

Update on the LIGO-Virgo-KAGRA O3 results

Ornella Juliana Piccinni on behalf of the LVK





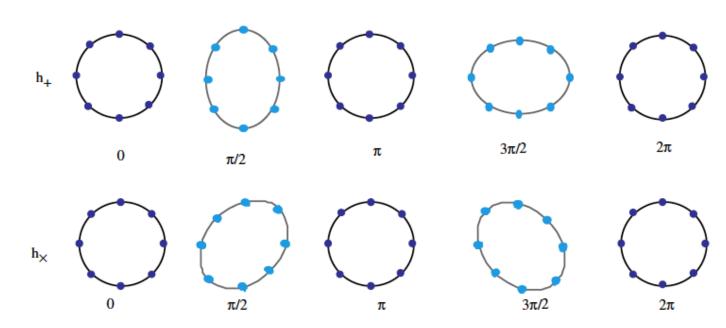


Gravitational waves

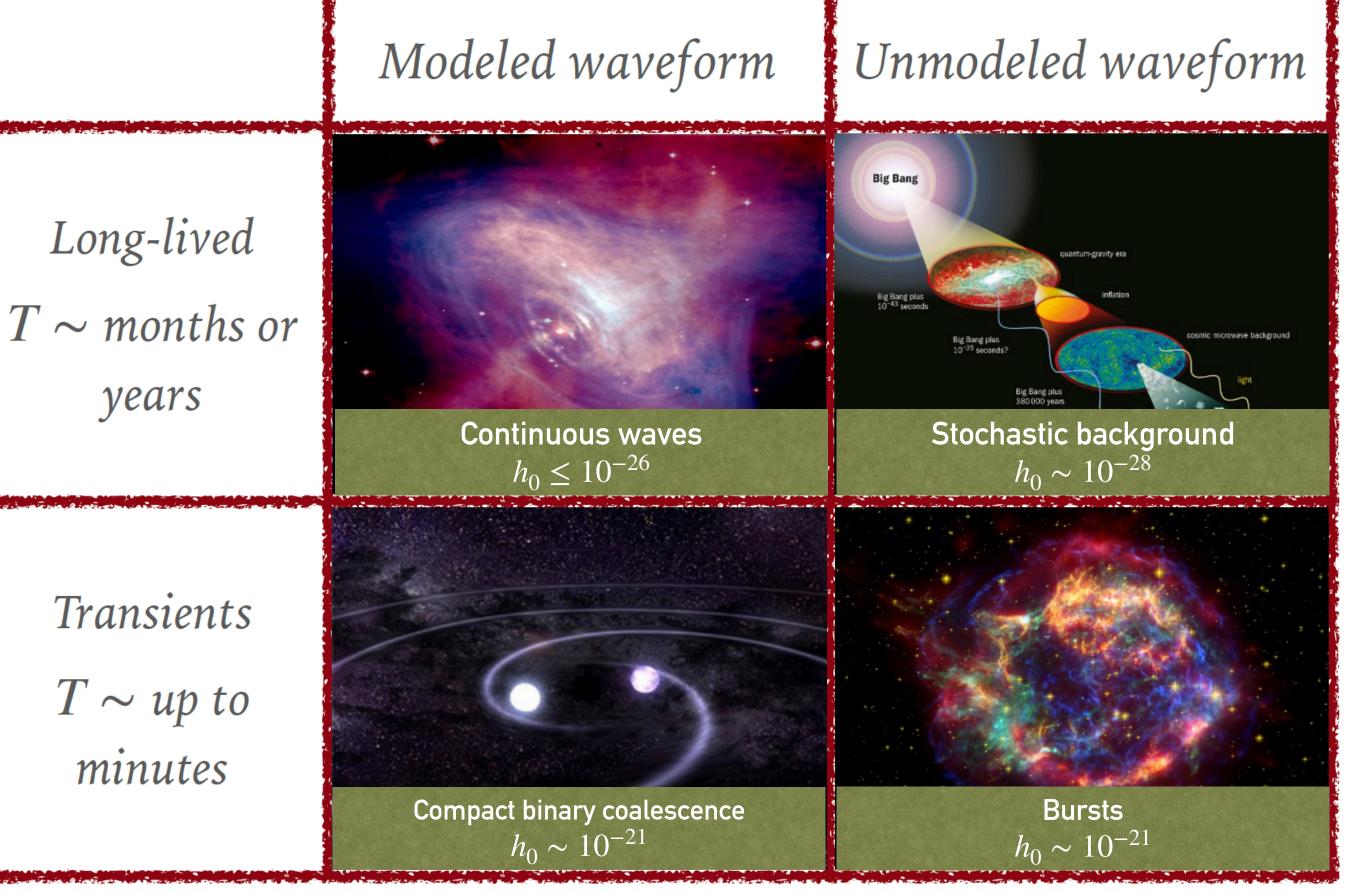
Long-lived

years

- Ripples of the spacetime, predicted by General Relativity (GR)
- Produced by non-axisimmetric accelerating masses
- A wave with 2 polarizations (+,x)



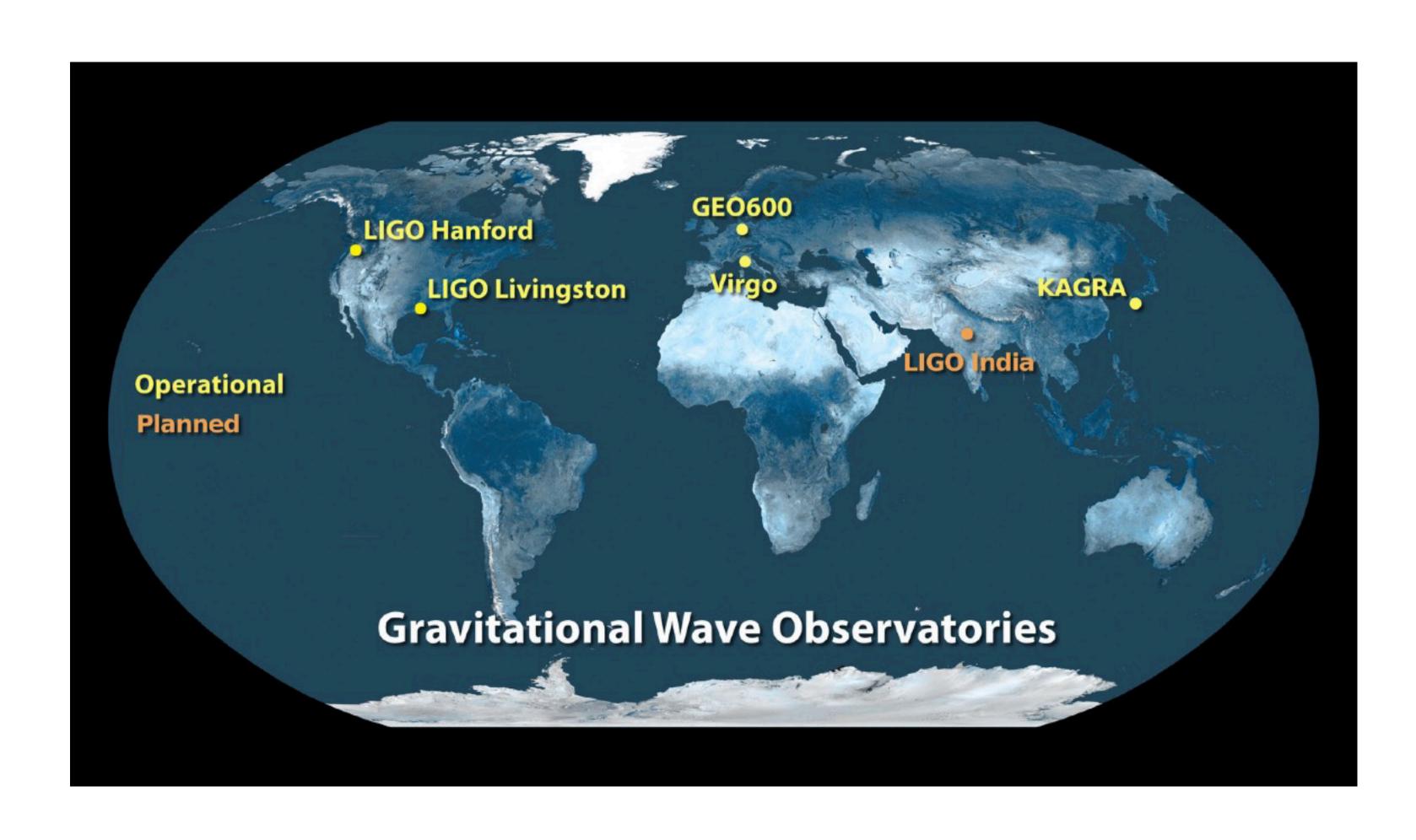
- Traveling at the speed of light
- Relative displacement between test masses can be measured



Transients $T \sim up to$ minutes

$$h \sim \frac{\Delta L}{L} \sim 10^{-21}$$

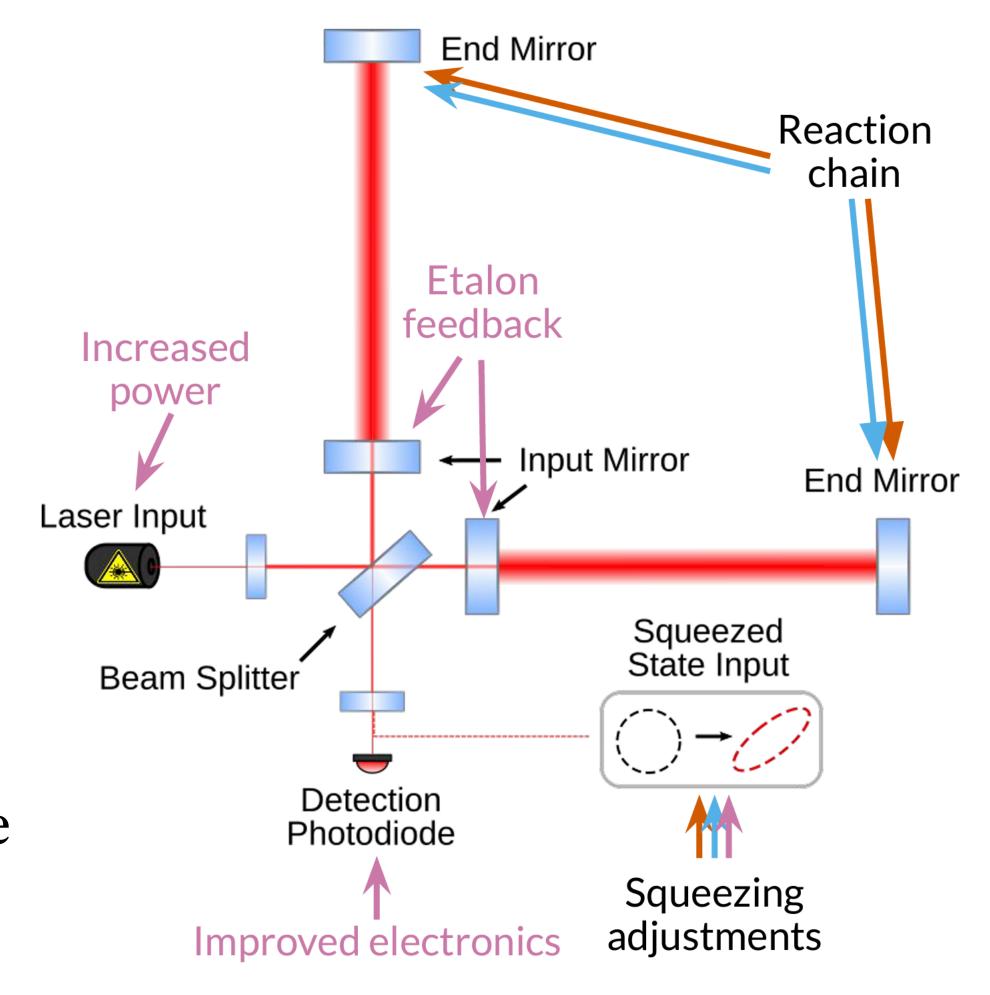
The network of GW detectors



- increases detection confidence
- improves sky localization
- allows for polarization determination
- improves source parameters inference
- O3: April 2019 March2020 [O3a,O3b]

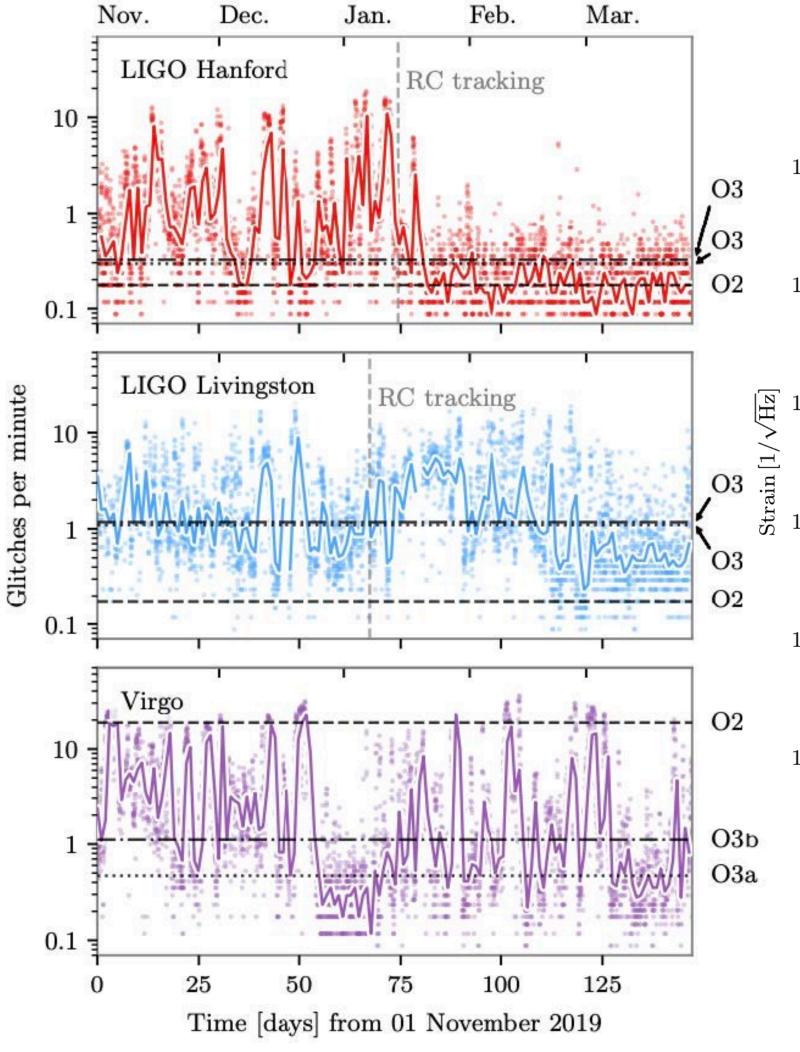
Ground-based GW detectors

- From O2 to O3a the main improvements were:
 - adjustment of in-vacuum *squeezing* for LIGO Hanford and Livingston
 - increase of *laser power* for Virgo
- After October commissioning break:
 - LIGO: Adjustments to the *squeezing* subsystem and reduction of *scattered light* noise; mplementation of reaction-chain tracking
 - Virgo: Increased *laser power*; improved electronics, alignment, squeezing and software

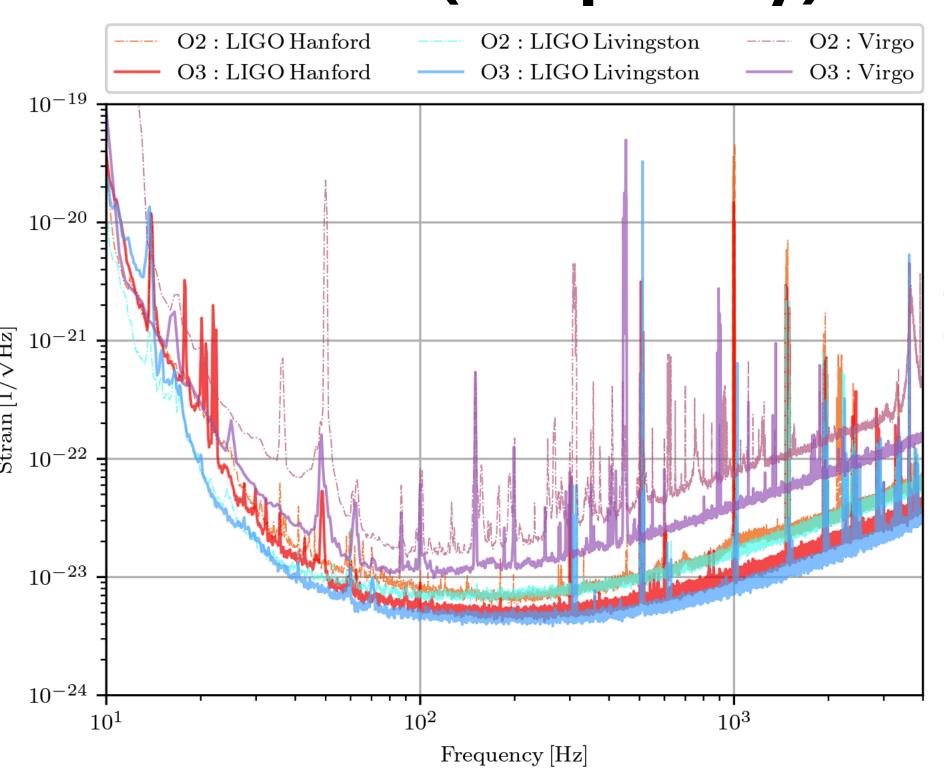


Data quality

glitches (time)

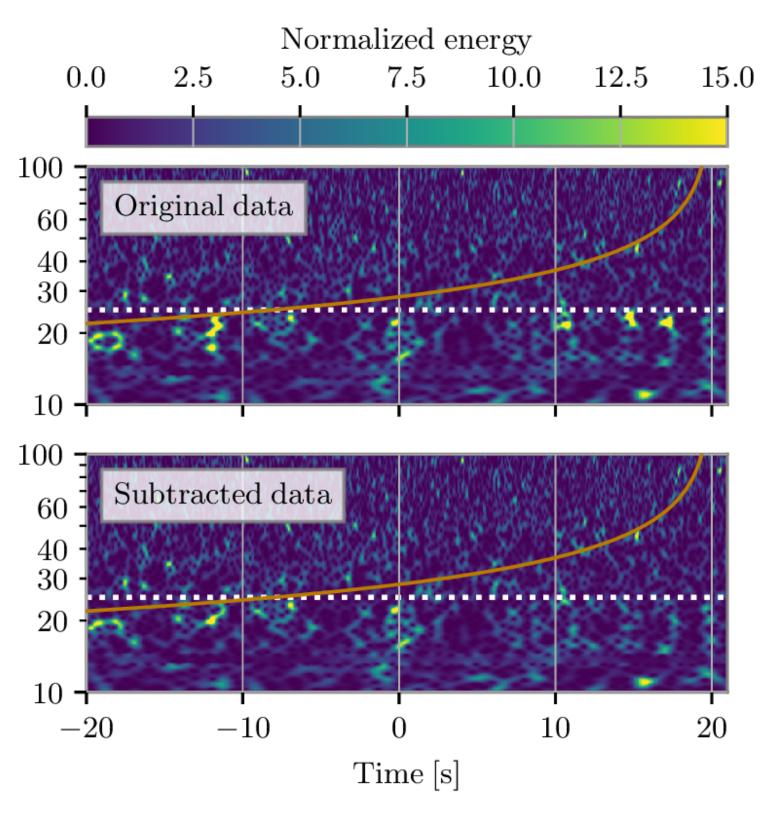


lines (frequency)



Davis et al., arXiv:2101.11673 (2021), LVK, 2111.03606 (2021), Virgo, arXiv:2205.01555 (2022)

an example of GW event impacted by glitches

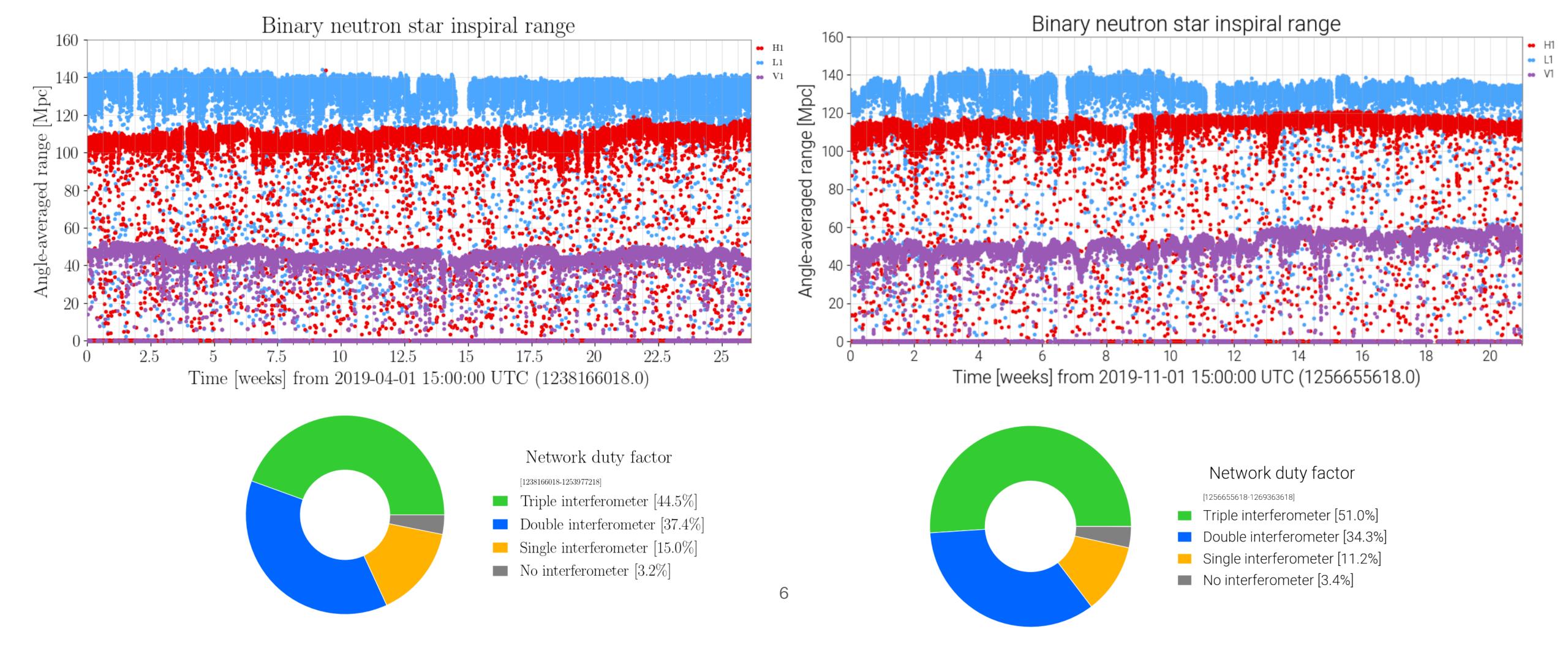


GW200115_042309

O3 run

GWOSC https://www.gw-openscience.org

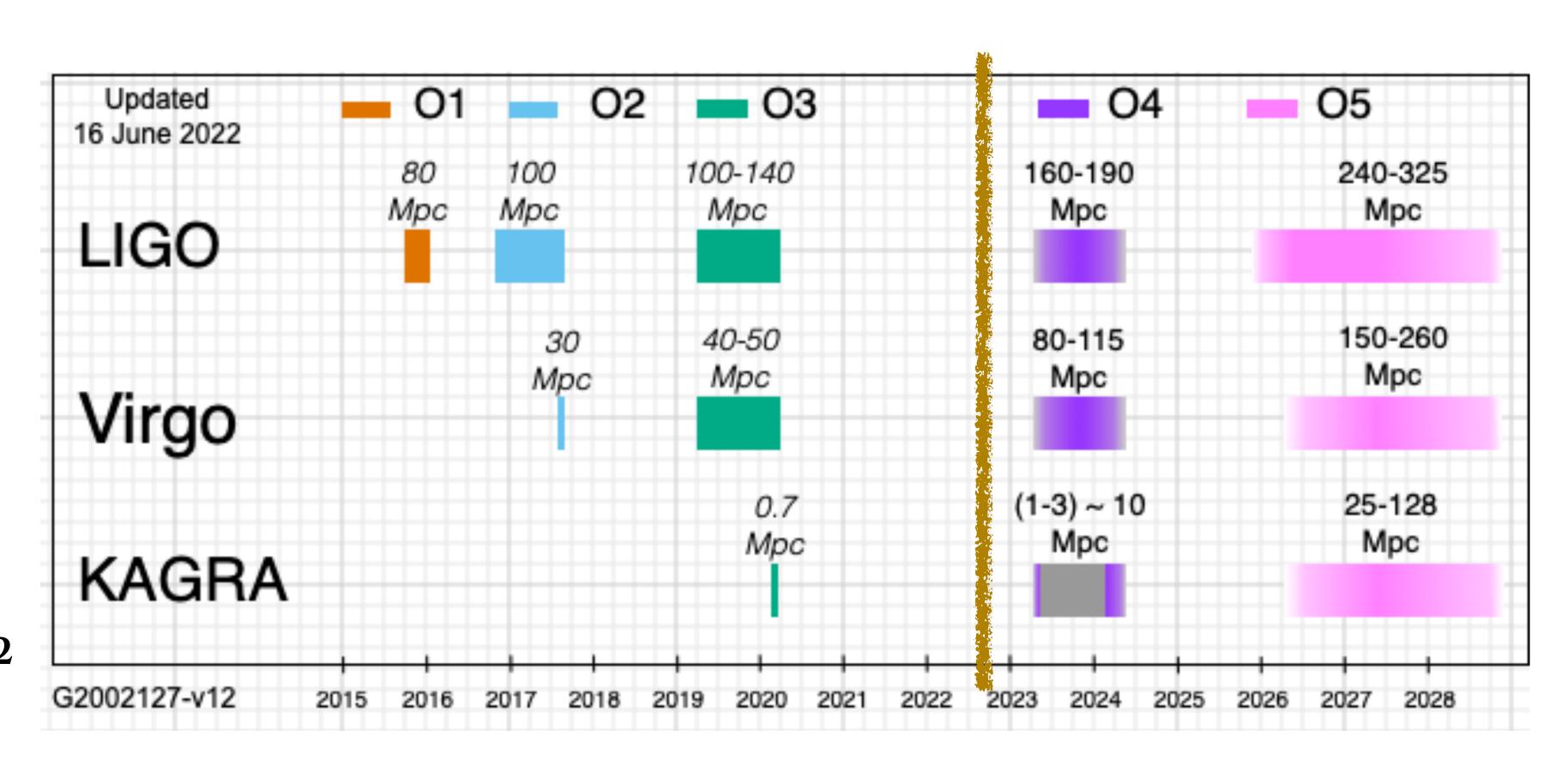




Observing runs timeline

- O3 is concluded
- O4 preparation is ongoing
- New run expected for April 2023

O4 rate (CBC) ~ 1/2days

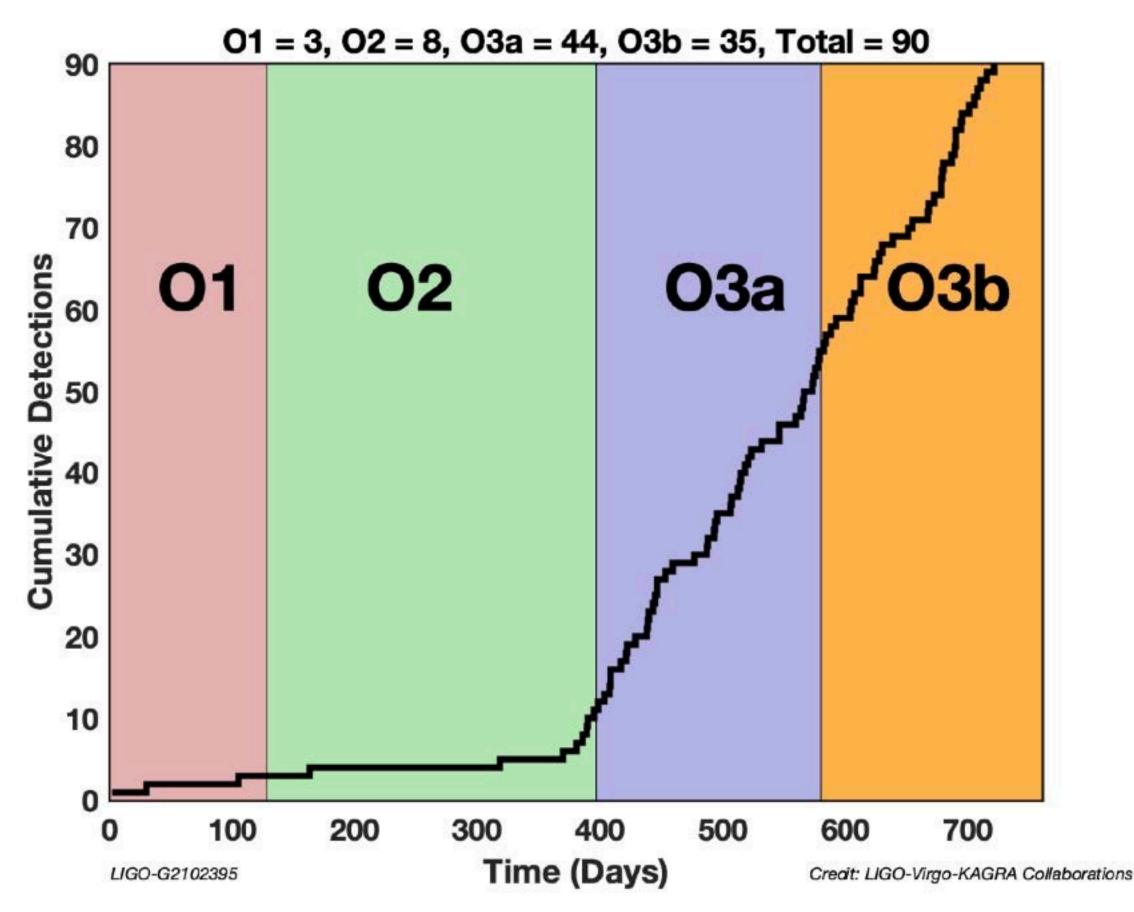


Observing plans updates here: https://observing.docs.ligo.org/plan/

GW observations and catalogues

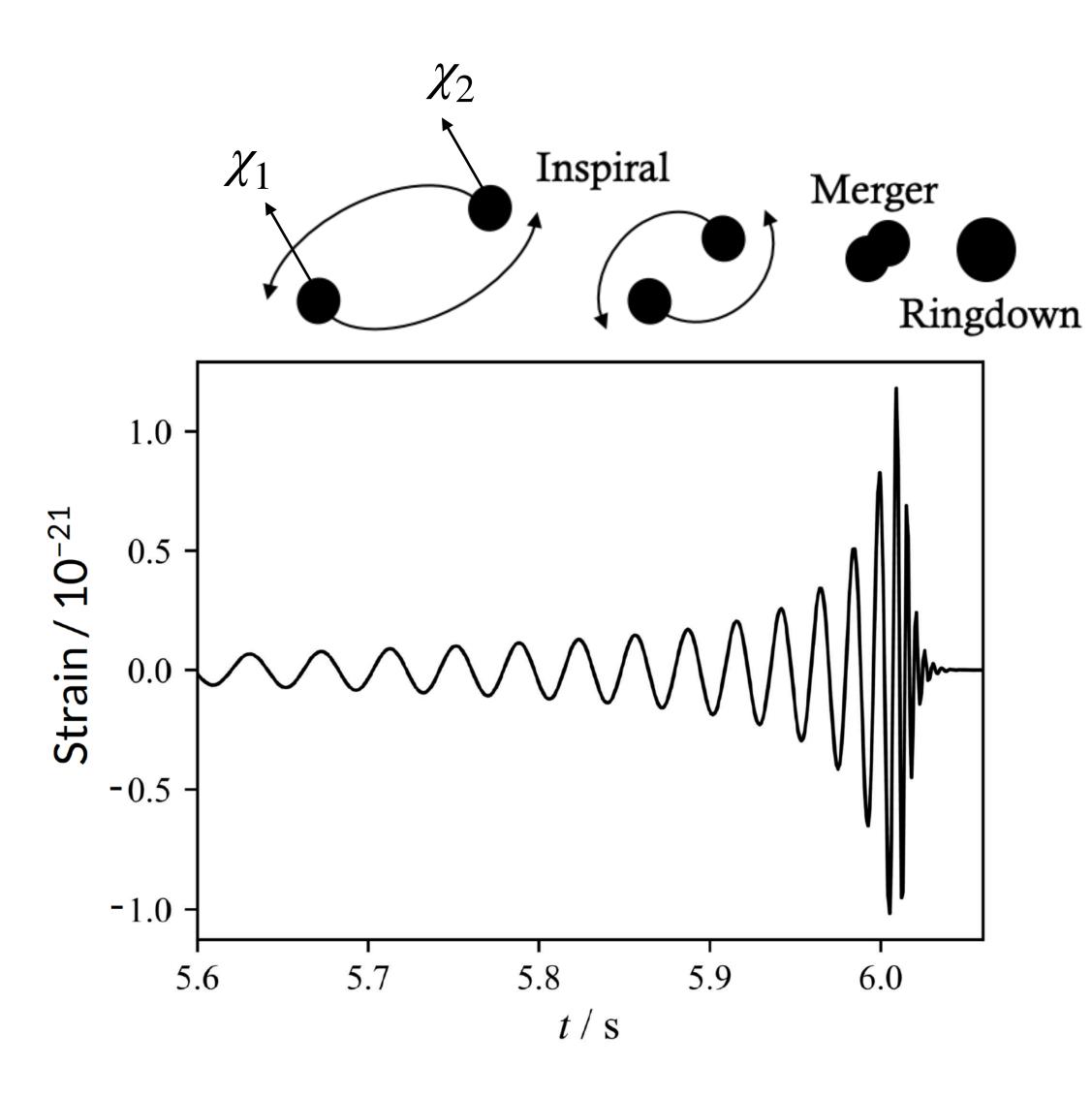
- GWTC-1 (O1 & O2):
 11 GW events including the first GW discovery and first BNS
- GWTC-2 & GWTC-2.1 (O3a): 44 new GW events
- GWTC-3 (O3b):
 35 new GW events

all coalescing binaries



O3 detection rate ~ 1 event every 5 days

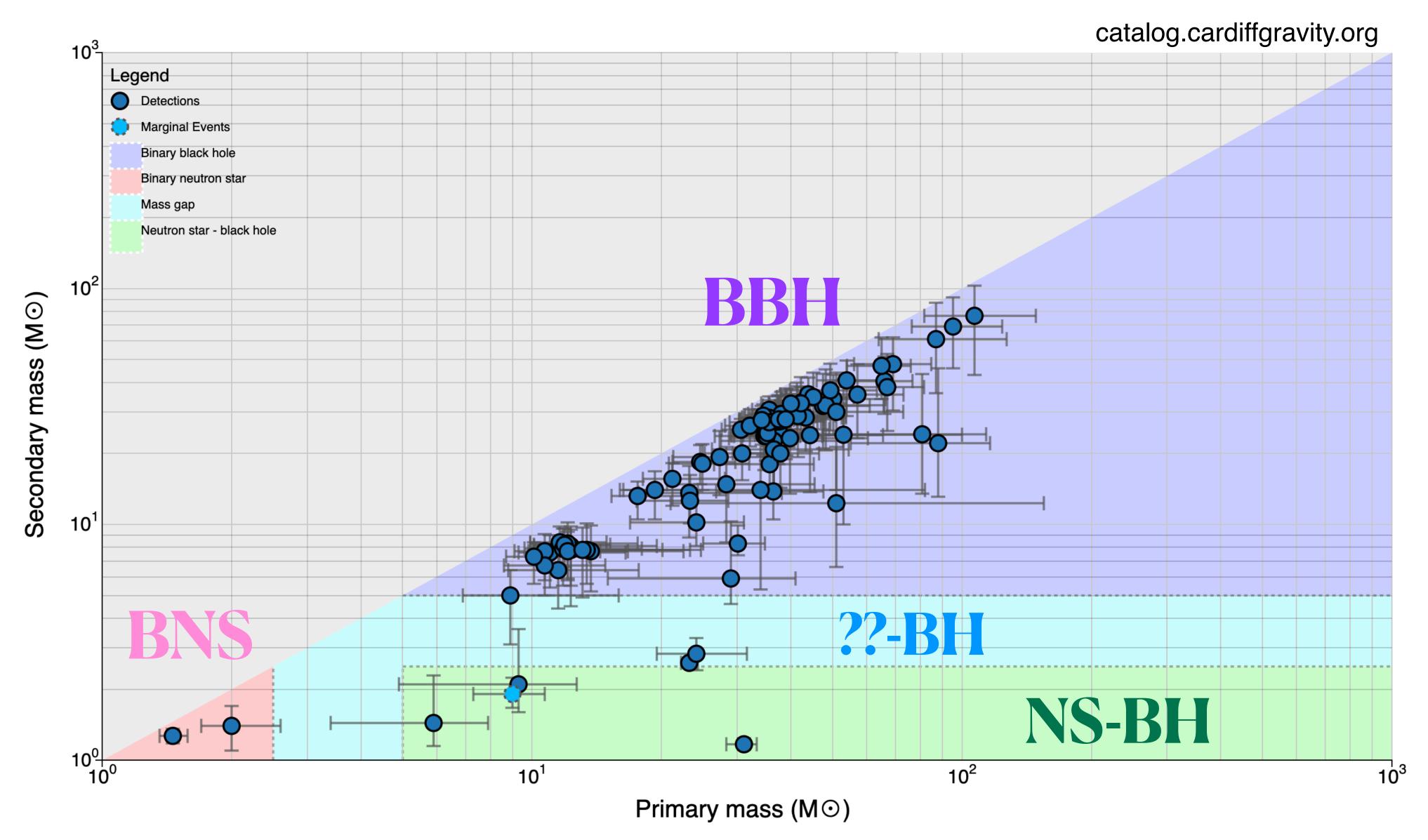
Compact binaries coalescences



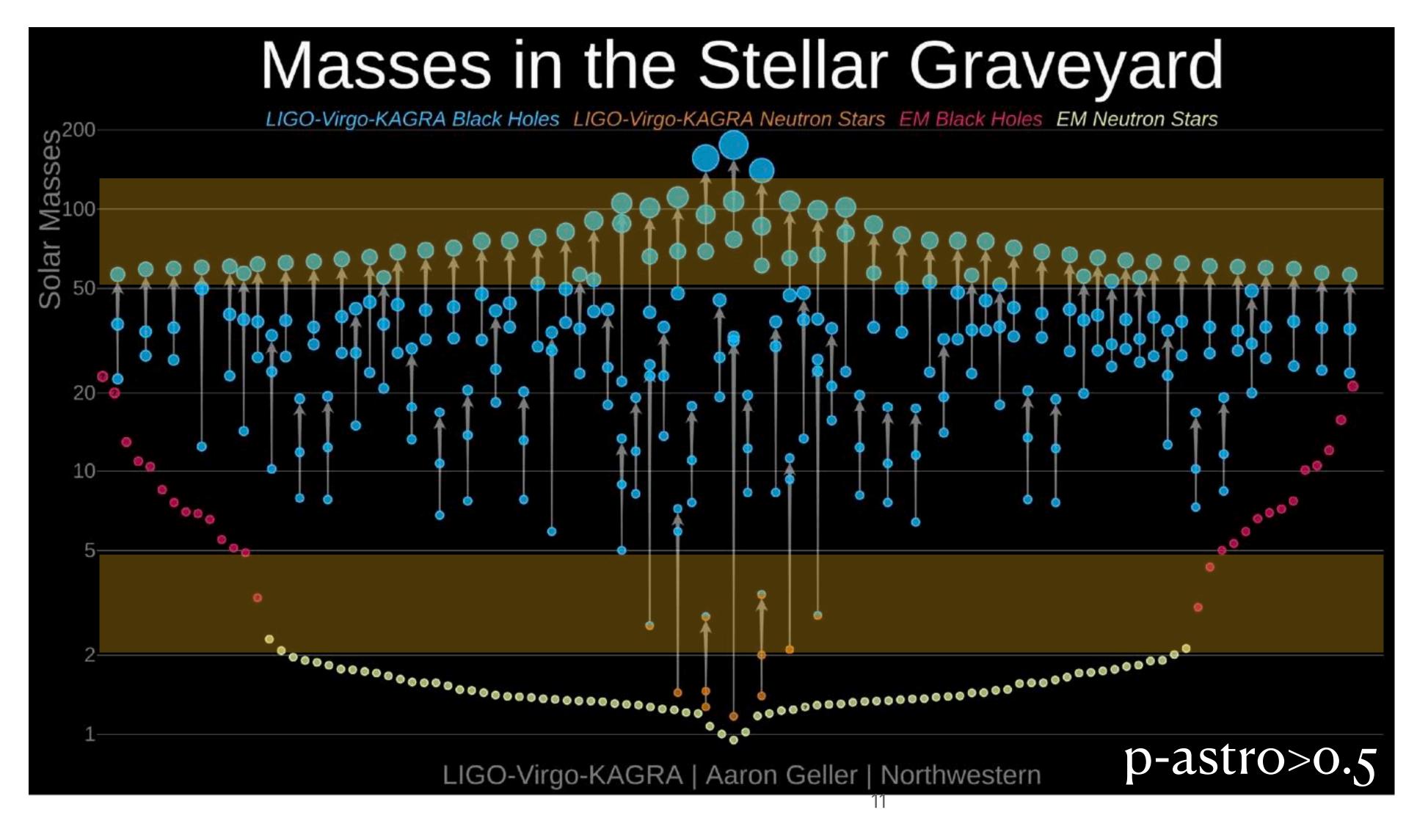
- Short-lived signals produced by a pair of compact objects (BH, NS)
- Electromagnetic emission might be present e.g if one NS
- Typical search methods include matched-filter and/or minimally modeled searches
- Parameter estimation like:
 - Masses: chirp mass, total mass, mass ratio
 - Spins
 - Distance
 - Energy dissipated
 - Geometry and polarization

$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}\,.$$
 $\chi_{\mathrm{eff}} = rac{(m_1 oldsymbol{\chi_1} + m_2 oldsymbol{\chi_2}) \cdot \hat{oldsymbol{L}}}{m_1 + m_2},$ $q = m_2/m_1$

GW events masses

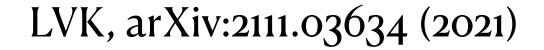


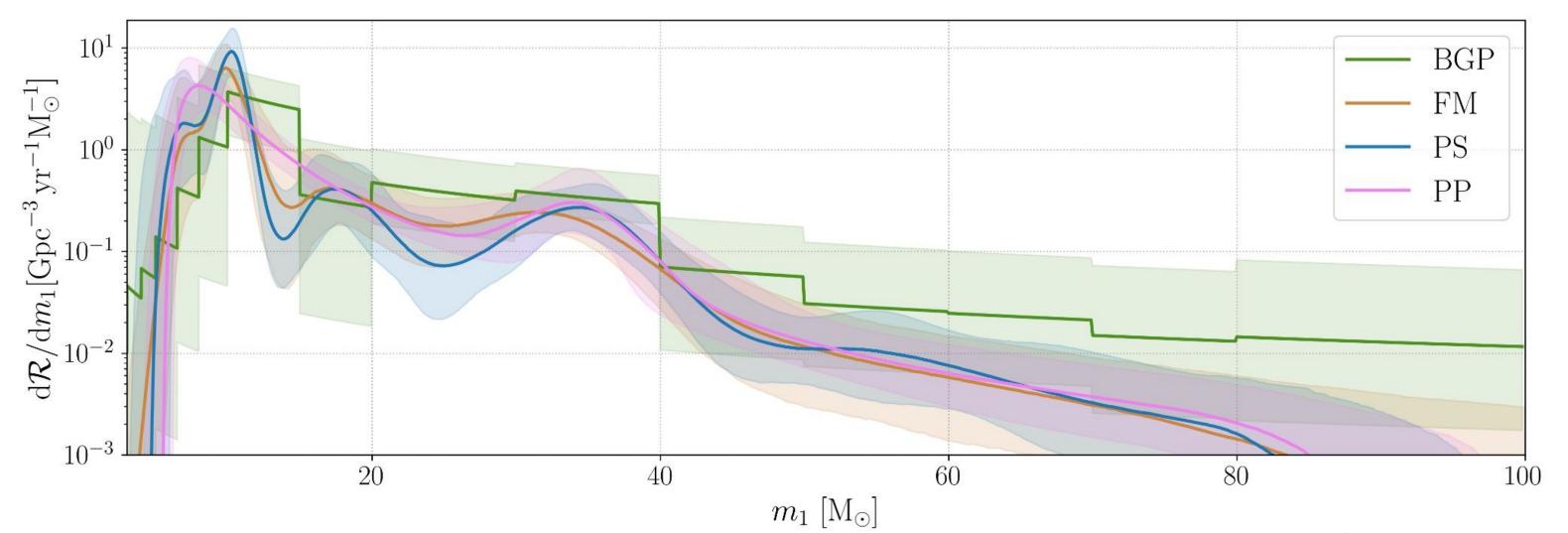
GW events masses



- Black holes exist in pair instability mass gap
- Compact objects
 exist with masses
 between 2-5 M_☉

BBH population

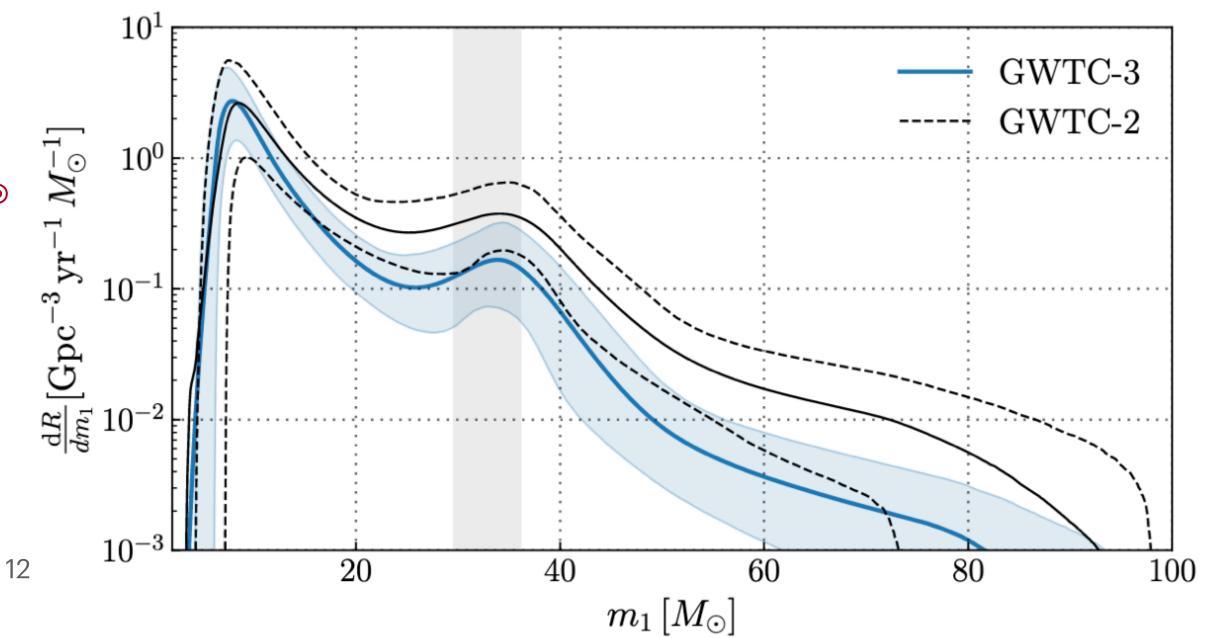




Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model

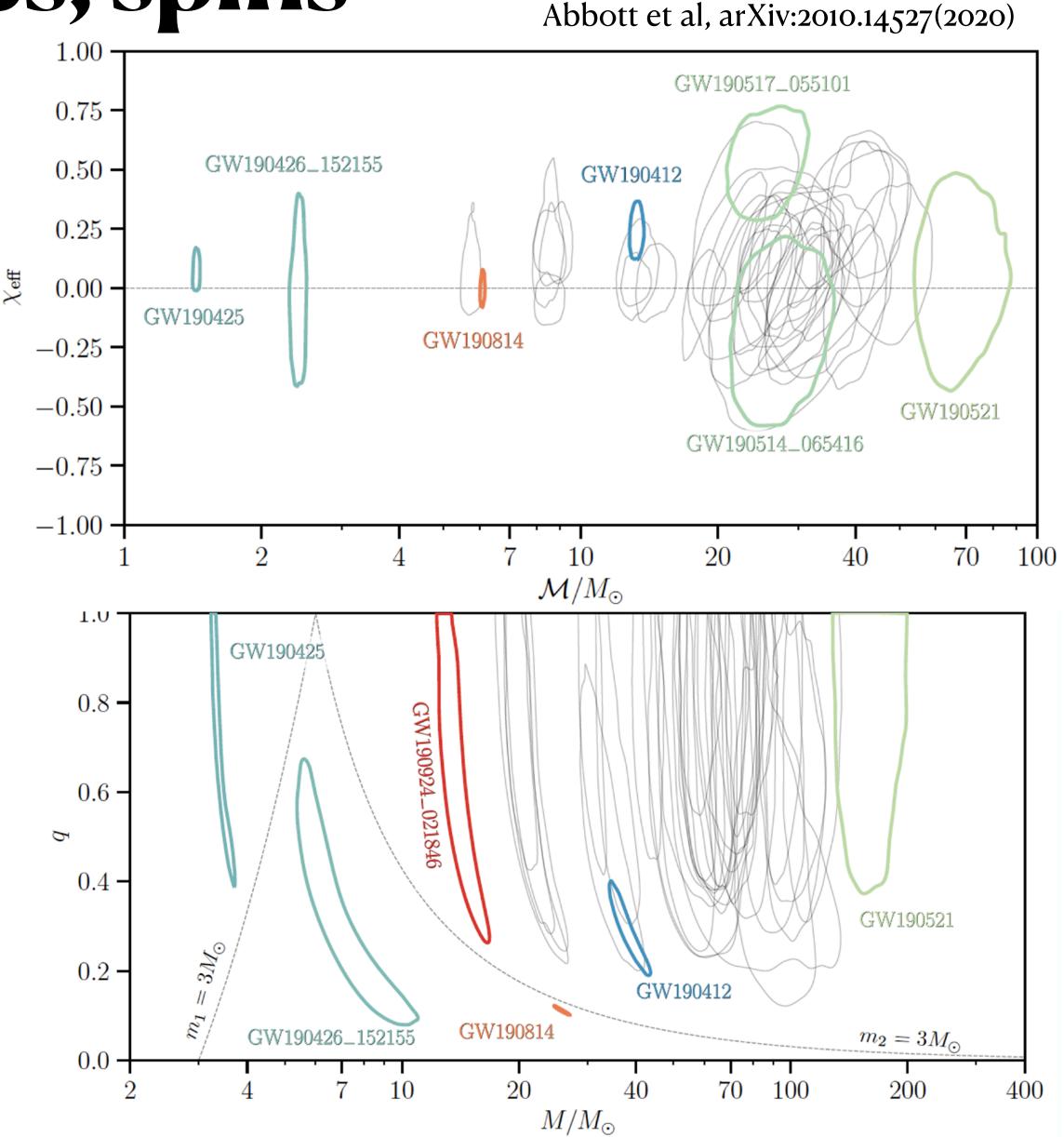
- 1) Observation of a mass feature at 34 M $_{\odot}$ and ~11 M $_{\odot}$
- 2) No identification of a clear upper mass cut-off.

distributions for the fiducial PP model consistent between GWTC-3 and GWTC-2

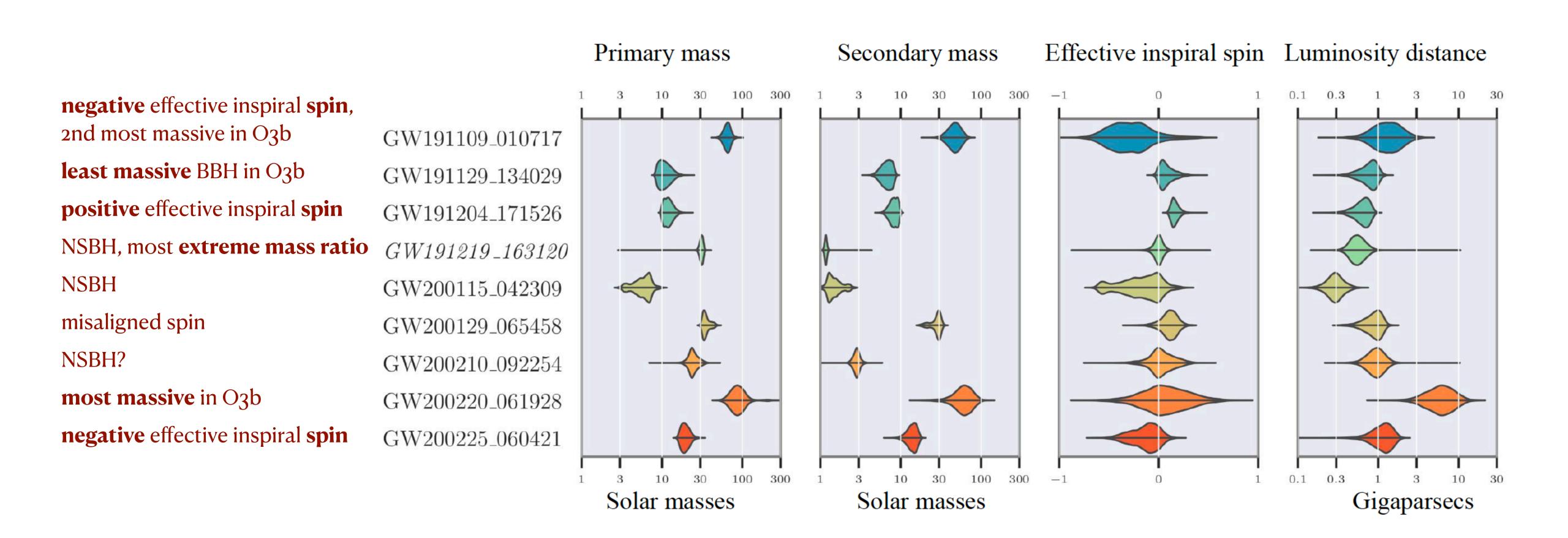


O3a masses, spins

- Higher BH masses seem to support higher spin magnitudes.
- Evidence for a preference of BHs spins aligned with the orbital angular momentum
- Spin magnitude seems to correlate with mass ratio



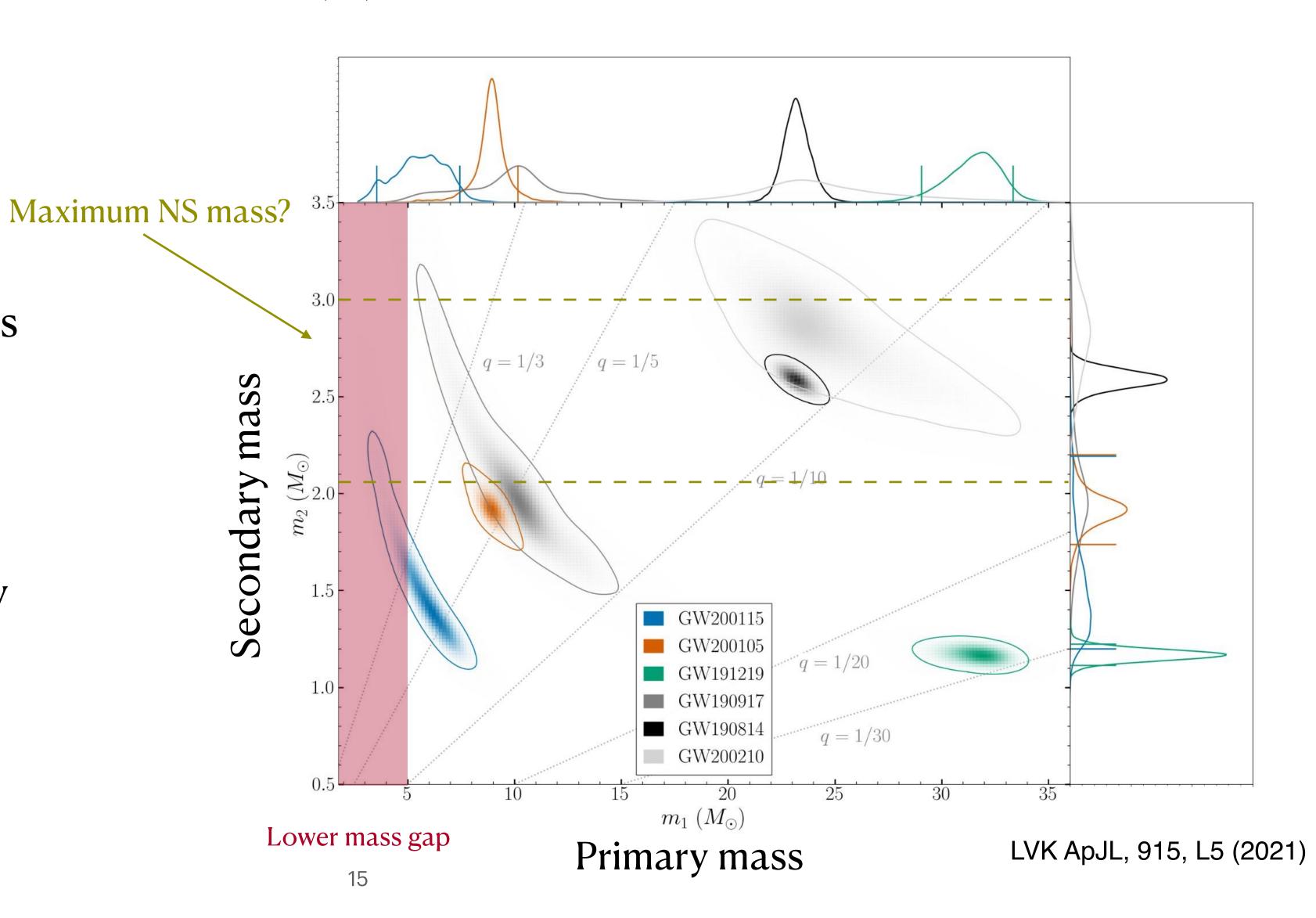
O3b, masses, spins,...



NS-BH(?) masses

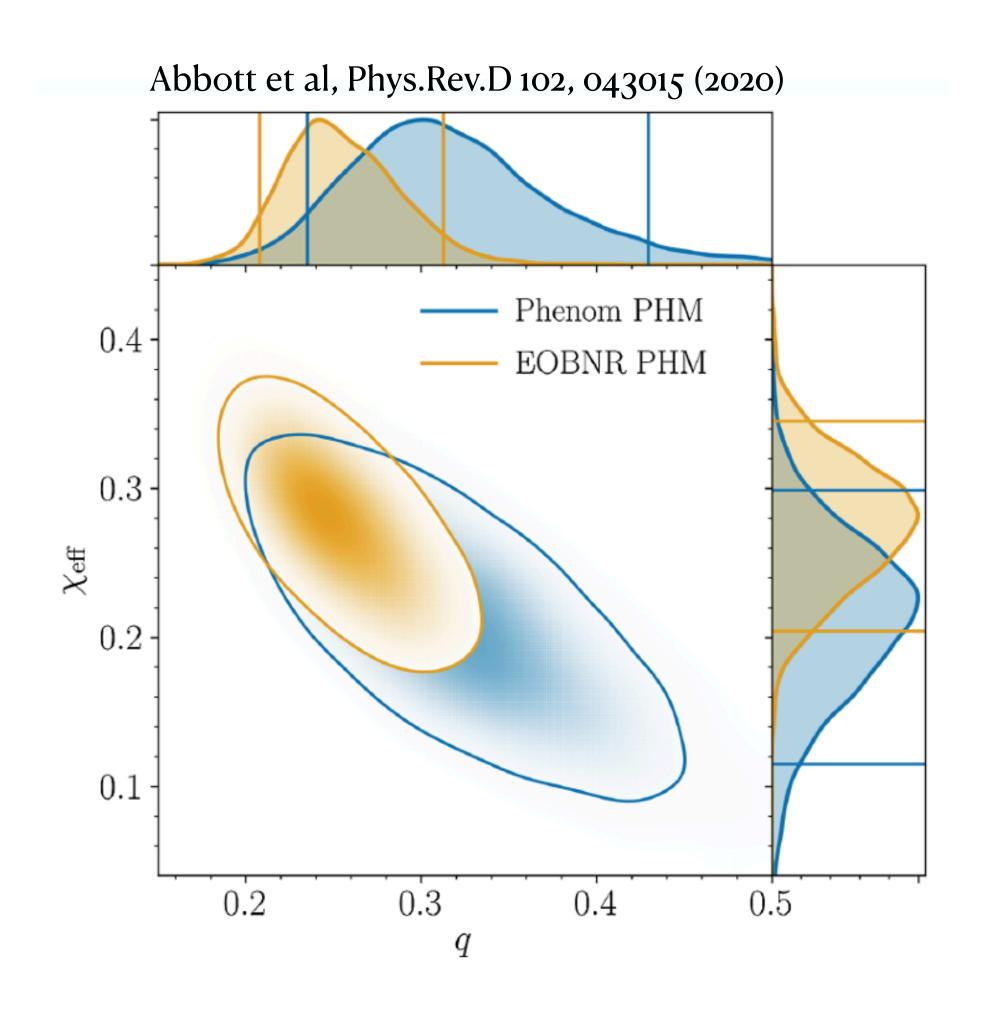
GW200105 Ma GW191219 are consistent with NS-BHs pairs

Grey events are ambiguous, with secondary mass that may be a BH or a NS



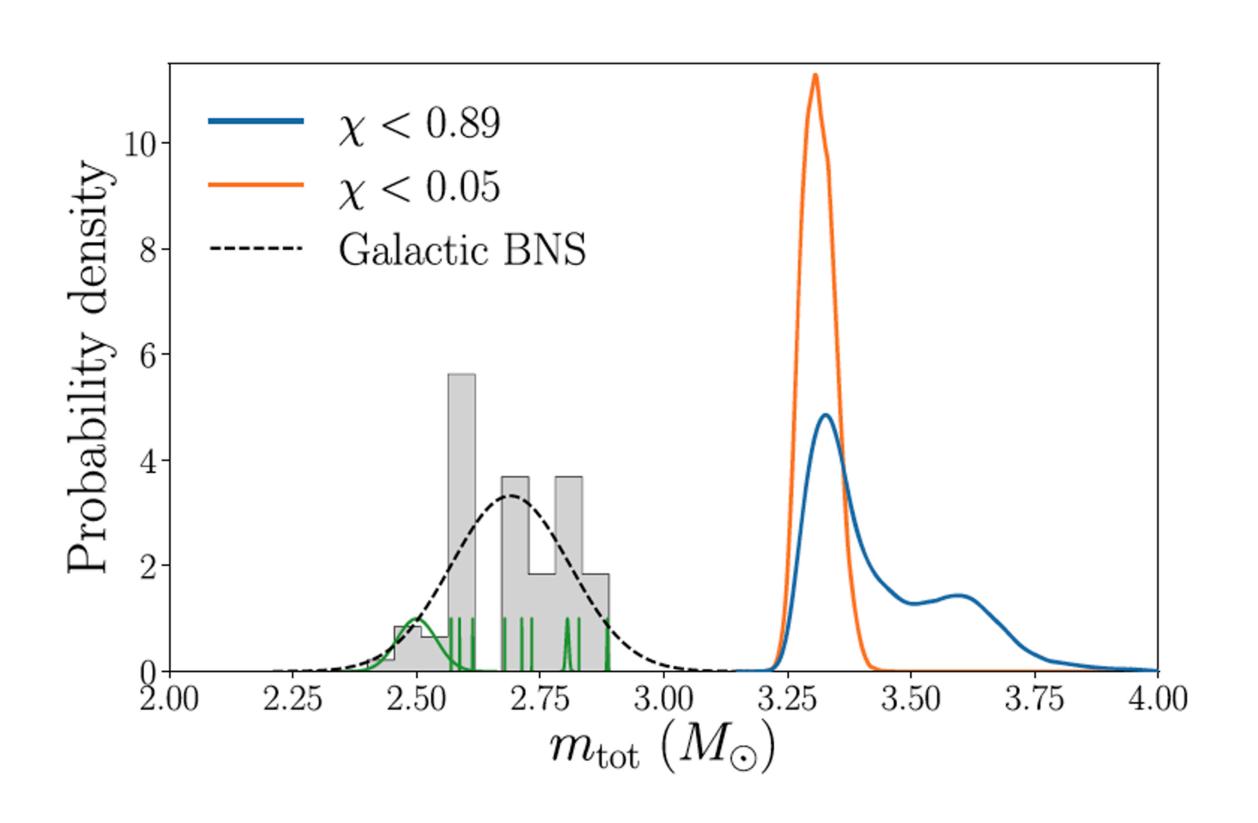
a merger of unequal-mass BHs

- BBH with $(m_1, m_2) = (30, 8) M_{\odot}$
- $D_L = 740 \text{ Mpc}$, z = 0.15
- not necessarily the most unequal mass merger in O3 with $m_2 > 3M_{\odot}$ (because of broad q mass ratio posteriors on other events.)
- Mild evidence for spin precession
- First evidence of higher order multipoles as predicted by GR



a merger involving a massive NS

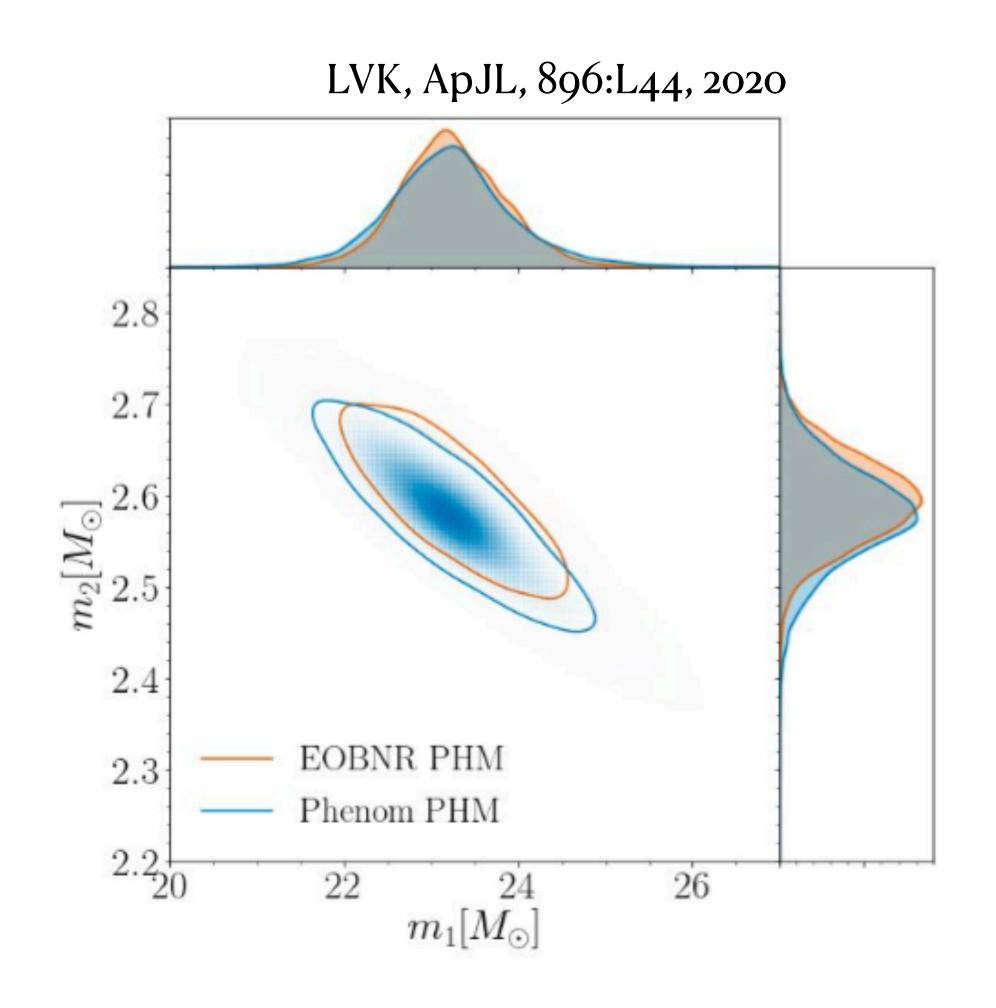
- Both components of mass < 3M_☉
- Consistent with binary neutron star merger (but might be BBH or NSBH)
- Total mass of 3.4 M_☉
- Masses significantly larger than any other known BNS
- sky localization poor, no EM
- only LIGO L and Virgo
- Negligible spins favored by data



LVK, ApJ Letters 892, L3 (2020)

Maybe the first observed NSBH merger, 23M_® and 2.6 M_®

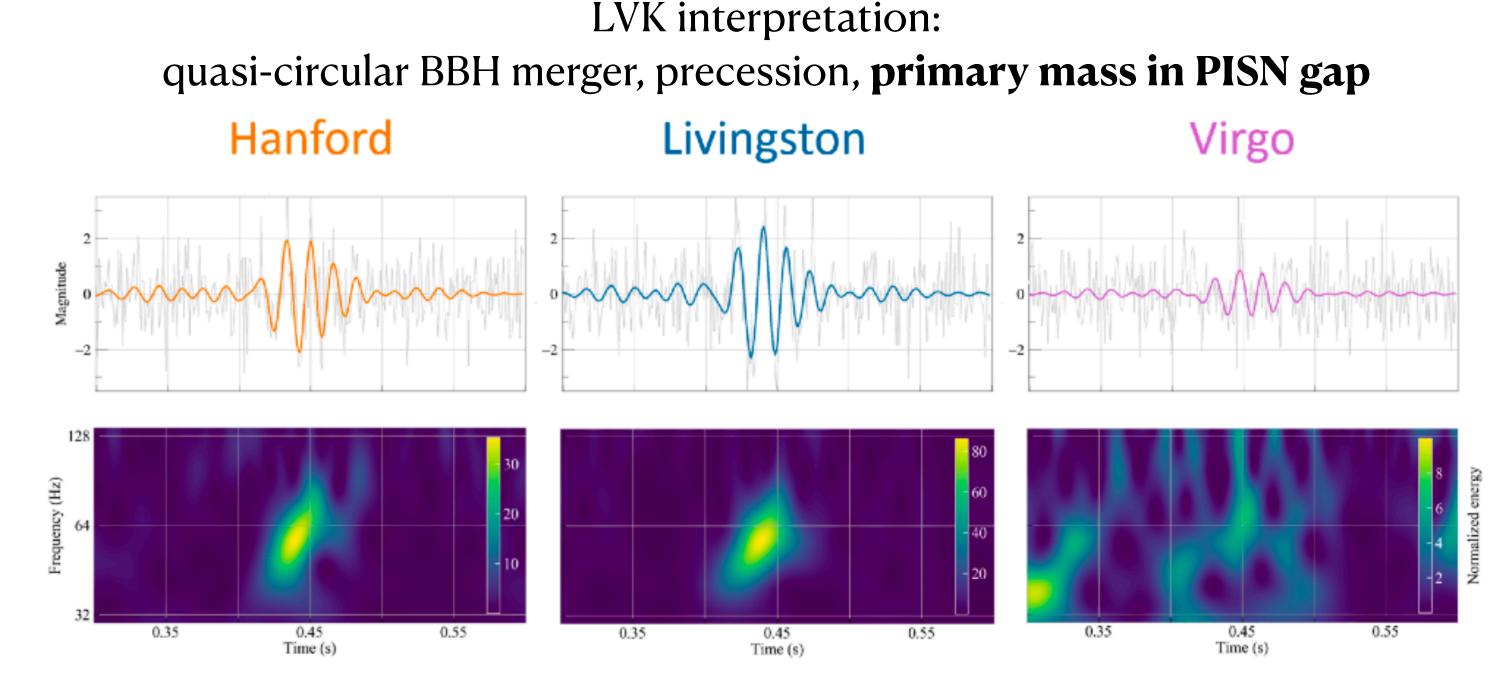
- $m_2 < 3 M_{\odot}$, spin of the most massive object constrained to near zero.
- 3 detector (L,H,V) observation with network SNR of 25.
- Well localized event but no EM counterpart
- Asymmetric masses (9:1 ratio)
- No clear evidence of tides on inspiral
- Nature of compact object in the mass gap: NS or BH?



a merger of remarkably massive BH

(LVC, PRL, 125, 101102 (2020))

- A BBH with a total mass of 150 M_☉
- First observation of an intermediate mass BH (M_{\odot} >100)
- Mild evidence for spin precession
- Farthest source observed so far (z~0.8)



• Can be interpreted as a BBH (e.g. Romero-Shaw+ 2020: weakly eccentric BBH merger) or something else, including DM origin (Calderón-Bustillo+ 2021: collisions of boson stars; De Luca+ 2021: PBH origin)

LVK, 2112.06861 (2021)

Testing GR

- The model waveform is constructed using the predictions of GR.
- Gravitational-wave sources can be used to probe strong-field, dynamical and nonlinear aspects of gravity
- Tests predictions of GR are performed by:
- introducing small modifications to our waveform models and compare the data with these waveforms
- Three theory-agnostic tests (parameterized tests, inspiral-merger-ringdown consistency tests, and gravitational-wave propagation tests) have been done

Testing GR

LVK, 2112.06861 (2021)

Tests	Question to answer	Description	Results
Residual Test	Are the residual consistent with detector noise?	Subtracts the best-fit GR waveform from the data and asks whether there is any statistically significant residual power.	No evidence for violation of GR
Parametrized test $\varphi_{\rm PN}(f) = 2\pi f t_{\rm c} - \varphi_{\rm c} - \frac{\pi}{4} +$	Is the inspiral phase consistent with GR? $\frac{3}{128\eta} (\pi \tilde{f})^{-5/3} \sum_{i=0}^{r} \left[\varphi_i + \varphi_{il} \log(\pi \tilde{f}) \right] (\pi \tilde{f})^{i/3}$	framework. PN coefficients: measurable parameters of the waveform —> sensible	

Testing GR

LVK, 2112.06861 (2021)

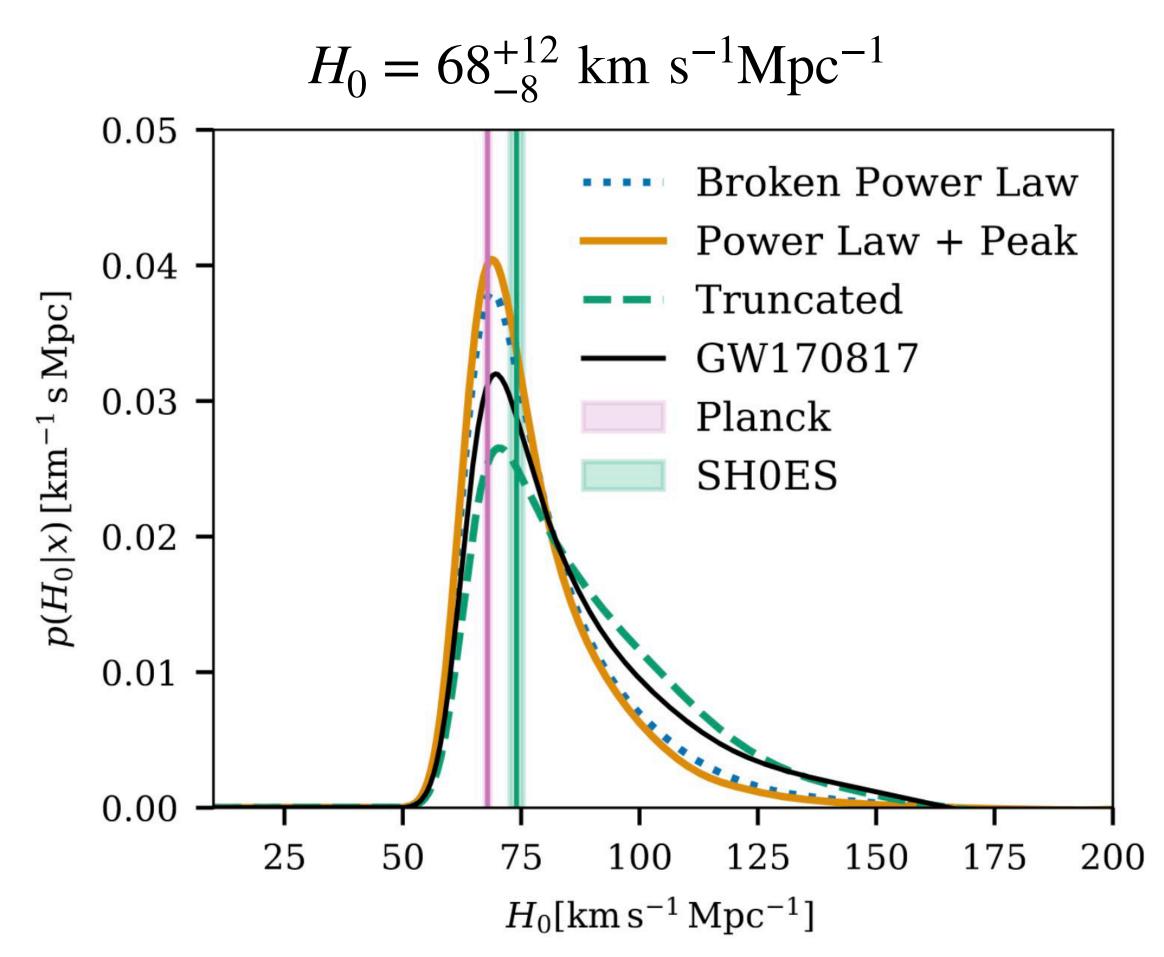
Tests	Question to answer	Description	Results
Modified dispersion	Modified theory predict dispersion of GW	Affect the morphology of the signal —> effective dephasing of the GW signal can be measured. $E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$ Different choices of α —> leads to a deviation in the GR phasing formula. Mass of the graviton : $m_g = \sqrt{A_0/c^2}$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$
Test for GW echoes	If the merger remnant is not a classical BH but an exotic compact object without an event horizon but a reflective surface	Search for post-merger echoes in a morphology independent way.	No evidence for echoes

Testing GR

- Many more tests of General Relativity have been done:
 - Spin-induced quadrupole moment test
 - GW polarizations test
 - BH remnant test
 - Ringdown test
 - •
- Found no statistically significant evidences for any deviation from GR
- Update limits on deformation parameters in the case of parametrized tests
- Testing GR is very hard, even if a deformation is found:
 - is the deformation due to non-GR?
 - Are we considering all possible models?
 - Are (GR-)waveform built in the most precise way?

Cosmology with GW-GWTC-3

- A previous measure of the Hubble constant with GW170817
- New: 47 GW signals from GWTC-3
 - Each GW signal provides luminosity distance.
 - Redshift estimated with GLADE+ galaxy catalog.
- Assuming a fixed BBH population yields Improvement of 42% w.r.t. GWTC-1 and 20% w.r.t. GWTC-2



Other searches

Other searches conducted during O3:

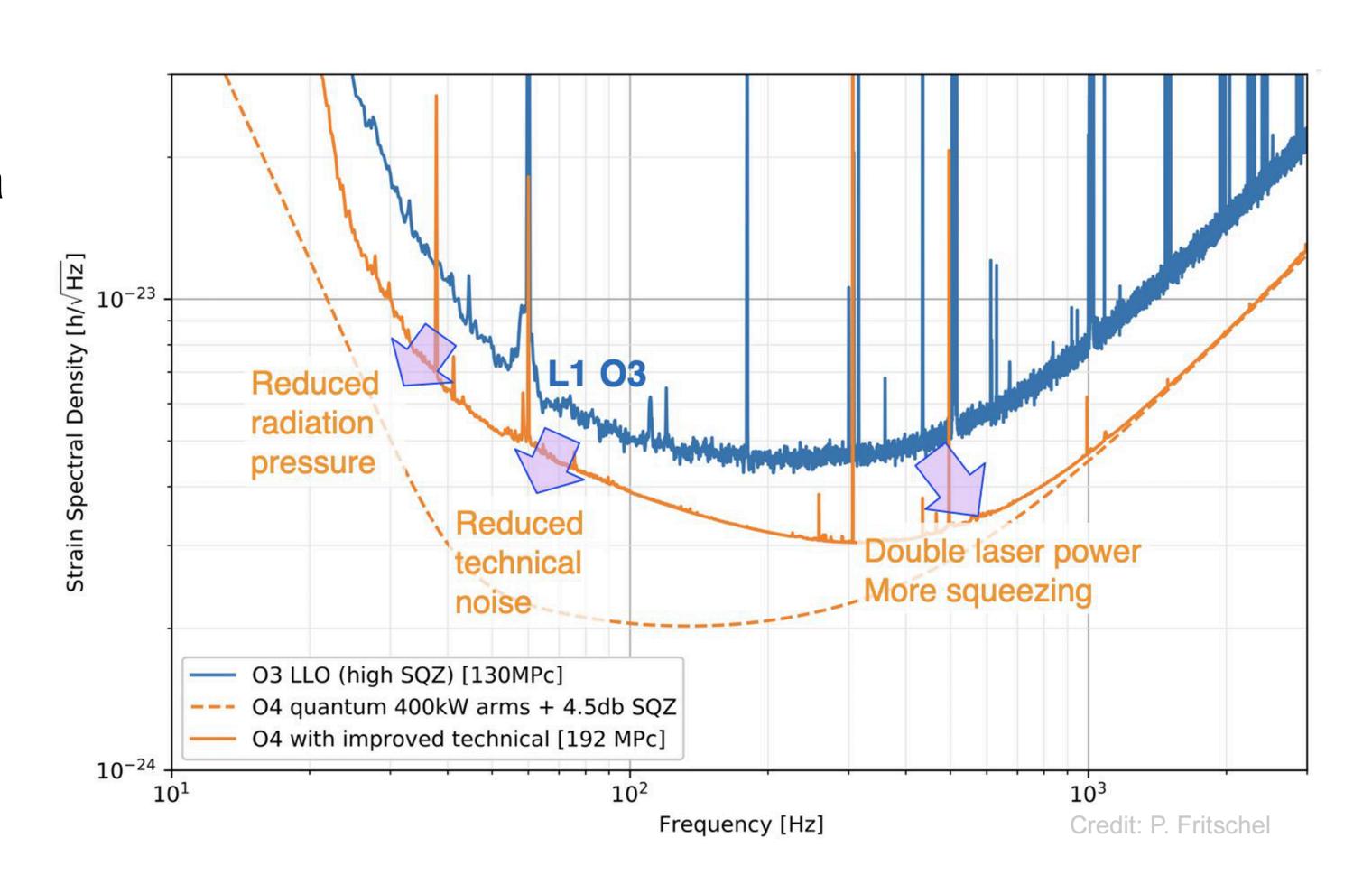
- Continuous wave searches: mountains or r-mode oscillations in isolated spinning neutron stars (including SNR) or accreting systems (LVK, arXiv:2107.00600, PRD 106, 042003, Apj 921 80 (2021))
- Short and long burst searches: f-mode oscillations in pulsar glitches and CCSN (LVK, arXiv:2107.03701); non-axisymmetric deformations in magnetars and eccentric binary mergers (LVK, arXiv:2107.13796); GRB searchers (with Fermi and Swift) (ApJ, 915, 86 (2021))
- Stochastic GW searches (LVK, PRD, 104, 022004 (2021); PRD, 104, 022005 (2021))
- Cosmic strings (LVK, PRL, 126, 241102 (2021))
- Lensed GW signals (LVK, arXiv:2105.06384)
- Dark matter searches:
 - Direct search for sub-solar mass BHs (LVK, arXiv:2109.12197)
 - Direct search for ultralight scalar boson clouds around Kerr BHs (LVK, PRD, 105, 102001 (2022))
 - Constraints on the existence of dark photons (LVK, arXiv:2105.13085)

No new detections reported, but present updated and stringent upper limits of different physical quantities

Beyond O3: detector upgrades

LIGO upgrades include

- Doubling arm power (~200 kW in O3)
- New filter cavity for frequency dependent squeezing (and more efficient)
- Low frequency technical noise reduction <100 Hz (scattered light, control noise, electronics)



Beyond O3: detector upgrades

O4high 33W: 92 Mpc O4high 33W-NOSQZ: 82 Mpc

O4low 33W-NOSQZ: 91 Mpc

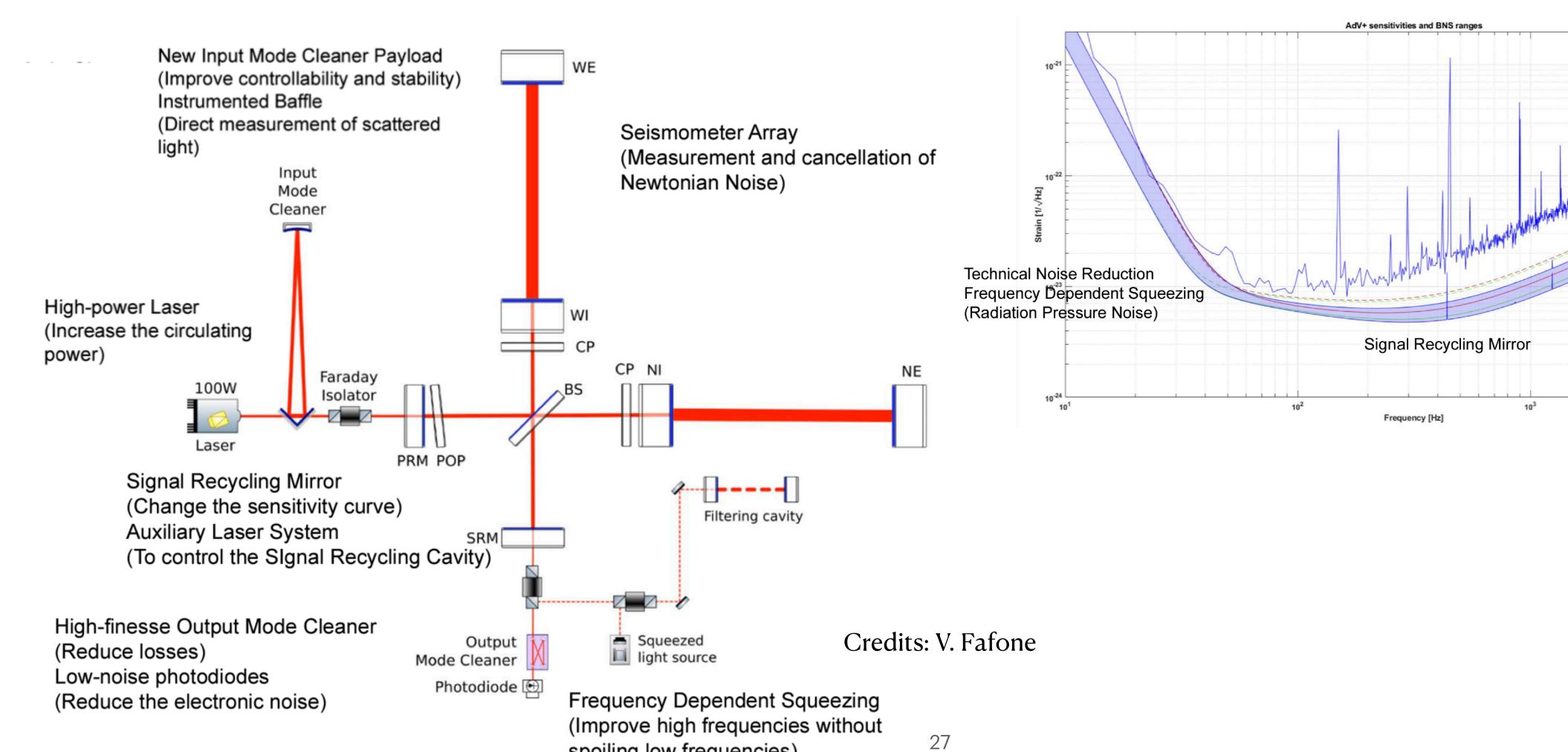
Signal Recycling Mirror

Frequency Dependent Squeezing

Input Power increase

(Shot Noise)

Virgo upgrades:

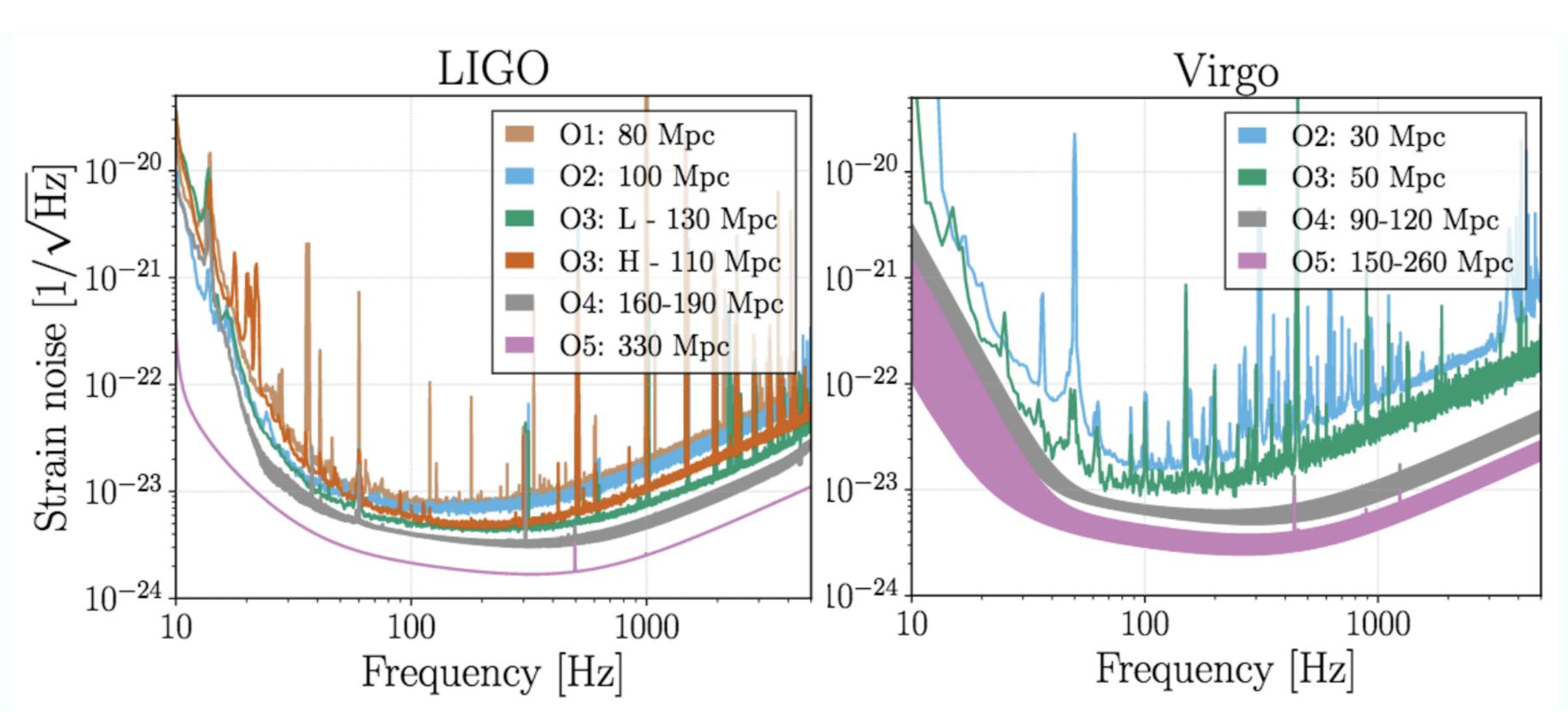


spoiling low frequencies)

What to expect in 04

Observing scenarios

LVK, DCC-P1200087 (Observing Scenarios)



BNS:

Estimated O₄ detection rate for LHVK network: 0-62 (90%)

Estimated median localisation: 33 deg²

NSBH:

Estimated O4 detection rate for LHVK network: 0-92 (90%)

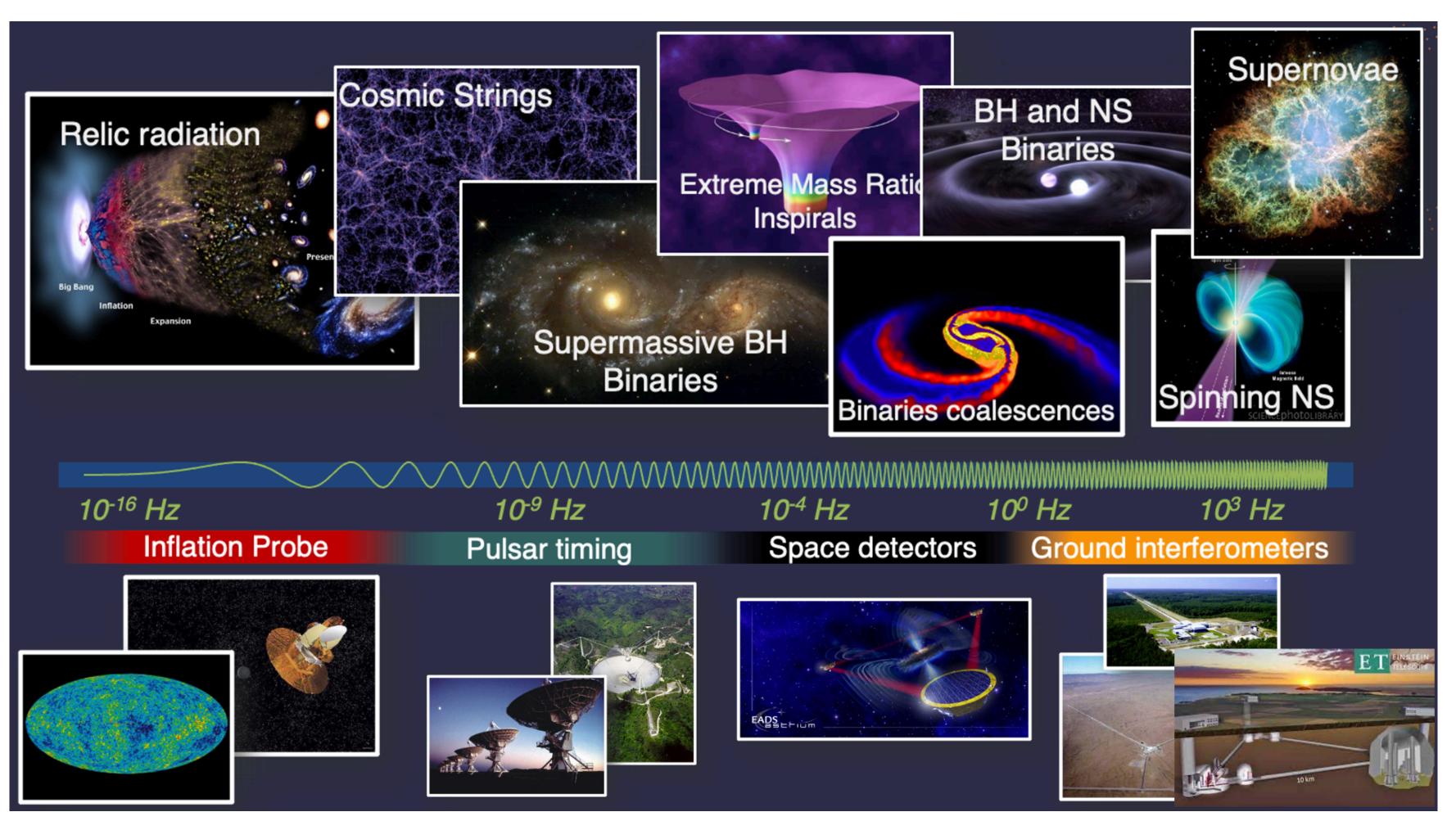
Estimated median localisation: 50 deg²

BBH:

Estimated O4 detection rate for LHVK network: 35-168 (90%)

Estimated median localisation: 41 deg²

The future of GW astronomy



- 3G Earth-based detectors
 - Einstein Telescope
 - Cosmic Explorer
- improvements of current the detectors
- improvement of DA techniques
- widen the possibility to do more physics (sources, interpretations, limits)

Summary

- Public full O3 data released: www.gw-openscience.org
- 90 GW events reported as confirmed
- Some are "exceptional events" and other are missing:
 - Probing the extremes of the NS/BH mass distribution
 - Spins? Orbital precession?
 - No other multi-messenger discoveries since GW170817
 - No evidence of violations of general relativity
 - Cosmology
- LVK science is wide, not only compact binary searches

We are sure O4 will be a very satisfying run!



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