### Image credit: AURORE SIMONNET/LIGO/CALTECH/MIT/SONOMA STATE







LIGO Hanford

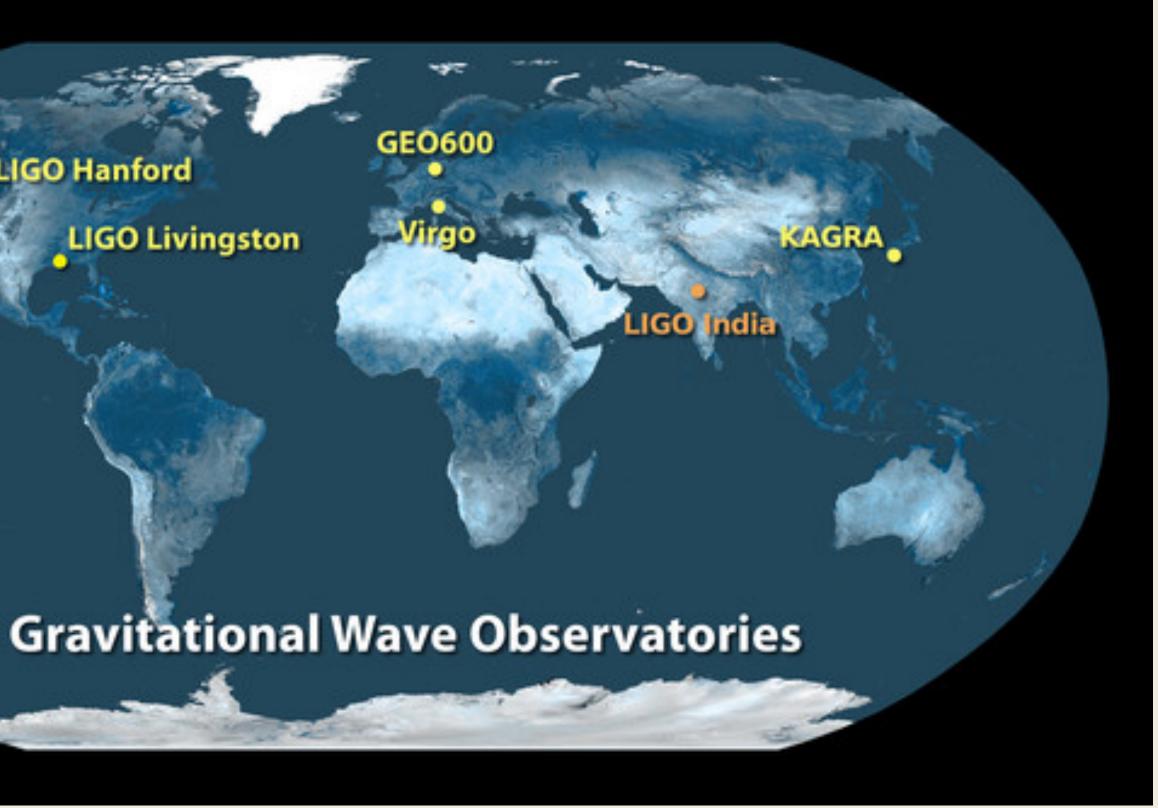
### **Current generation ground-based** detectors

Operational Planned

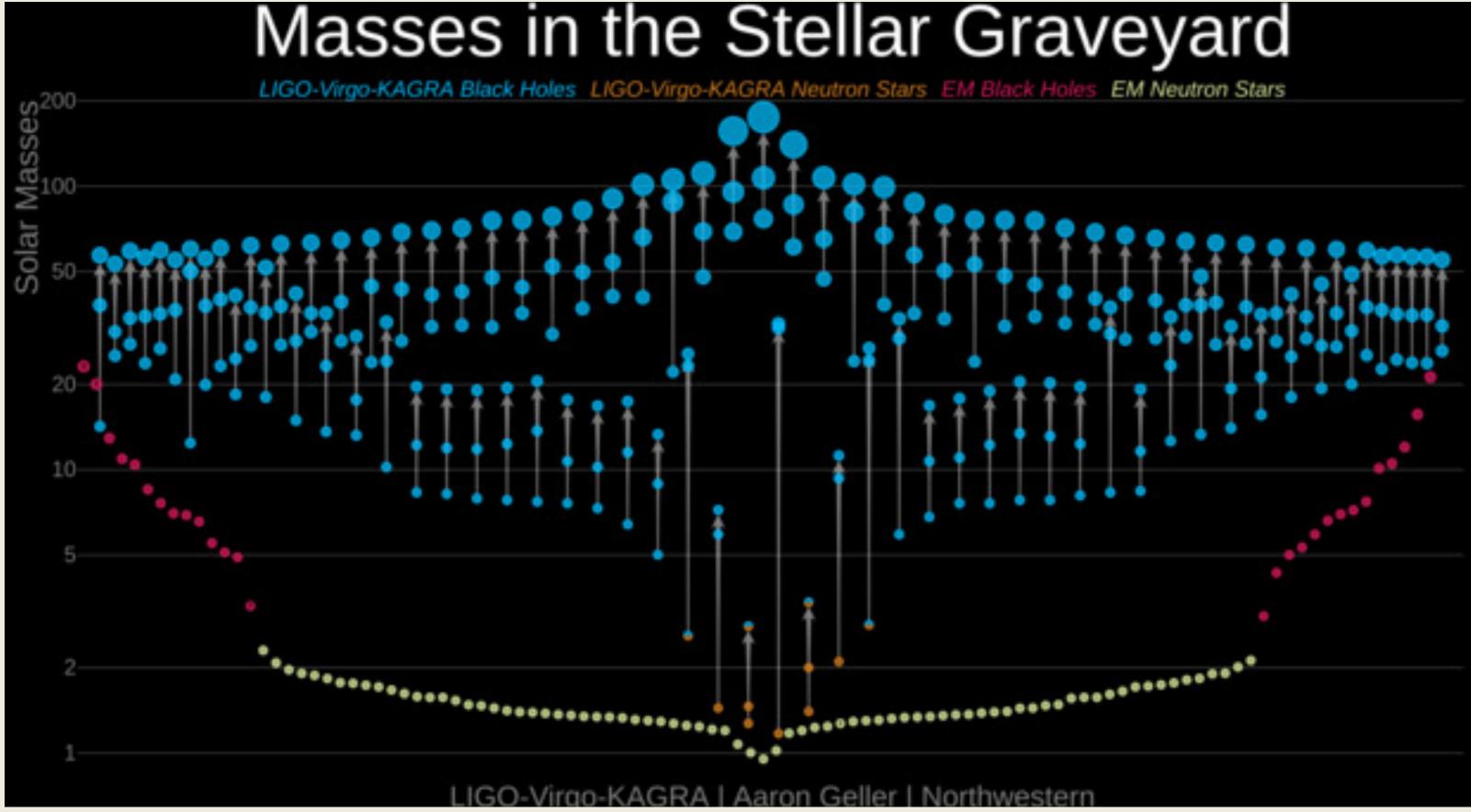
LIGO Livingston

Credit: <u>https://www.ligo.caltech.edu/image/ligo20160211c</u>

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## **Gravitational wave observations**



Credit: LIGO-Virgo / Aaron Geller / Northwestern University

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### Detection highlights

- GW170817: BNS + EM counterparts
- GW200105 and GW200115: NSBH
- GW190814: mystery mass gap object
- GW190521: first IMBH detection
- GW190412 and GW200129: spinning black holes

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### GW170817: **BNS + EM counterpart**

- Gravitational wave signal detected strongly by LIGO but only weakly by Virgo
- Multi-messenger event very informative:
  - BNS are a source of short gamma ray bursts
  - Origin of gold and platinum

### GW170817 FACTSHEET

LIGO-Hanford

observed by

source type

time of merger

false alarm rate

primary NS mass

secondary NS mass

radiated GW energy

radius of a 1.4 M, NS

distance

total mass

mass ratio

effective spin

signal-to-noise ratio

date

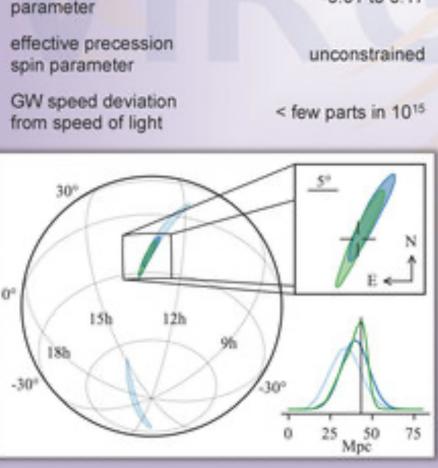
LIGO-Livingston

Virgo

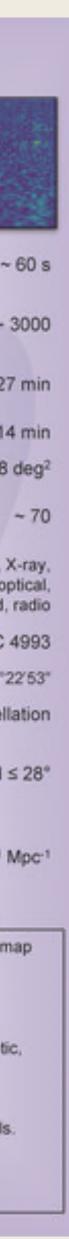
H, L, V	inferred duration from 30 Hz to 2048 Hz**	~ 60 s
binary neutron star (NS) 17 August 2017	inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
12:41:04 UTC 32.4	initial astronomer alert latency*	27 min
< 1 in 80 000 years	HLV sky map alert latency*	5 hrs 14 min
85 to 160 million	HLV sky area†	28 deg <sup>2</sup>
light-years 2.73 to 3.29 M	# of EM observatories that followed the trigger	~ 70
1.36 to 2.26 M, 0.86 to 1.36 M,	also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
0.4 to 1.0	host galaxy	NGC 4993
> 0.025 M <sub>*</sub> c <sup>2</sup>	source RA, Dec	13*09**48*, -23*22'53*
likely ≈ 14 km	sky location	in Hydra constellation
-0.01 to 0.17 unconstrained	viewing angle (without and with host galaxy identification)	$\leq 56^{\circ}$ and $\leq 28^{\circ}$
< few parts in 1015	Hubble constant inferred from host galaxy identification	62 to 107 km s <sup>-1</sup> Mpc <sup>-1</sup>
	Images: time frequency tra (left, HL = light blue, improved HLV optical source locat	HLV = dark blue, / = green,

GW=gravitational wave, EM = electromagnetic, M\_=1 solar mass=2x10<sup>30</sup> kg. H/L=LIGO Hanford/Livingston, V=Virgo

Parameter ranges are 90% credible intervals. \*referenced to the time of merger \*\*maximum likelihood estimate 190% credible region



Credit: https://www.ligo.caltech.edu/image/20171016g





### FACT SHEET GW200105 GW200115

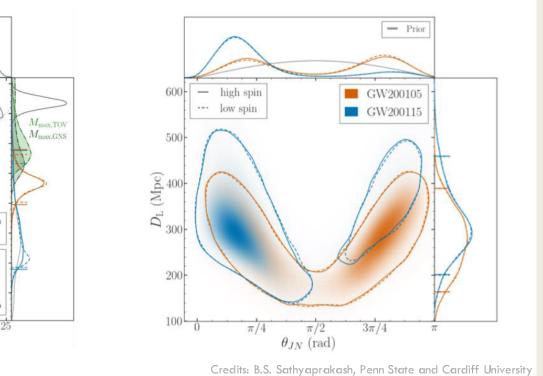
First observation of neutron star-black hole (NSBH) binaries

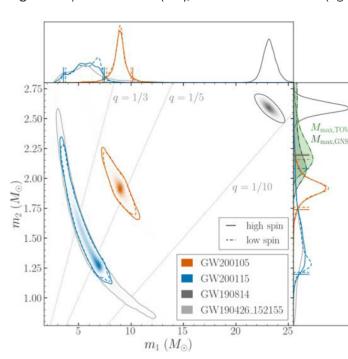
All parameter ranges correspond to 90% credible bounds. Quoted values are for high spin (<0.99) neutron-star priors

	GW200105	GW200115
observed by	LIGO Livingston and Virgo	LIGO Livingston & Hanford and Virgo
date, time	5 Jan 2020, 16:24:26 UTC	15 Jan 2020, 04:23:10 UTC
likely distance	170 to 390 Mpc	200 to 450 Mpc
source redshift	0.04 to 0.08	0.05 to 0.10
signal-to-noise ratio	13.9	11.6
false alarm rate	< 1 in 2.8 yr	< 1 in 100,000 yr
Source masses (M <sub>☉</sub> )		
total mass	9.7 to 12.0	5.7 to 8.6
primary (BH)	7.4 to 10.1	3.6 to 7.5
secondary (NS)	1.7 to 2.2	1.2 to 2.2
mass ratio	0.18 to 0.30	0.16 to 0.61
BH spin	0.00 to 0.30	0.04 to 0.81
effective inspiral spin	-0.16 to 0.10	-0.54 to 0.04
effective precession spin	0.02 to 0.23	0.04 to 0.51
Inferred merger rate density of NSBH systems*: 12 to 120 yr <sup>-1</sup> Gpc <sup>-3</sup>		

\* Assuming GW 200105 and GW 200115 are representative of the NSBH population

Images: companion masses (left), distance vs inclination (right), both with low (<0.05) and high (<0.99) spin priors for the neutron stars





Credit: B. S. Sathyaprakash, Penn State and Cardiff University

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## **GW200105 and GW200115: NSBH systems**

• First ever evidence of a binary composed of a neutron star and a black hole

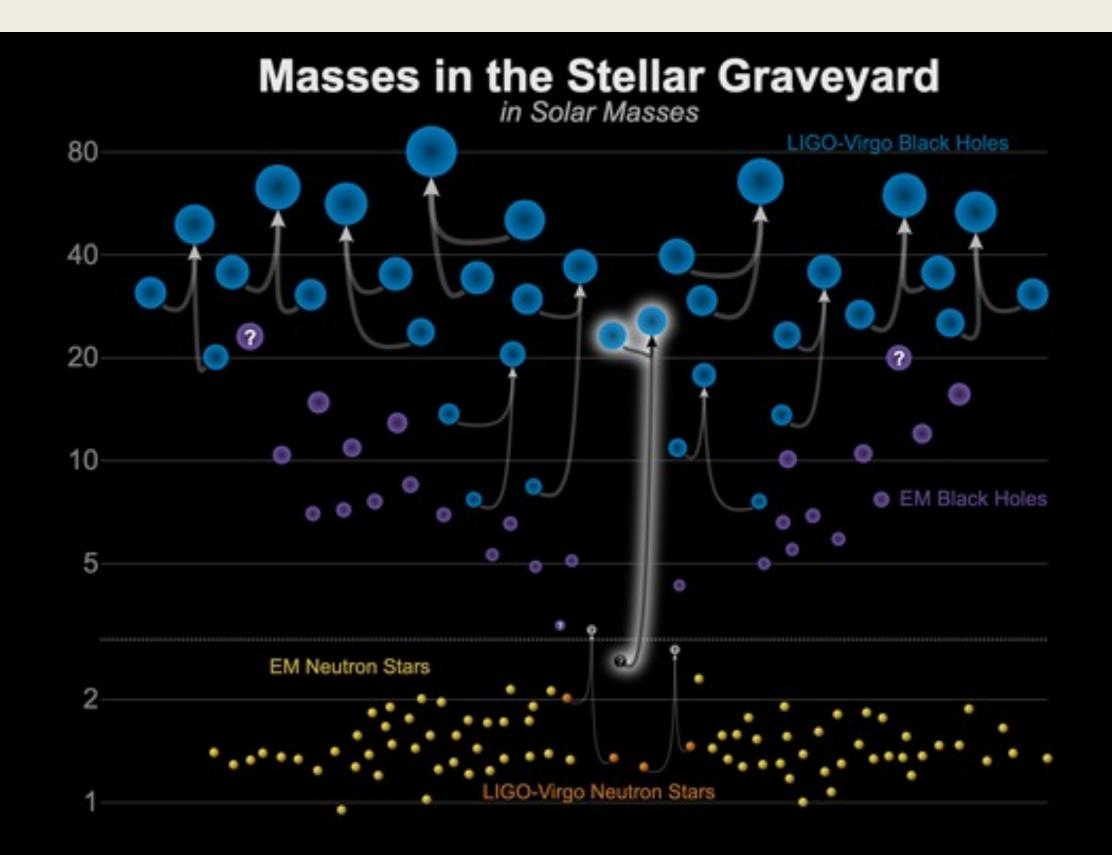
• No EM counterpart

 Estimated NSBH merger rate of ~1/month within 1 billion light years from Earth



# **GW190814: mystery mass gap object**

- Binary contains a  $23M_{\odot}$  black hole and a  $2.6M_{\odot}$  object
- Nature of lighter object is unknown
- No EM counterpart



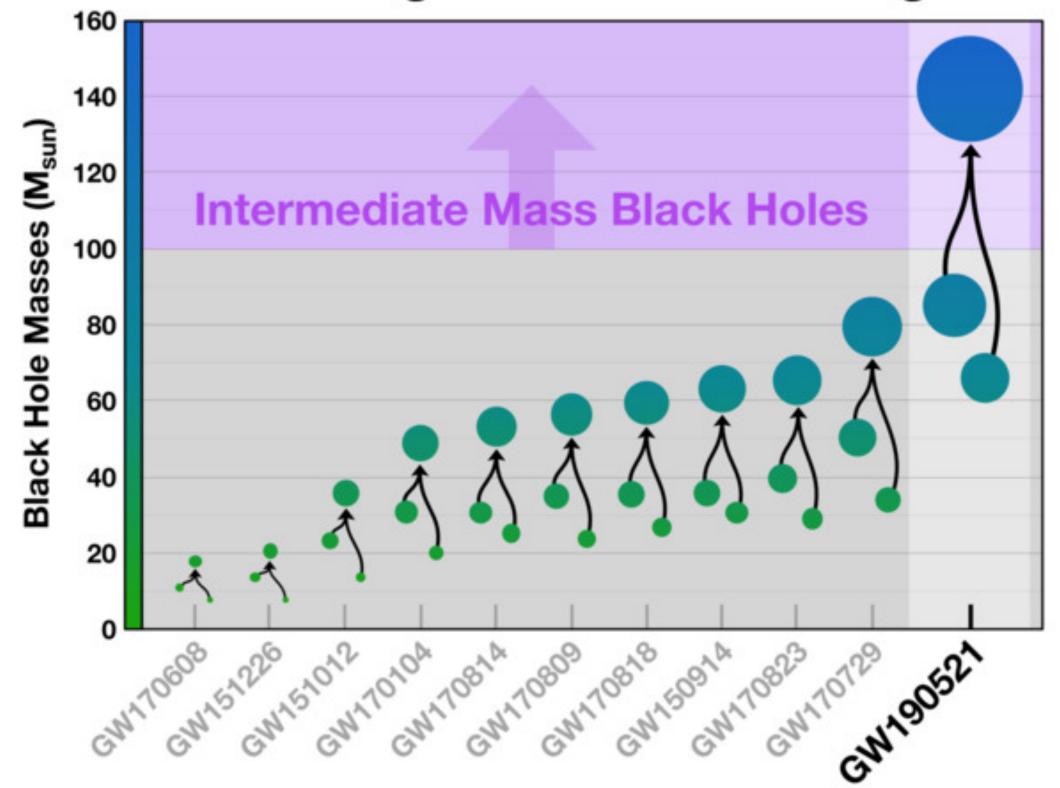
Updated 2020-05-16 LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Credit: LIGO-Virgo / Frank Elavsky & Aaron Geller (Northwestern)



### **GW190521: first IMBH detection**

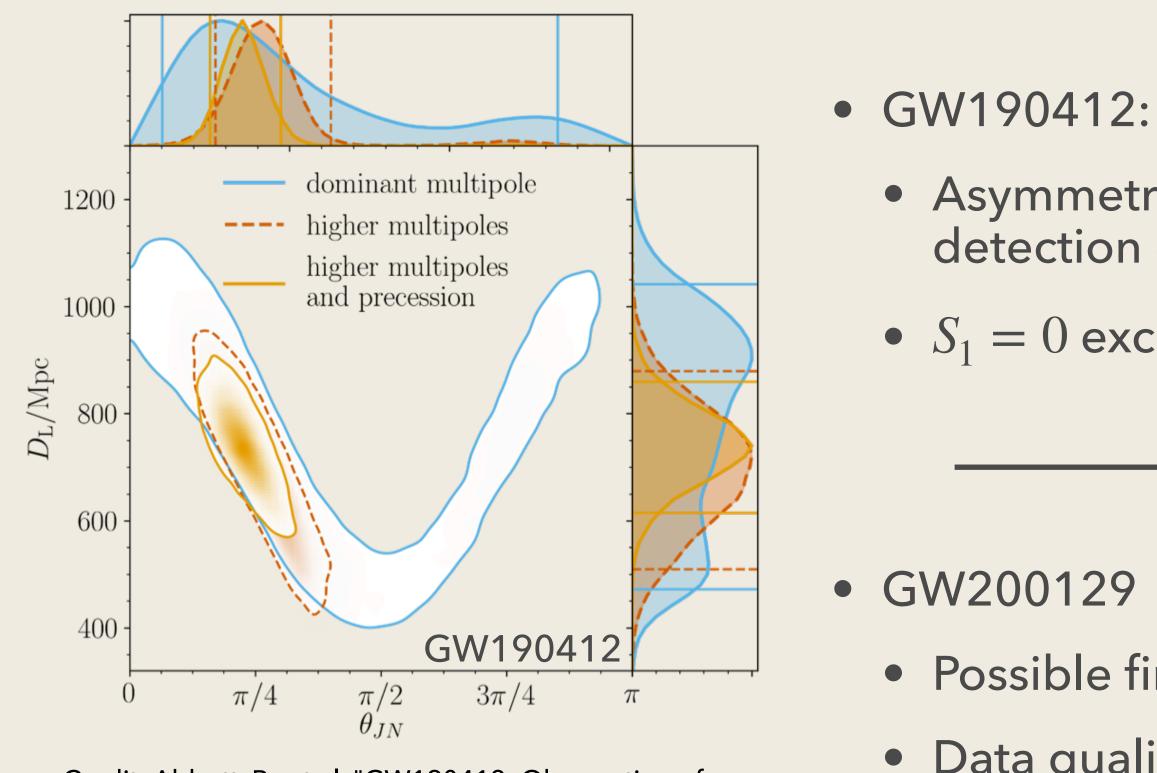
### LIGO-Virgo Black Hole Mergers



Credit: LIGO/Caltech/MIT/R. Hurt (IPAC)

- First ever detection of an intermediate mass black hole
  - $m_1 = 85M_{\odot}; m_2 = 66M_{\odot}, m_1 = 142M_{\odot}$
- Extremely short (burst-like) signal

## GW190412 + GW200129: spinning black holes

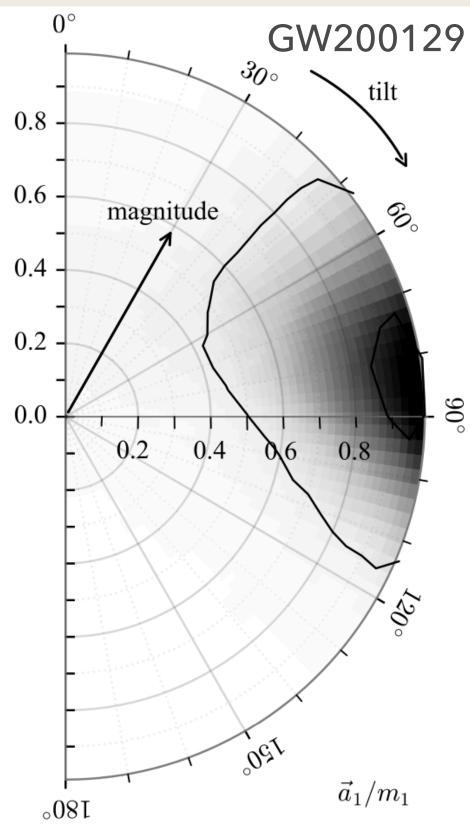


Credit: Abbott, R., et al. "GW190412: Observation of a binary-black-hole coalescence with asymmetric masses." Physical Review D 102.4 (2020): 043015.

• Asymmetric masses allow for detection of higher harmonics

•  $S_1 = 0$  excluded at 90% confidence

• Possible first detection of precession Data quality issues at time of event



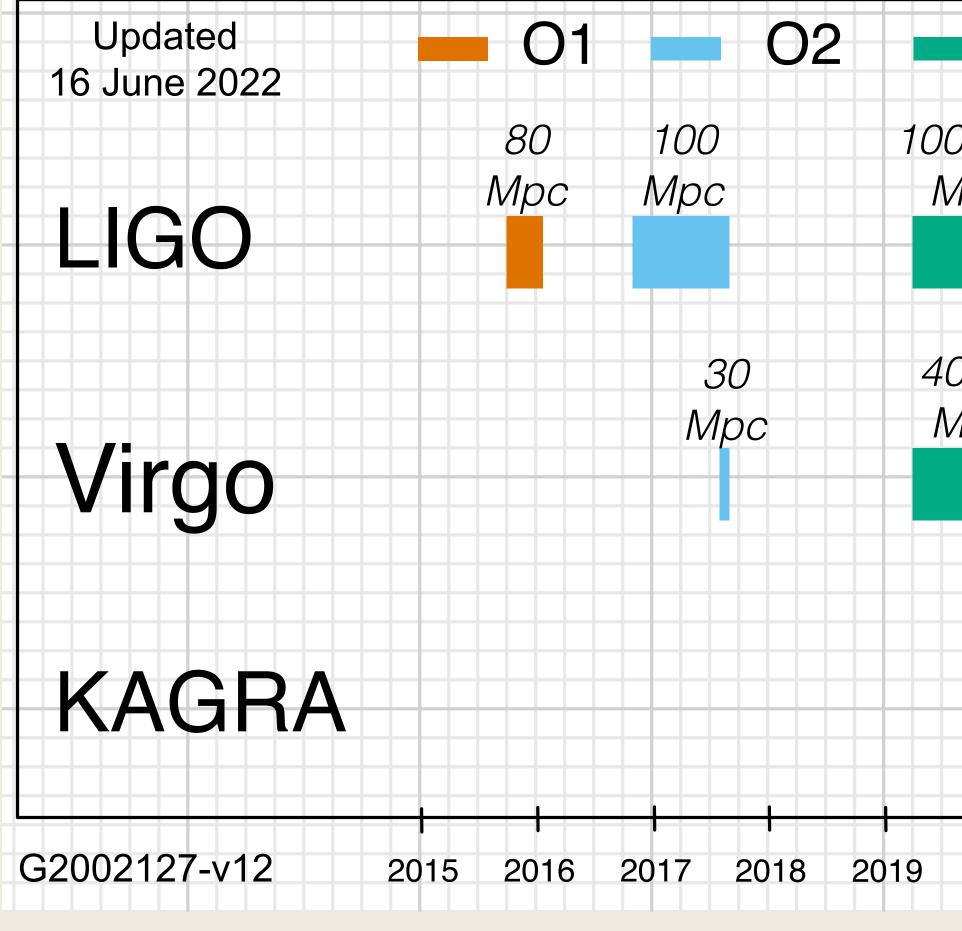
Credit: Hannam, Mark, et al. "Measurement of general-relativistic precession in a black-hole binary."

Image credit: https://www.ligo.caltech.edu/image/ligo20150731c



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### **Short term future plans**



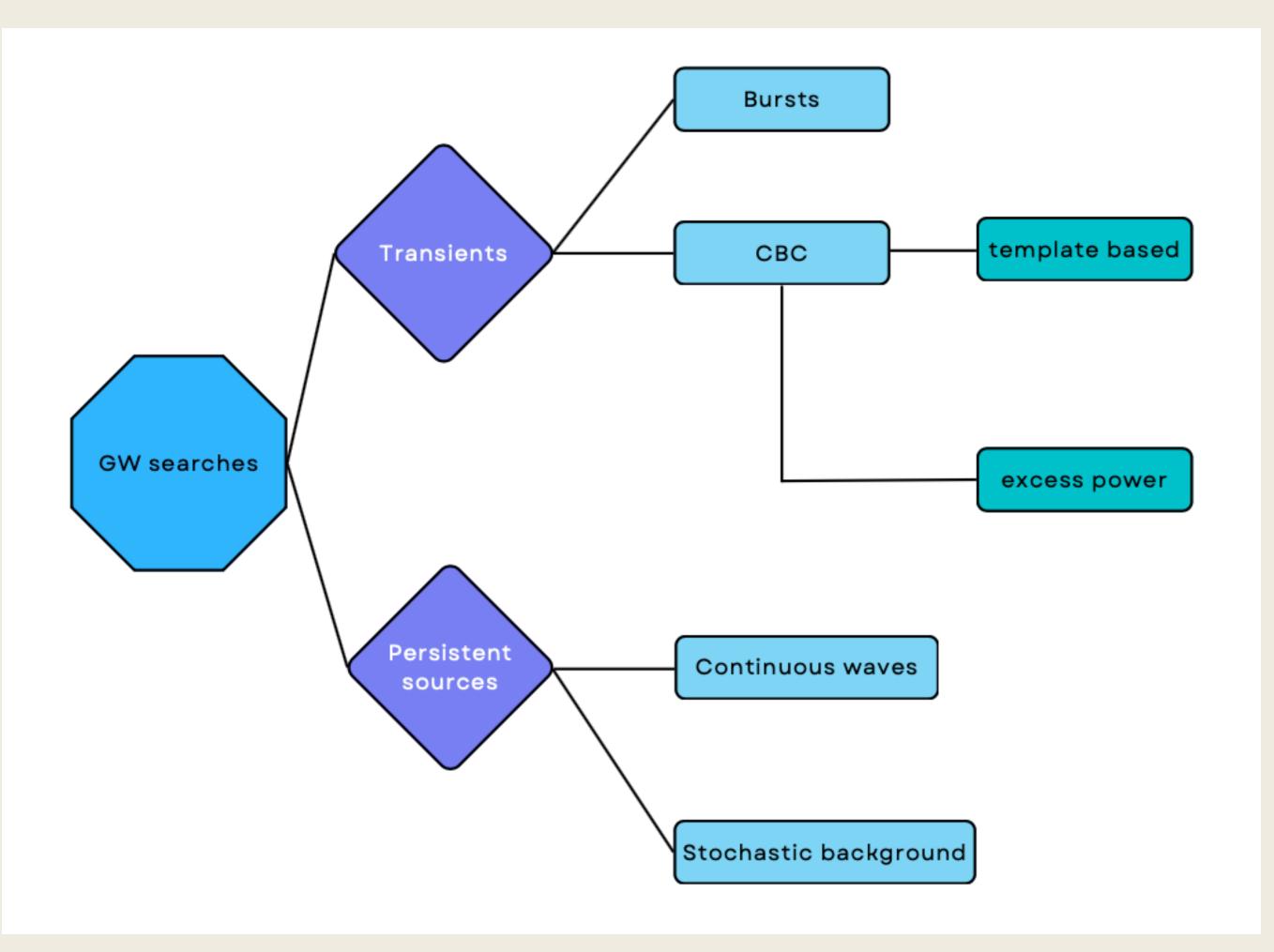
Observing scenario timeline. Credit: https://dcc.ligo.org/LIGO-G2002127/public

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## **04 plans**

<b>O</b> 3	<b>04</b>	05
0-140	160-190	240-325
Лрс	Mpc	Mpc
0-50	80-115	150-260
Mpc	Mpc	Mpc
0.7	(1-3) ~ 10	25-128
Mpc	Mpc	Mpc
2020 2021	2022 2023 2024 2025 2	2026 2027 2028

### **GW searches**



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### **PROMOTING SWISS INVOLVEMENT IN GW SCIENCE – 24.10.2022**

# **GW modelling**

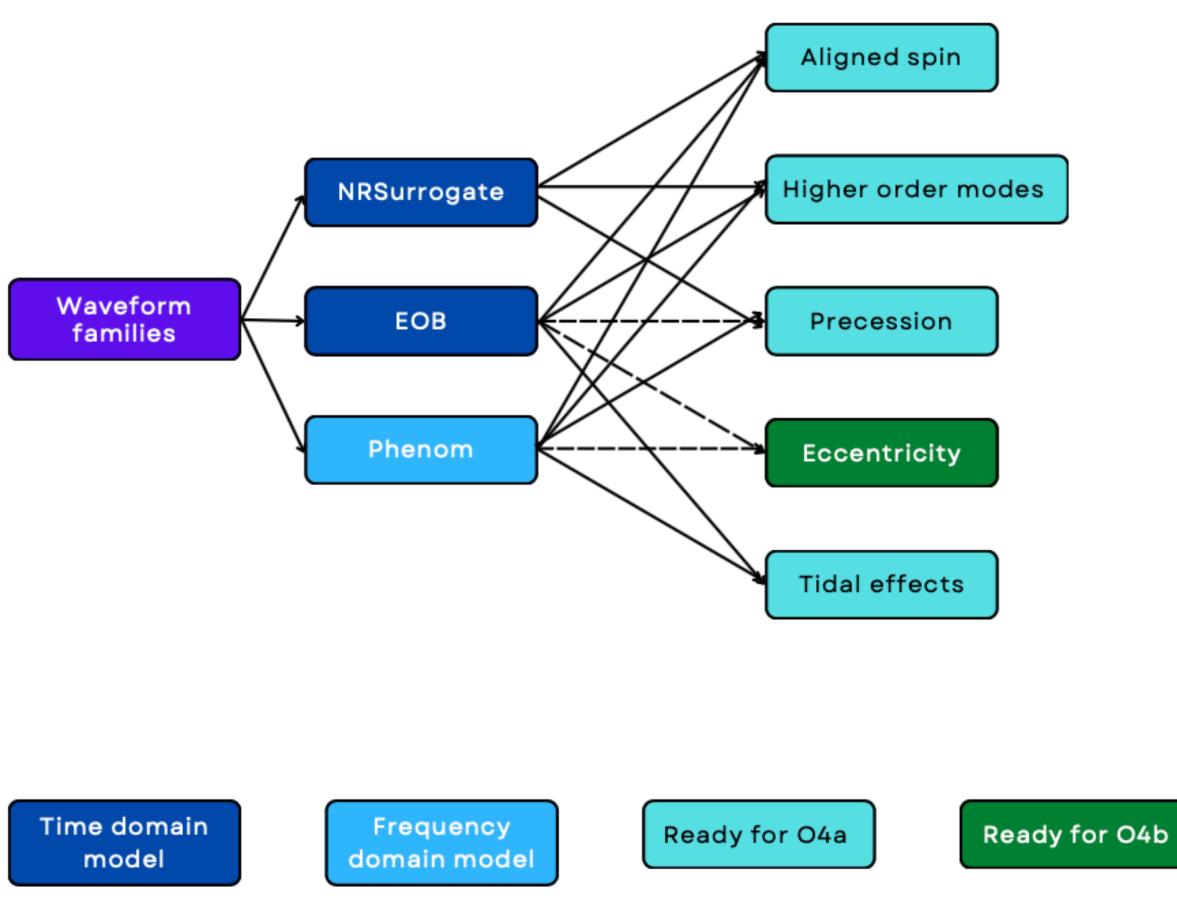


Image credit: https://www.ligo.caltech.edu/image/ligo20160211f

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### Conclusions

- O4 projected to being in March 2023
- 4 detector network
- Detectors will have greatly improved sensitivity
- Expect many more varied GW detections