LOOKING OUT THROUGH A NEW WINDOW ON THE UNIVERSE

doing science with gravitational waves

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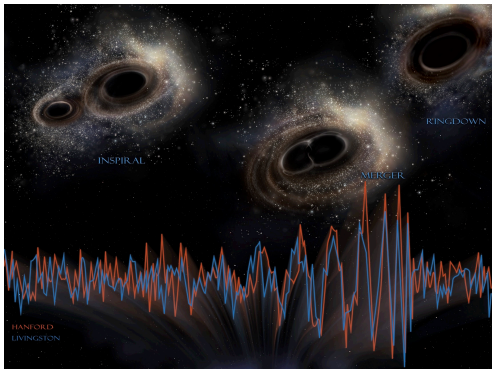
FIRSTS - GW150914

First direct detection of gravitational waves (100 years after Einstein's GR and Schwarzschild solution)

First observation of black holes through GW



First observation of the largest known stellar mass BH (>25 $M_{\odot}$)

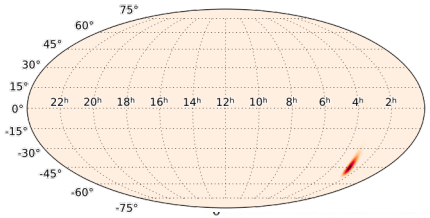
First tests of general relativity in strong field (extreme) conditions

First observation of a binary black hole (BBH) system

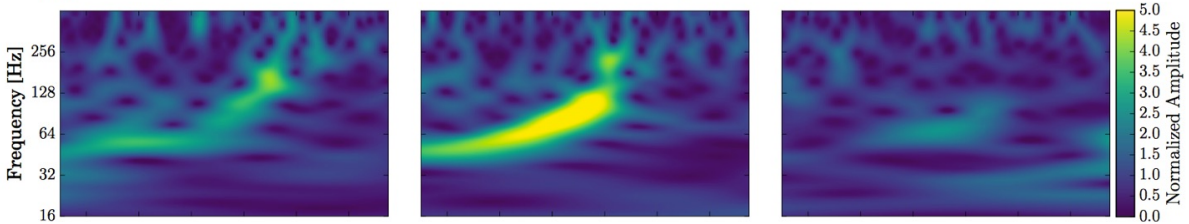
First observation of a BBH merger

ONE MORE LESSON: the ground-based interferometers are the right instruments!

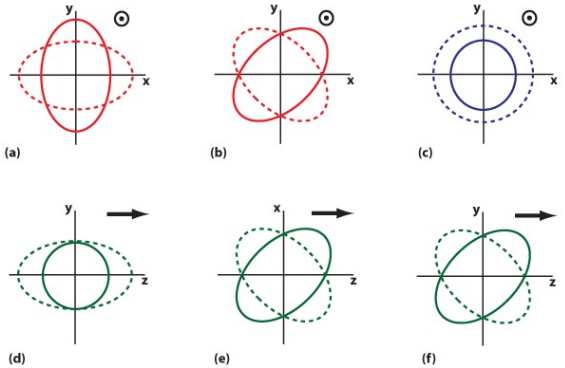
FIRSTS – GW190814



FIRST EVENT SEEN BY 3 DETECTORS: ACCURATE SKY LOCALIZATION AREA, ENABLING EFFICIENT MULTI-MESSENGER OBSERVATIONS



FIRST EVENT ALLOWING GW POLARIZATION STUDIES

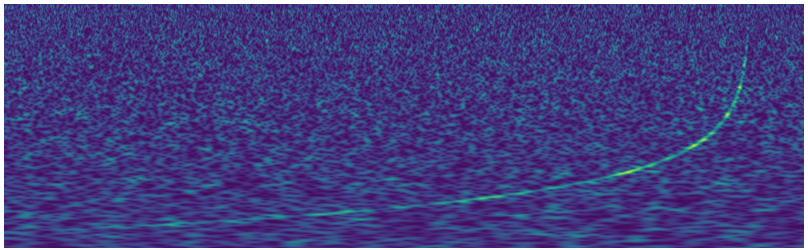


FIRSTS – GW170817

First multimessenger event (with GW)

First evidence that short GRB can be produced by BNS

First observation of a BNS merger



First observation of a kilonova and evidence of heavy elements synthesis

First measurement of H_0 using GW

First measurement of GW speed with accuracy ~1e-15

O1: 12 Sep 2015 → 19 Jan 2016 (H,L)
O2: 30 Nov 2016 → 25 Aug 2017 (H,L,V [1 Aug 2017 → 25 Aug 2017])

The O3 run

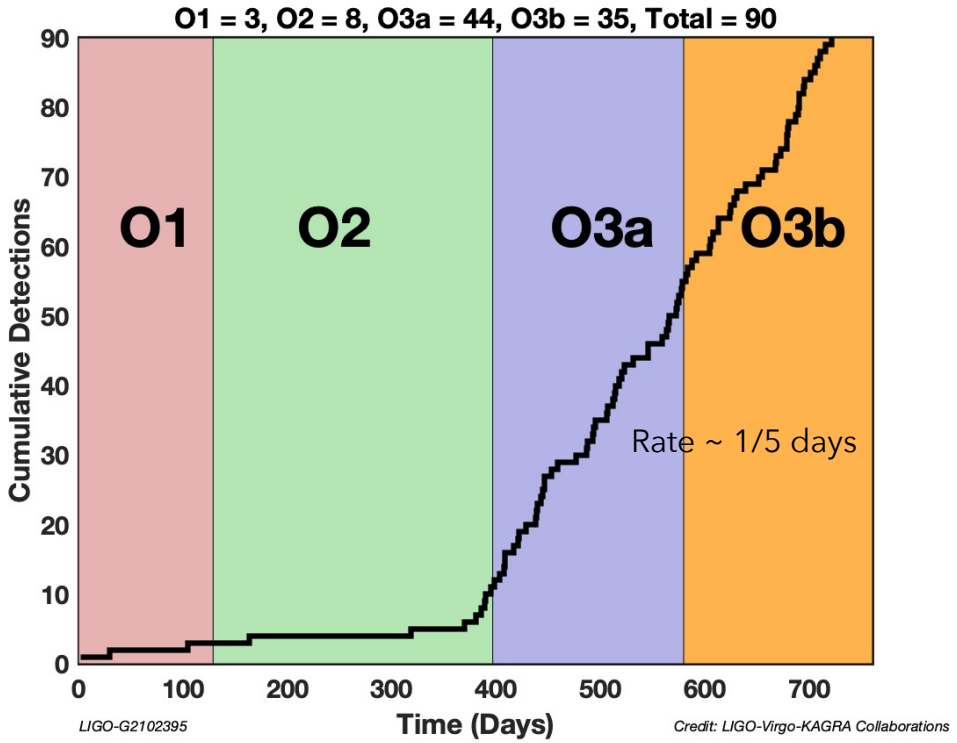
O3a: Apr 1 2019 → Oct 1 2019

O3b: Nov 1 2019 → March 27* 2020 (with KAGRA)

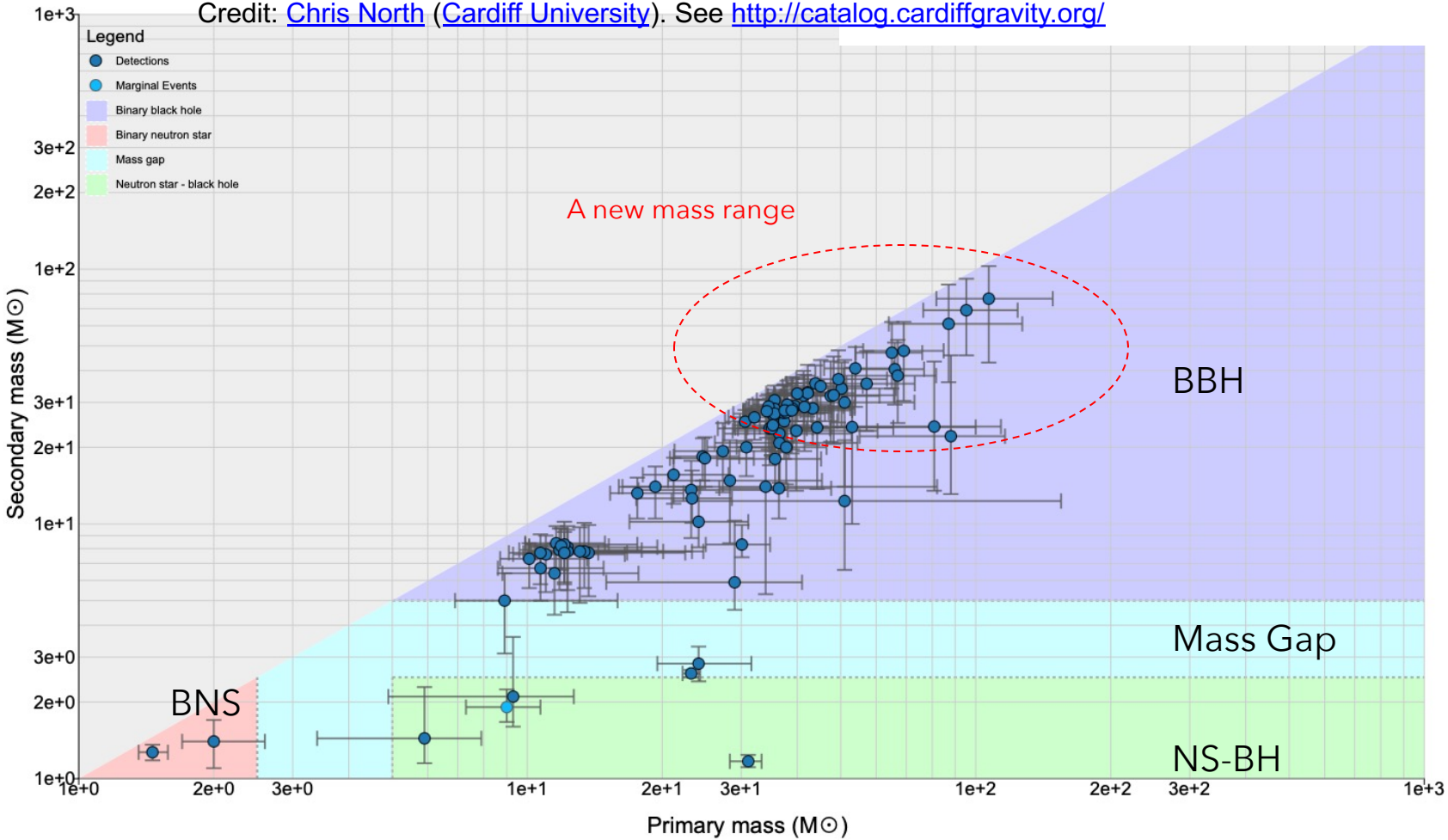
*Early end due to COVID19

OBSERVING RUN O3

- High network duty cycle
  - triple coincidence: 47.4
  - double coincidence: 36%
  - None: 3%
- Significant improvement of the detection rate!
  - BH population studies
  - More distant sources detected (z ~ 0.8)
- Several *exceptional* events published



Credit: Chris North (Cardiff University). See http://catalog.cardiffgravity.org/



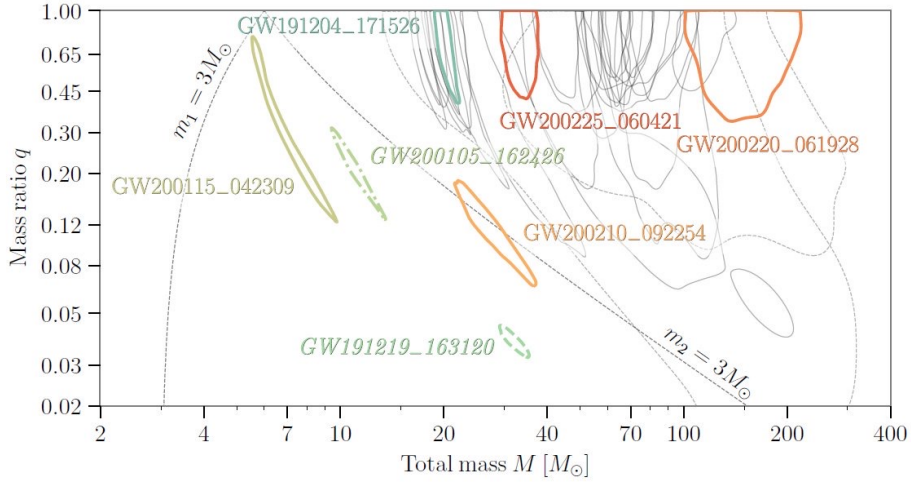
GWTC-3 RELEASED

35 new events in O3b, 90 detected so far

GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run

R. Abbott,[1] T. D. Abbott,[2] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] N. Adhikari,[7] R. X. Adhikari,[1] V. B. Adya,[8] C. Affeldt,[9,10] D. Agarwal,[11] M. Agathos,[12,13] K. Agatsuma,[14] N. Aggarwal,[15] O. D. Aguiar,[16] L. Aiello,[17] A. Ain,[18] P. Ajith,[19] S. Akcay,[13,20] T. Akutsu,[21,22] S. Albanesi,[23] A. Allocca,[24,4] P. A. Altin,[8] A. Amato,[25]

https://arxiv.org/abs/2111.03606



Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	$M_{\rm f}$ ($M_\odot$)	$\chi_{\rm f}$	$\Delta\Omega$ (deg^2)	SNR
GW191103_012549	$20.0^{+3.7}_{-1.8}$	$8.34^{+0.66}_{-0.57}$	$11.8^{+6.2}_{-2.2}$	$7.9^{+1.7}_{-2.4}$	$0.21^{+0.16}_{-0.10}$	$0.99^{+0.50}_{-0.47}$	$0.20^{+0.09}_{-0.09}$	$19.0^{+3.8}_{-1.7}$	$0.75^{+0.06}_{-0.05}$	2500	$8.9^{+0.3}_{-0.5}$
GW191105_143521	$18.5^{+2.1}_{-1.3}$	$7.82^{+0.61}_{-0.45}$	$10.7^{+3.7}_{-1.6}$	$7.7^{+1.4}_{-1.9}$	$-0.02^{+0.13}_{-0.09}$	$1.15^{+0.43}_{-0.48}$	$0.23^{+0.07}_{-0.09}$	$17.6^{+2.1}_{-1.2}$	$0.67^{+0.04}_{-0.05}$	640	$9.7^{+0.3}_{-0.5}$
GW191109_010717	112^{+20}_{-16}	$47.5^{+9.6}_{-7.5}$	65^{+11}_{-11}	47^{+15}_{-13}	$-0.29^{+0.42}_{-0.31}$	$1.29^{+1.13}_{-0.65}$	$0.25^{+0.18}_{-0.12}$	107^{+18}_{-15}	$0.61^{+0.18}_{-0.19}$	1600	$17.3^{+0.5}_{-0.5}$
GW191113_071753	$34.5^{+10.5}_{-9.8}$	$10.7^{+1.1}_{-1.0}$	29^{+12}_{-14}	$5.9^{+4.4}_{-1.3}$	$0.00^{+0.37}_{-0.29}$	$1.37^{+1.15}_{-0.62}$	$0.26^{+0.18}_{-0.11}$	34^{+11}_{-10}	$0.45^{+0.33}_{-0.11}$	3600	$7.9^{+0.5}_{-1.1}$
GW191126_115259	$20.7^{+3.4}_{-2.0}$	$8.65^{+0.95}_{-0.71}$	$12.1^{+5.5}_{-2.2}$	$8.3^{+1.9}_{-2.4}$	$0.21^{+0.15}_{-0.11}$	$1.62^{+0.74}_{-0.74}$	$0.30^{+0.12}_{-0.13}$	$19.6^{+3.5}_{-2.0}$	$0.75^{+0.06}_{-0.05}$	1400	$8.3^{+0.2}_{-0.5}$
GW191127_050227	80^{+39}_{-22}	$29.9^{+11.7}_{-9.1}$	53^{+47}_{-20}	24^{+17}_{-14}	$0.18^{+0.34}_{-0.36}$	$3.4^{+3.1}_{-1.9}$	$0.57^{+0.40}_{-0.29}$	76^{+39}_{-21}	$0.75^{+0.13}_{-0.29}$	980	$9.2^{+0.7}_{-0.6}$
GW191129_134029	$17.5^{+2.4}_{-1.2}$	$7.31^{+0.43}_{-0.28}$	$10.7^{+4.1}_{-2.1}$	$6.7^{+1.5}_{-1.7}$	$0.06^{+0.16}_{-0.08}$	$0.79^{+0.26}_{-0.33}$	$0.16^{+0.05}_{-0.06}$	$16.8^{+2.5}_{-1.2}$	$0.69^{+0.03}_{-0.05}$	850	$13.1^{+0.2}_{-0.3}$
GW191204_110529	$47.2^{+9.2}_{-8.0}$	$19.8^{+3.6}_{-3.3}$	$27.3^{+11.0}_{-6.0}$	$19.3^{+5.6}_{-6.0}$	$0.05^{+0.26}_{-0.27}$	$1.8^{+1.7}_{-1.1}$	$0.34^{+0.25}_{-0.18}$	$45.0^{+8.6}_{-7.6}$	$0.71^{+0.12}_{-0.11}$	3700	$8.8^{+0.4}_{-0.6}$
GW191204_171526	$20.21^{+1.70}_{-0.96}$	$8.55^{+0.38}_{-0.27}$	$11.9^{+3.3}_{-1.8}$	$8.2^{+1.4}_{-1.6}$	$0.16^{+0.08}_{-0.05}$	$0.65^{+0.19}_{-0.25}$	$0.13^{+0.04}_{-0.05}$	$19.21^{+1.79}_{-0.95}$	$0.73^{+0.03}_{-0.05}$	350	$17.5^{+0.2}_{-0.2}$
GW191215_223052	$43.3^{+5.3}_{-4.3}$	$18.4^{+2.2}_{-1.7}$	$24.9^{+7.1}_{-4.1}$	$18.1^{+3.8}_{-4.1}$	$-0.04^{+0.17}_{-0.21}$	$1.93^{+0.89}_{-0.86}$	$0.35^{+0.13}_{-0.14}$	$41.4^{+5.1}_{-4.1}$	$0.68^{+0.07}_{-0.07}$	530	$11.2^{+0.3}_{-0.4}$
GW191216_213338	$19.81^{+2.69}_{-0.94}$	$8.33^{+0.22}_{-0.19}$	$12.1^{+4.6}_{-2.3}$	$7.7^{+1.6}_{-1.9}$	$0.11^{+0.13}_{-0.06}$	$0.34^{+0.12}_{-0.13}$	$0.07^{+0.02}_{-0.03}$	$18.87^{+2.80}_{-0.94}$	$0.70^{+0.03}_{-0.04}$	490	$18.6^{+0.2}_{-0.2}$
GW191219_163120	$32.3^{+2.2}_{-2.7}$	$4.32^{+0.12}_{-0.17}$	$31.1^{+2.2}_{-2.8}$	$1.17^{+0.07}_{-0.06}$	$0.00^{+0.07}_{-0.09}$	$0.55^{+0.25}_{-0.16}$	$0.11^{+0.05}_{-0.03}$	$32.2^{+2.2}_{-2.7}$	$0.14^{+0.06}_{-0.06}$	1500	$9.1^{+0.5}_{-0.8}$
GW191222_033537	79^{+16}_{-11}	$33.8^{+7.1}_{-5.0}$	$45.1^{+10.9}_{-8.0}$	$34.7^{+9.3}_{-10.5}$	$-0.04^{+0.20}_{-0.25}$	$3.0^{+1.7}_{-1.7}$	$0.51^{+0.23}_{-0.26}$	$75.5^{+15.3}_{-9.9}$	$0.67^{+0.08}_{-0.11}$	2000	$12.5^{+0.2}_{-0.3}$
GW191230_180458	86^{+19}_{-12}	$36.5^{+8.2}_{-5.6}$	$49.4^{+14.0}_{-9.6}$	37^{+11}_{-12}	$-0.05^{+0.26}_{-0.31}$	$4.3^{+2.1}_{-1.9}$	$0.69^{+0.26}_{-0.27}$	82^{+17}_{-11}	$0.68^{+0.11}_{-0.13}$	1100	$10.4^{+0.3}_{-0.4}$
GW200105_162426	$11.0^{+1.5}_{-1.4}$	$3.42^{+0.08}_{-0.08}$	$9.0^{+1.7}_{-1.7}$	$1.91^{+0.33}_{-0.24}$	$0.00^{+0.13}_{-0.18}$	$0.27^{+0.12}_{-0.11}$	$0.06^{+0.02}_{-0.02}$	$10.7^{+1.5}_{-1.4}$	$0.43^{+0.05}_{-0.02}$	7900	$13.7^{+0.2}_{-0.4}$
GW200112_155838	$63.9^{+5.7}_{-4.6}$	$27.4^{+2.6}_{-2.1}$	$35.6^{+6.7}_{-4.5}$	$28.3^{+4.4}_{-5.9}$	$0.06^{+0.15}_{-0.15}$	$1.25^{+0.43}_{-0.46}$	$0.24^{+0.07}_{-0.08}$	$60.8^{+5.3}_{-4.3}$	$0.71^{+0.06}_{-0.06}$	4300	$19.8^{+0.1}_{-0.2}$
GW200115_042309	$7.4^{+1.8}_{-1.2}$	$2.43^{+0.05}_{-0.07}$	$5.9^{+2.0}_{-2.5}$	$1.44^{+0.85}_{-0.29}$	$-0.15^{+0.24}_{-0.42}$	$0.29^{+0.15}_{-0.10}$	$0.06^{+0.03}_{-0.02}$	$7.2^{+1.8}_{-1.7}$	$0.42^{+0.09}_{-0.09}$	370	$11.3^{+0.5}_{-0.5}$
GW200128_022011	75^{+17}_{-12}	$32.0^{+7.5}_{-5.5}$	$42.2^{+11.6}_{-8.1}$	$32.6^{+9.5}_{-9.2}$	$0.12^{+0.24}_{-0.25}$	$3.4^{+2.1}_{-1.8}$	$0.56^{+0.28}_{-0.28}$	71^{+16}_{-11}	$0.74^{+0.10}_{-0.10}$	2600	$10.6^{+0.3}_{-0.4}$
GW200129_065458	$63.4^{+4.3}_{-3.6}$	$27.2^{+2.1}_{-2.3}$	$34.5^{+9.9}_{-3.2}$	$28.9^{+3.4}_{-9.3}$	$0.11^{+0.11}_{-0.16}$	$0.90^{+0.29}_{-0.38}$	$0.18^{+0.05}_{-0.07}$	$60.3^{+4.0}_{-3.3}$	$0.73^{+0.06}_{-0.05}$	130	$26.8^{+0.2}_{-0.2}$
GW200202_154313	$17.58^{+1.78}_{-0.67}$	$7.49^{+0.24}_{-0.20}$	$10.1^{+3.5}_{-1.4}$	$7.3^{+1.1}_{-1.7}$	$0.04^{+0.13}_{-0.06}$	$0.41^{+0.15}_{-0.16}$	$0.09^{+0.03}_{-0.03}$	$16.76^{+1.87}_{-0.66}$	$0.69^{+0.03}_{-0.04}$	170	$10.8^{+0.2}_{-0.4}$
GW200208_130117	$65.4^{+7.8}_{-6.8}$	$27.7^{+3.6}_{-3.1}$	$37.8^{+9.2}_{-6.2}$	$27.4^{+6.1}_{-7.4}$	$-0.07^{+0.22}_{-0.27}$	$2.23^{+1.00}_{-0.85}$	$0.40^{+0.15}_{-0.14}$	$62.5^{+7.3}_{-6.4}$	$0.66^{+0.09}_{-0.13}$	30	$10.8^{+0.3}_{-0.4}$
GW200208_222617	63^{+100}_{-25}	$19.6^{+10.7}_{-5.1}$	51^{+104}_{-30}	$12.3^{+9.0}_{-5.7}$	$0.45^{+0.43}_{-0.44}$	$4.1^{+4.4}_{-1.9}$	$0.66^{+0.54}_{-0.28}$	61^{+100}_{-25}	$0.83^{+0.14}_{-0.27}$	2000	$7.4^{+1.4}_{-1.2}$
GW200209_085452	$62.6^{+13.9}_{-9.4}$	$26.7^{+6.0}_{-4.2}$	$35.6^{+10.5}_{-6.8}$	$27.1^{+7.8}_{-7.8}$	$-0.12^{+0.24}_{-0.30}$	$3.4^{+1.9}_{-1.8}$	$0.57^{+0.25}_{-0.26}$	$59.9^{+13.1}_{-8.9}$	$0.66^{+0.10}_{-0.12}$	730	$9.6^{+0.4}_{-0.5}$
GW200210_092254	$27.0^{+7.1}_{-4.3}$	$6.56^{+0.38}_{-0.40}$	$24.1^{+7.5}_{-4.6}$	$2.83^{+0.47}_{-0.42}$	$0.02^{+0.22}_{-0.21}$	$0.94^{+0.43}_{-0.34}$	$0.19^{+0.08}_{-0.06}$	$26.7^{+7.2}_{-4.3}$	$0.34^{+0.13}_{-0.08}$	1800	$8.4^{+0.5}_{-0.7}$
GW200216_220804	81^{+20}_{-14}	$32.9^{+9.3}_{-8.5}$	51^{+22}_{-13}	30^{+14}_{-16}	$0.10^{+0.34}_{-0.36}$	$3.8^{+3.0}_{-2.0}$	$0.63^{+0.37}_{-0.29}$	78^{+19}_{-13}	$0.70^{+0.14}_{-0.24}$	2900	$8.1^{+0.4}_{-0.5}$
GW200219_094415	$65.0^{+12.6}_{-8.2}$	$27.6^{+5.6}_{-3.8}$	$37.5^{+10.1}_{-6.9}$	$27.9^{+7.4}_{-8.4}$	$-0.08^{+0.23}_{-0.29}$	$3.4^{+1.7}_{-1.5}$	$0.57^{+0.22}_{-0.22}$	$62.2^{+11.7}_{-7.8}$	$0.66^{+0.10}_{-0.13}$	700	$10.7^{+0.3}_{-0.5}$
GW200220_061928	148^{+55}_{-33}	62^{+23}_{-15}	87^{+40}_{-23}	61^{+26}_{-25}	$0.06^{+0.40}_{-0.38}$	$6.0^{+4.8}_{-3.1}$	$0.90^{+0.55}_{-0.40}$	141^{+51}_{-31}	$0.71^{+0.15}_{-0.17}$	3000	$7.2^{+0.4}_{-0.7}$
GW200220_124850	67^{+17}_{-12}	$28.2^{+7.3}_{-5.1}$	$38.9^{+14.1}_{-8.6}$	$27.9^{+9.2}_{-9.0}$	$-0.07^{+0.27}_{-0.33}$	$4.0^{+2.8}_{-2.2}$	$0.66^{+0.36}_{-0.31}$	64^{+16}_{-11}	$0.67^{+0.11}_{-0.14}$	3200	$8.5^{+0.3}_{-0.5}$
GW200224_222234	$72.2^{+7.2}_{-5.1}$	$31.1^{+3.2}_{-2.6}$	$40.0^{+6.9}_{-4.5}$	$32.5^{+5.0}_{-7.2}$	$0.10^{+0.15}_{-0.15}$	$1.71^{+0.49}_{-0.64}$	$0.32^{+0.08}_{-0.11}$	$68.6^{+6.6}_{-4.7}$	$0.73^{+0.07}_{-0.07}$	50	$20.0^{+0.2}_{-0.2}$
GW200225_060421	$33.5^{+3.6}_{-3.0}$	$14.2^{+1.5}_{-1.4}$	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$	$-0.12^{+0.17}_{-0.28}$	$1.15^{+0.51}_{-0.53}$	$0.22^{+0.09}_{-0.10}$	$32.1^{+3.5}_{-2.8}$	$0.66^{+0.07}_{-0.13}$	370	$12.5^{+0.3}_{-0.4}$
GW200302_015811	$57.8^{+9.6}_{-6.9}$	$23.4^{+4.7}_{-3.0}$	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$	$0.01^{+0.25}_{-0.26}$	$1.48^{+1.02}_{-0.70}$	$0.28^{+0.16}_{-0.12}$	$55.5^{+8.9}_{-6.6}$	$0.66^{+0.13}_{-0.15}$	6000	$10.8^{+0.3}_{-0.4}$
GW200306_093714	$43.9^{+11.8}_{-7.6}$	$17.5^{+3.5}_{-3.0}$	$28.3^{+17.1}_{-7.7}$	$14.8^{+6.5}_{-6.4}$	$0.32^{+0.28}_{-0.46}$	$2.1^{+1.7}_{-1.1}$	$0.38^{+0.24}_{-0.18}$	$41.7^{+12.3}_{-6.9}$	$0.78^{+0.13}_{-0.20}$	4600	$7.8^{+0.4}_{-0.6}$
GW200308_173609*	$50.6^{+10.9}_{-8.5}$	$19.0^{+4.8}_{-3.8}$	$36.4^{+11.2}_{-9.6}$	$13.8^{+7.2}_{-3.3}$	$0.65^{+0.17}_{-0.21}$	$5.4^{+2.7}_{-2.6}$	$0.83^{+0.32}_{-0.35}$	$47.4^{+11.1}_{-7.7}$	$0.91^{+0.03}_{-0.08}$	2000	$7.1^{+0.5}_{-0.5}$
GW200311_115853	$61.9^{+5.3}_{-4.2}$	$26.6^{+2.4}_{-2.0}$	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$	$-0.02^{+0.16}_{-0.20}$	$1.17^{+0.28}_{-0.40}$	$0.23^{+0.05}_{-0.07}$	$59.0^{+4.8}_{-3.9}$	$0.69^{+0.07}_{-0.08}$	35	$17.8^{+0.2}_{-0.2}$
GW200316_215756	$21.2^{+7.2}_{-2.0}$	$8.75^{+0.62}_{-0.55}$	$13.1^{+10.2}_{-2.9}$	$7.8^{+1.9}_{-2.9}$	$0.13^{+0.27}_{-0.10}$	$1.12^{+0.47}_{-0.44}$	$0.22^{+0.08}_{-0.08}$	$20.2^{+7.4}_{-1.9}$	$0.70^{+0.04}_{-0.04}$	190	$10.3^{+0.4}_{-0.7}$
GW200322_091133*	55^{+37}_{-27}	$15.5^{+15.7}_{-3.7}$	34^{+48}_{-18}	$14.0^{+16.8}_{-8.7}$	$0.24^{+0.45}_{-0.51}$	$3.6^{+7.0}_{-2.0}$	$0.60^{+0.84}_{-0.30}$	53^{+38}_{-26}	$0.78^{+0.16}_{-0.17}$	6500	$6.0^{+1.7}_{-1.2}$

MORE EXCEPTIONAL EVENTS

- GW190412: first observed BBH with unequal mass ratio
  - Masses: ~8, ~30 (mass ratio: q ~ 0.3)
  - [Abbott et al. (LIGO/Virgo Coll.), Phys. Rev. D **102**, 043015]

- GW190814: the most asymmetric mass ratio merger ever observed
  - Masses: ~2.6, ~23 $M_\odot$ (q ~ 0.1)
  - The secondary mass of 2.6 $M_\odot$ lies in the lower *'mass gap'* → either the lightest BH or the heaviest NS ever observed
  - [Abbott *et al* (LIGO/Virgo Coll.), *ApJL* **896** L44]

- GW190425: BNS merger of total mass of ~3.4 $M_\odot$
  - Significantly larger than any other known BNS system
  - [Abbott *et al* (LIGO/Virgo Coll.) *ApJL* **892** L3]

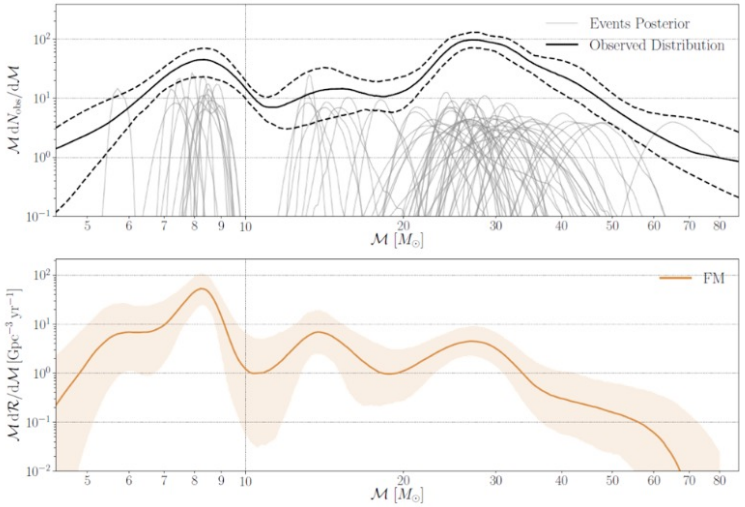
MORE EXCEPTIONAL EVENTS

- GW190521: BBH with primary masses ~66 and ~85 $M_\odot$, final mass of ~150 $M_\odot$
  - First observation of an intermediate mass BH ($M_f > 100$).
  - First observation of a BH in the (pulsational) pair instability upper mass gap 65 - 120 $M_\odot$.
  - Farthest source so far (z ~ 0.8)
  - [Abbott *et al* (LIGO/Virgo Coll.) Phys. Rev. Lett. **125**, 101102]

- GW200105-GW200115: 1st unambiguous detection of NSBH
  - [Abbott *et al* (LIGO/Virgo/KAGRA Coll.) *ApJL* **915** L5]

FROM ONE TO MANY: POPULATIONS

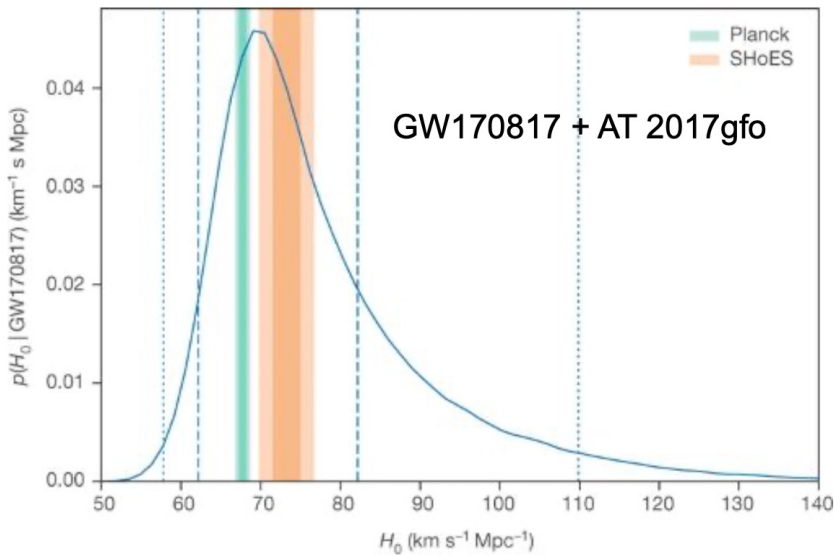
- Entering in the «statistical information driven» regime
  - NSBH binaries
  - Lower mass gap
  - NS mass distribution
  - Substructure in BBH mass distribution
  - BBH rate evolution with redshift
- Providing data for many studies
  - E.g. talk by A Dolgov, this session



https://arxiv.org/abs/2111.03634

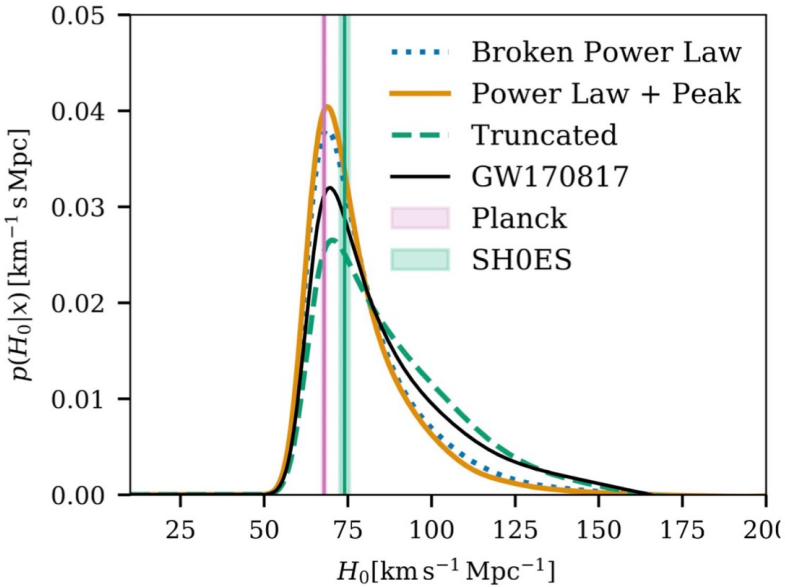
GW and COSMOLOGY

B P Abbott *et al. Nature* **551,** 85–88 (2017) doi:10.1038/nature24471



$$H_0 = 70^{12.0}_{-8.0}\ \mathrm{km\ s^{-1}Mpc}$$

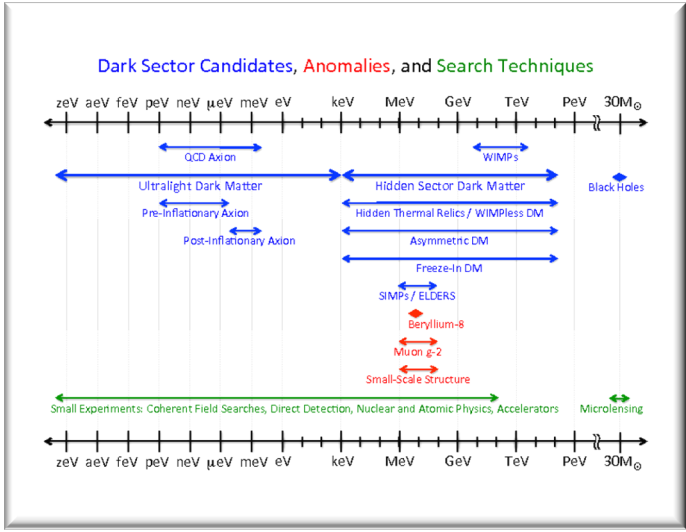
R Abbott *et al. arXiv:2111.03604 (2021)*



$$H_0 = 68^{8.0}_{-6.0}\ \mathrm{km\ s^{-1}Mpc}$$

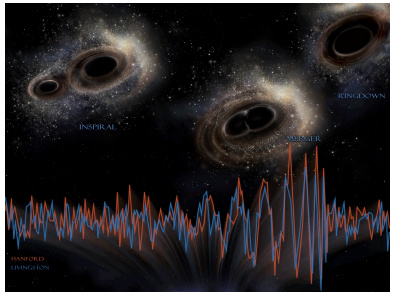
GW and DARK MATTER

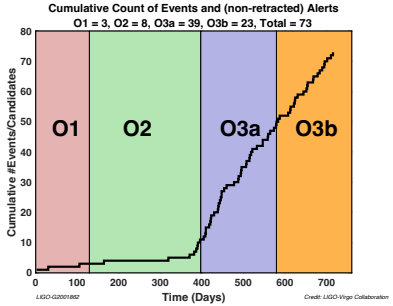
- Evidences: CMB power spectrum, cluster & galactic rotation curves, gravitational lensing
- Large span for DM candidate masses: from ultralight bosons ($\sim 10^{-22}$eV) to BH ($\sim 1 - 100\, M_\odot$).
- Gravitationally interacting, gravitational physics can help!
- GW sources can be affected by DM
  - By changes of their evolution by environmental effects
  - By changes of their nature and dynamics (when new interactions exist in the DM sector). They can be DM candidates by itself (SSM black holes)



arXiv:1707.04591

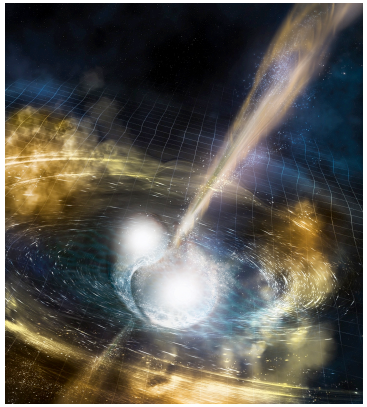
In just 5 years…

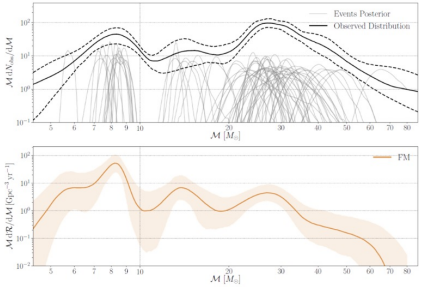




…to population studies

From discovery…



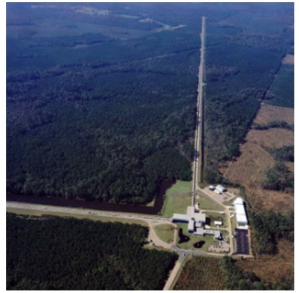


Gravitational Wave Open Science Center

Data Software Online Tools About GWOSC

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

LIGO Hanford Observatory, Washington
(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

- **O3b Bulk Data Now Available**
- **GWTC-3 Catalog Data Now Available**
- **Start with a Learning Path**
- **Browse the Event Portal**
- **Download data**
- **Join the email list**
- **Open Data Workshops**
- **Attend Office Hours**

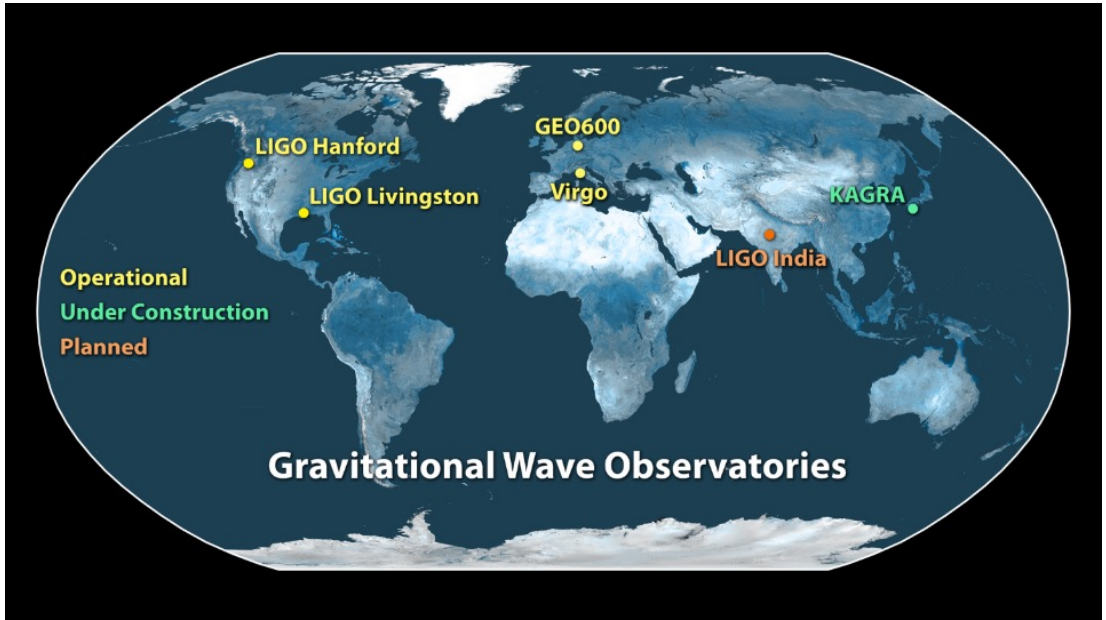
https://www.gw-openscience.org/

LIGO and Virgo's portal for

- Bulk data
- Event 1-hour time-series data, etc.
- Pointers to papers, data behind figures, posterior samples
- Pointers to analysis codes
- Pointers to Workshop materials

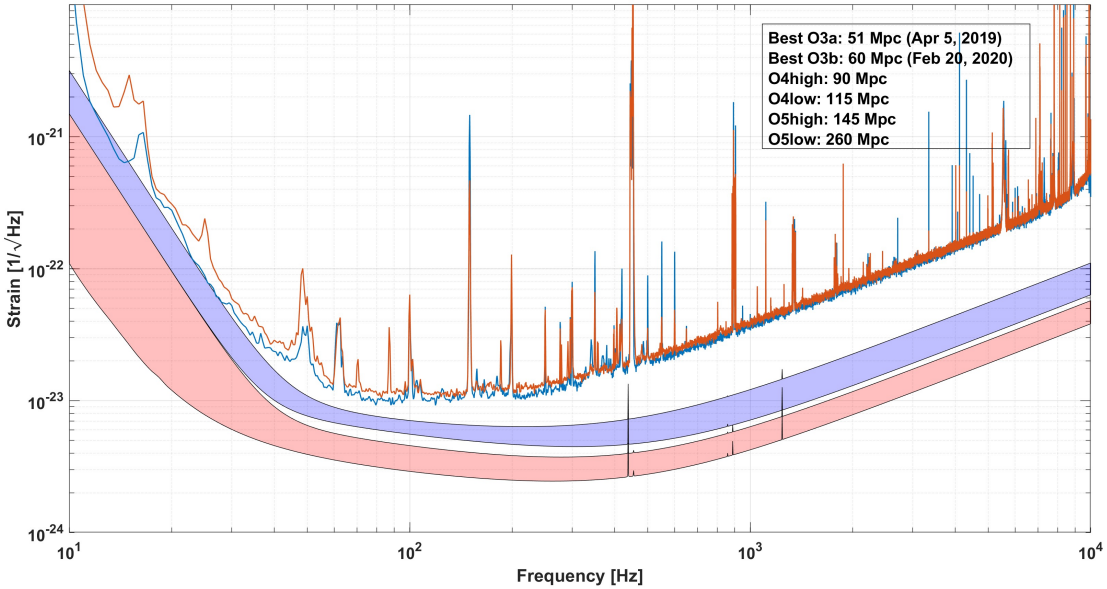
MID-TERM OUTLOOK

- KAGRA has joined the network in O3b
- Ligo/Virgo are being upgraded (A+/AdV+)
- Ligo India to join the network in ~202?

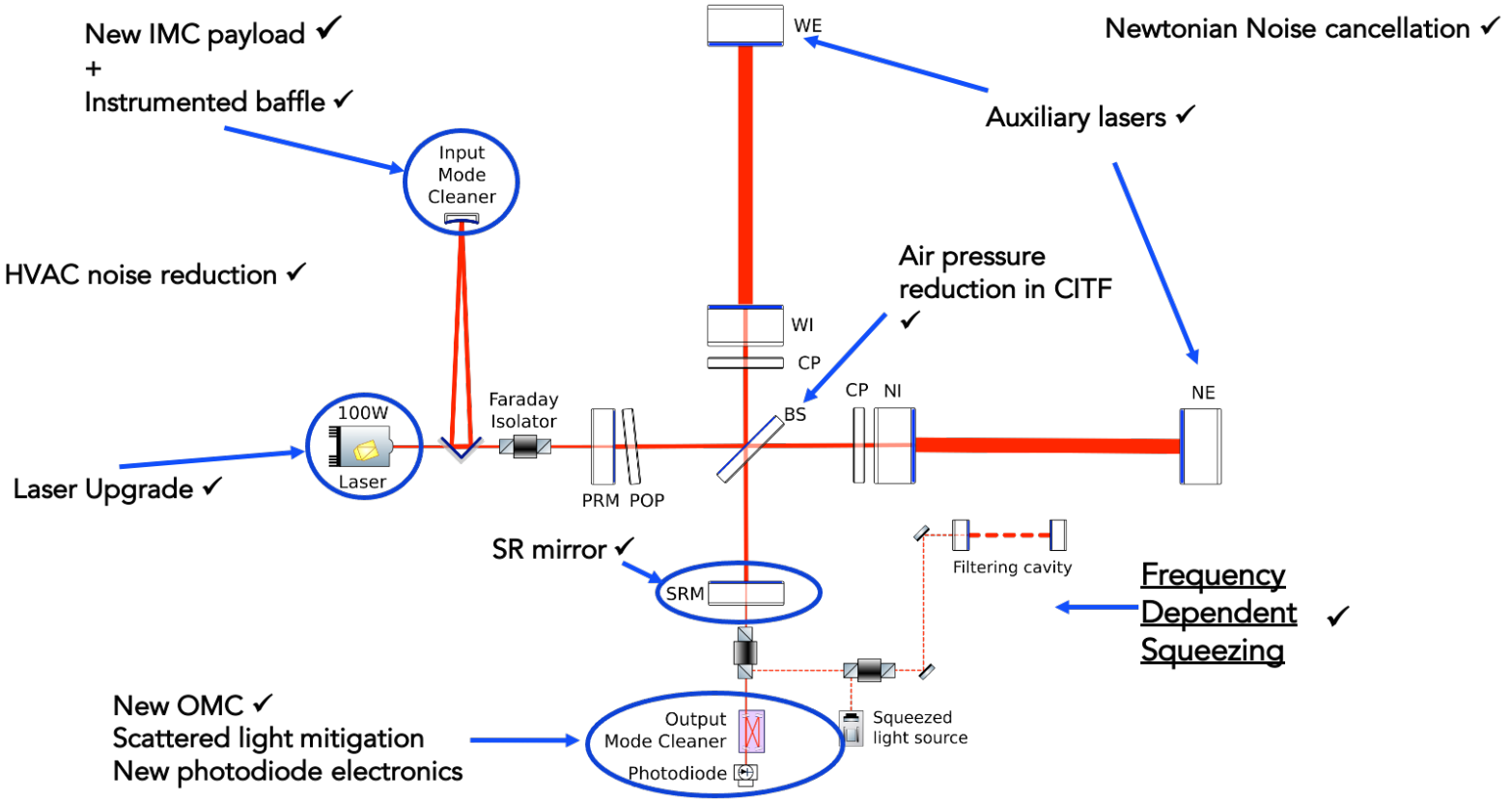


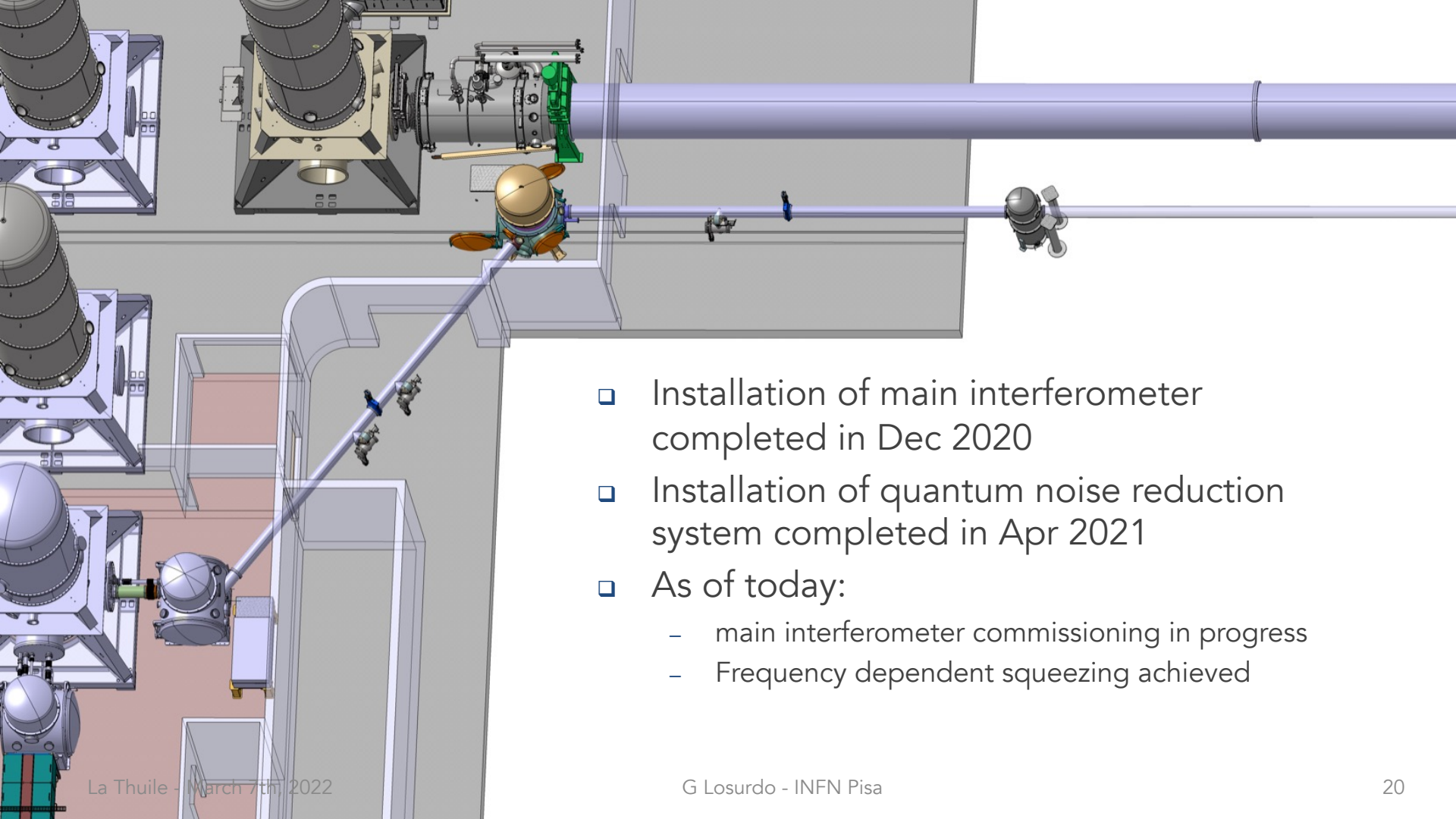
ADV+

- Virgo has a phased plan to increase its sensitivity: AdV+
  - Phase 1: BNS range from 60 Mpc (O3) to 90-115 Mpc (O4)
  - Phase 2: BNS range 145-260 Mpc (O5)



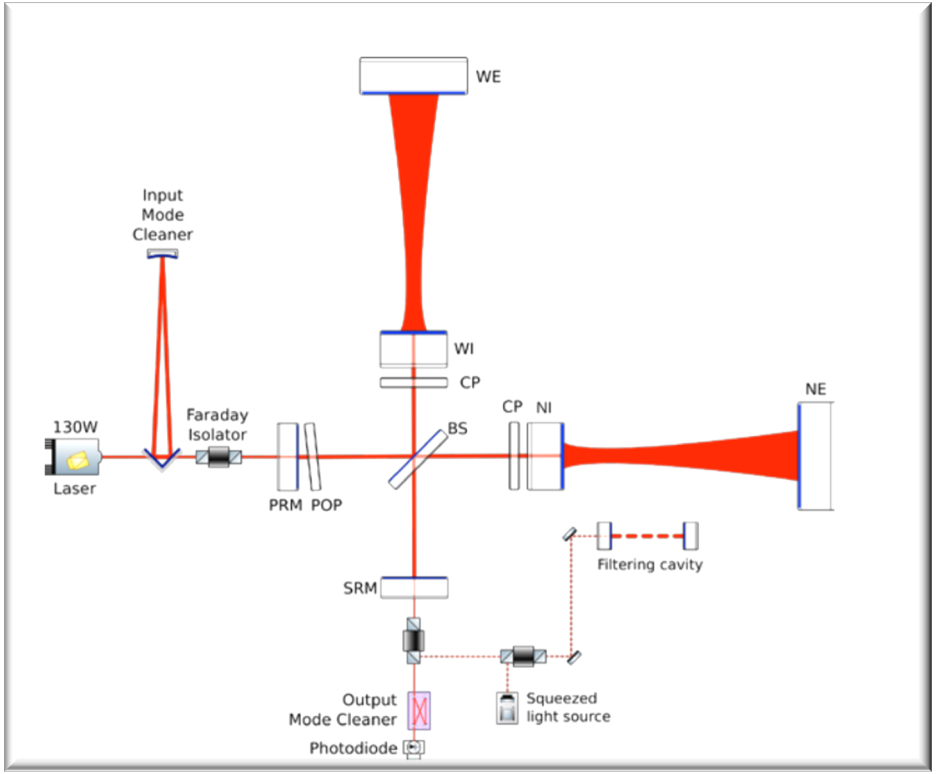
AdV+/Phase 1


New IMC payload ✓
+
Instrumented baffle ✓
HVAC noise reduction ✓
Laser Upgrade ✓
SR mirror ✓
New OMC ✓
Scattered light mitigation
New photodiode electronics
Newtonian Noise cancellation ✓
Auxiliary lasers ✓
Air pressure reduction in CITF ✓
Frequency Dependent Squeezing ✓
Input Mode Cleaner
100W
Laser
Faraday Isolator
PRM
POP
WE
WI
CP
BS
CP
NI
NE
SRM
Filtering cavity
Output Mode Cleaner
Photodiode
Squeezed light source



- Installation of main interferometer completed in Dec 2020
- Installation of quantum noise reduction system completed in Apr 2021
- As of today:
  - main interferometer commissioning in progress
  - Frequency dependent squeezing achieved

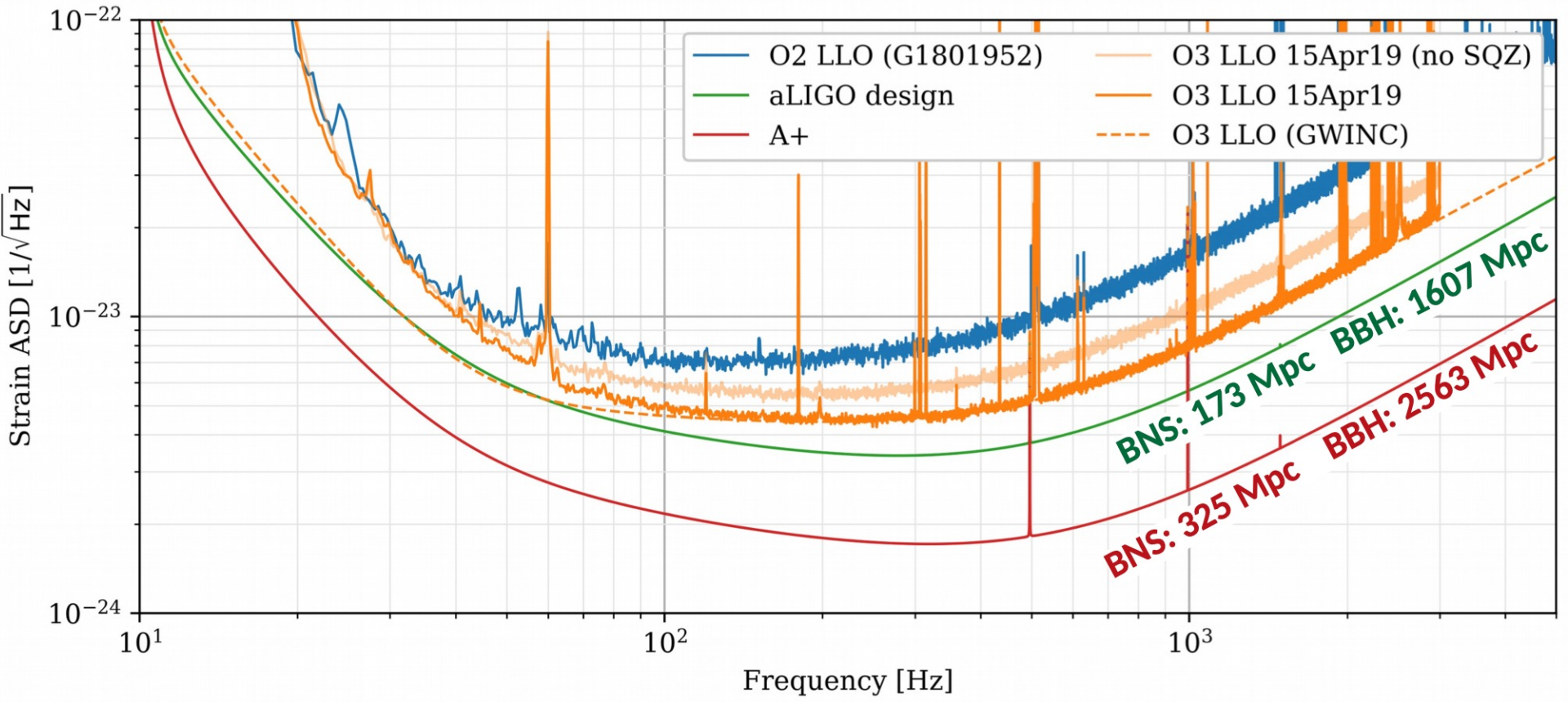
AdV+/Phase 2



Reducing the thermal noise limit:
larger test masses (larger beam spot) +
better coatings

A+

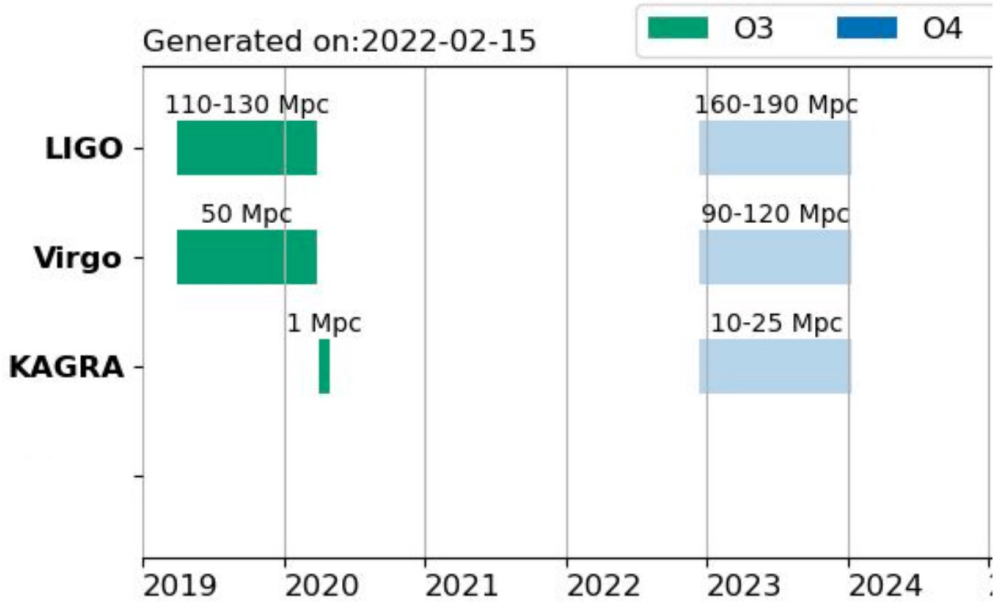
McCuller, LIGO-G1900980



NEXT RUN(S)

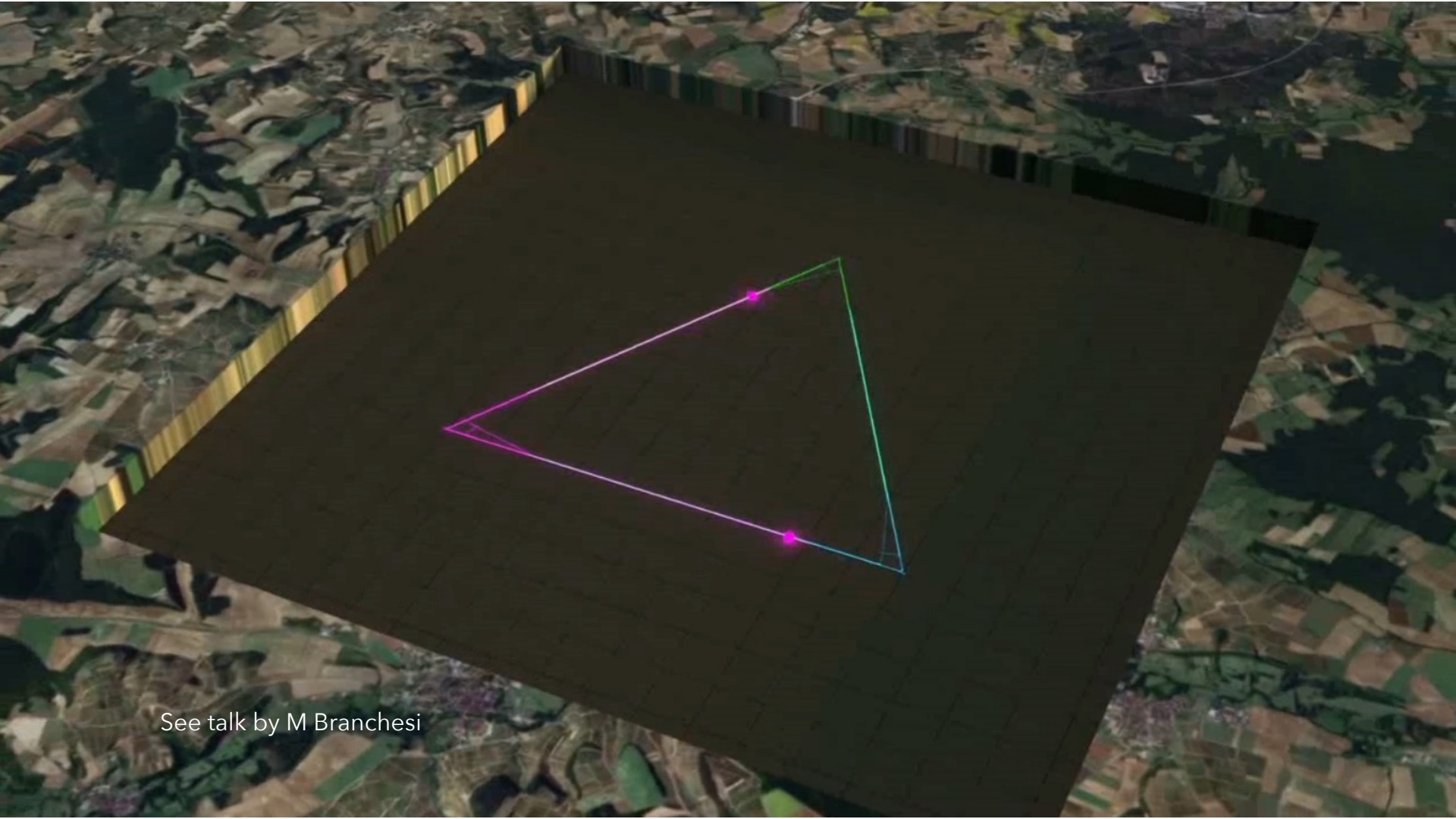
- O4 to start mid-Dec 2022
  - Delay mainly due to COVID impact
- Baseline: 1 yr with 1 month commissioning break
- Expected event rate (CBC): ~1/2 days

- O5 to start 1.5-2 yrs after O4
  - Expected rate: ~a few/day



POST-O5

- Bridge the gap between 2G+ and 3G
- Virgo and LIGO are studying the potential of a new upgrade capable with the potential of a further, significant improvement in sensitivity
- Exploit the existing infrastructure until the advent of 3G detectors
- Provide full scale testing of 3G technologies and act as risk reducer for 3G


See talk by M Branchesi

INFN PISA -1984

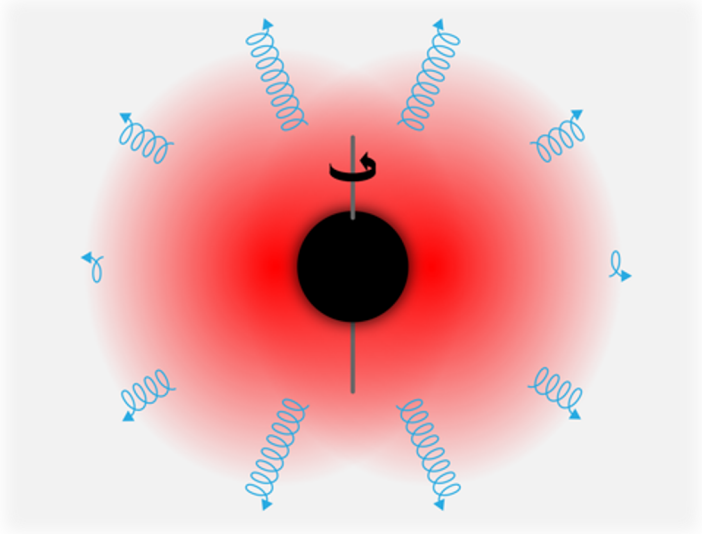
"La Chiesina"

BACKUP

DM candidates searchable with GW

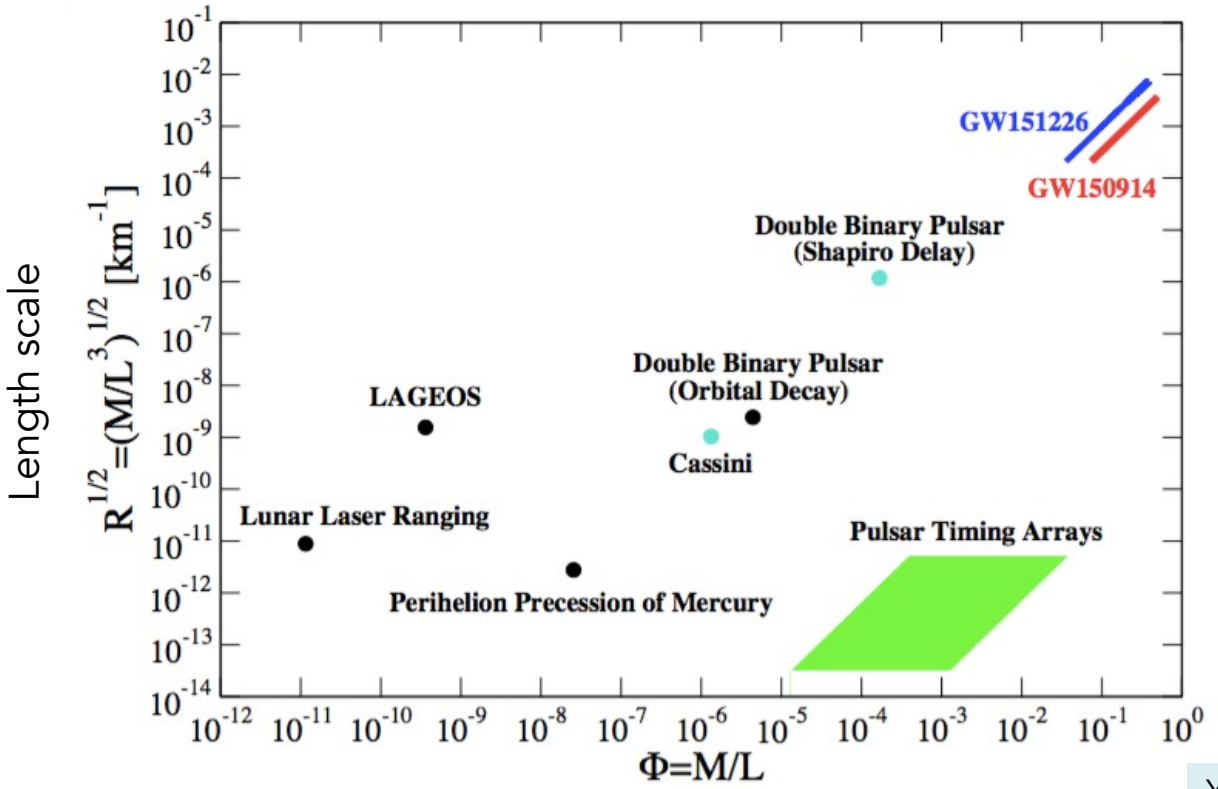
- Environmental effects on compact objects
  - The **compact object structure** can be changed: accretion disk, spin down effects, formation of a DM core
  - The GW **production mechanism** can be changed
  - **Inpact on propagation** of generated GW and EM waves
  - ***Signature:*** *Unusual waveform*
- Primordial black holes
  - Microlensing data seems to exclude that ALL DM can be explained in this way.
  - Not completely uncontroversial, some assumptions can be weakened;
  - Could be responsible for a fraction of DM;
  - ***Signature:*** *Subsolar mass BH evidence*

- Exotic objects
  - GW190521 is compatible with a merger between two complex vector boson star, with $m_b \sim 8.7\times10^{-13}$ eV (head on collision) [Phys. Rev. Lett. **126**, 081101]
- Superradiance effects
  - A Kerr BH can transfer efficiently its energy to a cloud of ultra-light bosons, (scalar or vector) when $\lambda_c \sim R_s$ (which means $10^{-21}eV < m_b < 10^{-11}eV$)
  - The cloud can emit a nearly-periodic, long duration GW signal potentially detectable by LIGO-Virgo-KAGRA if $10^{-13}eV < m_b < 10^{-11}eV$



From: https://physics.aps.org/articles/v10/83

PRL 123, 171101 (2019)
PRD 101, 063020 (2020)
PRD 99, 084042 (2019)
PRD 98, 103017 (2018)



Yunes et al., arXiv1603.08955