GWOSC
Open Data Workshop
May 2023

CBC science

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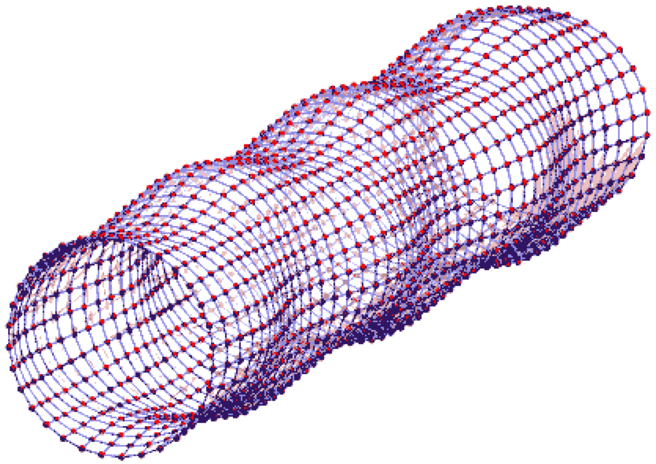
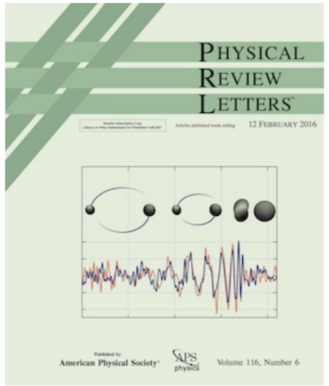
Gravitational Waves

Ripples in the spacetime metric generated by the acceleration of masses, propagating at the speed of light

- GW cause the the space itself to stretch/compress
- Predicted by Einstein's General Relativity (1916) - first direct observation 2015 (LIGO)
- Probe gravity in unprecedented conditions, new messenger from the Universe
- Possible sources of detectable GW are some of the most violent events in the Universe involving massive and compact objects in relativistic regime

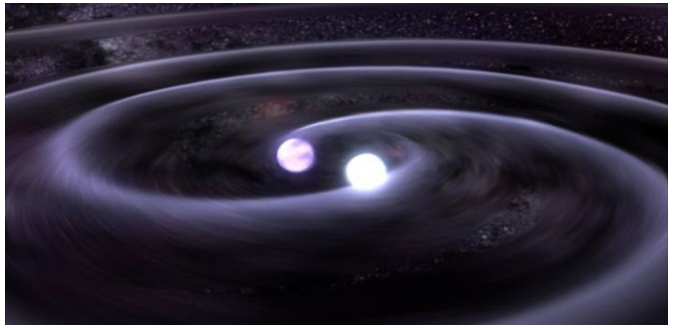




LIGO-Virgo-KAGRA physics program

Transient GW signals

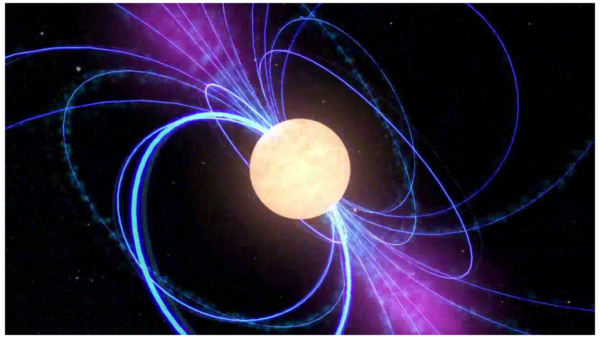
- Compact Binary Coalescences (CBC) – modelled



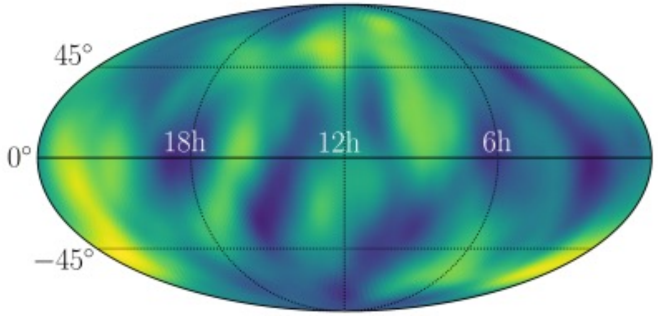
- Other "bursts", e.g. supernovae - unmodelled

Longer duration GW signals

- Continuous emission from rotating neutron stars



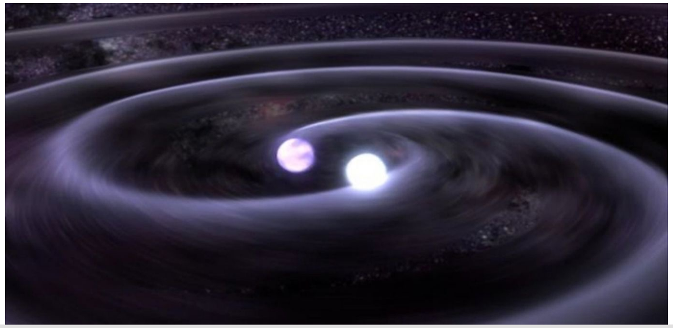
- Stochastic GW background



LIGO Virgo KAGRA physics program

Transient GW signals

- Compact Binary Coalescences (CBC) – modelled



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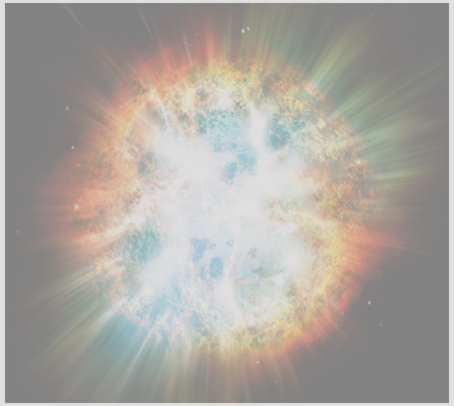
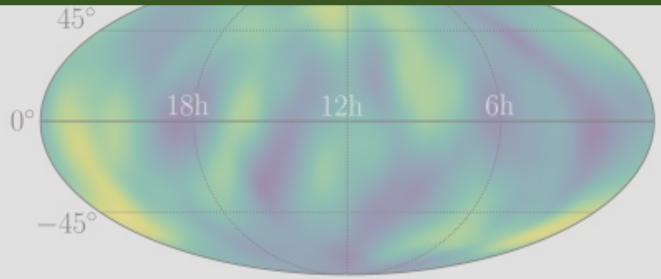


Lo… …ars

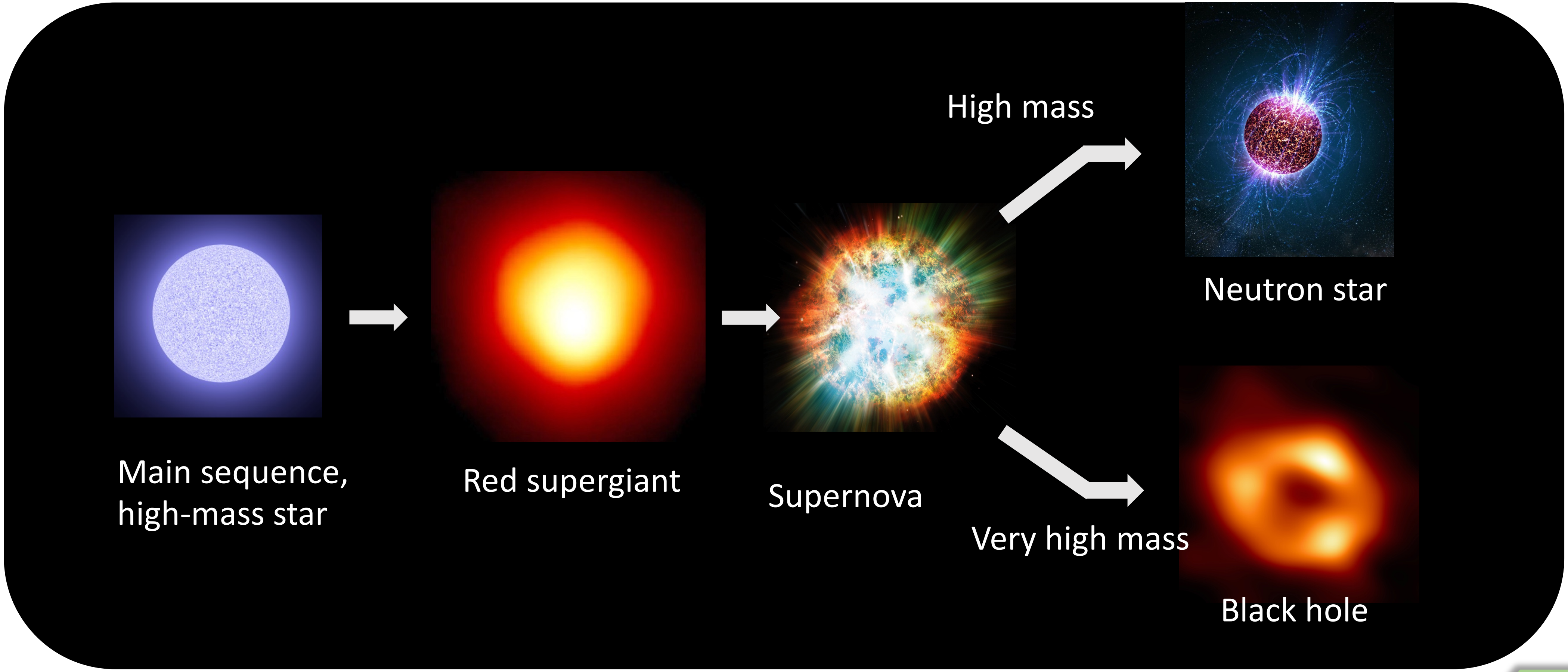


Focus on CBC

- Coalescences of compact objects (BH, NS)
- 2015: 1st BBH detection
- 2017: 1st BNS detection
- Observed ~90 events !

Compact objects

Stellar evolution gives rise to compact objects



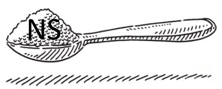
Compact objects

Neutron star (NS)

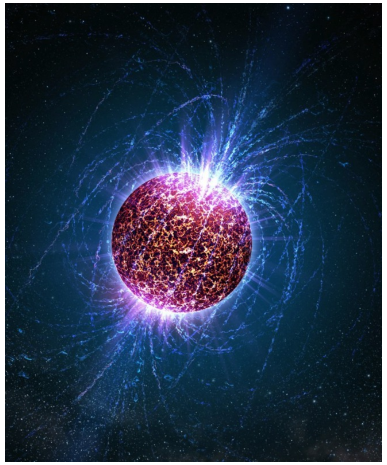
Compact object

Mostly neutrons, crust of heavy nuclei, hot plasma atmosphere (+a core of unknown exotic matter?)

1.4 $M_{\odot}$ NS has a radius of ~10km



= 100 million tonnes!



Black hole (BH)

Region of space-time with extremely intense gravitational field

Matter or light cannot escape

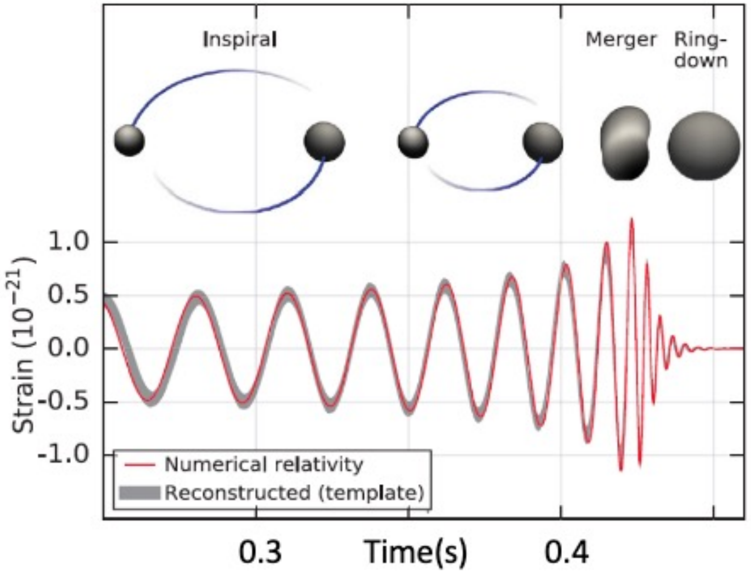
Masses between ~5 and millions of times the mass of the sun

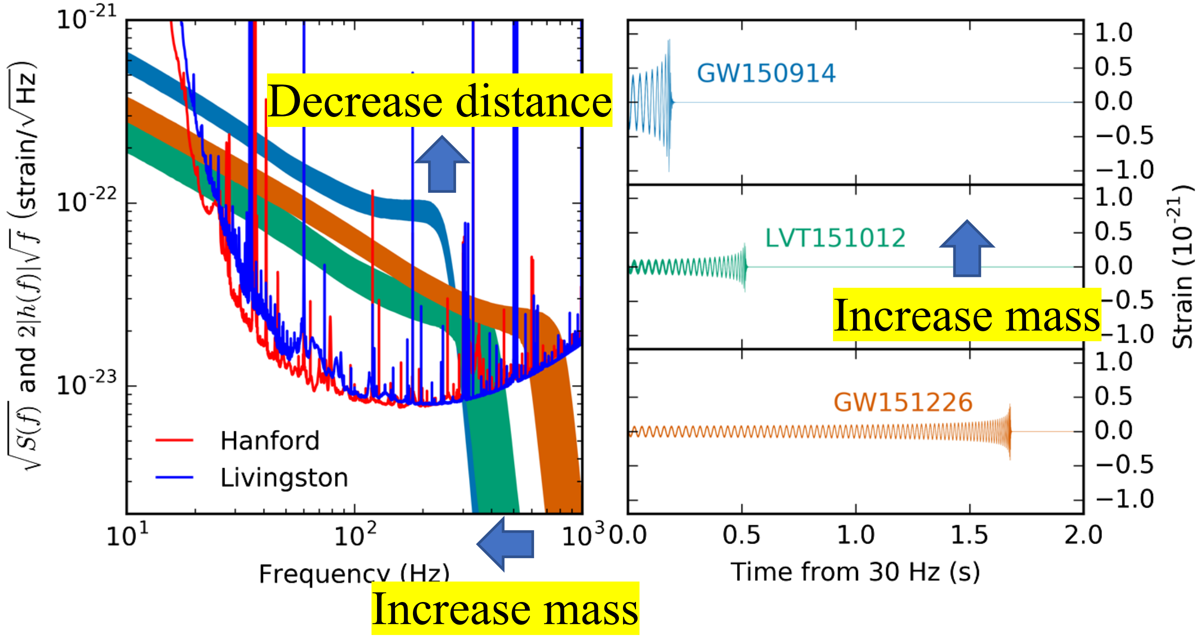

Event Horizon Telescope

We will consider binary systems: Binary Neutron Star (BNS), Neutron Star Black Hole (NSBH), Binary Black Hole (BBH)

CBC waveforms

- GW waveforms for Compact Binary Coalescences assume general relativity
- Different techniques (analytic approximation for inspiral, numerical relativity for merger, perturbation theory for ringdown)
- Amplitude scales (at first approximation) with total **mass** and **inverse of distance**



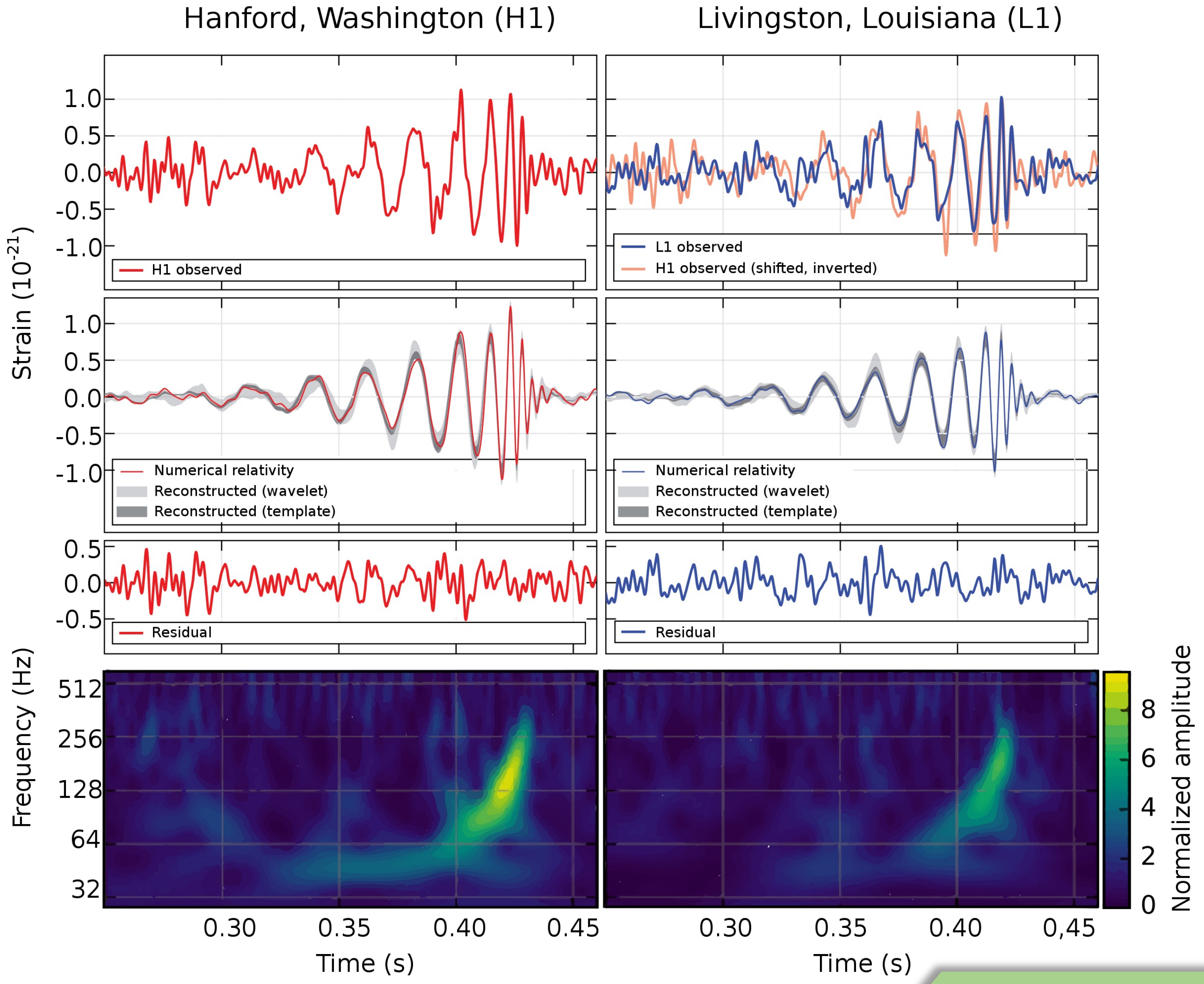


3. Milestone observations

GW150914 – the first direct detection

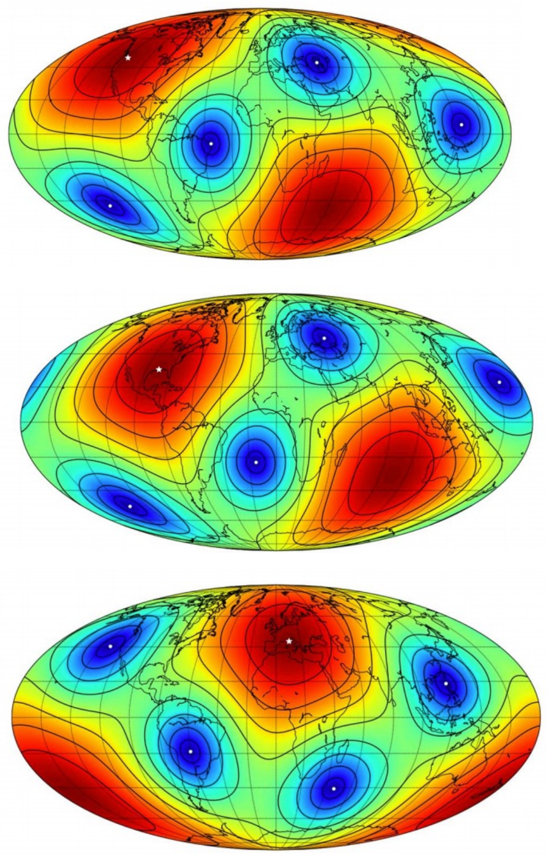
- Merger of two of black holes of 35 and 30 solar masses to form a 62 solar masses black hole
- The mass–energy of the missing 3 solar masses was radiated away in the form of gravitational waves
- Great success of General Relativity, and of LIGO experiments!

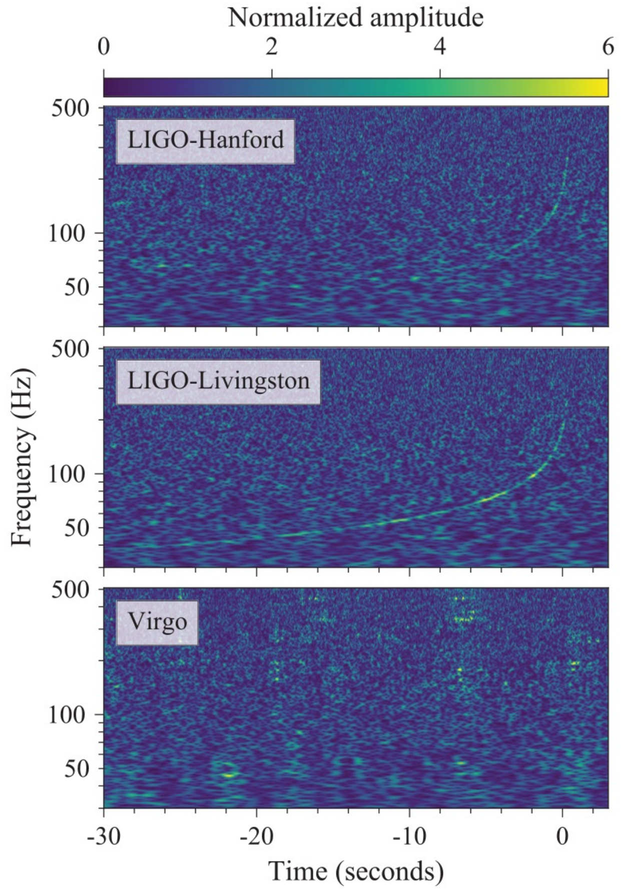
R. Weiss, K. S. Thorne, B. C. Barish



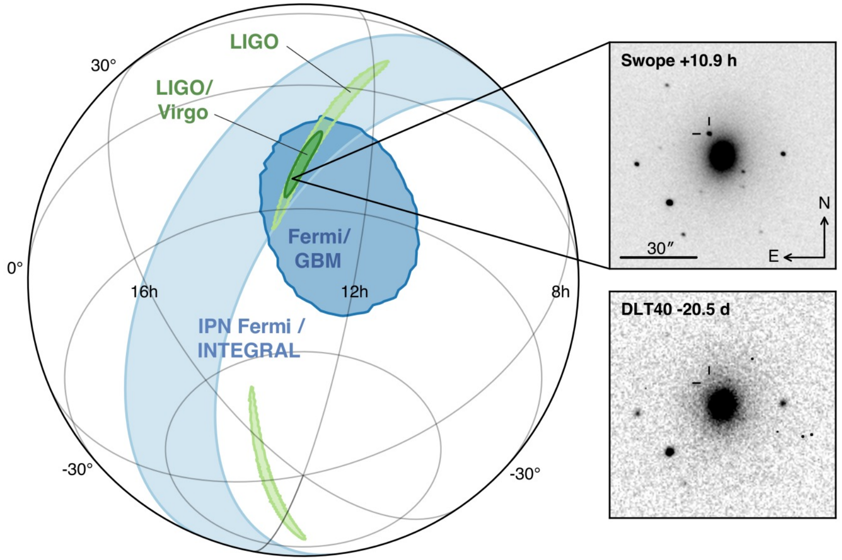
GW170817 - BNS + EM counterpart !

- Detectors have different sensitivities and antenna patterns
- Better sky-localisation - host galaxy identified to be NGC4933

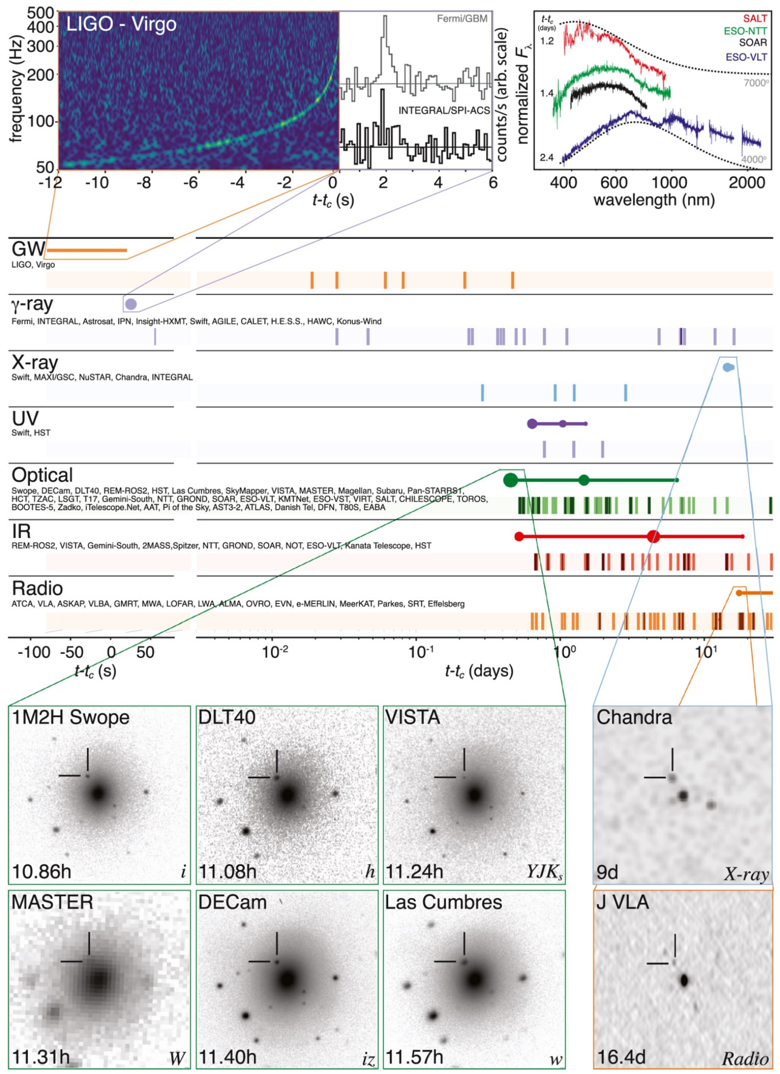




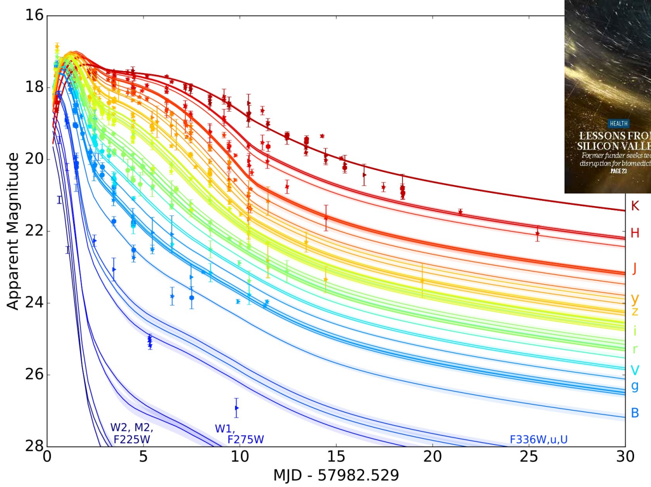
Virgo joins the fun!



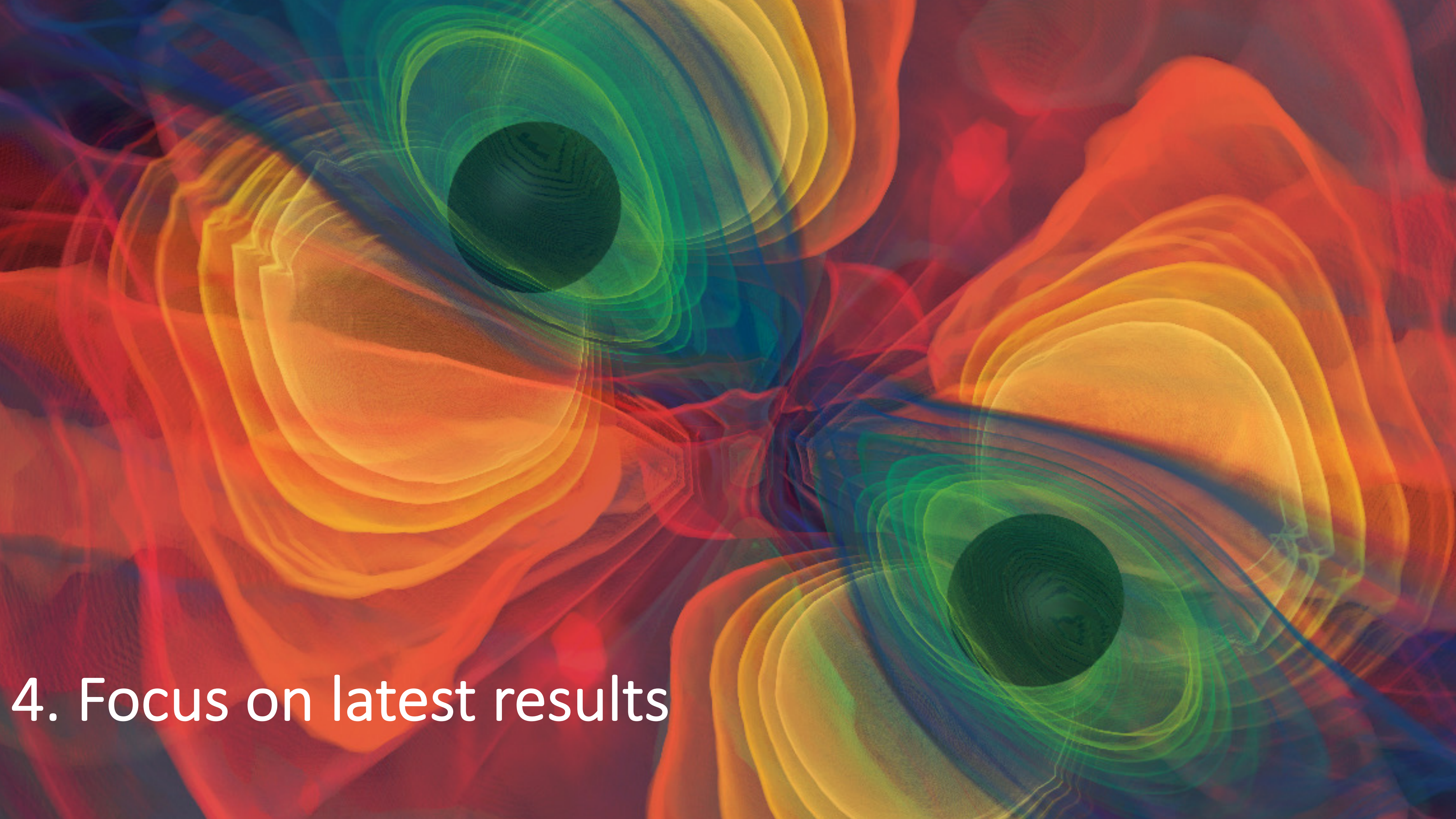
GW170817 – Multi-Messenger event



Nucleosynthesis

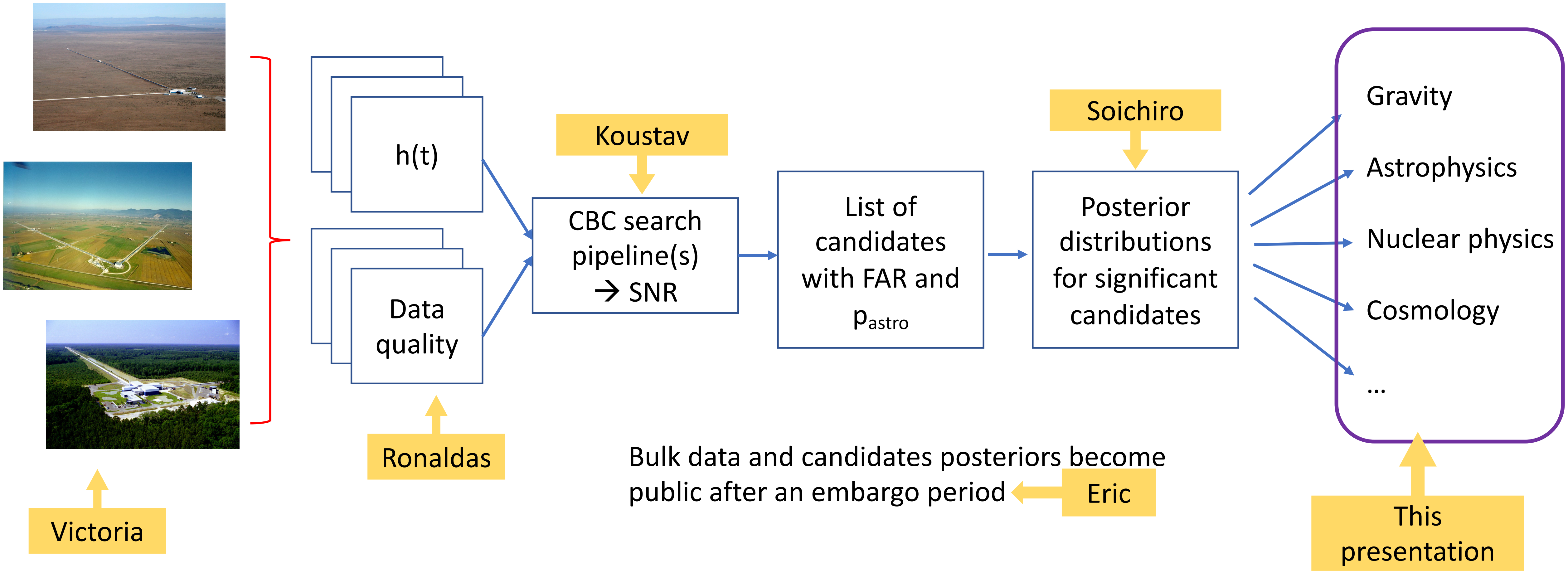


- New insight on the creation of heavy elements



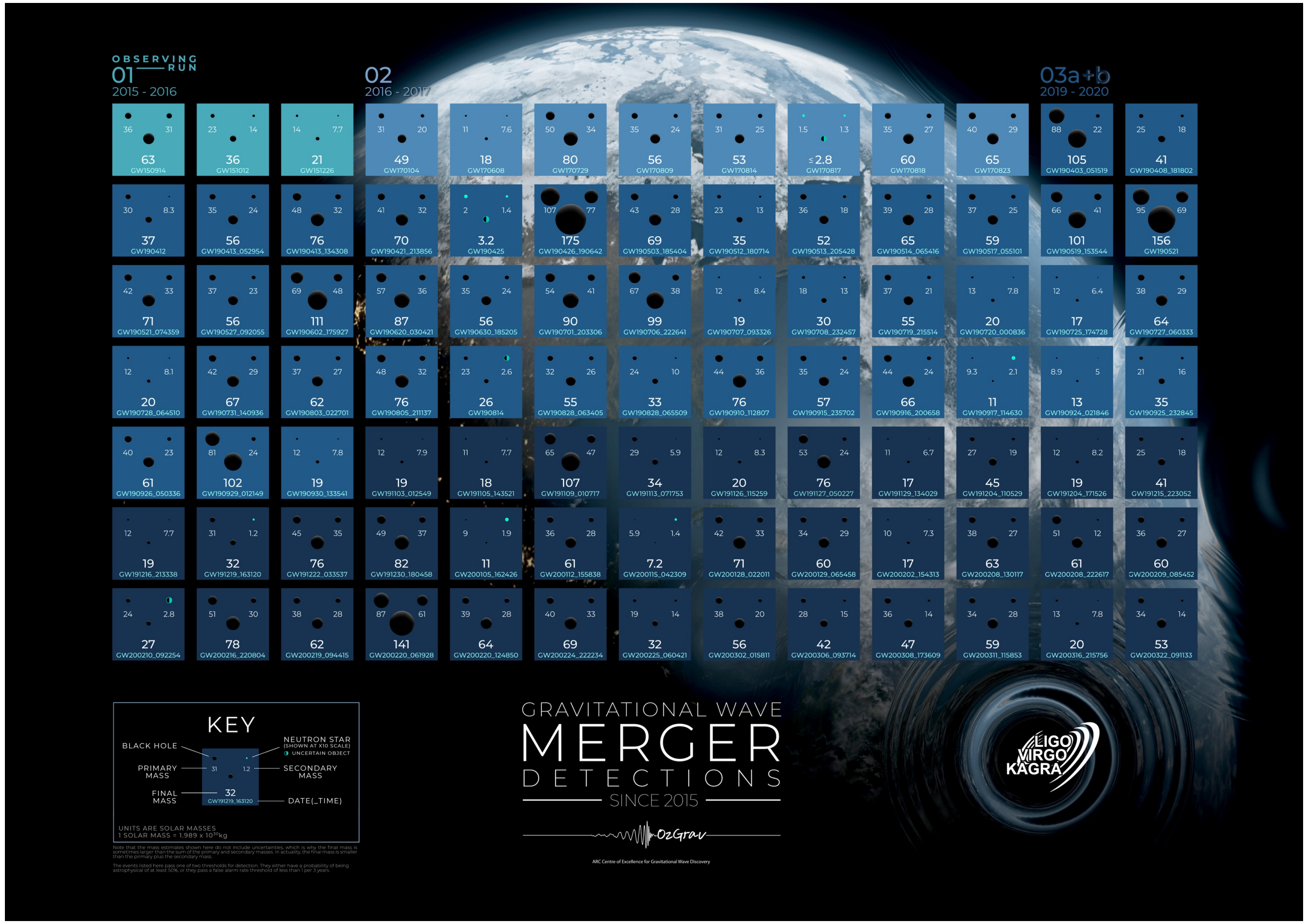
4. Focus on latest results

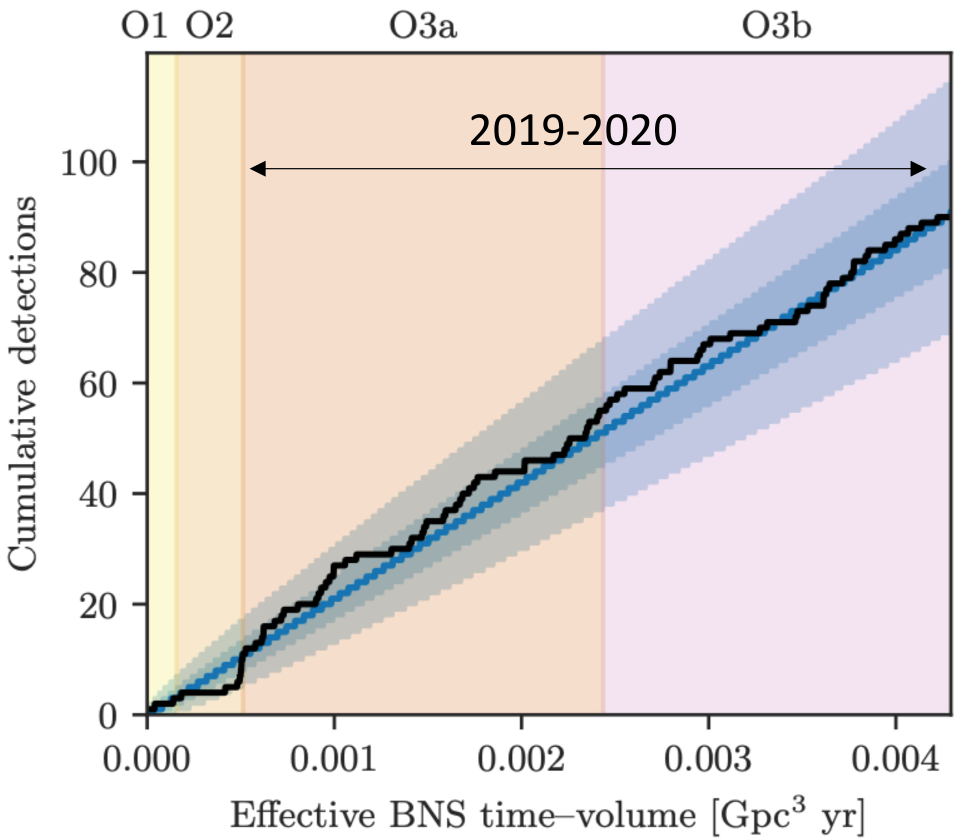
CBC searches



Implications of the CBC observations

CBC detections have become a routine for GW astronomy !





Gravitational Waves Transient Catalogs

- List of events, with significance as estimated by the several analyses
- Data around each candidate is analysed with Parameter Estimation to determine astrophysical sources properties (masses, spins, localisation..)

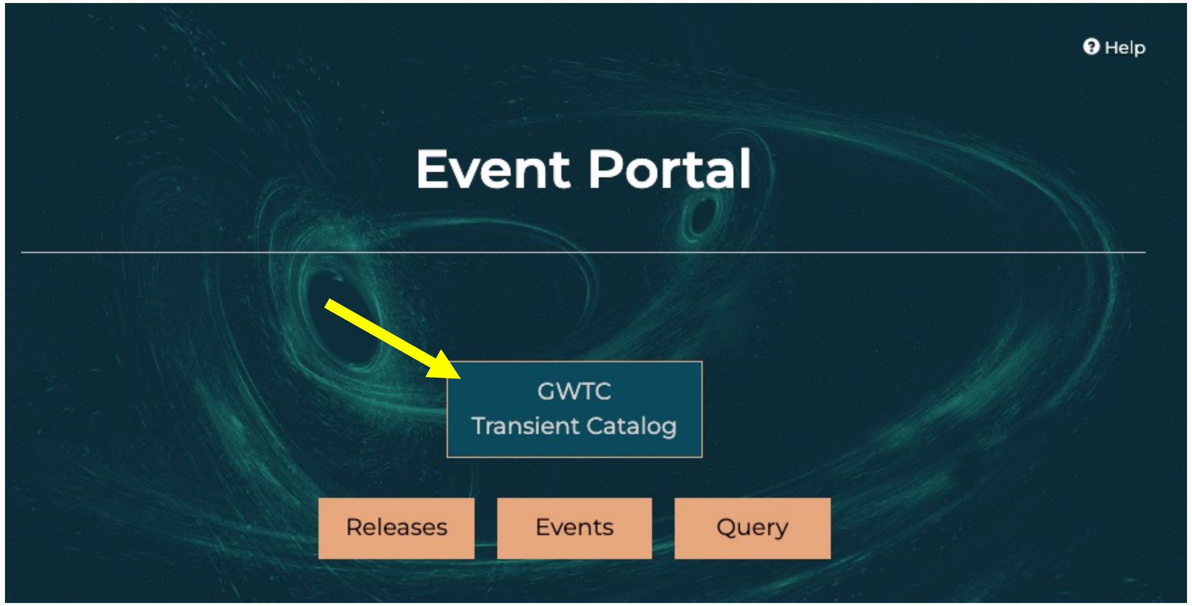
PHYSICAL REVIEW X **11,** 021053 (2021)

GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo during the First Half of the Third Observing Run

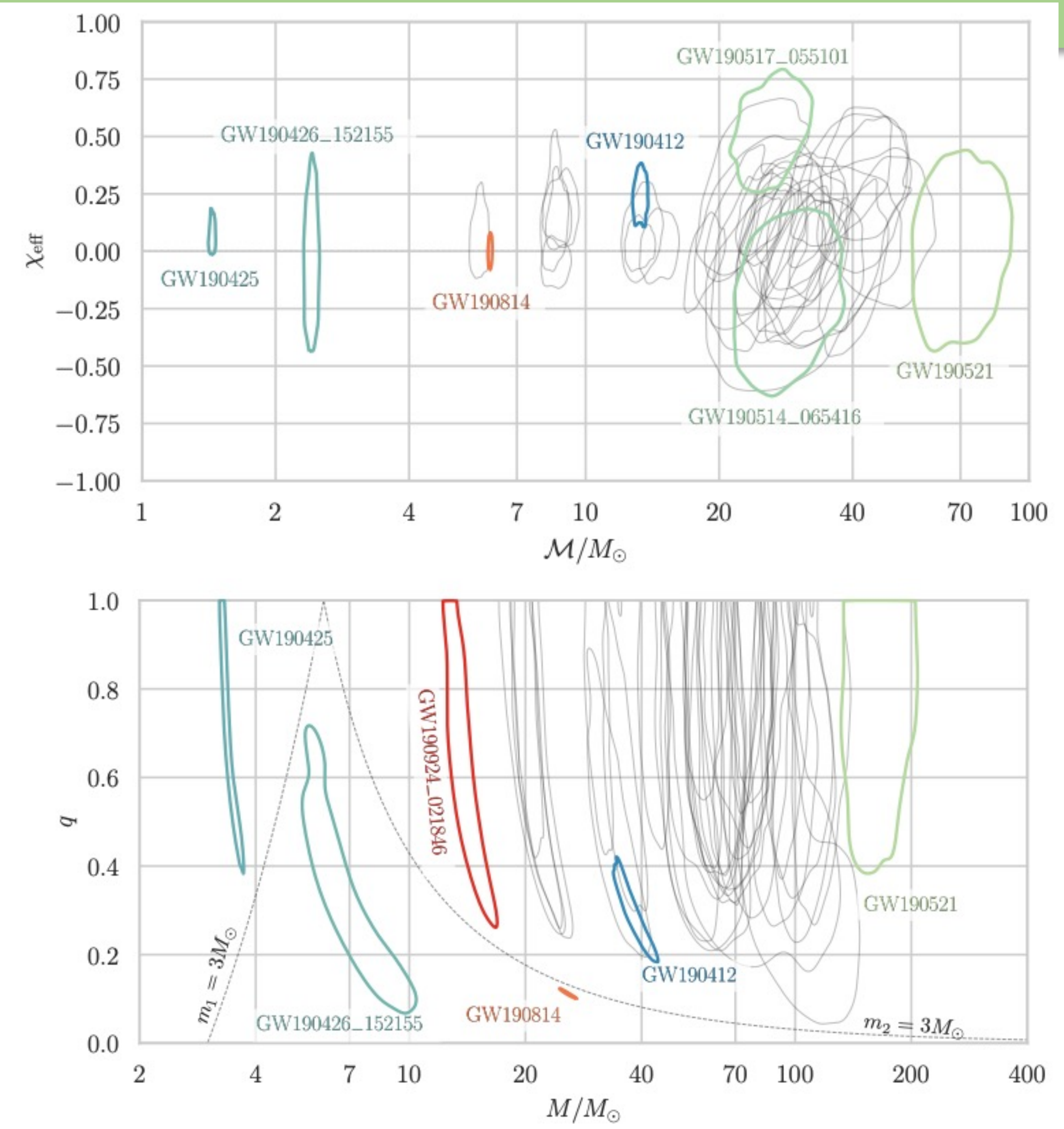
R. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

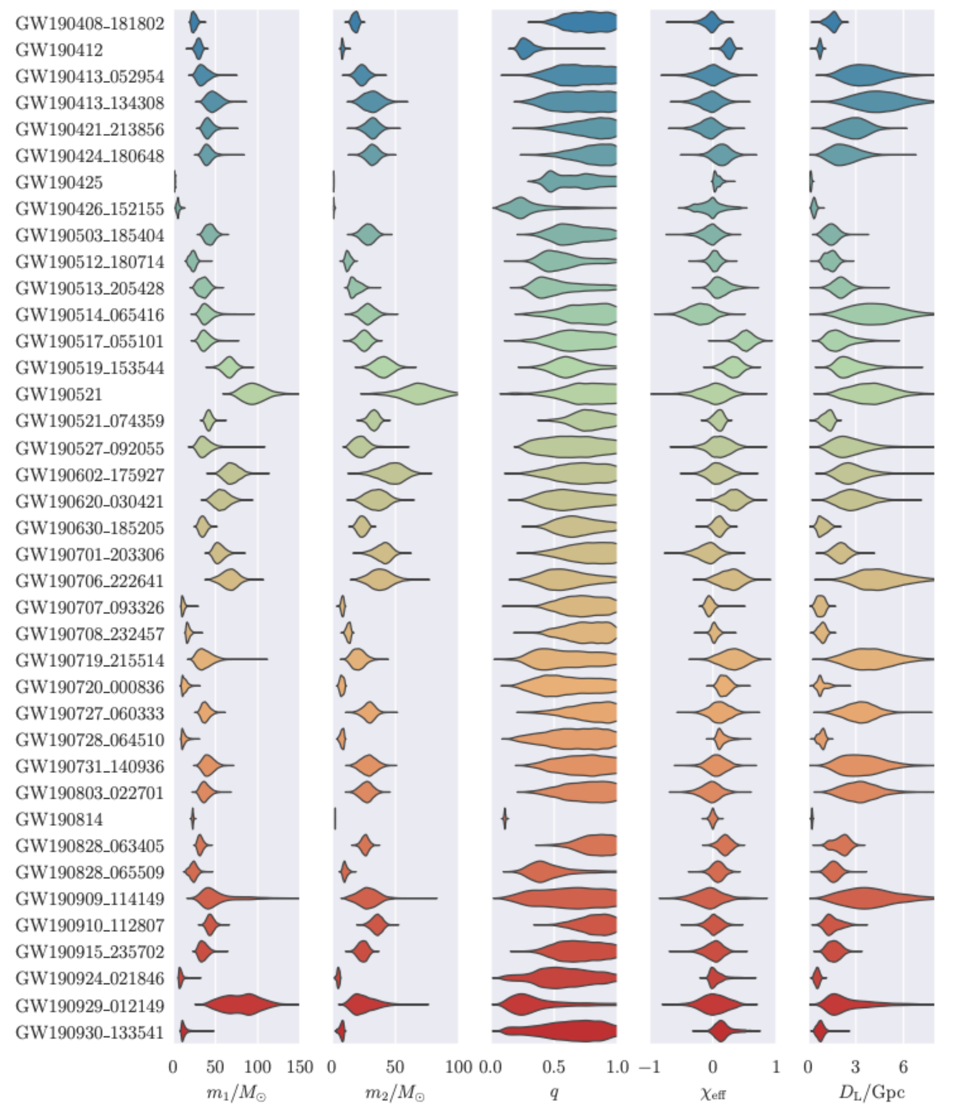
(Received 30 October 2020; revised 23 February 2021; accepted 20 April 2021; published 9 June 2021; corrected 1 September 2021 and 27 April 2022)

We report on gravitational-wave discoveries from compact binary coalescences detected by Advanced LIGO and Advanced Virgo in the first half of the third observing run (O3a) between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC. By imposing a false-alarm-rate threshold of two per year in each of the four search pipelines that constitute our search, we present 39 candidate gravitational-wave events. At this threshold, we expect a contamination fraction of less than 10%. Of these, 26 candidate events were reported previously in near-real time through gamma-ray coordinates network notices and circulars; 13 are reported here for the first time. The catalog contains events whose sources are black hole binary mergers up to a redshift of approximately 0.8, as well as events whose components cannot be unambiguously identified as black holes or neutron stars. For the latter group, we are unable to determine the nature based on estimates of the component masses and spins from gravitational-wave data alone. The range of candidate event masses which are unambiguously identified as binary black holes (both objects $\geq 3\ M_\odot$) is increased compared to GWTC-1, with total masses from approximately $14\ M_\odot$ for GW190924_021846 to approximately $150\ M_\odot$ for GW190521. For the first time, this catalog includes binary systems with significantly asymmetric mass ratios, which had not been observed in data taken before April 2019. We also find that 11 of the 39 events detected since April 2019 have positive effective inspiral spins under our default prior (at 90% credibility), while none exhibit negative effective inspiral spin. Given the increased sensitivity of Advanced LIGO and Advanced Virgo, the detection of 39 candidate events in approximately 26 weeks of data (approximately 1.5 per week) is consistent with GWTC-1.



Sources Parameters Estimation



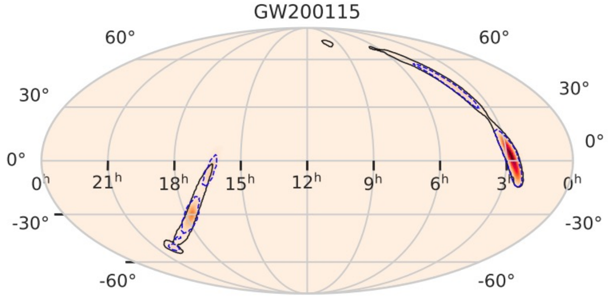


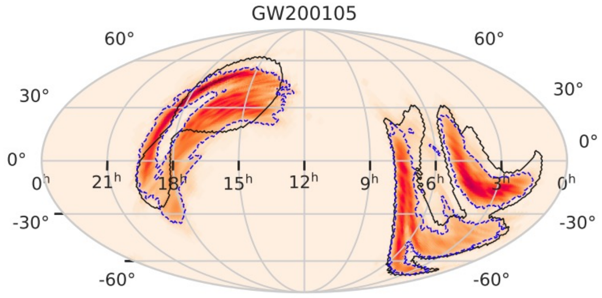
NB
O3 observations described in several catalog papers (O3a: GWTC-2, 2.1
O3b: GWTC-3)

Plot here taken from GWTC-2

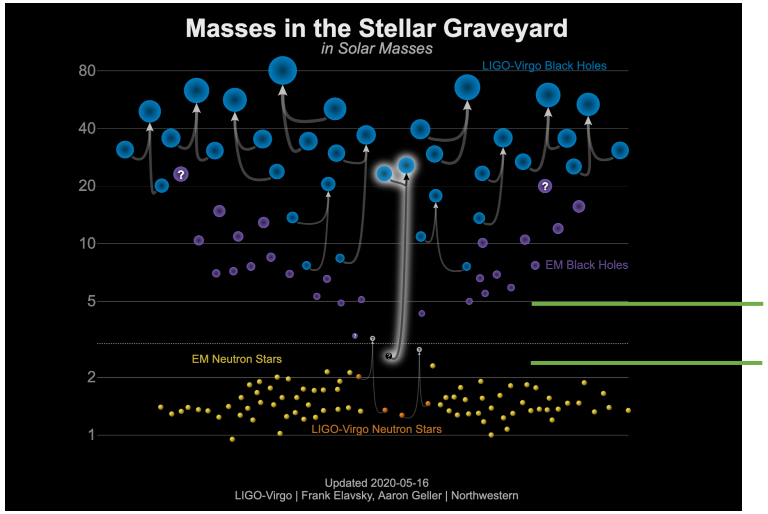
Some remarkable events

- First observation of GW from mixed NSBH systems. Two candidates GW200115, GW200105



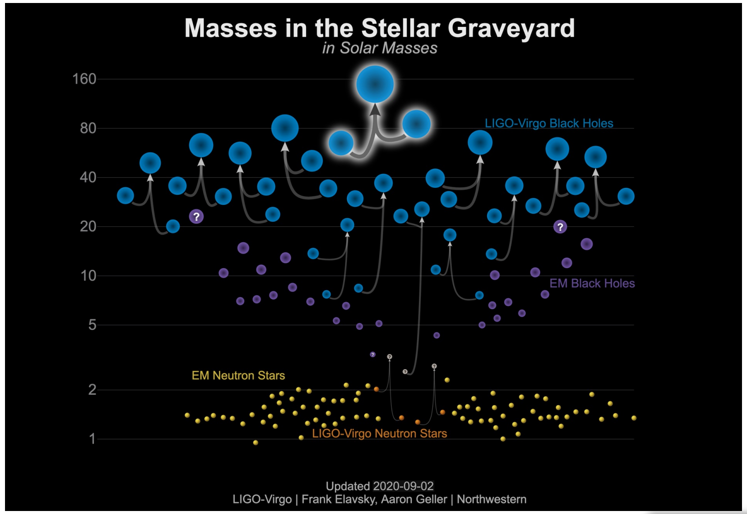


- GW190814 Coalescence of 23 $M_\odot$ BH with a mystery object of 2.6 $M_\odot$



"mass gap"

- GW190521 very-high mass system: two BH of 66 and 85 $M_\odot$ merge to form a BH remnant of 142 $M_\odot$



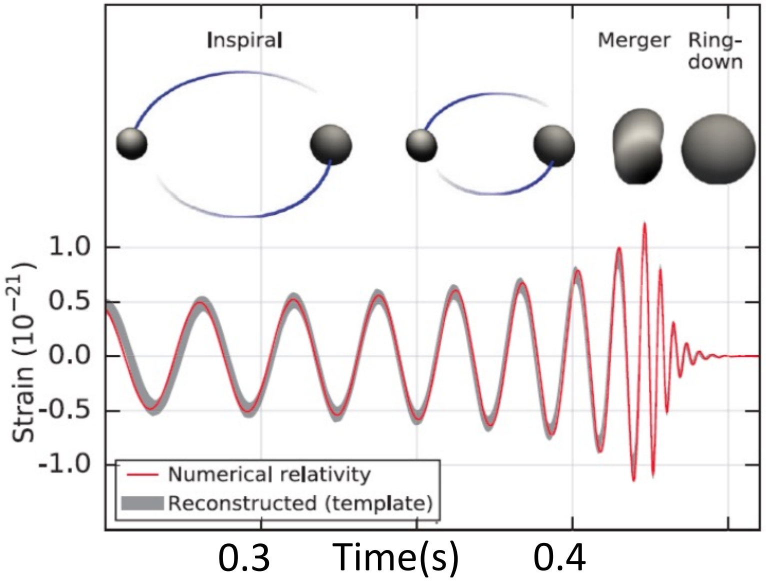
These observations are used to…

- ✓ Understand gravity

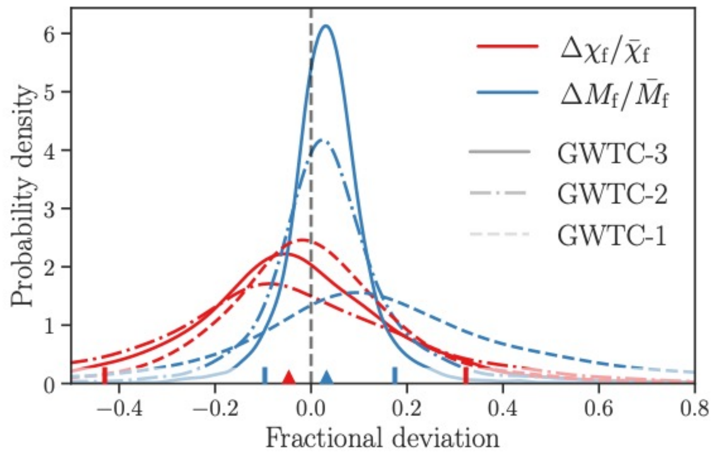
Tests of General Relatvity

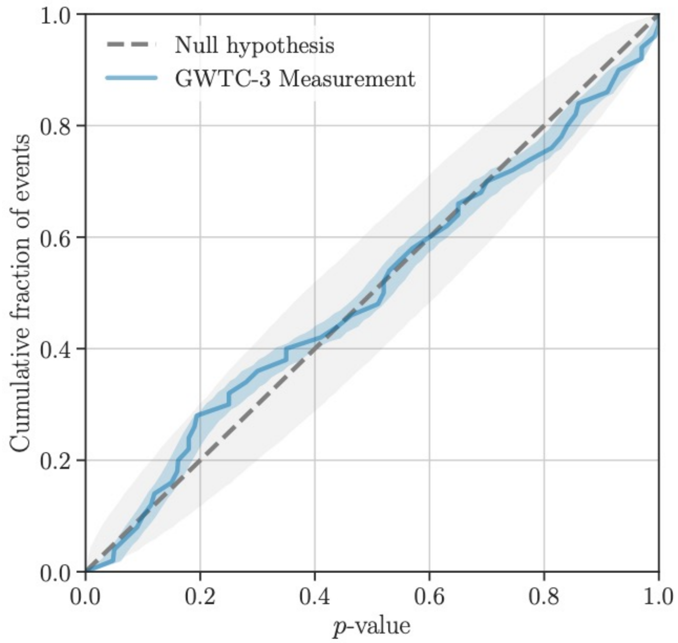
Phys. Rev. D 103 122002 (2021) (arXiv)

- CBC waveforms assume General Relativity
- Residual test measures the coherent residual signal-to-noise ratio after subtracting the best-fit GR waveform



$$\frac{\Delta M_f}{\bar{M}_f} = 2\frac{M_f^{\text{insp}} - M_f^{\text{postinsp}}}{M_f^{\text{insp}} + M_f^{\text{postinsp}}}$$





- Inspiral-(merger-ringdown) consistency checks (mass and spin of remnant BH)
- Generic modifications to waveforms varying coefficients for the inspiral part

Tests of General Relatvity

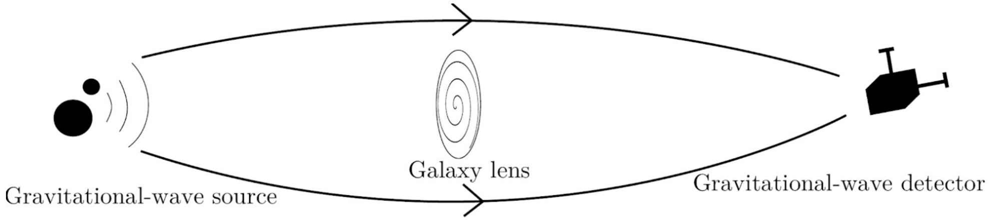
GW vs EM measurements

- GW170817 coincident with Gamma Ray Burst GRB170817A within 1.7 s → constraints on **GW propagation speed**, consistent with speed of light within uncertainties
- Luminosity distance of NGC4933 host galaxy from GW and EM compared

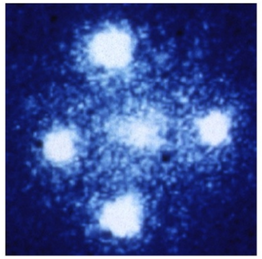
Constraints on alternative theories of gravity

Gravitational lensing

- General Relativity predicts the effect of gravitational lensing, affecting light but also GW
- A detection would be a test of GR, and would allow population studies
- No evidence until now




ESA/Hubble & NASA


NASA, ESA, and STScI


NASA, ESA, Hubble SM4 ERO Team, ST-ECF

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Rates and populations

O3a ApJL **913** L7 (2021) (arXiv)

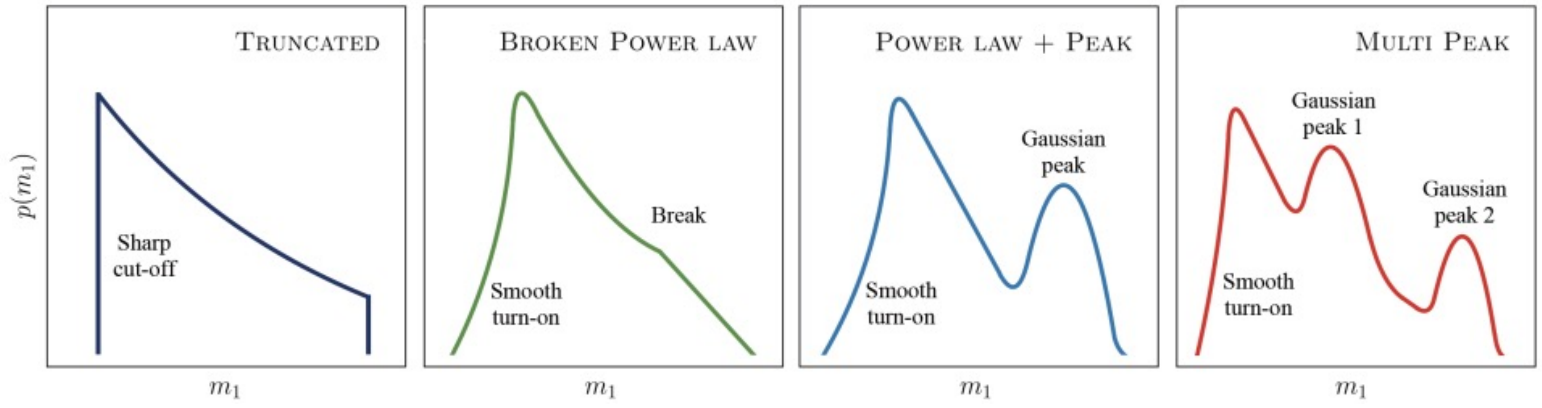
O3b (arXiv)

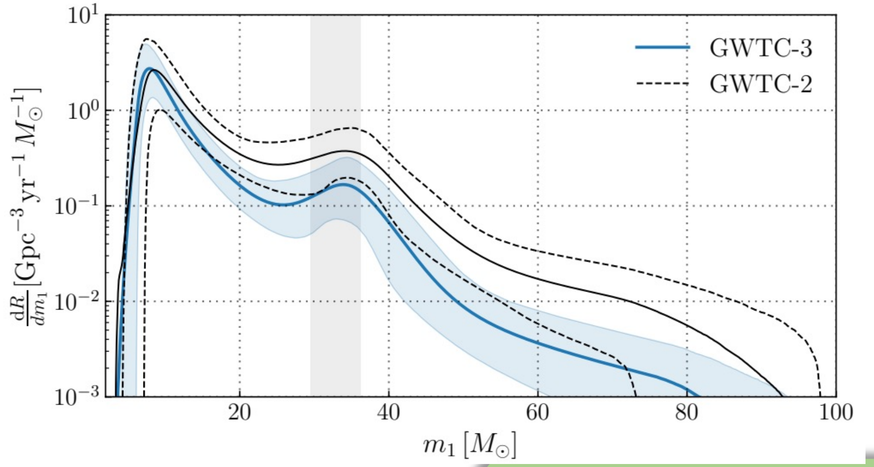
Number of coalescences per Gpc^3 per year

	BNS	NSBH	BBH
	$m_1 \in [1, 2.5] M_\odot$	$m_1 \in [2.5, 50] M_\odot$	$m_1 \in [2.5, 100] M_\odot$
	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [1, 2.5] M_\odot$	$m_2 \in [2.5, 100] M_\odot$
PDB (pair)	170^{+270}_{-120}	27^{+31}_{-17}	$25^{+10}_{-7.0}$
PDB (ind)	44^{+96}_{-34}	73^{+67}_{-37}	$22^{+8.0}_{-6.0}$
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}
BGP	$98.0^{+260.0}_{-85.0}$	$32.0^{+62.0}_{-24.0}$	$33.0^{+16.0}_{-10.0}$
MERGED	10 – 1700	7.8 – 140	16 – 61

Population properties of compact objects involved in coalescences

- Merger rates
- Mass distribution of NS in binaries, slightly heavier than galactic NS
- New insight on BH population properties
  - BH mass distribution has a substructure.
  - Evidence of spin precession, hints of dynamical formation (large spin magnitudes and/or anti-aligned spins)
  - R_{BBH} z evolution consistent with one of star formation rate



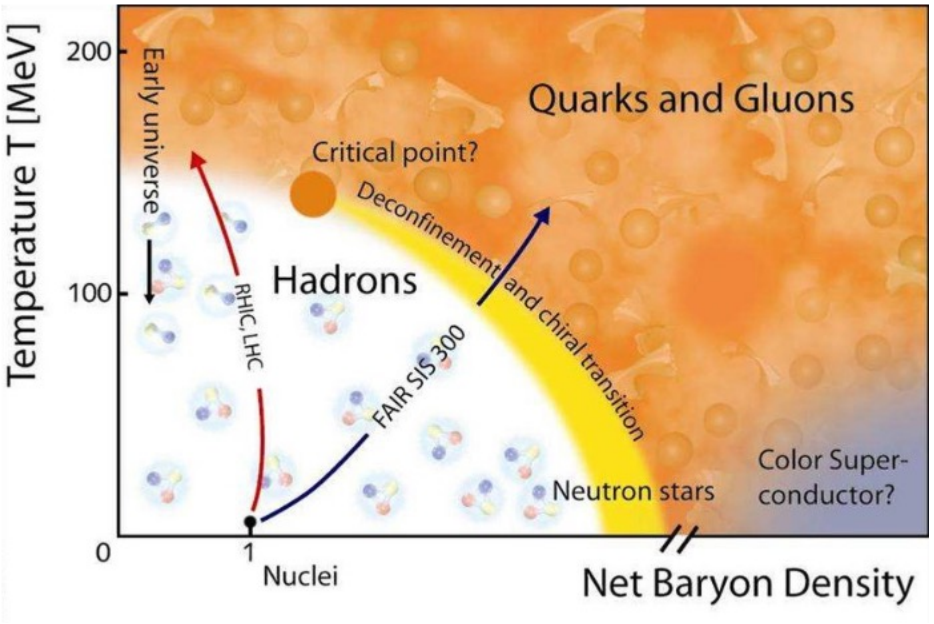


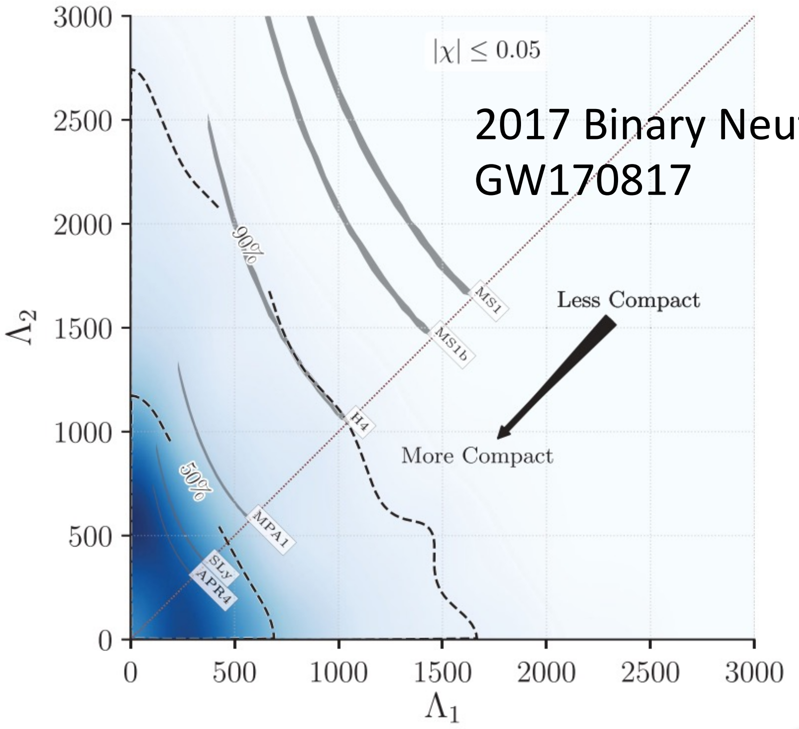
These observations are used to…

- ✓ Understand gravity
- ✓ Astrophysics – understand the objects that generated the GW signal
- ✓ Explore extremely dense nuclear matter

Extreme Matter

- Neutron stars are invaluable laboratories to study extremely dense matter
- NS nature will affect their behaviour during the coalescence and modify the GW signal we can detect
- With GW we can measure the NS tidal deformability and constrain NS models





2017 Binary Neutron Star GW170817

These observations are used to…

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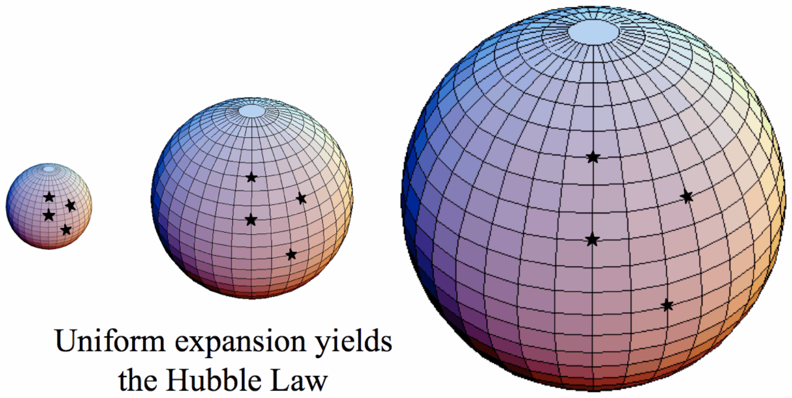
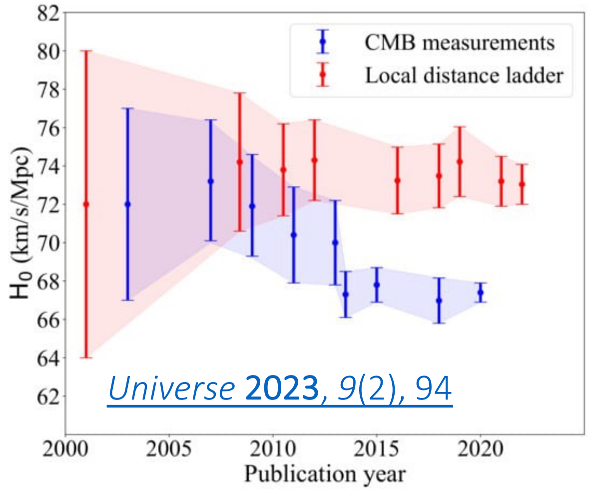
- ✓ Explore extremely dense nuclear matter
- ✓ Cosmology – understand the history of the Universe

Cosmology



- Universe is expanding
- Luminosity distance d_L - reduction of flux from a source
- Redshift **z** - light stretch from cosmological expansion
- For "close" sources (Hubble-Lemaître law) $$z = \frac{H_0}{c} d_L$$
- H_0 describes the rate at which the Universe is currently expanding



Universe **2023**, *9*(2), 94

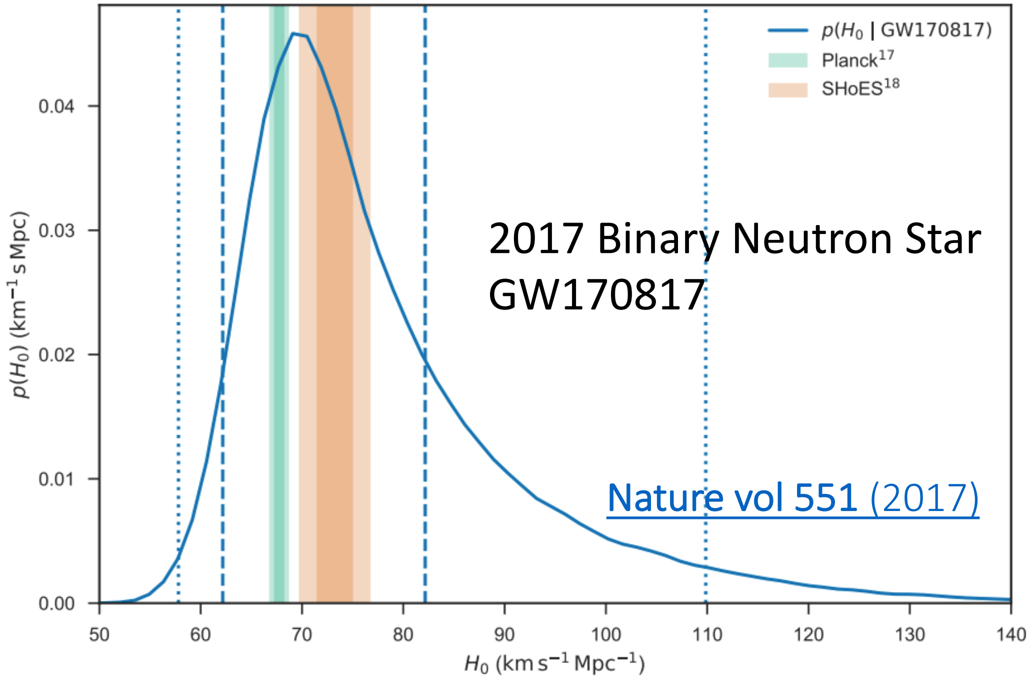
Cosmology with CBC

- GW detection → measurement of luminosity distance

redshift? $z = \frac{H_0}{c} d_L$ from GW

Different methods to constrain H_0

- If EM counterpart
  - Redshift information from EM counterpart (only for GW170817)



2017 Binary Neutron Star GW170817

Nature vol 551 (2017)

Cosmology with CBC

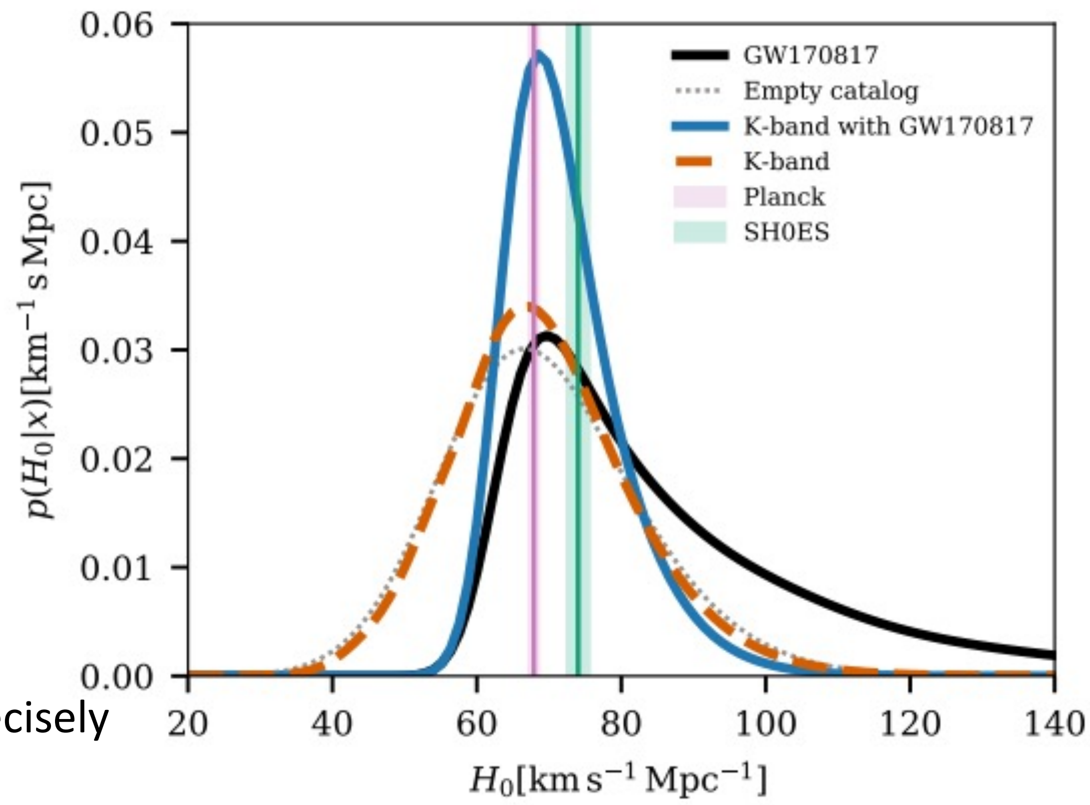
(arXiv)

- GW detection → measurement of luminosity distance

redshift? $z = \frac{H_0}{c} d_L$ from GW

Different methods to constrain H_0

- If EM counterpart
  - Redshift information from EM counterpart (only for GW170817)
- And what about all the BBH we observed?
  - Infer redshift using galaxy catalogues (works well for precisely localised events)
  - Jointly constrain the cosmological parameters and the source population properties of BBHs



These observations are used to…

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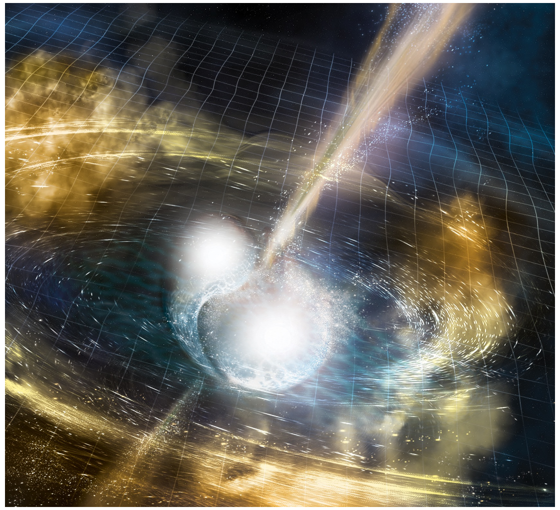
- ✓ Astrophysics – understand the objects that generated the GW signal
- ✓ Explore extremely dense nuclear matter
- ✓ Cosmology – understand the history of the Universe
- ✓ Multi-messenger – triggered searches

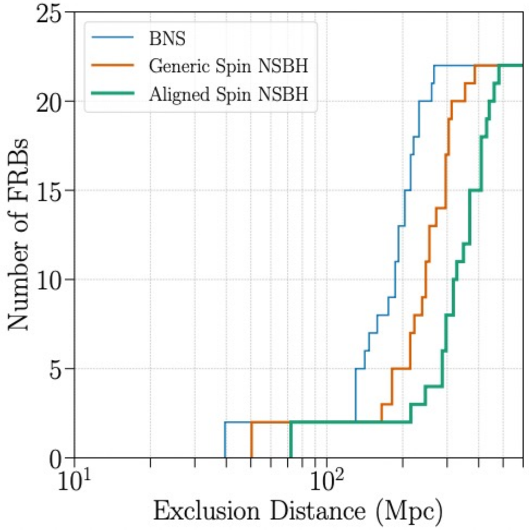
Triggered searches (GRB, FRB)

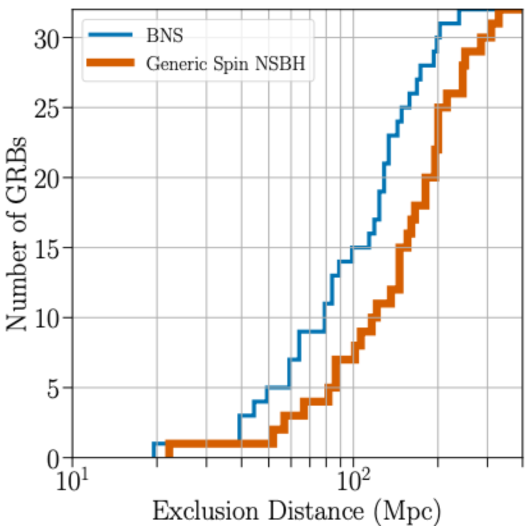
ApJ. 915, 86 (2021) (arXiv)
ApJ 928 186 (2022) (arXiv)
(arXiv)

Search for GW transients associated with Gamma Ray Bursts (GRBs) or Fast Radio Bursts (FRBs)

- Coalescences of compact objects involving a NS have been thought to be associated to GRB for a long time, the connection was demonstrated by GW170817
- FRB emission mechanism still unknown
- Coalescences of compact objects are possible sources, a GW-FRB detection would be a hint.
- No GW signal associated to a GRB (apart from GW170817) or FRB. Sensitivity determined on simulation. Exclusion distance.



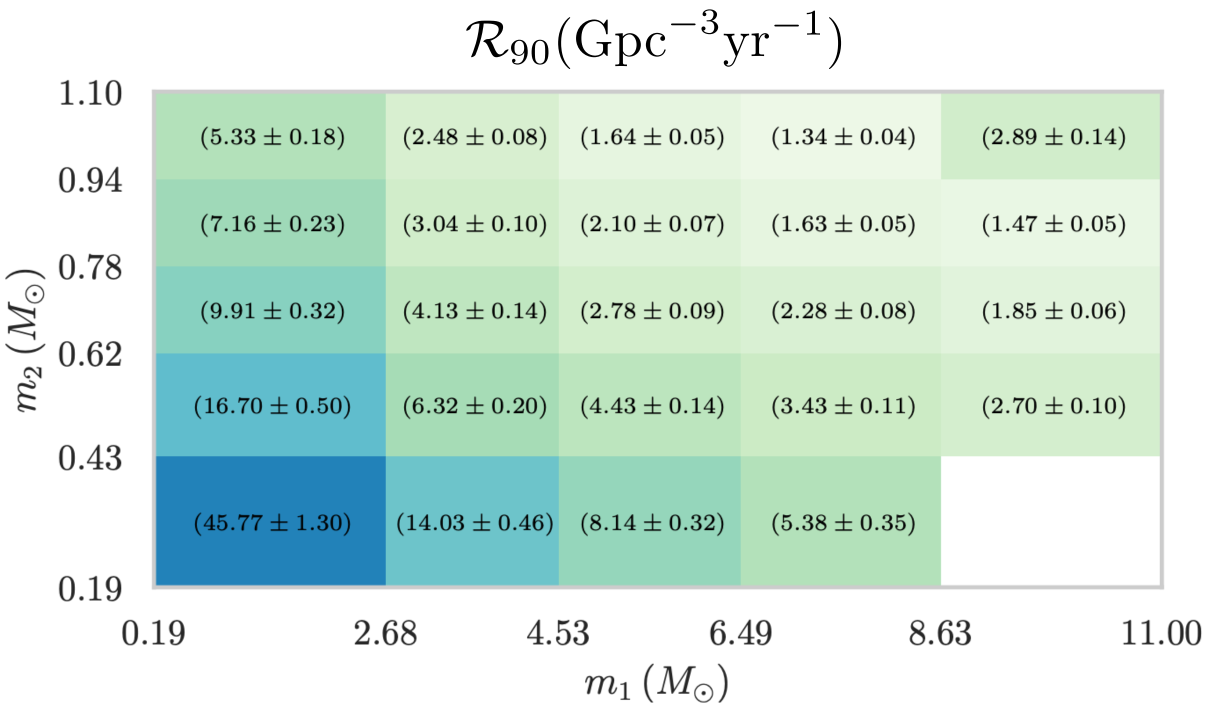




Search for exotic compact objects

(MNRAS)

- Sub-solar compact objects predicted by many models
- We can use classic CBC techniques to look for coalescences involving at least one such object
- No observation → limit on the merger rate
- Constraints on models for primordial BH, BH from dissipative Dark Matter..



Conclusions

- The 2019-2020 observation period was a big success and a change of gear for the LIGO-Virgo-KAGRA collaborations : GW astronomy is entering the era of statistics accumulation – at least for CBC signals
- New observation period starting **on May 24th**
  - Better sensitivities and two years run → expect overall ~3 times the number of CBC observations
- Many varied scientific results
  - ~90 high-probability CBC candidates since first detection
  - Only one with EM counterpart observed until now (GW170817), with rich implications
  - Constraints on sources populations and rates, tests of General Relativity, cosmology..
- Reminder: we do searches for non-CBC GW signals, although no evidence for the moment, improvements in sensitivity
- GWs remain a newcomer among the Universe messengers – still room for unexpected !