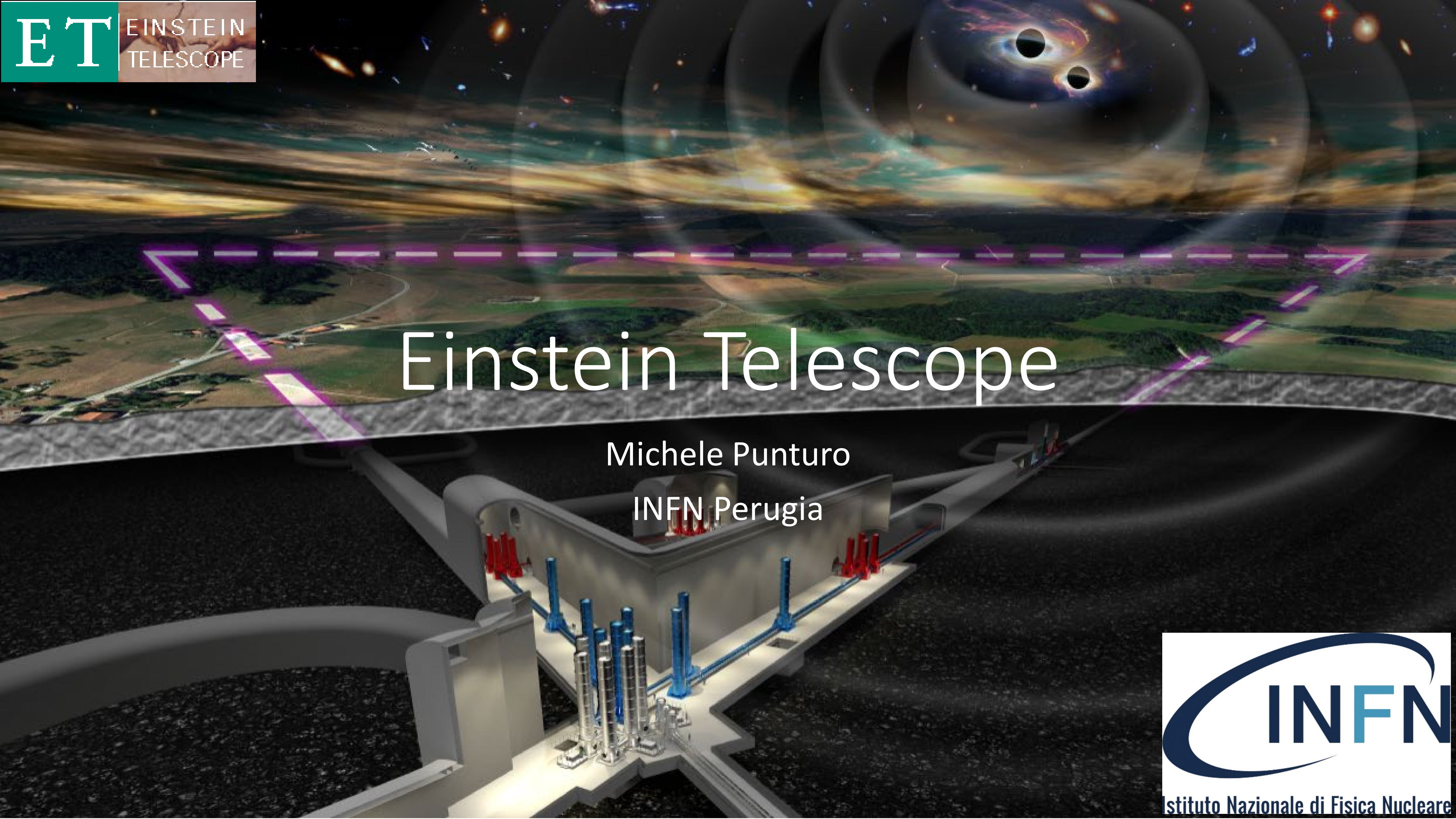


Einstein Telescope

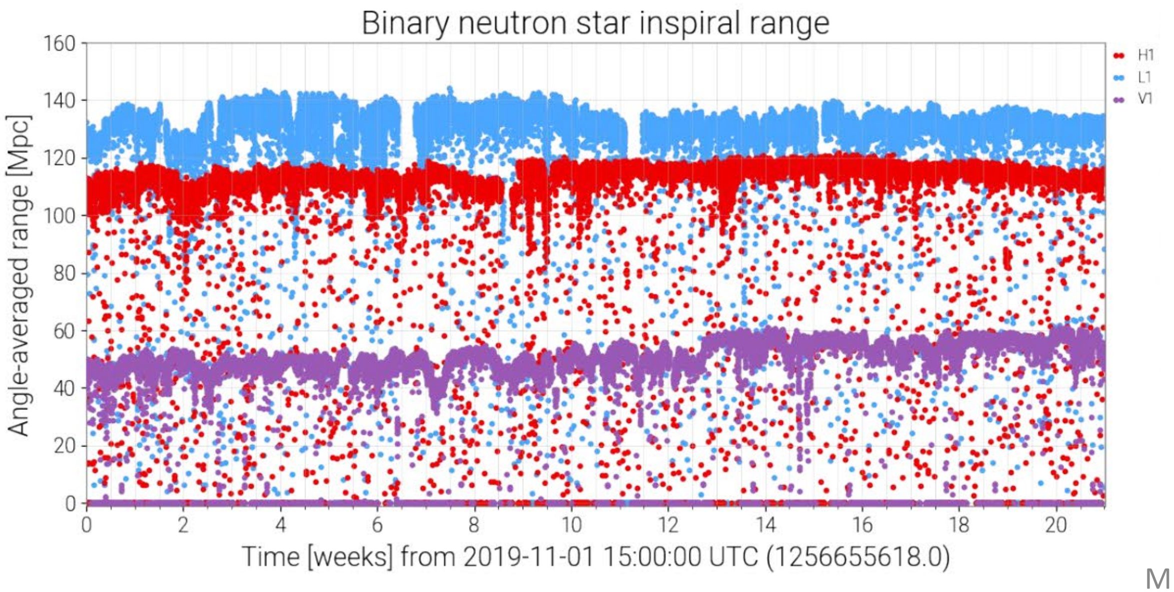
Michele Punturo

INFN Perugia

Let start from the Advanced detectors

LIGO/Virgo O3 Run

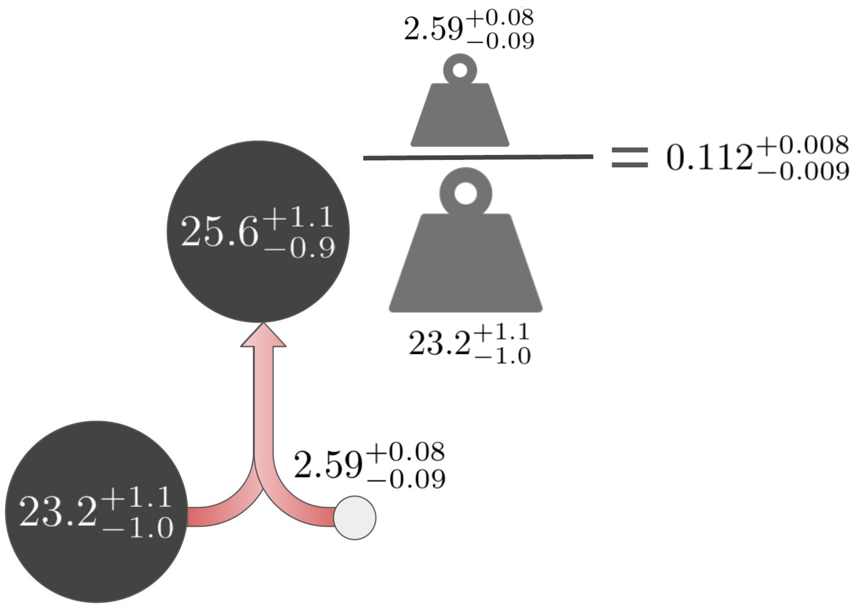
- 11 months of data taking
- 56 public alerts
- 39 candidates published in the O3a catalogue

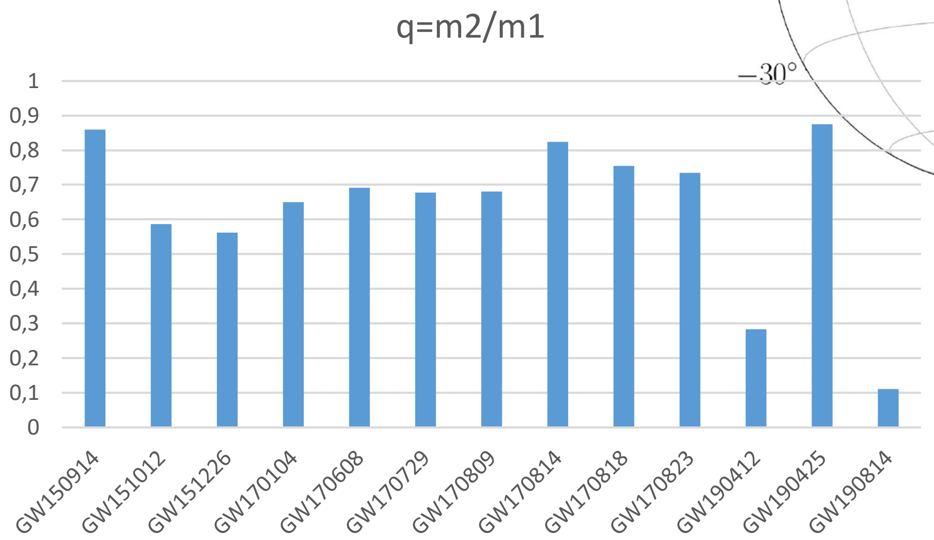


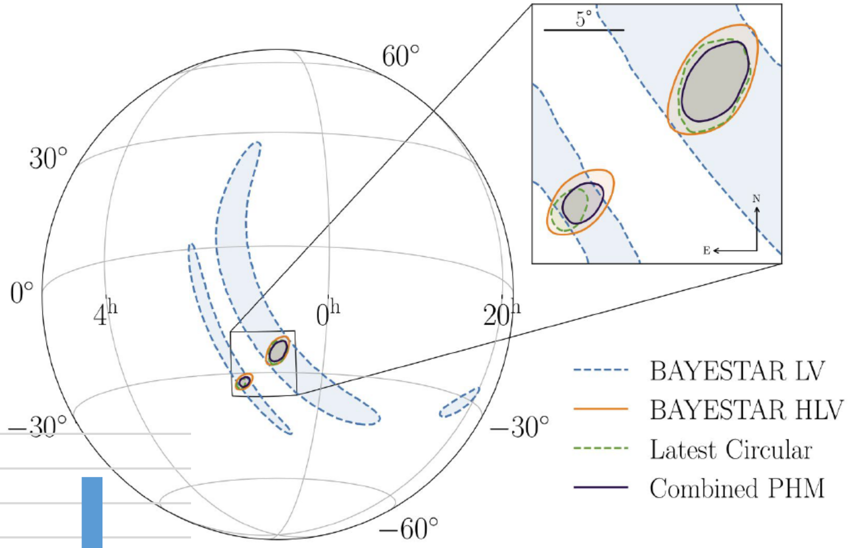
Event	M ($M_\odot$)	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	$\chi_{\rm eff}$	$D_{\rm L}$ (Gpc)	z	$M_{\rm f}$ ($M_\odot$)	$\chi_{\rm f}$	$\Delta\Omega$ (deg^2)	SNR
GW190408_181802	$43.0^{+4.2}_{-3.0}$	$18.3^{+1.9}_{-1.2}$	$24.6^{+5.1}_{-3.4}$	$18.4^{+3.3}_{-3.6}$	$-0.03^{+0.14}_{-0.19}$	$1.55^{+0.40}_{-0.60}$	$0.29^{+0.06}_{-0.10}$	$41.1^{+3.9}_{-2.8}$	$0.67^{+0.06}_{-0.07}$	150	$15.3^{+0.2}_{-0.3}$
GW190412	$38.4^{+3.8}_{-3.7}$	$13.3^{+0.4}_{-0.3}$	$30.1^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$0.25^{+0.08}_{-0.11}$	$0.74^{+0.14}_{-0.17}$	$0.15^{+0.03}_{-0.03}$	$37.3^{+3.9}_{-3.8}$	$0.67^{+0.05}_{-0.06}$	21	$18.9^{+0.2}_{-0.3}$
GW190413_052954	$58.6^{+13.3}_{-9.7}$	$24.6^{+5.5}_{-4.1}$	$34.7^{+12.6}_{-8.1}$	$23.7^{+7.3}_{-6.7}$	$-0.01^{+0.29}_{-0.34}$	$3.55^{+2.27}_{-1.66}$	$0.59^{+0.29}_{-0.24}$	$56.0^{+12.5}_{-9.2}$	$0.68^{+0.12}_{-0.13}$	1500	$8.9^{+0.4}_{-0.7}$
GW190413_134308	$78.8^{+17.4}_{-11.9}$	$33.0^{+8.2}_{-5.4}$	$47.5^{+13.5}_{-10.7}$	$31.8^{+11.7}_{-10.8}$	$-0.03^{+0.25}_{-0.29}$	$4.45^{+2.48}_{-2.12}$	$0.71^{+0.31}_{-0.30}$	$75.5^{+16.4}_{-11.4}$	$0.68^{+0.10}_{-0.12}$	730	$10.0^{+0.4}_{-0.5}$
GW190421_213856	$72.9^{+13.4}_{-9.2}$	$31.2^{+5.9}_{-4.2}$	$41.3^{+10.4}_{-6.9}$	$31.9^{+8.0}_{-8.8}$	$-0.06^{+0.22}_{-0.27}$	$2.88^{+1.37}_{-1.38}$	$0.49^{+0.19}_{-0.21}$	$69.7^{+12.5}_{-8.7}$	$0.67^{+0.10}_{-0.11}$	1200	$10.7^{+0.2}_{-0.4}$
GW190424_180648	$72.6^{+13.3}_{-10.7}$	$31.0^{+5.8}_{-4.6}$	$40.5^{+11.1}_{-7.3}$	$31.8^{+7.6}_{-7.7}$	$0.13^{+0.22}_{-0.22}$	$2.20^{+1.58}_{-1.16}$	$0.39^{+0.23}_{-0.19}$	$68.9^{+12.4}_{-10.1}$	$0.74^{+0.09}_{-0.09}$	28000	$10.4^{+0.2}_{-0.4}$
GW190425	$3.4^{+0.3}_{-0.1}$	$1.44^{+0.02}_{-0.02}$	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	$0.06^{+0.11}_{-0.05}$	$0.16^{+0.07}_{-0.07}$	$0.03^{+0.01}_{-0.02}$	–	–	10000	$12.4^{+0.3}_{-0.4}$
GW190426_152155	$7.2^{+3.5}_{-1.5}$	$2.41^{+0.08}_{-0.08}$	$5.7^{+3.9}_{-2.3}$	$1.5^{+0.8}_{-0.5}$	$-0.03^{+0.32}_{-0.30}$	$0.37^{+0.18}_{-0.16}$	$0.08^{+0.04}_{-0.03}$	–	–	1300	$8.7^{+0.5}_{-0.6}$
GW190503_185404	$71.7^{+9.4}_{-8.3}$	$30.2^{+4.2}_{-4.2}$	$43.3^{+9.2}_{-8.1}$	$28.4^{+7.7}_{-8.0}$	$-0.03^{+0.20}_{-0.26}$	$1.45^{+0.69}_{-0.63}$	$0.27^{+0.11}_{-0.11}$	$68.6^{+8.8}_{-7.7}$	$0.66^{+0.09}_{-0.12}$	94	$12.4^{+0.2}_{-0.3}$
GW190512_180714	$35.9^{+3.8}_{-3.5}$	$14.6^{+1.3}_{-1.0}$	$23.3^{+5.3}_{-5.8}$	$12.6^{+3.6}_{-2.5}$	$0.03^{+0.12}_{-0.13}$	$1.43^{+0.55}_{-0.55}$	$0.27^{+0.09}_{-0.10}$	$34.5^{+3.8}_{-3.5}$	$0.65^{+0.07}_{-0.07}$	220	$12.2^{+0.2}_{-0.4}$
GW190513_205428	$53.9^{+8.6}_{-5.9}$	$21.6^{+3.8}_{-1.9}$	$35.7^{+9.5}_{-9.2}$	$18.0^{+7.7}_{-4.1}$	$0.11^{+0.28}_{-0.17}$	$2.06^{+0.88}_{-0.80}$	$0.37^{+0.13}_{-0.13}$	$51.6^{+8.2}_{-5.8}$	$0.68^{+0.14}_{-0.12}$	520	$12.9^{+0.3}_{-0.4}$
GW190514_065416	$67.2^{+18.7}_{-10.8}$	$28.5^{+7.9}_{-4.8}$	$39.0^{+14.7}_{-8.2}$	$28.4^{+9.3}_{-8.8}$	$-0.19^{+0.29}_{-0.32}$	$4.13^{+2.65}_{-2.17}$	$0.67^{+0.33}_{-0.31}$	$64.5^{+17.9}_{-10.4}$	$0.63^{+0.11}_{-0.15}$	3000	$8.2^{+0.3}_{-0.6}$
GW190517_055101	$63.5^{+9.6}_{-9.6}$	$26.6^{+4.0}_{-4.0}$	$37.4^{+11.7}_{-7.6}$	$25.3^{+7.0}_{-7.3}$	$0.52^{+0.19}_{-0.19}$	$1.86^{+1.62}_{-0.84}$	$0.34^{+0.24}_{-0.14}$	$59.3^{+9.1}_{-8.9}$	$0.87^{+0.05}_{-0.07}$	470	$10.7^{+0.4}_{-0.6}$
GW190519_153544	$106.6^{+13.5}_{-14.8}$	$44.5^{+6.4}_{-7.1}$	$66.0^{+10.7}_{-12.0}$	$40.5^{+11.0}_{-11.1}$	$0.31^{+0.20}_{-0.22}$	$2.53^{+1.83}_{-0.92}$	$0.44^{+0.25}_{-0.14}$	$101.0^{+12.4}_{-13.8}$	$0.79^{+0.07}_{-0.13}$	860	$15.6^{+0.2}_{-0.3}$
GW190521	$163.9^{+39.2}_{-23.5}$	$69.2^{+17.0}_{-10.6}$	$95.3^{+28.7}_{-18.9}$	$69.0^{+22.7}_{-23.1}$	$0.03^{+0.32}_{-0.39}$	$3.92^{+2.19}_{-1.95}$	$0.64^{+0.28}_{-0.28}$	$156.3^{+36.8}_{-22.4}$	$0.71^{+0.12}_{-0.16}$	1000	$14.2^{+0.3}_{-0.3}$
GW190521_074359	$74.7^{+7.0}_{-4.8}$	$32.1^{+3.2}_{-2.5}$	$42.2^{+5.9}_{-4.8}$	$32.8^{+5.4}_{-6.4}$	$0.09^{+0.10}_{-0.13}$	$1.24^{+0.40}_{-0.57}$	$0.24^{+0.07}_{-0.10}$	$71.0^{+6.5}_{-4.4}$	$0.72^{+0.05}_{-0.07}$	550	$25.8^{+0.1}_{-0.2}$
GW190527_092055	$59.1^{+21.3}_{-9.8}$	$24.3^{+9.1}_{-4.2}$	$36.5^{+16.4}_{-9.0}$	$22.6^{+10.5}_{-8.1}$	$0.11^{+0.28}_{-0.28}$	$2.49^{+2.48}_{-1.24}$	$0.44^{+0.34}_{-0.20}$	$56.4^{+20.2}_{-9.3}$	$0.71^{+0.12}_{-0.16}$	3700	$8.1^{+0.3}_{-0.9}$
GW190602_175927	$116.3^{+19.0}_{-15.6}$	$49.1^{+9.1}_{-8.5}$	$69.1^{+15.7}_{-13.0}$	$47.8^{+14.3}_{-17.4}$	$0.07^{+0.25}_{-0.24}$	$2.69^{+1.79}_{-1.12}$	$0.47^{+0.25}_{-0.17}$	$110.9^{+17.7}_{-14.9}$	$0.70^{+0.10}_{-0.14}$	690	$12.8^{+0.2}_{-0.3}$
GW190620_030421	$92.1^{+18.5}_{-13.1}$	$38.3^{+8.3}_{-6.5}$	$57.1^{+16.0}_{-12.7}$	$35.5^{+12.2}_{-12.3}$	$0.33^{+0.22}_{-0.25}$	$2.81^{+1.68}_{-1.31}$	$0.49^{+0.23}_{-0.20}$	$87.2^{+16.8}_{-12.1}$	$0.79^{+0.08}_{-0.15}$	7200	$12.1^{+0.3}_{-0.4}$
GW190630_185205	$59.1^{+4.6}_{-4.8}$	$24.9^{+2.1}_{-2.1}$	$35.1^{+6.9}_{-5.6}$	$23.7^{+5.2}_{-5.1}$	$0.10^{+0.12}_{-0.13}$	$0.89^{+0.56}_{-0.37}$	$0.18^{+0.10}_{-0.07}$	$56.4^{+4.4}_{-4.6}$	$0.70^{+0.05}_{-0.07}$	1200	$15.6^{+0.2}_{-0.3}$
GW190701_203306	$94.3^{+12.1}_{-9.5}$	$40.3^{+5.4}_{-4.9}$	$53.9^{+11.8}_{-8.0}$	$40.8^{+8.7}_{-12.0}$	$-0.07^{+0.23}_{-0.29}$	$2.06^{+0.76}_{-0.73}$	$0.37^{+0.11}_{-0.12}$	$90.2^{+11.3}_{-8.9}$	$0.66^{+0.09}_{-0.13}$	46	$11.3^{+0.2}_{-0.3}$
GW190706_222641	$104.1^{+20.2}_{-13.9}$	$42.7^{+10.0}_{-7.0}$	$67.0^{+14.6}_{-16.2}$	$38.2^{+14.6}_{-13.3}$	$0.28^{+0.26}_{-0.29}$	$4.42^{+2.59}_{-1.93}$	$0.71^{+0.32}_{-0.27}$	$99.0^{+18.3}_{-13.5}$	$0.78^{+0.09}_{-0.18}$	650	$12.6^{+0.2}_{-0.4}$
GW190707_093326	$20.1^{+1.9}_{-1.3}$	$8.5^{+0.6}_{-0.5}$	$11.6^{+3.3}_{-1.7}$	$8.4^{+1.4}_{-1.7}$	$-0.05^{+0.10}_{-0.08}$	$0.77^{+0.38}_{-0.37}$	$0.16^{+0.07}_{-0.07}$	$19.2^{+1.9}_{-1.3}$	$0.66^{+0.03}_{-0.04}$	1300	$13.3^{+0.2}_{-0.4}$
GW190708_232457	$30.9^{+2.5}_{-1.8}$	$13.2^{+0.9}_{-0.6}$	$17.6^{+4.7}_{-2.3}$	$13.2^{+2.0}_{-2.7}$	$0.02^{+0.10}_{-0.08}$	$0.88^{+0.33}_{-0.39}$	$0.18^{+0.06}_{-0.07}$	$29.5^{+2.5}_{-1.8}$	$0.69^{+0.04}_{-0.04}$	14000	$13.1^{+0.2}_{-0.3}$
GW190719_215514	$57.8^{+18.3}_{-10.7}$	$23.5^{+6.5}_{-4.0}$	$36.5^{+18.0}_{-10.3}$	$20.8^{+9.0}_{-7.2}$	$0.32^{+0.29}_{-0.31}$	$3.94^{+2.59}_{-2.00}$	$0.64^{+0.33}_{-0.29}$	$54.9^{+17.3}_{-10.2}$	$0.78^{+0.11}_{-0.17}$	2900	$8.3^{+0.3}_{-0.8}$
GW190720_000836	$21.5^{+4.3}_{-2.3}$	$8.9^{+0.5}_{-0.8}$	$13.4^{+6.7}_{-3.0}$	$7.8^{+2.3}_{-2.2}$	$0.18^{+0.14}_{-0.12}$	$0.79^{+0.69}_{-0.32}$	$0.16^{+0.12}_{-0.06}$	$20.4^{+4.5}_{-2.2}$	$0.72^{+0.06}_{-0.05}$	460	$11.0^{+0.3}_{-0.7}$
GW190727_060333	$67.1^{+11.7}_{-8.0}$	$28.6^{+5.3}_{-3.7}$	$38.0^{+9.5}_{-6.2}$	$29.4^{+7.1}_{-8.4}$	$0.11^{+0.26}_{-0.25}$	$3.30^{+1.54}_{-1.50}$	$0.55^{+0.21}_{-0.22}$	$63.8^{+10.9}_{-7.5}$	$0.73^{+0.10}_{-0.10}$	830	$11.9^{+0.3}_{-0.5}$
GW190728_064510	$20.6^{+4.5}_{-1.3}$	$8.6^{+0.5}_{-0.3}$	$12.3^{+7.2}_{-2.2}$	$8.1^{+1.7}_{-2.6}$	$0.12^{+0.20}_{-0.07}$	$0.87^{+0.26}_{-0.37}$	$0.18^{+0.05}_{-0.07}$	$19.6^{+4.7}_{-1.3}$	$0.71^{+0.04}_{-0.04}$	400	$13.0^{+0.2}_{-0.4}$
GW190731_140936	$70.1^{+15.8}_{-11.3}$	$29.5^{+7.1}_{-5.2}$	$41.5^{+12.2}_{-9.0}$	$28.8^{+9.7}_{-9.5}$	$0.06^{+0.24}_{-0.24}$	$3.30^{+2.39}_{-1.72}$	$0.55^{+0.31}_{-0.26}$	$67.0^{+14.6}_{-10.8}$	$0.70^{+0.10}_{-0.13}$	3400	$8.7^{+0.2}_{-0.5}$
GW190803_022701	$64.5^{+12.6}_{-9.0}$	$27.3^{+5.7}_{-4.1}$	$37.3^{+10.6}_{-7.0}$	$27.3^{+7.8}_{-8.2}$	$-0.03^{+0.24}_{-0.27}$	$3.27^{+1.95}_{-1.58}$	$0.55^{+0.26}_{-0.24}$	$61.7^{+11.8}_{-8.5}$	$0.68^{+0.10}_{-0.11}$	1500	$8.6^{+0.3}_{-0.5}$
GW190814	$25.8^{+1.0}_{-0.9}$	$6.09^{+0.06}_{-0.06}$	$23.2^{+1.1}_{-1.0}$	$2.59^{+0.08}_{-0.09}$	$0.00^{+0.06}_{-0.06}$	$0.24^{+0.04}_{-0.05}$	$0.05^{+0.009}_{-0.010}$	$25.6^{+1.1}_{-0.9}$	$0.28^{+0.02}_{-0.02}$	19	$24.9^{+0.1}_{-0.2}$
GW190828_063405	$58.0^{+7.7}_{-4.8}$	$25.0^{+3.4}_{-2.1}$	$32.1^{+5.8}_{-4.0}$	$26.2^{+4.6}_{-4.8}$	$0.19^{+0.15}_{-0.16}$	$2.13^{+0.66}_{-0.93}$	$0.38^{+0.10}_{-0.15}$	$54.9^{+7.2}_{-4.3}$	$0.75^{+0.06}_{-0.07}$	520	$16.2^{+0.2}_{-0.3}$
GW190828_065509	$34.4^{+5.4}_{-4.4}$	$13.3^{+1.2}_{-1.0}$	$24.1^{+7.0}_{-7.2}$	$10.2^{+3.6}_{-2.1}$	$0.08^{+0.16}_{-0.16}$	$1.60^{+0.62}_{-0.60}$	$0.30^{+0.10}_{-0.10}$	$33.1^{+5.5}_{-4.5}$	$0.65^{+0.08}_{-0.08}$	660	$10.0^{+0.3}_{-0.5}$
GW190909_114149	$75.0^{+55.9}_{-17.6}$	$30.9^{+17.2}_{-7.5}$	$45.8^{+52.7}_{-13.3}$	$28.3^{+13.4}_{-12.7}$	$-0.06^{+0.37}_{-0.36}$	$3.77^{+3.27}_{-2.22}$	$0.62^{+0.41}_{-0.33}$	$72.0^{+54.9}_{-16.8}$	$0.66^{+0.15}_{-0.20}$	4700	$8.1^{+0.4}_{-0.6}$
GW190910_112807	$79.6^{+9.3}_{-9.1}$	$34.3^{+4.1}_{-4.1}$	$43.9^{+7.6}_{-6.1}$	$35.6^{+6.3}_{-7.2}$	$0.02^{+0.18}_{-0.18}$	$1.46^{+1.03}_{-0.58}$	$0.28^{+0.16}_{-0.10}$	$75.8^{+8.5}_{-8.6}$	$0.70^{+0.08}_{-0.07}$	11000	$14.1^{+0.2}_{-0.3}$
GW190915_235702	$59.9^{+7.5}_{-6.4}$	$25.3^{+3.2}_{-2.7}$	$35.3^{+9.5}_{-6.4}$	$24.4^{+5.6}_{-6.1}$	$0.02^{+0.20}_{-0.25}$	$1.62^{+0.71}_{-0.61}$	$0.30^{+0.11}_{-0.10}$	$57.2^{+7.1}_{-6.0}$	$0.70^{+0.09}_{-0.11}$	400	$13.6^{+0.2}_{-0.3}$
GW190924_021846	$13.9^{+5.1}_{-1.0}$	$5.8^{+0.2}_{-0.2}$	$8.9^{+7.0}_{-2.0}$	$5.0^{+1.4}_{-1.9}$	$0.03^{+0.30}_{-0.09}$	$0.57^{+0.22}_{-0.22}$	$0.12^{+0.04}_{-0.04}$	$13.3^{+5.2}_{-1.0}$	$0.67^{+0.05}_{-0.05}$	360	$11.5^{+0.3}_{-0.4}$
GW190929_012149	$104.3^{+34.9}_{-25.2}$	$35.8^{+14.9}_{-8.2}$	$80.8^{+33.0}_{-33.2}$	$24.1^{+19.3}_{-10.6}$	$0.01^{+0.34}_{-0.33}$	$2.13^{+3.65}_{-1.05}$	$0.38^{+0.49}_{-0.17}$	$101.5^{+33.6}_{-25.3}$	$0.66^{+0.20}_{-0.31}$	2200	$10.1^{+0.6}_{-0.8}$
GW190930_133541	$20.3^{+8.9}_{-1.5}$	$8.5^{+0.5}_{-0.5}$	$12.3^{+12.4}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	$0.14^{+0.31}_{-0.15}$	$0.76^{+0.36}_{-0.32}$	$0.15^{+0.06}_{-0.06}$	$19.4^{+9.2}_{-1.5}$	$0.72^{+0.07}_{-0.06}$	1700	$9.5^{+0.3}_{-0.5}$

GW190814 – Loud event

- Detected online by Livingstone and Virgo, Hanford in commissioning mode, but undisturbed
  - Hanford data recovered offline
  - Best localised source (green skymap 23 deg^2)
  - The most mass asymmetric GW event detected

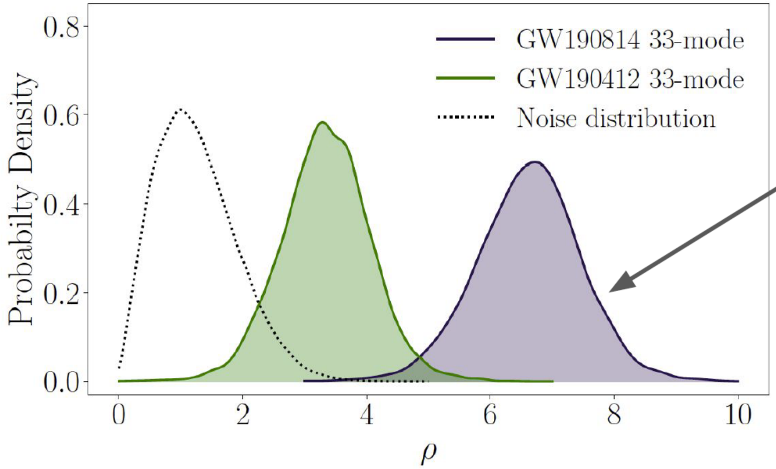




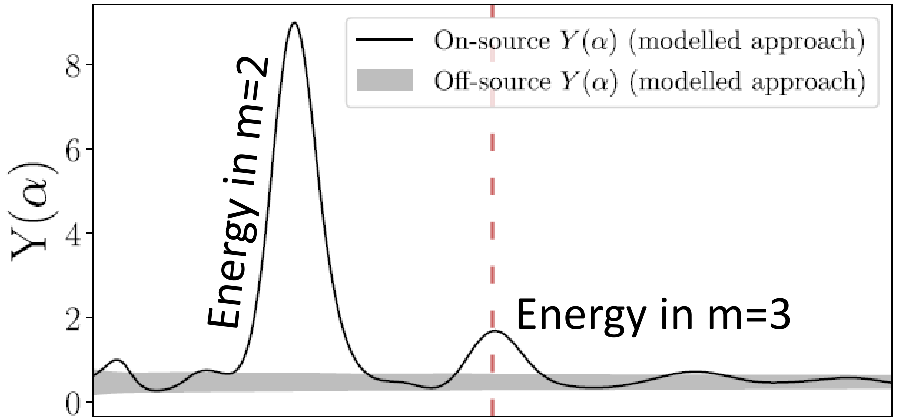


GW190814 – Higher order multipoles

- Being the mass distribution so asymmetric:

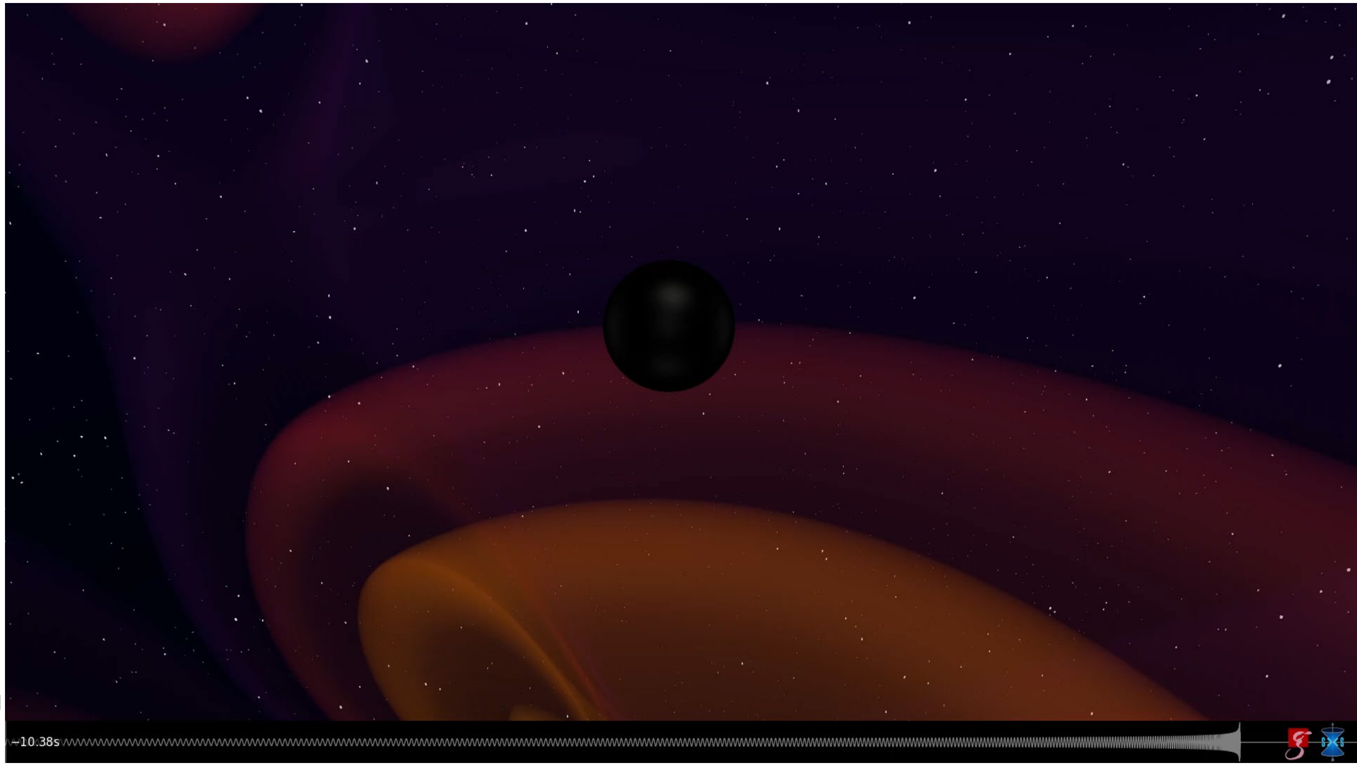


GW190814 has the strongest evidence for Higher order multiples that we have ever detected.



SNR in 33 multipole nearly as high as the total SNR of GW151012

- Test of GR on strongly asymmetric mass distribution (GR “validated”)

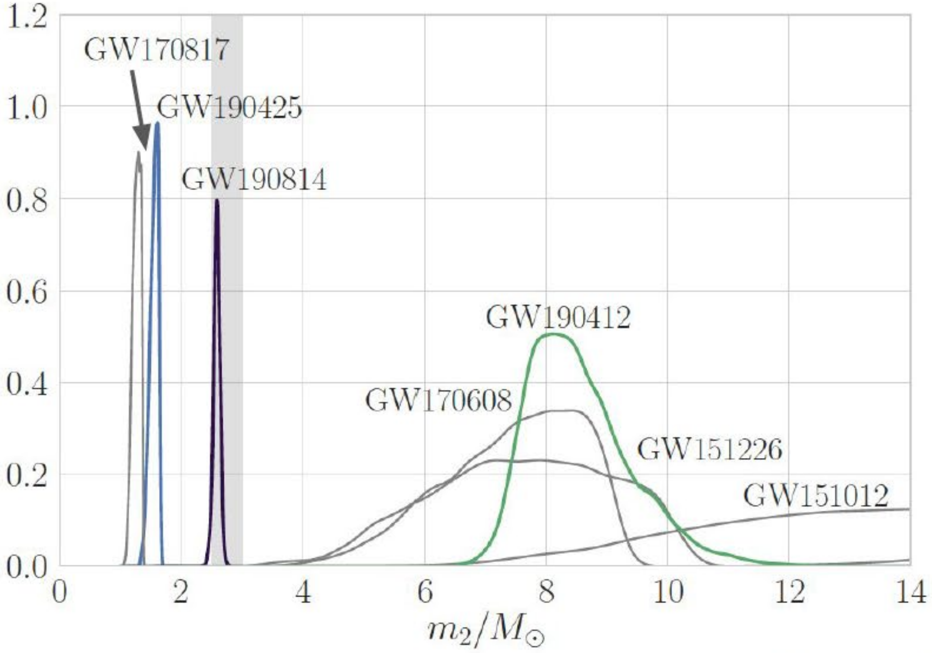


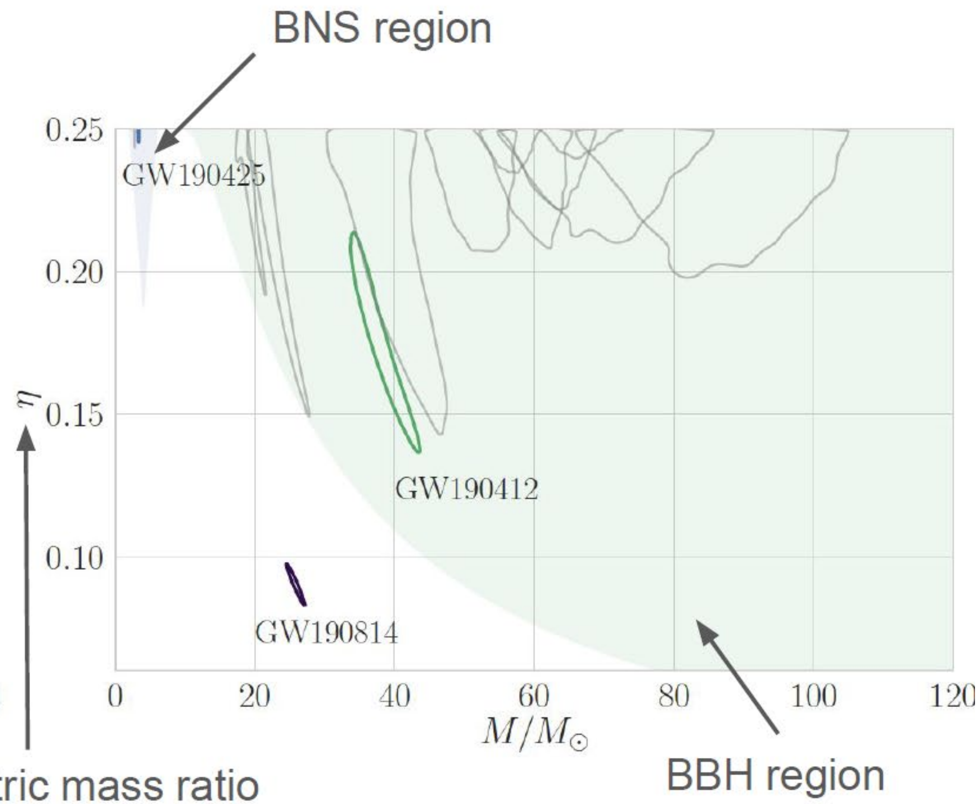
GW190814 - Cosmology with GW signal only

- The localisation of GW190814 is so good that it is possible to attempt a H_0 measurement only with GW signal (and galaxies catalogues):

GW190814 – New class of compact binary mergers

GW190814 - Source frame masses





Symmetric mass ratio

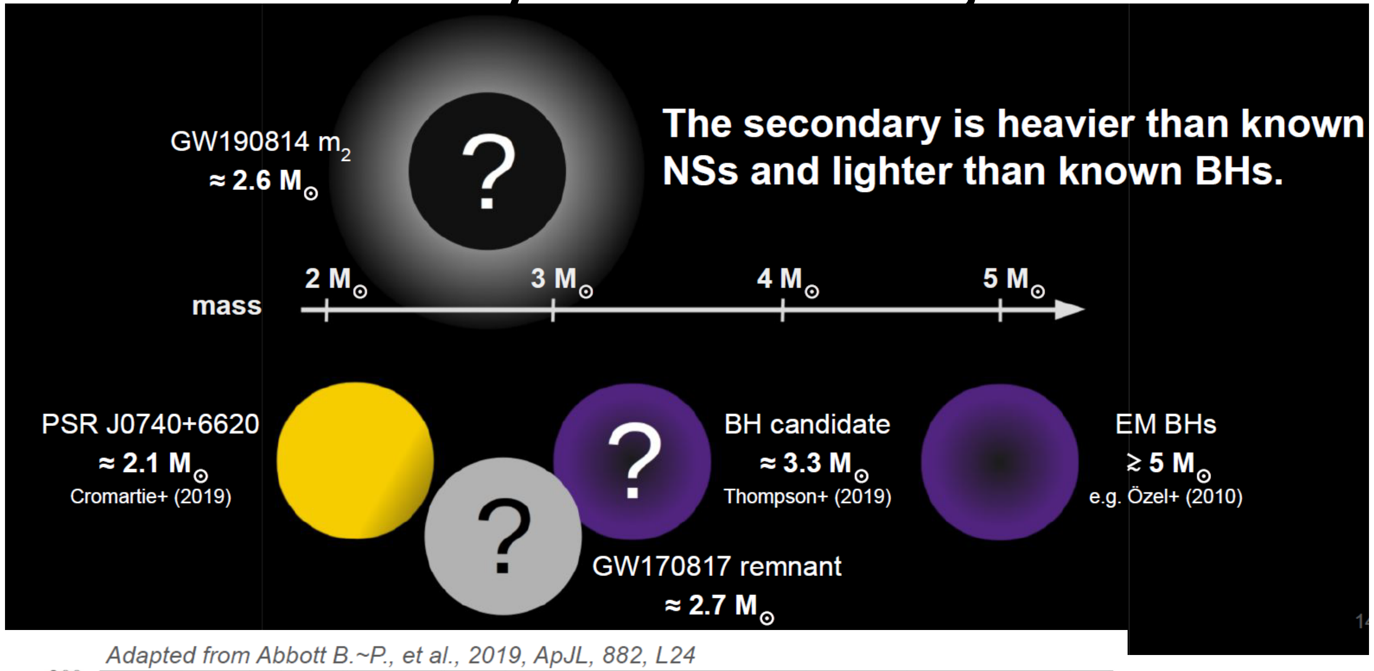
$$\eta \equiv \frac{m_1 m_2}{(m_1 + m_2)^2}$$

GWTC-1: LIGO Scientific Collaboration, and Virgo Collaboration (2019)
GW190425: LIGO Scientific Collaboration, and Virgo Collaboration (2020)
GW190412: LIGO Scientific Collaboration, and Virgo Collaboration (2020)

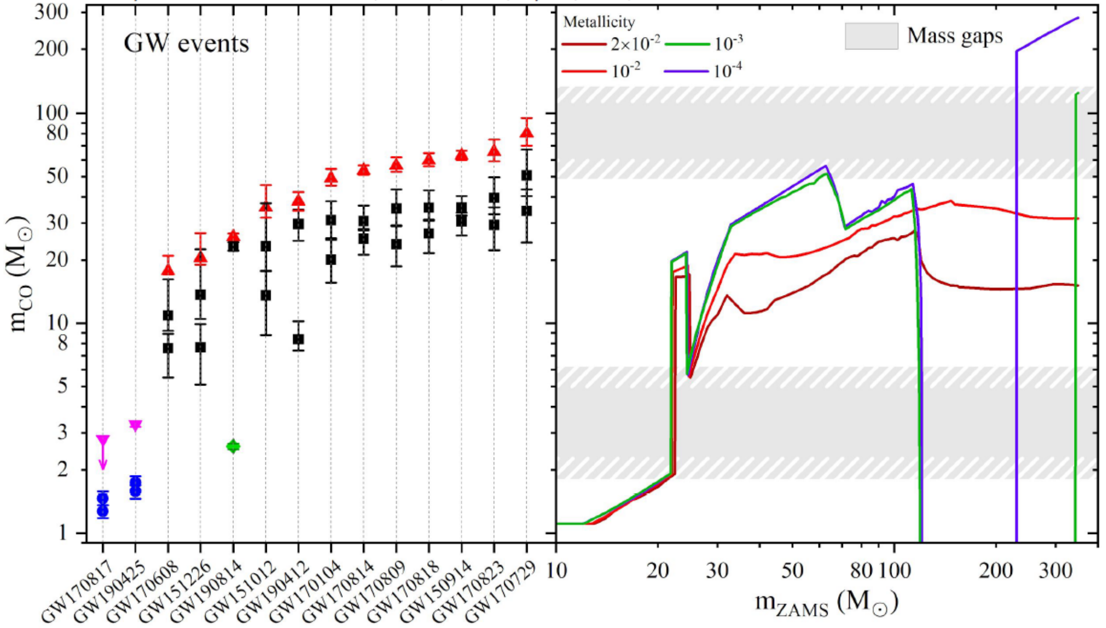
9

GW190814 - What is the secondary mass object?

- What is m_2?
- How is it formed?
  - Implications of the Supernova explosion mechanisms
- It is in the mass gap:
  - Implications on the existence of the lower mass gap

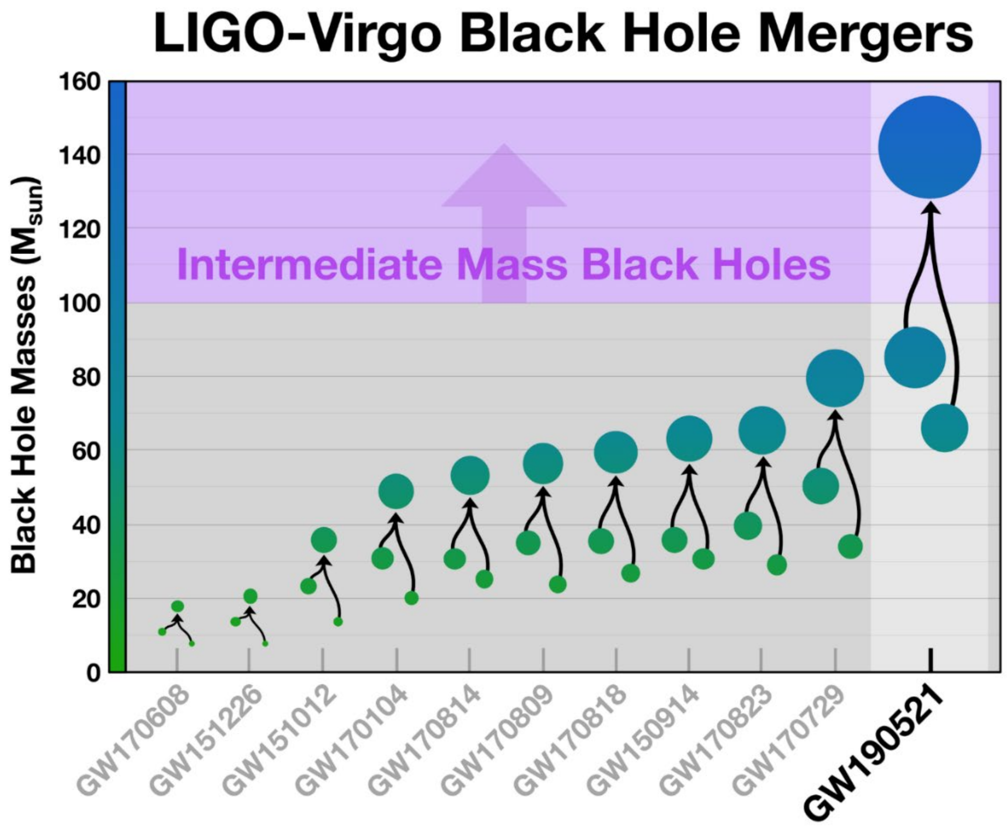


Adapted from Abbott B.~P., et al., 2019, ApJL, 882, L24



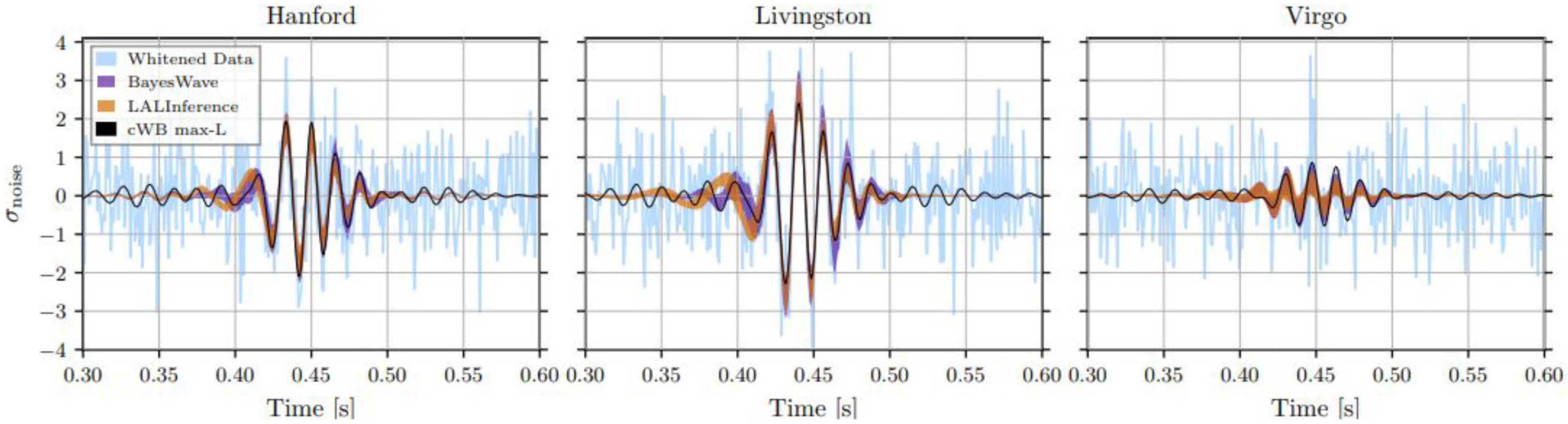
GW190521

$M_1 = 85^{+21}_{-14} M_\Theta$, $M_2 = 66^{+17}_{-18} M_\Theta$
at $z \sim 0.82$ (5.3Gpc)
Remnant $M_f = 142^{+28}_{-16} M_\Theta$



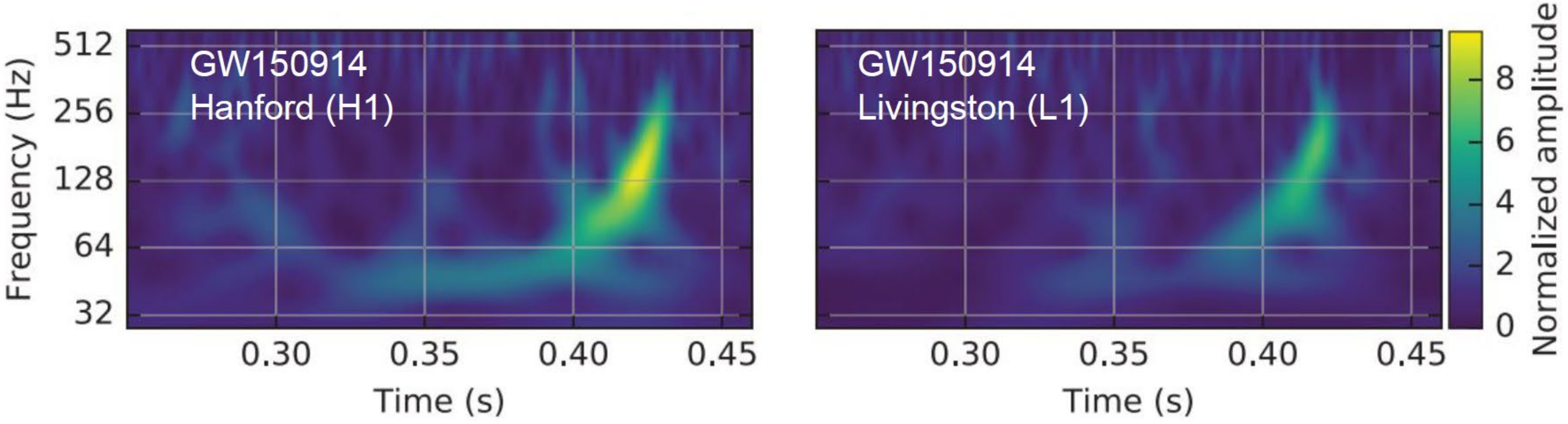
- Very special event:
  - M_1, the black hole that should not exist
  - M_f, the first IMBH ever seen

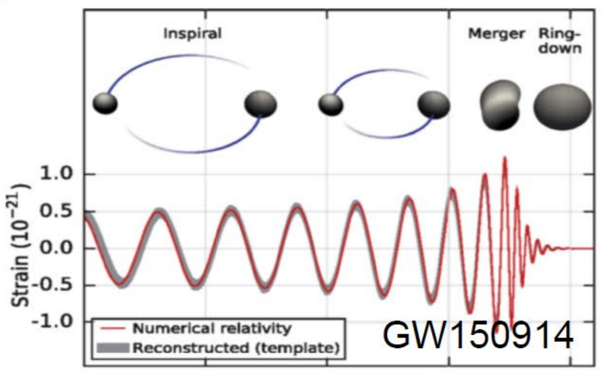
Phys. Rev. Lett. 125, 101102 (2020)
Astrophys. J. Lett. 900, L13 (2020)

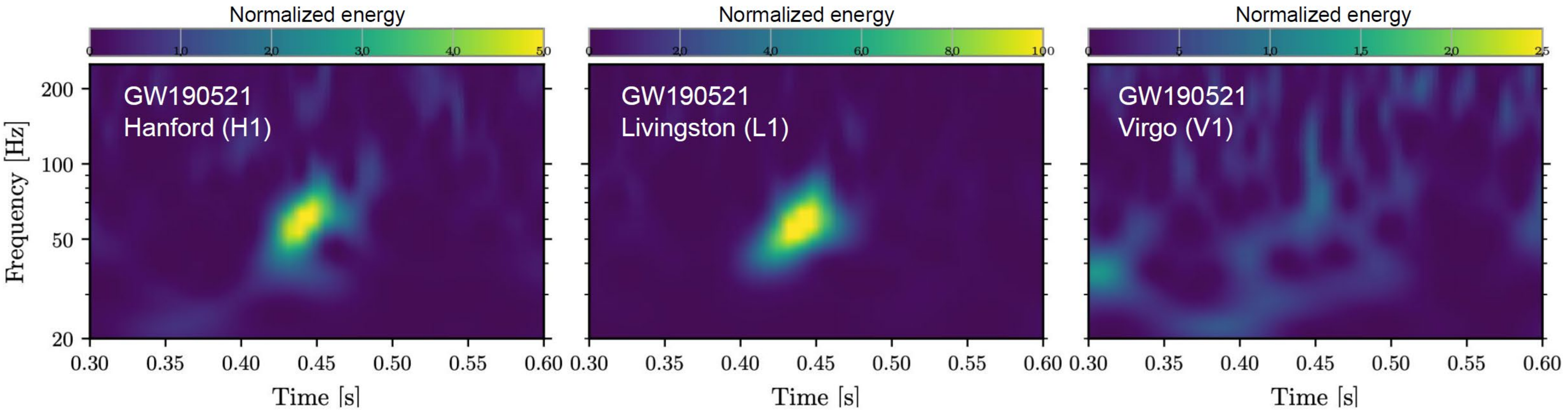


Where is the chirp?

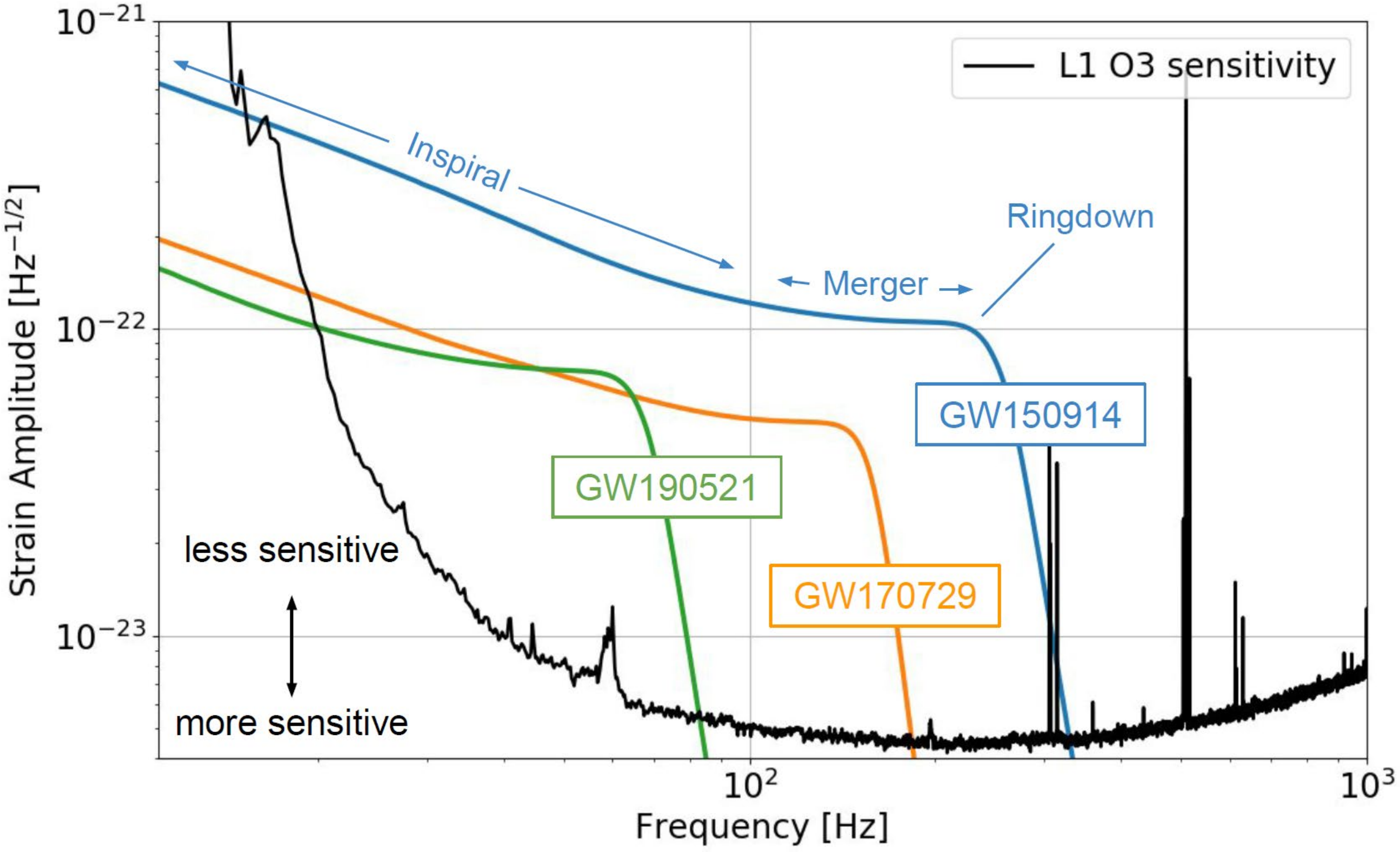
GW190521: signal morphology







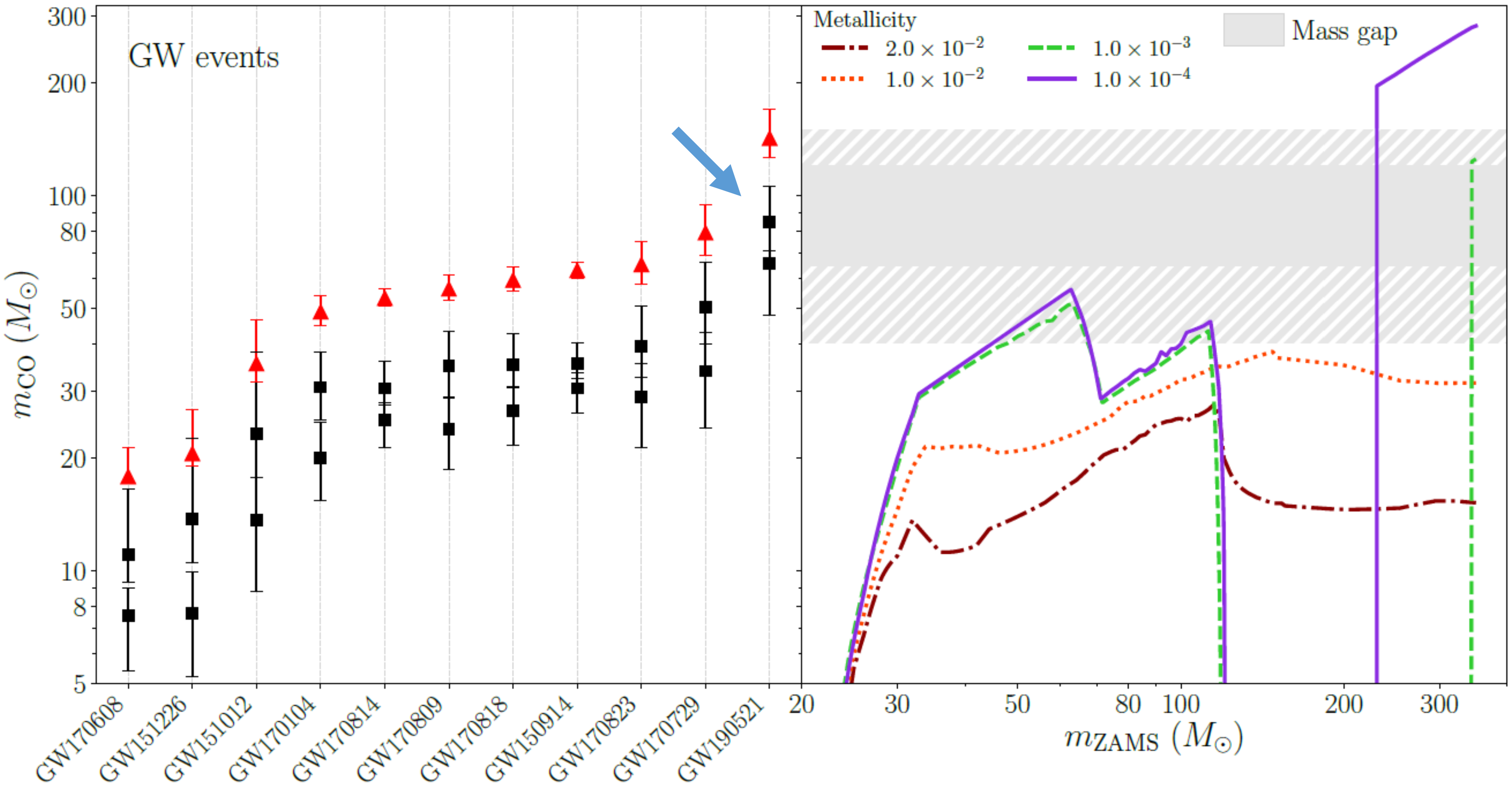
GW190521: LIGO-Virgo sensitivity to the BBH merger



- Higher masses correspond to lower frequency GW emission

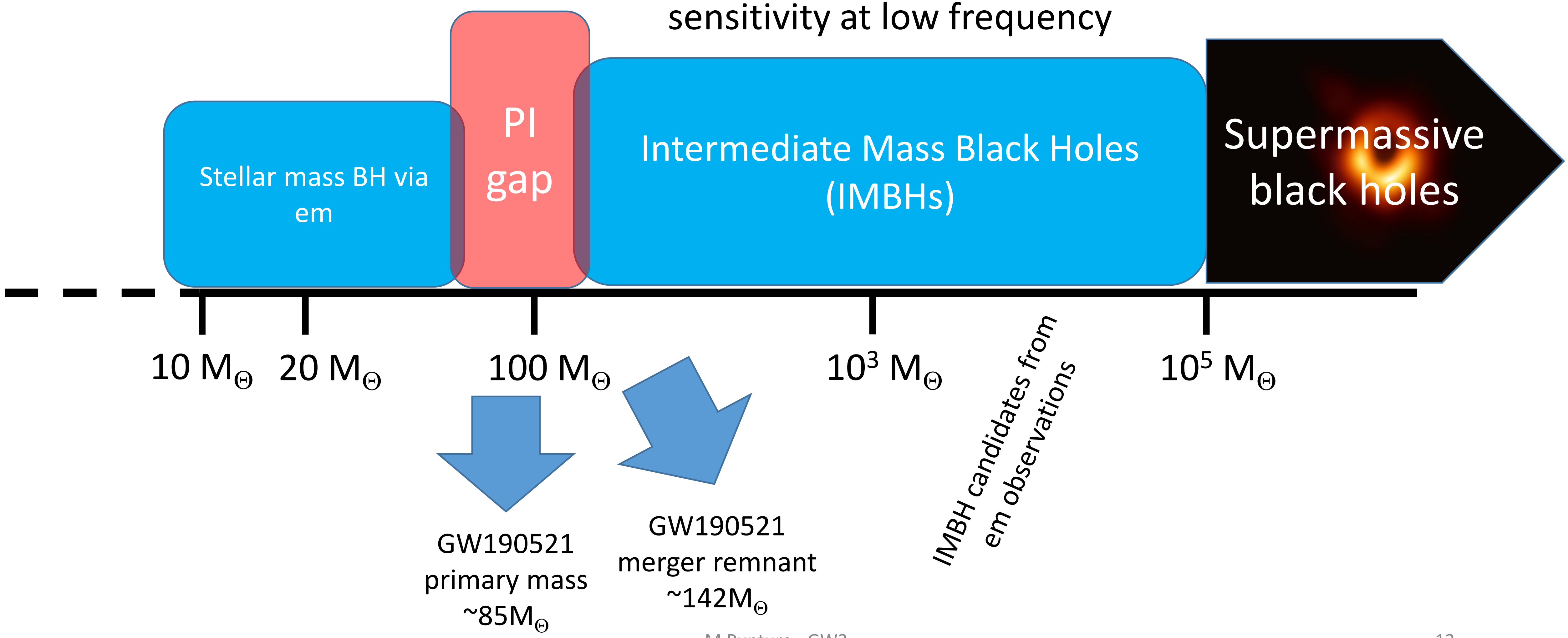
GW190521: M_1, what is that?

- M_1 has a mass of $M_1 = 85^{+21}_{-14} M_{\odot}$
  - It falls in the upper gap for black hole formation, due to Pair Instability (PI) and Pulsation Pair Instability (PPI)



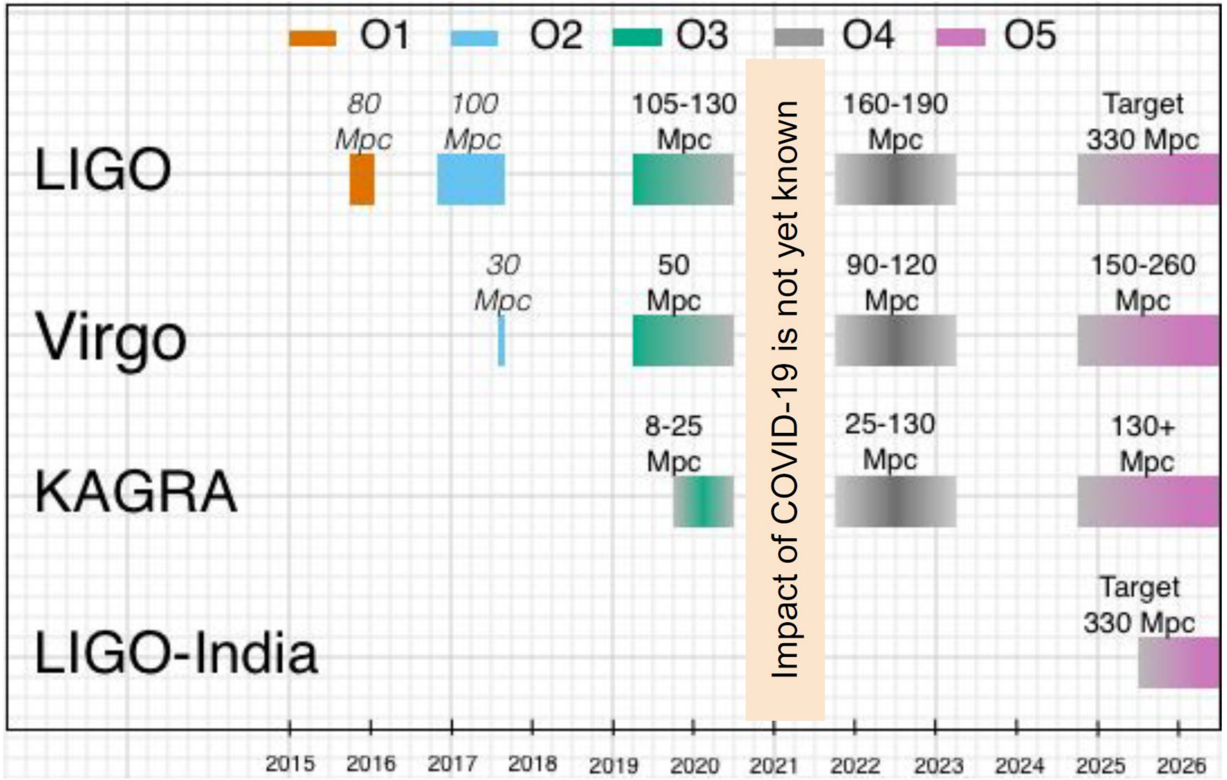
BH masses

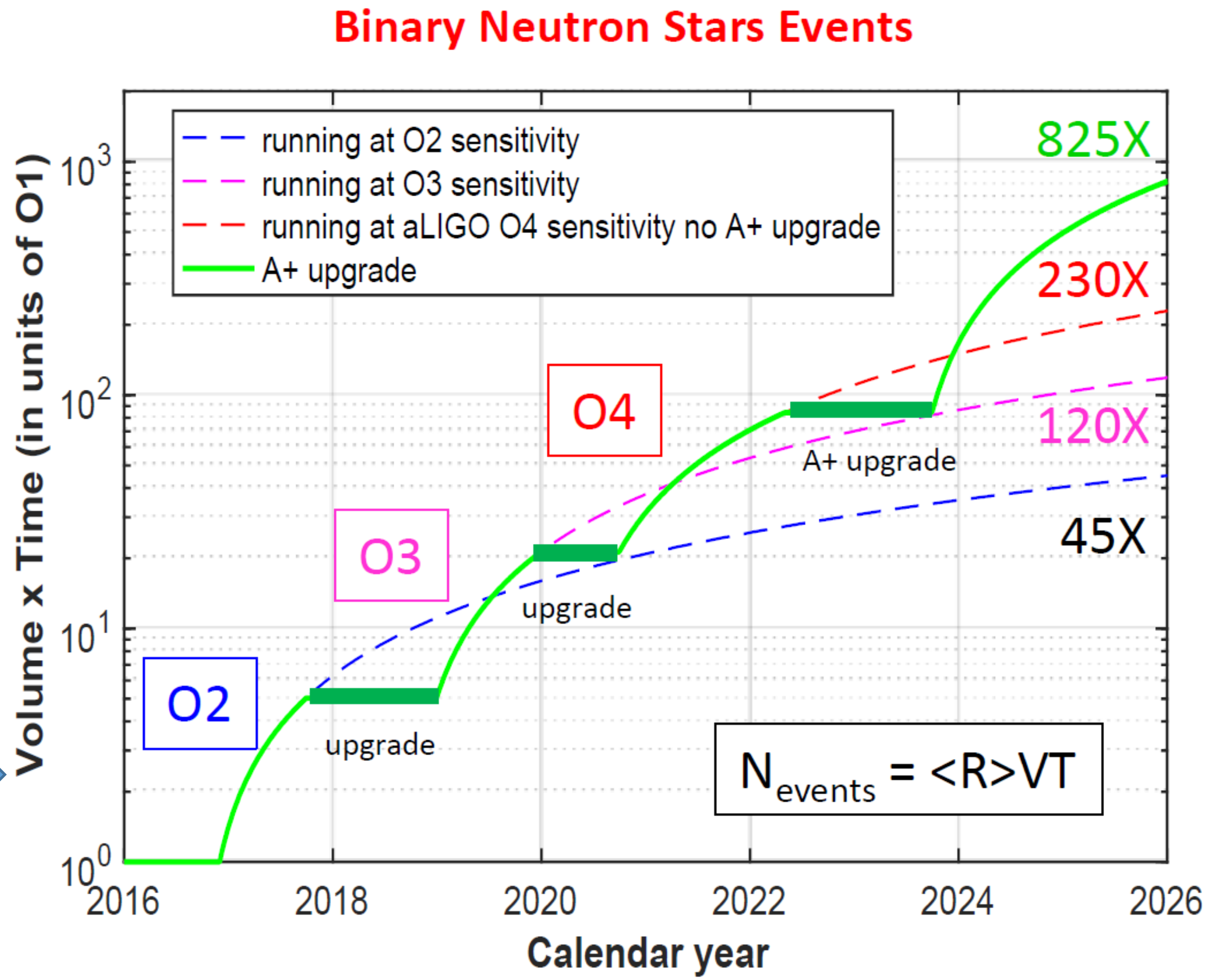
LIGO & Virgo will have marginal access to IMBH because of the "seismic wall" limiting the sensitivity at low frequency



Next Future

Plans for LIGO-KAGRA-Virgo runs





Luminosity $\mathcal{L}$

HEPP physicists?

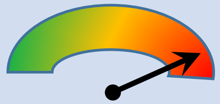
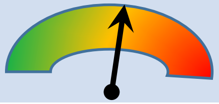
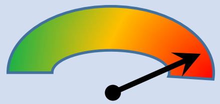
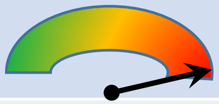
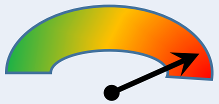
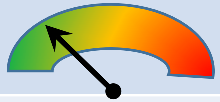
Branching ratio $\mathcal{R}$

- <R> average astrophysical rate
- V volume of the universe probed → (Range)^3
- T coincident observing time

What Next?

2029 outlook

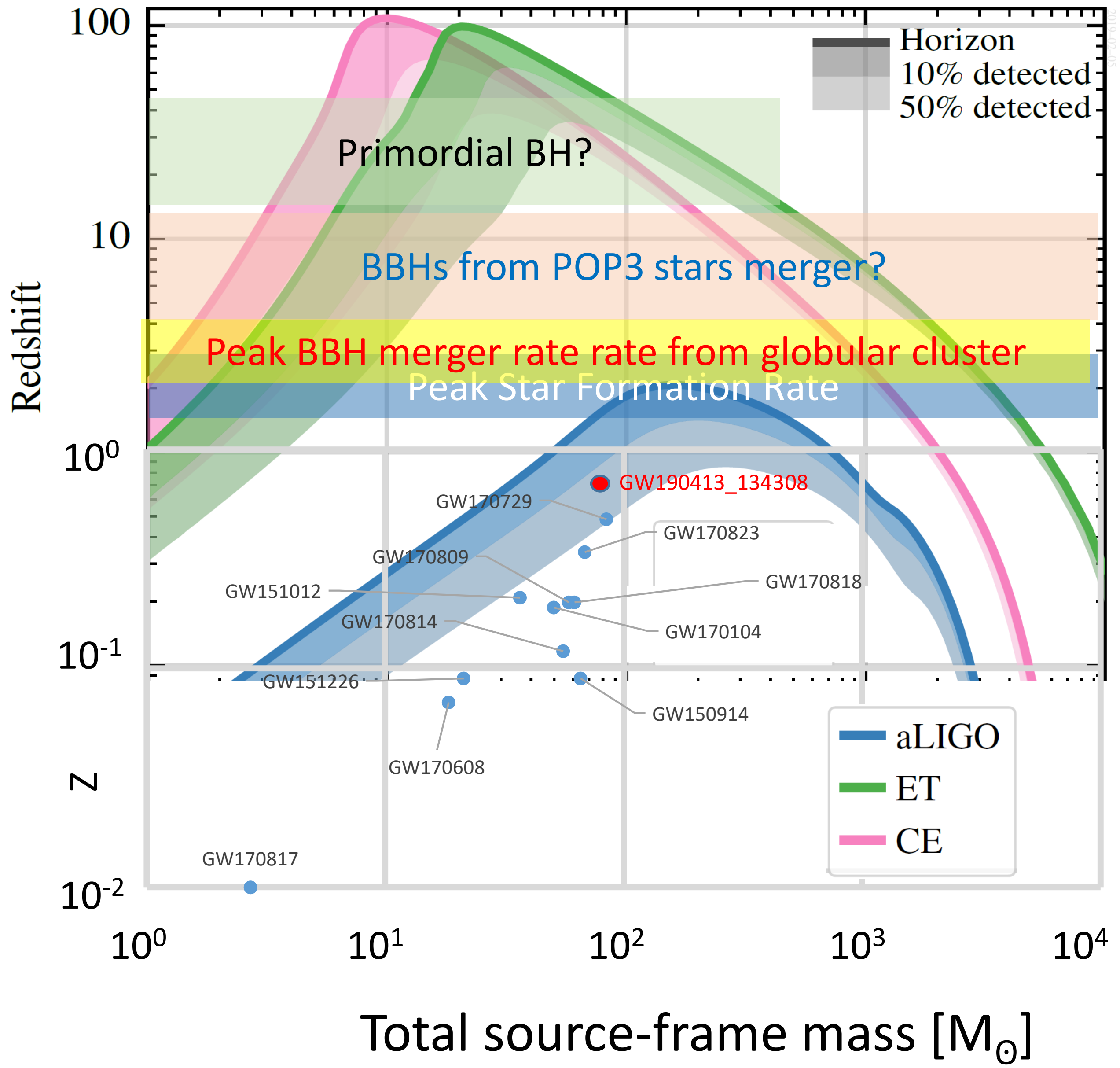
- In 2029 we will have a really heterogeneous 2.xG network
  - The concepts of “obsolescence” and “limit of the infrastructure”, that are driving the quest for new research infrastructures (rather more than a new detector) apply differently to the different continents

Continent	Detector	Obsolescence	Limits
America	LIGO H1		
	LIGO L1		
Europe	GEO600		
	Virgo		
Asia	KAGRA		
	LIGO India		

OK, all done?

- aLIGO and AdV achieved awesome results with a reduced sensitivity
- When they will reach or over-perform their nominal sensitivity can we exploit all the potential of GW observations?

- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed



GWTC-1: A gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs - arXiv:1811.12907 [astro-ph.HE]

Detection distance of GWD

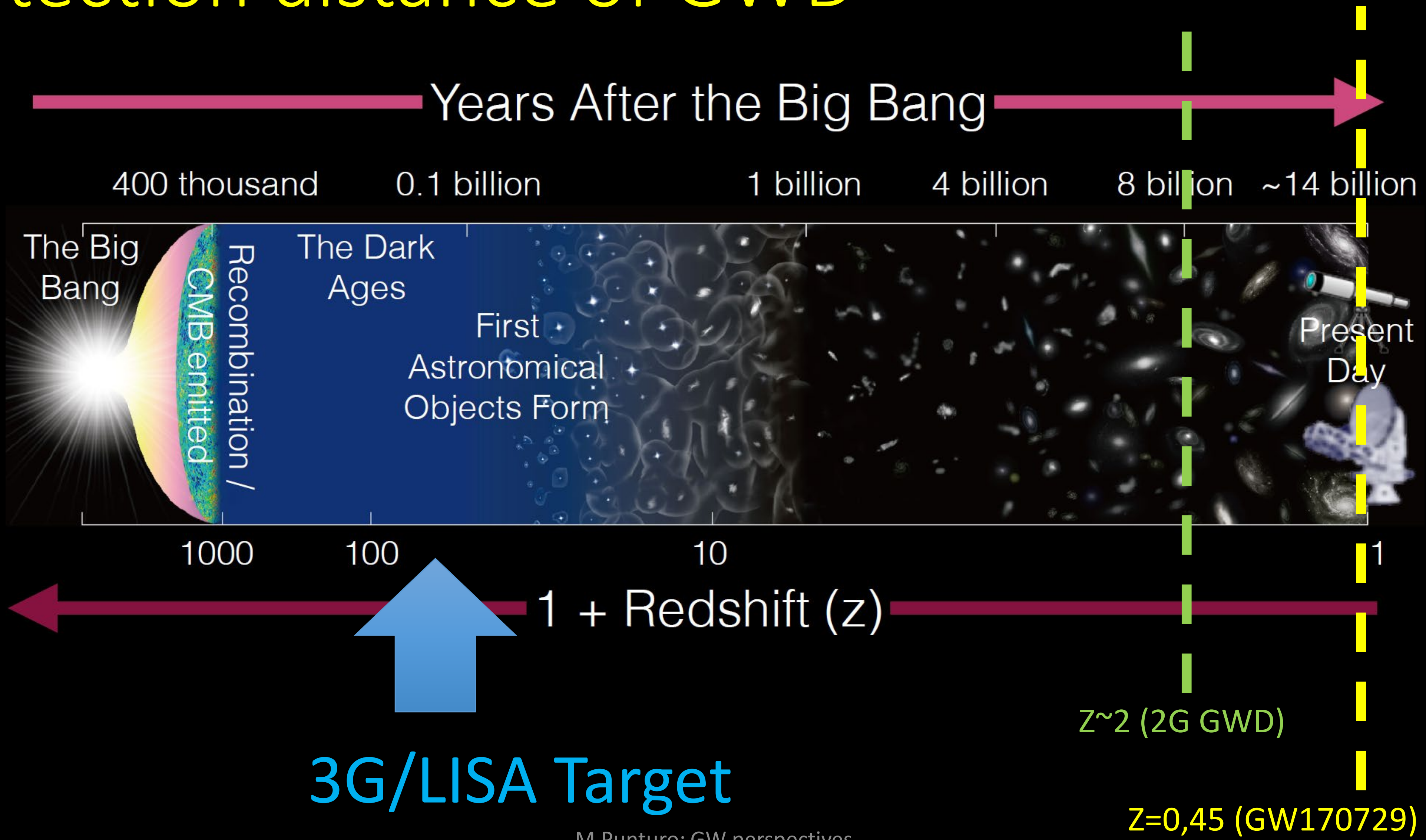
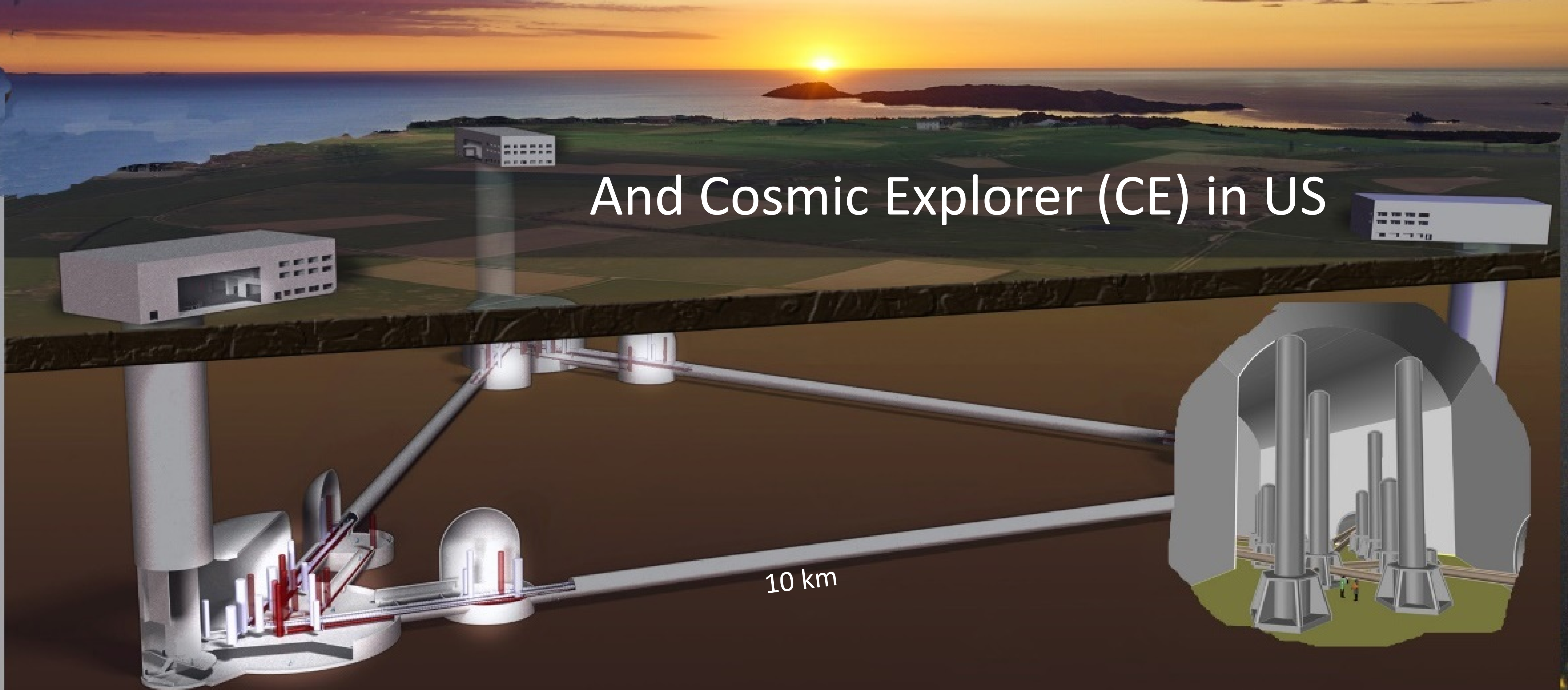


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

The Einstein Telescope

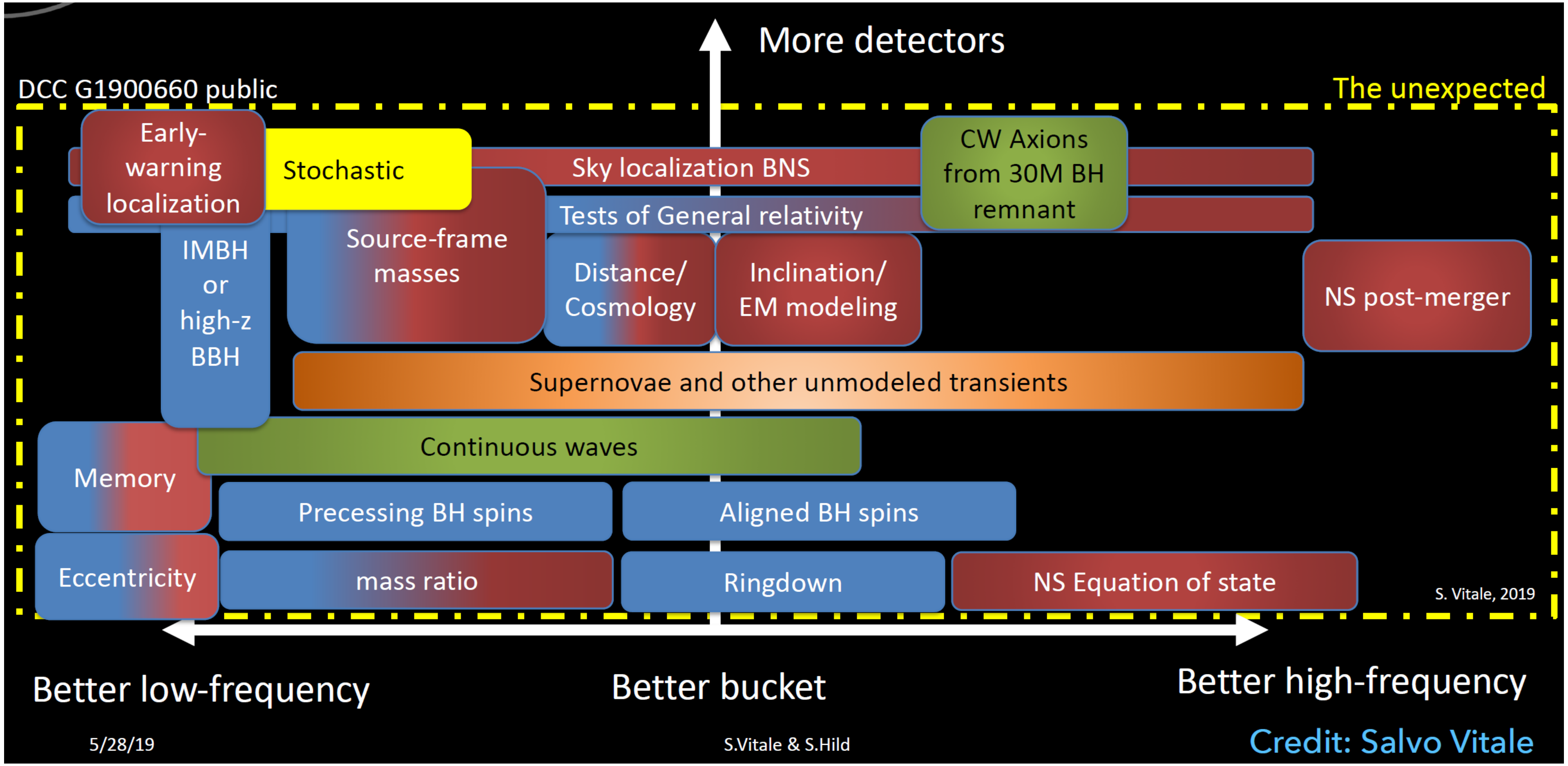


The 3G/ET key points

- ET is THE 3G new GW observatory
  - 3G: Factor 10 better than advanced (2G) detectors
  - New:
    - We need a new infrastructures because
      - Current infrastructures will limit the sensitivity of future upgrades
      - In 2030 current infrastructures will be obsolete
  - Observatory:
    - Wide frequency, with special attention to low frequency (few HZ)
      - See later
    - Capable to work alone (characteristic to be evaluated in the international scenario)
      - (poor) Localization capability
      - Polarisations (triangle)
      - High duty cycle: redundancy
    - 50-years lifetime of the infrastructure
      - Compliant with the upgrades of the hosted detectors

Wideband or Narrow band?

- The design of the ET observatory is driven by the physics objectives
  - At what frequency are they?



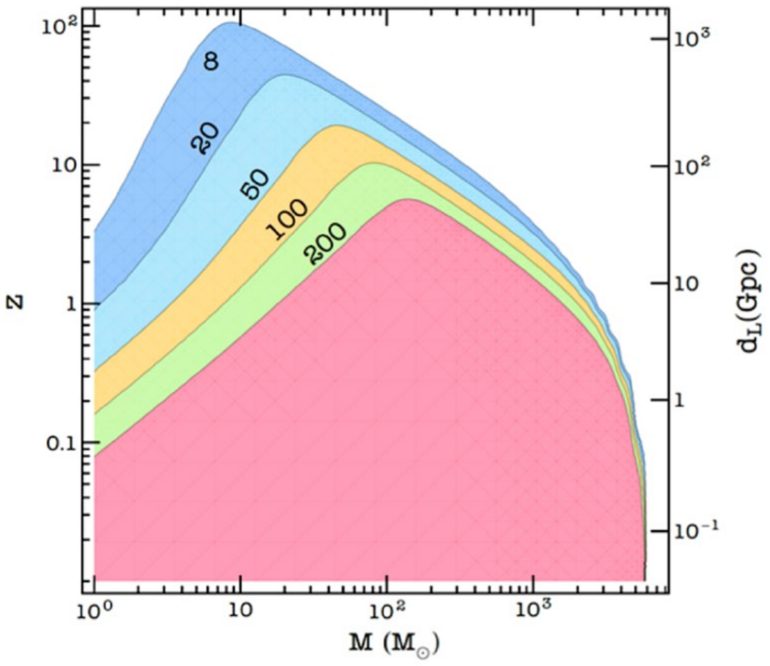
Everywhere!

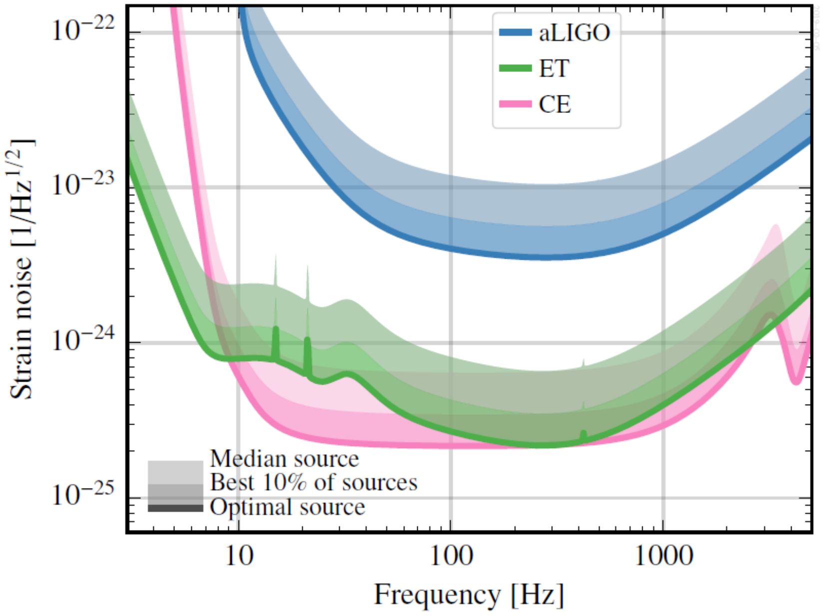
We need a wide band observatory

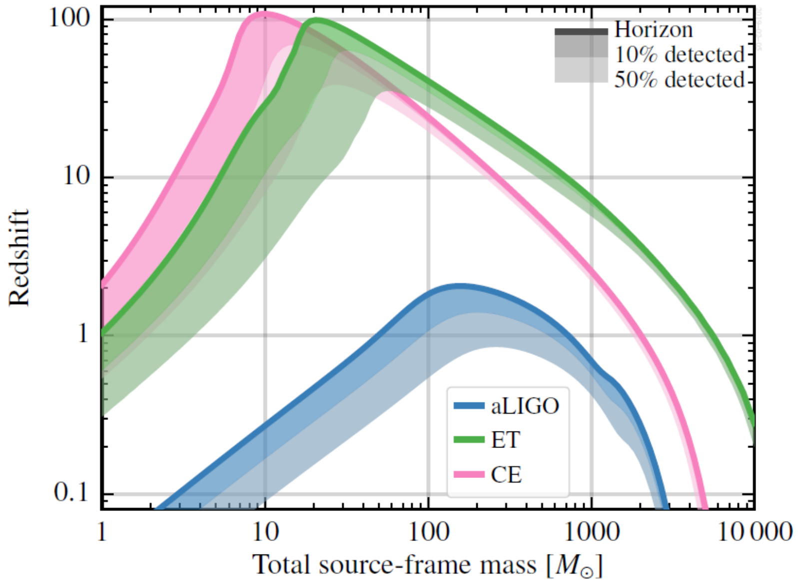
(with special attention to low frequency)

Key performances expected in ET

- BBH up to z~50
  - 10^6 BBH/year
  - Masses $M_T \gtrsim 10^3 M_\odot$
- BNS to z~2
  - 10^5 BNS/year
  - Possibly O(10-100)/year with e.m. counterpart
- High SNR







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ET science targets

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- A recent science case study for ET is here:
  - M.Maggiore et al, JCAP, 2020, 03, pp.050. ⟨10.1088/1475-7516/2020/03/050⟩
  - Hereafter a short list

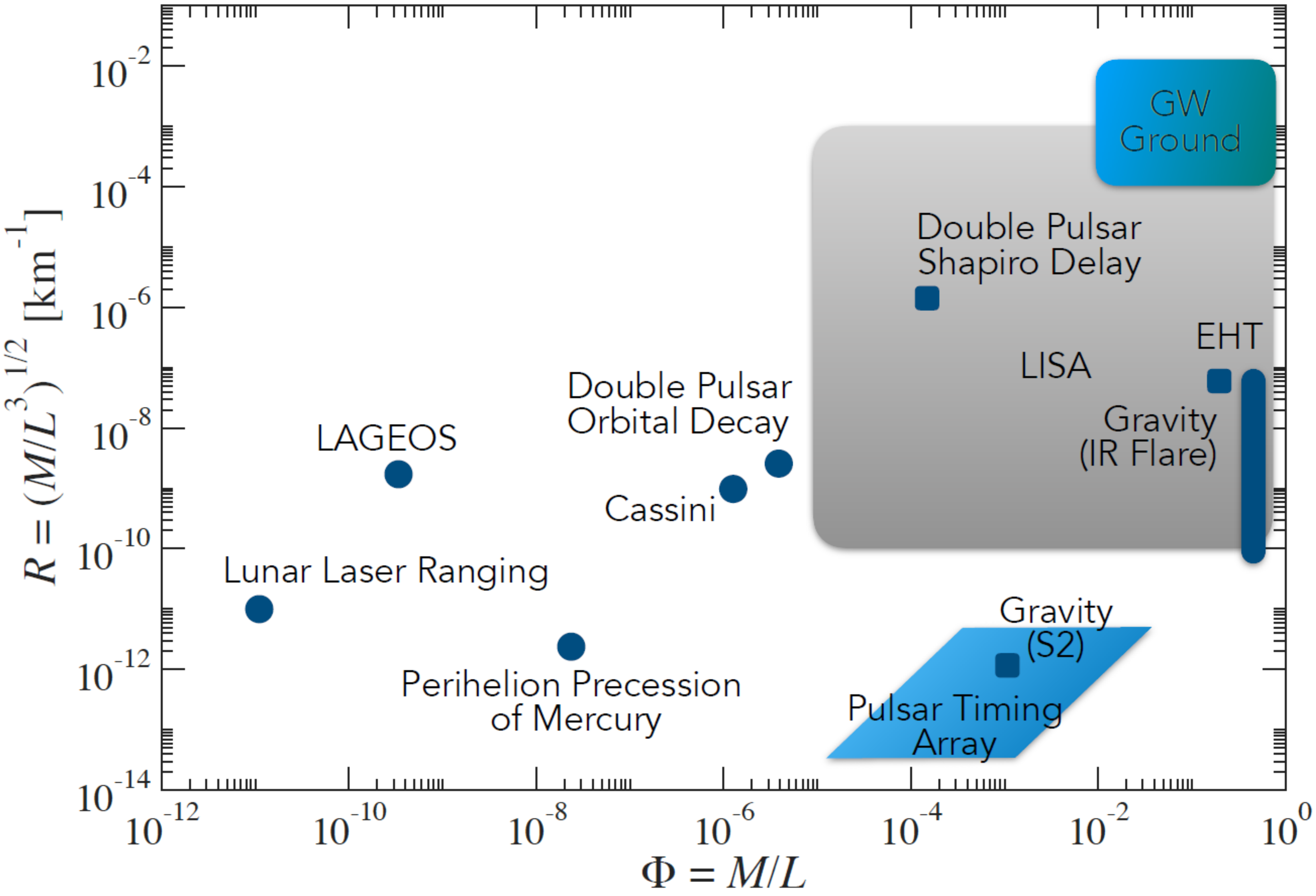
- Astrophysics
  - Black Hole physics
  - Neutron star physics
  - Multi-messenger astronomy
  - Core Collaps Sne
  - Isolated NS

- Fundamental physics
  - Testing GR
    - Perturbative regime
      - Inspiral phase of BH, post Newtonian expansion
    - Strong field regime
      - Physics near BH horizon
      - Exotic objects
  - QCD
    - NS interior structure
  - Dark matter
    - Primordial black holes
    - Axions
  - Dark Energy
    - DE equation of state
    - Modified propagation of GW

- The “Unexpected”
  - ???

Probing GR in strong field conditions

- BBH coalescences allow to test GR in strong field conditions

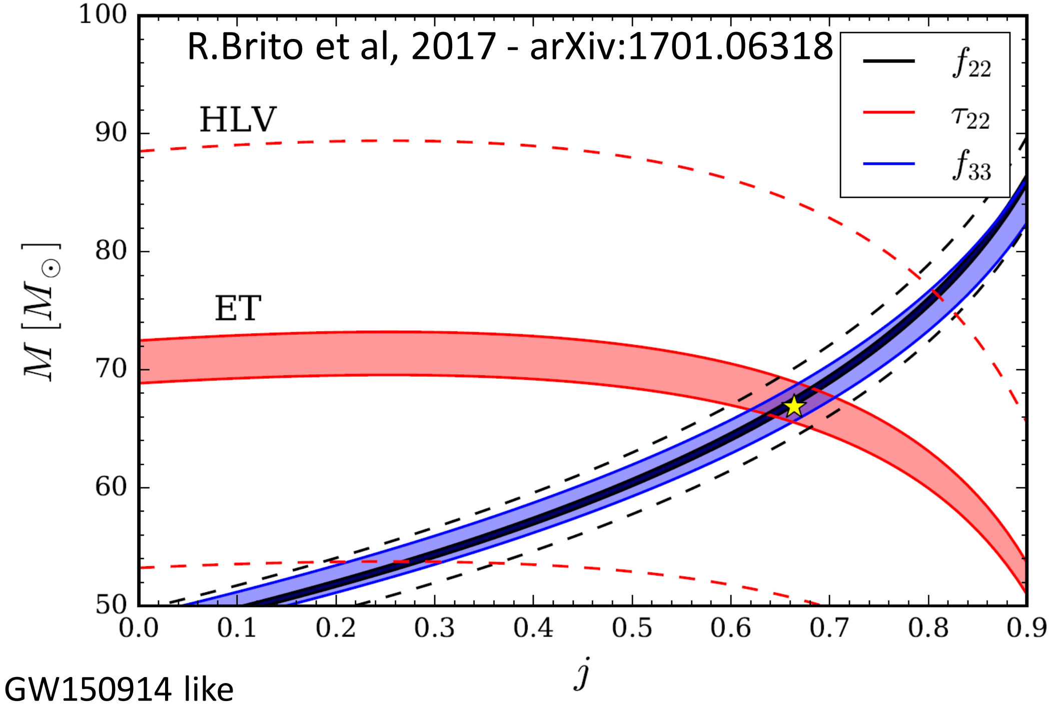


Yunes N. et al.
Phys. Rev. D 94, 084002 (2016)
Edited by ET science case team

Extreme gravity

- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the “elasticity” of the space-time fabric
  - Exotic compact bodies could have a different QN emission and have echoes

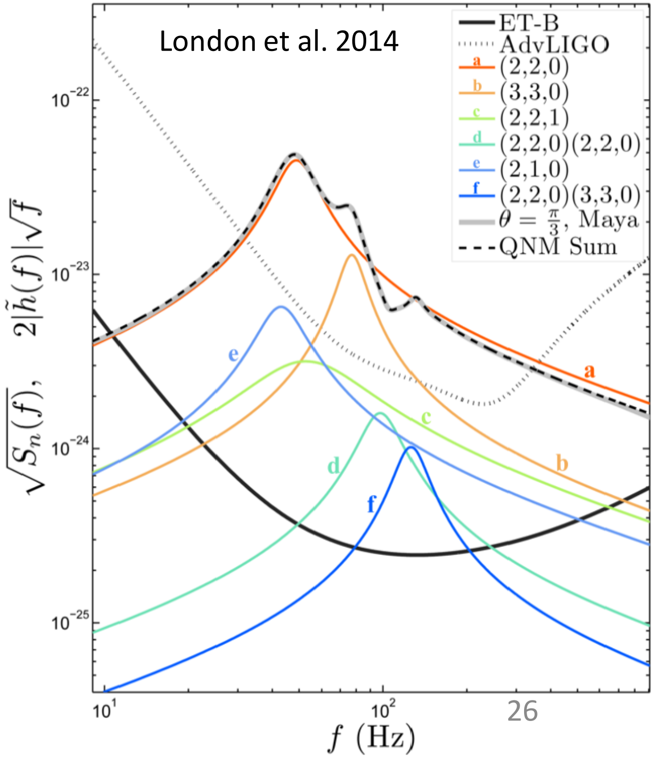
- In ET accurate BH spectroscopy already from single events
- 10^4-10^5 events/yr with detectable ringdown
- 20-50 events/yr with detectable higher modes



J=J/M² dimensionless spin

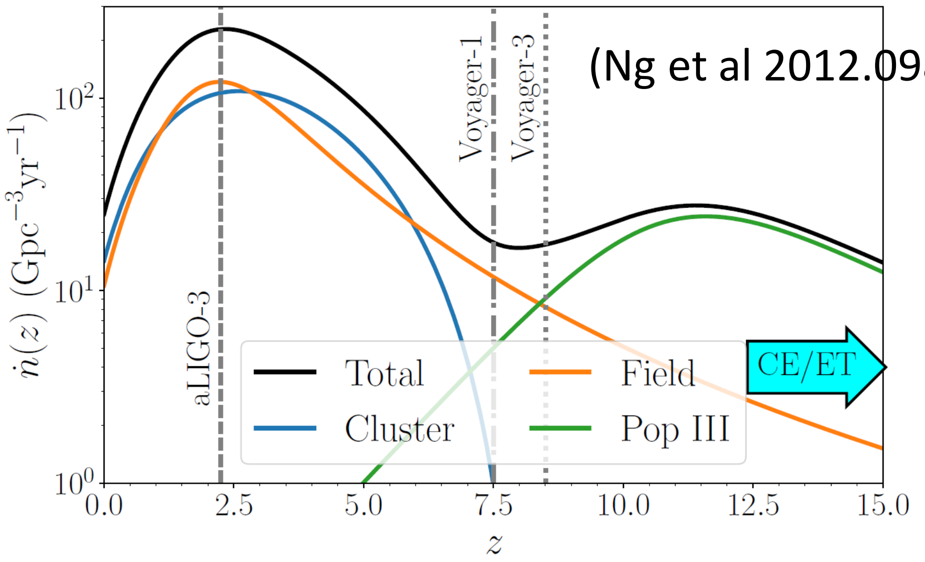
GW150914 like

350 Msun binary @ 100 Mpc



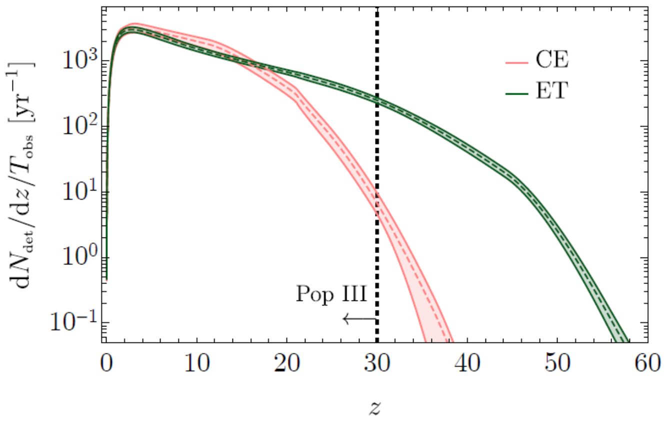
Probing multiple populations of BH: PBHs

- We have different BBH populations:
  - binary stellar evolution in galactic fields
  - dynamical formation through multi-body interactions in star clusters or AGN
  - from Population III (Pop III) stars
    - BHs from Pop III stars peak at z≃12 and could form binaries (and merge) up to z≃25-30 (conservatively)
  - Primordial blackholes
    - Any BBH merger at z>30 (very conservatively) will be of primordial origin
    - ET reaches z~50 !!



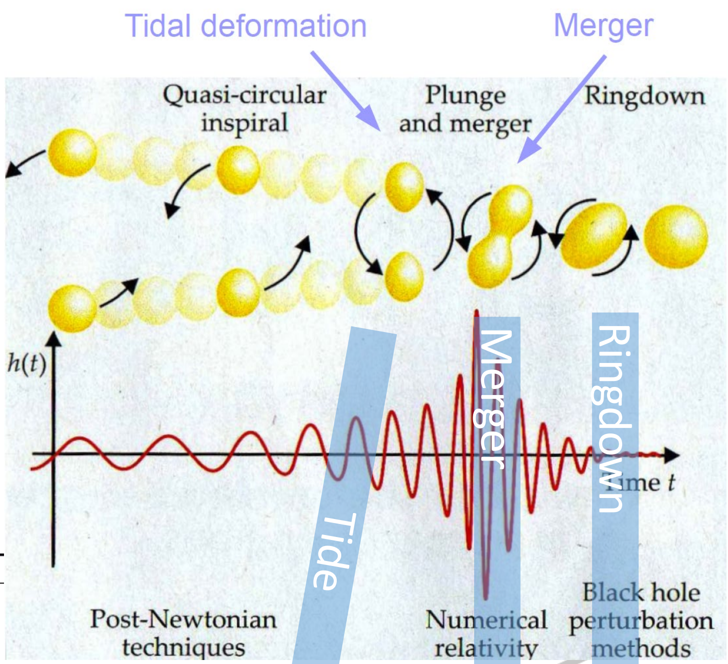
(Ng et al 2012.09876)

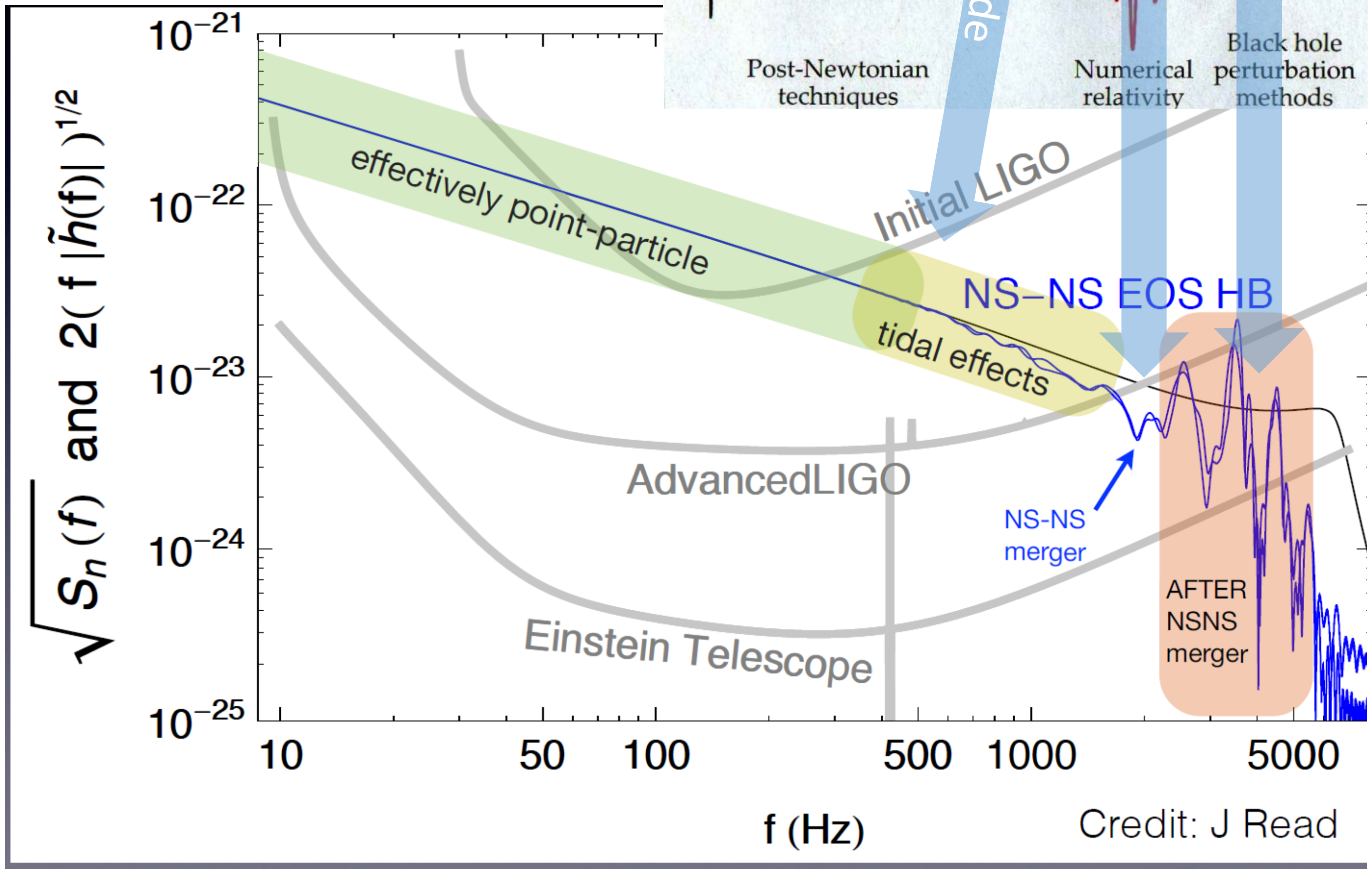
$$N_{\rm det}^{\rm ET}(z>30) = 1315^{+305}_{-168}\,{\rm yr}^{-1}$$

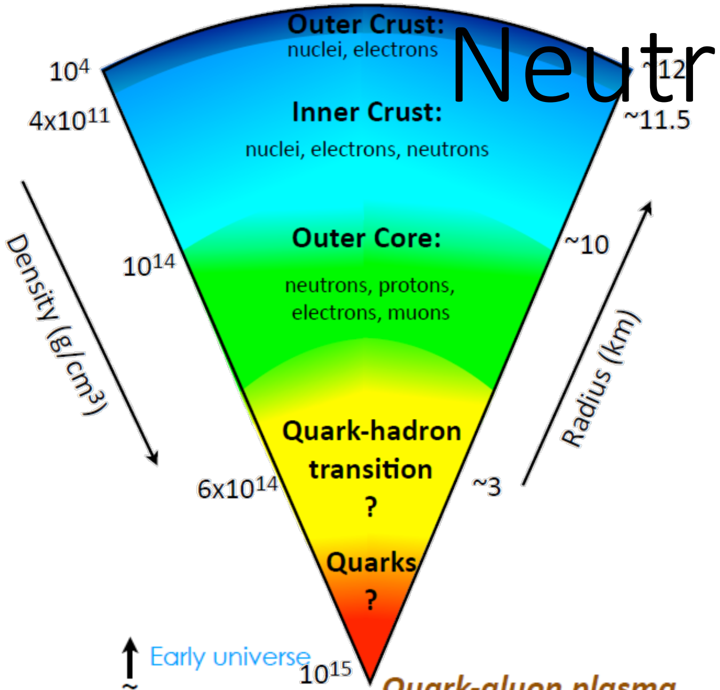


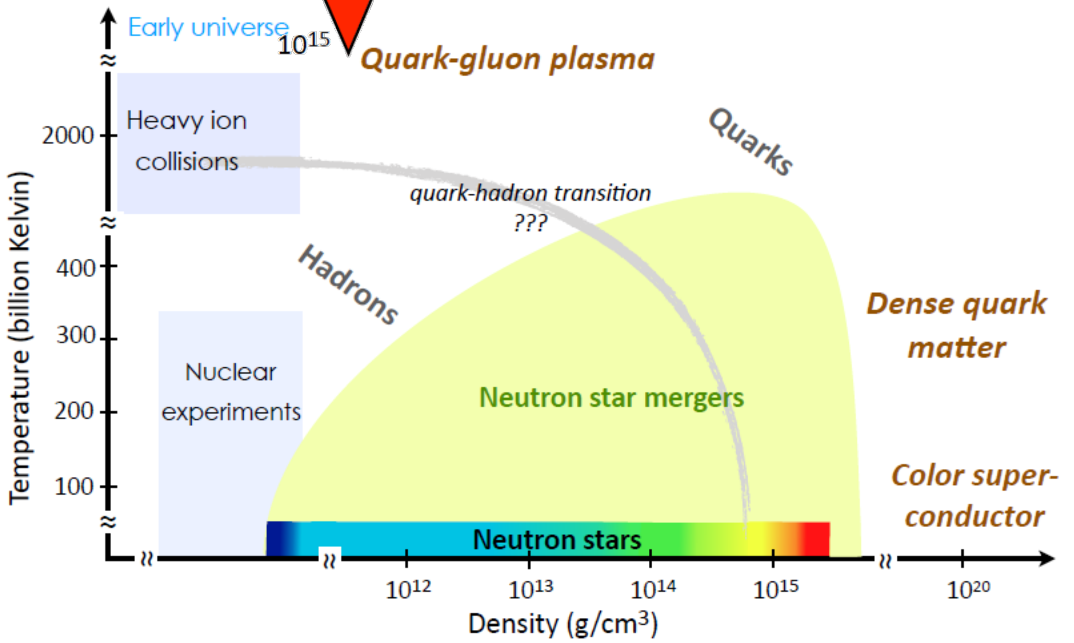
QCD -Structure of a Neutron Star

Stephen Fairhurst
ET meeting 27-28 March 2017



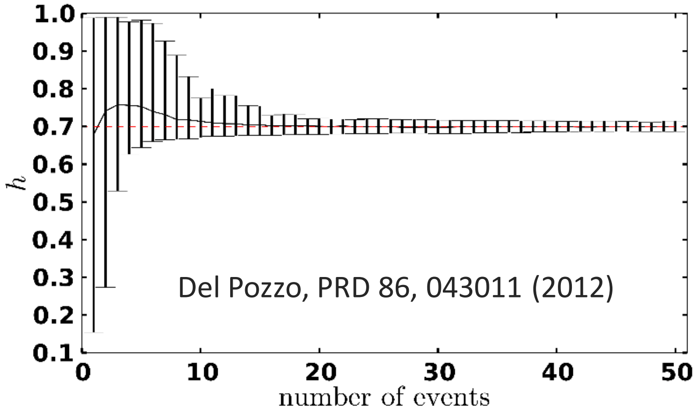


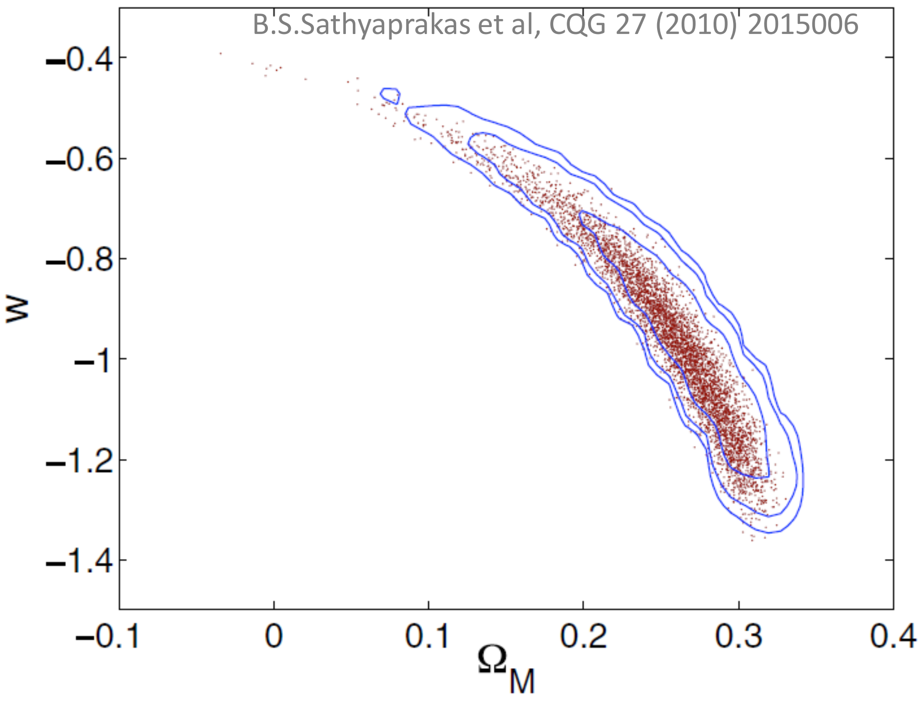




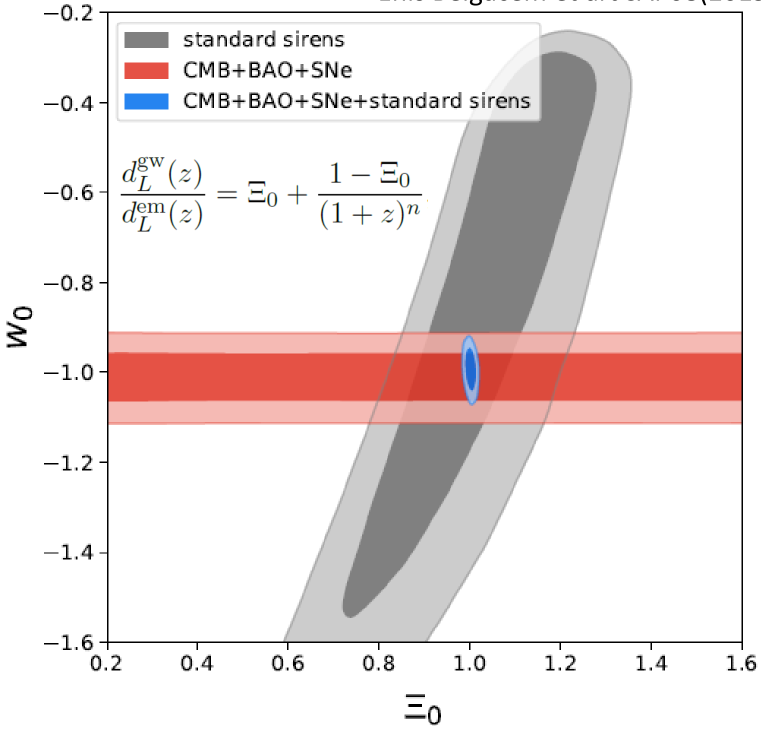
Cosmology with ET

- ET will reveal 10^5-10^6 BBH/BNS coalescences per year
- A fraction (about 10^3/year?) of the BNS will have a electromagnetic counterpart (thanks also to new telescopes like THESEUS, E-ELT, …





Enis Belgacem et al JCAP08(2019)015

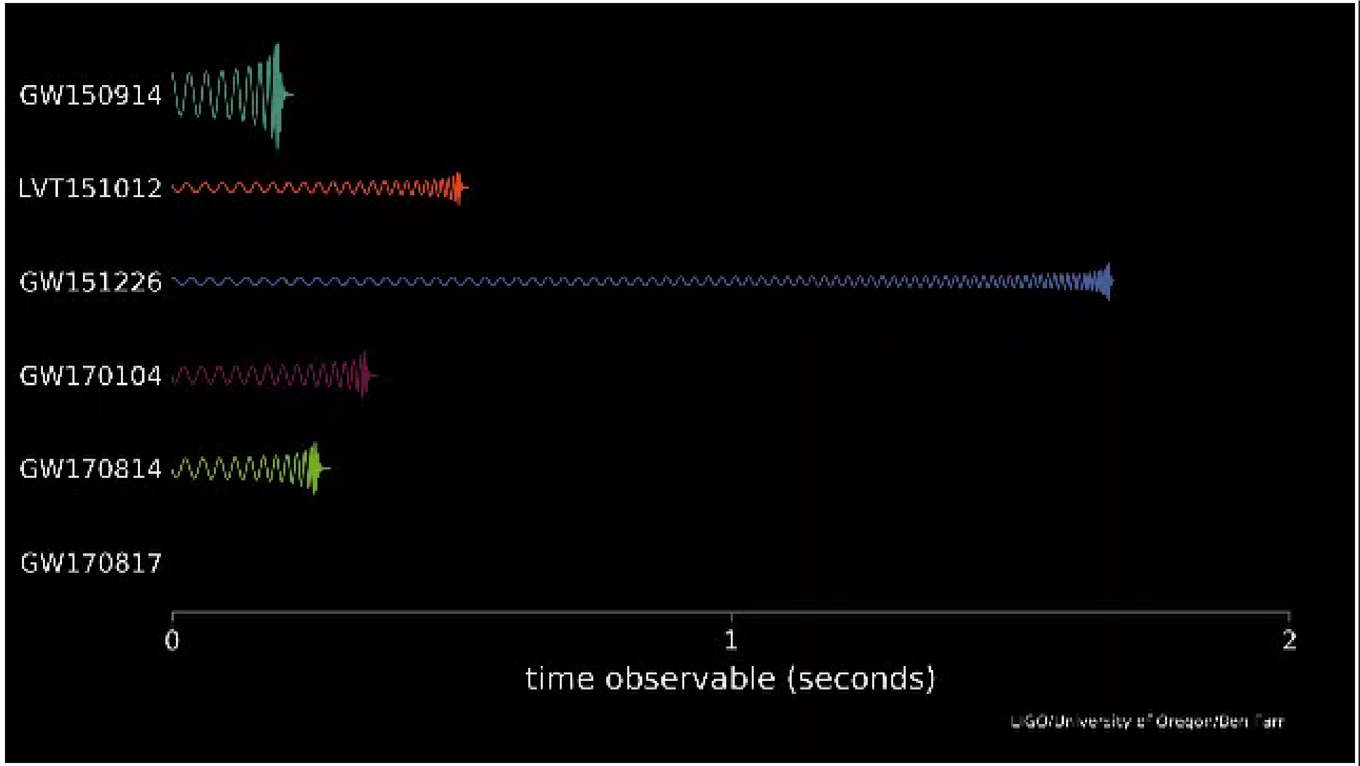


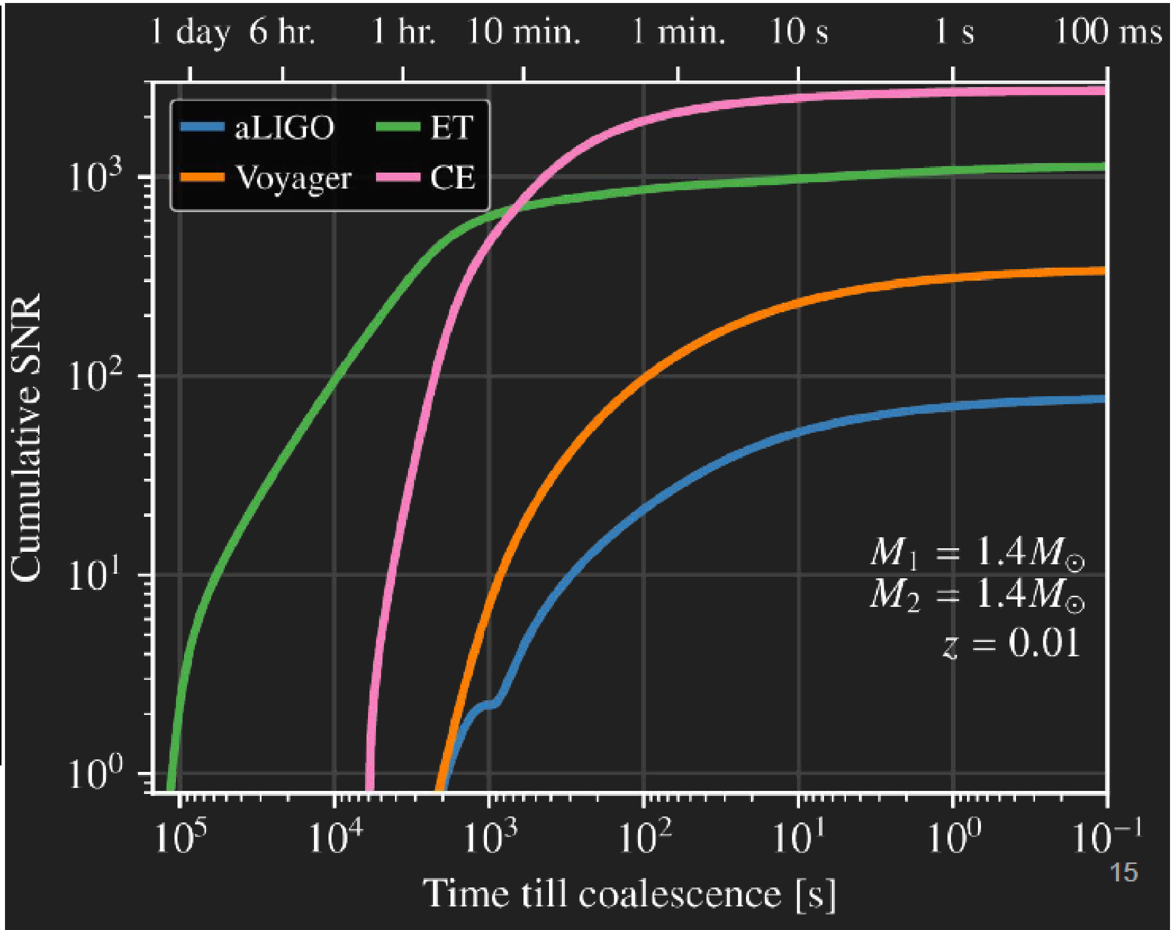
$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

Investigating the DE sector in modified theories of gravity

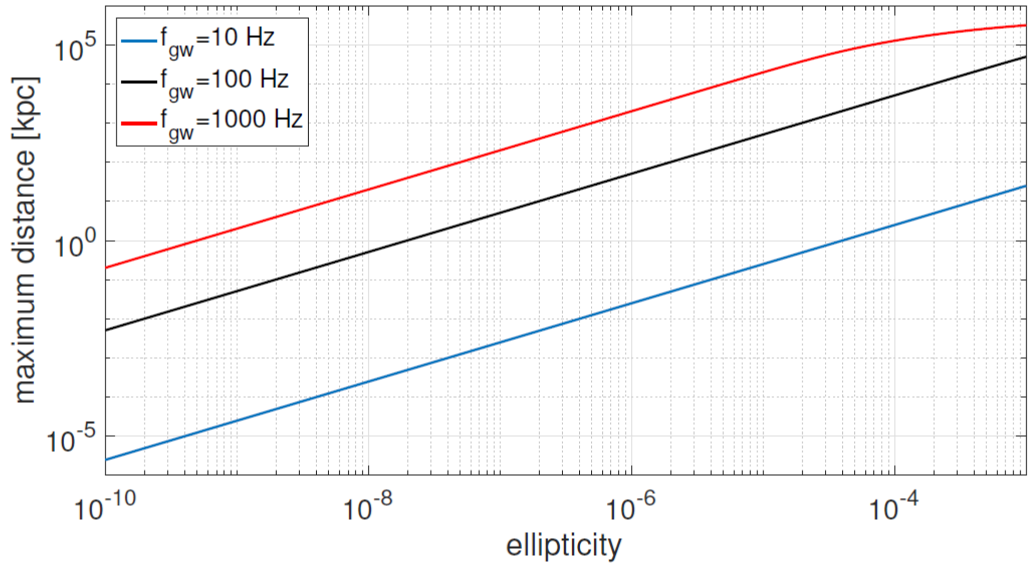
Low frequency: Multi-messenger astronomy

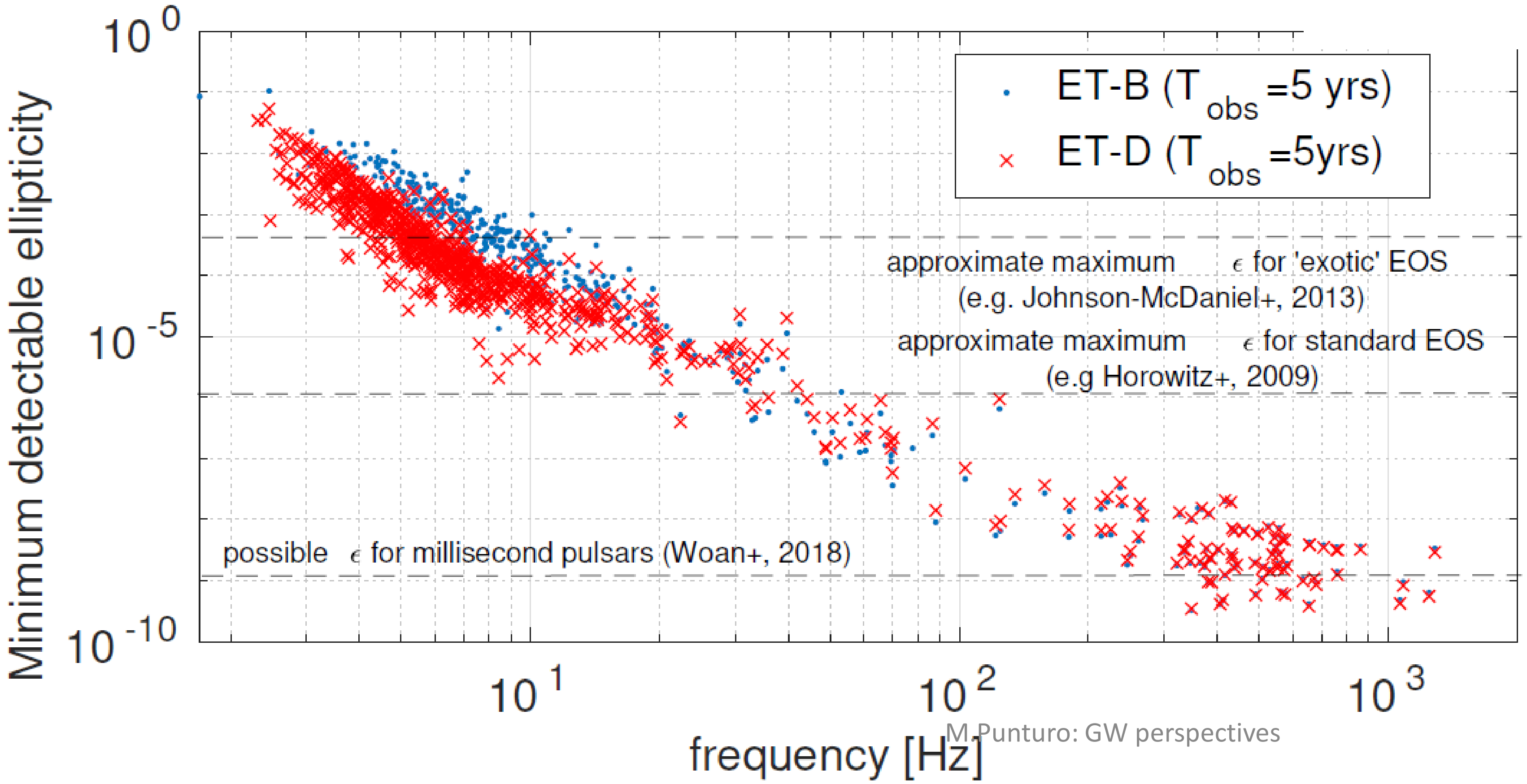
- If we are able cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity:





Isolated NS (pulsars)

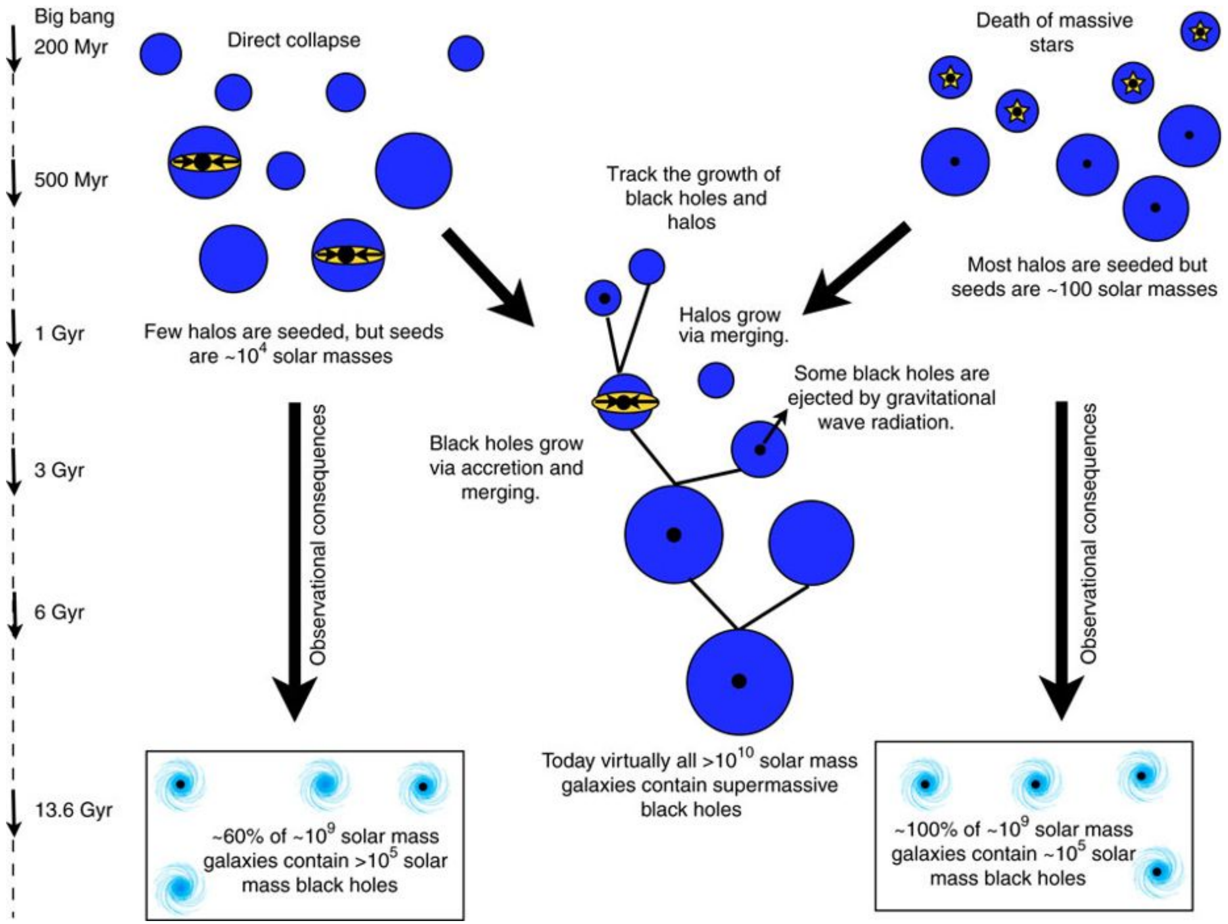


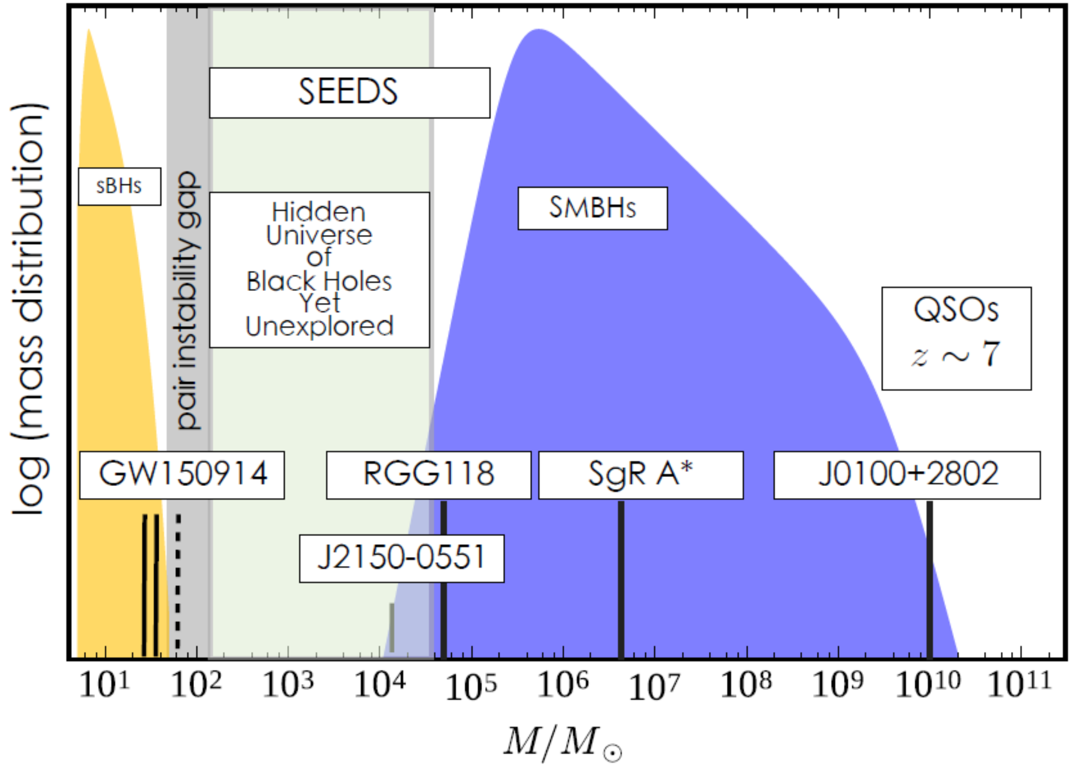


$\epsilon = 10^{-7}$ corresponds to a "mountain" of 1 mm on the NS surface

Seeds and Supermassive Black Holes

- Supermassive Black Holes (SMBHs) are present at the center of many galaxies:
  - What is their history? How they formed? What are the seeds?





Seeds and Supermassive Black Holes

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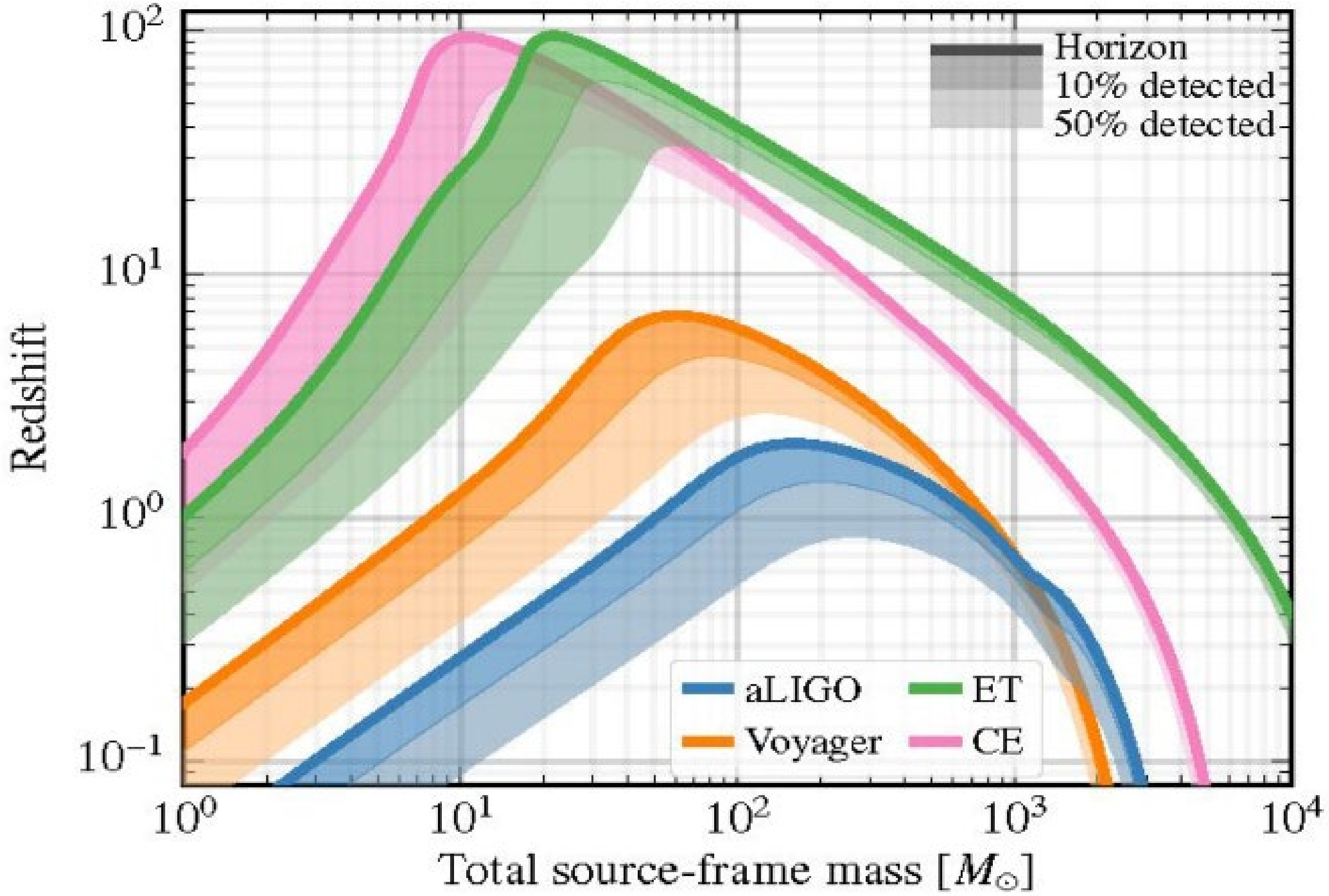
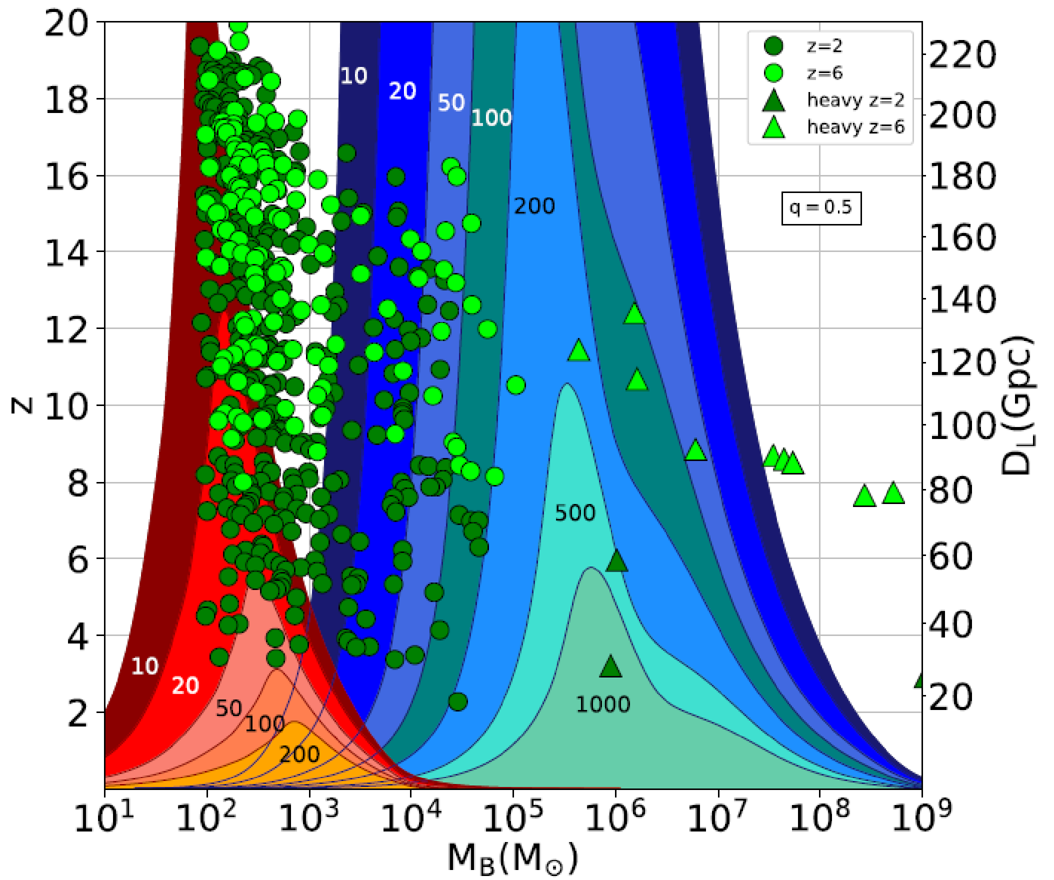
- LISA will detect the coalescences of SMBHs, but what about the seeds?

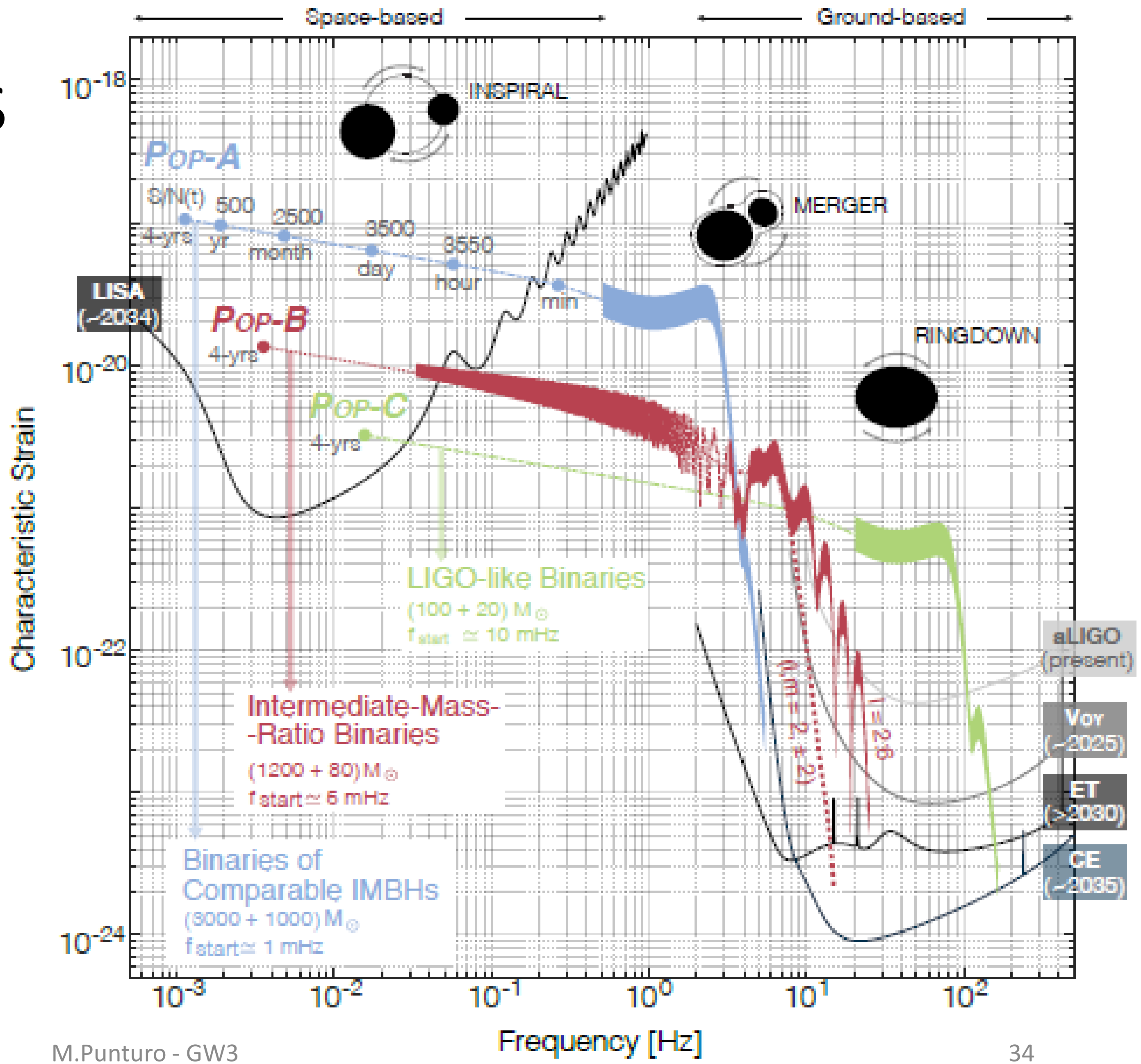


Black Holes in the Gravitational Universe



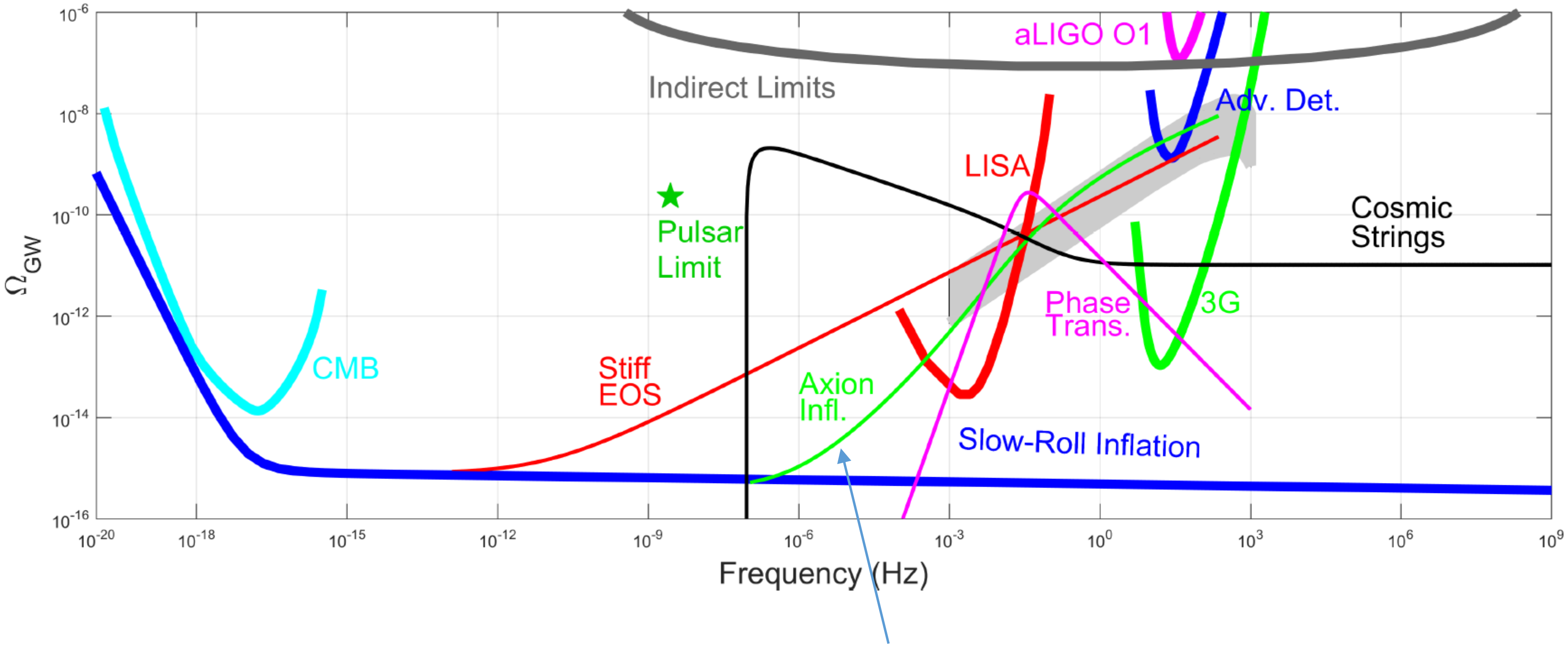
Multi-Band analysis

- Space based GW observatory and terrestrial GW observatory can observe different phases of the coalescence of specific sources (IMBH)
  - Localisation
  - GR tests



GW Stochastic Background and inflation

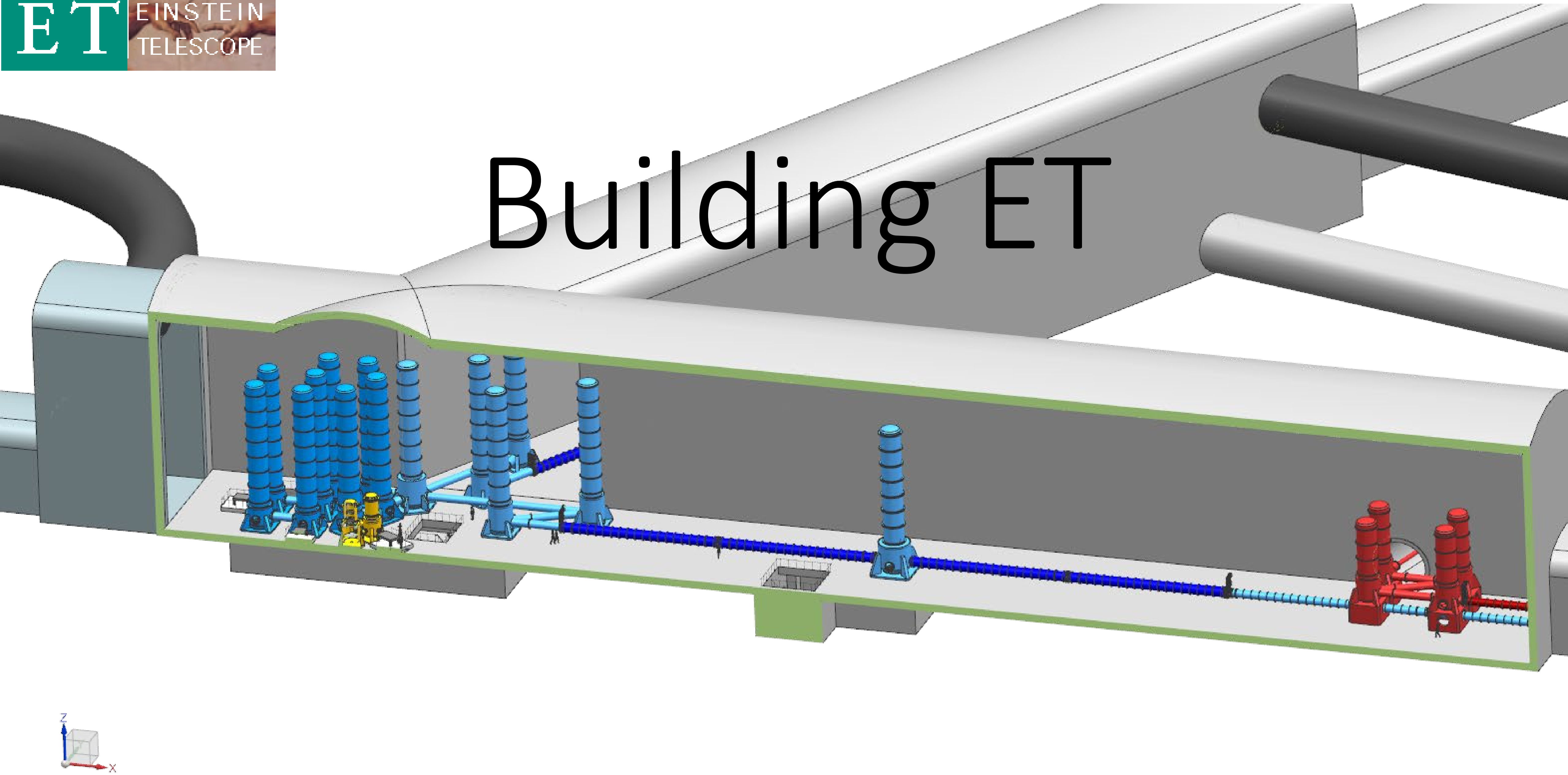
- Inflation, reheating, preheating models could be distinguishible in the GW stochastich background in case of some blue-shift mechanism
  - information on: new additional degrees of freedom, interactions and/or new symmetry patterns underlying high energy physics of early universe



Abbot, B.P. et al, Phys Rev Lett 118 (12), 2017, 121101

Axion inflation
(see for example V. Domcke arXiv:1704.03464)

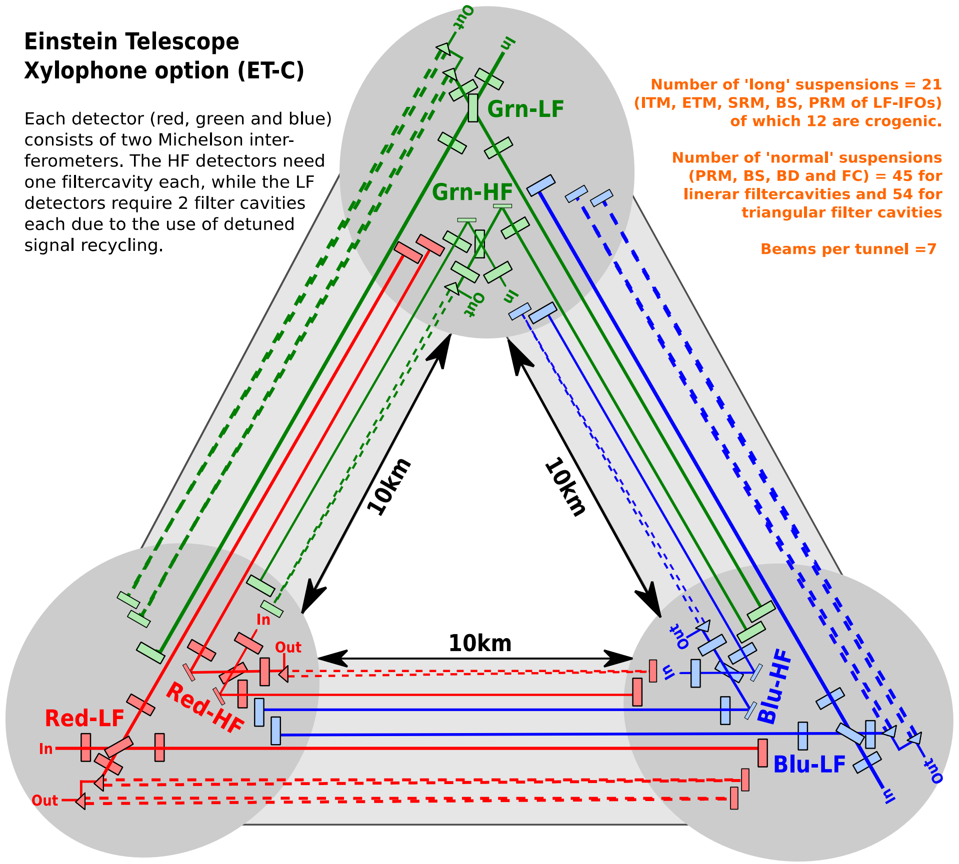
Building ET



ET Key ingredients

Factor 10 better sensitivity in a wide range of frequency
with a specific attention to low frequency (<10Hz)

- Einstein Telescope is a 3rd generation Gravitational Wave Observatory
  - It is, first of all, a new Research Infrastructure



- Capable to host ET and its upgrades
- Capable to host 4G, 6G, …

Observation (rather than detection) is the core business:

Requirements	Design Specifications
Wide frequency range	Xylophone (multi-interferometer) Design
Massive black holes (LF focus)	Underground
Localisation capability	Cryogenic
(more) Uniform sky coverage	Triangular shape
Polarisation disentanglement	Multi-detector design
High Reliability (high duty cycle)	Longer arms
High SNR	

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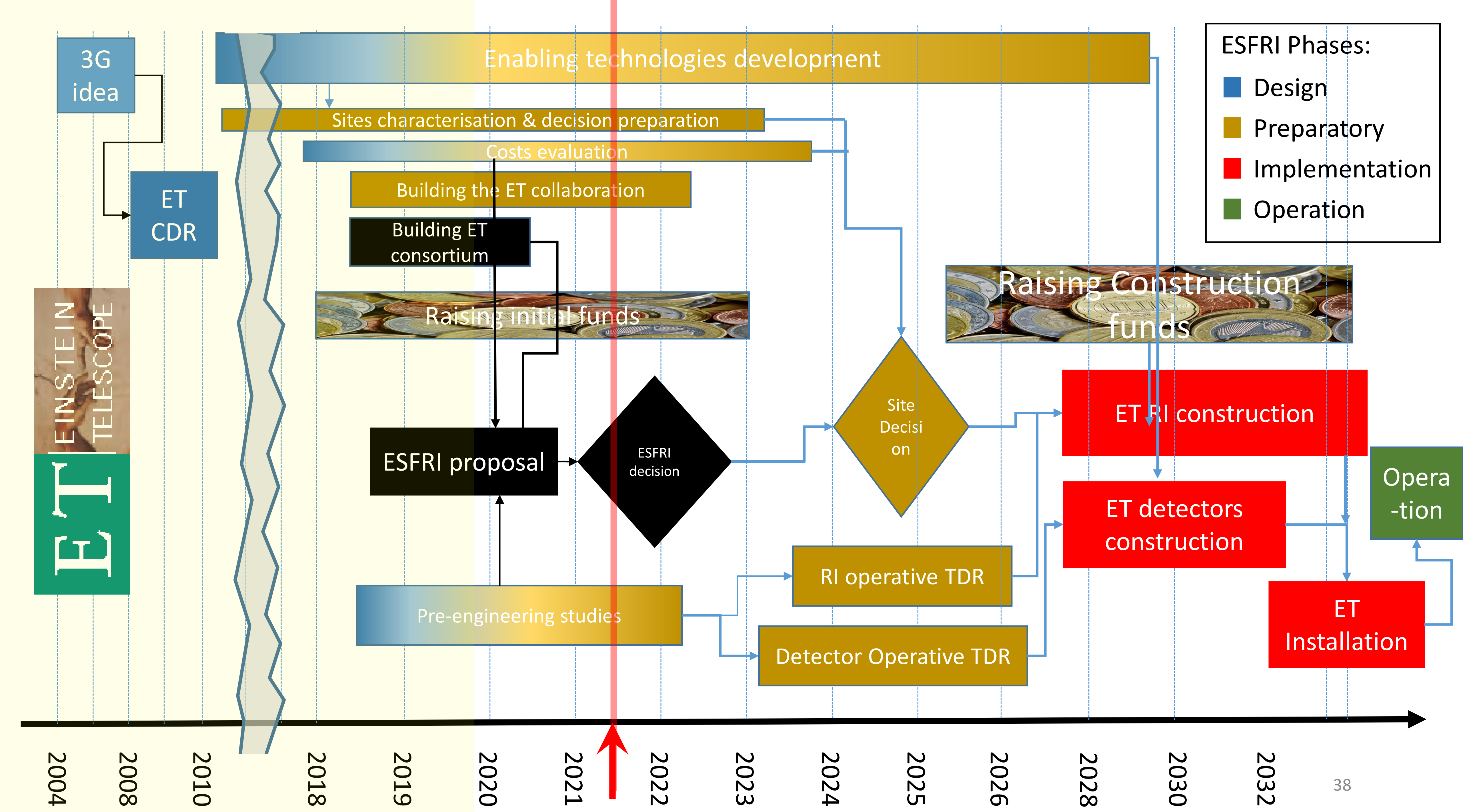

3G idea
ET CDR
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ET
Enabling technologies development
Sites characterisation & decision preparation
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decision
Pre-engineering studies
RI operative TDR
Detector Operative TDR
Site Decisi on
Raising Construction funds
ET RI construction
ET detectors construction
ET Installation
Opera -tion
ESFRI Phases:
Design
Preparatory
Implementation
Operation
2004
2008
2010
2018
2019
2020
2021
2022
2023
2024
2025
2026
2028
2030
2032

European Strategy Forum on Research Infrastructures

ESFRI Roadmap

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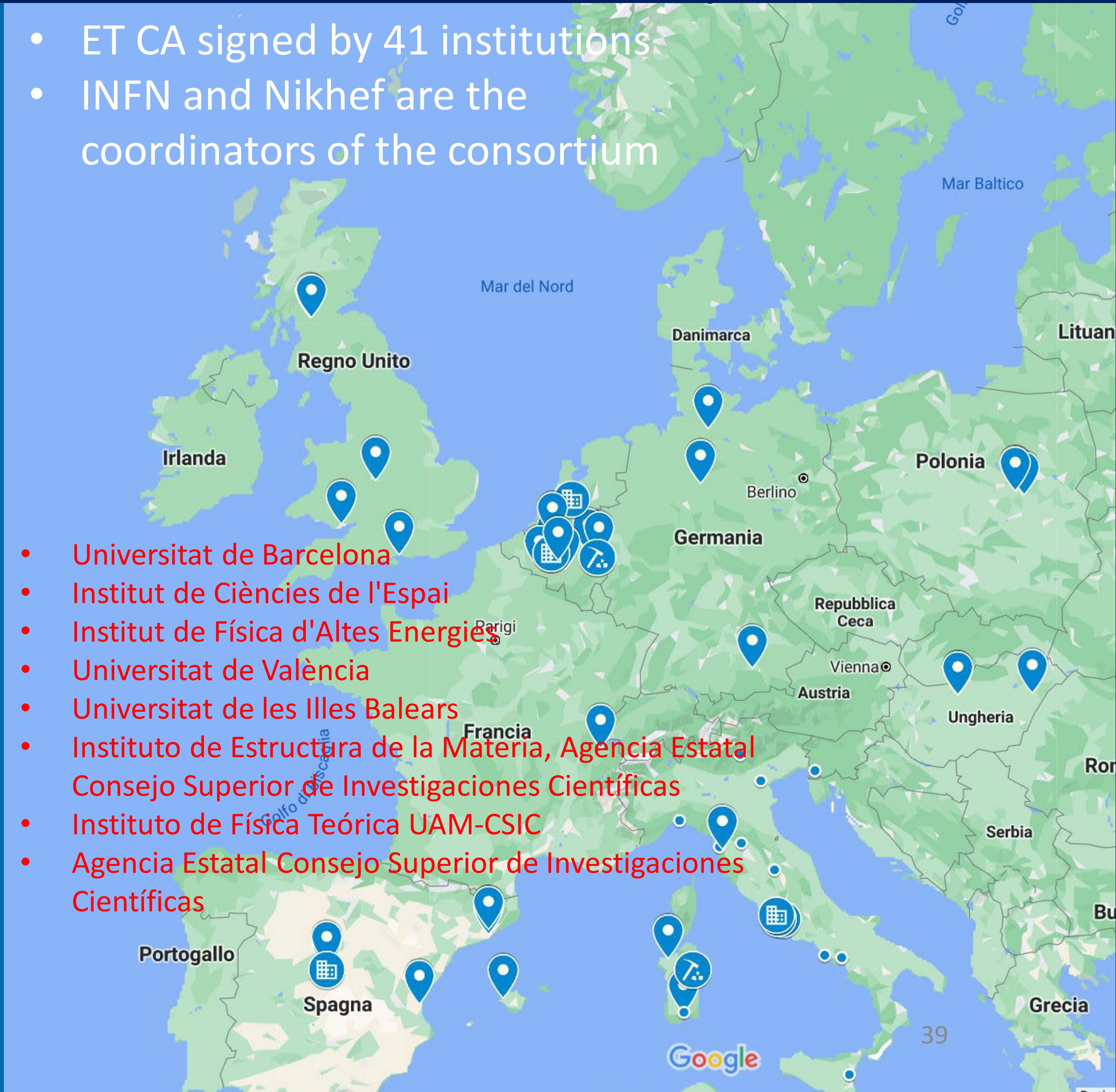
Proposal submitted by:

- **Italy** (Lead Country)
- Netherlands
- Belgium
- Spain
- Poland

- ET CA signed by 41 institutions
- INFN and Nikhef are the coordinators of the consortium

- Universitat de Barcelona
- Institut de Ciències de l'Espai
- Institut de Física d'Altes Energies
- Universitat de València
- Universitat de les Illes Balears
- Instituto de Estructura de la Materia, Agencia Estatal Consejo Superior de Investigaciones Científicas
- Instituto de Física Teórica UAM-CSIC
- Agencia Estatal Consejo Superior de Investigaciones Científicas



European Strategy Forum on Research Infrastructures

ESFRI

Roadmap 2021: next steps

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- OPEN CALL FOR PROPOSALS - 25 September 2019 ✓
- SUBMISSION OF PROPOSALS - 9 September 2020 ✓
- CRITICAL QUESTIONS & INVITATION TO HEARINGS – February-March 2021 ✓
- HEARING – April 14 2021 ✓
- ESFRI FORUM DECISION - June-September 2021
- ESFRI ROADMAP LAUNCH - October - November 2021

ESFRI

ET collaboration current organisation

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ET Steering Committee

Specific Boards

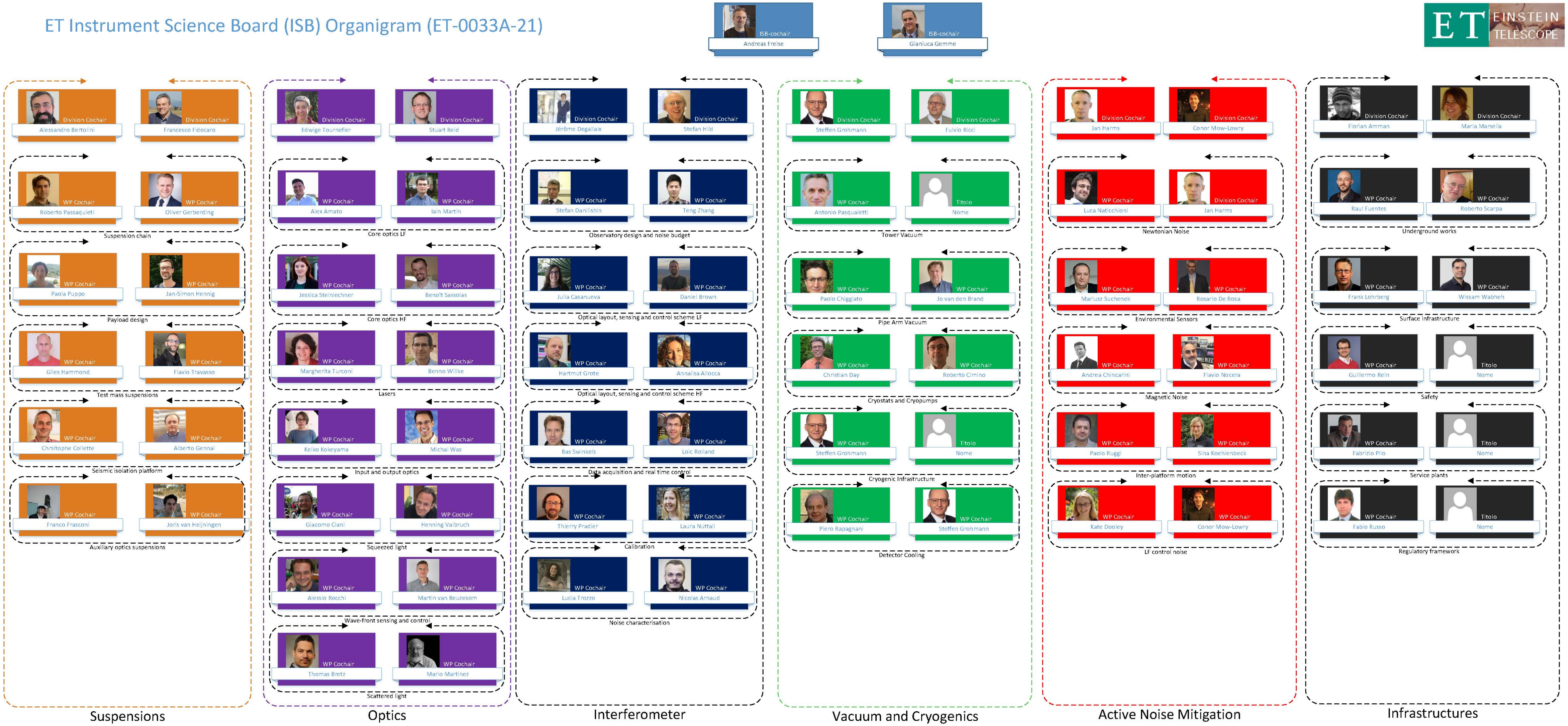
- **SPB** – Site Preparation Board
  - Site Studies
  - Environmental studies
  - Geophysical studies
  - Data management std.
  - Analysis tools and data comparison
  - Detector Optimisation
  - Community relations
  - Costs and socio-economic impact
  - Legal
- **OSB** – Observation Science Board
  - Fundamental Physics
  - Cosmology
  - Population Studies
  - Multimessenger Obs.
  - Synergies with GWDs
  - Nuclear Physics
  - Transient GW Sources
  - Waveforms
  - Scientific potentials …
  - Data Analysis Platform
- **ISB** – Instrument Science Board
  - Suspensions
  - Optics
  - Interferometer
  - Vacuum and Cryogenics
  - Active Noise Mitigation
  - Civil Infrastructures
- **EIB** – E-Infrastructure Board
  - On-site Infrastructure
  - Distributed infrastructure
  - Software & frameworks

Divisions

ISB: Instrument Science Board

ESFRI

ET Instrument Science Board (ISB) Organigram (ET-0033A-21)



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OSB: Observational Science Board

Marica Branchesi - Michele Maggiore - Ed Porter

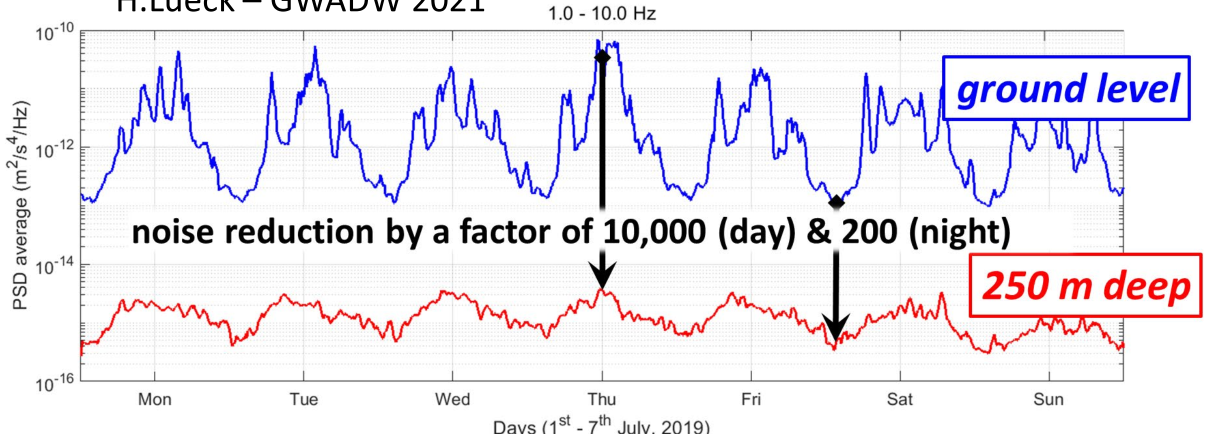
- **Fundamental physics**
  - Physics near BH horizons
  - Tests of GR
  - Exotic compact objects
- **Cosmology**
  - Dark Energy
  - Dark matter
  - Estimation of cosmological parameters
  - Modifications of gravity at cosmological scales
  - Stochastic background of cosmological origin
- **Population Studies**
  - Predictions of population of astrophysical origin
  - Predictions of primordial BHs
  - Stochastic backgrounds of astrophysical origin
- **MM observations**
  - ET / high-energy
  - ET / optical
  - ET / radio
  - ET / neutrinos
- **Synergies w. other GW observ.**
  - Synergies with 2G+ detector
  - Synergies with CE, 3G
  - Synergies with LISA
- **Nuclear physics**
  - EoS of NSs in isolated systems
  - EoS in NSs in binary systems
  - Nucleo-synthesis in BNS mergers
- **Transient GW Sources**
  - Predictions for Supernovae
  - Predictions for magnetars
  - Predictions for cosmic string bursts
- **Waveforms**
  - Waveforms relevant for ET
  - Improvement of waveforms for BBH
  - Improvement of waveforms for NSBH
  - Improvement of waveforms for BNS
- **Science Potential**
  - Science potential for various detector configurations
  - Common tools
- **DA platform**
  - DA platform

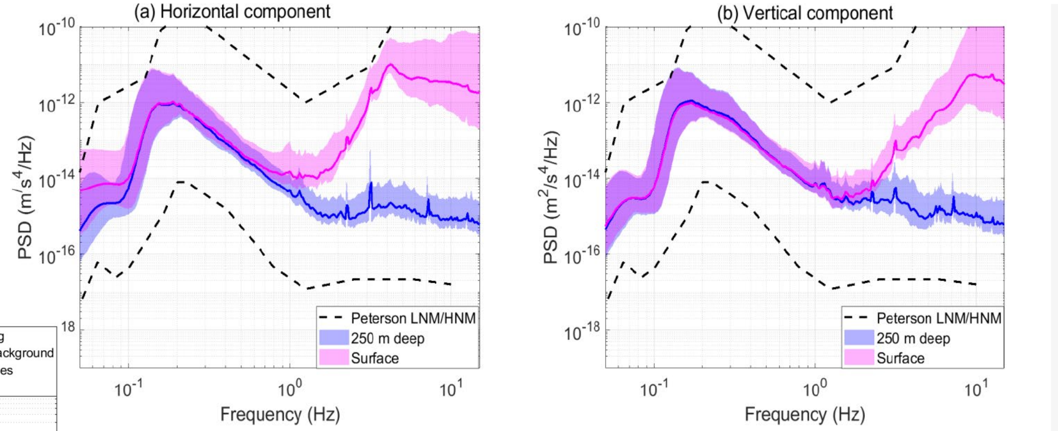
SPB: ET sites under characterisation

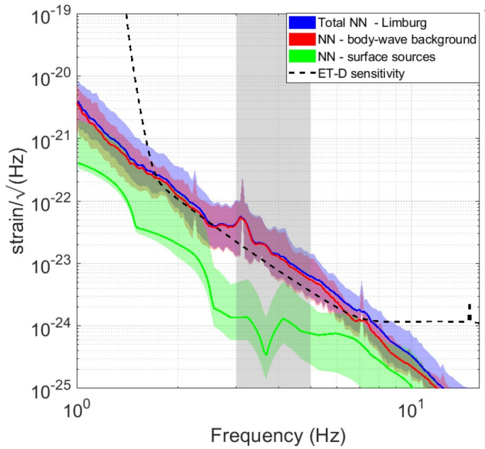
Euregio Meuse-Rhine

- A 250-m deep borehole has been excavated and equipped
  - Seismic data under acquisition and analysis
- 3-5 other boreholes expected
- Extensive active and passive site characterisation with sensor arrays in 2021
- Good seismic noise attenuation given by the particular geological structure
- ET pathfinder centre under construction
- 15+15M€ funding through Interreg grants

H.Lueck – GWADW 2021







Soumen Koley, GWADW 2021

SPB: ET sites under characterisation

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Sardinia

- Long standing characterisation of the mine in one of the corners continuing
  - Seismic, magnetic and acoustic noise characterisation ongoing at different depth in the mine
- Underground laboratory under construction (SarGrav)
- A 290m borehole has been excavated and it will be equipped
- A second borehole to be excavated in the summer 2021
- Intense & international surface investigations programme in Summer 2021
- 17+3.5+1+11M€ funding through national and regional funds

SPB: ET sites under characterisation

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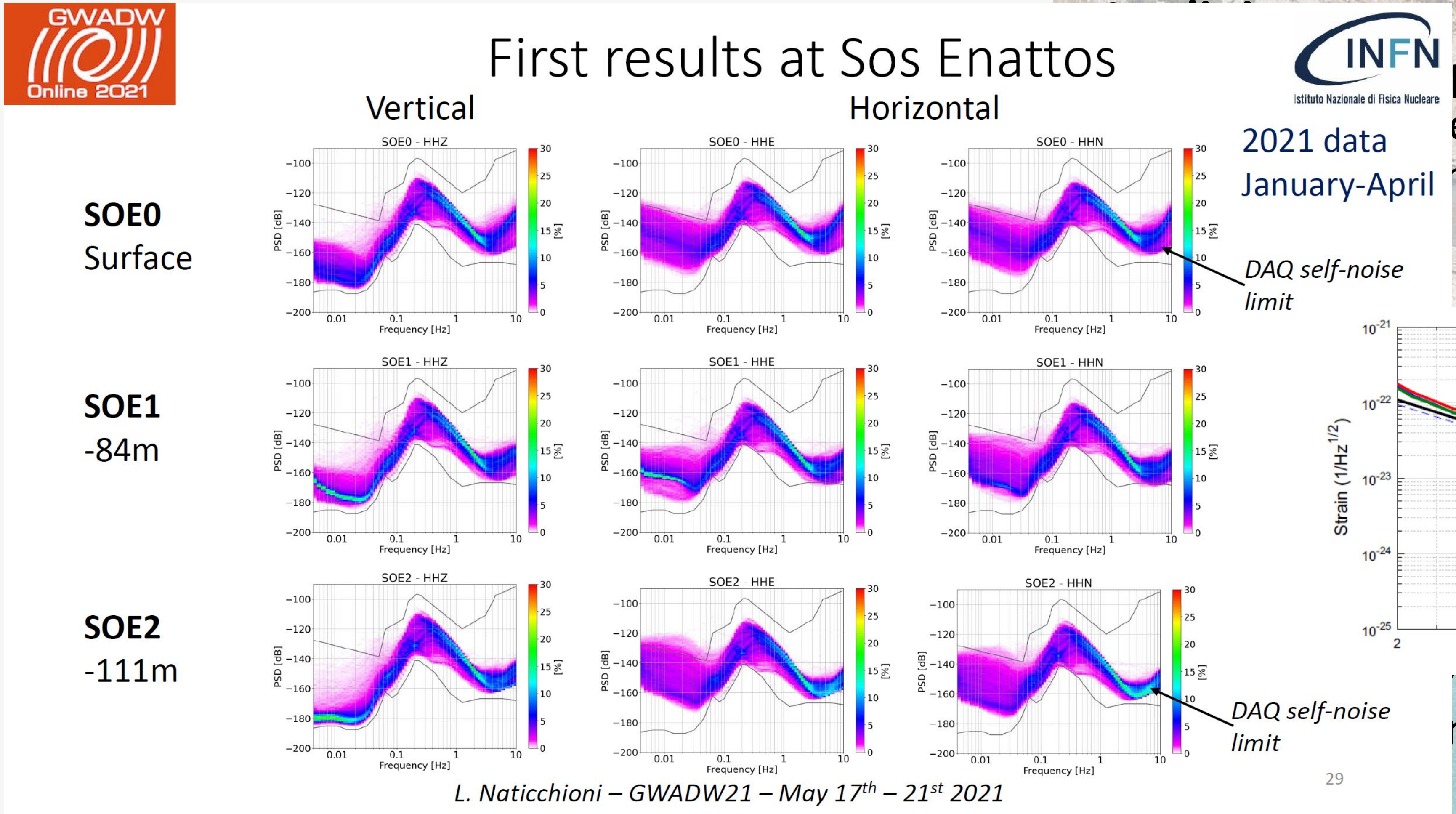

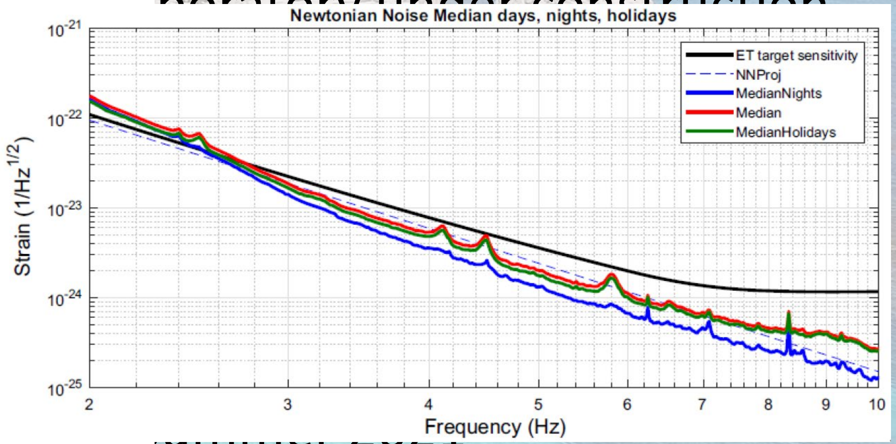

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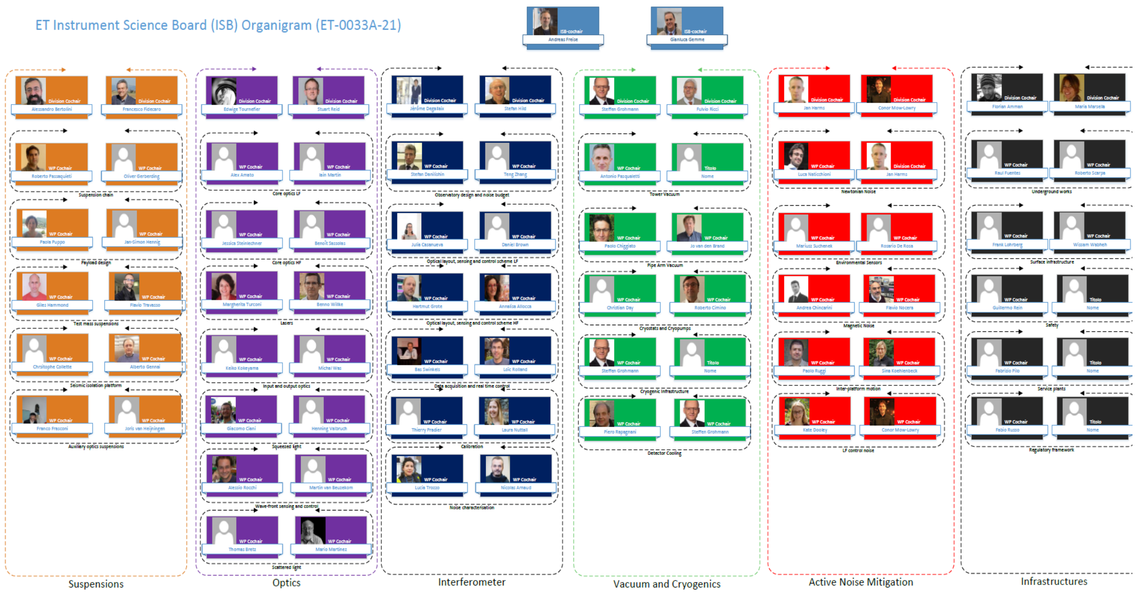
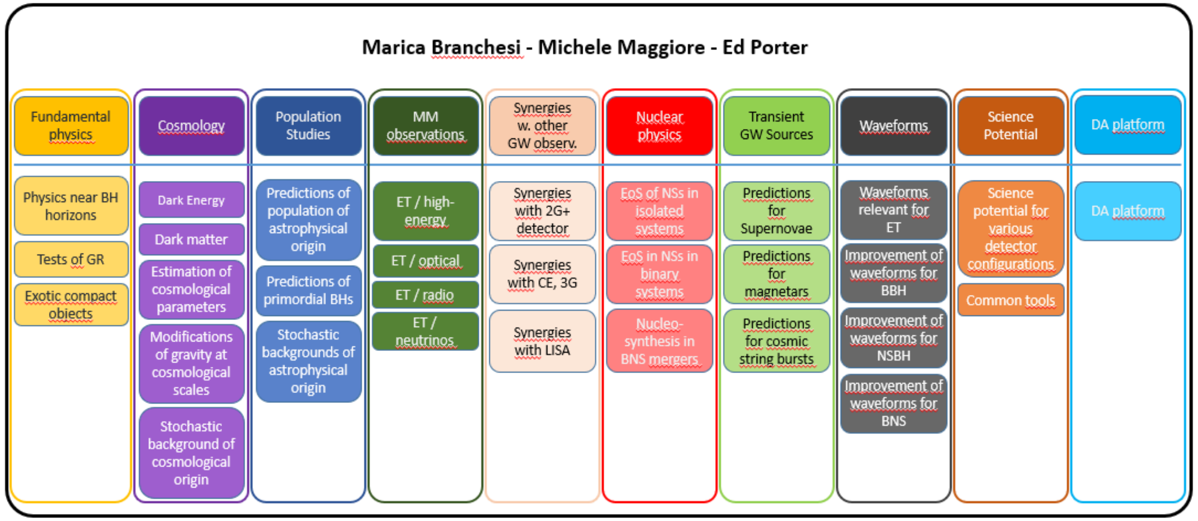
nding through national and

-L.Naticchioni e tal.,***Characterization of the Sos Enattos site for the Einstein Telescope***,**JPCS**1468,2020
-M.DiGiovanni et al.,***A seismological study of the Sos Enattos Area–the Sardinia Candidate Site for the Einstein Telescope***, **SRL**,2020https://doi.org/10.1785/0220200186
-A.Allocca et al.,***Seismic glitchness at Sos Enattos site: impact on intermediate black hole binaries detection efficiency***, **EPJP**,2021https://doi.org/10.1140/epjp/s13360-021-01450-8

Instrument Science Board



Observational Science



How to join?

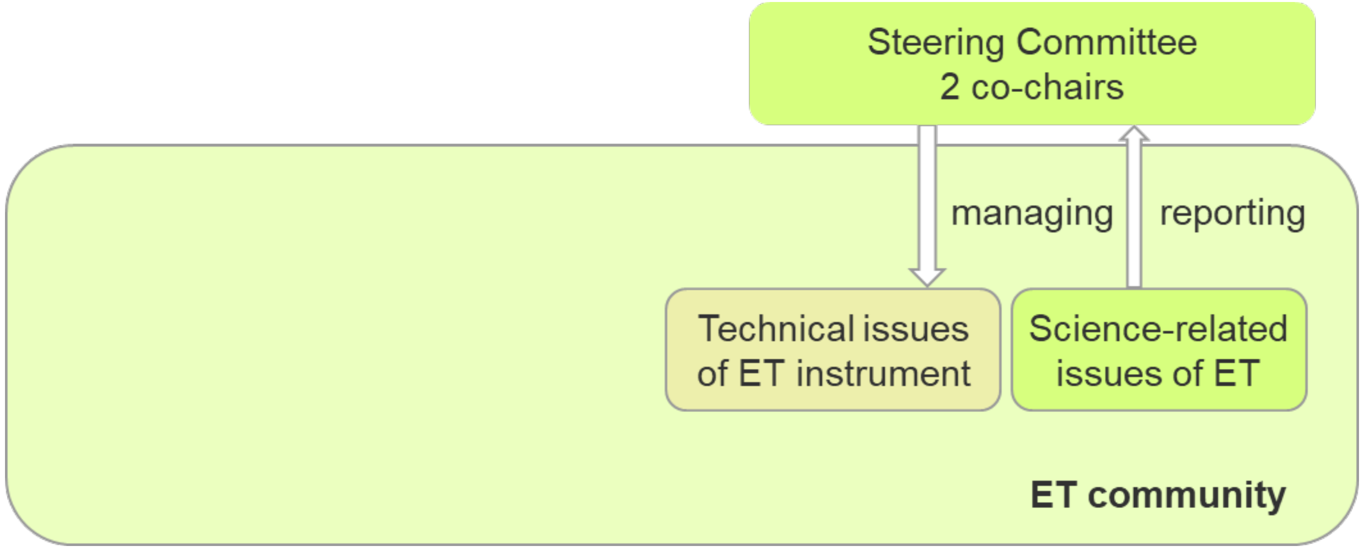
If you are interested in contributing, please get in touch with one of the division or working group chairs

Check out the ISB webpage: https://wiki.et-gw.eu/ISB/WelcomePage

The Instrument Science Board (ISB) is described in more detail in:
https://apps.et-gw.eu/tds/ql/?c=15709
https://apps.et-gw.eu/tds/ql/?c=15707

ET Structure - 2020

- Until now: A broad ET scientific community;



Governance proposal for the Preparation phase

ESFRI

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An interim structure for the ET project organization until establishment of a Council

Consortium

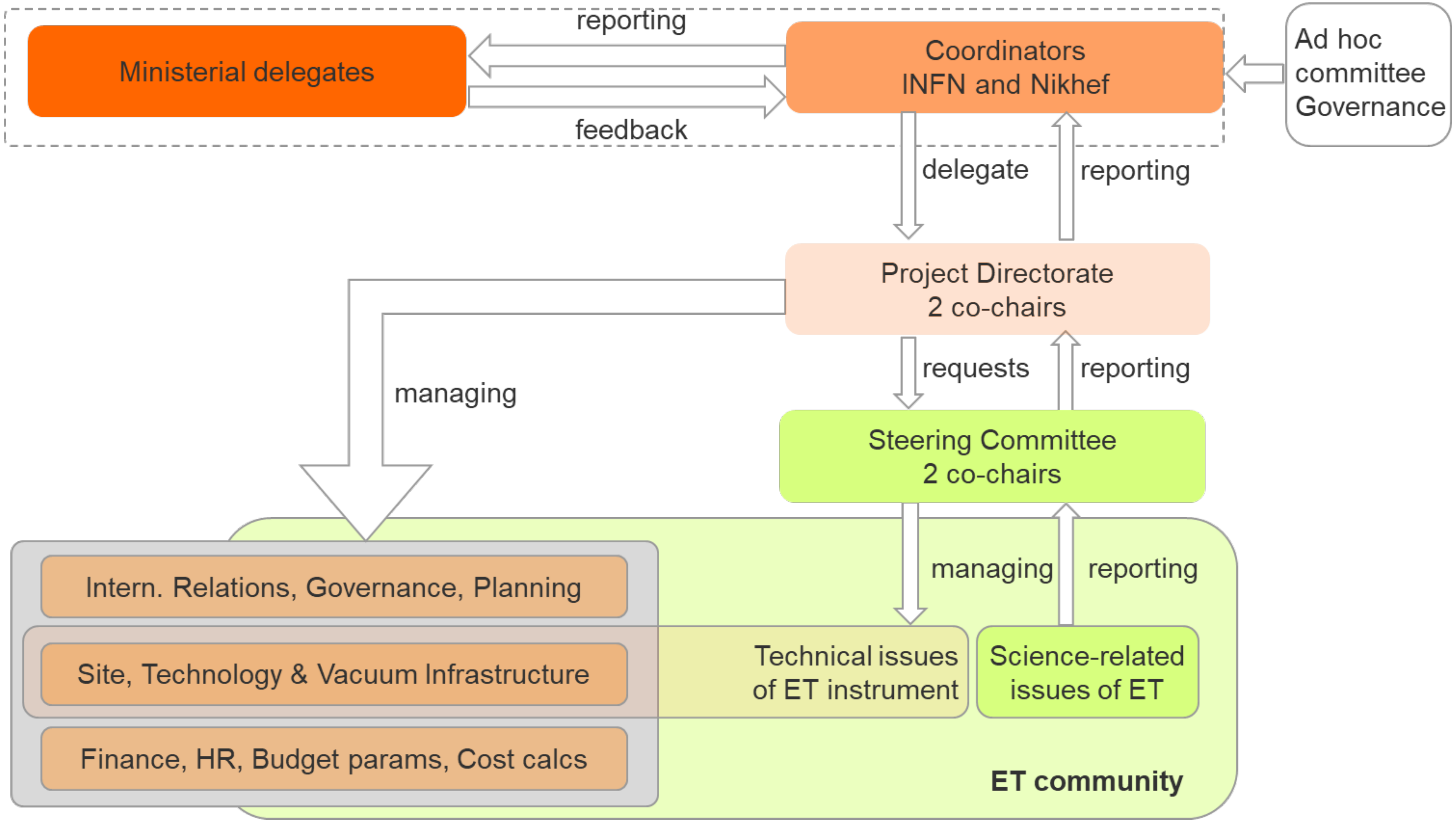
Stan Bentvelsen
Antonio Zoccoli

Project directorate

Jo v.d. Brand
Fernando Ferroni

ET Collaboration

Michele Punturo
Harald Lück



Proposal for governance in the construction phase

Structure during Implementation phase

Council
Assisted by several bodies (*e.g.* STAC)

Project Directorate
evolves into Einstein Telescope Observatory

ET Observatory will be a legal entity
and will have significant staff

Verify by expert panel on governance and project organization