Looking forward to O4

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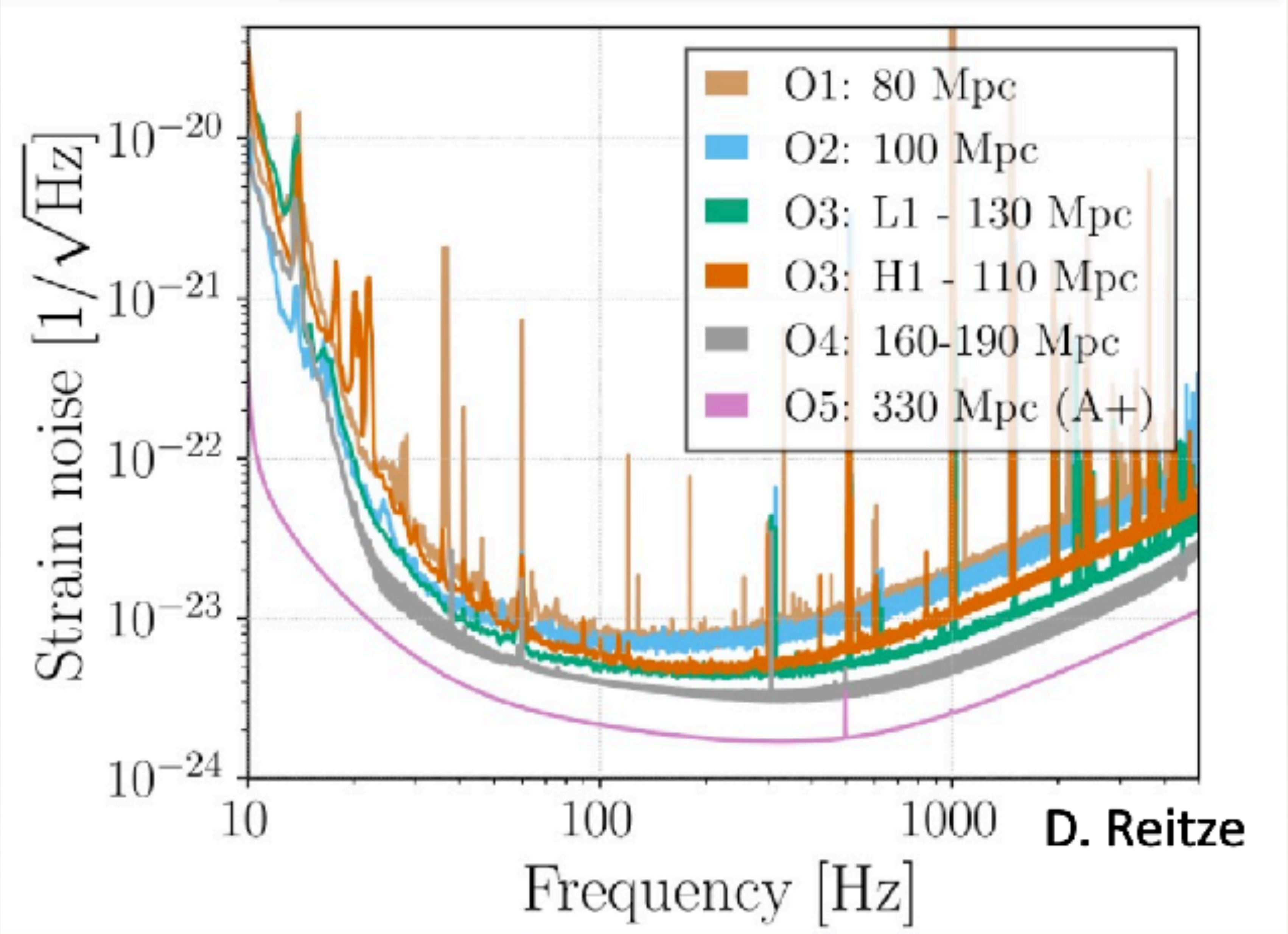


Talk outline

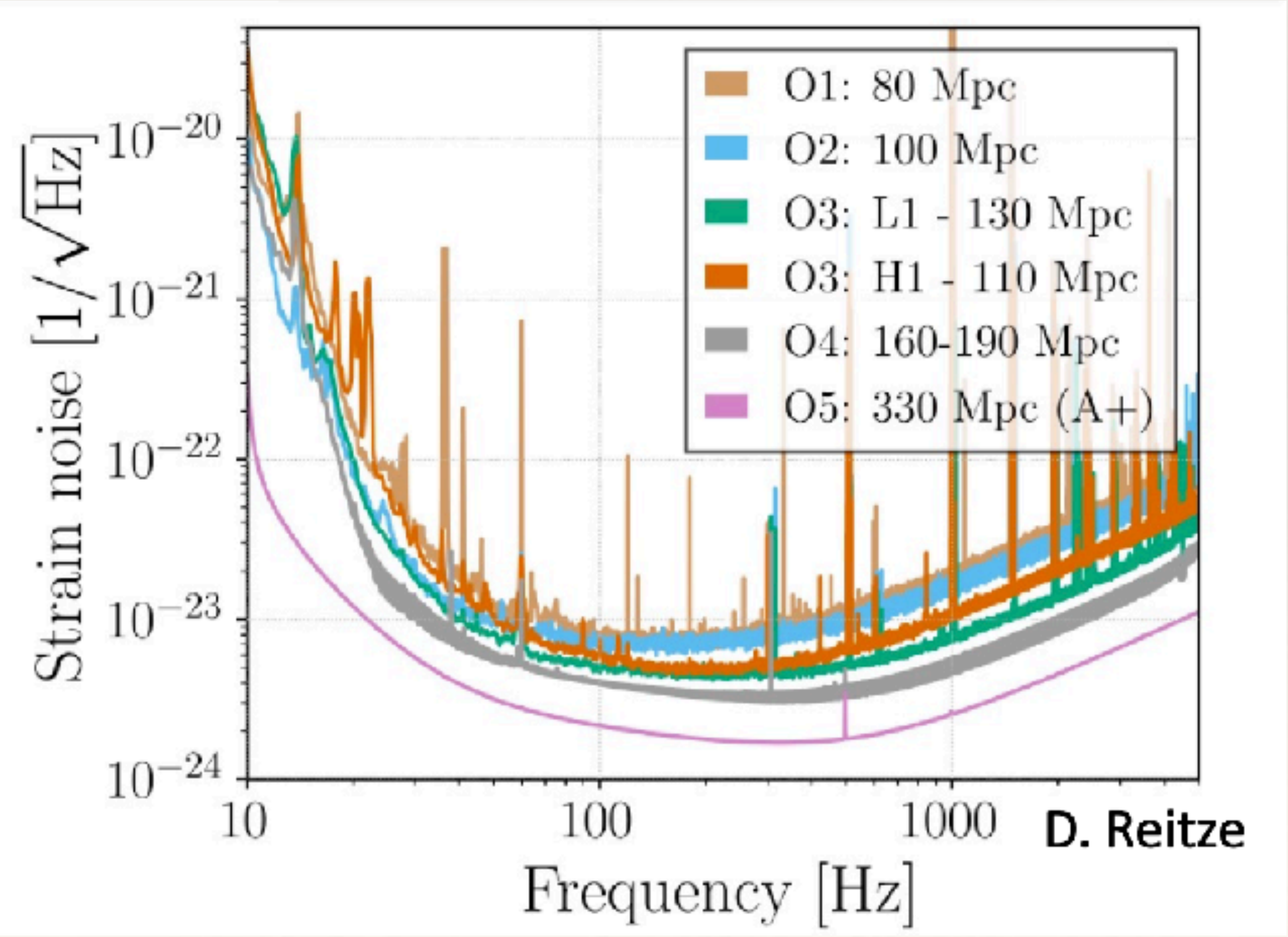
- Review of results to end of O3
- Upgrades introduced for O4
- Expected O4 sensitivity and implications for event rate
- Plans for alerts in O4
- (if time permits) Things I'm looking forward to in O4: cosmology, rapid and robust PE with Dingo

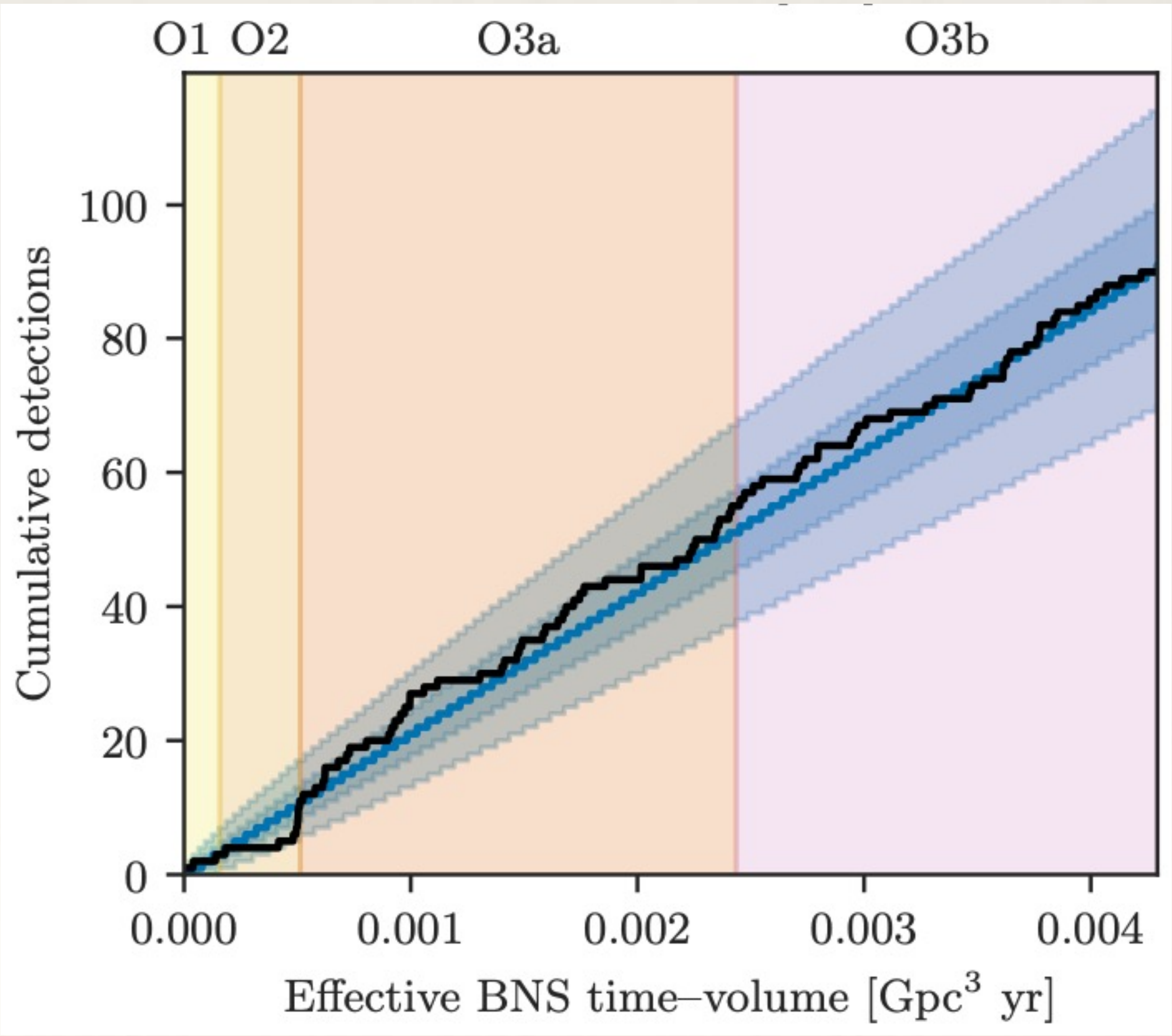
Gravitational wave detectors

- A network of ground-based detectors is currently operating
  - LIGO: two 4km interferometers in Hanford, WA and Livingston, LA. Advanced LIGO began taking data in September 2015. O4 observing run starting May 2023.
  - Virgo: 3km interferometer at Cascina, near Pisa, Italy. Advanced Virgo began to collect data in late July 2017.
  - Japanese detector, KAGRA, came online early in 2020. Third LIGO detector in India under construction.

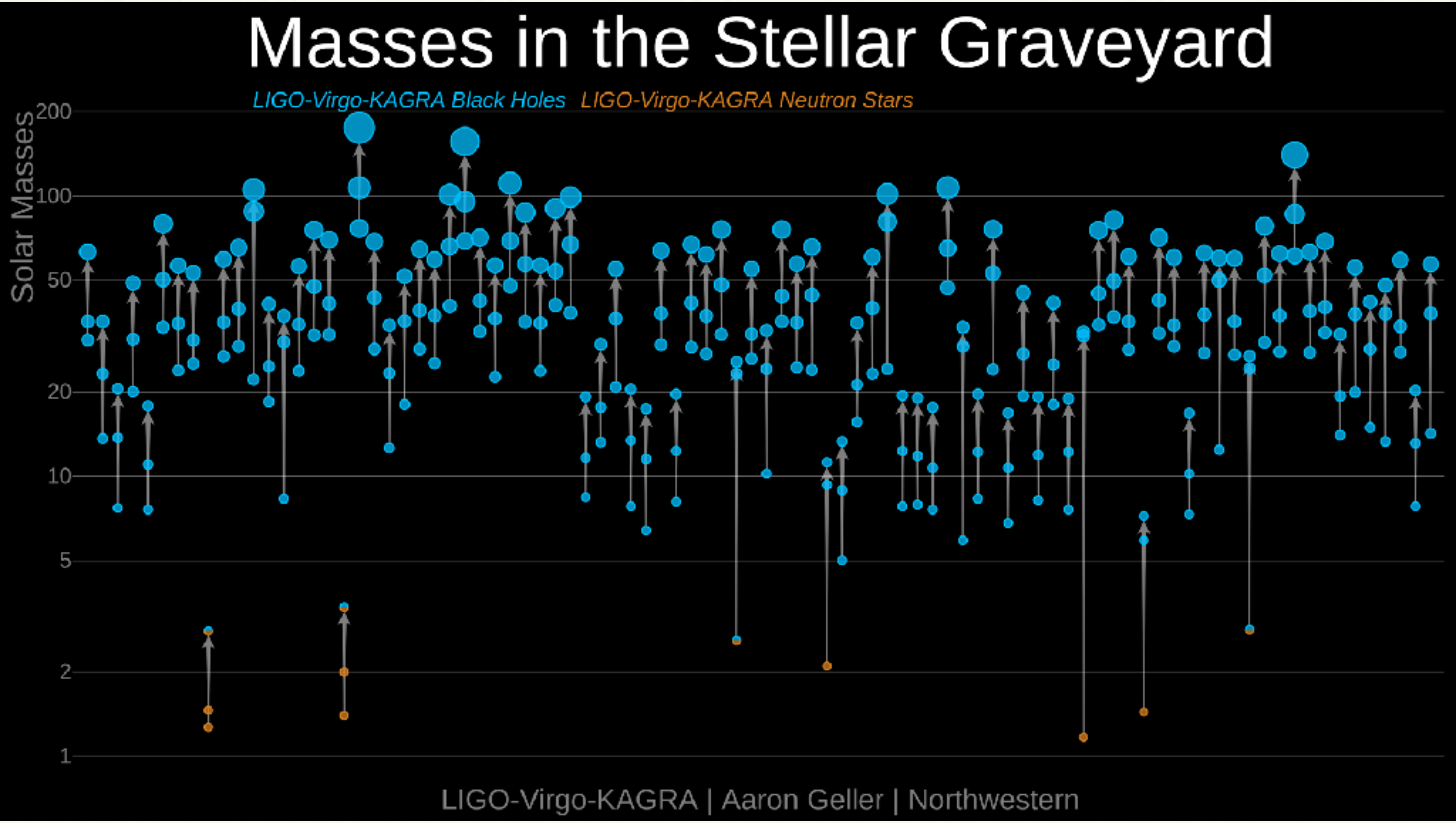
Previous observing runs

- O1: Sept to Dec 2015; O2: Jan to Aug 2017; O3a: April 1 to Oct 1 2019; O3b: Nov 1 2019 to Mar 27 2020.
- O4: currently carrying out an engineering run. Observing run scheduled to start on May 24th.



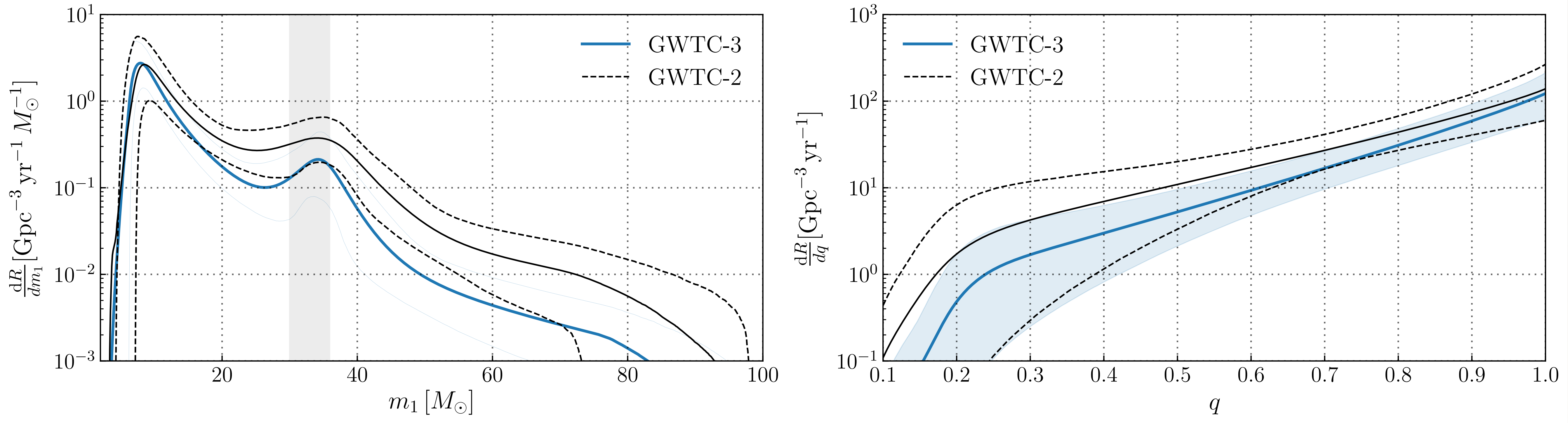


Previous events



Previous events: black holes

- To date LIGO has seen 90 events with >50% chance of astrophysical origin.
- The majority (84) are likely BBH events.

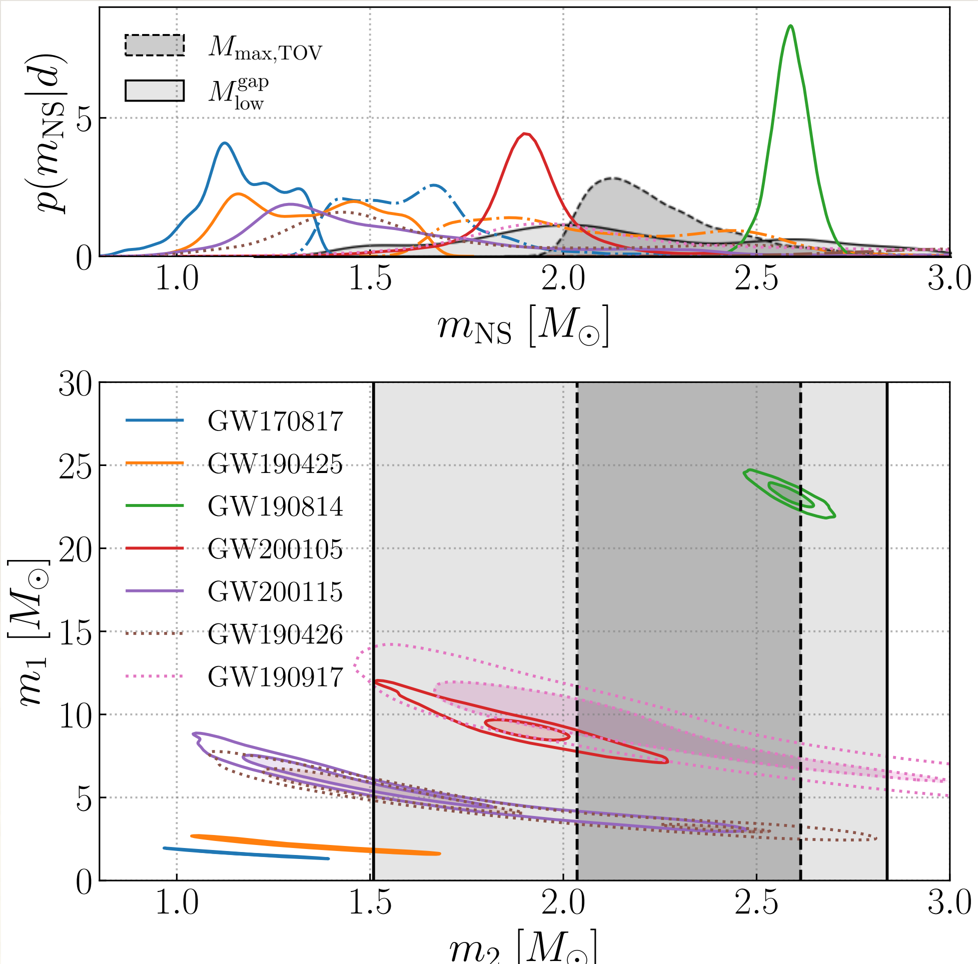


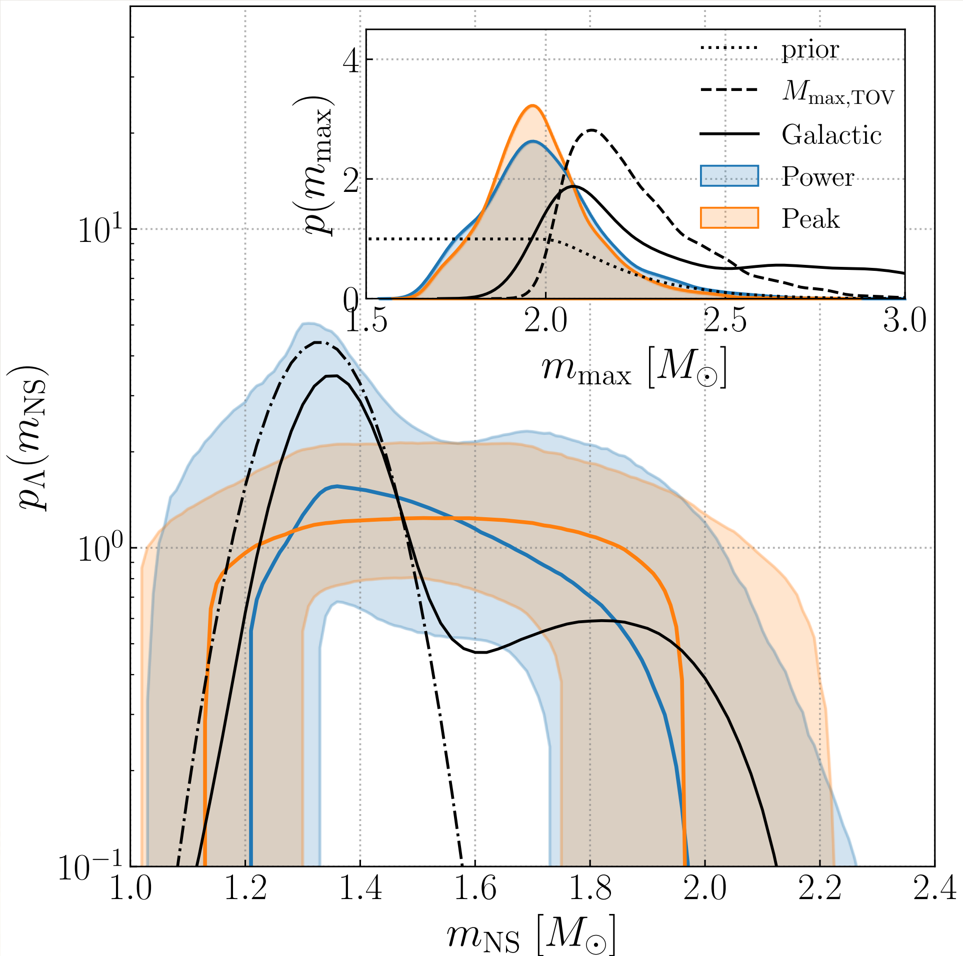
LVC *BBH properties from GWTC-3* (2021)

Previous events: neutron stars

- Have also seen 7 events which may contain neutron stars. 2 BNS, 2 + NSBH, 1 probably BBH.

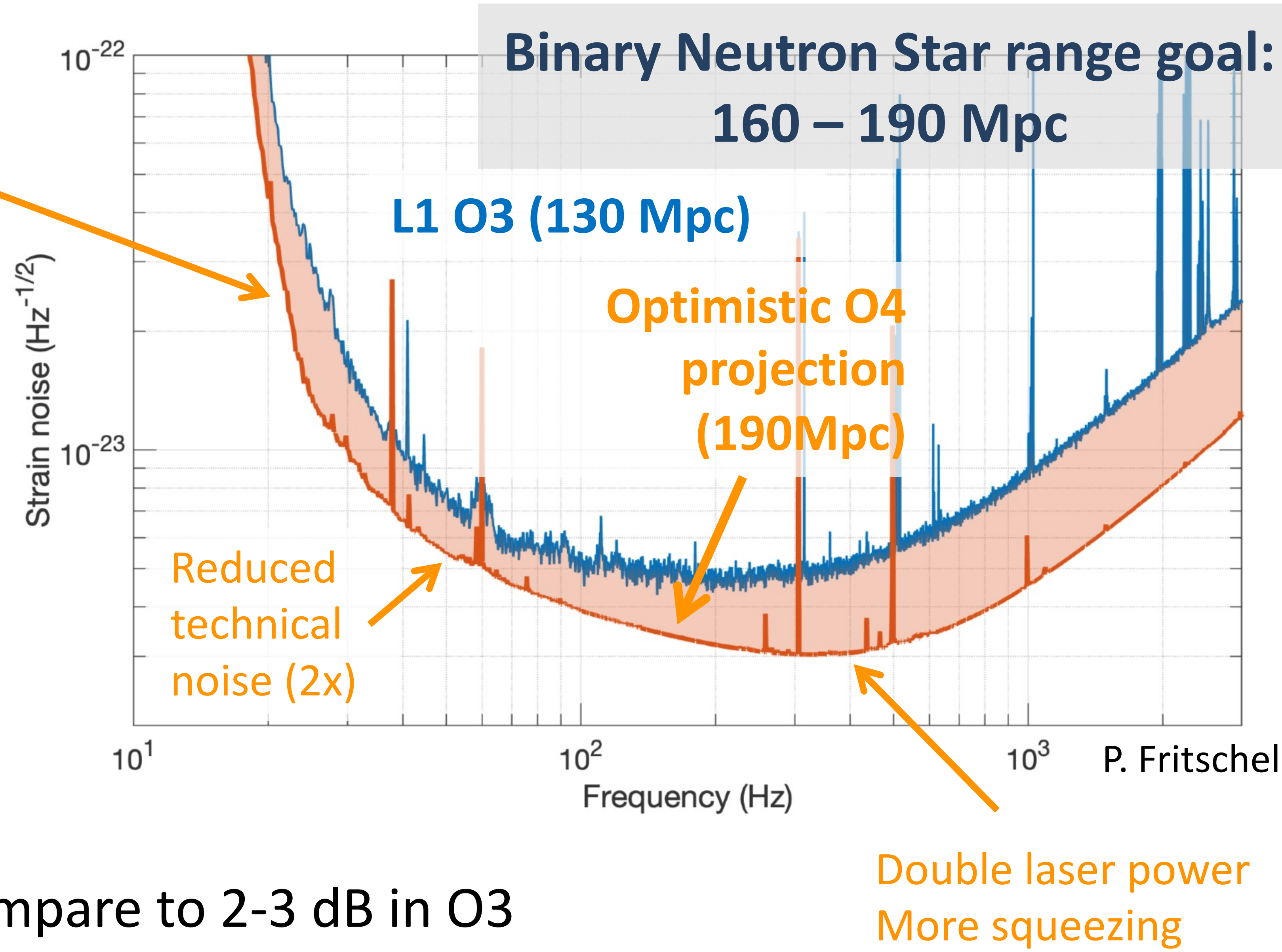
Name	FAR_{min} (yr^{-1})	$P(m < M_{max,TOV})$	$P(m < M^{gap}_{low})$	Classification
GW170817	$< 1 \times 10^{-5}$	0.99	0.97	BNS
GW190425	3.38×10^{-02}	0.67	0.71	BNS
GW190814	$< 1 \times 10^{-5}$	0.06	0.24	BBH
GW200105	2.04×10^{-01}	0.94	0.73	NSBH
GW200115	$< 1 \times 10^{-5}$	0.93	0.96	NSBH
GW190426	9.12×10^{-01}	0.82	–	NSBH
GW190917	6.56×10^{-01}	0.56	–	NSBH





LVC *BBH properties from GWTC-3* (2021)

Detector Improvements O3 to O4



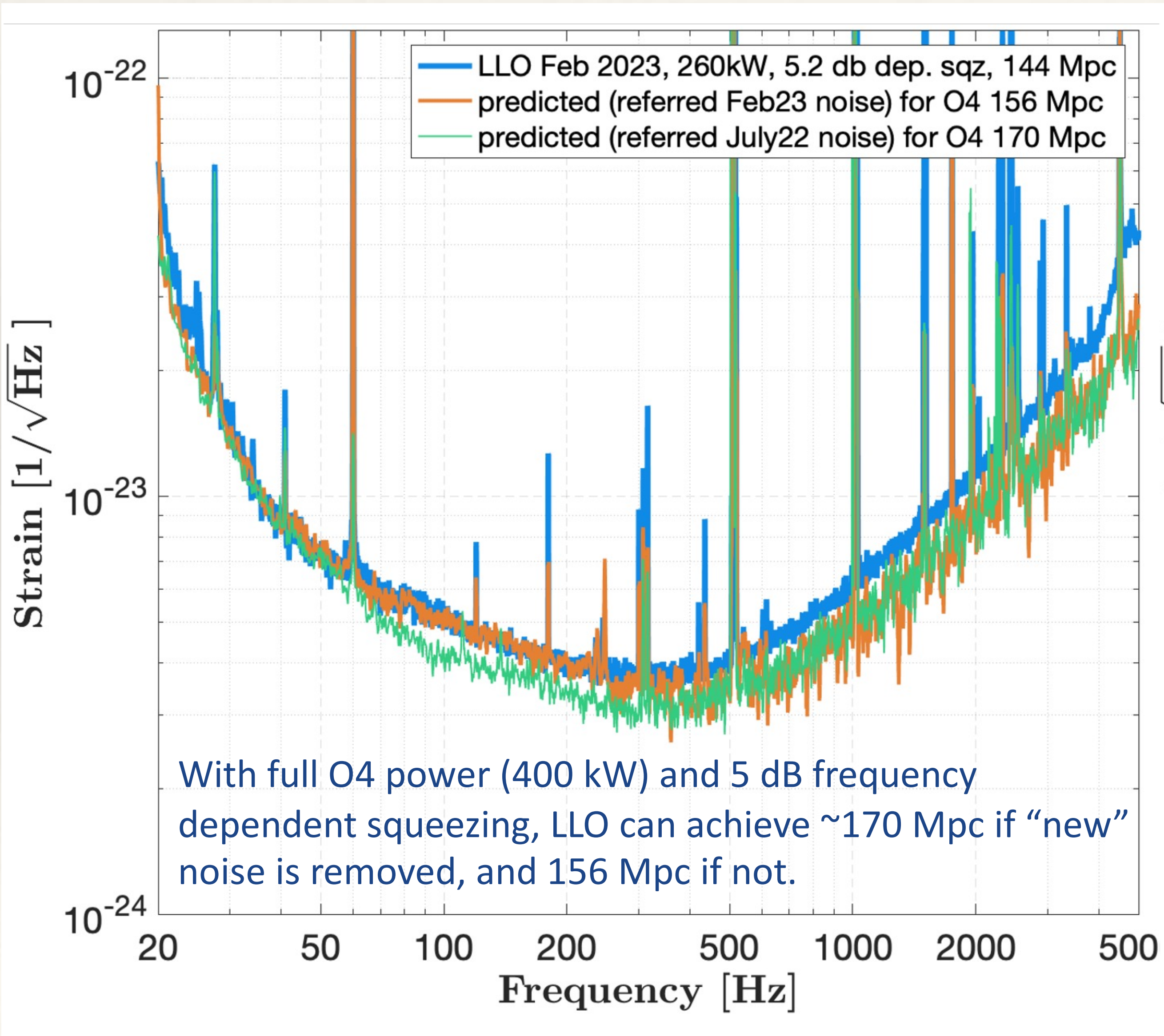
GOALS

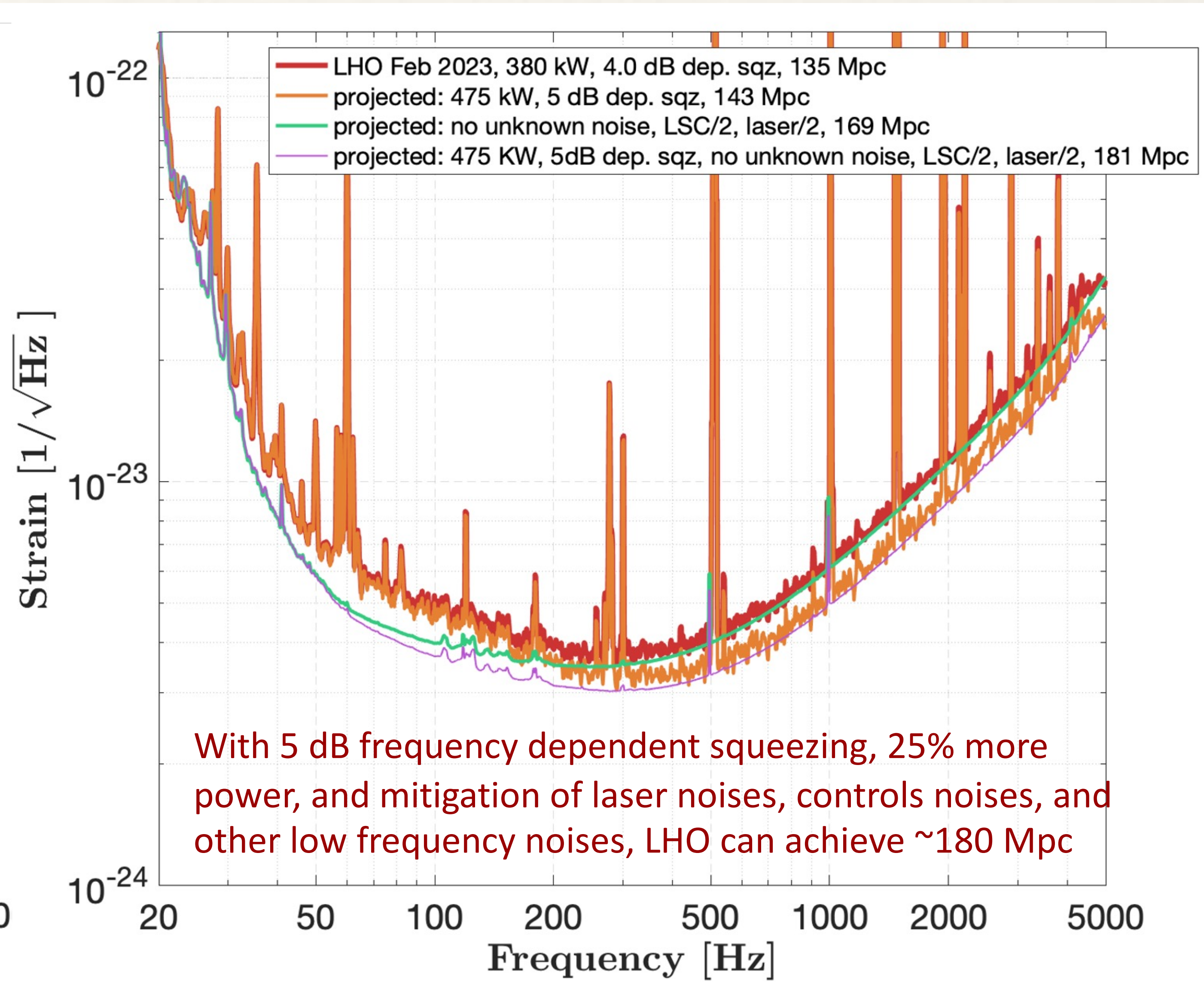
- **400 kW circulating arm power**
  – Compare to 200 kW in O3
- **Squeezed light efficacy*: 4.5 dB**
  – Shot noise region; compare to 2-3 dB in O3
- **300 m filter cavity*** for frequency dependent squeezing
  – No radiation pressure enhancement from squeezing
- **Low frequency technical noise reduction**
  – Below 100 Hz

Slide from Gabriele Vajente

O4 sensitivity: improvements

- As of February, BNS range of 145Mpc/135Mpc achieved in LLO/LHO respectively. Expected final range of 156/143 Mpc to 170 Mpc.

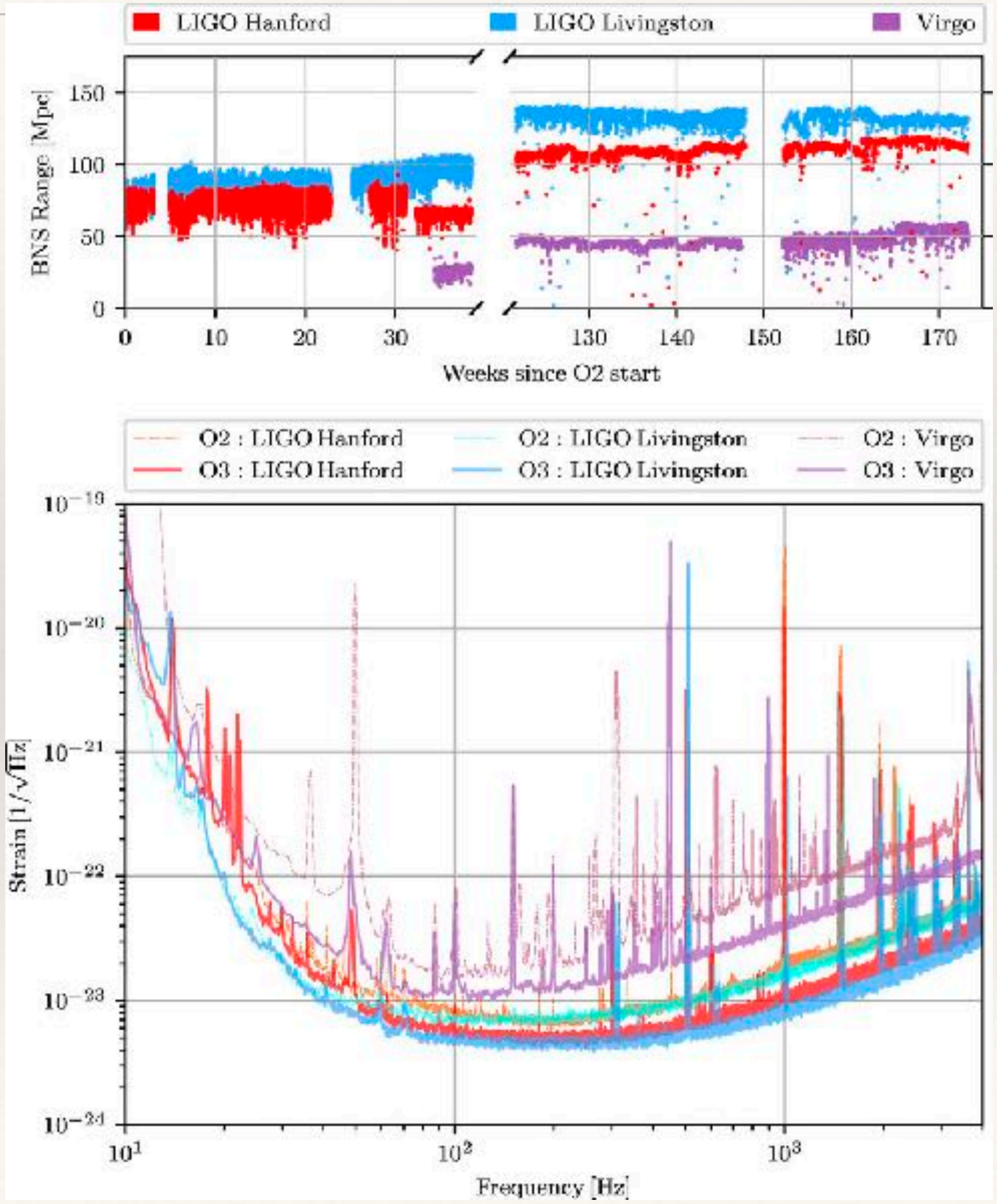




Slide from Gabriele Vajente. Figure credit: J. Driggers, A. Effler

O4 sensitivity

- O3 BNS range was 130 Mpc for L1 and 110 Mpc for H1.
- If both L1 and H1 achieve 170 Mpc BNS range, increase sensitive distance by ~40%, sensitive volume by a factor of ~2.8.
- If L1/H1 reach only 156/143 Mpc, increase sensitive range by ~25%, sensitive volume by a factor of ~1.9.



O4 sensitivity: event rates

- Inferred merger rates after O3:
  - BNS: 10 - 1700 Gpc^{-3} yr^{-1}
  - NSBH: 7.8 - 140 Gpc^{-3} yr^{-1}
  - BBH: 17.9 - 44 Gpc^{-3} yr^{-1}

	$m_1 \in [5, 20] M_\odot$ $m_2 \in [5, 20] M_\odot$	$m_1 \in [20, 50] M_\odot$ $m_2 \in [5, 50] M_\odot$	$m_1 \in [50, 100] M_\odot$ $m_2 \in [5, 100] M_\odot$	All BBH
PDB (pair)	$17^{+10}_{-6.0}$	$6.8^{+2.2}_{-1.7}$	$0.68^{+0.42}_{-0.29}$	$25^{+10}_{-7.0}$
PDB (ind)	$9.4^{+5.6}_{-3.7}$	$11^{+3.0}_{-2.0}$	$1.6^{+0.9}_{-0.7}$	$22^{+8.0}_{-6.0}$
MS	30^{+23}_{-13}	$6.6^{+2.9}_{-2.3}$	$0.73^{+0.87}_{-0.52}$	37^{+24}_{-13}
BGP	$20.0^{+11.0}_{-8.0}$	$6.3^{+3.0}_{-2.2}$	$0.75^{+1.1}_{-0.46}$	$33.0^{+16.0}_{-10.0}$
PS	$27^{+12}_{-8.8}$	$3.5^{+1.5}_{-1.1}$	$0.19^{+0.16}_{-0.09}$	$31^{+13}_{-9.2}$
FM	$21.1^{+11.6}_{-7.8}$	$4.3^{+2.0}_{-1.4}$	$0.2^{+0.2}_{-0.1}$	$26.5^{+11.7}_{-8.6}$
PP	$23.6^{+13.7}_{-9.0}$	$4.5^{+1.7}_{-1.3}$	$0.2^{+0.1}_{-0.1}$	$28.3^{+13.9}_{-9.1}$
MERGED	13.3 – 39	2.5 – 6.3	0.099 – 0.4	17.9 – 44
PP (O3a)	$16.0^{+13.0}_{-7.7}$	$6.8^{+2.7}_{-1.9}$	$0.5^{+0.4}_{-0.3}$	$25.3^{+16.1}_{-9.9}$

O4 sensitivity: event rates

- O4 extended to 18 months to enhance prospects for multi-messenger detections.
- With a 170 Mpc BNS range in both detectors, expect to accumulate 20 times as much VT as O2 (3 times sensitive time, ~7 times sensitive volume) and ~5 times as much as O3 (~1.5 times sensitive time, ~3 times sensitive volume).

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	1^{+12}_{-1}	0^{+19}_{-0}	17^{+22}_{-11}
O4	HLVK	10^{+52}_{-10}	1^{+91}_{-1}	79^{+89}_{-44}

5.2 O4: aLIGO 160 – 190 Mpc, AdV 90 – 120 Mpc, KAGRA 25 – 130 Mpc

LVC, Liv. Rev. Rel. **19** 1 (2018)

O4 plans: alerts

- **Updated Public Alert Threshold for O4***
- The false alarm rate threshold for public alerts will be lowered to 2/day starting in O4. There will therefore be two classes of alerts:
  - ***Low Significance*** (“Subthreshold” in O3) ***gravitational-wave alerts*** with false alarm rate greater than 1/month for CBC and 1/year for Burst
  - ***Significant gravitational-wave alerts*** with false alarm rate less than 1/month and 1/year for Burst that pass automated and manual verification tests.

*May be tuned slightly during the engineering run.

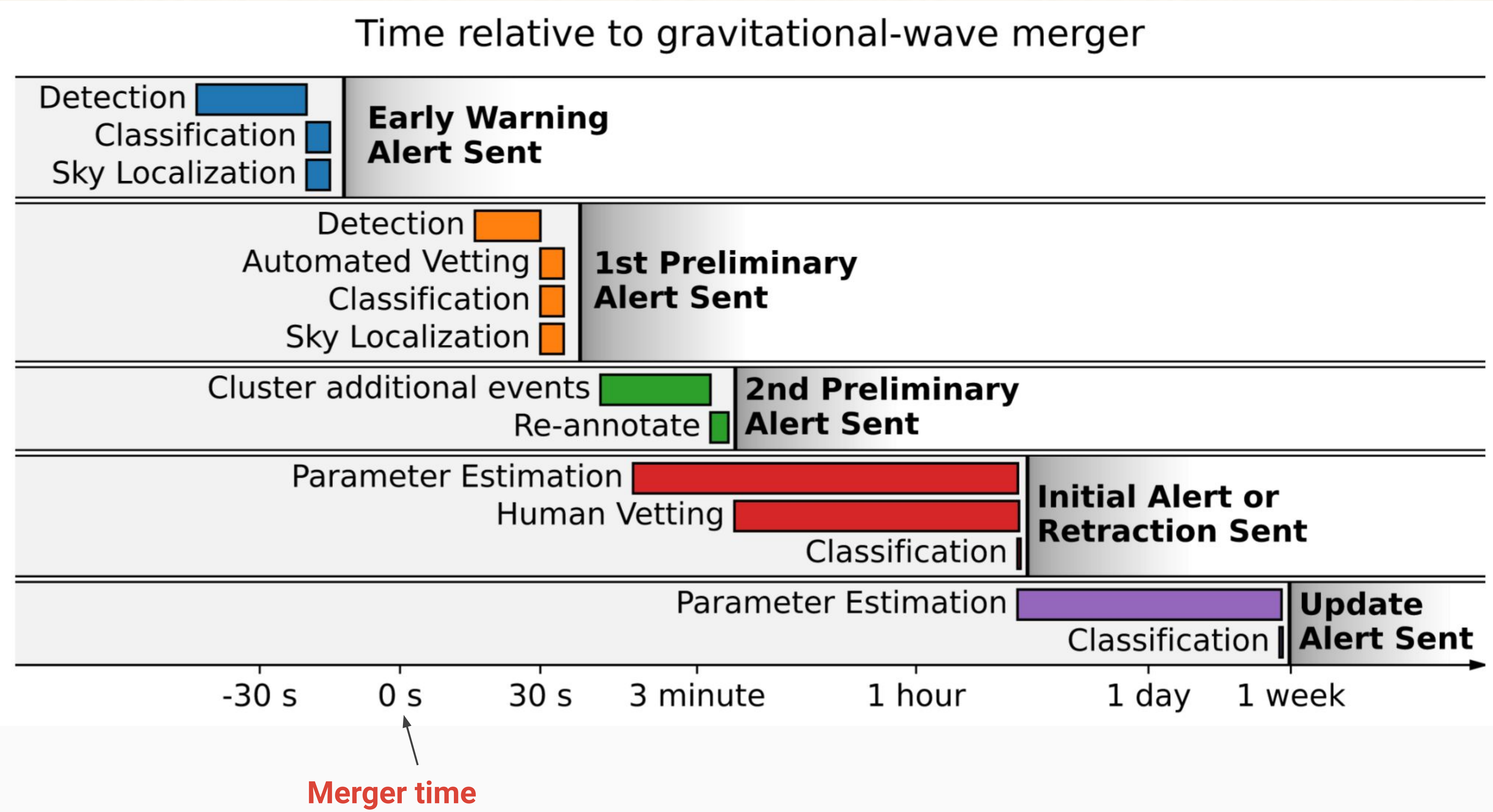
Credit: Shaon Ghosh, Roberto De Pietri, Soichiro Morisaki

O4 plans: other changes to alerts

- Early warning (pre-merger) alerts will be provided
- Multiple distribution channels for alerts:
  - GCN Notices and Circulars as in O3.
  - Kafka based alerts with embedded skymap via SCiMMA and GCN
- EM-Bright probabilities (*HasNS* and *HasRemnant*) marginalized over large number of equation of neutron star models.
- Mass-gap moved from p_{astro} to source-properties section of GCN. Called *HasMassGap*.
- New "*significant*" field introduced in the notices.

Credit: Shaon Ghosh, Roberto De Pietri, Soichiro Morisaki

O4 plans: alert timeline



https://emfollow.docs.ligo.org/userguide/analysis/index.html

Credit: Shaon Ghosh, Roberto De Pietri, Soichiro Morisaki

O4 plans: example alert

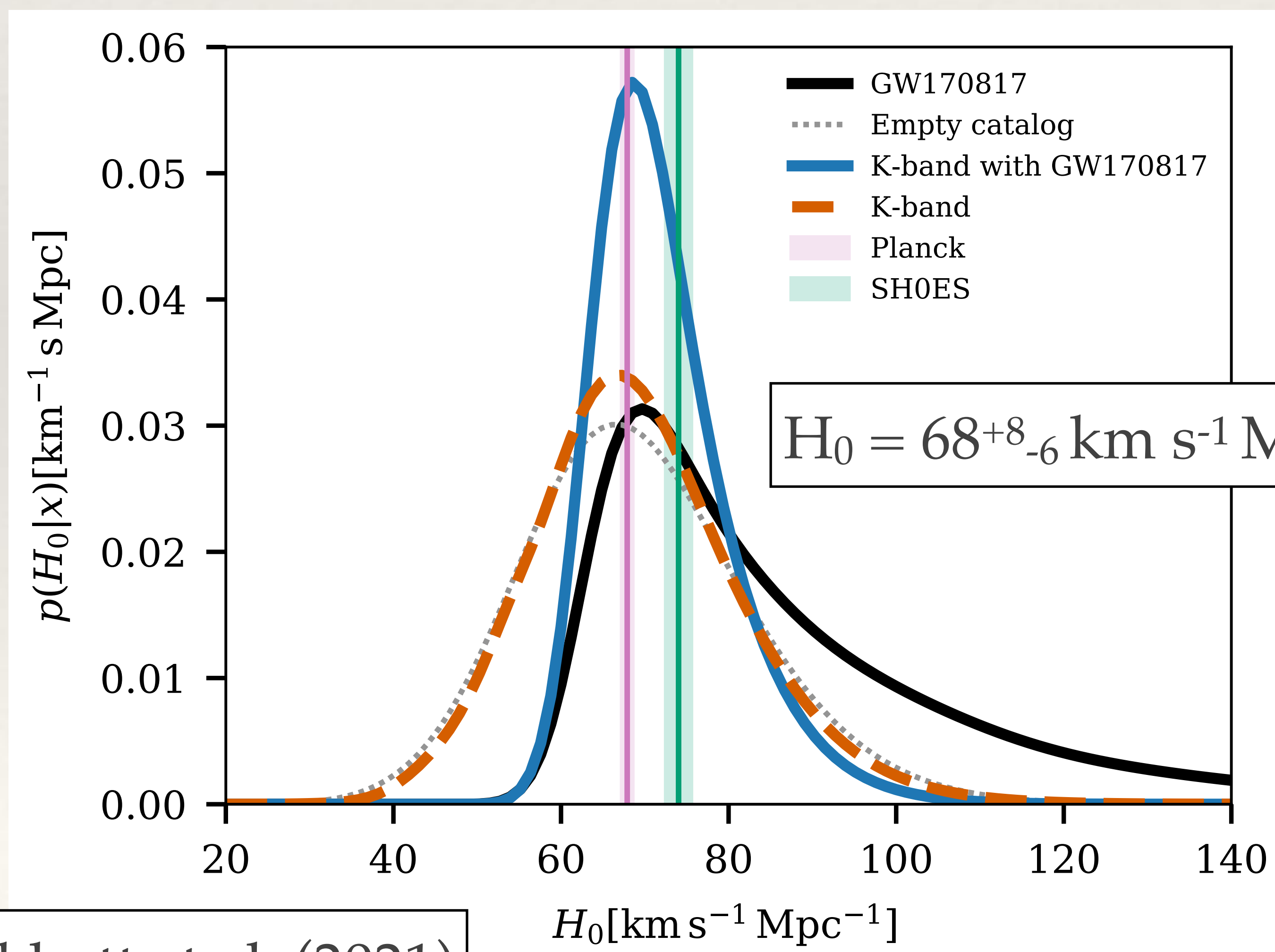

```
{   "alert_type": "Preliminary",
    "time_created": "2018-11-01T22:34:49Z",
    "superevent_id": "MS181101ab",
    "urls": { "gracedb": "https://example.org/superevents/MS181101ab/view/" },
    "event": {
        "time": "2018-11-01T22:22:46.654Z",
        "far": 9.11069936486e-14,  # FAR < (2/day)
        "significant": False      # FAR > 1/month CBC and 1/year BURST
                       True       # FAR < 1/month CBC and 1/year BURST
        "instruments": [ "H1", "L1", "V1"],
        "group": "CBC",
        "pipeline": "gstlal",
        "search": "MDC",
        "classification": { "BNS": 0.95, "NSBH": 0.01, "BBH": 0.03, "Terrestrial": 0.01},
        "properties": { "HasNS": 0.95, "HasRemnant": 0.91, "HasMassGap": 0.01},
        "skymap": "U0lNUExFICA9ICAgICAgICAgICAgICAgICAgICBUIC8gY29uZm..."
         },
    "external_coinc": null }
```


Credit: Shaon Ghosh, Roberto De Pietri, Soichiro Morisaki

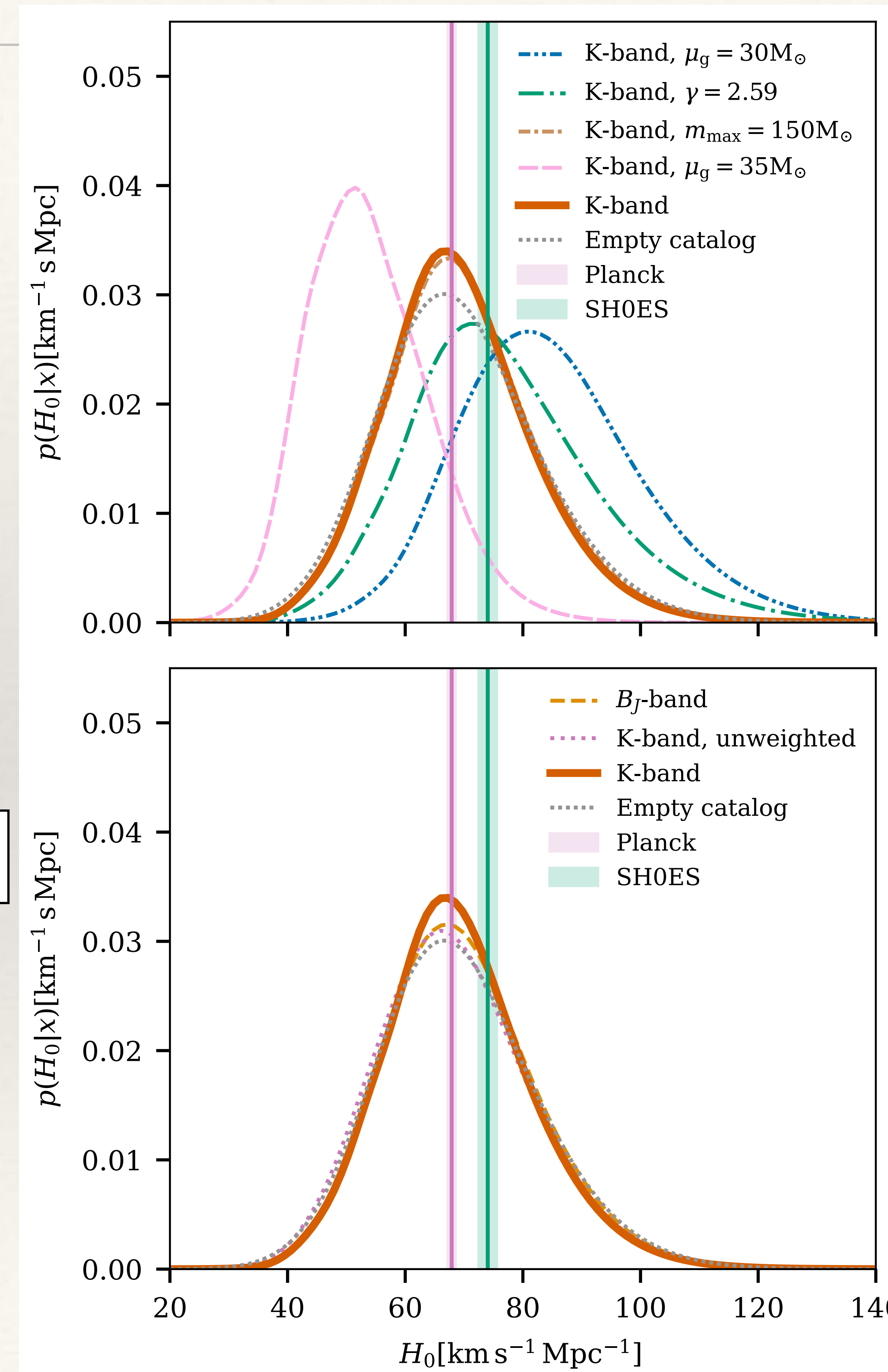
Things to look forward to

Standard siren cosmology

- LVK and external groups use GW events to constrain H_0 using bright and dark sirens.
- Result still dominated by GW170817.



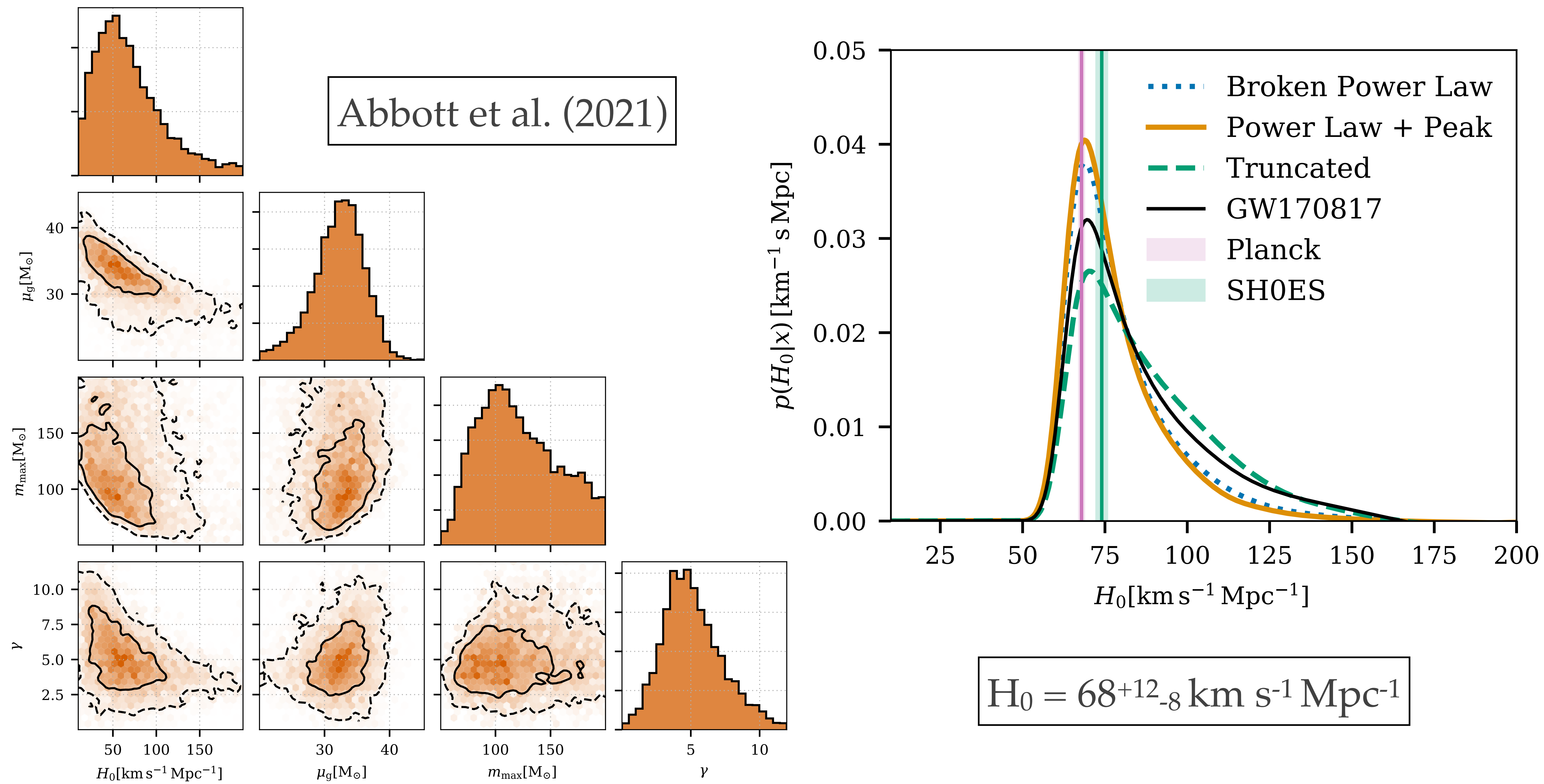
$H_0 = 68^{+8}_{-6}$ km s^{-1} Mpc^{-1}



Abbott et al. (2021)

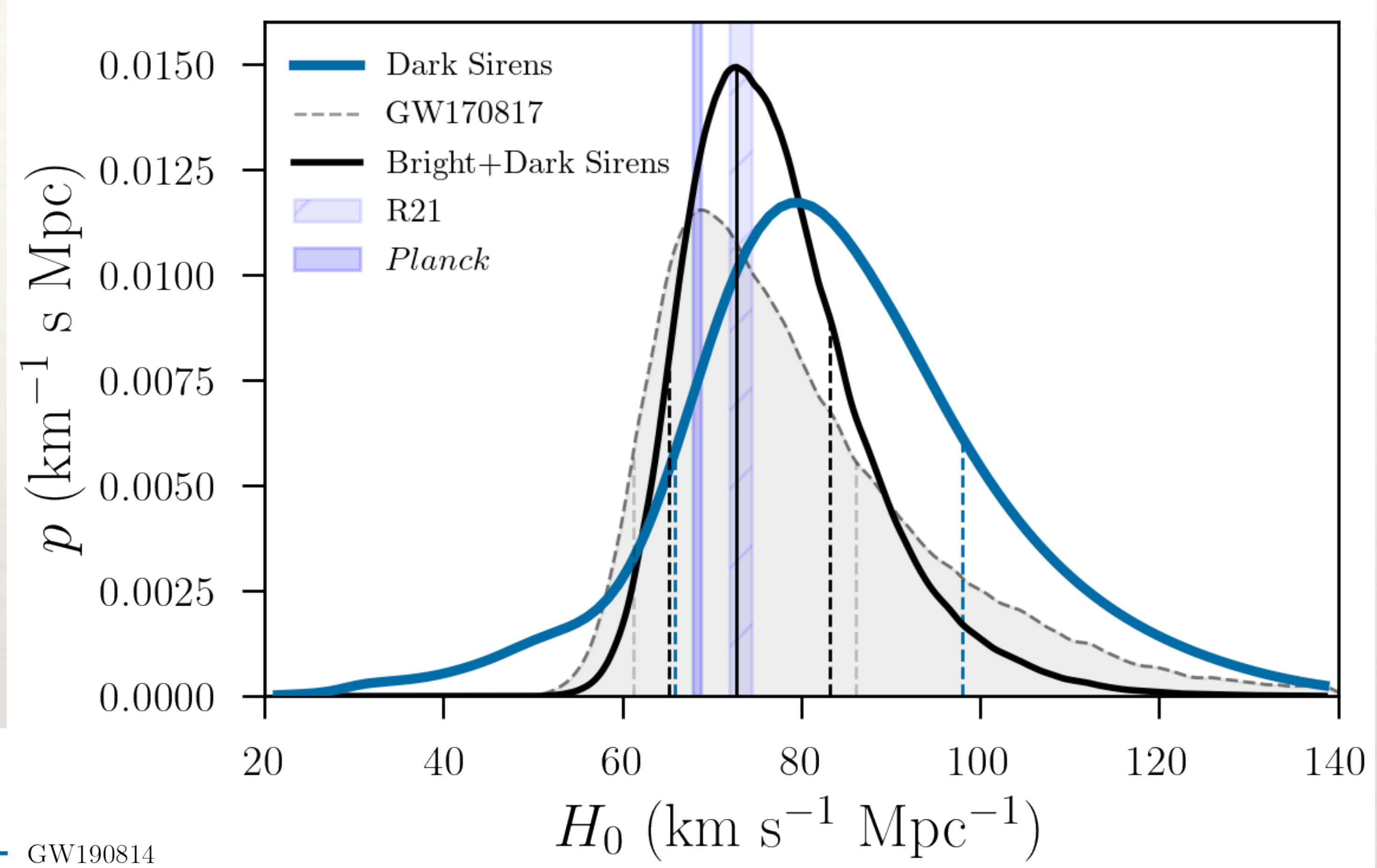
Standard siren cosmology

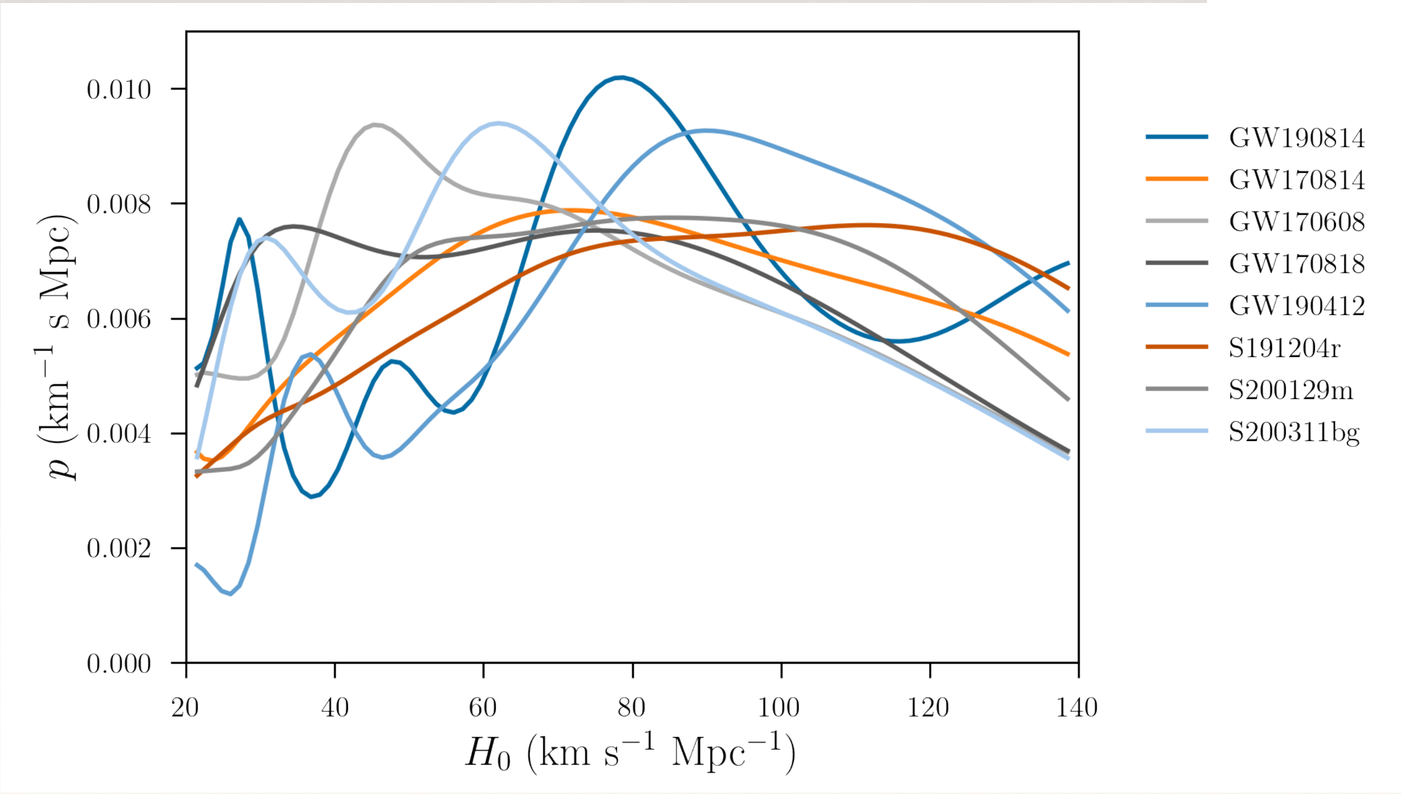
- Even less information in dark sirens when accounting for uncertainties in population model.



Standard siren cosmology

- With better galaxy catalogues (e.g., from DES) can get more information from dark sirens, but bright sirens much more robust.
- Need more counterpart events!



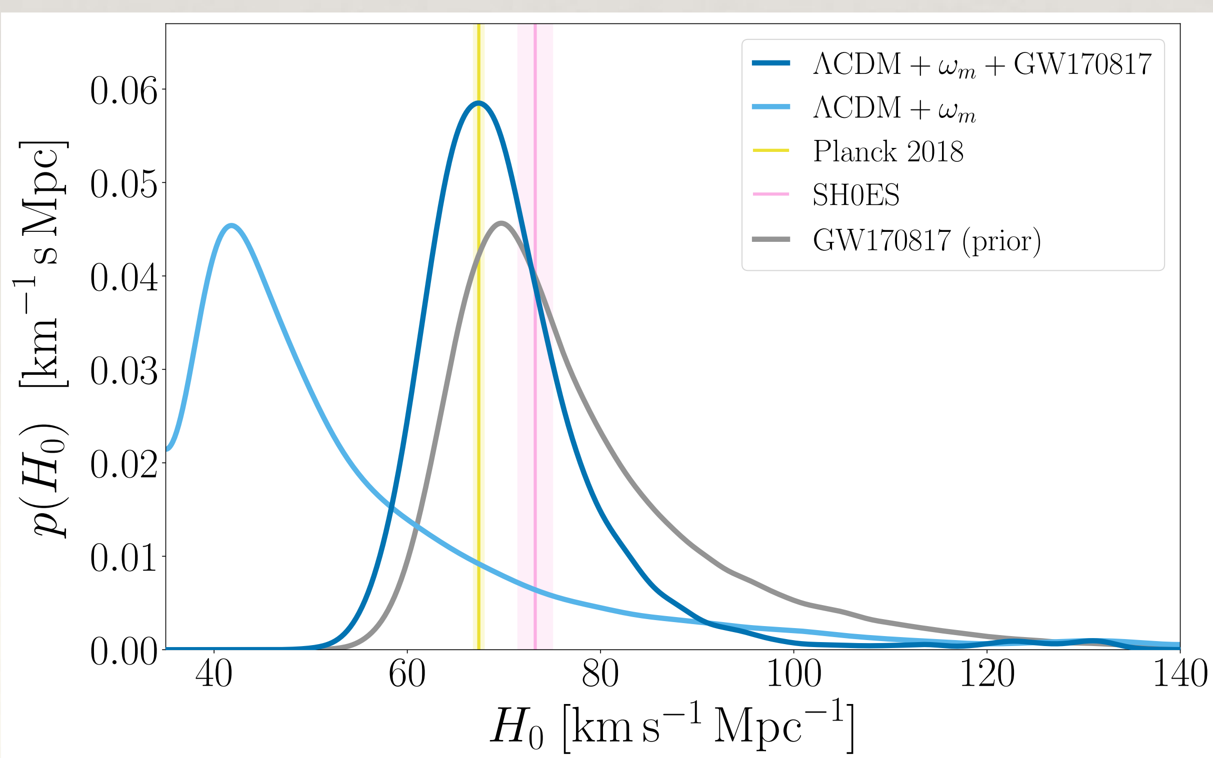


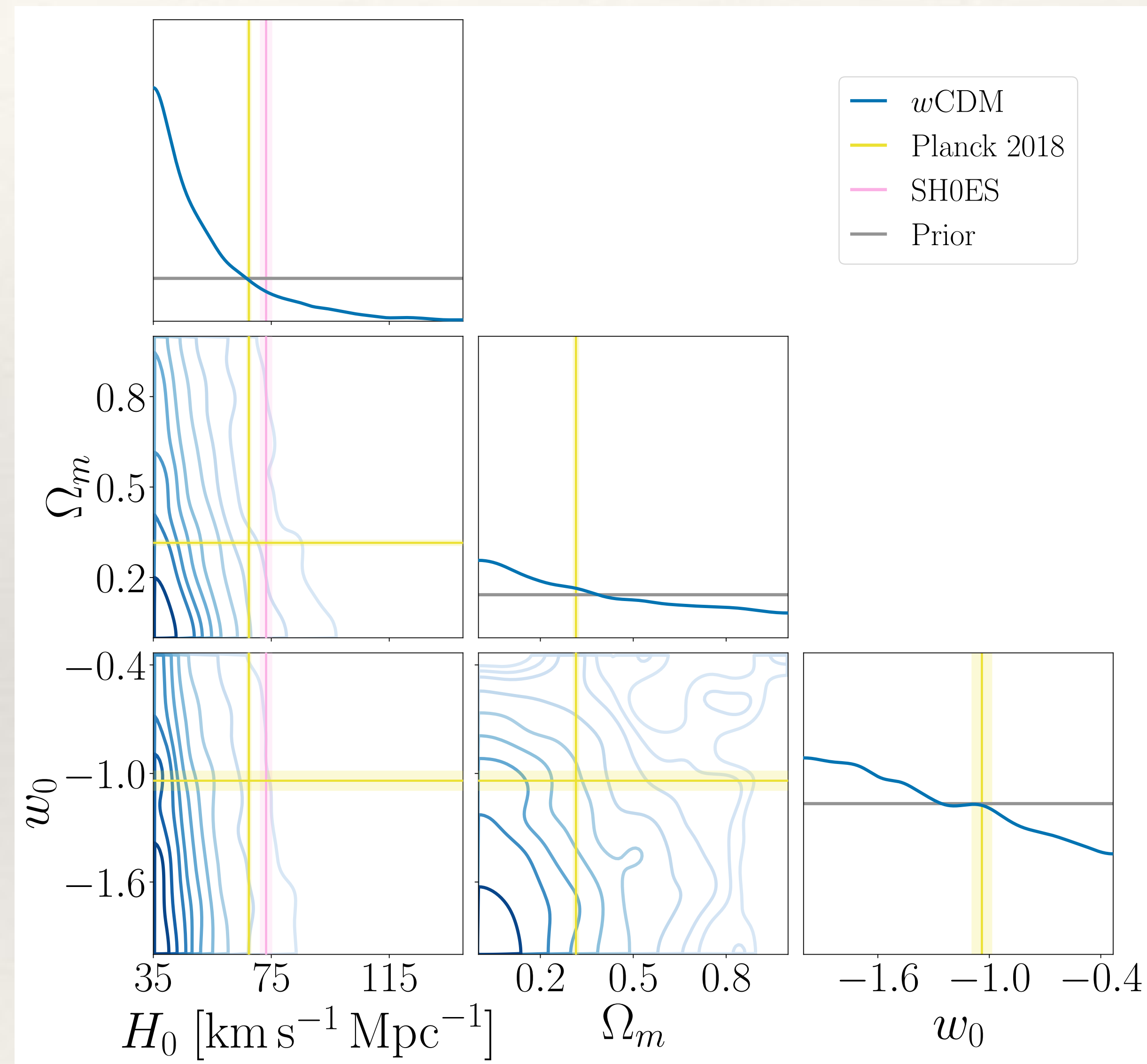
$H_0 = 72.77^{+11}_{-7.55}$ km s^{-1} Mpc^{-1}

Palmese et al. (2021)

High mass BBH counterparts (?)

- Could also see more high-mass BBH events with possible counterparts, like GW190521.
- If these are real associations, the events can be used for cosmology, as well as providing insights into BBH formation.

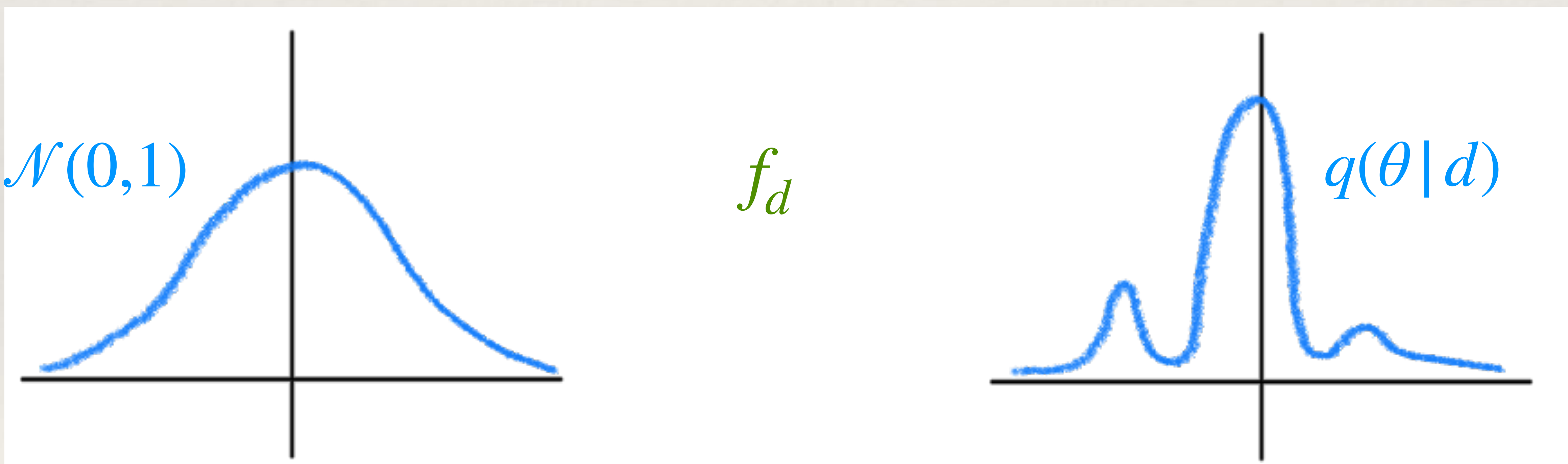




Chen+ (2021)

Rapid and robust PE: DINGO

- In O4 we will start to use DINGO for parameter estimation.
- This is a machine learning framework that can directly generate samples from the posterior distribution given input data.
- It represents the posterior via a *normalising flow*, i.e., a mapping to a Normal distribution.

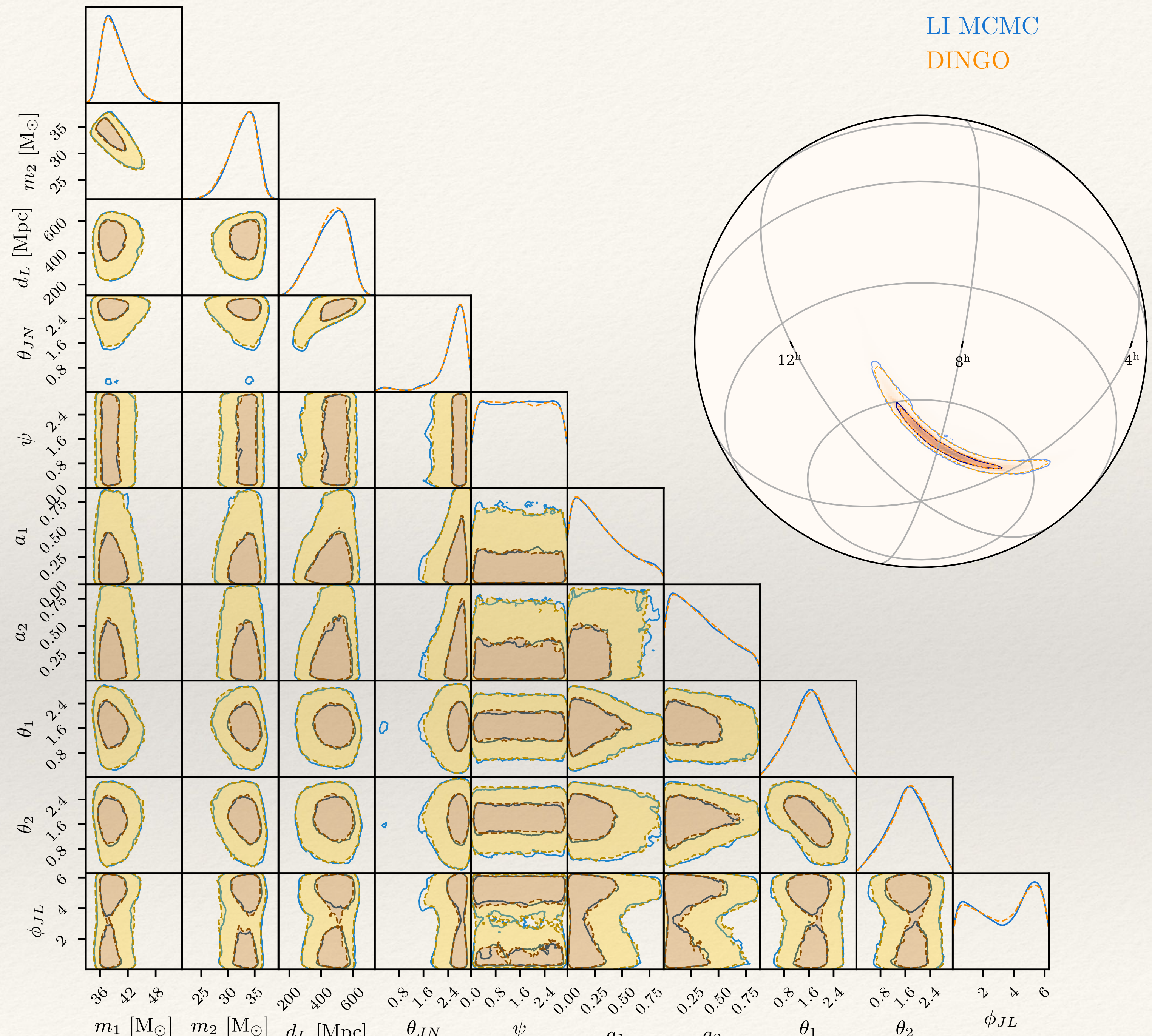


- Allows inference in O(seconds). Posterior distributions are near-indistinguishable from those produced via standard methods. Also have DINGO-IS that uses importance sampling to correct the final results (slower, O(hours)).

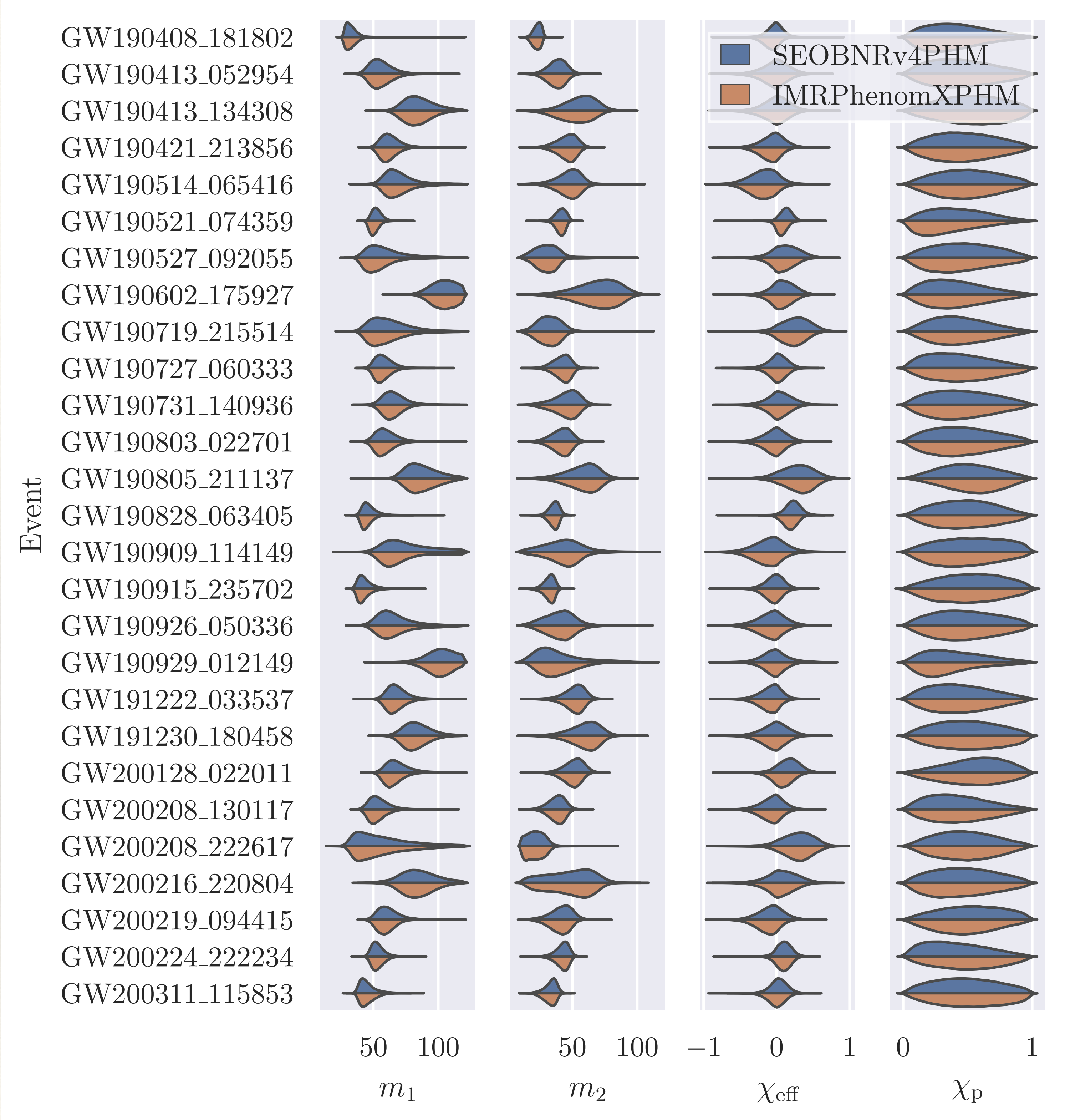
DINGO performance

GW150914

- Much better agreement with standard samplers using GNPE.
- Quantitatively indistinguishable in many cases.



DINGO performance: O3 events



- DINGO allows the use of the most expensive waveform models in parameter estimation.
- At present, have working implementations for BBH systems with component masses > 10 solar masses.
- Working to extend into BNS and NSBH regime.
- Long term goal: rapid and robust PE for use in low-latency.

Summary

- O4 will start on May 24th and run for 18 months, over a period of 20 months.
- O4 will start with slightly better sensitivity than O3, and BNS range could reach 170 Mpc later in the run.
- Expect a few BNS and NSBH detections over the duration of O4.
- Alerts will be sent out. You should expect these alerts with a rate of:
  - **one per day** (Significant gravitational-wave alerts) - based on expected rate of real GW alerts
  - **two per day** (Low Significance gravitational-wave alerts) - based on new threshold
- Exciting prospects for further multi messenger events, with many applications including cosmology.
- Various new data analysis methods will be trialled for the first time in O4, include rapid parameter inference using DINGO.