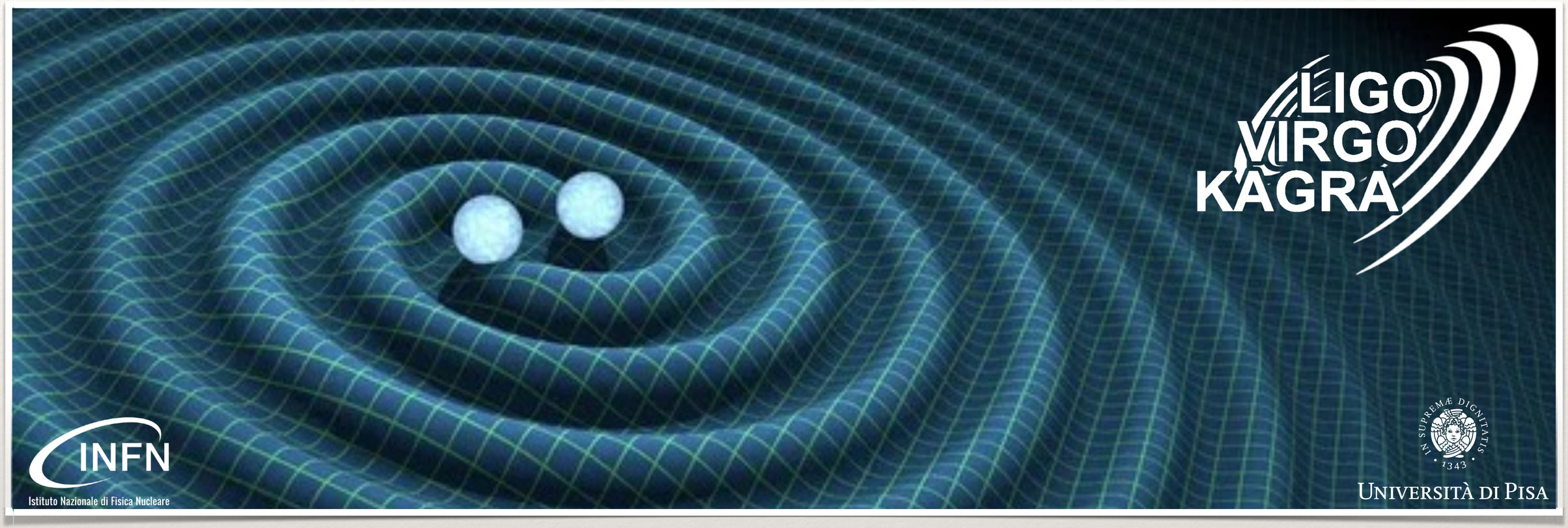


Past, present and future of gravitational-wave astronomy

Stefano Rinaldi
for the LVK collaboration

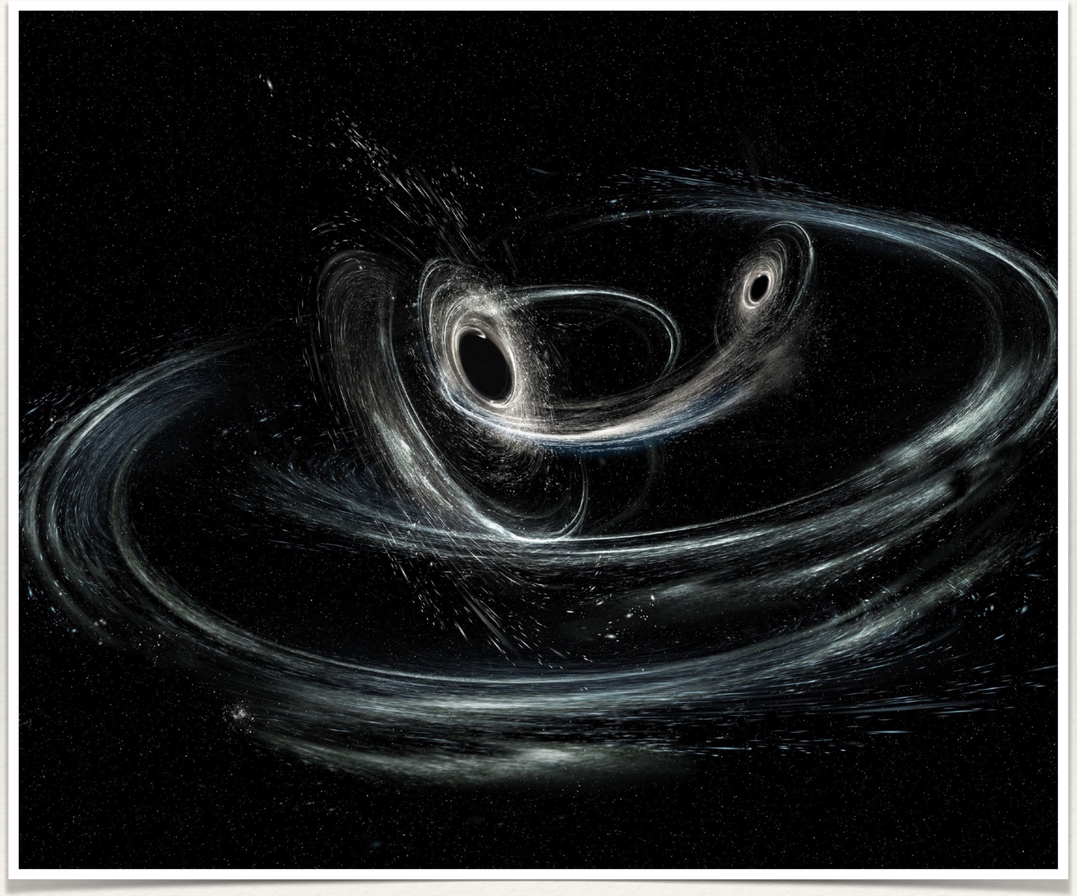
Third Gravi-Gamma Workshop
Volterra - October 5, 2022

Cover image credits: LIGO/Caltech

stefano.rinaldi@phd.unipi.it

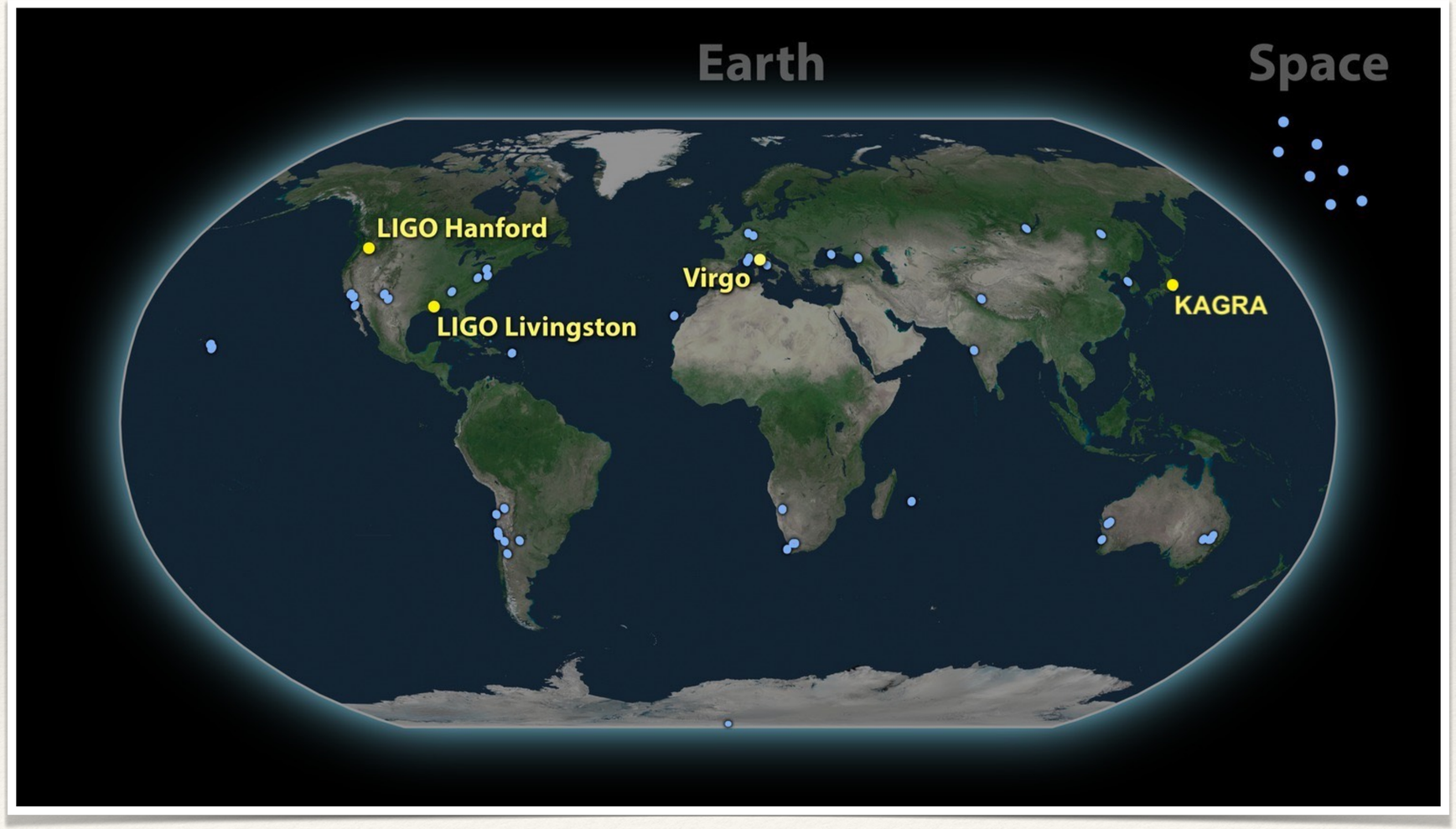
Outline

- Past: Detectors and observational science goals
- Present: Selected results from the third observing run
- Future: What to expect from the fourth observing run



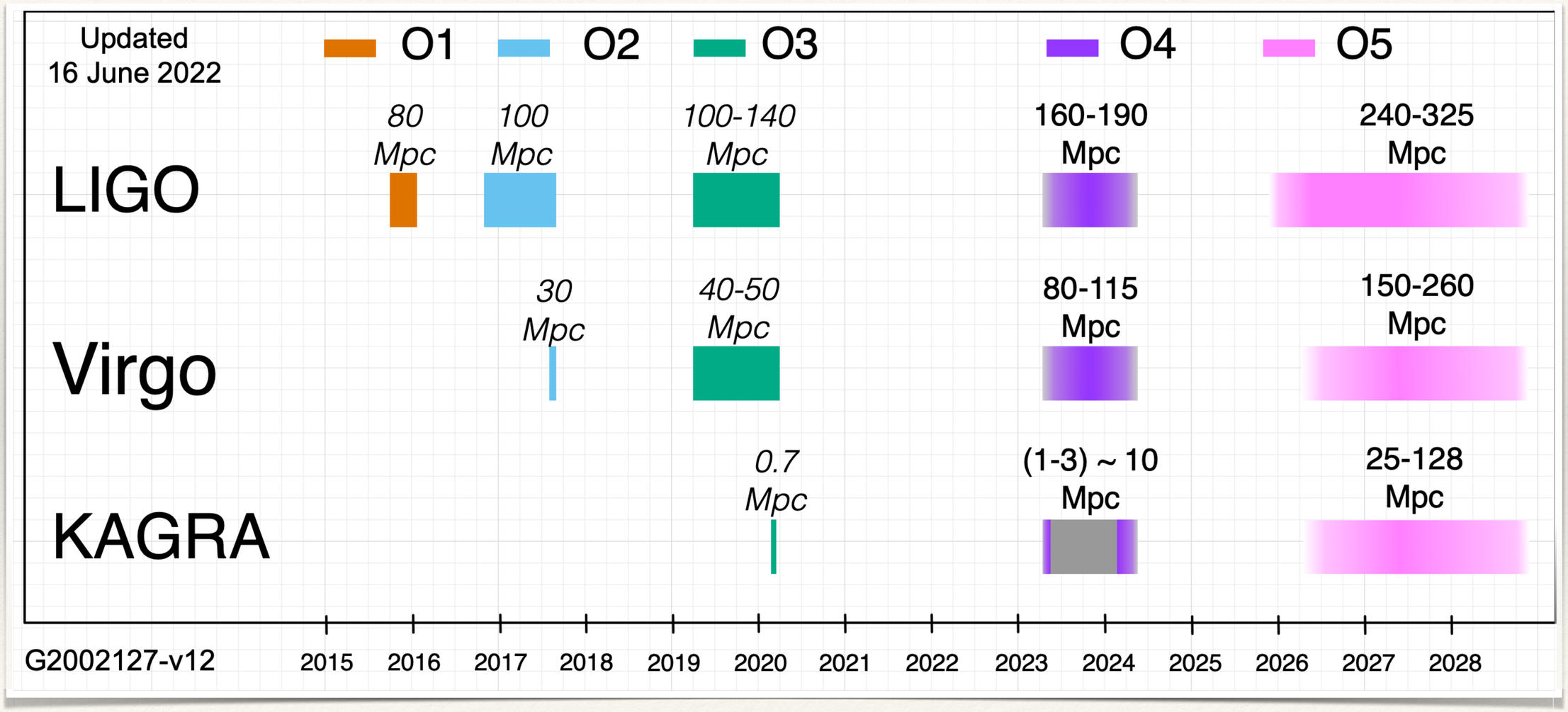
Two black holes merging, artist's impression
Aurore Simonnet, LIGO/CalTech/MIT/Sonoma State

GW Observatories



Credits: LIGO/Virgo (adapted)

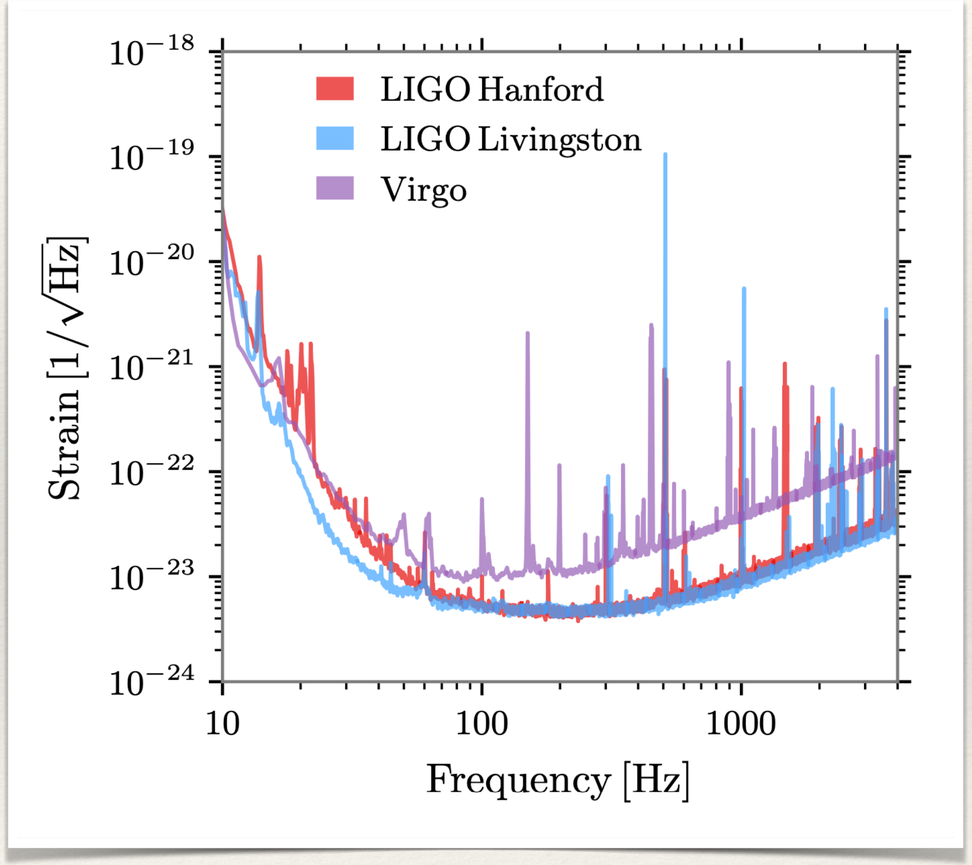
Observing runs



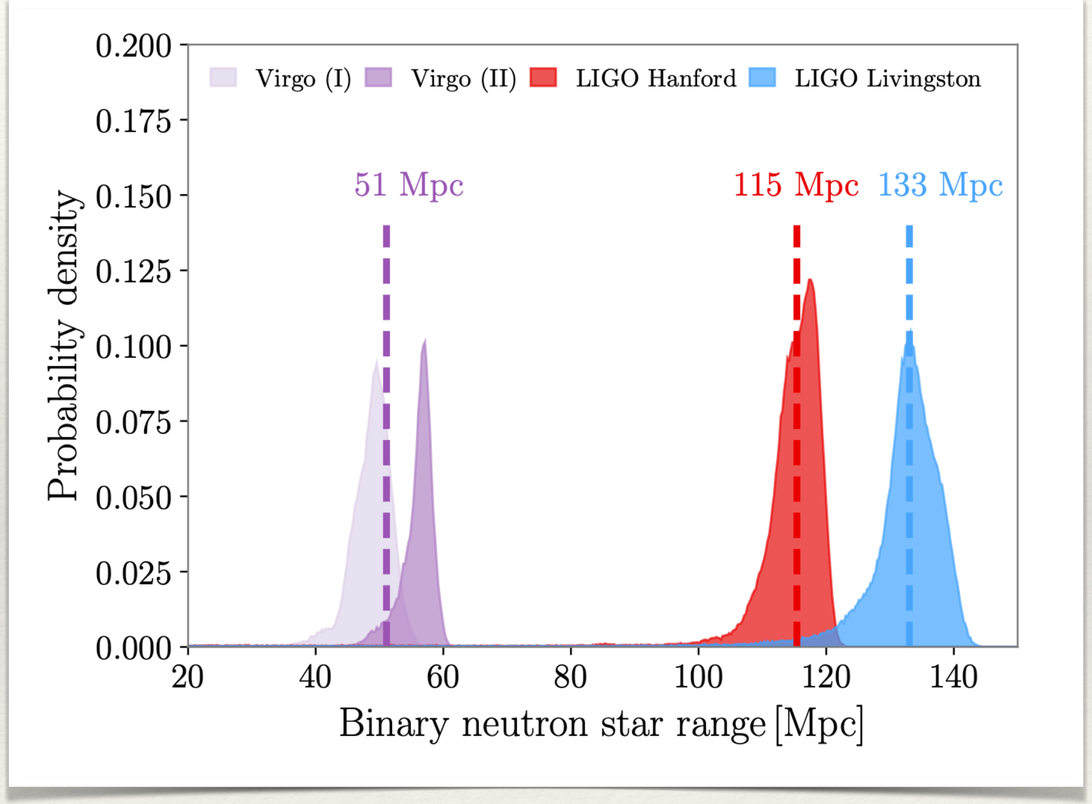
https://dcc.ligo.org/LIGO-G2002127/public

Instruments

Abbott+ 2021a



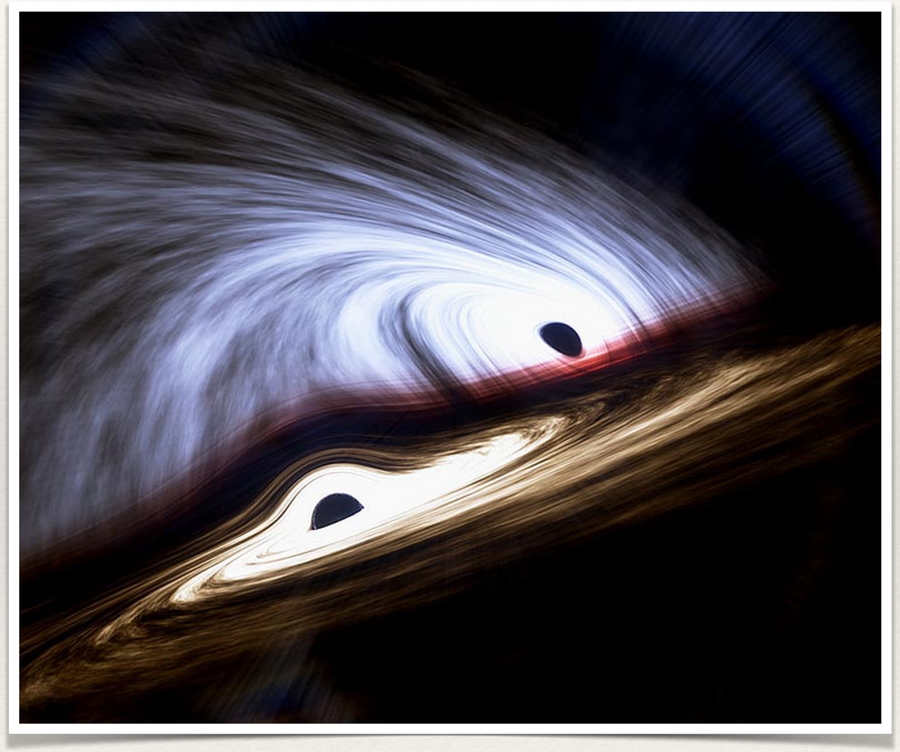
Representative amplitude spectral density of the three interferometers' strain sensitivity at the beginning of 2020



BNS inspiral range of LIGO and Virgo during O3b

Observational science goals

- Burst (generic transient)
- Compact binary coalescences (CBC)
- Continuous waves
- Stochastic background



Two black holes about to merge, artist's impression - Mark Myers
ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav)

https://dcc.ligo.org/LIGO-T2000424/public

Observational science goals

Colours reflect priority:
highest or high

- **Burst (generic transient)**
- Compact binary coalescences (CBC)
- Continuous waves
- Stochastic background

Short duration bursts

Long duration bursts

Multimessenger detections

Burst characterisation

BNS post-merger signals

https://dcc.ligo.org/LIGO-T2000424/public

Observational science goals

Colours reflect priority:
highest or high

- Burst (generic transient)
- **Compact binary coalescences (CBC)**
- Continuous waves
- Stochastic background

Exceptional detections

Catalog of detections

Multimessenger astronomy

Astrophysical distribution

Testing GR

Neutron star EOS

Hubble constant measurement

IMBH and IMRI

Subsolar mass CBC

Gravitational lensing

https://dcc.ligo.org/LIGO-T2000424/public

Observational science goals

Colours reflect priority:
highest or high

- Burst (generic transient)
- Compact binary coalescences (CBC)
- **Continuous waves**
- Stochastic background

High-interest pulsars

High-interest point sources

All-sky searches

Known pulsars

Known point sources

NS post-mergers

https://dcc.ligo.org/LIGO-T2000424/public

Observational science goals

Colours reflect priority:
highest or high

- Burst (generic transient)
- Compact binary coalescences (CBC)
- Continuous waves
- **Stochastic background**

Isotropic background

Anisotropic background

Very long transients

Implications

Astrophysical modeling

https://dcc.ligo.org/LIGO-T2000424/public

Searches - CBC

Abbott+ 2021a

Modeled (waveform)

GstLAL

MBTA

pyCBC

Minimal Assumptions

cWB

Parameter space

- Total mass (detector): $[2\ M_\odot,\ o(100)\ M_\odot]$
- Mass ratio: $[\ \sim 0.1,\ 1]$
- Dimensionless spin: $[0,\ 1]$

Statistics

Signal-to-noise ratio (SNR)

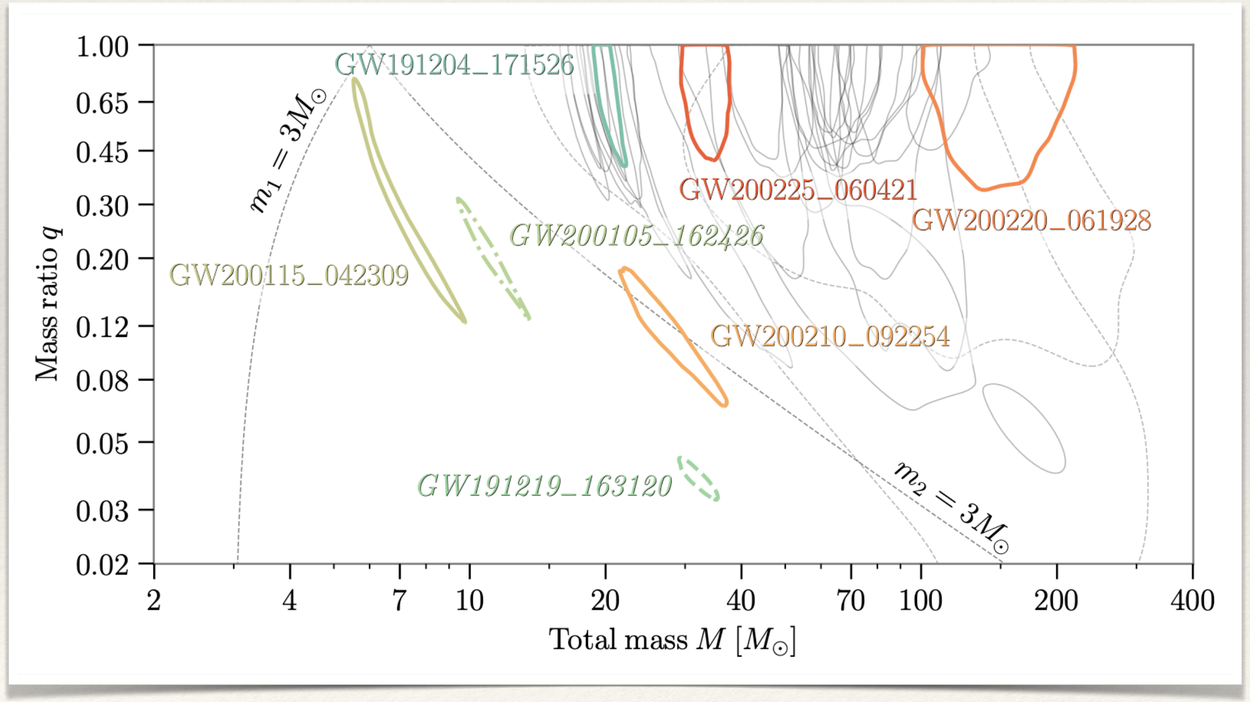
False-alarm rate (FAR) $< 2\ \mathrm{day}^{-1}$

$p_{\mathrm{astro}} > 0.5$

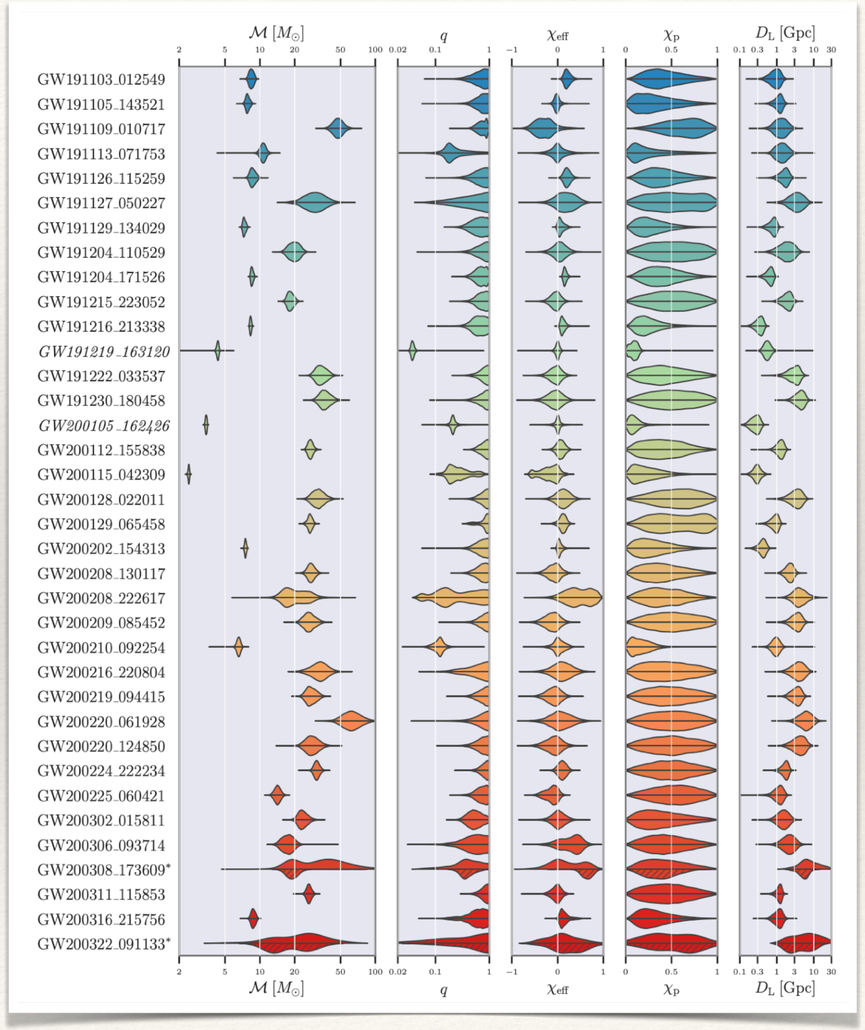
Detections after O3

Abbott+ 2021a

- 90 GW candidates (11 O1+O2, 44 O3a, 35 O3b)
- 2 NSBH events and 2 BNS events

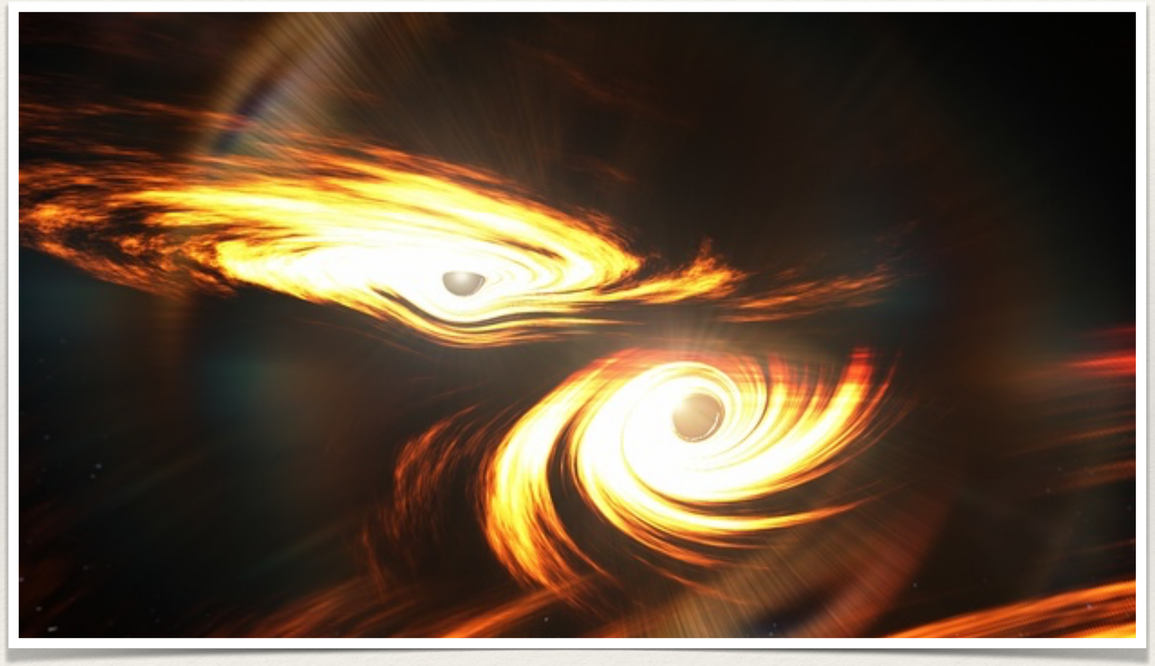


Credible-region contours in the total mass - mass ratio plane for O3b candidates. Highlighted contours are peculiar events (solid) or uncertain detections (dashed)



Marginal posteriors for the 35 O3b candidates ($p_{\rm astro} > 0.5$)

Selected results from O3

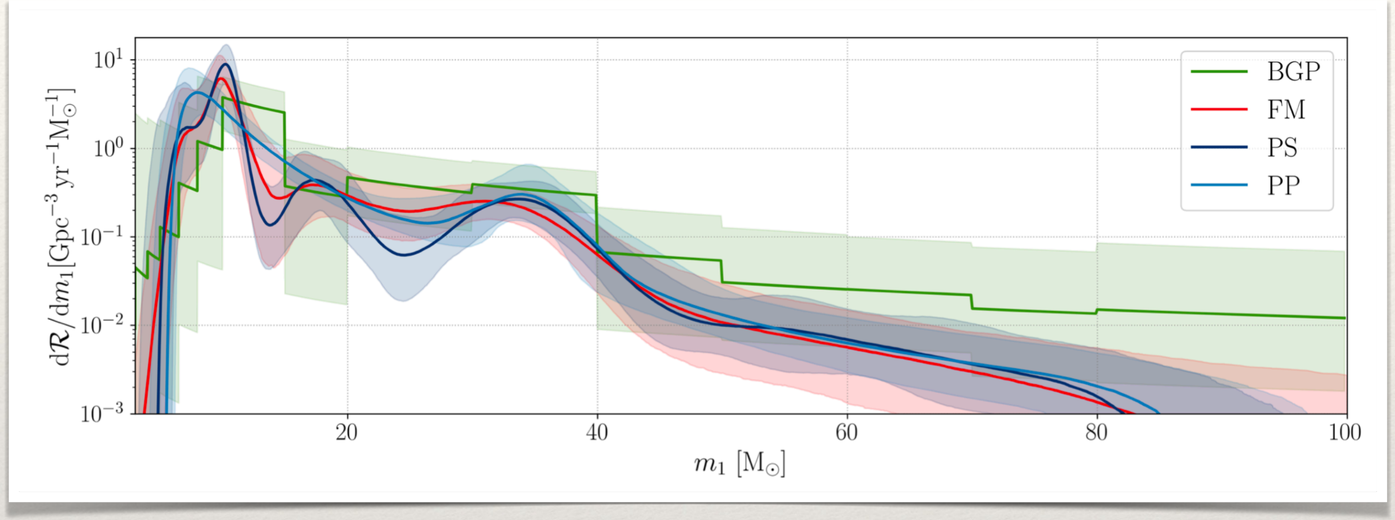


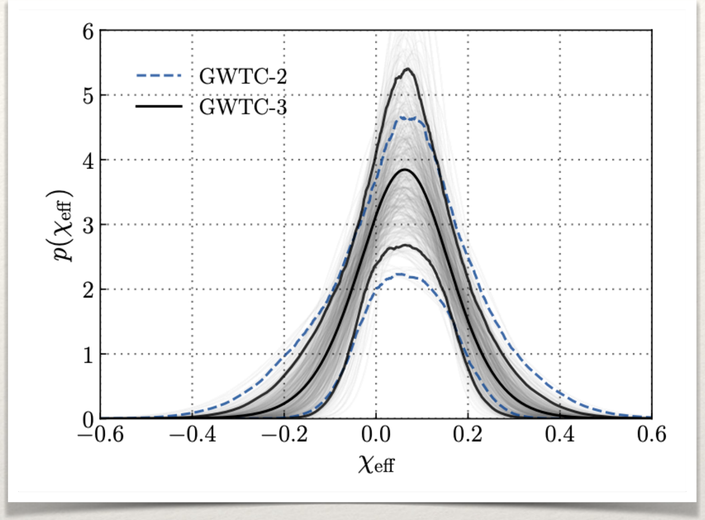
Hierarchical scheme for merging black hole, artist's concept
LIGO/Caltech/R. Hurt (IPAC)

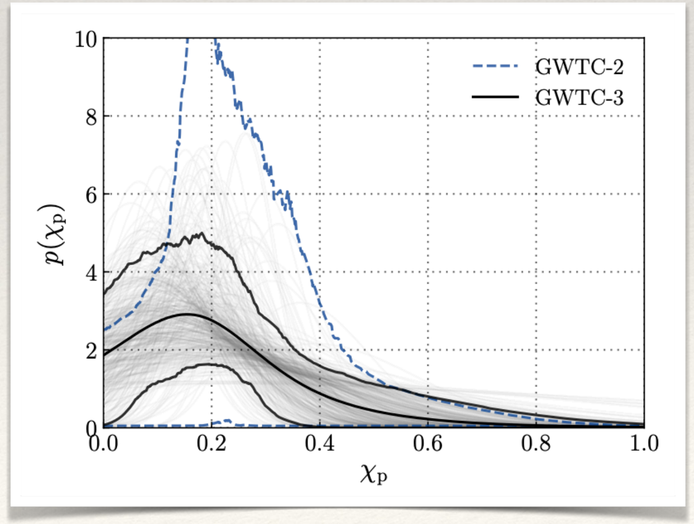
- Astrophysical population
- Tests of general relativity
- Cosmology

Astrophysical population - BH mass & spin

Abbott+ 2021b







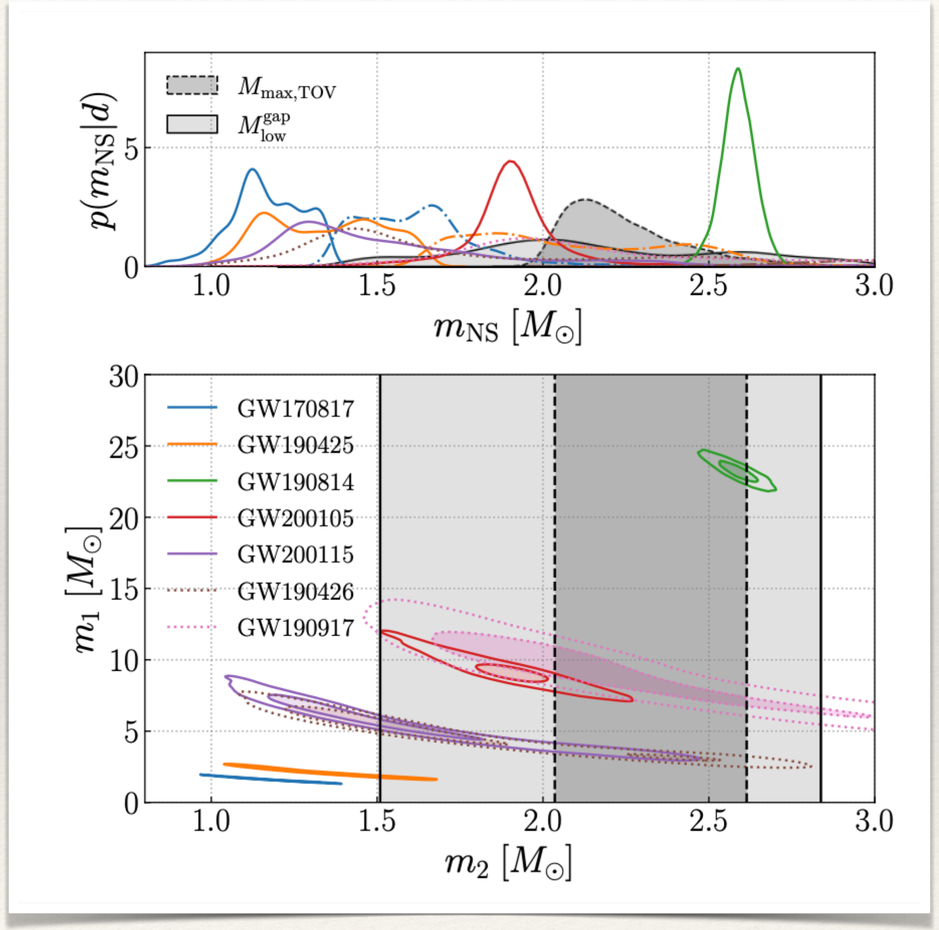
Clockwise:

- Differential merger rate for the primary mass using three non-parametric models compared to the fiducial PowerLaw+Peak model;
- Inferred distribution for $\chi_{\rm eff}$;
- Inferred distribution for $\chi_{\rm p}$.

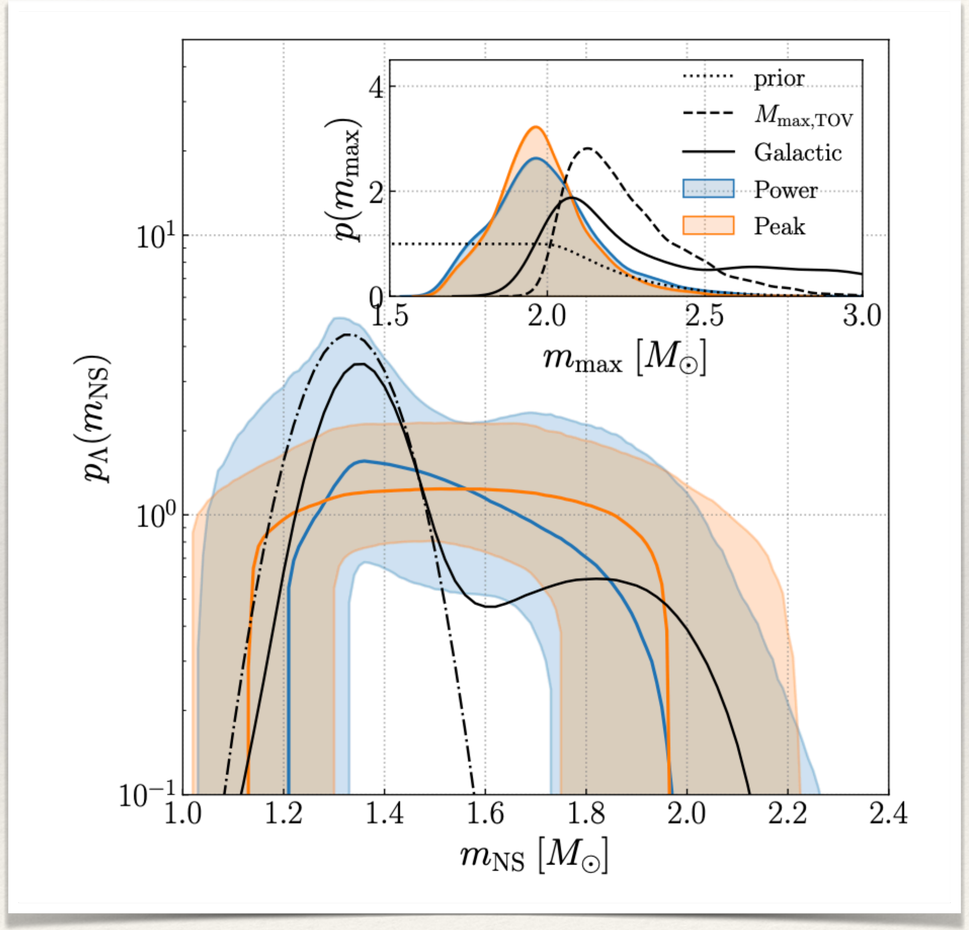
More on this from Barbara Patricelli at 11 am!

Astrophysical population - NS mass

Abbott+ 2021b



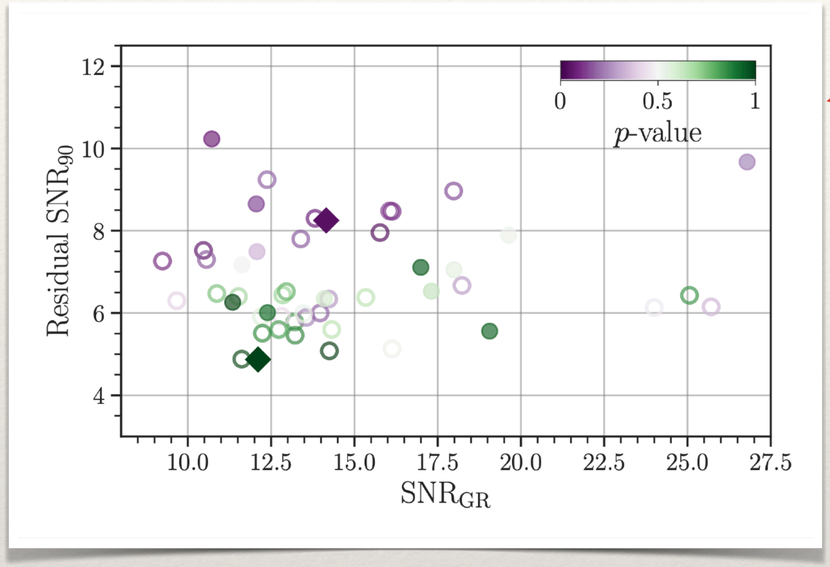
Masses for events with at least one candidate neutron star



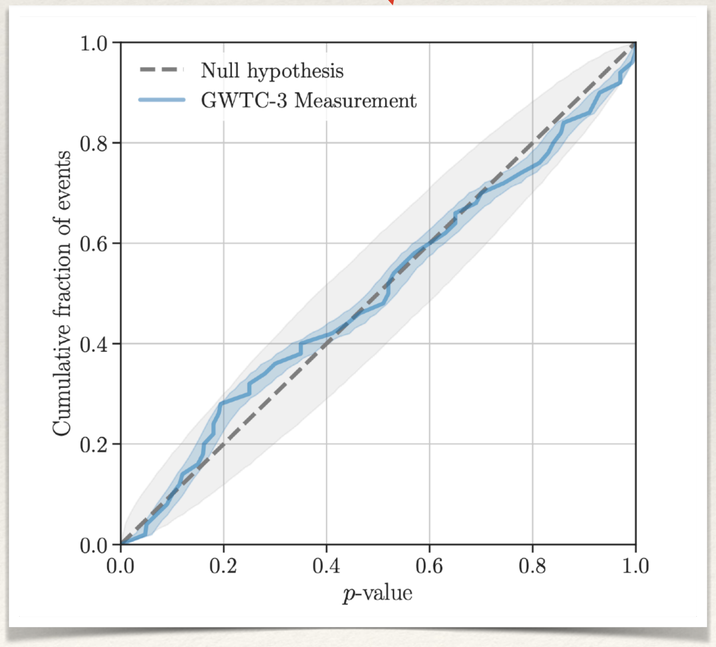
Inferred neutron star mass distribution

Tests of General Relativity

Abbott+ 2021c

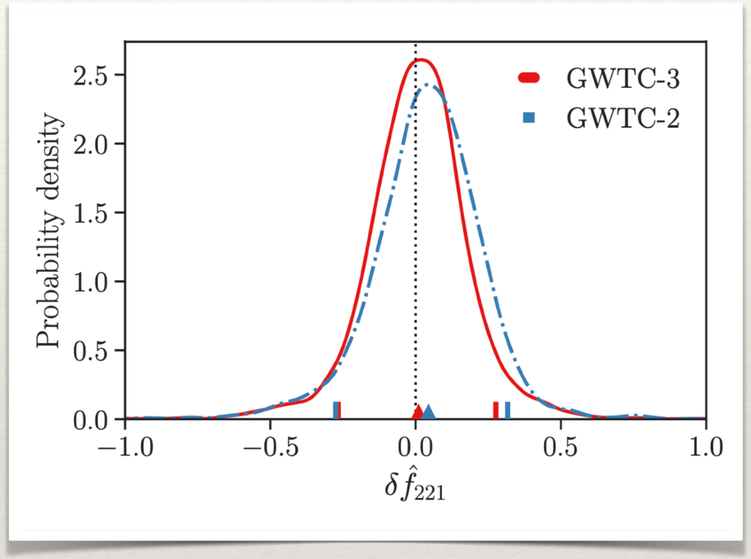


Residual analysis



- Above: scatter plot of the maximum-likelihood template (GR) and upper limit on the residual network (90) SNR;
- Right: p-value PP-plot.

Ringdown



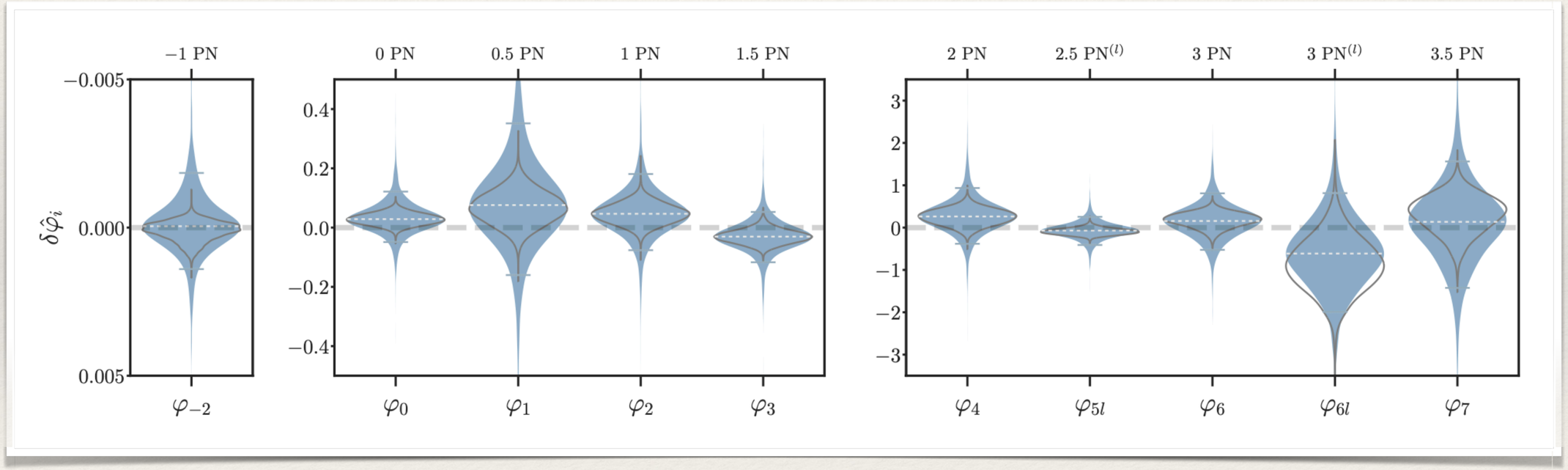
Posterior distribution of the fractional frequency deviation for the 221 mode ($\ell = |m| = 2$, $n = 1$)

Vasco Gennari at 17:40!

Tests of General Relativity

Abbott+ 2021c

Parametrised Post-Newtonian modifications

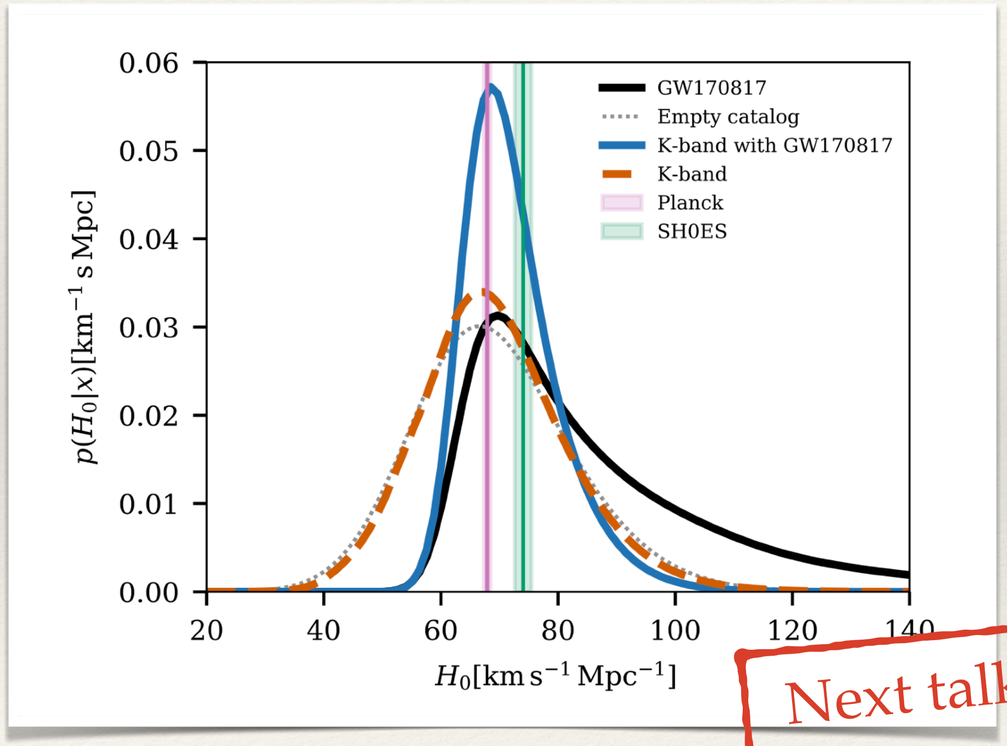


Combined GWTC-3 results for the parametrised deviation coefficients

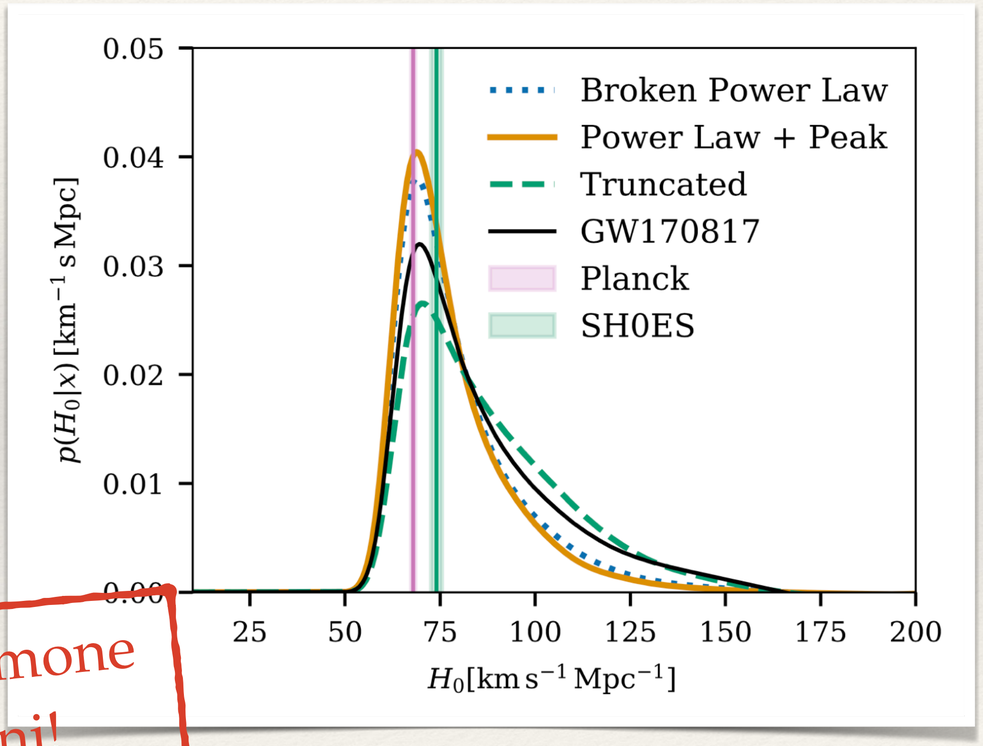
H_0 measurement

Abbott+ 2021d

Galaxy catalog method



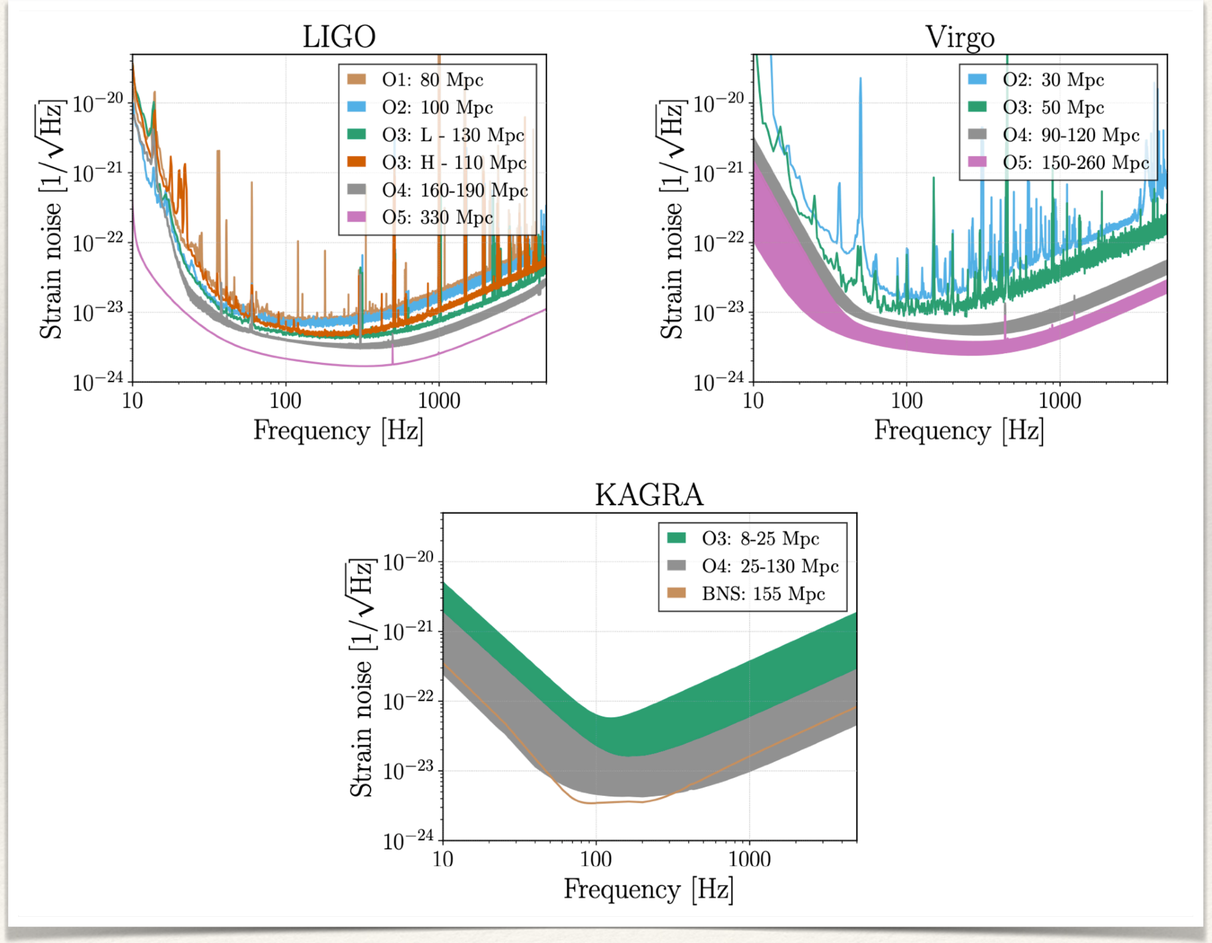
Joint cosmology-population inference



Next talk from Simone Mastrogiovanni!

Towards O4: Detectors

Abbott+ 2020



Towards O4: Observational science

Abbott+ 2020

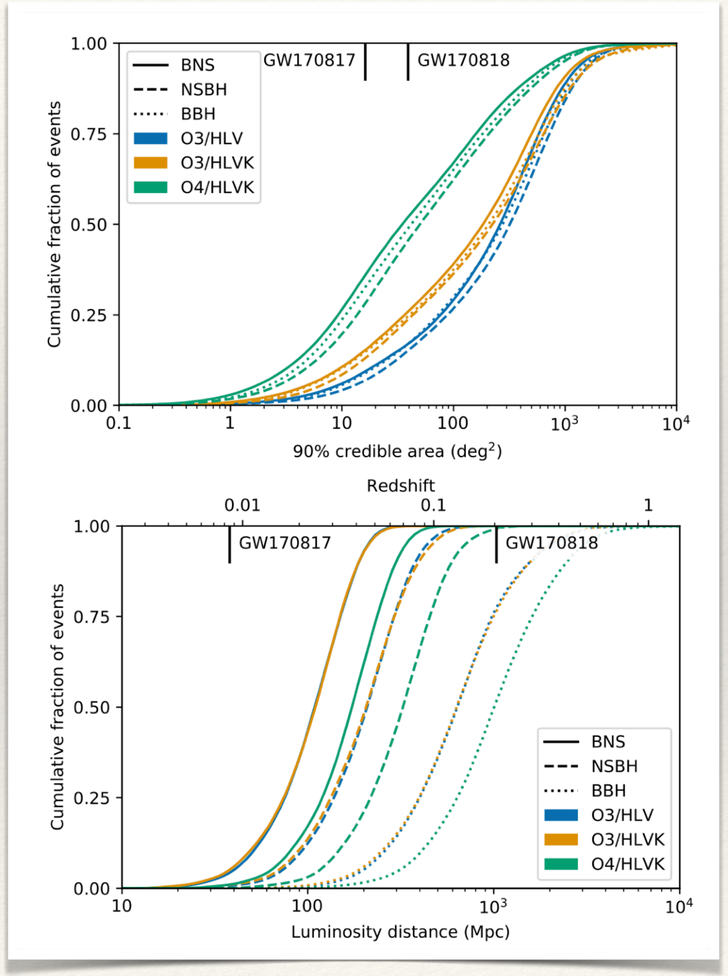
- Expected 10^{+52}_{-10} BNSs and 79^{+89}_{-44} BBHs
- Almost twice the events in GWTC-3 after O4
- Improvement of O3 results (CBC)
- Potential new detections: Lensed pair of GWs, sub-solar mass BH (fingers crossed!)

Artwork of a neutron star-black hole merger.
Carl Knox, OzGrav - Swinburne University

Towards O4: Multimessenger

Abbott+ 2020

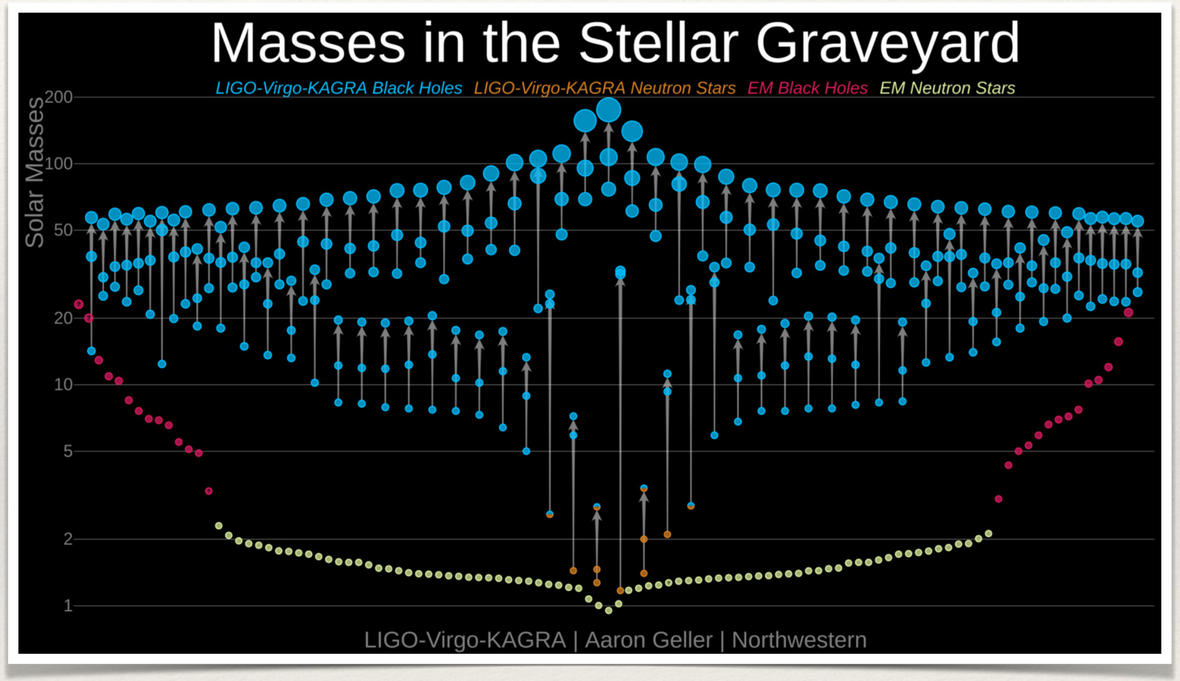
- GW170817: first multimessenger detection *(Abbott+ 2017)*
- Median localisation area: 33^{+5}_{-5} deg^2 (BNS), 41^{+7}_{-6} deg^2 (BBH)
- GCN notices to be sent in minutes (preliminary) and hours (initial) for BNS and NSBH
- $o(1)$ yr^{-1} joint GW-EM detection *(Patricelli+ 2022)*



Anticipated GW sky localisation and luminosity distance for O3 and O4

Conclusions

- 90 GW events up to date
- More to come in the next observing run
- Potentially, new detections (SSM, lensing)
- Fingers crossed for a second GW-EM detection
- Let’s hear more on GW science from colleagues in the following talks!



Credit: LIGO-Virgo / Aaron Geller / Northwestern University.

References

- *B. P. Abbott et al.*, Multi-Messenger Observations of a Binary Neutron Star Merger, *ApJL **848** L12 (2017)*
- *B. P. Abbott et al.*, Prospects for observing and localising gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, *Living Reviews in Relativity* **23**, *Article number: 3 (2020)*
- *R. Abbott et al.*, GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run, *arXiv e-prints, arXiv:2111.03606 (2021a)*
- *R. Abbott et al.*, The population of merging compact binaries inferred using gravitational waves through GWTC-3, *arXiv e-prints, arXiv:2111.03634 (2021b)*
- *R. Abbott et al.*, Tests of general relativity with GWTC-3, *arXiv e-prints, arXiv:2111.06861 (2021c)*
- *R. Abbott et al.*, Constraints on the cosmic expansion history from GWTC-3, *arXiv e-prints, arXiv:2111.03604 (2021d)*
- *B. Patricelli et al.*, Prospects for multi messenger detection of binary neutron star mergers in the fourth LIGO-Virgo-KAGRA observing run, *MNRAS, Volume 513, Issue 3, Pages 4159-4168 (2022)*