Gravitational waves and Multi-messenger astronomy: the new exploration of the Universe

Barbara Patricelli[1,2,3]

[1] Scuola Normale Superiore di Pisa

[2] INFN - Sezione di Pisa

[3] INAF - Osservatorio Astronomico di Roma

Astrophysics + MAGIC

June 26-29, 2018

La Palma, Spain

Istituto Nazionale Fisica Nucleare Sezione di Pisa

SCUOLA NORMALE SUPERIORE

on behalf of
the LIGO Scientific Collaboration
and the Virgo Collaboration

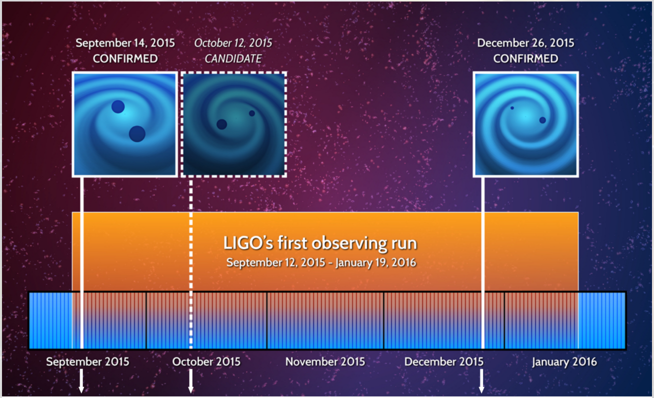
LSC LIGO Scientific Collaboration

VIRGO

Outline

O1: Advanced LIGO's first observing run

The beginning of GW astronomy



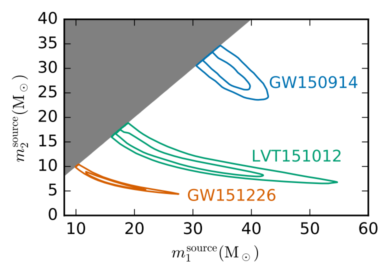
SNR=23.7
Significance > 5.3 σ

SNR=9.7
Significance = 1.7 σ

SNR=13.0
Significance > 5.3 σ

Image credit: LIGO
Abbott et al. 2016, Phys. Rev. X, 6, 041015

Physical parameters of O1 BBH systems



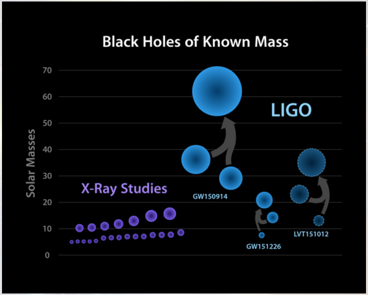


Image credit: LIGO

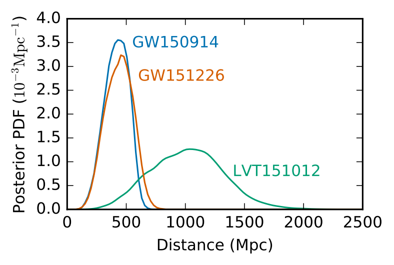
Event	GW150914	GW151226	LVT151012
m_1 ($M_\odot$)	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
m_2 ($M_\odot$)	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}

- First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)
- Heavy stellar mass BBHs most likely formed in low-metallicity environment ($\lesssim 0.5\ Z_\odot$)

Abbott et al. 2016, Phys. Rev. X, 6, 041015
Abbott et al. 2016, ApJL 818, 22

Where did the BBH mergers occur?

Luminosity distance



Event	GW150914	GW151226	LVT151012
D_L (Mpc)	420^{+150}_{-180}	440^{+180}_{-190}	1000^{+500}_{-500}

Abbott et al. 2016, Phys. Rev. X, 6, 041015

Final sky localization

Event	GW150914	GW151226	LVT151012
$\Delta\Omega$ (deg^2)	230	850	1600

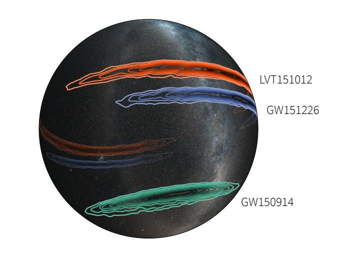
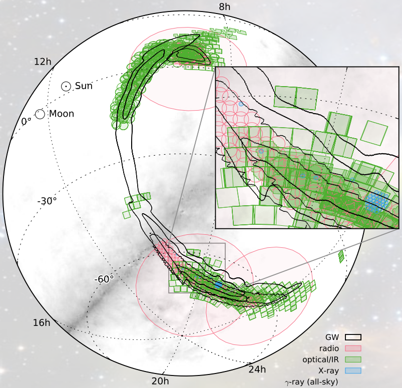


Image credit: LIGO/L. Singer/A. Mellinger

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

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

Searches for EM counterparts to BBH mergers



- Although no EM counterpart was expected from BBH mergers, intense EM follow-up campaigns have been performed
- Several candidate counterparts have been found, all identified to be normal population SNe, dwarf novae and AGN unrelated to the GW events

Abbott et al. 2016, ApJL, 826, L13

Abbott et al. 2016, ApJS, 225, 8

O2: the second observing run

November 30, 2016 - August 25, 2017

Other BBH mergers detected by Advanced LIGO...

GW 170104

- *Primary BH mass* m_1:
  $31.2^{+8.4}_{-6.0}$ $M_\odot$
- *Secondary BH mass* m_2:
  $19.4^{+5.3}_{-5.9}$ $M_\odot$
- *Final BH mass* M_f:
  $48.7^{+5.7}_{-4.6}$ $M_\odot$
- *Radiated energy* $E_{\rm rad}$:
  $2.0^{+0.6}_{-0.7}$ $M_\odot$ c^2
- *Luminosity distance* D_L:
  880^{+450}_{-390} *Mpc*

Abbott et al. 2017, PRL, 118, 221101

GW170608

- *Primary BH mass* m_1:
  12^{+7}_{-2} $M_\odot$
- *Secondary BH mass* m_2:
  7^{+2}_{-2} $M_\odot$
- *Final BH mass* M_f:
  $18.0^{+4.8}_{-0.9}$ $M_\odot$
- *Radiated energy* $E_{\rm rad}$:
  $0.85^{+0.07}_{-0.17}$ $M_\odot$ c^2
- *Luminosity distance* D_L:
  340^{+140}_{-140} *Mpc*

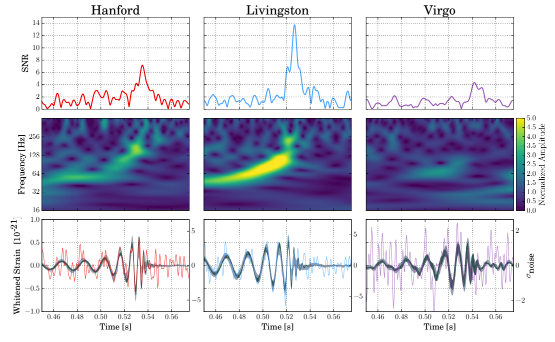
Abbott et al. 2017, ApJL, 851, 35

BBH merger rate (O1 + GW170104): 12 - 213 Gpc^{-3} yr^{-1}

GW170814

On August 1st, 2017 Virgo joined Advanced LIGO.

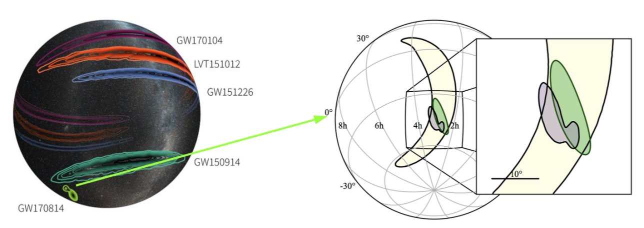
On August 14: **the first three-detector observation** of a GW signal!



- Combined SNR: 18
- $D_L = 540^{+130}_{-210}$ Mpc
- $m_1 = 30.5^{+5.7}_{-3.0}$ $M_\odot$; $m_2 = 25.3^{+2.8}_{-4.2}$ $M_\odot$;
- $M_f = 53.2^{+3.2}_{-2.5}$ $M_\odot$
- $E_{rad} = 2.7^{+0.4}_{-0.3}$ $M_\odot$ c^2

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

GW170814: sky localization



Sky localization:

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

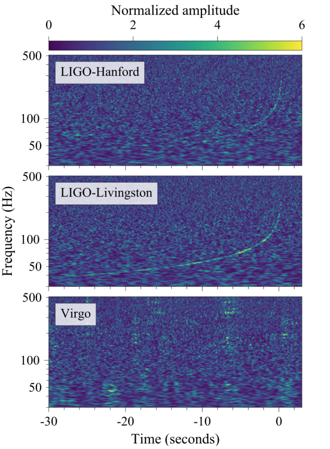
Image credit:

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

Virgo significantly improved the sky localization!

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!**



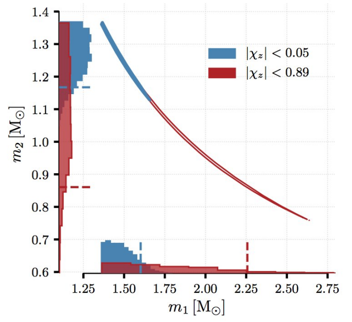
- GW170817 swept through the detectors' sensitive band for $\sim$ 100 s ($f_{\mathrm{start}} = 24$ Hz)
- The SNR is 18.8, 26.4 and 2.0 in the LIGO-Hanford, LIGO-Livingston and Virgo data respectively;

  the combined SNR is 32.4

  $\Rightarrow$ This is the loudest signal yet observed!

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

BNS detection: component masses



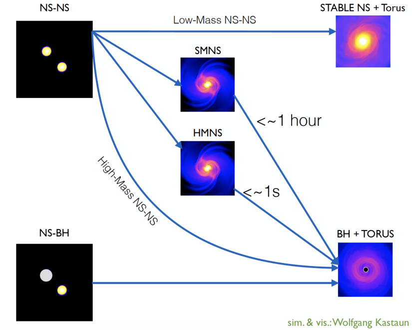
	low-spin ($|\chi| \leq 0.05$)	high-spin ($|\chi| \leq 0.89$)
m_1	1.36 - 1.60 $M_\odot$	1.36 - 2.26 $M_\odot$
m_2	1.17- 1.36 $M_\odot$	0.86 - 1.36 $M_\odot$
M_{chirp}	$1.188^{+0.004}_{-0.002}$ $M_\odot$	$1.188^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.74^{+0.04}_{-0.01}$ $M_\odot$	$2.82^{+0.47}_{-0.09}$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

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

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

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.

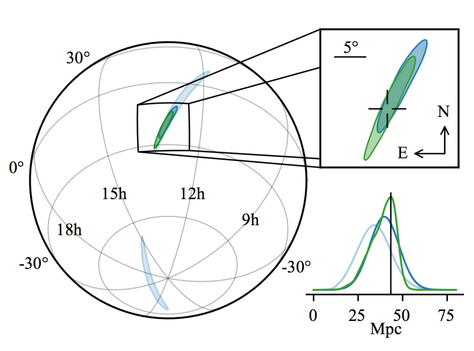


- Stable NS (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s (burst-like GW signal)
- BH prompt formation (high frequency quasi normal mode ringdown GW signal)

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 transients are currently ongoing

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 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).

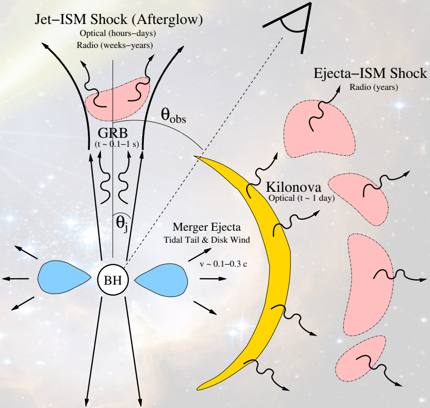
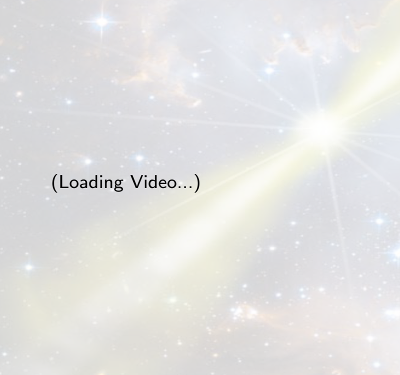


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

Gamma-rays: short GRB

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



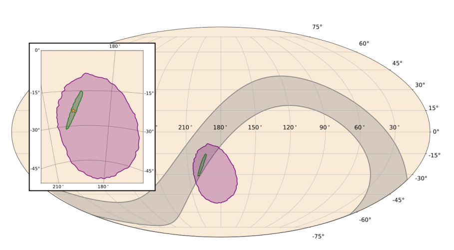
Credit: NASA/Caltech/MIT/LIGO Lab

- 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.

  structured jet? cocoon emission?

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)

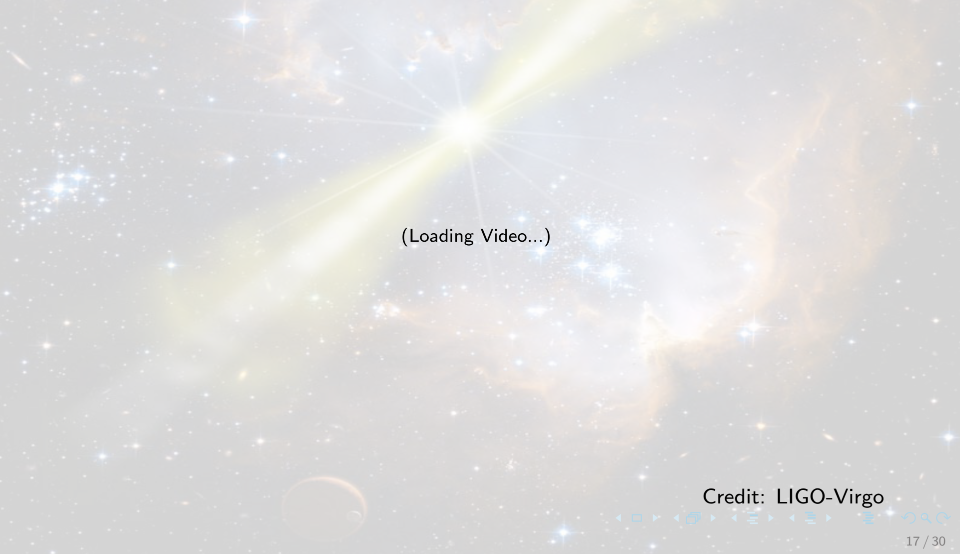
The probability that GRB 170817A and GW170817 occurred this close in time and with this level of location agreement by chance is 5.0×10^{-8}: a 5.3 σ Gaussian-equivalent significance

⇒ 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



(Loading Video...)

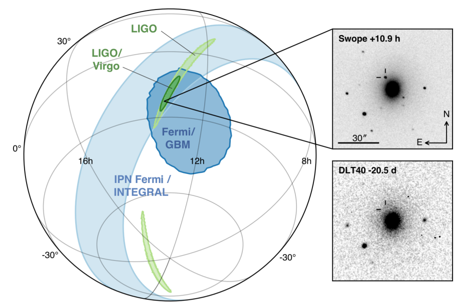
Credit: LIGO-Virgo

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 spectroscopic identification of the kilonova

(Loading Video...)

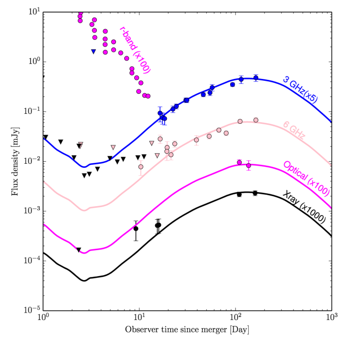
Credit: ESO/E. Pian et al./S. Smartt & ePESSTO

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). Observations are still ongoing...

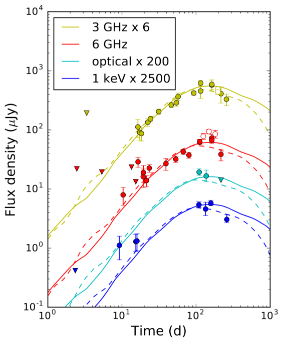
Two possible interpretations:

cocoon emission



Xie et al. 2018

off-axis afterglow from a structured jet

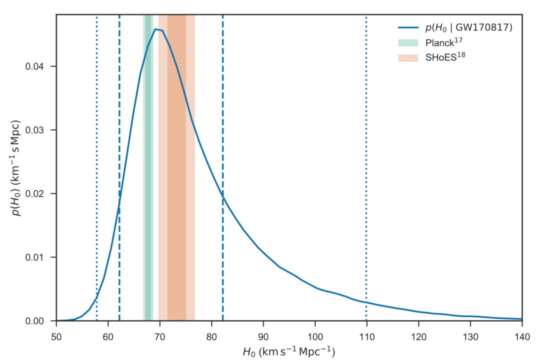


Alexander et al. 2018

Implications for Cosmology

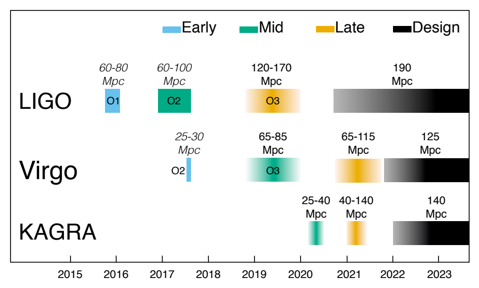
GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**

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



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

Prospects: LIGO-Virgo-KAGRA Observing scenario



Abbott et al. 2018, LRR, 21, 3

The third observing run (O3) is approaching!

- Expected to start on February 2019
- Duration: 1 year
- Open public alerts!
- a few BBH per month
- 1-10 BNS (total)

Conclusions

- We observed for the first time GWs from merging binary BH and NS systems
- We had the first multi-messenger (GWs+photons) observation of a binary system
- Other sources still to be detected (supernovae, pulsars...)
- Plans are under way to improve LIGO and Virgo sensitivity for O3 and beyond

Many other discoveries are expected in the near future... stay tuned!

Backup slides

BH and NS masses

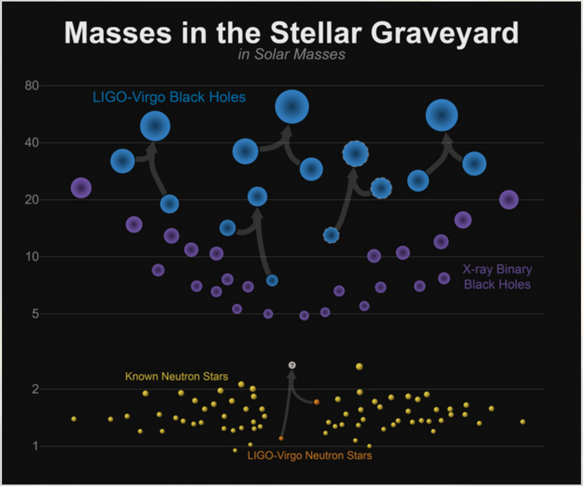


Image credit: LIGO-Virgo/Frank Elavsky/Northwestern University

GW170814: GW polarization

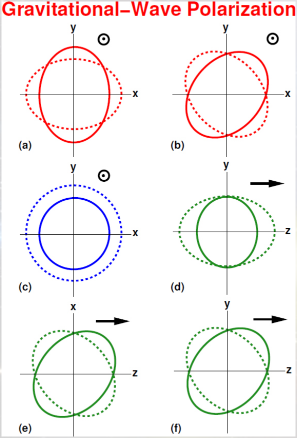


Image credit: Will 2014, LLR, 17, 117

- General Relavitity: two tensor polarizations only
- generic metric theories: allow up to six polarization states

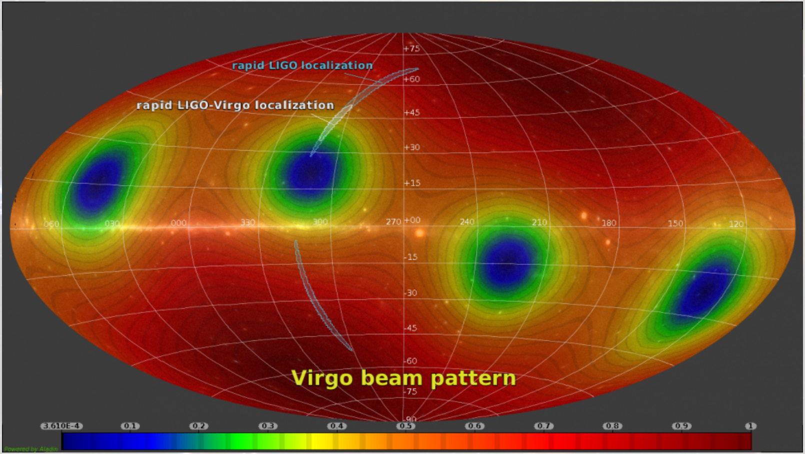
LIGO-Hanford and Livingston have similar orientations → little information about GW polarizations

With Virgo we can project the GW amplitude onto the 3 detectors → probe the nature of GW polarizations

Only models with "pure" polarization states (tensor, vector or scalar) have been considered.
Result: purely tensor polarization is strongly favored over purely scalar or vector polarizations

Abbott et al. 2017, PRL, 119, 141101

The role of Virgo in the sky localization



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

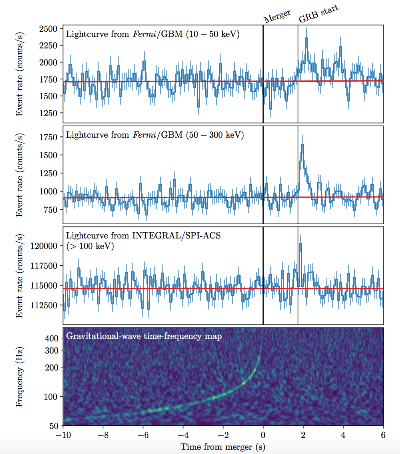
The role of Virgo in the sky localization

(Loading Video...)

Credit: L. Singer

Constraints on fundamental physics

The observed time delay between GRB170817A and GW170817 (~1.7 s) can be used to put constraints on fundamental physics:



- **Speed of gravity vs speed of light**

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

- **Test of Equivalence Principle**
  - Shapiro delay δt_S: time difference travelling in a curved spacetime relative to a flat one
  - Effects of curvature quantified with the parameter $\gamma \to \delta t_S \propto (1+\gamma)$
  - Weak equivalence principle:

    Shapiro delay affects both GW and EM waves in the same manner ($\gamma_{\rm GW}=\gamma_{\rm EM}$)

$$-2.6 \times 10^{-7} \leq \gamma_{\rm GW} - \gamma_{\rm EM} \leq 1.2 \times 10^{-6}$$

Abbott et al. 2017, ApJL, 848, 13

Prospects: a global GW detector network

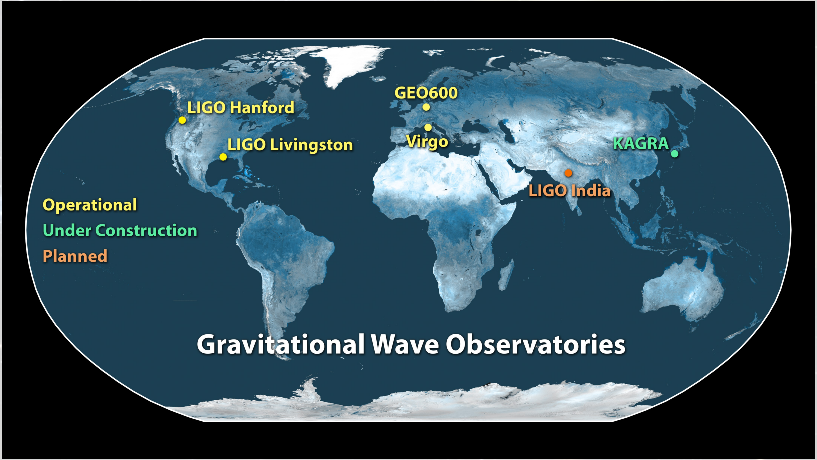


Image credit: Caltech/MIT/LIGO Lab