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

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Cosmology 2018
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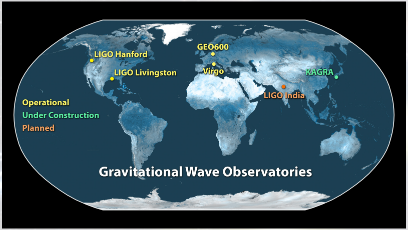
on behalf of
the LIGO Scientific Collaboration
and the Virgo Collaboration

Outline

The first observing runs of Advanced LIGO and Advanced Virgo

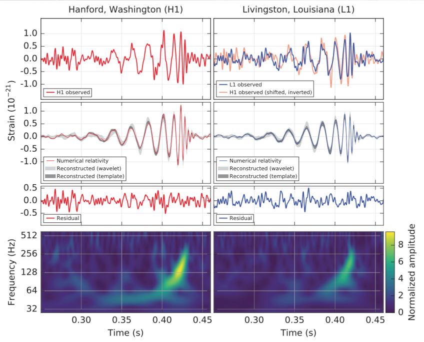


Credit: LIGO-Virgo

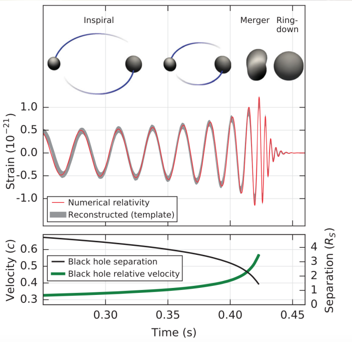
- *O1: September 2015 - January 2016*
  Only the two LIGO detectors were operating
- *O2: November 2016 - August 2017*
  Virgo joined the network on August 1

GW150914: The first observation of GWs

The observation



The model

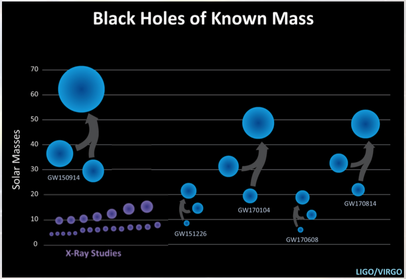


Abbott et al. 2016, PRL, 116, 061102

The BBH detections

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

- 2015 September 14: GW150914
- 2015 December 26: GW151226
- 2015 October 12: LVT151012
- 2017 January 4: GW170104
- 2017 June 8: GW170608
- 2017 August 14: GW170814



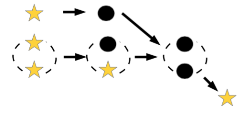
- First direct evidences for "heavy" stellar mass BHs ($> 25\ M_\odot$)
- Heavy stellar mass BBHs most likely formed in low-metallicity environment ($\leq 0.5\ Z_\odot$)
- BBH merger rate (O1 + GW170104): 12 - 213 $\text{Gpc}^{-3}\ \text{yr}^{-1}$

Abbott et al. 2016, ApJL, 818, 22
Abbott et al. 2016, PRX, 6, 041015
Abbott et al. 2017, PRL 118, 221101

How do BHs form binary systems?

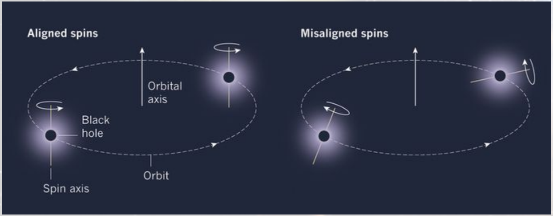
Isolated binary in galactic fields

Dynamical interactions in clusters



How can we discriminate between these two formation mechanisms?

$\rightarrow$ Spin!



Isolated binary:

Spins preferentially aligned with the binary orbital angular momentum

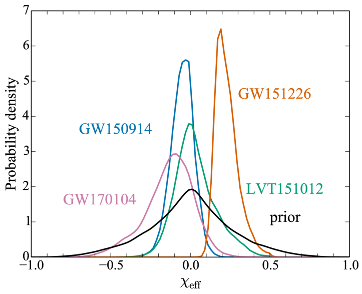
Cluster binary:

Isotropic spin orientations

Spin estimate with GWs

The effective orbital spin

$$\boxed{\chi_{eff} = \frac{c}{GM}\left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m2}\right)\hat{\mathbf{L}}}$$

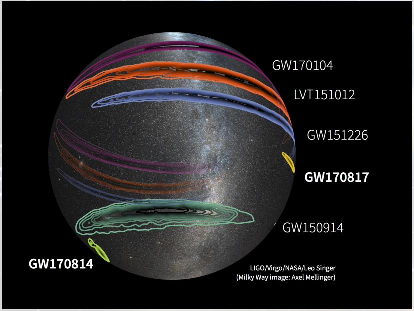


Abbott et al. 2017, arXiv:1706.01812

- Spins are typically misaligned (with the orbital angular momentum or each other) or are typically small (or both)
- $\sim$10 additional detections will be sufficient to distinguish between a pure aligned or isotropic population (Farr et al. 2018, ApJL, 854, 9)

  (see also Talbot & Thrane 2017, Stevenson et al. 2017)

Which is the host galaxy?



Event	$\Delta\Omega$ (deg^2)	D$_L$ (Mpc)
GW150914	230	420^{+150}_{-180}
GW151226	850	440^{+180}_{-190}
GW170104	1200	880^{+450}_{-390}
GW170608	860	340^{+140}_{-140}
GW170814	60	540^{+130}_{-210}

Abbott et al. 2016, PRX, X 6, 041015
Abbott et al. 2017, PRL 118, 221101
Abbott et al. 2017, PRL 119, 141101
Abbott et al. 2017, ApJL, 851, 35

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

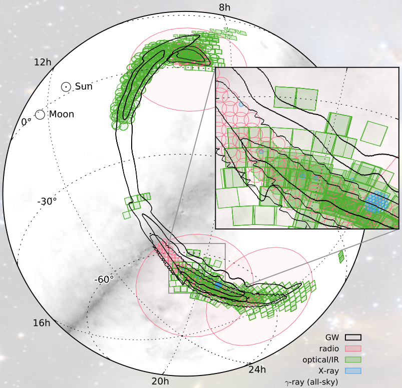
GW

- *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*

Searches for EM counterparts to BBH mergers



- Although no EM counterpart was expected from BBH mergers, intense EM follow-up campaign 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 (see, e.g., Kasliwal et al. 2016, Smartt et al. 2016)

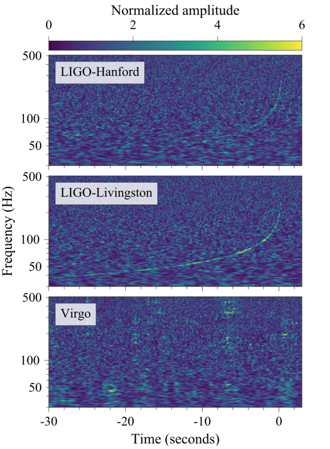
Abbott et al. 2016, ApJL, 826, L13

Abbott et al. 2016, ApJS, 225, 8

For all the detected BBH mergers no firm EM counterpart has been found

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!

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

BNS detection: component masses

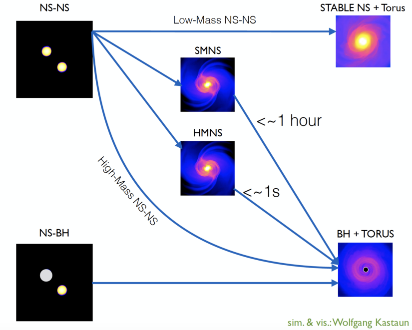
	low-spin ($\lvert\chi\rvert \leq 0.05$)	high-spin ($\lvert\chi\rvert \leq 0.89$)
m_1	1.36 - 1.60 $M_\odot$	1.36 - 1.89 $M_\odot$
m_2	1.16 - 1.36 $M_\odot$	1.00 - 1.36 $M_\odot$
M_{chirp}	$1.186^{+0.001}_{-0.001}$ $M_\odot$	$1.186^{+0.004}_{-0.002}$ $M_\odot$
M_{Tot}	$2.73^{+0.04}_{-0.01}$ $M_\odot$	$2.77^{+0.22}_{-0.05}$ $M_\odot$

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. 2018, arXiv: 1805.11579

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.

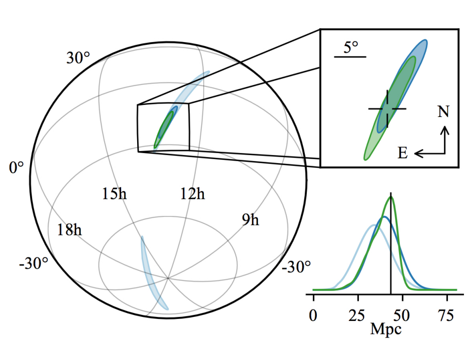


- Stable NS (continuous-wave GW signal)
- Supramassive NS (SMNS) collapsing to a BH in 10 - 10^4 s (long-transient GW signal)
- Hypermassive NS (HMNS) collapsing to a BH in < 1 s (burst-like GW signal)
- BH prompt formation (high frequency quasi normal mode ringdown GW signal)

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. 2018, arXiv: 1810.02581)

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:

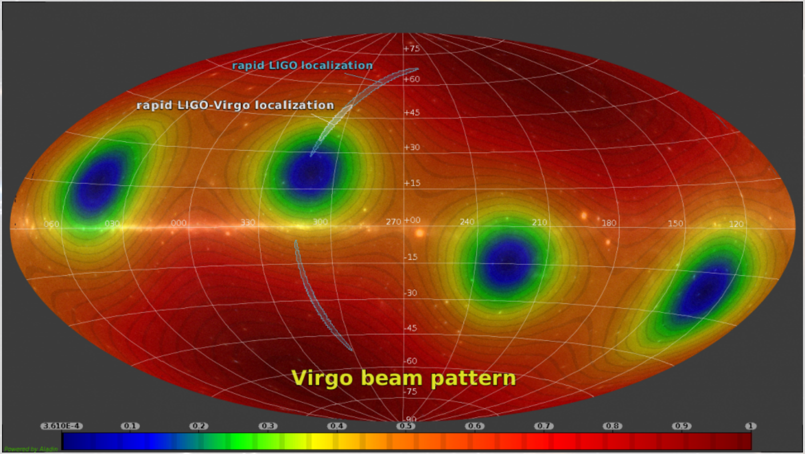
40^{+8}_{-14} Mpc

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

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

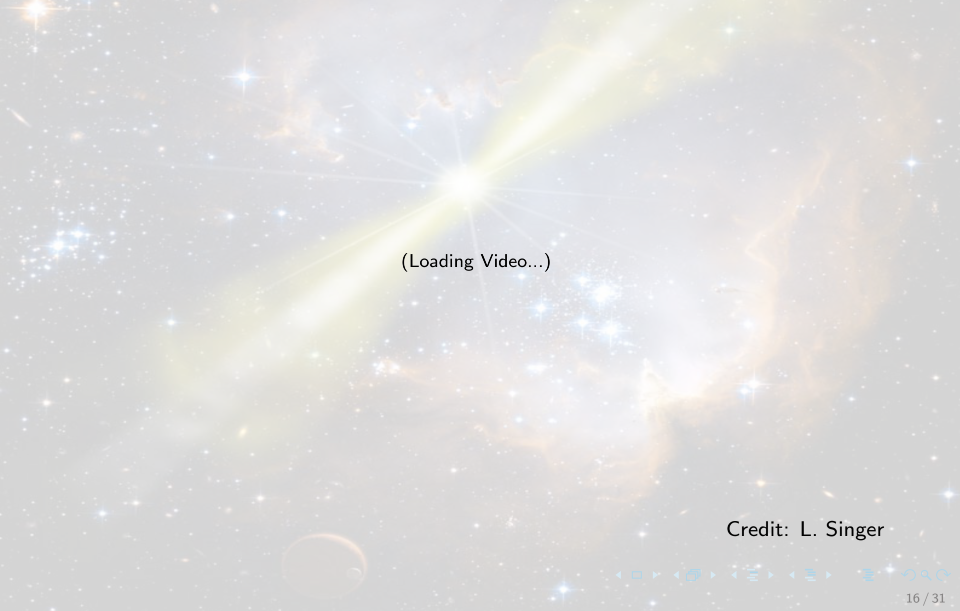
* More refined analysis allowed to reduce the sky localization to 16 deg^2 (Abbott et al. 2018, arXiv: 1805.11579)

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

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).

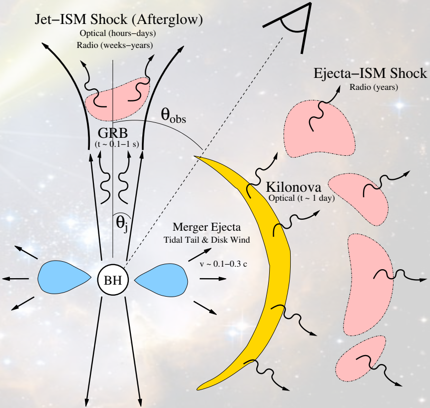


Image credit:
Metzger & Berger, ApJ, 746, 48 (2012)

Gamma-rays: short GRB

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

(Loading Video...)

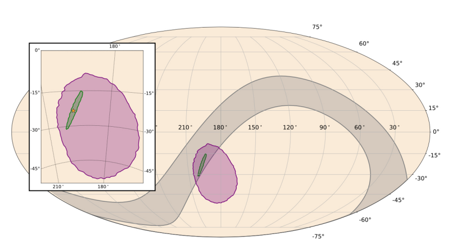
Credit: NASA/Caltech/MIT/LIGO Lab

- 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)
Goldstein et al., ApJL, 848, 14 (2017)
Savchenko et al., ApJL, 848, 15 (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

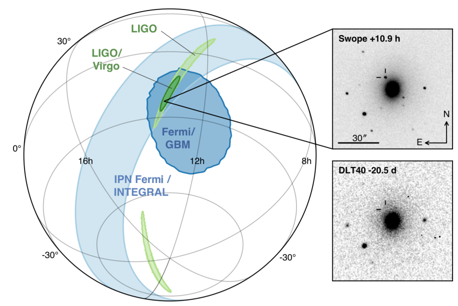
Credit: LIGO-Virgo

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

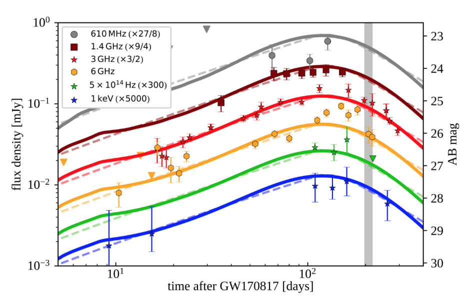
X-ray and radio observations

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
- — afterglow emission from a structured jet

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

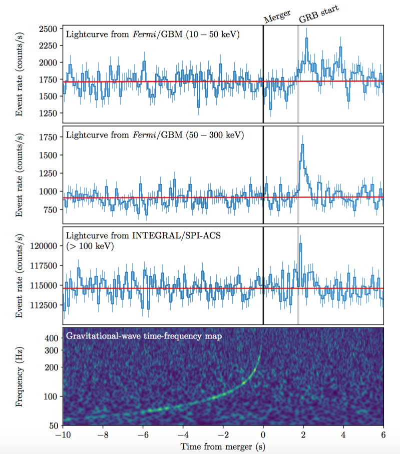


Ghirlanda et al. 2018

... 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. 2018, Mooley et al. 2018)

GW-GRB association: constraints on fundamental physics

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



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

$$\frac{\Delta\nu}{\nu_{\rm EM}} \sim \frac{\nu_{\rm EM}\Delta t}{D}$$

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

- **Test of Equivalence Principle**
  - Shapiro delay: time difference travelling in a curved spacetime relative to a flat one

$$\delta t_S = -\frac{1+\gamma}{c^3}\int_{r_e}^{r_o} U(r(l))dl$$

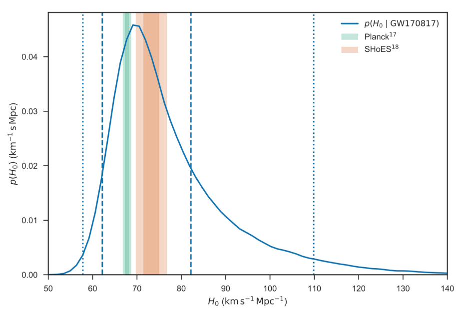
  - GW and EM affected the same way ($\gamma_{\rm GW}=\gamma_{\rm EM}$)

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

Abbott et al. 2017, ApJL, 848, 13

Implications for Cosmology

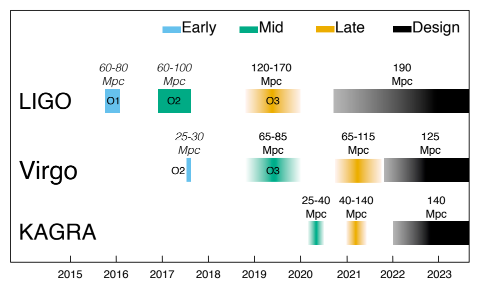
GW170817 as a standard siren:
the association with the host galaxy NGC 4993 and the luminosity distance directly measured from the GW signal have been used to determine the **Hubble constant**



- $H_0 = 70.0^{+12.0}_{-8.0}$ 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)

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

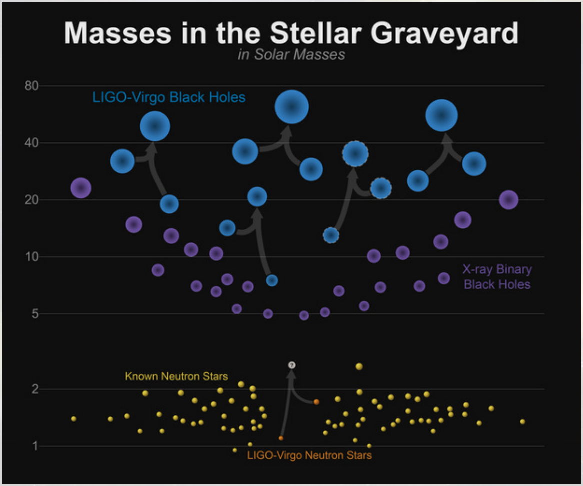
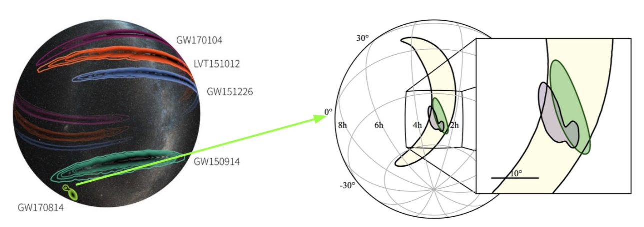


Image credit: LIGO-Virgo/Frank Elavsky/Northwestern University

GW170814: 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!

GW170814: GW polarization

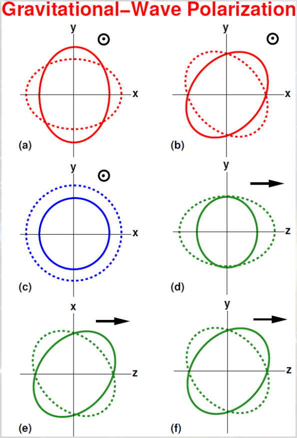


Image credit: Will 2014, LLR, 17, 117

- 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