Gravitational waves and Multi-messenger astronomy: a new window on the Universe

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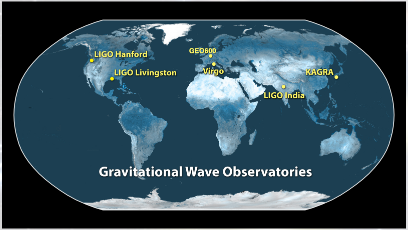
Outline

The first observing runs of Advanced LIGO and Advanced Virgo



Credit: LIGO-Virgo

- *O1: September 2015 - January 2016*

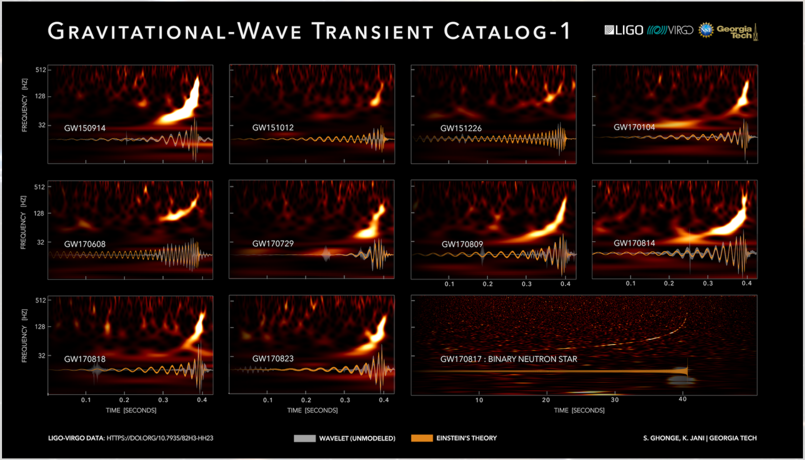
  Only the two LIGO detectors were operating

- *O2: November 2016 - August 2017*

  Virgo joined the network on August 1

The first GW transient catalog

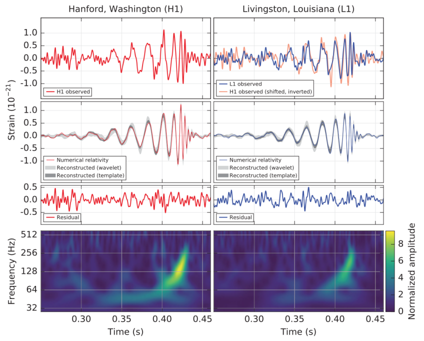
During O1 and O2 there were 11 GW detections!



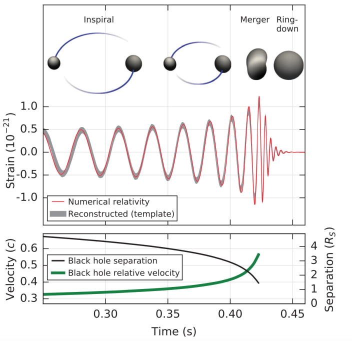
Abbott et al. 2019, PRX, 9, 031040

GW150914: The first observation of GWs

The observation



The model



Abbott et al. 2016, PRL, 116, 061102

The BBH detections

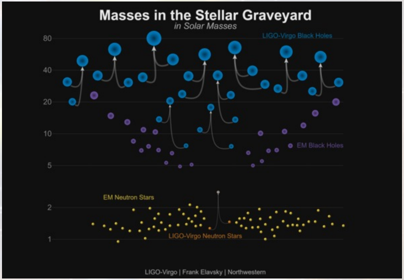
A new population of stellar mass BBH systems has been observed!

O1

GW150914, GW151012, GW151226

O2

GW170104, GW170608, GW170729, GW170809, GW170814, GW170818, GW170823



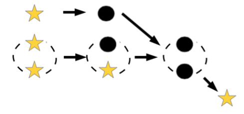
- First direct evidences for "heavy" stellar mass BHs (> 25 M$_\odot$)
- From the masses we can infer information on the environment:
  $\rightarrow$ events like GW150914 most likely formed in low-metallicity environment ($\lesssim 0.5$ Z$_\odot$)
- BBH merger rate: $53.2^{+58.5}_{-28.8}$ Gpc^{-3} yr^{-1}

Abbott et al. 2016, ApJL, 818, 22
Abbott et al. 2017, PRL 118, 221101
Abbott et al. 2019, PRX, 9, 031040; ApJL, 882, 24

How do BHs form binary systems?

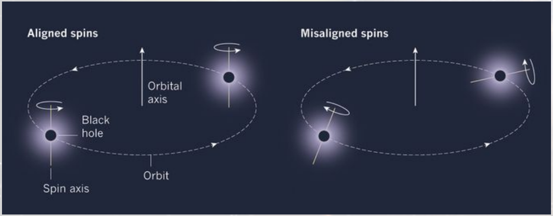
Isolated binary in galactic fields

Dynamical interactions in clusters



How can we discriminate between these two formation mechanisms?

A possibility is to look at the spins



Isolated binary:

Spins preferentially aligned with the binary orbital angular momentum

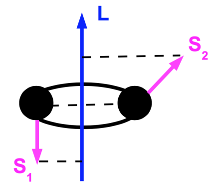
Cluster binary:

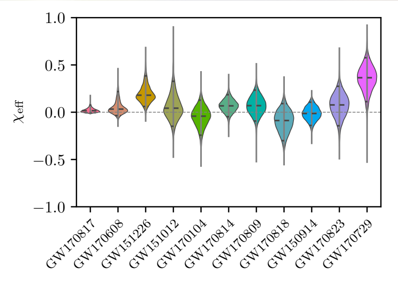
Isotropic spin orientations

Spin estimate with GWs

With GWs we can estimate the **effective orbital spin**

$$\chi_{eff} = \frac{c}{GM}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\hat{\mathbf{L}}$$

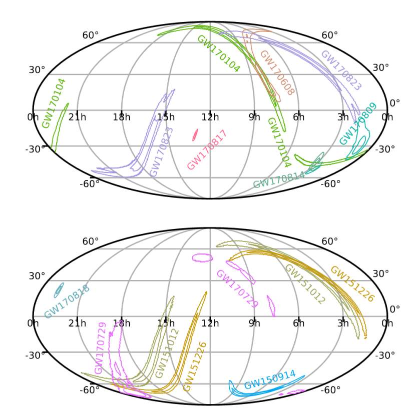




Abbott et al. 2019, PRX, 9, 031040

- Scenarios in which most BHs merge with large spins aligned with the binary's orbital angular momentum are disfavoured.
- With more detections it will be possible to determine if the BH spin is preferentially aligned or isotropically distributed (see, e.g., Farr et al. 2018).

Which is the host galaxy?



Event	$\Delta\Omega$ (deg^2)	D$_L$ (Mpc)
GW150914	180	430^{+150}_{-170}
GW151012	1555	1060^{+540}_{-480}
GW151226	1033	440^{+180}_{-190}
GW170104	924	960^{+430}_{-410}
GW170608	396	320^{+120}_{-110}
GW170729	1033	2750^{+1350}_{-1320}
GW170809	340	990^{+320}_{-380}
GW170814	87	580^{+160}_{-210}
GW170818	39	1020^{+430}_{-360}
GW170823	1651	1850^{+840}_{-840}

Abbott et al. 2019, PRX, 9, 031040

Many galaxies in the universe volume corresponding to the GW events...

$\Rightarrow$ **Multi-messenger astronomy is needed!**

Why multi-messenger astronomy?

GWs and photons provide complementary information about the physics of the source and its environment

GW

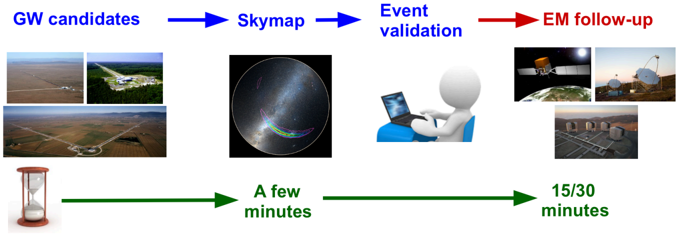
- *mass*
- *spin*
- *eccentricity*
- *system orientation*
- *luminosity distance*
- *compact object binary rate*

EM

- *precise (arcsec) sky localization*
- *host galaxy*
- *redshift*
- *local environment*
- *emission processes*
- *acceleration mechanisms*

EM follow-up during O1 and O2

Low-latency GW data analysis pipelines promptly identify GW candidates and send GW alerts to trigger prompt EM observations and start archival searches

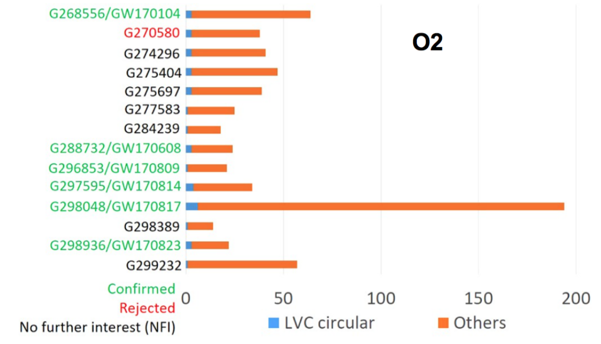


During O1 and O2 GW alerts shared only with MoU partners

GW alerts during O1 and O2

17 GW Alerts have been issued during O1 and O2:

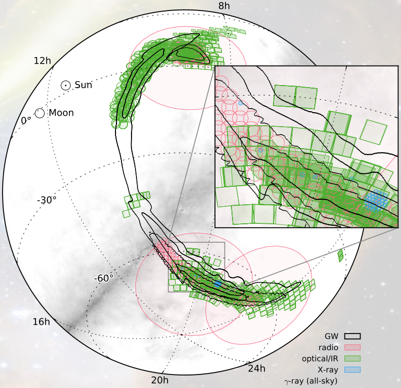
- 3 Alerts during O1; all GW candidates have been confirmed as GW events
- 14 Alerts during O2; 6 GW candidates have been confirmed as GW events



Abbott et al. 2019, ApJ, 875, 161

Searches for EM counterparts to BBH mergers

- Although no EM counterpart was expected from BBH mergers, intense EM follow-up campaigns have been performed (see, e.g., GW150914) ⇒
- Several candidate counterparts have been found, all identified to be normal population SNe, dwarf novae and AGN unrelated to the GW events (see, e.g., Kasliwal et al. 2016, Smartt et al. 2016)
- For all the detected BBH mergers no firm EM counterpart has been found

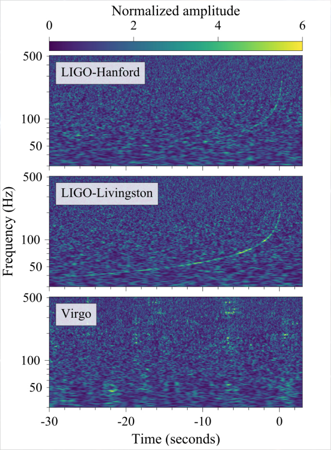


Abbott et al. 2016, ApJL, 826, L13

Abbott et al. 2019, ApJ, 875, 161

GW170817

On August 17, 2017 at 12:41:04 UTC Advanced LIGO and Advanced Virgo made their **first observation of a binary neutron star (BNS) inspiral!**



- GW170817 swept through the detectors' sensitive band for ~ 100 s ($f_{start} = 24$ Hz)
- The SNR is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

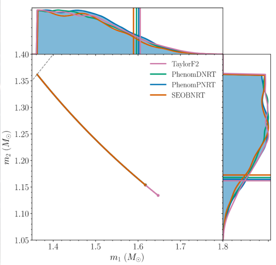
  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal among the ones observed in O1 and O2!

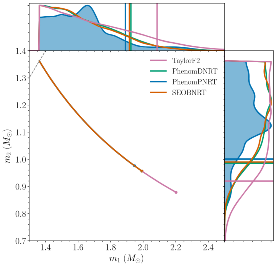
Abbott et al., PRL, 119, 161101 (2017)

BNS detection: component masses

low-spin $(|\chi| \leq 0.05)$



high-spin $(|\chi| \leq 0.89)$



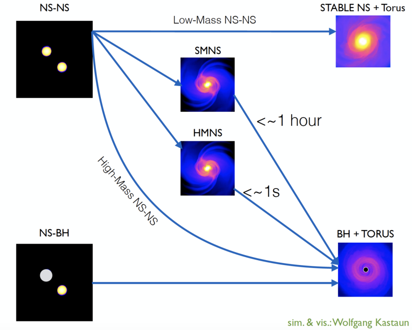
	low-spin	high-spin
m_1	1.36 - 1.60 $M_\odot$	1.36 - 1.89 $M_\odot$
m_2	1.16 - 1.36 $M_\odot$	1.00 - 1.36 $M_\odot$

Estimated masses (m_1 and m_2) are consistent with the masses of all known neutron stars

Abbott et al., PRX, 9, 011001 (2019)

BNS detection: the compact remnant

The outcome of a BNS coalescence depends primarily on the masses of the inspiraling objects and on the equation of state of nuclear matter.

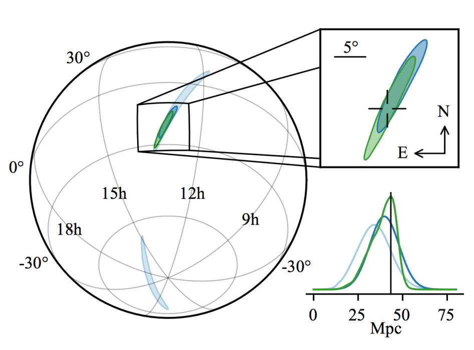


- Stable NS (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s (burst-like GW signal)
- BH prompt formation (high frequency quasi normal mode ringdown GW signal)

Searches for short (<1 s) and medium ($<$ 500 s) duration transients have not found any post-merger signals (Abbott et al. 2017, ApJL, 851, 16).

Searches for long-duration signals have not found any significant signal candidate (Abbott et al. 2019, ApJ, 875, 160)

Where did the BNS merger occur?



Sky localization:

- rapid loc., HL: 190 deg^2
- rapid loc., HLV: 31 deg^2
- final loc.*, HLV: 28 deg^2

Luminosity distance:

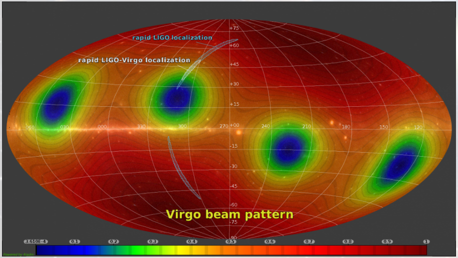
40^{+8}_{-14} Mpc

This is the closest and most precisely localized gravitational-wave signal!

Abbott et al., PRL, 119, 161101 (2017)

* More refined analysis allowed to reduce the sky localization to 16 deg^2
(Abbott et al. 2019, PRX, 9, 031040; PRX, 9, 011001)

The role of Virgo in the sky localization of GW170817



(Loading Video...)

Credits:
G. Greco, N. Arnaud, M. Branchesi, A. Vicere

Credit: L. Singer

Which were the expected EM counterparts?

- Short GRBs:
  - *Prompt* γ-ray emission (< 2 s).
  - Multiwavelegth *afterglow* emission: X-ray, optical and radio (minutes, hours, days, months).
- Kilonova: optical and NIR (days-weeks).
- Late blast wave emission: radio ($\sim$ months, years).

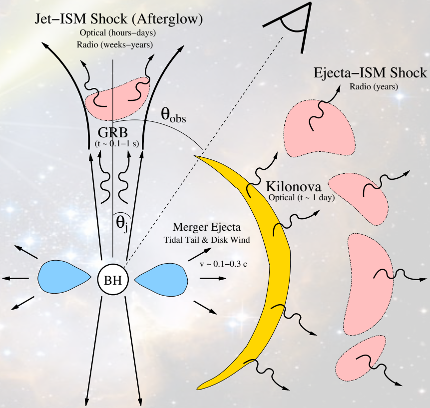
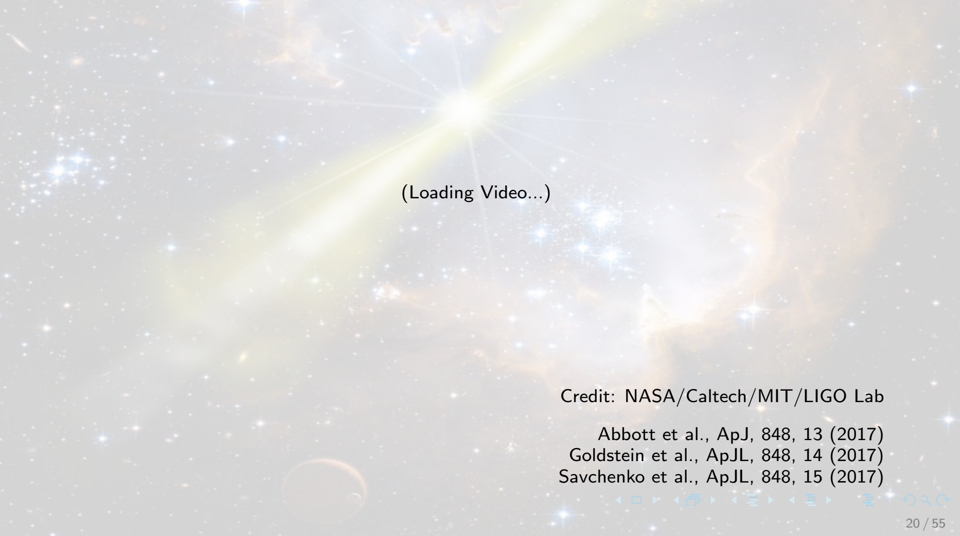


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

Gamma-rays: short GRB

A GRB (GRB170817A) was independently detected by Fermi-GBM and INTEGRAL

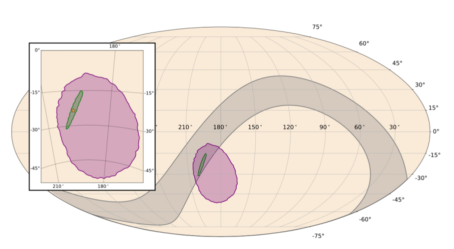


Credit: NASA/Caltech/MIT/LIGO Lab

Abbott et al., ApJ, 848, 13 (2017)
Goldstein et al., ApJL, 848, 14 (2017)
Savchenko et al., ApJL, 848, 15 (2017)

GW170817 and GRB 170817A association

- Temporal coincidence: the start of the gamma-ray emission relative to the merger time is $\sim$ 1.7 s
- Spatial coincidence:



90 % Fermi-GBM sky localization (1100 deg^2)

90 % sky localization from Fermi and INTEGRAL timing

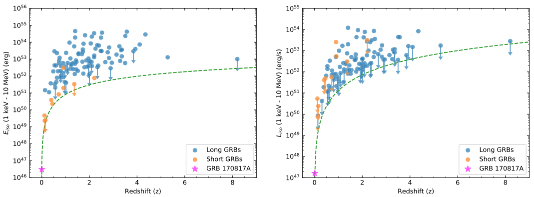
LIGO-Virgo 90 % credible region (28 deg^2)

The probability that GRB 170817A and GW170817 occurred this close in time and with this level of location agreement by chance is 5.0×10^{-8}: a 5.3 σ Gaussian-equivalent significance

$\Rightarrow$ First direct evidence that BNS mergers are progenitors of (at least some) short GRBs!

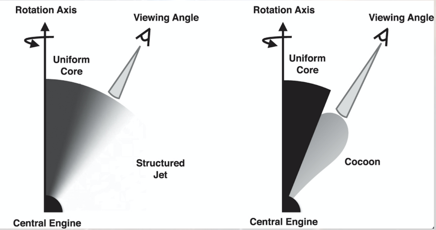
Abbott et al., ApJ, 848, 13 (2017)

GRB 170817A: properties



GRB 170817A between 2 and 6 orders of magnitude less energetic than other observed bursts with measured redshift!

- Intrinsically sub-luminous GRB?
- structured jet?
- cocoon emission?



Abbott et al., ApJ, 848, 13 (2017)

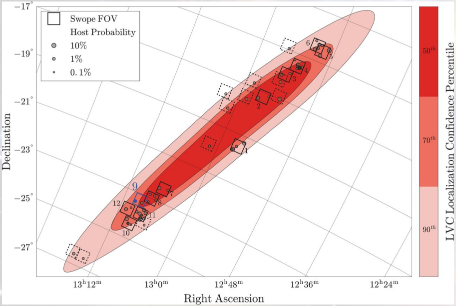
The EM follow-up campaign

A wide-ranging EM follow-up campaign started in the hours immediately after the observation of GW170817 and GRB170817A

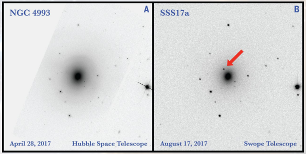
(Loading Video...)

The identification of the optical counterpart

The key strategy: galaxy targeted search



- An optical counterpart has been discovered on August 18, 2017
- Transient is located at $\sim$ 10" from the center of the galaxy NGC 4993, at a distance of 40 Mpc



Coulter et al. 2017, Science, 358, 1556

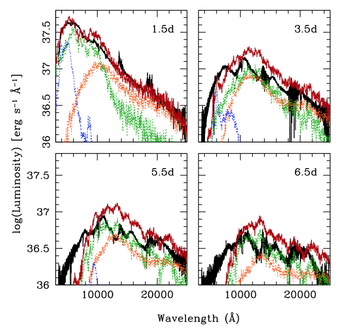
The discovery has been confirmed by other teams (Abbott et al 2017, ApJ Letters, 848, 12)

The spectroscopic identification of the kilonova

Credit: ESO/E. Pian et al./S. Smartt & ePESSTO

The spectroscopic identification of the kilonova

- The evolution of the observed spectrum with time is in a good match with the expectations for kilonovae (Pian et al., Nature, 2017)



- observational data
- 3-component model
  - wind region with lanthanide-free composition
  - lanthanide-rich dynamical ejecta region
  - wind region with mixed composition

The comparison with spectral models suggests that the merger ejected 0.03-0.05 $M_\odot$ of material, including high-opacity lanthanides.

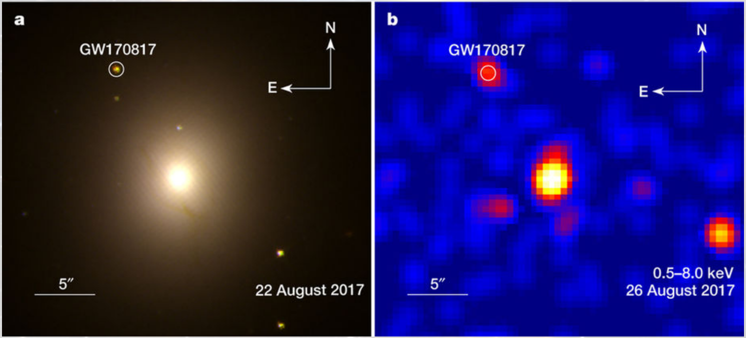
- A recent re-analysis of the spectra led to the identification of the strontium (Watson et al., Nature, 2019)

First direct proof that neutron star mergers are heavy elements factory

(r-process nucleosynthesis)

X-ray and radio observations

9 days and 16 days after the GW trigger, an X-ray and a radio counterparts have been discovered (Troja et al. 2017, Hallinan et al. 2017)



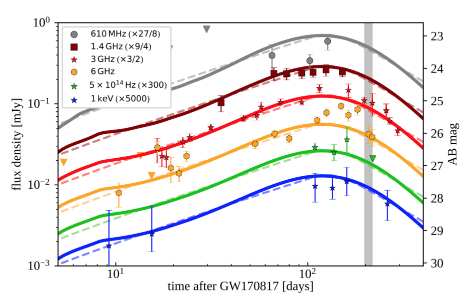
Source monitored for hundreds of days...

X-ray and radio observations

Two possible interpretations:

- - - cocoon emission
- — afterglow emission from a structured jet

Both models are consistent with the multiwavelength light curve... ⇒

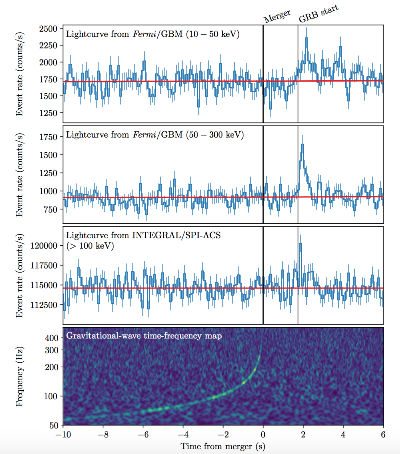


Ghirlanda et al. 2019

... But recent Very Long Baseline Interferometry observations allowed to constrain the size and the proper motion of the radio source ⇒ **the source is consistent with a jet!** (Ghirlanda et al. 2019, Mooley et al. 2018)

GW-GRB association: Speed of gravity vs speed of light

The observed time delay between GRB170817A and GW170817 can be used to put constraints on the difference between the speed of gravity and the speed of light



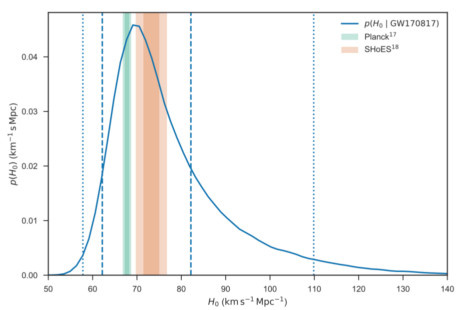
- $\Delta\nu = \nu_{\rm GW} - \nu_{\rm EM}$
- $\frac{\Delta\nu}{\nu_{\rm EM}} \sim \frac{\nu_{\rm EM}\Delta t}{D}$
- lower bound on distance: 26 Mpc
- observed time delay ($\sim$1.7 s)
- Two cases:
  - The GRB and GW signals emitted simultaneously
  - The GRB signal was emitted 10 s after the GW signal

$$-3 \times 10^{-15} \leq \frac{\Delta\nu}{\nu_{\rm EM}} \leq 7 \times 10^{-16}$$

Abbott et al. 2017, ApJL, 848, 13

GW-NGC4993 association: implications for Cosmology

GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**



- $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1}*
- $H_0 = 67.74^{\pm 0.46}$ km s^{-1} Mpc^{-1}
- $H_0 = 73.24^{\pm 1.74}$ km s^{-1} Mpc^{-1}

Abbott et al., Nature, 551, 85 (2017)

* More recent estimates, obtained assuming a priori that the GW source is in NGC 4993, are:
- $H_0 = 70^{+13}_{-7}$ km s^{-1} Mpc^{-1} (high-spin case)
- $H_0 = 70^{+19}_{-8}$ km s^{-1} Mpc^{-1} (low-spin case)

Abbott et al. 2019, PRX, 9, 011001

GW170817 and its EM counterparts: summary

- First identification of the host galaxy of a GW event
- First direct evidence of the association of short GRBs with BNS mergers
- First detection of the off-axis GRB afterglow
- First detailed study of GRB jet structure
- First clear identification of a kilonova
- First BNS merger/kilonova association
- First evidence that the heaviest elements in the Universe can form in BNS mergers
- Constraints on fundamental physics
- A new, independent method to estimate H_0

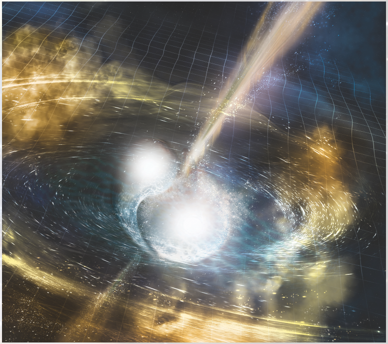
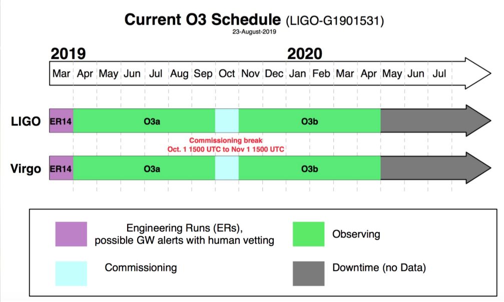


Image credit:
NSF/LIGO/Sonoma State University/A. Simonnet

The third observing run: O3

The third observing run: O3

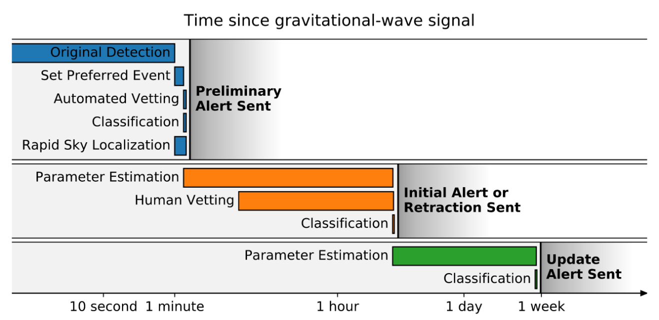
- O3a: April 1st, 2019 - October 1st, 2019
- ∼1 month commissioning break: 1/Oct/2019 - 31/Oct/2019
- O3b started on November 1st, 2019; it is expected to continue until at least the end of April 2020



- An extension of O3b will be possible, but limited so that the run will end no later than June 30, 2020 (Abbott et al. 2019, arXiv:1304.0670)
- KAGRA is planning to join later this year, no firm date yet

Public GW alerts

GW alerts in O3 are public!



A few modifications are planned for O3b:

- Two preliminary alerts
- Automated alerts for coincident GW candidates associated with a GRB or a SN

Public alerts user guide: `https://emfollow.docs.ligo.org/userguide`

The public GW alerts: threshold and content

False Alarm Rate threshold to release automatic alerts

- CBC events: 1/(2 months)
- Unmodeled burst events: 1/yr

Content of public alerts:

- Estimate of the False Alarm Rate (FAR) of the event candidate
- Event time and sky localization (2D skymaps)
- For Burst candidates: central frequency (Hz), duration (s) and GW fluence (erg/cm^2)
- For CBC candidates:
  - 3D skymaps with direction-dependent luminosity distance (Singer et al. 2016)
  - Luminosity Distance marginalized over the whole sky
  - Source **Classification** and **Properties**

The content of public GW alerts - CBC

Classification

p_astro probability that the source is astrophysical;

it comes from evaluating whether the source belongs to one of five categories:

BNS, mass gap, NS-BH, BBH,

Terrestrial (i.e., noise)

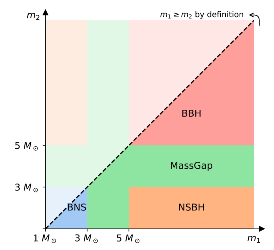


Image credit: Public alerts user guide

Properties

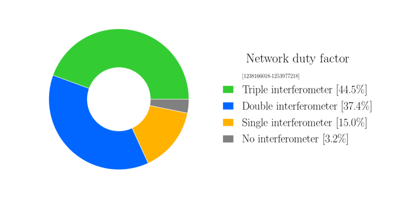
Under the assumption that the source is not noise:

Source classifier: probability that at least one of the compact objects is a NS ($m < 3\ M_\odot$)

Remnant classifier: probability that the system ejected a non-zero amount of NS matter (Foucart 2012, 2018, Pannarale & Ohme, 2014)

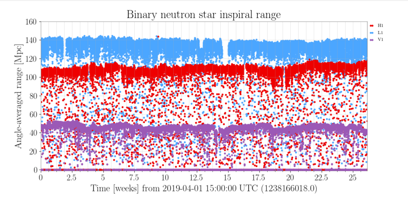
O3a: detector performance

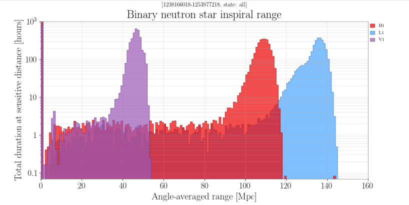
Network duty cycle



- H, L, V online together: 44.5 % of time
- 2 or 3 detectors online together: 81.9 % of time

BNS range





O3a candidate GW alerts

Public alerts can be found here:

https://gracedb.ligo.org/latest/

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

Latest — as of 1 October 2019 07:26:47 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

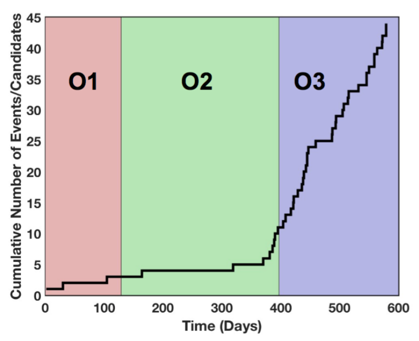
Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
S190930s	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253885758.235347	1253885759.246810	1253885760.253734	3.008e-09	2019-09-30 13:36:04 UTC
S190928c	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1253671923.328316	1253671923.364500	1253671923.400684	6.729e-09	2019-09-28 02:14:18 UTC
S190924h	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253326743.785645	1253326744.846654	1253326745.876674	8.928e-19	2019-09-24 02:19:25 UTC
S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC
S190910h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252139415.544299	1252139416.544448	1252139417.544448	3.584e-08	2019-09-10 08:30:21 UTC
S190910d	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252113996.241211	1252113997.242676	1252113998.264918	3.717e-09	2019-09-10 01:26:35 UTC
S190901ap	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251415878.837767	1251415879.837767	1251415880.838844	7.027e-09	2019-09-01 23:31:24 UTC
S190829u	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251147973.281494	1251147974.283940	1251147975.283940	5.151e-09	2019-08-29 21:06:19 UTC
S190828l	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251010526.884921	1251010527.886557	1251010528.913573	4.629e-11	2019-08-28 06:55:26 UTC
S190828j	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251009262.739486	1251009263.756472	1251009264.796332	8.474e-22	2019-08-28 06:34:21 UTC
S190822c	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1250472616.589125	1250472617.589203	1250472618.589203	6.145e-18	2019-08-22 01:30:23 UTC
S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
S190808ae	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249338098.496141	1249338099.496141	1249338100.496141	3.366e-08	2019-08-08 22:21:45 UTC
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
S190707q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

O3a candidate GW alerts

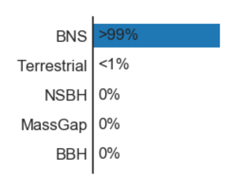


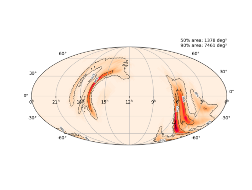
- 41 Alerts, 8 retractions
- Almost all of the GW candidates consistent with BBH mergers
- 3 GW candidates with the highest probability assigned to the **BNS category**
- 4 GW candidates with the highest probability assigned to the **NS-BH category**

Events with highest probability assigned to BNS

S190425z

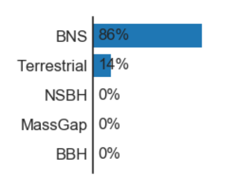
Detectors: L,V
FAR: $< 1/100$ yr
Distance:156 $\pm$ 41 Mpc
90 % c.r.: 7461 deg^2
GCN: 24168, 24228
No EM counterpart

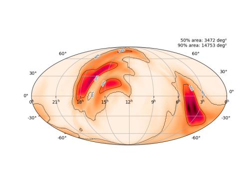




S190901ap

Detectors: L, V
FAR: 1 per 4.5 years
Distance: 241 $\pm$ 79 Mpc
90 % c.r.: 14753 deg^2
GCN: 25606, 25614
No EM counterpart

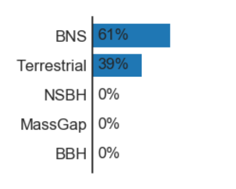


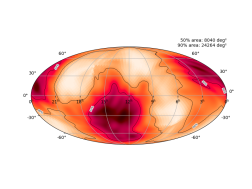


Events with highest probability assigned to BNS

S190910h

Detectors: L
FAR: 1.1 per year
Distance: 230 ± 88 Mpc
90 % c.r.: 24264 deg^2
GCN: 25707, 25778
No EM counterpart

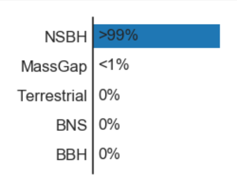


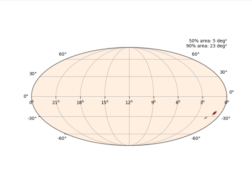


Events with highest probability assigned to NS-BH

S190814bv

Detectors: H, L, V
FAR: $< 1/100$ yr
Distance: 276 ± 56 Mpc
90 % c.r.: 23 deg^2
GCN: 25324, 25333
No EM counterpart





S190910d

Detectors: H, L
FAR: 1 per 8.5 years
Distance: 632 ± 186 Mpc
90 % c.r.: 2482 deg^2
GCN: 25695, 25723
No EM counterpart

S190923y

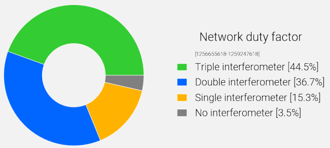
Detectors: H, L
FAR: 1.5 per year
Distance: 438 ± 133 Mpc
90 % c.r.: 2107 deg^2
GCN: 25814
No EM counterpart

S190930t

Detectors: L
FAR: 1 per 2.05 years
Distance: 108 ± 38 Mpc
90 % c.r.: 24220 deg^2
GCN: 25876
No EM counterpart

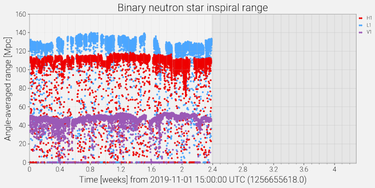
From November 1st: O3b

Network duty cycle



- H, L, V online together: 44.5 % of time
- 2 or 3 detectors online together: 81.2 % of time

BNS range

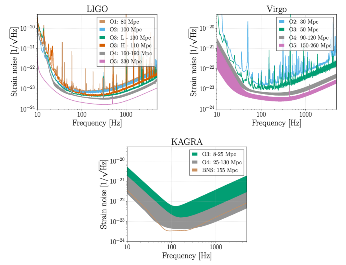


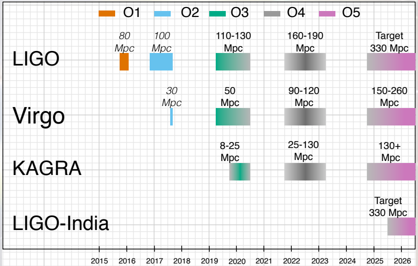
GW alerts

- 5 GW alerts, 3 retractions
- The 2 GW candidates are consistent with BBH mergers
- No EM counterpart so far

Prospects

Prospects





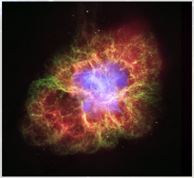
Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}
		Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.	Area (deg^2) 90% c.r.
O3	HLV	250 – 310	310 – 390	250 – 340
O4	HLVK	29 – 48	48 – 69	33 – 47

Abbott et al. 2019, arXiv: 1304.0670

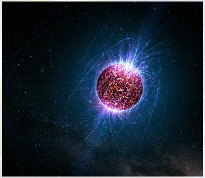
Prospects

There are many other sources still to be detected...

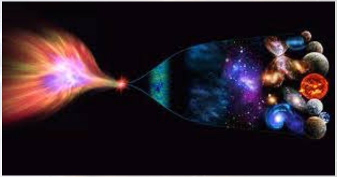
Core collapse of massive stars



Isolated Neutron Stars



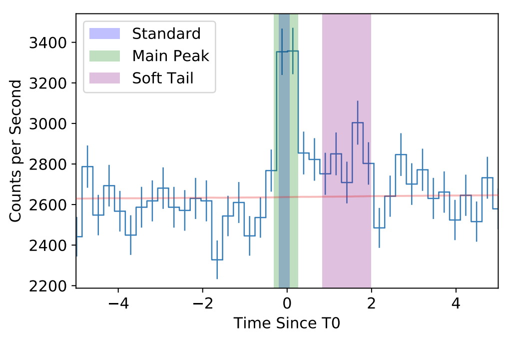
Astrophysical and cosmological background



Stay tuned!

Backup slides

GRB 170817A: some details



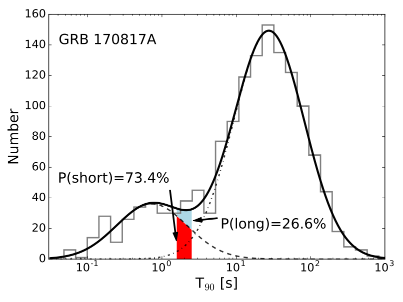
256 ms binned light curve in the 10-300 keV band for NaI 1, 2 and 5

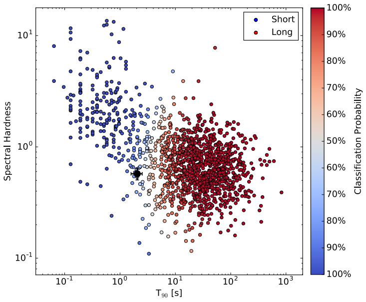
- Main pulse:
  - $\sim$ 0.5 s
  - Comptonized spectrum, E_{peak}=185 $\pm$ 62 keV, Index=-0.62 $\pm$ 0.40
- Soft tail:
  - $\sim$ 1.1 s
  - Blackbody spectrum, T=10.3 $\pm$ 1.5 keV

Goldstein et al., ApJL, 848, 14 (2017)

GRB 170817A: duration and spectral hardness

To which GRB class does GRB 170817A belong?

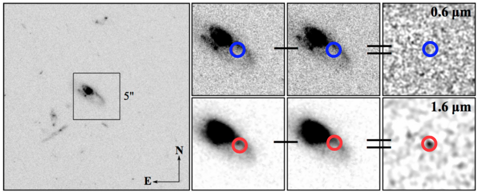




GRB 170817A is $\sim$ 3 times more likely to be a **short GRB** than a long GRB

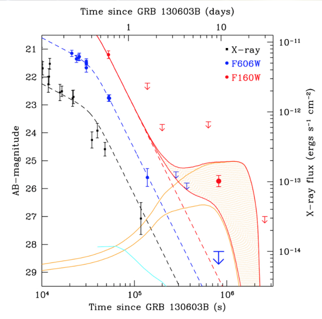
Goldstein et al., ApJL, 848, 14 (2017)

A kilonova detection for GRB 130603B?



F606W/optical

NIR/F160W



- blue curve: optical afterglow
- orange curves: kilonova NIR model

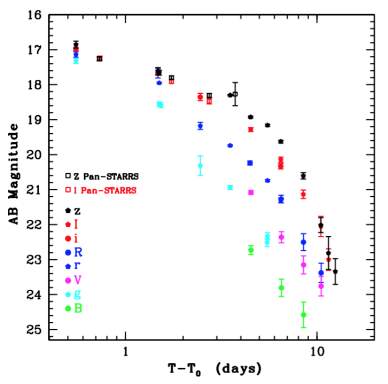
  ejected masses:
  10^{-2} $M_\odot$ and 10^{-1} $M_\odot$
- cyan curve: kilonova optical model
- solid red curves: afterglow+kilonova

Tanvir et al, Nature, 500, 547 (2013)

The optical and near infrared light curve

The optical transient was later observed with different instruments

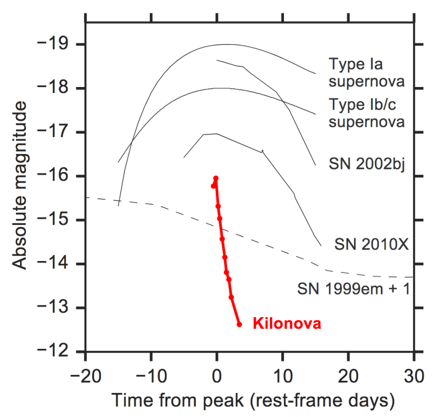
(REM, ESO-VST, ESO-VLT...)



Pian et al., 2017, Nature, 551, 67

Kilonova vs supernova: the light curve

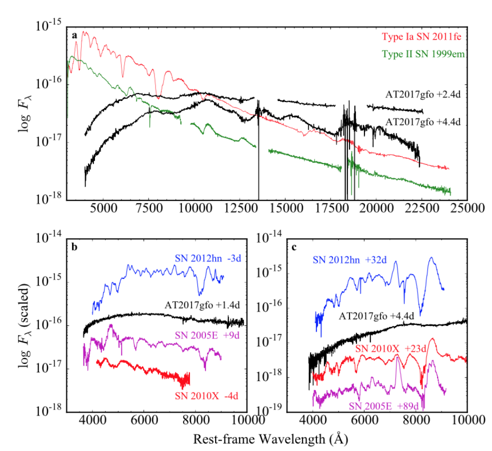
The optical transient evolves much faster than any supernova



Arcavi et al., 2017, Nature, 551, 64

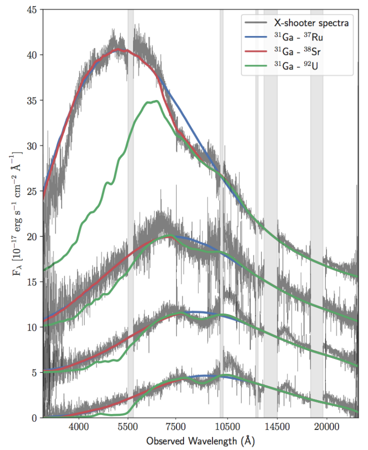
Kilonova vs supernova: the spectrum

The spectral evolution is inconsistent with any supernova type



Smartt et al., 2017, Nature, 551, 75

The identification of the strontium in the kilonova spectrum



Watson et al. 2019, Nature, 574, 497

A new joint GW-EM detection?

```
TITLE:   GCN CIRCULAR
NUMBER:  25406
SUBJECT: Fermi GBM-190816: A subthreshold GRB candidate potentially associated with a subthreshold LIGO/Virgo compact
binary merger candidate
DATE:    19/08/20 05:23:25 GMT
FROM:    Adam Goldstein at Fermi-GBM, USRA  <adam.michael.goldstein@gmail.com>

The LIGO Scientific Collaboration, the Virgo Collaboration and the Fermi
GBM team report:

In routine Fermi GBM follow-up analysis of subthreshold GW triggers from
LIGO/Virgo, a potential short gamma-ray burst counterpart GBM-190816 was
identified.
```

- candidate gamma-ray signal found 1.5 s after the GW trigger time;
- duration and spectral properties of gamma-ray signal are consistent with a short GRB;
- from preliminary GW analysis: if the signal is astrophysical, the lighter compact object may have $m < 3\ M_{\odot}$

Further analysis is ongoing