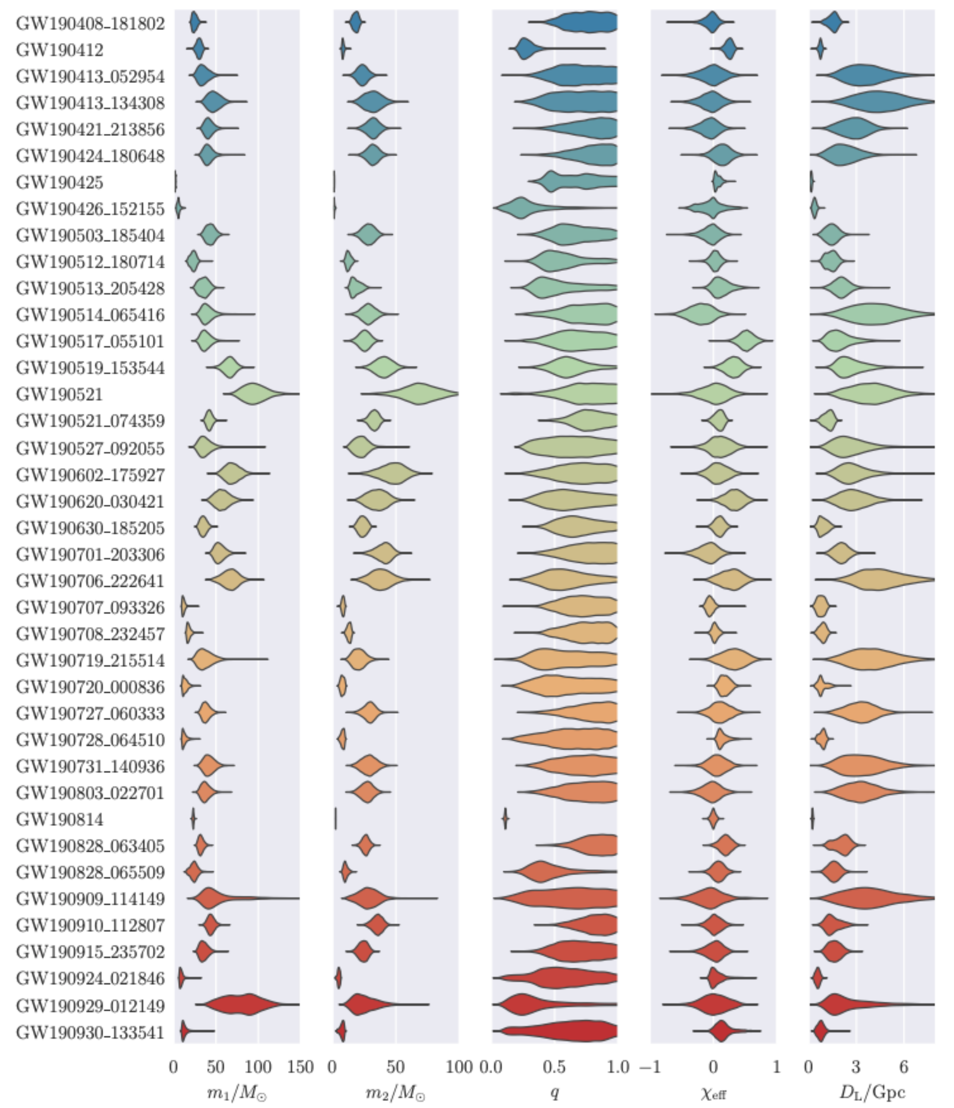
- List of events
- Significance as estimated by the several analyses

Name	Inst.	cWB FAR (yr^{-1})	cWB SNR	cWB p_{astro}	GstLAL FAR (yr^{-1})	GstLAL SNR	GstLAL p_{astro}	MBTA FAR (yr^{-1})	MBTA SNR	MBTA p_{astro}	PyCBC-broad FAR (yr^{-1})	PyCBC-broad SNR	PyCBC-broad p_{astro}	PyCBC-BBH FAR (yr^{-1})	PyCBC-BBH SNR	PyCBC-BBH p_{astro}
GW191103_012549	HL	–	–	–	–	–	–	*27*	*9.0*	*0.13*	4.8	9.3	0.77	0.46	9.3	0.94
GW191105_143521	HLV	–	–	–	*24*	*10.0*	*0.07*	0.14	10.7	> 0.99	0.012	9.8	> 0.99	0.036	9.8	> 0.99
GW191109_010717	HL	< 0.0011	15.6	> 0.99	0.0010	15.8	> 0.99	1.8×10^{-4}	15.2	> 0.99	0.096	13.2	> 0.99	0.047	14.4	> 0.99

- Data around each candidate is analysed again to determine astrophysical sources properties (masses, spins, localisation..)
- Obtained with expensive Bayesian inference algorithms (parameter estimation)
- Noise assumed to be Gaussian, stationary, and uncorrelated between detectors
- Multiple waveform models (different modelling techniques, including different physical effects), different samplers
- If at least one component with $m<3M_{sun}$ → waveforms with matter effects

Sources parameters Estimation





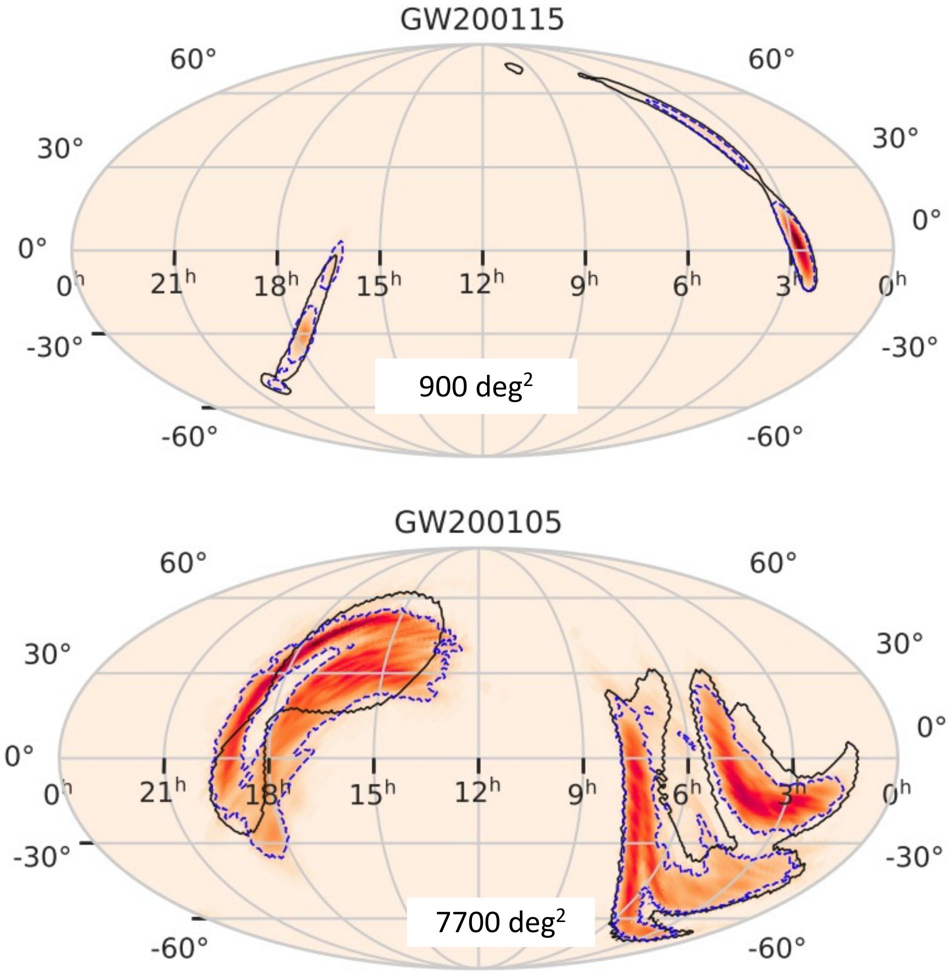
From GWTC-2

+ Dedicated IMBH search (GW190521+2 marginal candidates) - A&A 659, A84 (2022) (arXiv)

NSBH discovery

ApJL, 915, L5 (2021)
(arXiv)

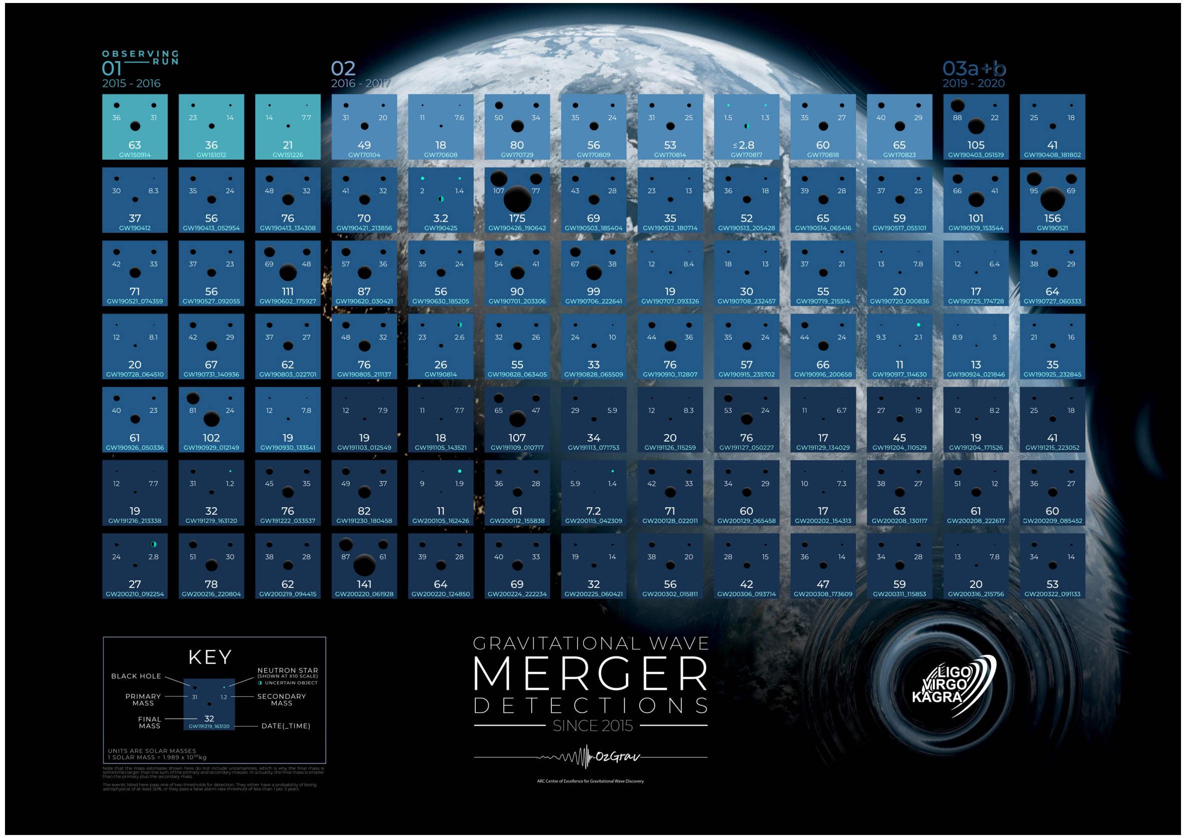
- No EM counterpart to date
- GW200115 - HL(V) coincidence, (best) FAR $10^{-5}yr^{-1}$
- GW200105 - Single-detector (L) event, FAR $(1/2.8)yr^{-1}$
- Secondary objects masses consistent with limits for NS masses (for non-rotating NS and Galactic NS)
- No evidence of tidal effects or precession
- GW200115 BH spin negatively aligned with respect to the orbital angular momentum, no formation process is excluded.
- Lensing excluded by non-overlapping posteriors



Event		GstLAL	MBTA	PyCBC	SPIIR
GW200105	low-latency	13.9	13.3	13.2*	13.2
	offline	13.9	13.4	13.1*	–
GW200115	low-latency	11.4	11.4	11.3	11.0
	offline	11.6	11.2	10.8*	–

Implications of the CBC observations

- CBC detections have become a routine for GW astronomy !
- An input to several studies
  - Astrophysical populations studies
  - Tests of General Relativity
  - Cosmology
  - Targeted searches (GRBs, FRBs..)
  - Lensing signatures searches



Rates and populations

O3a ApJL **913** L7 (2021) (arXiv)

O3b (arXiv)

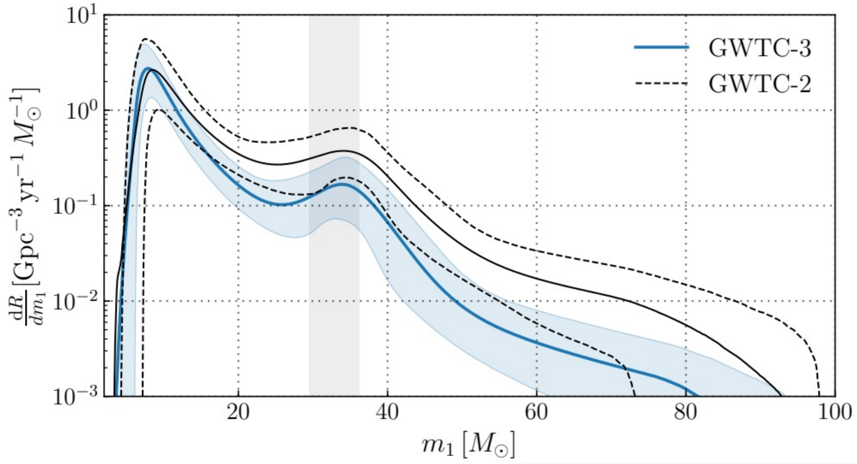
Population properties of compact objects based on 67 CBC from GWTC-3 (FAR<0.25/yr)

- Merger rates depend on models assumed for masses (Power Law + Dip + Break, Binned Gaussian process, Multi source), spins. 6 events have >5% probability of being in the gap.
- Mass distribution of NS in binaries, different from galactic NS (peak at 1.35 Msun)

New insight on BH population properties

- Mass distribution has a substructure. Decrease for M>50Msun, inconclusive evidence of upper mass gap. Correlation between spins and masses (mass ratios?)
- R_{BBH} z evolution consistent with one of star formation rate

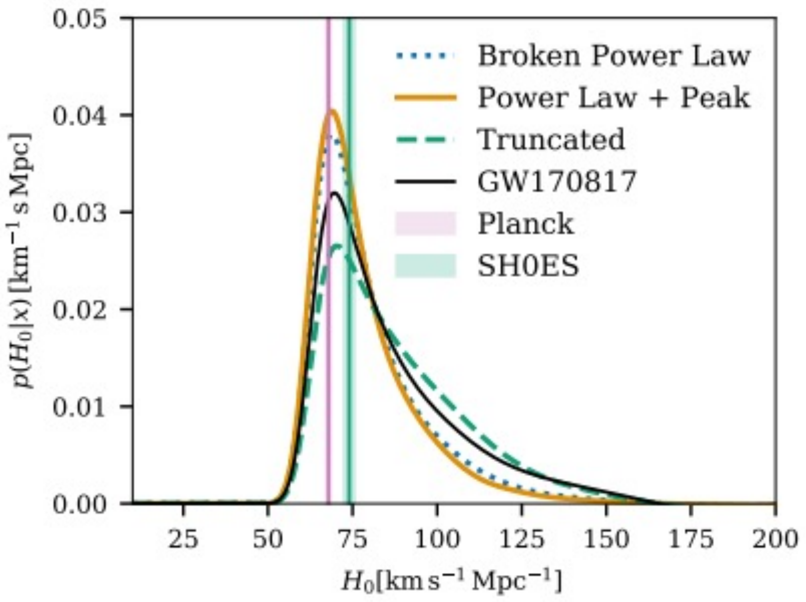
	BNS	NSBH	BBH	NS-Gap	BBH-gap	Full
	$m_1 \in [1, 2.5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 50]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 100]M_\odot$	$m_1 \in [2.5, 5]M_\odot$ $m_2 \in [1, 2.5]M_\odot$	$m_1 \in [2.5, 100]M_\odot$ $m_2 \in [2.5, 5]M_\odot$	$m_1 \in [1, 100]M_\odot$ $m_2 \in [1, 100]M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$	19^{+28}_{-13}	$9.3^{+15.7}_{-7.2}$	240^{+270}_{-140}
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$	$12^{+18}_{-9.0}$	$9.7^{+11.3}_{-7.0}$	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	$3.7^{+35.3}_{-3.4}$	$0.12^{+24.88}_{-0.12}$	770^{+1030}_{-530}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$	$1.7^{+30.0}_{-1.7}$	$5.2^{+12.0}_{-4.1}$	$180.0^{+270.0}_{-110.0}$
MERGED	10 – 1700	7.8 – 140	16 – 61	0.02 – 39	9.4×10^{-5} – 25	72 – 1800

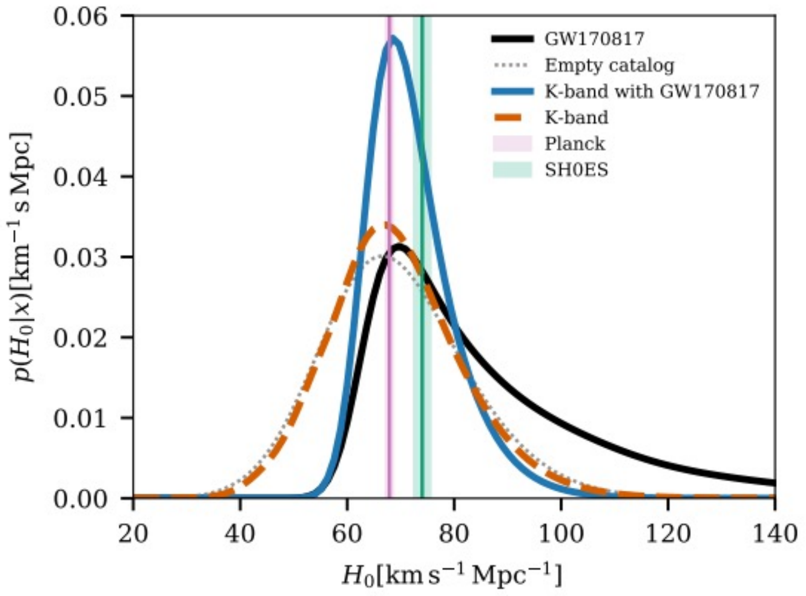


Cosmology with CBC

(arXiv, accepted by ApJ)

- Based on 47 highly significant (FAR<0.25yr-1, SNR>11) CBC observations: 42 BBH, 2 BNS, 2NSBH, GW190814
- GW detection → measurement of luminosity distance
- Different methods to constrain H_0
  - Jointly fitting the cosmological parameters and the source population properties of BBHs
  - Fixing the source population properties, and inferring the cosmological parameters using statistical galaxy catalog information (use population for out of catalog)
  - (Redshift information from EM counterpart - only for GW170817)

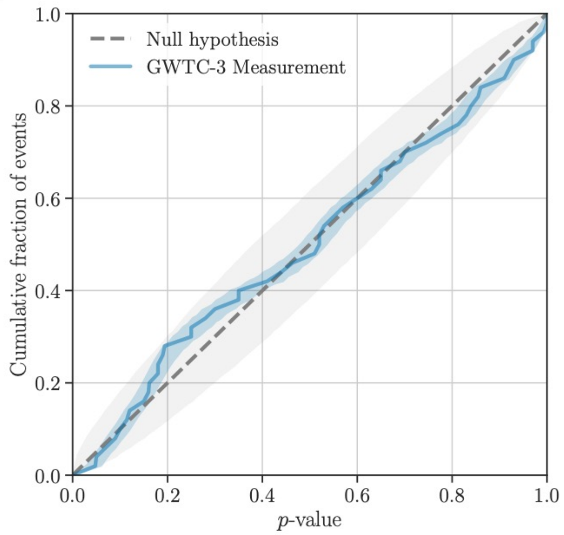


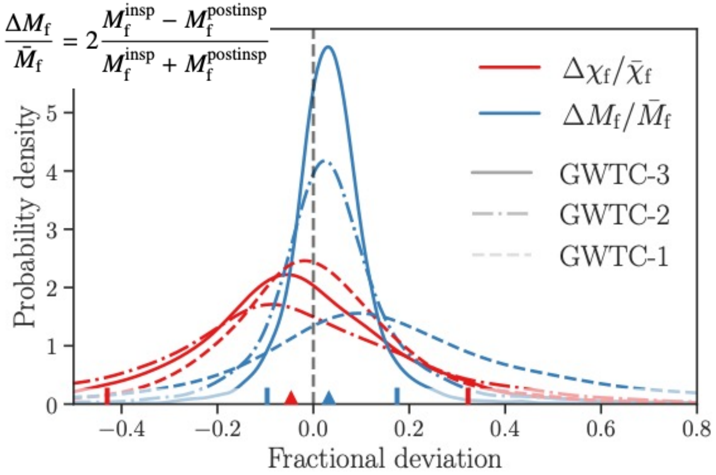


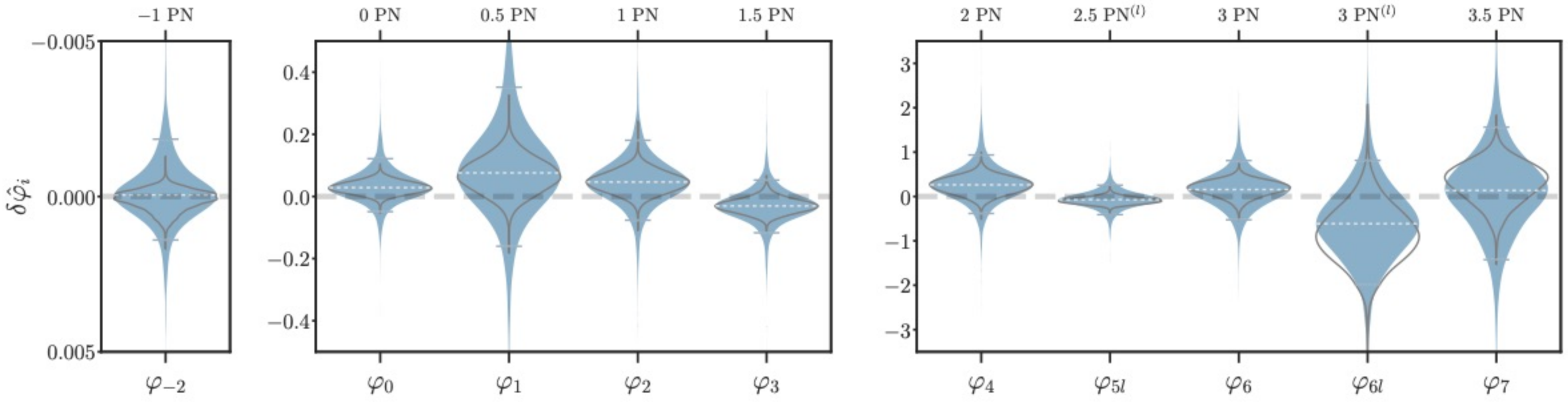
Tests of GR with CBC

Phys. Rev. D 103 122002 (2021) (arXiv)

- Tests of GR using 47 CBC from GWTC-2 + 15 from GWTC-3 (FAR<10^{-3}/yr) - no evidence for new physics beyond general relativity. Using a large variety of waveform approximants
- Residual tests from remnant coherent power in network data after subtraction of candidates
- Inspiral-merger-ringdown consistency checks (mass and spin of remnant BBH)
- Generic modifications to waveforms (varying post-Newtonian and phenomenological coefficients) → constraints ~2x stronger than previous
- Gravitational-wave dispersion (null in GR) → constraints on Lorentz-violating coefficients, graviton mass $m_g \leq 1.27 \times 10^{-23}$ eV/c2 @90%CL
- Data consistent with tensorial polarization, no deviation from Kerr BH, no post-merger echoes



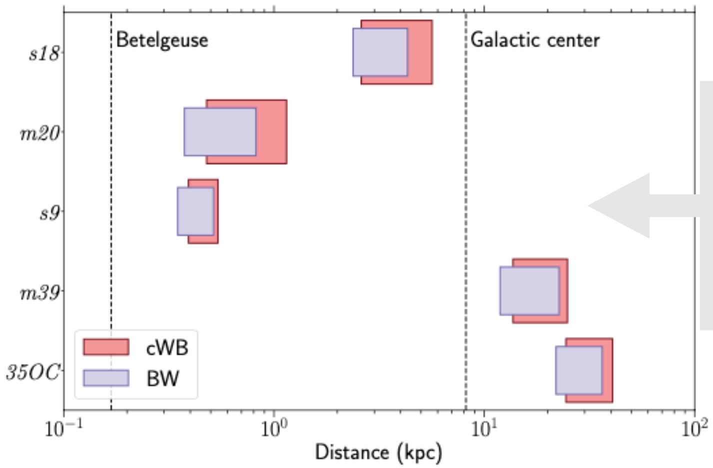




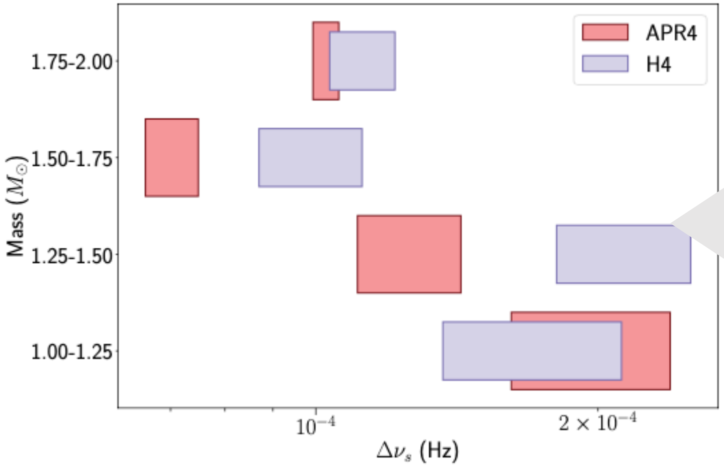
O3 Search for short GW bursts

Phys. Rev. D 104, 122004 (arXiv)

- Transient [ms-s] GW signals in [24–4096] Hz, no assumption on signal morphology
- Two independent analyses look for excesses of signal power in time– frequency (**Coherent WaveBurst** and **BayesWaves** as a followup on interesting times)
- No GW detection (iFAR>100 yr) beyond the CBC ones, sensitivity studies based on simulations
- Generic signal morphologies: sine-Gaussian wavelets (SG), Gaussian pulses (GA), and band-limited white-noise bursts (WNB).
- CCSNe: different models (s18, m10, s9, m39, 35OC)
- Pulsar glitches (GW bulk emission described by f-mode), Vela Pulsar standard candle. EoS: APR4 (soft) and H4 (hard)



Distances at which [10%-50%] efficiency is reached.



Detectable glitch size for ε=0.5, iFAR ≥ 100 yr.
Box width = variation over mass bin.
Glitch sizes for Vela-like pulsars need to be >~10^{-4} to have 50% chances of being detected in O3.

No confident candidate for long-duration bursts - Phys. Rev. D 104, 102001 (arXiv)

Other transient searches

Lensing of O3a BBH

- Multiple images (sky-localisation and most parameters consistent, constrained time-delay)
- Analyse posterior overlap of all GWTC-2 candidates → Joint-PE analysis for most promising
- 11 GWTC-2 pairs with high parameters consistency, none prefers the lensed hypothesis

2021 ApJ 923 14 (arXiv)

Triggered searches

- Search for GW transient associated with GRB (Fermi/Swift) or FRB(CHIME/FRB)
- Two independent pipelines
- No GW signal associated to a GRB or FRB. Sensitivity determined on simulation. Exclusion distance.

ApJ. 915, 86 (2021) (arXiv)
ApJ 928 186 (2022) (arXiv)
(arXiv)

CBC techniques used to **search for sub-solar mass objects**, constraints on PBH models (arXiv)

Not only transient !

- Early O3 all-sky binaries CW - Phys. Rev. D 103, 064017 arXiv
- Full O3 targeted J0537-6910 CW - 2021 ApJ 922 71 arXiv
- Full O3 PSR J0537-6910 pulsar r-mode CW - 2021 ApJ 922 71 arXiv
- O3 SN remnants CW 2021 ApJ 921 80 arXiv, Phys. Rev. D 105, 082005 arXiv
- O3 all-sky isolated CW – (early Phys. Rev. D 104, 082004 arXiv), arXiv
- O3 twenty AMXPs CW - Phys. Rev. D 105, 022002 arXiv
- Full O3 BH boson cloud CW - Phys. Rev. D 105, 102001 arXiv
- Early O3 Cas A / Vela Jr CW - Phys. Rev. D 105, 082005 arXiv
- O3 isotropic stochastic - Phys. Rev. D 100, 061101(R) arXiv
- O3 anisotropic stochastic - Phys. Rev. D 104, 022005 arXiv
- O3 all-sky cosmic strings search - Phys. Rev. Lett. 126, 241102 arXiv
- O3 constraints on dark photon and dark matter - Phys. Rev. D 105, 063030 arXiv

Conclusions

- O3 big success for the LIGO-Virgo collaboration
- 1 year run with 3-interferometers network. Efficient operation, detector characterisation and noise handling. Automatic alerts.
- Many varied scientific results
  - 90 high-probability CBC candidates since first detection
  - Unfortunately only one EM counterpart observed until now (GW170817)
  - Constraints on sources populations and rates, tests of GR, cosmology
  - Searches performed for (non-CBC) bursts, CW emission, SGWB, DM..
  - Although no evidence (other than CBC) for the moment, sensible improvements in constraints
- New observation period to start end of 2022
  - 4 interferometers network
  - expect 3-4 times more observations !