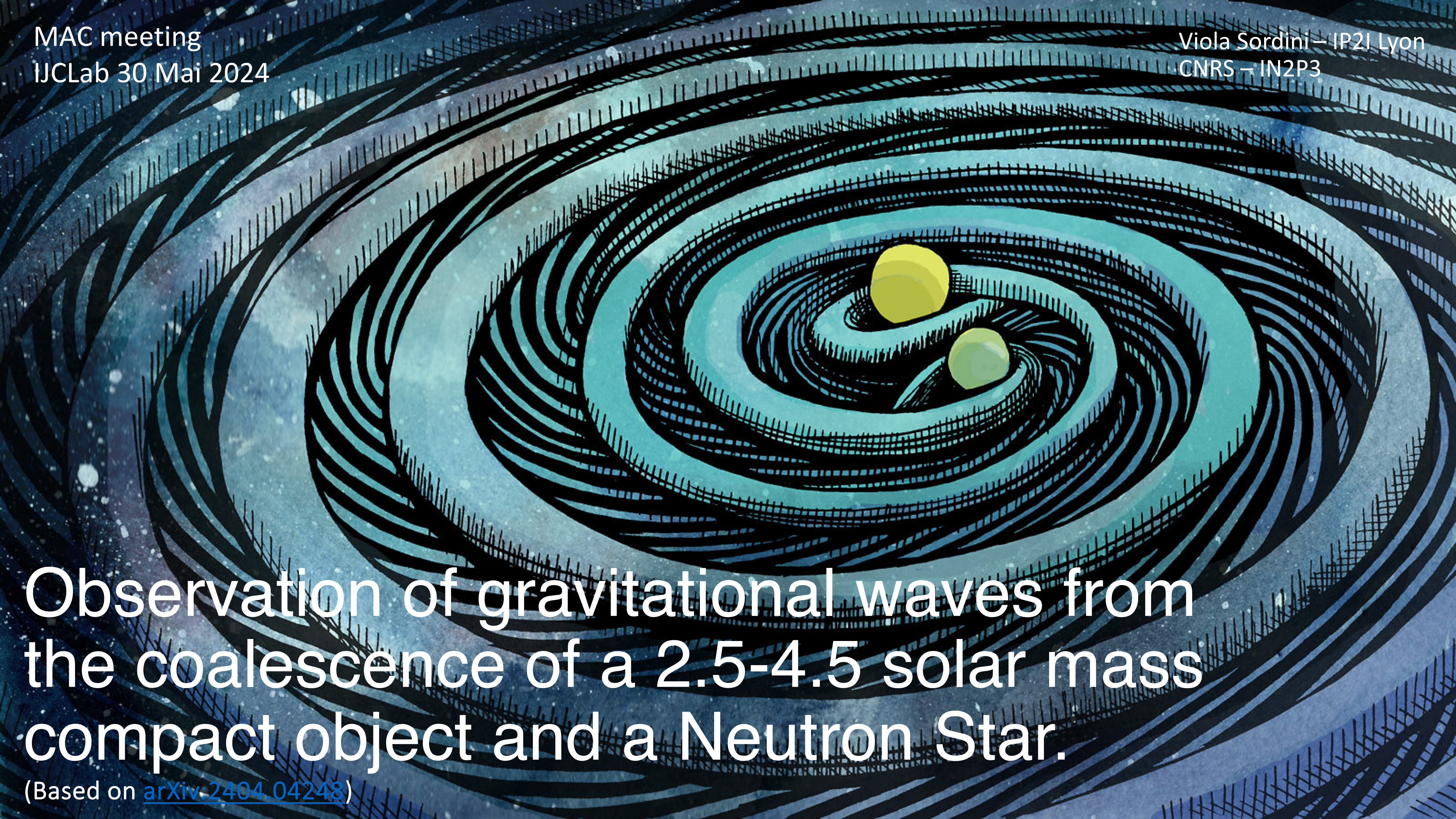
MAC meeting
IJCLab 30 Mai 2024

Viola Sordini – IP2I Lyon
CNRS – IN2P3



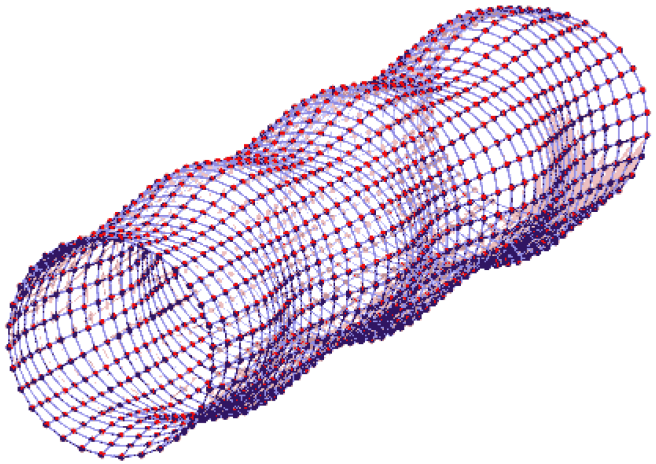
Observation of gravitational waves from the coalescence of a 2.5-4.5 solar mass compact object and a Neutron Star.

(Based on arXiv:2404.04248)

Gravitational Waves

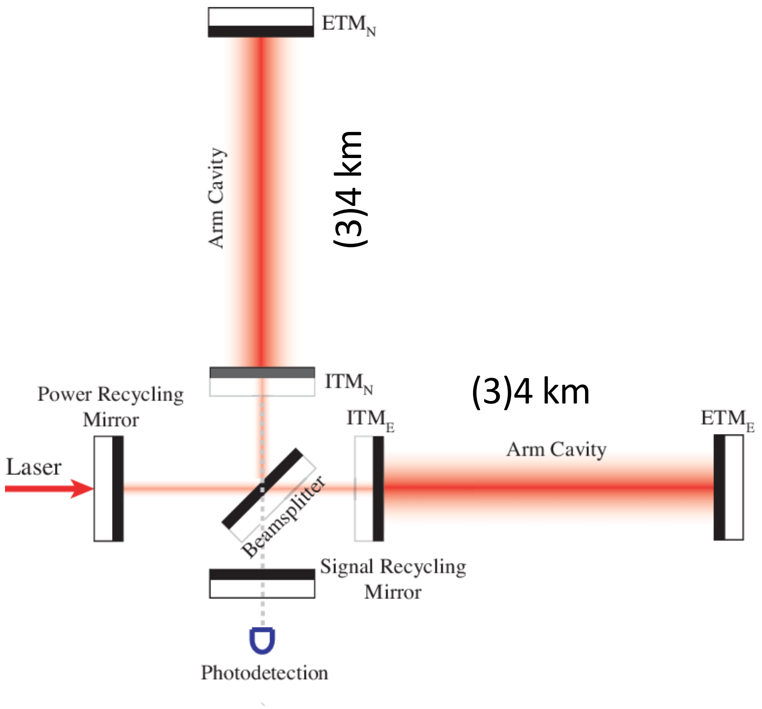
Ripples in the spacetime metric generated by the acceleration of masses, propagating at the speed of light

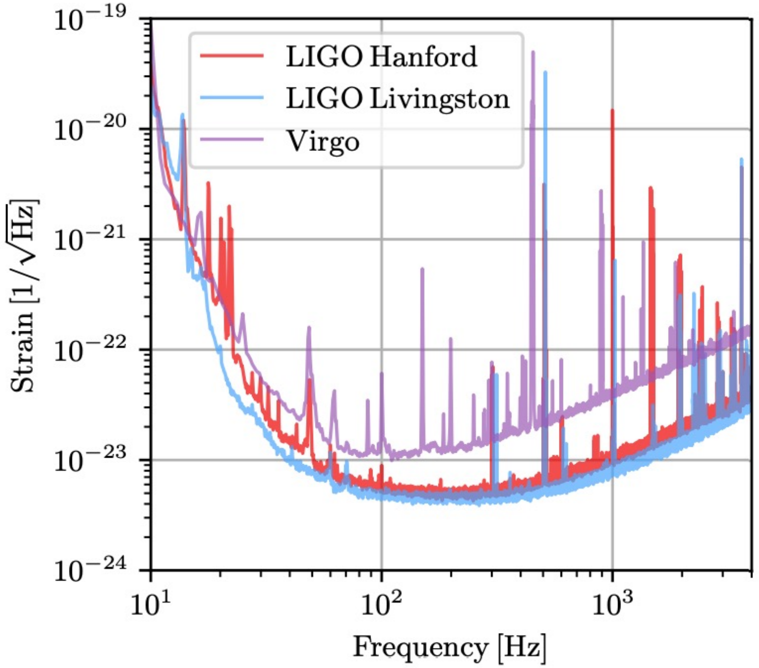
- GW cause the the space itself to stretch/compress
- Predicted by Einstein's General Relativity (1916) - first direct observation 2015 (LIGO)
- Probe gravity in unprecedented conditions, new messenger from the Universe
- Possible sources of detectable GW are some of the most violent events in the Universe involving massive and compact objects in relativistic regime



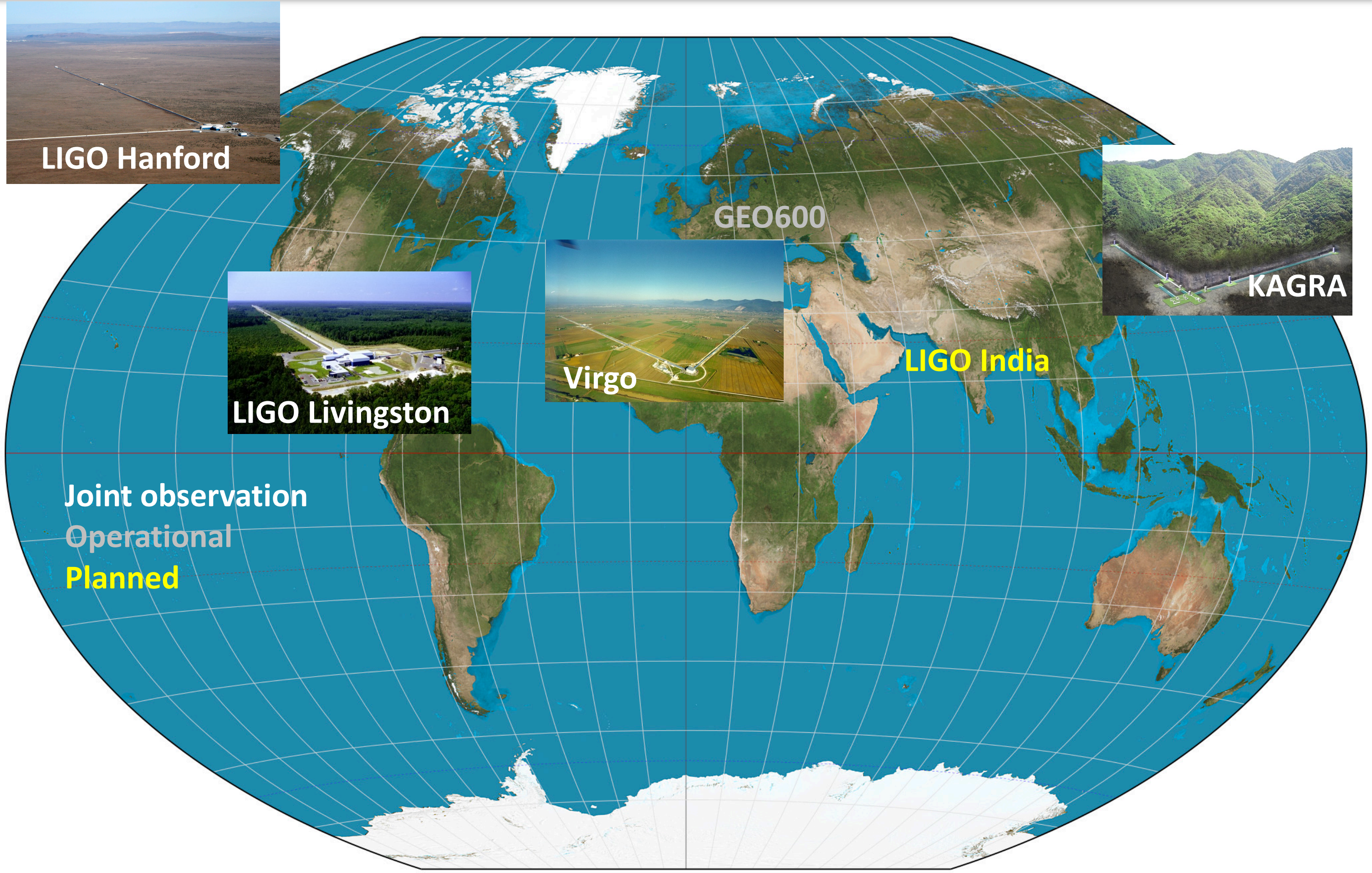
GW terrestrial detectors

- Michelson interferometers with Fabry-Pérot cavities in the arms, operating on dark fringe
- Observable: h(t) – "strain". $\delta L = hL$ → km-long arms ($h \sim 10^{-21}$)
- Sensitive in the ~10Hz – ~kHz frequency band





GW terrestrial detectors

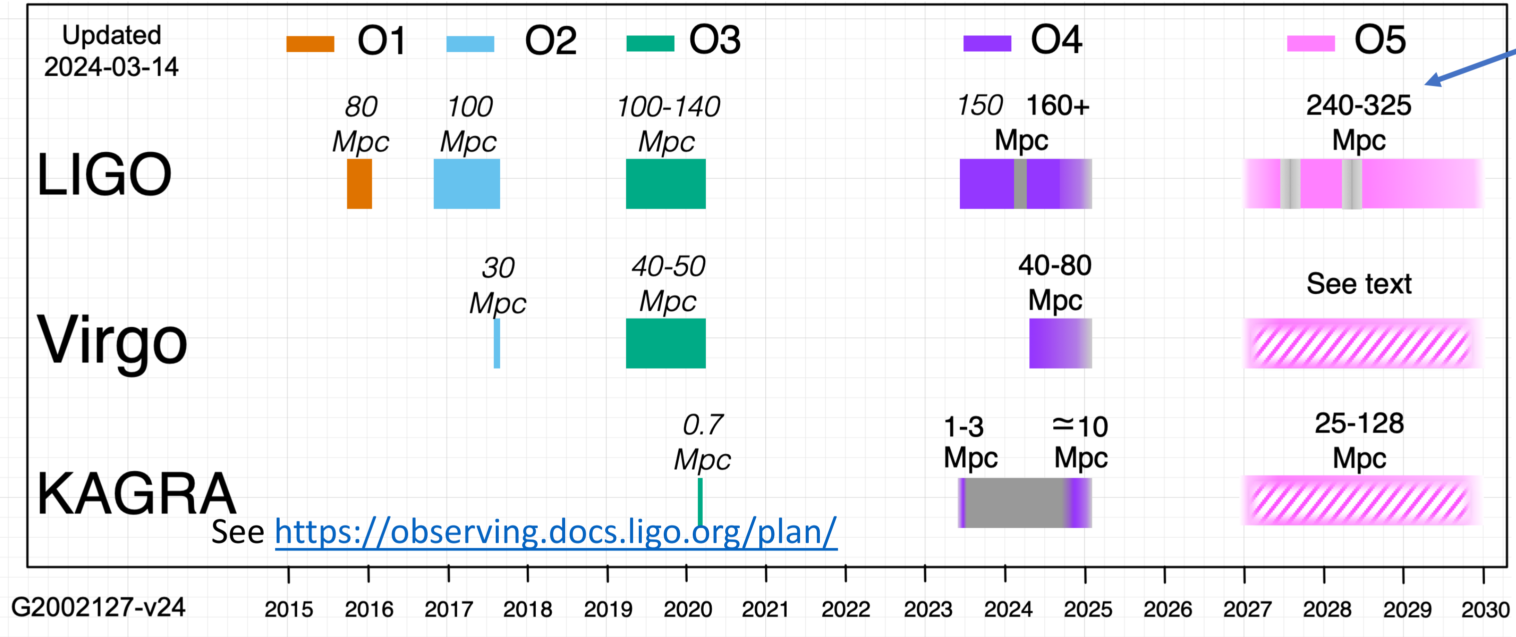


LIGO-Virgo-KAGRA (LVK) network, evolving to IGWN

The LVK network

- O4 ongoing since May 2023, until February(?) 2025
- Data are made public after an embargo period
- Data, results and explanations available on GWOSC

GWOSC

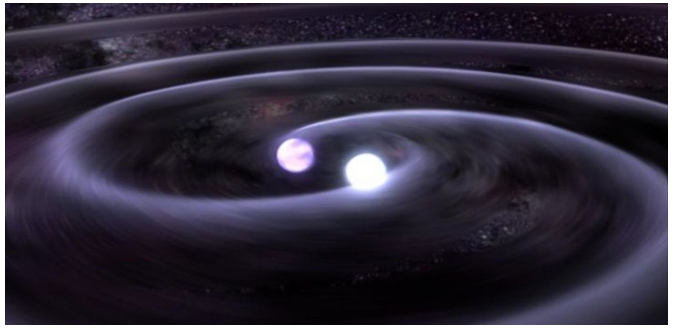


BNS range

LIGO-Virgo-KAGRA physics program

Transient GW signals

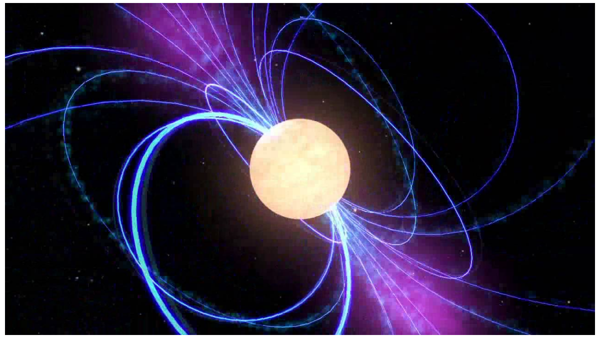
- Compact Binary Coalescences (CBC) – modelled



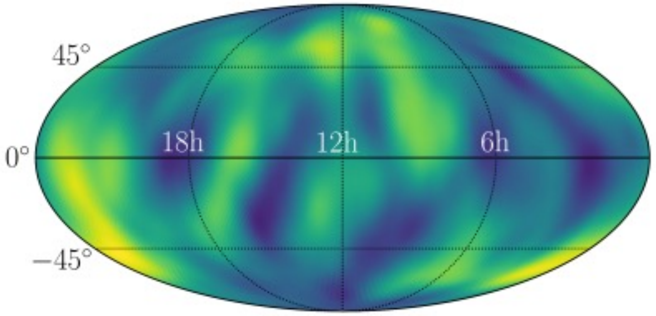
- Other “bursts”, e.g. supernovae - unmodelled

Longer duration GW signals

- Continuous emission from rotating neutron stars



- Stochastic GW background



LIGO Virgo KAGRA physics program

Transient GW signals

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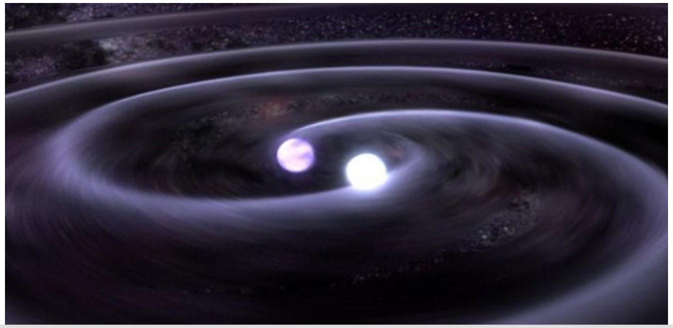

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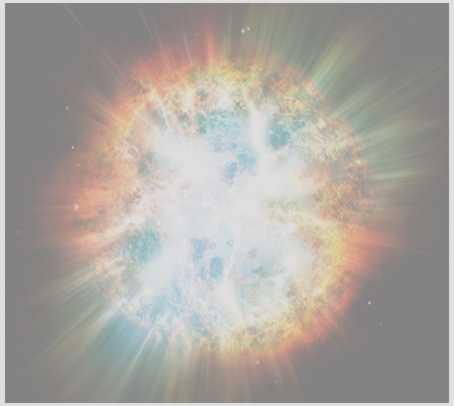

Lo

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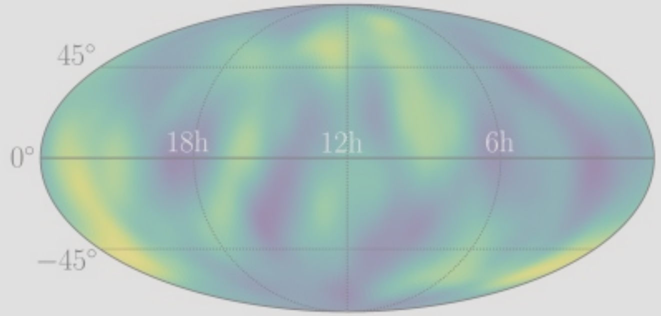
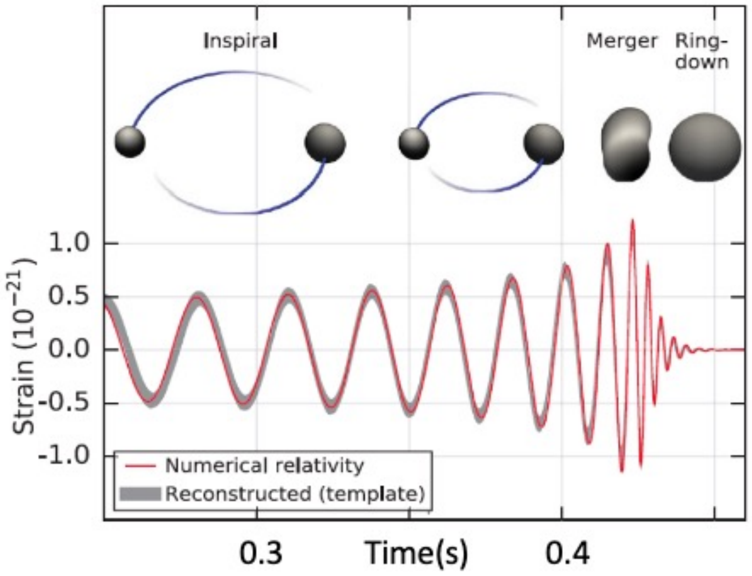
Focus on CBC

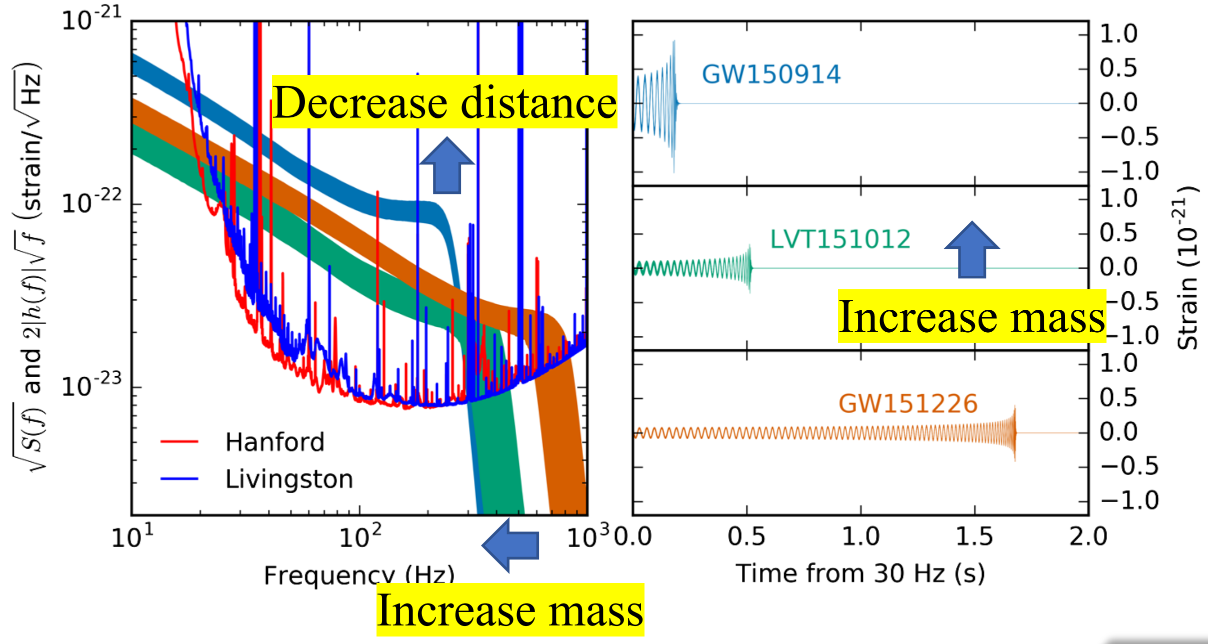
- Coalescences of compact objects (BH, NS)
- 2015: 1st BBH detection
- 2017: 1st BNS detection
- ~90 confirmed events !
- + ~100 alerts since May 2024



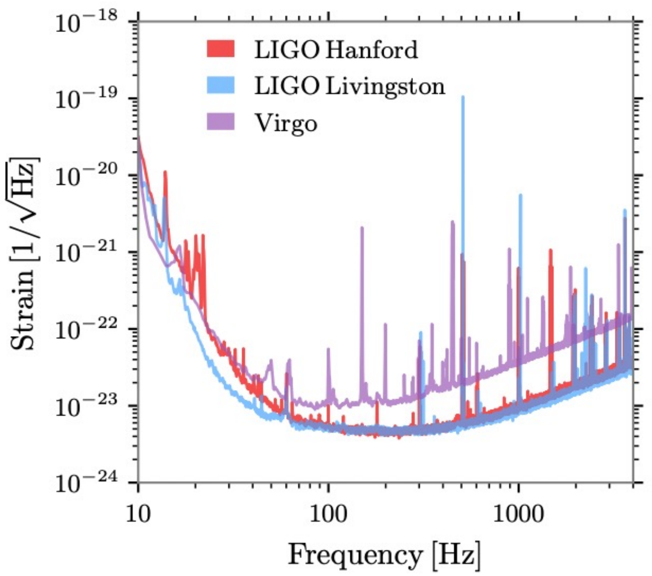
CBC waveforms

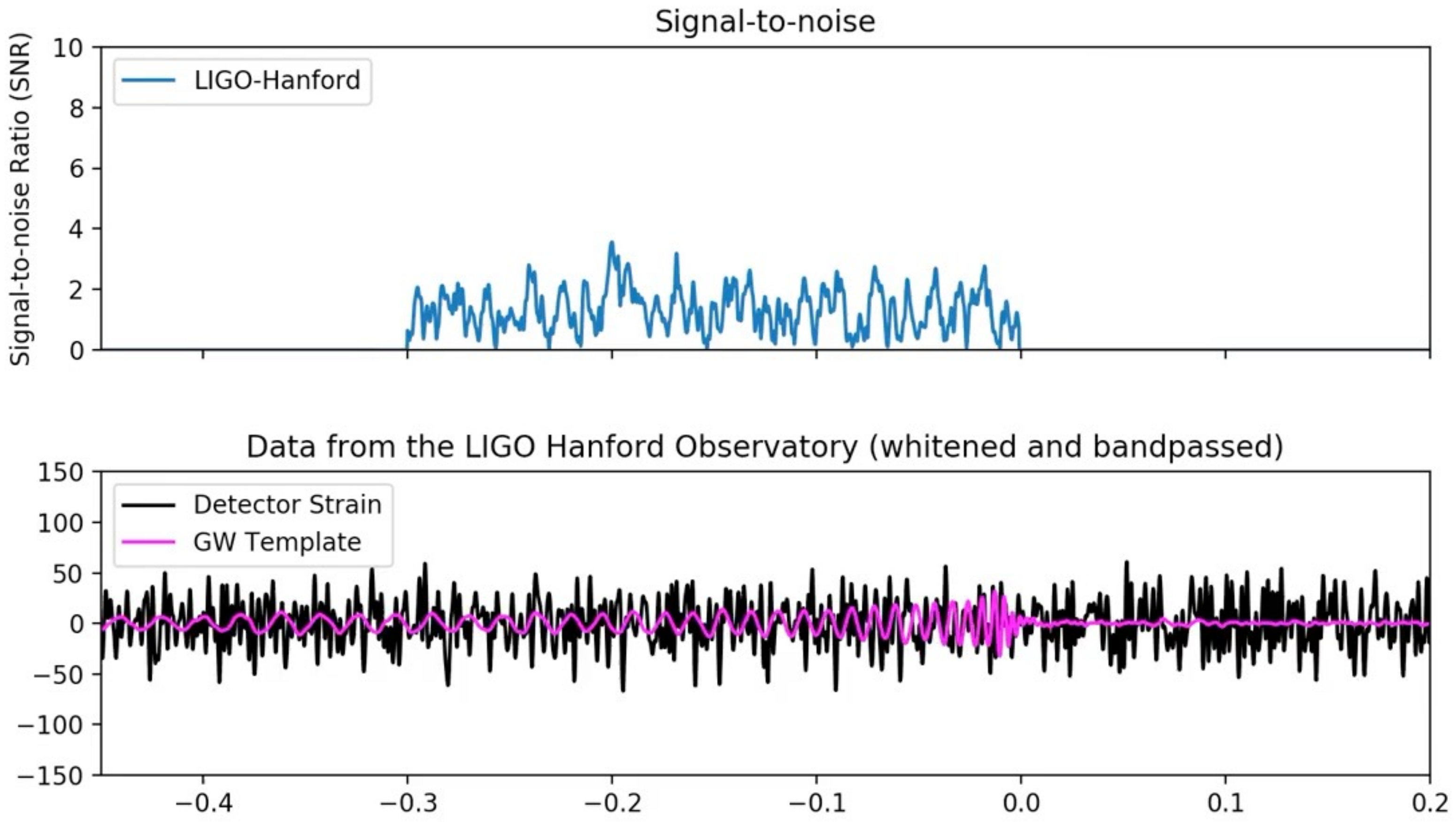
- GW waveforms for Compact Binary Coalescences assume general relativity
- Different techniques (analytic approximation for inspiral, numerical relativity for merger, perturbation theory for ringdown)
- Waveforms are affected by compact objects properties (masses, spins, tidal deformabilities..)
- Amplitude scales (at first approximation) with total **mass** and **inverse of distance**





Model-dependent searches





data

signal template

$$\mathcal{C}(t) = \int_{-\infty}^{\infty} \frac{\tilde{x}(f)\tilde{h}^*(f)}{S_n(f)} e^{2\pi i f t} df$$

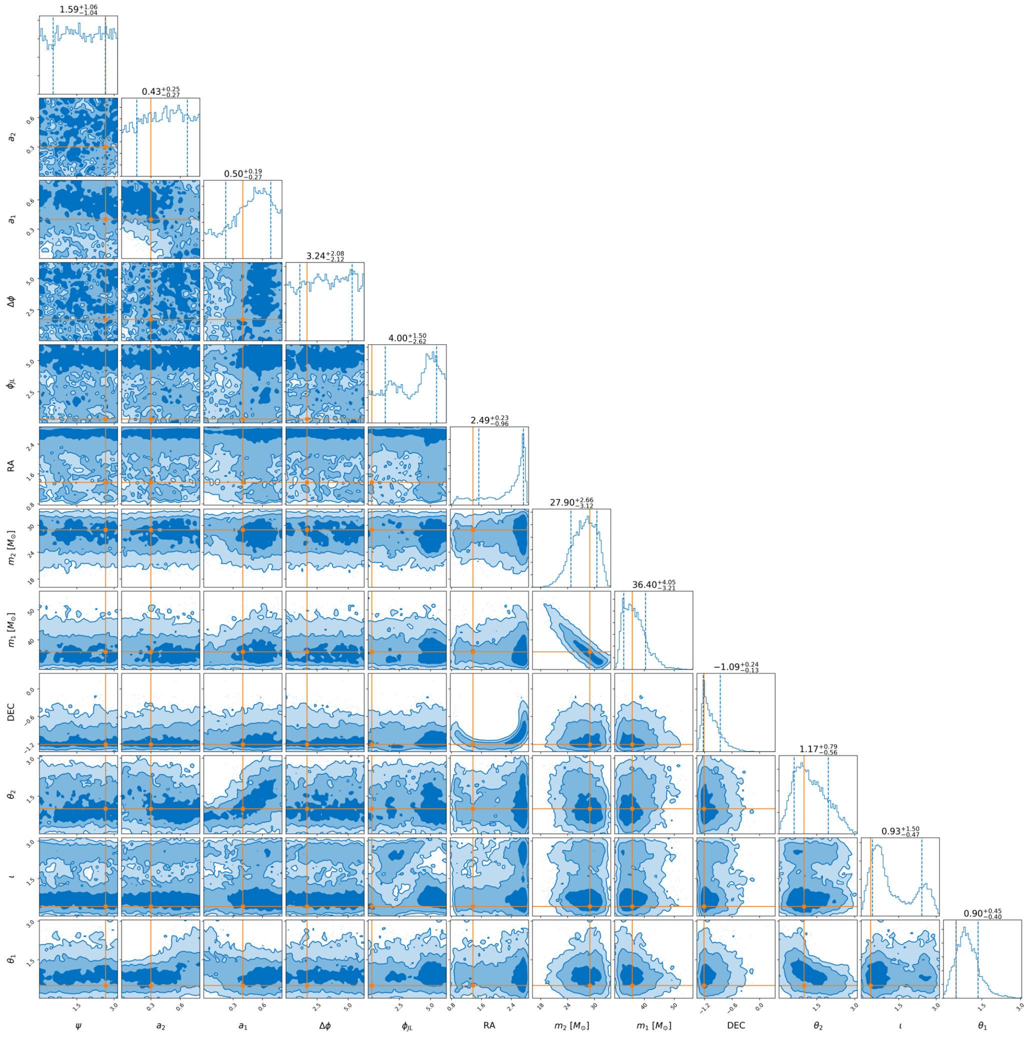
PSD

Parameter Estimation

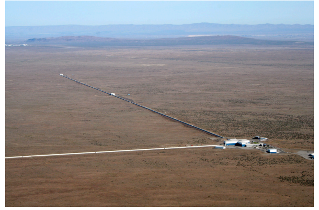
- Data around the detection analysed in more detail with resource-demanding Bayesian inference algorithms
- Waveform depends on a large number of intrinsic (mass, spin..) and extrinsic (position, distance) parameters
- Often we're mostly sensitive to a combination of parameters from the two compact objects (chirp mass, total mass, effective spin, effective tidal deformability..)

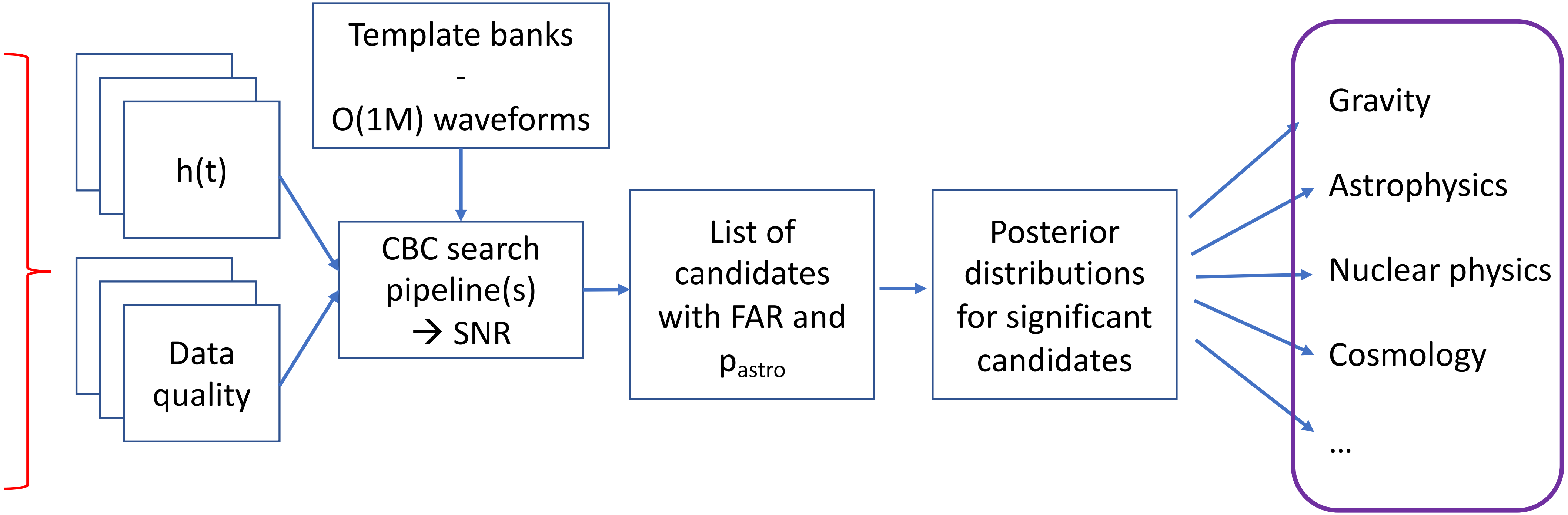
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\chi_{eff} = \frac{m_1 s_1 \cos(\theta_1) + m_2 s_2 \cos(\theta_2)}{m_1 + m_2}$$



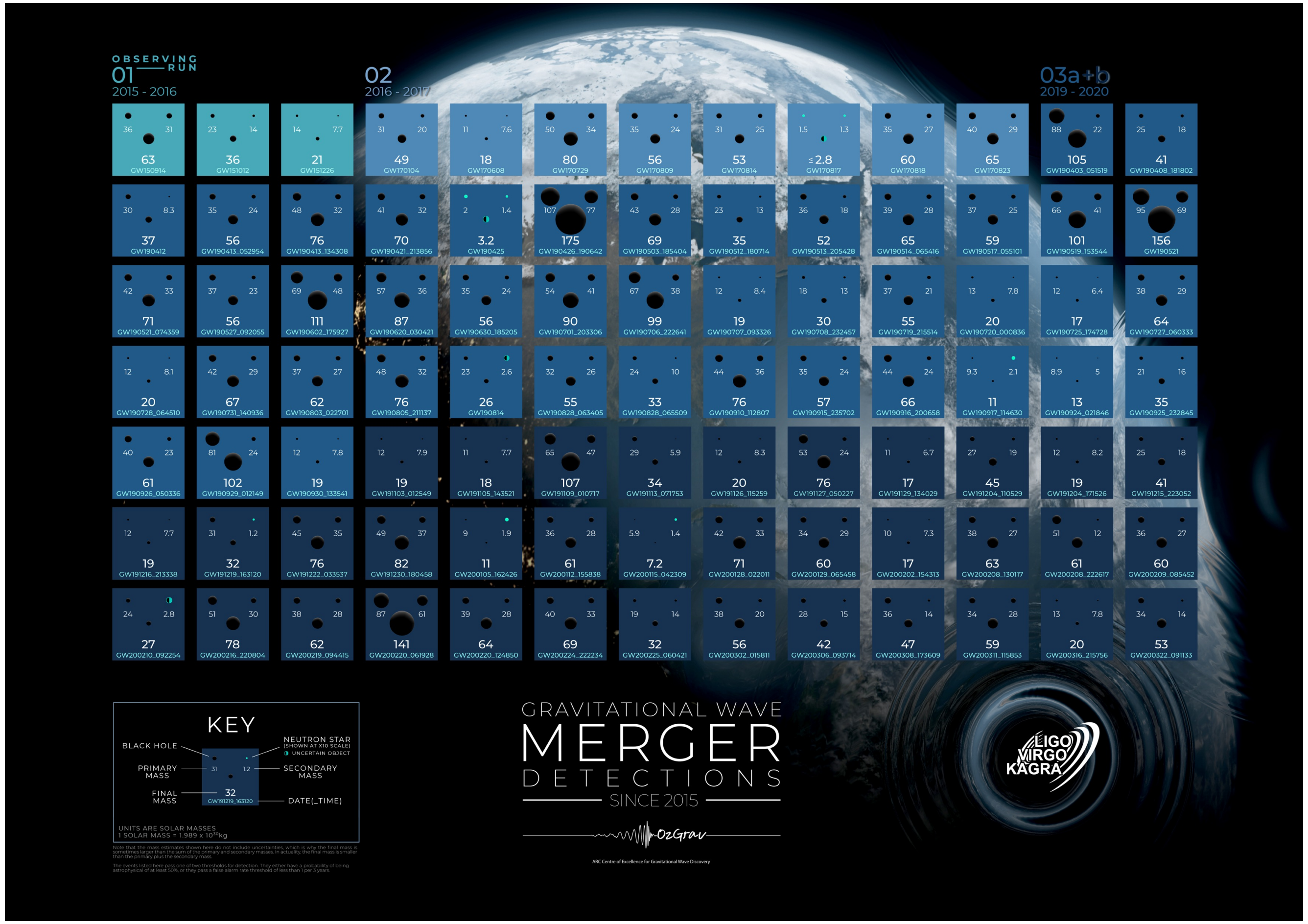
CBC searches

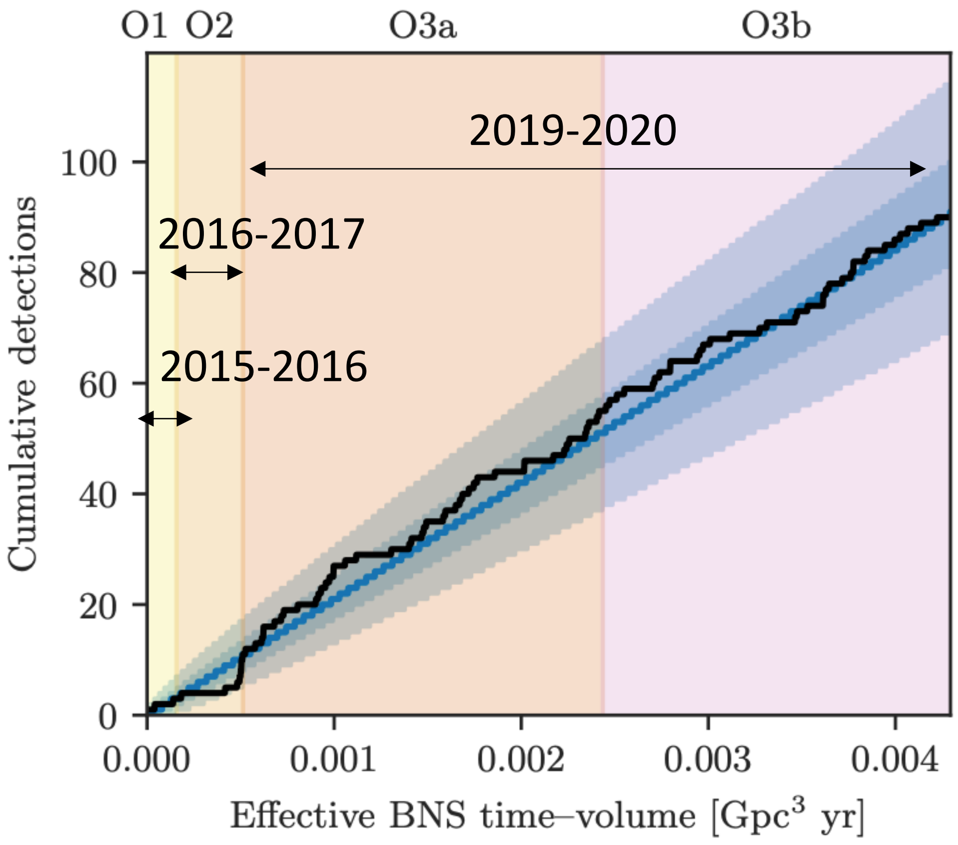




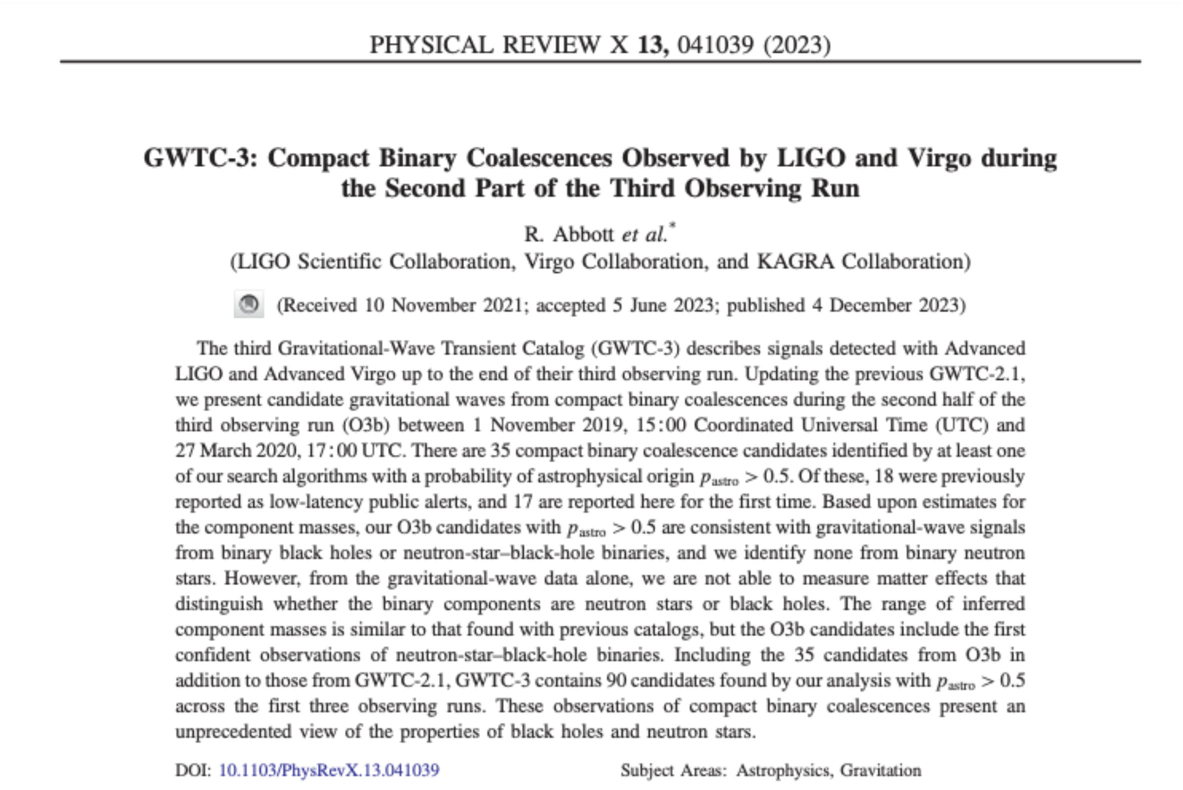
Implications of the CBC observations

CBC detections have become a routine for GW astronomy !





Gravitational Waves Transient Catalogs



PHYSICAL REVIEW X **13,** 041039 (2023)

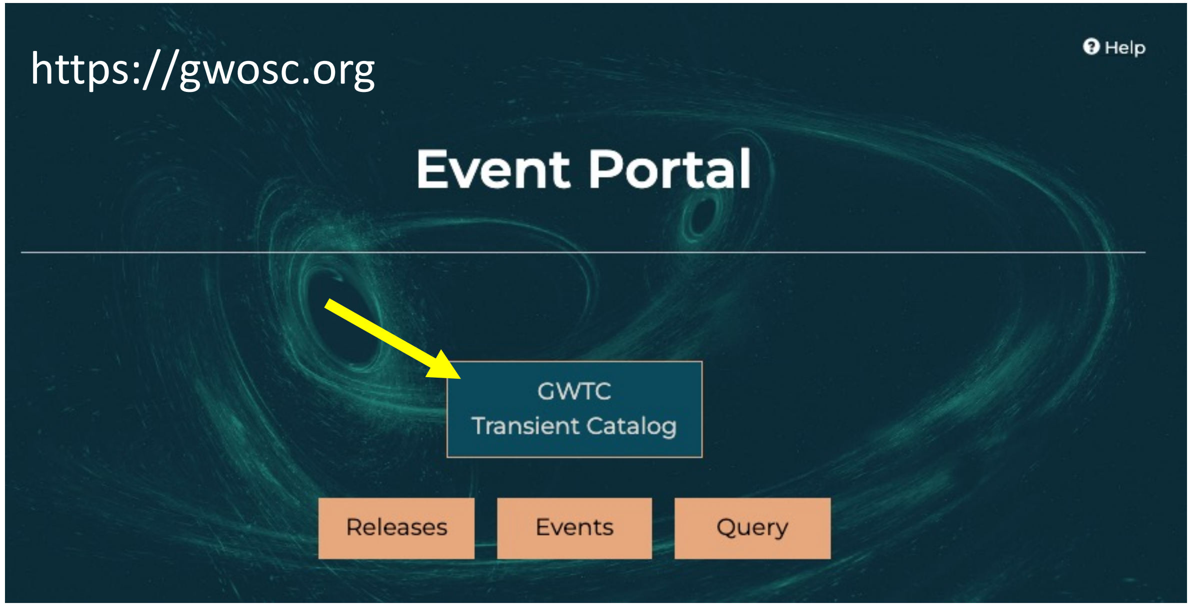
GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run

R. Abbott *et al.**
(LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration)

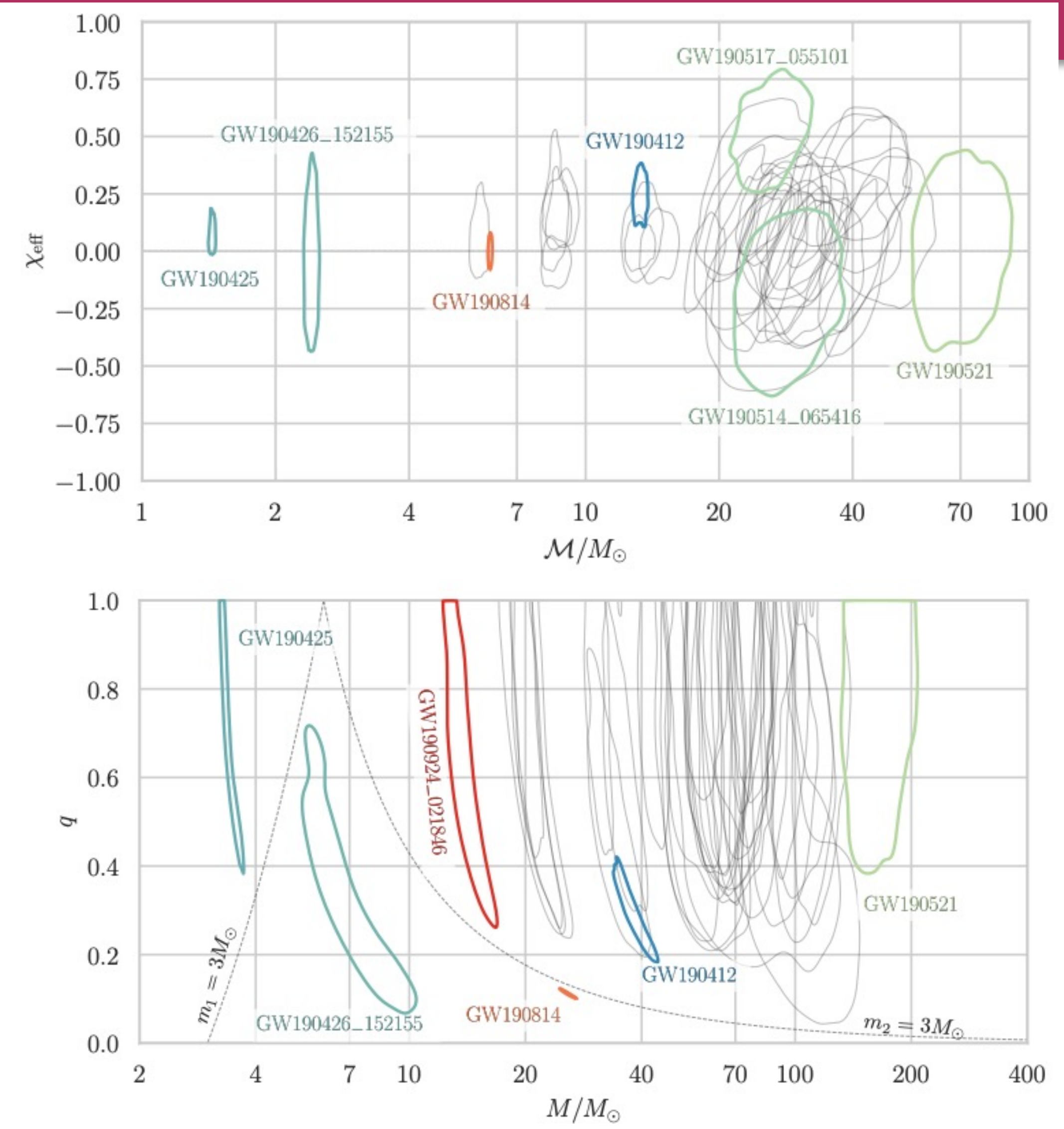
(Received 10 November 2021; accepted 5 June 2023; published 4 December 2023)

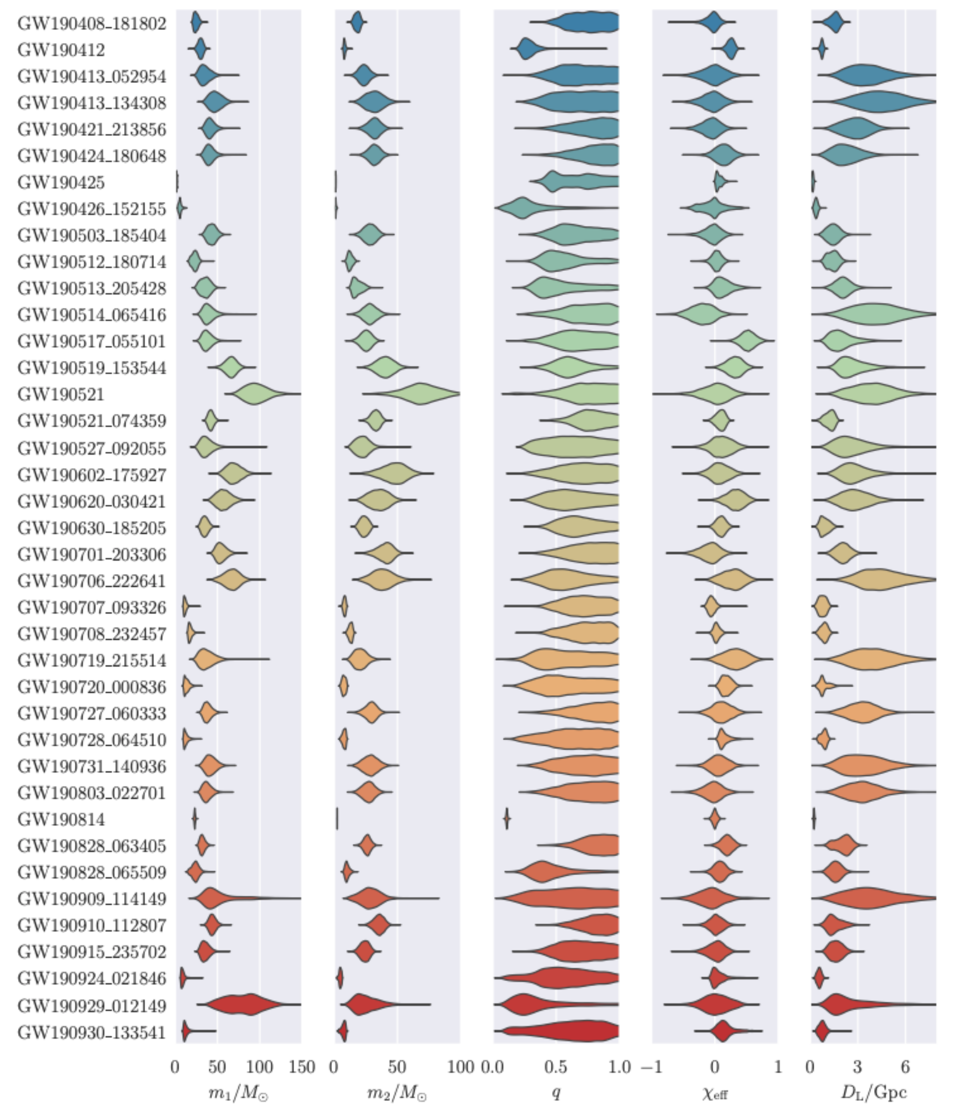
The third Gravitational-Wave Transient Catalog (GWTC-3) describes signals detected with Advanced LIGO and Advanced Virgo up to the end of their third observing run. Updating the previous GWTC-2.1, we present candidate gravitational waves from compact binary coalescences during the second half of the third observing run (O3b) between 1 November 2019, 15:00 Coordinated Universal Time (UTC) and 27 March 2020, 17:00 UTC. There are 35 compact binary coalescence candidates identified by at least one of our search algorithms with a probability of astrophysical origin $p_{\mathrm{astro}} > 0.5$. Of these, 18 were previously reported as low-latency public alerts, and 17 are reported here for the first time. Based upon estimates for the component masses, our O3b candidates with $p_{\mathrm{astro}} > 0.5$ are consistent with gravitational-wave signals from binary black holes or neutron-star–black-hole binaries, and we identify none from binary neutron stars. However, from the gravitational-wave data alone, we are not able to measure matter effects that distinguish whether the binary components are neutron stars or black holes. The range of inferred component masses is similar to that found with previous catalogs, but the O3b candidates include the first confident observations of neutron-star–black-hole binaries. Including the 35 candidates from O3b in addition to those from GWTC-2.1, GWTC-3 contains 90 candidates found by our analysis with $p_{\mathrm{astro}} > 0.5$ across the first three observing runs. These observations of compact binary coalescences present an unprecedented view of the properties of black holes and neutron stars.

DOI: 10.1103/PhysRevX.13.041039 Subject Areas: Astrophysics, Gravitation



Sources Parameters Estimation





NB
O3 observations described in several catalog papers (O3a: GWTC-2, 2.1 O3b: GWTC-3)

Plot here taken from GWTC-2

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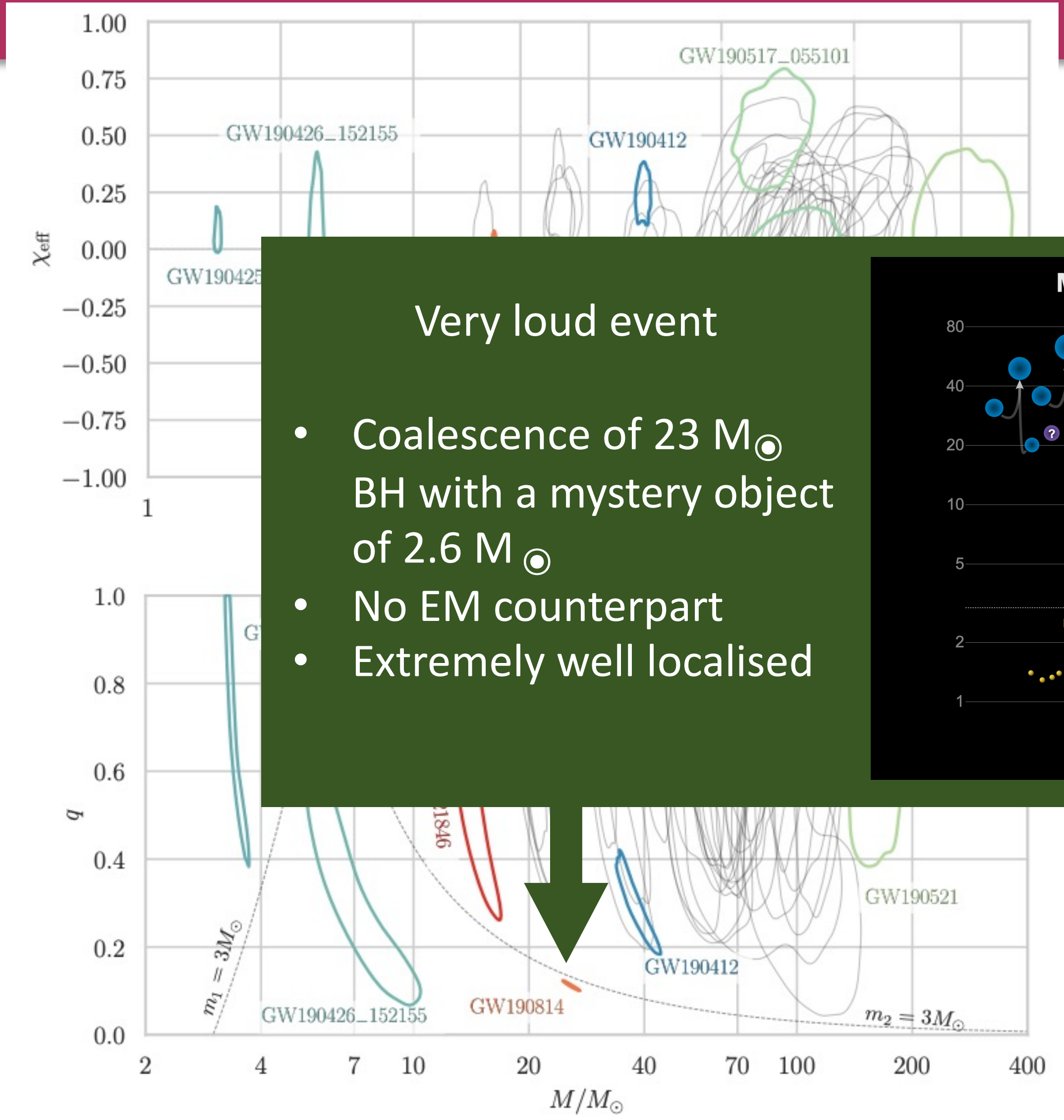
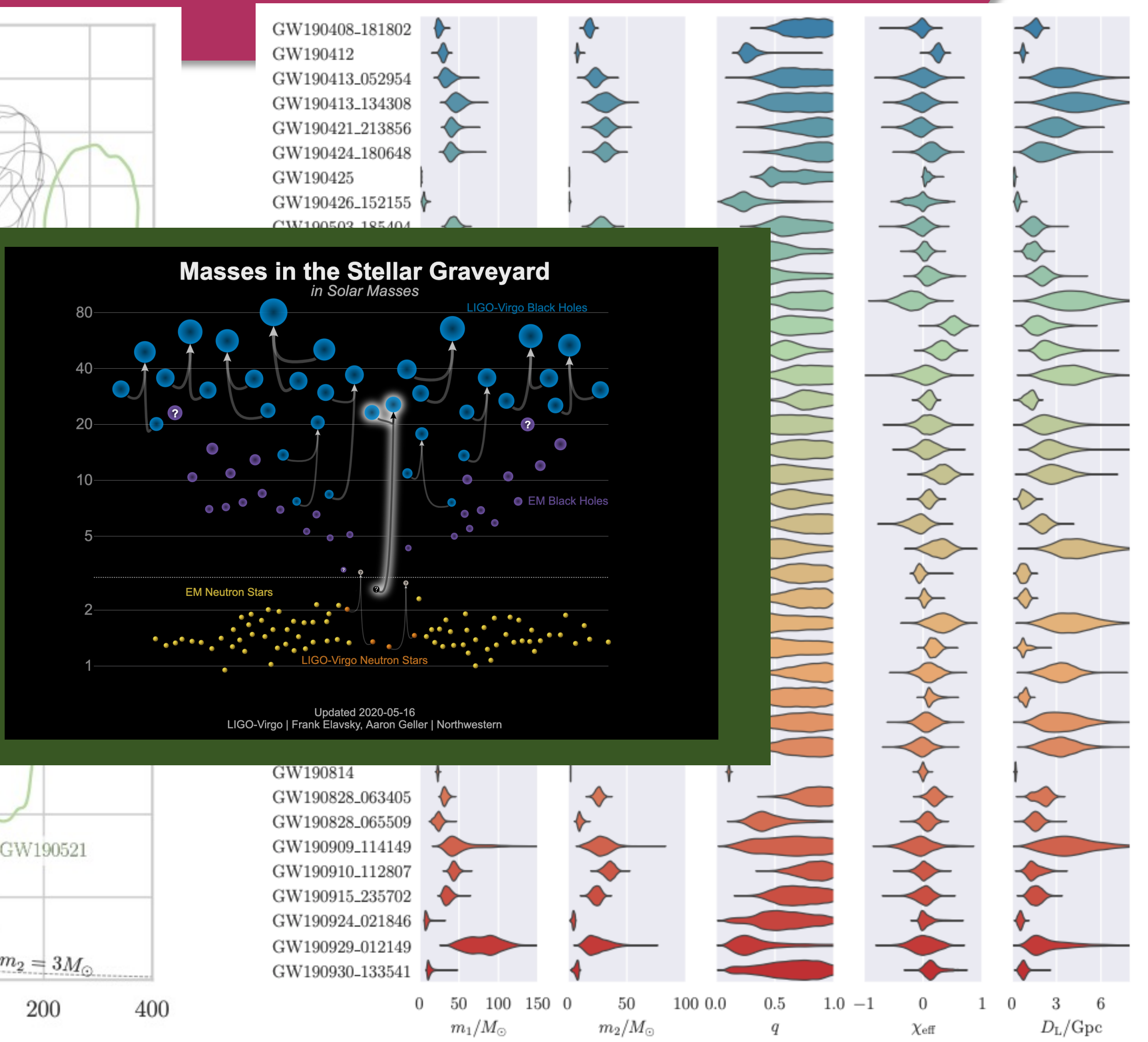


Very loud event

- Coalescence of 23 $M_\odot$ BH with a mystery object of 2.6 $M_\odot$
- No EM counterpart
- Extremely well localised



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LVK science

The catalog results are used to:

- Understand gravity
- Study the population of compact objects and binary systems
- Explore extremely dense nuclear matter
- Constrain cosmology

..but we also:

- Perform multi-messenger triggered searches (GRB, FRB..)
- Search for GW lensing signatures
- Search for sub-solar mass compact objects

(and search for other unmodelled and/or long-duration GW signals)

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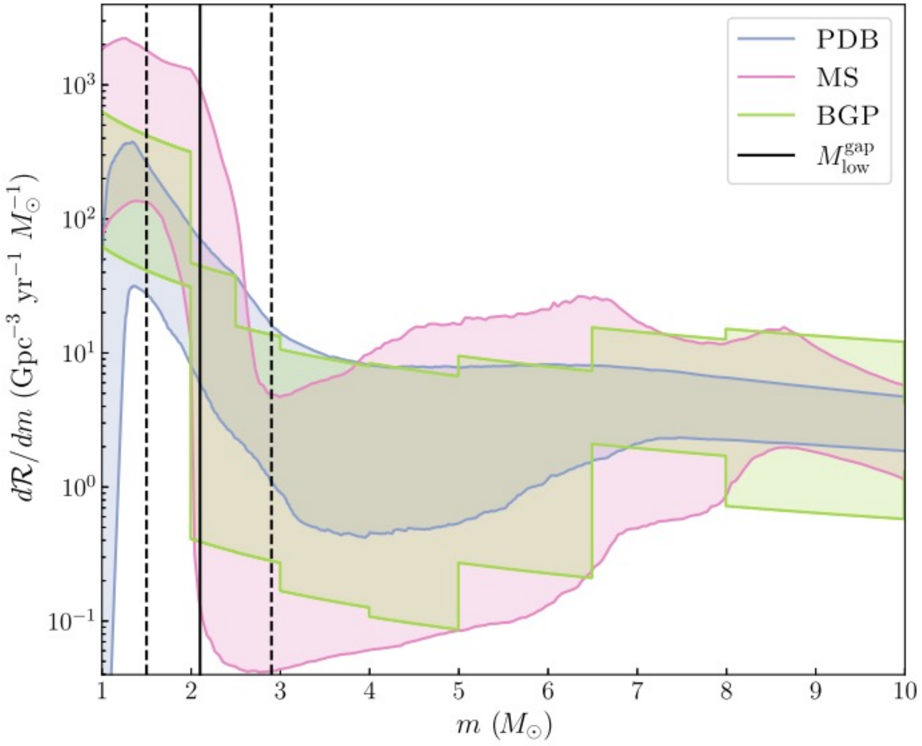
A lower mass gap?

- Dynamical mass measurements of X-ray binary systems within the Milky Way suggests a drop (absence?) of compact objects in the range 3-5 $M_\odot$
- The lower mass gap would separate NS (maximal mass ~2.5/3, depending on the EoS) from BH (minimal mass ~5 from stellar evolution)
- Previous GW observations are in general agreement with a reduction of the number of observed events in the lower mass gap.
- But..

Phys. Rev. X 13, 011048 (2023)

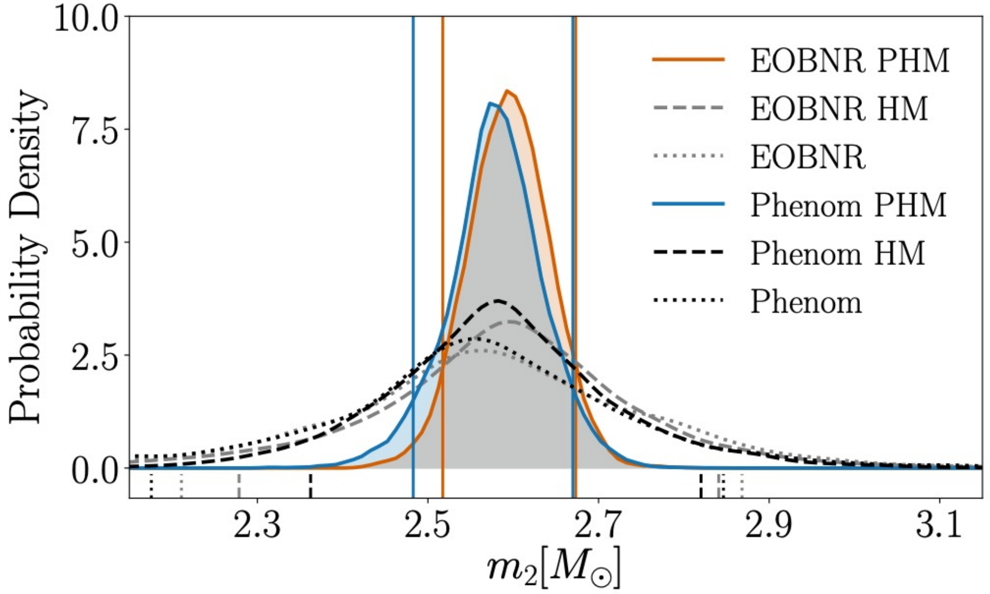


A lower mass gap?

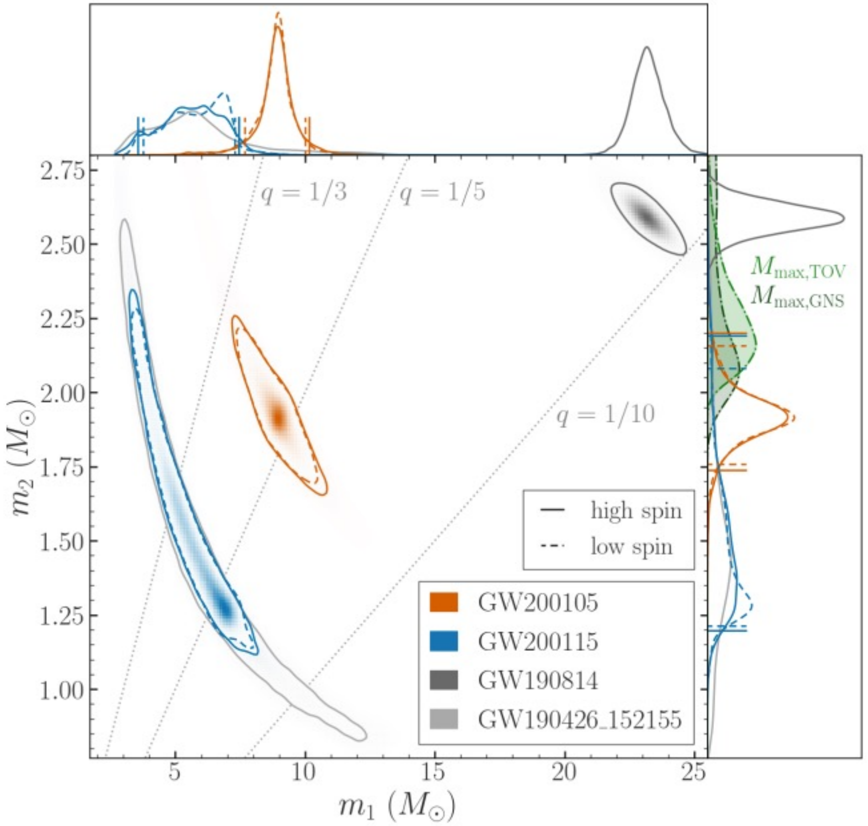
- Several GW observations challenge this paradigm
  - Secondary of GW190814
  - Primary of GW200115
- The lower mass gap is not completely empty…

(NB: often our component masses have large uncertainties)

[Astrophys. J. Lett. 896, L44 (2020)]

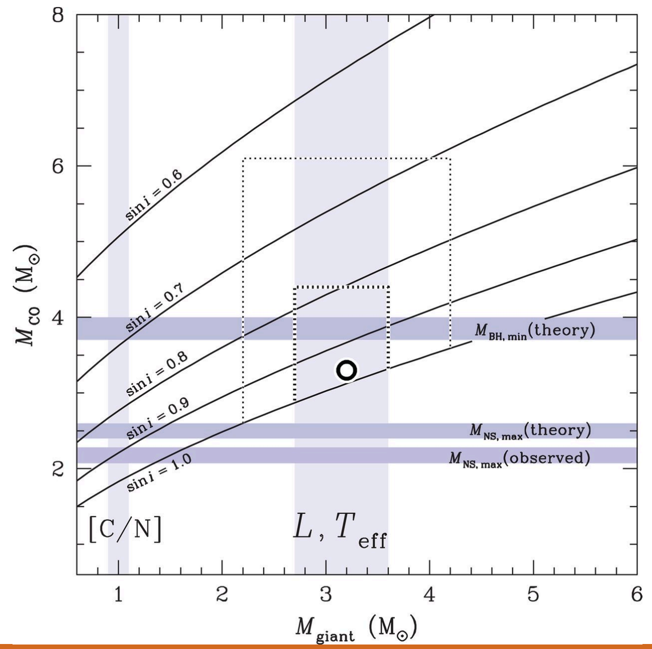


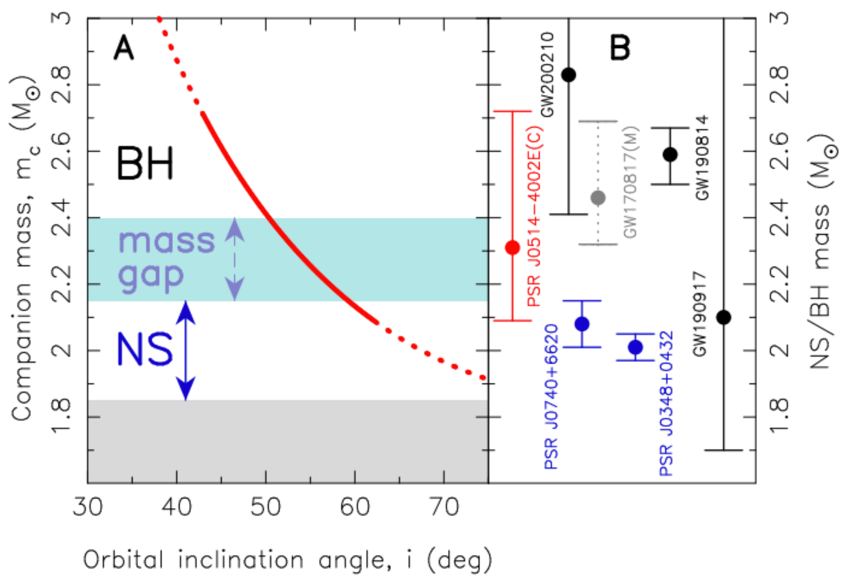
[Astrophys. J. Lett. 915, L5 (2021)]



A lower mass gap?

- GW are not alone !
- Non-interacting binary systems
  - Dark companion to the V723 Mon red giant star, with mass 3.04 ± 0.06 $M_\odot$, ASAS+KELT+TESS (MNRAS, V. 504, 2021).
  - Dark companion on a red giant in 2MASS J05215658+4359220 binary system of mass $3.3^{+2.8}_{-0.7}$. $M_\odot$, ASAS+APOGEE, (Science 2019, V. 366, 6465).
- Radio pulsars surveys: dark object in binary system with the PSR J0514−4002E pulsar, MeerKAT (Science 2024 Vol. 383, 6680)



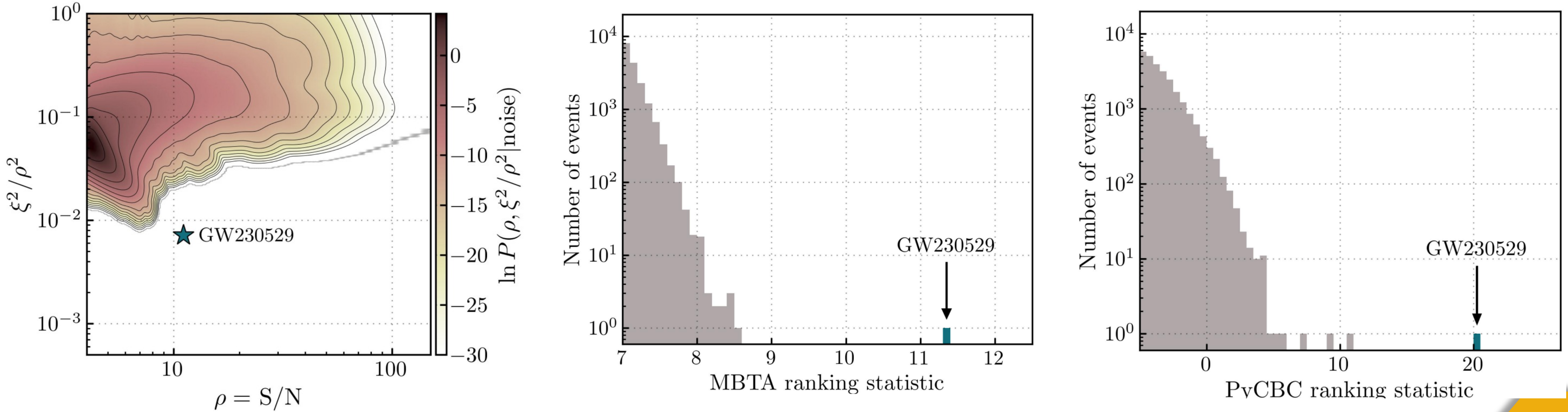


GW230529

- First alert of O4a, GCN thread
- 60% probability of being an NSBH
- Distance ~200 Mpc
- Detected in low-latency by three independent pipelines

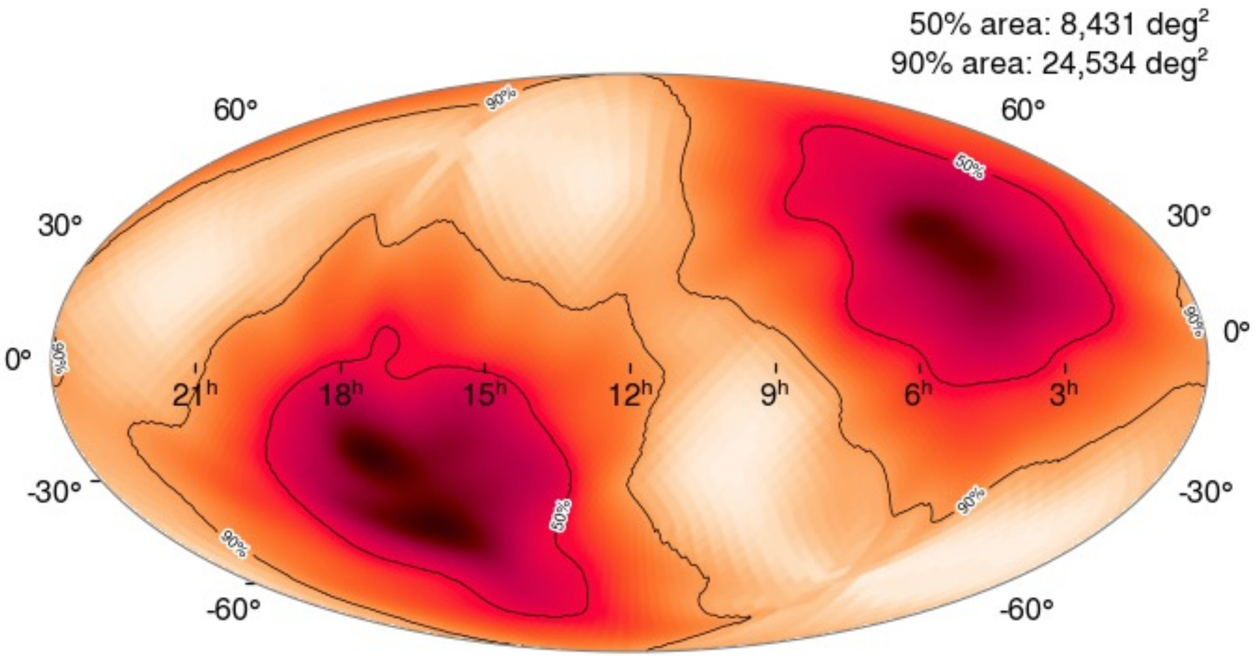
	GstLAL	MBTA	PyCBC
Online S/N	11.3	11.4	11.6
Online inverse FAR (yr)	1.1	1.1	160.4
Offline inverse FAR (yr)	60.3	>1000	>1000

- Only LIGO Livingston was in science (since ~70 hours), with a BNS range ~150 Mpc
- Single-detector triggers are tricky



GW230529

- Single-detector triggers are poorly localised

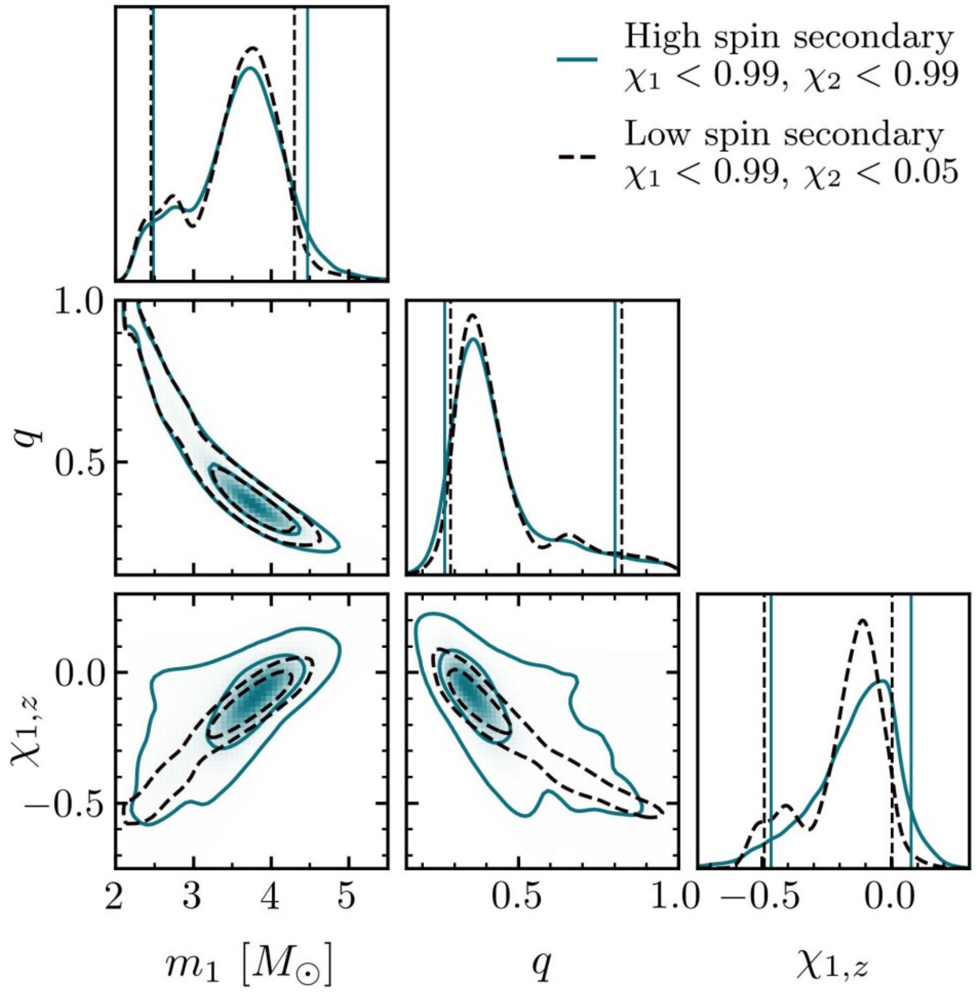


Parameter Estimation

- 128 seconds of data (20-1792 Hz) around the event analysed with Bayesian inference algorithms
- Primary analysis : BBH waveform models (HOM, precession, no tidal effects)
  - Combination of results from phenomenological frequency-domain model IMRPhenomXPHM and time-domain effective-one-body model SEOBNRv5PHM
- Runs with waveforms with tidal effects show no evidence of preference (expected for NSBH at this SNR)

Waveform Model	Precession	Higher Multipoles	Tides	Disruption	Spin Prior
IMRPhenomNSBH	–	–	✓	✓	$\chi_1 < 0.50, \chi_2 < 0.05$
IMRPhenomPv2_NRTidalv2	✓	–	✓	–	$\chi_1 < 0.99, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
SEOBNRv5PHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
SEOBNRv4_ROM_NRTidalv2_NSBH	–	–	✓	✓	$\chi_1 < 0.90, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.05$
IMRPhenomXP	✓	–	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXHM	–	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXAS	–	–	–	–	$\chi_1 < 0.99, \chi_2 < 0.99$
IMRPhenomXAS	–	–	–	–	$\chi_1 < 0.50, \chi_2 < 0.05$
IMRPhenomPv2_NRTidalv2	✓	–	✓	–	$\chi_1 < 0.05, \chi_2 < 0.05$
IMRPhenomXPHM	✓	✓	–	–	$\chi_1 < 0.05, \chi_2 < 0.05$
SEOBNRv5PHM	✓	✓	–	–	$\chi_1 < 0.99, \chi_2 < 0.05$

Source properties



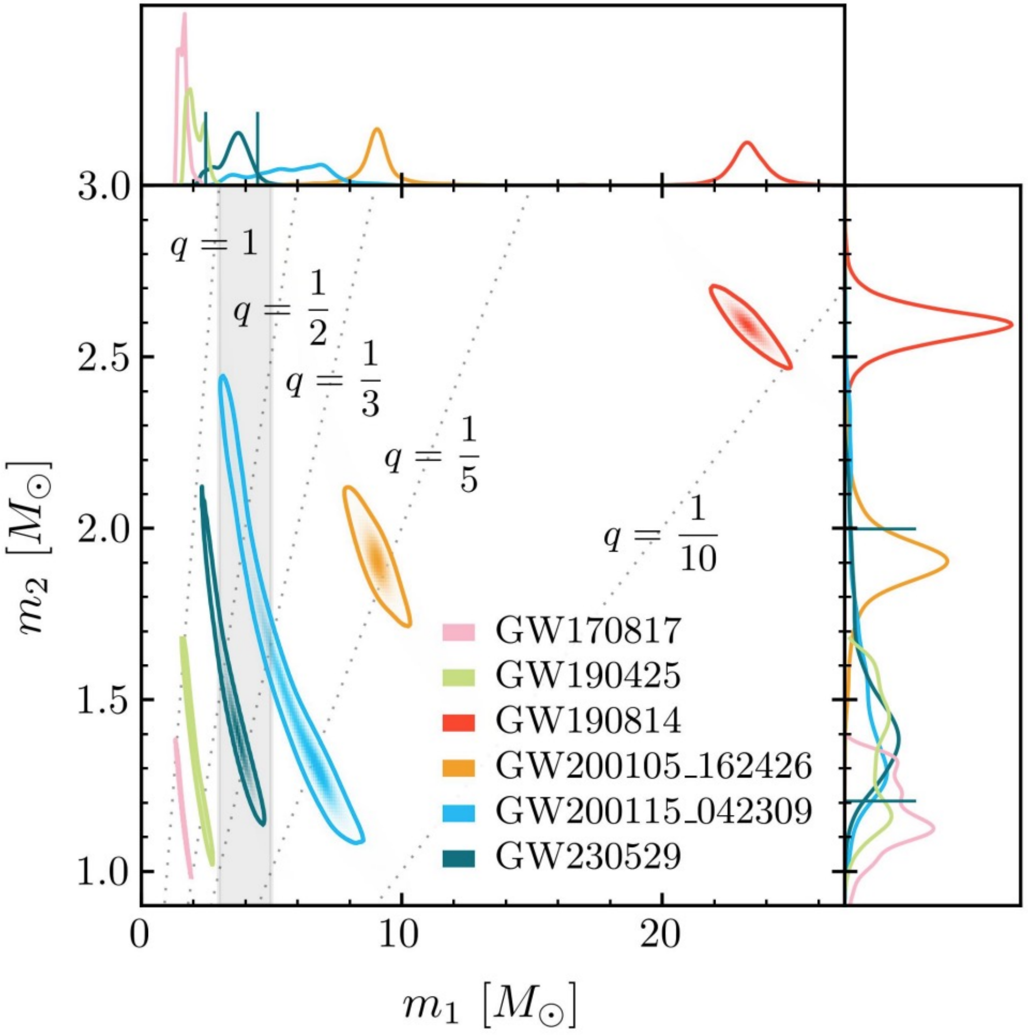
Primary mass $m_1/M_\odot$	$3.6^{+0.8}_{-1.2}$
Secondary mass $m_2/M_\odot$	$1.4^{+0.6}_{-0.2}$
Mass ratio $q = m_2/m_1$	$0.39^{+0.41}_{-0.12}$
Total mass $M/M_\odot$	$5.1^{+0.6}_{-0.6}$
Chirp mass $\mathcal{M}/M_\odot$	$1.94^{+0.04}_{-0.04}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$2.026^{+0.002}_{-0.002}$
Primary spin magnitude χ_1	$0.44^{+0.40}_{-0.37}$
Effective inspiral-spin parameter $\chi_{\rm eff}$	$-0.10^{+0.12}_{-0.17}$
Effective precessing-spin parameter $\chi_{\rm p}$	$0.40^{+0.39}_{-0.30}$
Luminosity distance $D_{\rm L}/{\rm Mpc}$	201^{+102}_{-96}
Source redshift z	$0.04^{+0.02}_{-0.02}$

$$p(m_1 < 5M_\odot) = 99\%$$

$$p(m_2 < 2M_\odot) = 95\%$$

$$p(\chi_{1,z} < 0) = 83\%$$

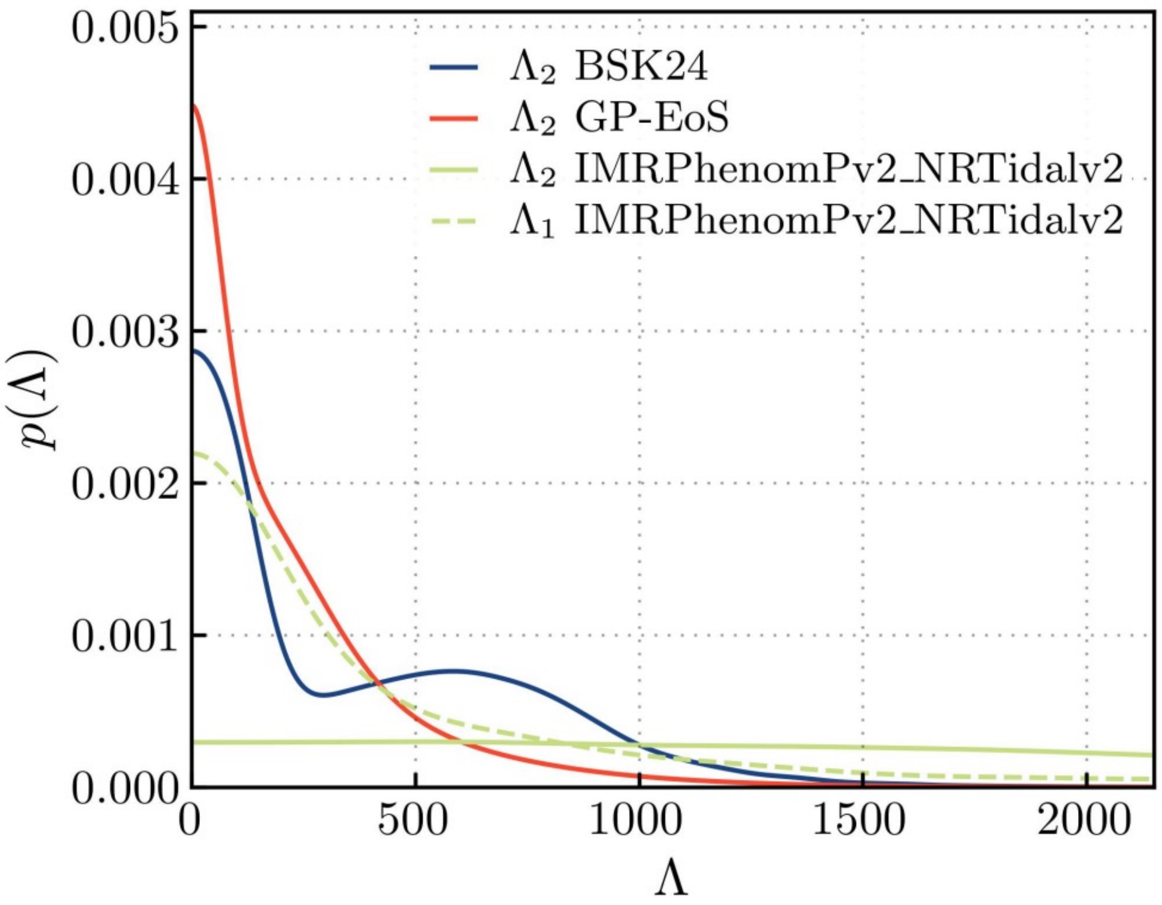
Source properties



The lower mass gap keeps being populated by GW events !

Tidal deformabilities

- Data analysed with NSBH and BNS waveforms
- Tidal deformability of primary object peaks at zero, of secondary object is unconstrained
- Consistent with EoS predictions in this mass range
- Constrain EoS using spectral and Gaussian Process representations.
  - Consistency with heavy pulsars (s PSR J0740+6620 and J0348+0432) observations, enforce thermodynamic stability and causality
  - Only pulsar constraints in priors
  - Results uninformative



Impact on merger rates

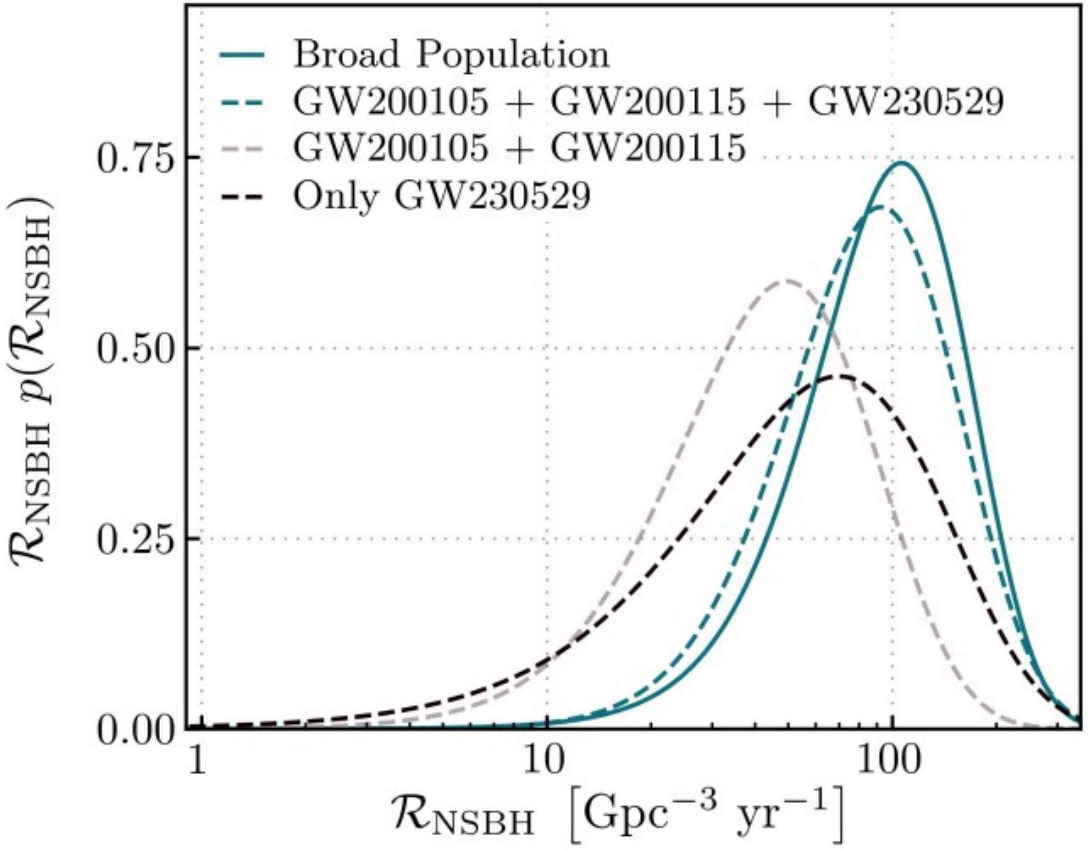
- Update of merger rates constraints (previous data + first two weeks of O4)
- Event-based and population-based approach

$$\mathcal{R}_{230529} = 55^{+127}_{-47}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

$$\mathcal{R}_{\mathrm{NSBH}} = 94^{+109}_{-64}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$

- Reminder, in GWTC-3:

$$\mathcal{R}_{\mathrm{NSBH}} = 85^{+116}_{-57}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$$



Impact on populations

Impact on masses and spins of compact binary populations.

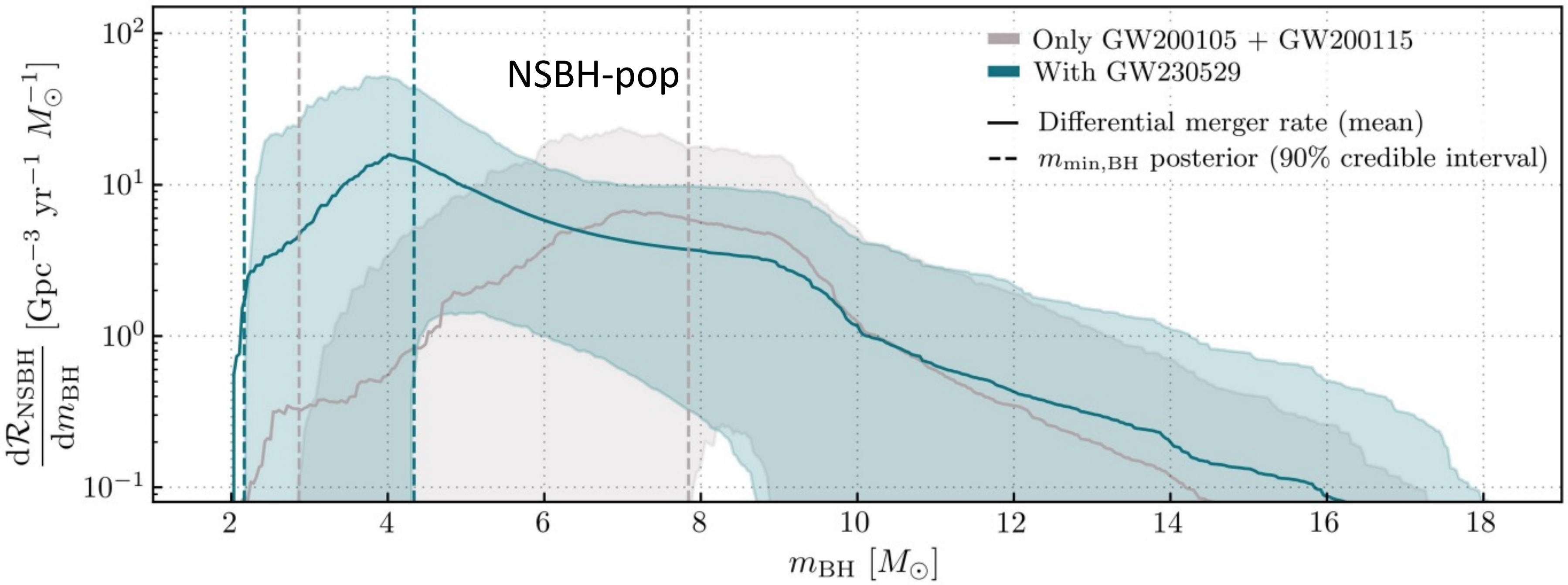
Inference can be run on several events to constrain hyperparameters.

Assuming different models :

- **Power law + Dip + Break** (dip separating masses of NS from BH)
- **Binned Gaussian Process** (capture the structure of the mass distribution with minimal assumptions on the population)
- **NSBH-pop** (parametric model designed to constrain the population distributions of NSBH masses and black hole spin magnitudes)

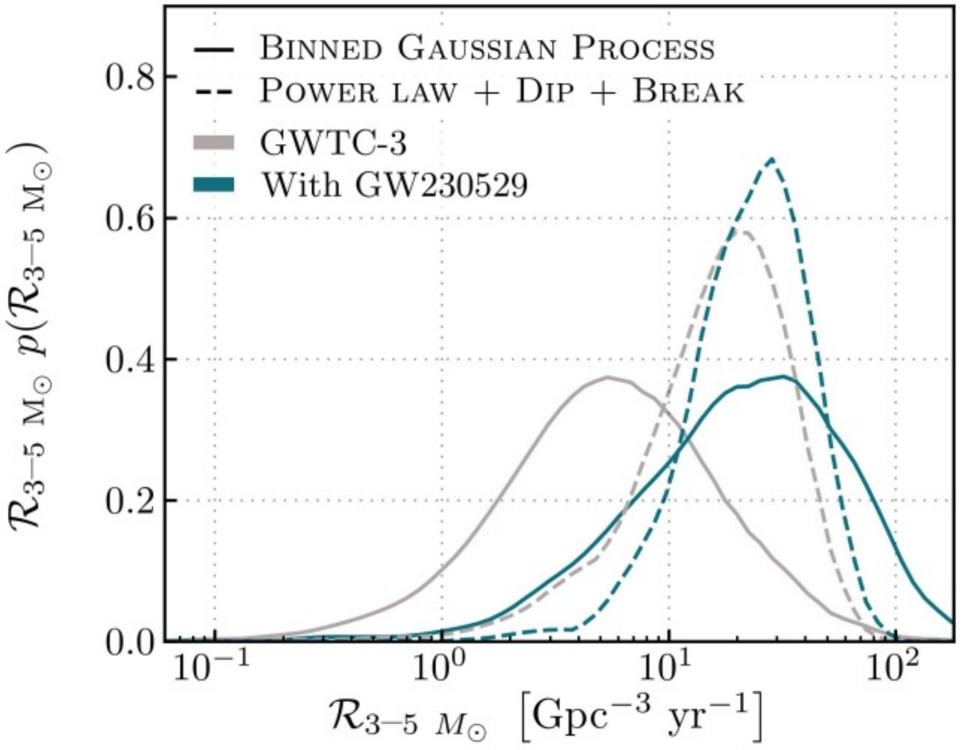
Impact on populations

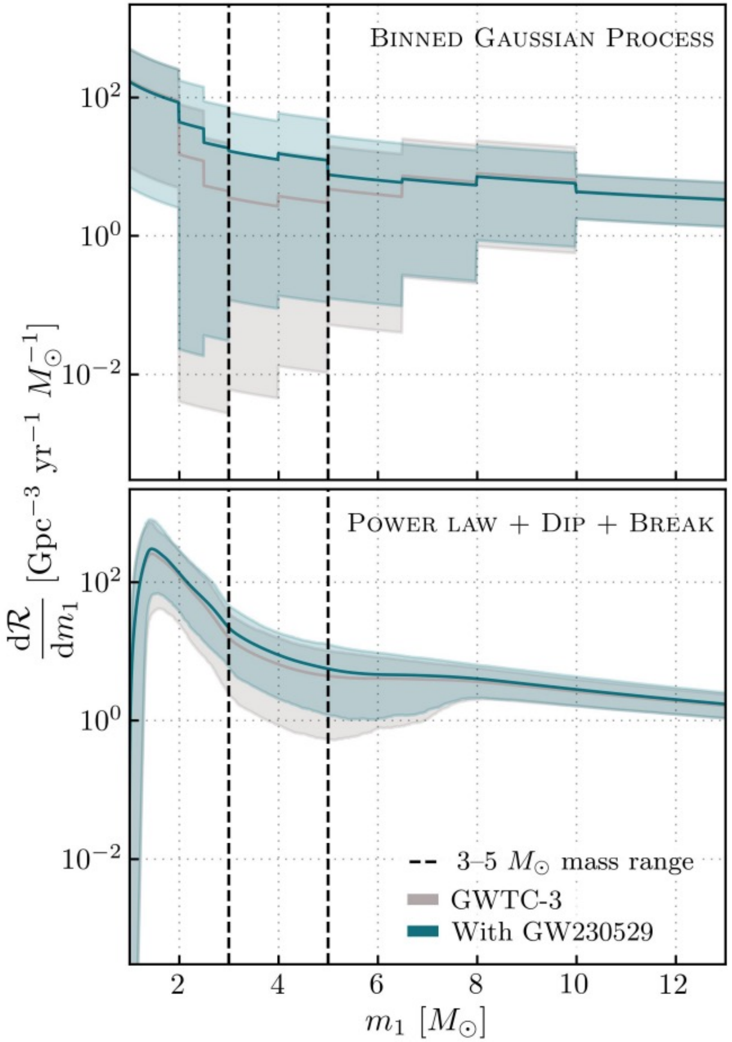
- NSBH-pop (all NSBH with FAR<0.25 yr^{-1}, no GW190814)
- Assume primary object is a BH, secondary is a NS
- Minimum BH mass decreases
- No significant shift in low-edge of the dip in Powerlaw + Dip + Peak (global fit to population)



Impact on populations

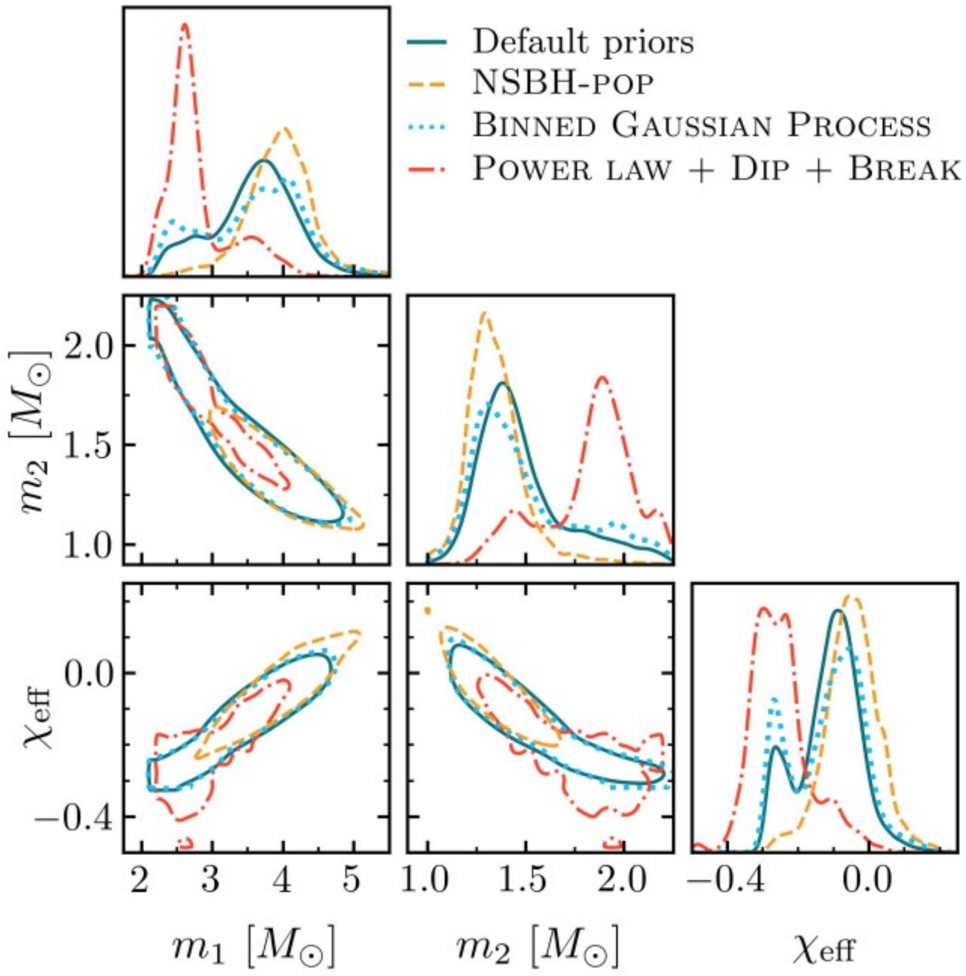
- Higher rate of mergers with one or both components in the 3-5 $M_\odot$ range
- GW230529 not an outlier wrt previous results





Population assumptions

- Inferred component masses differ depending on the population assumptions
- Either asymmetric components and low BH spins, or symmetric masses and negative effective spins



Nature of compact objects

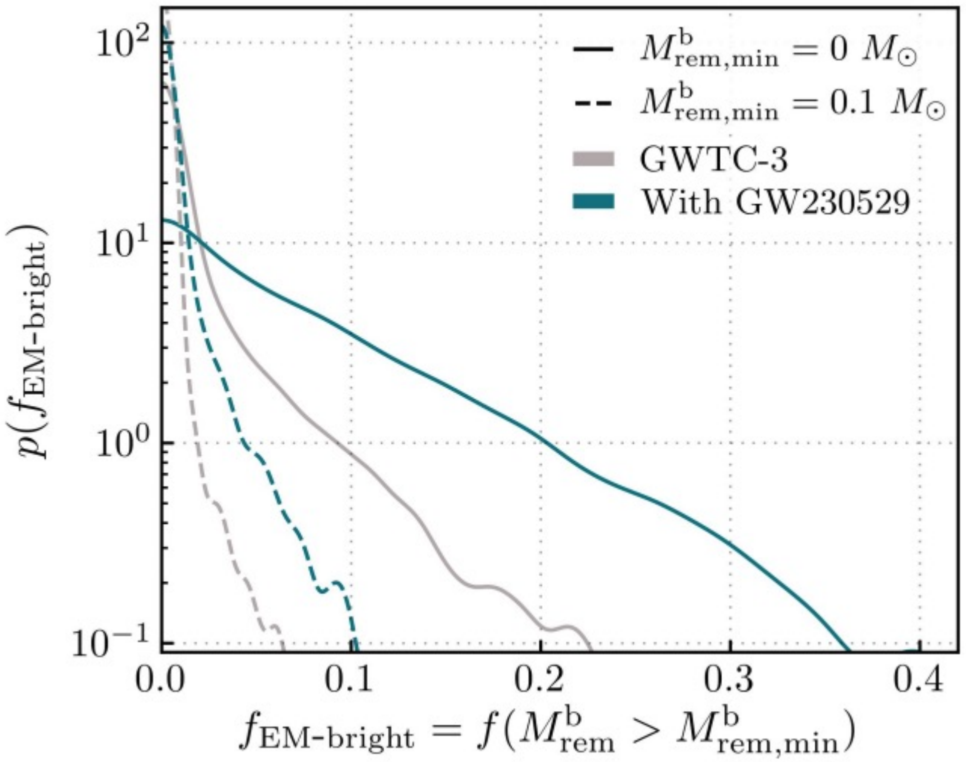
- Try and determine the nature of the compact objects by comparing masses and spins to limits imposed by previous observations
- Two populations are considered :
  - Powerlaw+Dip+Break fit to GWTC-3 candidates
  - Astrophysically-agnostic population model (uniform in source-frame component masses and spin magnitudes and isotropic in spin orientations) - low and high spin
- Marginalize over the uncertainty in masses and spins, population and EoS, to determine the probability that masses and spins are below maximum allowed for neutron stars (anything below the max IS a NS)

	$\chi_1, \chi_2 \leq 0.99$	$\chi_1, \chi_2 \leq 0.05$	Power law + Dip + Break
$P(m_1$ is NS)	$(2.9 \pm 0.4)\%$	$< 0.1\%$	$(8.8 \pm 2.8)\%$
$P(m_2$ is NS)	$(96.1 \pm 0.4)\%$	$> 99.9\%$	$(98.4 \pm 1.3)\%$

Can be as high as ~30% if high-spin NS are allowed (similar to second component of GW190814)

Implication for MMA

- Tidal disruption influenced by binary mass ratio, NS compactness, BH aligned spin component
- Assume GW230529 is an NSBH, constrain remnant mass outside the final black hole
- Of the LVK NSBHs, 230529 is the most likely to have undergone tidal disruption because of the mass ratio
- For the high(low)-spin case
  - probability of neutron star tidal disruption 0.1(0.042) at 99%
  - upper limit on the remnant baryon mass produced in the merger of 0.052(0.011) $M_{\odot}$ at 99%
- Upper limits (90%) to the NSBH contribution to production of heavy elements (1.1 $M_{\odot}$ $Gpc^{-3}yr^{-1}$) and GRB (23 $Gpc^{-3}yr^{-1}$)
- No significant EM counterpart observed (but poor sky localization)



$$f_{EM\text{-}bright} = 0.13^{+0.19}_{0.11}$$

If we include NICER

Considerations

- Another hint of compact object in the 3-5 $M_\odot$ region. Low-mass gap is not empty, maybe just less populated?
- Many open questions on the nature of the compact objects
- Primary is a BH – not from direct stellar collapse
  - Unless stochastic effects
  - Formation by fallback
  - Timescale for instability growth in core-collaspe – proto-NS grows to a mass gap object before the explosion
  - NS accretion
  - Pure-helium star models
  - Primary is a result of a BNS coalescence? Triple/quadruple system?
  - Dynamical capture
- Lensed BNS
- Primordial BH
- If primary is a NS – GW230529 heaviest BNS ever observed, 2 components with $M>2M_\odot$ and high, anti-aligned spins..

Practical information

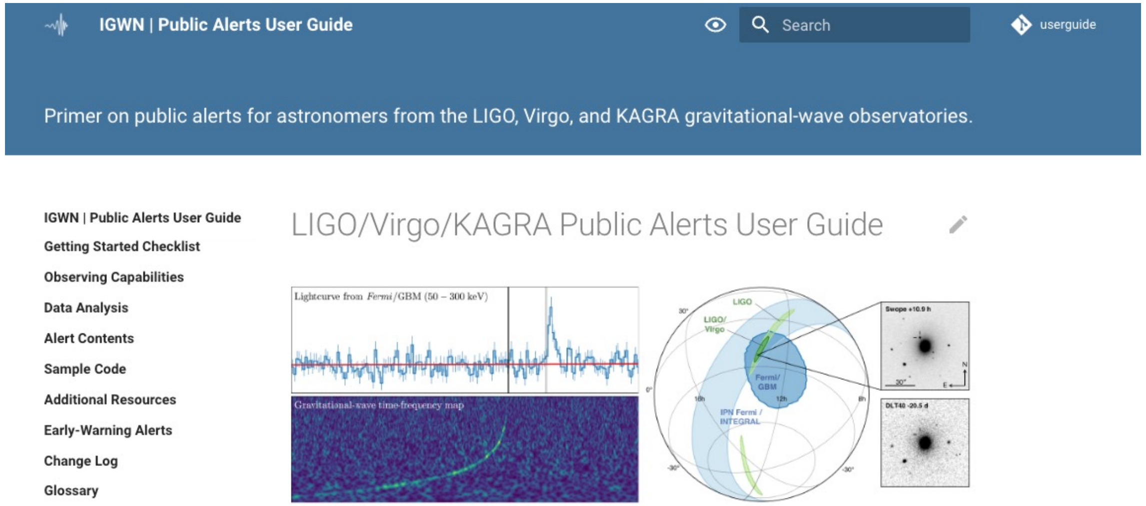
GW230529 LVK data are public!

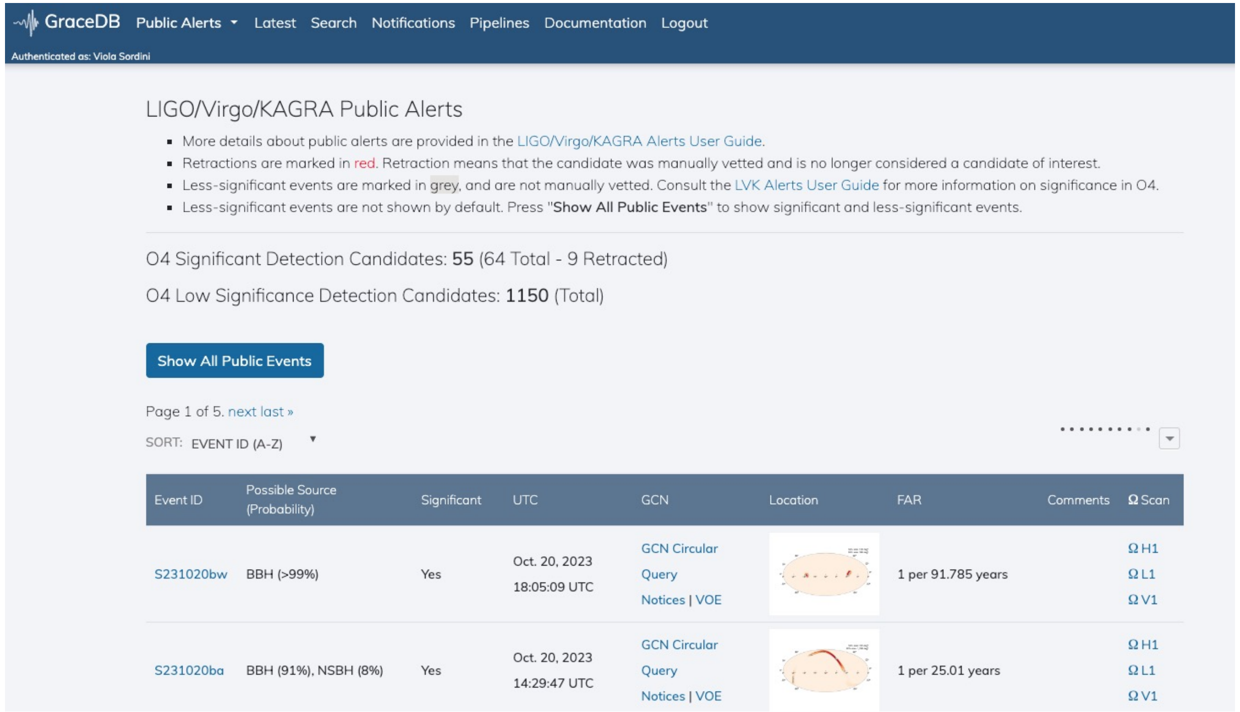
- Go here to get the strain data and all information
- Go here to get
  - Samples from the posterior distributions of the source parameters
  - Hyperposterior distributions from population analyses
  - Notebooks for reproducing all results and figures in the paper

Before we conclude..

A look at O4

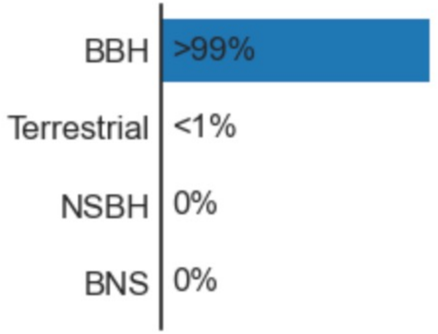
- May 2023 - January 2024 (O4a) – data will be public August 2025
- April 2024 - February 2025 (O4vb) – data will be public May 2026
- Alerts for CBC events (including early warning searches) on GraceDB and distributed through GCN and SCiMMA
- All explanations here
- Follow the news in the open LVK-EM community



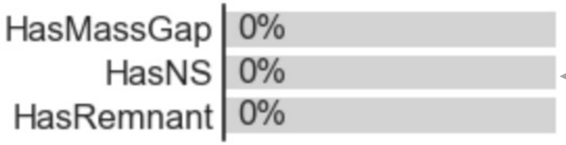


A look at O4

- We provide alerts for all low-significance CBC events with FAR<2/day (generating only notices), and significant ones (FAR<1/month – notices and circulars).
- Typical alert latency < 1 minute. Information is possibly refined within 5 minutes. Updates follow ~hours later (after human vetting, and possibly with refined skymap).



Probability of being of astrophysical origin (1-Terrestrial) and source classification



Source property – **assuming the signal is astrophysical**

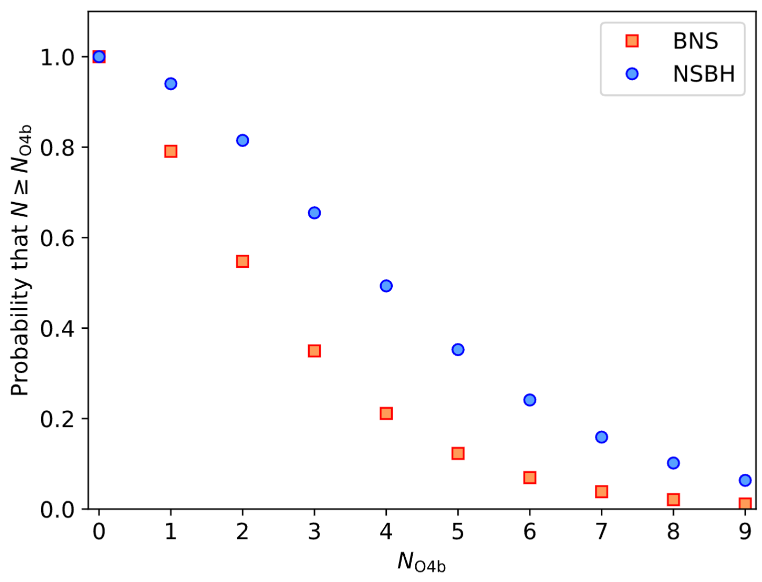
Summary information of all pipelines that detected the event as significant

Per-Pipeline Event Information

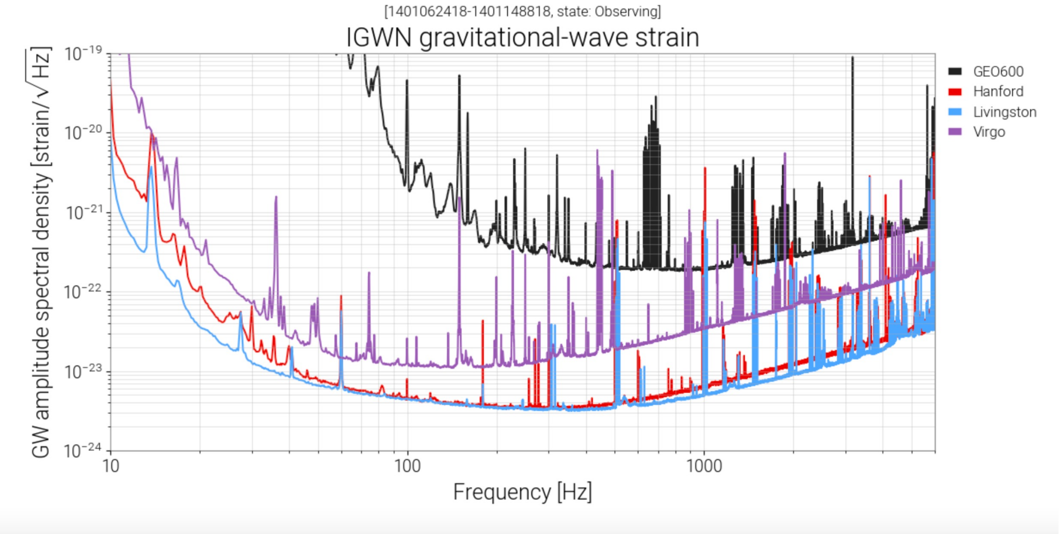
UID	Group	Pipeline	Search	gpstime	FAR (Hz)
G451504	CBC	spiir	AllSky	1383483120.464	8.102e-08
G451505	CBC	MBTA	AllSky	1383483120.457	1.344e-09
G451506	CBC	pycbc	AllSky	1383483120.463	3.168e-10
G451508	Burst	CWB	BBH	1383483120.465	6.563e-11
G451502	CBC	gstlal	AllSky	1383483120.464	7.030e-25

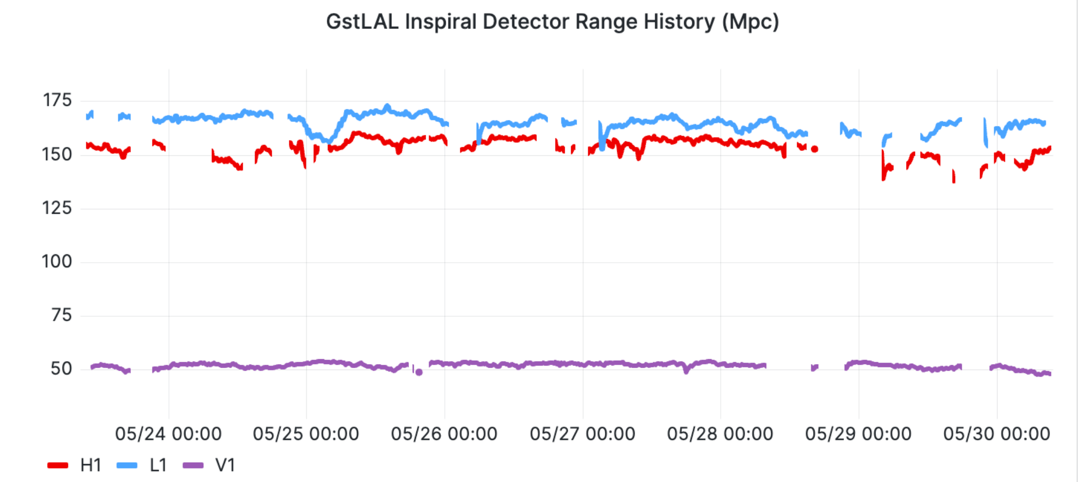
Status and perspectives

- Assuming ~300 days O4 duration, O3b-like duty cycle, HLV ranges 150, 160, 50 Mpc
- Based on previous runs BNS (2) and NSBH (4) observations
- Probability of at least one BNS detection ~70%
- Probability of at least one NSBH ~90%



https://gwosc.org/detector_status/





Conclusion

- LVK O4 period ongoing since May 2023
- Already ~100 alerts for CBC signals
- Today we focused on GW230529, single-detector signal from early O4. Most likely an NSBH, with the heaviest object in the lower mass gap and interesting implications for populations.
- More O4 results to come in the next months.
- Reminder: we do searches for non-CBC GW signals, although no evidence for the moment, improvements in sensitivity

- GWs remain a newcomer among the Universe messengers – still room for unexpected !
- New, more sensitive, experiments are foreseen in the next ~decade
- Stay tuned for more exciting science!