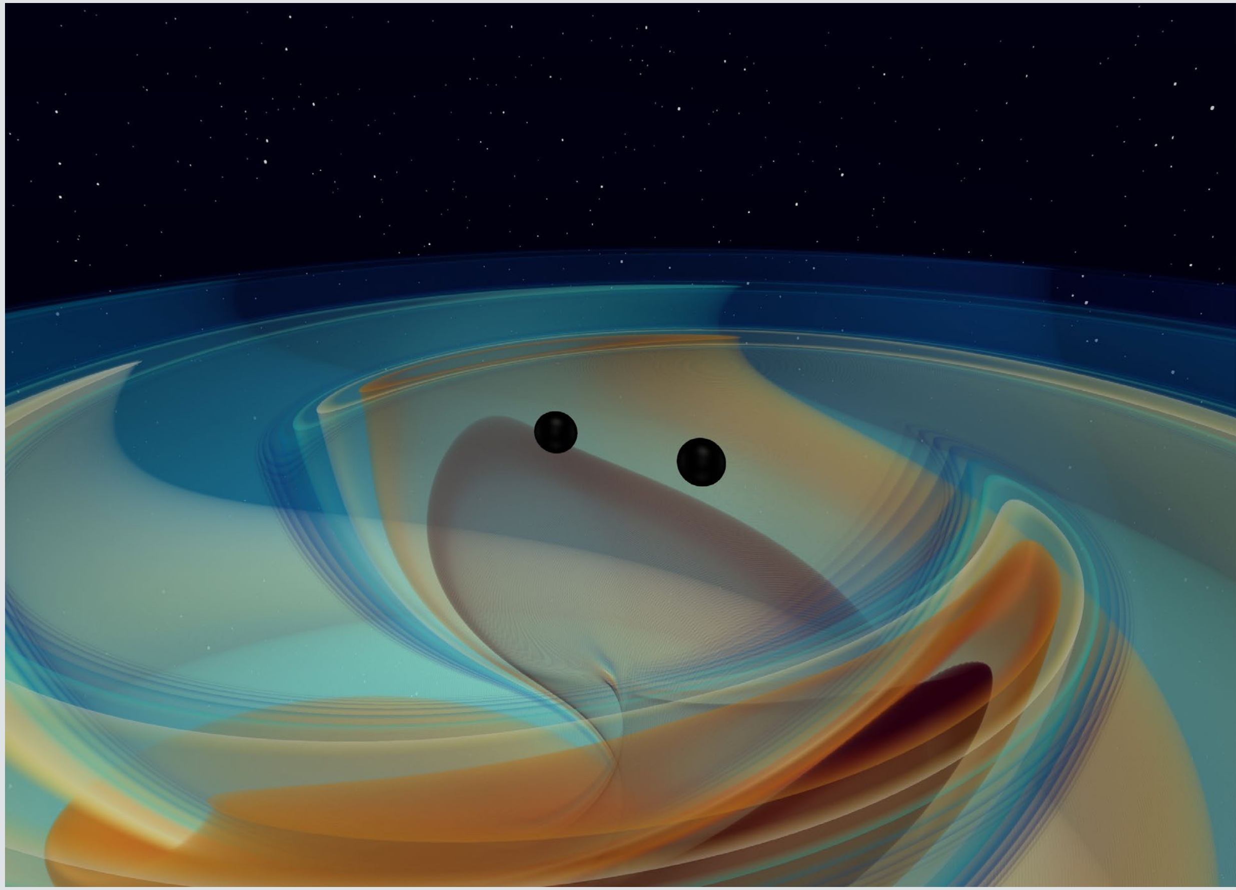
FIVE YEARS OF GRAVITATIONAL WAVE OBSERVATIONS: WHERE WE STAND.

G. Cella – INFN Pisa
LIGO-Virgo-KAGRA collaboration

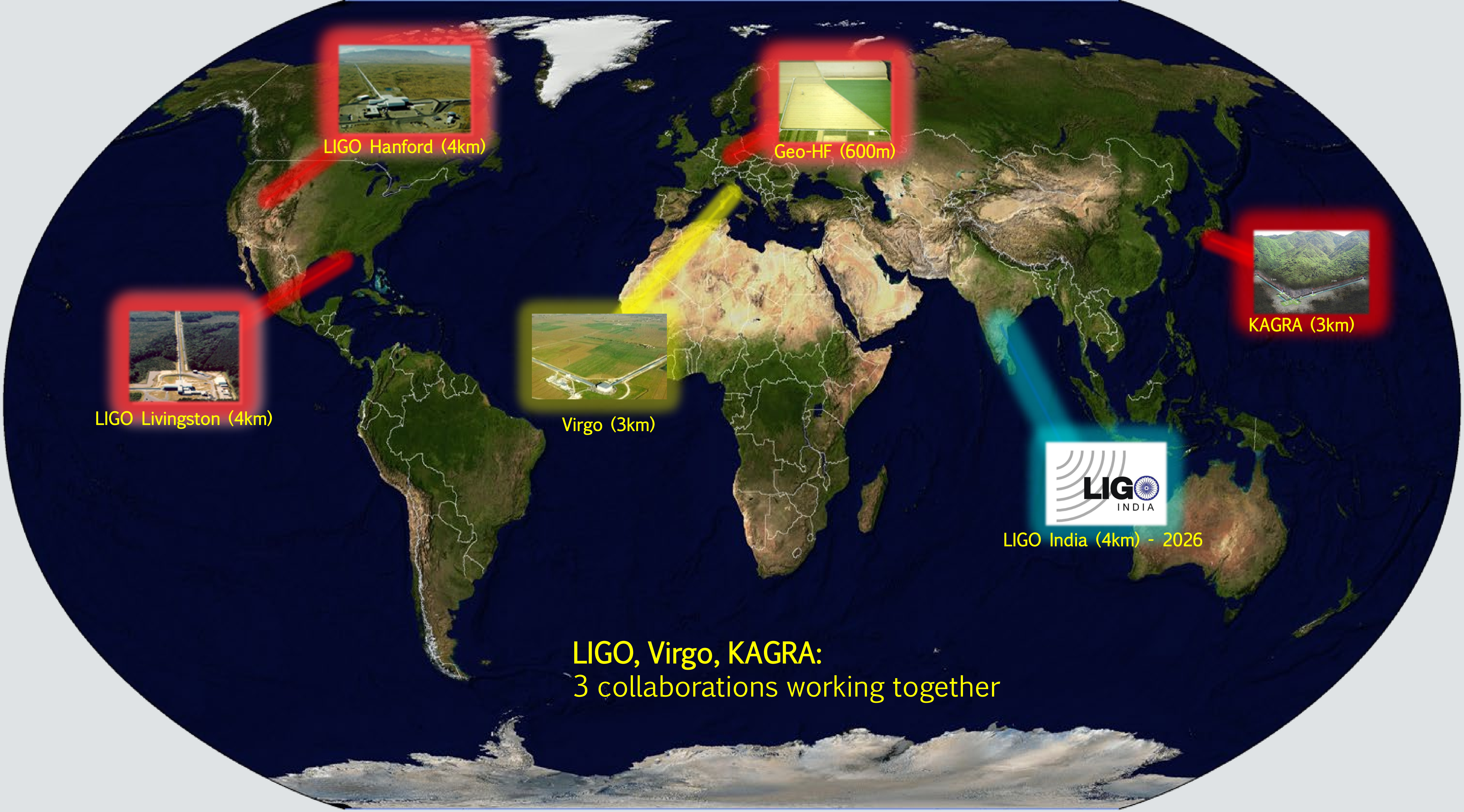
La Thuile 2021 – Les Rencontres de Physique de la Vallée d'Aoste. March 9, 2021-March 11,2021



LIGO VIRGO KAGRA

INFN PISA Istituto Nazionale di Fisica Nucleare Sezione di Pisa

VIRGO

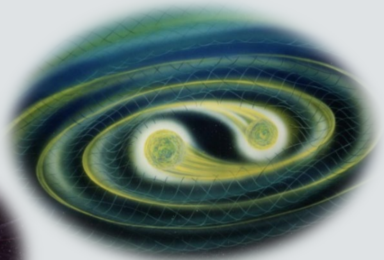

LIGO Hanford (4km)
Geo-HF (600m)
KAGRA (3km)
LIGO Livingston (4km)
Virgo (3km)
LIGO INDIA
LIGO India (4km) - 2026
LIGO, Virgo, KAGRA:
3 collaborations working together

Gravitational wave observations

Several kind of searches, roughly classified in 4 groups:

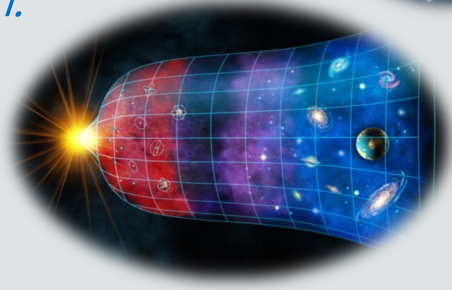
- **Burst:** search for transients with minimal assumptions about signal's shape
- **CBC:** *signals from compact binary coalescences, searched with specific, theoretically motivated (GR or alternative models) waveforms.*
- **CW:** *continuous signals: rotating neutron stars, …..*
- **Stochastic:** *stochastic signals, astrophysical or cosmological origin.*

Core collapse massive stars, cosmic strings, …



Coalescing binaries: BH-BH, NS-NS, BH-NS

Spinning NS (Isolated or not), Instabilities, …

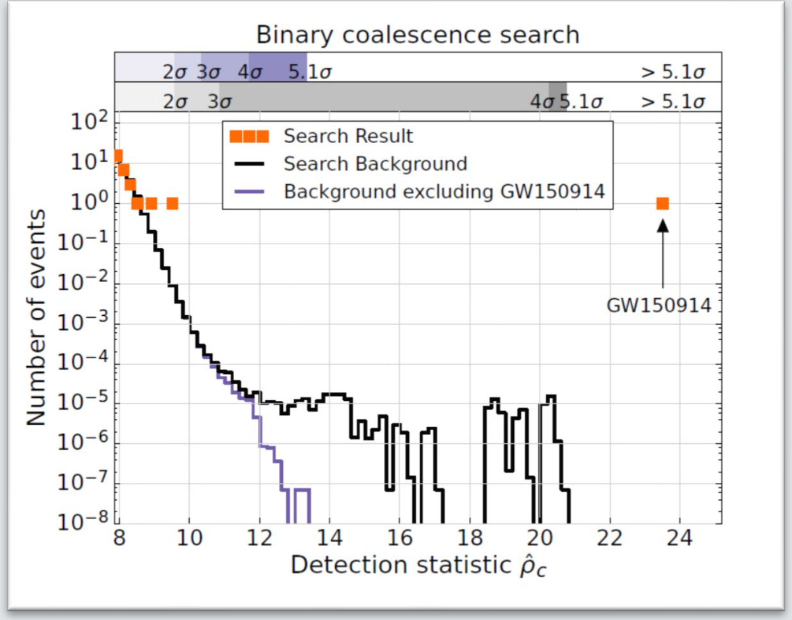


Inflation, phase transitions, cosmic strings, astrophysical backgrounds,…

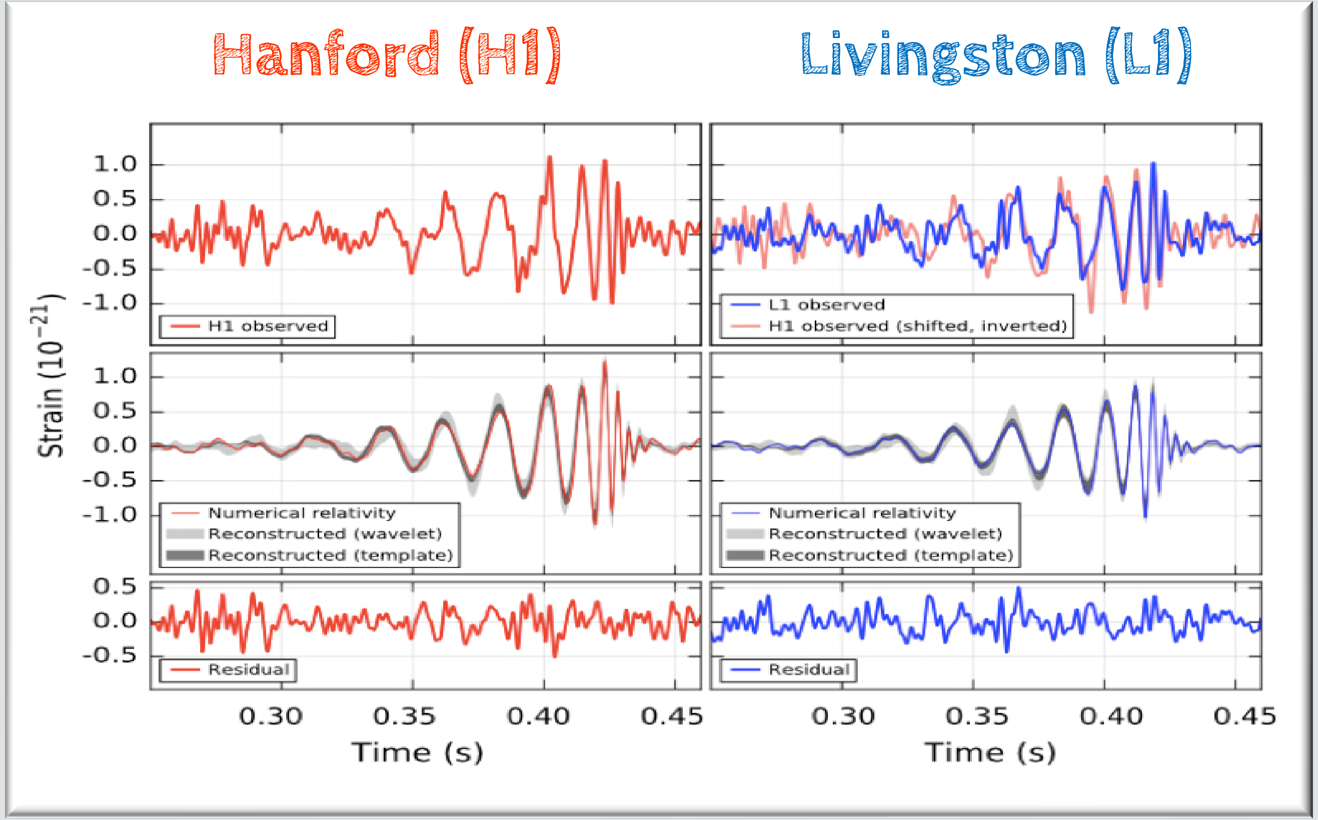
Direct information about mass-energy distribution, unique or complementary observative channel.

GW150914: the first direct GW observation

Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$



- P_{FA} = 1/203000 yr^{-1}
- Significativity > 5.3σ

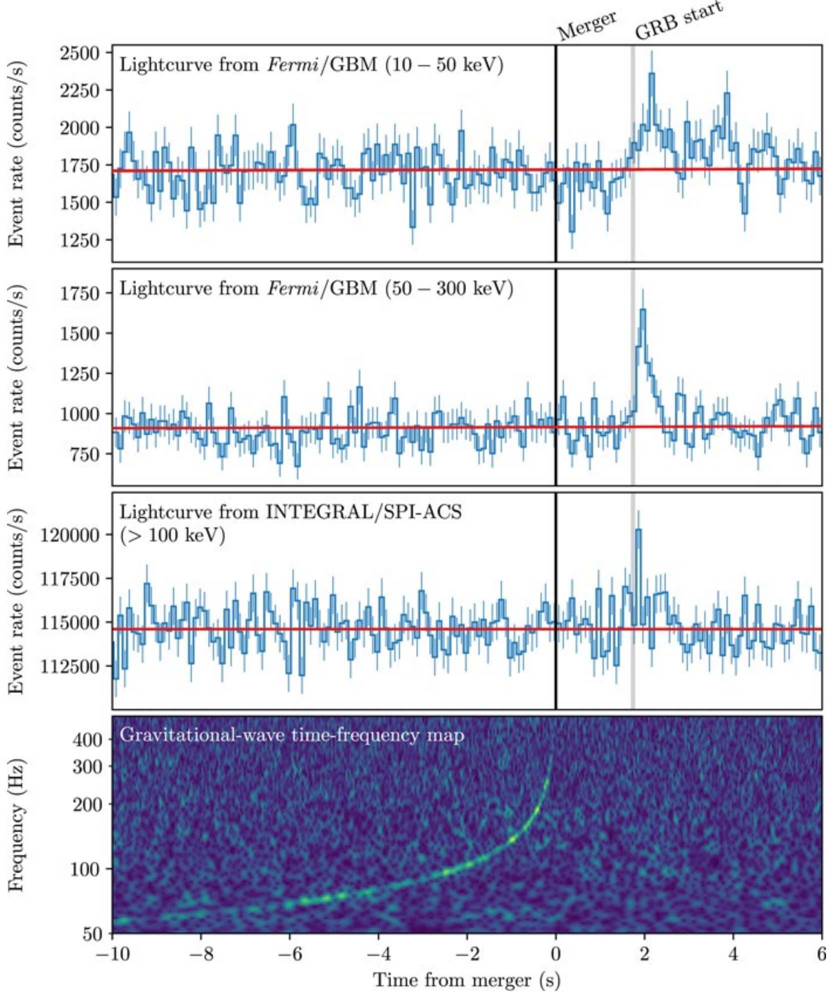


Interpretation: BBH coalescence
Similar events followed:

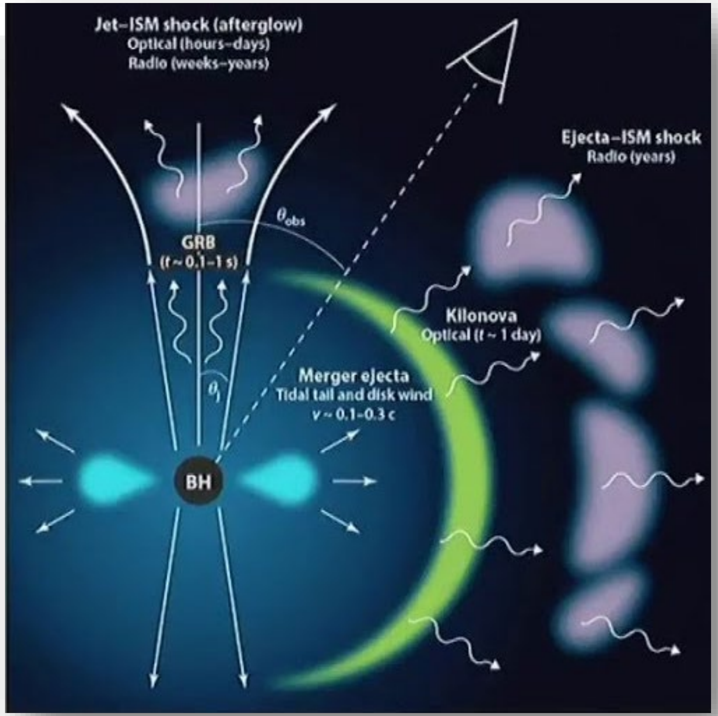
- **GW150914** (September 14th 2015)
- **GW151226** (December 26th 2015)
- **GW170104** (January 4th 2016)

Phys. Rev. Lett. 119, 161101 (2017) Astrophys. J. Lett. 848, L12 (2017) Astrophys. J. Lett. 848, L13 (2017)

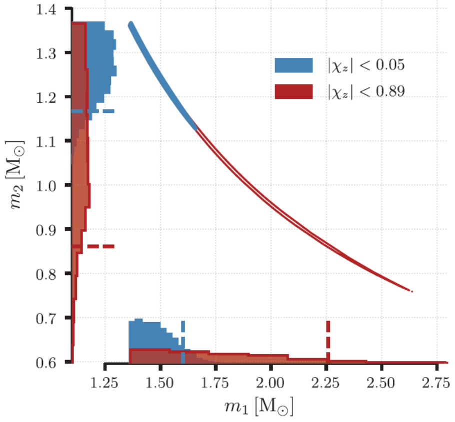
GW170817: a BNS coalescence

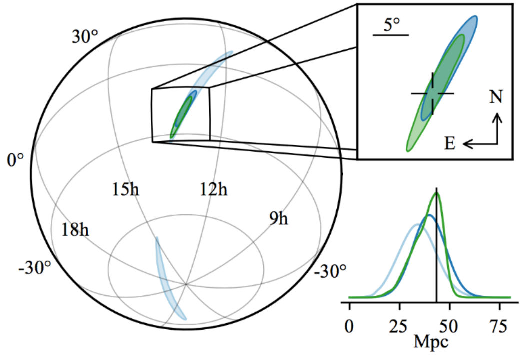


- Seen in GW data
- Cohincident (in 2s) with a short GRB detected by Fermi/GBM & INTEGRAL (not so energetic, probably off axis)
- Well localized (31 deg^2 ➔ 16 deg^2)
- Optical counterpart found in host galaxy NGC 4993
- Kilonova
- Afterglow observations



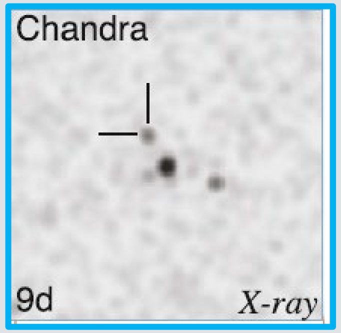
Credit: Metzger

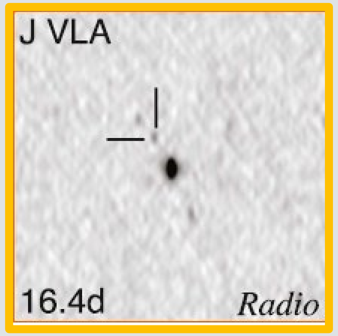




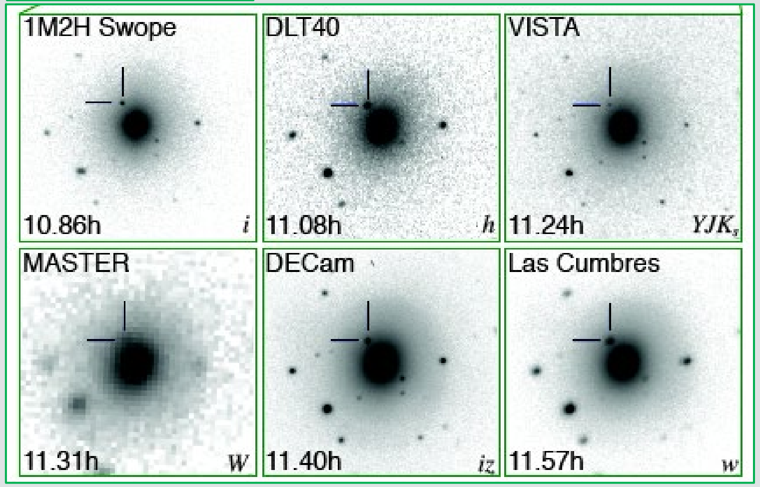
	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–1.60 $M_\odot$	1.36–2.26 $M_\odot$
Secondary mass m_2	1.17–1.36 $M_\odot$	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0	0.4–1.0
Total mass m_{tot}	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy E_{rad}	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance D_L	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Counterparts

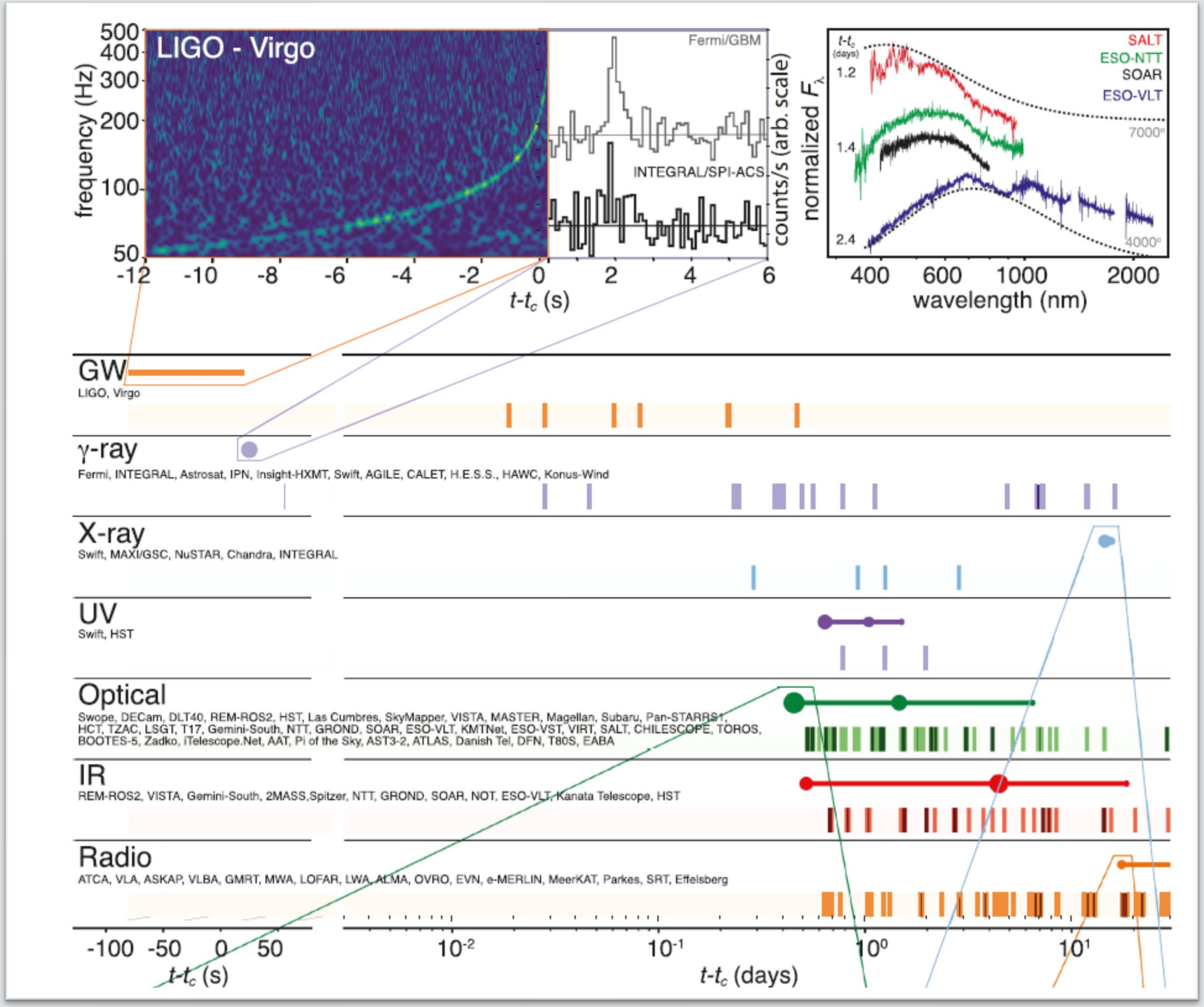




Coulter et al. 2017 | *Yang et al. 2017* | *Tanvir et al. 2017*



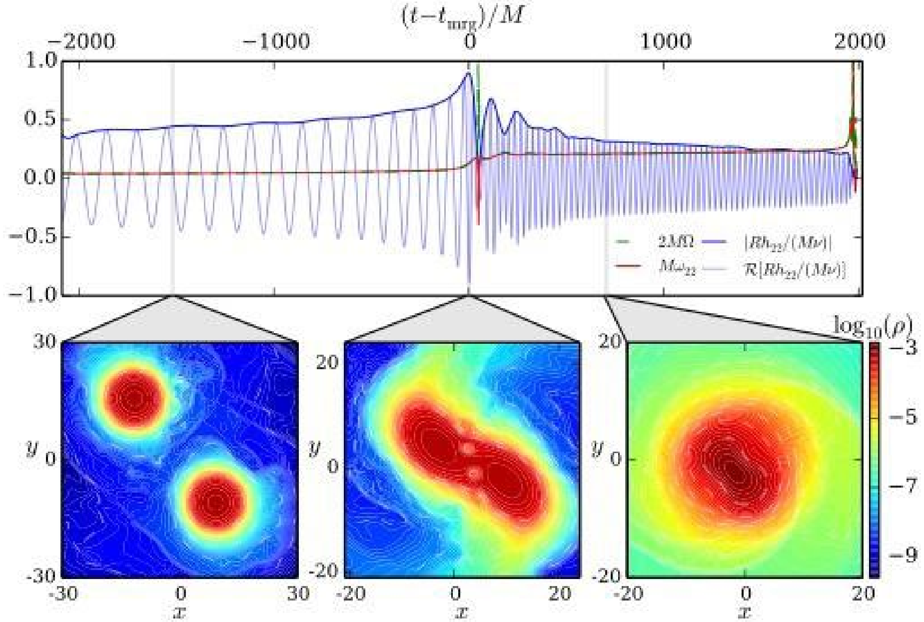
Lipunov et al. 2017 | *Allam et al. 2017* | *Accavi et al. 2017*

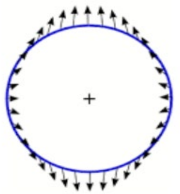


Observatories are still looking at this today.

Nuclear matter EOS

Phys. Rev. Letter **121**, 161101 (2018) Phys. Rev. Lett. **111**, 071101

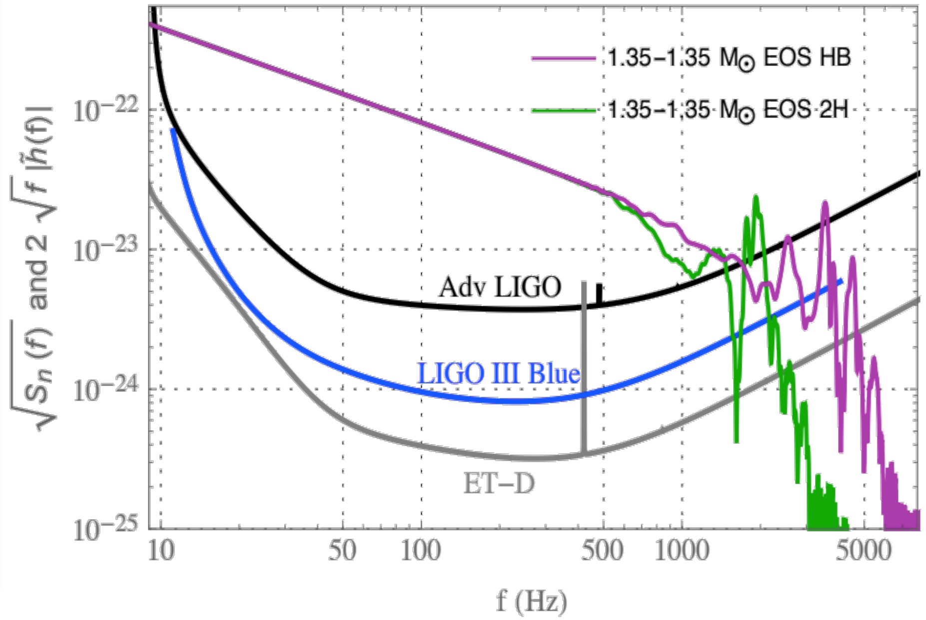


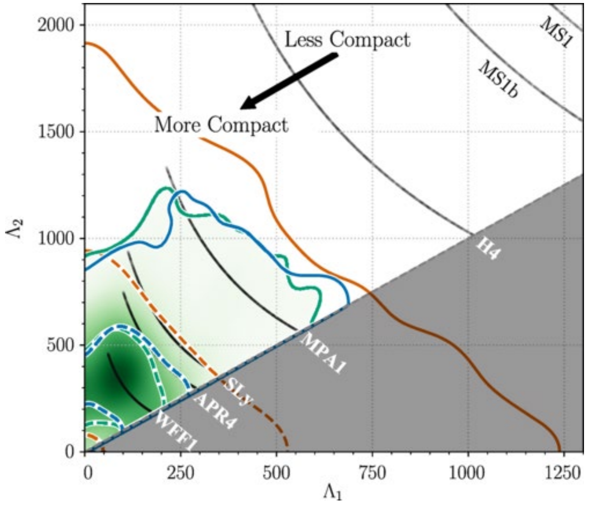


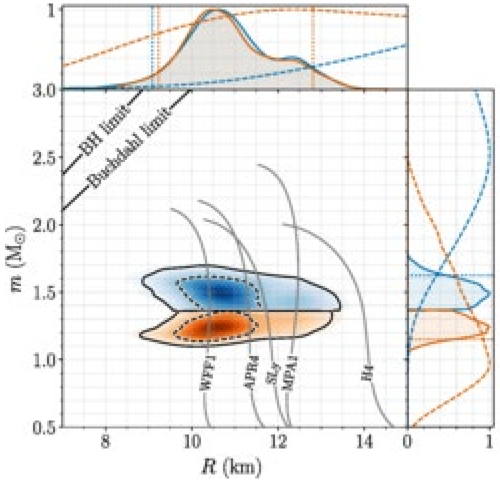
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

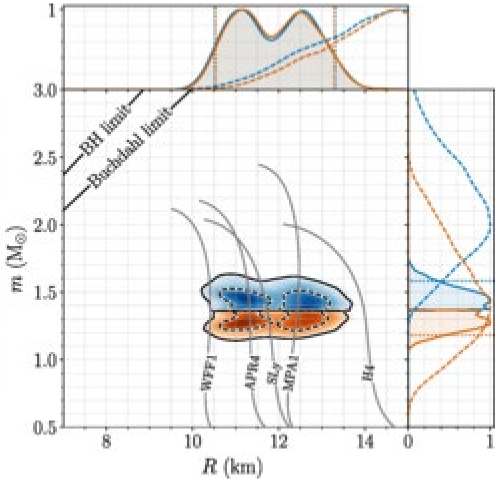
$$\lambda = \frac{2}{3} k_2 R^5$$

- Simplest effect: quadrupolar deformation induced by gravitational strain
- These tidal effects are imprinted on GW signal…
- … which contains information about nuclear matter Equation of State









- «More compact» NS favoured
- «Too stiff» equation of state disfavoured
- But a large amount of information is coded in high frequency components of the signal: **we will be able to look at this much better in the future**

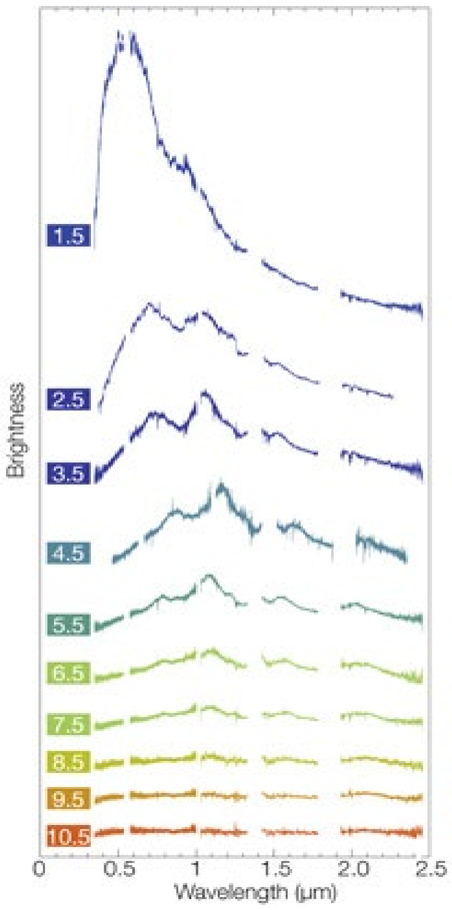
$$\Lambda = \lambda \left(\frac{c^2}{GM} \right)^5$$

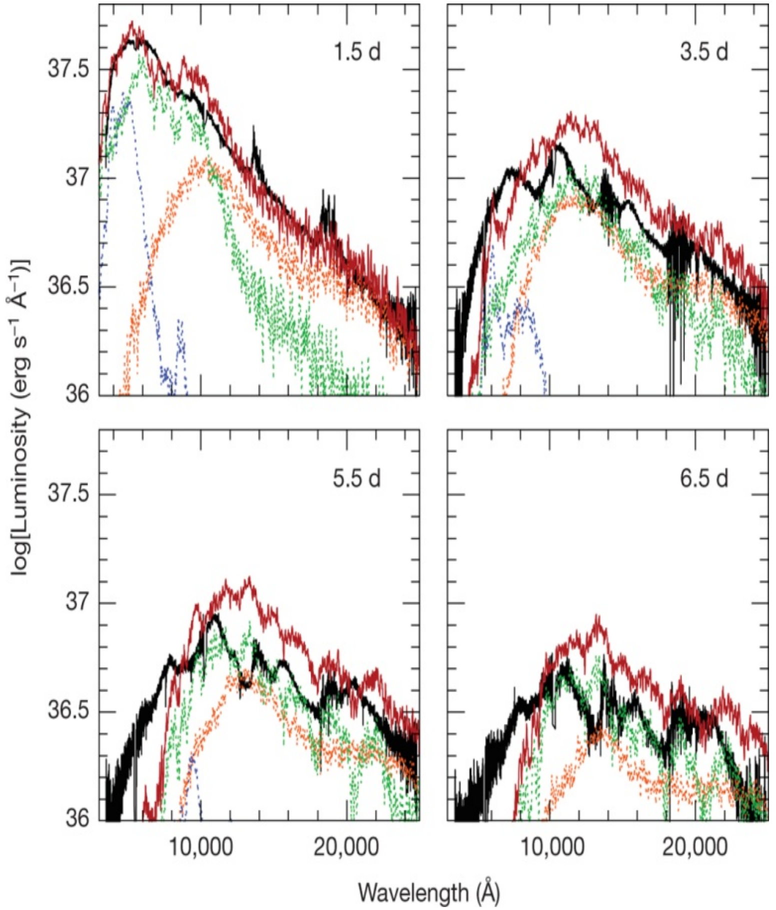
Kilonova

Siegel & Metzger 2017b, arXiv:1711.00868

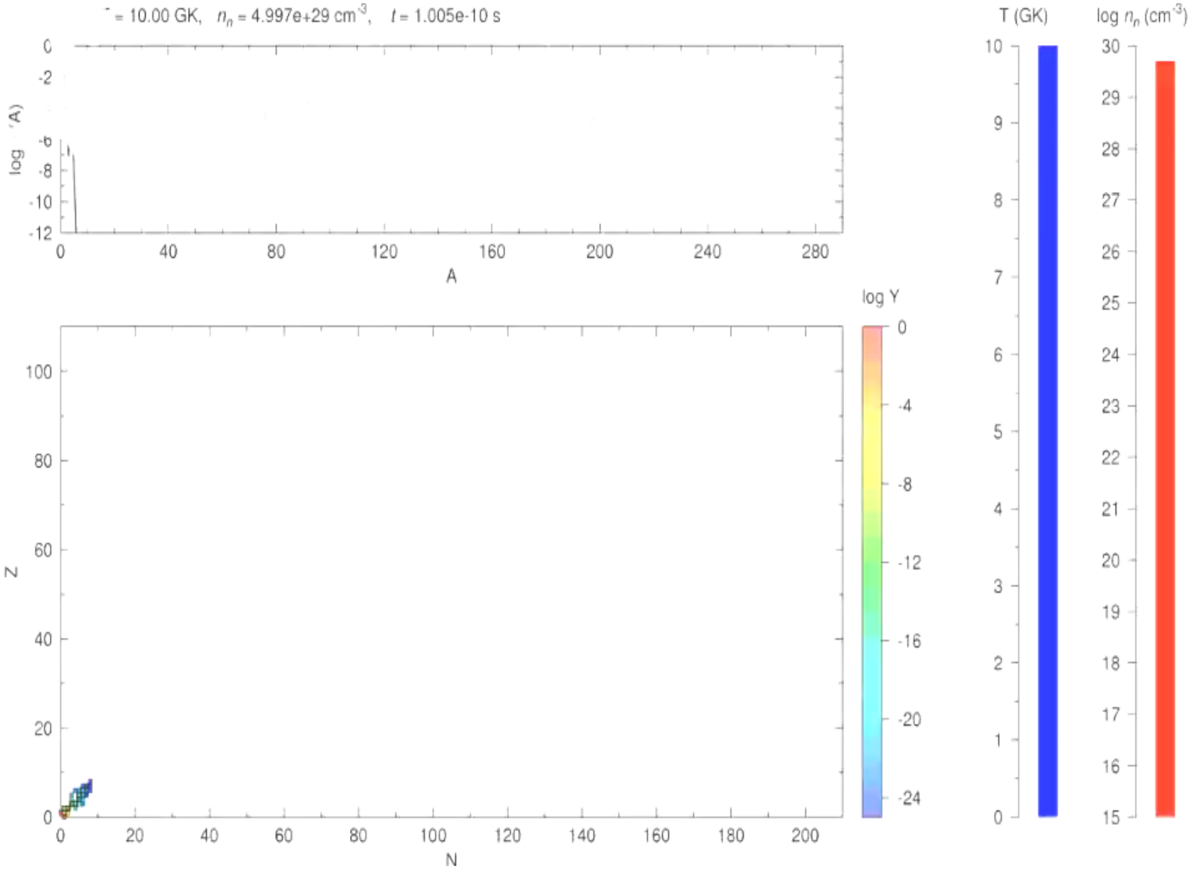
Siegel & Metzger 2017a, PRL, arXiv:1705.05473

Credits: Eso/E. Pian et al./S. Smartt & ePessto



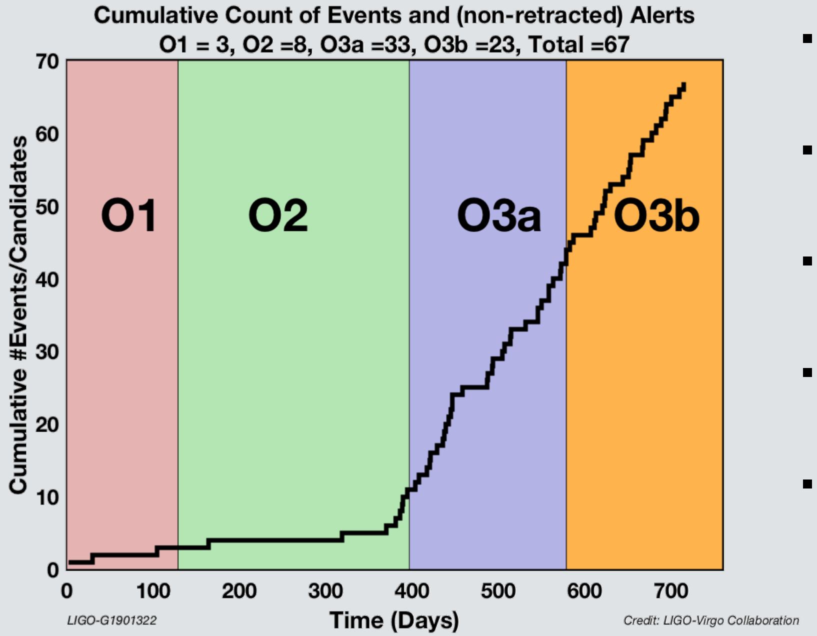


E Pian *et al. Nature* **551,** 67–70 (2017)
doi:10.1038/nature24298

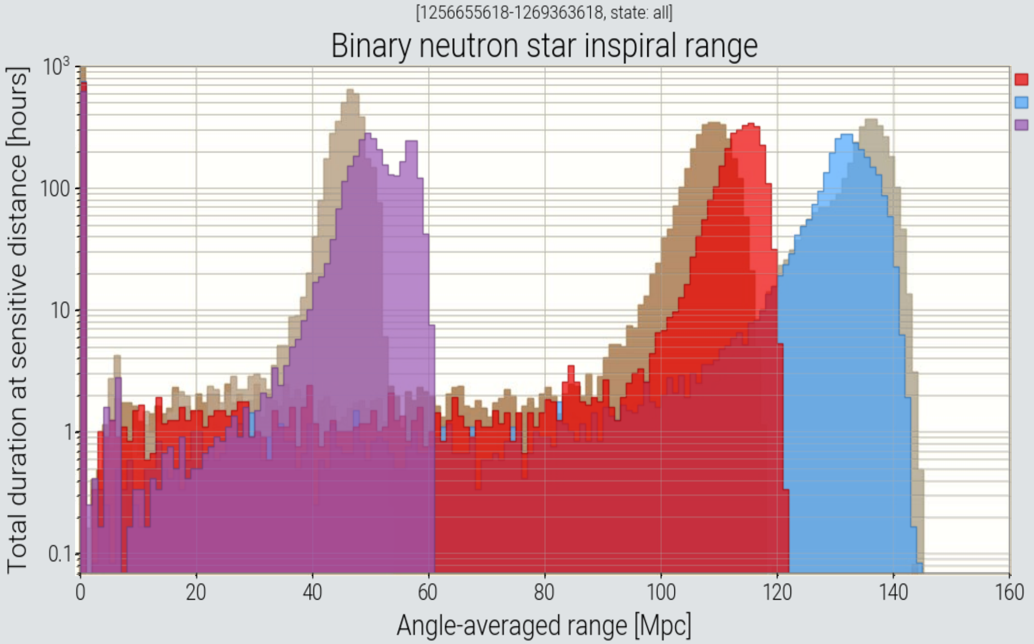


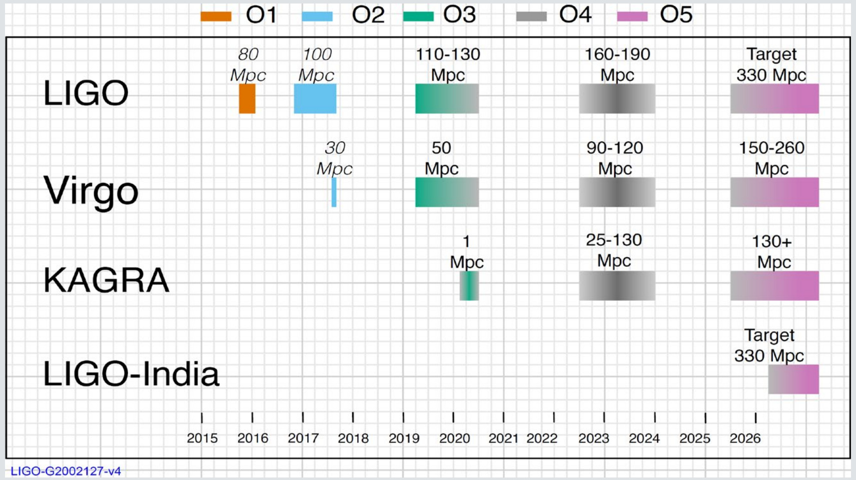
Matter ejected in the post-merger phase undergoes r-process

The last scientific run

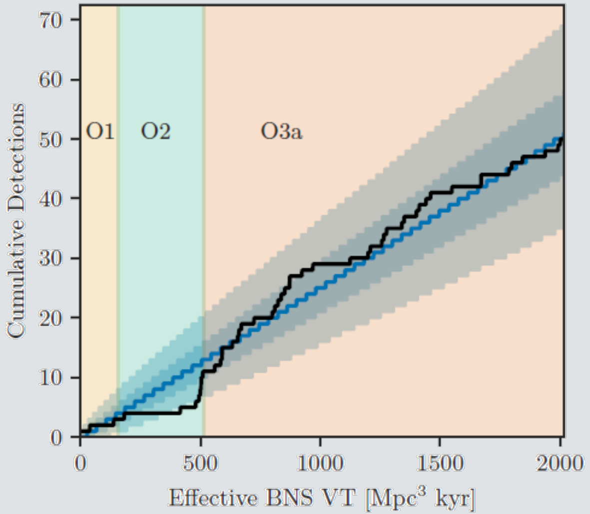


- Very productive run (in spite of COVID pandemy)
- Events rate scaled as expected
- Continuous improvement of detector sensitivities
- Many alerts sent to the astrophysics community
- A new scenario, which tested the capabilities of the LVK collaboration



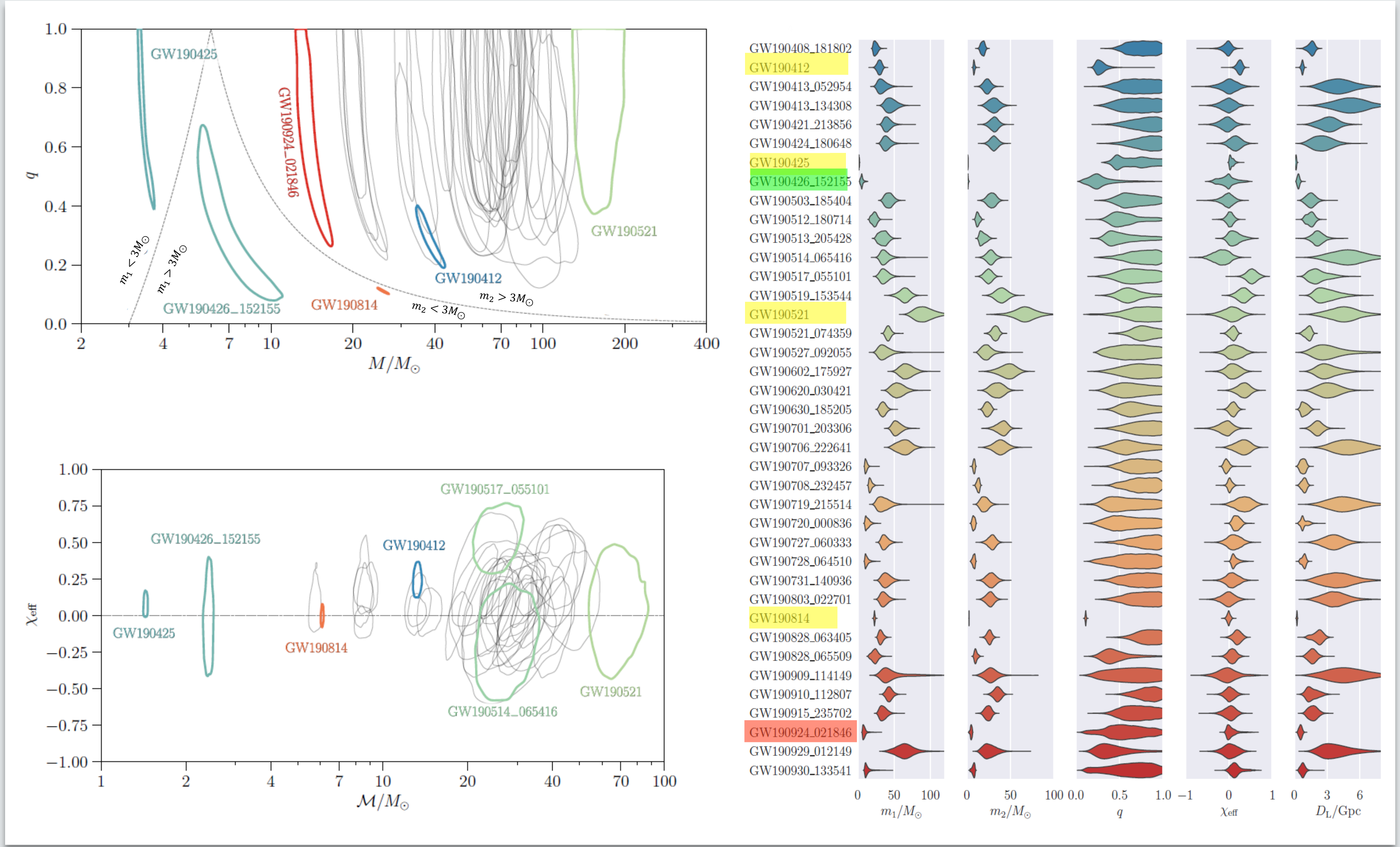


- Huge amount of information to elaborate (still in progress)
- We are now in an upgrade phase (still slowed down by pandemy)
- O4 run will change again the scenario:
  - about a factor 8 in events rate
  - New discoveries?

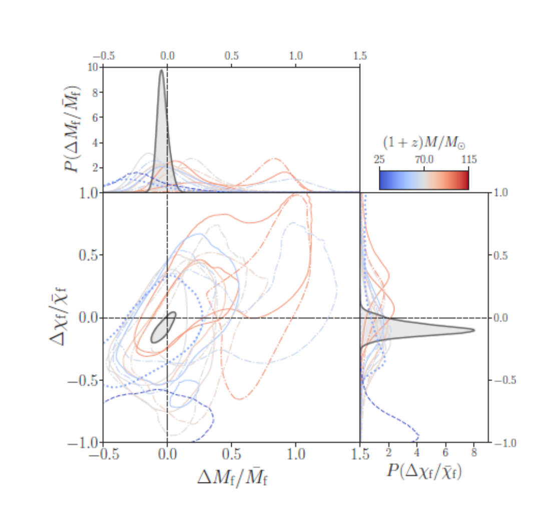


A bird eye view of O3a events https://arxiv.org/abs/2010.14527v2

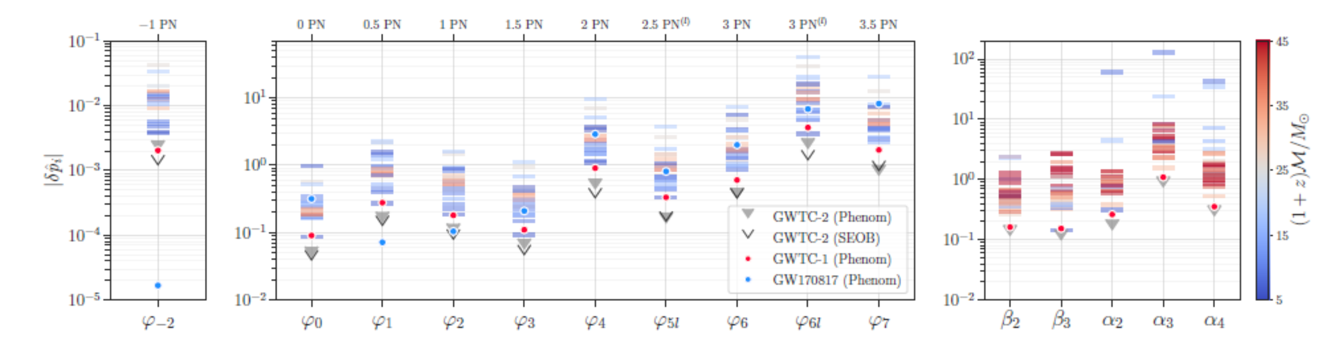
- O3a catalog paper: Characterization of the O3a CBC events. Basic reference for GW physics.
- Available events (both exceptional and non exceptional) start shaping our understanding of populations
- Statistical recovery of key information (H_0, lensing, spin distribution, higher order corrections, eccentricity, …) is becoming possible: ➔ O4 ➔ O5



O3a CBC Testing GR https://arxiv.org/abs/2010.14529



Event	Inst.	Properties					SNR	Tests performed							
		D_L [Gpc]	$(1+z)M$ [$M_\odot$]	$(1+z)\mathcal{M}$ [$M_\odot$]	$(1+z)M_f$ [$M_\odot$]	χ_f		RT	IMR	PAR	SIM	MDR	RD	ECH	POL
GW190408_181802	HLV	$1.58^{+0.40}_{-0.59}$	$55.6^{+3.4}_{-3.8}$	$23.8^{+1.4}_{-1.7}$	$53.1^{+3.2}_{-3.4}$	$0.67^{+0.06}_{-0.07}$	$15.3^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	✓	✓	✓
GW190412	HLV	$0.74^{+0.14}_{-0.17}$	$44.2^{+4.4}_{-4.6}$	$15.2^{+0.2}_{-0.2}$	$42.9^{+4.5}_{-4.7}$	$0.67^{+0.05}_{-0.06}$	$18.9^{+0.2}_{-0.3}$	✓	–	✓	✓	✓	–	✓	✓
GW190421_213856	HL	$3.15^{+1.37}_{-1.42}$	$109.7^{+16.1}_{-12.5}$	$47.0^{+6.8}_{-6.0}$	$104.8^{+14.7}_{-11.5}$	$0.68^{+0.10}_{-0.11}$	$10.7^{+0.2}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	–
GW190503_185404	HLV	$1.52^{+0.71}_{-0.66}$	$91.9^{+11.6}_{-11.7}$	$38.8^{+5.5}_{-5.9}$	$88.0^{+10.5}_{-10.7}$	$0.67^{+0.09}_{-0.12}$	$12.4^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	✓
GW190512_180714	HLV	$1.49^{+0.53}_{-0.59}$	$45.3^{+3.9}_{-2.8}$	$18.6^{+0.9}_{-0.8}$	$43.4^{+4.1}_{-2.8}$	$0.65^{+0.07}_{-0.07}$	$12.2^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	✓	✓	✓
GW190513_205428	HLV	$2.16^{+0.94}_{-0.80}$	$73.9^{+13.6}_{-7.0}$	$29.7^{+6.1}_{-2.6}$	$70.8^{+12.2}_{-6.9}$	$0.69^{+0.14}_{-0.12}$	$12.9^{+0.3}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	✓
GW190517_055101	HLV	$2.11^{+1.79}_{-1.00}$	$85.8^{+9.7}_{-7.6}$	$36.1^{+4.0}_{-3.5}$	$80.0^{+8.9}_{-6.6}$	$0.87^{+0.05}_{-0.07}$	$10.7^{+0.4}_{-0.6}$	✓	–	✓	–	✓	–	✓	✓
GW190519_153544	HLV	$2.85^{+2.02}_{-1.14}$	$156.8^{+16.3}_{-18.1}$	$65.9^{+7.5}_{-10.3}$	$148.2^{+14.5}_{-15.5}$	$0.80^{+0.07}_{-0.12}$	$15.6^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	✓
GW190521	HLV	$4.53^{+2.30}_{-2.13}$	$272.6^{+40.0}_{-33.1}$	$116.3^{+14.9}_{-17.1}$	$259.2^{+36.6}_{-29.0}$	$0.73^{+0.11}_{-0.14}$	$14.2^{+0.3}_{-0.3}$	✓	–	✓	–	–	✓	✓	✓
GW190521_074359	HL	$1.28^{+0.38}_{-0.57}$	$92.7^{+4.8}_{-5.5}$	$39.9^{+2.2}_{-2.9}$	$88.1^{+4.3}_{-4.9}$	$0.72^{+0.05}_{-0.07}$	$25.8^{+0.1}_{-0.2}$	✓	✓	✓	✓	✓	✓	✓	–
GW190602_175927	HLV	$2.99^{+2.02}_{-1.26}$	$173.9^{+23.0}_{-21.5}$	$74.0^{+10.5}_{-13.4}$	$165.6^{+20.5}_{-19.2}$	$0.71^{+0.10}_{-0.13}$	$12.8^{+0.2}_{-0.3}$	✓	–	✓	–	✓	✓	✓	✓
GW190630_185205	LV	$0.93^{+0.56}_{-0.40}$	$69.7^{+4.2}_{-3.5}$	$29.5^{+1.6}_{-1.6}$	$66.4^{+4.2}_{-3.3}$	$0.70^{+0.06}_{-0.07}$	$15.6^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	–	✓	–
GW190706_222641	HLV	$5.07^{+2.57}_{-2.11}$	$183.7^{+21.4}_{-26.8}$	$77.0^{+10.0}_{-16.9}$	$173.6^{+18.8}_{-22.9}$	$0.80^{+0.08}_{-0.17}$	$12.6^{+0.2}_{-0.4}$	✓	✓	✓	–	✓	✓	✓	✓
GW190707_093326	HL	$0.80^{+0.37}_{-0.38}$	$23.1^{+1.7}_{-0.5}$	$9.89^{+0.1}_{-0.09}$	$22.1^{+1.8}_{-0.5}$	$0.66^{+0.03}_{-0.04}$	$13.3^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	–	✓	–
GW190708_232457	LV	$0.90^{+0.33}_{-0.40}$	$36.1^{+2.6}_{-0.8}$	$15.5^{+0.3}_{-0.2}$	$34.4^{+2.7}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$13.1^{+0.2}_{-0.3}$	✓	–	✓	✓	✓	✓	✓	–
GW190720_000836	HLV	$0.81^{+0.71}_{-0.33}$	$24.9^{+4.9}_{-1.2}$	$10.4^{+0.2}_{-0.1}$	$23.7^{+5.1}_{-1.2}$	$0.72^{+0.06}_{-0.05}$	$11.0^{+0.3}_{-0.8}$	✓	–	✓	✓	✓	–	✓	✓
GW190727_060333	HLV	$3.60^{+1.56}_{-1.51}$	$105.2^{+11.9}_{-11.0}$	$45.1^{+5.3}_{-5.8}$	$100.0^{+10.5}_{-10.0}$	$0.73^{+0.10}_{-0.10}$	$11.9^{+0.3}_{-0.5}$	✓	✓	✓	–	✓	✓	✓	✓
GW190728_064510	HLV	$0.89^{+0.25}_{-0.37}$	$23.9^{+5.3}_{-0.7}$	$10.1^{+0.09}_{-0.08}$	$22.7^{+5.5}_{-0.7}$	$0.71^{+0.04}_{-0.04}$	$13.0^{+0.2}_{-0.4}$	✓	–	✓	✓	✓	–	✓	✓
GW190814	LV[a]	$0.24^{+0.04}_{-0.05}$	$27.1^{+1.1}_{-1.0}$	$6.41^{+0.02}_{-0.02}$	$26.9^{+1.1}_{-1.0}$	$0.28^{+0.02}_{-0.02}$	$24.9^{+0.1}_{-0.2}$	✓	✓	✓	–	✓	–	–	–
GW190828_063405	HLV	$2.22^{+0.63}_{-0.95}$	$80.1^{+6.8}_{-5.9}$	$34.6^{+2.9}_{-2.7}$	$75.9^{+6.0}_{-5.2}$	$0.76^{+0.06}_{-0.07}$	$16.2^{+0.2}_{-0.3}$	✓	✓	✓	✓	✓	✓	✓	✓
GW190828_065509	HLV	$1.66^{+0.63}_{-0.61}$	$44.3^{+6.6}_{-3.9}$	$17.4^{+0.6}_{-0.7}$	$42.7^{+6.8}_{-4.1}$	$0.65^{+0.09}_{-0.08}$	$10.0^{+0.3}_{-0.5}$	✓	–	✓	✓	✓	–	✓	✓
GW190910_112807	LV	$1.57^{+1.07}_{-0.64}$	$102.1^{+10.5}_{-7.8}$	$44.0^{+4.7}_{-3.7}$	$97.3^{+9.4}_{-7.1}$	$0.70^{+0.08}_{-0.07}$	$14.1^{+0.2}_{-0.3}$	✓	✓	✓	–	✓	✓	✓	–
GW190915_235702	HLV	$1.70^{+0.71}_{-0.64}$	$78.5^{+8.3}_{-8.0}$	$33.3^{+3.3}_{-3.7}$	$75.0^{+7.7}_{-7.3}$	$0.71^{+0.09}_{-0.11}$	$13.6^{+0.2}_{-0.3}$	✓	–	✓	–	✓	✓	✓	✓
GW190924_021846	HLV	$0.57^{+0.22}_{-0.22}$	$15.5^{+5.7}_{-0.7}$	$6.44^{+0.04}_{-0.03}$	$14.8^{+5.9}_{-0.7}$	$0.67^{+0.05}_{-0.05}$	$11.5^{+0.3}_{-0.4}$	✓	–	✓	✓	✓	–	✓	✓



- *RT Residual test*
- *IMR Inspiral Merger Ringdown consistency test*
- *PAR parameterized test of GW generation*
- *SIM Spin Induced Moments:*

$$Q = -\kappa\chi^2 m^3$$

- *MDR Modified Dispersion Relations:*

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

- *RD Ringdown*
- *ECH Echoes*
- *POL Polarization content*

- Improved constraints on Lorentz violation
- Graviton mass $m_g \leq 1.76 \times 10^{-23}\ \mathrm{eV}/c^2$
- Constraints on post-Newtonian parameters improved by a factor 2

O3a astrophysical distribution

https://arxiv.org/abs/2010.14533

- Estimates for merger rates:
  - $\mathcal{R}_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
  - $\mathcal{R}_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
- Mass distribution of BBH information
  - (GW190814 $q = 0.112^{+0.008}_{-0.009}$ GW190412 $0.28^{+0.13}_{-0.09}$)
- Does the merger rate evolve with redshift?
  - Fast evolution scenarios ruled out
- Evidence of spin induced precession effects
  - Not an outlier effect
- What is the minimum black hole mass?
  - Cut off below at about $5.7 - 10 M_{\odot}$?
  - Extends below $5 M_{\odot}$ if we trust GW190814 as a BBH

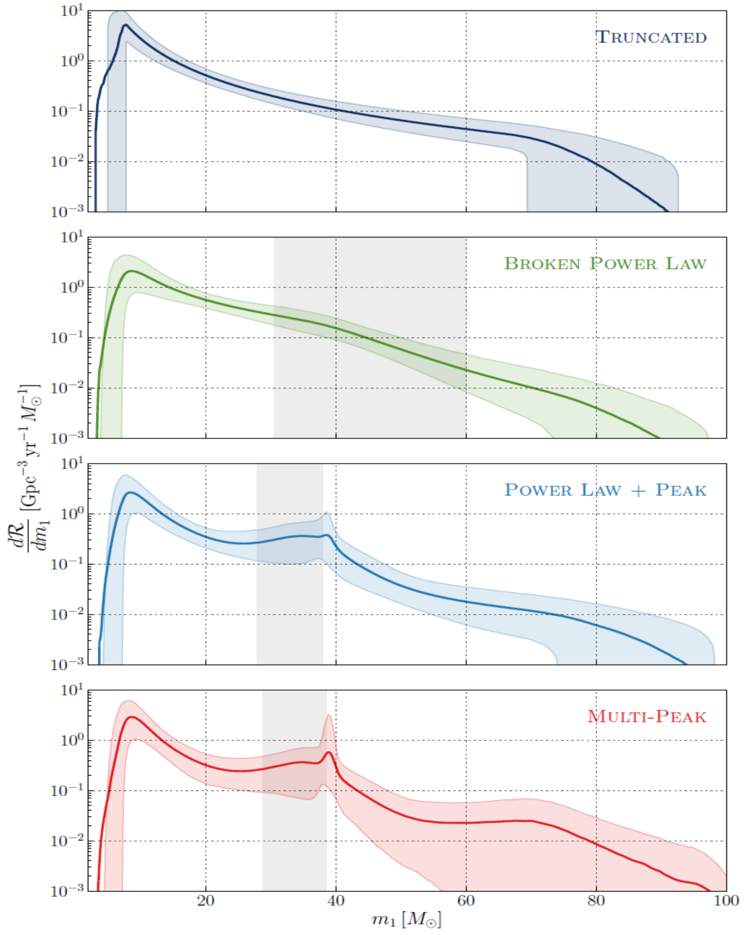
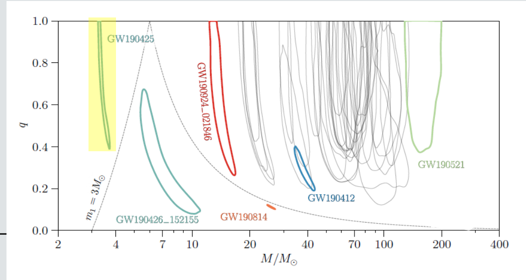


Figure 3. *Astrophysical* primary black hole mass distribution for the Truncated, Broken Power Law, Power Law + Peak and Multi Peak models. The solid curve is the posterior population distribution (averaging over model uncertainty) while the shaded region shows the 90% credible interval. Note that while the median rate is always inside the credible region, the solid curve represents the *mean*, which can be outside the credible region. Top (navy) is the Truncated model, second from the top (green) is the Broken Power Law model, third from the top (blue) is for the Power Law + Peak model, and bottom (red) is for the Multi Peak model. The Truncated model is disfavored compared to the three latter models that predict a feature at ∼ 40 $M_\odot$: a break in the mass spectrum in the Broken Power Law model or additional Gaussian peaks in the Power Law + Peak and Multi Peak models. The vertical grey bands show 90% credible bounds on the locations of these additional features.

GW190425: Observation of a Compact Binary Coalescence with total mass $\sim 3.4 M_{\odot}$
AJL 892 (2020) L3



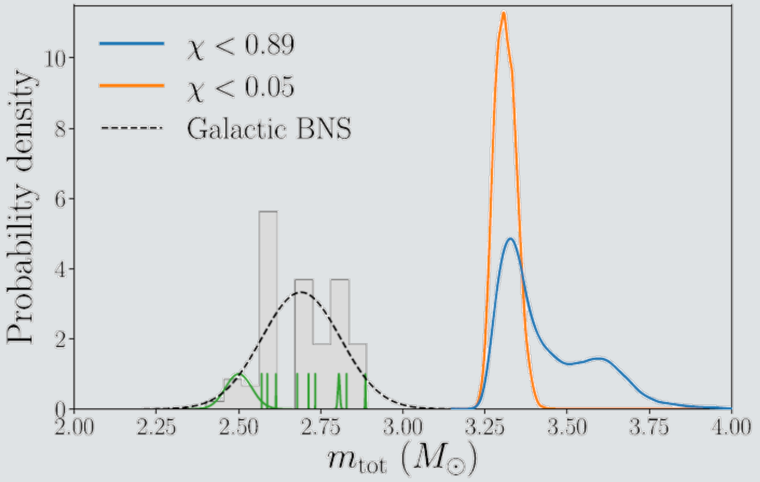
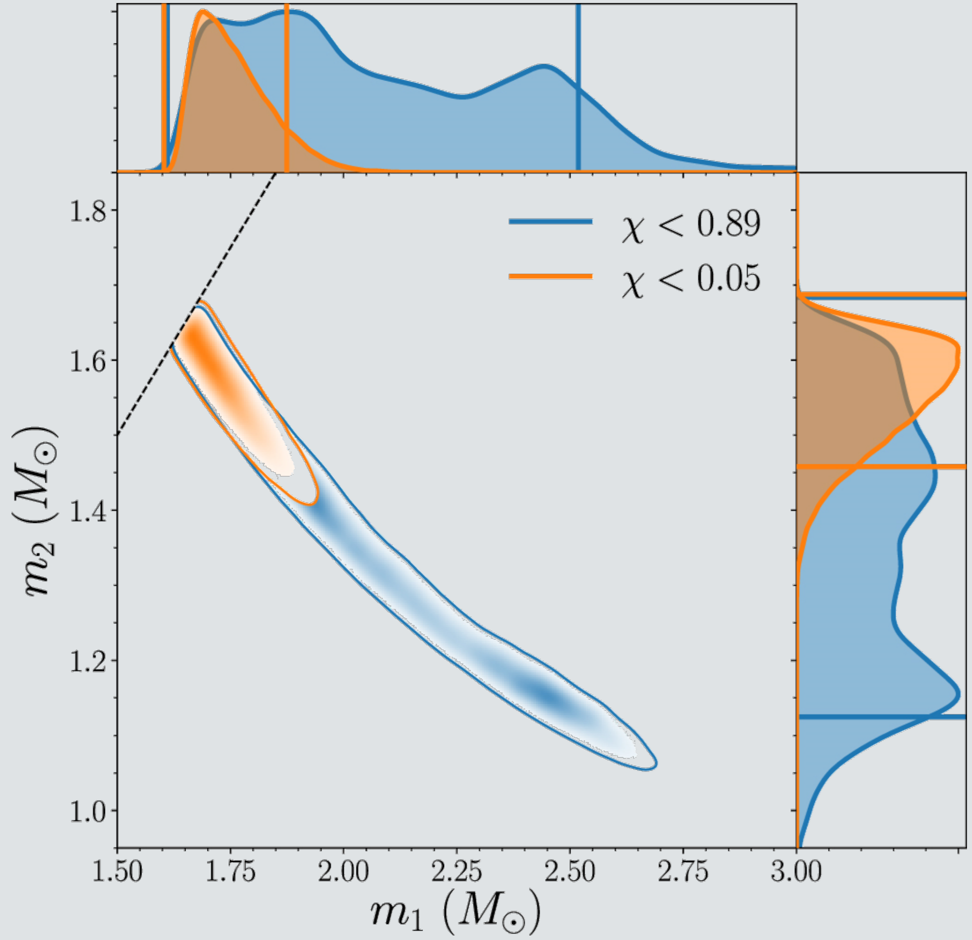
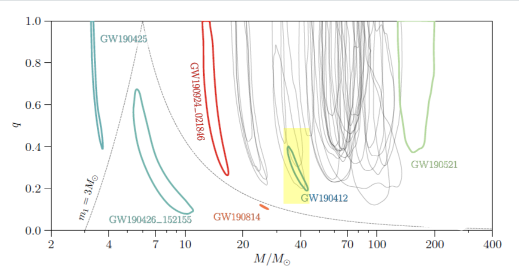


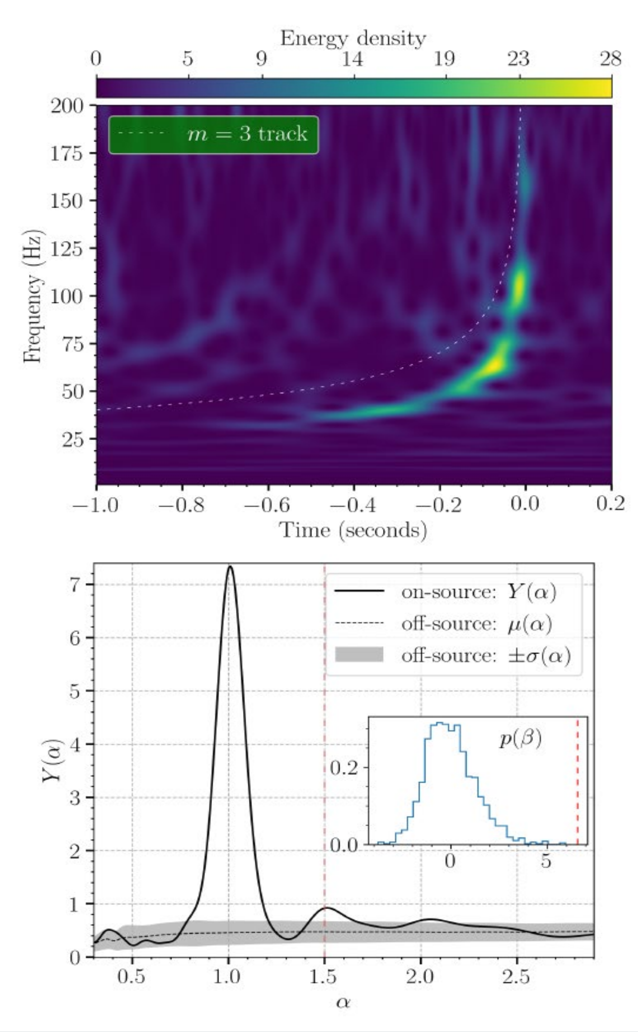
Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.



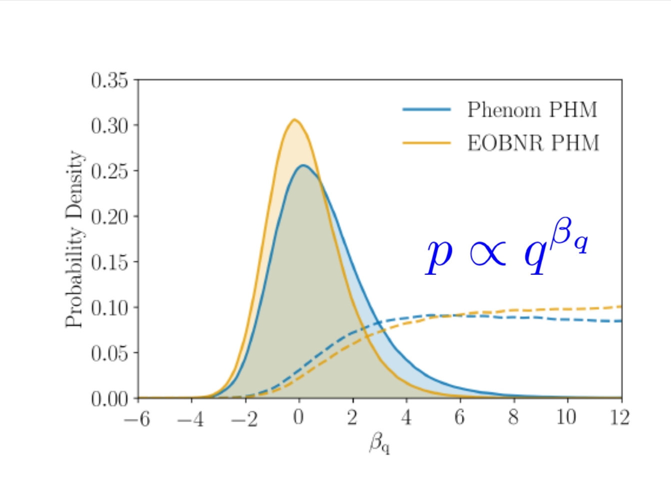
- *Most likely BNS system: another BNS detection but…*
- *…no solid electromagnetic counterpart*
- *Total mass* $3.4^{+0.3}_{-0.1} M_{\odot}$ $\quad D_L = 159^{+69}_{-71}\ Mpc$
- *Significantly different from the known population of Galactic BNS systems*
- *Cannot rule out BBH or BHNS*

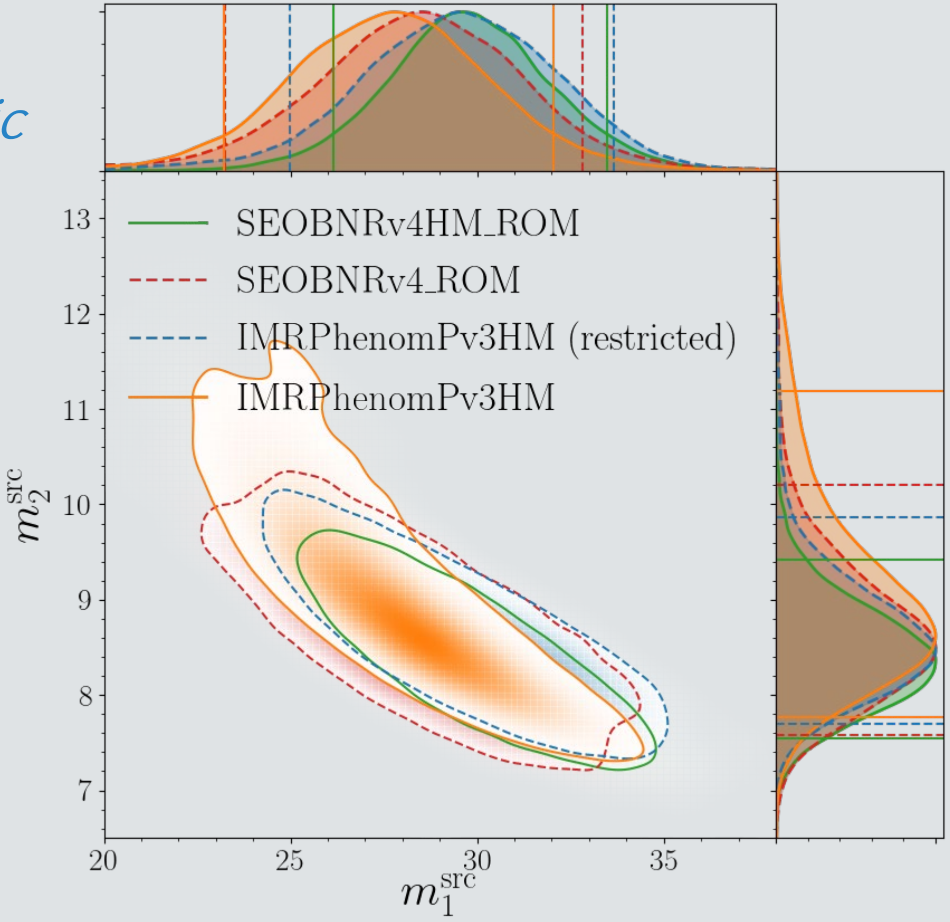
GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric masses
Phys. Rev. D 102, 043015 (2020)



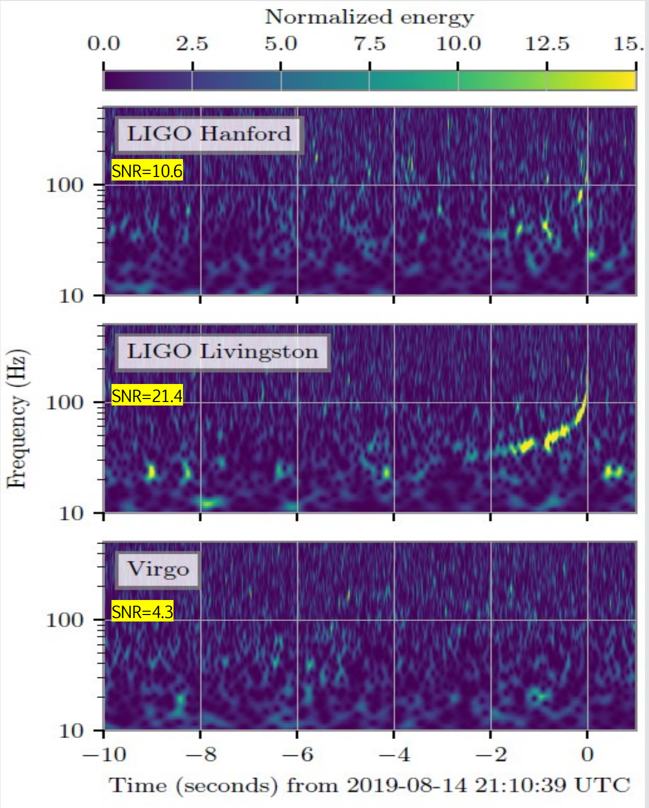


- *Evidence for (3,3) multipole: $f_\alpha(t) = \alpha f_{22}(t)$*
- *Tighter bounds on intrinsic source parameters*
- *Bounds on abundances*
- *Consistency with GR*

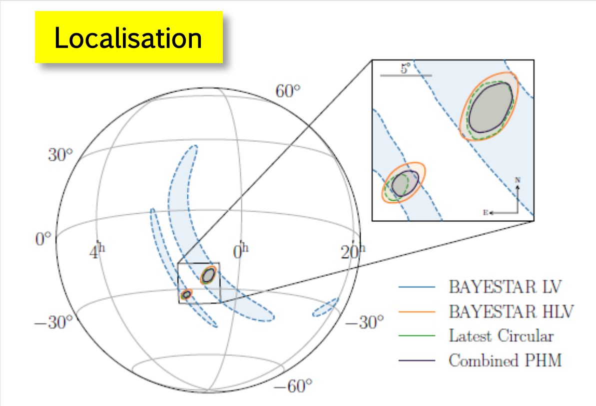


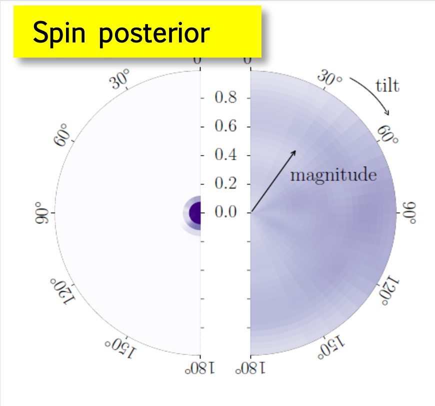


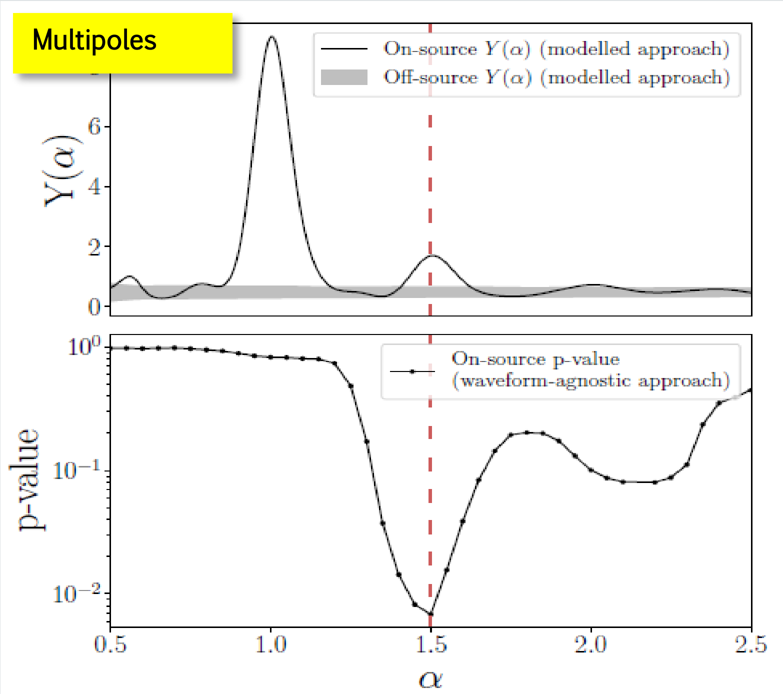
GW190814: Gravitational Waves from the Coalescence of a 23 $M_\odot$ Compact Object
Abbott et al 2020 ApJL 896 L44

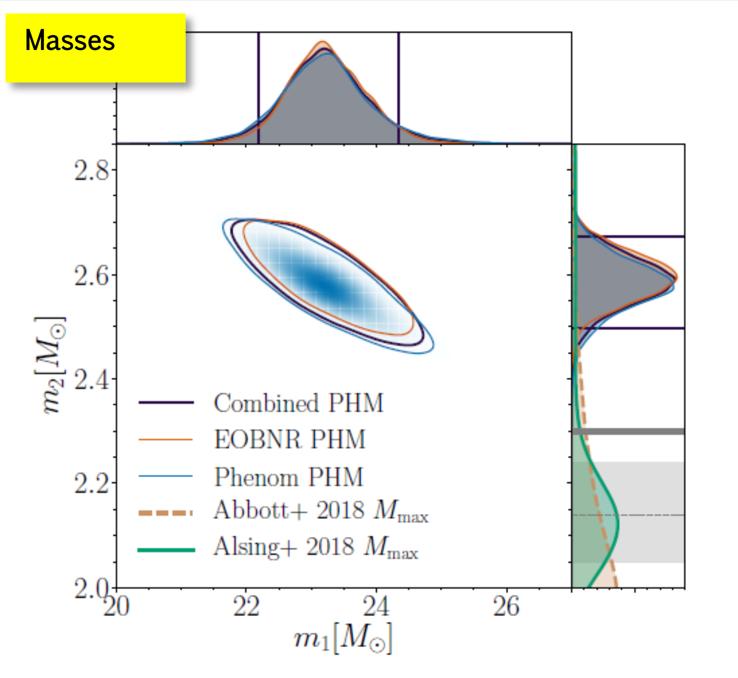


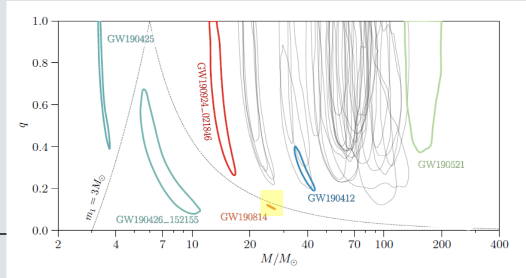
- *Network SNR=25*
- *No em counterpart*
- $q = 0.112^{+0.008}_{-0.009}$
- *NSBH or BBH?*
- *Multipole evidence*
- *No GR violation evidence*
- *Challenge for formation models*



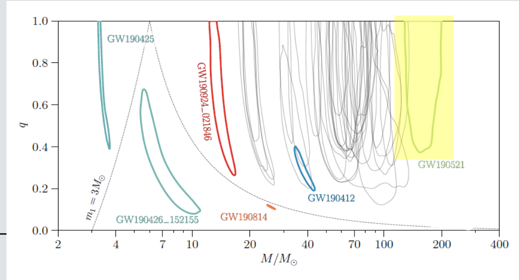


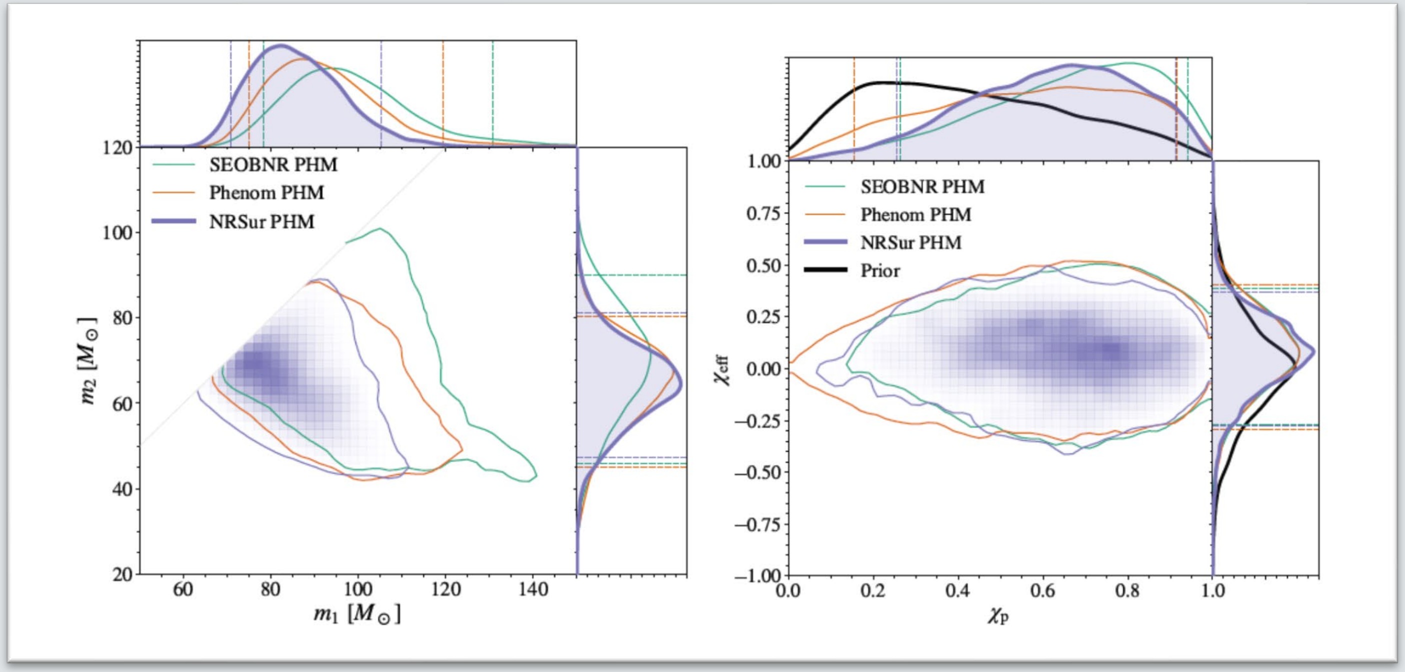


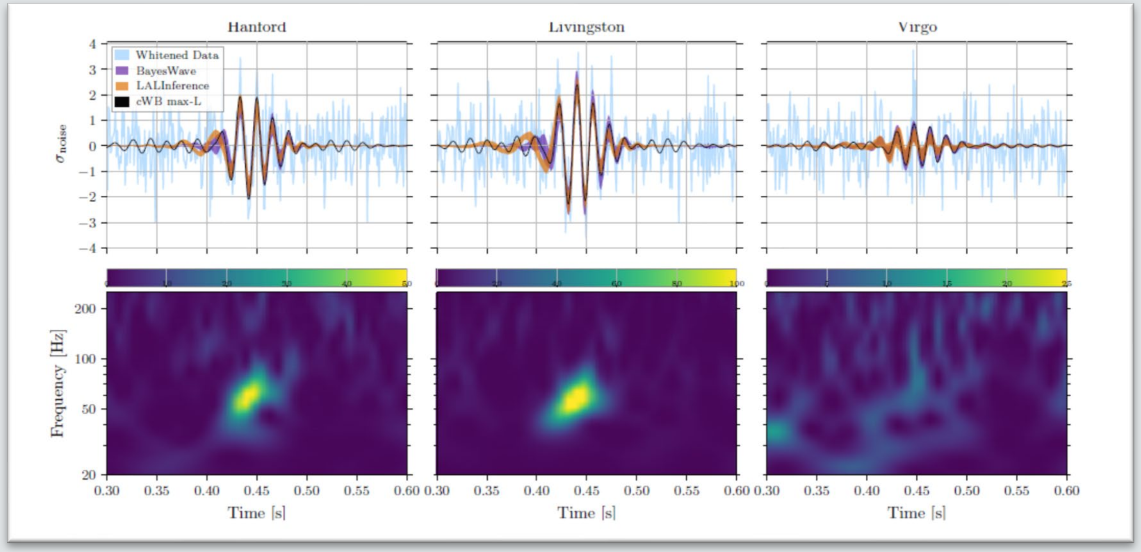




GW190521: A Binary Black Hole Merger with a Total Mass of 150 $M_\odot$







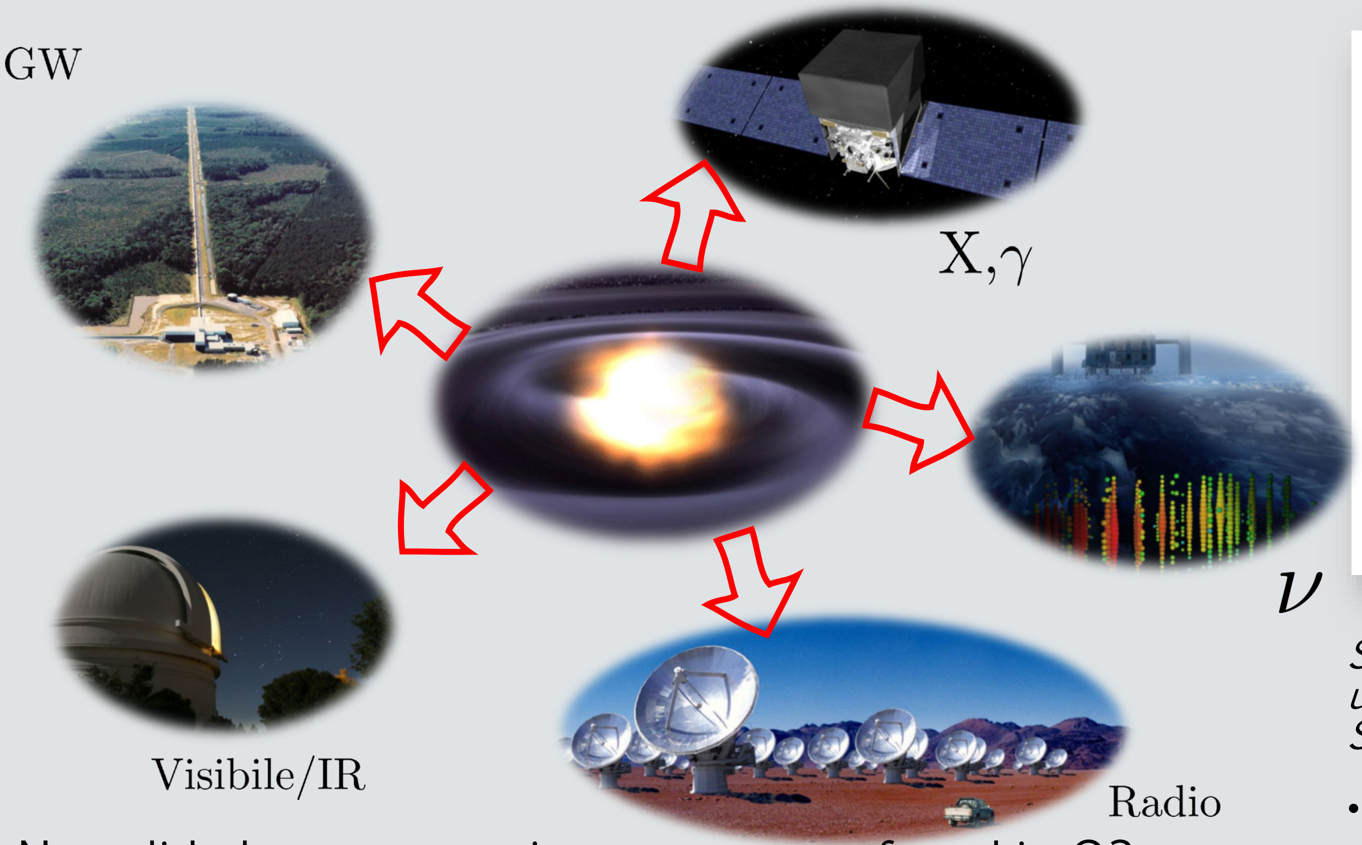
- Short signal, difficult to analyze

- Network SNR about 14-15
- BBH z=0.8 with unusually high component masses
- Mild evidence for spin-induced orbital precession
- **Primary in mass gap for pair-instability SN theory**
- Final: IMBH
- Formation channels?
  - Multiple stellar coalescence
  - Hierarchical merger of lower-mass black holes

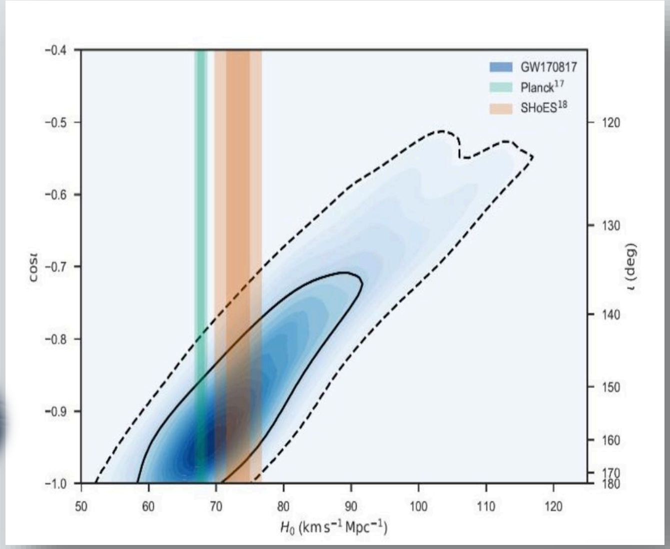
Phys. Rev. Lett. 125, 101102 (2020)

Astrophys. J. Lett. 900, L13 (2020)

Multimessenger



No solid electromagnetic counterparts found in O3
Several attempts, not confirmed
We are looking far, and GW are not beamed.
What we could do better?
GW side ➔ improve localization
em side ➔ improve sensitivity

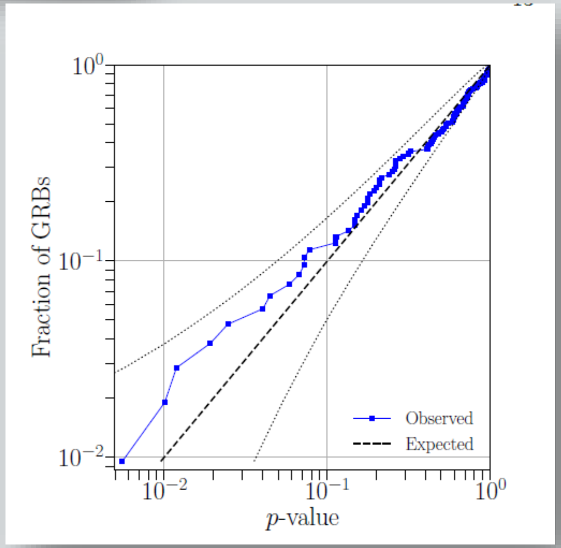


Independent method for Hubble parameter determination: GW are a new cosmic distance marker
Abbott et al. 2017, Nature, 551, 85A

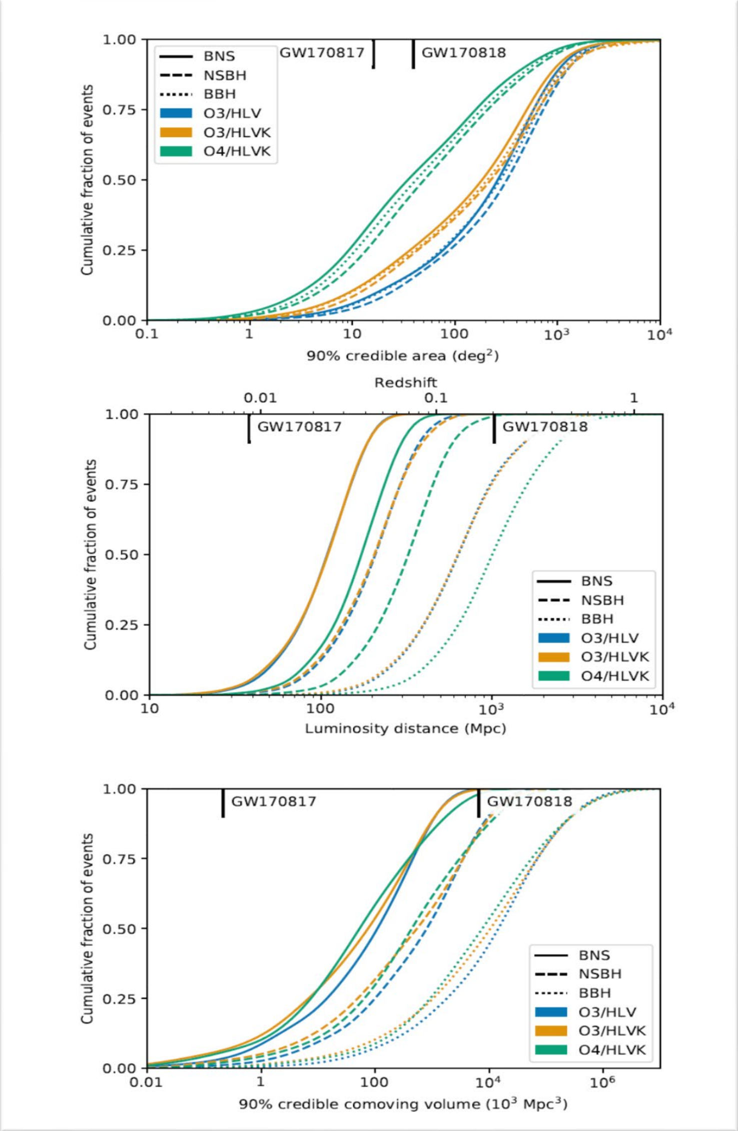
- Most direct way: when we have an optical counterpart
- Alternatively: by localizing the host galaxy
- And/or: statistically, on a large sample of events

Search on O3a data set, using detection from Fermi & Swift satellites.

- No significant evidence for gravitational-wave signals associated with the followed-up GRB
- Lower bounds on the rate of short gamma-ray bursts as a function of redshift for $z \leq 1$



O4: what we expect

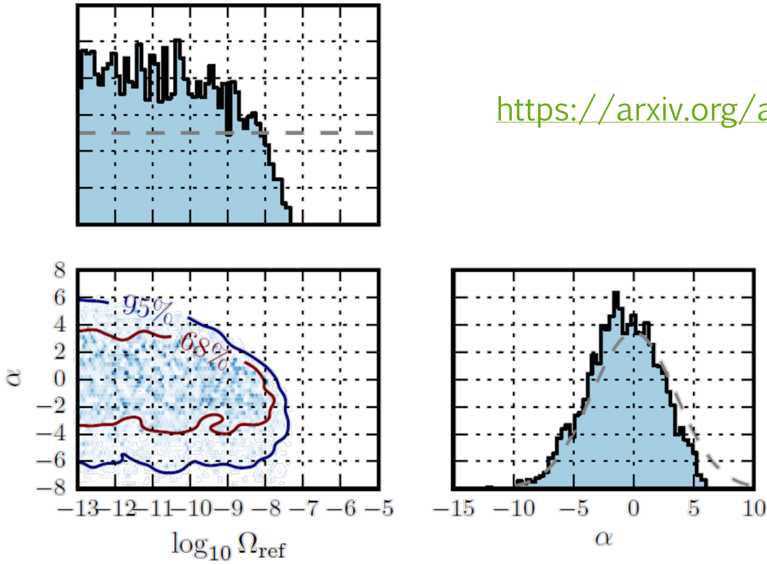


		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	-	30	50	90 – 120	150 – 260
$1.4M_\odot + 30M_\odot$	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
$30M_\odot + 30M_\odot$	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
$1.4M_\odot + 10M_\odot$	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_\odot c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_\odot c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

SNR = 8 on each detector

Stochastic background searches

Upper Limits on the Isotropic Gravitational-Wave Background from Advanced LIGO's and Advanced Virgo's Third Observing Run

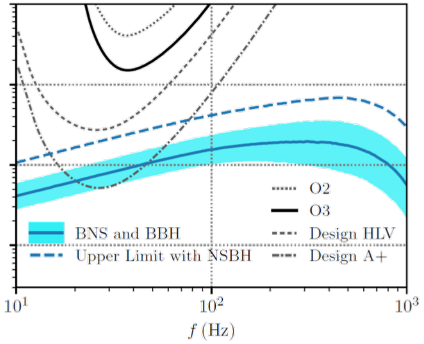


https://arxiv.org/abs/2101.12130

$$\Omega_{\mathrm{GW}}(f) = \Omega_{\mathrm{ref}} \left(\frac{f}{f_{\mathrm{ref}}} \right)^{\alpha}$$

	Uniform prior			Log-uniform prior		
α	O3	O2 [43]	Improvement	O3	O2 [43]	Improvement
0	1.7×10^{-8}	6.0×10^{-8}	3.6	5.8×10^{-9}	3.5×10^{-8}	6.0
2/3	1.2×10^{-8}	4.8×10^{-8}	4.0	3.4×10^{-9}	3.0×10^{-8}	8.8
3	1.3×10^{-9}	7.9×10^{-9}	5.9	3.9×10^{-10}	5.1×10^{-9}	13.1
Marg.	2.7×10^{-8}	1.1×10^{-7}	4.1	6.6×10^{-9}	3.4×10^{-8}	5.1

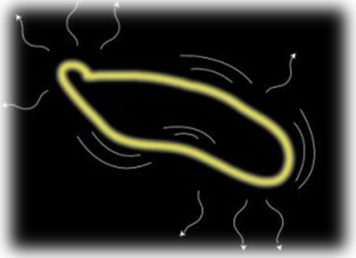
Polarization	O3	O2 [43]	Improvement
Tensor	6.4×10^{-9}	3.2×10^{-8}	5.0
Vector	7.9×10^{-9}	2.9×10^{-8}	3.7
Scalar	2.1×10^{-8}	6.1×10^{-8}	2.9

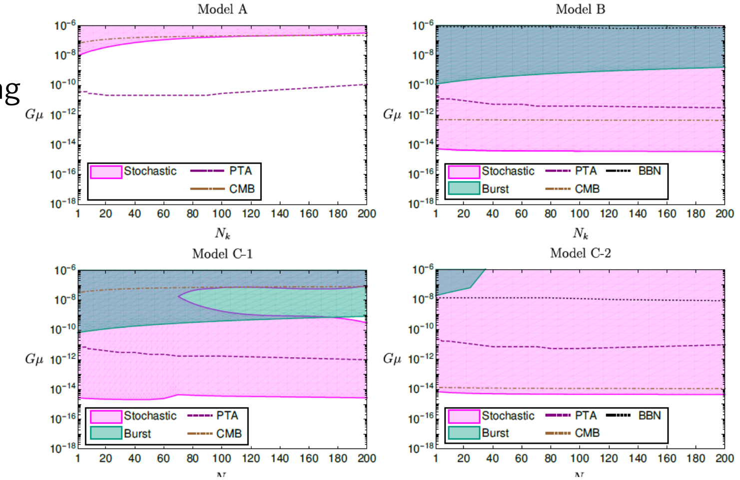


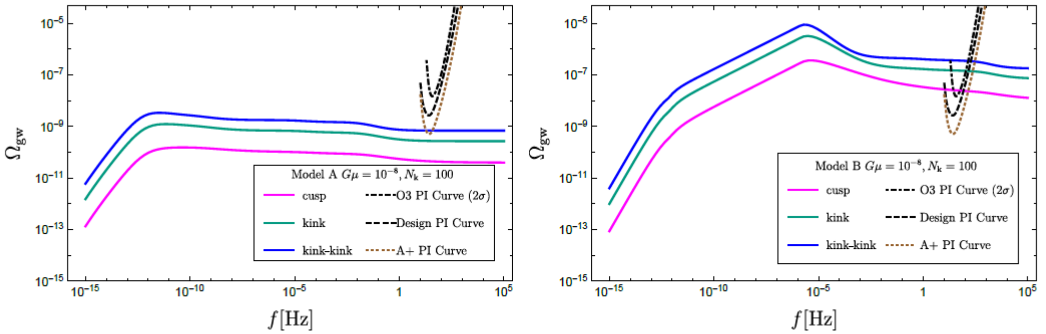
Constraints on cosmic strings using data from the third Advanced LIGO–Virgo observing run

https://arxiv.org/abs/2101.12248

- Joint (and complementary) Stochastic-Burst search
- Put constraints on cosmic string models





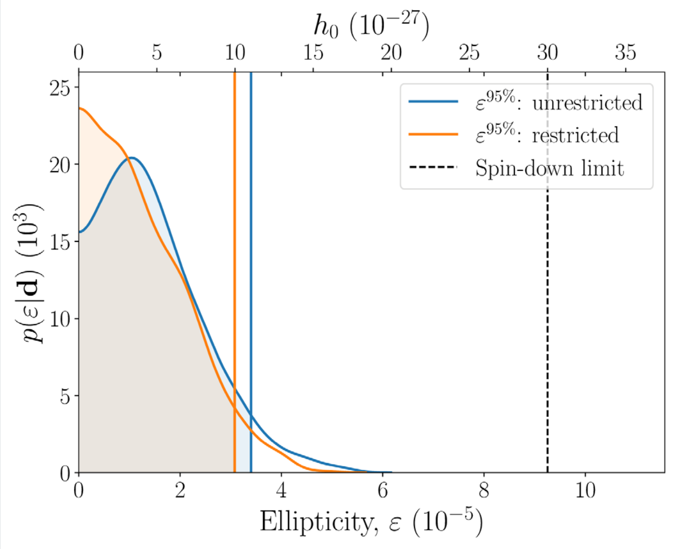


Also: directional limits & Astrophysically motivated SB

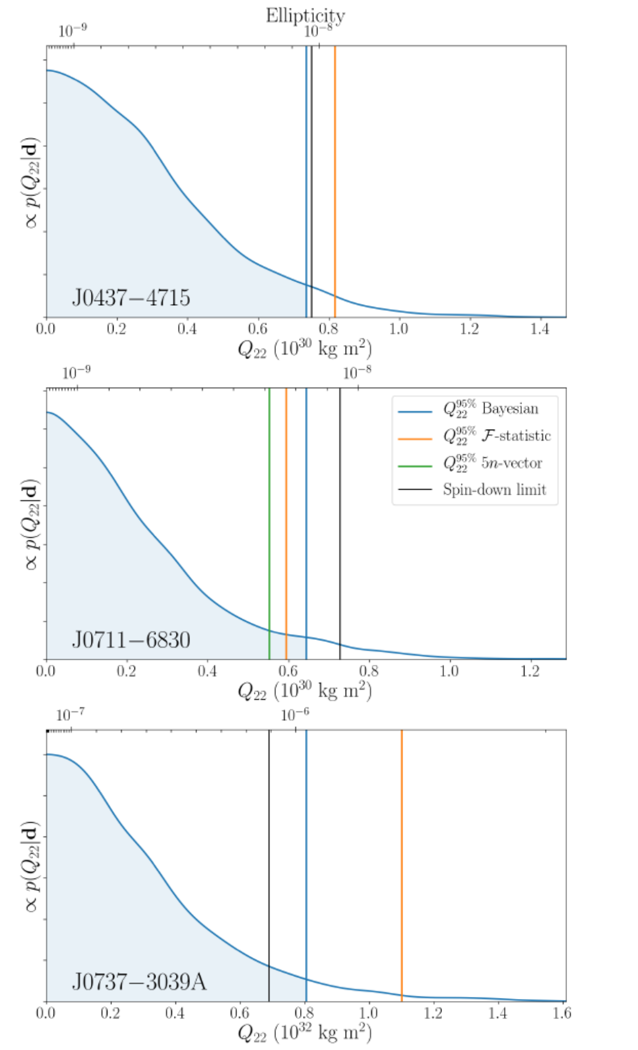
CW searches

- Weak and persistent signal.
  - Targeted (particular source)
  - All sky (unknown sources)
- Not really monocromatic
  - Modulations
  - Spin down, environment effects, glitches

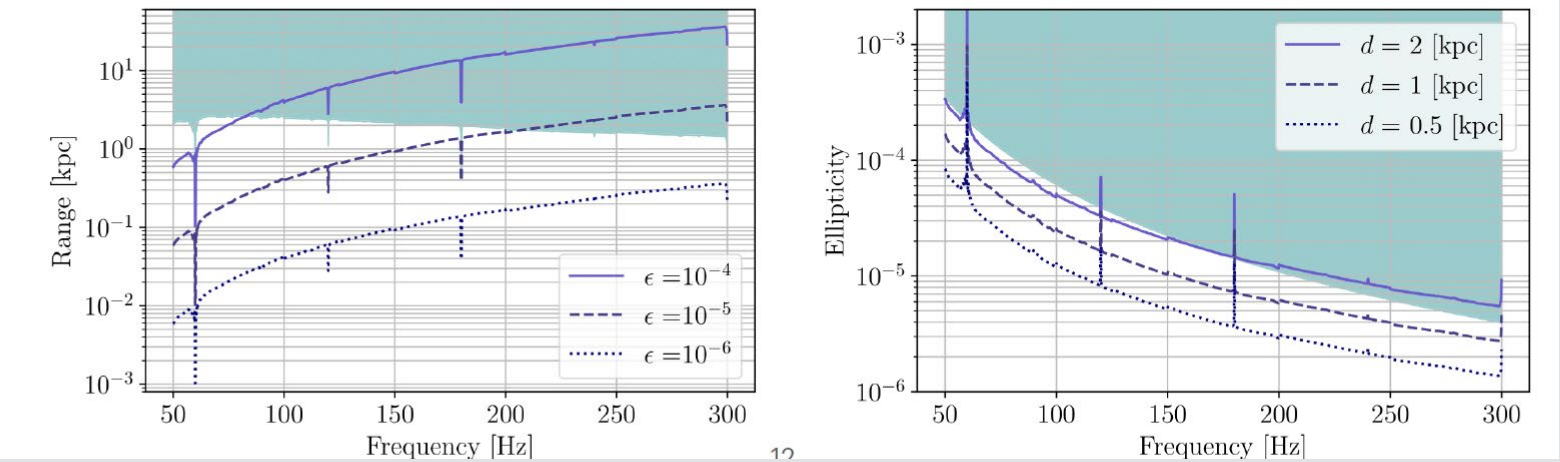
J0537-6910
Abbott et al. arXiv:2012.12926



Beating spindown limit
Abbott et al. ApJL 902 L21

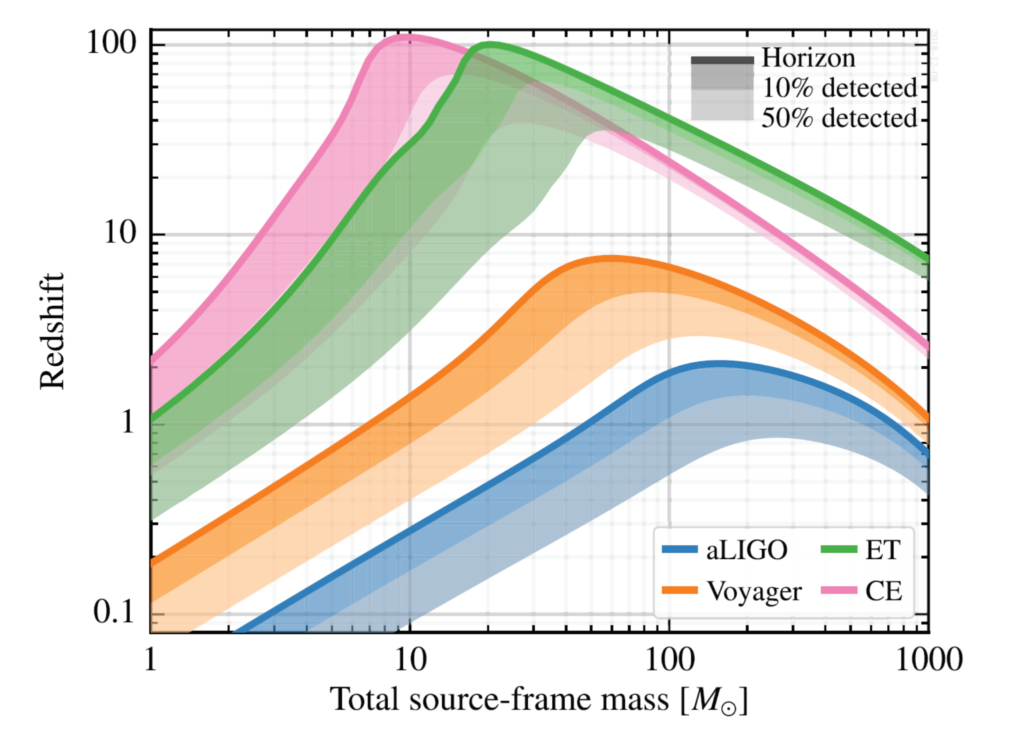


All-sky search
Abbott et al. arXiv:2012.12926



Summary

- LIGO-Virgo and future GW detectors opening new windows for study of extreme astrophysical systems
- O3 provides new constraints on BBH population models, deviations from general relativity, masses of BHs, formation channels of massive BHs, and more
- Starting to explore
  - Neutron star astrophysics (structure? EOS? Vortex dynamics?)
  - Merger physics
  - Cosmology
  - Lensing
  - Multi-messenger astronomy (GRB, kilonova)
  - Connections with fundamental theories (dark matter, dark energy, graviton mass, Lorentz invariance bounds, speed of light, speed of GW, test of Equivalence principle)
  - Beyond GR (polarization of gravitational waves, testing GR in dynamic strong field regime)
  - Structure of BH (no hair theorem, exotic objects, QNM, echos, parity violation, axions)



A lot of work to do, and (hopefully) a lot of new scientific discoveries ahead.

Thank you for your attention.