



**November 9-15, 2019** An-Najah N. University, Nablus, Palestine

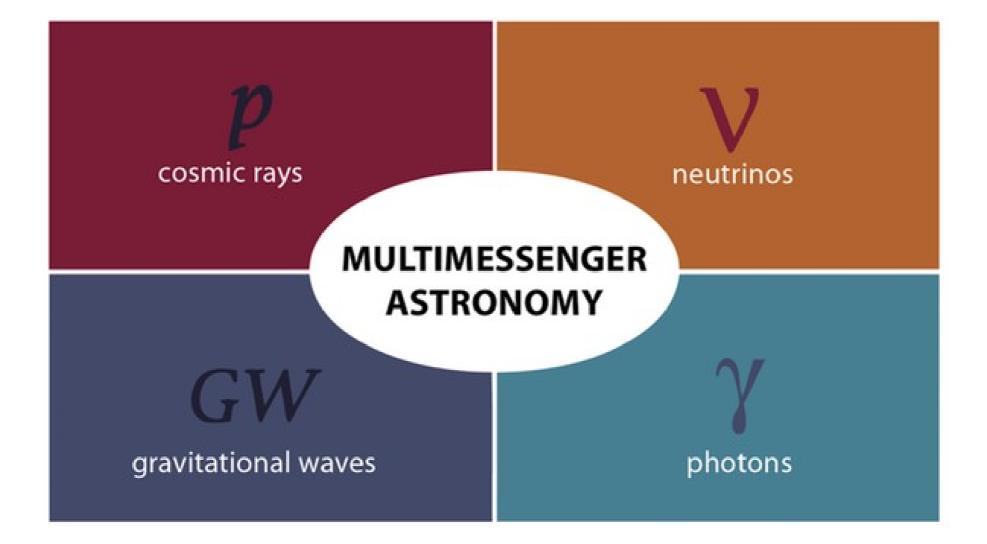
## Multi-messenger astronomy

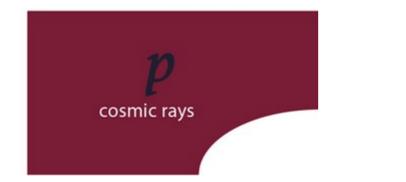
- → Definition
- → Low-latency gravitational waves detection
- → EM follow-up
- → The story of GW170817



Florent Robinet Laboratoire de l'Accélérateur Linéaire

robinet@lal.in2p3.fr

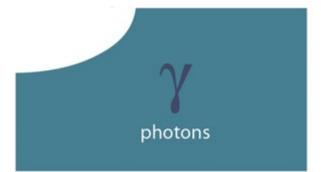


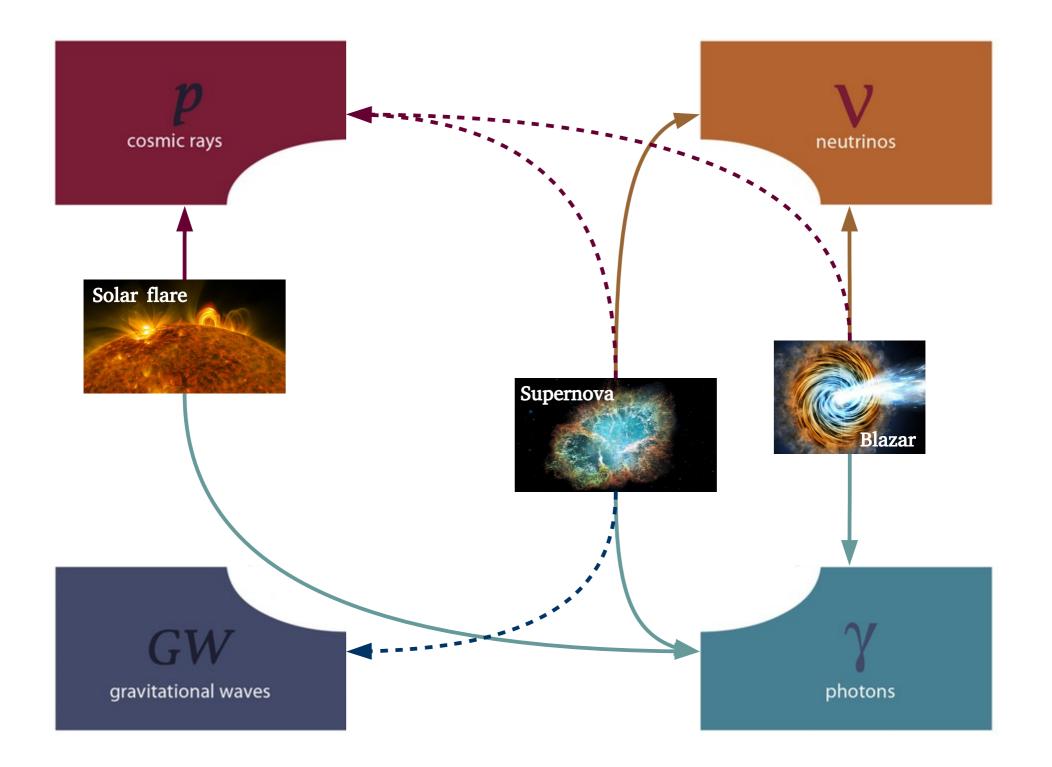


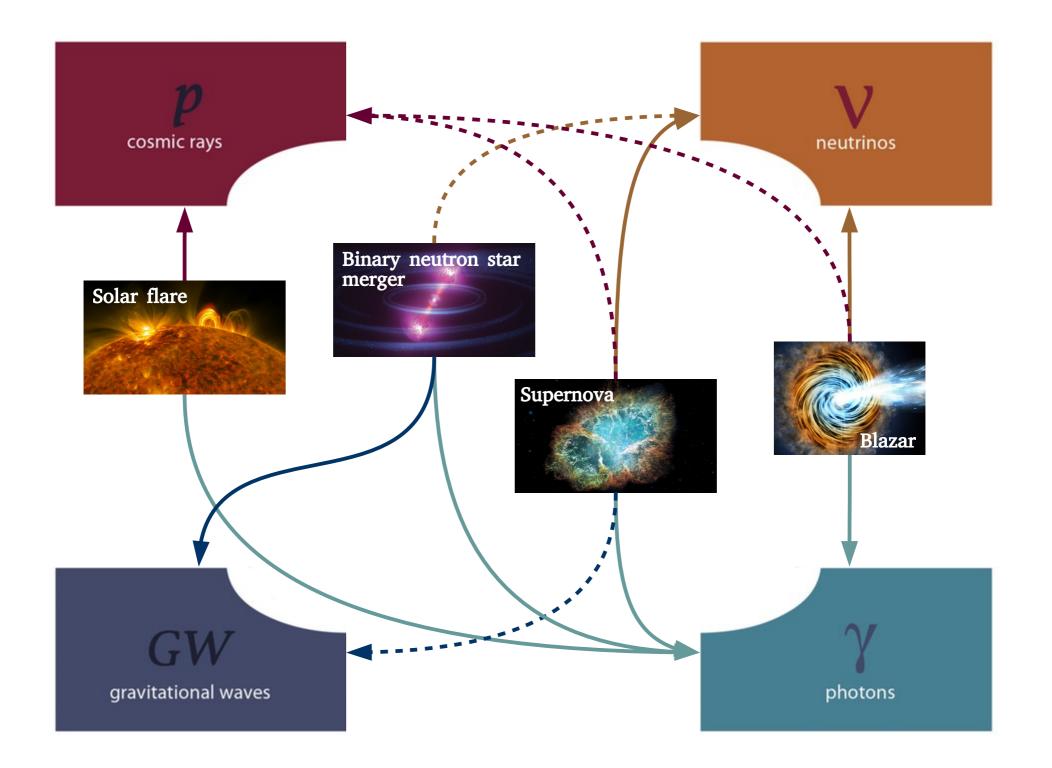


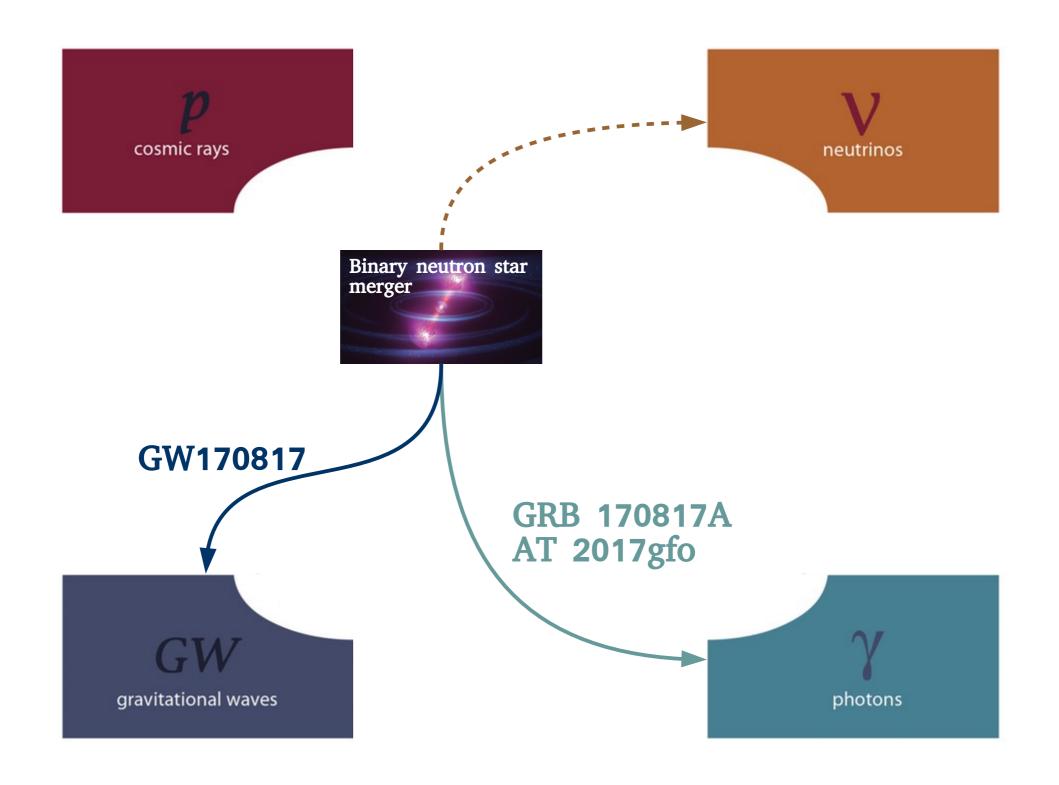
### Use multiple and complementary channels to study astrophysical objects











### Gravitational waves

- → mass
- $\rightarrow$  spin
- $\rightarrow$  eccentricity
- $\rightarrow$  system orientations
- $\rightarrow$  luminosity distance
- $\rightarrow$  rate of CBC events
- $\rightarrow$  internal physics



### Photons

- $\rightarrow$  precise sky location (~arcsec)
- $\rightarrow$  host galaxy
- $\rightarrow$  redshift
- $\rightarrow$  local environment
- $\rightarrow$  emission processes
- $\rightarrow$  acceleration mechanisms
- $\rightarrow$  internal physics



GRB 170817A AT 2017gfo

photons

gravitational waves

### GW low-latency analysis

Virgo

### - 10 seconds

LIGO-Virgo data are recorded at the sites: – O(100,000) channels / detector – ~ 4 TB of data is recorded – Calibration  $\rightarrow h(t)$  data

Handford

Livingston

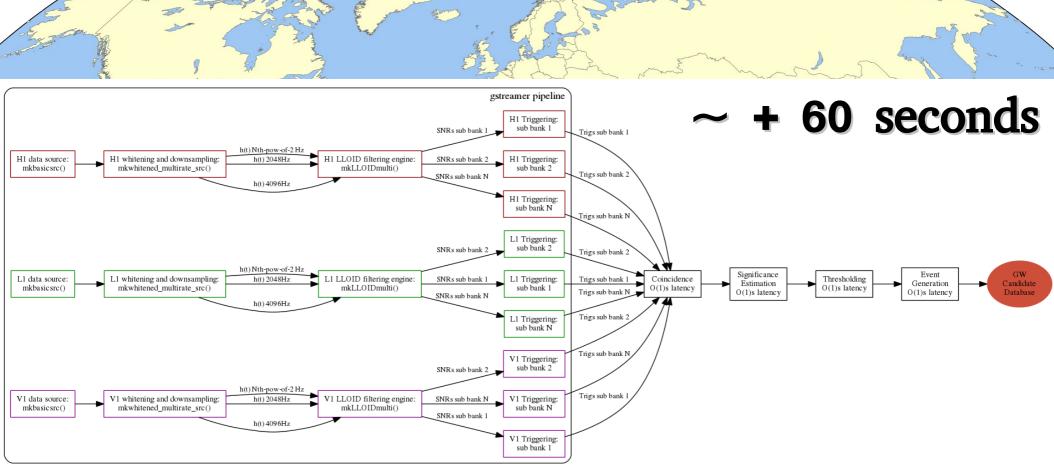
## GW low-latency analysis



LIGO-Virgo data are transferred to computing centers:

- Caltech, USA
- Virgo, İtaly
- Hannover, Germany
- → Low-latency searches are conducted

### GW low-latency analysis



gstlal\_inspiral



HOME SFA	1 <b>C.</b> 1	CREATE	REPORTS	RSS	LAT	EST OPT	TIONS	DOCUMENTATION					AUTHENTICATED AS: FLORENT ROB
Basic mfo													
UID		Lab	els		Group	Pipeline	Sea	rch Instrument	s	UTC - Event Time	FAR (Hz)	Links	UTC 🖵 Submitted
<b>1211117</b> Н:	10K L10	K ADVOK EM	READY	С	BC	gstlal	HighMas	s H1,L1	2015-12-	-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC
Coinc Table	es					Sin IFO	-	piral Tables	H1				
End Time (GPS)		113513635	50 6478 s				nnel	GDS-CALIB STRA		DS-CALIB STRAIN			
							Time (GF	-		35136350.647757924 s			
								ration 2.25322770554		25322770554 s			
Total Mass		26.3501 M <sub>G</sub>	Э					ance 472.93436 Mpc		1.88879 Mpc			
						COA	Phase	2.7356486 rad	0.1	13969257 rad			
Chirp Mass		9.5548 M₀				Mas	s 1	$19.924686~M_{\odot}$	19.	.924686 M <sub>☉</sub>			
Chip Mass		9.0040 M <sub>☉</sub>				Mas	is 2	$6.4254546~M_{\odot}$	6.4	1254546 M <sub>☉</sub>			
						η		0.18438664	0.1	18438664			
SNR		11.7103				F Fi	nal	1024.0 Hz	102	24.0 Hz			
						SNR	ł	7.3947201		0802174			
False Alarm Pro	hability	1 1200-04				χ²		1.0857431		069774			
Tube Alarm Plu	sability	1.1206-04				χ <sup>2</sup> D		1	1				
						spin		0.33962944		33962944			
Log Likelihood I	Ratio	22.5996				spin	122	-0.1238557	-0.1	1238557			

#### Crewitational Ways Condidate Event Database CreacDD

#### Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time ▼ Event Time	∆gpstime	FAR (Hz)	Links	UTC - Submitted
<u>G211182</u>		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		<u>Data</u>	2015-12-26 09:44:37 UTC
<u>G211115</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	<u>Data</u>	2015-12-26 03:39:59 UTC
<u>G211118</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	<u>Data</u>	2015-12-26 03:40:00 UTC
<u>G216856</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
<u>G211116</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	<u>Data</u>	2015-12-26 03:40:00 UTC

#### GraceDB — Gravitational Wave Candidate Event Database

	CREATE	REPORTS	RSS	LATEST	OPTIONS	DOC	UMENTATION		AUTHENTICATED AS: FLORENT I	ROBIN
Basic info										
<b>UR</b>	Labels		G	iroup Pip	eline	Search	Instruments	UTC - Event Time	UTC → FAR (Hz) Links Submitted	
211117 H10K L10	K ADVOK EM_RE	ADY	СВ	C gstla	Hig	hMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11 Data 2015-12-26 03:40:00 UTC	
Coinc Tables		mo	odele	ed sear		Inspira	al Tables			
					IFO	mspire		H1	+1 min	
End Time (GPS)	1135136350.6	478 s			Channel	/	GDS-CALIB STRAIN	GDS-CALIB STRAIN		
					End Time	e (GP5)	1135136350.64688		24 s	
					Template	<b>Duration</b>	2.25322770554 s	2.25322770554 s		
Total Mass	$26.3501 \ \mathrm{M}_{\odot}$				Effective	Distance	472.93436 Mpc	461.88879 Mpc		
					COA Ph	se	2.7356486 rad	0.13969257 rad		
Chim Mass	9.5548 M₀				Mass 1		$19.924686~M_{\odot}$	$19.924686\ M_\odot$		
Chirp Mass	9.5546 M <sub>O</sub>				Mass 2		6.4254546 M <sub>☉</sub>	$6.4254546~M_{\odot}$		
					η		0.18438664	0.18438664		
SNR	11.7103				F Final		1024.0 Hz	1024.0 Hz		
					SNR		7.3947201	9.0802174		
					χ²		1.0857431	1.0069774	/physical parameters	
False Alarm Probability	1.120e-04				χ <sup>2</sup> DOF	$\mathbf{\Lambda}$	1	1	(preliminary)	
					spin1z		0.33962944	0.33962944	(Preminary)	
Log Likelihood Ratio	22.5996				spin2z		-0.1238557	-0.1238557		

#### Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time ▼ Event Time	∆gpstime	FAR (Hz)	Links	UTC 🔻 Submitted
<u>G211182</u>		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		<u>Data</u>	2015-12-26 09:44:37 UTC
<u>G211115</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	<u>Data</u>	2015-12-26 03:39:59 UTC
<u>G211118</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	<u>Data</u>	2015-12-26 03:40:00 UTC
<u>G216856</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
<u>G211116</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	<u>Data</u>	2015-12-26 03:40:00 UTC

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HOME SEATCL	CREATE RE	EPORTS	RSS	LATEST	OPTION	IS DOC	UMENTATION						AUTHENTICA	TED AS: FLORENT	ROBIN
. <b>1</b> .															
Basic mfo									-		050				
	Labels		G	iroup Pip	peline	Search	Instruments		UTC - Event Time	FAK	~ 950 FAR (Hz)	yr-1 Links		UTC - Submitted	
211117 H10K L10	K ADVOK EM_READ	DY	СВ	C gstla	Р	ighMass	H1,L1	2015-12-	26 03:38:53 UTC	>	3.333e-11	Data	2015-12-26	03:40:00 UTC	
		ma	odele	ed sear	rch					1					
Coinc Tables		1110	Jucit	u beu		e Inspira	d Tables								
					IFO	•	4	H1		+	1 min				
End Time (GPS)	1135136350.647	78 s			Channe	el 🖉	GDS-CALIB_STRAII	N GD	S-CALIB_STRAIN	$\overline{}$					
					End Tin	ne (GP5)	1135136350.646	883043 s 113	5136350.64775	7924 s					
T-4-1 M	26 2501 M				Templa	te Duration	2.25322770554	5 2.2	5322770554 s						
Total Mass	26.3501 M <sub>☉</sub>				Effectiv	e Distance	472.93436 Mpc	461	88879 Mpc						
					COA Ph	ase	2.7356486 rad	0.1	3969257 rad		1				
Chirp Mass	9.5548 M₀				Mass 1		$19.924686~M_{\odot}$	19.	924686 M <sub>☉</sub>						
	5.55161.10				Mass 2		$6.4254546~M_{\odot}$	6.4	254546 M <sub>☉</sub>						
					η		0.18438664	0.1	8438664						
SNR	11.7103				F Final		1024.0 Hz	102	4.0 Hz						
					SNR		7.3947201	9.0	802174		1				
					χ²		1.0857431	1.0	069774		/physic	al pai	ramete	ers	
False Alarm Probability	1.120e-04				$\chi^2 DOF$		1	1			(prelin	ninary	7)		
					spin1z		0.33962944	0.3	3962944		'L' cum	Junior y			
Log Likelihood Ratio	22.5996				spin2z		-0.1238557	-0.1	.238557						
-															

#### Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time ▼ Event Time	∆gpstime	FAR (Hz)	Links	UTC 🔻 Submitted
<u>G211182</u>		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		<u>Data</u>	2015-12-26 09:44:37 UTC
<u>G211115</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	<u>Data</u>	2015-12-26 03:39:59 UTC
<u>G211118</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	<u>Data</u>	2015-12-26 03:40:00 UTC
<u>G216856</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	<u>Data</u>	2016-01-15 14:31:22 UTC
<u>G211116</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	<u>Data</u>	2015-12-26 03:40:00 UTC

#### GraceDB — Gravitational Wave Candidate Event Database

HOME SPATC	CREATE F	REPORTS	RSS	LATEST	OPTIONS	S DOC	UMENTATION				Α	UTHENTICATED A	S: FLORENT ROBINE
2													
Basic info									ΕΛD	050	T7P 1		
UID	Labels		G	iroup Pip	peline	Search	Instruments			~ 950 FAR (Hz)	yı−ı Links		rc 🗸 mitted
0211117 H10K L10	K ADVOK EM_REA	ADY	СВ	C gstla		ghMass	H1,L1	2015-12-26 03:38:	53 UTC	3.333e-11	Data	2015-12-26 03:40	0:00 UTC
		ma	odele	d sea	rch								
Coinc Tables			Jucit	u beu		Inspira	l Tables						
					IFO	-	4	H1	<u> </u>	+1 min			
End Time (GPS)	1135136350.64	178 s			Channel		GDS-CALIB_STRAIN	GDS-CALIB_S	TRAIN				
					End Tim	e (GPS)	1135136350.646	883043 s 1135136350	.647757924 s				
Total Mana	26 2501 M				Templat	e Duration	2.25322770554 s	2.25322770	554 s				
Total Mass	26.3501 M <sub>☉</sub>				Effective	Distance	472.93436 Mpc	461.88879 N	1pc				
					COA Ph	se	2.7356486 rad	0.13969257	rad				
Chirp Mass	9.5548 M <sub>☉</sub>				Mass 1		$19.924686~\text{M}_\odot$	19.924686 N	1 <sub>⊙</sub>				
child has	5.5516110				Mass 2		$6.4254546~\text{M}_\odot$	6.4254546 N	1 <sub>⊙</sub>				
					η		0.18438664	0.18438664					
SNR	11.7103				F Final		1024.0 Hz	1024.0 Hz					
					SNR		7.3947201	9.0802174		1			
					χ <sup>2</sup>	$\mathbf{N}$	1.0857431	1.0069774		/physica	al para	ameters	
False Alarm Probability	1.120e-04				$\chi^2 DOF$		1	1		(prelin			
					spin1z		0.33962944	0.33962944		Prenn	iiiiai y /		
Log Likelihood Ratio	22.5996				spin2z		-0.1238557	-0.1238557					
-													

#### Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time ▼ Event Time	∆gpstime	FAR (Hz)	Links	UTC • Submitted
<u>G211182</u>		Burst ,	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		<u>Data</u>	2015-12-26 09:44:37 UTC
<u>G211115</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	<u>Data</u>	2015-12-26 03:39:59 UTC
<u>G211118</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	<u>Data</u>	2015-12-26 03:40:00 UTC
<u>G216856</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6480	0.000278	1.187e-12	<u>Data</u>	2016-01-15 14:31:22 UTC
<u>G211116</u>		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	<u>Data</u>	2015-12-26 03:40:00 UTC

multiple detections over time

### Human Vetting

GraceDB — Gravitational Wave Candidate Event Database

HOME	SEARCH	CF	EATE	REPORTS	RSS LAT	EST	OPTIONS DOC	UMENTATION				AUTHENTICATED AS: FLORENT ROBIN
Basic Inf	fo											
UID			Labels		Group	Pipeli	ne Search	Instruments	UTC • Event Time	FAR	(Hz) LI	UTC • nks Submitted
G211117	H10K	10K AD	OVOK EM_RE	ADY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-	11 <u>Dat</u>	2015-12-26 03:40:00 UTC
Coinc Ta	ables					5	Single Inspira	d Tables				
						1	FO	11	H1			
End Time (G	GPS)	11	35136350.6	478 s			Channel	GDS-CALIB STRAIN	GDS-CALIB STRAIN			
							End Time (GPS)	1135136350.6468	- 33043 s 1135136350.647757	924 s		
							Template Duration	2.25322770554 s	2.25322770554 s			
Total Mass	Mass 26.3501 M		3501 M <sub>o</sub>				Effective Distance	472.93436 Mpc	461.88879 Mpc			
							COA Phase	2.7356486 rad	0.13969257 rad			
							Mass 1	19.924686 M <sub>o</sub>	19.924686 M <sub>o</sub>			
Chirp Mass		9.5	548 M <sub>☉</sub>				Mass 2	6.4254546 M <sub>o</sub>	6.4254546 Mo			
							η	0.18438664	0.18438664			
5NR		11.	7103			i i	F Final	1024.0 Hz	1024.0 Hz			
							SNR	7.3947201	9.0802174			
							x <sup>2</sup>	1.0857431	1.0069774			
False Alarm	Probabi	lity 1.1	20e-04				2 DOF	1	1			
						,	spin1z	0.33962944	0.33962944			
Log Likeliho	ood Ratio	. 22	5996				spin2z	-0.1238557	-0.1238557			
Log Likeline	oou nuun		5550									
Veighbor		. 51										
vergnbor	rs [-0	,+0]						GPS Time				UTC -
UID	L	abels	Group	Pipeline	Searc	h	Instruments	Event Ti		FAR (Hz)	Links	Submitted
G211182			Burst	CWB2G	AllSky	H1	,11	1135136350.6291	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115			CBC	gstial	HighMass	H1	,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118			CBC	gstial	HighMass	H1	.L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856			CBC	gstial	HighMass	H1	,L1	1135136350.6480	0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
G211116			CBC	gstlal	HighMass	H1	.L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

 $\rightarrow$  Preliminary GCN notice is issued

 $\rightarrow$  Electronic alerts (emails, texts, phone calls) are sent to LIGO-Virgo people

- $\rightarrow$  Virtual meeting with many people
  - detector control rooms
  - detector experts
  - run coordinators
  - detector characterization experts
  - search pipeline managers
  - calibration experts
- $\rightarrow$  The gravitational-wave candidate is scrutinized:
  - data quality
  - detector status
  - event preliminary parameters
  - first sky map
- $\rightarrow$  GCN notice is updated



The LIGO Scientific Collaboration and Virgo report:

The online gstlal CBC analysis, which is sensitive to binary coalescence events from systems containing neutron stars and/or black holes, identified candidate G211117 during real-time processing of data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2015-12-26 03:38:53.648 UTC (GPS time: 1135136350.648).

The candidate was identified by an expanded low-latency pipeline configuration that is sensitive to stellar-mass BNS, NSBH, and BBH mergers. G211117 is an event of interest because its false alarm rate, as determined by the online analysis, passed our stated alert threshold of ~1/month. The event's properties can be found at this URL:

https://gracedb.ligo.org/events/G211117

If confirmed as astrophysical, the system contains at least one and most likely two black holes.

The candidate was below the threshold for detection by the low-latency un-modeled burst searches. However, manual offline analysis with Coherent

### Human Vetting

GraceDB — Gravitational Wave Candidate Event Database

HOME	SEARCH	CREATE	REPORTS	RSS LAT	EST C	OPTIONS DOC	UMENTATION					AUTHENTICATED AS: FLORENT ROBIN
Basic In	ıfo											
UID		Labels		Group	Pipelin	e Search	Instruments		UTC • Event Time	FAR	(Hz) L	UTC - Inks Submitted
5211117	HIOK LIC	K ADVOK EM_RE	ADY	CBC	gstlal	HighMass	H1,L1	2015-12-2	26 03:38:53 UTC	3.333e	11 <u>Da</u>	ta 2015-12-26 03:40:00 UTC
Coinc T	ables				s	ingle Inspira	l Tables					
						FO	L1	H1				
nd Time	(GPS)	1135136350.6	478 s		c	hannel	GDS-CALIB STRAIN	GD	S-CALIB STRAIN			
					E	nd Time (GPS)	1135136350.64688		5136350.647757	924 s		
					Т	emplate Duration	2.25322770554 s	2.2	5322770554 s			
otal Mass		26.3501 M <sub>o</sub>			E	ffective Distance	472.93436 Mpc	461	.88879 Mpc			
					c	OA Phase	2.7356486 rad	0.1	3969257 rad			
		9.5548 Mo			M	lass 1	19.924686 M <sub>o</sub>	19.	924686 M <sub>o</sub>			
hirp Mas	5	9.5546 M <sub>☉</sub>			N	lass 2	6.4254546 Mg	6.4	254546 Mo			
					η		0.18438664	0.1	8438664			
NR		11,7103				Final	1024.0 Hz	102	4.0 Hz			
					s	NR	7.3947201	9.0	802174			
					x	2	1.0857431	1.0	069774			
alse Alar	m Probability	1.120e-04			x	2 DOF	1	1				
					s	pin1z	0.33962944	0.3	3962944			
og Likelij	hood Ratio	22,5996			s	pin2z	-0.1238557	-0.1	238557			
og Likeli	loou katio	22.5990										
eighbo	ors [-5,+4	51										
UID	Labe		Pipeline	Searc		Instruments	GPS Time Event Time		∆gpstime	FAR (Hz)	Links	UTC - Submitted
211182	Labe	Burst	CWB2G	AllSky	н н1,1		1135136350.6291		-0.018658	TAR (HZ)	Data	2015-12-26 09:44:37 UTC
2111102		CBC	gstlal	HighMass	H1,I		1135136350.6405		-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
2111118		CBC	gstial	HighMass	H1,I		1135136350.6477		-0.000043	3.279e-08	Data	2015-12-26 03:39:39 01C
216856		CBC	gstial	HighMass	H1,I		1135136350.6480		0.000278	1.187e-12	Data	2016-01-15 14:31:22 UTC
5210650		CBC	gstial	HighMass	H1,I		1135136350.6485		0.000278	4.507e-09	Data	2016-01-15 14:51:22 01C 2015-12-26 03:40:00 UTC

 $\rightarrow$  Preliminary GCN notice is issued

→ Electronic alerts (ALERTS IN O3 LIGO-View PUBLIC ALERTS IN O3) are sent to

- $\rightarrow$  Virtual meeting with many people
  - detector control rooms
  - detector experts
  - run coordinators
  - detector characterization experts
  - search pipeline managers
  - calibration experts
- $\rightarrow$  The gravitational-wave candidate is scrutinized:
  - data quality
  - detector status
  - event preliminary parameters
  - first sky map
- $\rightarrow$  GCN notice is updated



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The online gstlal CBC analysis, which is sensitive to binary coalescence events from systems containing neutron stars and/or black holes, identified candidate G211117 during real-time processing of data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2015-12-26 03:38:53.648 UTC (GPS time: 1135136350.648).

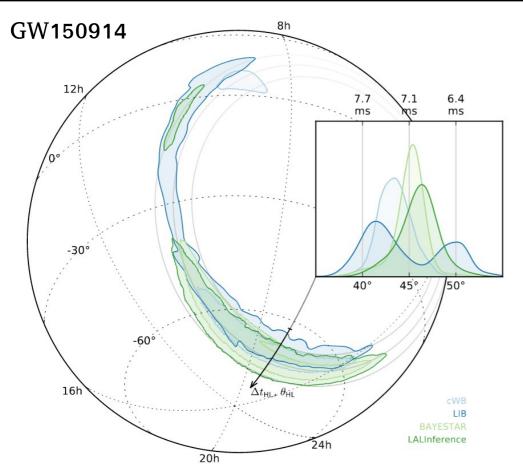
The candidate was identified by an expanded low-latency pipeline configuration that is sensitive to stellar-mass BNS, NSBH, and BBH mergers. G211117 is an event of interest because its false alarm rate, as determined by the online analysis, passed our stated alert threshold of ~1/month. The event's properties can be found at this URL:

https://gracedb.ligo.org/events/G211117

If confirmed as astrophysical, the system contains at least one and most likely two black holes.

The candidate was below the threshold for detection by the low-latency un-modeled burst searches. However, manual offline analysis with Coherent

# Sky maps



### ~1 minute

Preliminary parameter estimation given by the search pipeline:

- source parameters (template)
- rough sky position

### ~ a few minutes Rapid analysis for parameter estimation (*BAYESTAR*)

### ~ hours/days

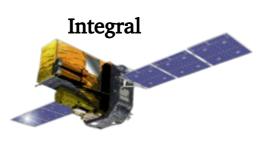
Full (and final) parameter estimation analysis (*LALInference*)

### $\rightarrow$ Notices are sent whenever a sky map is updated

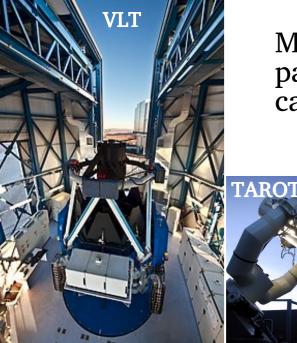
# EM follow-up











Many teams of astronomers participate to EM-follow campaigns, in every wavelengths





SkyMapper





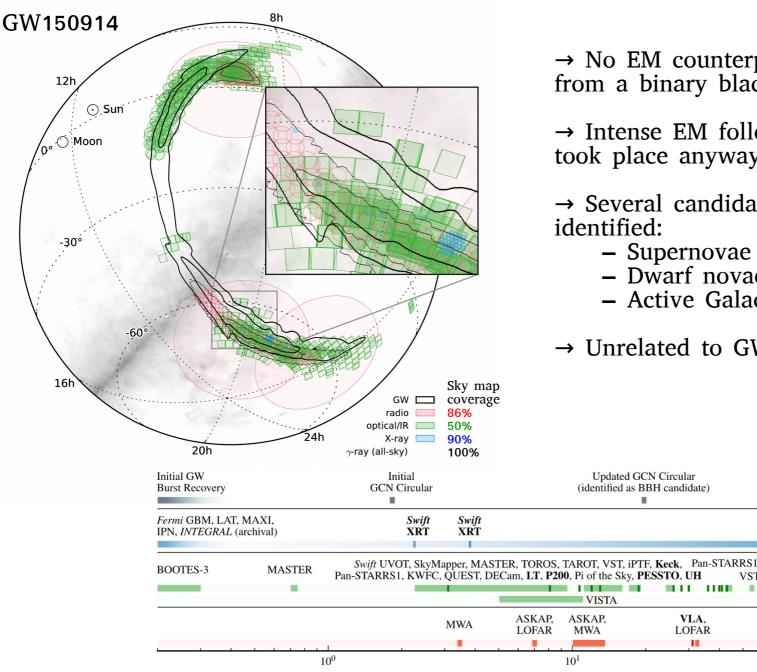




18

# EM follow-up

 $t - t_{\text{merger}}$  (days)



 $\rightarrow$  No EM counterpart is expected from a binary black hole merger

 $\rightarrow$  Intense EM follow-up campaign took place anyway

 $\rightarrow$  Several candidate counterparts were

- Supernovae population
- Dwarf novae
- Active Galactic Nucleus (AGN)

Final

sky map

MAXI

Fermi LAT.

TOROS

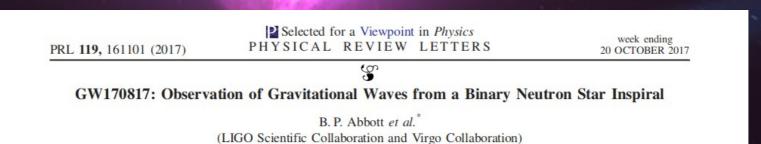
VLA, LOFAR VLA

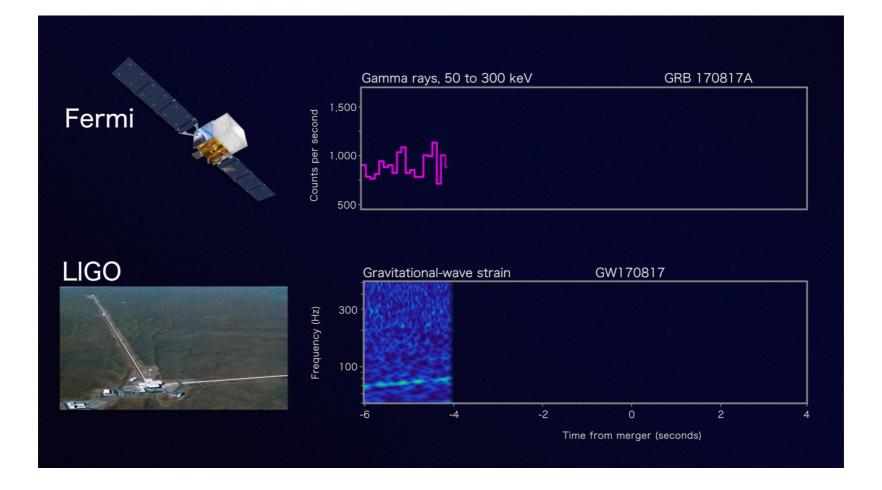
 $10^{2}$ 

VST

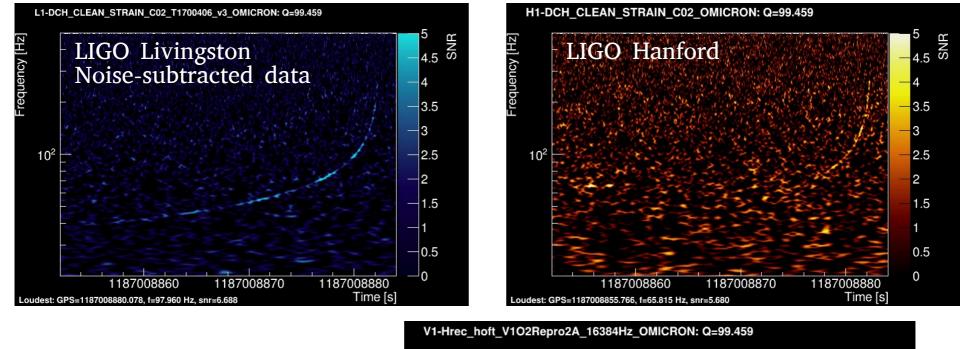
 $\rightarrow$  Unrelated to GW events

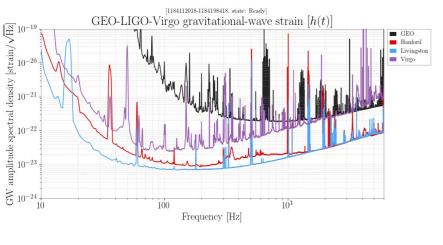
# 2017, Aug. 17

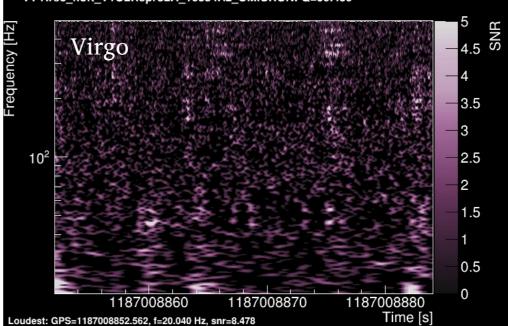




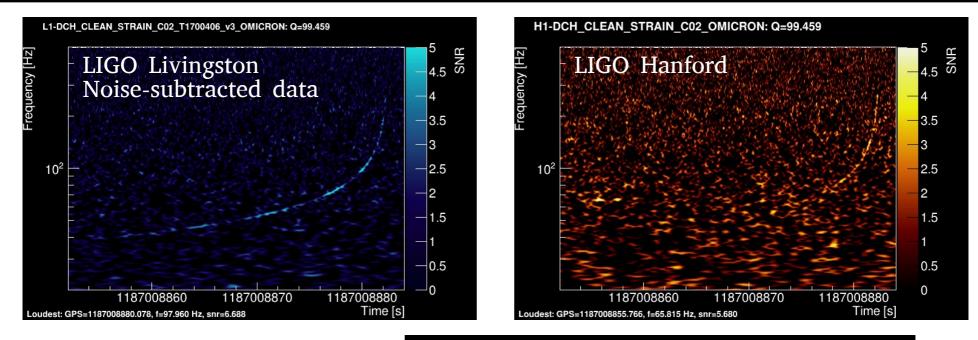
### GW detection







## GW detection

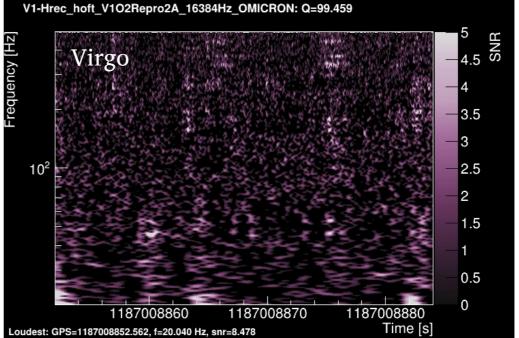


SNR  $\rightarrow$  26.4 (LIGO Livingston)  $\rightarrow$  18.8 (LIGO Hanford)  $\rightarrow$  2.0 (Virgo)

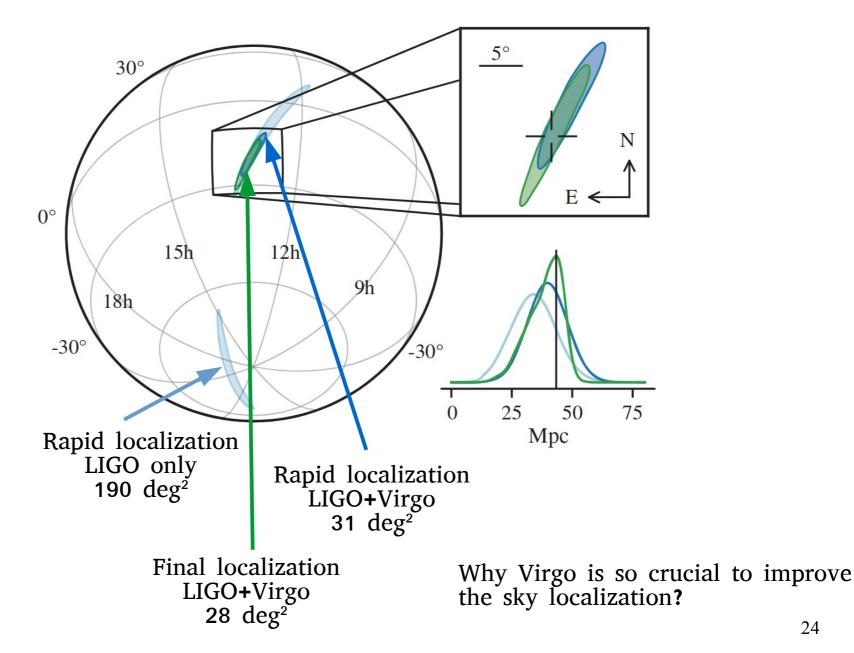
Combined SNR 32.4

False-alarm rate 10<sup>-6</sup>/year

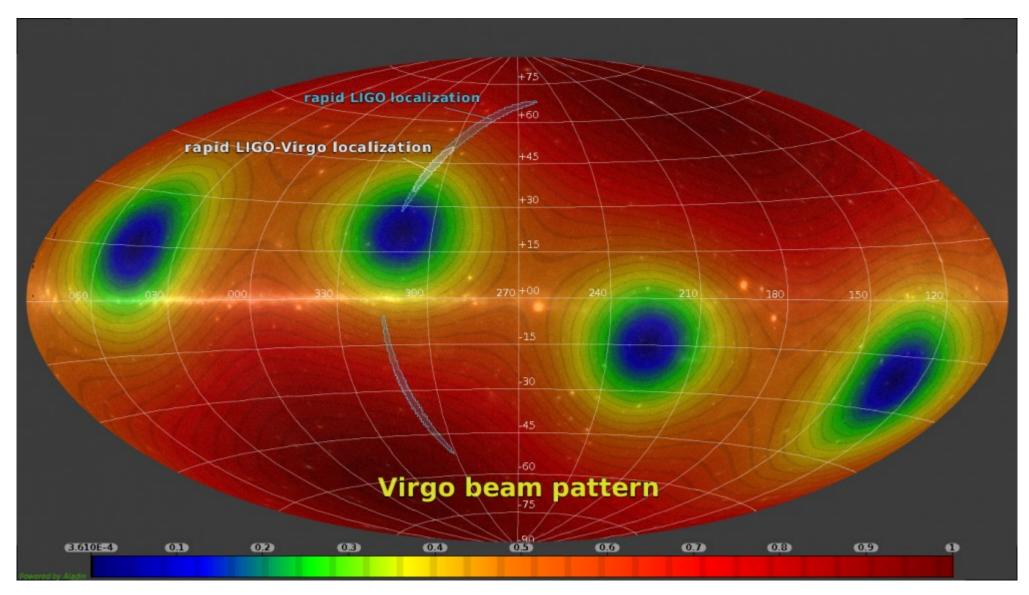
Long event in the data  $\sim 100 \text{ s}$ 



### GW sky localization



### Virgo beam pattern

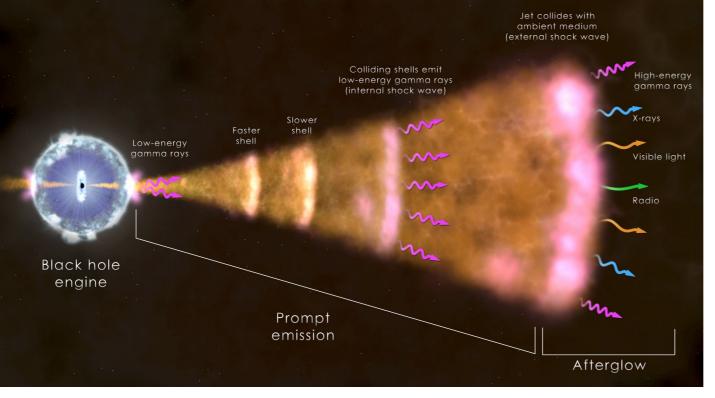


# GW170817: final parameters

	Low-spin priors $( \chi  \le 0.05)$	High-spin priors $( \chi  \le 0.89)$
Primary mass $m_1$	$1.36-1.60 M_{\odot}$	$1.36-2.26 \ M_{\odot}$
Secondary mass $m_2$	$1.17 - 1.36 M_{\odot}$	$0.86 - 1.36 M_{\odot}$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_{\odot}$	$1.188^{+0.004}_{-0.002} M_{\odot}$
Mass ratio $m_2/m_1$	0.7–1.0	0.4–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}M_{\odot}$	$2.82^{+0.47}_{-0.09} M_{\odot}$
Radiated energy $E_{\rm rad}$	$> 0.025 M_{\odot}c^{2}$	$> 0.025 M_{\odot}c^{2}$
Luminosity distance $D_{\rm L}$	$40^{+8}_{-14}$ Mpc	$40^{+8}_{-14}$ Mpc
Viewing angle $\Theta$	≤ 55°	$\leq 56^{\circ}$
Using NGC 4993 location	$\leq 28^{\circ}$	$\leq 28^{\circ}$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	$\leq 800$	$\leq 700$
Dimensionless tidal deformability $\Lambda(1.4M_{\odot})$	$\leq 800$	$\leq 1400$

- $\rightarrow$  Can we claim we are dealing with 2 neutron stars?
- $\rightarrow$  Why 2 spin hypotheses?
- $\rightarrow$  Why is the uncertainty better for a low-spin system?
- $\rightarrow$  Why is the distance  $\sim 1$  order magnitude lower than for black holes?

### Gamma ray burst

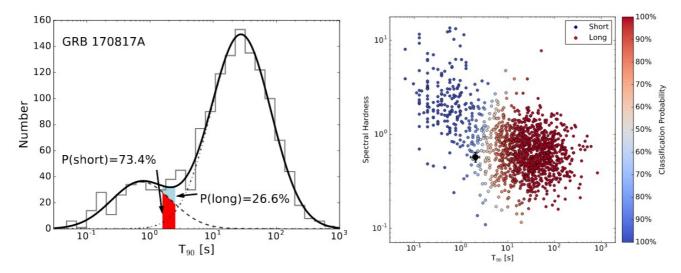


→ Brightest electromagnetic events in the Universe

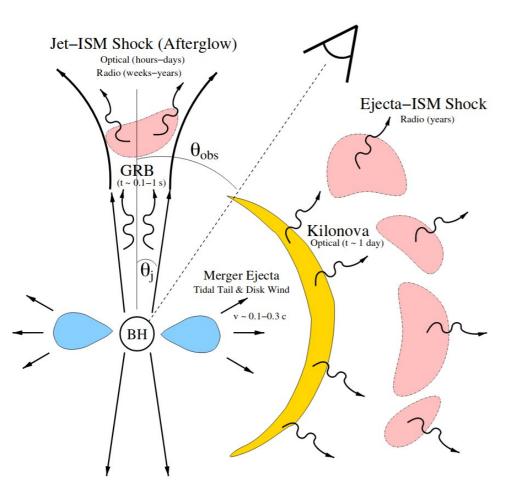
→ prompt emission: a few milliseconds to a few hours → afterglow in all wavelengths for months

→ progenitors: binary neutron star merger (short) or massive star collapse (long)

→ We detect ~1 GRB every day



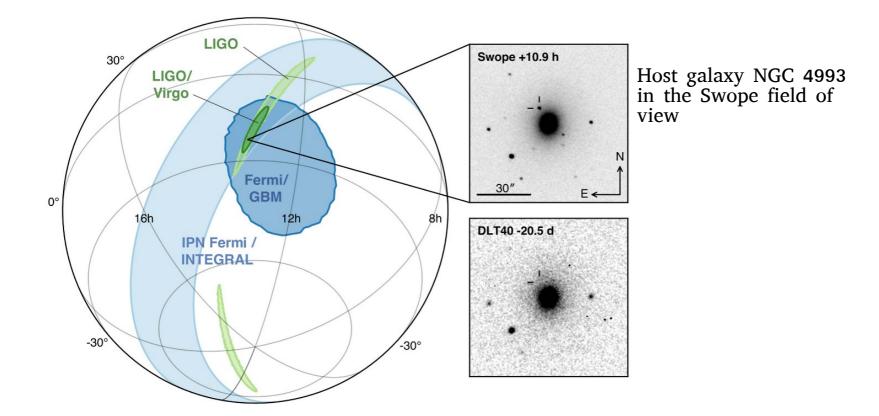
### EM emission



- $\rightarrow$  Merger (GW)
- $\rightarrow$  Rapid acretion (<1s)
- → Collimated relativistic jet
- $\rightarrow$  Short-duration GRB
- $\rightarrow$  Afterglow (interaction of the jet with circum-burst medium)
- → Kilonova

 $\rightarrow$  EM follow-up in every wavelengths and over a long time

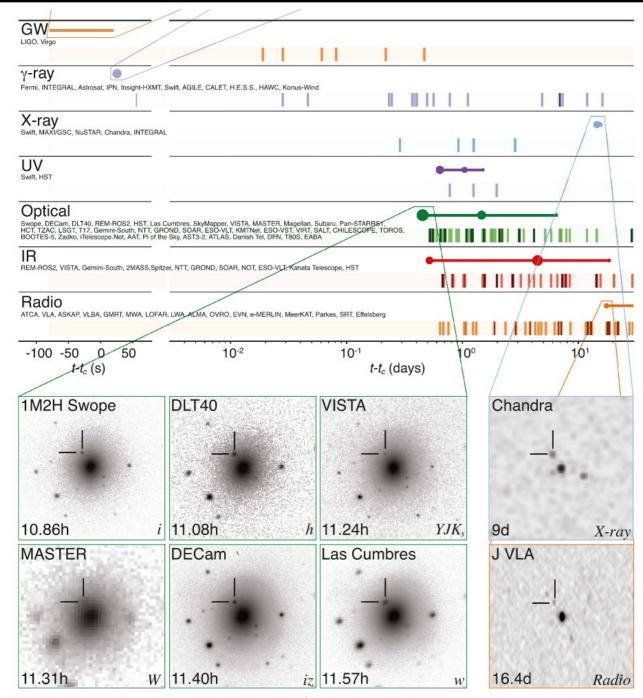
## 2017, Aug. 17



The discovery of an optical transient has been reported by 6teams:

- 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)

## EM follow-up sequence

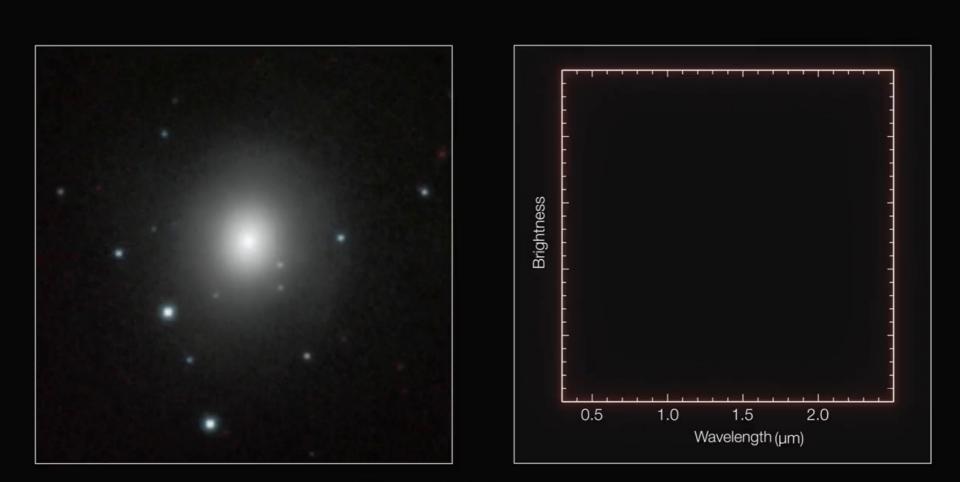


T0 = GW detection +1.7s: Gamma ray burst detected by Fermi

### +40 min: GW alert is sent

+9 d: detection of an X-ray counterpart+16 d: detection of a radio counterpart

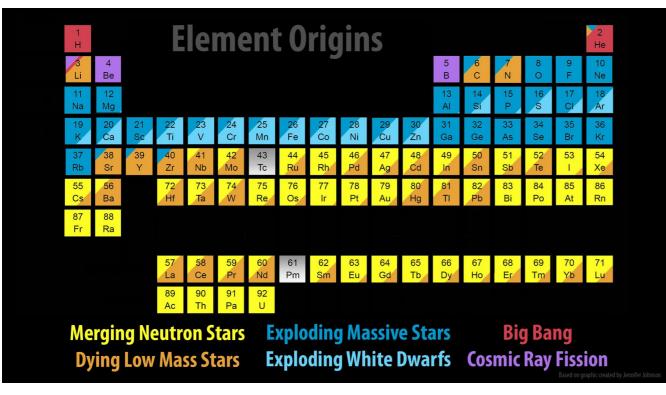
### Spectrum measurement

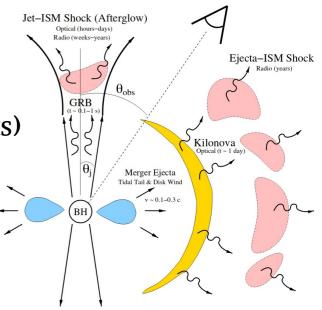


Time: -1225 days

## Kilonova

- $\rightarrow$  Concept introduced in 2010 by Metzger et al.
- $\rightarrow$  Main source of r-process nuclei (heavy elements)
- $\rightarrow$  First kilonova ever detected!



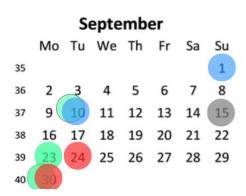


## GW170817



### 03

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	Mo 6 13	Tu 7 14	M	ay				22			Ju	ne	Fr 7 14	Sa 1 8 15	Su 2 9 16	27			Ju We	<b>ly</b> Th				Mo 5 12		-		Fr 2	3 10	4
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 $\rightarrow$  In O3, GW candidates are publicly and automatically released a few minutes after the detection

- $\rightarrow$  Sky maps and the source category are provided
- $\rightarrow$  Astronomers choose (or not) to follow-up the candidates

April

### Conclusions

 $\rightarrow$  The detection of gravitational waves has offered a new channel for multimessenger astronomy

 $\rightarrow$  First multi-messenger GW-EM event detected in 2017

 $\rightarrow$  Rich science can be accomplished

→ LIGO-Virgo O3 run started in April 2019 with improved sensitivities and will last  $\sim$ 1 year

- $\rightarrow$  What's next?
  - $\rightarrow$  new GW detectors will join the network (KAGRA, LIGO India)
  - $\rightarrow$  next generation of GW detectors is in preparation
    - Advanced LIGO and Virgo + (~2025)
    - LISA space interferometer (~2030)
    - Einstein telescope and cosmic explorer (>2030)