First results from Advanced LIGO and Advanced Virgo

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1st Quantum gases, fundamental interactions and cosmology Conference

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Pisa

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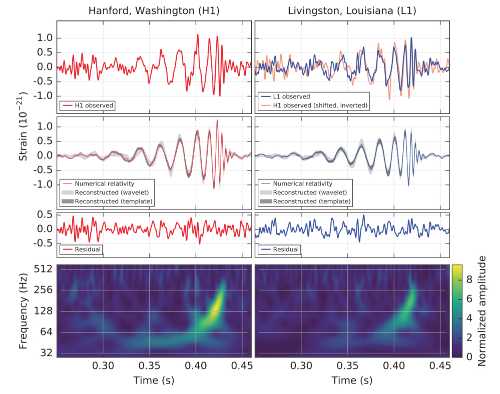
SCUOLA NORMALE SUPERIORE

Summary

GW150914: the first GW detection



- Combined SNR: 24
- FAR: 1 event per 203 000 years

  significance $> 5.1\ \sigma$
- $D_L = 410^{+160}_{-180}$ Mpc
- $m_1 = 36^{+5}_{-4}\ M_\odot$; $m_2 = 29^{+4}_{-4}\ M_\odot$;
- Final BH mass: $62^{+4}_{-4}\ M_\odot$

Abbott et al., PRL, 116, 061102 (2016)

After the first GW detection, other BBH mergers have been observed...

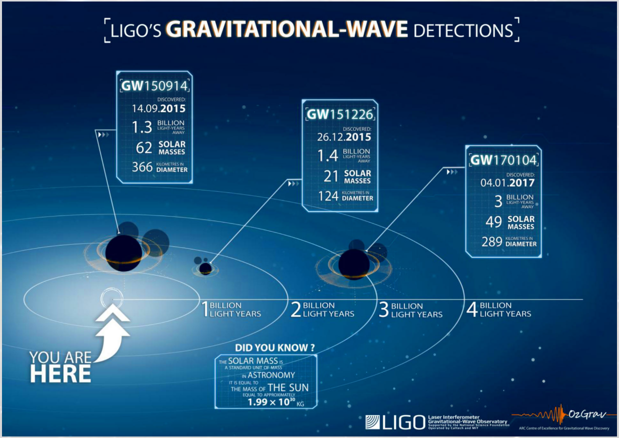
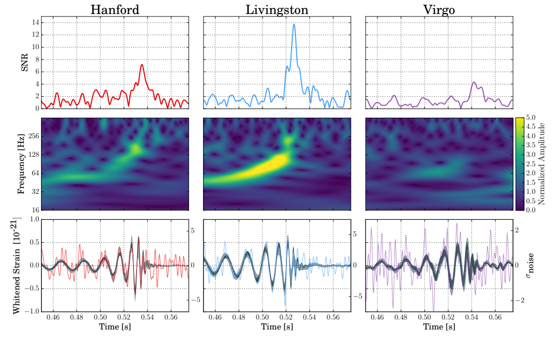


Image credit: LIGO, ARC Centre of Excellence for Gravitational Wave Discovery

GW170814

On August 1st, 2017 Virgo joined Advanced LIGO.

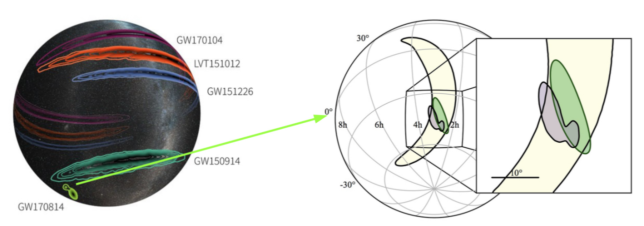
On August 14: the first three-detector observation of a GW signal!



- Combined SNR: 18
- FAR: $\lesssim$ 1 event per 27000 years
- $D_L = 540^{+130}_{-210}$ Mpc
- $m_1 = 30.5^{+5.7}_{-3.0}$ $M_\odot$; $m_2 = 25.3^{+2.8}_{-4.2}$ $M_\odot$;
- Final BH mass: $53.2^{+3.2}_{-2.5}$ $M_\odot$

Abbott et al., PRL, 119, 141101 (2017)

The sky localization of the GW events



Sky localization:

- rapid loc., HL: 1160 deg^2
- rapid loc., HLV: 100 deg^2
- final loc., HLV: 60 deg^2

Image credit:

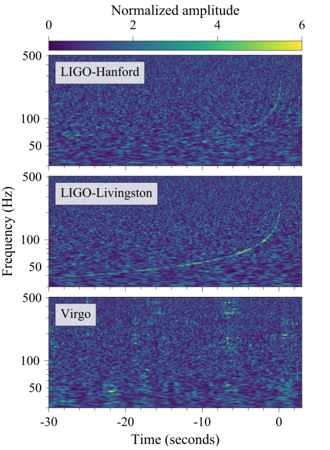
LIGO/CALTECH/MIT/L. Singer/A. Mellinger
Abbott et al., PRL, 119, 141101 (2017)

Virgo significantly improved the sky localization!

The first multi-messenger detection of a BNS system

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!



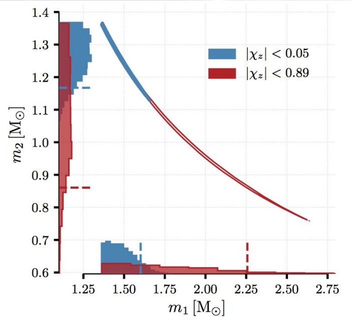
- GW170817 swept through the detectors' sensitive band for $\sim$ 100 s (f_{start} = 24 Hz)
- The SNR is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal yet observed!
- The F.A.R. is less than one per 8×10^4 years

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

BNS detection: component masses

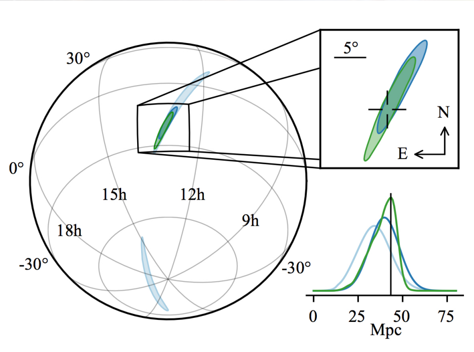


	low-spin ($\|\chi\| \leq 0.05$)	high-spin ($\|\chi\| \leq 0.89$)
m_1	1.36 - 1.60 $M_\odot$	1.36 - 2.26 $M_\odot$
m_2	1.17- 1.36 $M_\odot$	0.86 - 1.36 $M_\odot$
M_{chirp}	$1.188^{+0.004}_{-0.002}$ $M_\odot$	$1.188^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.74^{+0.04}_{-0.01}$ $M_\odot$	$2.82^{+0.47}_{-0.09}$ $M_\odot$

Estimated masses (m_1 and m_2) within the range of known NS masses and below those of known BHs ⇒ this suggests the source was composed of two NSs

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

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)

Which are 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).

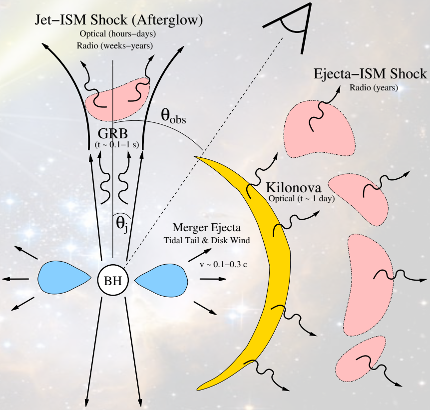
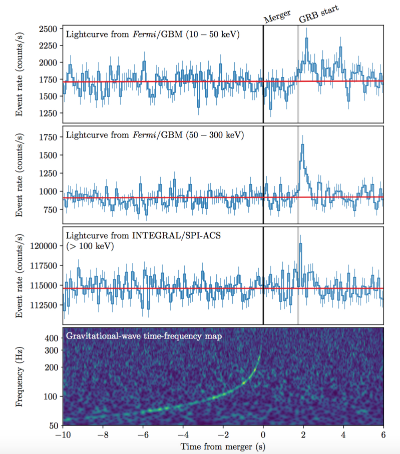


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

Gamma-rays: short GRB

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

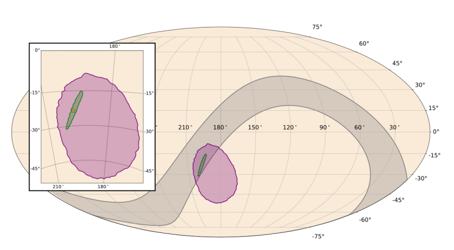


- The start of the gamma-ray emission relative to the merger time is $\sim$ 1.7 s
- GRB 170817A is $\sim$ 3 times more likely to be a short GRB than a long GRB
- $E^{\gamma}_{\rm iso} \sim 10^{46}$ erg: between 2 and 6 orders of magnitude less energetic than other observed bursts with measured redshift.

off-axis GRB? structured jet?...

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

Gamma-rays: short GRB



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

90 % sky localization from Fermi and INTEGRAL timing

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

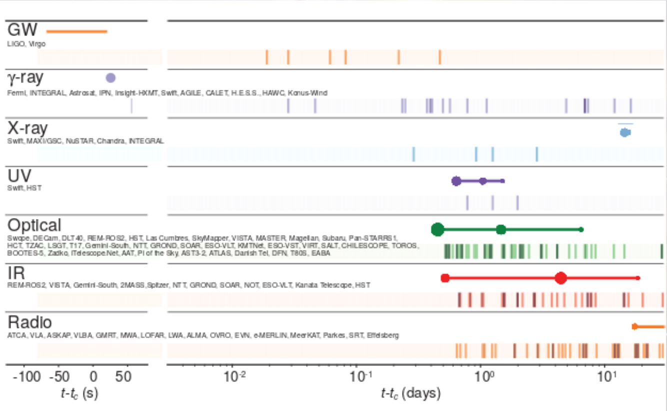
The probability that GRB 170817A and GW170817 occurred this close in time and with this level of location agreement by chance is 5.0×10^{-8}: a 5.3 σ Gaussian-equivalent significance

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

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

The EM follow-up campaign

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



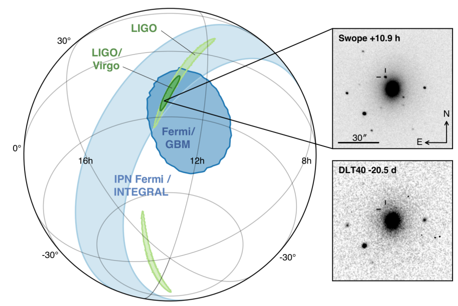
Abbott et al, ApJ Letters, 848, 12 (2017)

The identification of the host galaxy

An associated **optical transient** (SSS17a/AT 2017gfo) has been discovered on August 18, 2017; the transient is located at $\sim$ 10" from the center of the galaxy NGC 4993, at a distance of 40 Mpc

The discovery has been reported by 6 teams:

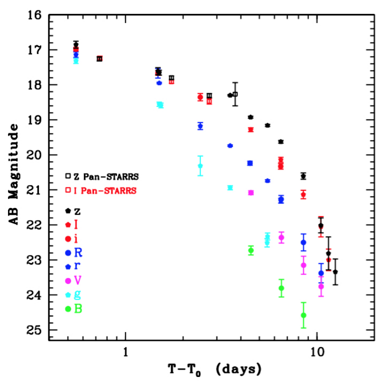
- SWOPE (10.86 h)
- DLT40 (11.08 h)
- VISTA (11.24 h)
- MASTER (11.31 h)
- DECam (11.40 h)
- Las Cumbres (11.57 h)



Abbott et al, ApJ Letters, 848, 12 (2017)

The optical transient

The optical transient was later observed in different bands...

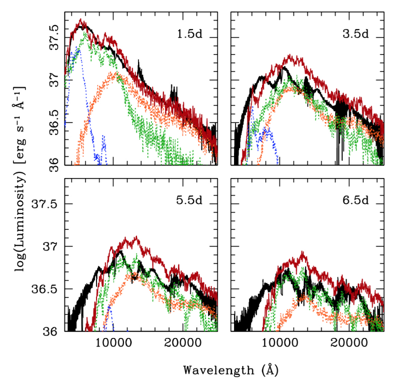


Pian et al., Nature, in press (2017)

The spectroscopic identification of the kilonova

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

The spectroscopic identification of the kilonova



- observational data
- lanthanide-rich dynamical ejecta region
- wind region with mixed (lanthanide-free and lanthanide-rich) composition
- wind region with lanthanide-free composition
- sum of the three model components

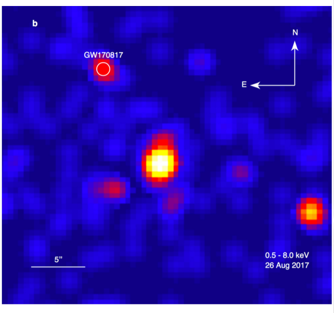
(Models from Tanaka et al. 2017)

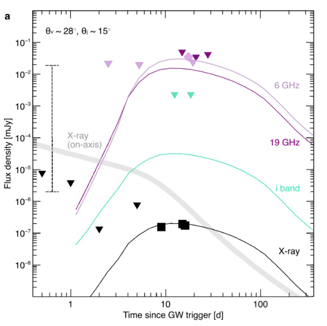
The evolution of the observed spectrum with time is in a good match with the expectations for kilonovae ⇒ this is the first spectroscopic identification of a kilonova!

Pian et al., Nature, in press (2017)

X-ray observations

9 days after the GW trigger, an X-ray counterpart has been discovered with Chandra



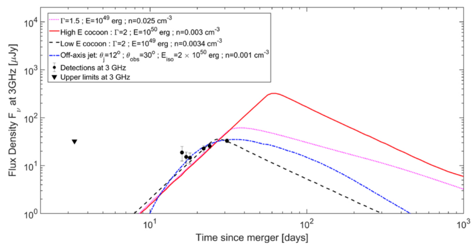


The x-ray light curve is consistent with the afterglow of a GRB viewed off-axis

Troja et al., Nature, in press (2017)

Radio observations

A radio counterpart detection consistent with the HST position of SSS17a/AT 2017gfo was observed 16 days after GW170817



Light curve consistent with:

- emission from an ultra-relativistic jet viewed off-axis;
- emission from a "cocoon" of mildly relativistic ejecta

Future observations will distinguish between these two models

Hallinan et al., Science, in press (2017)

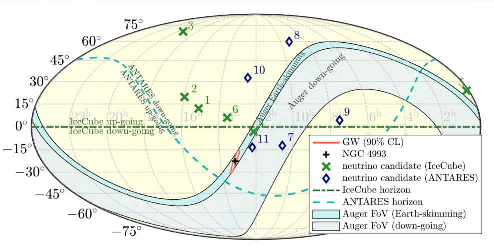
Neutrinos

Search for coincident neutrino candidates with data of IceCube, ANTARES and Pierre Auger

Within $\pm$ 500 s of GW170817:

- ANTARES neutrino candidates: 5
- IceCube neutrino candidates: 6
- Pierre Auger neutrino candidates: 0

  - **No one directionally coincident with GW150914**



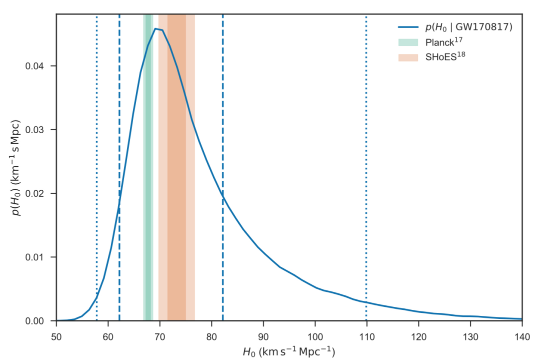
The non-detection of neutrinos is consistent with model predictions of short GRBs observed off-axis

Albert et al., submitted to ApJ, 2017

GW170817: 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**

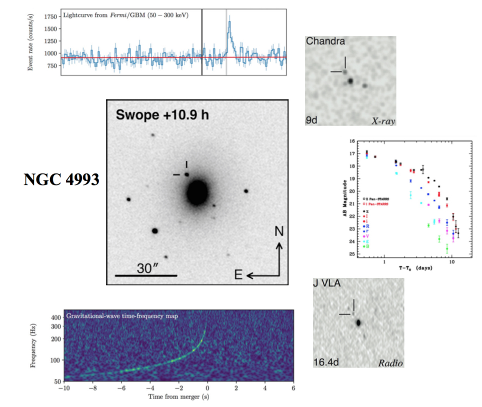
$$H_0 = 70.0^{+12.0}_{-8.0} \text{ km s}^{-1} \text{ Mpc}^{-1}$$



Abbott et al., Nature, in press (2017)

Multi-messenger astronomy has just begun,

many discoveries are expected in the near future!



Backup slides

BH and NS masses

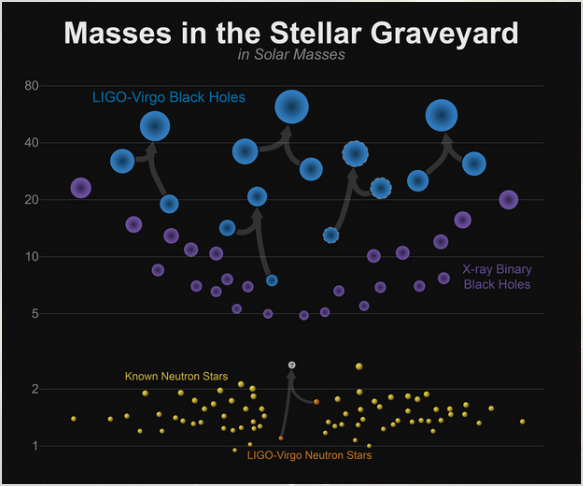


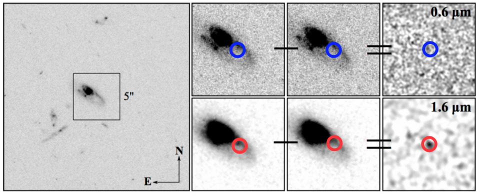
Image credit: LIGO-Virgo/Frank Elavsky/Northwestern University

LIGO and Virgo antenna patterns

(Loading Video...)

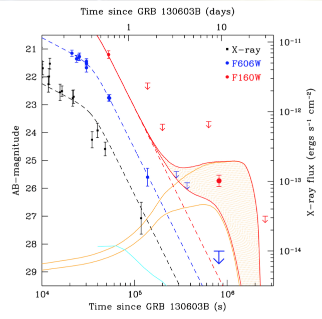
Credit: L. Singer

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)