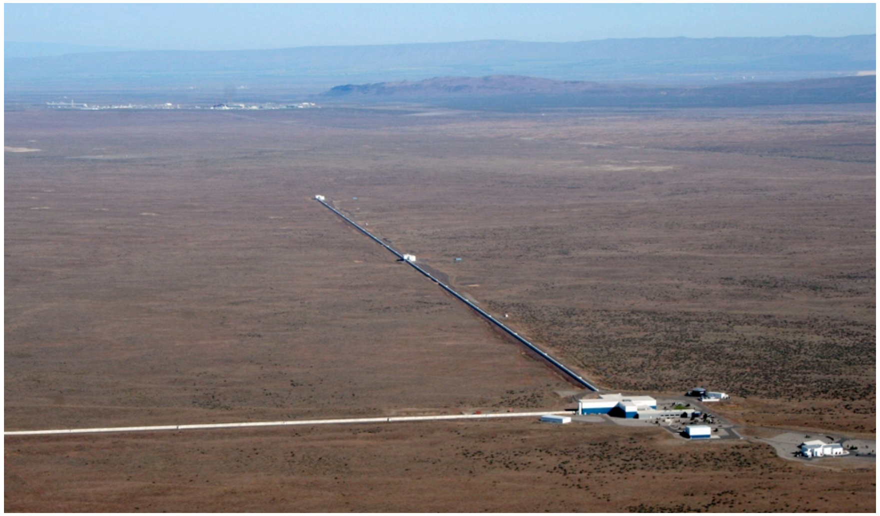
Advanced LIGO and Advanced Virgo GW detections: status update and future prospects

José Antonio Font
Universitat de València
www.uv.es/virgogroup

[on behalf of the LIGO Scientific Collaboration and the Virgo Collaboration]

Our current GW detector network

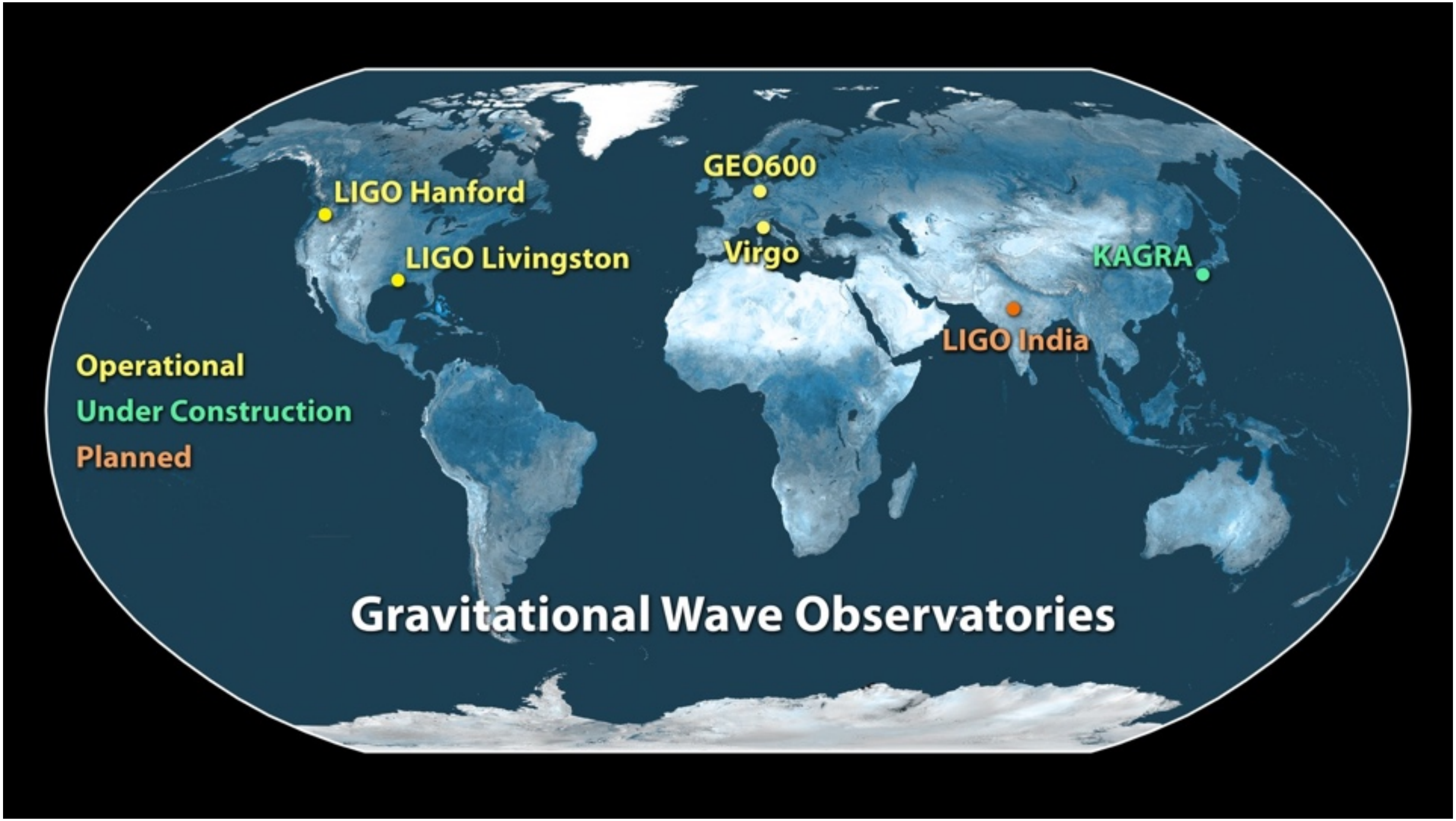
LIGO Hanford Observatory



LIGO Livingston Observatory

Virgo Observatory

Towards a global infrastructure



KAGRA inaugurated on October 4, 2019

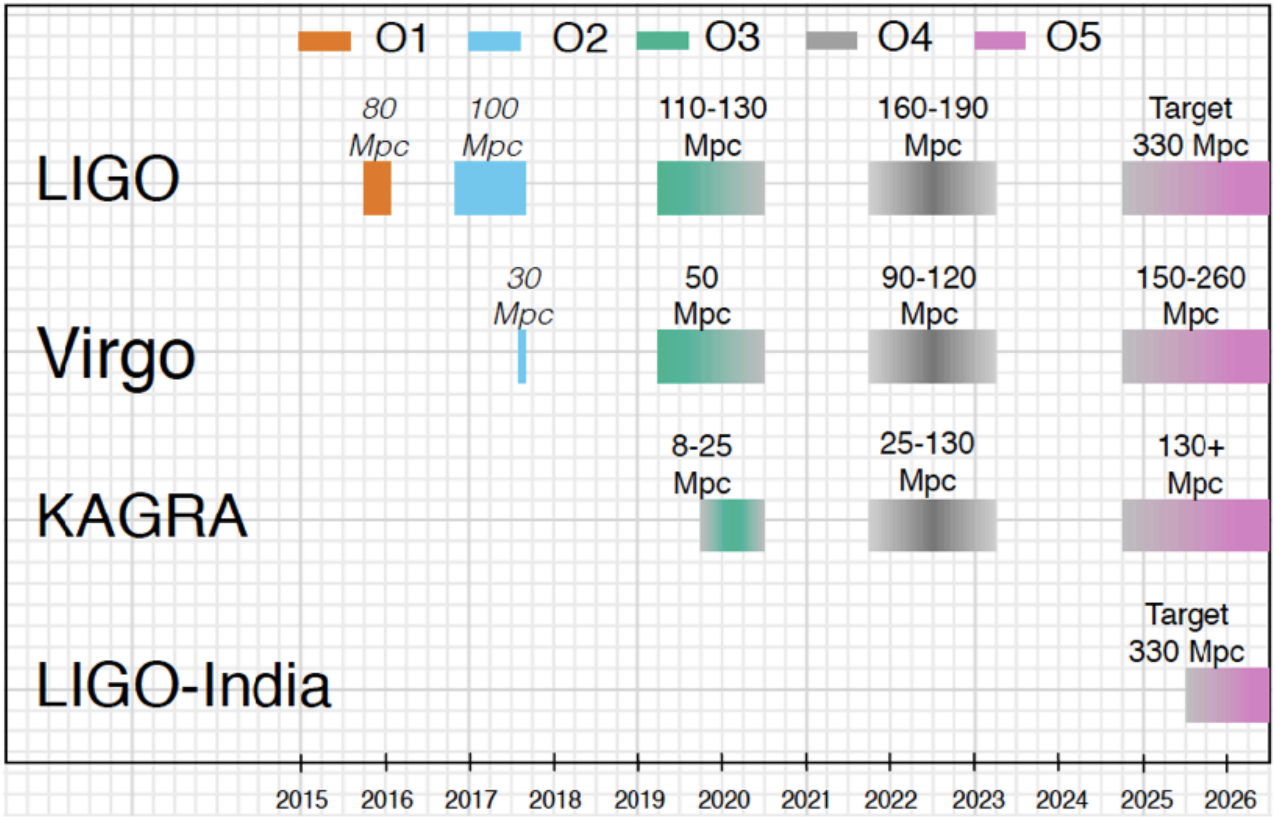
MoA signed with LIGO and Virgo

Observations began on Feb 25th 2020

LIGO/Virgo observing runs & BNS range

O1: Sep 12 2015 - Jan 19 2016.
O2: Nov 30 2016 - Aug 25 2017. [Virgo joined on Aug 1]
O3: Apr 1 2019 - Apr 30 2020. [KAGRA to join towards the end]

[original plan for O3]



See Abbott et al, arXiv:1304.0670 (updated Jan 2020)

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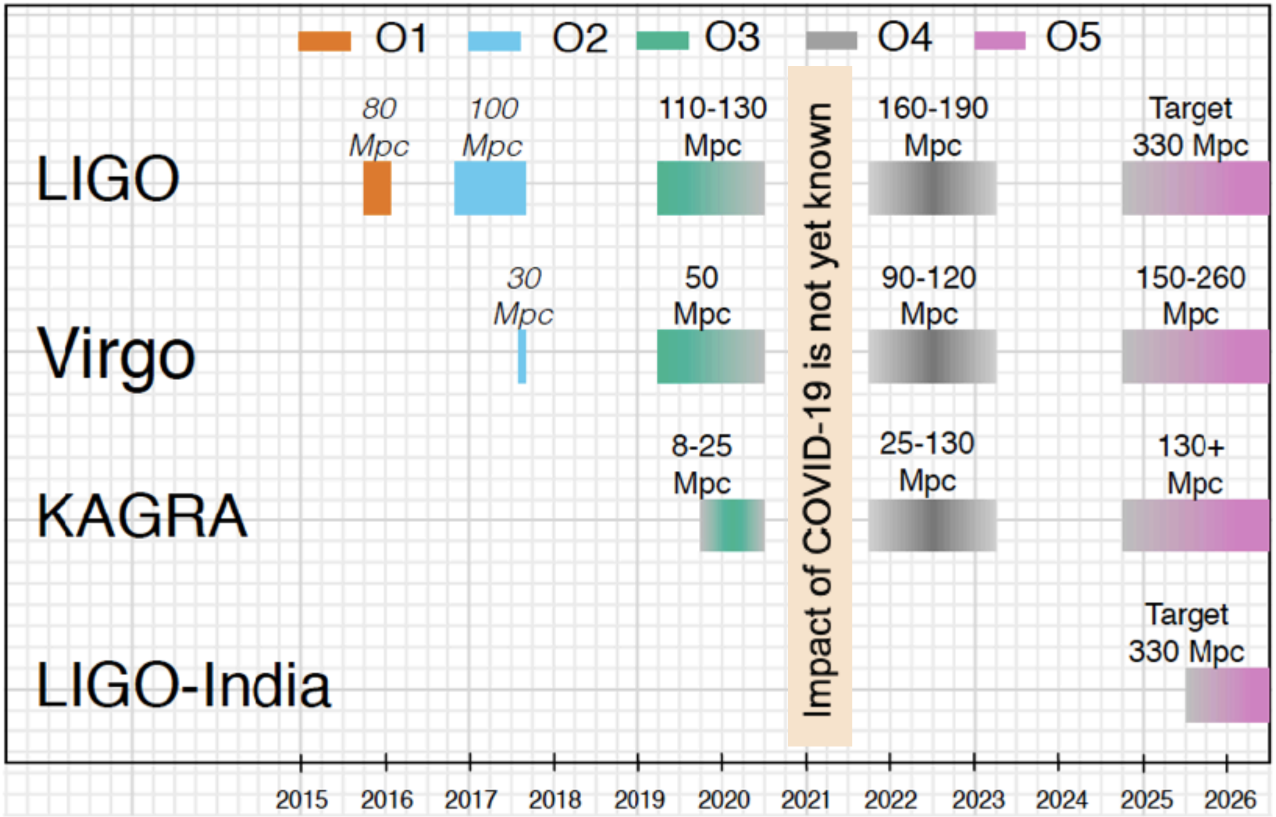

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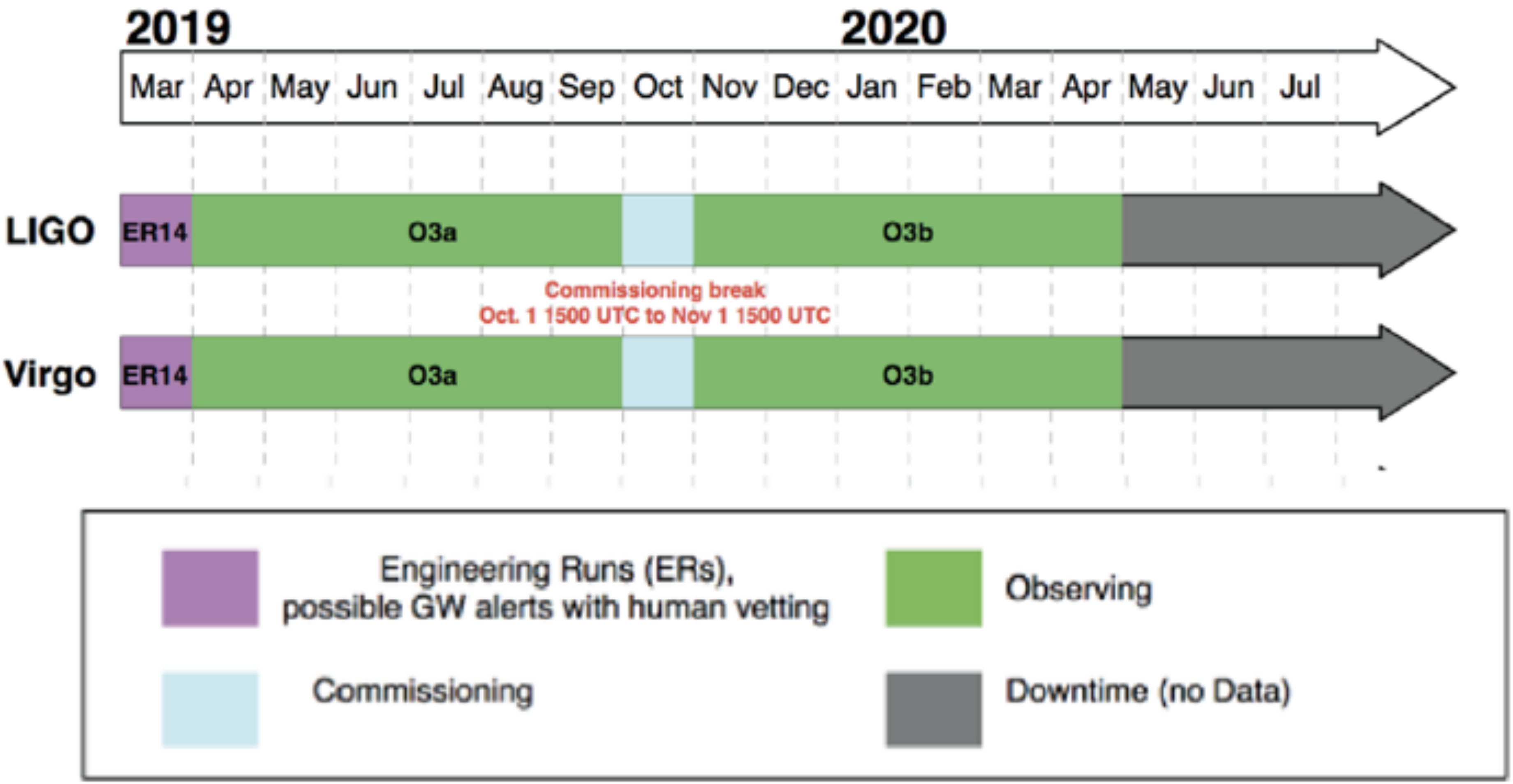
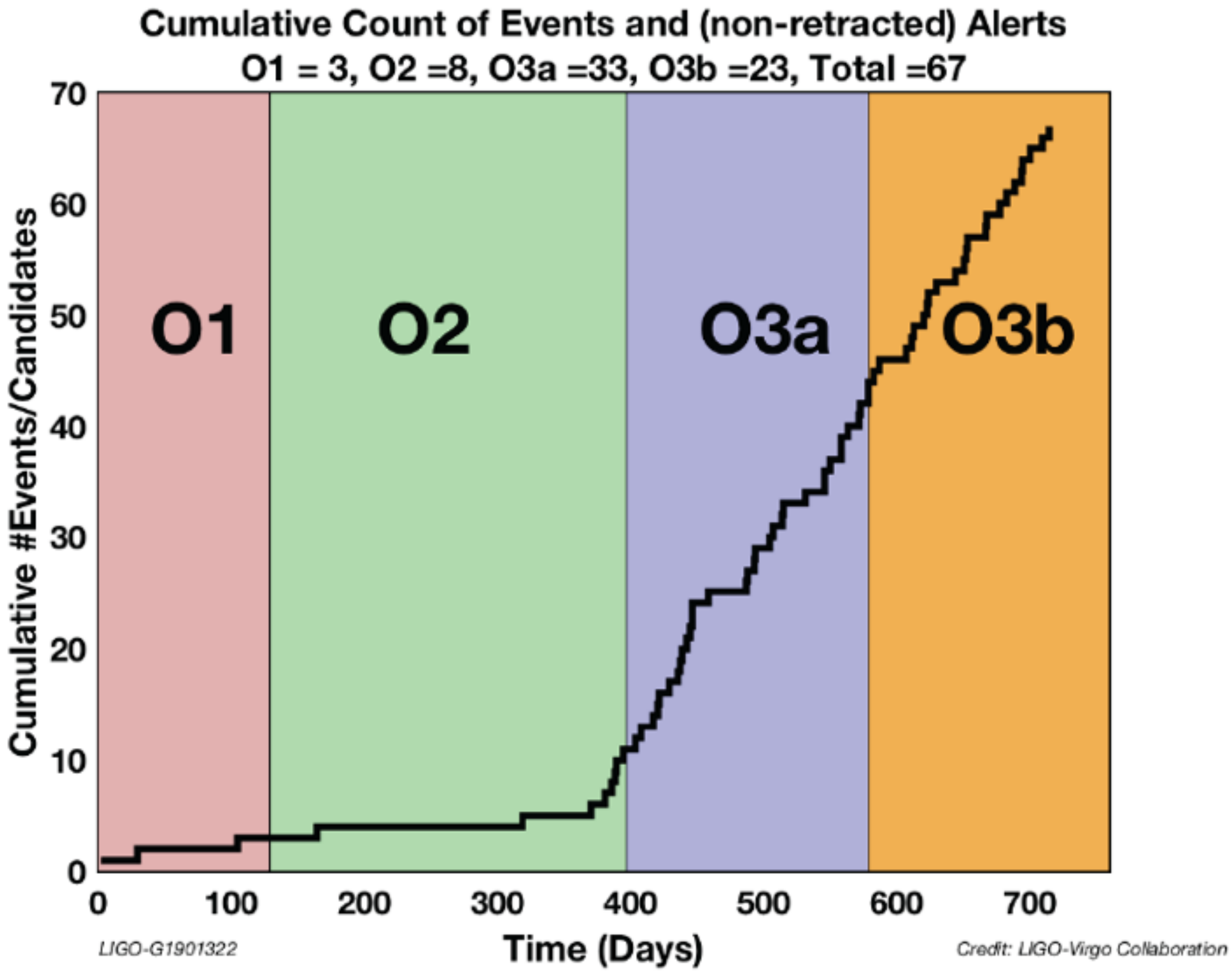
O3 original schedule (LIGO-G1901531)



O3b suspended on March 27th due to COVID-19 pandemic.

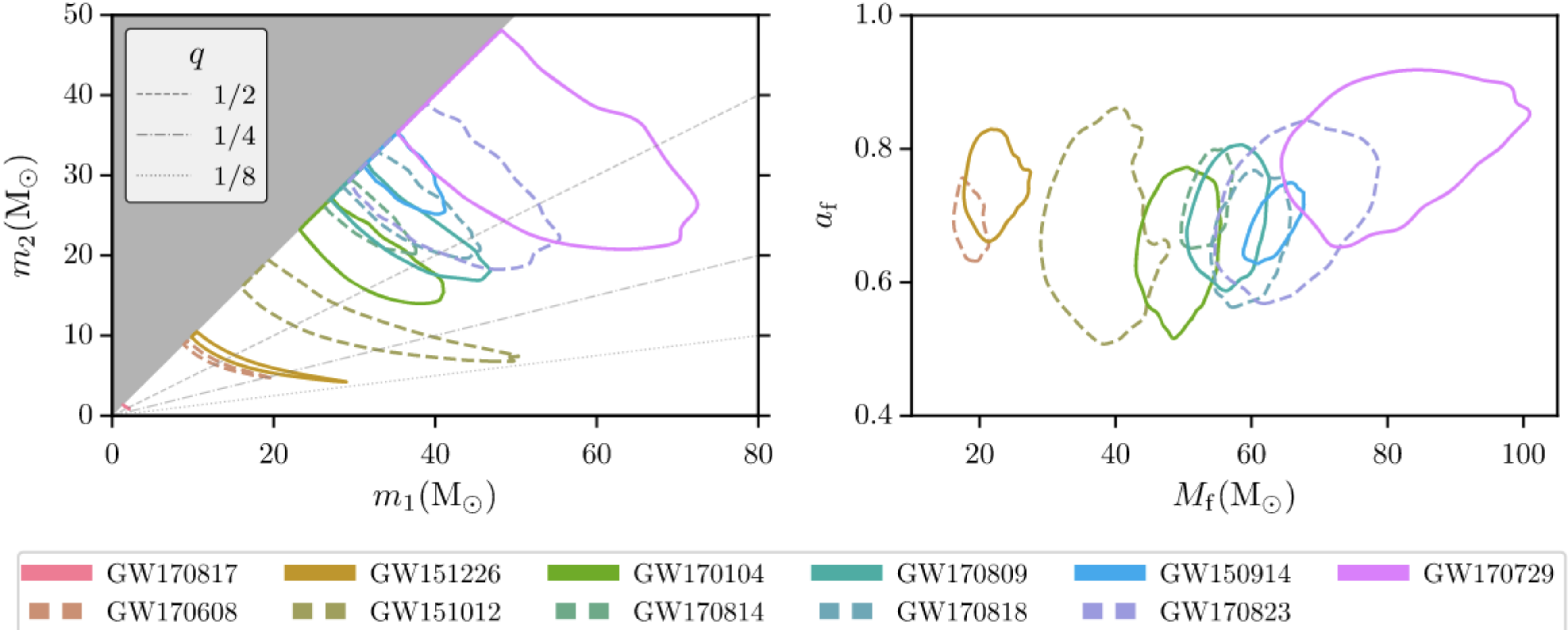
O1+O2+O3 cumulative list of events and alerts



O1-O2 BBH masses

GW astronomy has revealed a **new population** of stellar-mass BHs more massive than those known from X-ray observations.

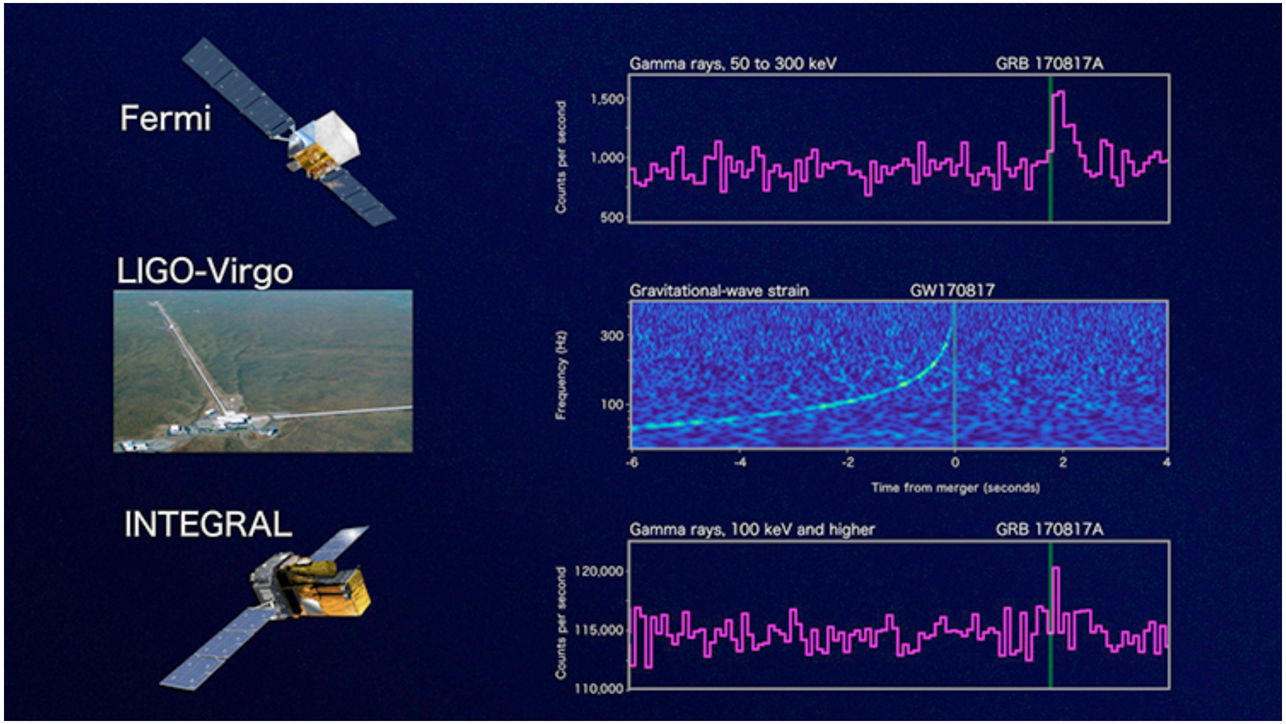
Total mass range: $18.6^{+3.2}_{-0.7} M_\odot - 84.4^{+15.8}_{-11.1} M_\odot$

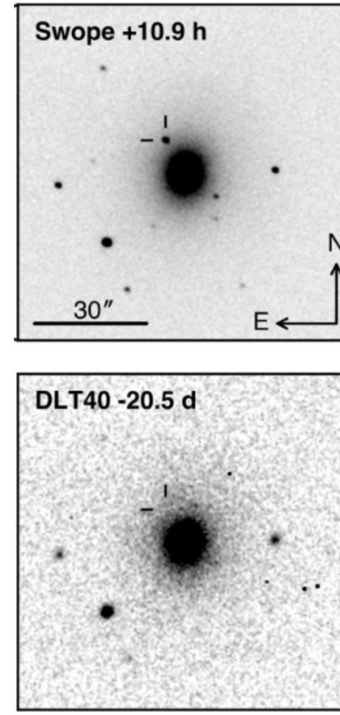


Dimensionless spin parameter range: $0.66^{+0.08}_{-0.11} - 0.81^{+0.07}_{-0.13}$

Abbott et al, 1811.12907 (GWTC-1 Catalog paper)

GW170817: 1st BNS merger ever observed



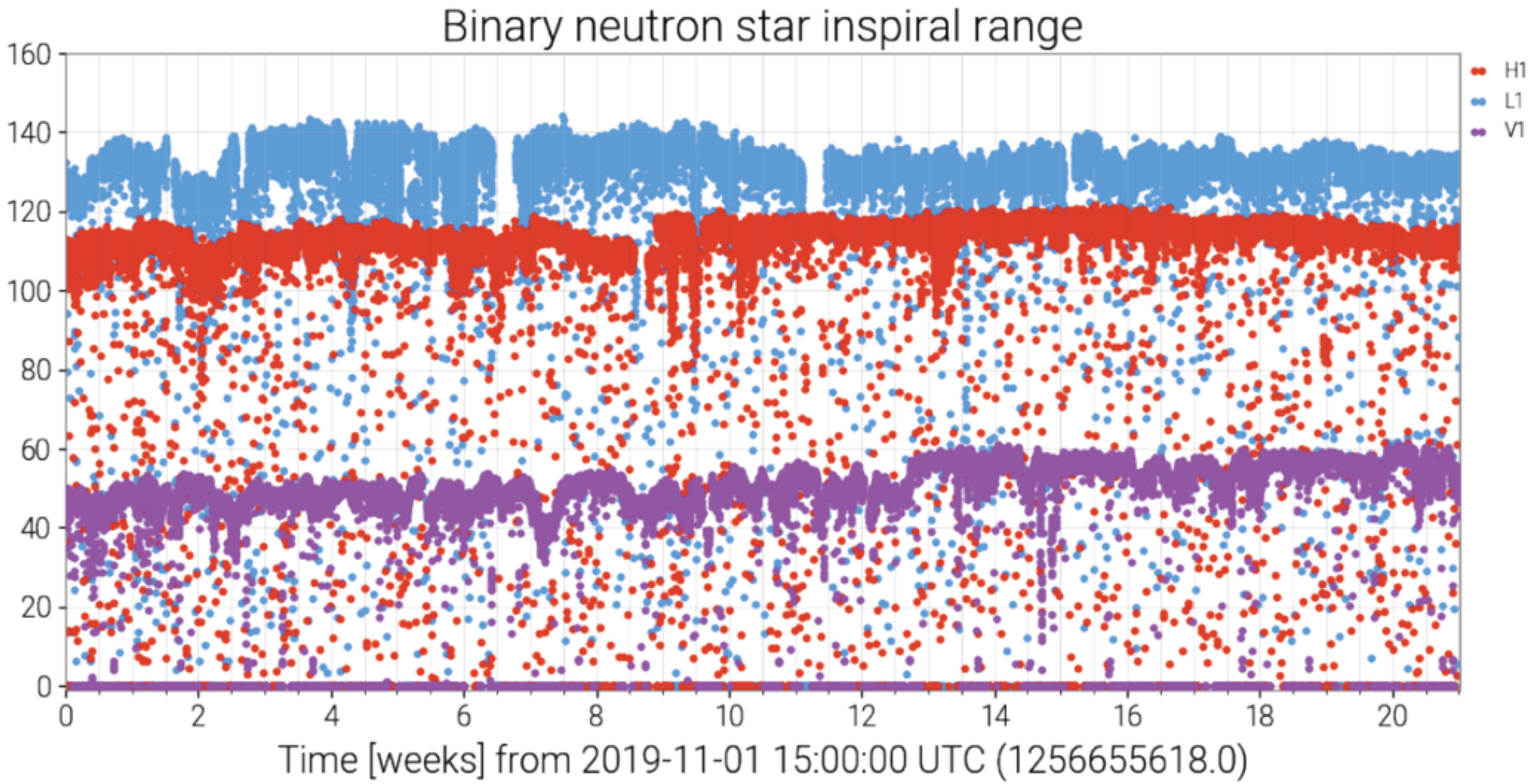


Dozens of EM follow-up observations: **multi-messenger astronomy.**

Large impact in astrophysics, cosmology, and nuclear physics:

- BNS/sGRB association.
- Support for the kilonova model, heavy element nucleosynthesis.
- Measurement of H_0 (BNS as standard siren).
- Constraints on EOS of high-density matter (tidal deformability).

Network's BNS inspiral range during O3b



H1: 110-120 Mpc L1: 120-140 Mpc V1: 50-60 Mpc

All three detectors at O3 design sensitivity or better.

O3: Public announcement of low-latency triggers

GW low-latency triggers released as **public alerts** during O3:

- Facilitate rapid identification of EM or neutrino counterparts to GW detections.
- Maximize science that the entire scientific community can do with them.

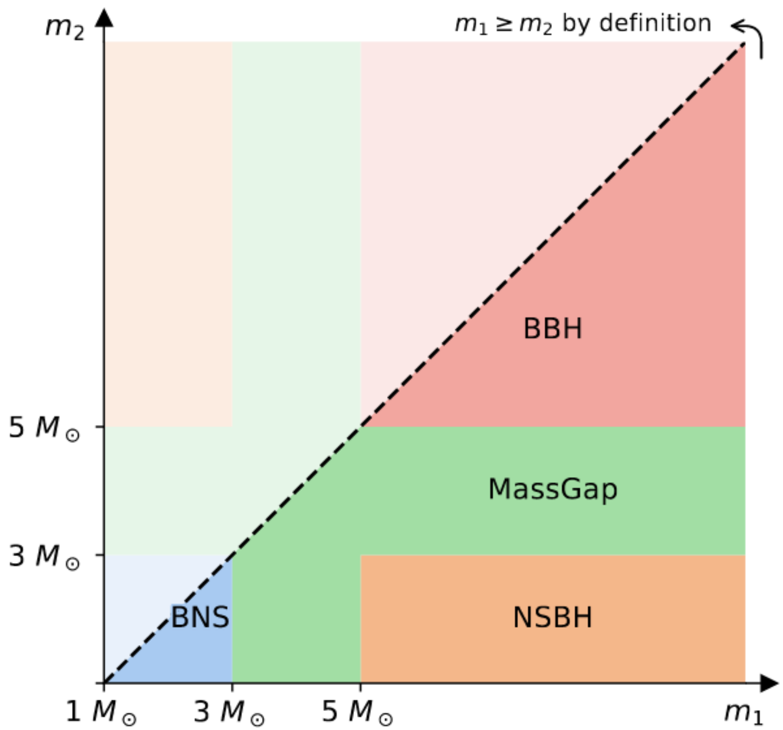
Circulars on the **G**amma-ray **C**oordination **N**etwork.

LIGO/Virgo Public Alerts User Guide
https://emfollow.docs.ligo.org/userguide/

GraceDB - GW Candidate Event Database
gracedb.ligo.org/superevents/public/O3/

O3: Contents of the alert (CBC)

- False Alarm Rate (FAR) estimate of the event candidate.
- Event time and sky localization.
- 3-D skymap with direction dependent luminosity distance.
- Luminosity distance marginalized over whole sky.
- Source classification and properties.



BNS: both masses < $3M_{sun}$

MassGap: $3M_{sun}$ < one mass < $5M_{sun}$

NSBH: one mass <$3M_{sun}$,
other mass > $5M_{sun}$

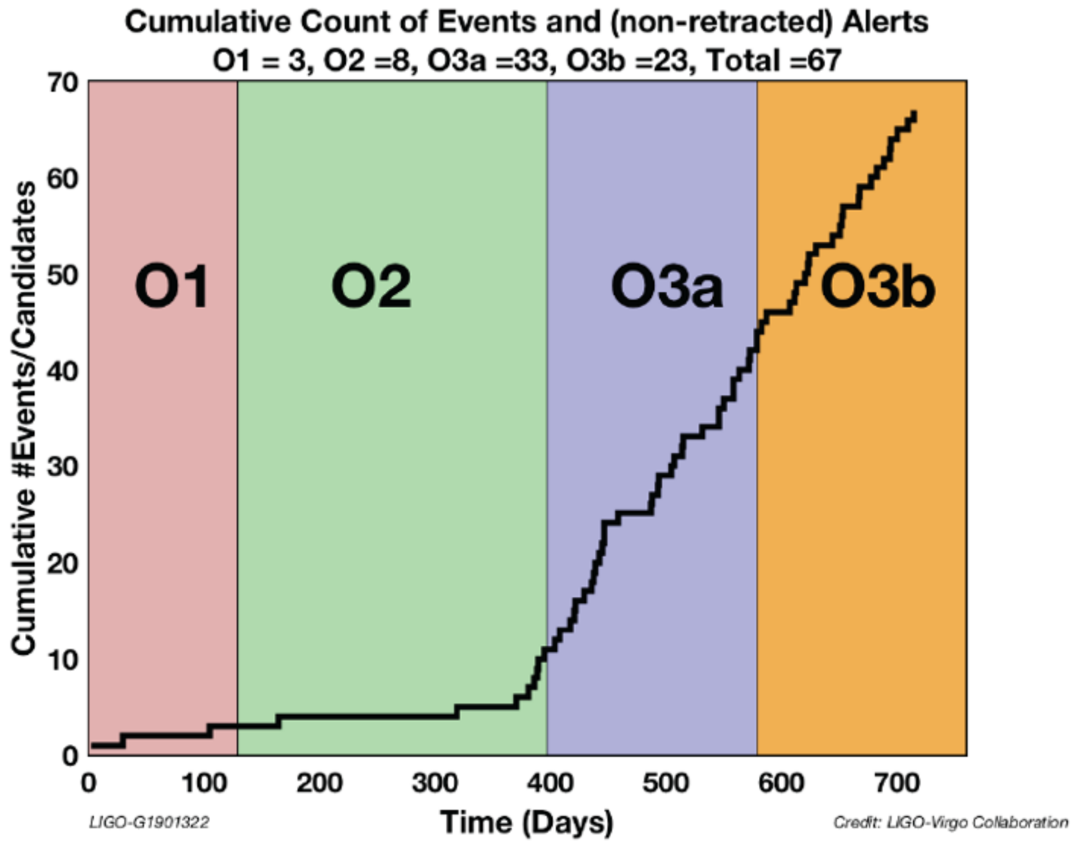
BBH: both masses > $5M_{sun}$

Terrestrial: noise

HasNS: probability one mass consistent with NS.

HasRemnant: probability system ejected NS matter.

O3 publicly anounced candidate events



O3 has been a very successful run: **56 candidate events**.

A few confirmed detections (exceptional events) have already been published: **GW190412, GW190425, GW190814.**

GW190412

GW190412: Observation of a Binary-Black-Hole Coalescence with ***Asymmetric Masses*** (LVC, arXiv:2004.08342)

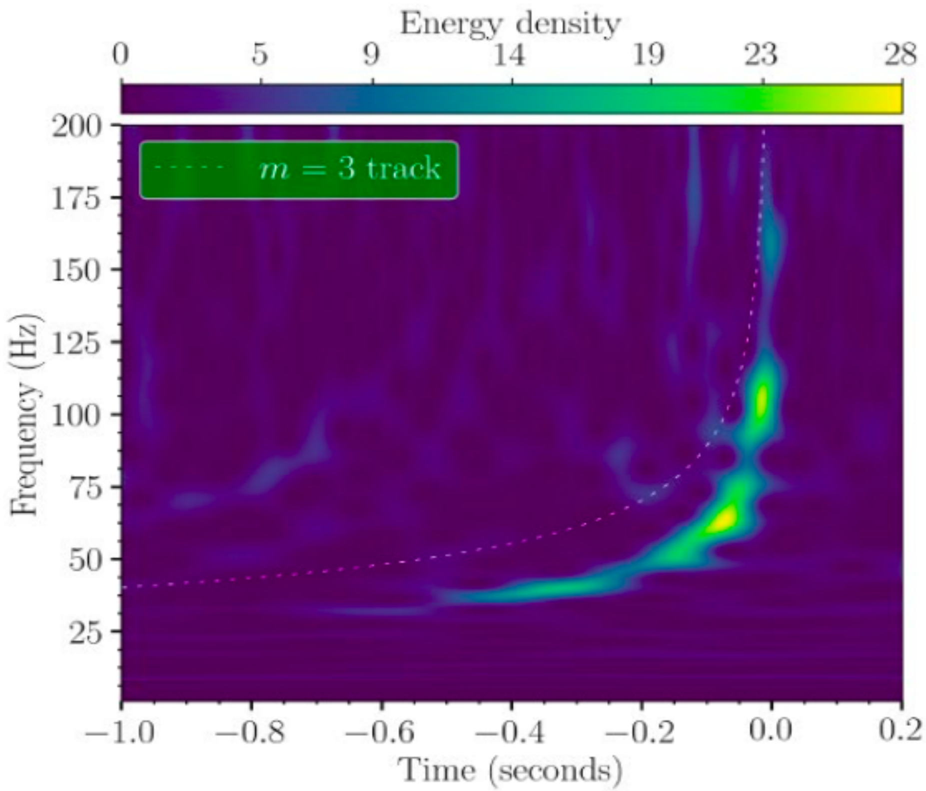
3 detector (L1,H1,V1) observation with network SNR of 19.

First observation of BBH merger with **significantly different masses** (30 and 8 M_{sun})

First observation of GW higher multipoles $(\ell = m = 3)$

- New tests of GR
- Further information on the source

Marginal hints of precession

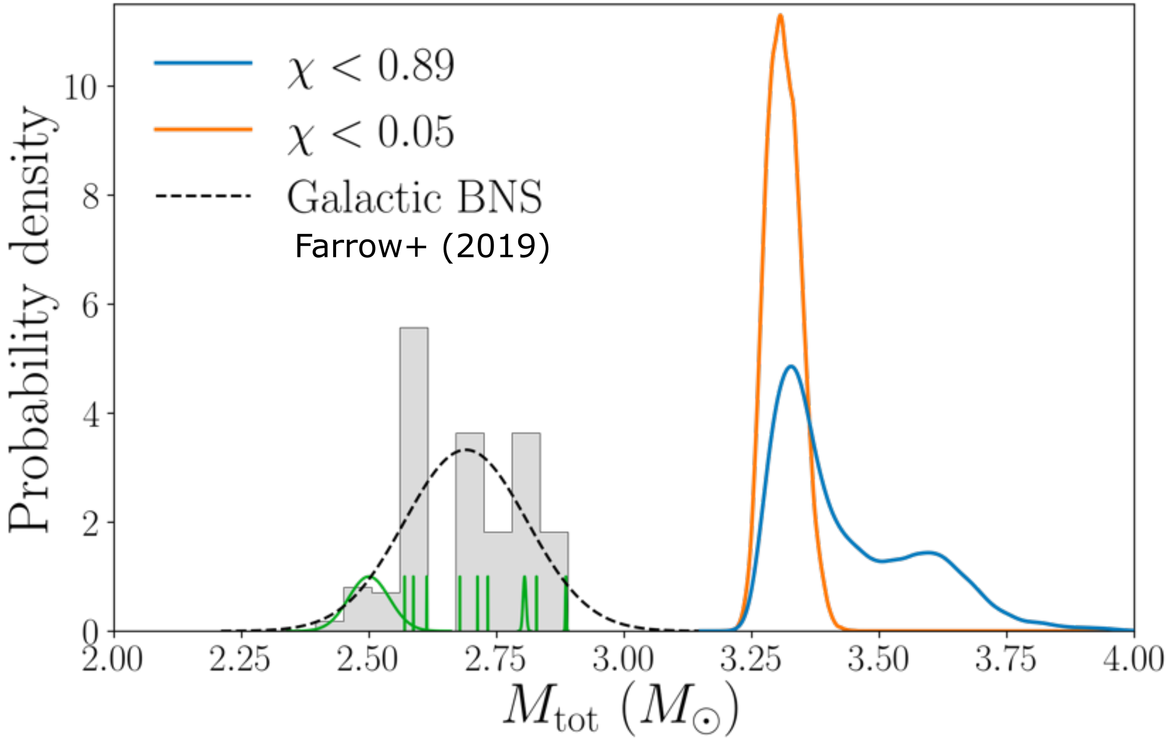


GW190412 and future similar detections will improve our knowledge on BBH populations (abundance and formation channels).

GW190425

GW190425: Observation of a Compact Binary Coalescence with ***Total Mass ~ 3.4 M_{sun}*** (LVC, ApJL, 892:L3, 2020)

Most likely **2^{nd} BNS merger** after GW170817 (BBH or NSBH cannot be ruled out)
2 interferometer detection: L1 + Virgo (poor sky localisation; no EM counterpart)



Total mass larger than any known system so far. **A new population?**

GW190814

GW190814: Gravitational Waves from the Coalescence of a 23 M_{sun} Black Hole with a 2.6 M_{sun} Compact Object (LVC, ApJL, 896:L44, 2020)

3 detector (L1,H1,V1) observation with network SNR of 25.

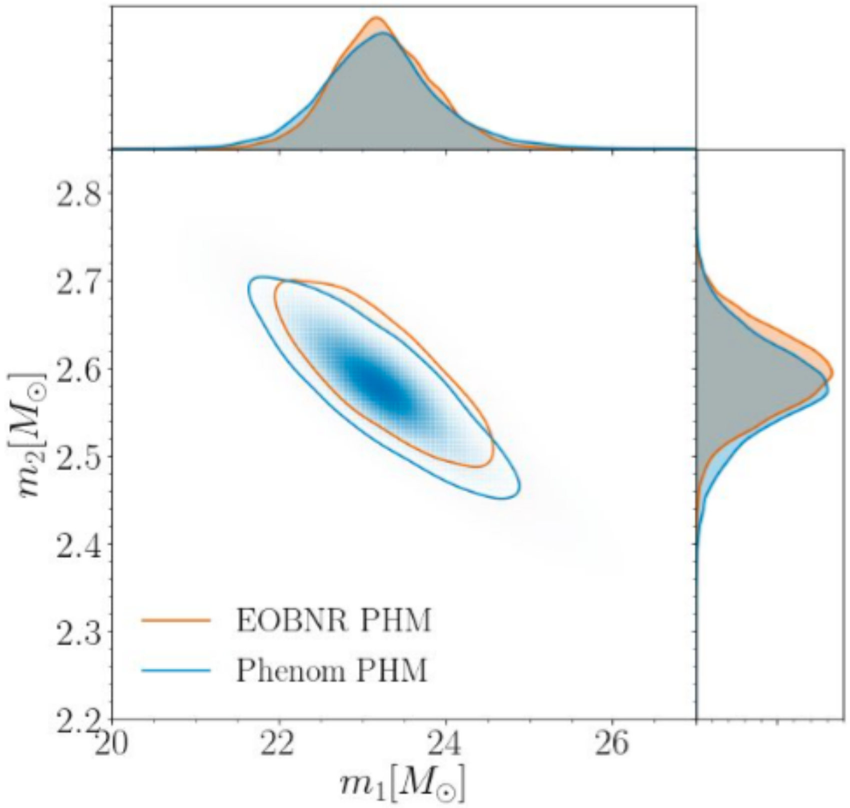
Nature of secondary component uncertain: **BBH or NSBH?**

Difficulties to identify the source:

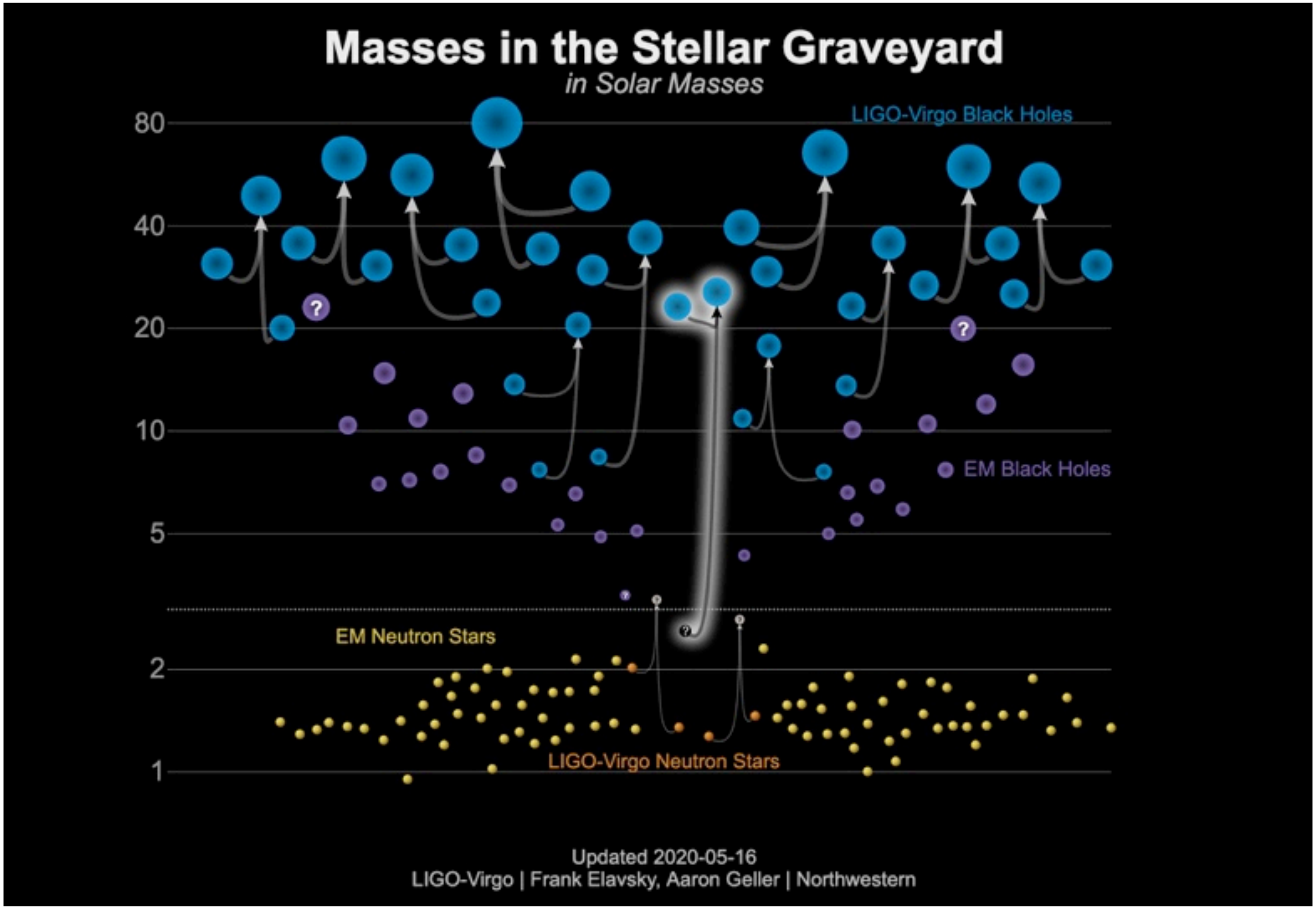
- Asymmetric masses (9:1 ratio)
- No EM counterpart
- No clear signature of tides on the inspiral waveform

Object of **2.6 M_{sun}** compatible with NS or BH depending on maximum mass supported by NS EOS.

Challenge for formation models.



GW190814: compact object in the mass gap



GW190814's secondary mass lies in the hypothesized lower mass gap (2.5-5 M_{sun}) between known NSs and BHs.

Observing scenarios for GW detectors over next decade

See Abbott et al, *Living Reviews in Relativity*, 21, 3 (2018); arXiv:1304.0670

Paper provides information to the astronomy community to facilitate planning for MMA with GWs. Focuses on the inspiral of BNS systems, as those are the most promising targets for MMA. Periodically updated.

BNS range:

O3b: H1: 110-120 Mpc, L1: 120-140 Mpc, V1: 50-60 Mpc

O4 (2022+ runs): A+: 160-190 Mpc, AdV+: 90-115 Mpc, KAGRA: 25-130 Mpc
O5 (2024+ runs): A+: 330 Mpc, AdV+: 145-260 Mpc, KAGRA: 140 Mpc

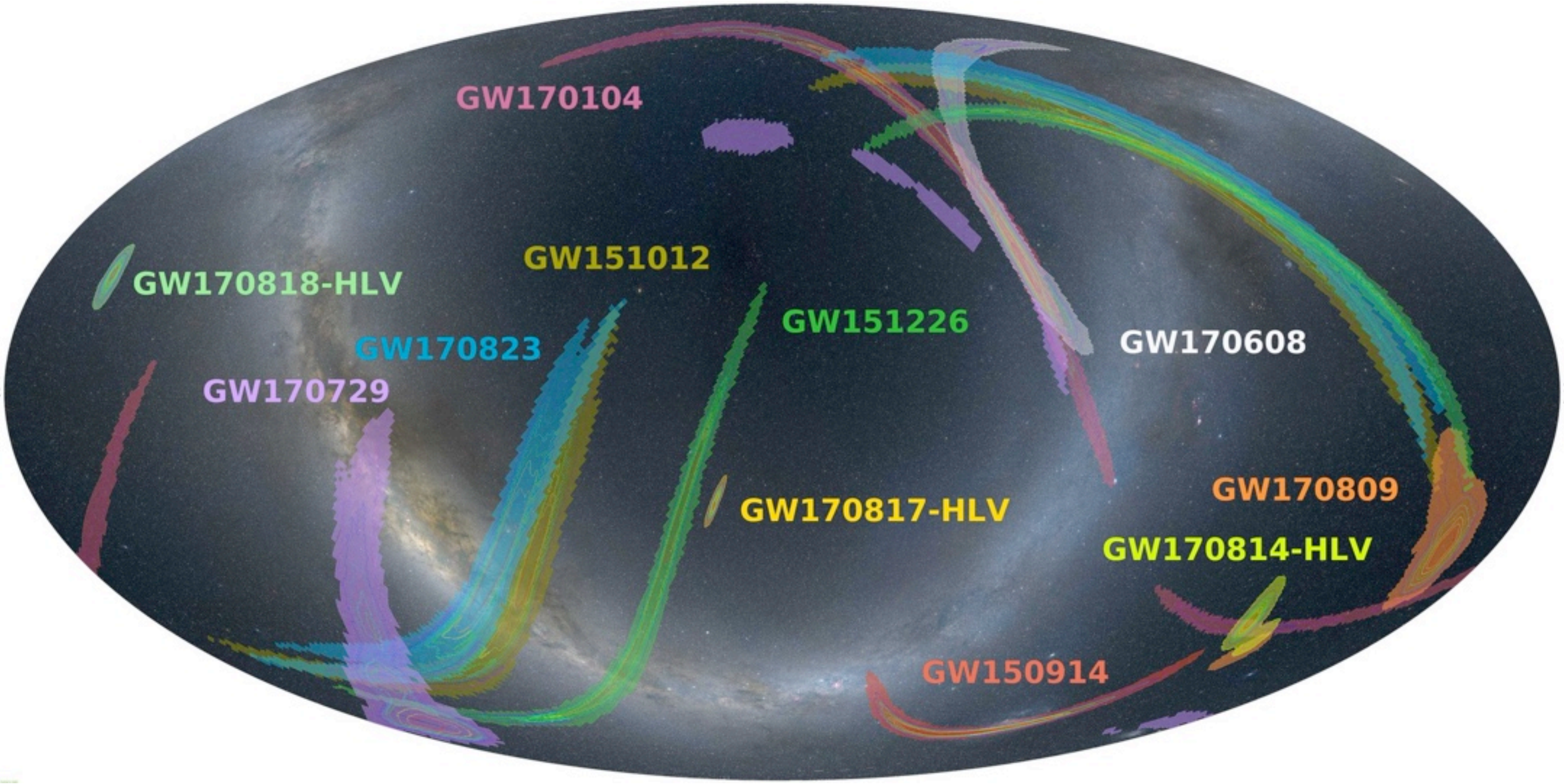
The per-year BNS search volume increases giving an expected **11–180** BNS detections annually (for O5).

With a four- or five-site detector network at design sensitivity, we may expect a significant fraction of GW signals to be localized to within a **few square degrees** by GW observations alone.

The median 90% credible region is 9–12 deg^2.

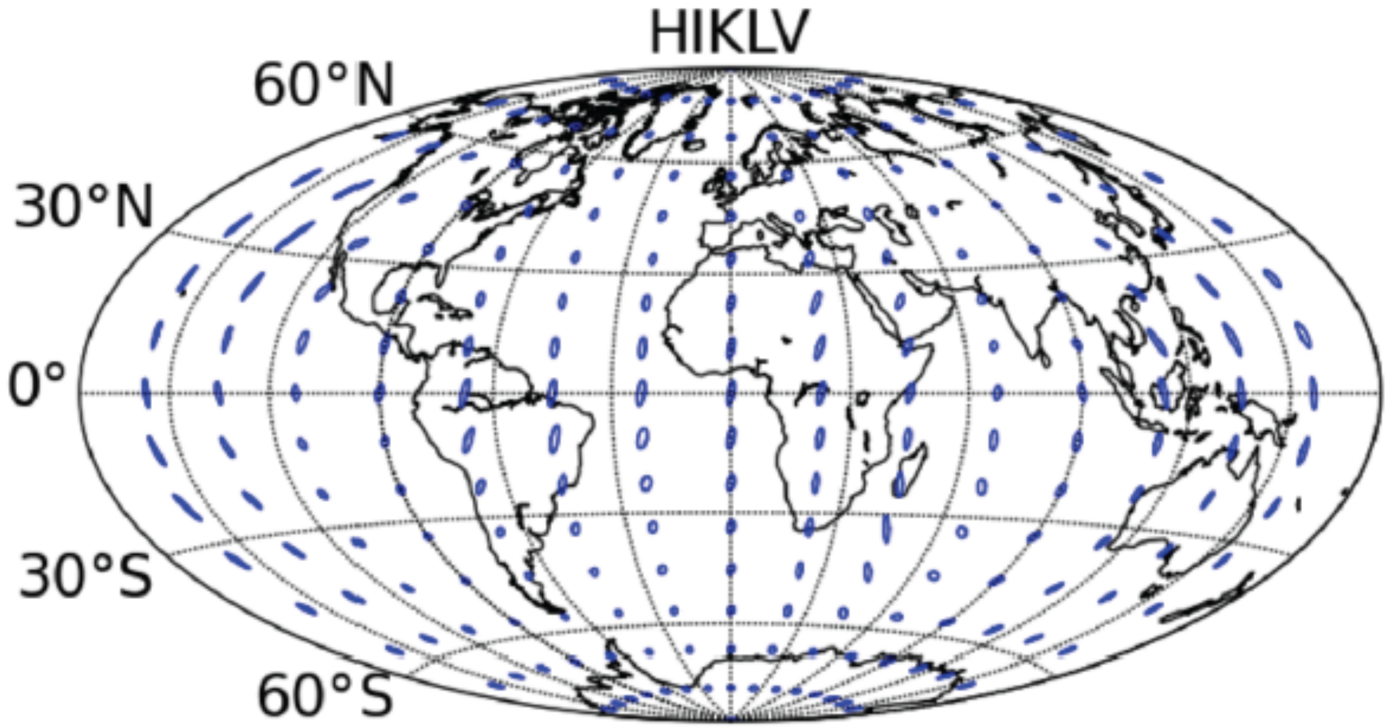
65–73% of events are expected to have CR smaller than 20 deg^2.

O1-O2 CBC detections: sky localisation



See Abbott et al, arXiv:1304.0670 (updated Jan 2020)

Mid-term goal improvement on sky localisation



S Fairhurst, CQG 28, 2001

Sky localization capability of advanced detectors by mid 2020s.
5 detector network.

More than 60% of sources could be localized with an accuracy better than **20 deg²** (GW170817 ~ 28 deg². , GW190814 ~ 19 deg²).

Conclusions

The third science run of the Advanced LIGO and Advanced Virgo detector network, **O3**, has recently come to an end.

All three detectors at O3 design sensitivities or better.

Despite termination of the run about a month earlier than originally planned due to the COVID-19 pandemic, it has been extremely successful, yielding a **record number of detections**.

For the first time since the Advanced LIGO and Advanced Virgo observations started, **low latency alerts during O3 have been publicly released.**

These public alerts facilitate follow-up observations by other telescopes and enhance the **great potential of multi-messenger astronomy.**

Stay tuned for further news from the LVC ...