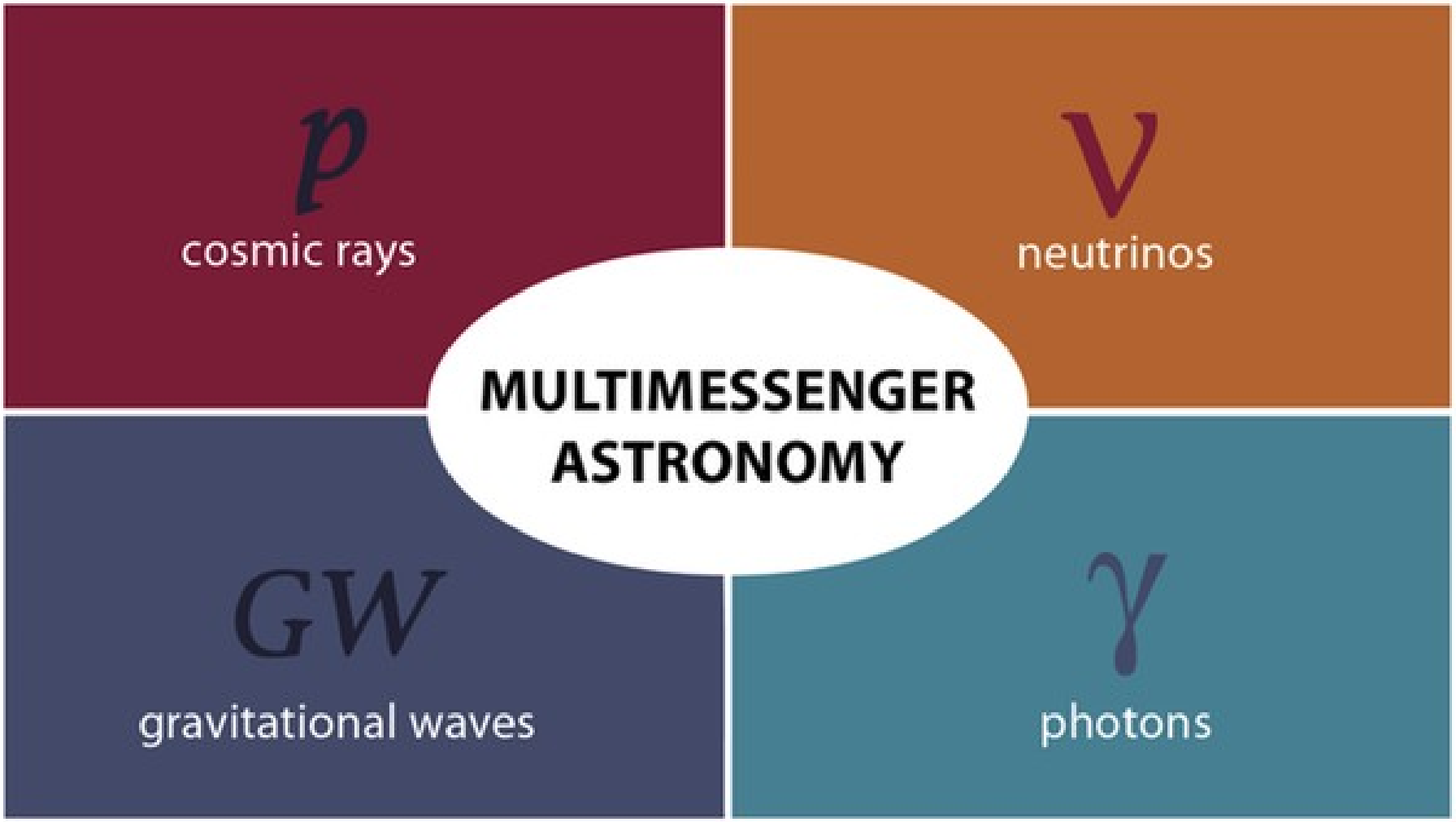
WISHEPP
4th Winter School in HEP
November 9-15, 2019
An-Najah N. University, Nablus, Palestine

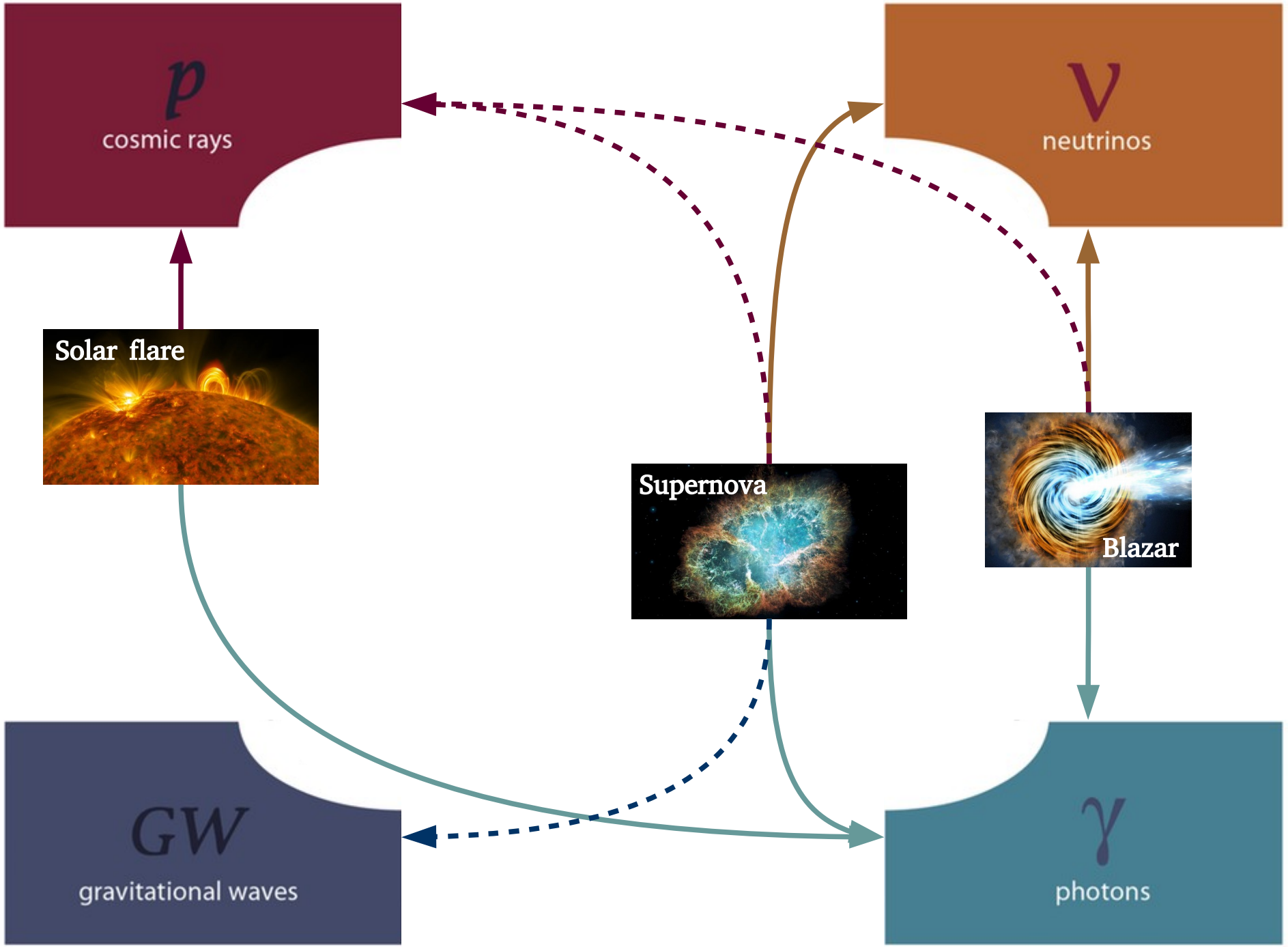
Multi-messenger astronomy

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

Florent Robinet
Laboratoire de l'Accélérateur Linéaire
robinet@lal.in2p3.fr


p
cosmic rays
ν
neutrinos
MULTIMESSENGER
ASTRONOMY
GW
gravitational waves
γ
photons

Use multiple and complementary channels
to study astrophysical objects


p
cosmic rays
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Solar flare
Supernova
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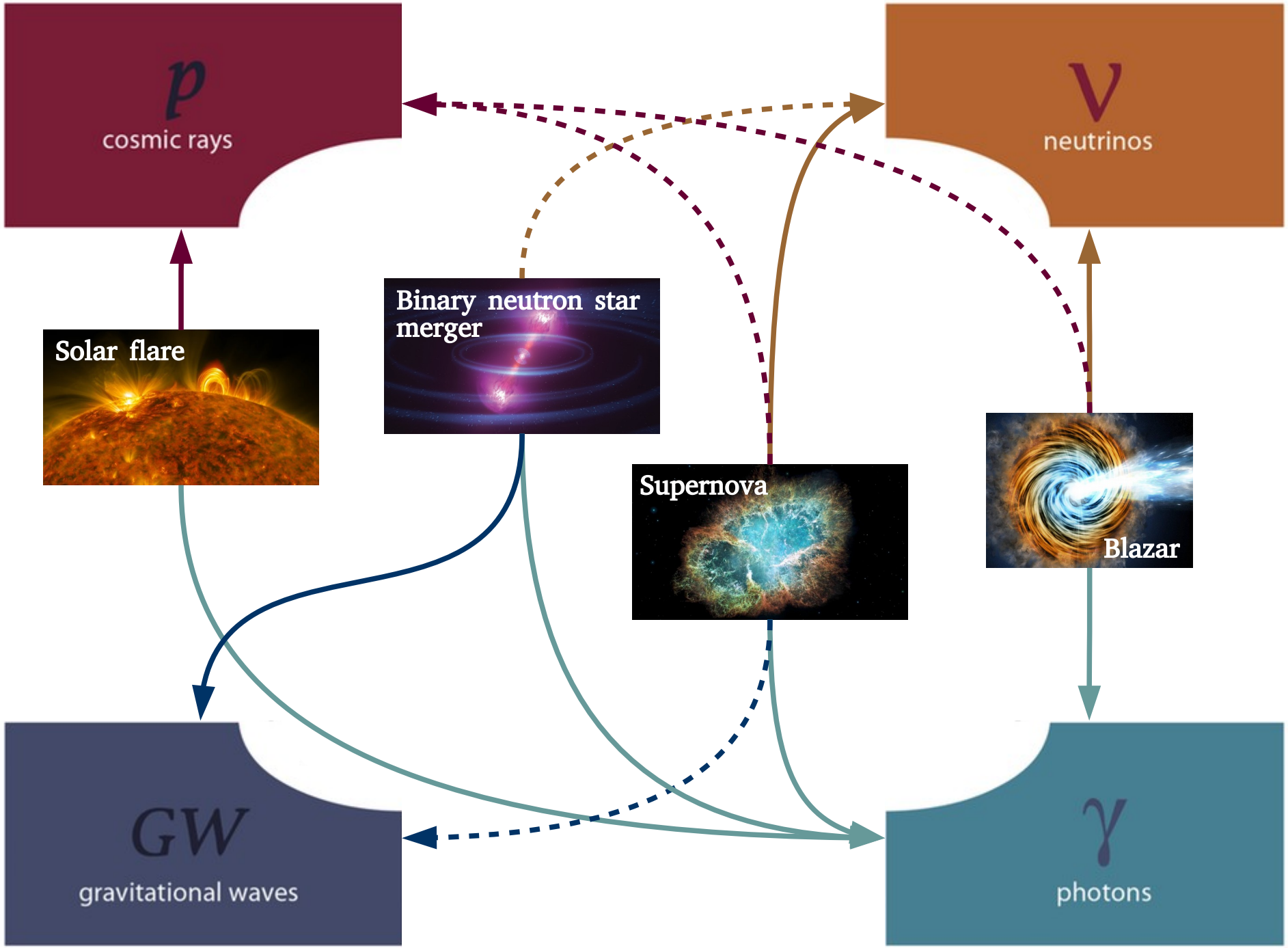
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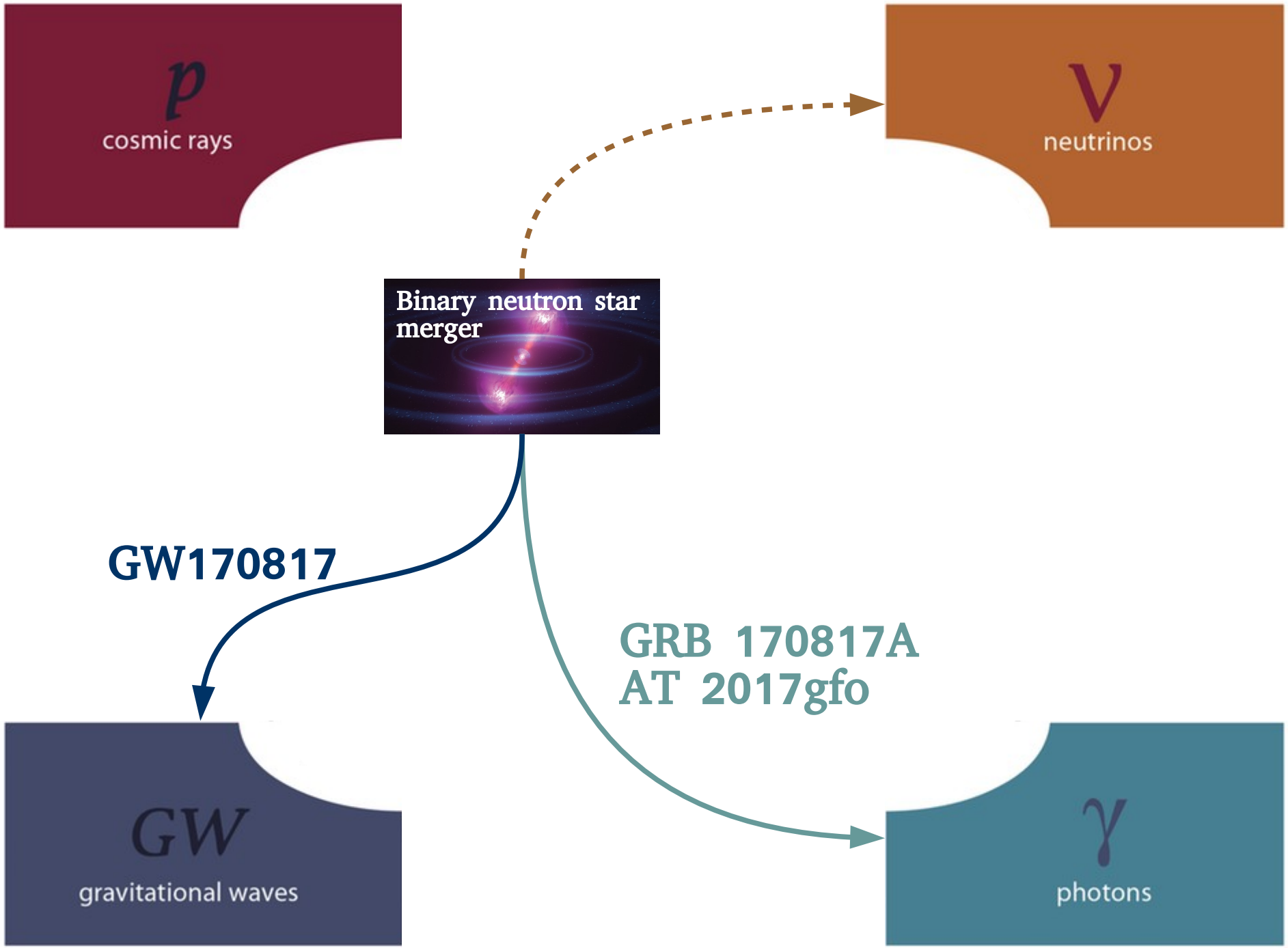
p
cosmic rays
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Binary neutron star merger
GW170817
GRB 170817A
AT 2017gfo
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Gravitational waves

→ mass
→ spin
→ eccentricity
→ system orientations
→ luminosity distance
→ rate of CBC events
→ internal physics

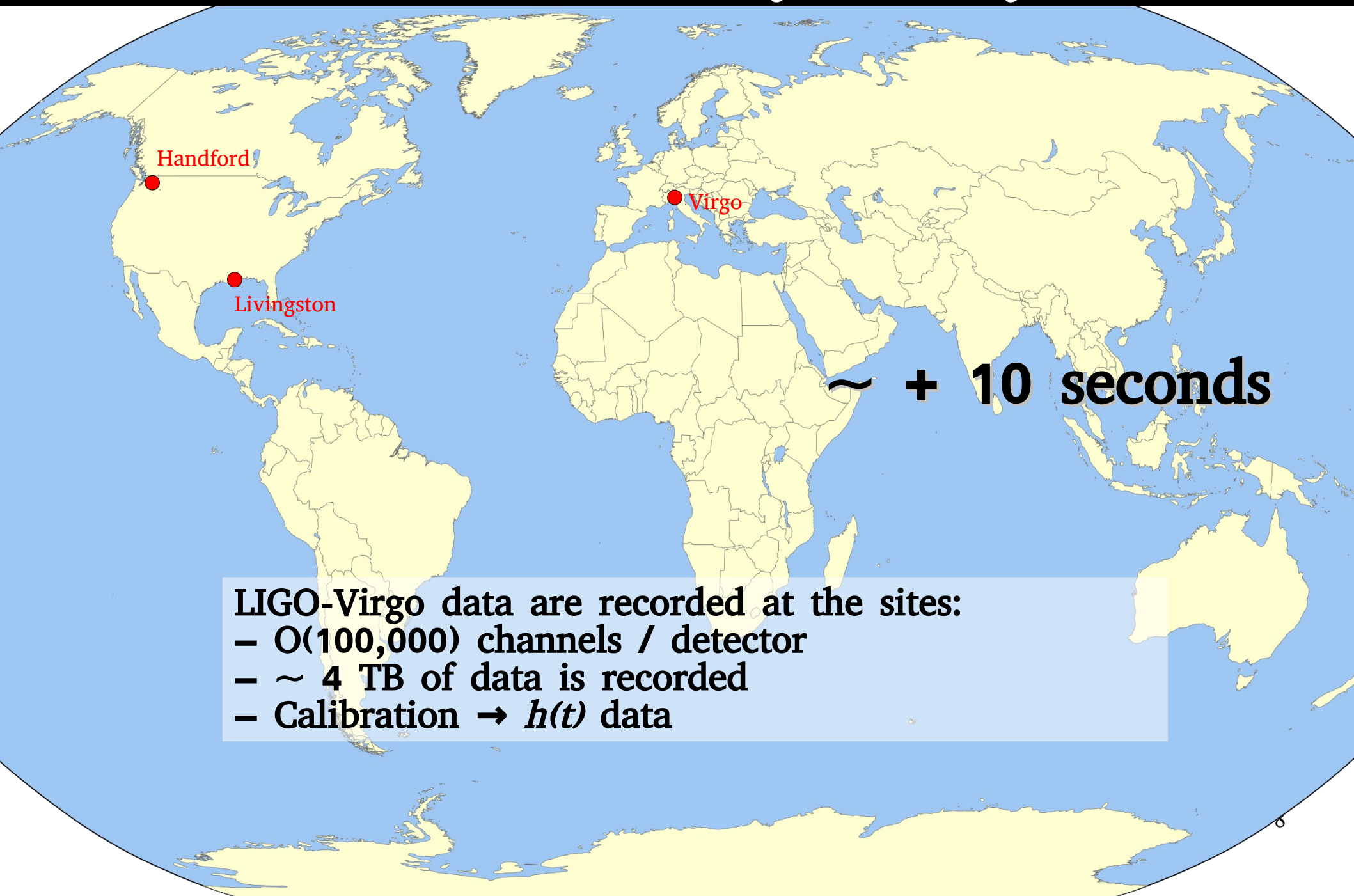
Photons

→ precise sky location (~arcsec)
→ host galaxy
→ redshift
→ local environment
→ emission processes
→ acceleration mechanisms
→ internal physics

GW170817

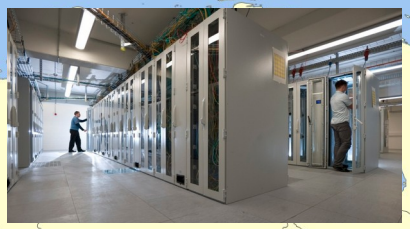
GRB 170817A
AT 2017gfo

GW low-latency analysis



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

GW low-latency analysis



Handford

Hannover

Virgo

Caltech

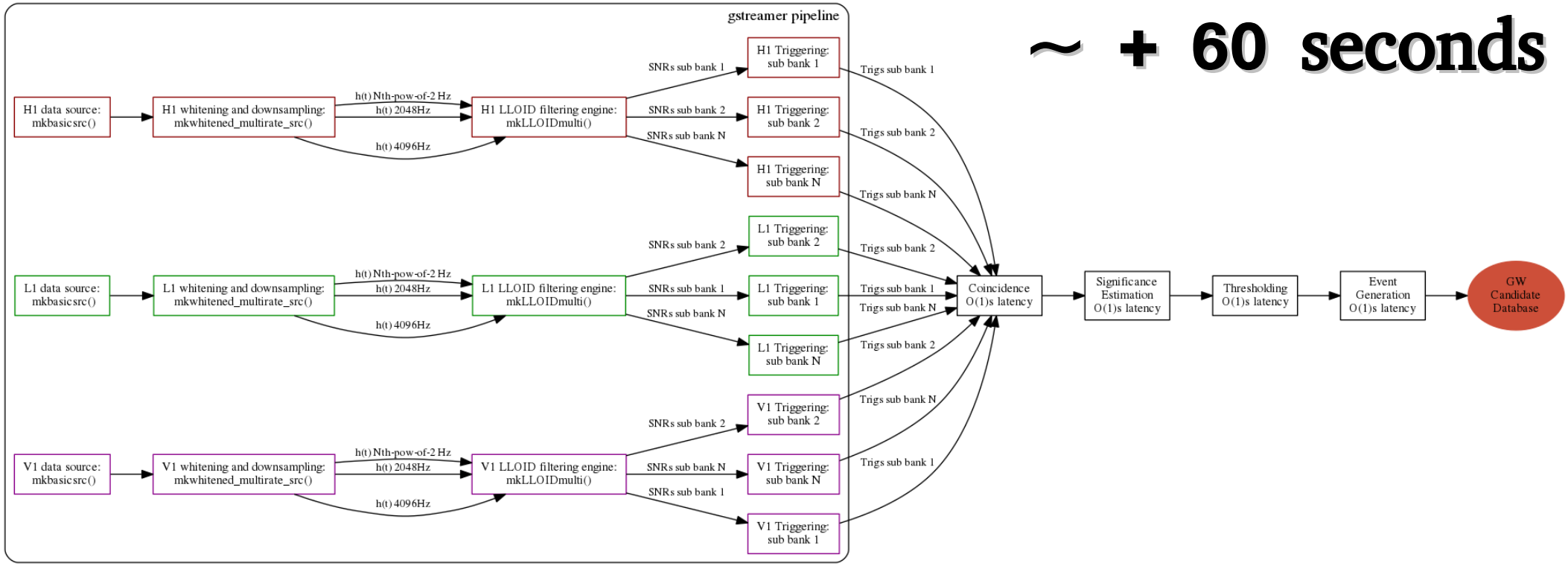
Livingston

~ + 1 second

LIGO-Virgo data are transfered to computing centers:
- **Caltech, USA**
- **Virgo, Italy**
- **Hannover, Germany**

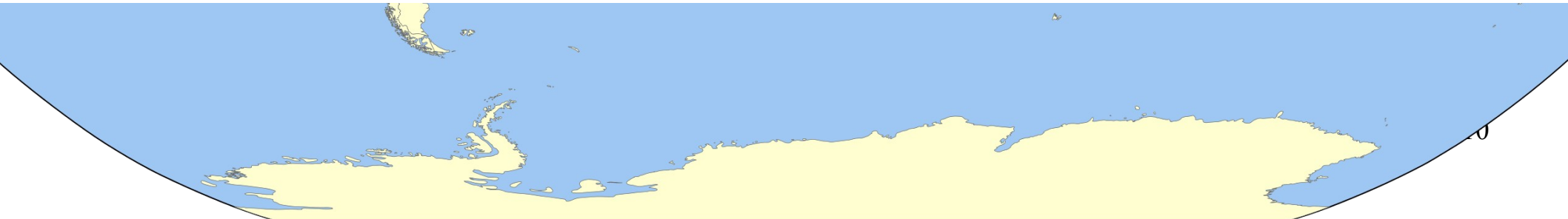
→ Low-latency searches are conducted

GW low-latency analysis



~ + 60 seconds

gstlal_inspiral



Candidate database

GraceDB — Gravitational Wave Candidate Event Database

GW151226

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: FLORENT ROBINET

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	Links	UTC Submitted
G211117	H1OK L1OK ADVOK EM_READY	CBC	gstlal	HighMass	H1,L1	2015-12-26 03:38:53 UTC	3.333e-11	Data	2015-12-26 03:40:00 UTC

Coinc Tables

End Time (GPS)	1135136350.6478 s
Total Mass	26.3501 $M_\odot$
Chirp Mass	9.5548 $M_\odot$
SNR	11.7103
False Alarm Probability	1.120e-04
Log Likelihood Ratio	22.5996

Single Inspiral Tables

IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
Template Duration	2.25322770554 s	2.25322770554 s
Effective Distance	472.93436 Mpc	461.88879 Mpc
COA Phase	2.7356486 rad	0.13969257 rad
Mass 1	19.924686 $M_\odot$	19.924686 $M_\odot$
Mass 2	6.4254546 $M_\odot$	6.4254546 $M_\odot$
η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
SNR	7.3947201	9.0802174
χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G211182		Burst	CWB2G	AllSky	H1,L1	1135136350.6291	-0.018658		Data	2015-12-26 09:44:37 UTC
G211115		CBC	gstlal	HighMass	H1,L1	1135136350.6405	-0.007229	1.032e-09	Data	2015-12-26 03:39:59 UTC
G211118		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
G216856		CBC	gstlal	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

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modeled search

+1 min

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physical parameters (preliminary)

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GW151226

FAR ~ 950 yr-1

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modeled search

+1 min

Coinc Tables

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FAR ~ 950 yr-1

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+1 min

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multiple detections over time

Human Vetting

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→ Preliminary GCN notice is issued

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

→ Virtual meeting with many people
- detector control rooms
- detector experts
- run coordinators
- detector characterization experts
- search pipeline managers
- calibration experts

→ The gravitational-wave candidate is scrutinized:
- data quality
- detector status
- event preliminary parameters
- first sky map

→ GCN notice is updated

```
//////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  18728
SUBJECT: LIGO/Virgo G211117: Identification of a GW CBC Candidate
DATE:    15/12/27 17:39:45 GMT
FROM:    Leo Singer at NASA/GSFC  <leo.p.singer@nasa.gov>

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
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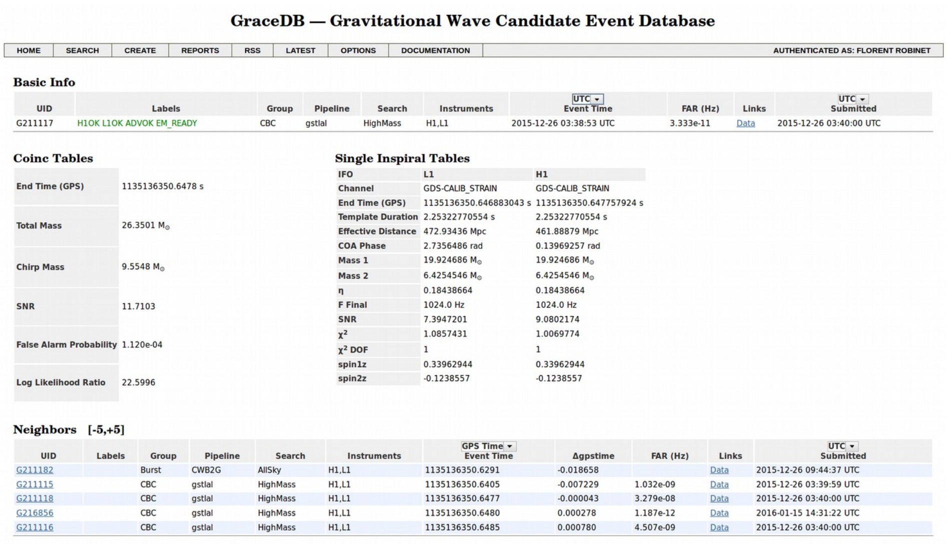
Human Vetting



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PUBLIC ALERTS IN O3

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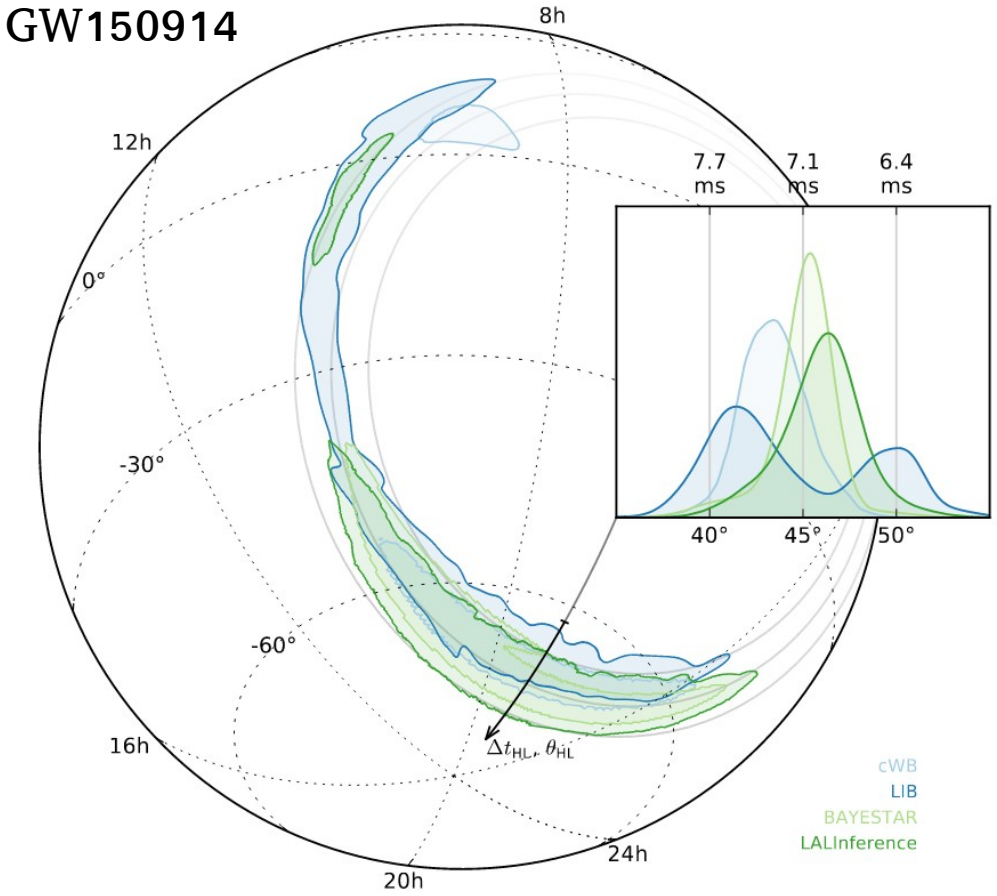
Sky maps



~1 minute
Preliminary parameter estimation given by the search pipeline:
- source parameters (template)
- rough sky position

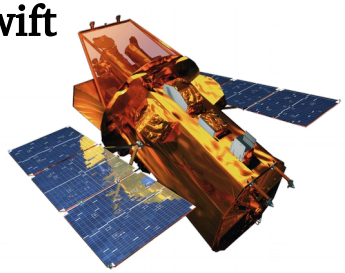
~ a few minutes
Rapid analysis for parameter estimation (*BAYESTAR*)

~ hours/days
Full (and final) parameter estimation analysis (*LALInference*)

→ Notices are sent whenever a sky map is updated

EM follow-up

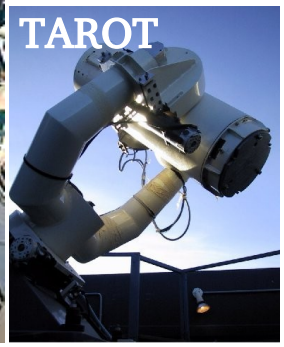
Swift



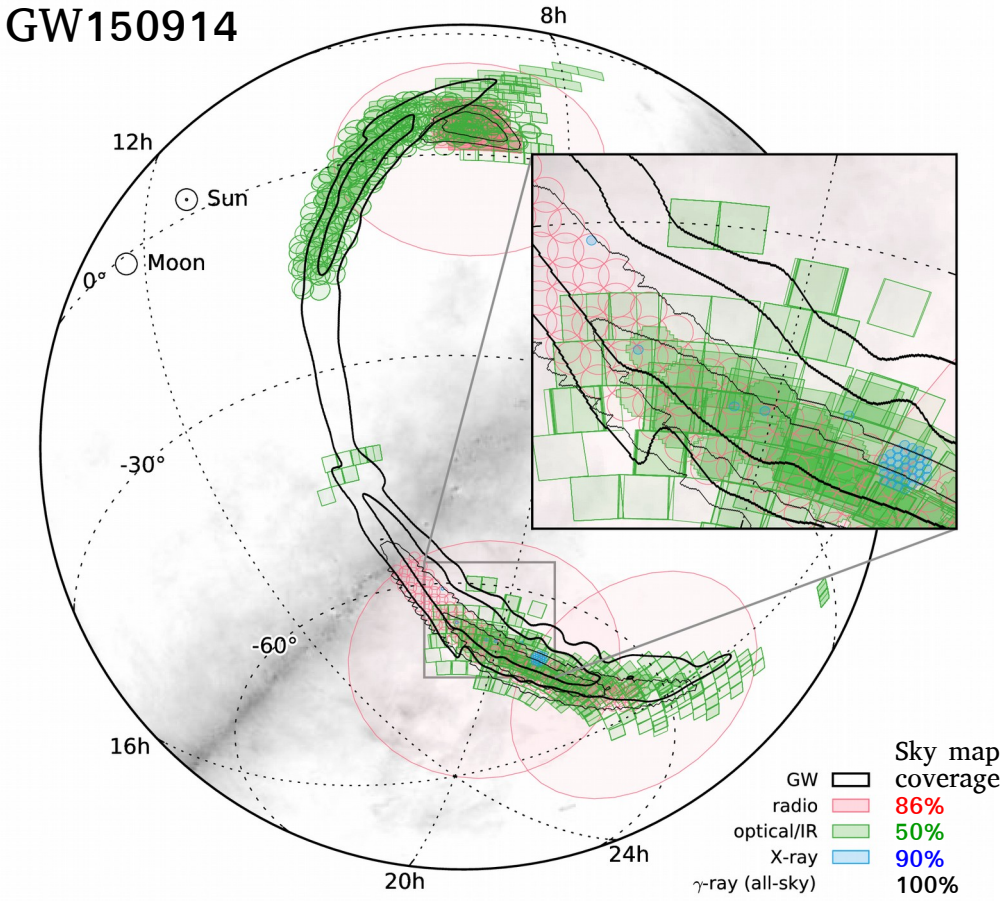
Fermi

Integral

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



EM follow-up



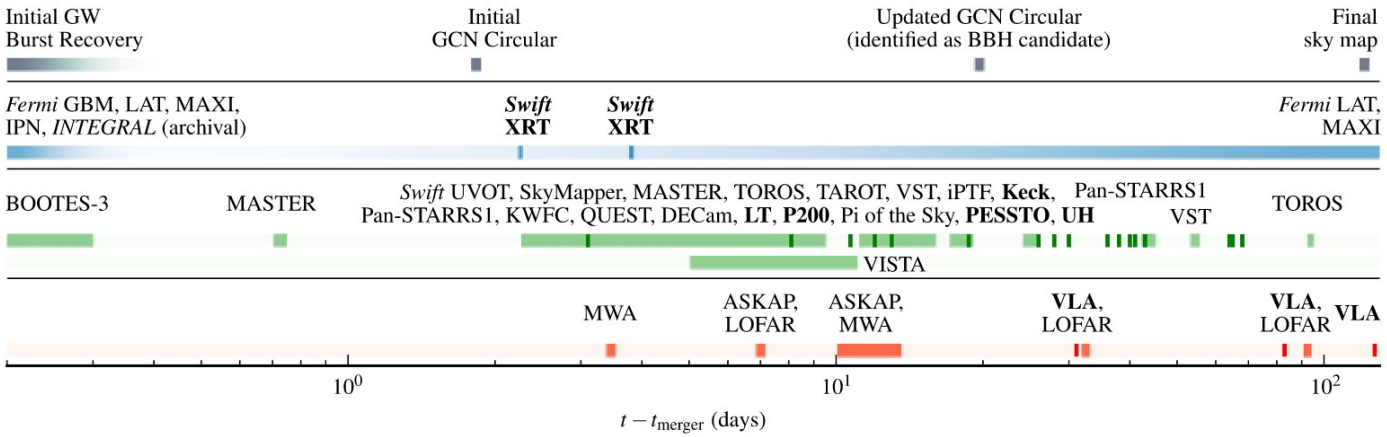
→ No EM counterpart is expected from a binary black hole merger

→ Intense EM follow-up campaign took place anyway

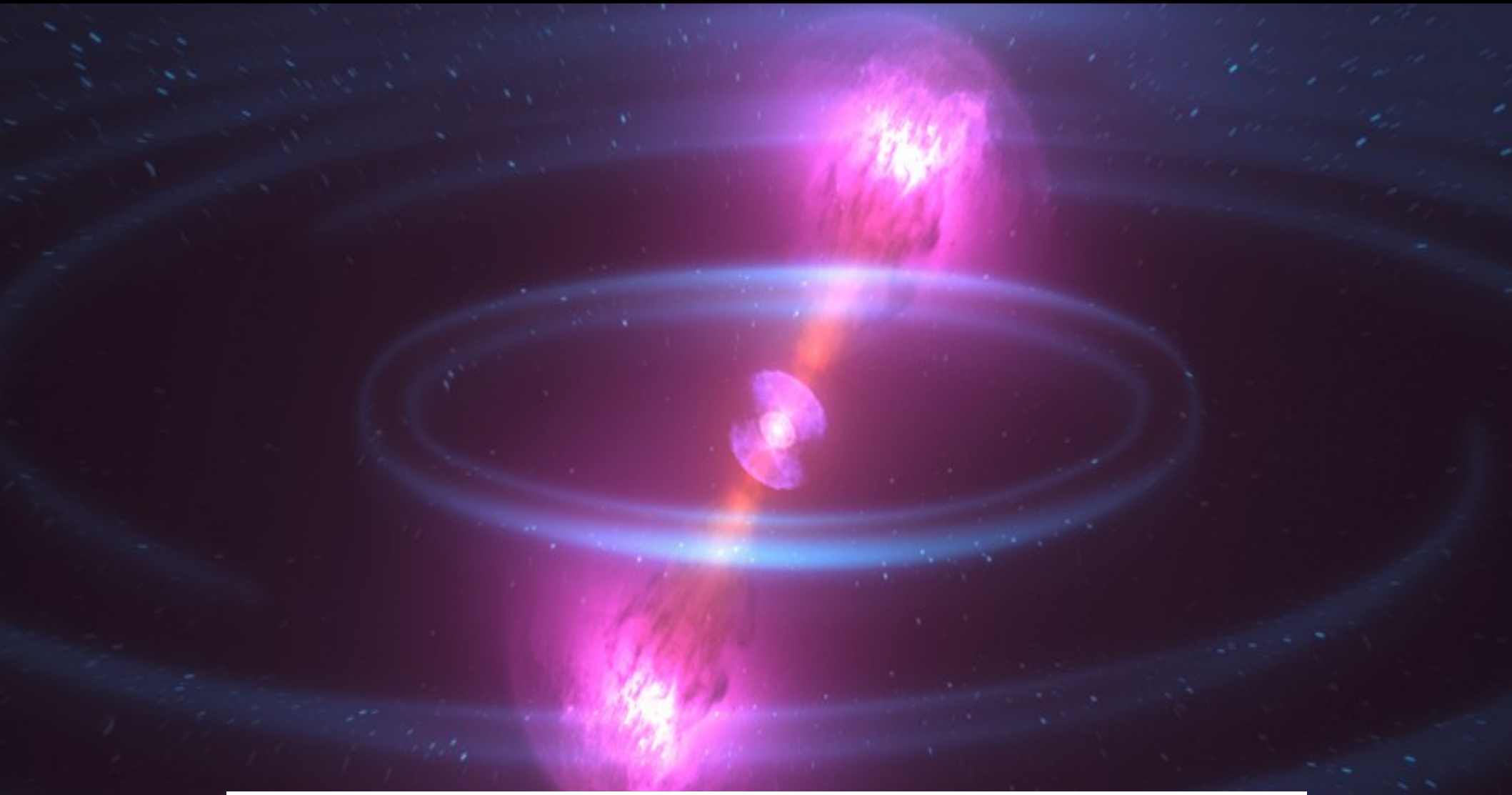
→ Several candidate counterparts were identified:

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

→ Unrelated to GW events



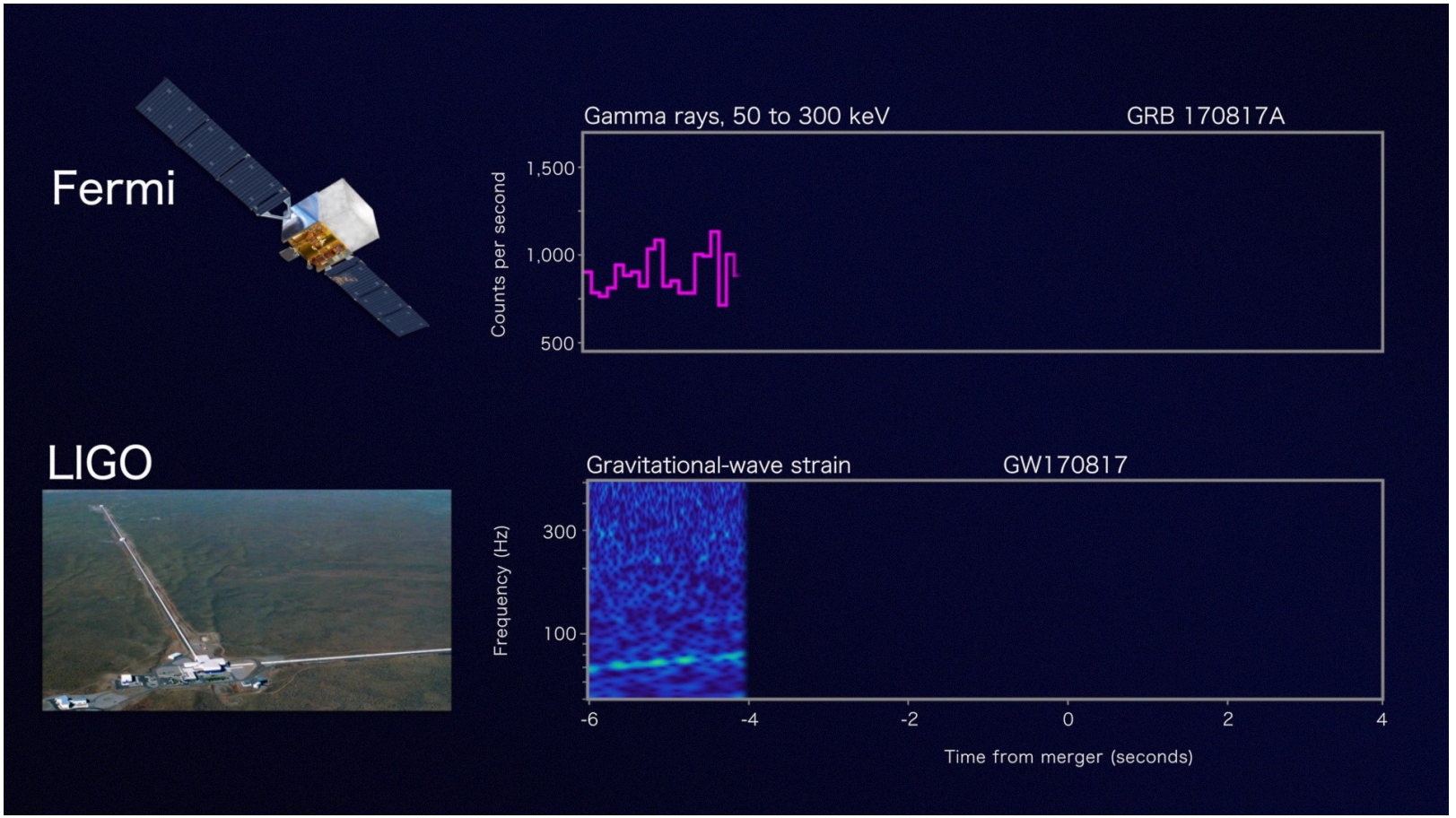
2017, Aug. 17



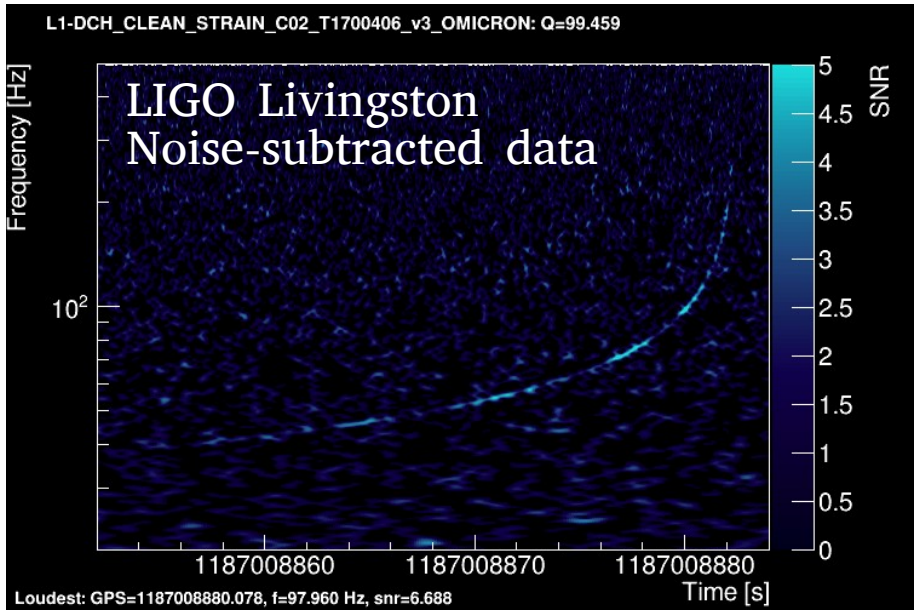
PRL 119, 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

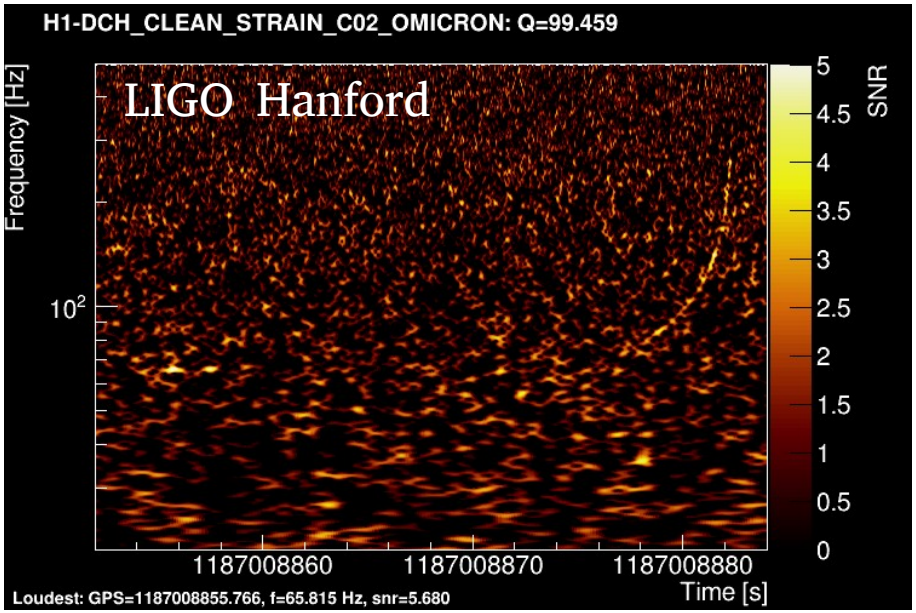
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

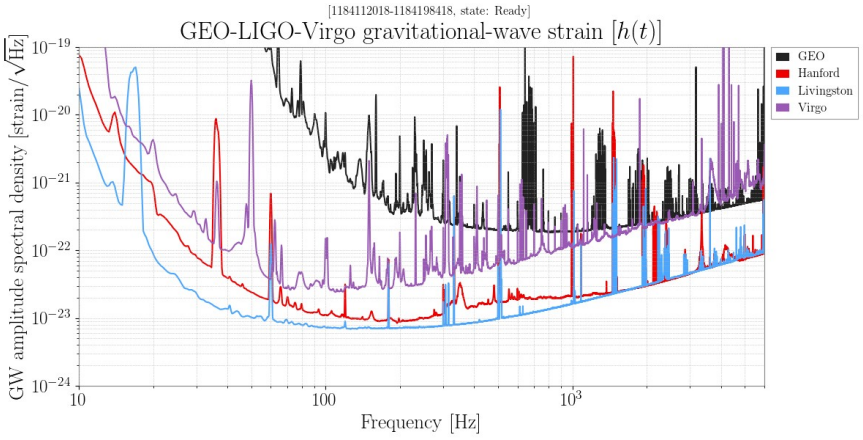
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)

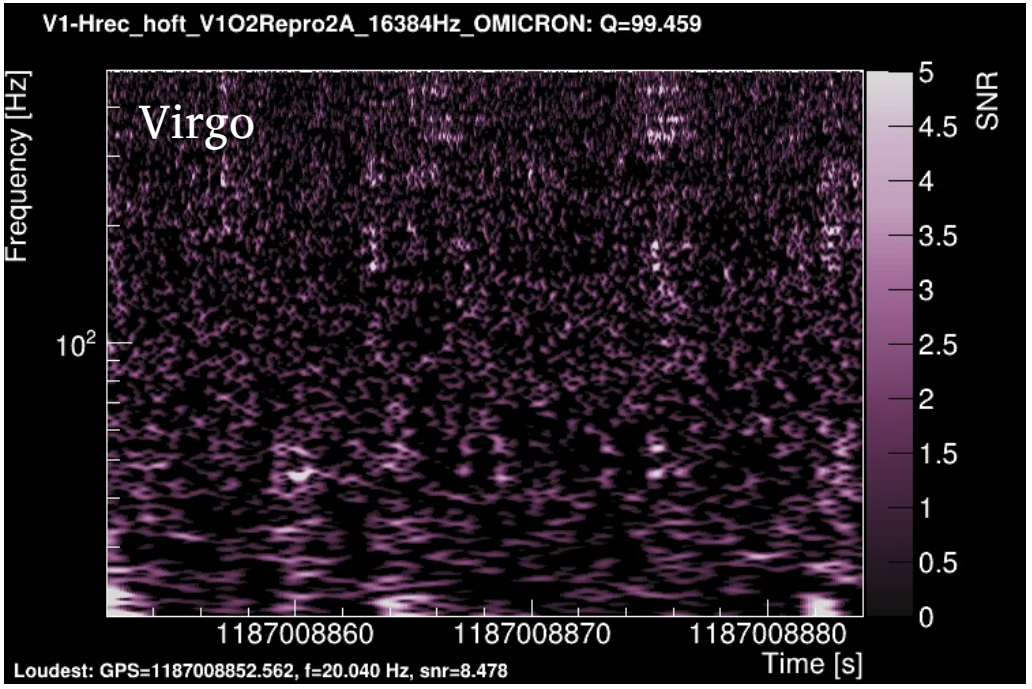

Fermi
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
500
LIGO
Gravitational-wave strain
GW170817
Frequency (Hz)
300
100
-6
-4
-2
0
2
4
Time from merger (seconds)

GW detection

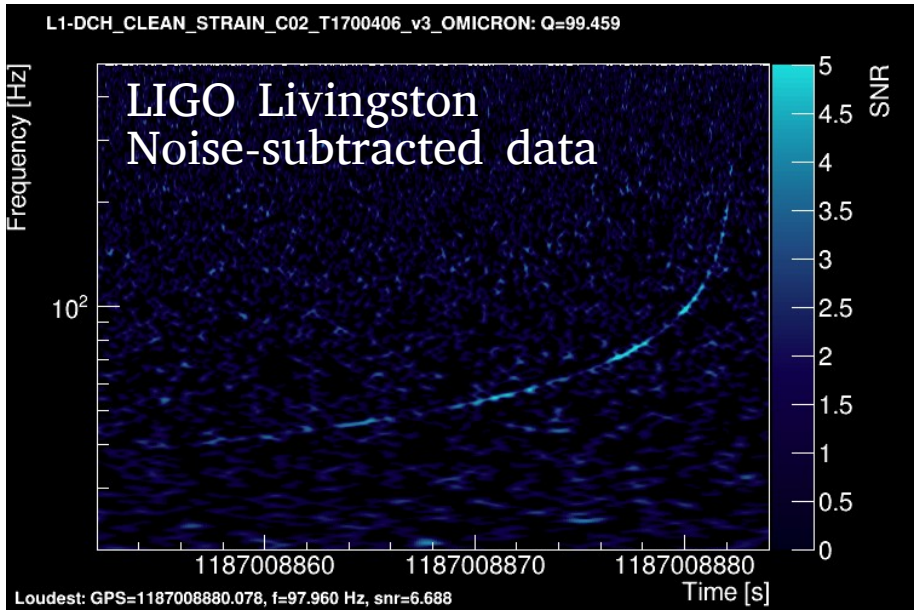


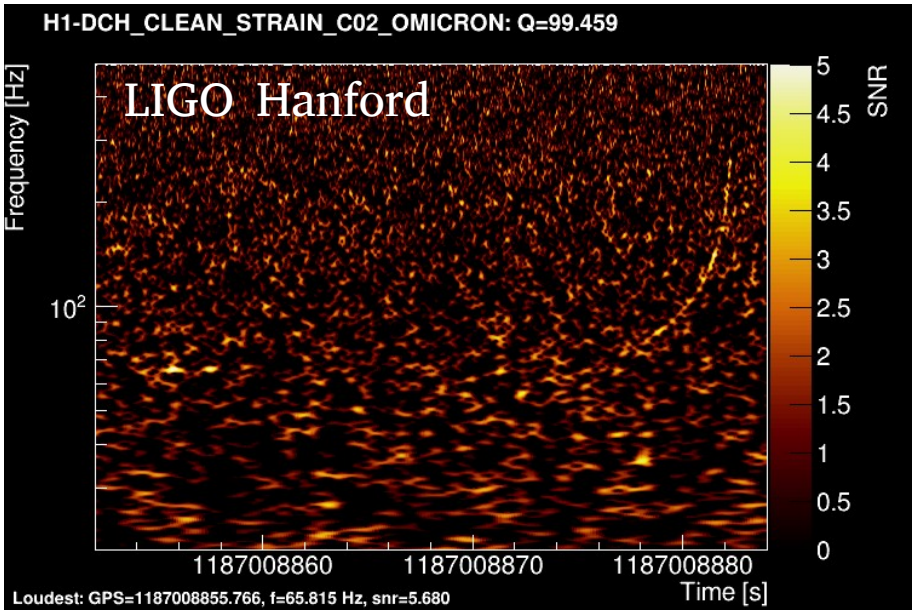






GW detection



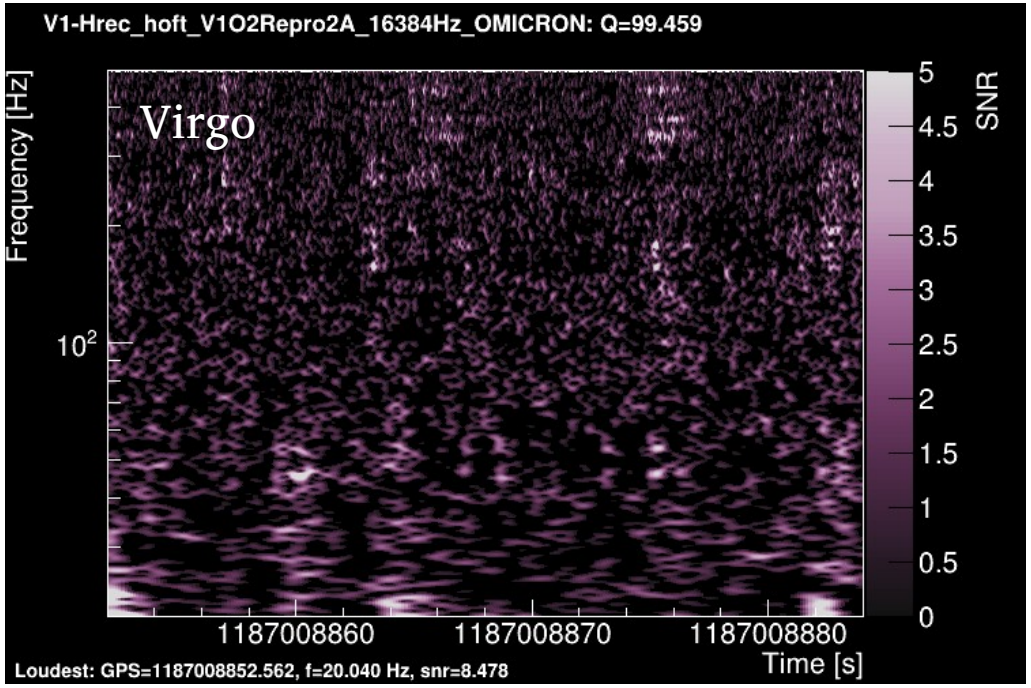


SNR
→ 26.4 (LIGO Livingston)
→ 18.8 (LIGO Hanford)
→ 2.0 (Virgo)

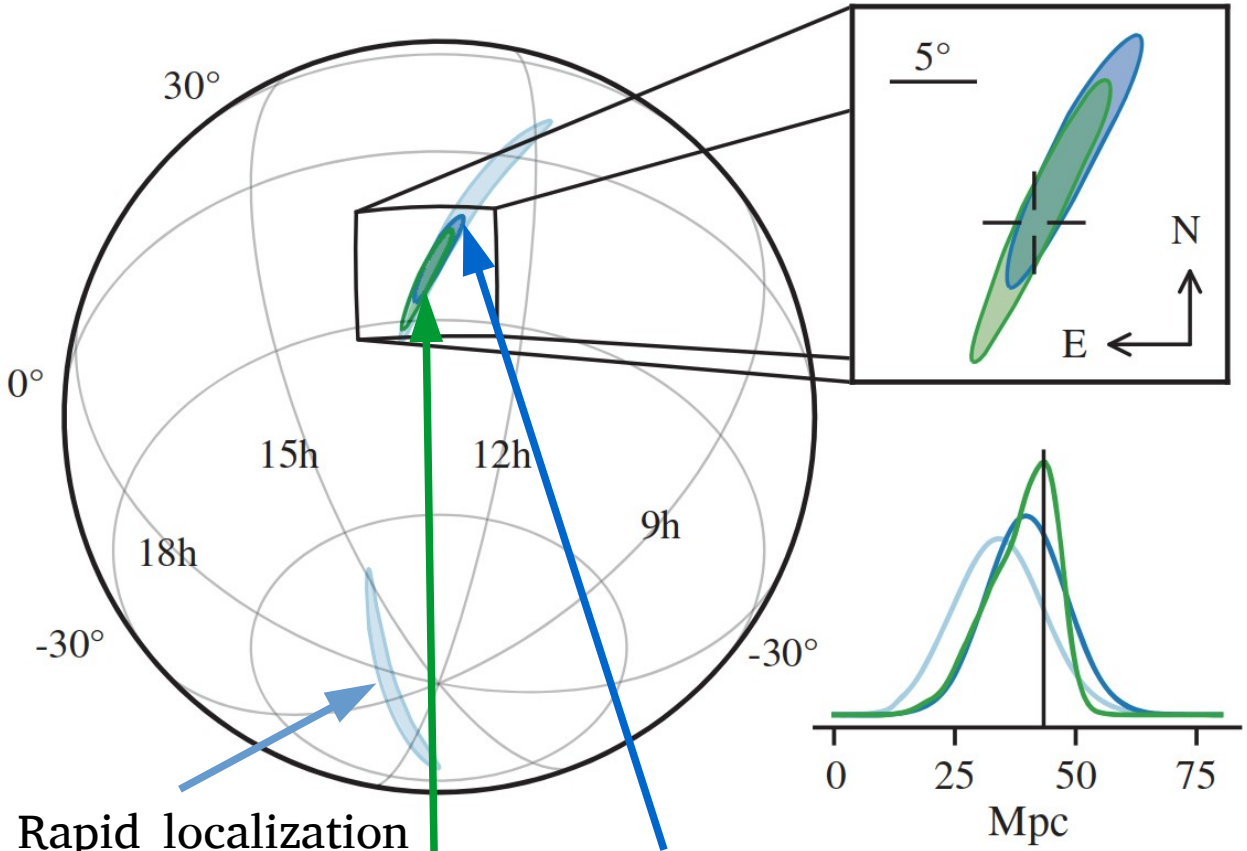
Combined SNR
32.4

False-alarm rate
10^{-6}/year

Long event in the data
~100 s



GW sky localization



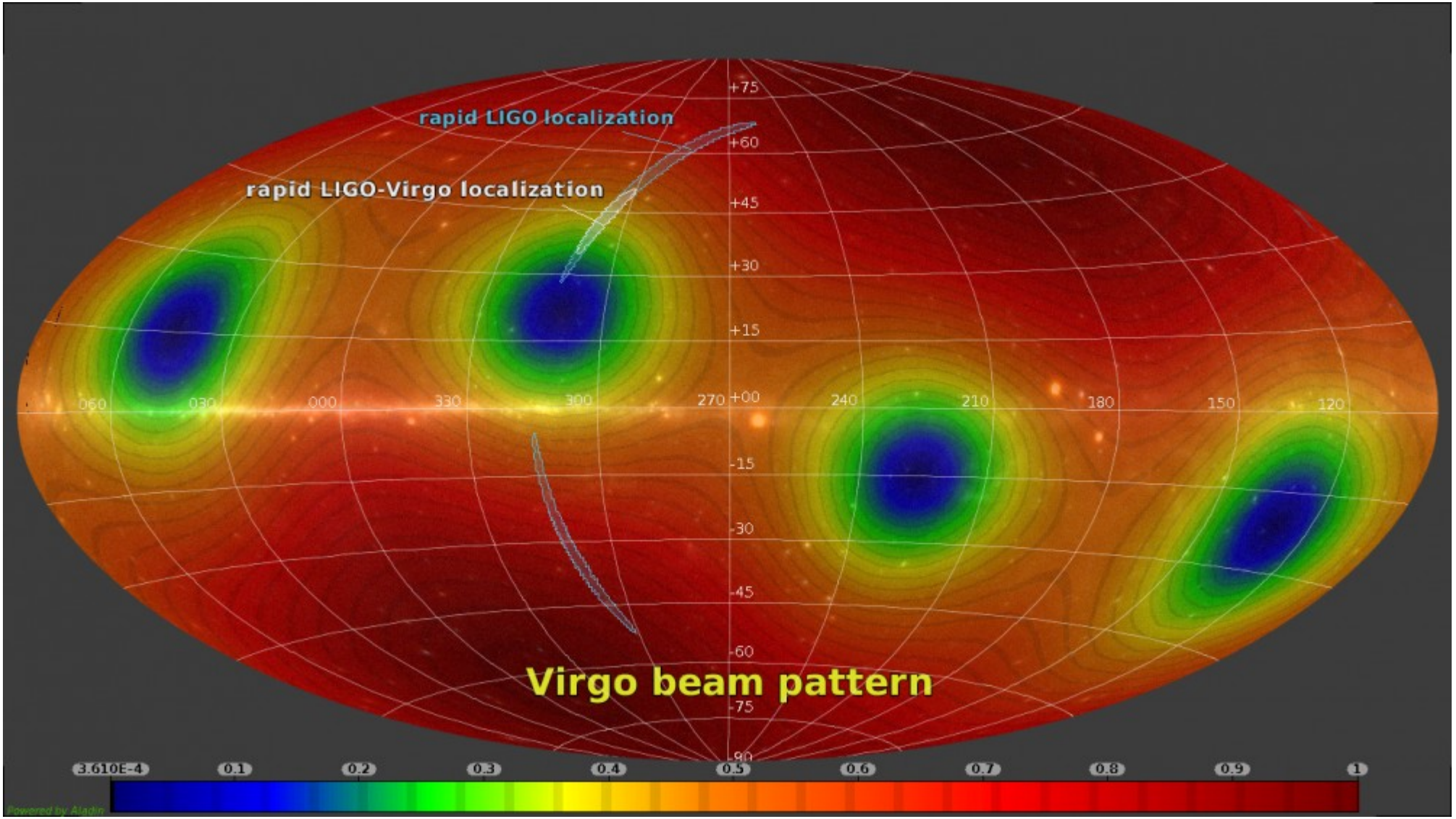
Rapid localization
LIGO only
190 deg²

Rapid localization
LIGO+Virgo
31 deg²

Final localization
LIGO+Virgo
28 deg²

Why Virgo is so crucial to improve the sky localization?

Virgo beam pattern



GW170817: final parameters

	Low-spin priors ($\lvert\chi\rvert \leq 0.05$)	High-spin priors ($\lvert\chi\rvert \leq 0.89$)
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 Θ	$\leq 55°$	$\leq 56°$
Using NGC 4993 location	$\leq 28°$	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

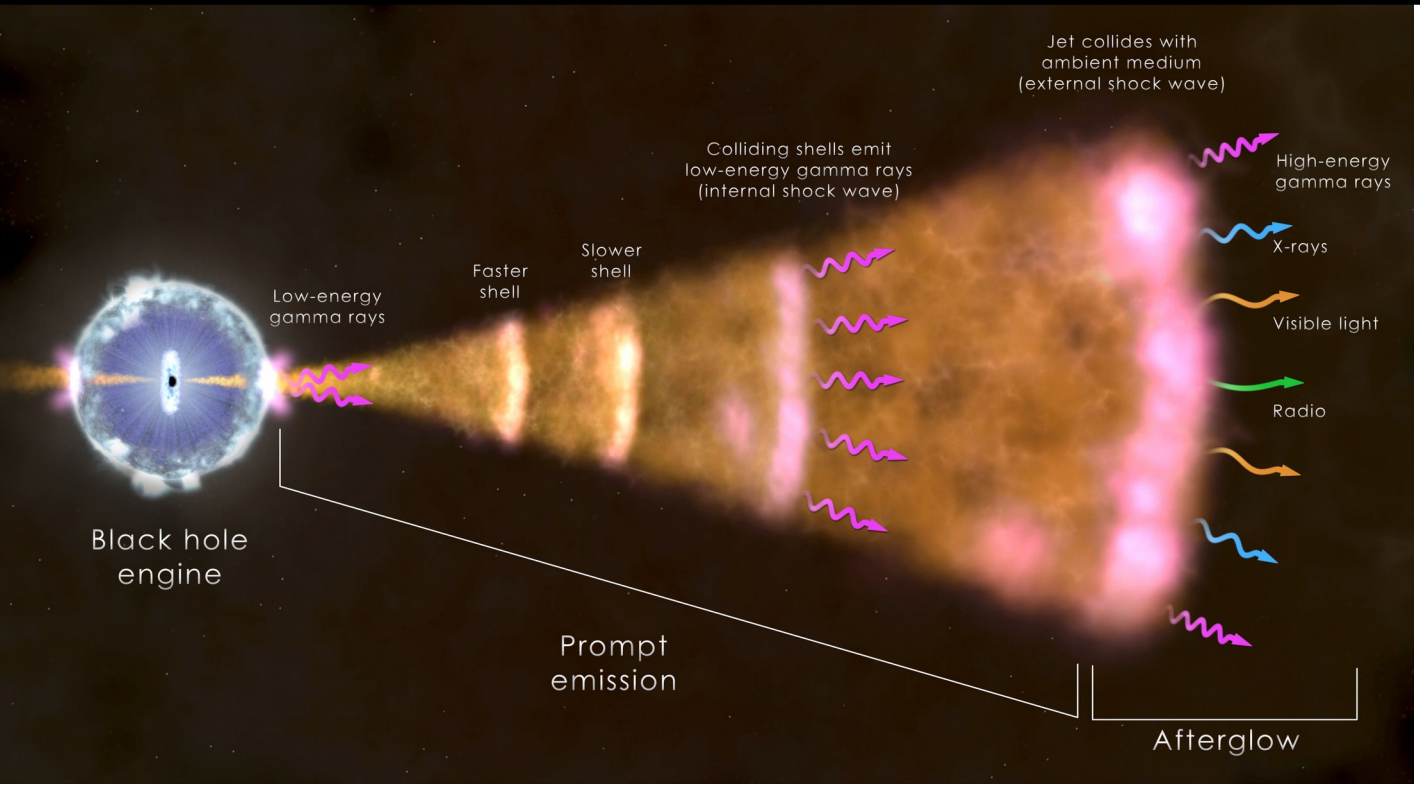
→ Can we claim we are dealing with 2 neutron stars?

→ Why 2 spin hypotheses?

→ Why is the uncertainty better for a low-spin system?

→ Why is the distance ~1 order magnitude lower than for black holes?

Gamma ray burst

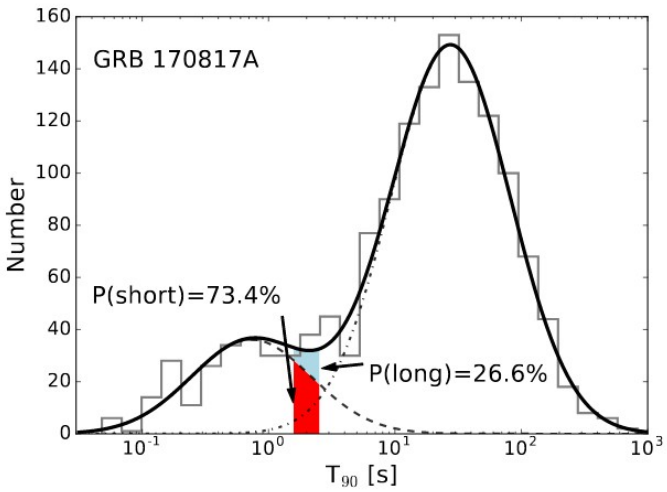


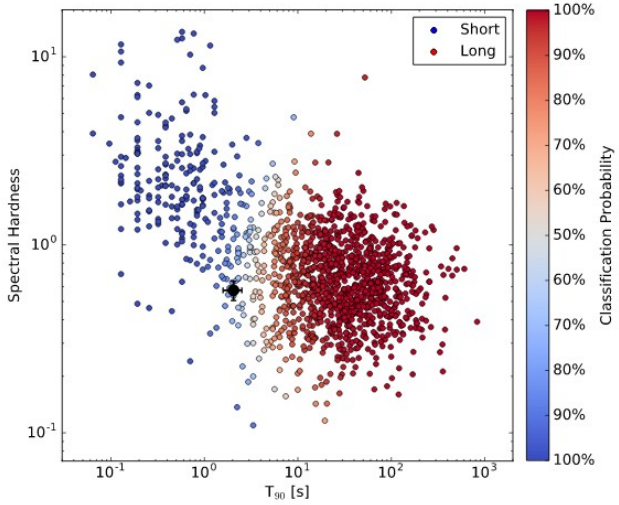
→ Brightest electromagnetic events in the Universe

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

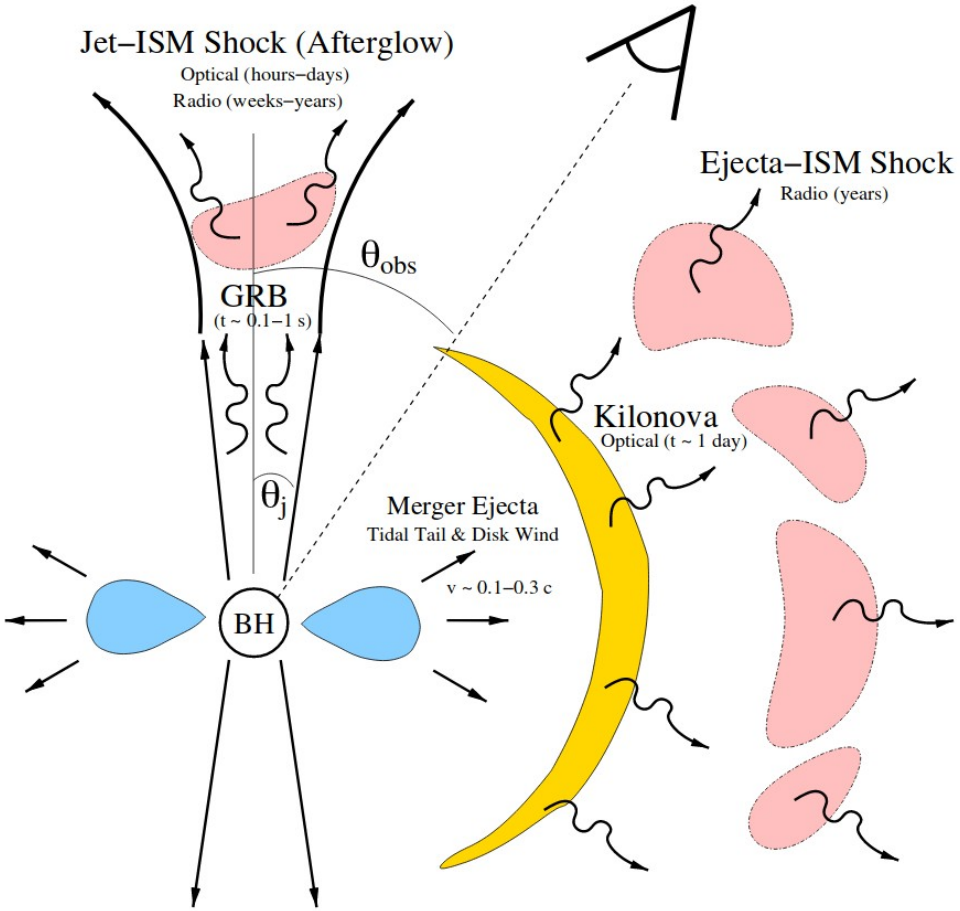
→ progenitors: binary neutron star merger (short) or massive star collapse (long)

→ We detect ~1 GRB every day





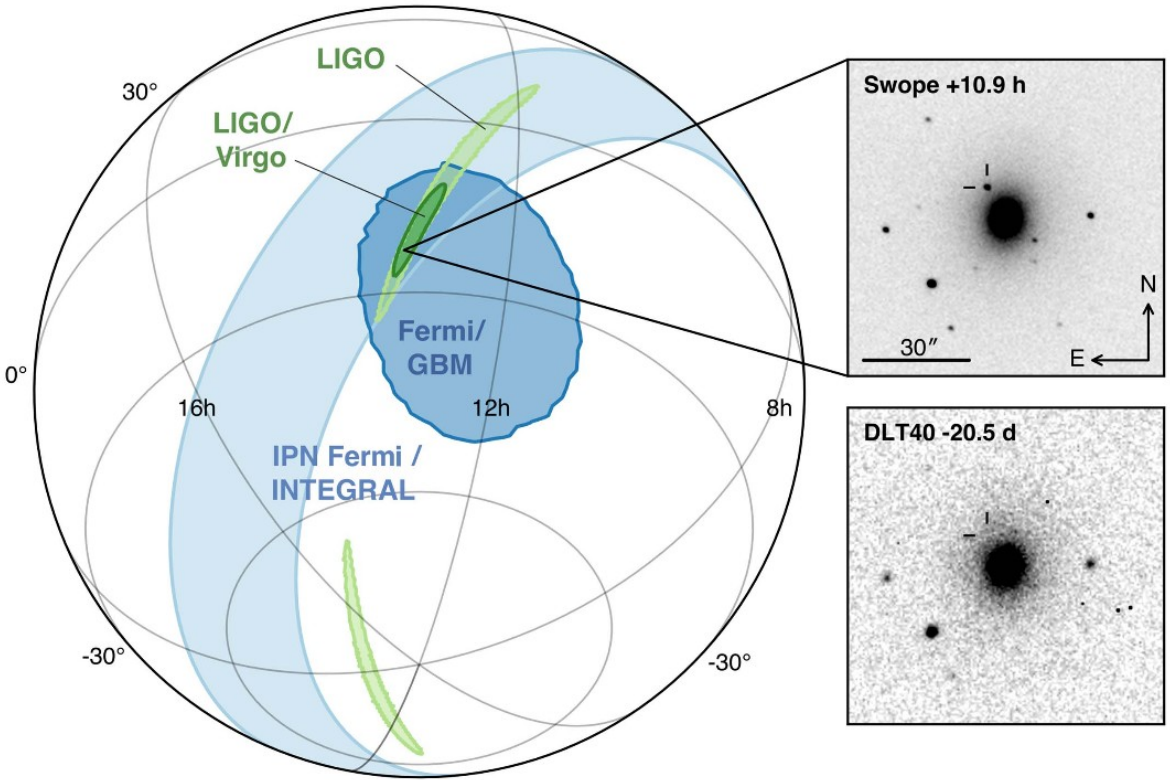
EM emission



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

→ EM follow-up in every wavelengths and over a long time

2017, Aug. 17

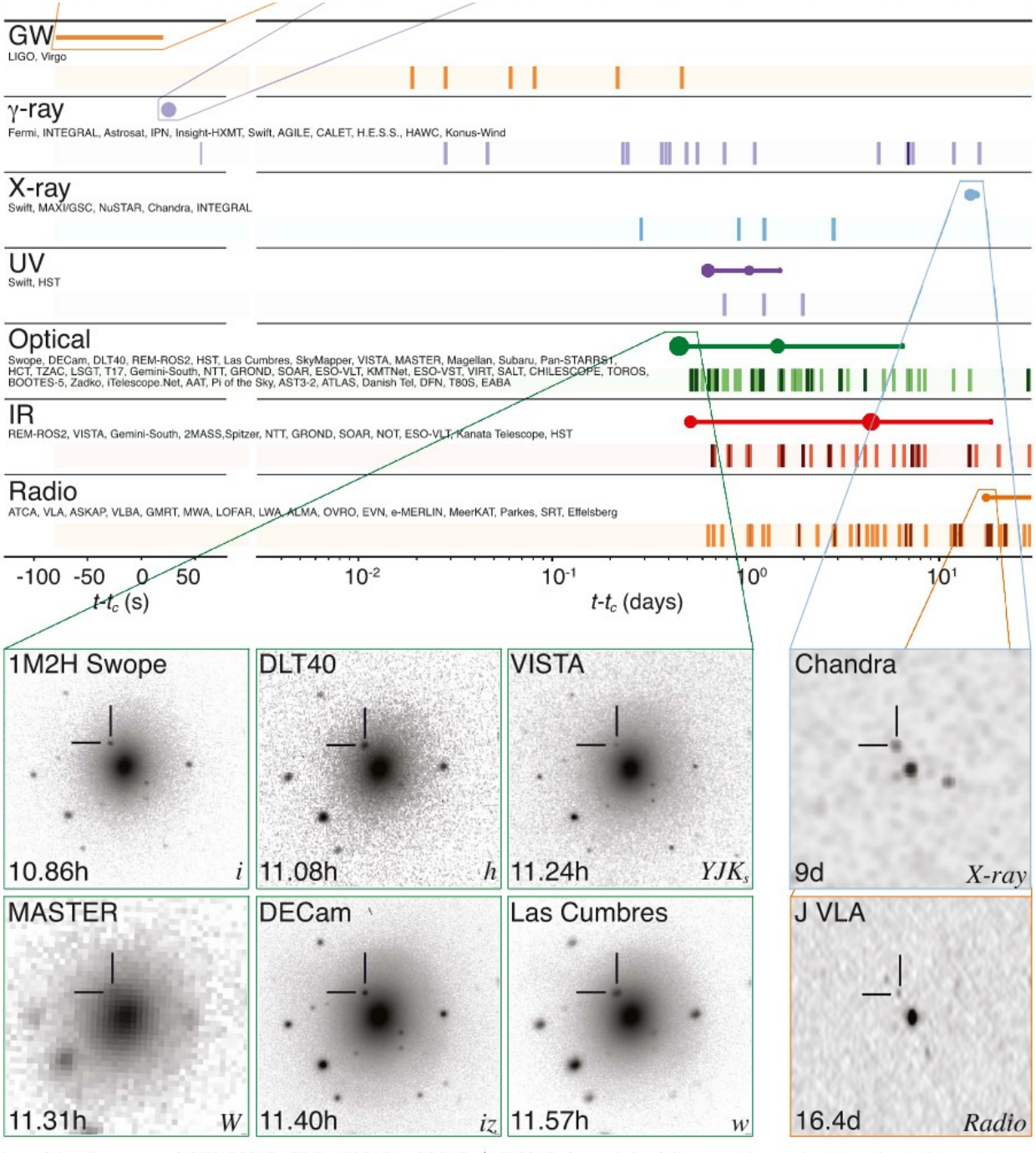


Host galaxy NGC 4993 in the Swope field of view

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

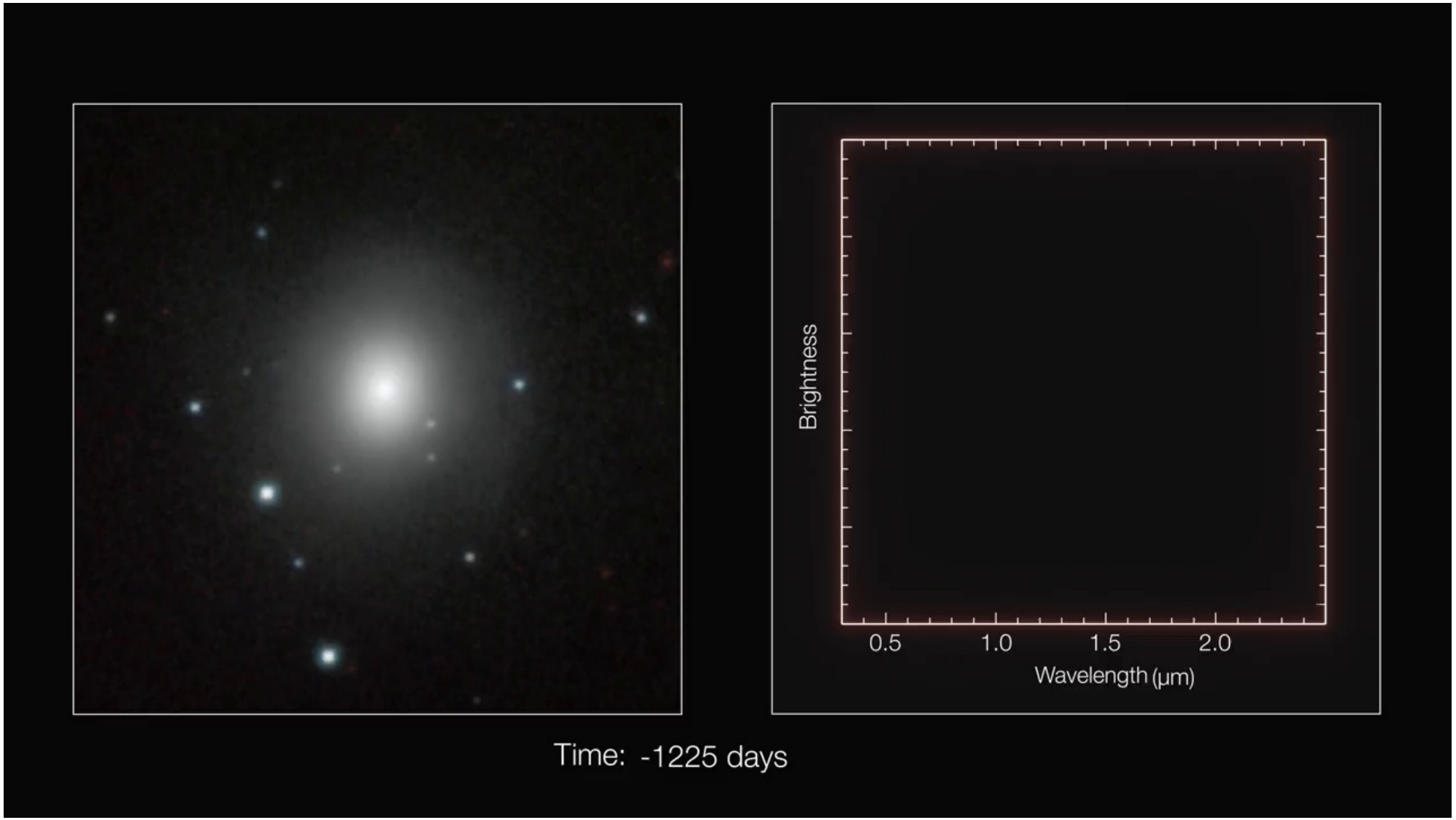


T0 = GW detection
+1.7s: Gamma ray burst detected by Fermi

+40 min: GW alert is sent

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

Spectrum measurement

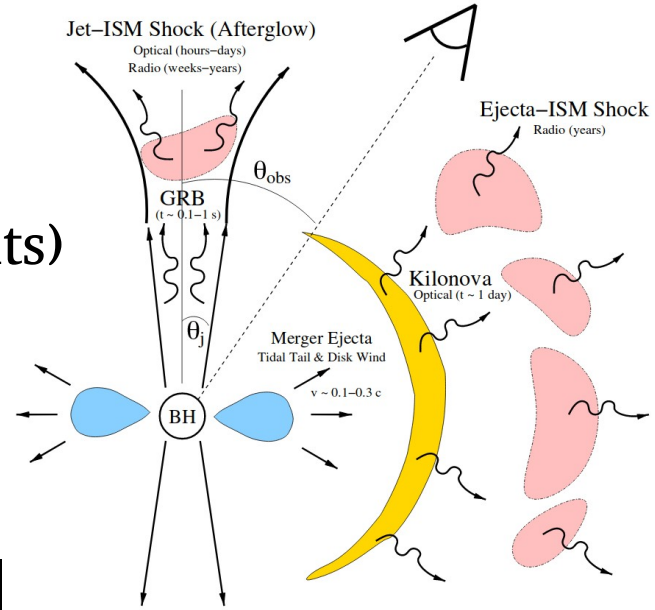


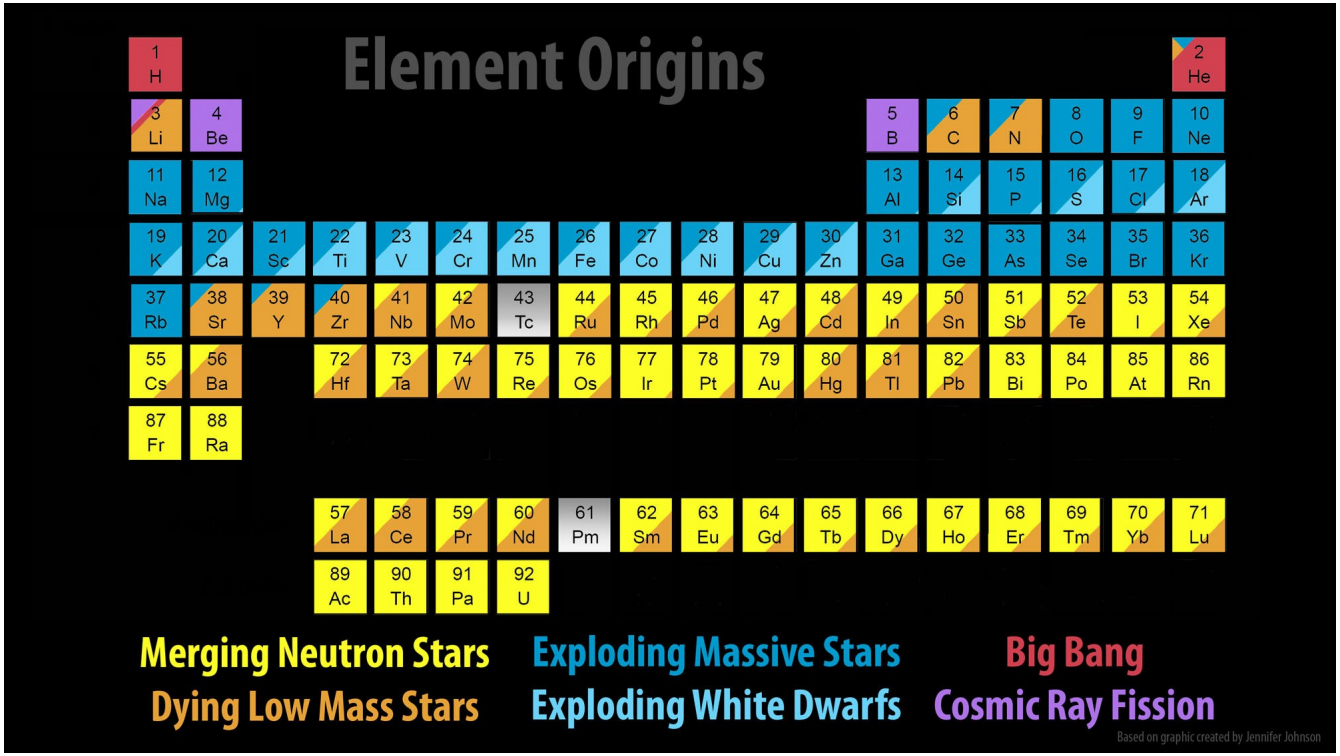
Kilonova

→ Concept introduced in 2010 by Metzger et al.

→ Main source of r-process nuclei (heavy elements)

→ First kilonova ever detected!





GW170817

O3

Binary black hole (21)

Binary neutron star (6)

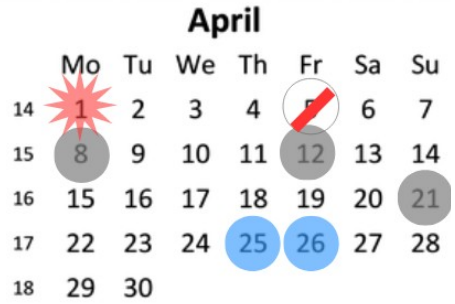
Neutron star-black hole (4)

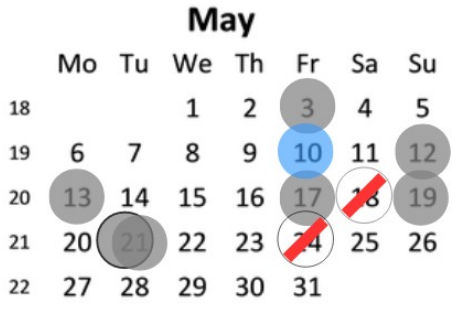
"Mass gap" – 3 to 5 M_{sun} (2)

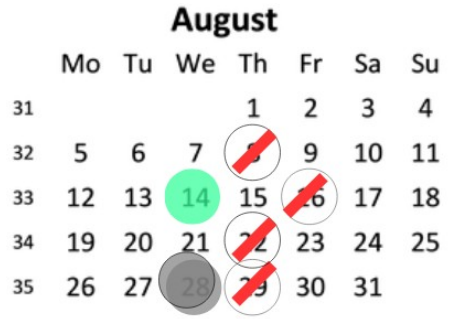
O3a summary

~ 1 alert/week

Alert retracted







→ In O3, GW candidates are publicly and automatically released a few minutes after the detection

→ Sky maps and the source category are provided

→ Astronomers choose (or not) to follow-up the candidates

Conclusions

→ The detection of gravitational waves has offered a new channel for multi-messenger astronomy

→ First multi-messenger GW-EM event detected in 2017

→ Rich science can be accomplished

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

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