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Gravitational Waves and Supernovae

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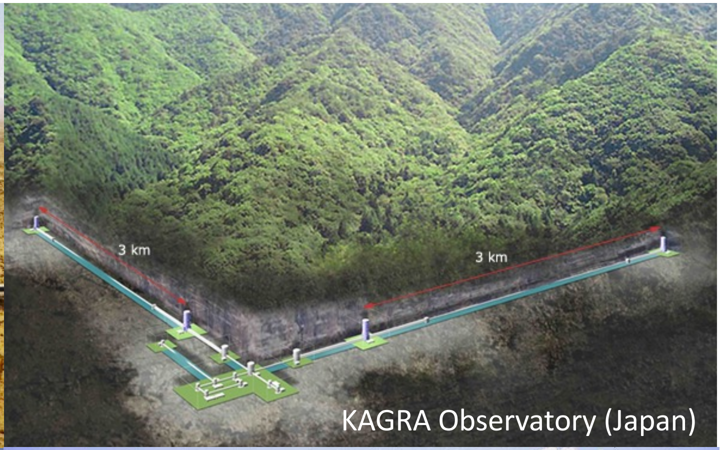
Outline

- Gravitational-wave detectors
- CCSNe as GW sources
- Observing schedule
- Science from CCSN GWs

The Global GW Observatory Network (2022)


LIGO Hanford Observatory (USA)



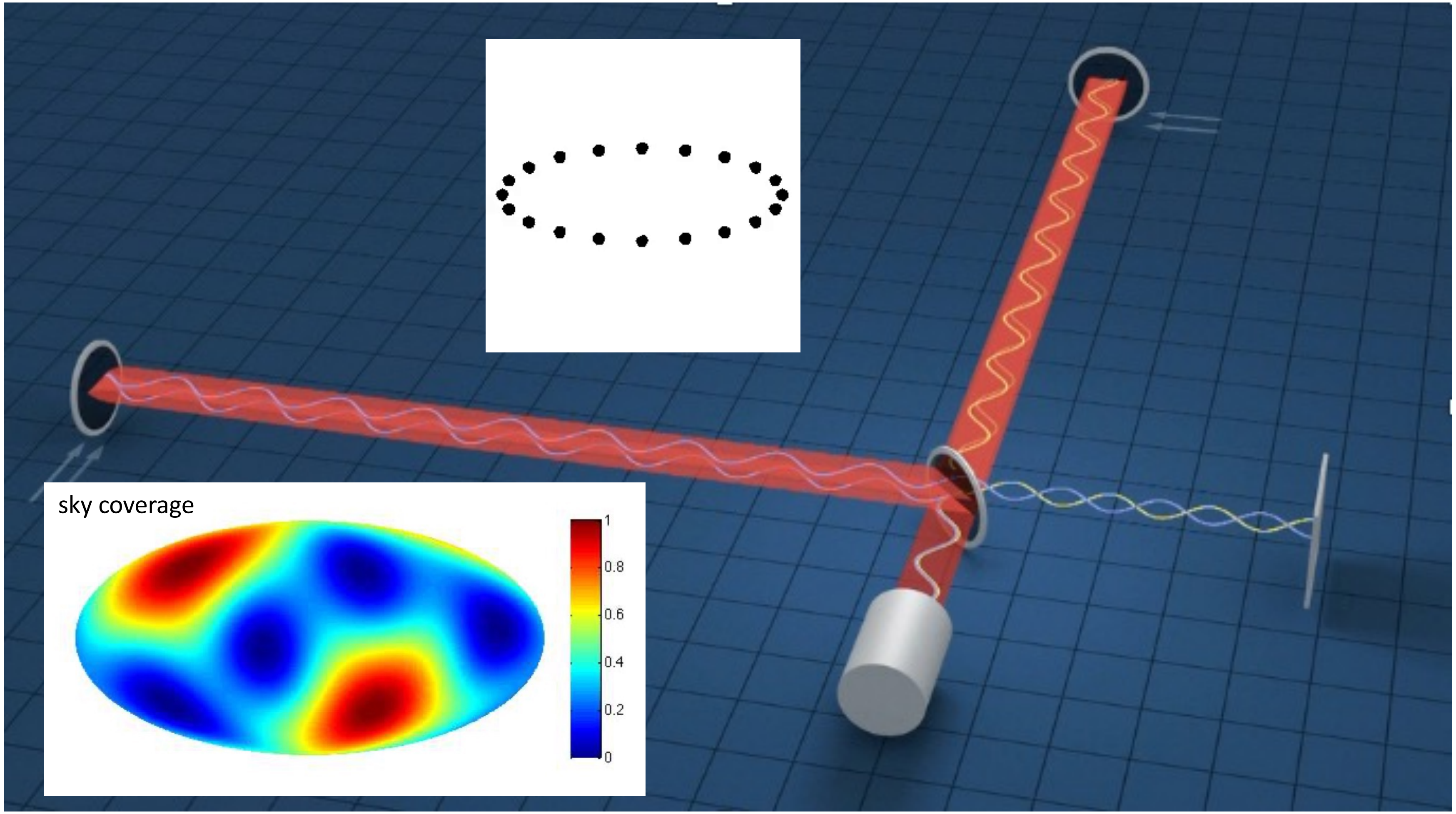
KAGRA Observatory (Japan)


LIGO Livingston Observatory (USA)


Virgo Observatory (Italy)

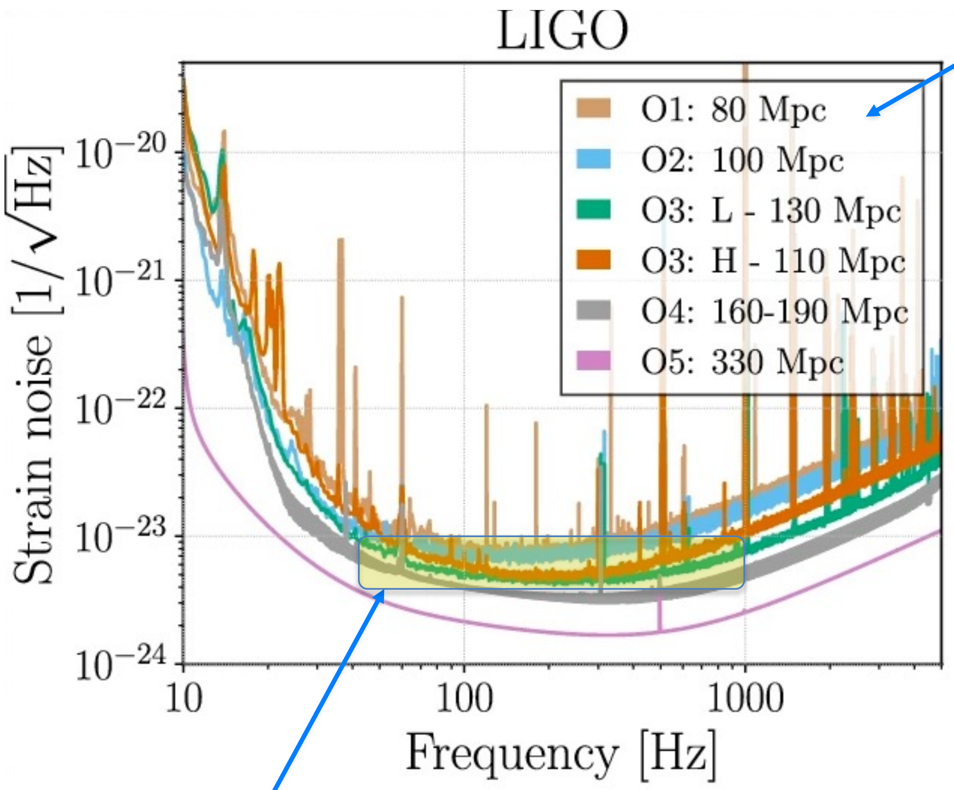
+ LIGO-India (c2025+)

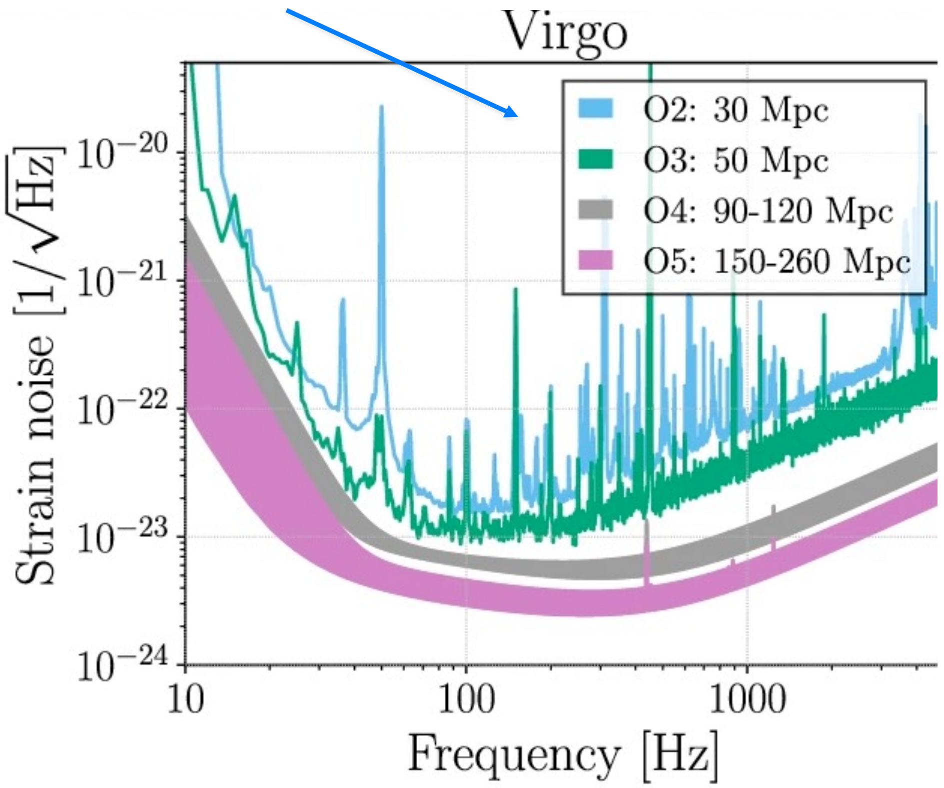
GW Detectors: Interferometers



Abbott et al. 1304.0670

average distance to which we can
detect a NS-NS merger with SNR>8





$10^{-23}\,\mathrm{Hz}^{-1/2} \times (1000\,\mathrm{Hz})^{1/2} \times 4\,\mathrm{km} \sim$ **0.001 fm**

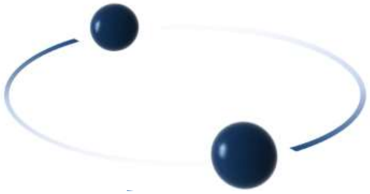
GW Sources

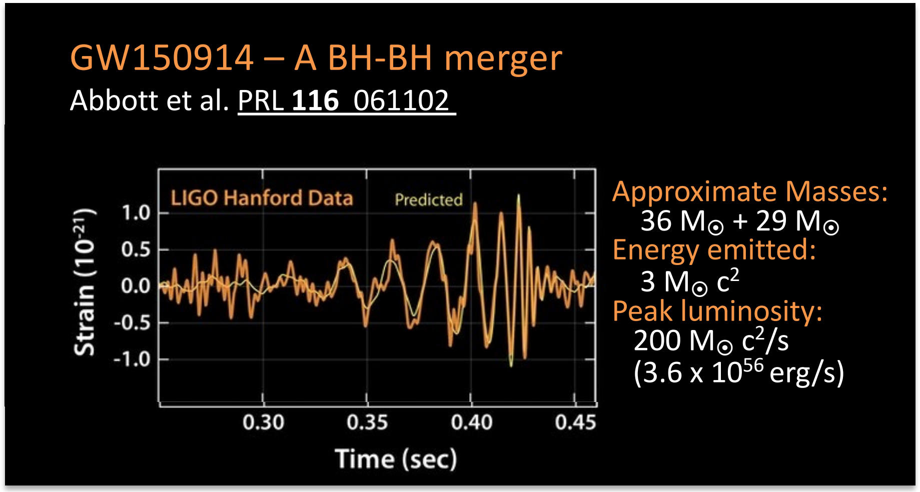
- Leading emission is due to time-varying quadrupole moment:

$$h \sim \frac{\underset{\text{non-sphericity}}{\epsilon}\,\overset{\text{mass}}{M}\,\overset{\text{frequency}}{\Omega^2}\,\overset{\text{size}}{R^2}}{\underset{\text{distance}}{d}}$$

- favour dense, fast-moving sources ("*small and dark*")
  - detectors only sensitive above seismic noise floor of ~10Hz

- Ideal source: BH & NS binaries





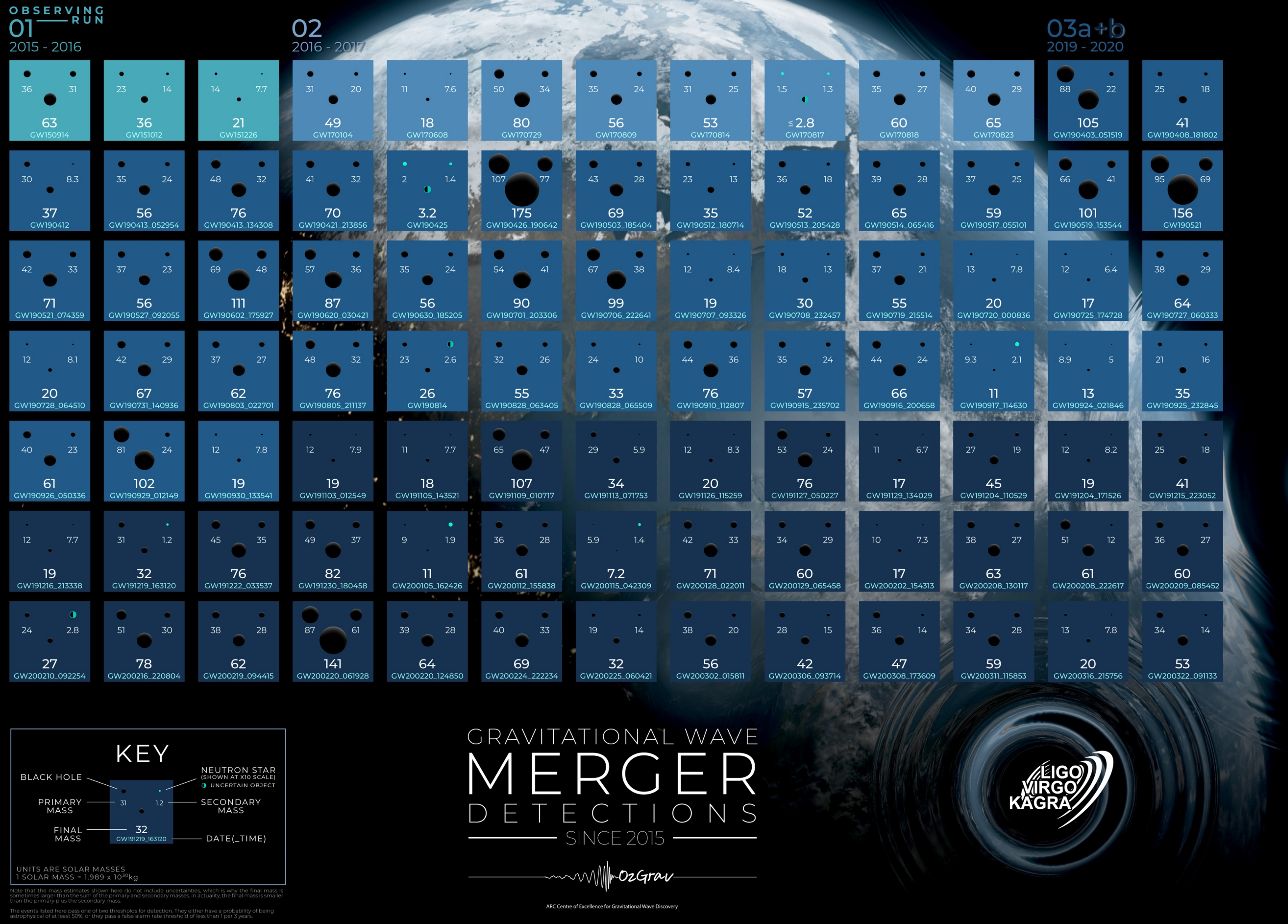
GW150914 – A BH-BH merger

Abbott et al. PRL **116** 061102

Approximate Masses:
$36\,M_\odot + 29\,M_\odot$

Energy emitted:
$3\,M_\odot\,c^2$

Peak luminosity:
$200\,M_\odot\,c^2/s$
(3.6×10^{56} erg/s)



GRAVITATIONAL WAVE MERGER DETECTIONS

SINCE 2015

OzGrav

ARC Centre of Excellence for Gravitational Wave Discovery

OBSERVING RUN 01

2015 - 2016

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW150914	36	31	63
GW151012	23	14	36
GW151226	14	7.7	21

02

2016 - 2017

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW170104	31	20	49
GW170608	11	7.6	18
GW170729	50	34	80
GW170809	35	24	56
GW170814	31	25	53
GW170817	1.5	1.3	≤ 2.8
GW170818	35	27	60
GW170823	40	29	65

03a+b

2019 - 2020

DATE(_TIME)	PRIMARY MASS	SECONDARY MASS	FINAL MASS
GW190403_051519	88	22	105
GW190408_181802	25	18	41
GW190412	30	8.3	37
GW190413_052954	35	24	56
GW190413_134308	48	32	76
GW190421_213856	41	32	70
GW190425	2	1.4	3.2
GW190426_190642	107	77	175
GW190503_185404	43	28	69
GW190512_180714	23	13	35
GW190513_205428	36	18	52
GW190514_065416	39	28	65
GW190517_055101	37	25	59
GW190519_153544	66	41	101
GW190521	95	69	156
GW190521_074359	42	33	71
GW190527_092055	37	23	56
GW190602_175927	69	48	111
GW190620_030421	57	36	87
GW190630_185205	35	24	56
GW190701_203306	54	41	90
GW190706_222641	67	38	99
GW190707_093326	12	8.4	19
GW190708_232457	18	13	30
GW190719_215514	37	21	55
GW190720_000836	13	7.8	20
GW190725_174728	12	6.4	17
GW190727_060333	38	29	64
GW190728_064510	12	8.1	20
GW190731_140936	42	29	67
GW190803_022701	37	27	62
GW190805_211137	48	32	76
GW190814	23	2.6	26
GW190828_063405	32	26	55
GW190828_065509	24	10	33
GW190910_112807	44	36	76
GW190915_235702	35	24	57
GW190916_200658	44	24	66
GW190917_114630	9.3	2.1	11
GW190924_021846	8.9	5	13
GW190925_232845	21	16	35
GW190926_050336	40	23	61
GW190929_012149	81	24	102
GW190930_133541	12	7.8	19
GW191103_012549	12	7.9	19
GW191105_143521	11	7.7	18
GW191109_010717	65	47	107
GW191113_071753	29	5.9	34
GW191126_115259	12	8.3	20
GW191127_050227	53	24	76
GW191129_134029	11	6.7	17
GW191204_110529	27	19	45
GW191204_171526	12	8.2	19
GW191215_223052	25	18	41
GW191216_213338	12	7.7	19
GW191219_163120	31	1.2	32
GW191222_033537	45	35	76
GW191230_180458	49	37	82
GW200105_162426	9	1.9	11
GW200112_155838	36	28	61
GW200115_042309	5.9	1.4	7.2
GW200128_022011	42	33	71
GW200129_065458	34	29	60
GW200202_154313	10	7.3	17
GW200208_130117	38	27	63
GW200208_222617	51	12	61
GW200209_085452	36	27	60
GW200210_092254	24	2.8	27
GW200216_220804	51	30	78
GW200219_094415	38	28	62
GW200220_061928	87	61	141
GW200220_124850	39	28	64
GW200224_222234	40	33	69
GW200225_060421	19	14	32
GW200302_015811	38	20	56
GW200306_093714	28	15	42
GW200308_173609	36	14	47
GW200311_115853	34	28	59
GW200316_215756	13	7.8	20
GW200322_091133	34	14	53

KEY

BLACK HOLE

NEUTRON STAR (SHOWN AT X10 SCALE)

◑ UNCERTAIN OBJECT

PRIMARY MASS — 31

SECONDARY MASS — 1.2

FINAL MASS — 32

DATE(_TIME) — GW191219_163120

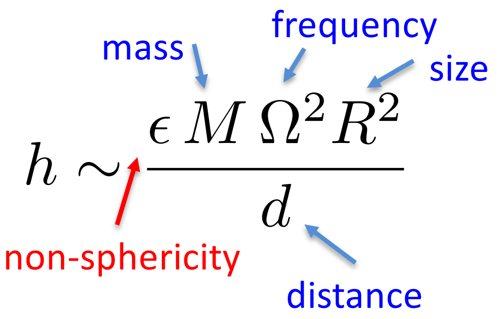
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^{30}kg

Note that the mass estimates shown here do not include uncertainties, which is why the final mass is sometimes larger than the sum of the primary and secondary masses. In actuality, the final mass is smaller than the primary plus the secondary mass.

The events listed here pass one of two thresholds for detection. They either have a probability of being astrophysical of at least 50%, or they pass a false alarm rate threshold of less than 1 per 3 years.

CCSNe as GW Sources

- Recall the quadrupole moment formula:



mass

frequency

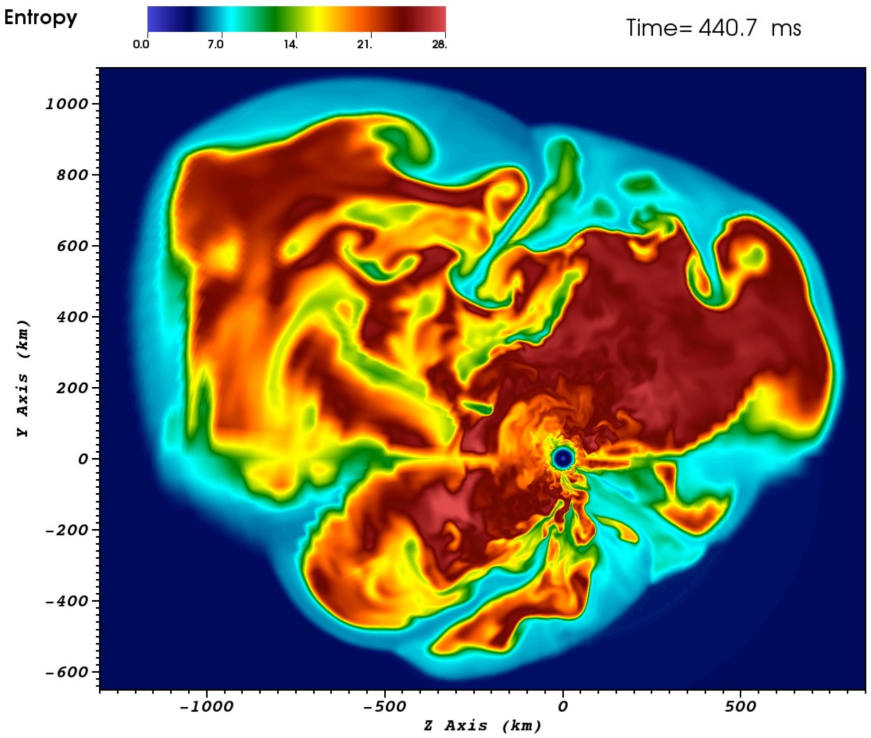
size

$$h \sim \frac{\epsilon\, M\, \Omega^2 R^2}{d}$$

non-sphericity

distance

  - BH/NS binaries: ε ~ 1
  - CCSNe: ε << 1



Mezzacappa *et al.*, 1501.01688

CCSNe as GW Sources

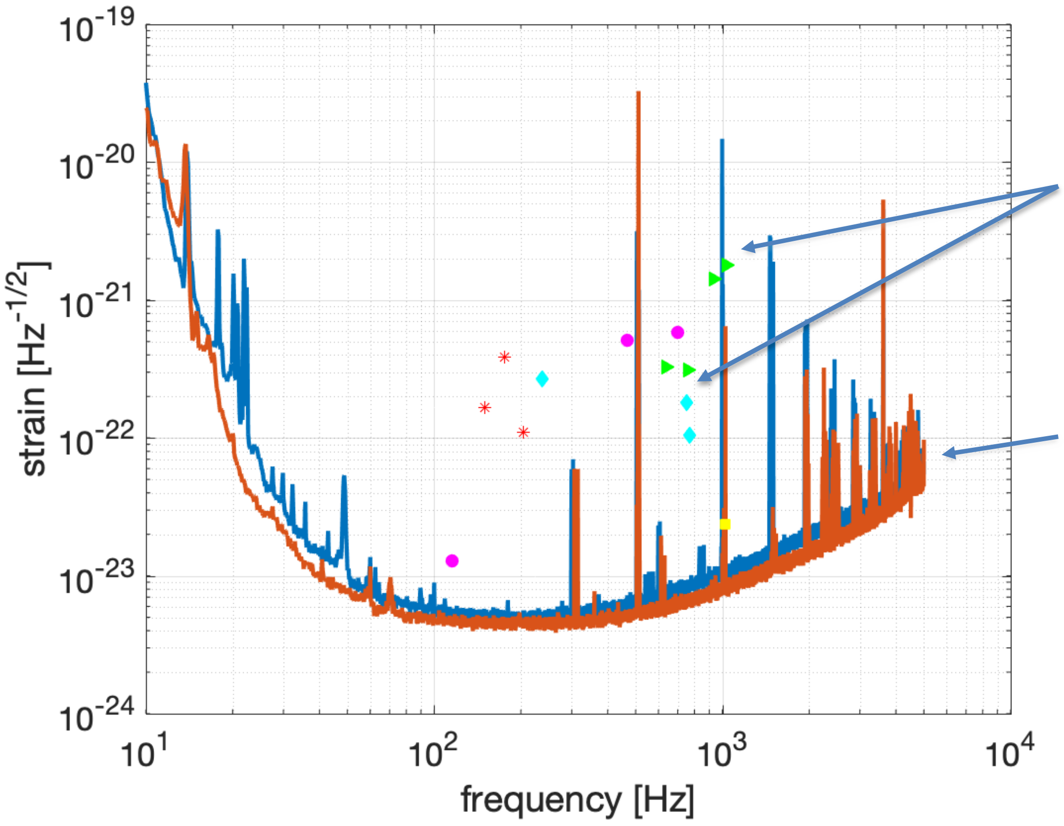
Muller *et al.* 3D simulations, neutrino-driven explosion, 15 / 20 $M_\odot$ ZAMS progenitor stars.

Ott *et al.* 3D simulation, neutrino-driven explosion, 27 $M_\odot$ ZAMS progenitor star.

Yakunin *et al.* 2D simulations, neutrino-driven explosion 12 / 15 / 20 / 25 $M_\odot$ ZAMS progenitors.

Scheidegger *et al.* 3D simulations, magneto-hydrodynamically-driven explosion, 15 $M_\odot$ ZAMS progenitors. Low to rapid rotation.

Dimmelmeier *et al.* 2D simulations, magneto-hydrodynamically-driven explosion, 15 $M_\odot$ ZAMS progenitor star. Moderate to rapid rotation.



GW signal amplitude at 10 kpc

Abbott et al. Phys. Rev. D **101**, 084002 (2020)

LIGO H and L noise spectra (2019)

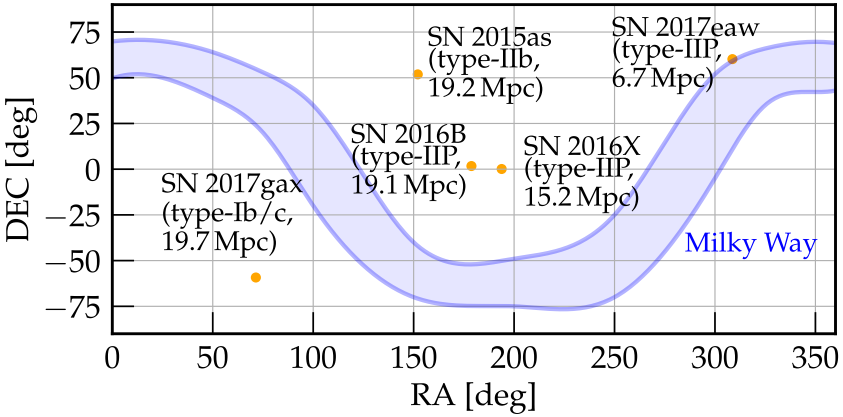
SNR ~ height above noise background

E. Muller et al., Astron. Astrophys. 537, A63 (2012)
C. D. Ott et al., Astrophys. J. 768, 115 (2013)
K. N. Yakunin et al., Phys. Rev. D. 92 084040 (2015).
S. Scheidegger et al., Astron. Astrophys. 514, A51 (2010).
H. Dimmelmeier et al., Phys. Rev. D. 78, 064056 (2008).

LIGO-Virgo Searches for CCSNe GWs

- No SNEWs alerts … (yet)
- LIGO & Virgo collaborations have searched for GW signals consistent with the time and sky position of nearby CCSNe observed optically (2015-2017).

Abbott et al. Phys. Rev. D **101**, 084002 (2020)

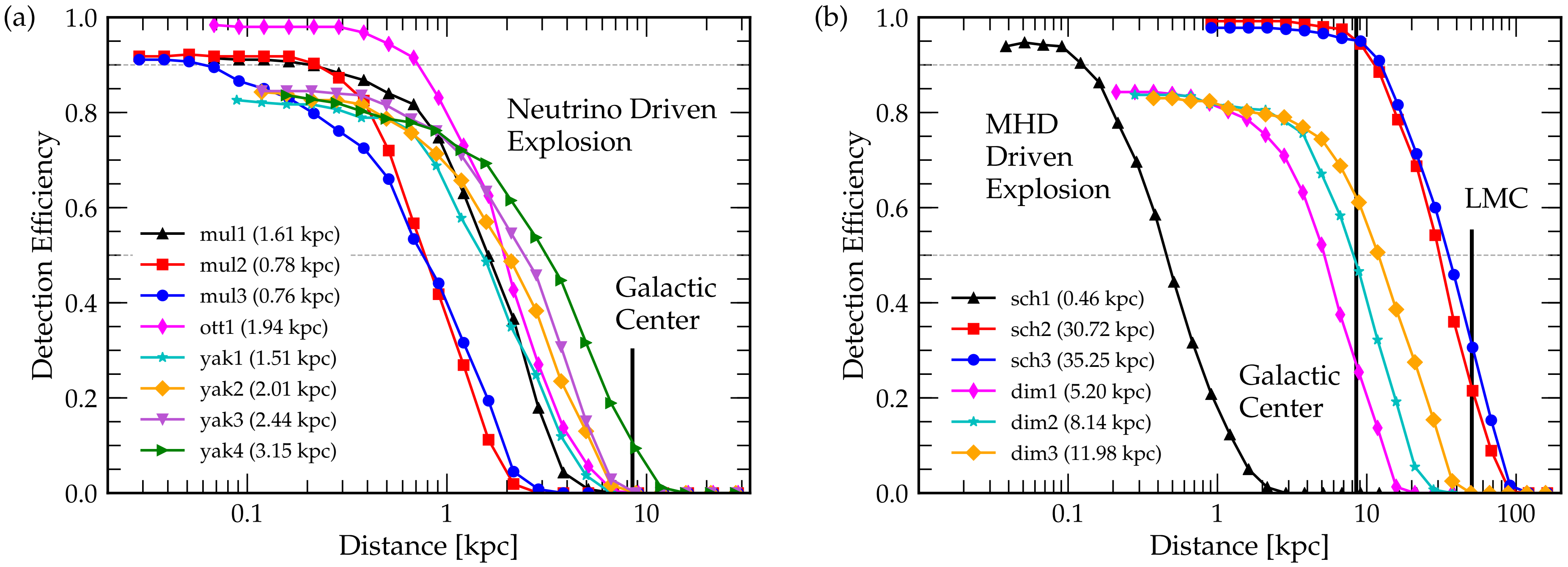


Supernova	Type	Host Galaxy	Distance [Mpc]	t_1 [UTC]	t_2 [UTC]	Δt [days]	OSW Method	Run	Active Detectors	Coincident Coverage
SN 2015as	IIb	UGC 5460	19.2	2015 Nov 14.77	2015 Nov 16.23	1.47	Early	O1	H1,L1	34.2%
SN 2016B	IIP	PGC 037392	19.1	2015 Dec 23.51	2015 Dec 27.55	4.03	Early	O1	H1,L1	34.3%
SN 2016X	IIP	UGC 08041	15.2	2016 Jan 17.72	2016 Jan 20.56	2.86	Early	O1	H1,L1	14.4%
SN 2017eaw	IIP	NGC 6946	6.72	2017 Apr 26.56	2017 Apr 27.96	1.39	EPM	O2	H1,L1	48.8%
SN 2017gax	Ib/c	NGC 1672	19.7	2017 Aug 14.28	2017 Aug 16.15	1.66	Early	O2	H1,L1,V1	61.5% (H1L1) 60.8% (H1L1V1)

Sensitivity

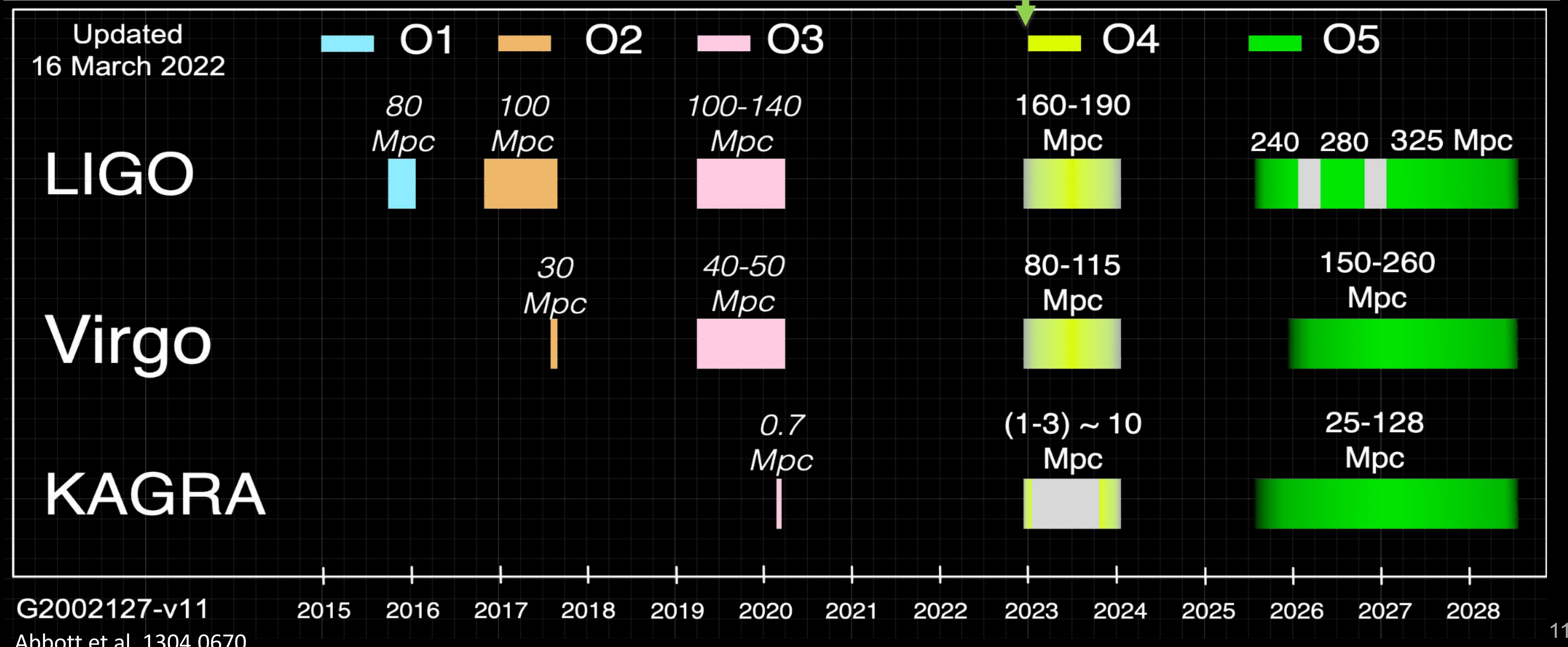
- No GW detections … (yet)

Abbott et al. [Phys. Rev. D **101**, 084002 (2020)]



Future observing runs

mid-December 2022



Abbott et al. 1304.0670

O3 (2019-20) Public Alerts

<u>Highest-probability classifications:</u>

BBH: 37
NS-BH: 5
BNS: 6
Mass gap: 4 *[3-5]* M_o
Other: 4
Total rate: ~1/week
false rate: ~1/month

Main focus is binaries but also have searches for "generic" GW bursts (including CCSNe).

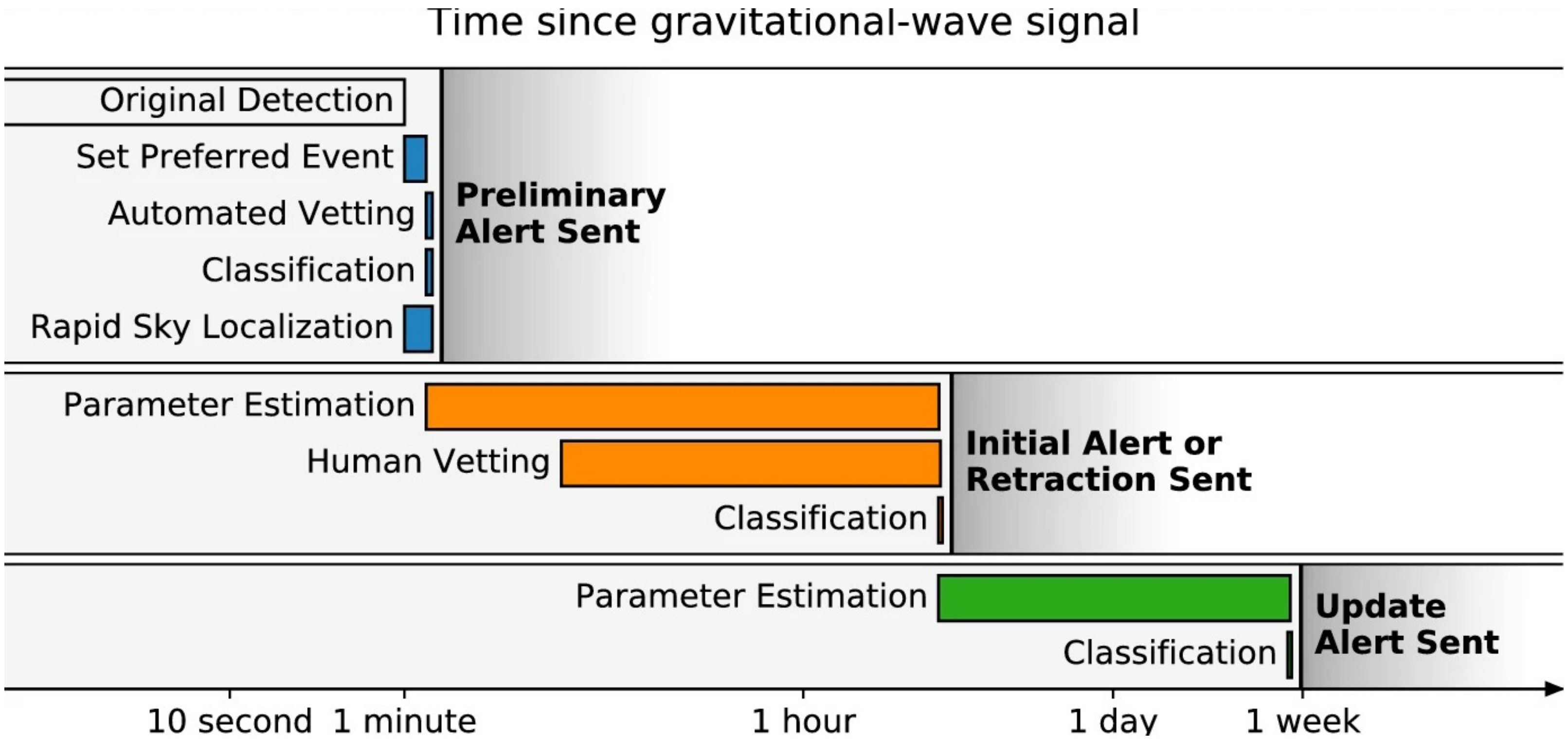
Also listen for SNEWS, GCNs (GRBs).

LIGO/Virgo O3 Public Alerts
Detection candidates: 56

https://gracedb.ligo.org/superevents/public/O3/

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S200316bj	MassGap (>99%)	March 16, 2020 21:57:56 UTC	GCN Circulars Notices | VOE		1 per 446.44 years	
S200311bg	BBH (>99%)	March 11, 2020 11:58:53 UTC	GCN Circulars Notices | VOE		1 per 3.5448e+17 years	
S200308e	NSBH (83%), Terrestrial (17%)	March 8, 2020 01:19:27 UTC	GCN Circulars Notices | VOE		1 per 8.757 years	RETRACTED
S200303ba	BBH (86%), Terrestrial (14%)	March 3, 2020 12:15:48 UTC	GCN Circulars Notices | VOE		1 per 2.4086 years	RETRACTED
S200302c	BBH (89%), Terrestrial (11%)	March 2, 2020 01:58:11 UTC	GCN Circulars Notices | VOE		1 per 3.3894 years	
S200225q	BBH (96%), Terrestrial (4%)	Feb. 25, 2020 06:04:21 UTC	GCN Circulars Notices |		1 per 3.4497 years	

Alert Latency



What can SNEWS do for us?

Pointing accuracy:

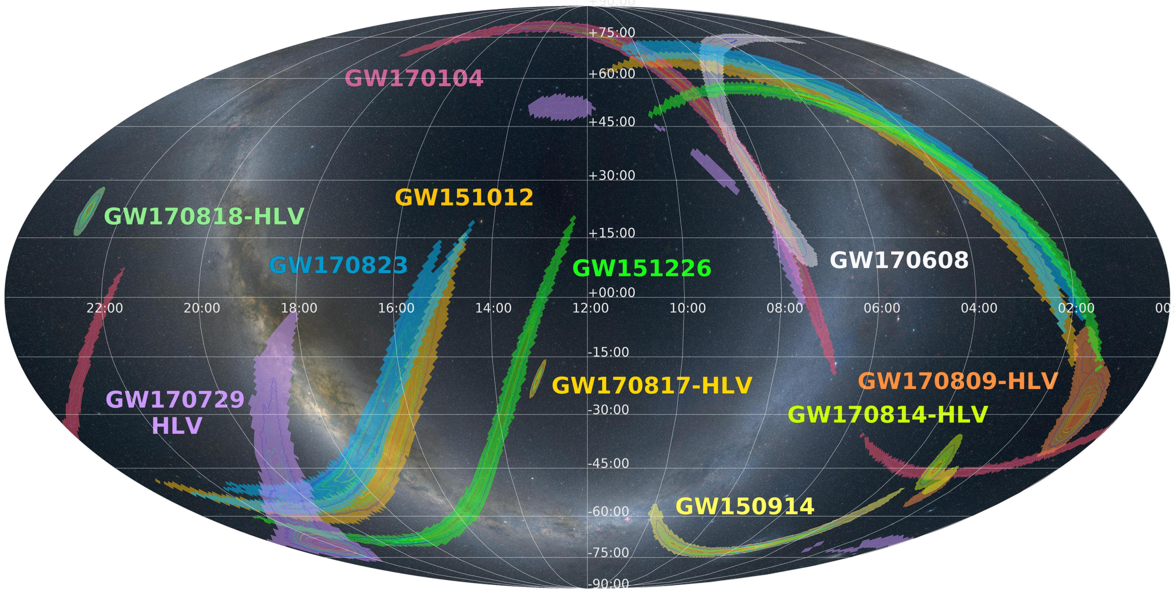
- More precise is better: faster to scan, lower false rate. But we don’t need much compared to EM telescopes.

Timing:

- O(1) s accuracy increases confidence / sensitive distance
  - rule of thumb: x2

Latency:

- Expect GW alerts on 10 s – 100 s scales.

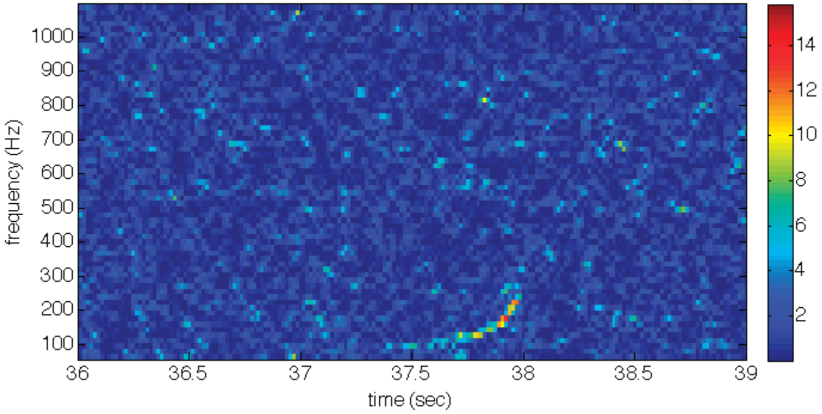


LIGO-Virgo 90% sky localization regions for sample binary merger events: 16 sq deg – 1666 sq deg.
Abbott et al. 1304.0670

What can GWs tell us about CCSNe?

- GW burst detection algorithms search for excess power that is correlated between detectors.
  - No need for precise signal models.

e.g., S. Klimenko et al., Phys. Rev. D 93, 042004 (2016).
P. Sutton et al., NJP 12 053034 (2010)



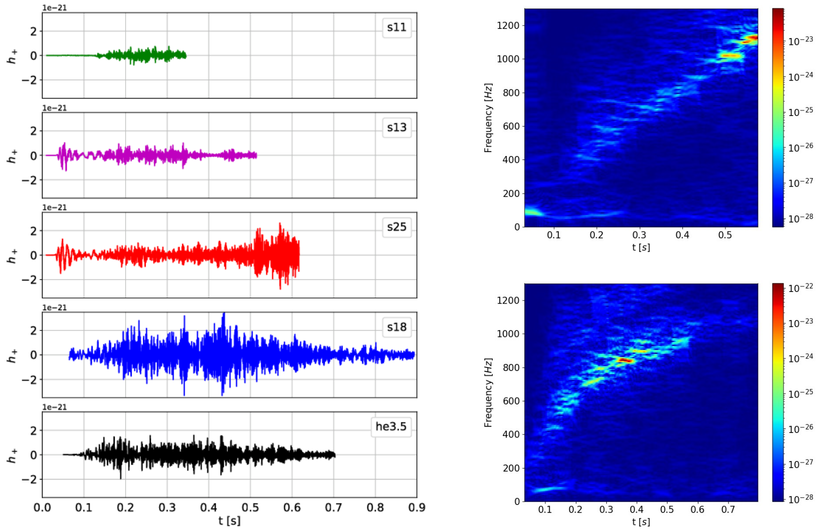
- Interpretation requires signal models.
- Recent examples:

M. L. Chan et al., Phys. Rev. D 102, 043022 (2020)
A. Iess et al., arXiv:2001.00279
P. Astone et al., Phys. Rev. D 98, 122002 (2018).
M. Lopez et al., Phys. Rev. D 103, 063011 (2021).

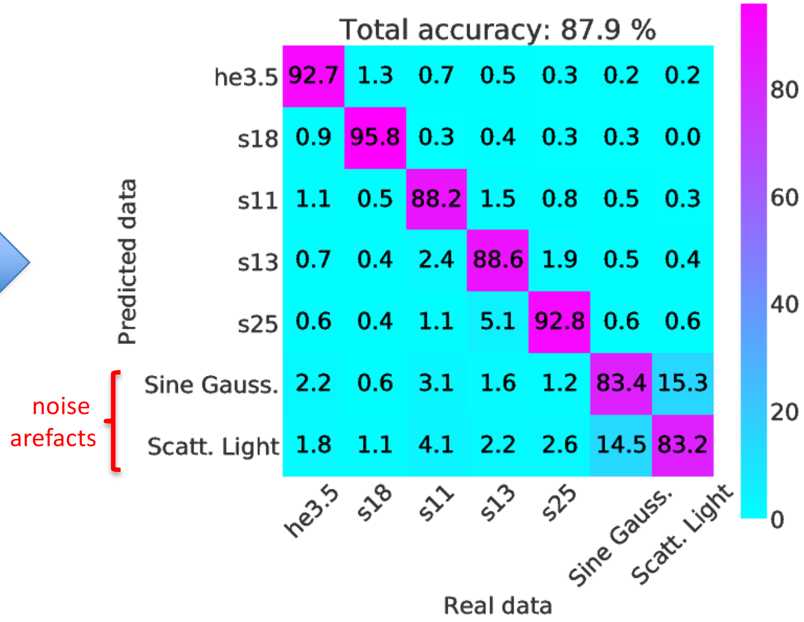
Example: Model Identification with Machine Learning

A. Iess et al., arXiv:2001.00279

- Train 1D and 2D convolutional neural networks (CNNs) with examples of CCSN GW signals, plus simulated detector noise artefacts.



- Able to distinguish models with ~90% accuracy at ~1 kpc.



Total accuracy: 87.9 %

Predicted data \ Real data	he3.5	s18	s11	s13	s25	Sine Gauss.	Scatt. Light
he3.5	92.7	1.3	0.7	0.5	0.3	0.2	0.2
s18	0.9	95.8	0.3	0.4	0.3	0.3	0.0
s11	1.1	0.5	88.2	1.5	0.8	0.5	0.3
s13	0.7	0.4	2.4	88.6	1.9	0.5	0.4
s25	0.6	0.4	1.1	5.1	92.8	0.6	0.6
Sine Gauss.	2.2	0.6	3.1	1.6	1.2	83.4	15.3
Scatt. Light	1.8	1.1	4.1	2.2	2.6	14.5	83.2

noise arefacts

Concluding Remarks

- GWs could provide a valuable multi-messenger probe of CCSNe:
  - GW observatory network provides approx. all-sky coverage at some fractional duty cycle (~70-80% during observing runs)
  - GW-CCSN detection is challenging, but we should be sensitive to the entire Milky Way for most cases.
  - GW sensitivity would be improved by dedicated SNEWS-GW searches.
  - Beginning to develop methods to distinguish CCSN explosion mechanism from the GW signal.

- Full exploitation of these rare events requires coordination between the GW/EM/ν communities
  - esp. strategies & partnerships for follow-up of candidate events
  - coordinated GW/EM/ν emission models (for detection & interpretation).