Latest results from LIGO-Virgo third observation run

Viola Sordini – IP2I Lyon

Since last presentation at a GdR meeting (Oct 2020)

on transient GW signals searches

~~Latest~~ results from LIGO-Virgo third observation run

a (non-exhaustive) selection

LSC

VIRGO

KAGRA

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Groupement de recherche Ondes gravitationnelles

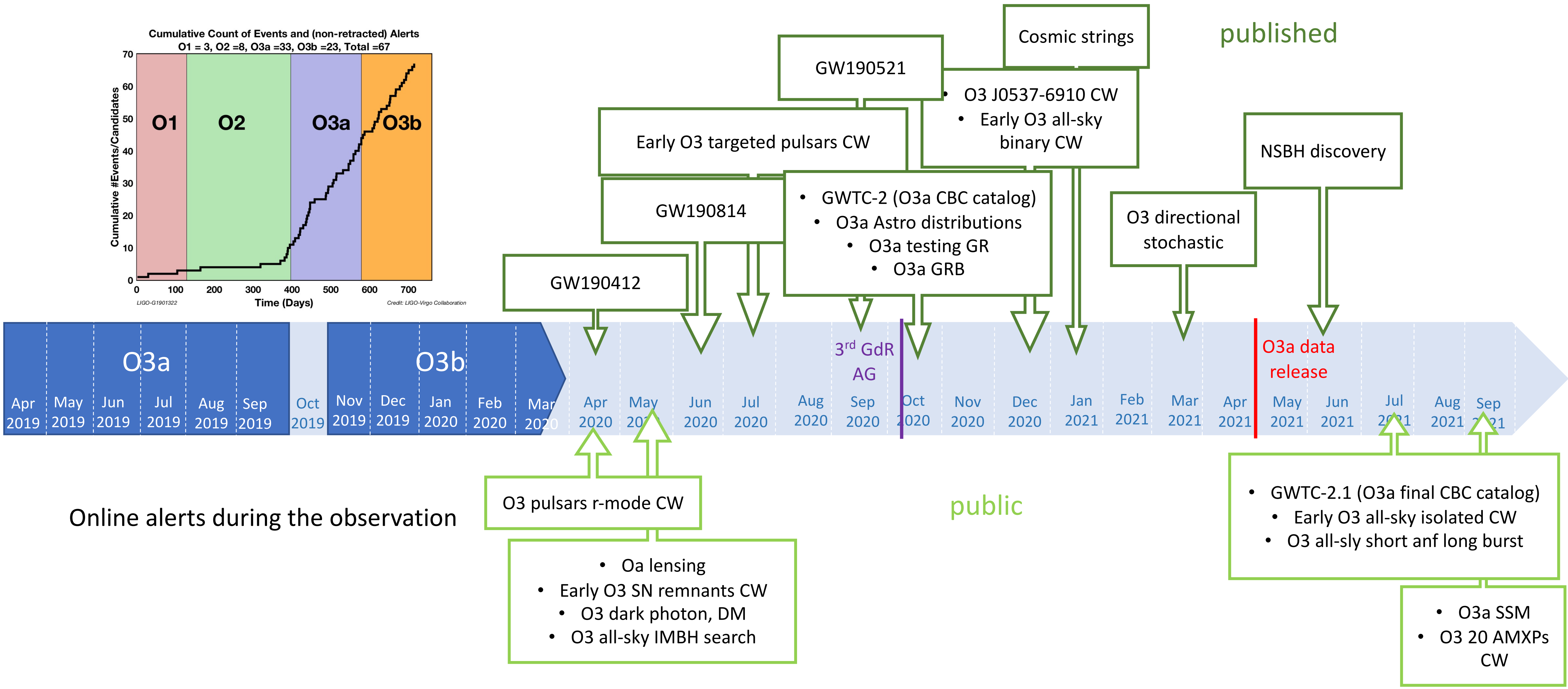
iP2i LES 2 INFINIS LYON

cnrs IN2P3

Introduction and outline

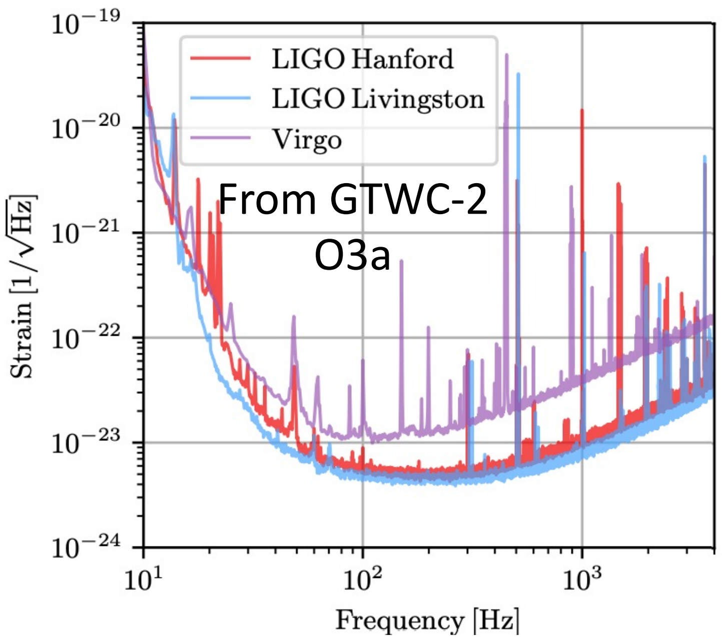
- O3 general
- CBC catalog(s)
- Rates and populations and tests of GR from CBC catalog events
- NSBH discovery
- O3a sub-solar mass
- O3 search for short-duration bursts
- Lensing signatures
- IMBH search
- O3a GRB

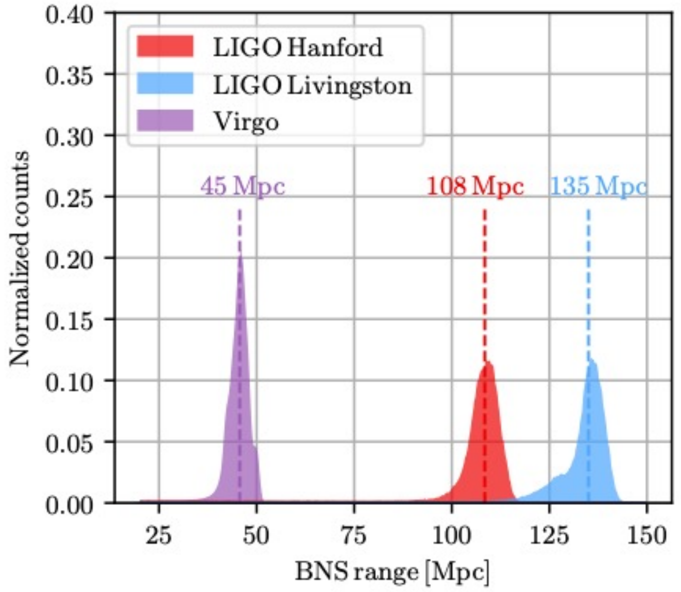
O3 observation and publications



O3 data taking

- O3a : 1st April 2019 – 1st October 2019
- O3b : 1st November 2019 – 27th March 2020
- O3a duty cycle ~71-76% for each detector, for an effective observation time of
  - 177 days – (at least) one detector
  - 139 days – (at least) two detectors
  - 81 days – three detectors
- Several improvements wrt previous data taking
- BNS range wrt O2 : x1.64 (LIGO Hanford), x1.53 (LIGO Livingston) x1.73 (Virgo)
- Similar order of magnitude (in some cases better) for O3b





O3a LVK CBC catalog(s)

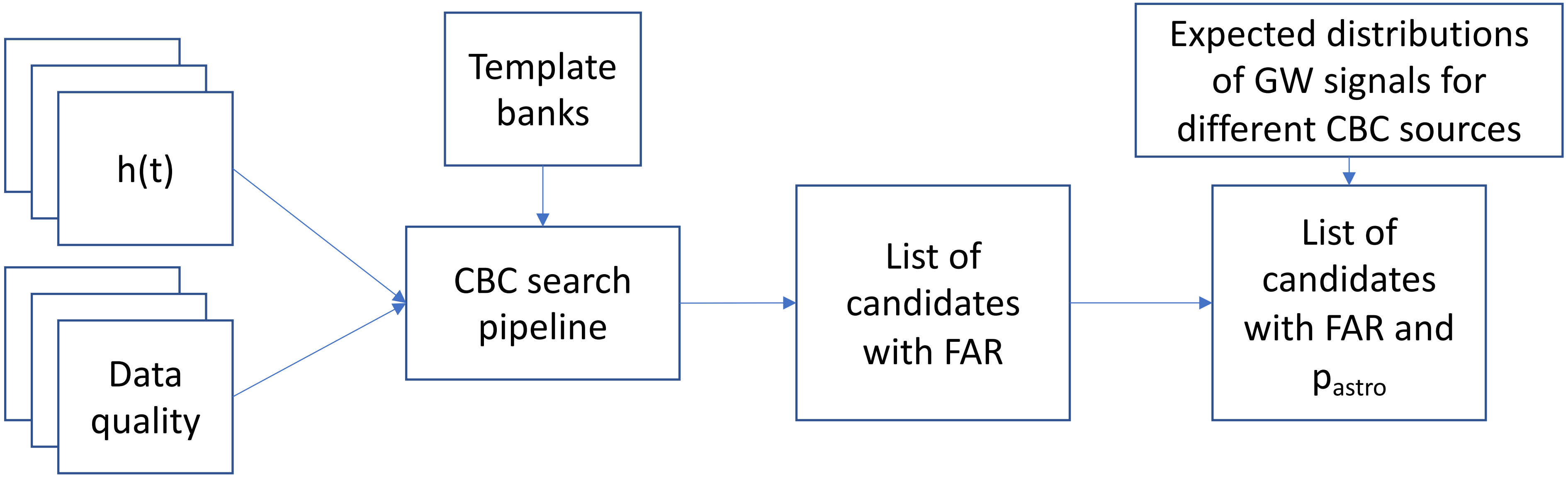
- Two available catalogues on O3a CBC observations !
- GWTC-2 (Phys. Rev. X 11, 021053 (2021) arXiv)
    - cWB, GstLAL, PyCBC
    - Mixture of low-latency and offline calibrated data
    - List of 39 candidates built based on the FAR
- GWTC-2.1 (arXiv) – superseding GWTC-2
    - GstLAL, MBTA, PyCBC
    - Offline calibrated data (improved noise subtraction), improved data quality
    - PE on 44 candidates built based on p_{astro}
    - Release 1201 subthreshold candidates (FAR $<$ 2/day)
- In the following mainly focus on GWTC-2.1
- Brief discussion on the few notable differences
- Population and testing GR publications based on GWTC-2

GWTC-2.1

- Three pipelines participated to the search :
  - GstLAL – also looking for single-trigger events
  - MBTA – splits analysis in two frequency bands
  - PyCBC - generic and focussed BBH
- All use data from LIGO Hanford, LIGO Livingston, and Virgo

Parameters space and waveforms

- Total masses up to 400 (GstLAL), 500 (PyCBC), 200 (MBTA)
- TaylorF2 for low mass, SEOBNRv4_ROM otherwise
- (anti-)aligned spins with $|\chi|<0.05$ if m<2, 0.998 otherwise



GWTC-2.1 – List of candidates (p_{astro}>0.5)

- 44 high-probability (p_{astro}>0.5) CBC candidates, including
  - 8 new candidates (not in GWTC-2)
  - 4 single-detector
  - 8 candidates with p_{BNS} or p_{NSBH}>0.01, one perefrred BNS, two preferred NSBH
- 1201 candidates with FAR<2/day in ANY of the search pipelines
- Number of observed events with FAR<2/day (ranges showing spread of different pipelines results)
  - 24.95 - 44.50 BBH
  - 0.66 - 3.80 NSBH
  - 0.22 – 0.81 BNS

Name	Inst.	MBTA			GstLAL			PyCBC			PyCBC-BBH		
		FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}	FAR (yr^{-1})	SNR	p_{astro}
GW190403_051519	HL	––	––	––	––	––	––	––	––	––	7.7	8.0	0.61
GW190408_181802	HLV	8.7×10^{-5}	14.4	1.00	$< 1.0 \times 10^{-5}$	14.7	1.00	2.5×10^{-4}	13.1	1.00	$< 1.2 \times 10^{-4}$	13.7	1.00
GW190412	HLV	$< 1.0 \times 10^{-5}$	18.2	1.00	$< 1.0 \times 10^{-5}$	19.0	1.00	$< 1.1 \times 10^{-4}$	17.4	1.00	$< 1.2 \times 10^{-4}$	17.9	1.00
GW190413_052954	HL	––	––	––	––	––	––	*170*	*8.5*	*0.13*	0.82	8.5	0.93
GW190413_134308	HLV	0.34	10.3	0.99	*39*	*10.1*	*0.04*	*21*	*9.3*	*0.48*	0.18	8.9	0.99
GW190421_213856	HL	1.2	9.7	0.99	0.0028	10.5	1.00	5.9	10.1	0.75	0.014	10.1	1.00

GWTC-2.1 vs GWTC-2 notable differences

- Non-recovered candidates (3)
  - 1 single-detector BBH, excluded because of better usage of data-quality information
  - 1 event with low p_{astro} (NSBH)
  - 1 event with significance lowered by better usage of data-quality information
- New high-probability candidates (8)
  - 1 candidate with $p_{NSBH}>0.2$
  - Only 2 have $p_{astro}>0.5$ from more than one pipeline
  - Most distant event ($z\sim1.14$)

GWTC-2.1 – BBH and BNS rates

- BBH and BNS events rates (re) measured from high number of events (not only significant ones)

	$R_{\mathrm{BBH}}(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$
GstLAL	$26.0^{+8.2}_{-6.8}$
MBTA	$25.0^{+7.2}_{-6.1}$
PyCBC	$25.6^{+9.6}_{-7.8}$

R_{BBH} from populations paper, using only significant (FAR< 1 yr^{-1}) events, and allowing for uncertainties in the population model parameters.

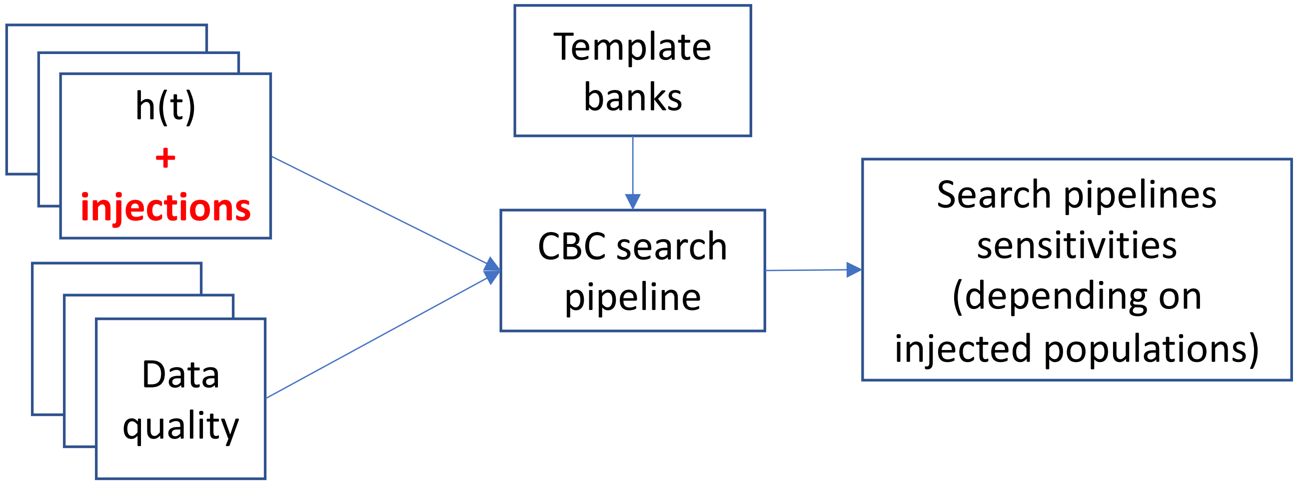
$$23.9^{+14.3}_{-8.6}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

	$R_{\mathrm{BNS}}(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$
GstLAL	286^{+510}_{-237}

R_{BNS} from populations paper

$$320^{+490}_{-240}\,\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

GWTC-2.1 Searches sensitivities



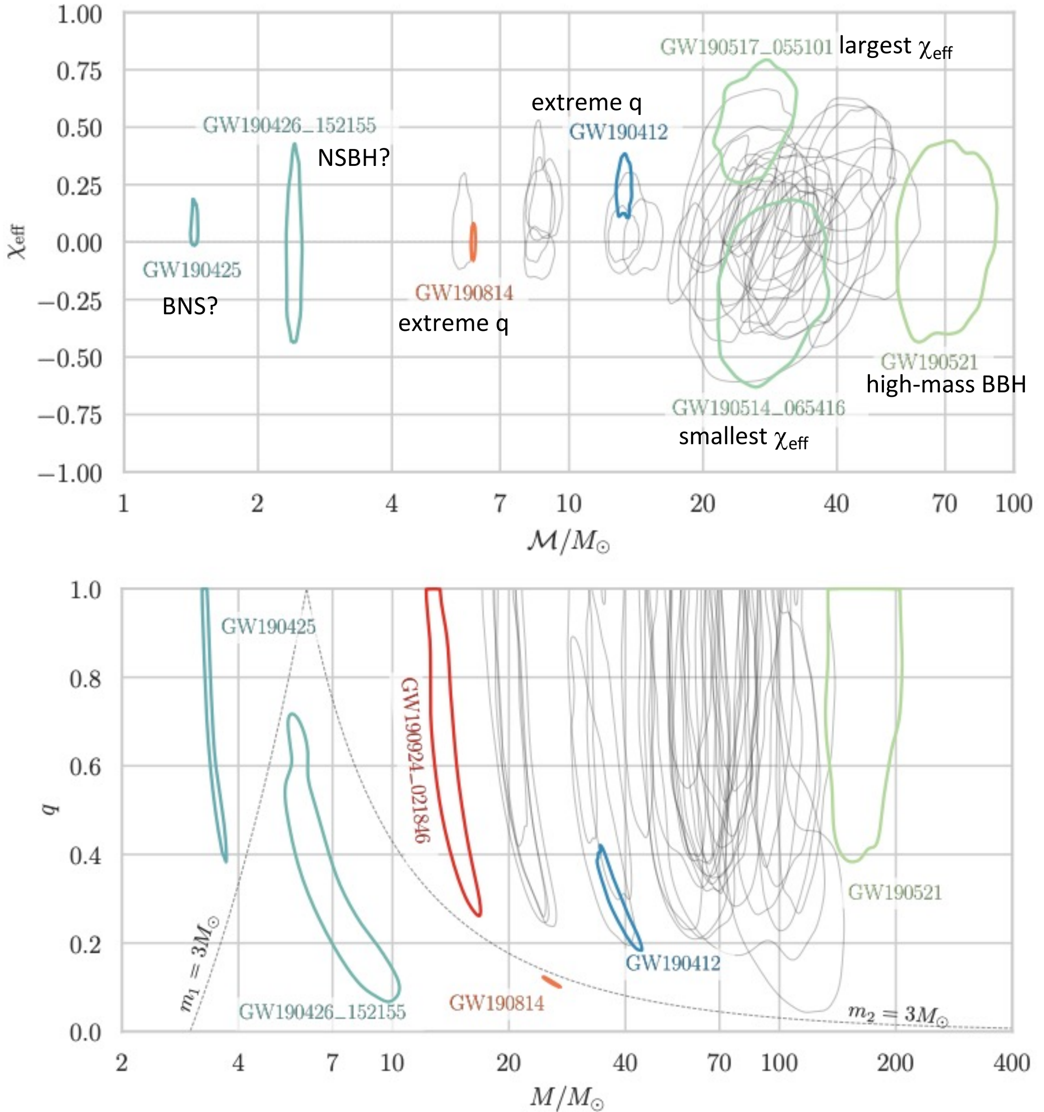
Injection populations						Sensitive hypervolume $\mathcal{V}$ (Gpc^3 yr)				
	mass distribution	mass range ($M_\odot$)	spin range	redshift evolution	max. redshift	GstLAL	MBTA	PyCBC	PyCBC BBH	All
BBH (INJ)	$p(m_1) \propto m_1^{-2.35}$ $p(m_2\|m_1) \propto m_2$	$2 < m_1 < 100$ $2 < m_2 < 100$	$\|\chi_{1,2}\| < 0.998$	$\kappa = 1$	1.9	0.258	0.196	0.194	0.234	0.308
BBH (POP)	Power Law + Peak	(see text)	$\|\chi_{1,2}\| < 0.998$	$\kappa = 0$	1.9	1.22	0.885	0.914	1.20	1.44
BNS	uniform	$1 < m_1 < 2.5$ $1 < m_2 < 2.5$	$\|\chi_{1,2}\| < 0.4$	$\kappa = 0$	0.15	0.00594	0.00631	0.00657	–	0.00781
NSBH	$p(m_1) \propto m_1^{-2.35}$ uniform	$2.5 < m_1 < 60$ $1 < m_2 < 2.5$	$\|\chi_1\| < 0.998$ $\|\chi_2\| < 0.4$	$\kappa = 0$	0.25	0.0174	0.0165	0.0181	–	0.0221

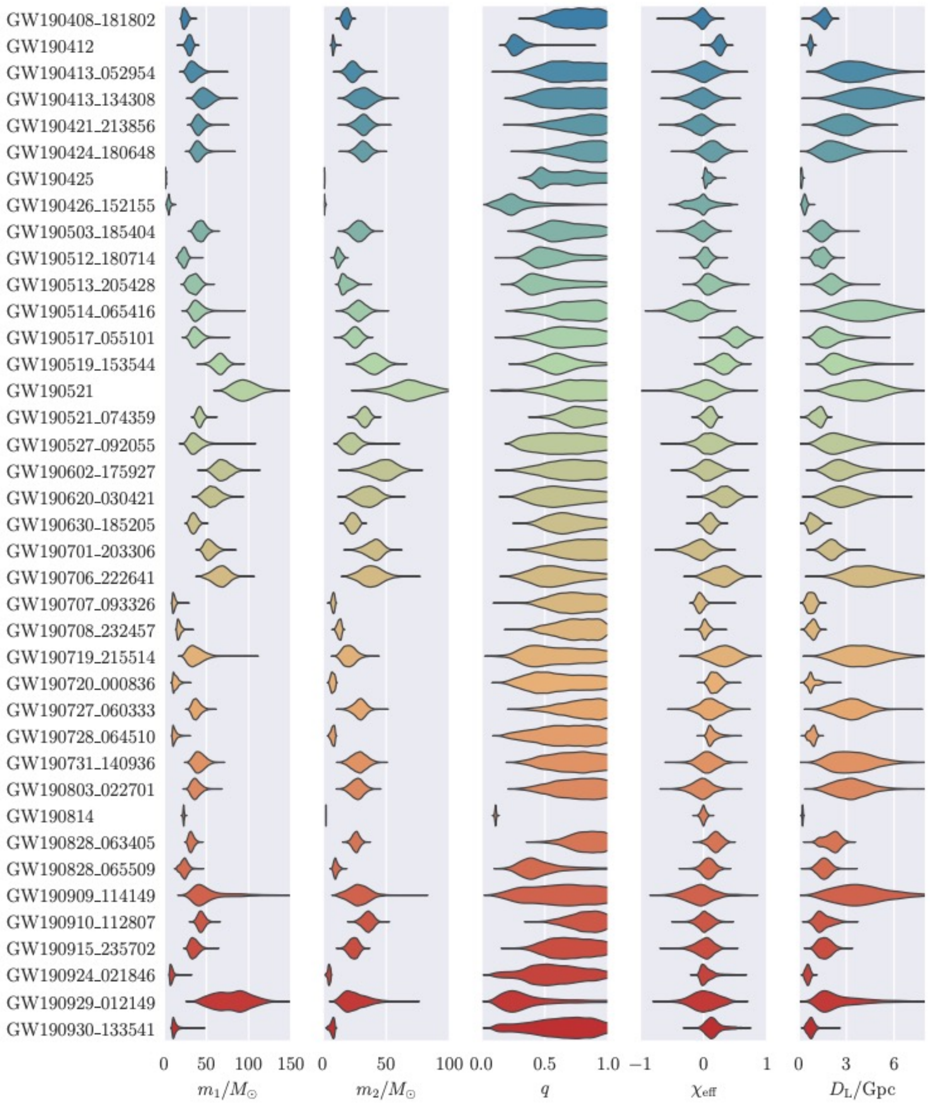
- Comparable sensitivities
- Pipelines complementarity

GWTC-2(.1) Sources parameters estimation

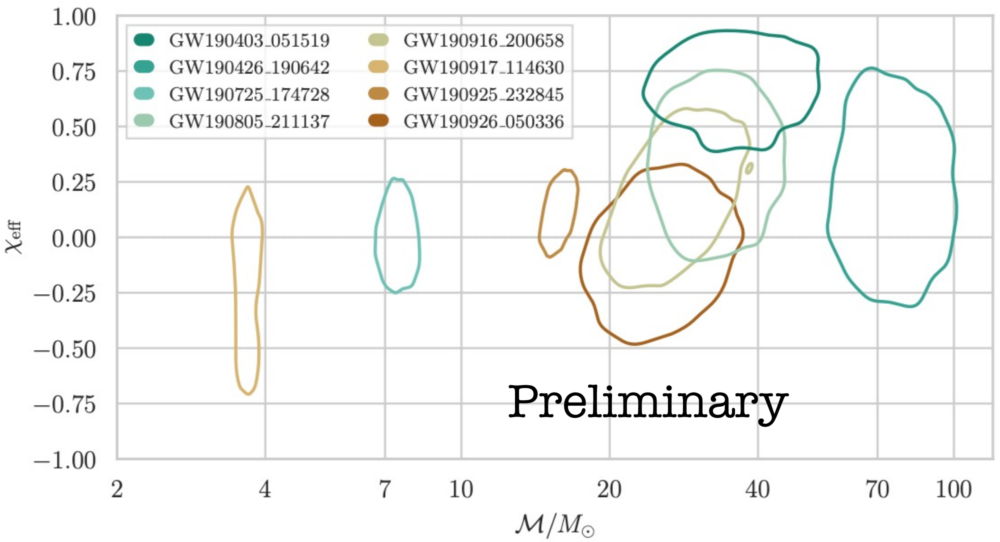
- Physical parameters of the candidates inferred with Bayesian inference algorithms
- Noise assumed to be Gaussian, stationary, and uncorrelated between detectors
- Different sampling methods (LALInference, RIFT, Bilby)
- Multiple waveform models (different modelling techniques, including different physical effects)
- BBH : IMRPhenomPv2, SEOBNRv4P, + at least one waveform with HM (IMRPhenomPv3HM, SEOBNRv4PHM, NRSur7dq4)
- If at least one component with $m<3M_{sun}$ → waveforms with matter effects (PhenomD NRTidal and IMRPhenomPv2, TaylorF2, TEOBResumS, SEOBNRv4T)
- For NSBH consistent candidates, both BBH and NSBH waveforms (SEOBNRv4_ROM_NRTidalv2_NSBH, IMRPhenomNSBH,)

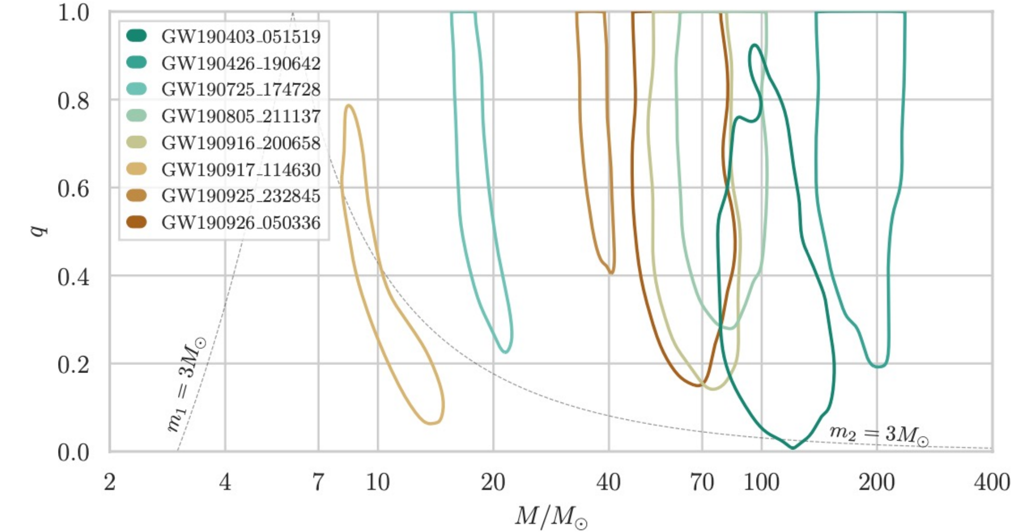
GWTC-2 Sources parameters Estimation

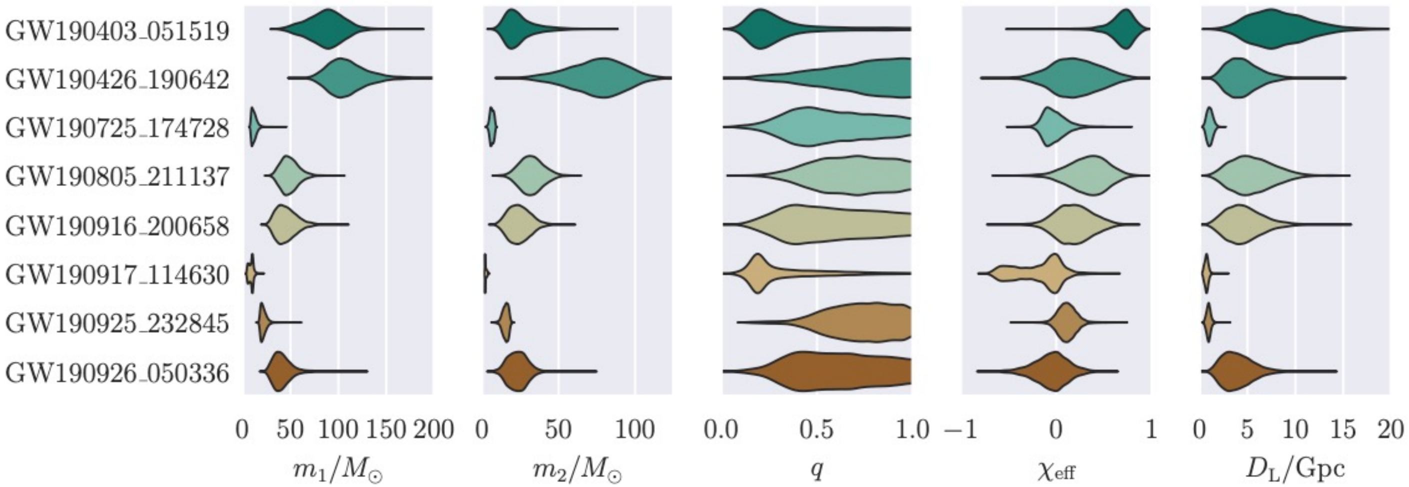




GWTC-2.1 Sources parameters Estimation







GW190917_114630 consistent with NSBH
GW190725_174728 one component in lower mass gap
GW190403_051519 and GW190426_190642 high total mass, component masses in pair-instablity mass gap → dynamical formation channel (CBC, repeated stellar collisions in dense star clusters, extreme gas accretion from disk, PBH, peculiar stellar evolution)
GW190403_051519 high χ_1, high positive $\chi_{\rm eff,}$ extreme q

O3a rates and populations

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

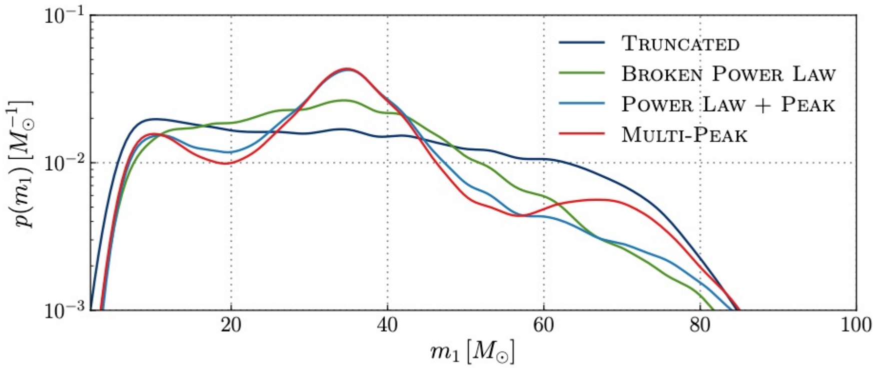
Population properties of compact objects based on 47 CBC from up to GWTC-2 (FAR<1/yr)

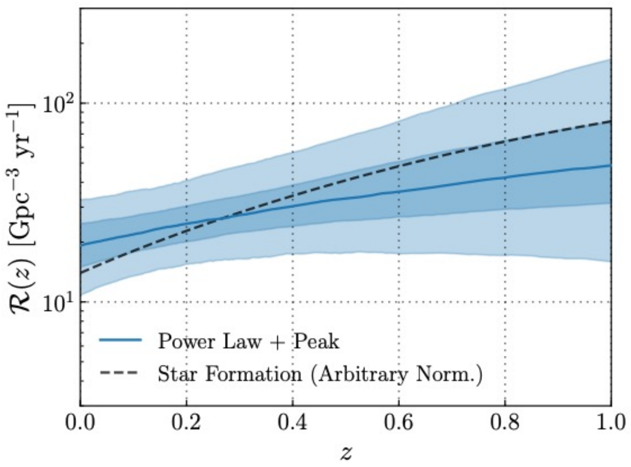
- Merger rates measurements

$$R_{\rm BBH} = 23.9^{+14.3}_{-8.6}\,{\rm Gpc}^{-3}{\rm yr}^{-1} \qquad R_{\rm BNS} = 320^{+490}_{-240}\,{\rm Gpc}^{-3}{\rm yr}^{-1}$$

New insight on BBH population properties

- A truncated power law for primary masses fails to fit the high-mass BBH events (Power law + peak? Broken power law ? Multi-peak?)
- Observe BBH systems with component spins misaligned with the orbital angular momentum, with 12 to 44% of BBH systems spins tilted by more than 90° (negative $\chi_{\rm eff}$) → a fraction of those formed by dynamical interaction?
- $R_{\rm BBH}$ z evolution consistent with one of star formation rate
- Masses from GW190412 (asymmetric) and GW190521 (high m_1) consistent with the models, the low secondary mass of GW190814 is an outlier.

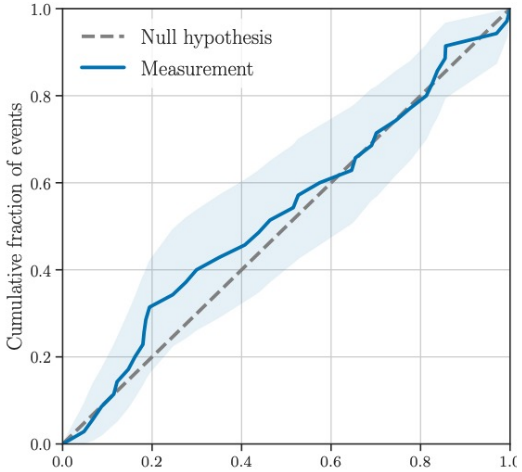


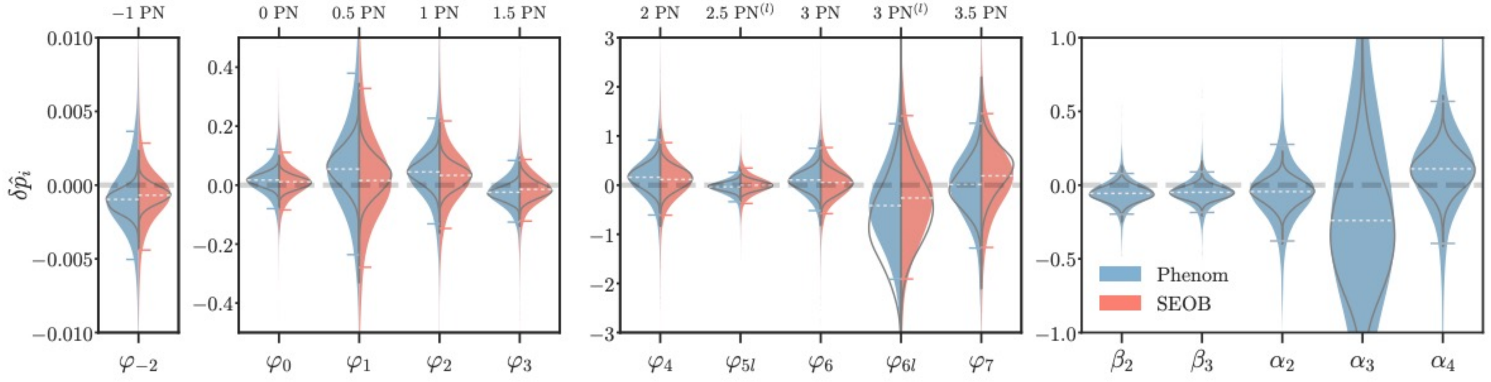


O3a testing GR

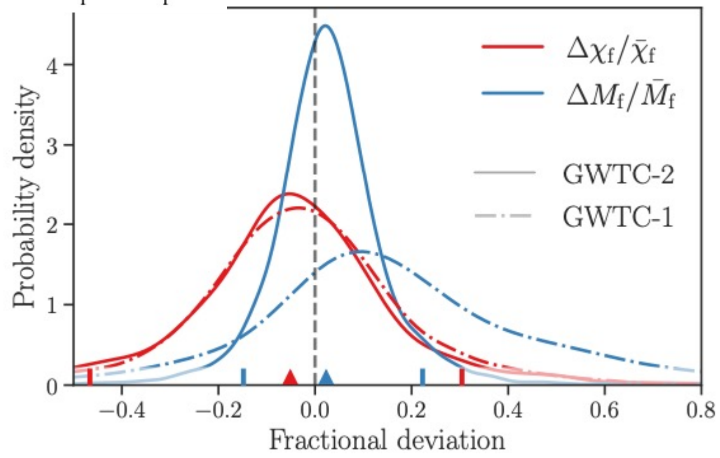
Phys. Rev. D 103, 122002 (2021) (arXiv)

- Tests of GR using 47 CBC from up to GWTC-2 (FAR<1/yr) - no evidence for new physics beyond general relativity
- Parameterised modifications to waveforms (varying post-Newtonian and phenomenological coefficients → constraints ~2x stronger than previous
- Gravitational-wave dispersion → constraints on Lorentz-violating coefficients improved by a factor of ∼2.6, graviton mass $m_g \leq 1.76 \times 10{-}23$ eV/c2 @90%CL.
- Ringdown frequencies, damping times → constrain fractional deviations from the Kerr frequency (fundamental and first overtone), no evidence of post-merger echoes.
- Data consistent with tensorial polarizations (template-independent method).





$$\frac{\Delta M_f}{\bar{M}_f} = 2\frac{M_f^{insp} - M_f^{postinsp}}{M_f^{insp} + M_f^{postinsp}}$$

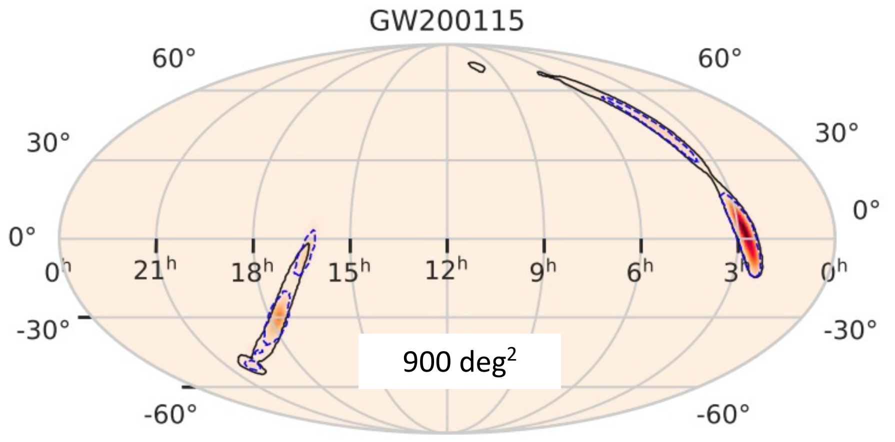


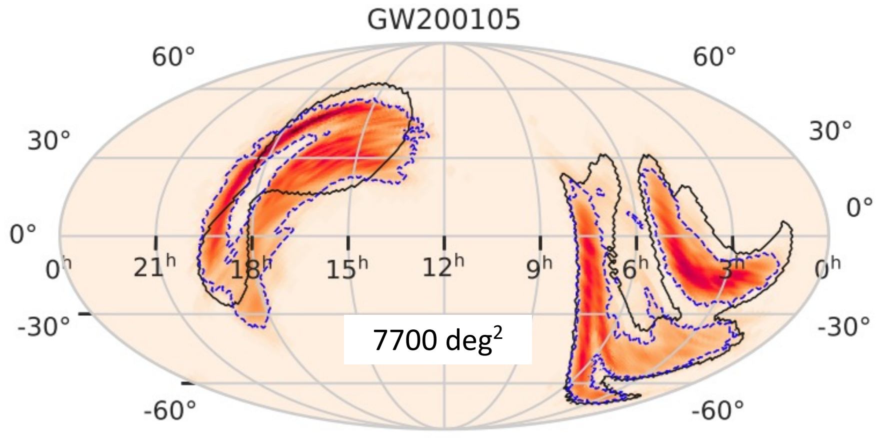
NSBH discovery

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 below limits for NS masses
- Lensing excluded by non-overlapping posterios
- Merger rate consistent with limits from O1 and O2

See Astrid's dedicated talk tomorrow





O3a Sub-solar mass

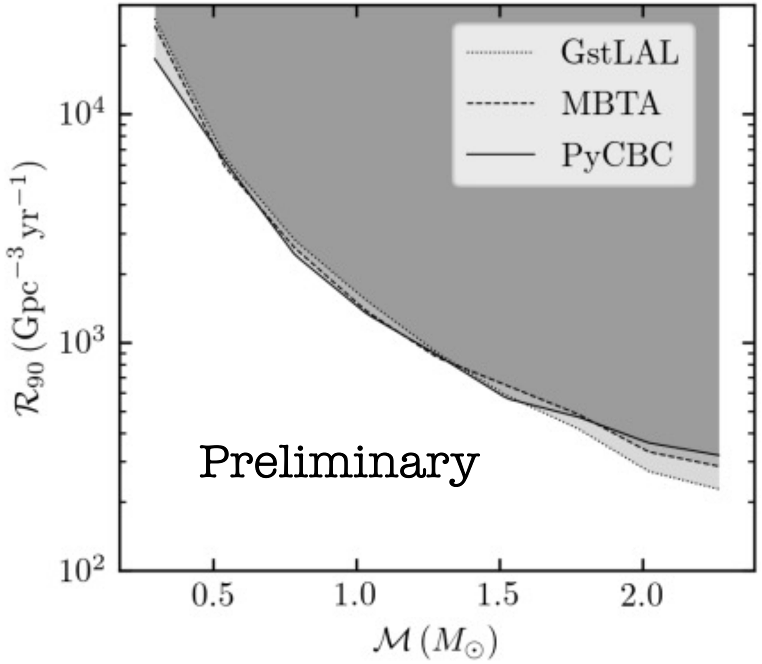
(arXiv)

- Sub-solar compact objects predicted by many models
  - Primordial Black Holes (BHs) from overdensities in early Universe
  - Dissipative Dark Matter (DM)
  - BH from DM accumulation in NS cores
- Observation of astrophysical compact objects with mass<$M_\odot$ would be a clear sign of new physics
- Duration up to ~450s (low frequency cut-off 45 Hz)
- x~2 number of templates wrt standard search
- Inspiral-only waveforms, with phase terms up to 3.5PN and no amplitude corrections
- No observation → constraint on the merger rate
- Interpretation in two models

$$0.2 < m_1 < 10 \quad 0.2 < m_2 < 1$$

$$0.1 < \frac{m_2}{m_1} < 1$$

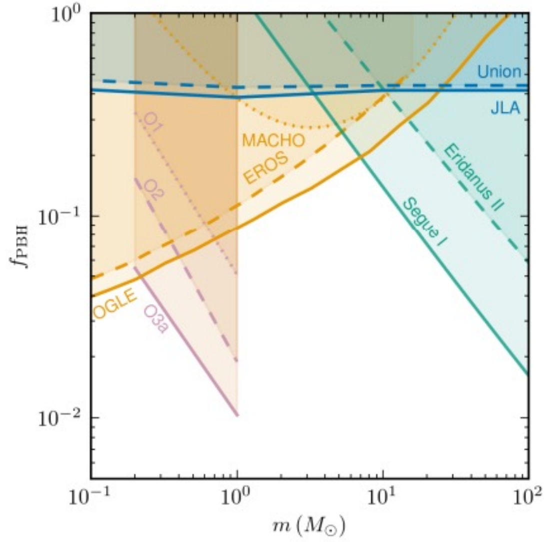
$$|\chi_i| < 0.1(0.9) \text{ if } m_i < 0.5 \text{ (otherwise)}$$



O3a Sub-solar mass: interpretations

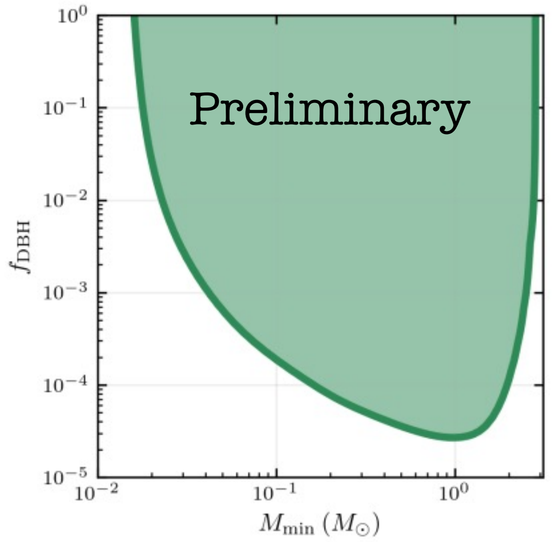
Phenomenological model from [Phys.Rev. D58 (1998) 063003]

- single mass PBH, randomly distributed in space
- Merger rate depends on the abundance of PBH, parametrised as a fraction of the dark matter density
- Fraction of DM in PBH f_{PBH}<5% for same-mass PBH with mass in [0.2,1]



Dissipative DM model from [Phys. Rev. Lett. 120, 051102 (2018)], with eccentricity ~1 approximation of the formulas from [Phys. Rev. 136, B1224])

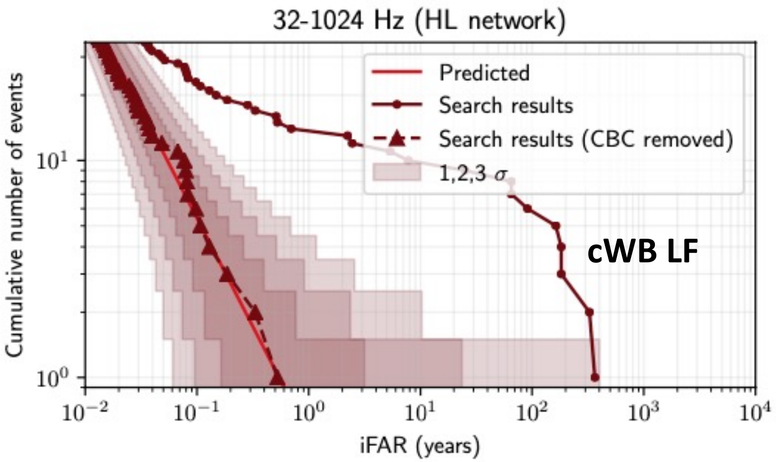
- Two dark fermions + 1 massless dark photon
- DM can form bound states, dissipate energy by radiation and collapse to form a BH
- Power-law distribution for BH masses (unknown cutoff M_{min})
- Upper limit (function of M_{min}) on the fraction of DM that ends up in BH
- Lowest upper limit : f_{DBH}<0.002% (M_{min} = 1$M_{\odot}$)

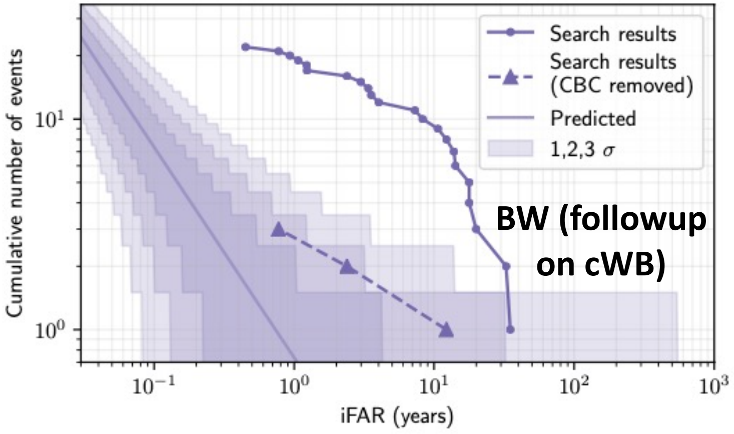


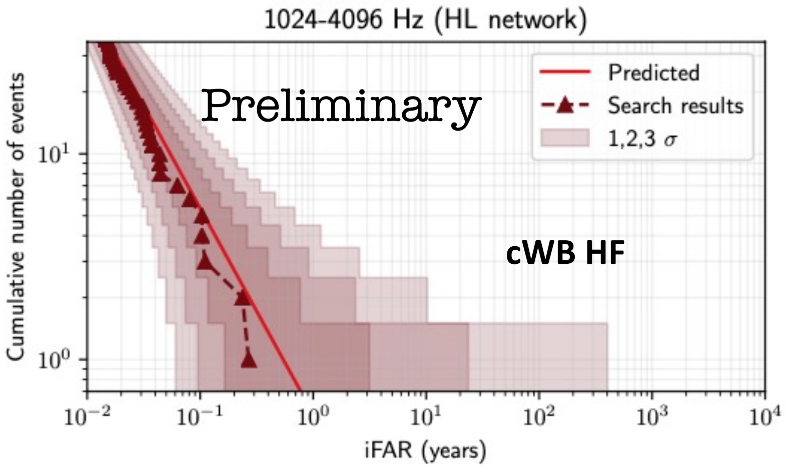
O3 Search for short GW bursts

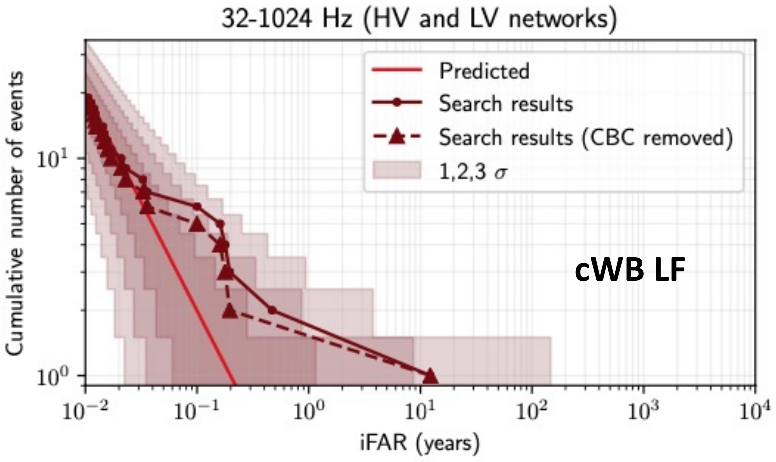
(arXiv)

- Transient [ms-s] GW signals in [24–4096] Hz, no assumption on signal morphology
- **Coherent WaveBurst (cWB)** ML ratio statistic applied to excesses of signal power in time–frequency. Wilson–Daubechies–Meyer wavelet transform with multiple resolutions, to adapt to signal features. Low and high frequency analysed separately. Cut on network correlation coefficient.
- **BayesWaves (BW)** Bayesian algorithm modelling GW signals and non-Gaussian noise transients as sums of sine-Gaussian wavelets. Detection statistic used is Bayes factor between signal+noise and noise only. Computationally very expensive – used to follow up on subset of dataset judged interesting by cWB, to better assess significance of candidates





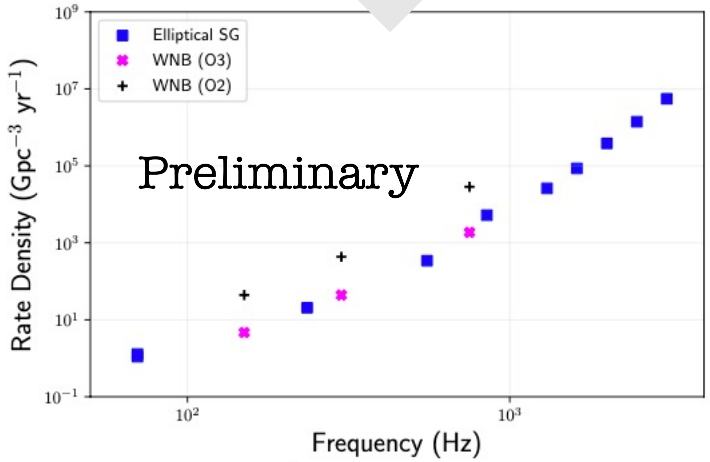


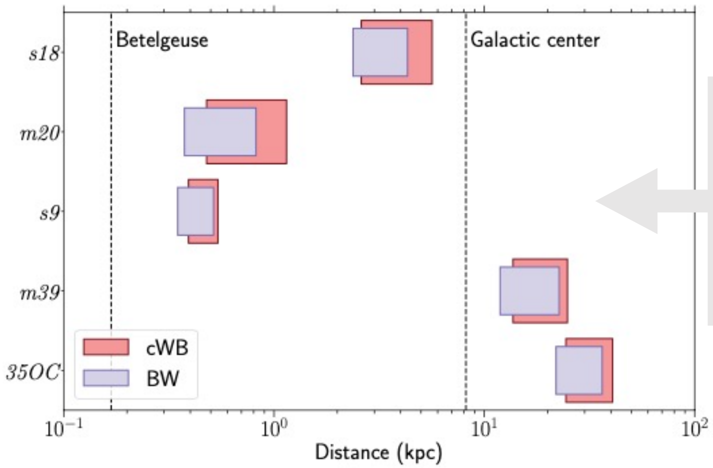


O3 Search for short GW bursts

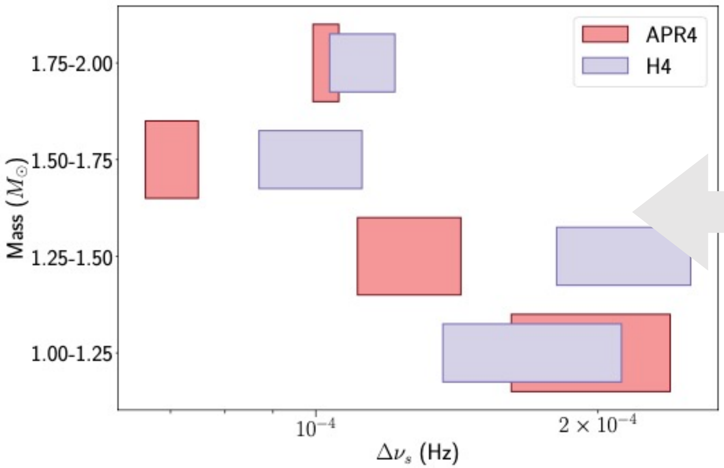
- No GW detection (iFAR>100 yr) beyond the CBC ones
- Sensitivity studies based on simulations
- Generic signal morphologies: sine-Gaussian wavelets (SG), Gaussian pulses (GA), and band-limited white-noise bursts (WNB).
- CCSNe: different models (s18, m10, s9, m39, 35OC) with max distance (25, 5, 5, 70, 70) kpc
- Pulsar glitches (GW bulk emission described by f-mode), Vela Pulsar standard candle. EoS: APR4 (soft) and H4 (hard)

Rate density 90% CL upper limit





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.

★ Search for long bursts (e.g. magnetars), no event with iFAR>50yr factor ~2 sensitivity improvement wrt O2 (see backup)

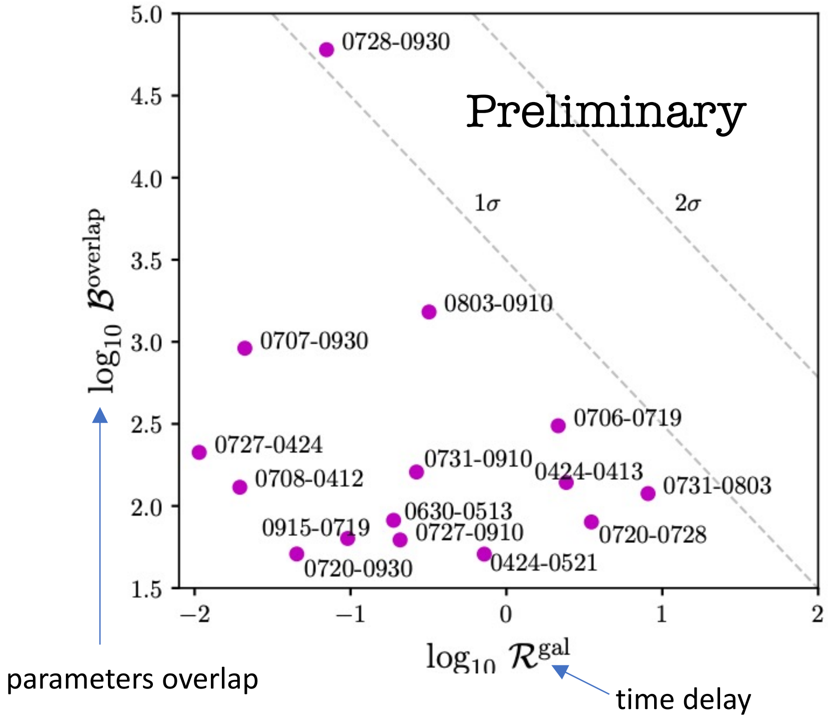
Lensing of O3a BBH

(arXiv)

- Studied high BBH with primary mass>50Msun, GW190425 (high-mass BNS), and GW190426 (low-significance NSBH)
- No robust conclusion based on magnification alone
- 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

- Coherent ratio (lensed/unlensed evidence), weighted by population and selection effects
- 11 GWTC-2 pairs with high parameters consistency, none prefers the lensed hypothesis
- No evidence of multiple images in additional sub-threshold events, or microlensing



All-sky IMBH search

(arXiv)

- cWB, GstLAL, PyCBC. Potential candidates → coherent Bayesian PE (NRSur7dq4, SEOBNRv4PHM, IMRPhenomXPHM - all with HOM and precession). Considered IMBH if :

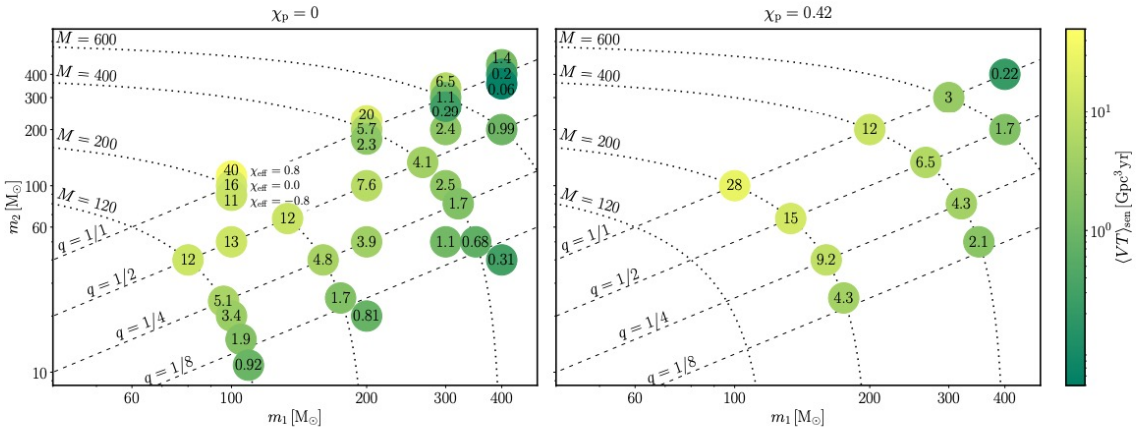
$$\int_{100}^{+\infty} \int_{65}^{+\infty} dm_1 \, dM_f \, p(M_f, m_1 | D, H) \geq 0.9$$

Events	GPS Time	cWB FAR (yr^{-1})	PyCBC FAR (yr^{-1})	GstLAL FAR (yr^{-1})	$\bar{p}$
GW190521	1242442967.5	2.0×10^{-4}	1.4×10^{-3}	1.9×10^{-3}	4.5×10^{-4}
200114_020818 †	1263002916.2	5.8×10^{-2}	$8.6 \times 10^{+2}$	$3.6 \times 10^{+4}$	1.2×10^{-1}
200214_224526	1265755544.5	1.3×10^{-1}	-	-	2.5×10^{-1}

$R = 0.08^{+0.19}_{-0.07} \mathrm{Gpc}^{-3} \mathrm{yr}^{-1}$

Marginally significant, and potentially affected by noise artifacts

- Sensitivity studies through injections campaign, added top the O3 strain data (363.38 days)
- 43 IMBH binary waveforms, over the parameter space studied in O1+O2+O3, M_{tot} up to 800, q in [0.1,1], 4 with aligned spins, 4 with anti-aligned spins, 11 with precessing spins
- NR simulations computed by the SXS, RIT, and GeorgiaTech codes.



O3a GRB

Astrophys. J. 915, 86 (2021) (arXiv)

Search for GW transient associated with GRB (Fermi/Swift)

- 105 GRB analysed (X-Pipeline) + BNS/NSBH specific search (PyGRB) for 32 (out of 105) short GRBs
- 141 GRB GCN notices during O3a from Fermi and Swift→ 105 where enough GW coincident data, of which 105 long (T90+|dT90|>4s) and 32 short (T90+|dT90|<2s) or ambiguous, w/wo z measurement
- **X-pipeline**: excess power coherent in different detectors, max{[T90-dT90, T90+dT90],[-600,60]} around GRB time stamp analysed in [20, 500]. Events = clusters of pixels in time-frequency.
- **PyGRB**: IMRPhenomD, mass in [1.0, 2.8]M for NSs, [1.0, 25.0] M for BHs, |chi|<0.05(0.98) for NS(BH). Data around GRBs timestamps (-5,1)s analysed in [30,1000]Hz, 30-90 minutes around used to establish PSD and build background.
- No GW signal associated to a GRB. Sensitivity determined on simulation

Modeled search (Short GRBs)	BNS	NSBH Generic Spins	NSBH Aligned Spins
D_{90} [Mpc]	119	160	231

Unmodeled search (All GRBs)	CSG 70 Hz	CSG 100 Hz	CSG 150 Hz	CSG 300 Hz
D_{90} [Mpc]	146	104	73	28

Unmodeled search (All GRBs)	ADI A	ADI B	ADI C	ADI D	ADI E
D_{90} [Mpc]	23	123	28	11	33

Not only transient !

- Full O3 all-sky binaries CW arXiv
- Full O3 targeted J0537-6910 CW arXiv
- O3 isotropic stochastic arXiv
- O3 all-sky cosmic strings search arXiv
- O3 directional stochastic arXiv
- Early O3 SN remnants CW arXiv
- O3 constraints on dark photon and dark matter arXiv
- O3 all-sky isolated CW arXiv
- O3 twenty AMXPs CW arXiv

Conclusions

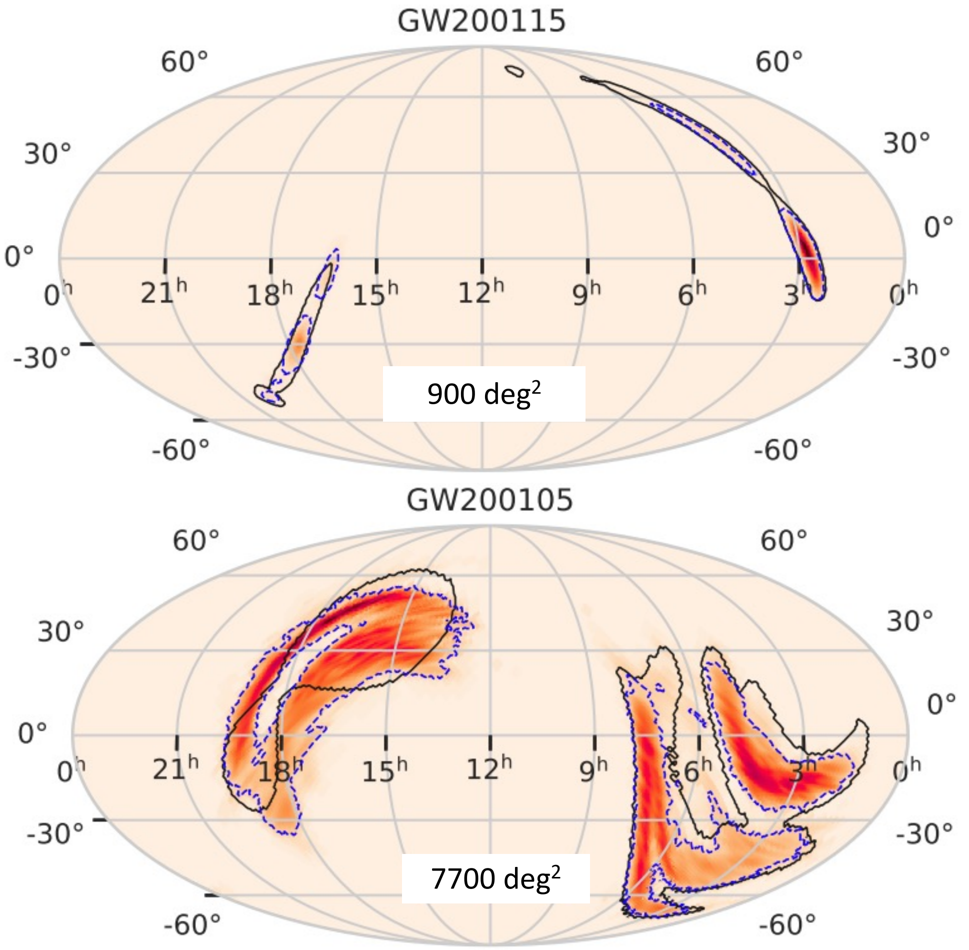
- O3 big success for the LIGO-Virgo collaboration
- 1 year run with 3-interferometers network. Efficient operation, detector characterisation and noise handling. Automatic alerts.
- Many varied scientific results
- 44 high-probability CBC candidates from O3a
- Unfortunately no EM counterpart observed until now
- Constraints on sources populations and rates, tests of GR
- Searches performed for (non-CBC) bursts, CW emission, SGWB, DM..
- Although no evidence (other than CBC) for the moment, sensible improvements in constraints
- Some results already on full O3, many other results from O3b coming soon

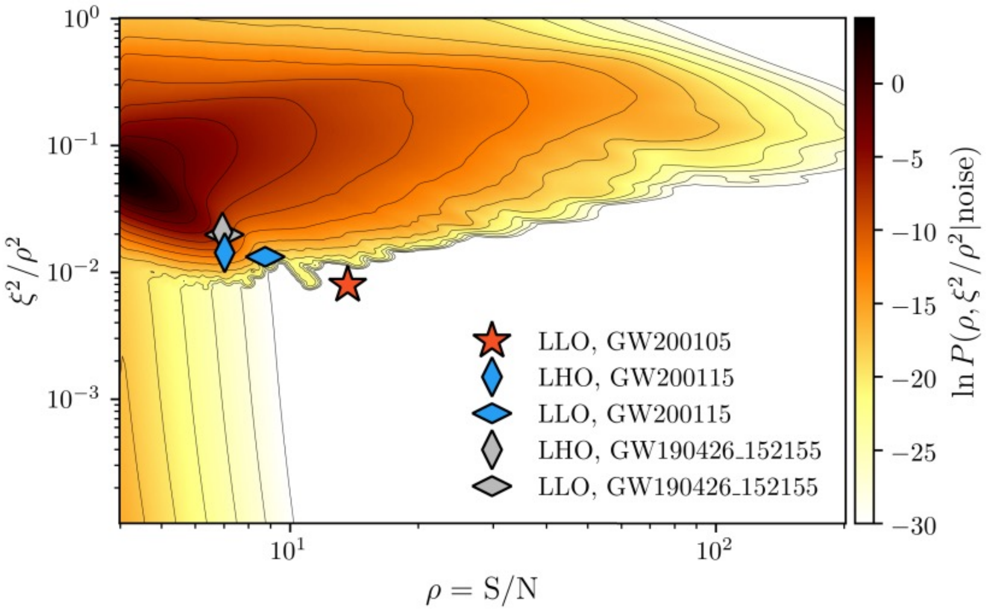
Backup

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}



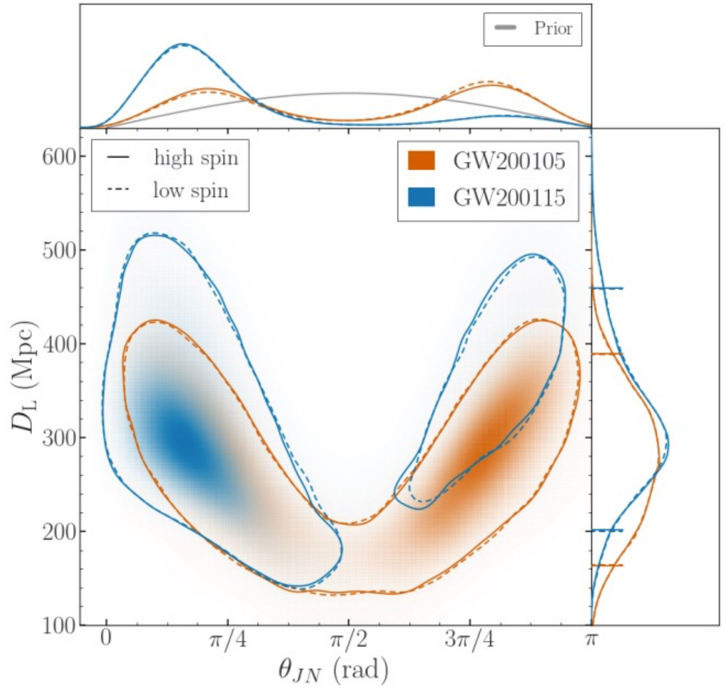


Event		GstLAL	MBTA	PyCBC	SPIIR
GW200105	low-latency	13.9	13.3	13.2*	13.2
	offline	13.9	13.4	13.1*	–
GW200115	low-latency	11.4	11.4	11.3	11.0
	offline	11.6	11.2	10.8*	–

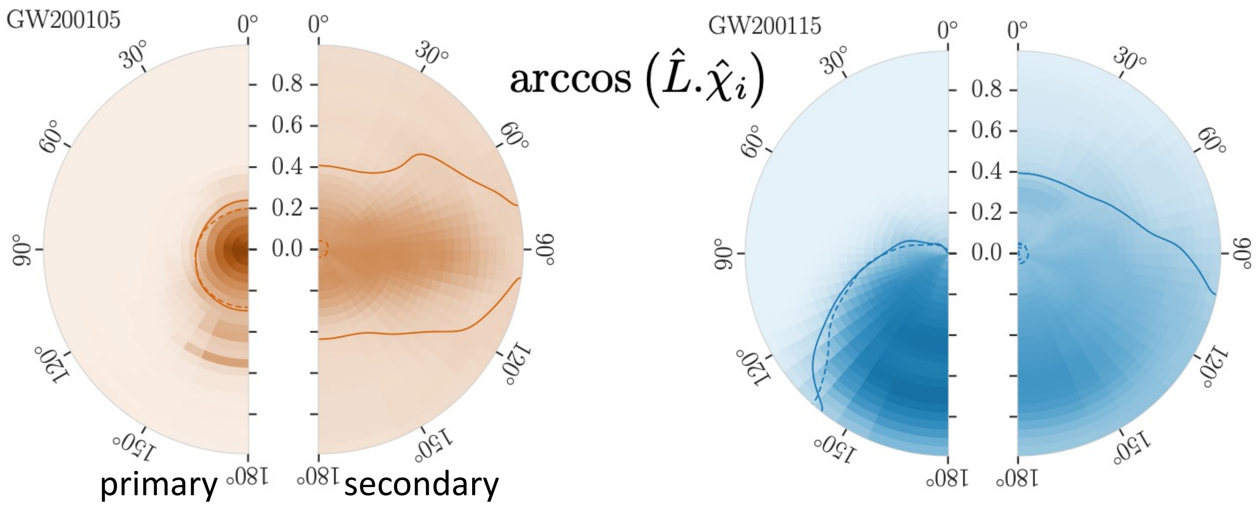
NSBH parameters

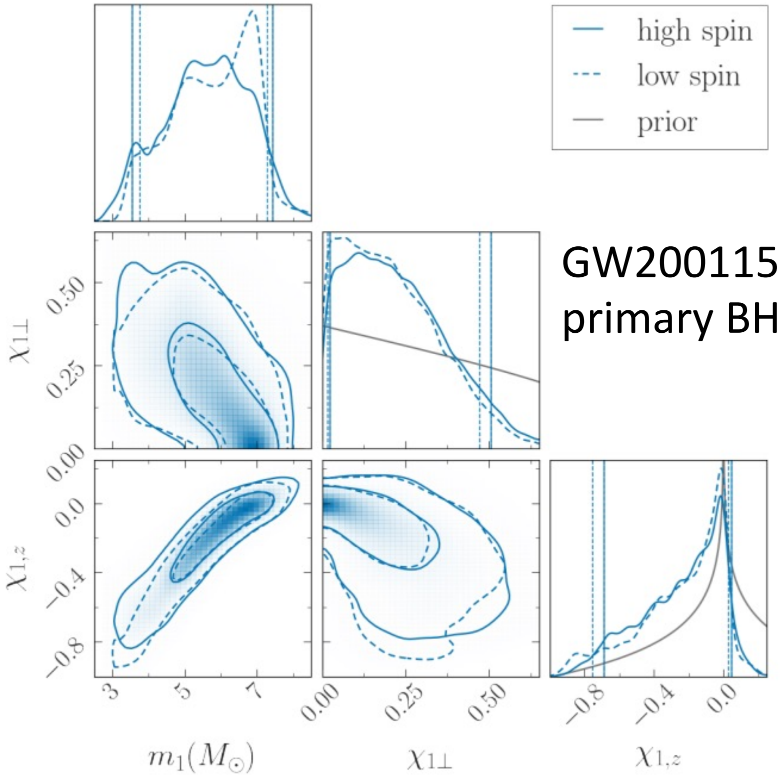
- Coherent Bayesian analysis of 32s of data for GW200105 and 64s for GW200115
- IMRPhenomXPHM, SEOBNRv4PHM
- Spin-induced orbital precession and higher order multipole GW moments, no tidal effects (checked)
- PBILBY+DINESTY (RIFT, LALInference)
- NS low-spin prior (galactic BNS), agnostic high-spin prior
- Standard flat ΛCDM cosmology (H_0=67.9kms^{-1}Mpc^{-1}, Ω_m=0.3065)

	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$



NSBH parameters



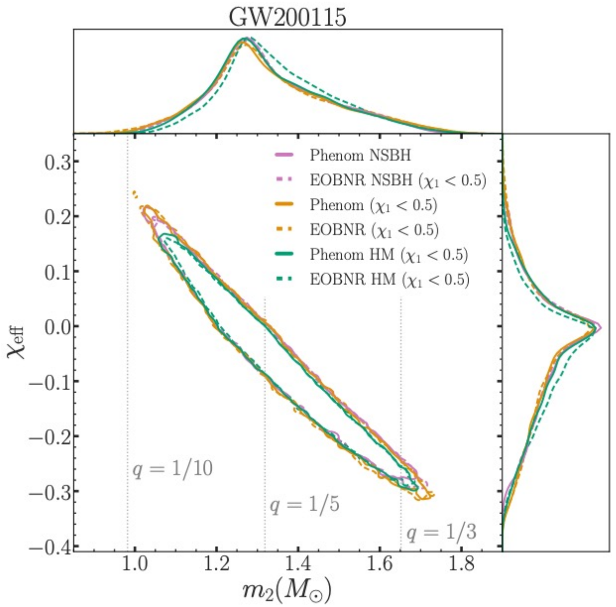


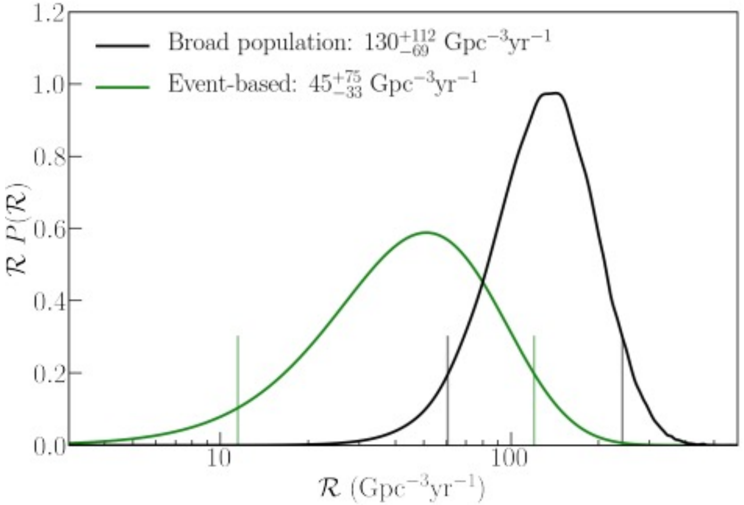
GW200115
primary BH

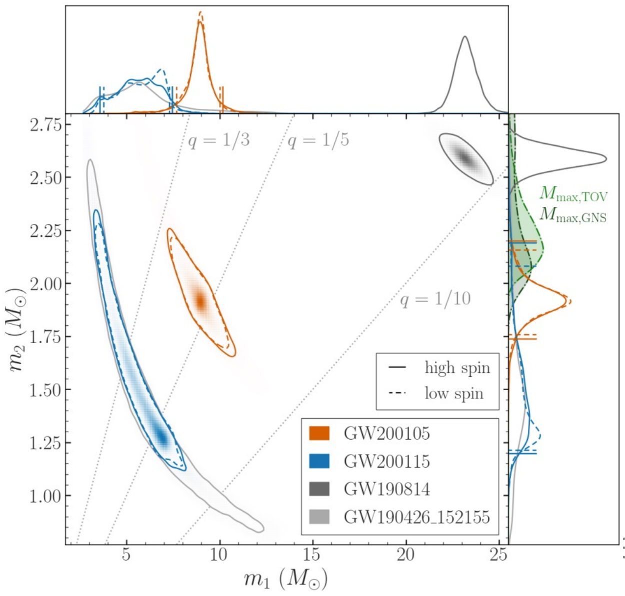
- GW200105 spin strongly peaked about zero
- GW200115 negative effective inspiral spin
- GW200115 BH spin negatively aligned with respect to the orbital angular momentum, correlated with smaller m1 → dynamical formation? No formation process is excluded.
- Compare precessing and non-precessing models → no evidence of precession (not a surprise given inclination and SNR)

NSBH interpretation

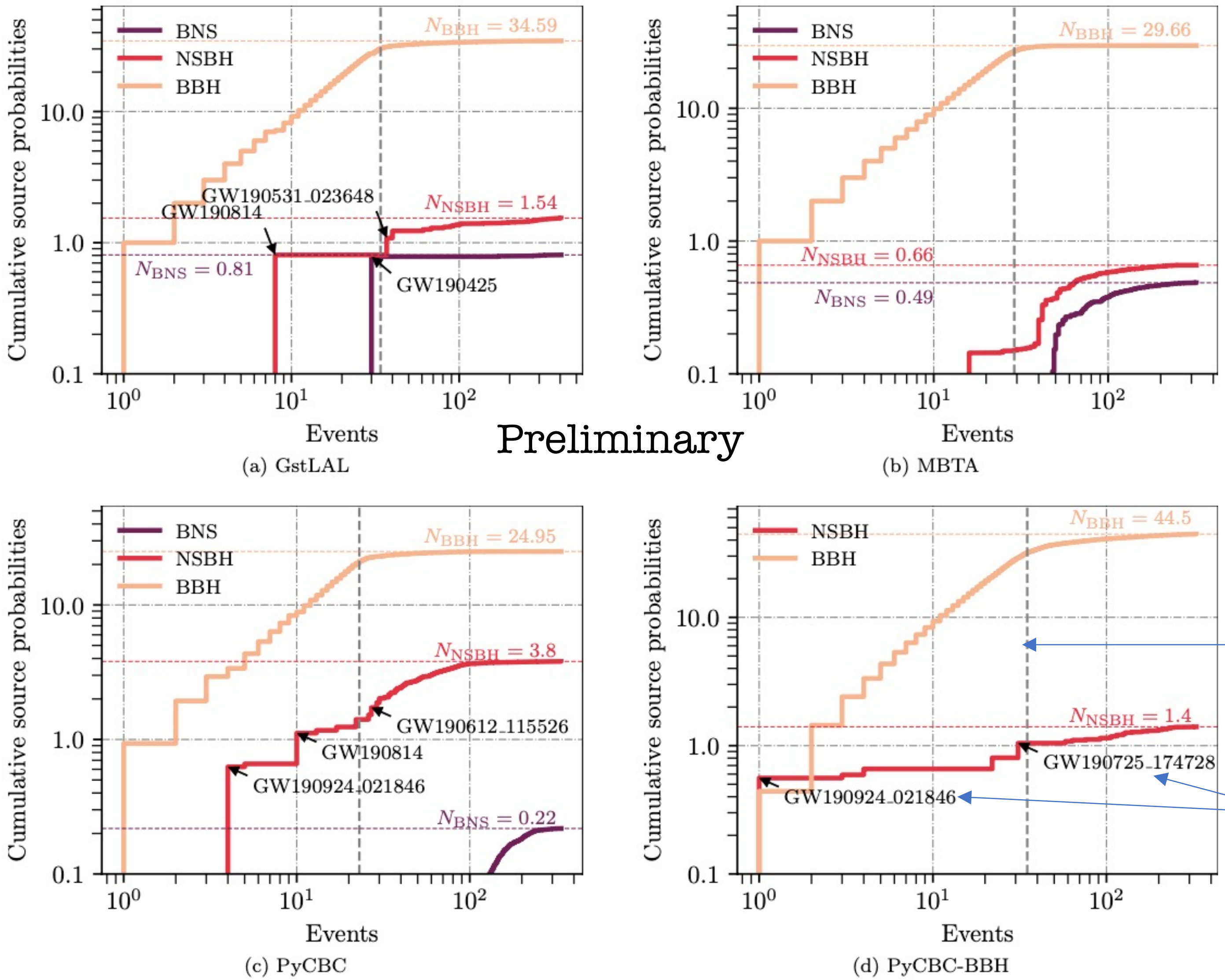
- Remnant properties, post-merger, testing GR – too small SNR to get useful constraints. No constraint on tidal deformabilities of secondary objects (no tidal disruption expected)
- Waveforms systematics (precession and higher-order modes have more impact than tidal)
- Secondary objects masses below limits for NS masses (for non-rotating NS and Galactic NS)
- Lensing excluded by non-overlapping posteriors
- Merger rate (based on the only two events, or on a larger population of less significant triggers with m_1 in[2.5,40] and m_2 in [1,3]), is consistent with limits from O1 and O2







GWTC-2.1 – Candidates



- 1201 candidates with FAR<2/day in ANY of the search pipelines
- Poisson rates of sources with FAR<2/day (ranges showing spread of different pipelines results)
  - 24.95 - 44.50 BBH
  - 0.66 - 3.80 NSBH
  - 0.22 – 0.81 BNS

Least significant candidate with pastro>0.5

Events with p_{BNS} or p_{NSBH}>0.2

GWTC-2.1 – Candidates

- List of candidates with non zero pBNS or pNSBH

Name	MBTA				GstLAL				PyCBC				PyCBC-BBH		
	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{BNS}	p_{astro}	p_{BBH}	p_{NSBH}	p_{astro}
GW190425_081805	–	–	–	–	0.00	0.00	0.78	0.78	–	–	–	–	–	–	–
GW190707_093326	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.93	0.07	0.00	1.00	0.93	0.07	1.00
GW190720_000836	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.95	0.05	0.00	1.00	1.00	0.00	1.00
GW190725_174728	0.59	0.00	0.00	0.59	–	–	–	–	0.79	0.17	0.00	0.96	0.58	0.24	0.82
GW190728_064510	1.00	0.00	0.00	1.00	1.00	0.00	0.00	1.00	0.97	0.03	0.00	1.00	0.97	0.03	1.00
GW190814_211039	0.93	0.07	0.00	1.00	0.19	0.81	0.00	1.00	0.54	0.46	0.00	1.00	–	–	–
GW190924_021846	0.92	0.07	0.00	0.99	1.00	0.00	0.00	1.00	0.44	0.56	0.00	1.00	0.44	0.56	1.00
GW190930_133541	0.87	0.00	0.00	0.87	0.76	0.00	0.00	0.76	0.93	0.07	0.00	1.00	0.85	0.15	1.00

GWTC2 and 2.1 parametes space

GstLAL
TaylorF2 is mchirp<1.73, SEOBNRv4_ROM otherwise
(anti-)aligned spins with |chi|<0.05 if m<2, 0.999 otherwise

mm	m_1	m_2	M	q	$\chi_{1,z}$	$\chi_{2,z}$	$f_{\min}$(Hz)
0.99	$1,3$	$1,3$	<6	$0.33,1$	low	low	15
0.97	$3,150$	$1,3$	<153	$0.02,1$	high	low	15
0.99	$3,91$	$3,50$	<100	$0.1,1$	high	high	15
0.97	$30,392$	$3,36$	<400	$0.02,0.1$	high	high	15
0.99	$50,400$	$9,400$	>100	$0.1,1$	high	high	10

MBTA
m1 in [1,195], m2 in [2,195] with mtot<200
m1 in [1,100], m2 in [1,2]
(anti-)aligned spins with |chi|<0.05 if m<2, 0.997 otherwise
TaylorF2 if m1 and m2<2 and SEOBNRv4_ROM otherwise

Region	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\lvert\chi_{1,z}\rvert_{\max}$	$\lvert\chi_{2,z}\rvert_{\max}$	f_0 (Hz)	f_c (Hz)	Waveform (bank)	Waveform (analysis)
1	[1;2]	[1;2]	0.05	0.05	25	80	TaylorF2	SpinTaylorT4
2	[1;2]	[2:100]	0.05	0.997	23	85	SEOBNRv4_ROM	SEOBNRv4
3	[2;195]	[2:195]	0.997	0.997	23	85	SEOBNRv4_ROM	SEOBNRv4
	$(m_1+m_2) < 200\,\mathrm{M}_\odot$							

PyCBC
TaylorF2 if Mtot<4, SEOBNRv4_ROM otherwise
(anti-)aligned spins with |chi|<0.05 if m<2, 0.998 otherwise

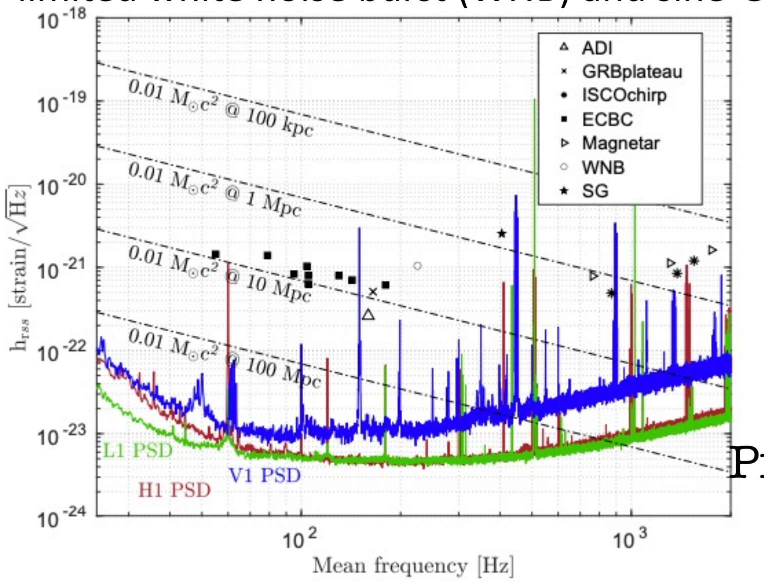
Class	Masses ($M_\odot$)	Aligned spins	Waveform model
BNS	$m_{1,2} \in [1,3]$	$\chi_{1,2} \in [\pm 0.05]$	Post-Newtonian
NSBH	$m_1 \in [2,50]$ $m_2 \in [1,3]$	$\chi_1 \in [\pm 1]$ $\chi_2 \in [\pm 0.05]$	Effective-one-body
BBH	$m_{1,2} > 3$ $M < 100$	$\chi_{1,2} \in [\pm 1]$	Effective-one-body
BBH	$M \in [100,500]$ $q \in [1,10]$	$\chi_{1,2} \in [\pm 1]$	Effective-one-body

Combined key	Waveform name	Precession	Multipoles $(\ell, \|m\|)$
ZeroSpinIMR*	IMRPhenomD	×	(2, 2)
AlignedSpinIMR	SEOBNRv4_ROM	×	(2, 2)
AlignedSpinIMRHM	IMRPhenomHM	×	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3)
	SEOBNRv4HM_ROM	×	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)
PrecessingSpinIMR	SEOBNRv4P	✓	(2, 2), (2, 1)
	IMRPhenomPv2	✓	(2, 2)
PrecessingSpinIMRHM	IMRPhenomPv3HM	✓	(2, 2), (2, 1), (3, 3), (3, 2), (4, 4), (4, 3)
	NRSur7dq4	✓	$\ell \leq 4$
	SEOBNRv4PHM	✓	(2, 2), (2, 1), (3, 3), (4, 4), (5, 5)
AlignedSpinTidal†	IMRPhenomD_NRTidal	×	(2, 2)
	TEOBResumS	×	(2, 2)
	SEOBNRv4T_surrogate	×	(2, 2)
PrecessingSpinIMRTidal†	IMRPhenomP_NRTidal	✓	(2, 2)
AlignedSpinInspiralTidal†	TaylorF2	×	(2, 2)
AlignedSpinIMRTidal_NSBH	SEOBNRv4_ROM_NRTidalv2_NSBH	×	(2, 2)
	IMRPhenomNSBH	×	(2, 2)

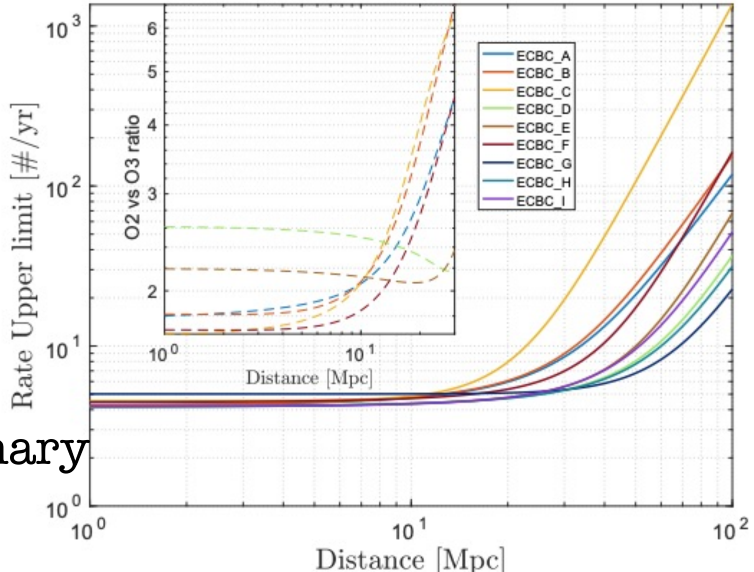
O3 Search for long GW bursts

(arXiv)

- Transient [2-500]s GW signals in [24–2048] Hz, no assumption on signal morphology
- Stochastic Transient Analysis Multidetector Pipeline - all sky (**STAMP-AS** Zebragard, seed-based and Lonetrack, seedless), **cWB** (long-duration config)
- No trigger with FAR<1/50 yr-1
- Sensitivity to many different signals is assessed : post-merger magnetars (Magnetar), BH accretion disk instabilities (ADI), newly formed magnetar powering a gamma-ray burst plateau (GRBplateau) [16], eccentric inspiral-merger-ringdown CBC waveforms (ECBC), broadband chirps from innermost stable circular orbit waves around rotating BH (ISCOchirp), band-limited white noise burst (WNB) and sine-Gaussian bursts (SG).



Preliminary



Factor ~2 improvement wrt O2

More expected for O4 !

All-sky IMBH search

(arXiv)

- cWB: minimal assumptions on signal morphology, multi-resolution wavelet transform in time-frequency pixels, signal-dependent vetoes to remove noise artifacts
- GstLAL: fmin 10Hz, SEOBNRv4, mtot in [50, 600], q in [0.1,1], (anti-)aligned spins (mag<0.98) . Signal consistency, penalty on significance for triggers in noisy periods. Also considers single-detector triggers.
- PyCBC: fmin 15 Hz, SEOBNRv4, mtot in [100, 600], q in [0.1,1], spins (projected mag<0.998). Gating, signal consistency, penalty on significance for triggers in noisy periods. VT sensitivity wrt BBH focussed search similar for redshifted total mass of 100, but up to a factor ~12 higher (for redshifted total mass of 600)
- Potential candidates → coherent Bayesian parameter estimation analysis (NRSur7dq4, SEOBNRv4PHM, IMRPhenomXPHM - all with higher-order multipole moments and orbital precession)

$$\int_{100}^{+\infty}\int_{65}^{+\infty} dm_1\, dM_{\mathrm{f}}\, p(M_{\mathrm{f}}, m_1|D, H) \geq 0.9$$

Events	GPS Time	cWB FAR (yr^{-1})	PyCBC FAR (yr^{-1})	GstLAL FAR (yr^{-1})	$\bar{p}$
GW190521	1242442967.5	2.0×10^{-4}	1.4×10^{-3}	1.9×10^{-3}	4.5×10^{-4}
200114_020818 †	1263002916.2	5.8×10^{-2}	$8.6\times10^{+2}$	$3.6\times10^{+4}$	1.2×10^{-1}
200214_224526	1265755544.5	1.3×10^{-1}	-	-	2.5×10^{-1}

Update on merger rate:
$R = 0.08^{+0.19}_{-0.07}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Marginally significant, and potentially affected by noise artifacts

All-sky IMBH search

- Sensitivity studies through injections campaign, added top the O3 strain data (363.38 days)
- 43 IMBH binary waveforms, over the parameter space studied in O1+O2+O3, M_{tot} up to 800, q in [0.1,1], 4 with aligned spins, 4 with anti-aligned spins, 11 with precessing spins
- NR simulations computed by the SXS, RIT, and GeorgiaTech codes.