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# L'astronomia “multi-messaggera”: stato attuale e prospettive future

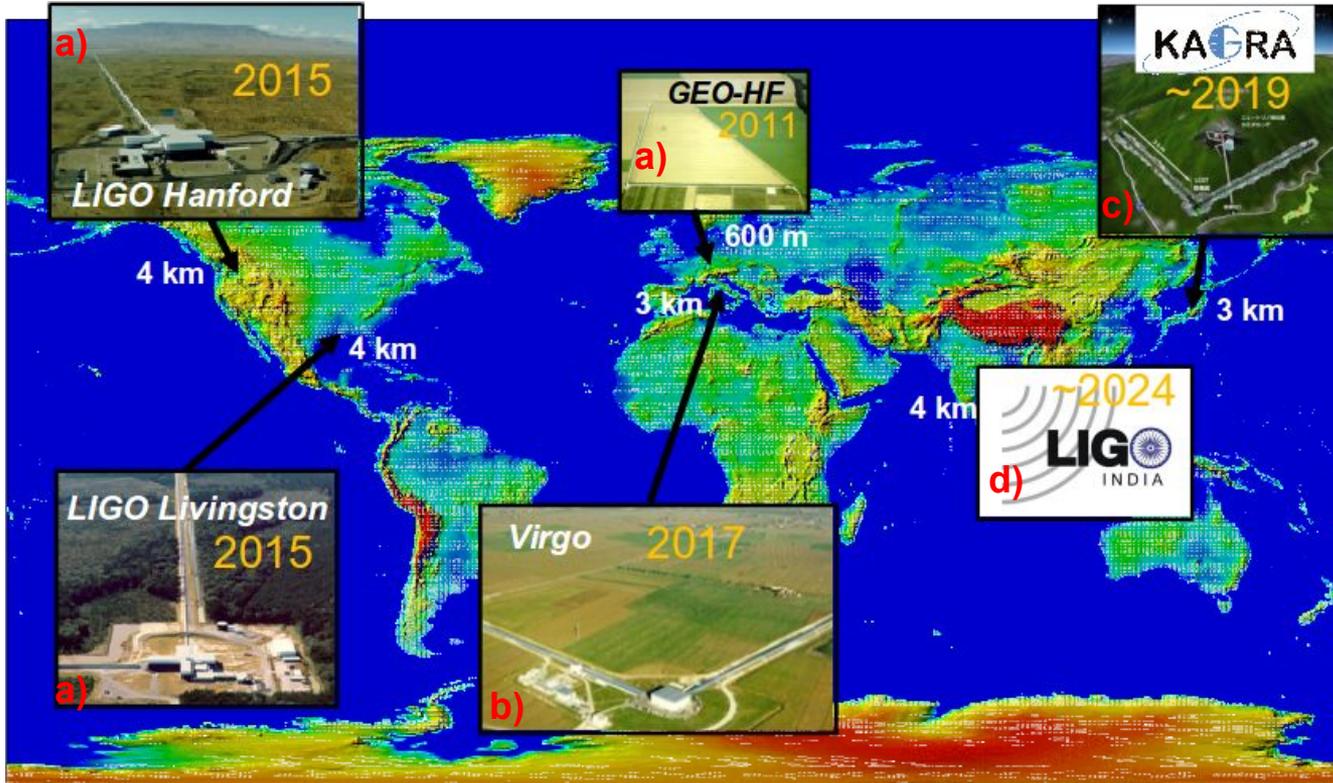
— G. Greco, M. Branchesi, G. Stratta —  
LIGO and Virgo Collaboration

**XVI Incontri di Fisica delle Alte Energie**

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**19-21 April 2017 Trieste - Italia**

# La rete mondiale degli interferometri di onde gravitazionali



**(a) Attualmente in uso**

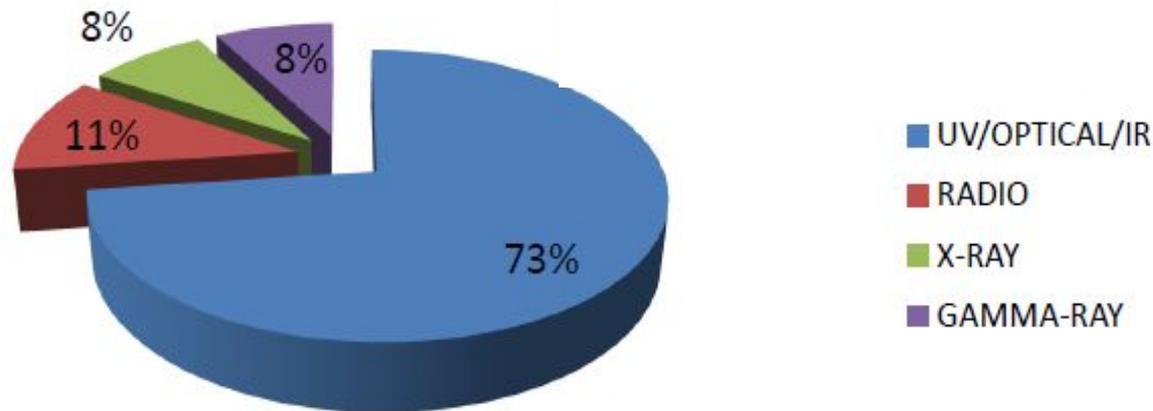
**(b) In fase di  
aggiornamento**

**(c) In costruzione**

**(d) Approvati**

Risposta a larga banda in grado di coprire l'intervallo di frequenze da ~10 Hz a ~1 kHz.

# La rete mondiale per la ricerca delle controparti e.m./neutrini

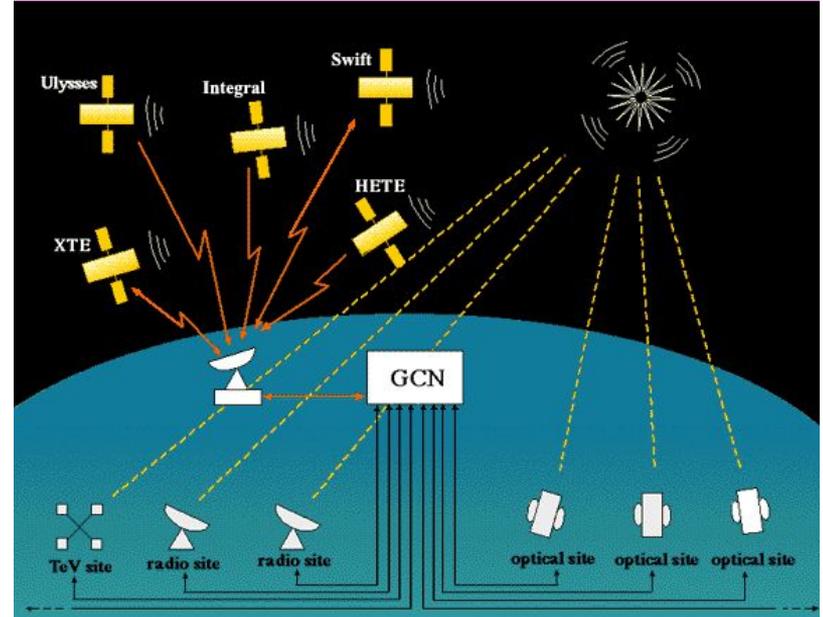
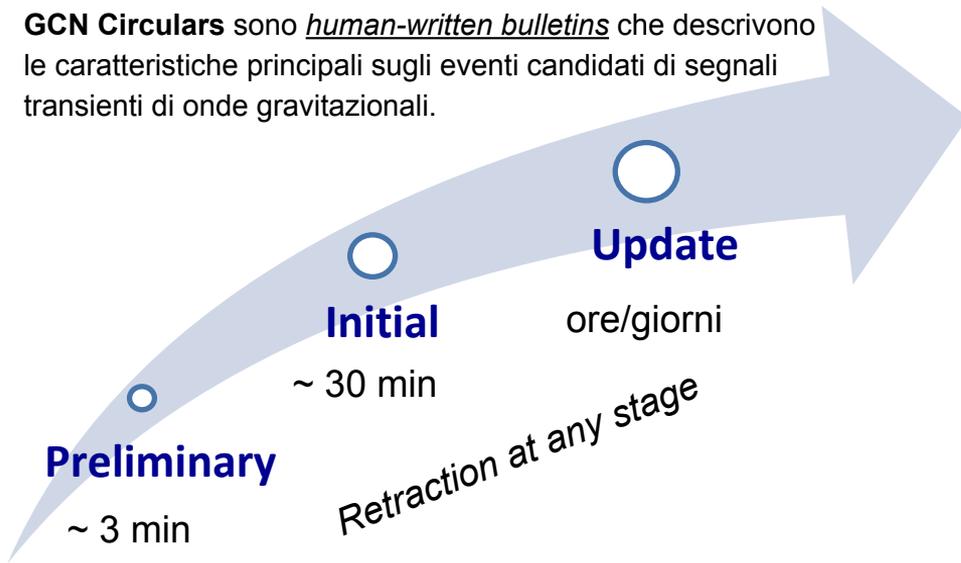


- ❑ Più di **160** strumenti coprono l'intero spettro elettromagnetico per un totale di **85** gruppi firmatari di un *protocollo di intesa* con la Collaborazione Ligo e Virgo (LVC). A questi si aggiungono gli esperimenti ANTARES e IceCube per la ricerca di emissioni di neutrini.
- ❑ Nel primo periodo di osservazione (O1) che va dal 12 Settembre 2015 al 19 Gennaio 2016 circa 40 gruppi si sono attivati per i **3 messaggi di allerta** lanciati da LVC.

# Il sistema di allerta: *notice/circular*

**GCN Notices** sono *machine-readable alerts* che comunicano informazioni prestabilite sugli eventi candidati di segnali transienti di onde gravitazionali.

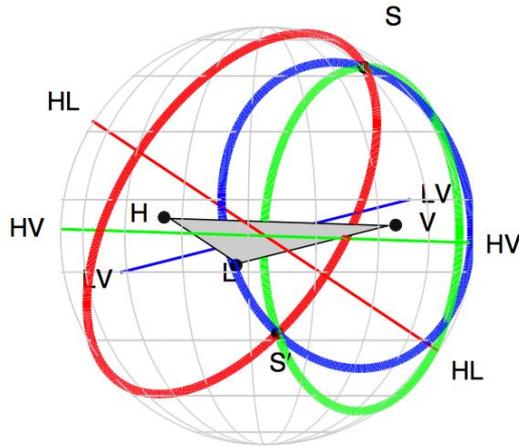
**GCN Circulars** sono *human-written bulletins* che descrivono le caratteristiche principali sugli eventi candidati di segnali transienti di onde gravitazionali.



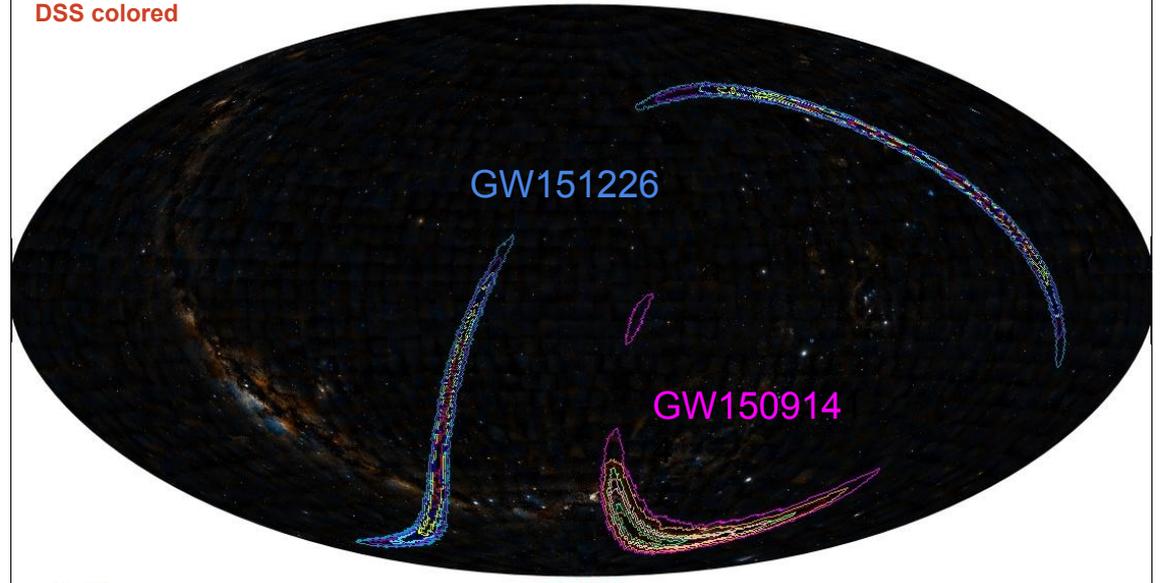
The Gamma-ray Coordinates Network

I 3 tipi di *notice* e i tempi stimati per il loro invio

# La localizzazione nel cielo delle sorgenti di OG



DSS colored



Metodo di triangolazione. Abbott et al. 2016  
*Living Reviews in Relativity*

Area = 616.4 deg<sup>2</sup> - 90% credible level MOC contour of GW150914 ([LALInference](#))  
Area = 887.9 deg<sup>2</sup> - 90% credible level MOC contour of GW151226 ([LALInference final](#))

Si stima che la localizzazione di GW150914 con la presenza dell'interferometro Virgo sarebbe stata di poche decine di gradi quadrati.

# TechInfo Page e materiale di supporto

[https://gw-astronomy.org/wiki/LV\\_EM/TechInfo](https://gw-astronomy.org/wiki/LV_EM/TechInfo)



## LIGO-Virgo EM Follow-Up Tutorial

by Leo P. Singer (NASA/GSFC) [leo.singer@ligo.org](mailto:leo.singer@ligo.org)

This document is LIGO-G1500442-v10.

### Abstract

This document explains how to receive, filter, and process gravitational-wave (GW) data. It includes sample code in Python and document alternatives for users of other programming languages.



## Handling gravitational-wave sky maps with Multi-Order Coverage (MOC)

This document explains how gravitational wave sky maps can be easily and efficiently visualized and processed using [Multi-Order Coverage \(MOC\)](#) based on [HEALPix](#) sky tessellation. We compute the MOC region at a given probability level and subsequently, we query databases whose position falls within this MOC map, we show operations between MOC maps and we check if a source is localized in a fixed region.

For this tutorial we use the simulated sky maps from [The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo](#) for compact

## Skymap Viewer

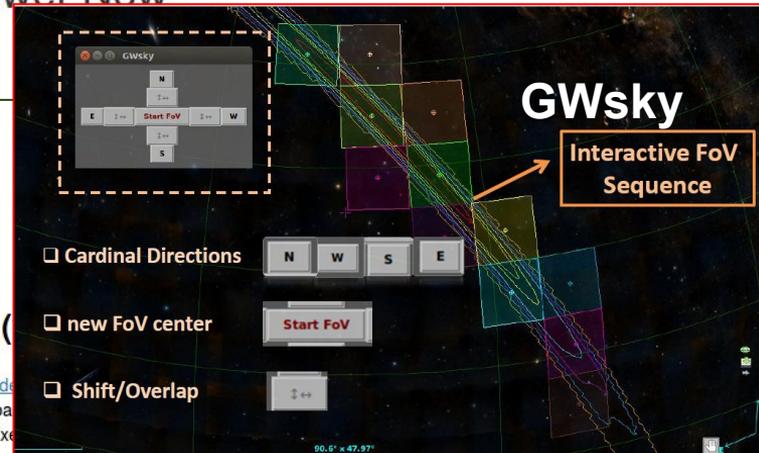
A sky atlas for understanding LIGO-Virgo skymaps. Help [here](#). Plenty of skymaps [here](#).



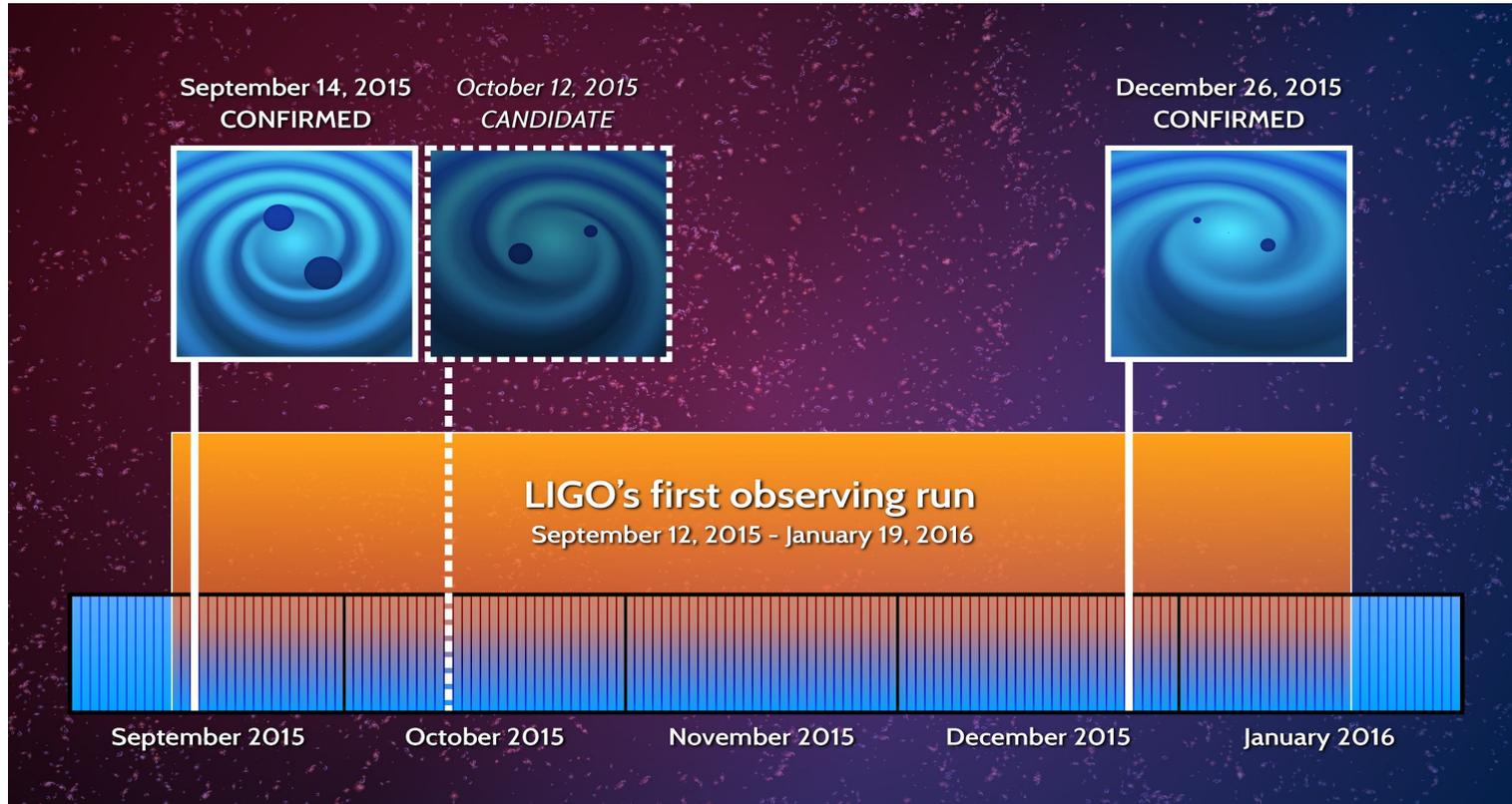
Watch a 10 min video about Skymap Viewer

## Start Skymap Viewer Now

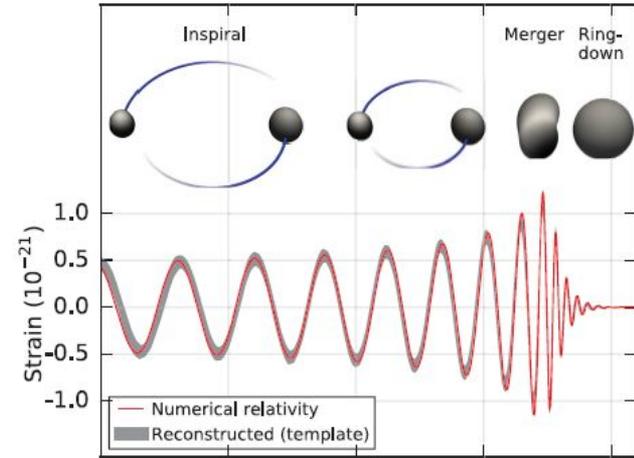
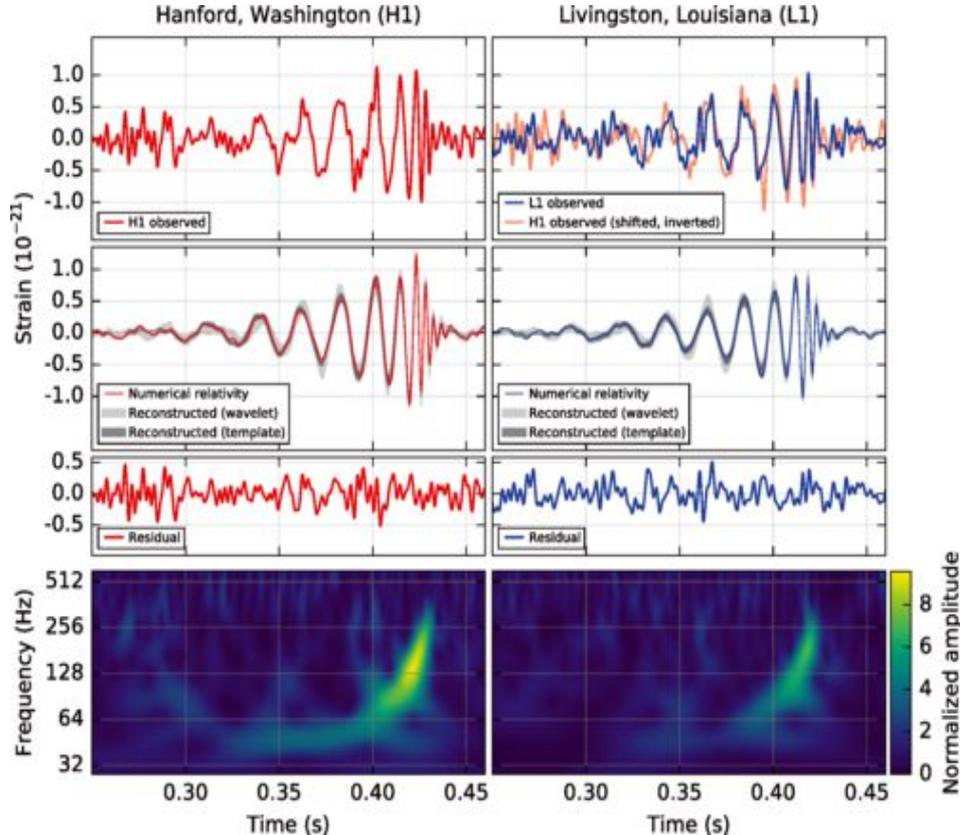
Simulated skymaps



# Risultati del primo periodo osservativo: 01

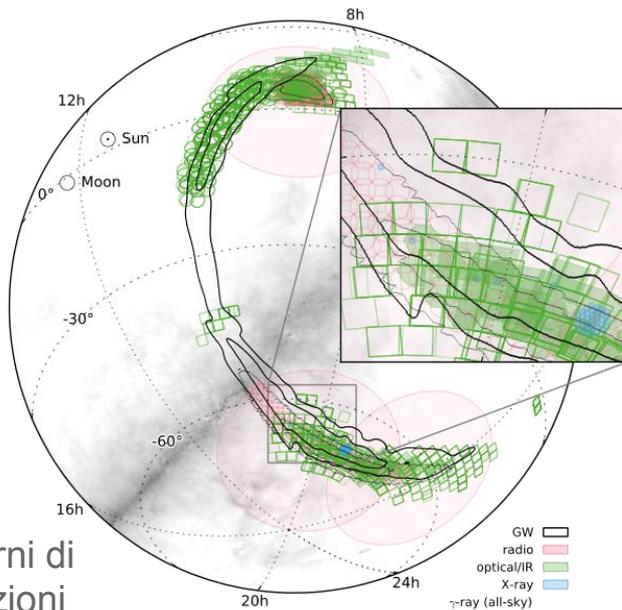


# GW150914: Coalescenza di 2 Buchi Neri in un Sistema Binario



Primary black hole mass	$36_{-4}^{+5} M_{\odot}$
Secondary black hole mass	$29_{-4}^{+4} M_{\odot}$
Final black hole mass	$62_{-4}^{+4} M_{\odot}$
Final black hole spin	$0.67_{-0.07}^{+0.05}$
Luminosity distance	$410_{-180}^{+160}$ Mpc
Source redshift $z$	$0.09_{-0.04}^{+0.03}$

# GW150914: ricerca della controparte e.m.

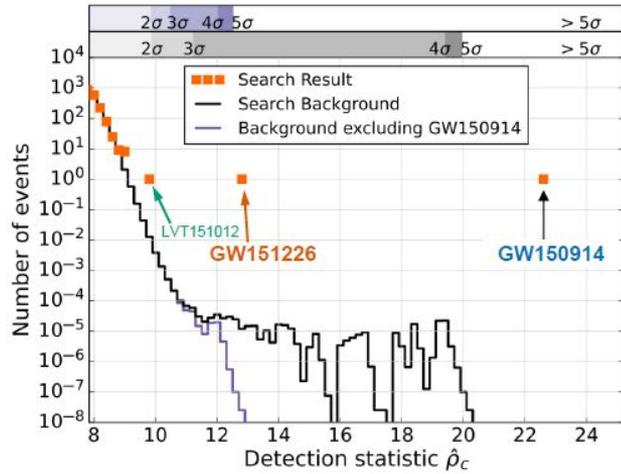


~100 giorni di osservazioni

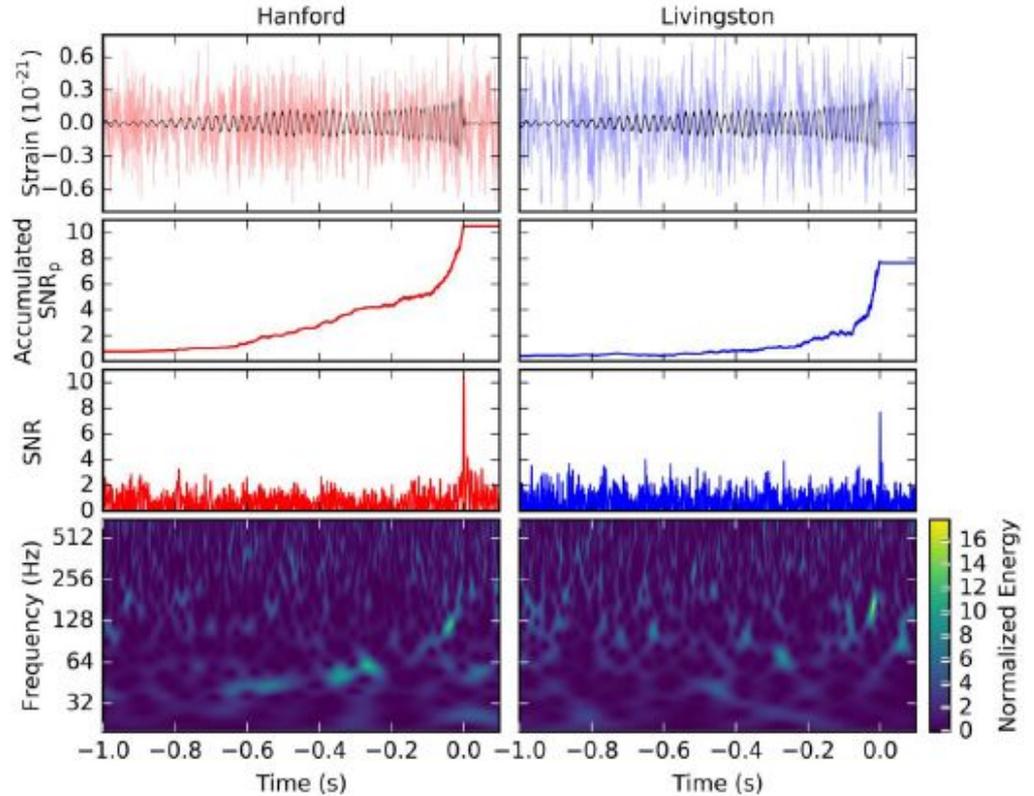
~30 fenomeni transienti nella regione di localizzazione di GW150914 sono stati classificati come Nuclei Galattici Attivi, Novae, Supernovae

Facility/ Instrument	Band <sup>a</sup>	Depth <sup>b</sup>	Time <sup>c</sup>	Area (deg <sup>2</sup> )	Contained Probability (%)			
					cWB	LIB	BSTR <sup>d</sup>	LALInf
Gamma-ray								
<i>Fermi</i> LAT	20 MeV– 300 GeV	$1.7 \times 10^{-9}$	(every 3 hr)	—	100	100	100	100
<i>Fermi</i> GBM	8 keV–40 MeV	$0.7\text{--}5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100
INTEGRAL	75 keV–1 MeV	$1.3 \times 10^{-7}$	(archival)	—	100	100	100	100
IPN	15 keV–10 MeV	$1 \times 10^{-7}$	(archival)	—	100	100	100	100
X-ray								
MAXI/GSC	2–20 keV	$1 \times 10^{-9}$	(archival)	17900	95	89	92	84
<i>Swift</i> XRT	0.3–10 keV	$5 \times 10^{-13}$ (gal.) $2\text{--}4 \times 10^{-12}$ (LMC)	2.3, 1, 1 3.4, 1, 1	0.6 4.1	0.03 1.2	0.18 1.9	0.04 0.16	0.05 0.26
Optical <sup>e</sup>								
DECam	$i, z$	$i < 22.5, z < 21.5$	3.9, 5, 22	100	38	14	14	11
iPTF	$R$	$R < 20.4$	3.1, 3, 1	130	2.8	2.5	0.0	0.2
KWFC	$i$	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1
MASTER	$C$	$C < 19.9$	-1.1, 7, 7	710	50	36	55	50
Pan-STARRS1	$i$	$i < 19.2\text{--}20.8$	3.2, 21, 42	430	28	29	2.0	4.2
La Silla– QUEST	$g, r$	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7
SkyMapper	$i, v$	$i < 19.1, v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9
<i>Swift</i> UVOT	$u$	$u < 19.8$ (gal.) $u < 18.8$ (LMC)	2.3, 1, 1 3.4, 1, 1	3	0.7	1.0	0.1	0.1
TAROT	$C$	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9
TOROS	$C$	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0
VST@ESO	$r$	$r < 22.4$	2.9, 6, 50	90	29	10	14	10
Near Infrared								
VISTA@ESO	$Y, J, K_S$	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0
Radio								
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86

# GW151226: Coalescenza di 2 Buchi Neri in un Sistema Binario

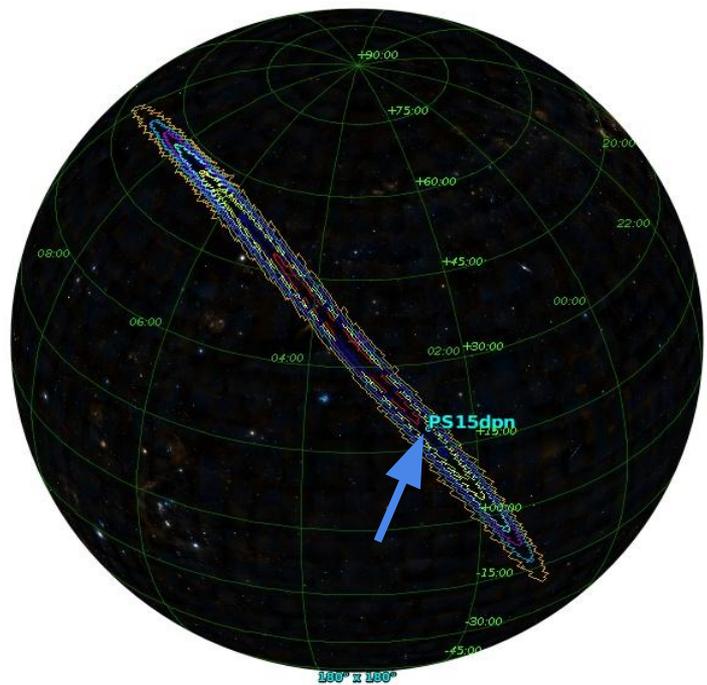


Primary black hole mass	$14.2^{+8.3}_{-3.7} M_{\odot}$
Secondary black hole mass	$7.5^{+2.3}_{-2.3} M_{\odot}$
Chirp mass	$8.9^{+0.3}_{-0.3} M_{\odot}$
Total black hole mass	$21.8^{+5.9}_{-1.7} M_{\odot}$
Final black hole mass	$20.8^{+6.1}_{-1.7} M_{\odot}$
Radiated gravitational-wave energy	$1.0^{+0.1}_{-0.2} M_{\odot} c^2$
Peak luminosity	$3.3^{+0.8}_{-1.6} \times 10^{56}$ erg/s
Final black hole spin	$0.74^{+0.06}_{-0.06}$
Luminosity distance	$440^{+180}_{-190}$ Mpc
Source redshift $z$	$0.09^{+0.03}_{-0.04}$

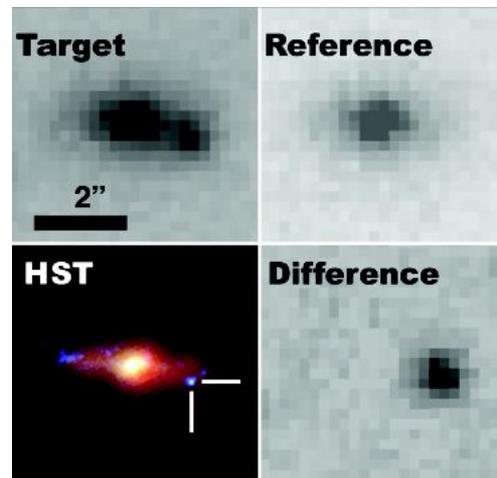


GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence, PRL 116, 241103 (2016)

# Il caso di *PS15dpm* nella regione di localizzazione di GW151226



Dati provenienti da *Smartt et al. ApJ 2016* ed elaborati con il codice nel tutorial *Handling gravitational-wave sky maps with Multi-Order Coverage*



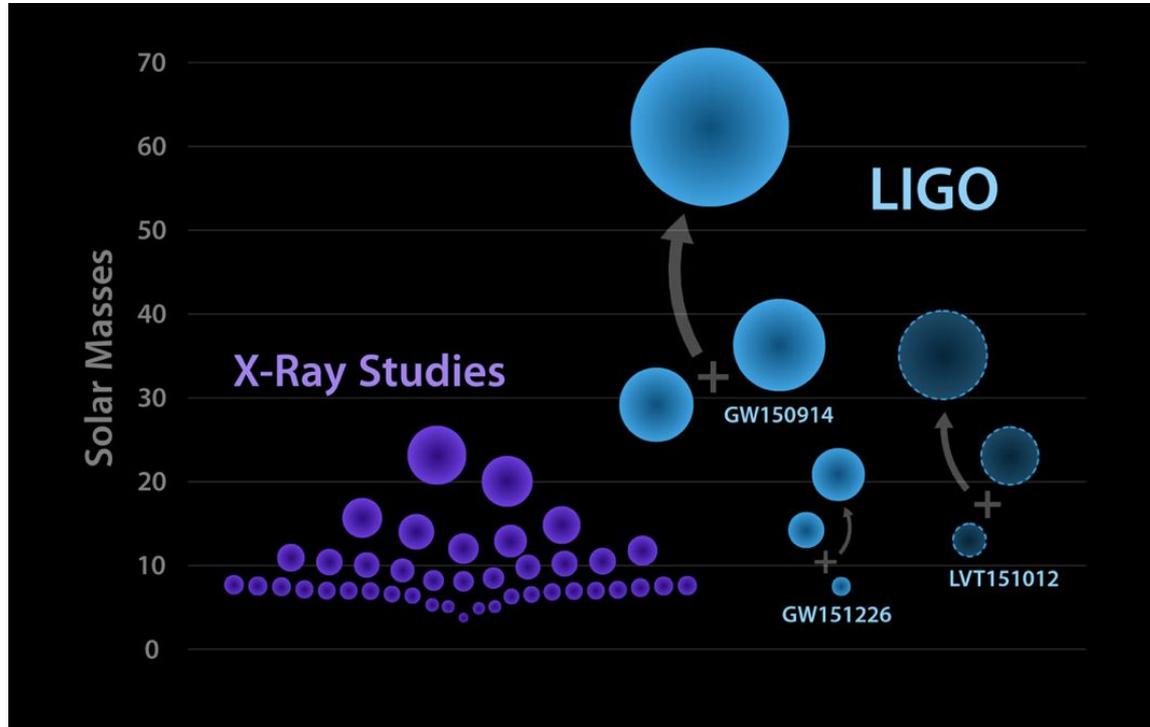
**Coincidenza temporale con GW151226...**

*accurate analisi spettroscopiche mostrano che evolve in una SN con una distanza di  $z = 0.1747 \pm 0.0001$  non consistente con quella di GW151226*

See GCN Circ. <https://gw-astronomy.org/circs/G211117.lvc3>

*PS15dpm* è stato identificato nella immagini ottenute da Pan-STARRS1 (*Smartt et al. ApJ 2016*) il quale ha osservato circa 290 gradi quadrati in banda ottica dopo circa 11.5 ore dal messaggio di allerta lanciato da LVC (GCN 18728).

# Come si formano sistemi binari di buchi neri così massicci?



## IPOTESI 1: *ambienti poco densi*

Sistema binario isolato di 2 stelle di grande massa con deboli venti stellari.

## IPOTESI 2: *ambienti molto densi*

Da ripetuti “incontri” di un sistema binario di buchi neri con altri buchi neri



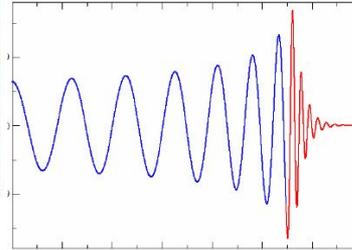
favoriscono la formazione di sistemi binari con buchi neri più massicci.

Quali sorgenti di onde gravitazionali identificabili nella banda di rilevazione tra 10 Hz - 1000 Hz prevedono la formazione di un transiente elettromagnetico?

Quali sono le caratteristiche di tale transiente?

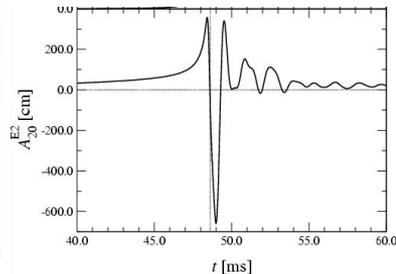
# Alcune tra le sorgenti di onde gravitazionali per LVC

## Coalescenza di Sistemi Compatti: *SNSN/BNBN/SNBN*



- filtro adattato (matched filtered)
- *precise waveforms*
- Energy emitted in GWs (BNS):  
 $\sim 10^{-2} M_{\text{sun}} c^2$

## Collasso asimmetrico durante eventi di Supernovae

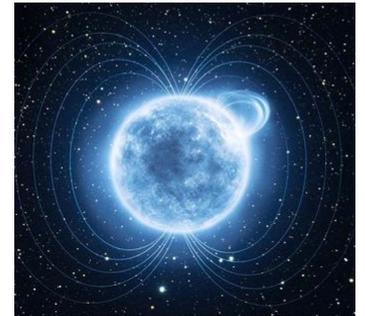


## Instabilità di stelle di neutroni isolate

- eccesso di potenza
- *uncertain waveforms*

Energy emitted in GWs:

- $\sim 10^{-8} - 10^{-5} M_{\text{sun}} c^2$  for the core-collapse
- $10^{-16} - 10^{-6} M_{\text{sun}} c^2$  for isolated NSs

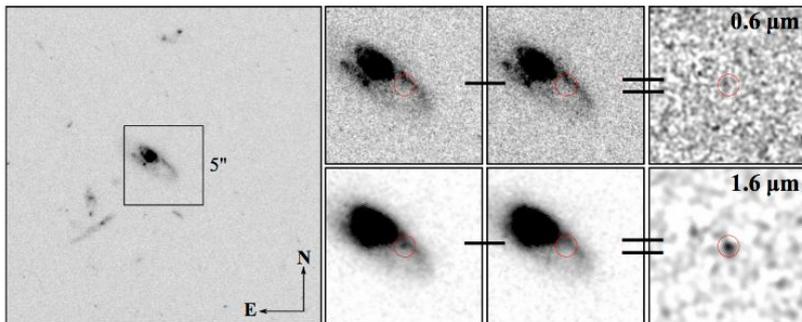
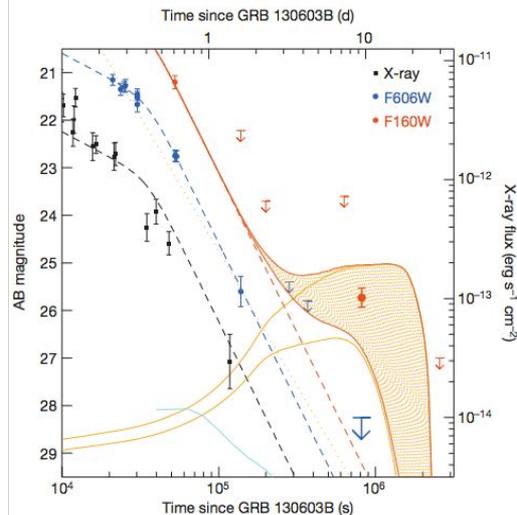
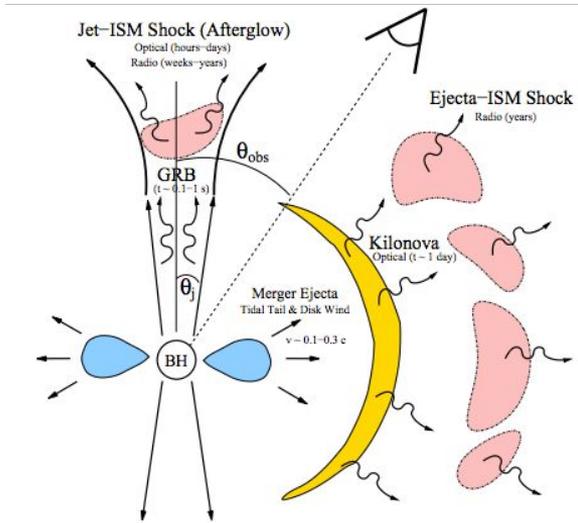


# Progenitori degli “Short GRB” e meccanismi di emissione

## Macronova/Kilonova

(*Li & Paczyński*)

I modelli indicano che la magnitudine attesa per una kilonova a 200 Mpc è circa **22 mag @  $t < 5$  giorni** (nella banda i o z). Rapidamente decade con una **mag > 24 entro dieci giorni**.



**Possibile identificazione di una macronova nello short GRB 130603B dopo 9.4 giorni.**

- ★ GRB 060614 *Jin, Z. P. et al. 2015, ApJL*
- ★ GRB 050709 *Jin, Z. P. et al. 2016, Nat. Commun.*



LIGO  
Scientific  
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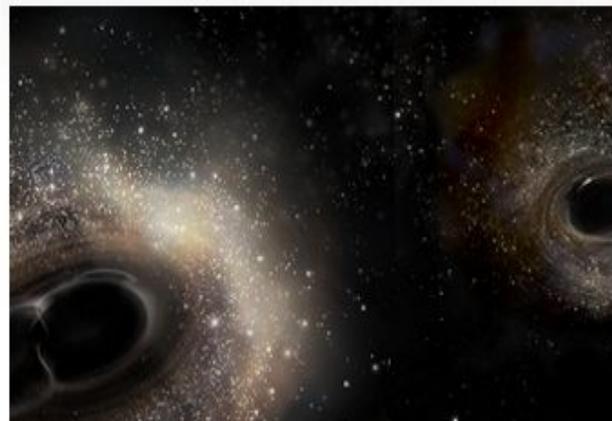
## NEWS

### APRIL 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

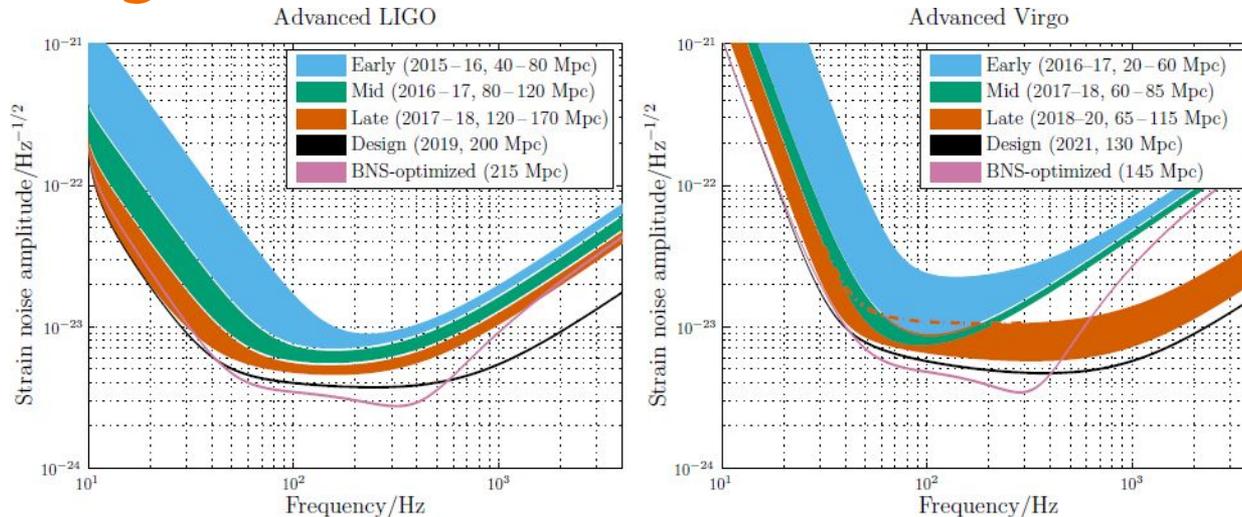
6 April 2017 – The second Advanced LIGO run began on [November 30, 2016](#) and is currently in progress. As of March 23 approximately [48 days](#) of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017. The average reach of the LIGO network for binary merger events has been around [70 Mpc](#) for [1.4+1.4 Msun](#), [300 Mpc](#) for [10+10 Msun](#) and [700 Mpc](#) for [30+30 Msun](#) mergers, with relative variations in time of the order of 10%.

As of March 23, [6 triggers](#), identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup. A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

## LIGO DETECTIONS



# Observing Scenario



Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+	2022+ (India)
Estimated run duration		4 months	6 months	9 months	(per year)	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105	105
	Virgo	—	20 – 40	40 – 50	40 – 80	80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200	200
	Virgo	—	20 – 60	60 – 85	65 – 115	130
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200	0.4 – 400

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo, *Living Reviews in Relativity*, December 2016.