Multi-messenger astronomy

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

Florent Robinet
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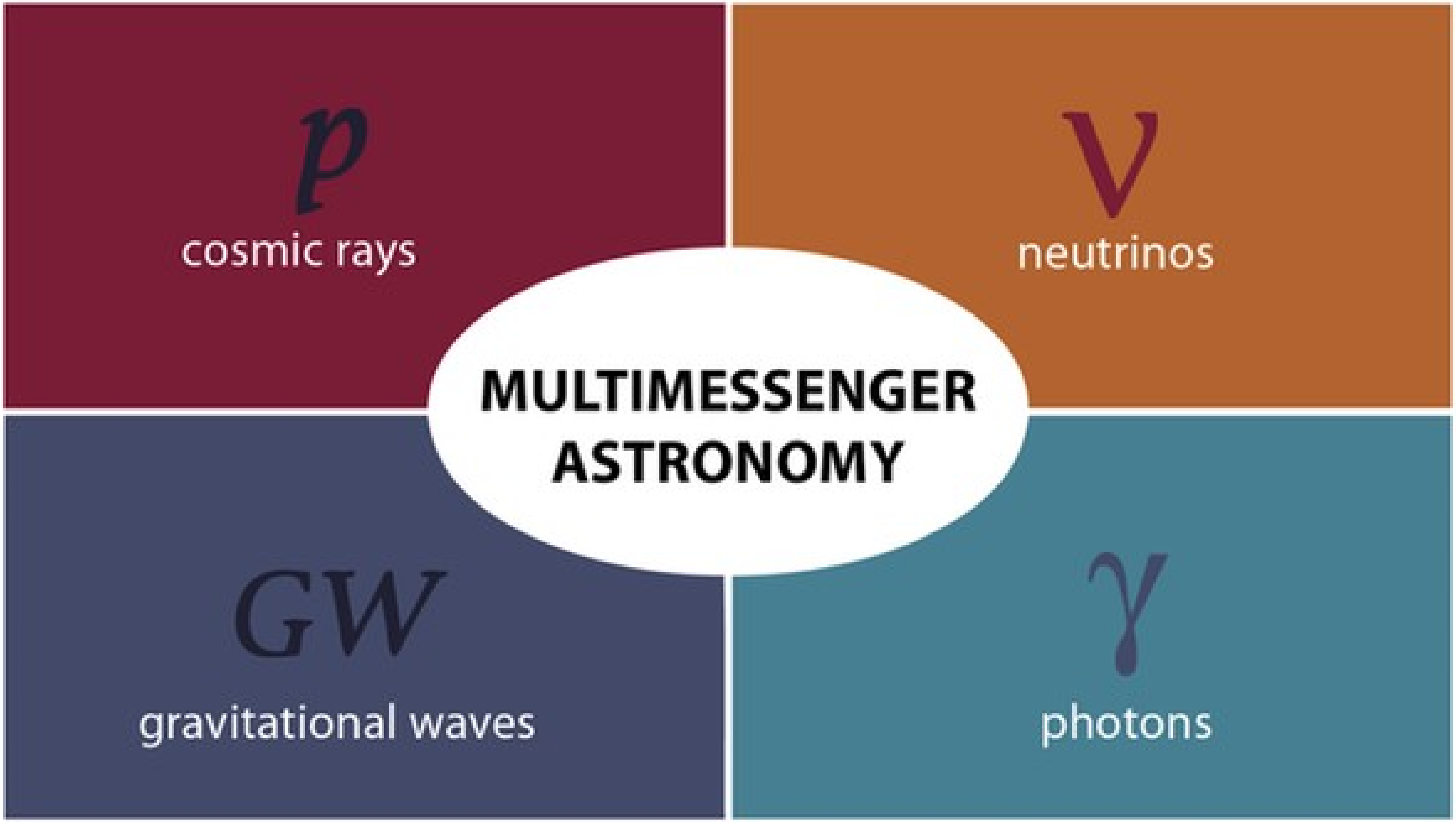
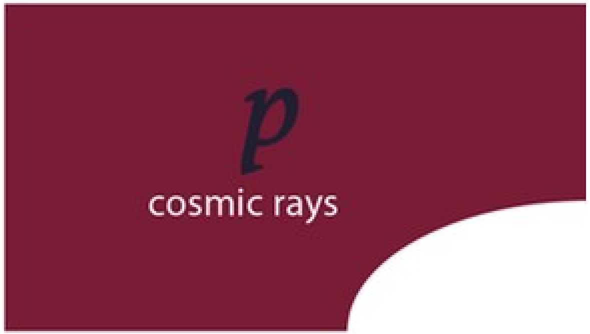
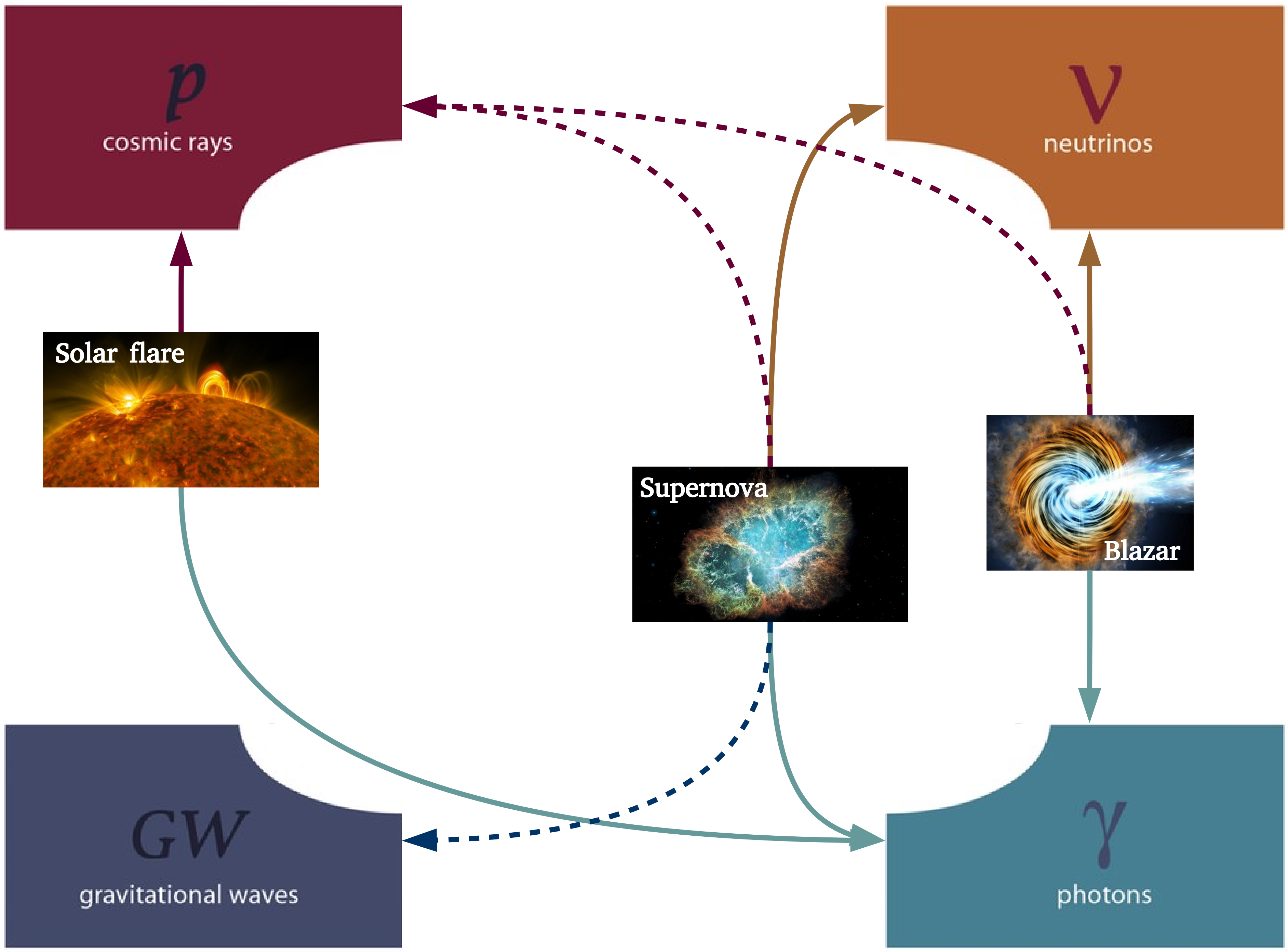
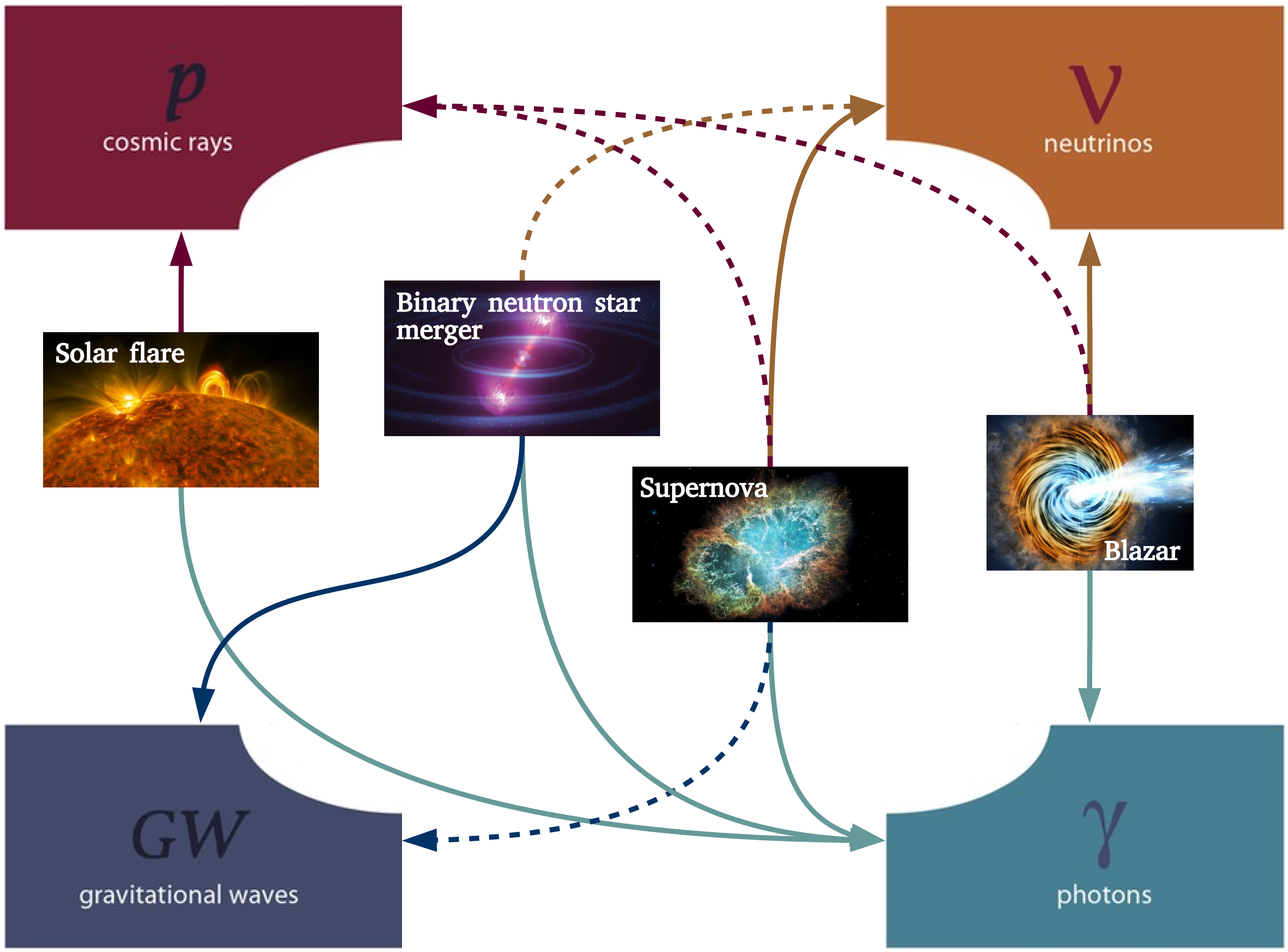

p
cosmic rays
ν
neutrinos
MULTIMESSENGER
ASTRONOMY
GW
gravitational waves
γ
photons



Use multiple and complementary channels
to study astrophysical objects



p
cosmic rays
ν
neutrinos
Solar flare
Supernova
Blazar
GW
gravitational waves
γ
photons



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cosmic rays
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neutrinos
Solar flare
Binary neutron star merger
Supernova
Blazar
GW
gravitational waves
γ
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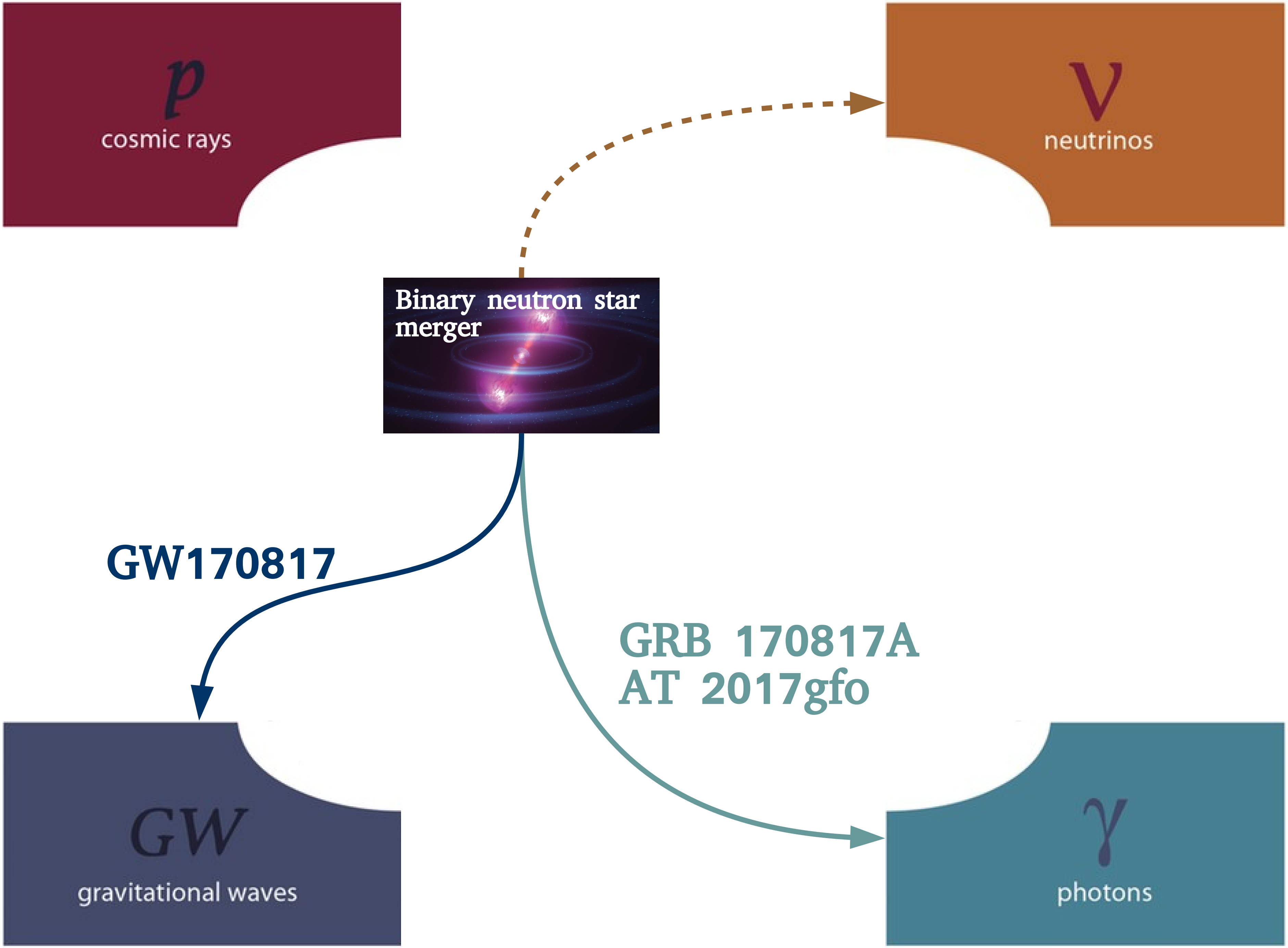
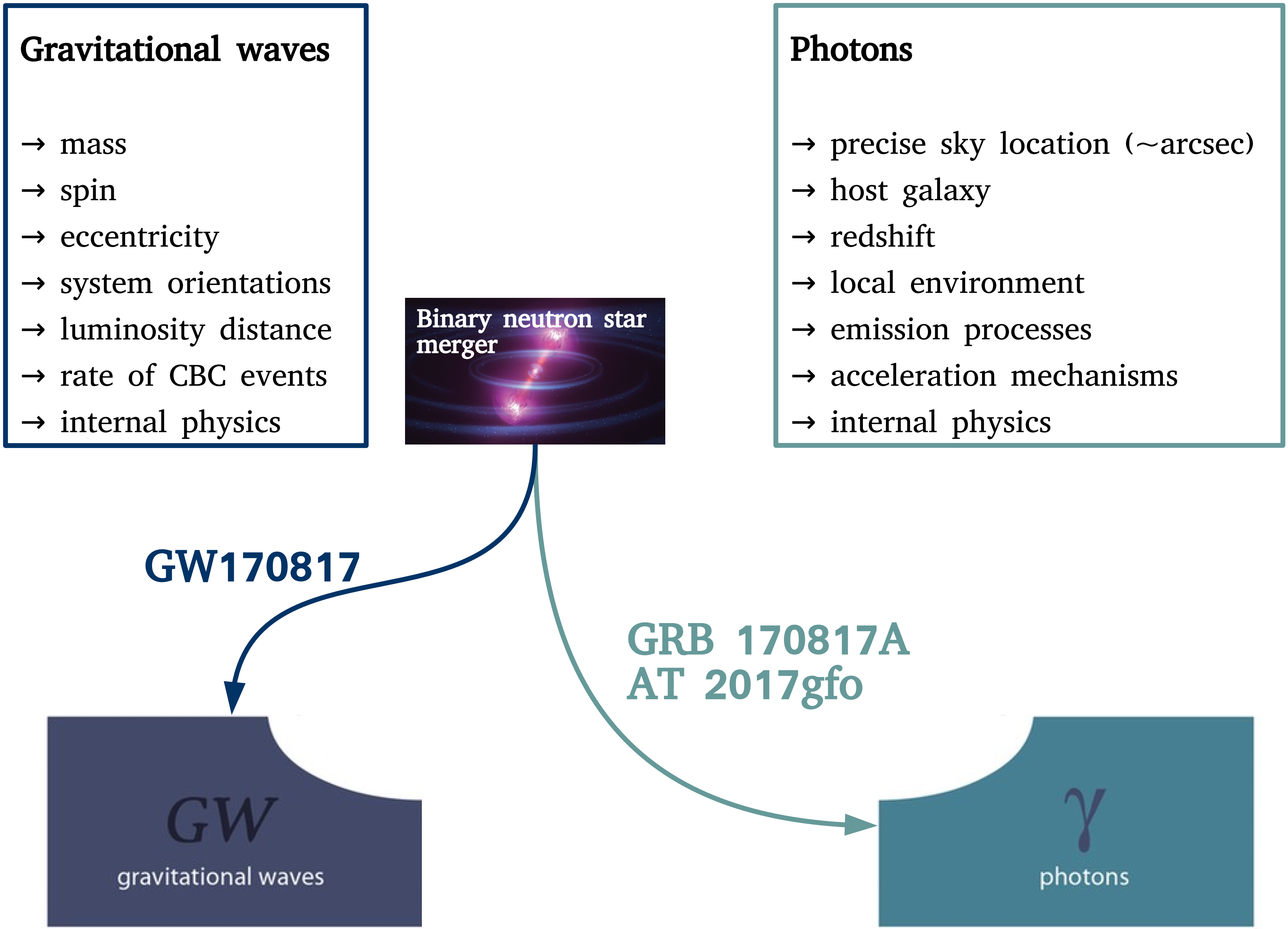
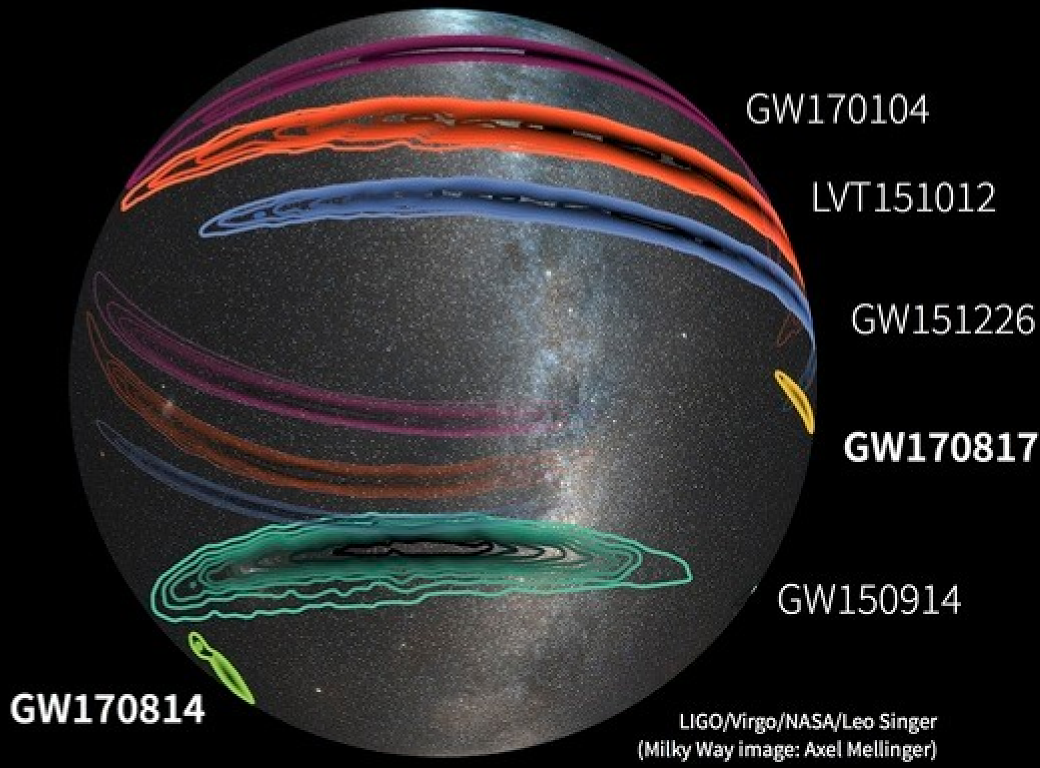


p
cosmic rays
ν
neutrinos
Binary neutron star merger
GW170817
GRB 170817A
AT 2017gfo
GW
gravitational waves
γ
photons


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
Binary neutron star merger
GW170817
GRB 170817A
AT 2017gfo
GW
gravitational waves
γ
photons

Multi-messenger astronomy



GW150914 → 230 deg^2

GW151226 → 850 deg^2

GW170104 → 1200 deg^2

GW170608 → 860 deg^2

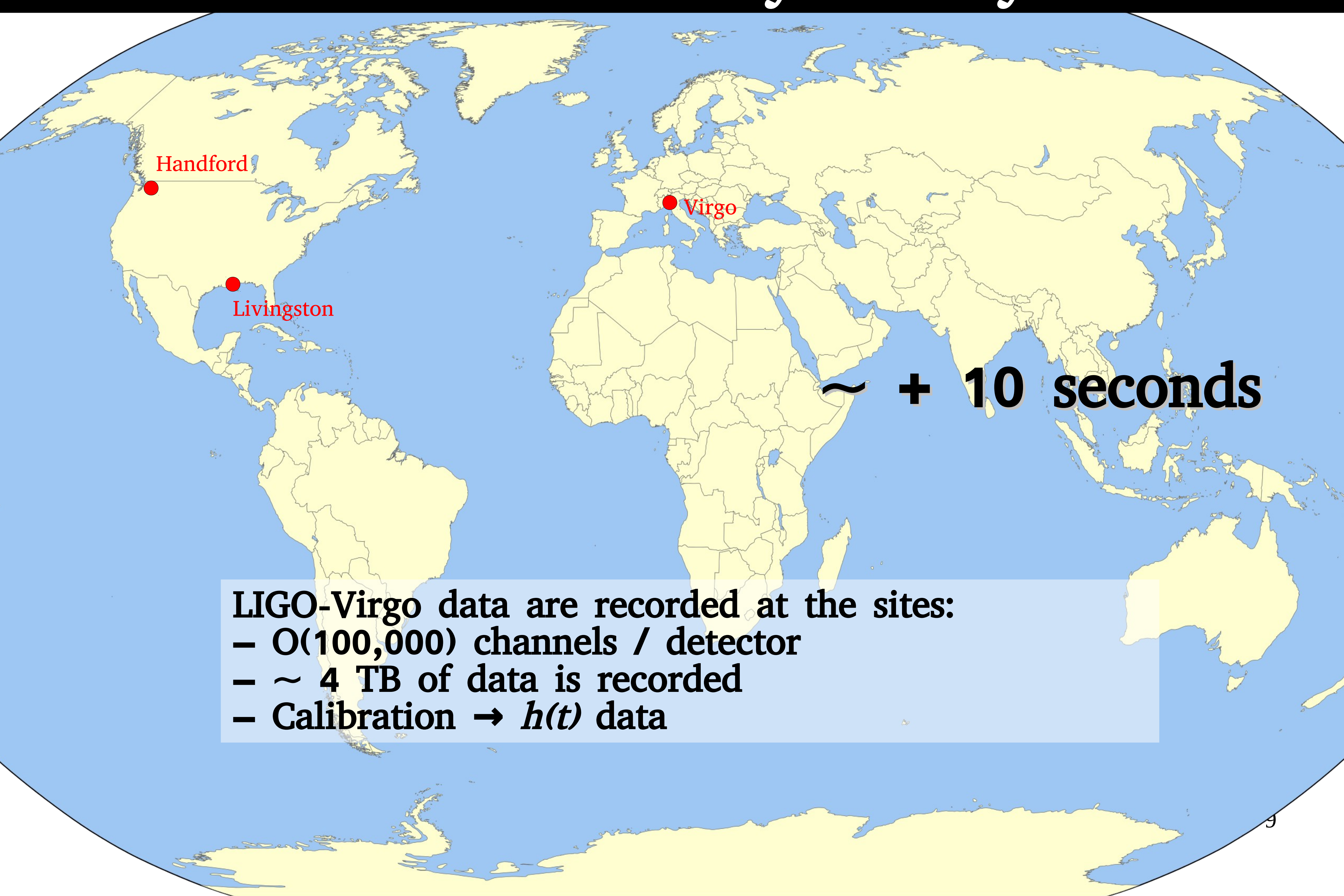
GW170814 → 60 deg^2

+ distance +/- 50%

Many many galaxies in the universe volume associated to the GW detections!

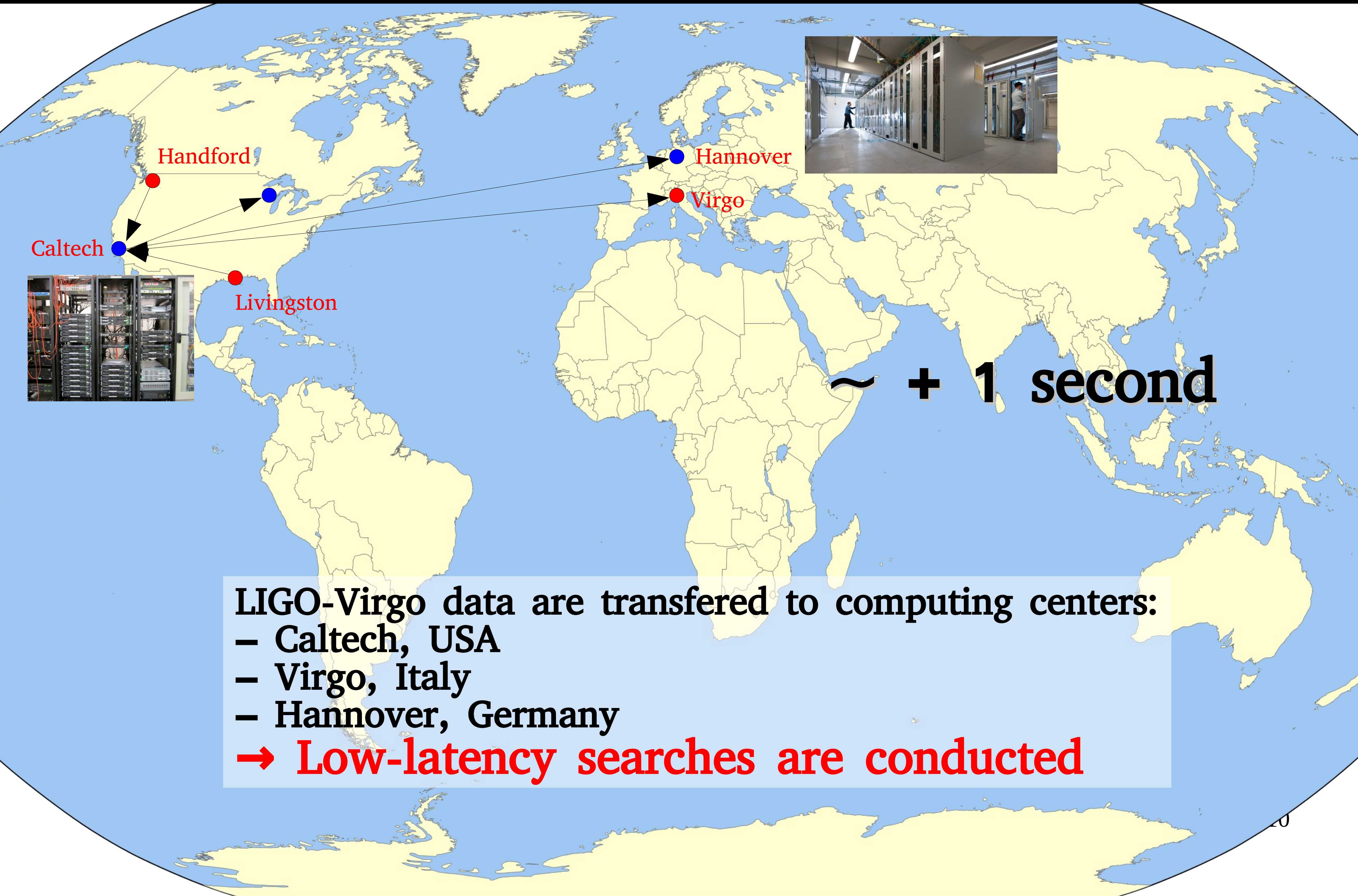
→ Multi-messenger astronomy is needed

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

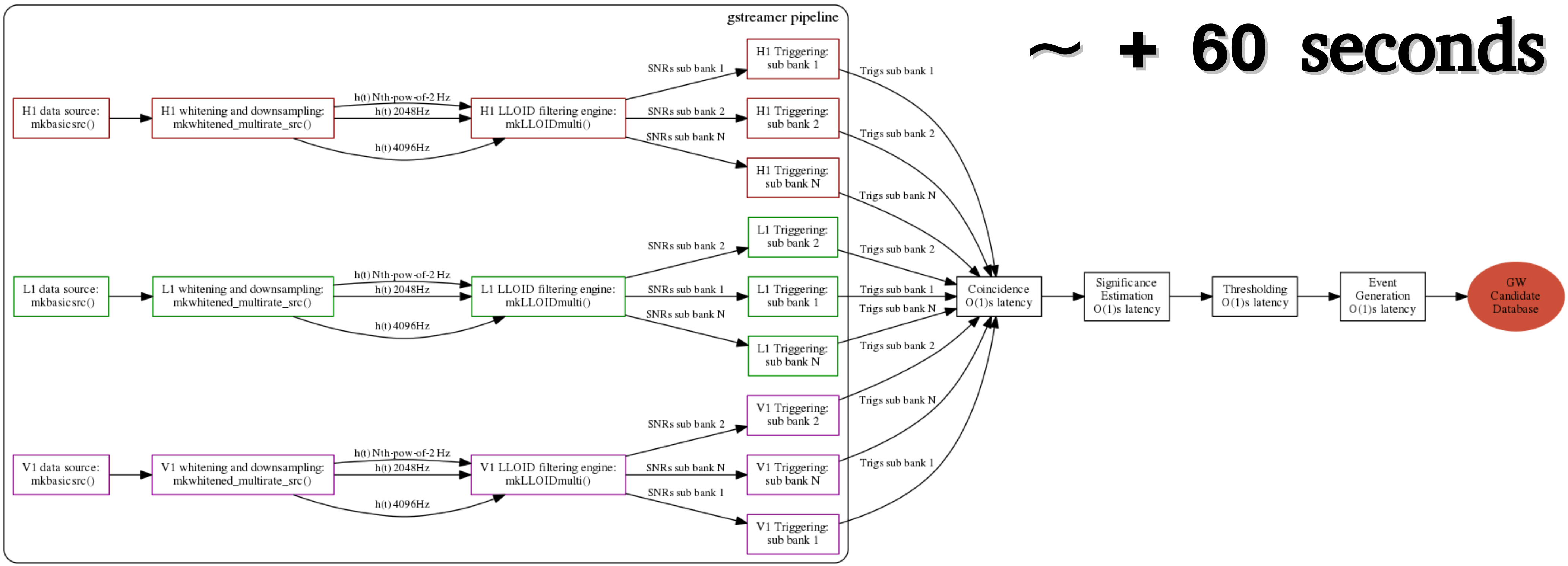


LIGO-Virgo data are transfered to computing centers:

- Caltech, USA
- Virgo, Italy
- Hannover, Germany

→ Low-latency searches are conducted

GW low-latency analysis



~ + 60 seconds

gstlal_inspiral

Candidate database

GW151226

GraceDB — Gravitational Wave Candidate Event Database

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

Candidate database

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GW151226

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

modeled search

+1 min

Coinc Tables

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IFO	L1	H1
Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
End Time (GPS)	1135136350.646883043 s	1135136350.647757924 s
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η	0.18438664	0.18438664
F Final	1024.0 Hz	1024.0 Hz
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χ^2	1.0857431	1.0069774
χ^2 DOF	1	1
spin1z	0.33962944	0.33962944
spin2z	-0.1238557	-0.1238557

physical parameters (preliminary)

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
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Candidate database

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GW151226

Basic Info

FAR ~ 950 yr-1

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

modeled search

+1 min

Coinc Tables

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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
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COA Phase	2.7356486 rad	0.13969257 rad
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(preliminary)

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Candidate database

GW151226

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FAR ~ 950 yr-1

modeled search

+1 min

Coinc Tables

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Single Inspiral Tables

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Channel	GDS-CALIB_STRAIN	GDS-CALIB_STRAIN
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physical parameters
(preliminary)

Neighbors [-5,+5]

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G211116		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

multiple detections over time

Human Vetting

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Basic Info

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IFO	L1	H1
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G211118		CBC	gstlal	HighMass	H1,L1	1135136350.6477	-0.000043	3.279e-08	Data	2015-12-26 03:40:00 UTC
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G211116		CBC	gstlal	HighMass	H1,L1	1135136350.6485	0.000780	4.507e-09	Data	2015-12-26 03:40:00 UTC

→ Preliminary GCN notice is issued

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

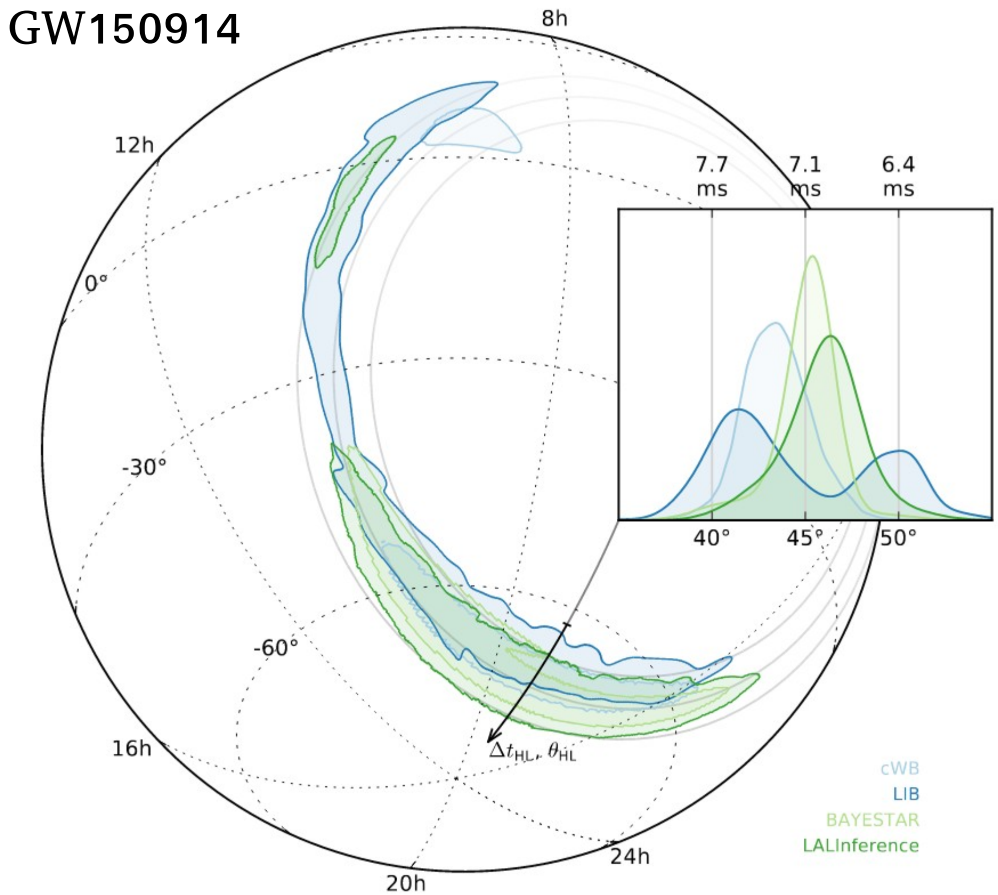
→ Virtual meeting with many people
- detector control rooms
- detector experts
- run coordinators
- detector characterization experts
- search pipeline managers
- calibration experts

→ 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
```

Sky maps



~1 minute
Preliminary parameter estimation given by the search pipeline:

- source parameters (template)
- rough sky position

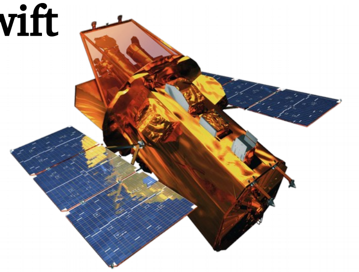
~ a few minutes
Rapid analysis for parameter estimation (*BAYESTAR*)

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

→ Notices are sent whenever a sky map is updated

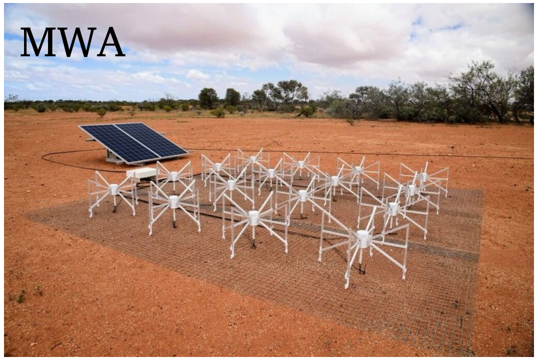
EM follow-up

Swift

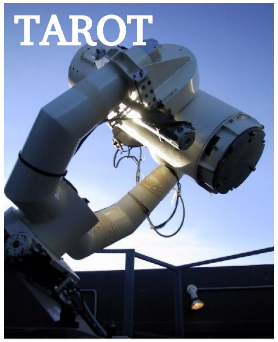


Fermi

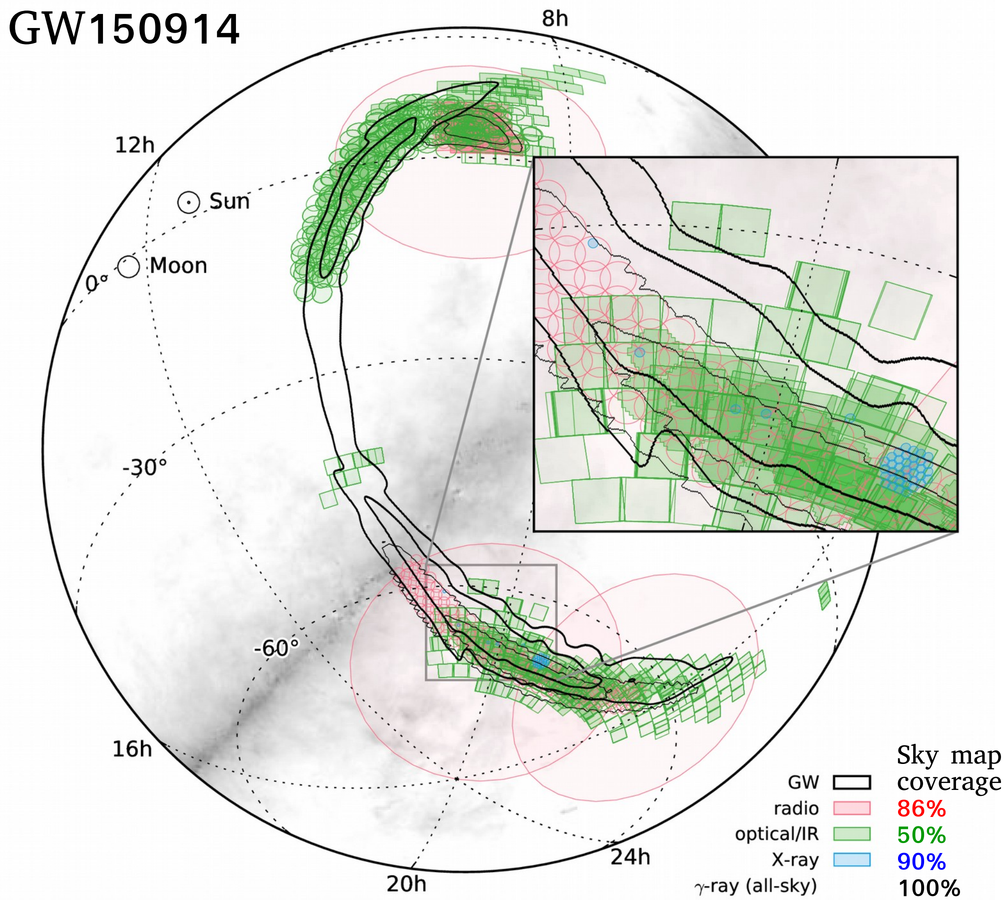
Integral



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



EM follow-up

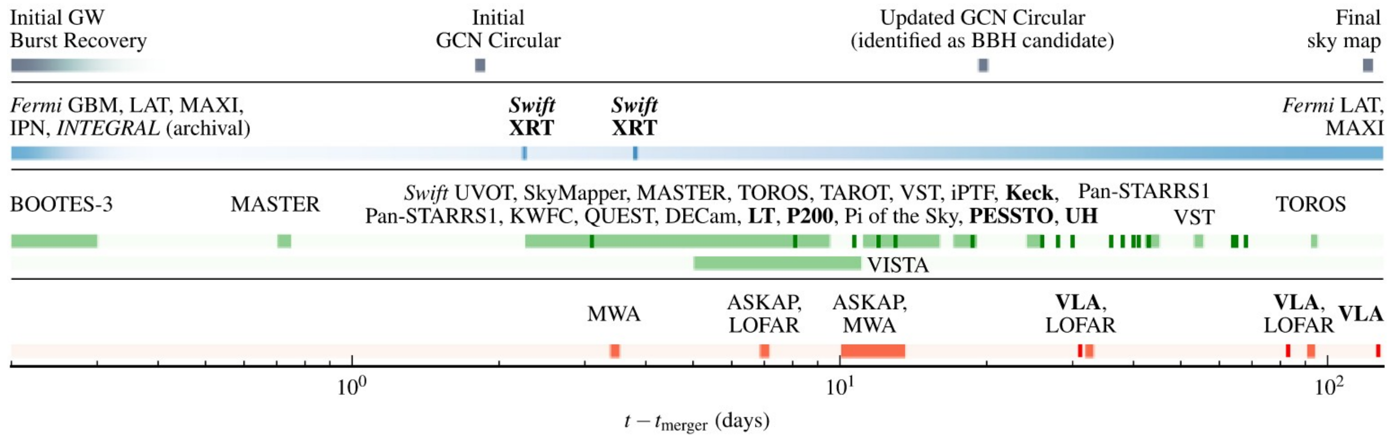


→ No EM counterpart is expected from a binary black hole merger

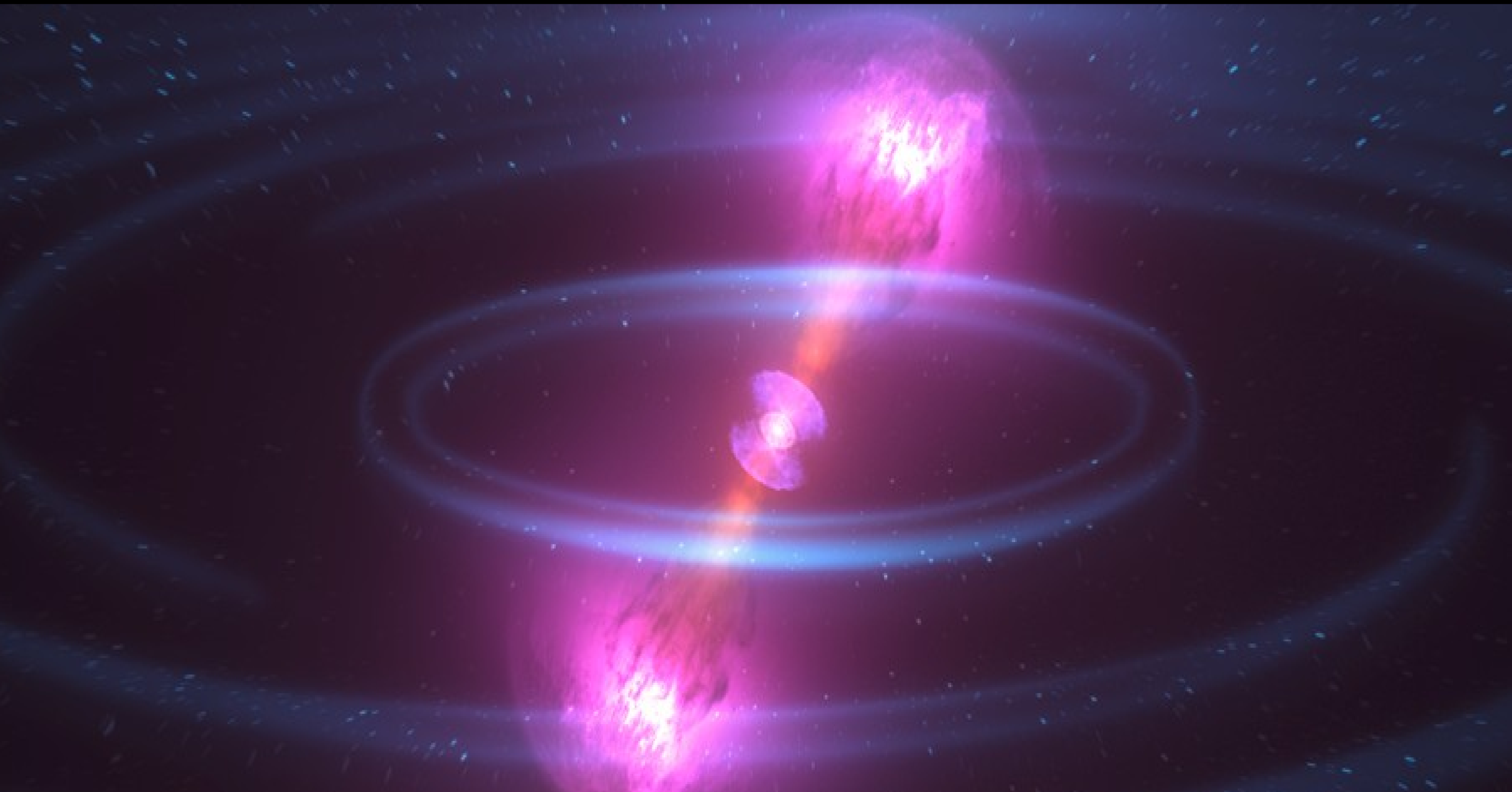
→ Intense EM follow-up campaign took place anyway

→ Several candidate counterparts were identified:
- Supernovae population
- Dwarf novae
- Active Galactic Nucleus (AGN)

→ Unrelated to GW events



2017, Aug. 17



Selected for a Viewpoint in *Physics*

PRL **119**, 161101 (2017) 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)

2017, Aug. 17

What happened this day?

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Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	FAR (yr^{-1})	Links	UTC Submitted
G298048	EM_COINC H1OK ADVOK L1OK V1OK	CBC	gstlal	O2VirgoTest	H1	2017-08-17 12:41:04 UTC	3.478e-12	1 per 9111.7 years	Data	2017-08-17 12:47:18 UTC

Coinc Tables

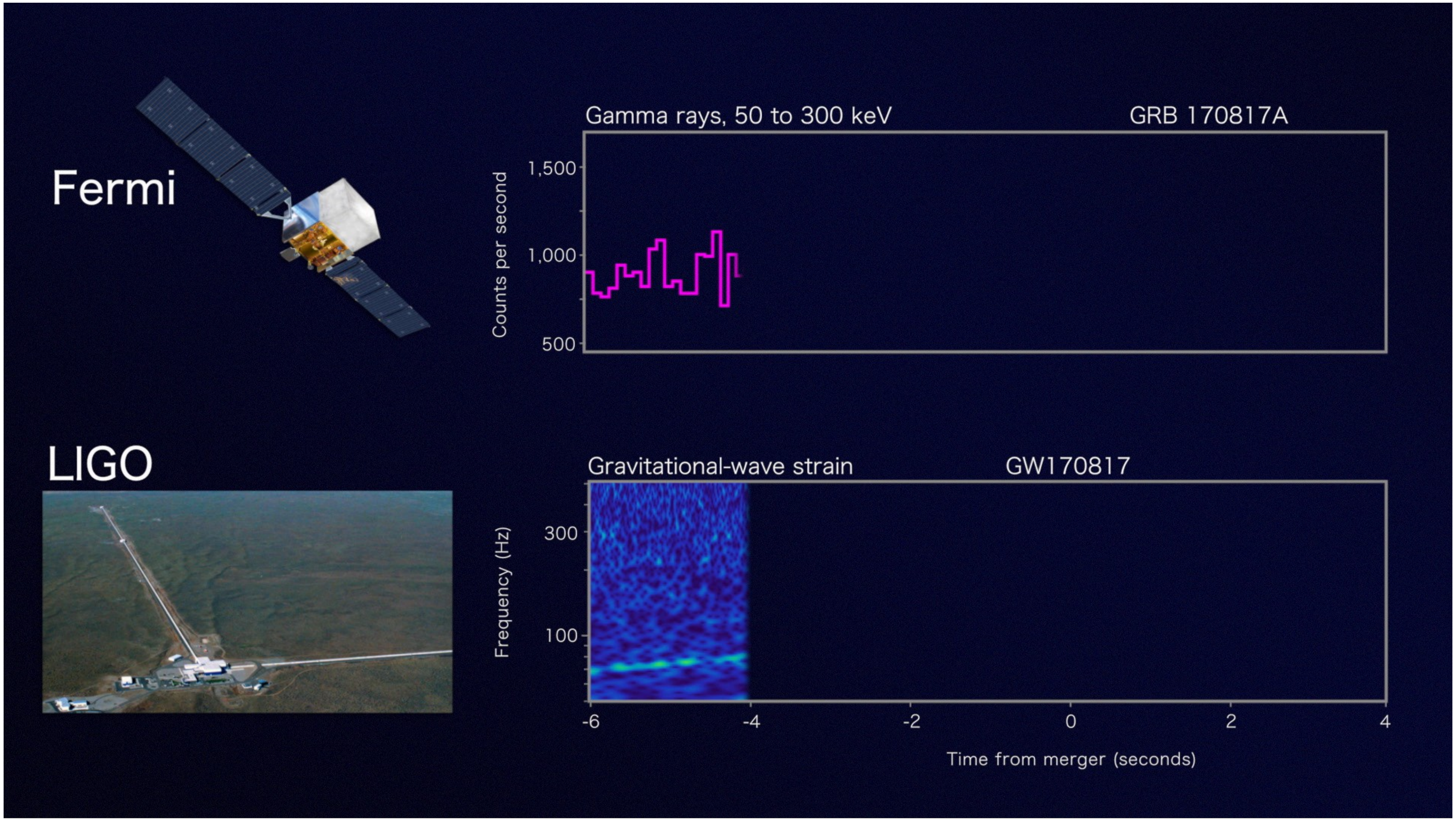
End Time (GPS)	1187008882.4457 s
Total Mass	2.7693 $M_\odot$
Chirp Mass	1.1977 $M_\odot$
SNR	14.4529
False Alarm Probability	5.089e-05
Log Likelihood Ratio	32.3969

Single Inspiral Tables

IFO	H1
Channel	GDS-CALIB_STRAIN
End Time (GPS)	1187008882.445709865 s
Template Duration	360.338000866 s
Effective Distance	85.493584 Mpc
COA Phase	-2.0127285 rad
Mass 1	1.5270051 $M_\odot$
Mass 2	1.2422962 $M_\odot$
η	0.24735758
F Final	1024.0 Hz
SNR	14.452881
χ^2	1.8652176
χ^2 DOF	1
spin1z	-0.015901944
spin2z	-0.035747342

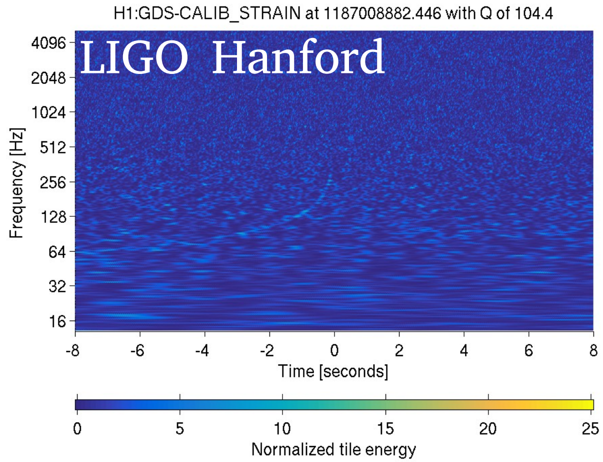
Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
G322759		CBC	gstlal	AllSky	H1,L1,V1	1187008882.4430	-0.002757	7.604e-59	Data	2018-09-06 16:50:51 UTC
G298107	EM_COINC	CBC	pycbc	AllSky	H1,L1,V1	1187008882.4434	-0.002351	1.291e-05	Data	2017-08-17 16:11:22 UTC
G298309	EM_COINC	CBC	pycbc	AllSky	H1,L1,V1	1187008882.4434	-0.002351	1.291e-05	Data	2017-08-19 01:47:59 UTC
E298046	EM_COINC	External	Fermi	GRB		1187008884.4700	2.024290		Data	2017-08-17 12:41:45 UTC



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)

2017, Aug. 17



GraceDB — Gravitational Wave Candidate Event Database

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

Basic Info

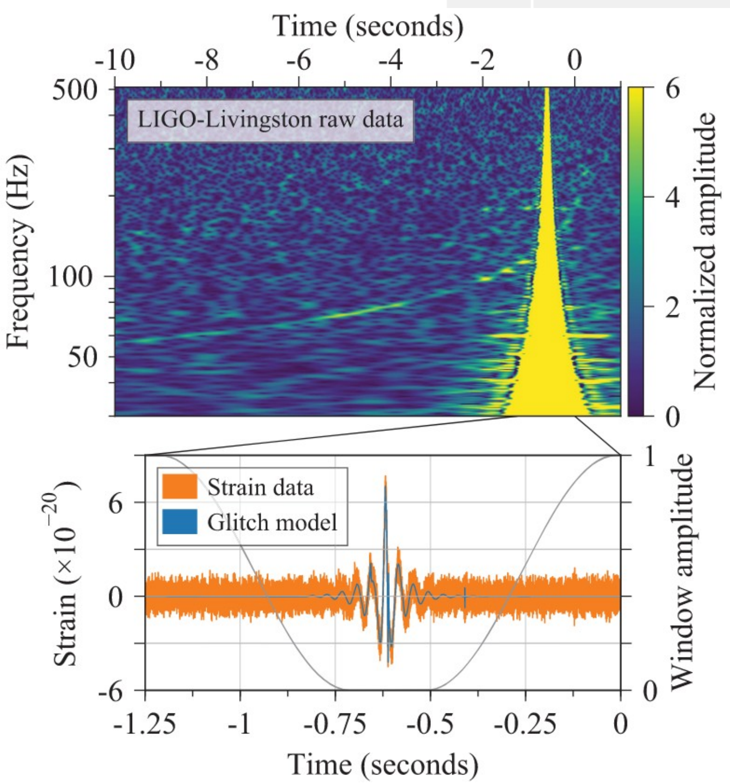
ls	Group	Pipeline	Search	Instruments	UTC Event Time	FAR (Hz)	FAR (yr^{-1})	Links	UTC Submitted
K L1OK V1OK	CBC	gstlal	O2VirgoTest	H1	2017-08-17 12:41:04 UTC	3.478e-12	1 per 9111.7 years	Data	2017-08-17 12:47:18 UTC

.4457 s

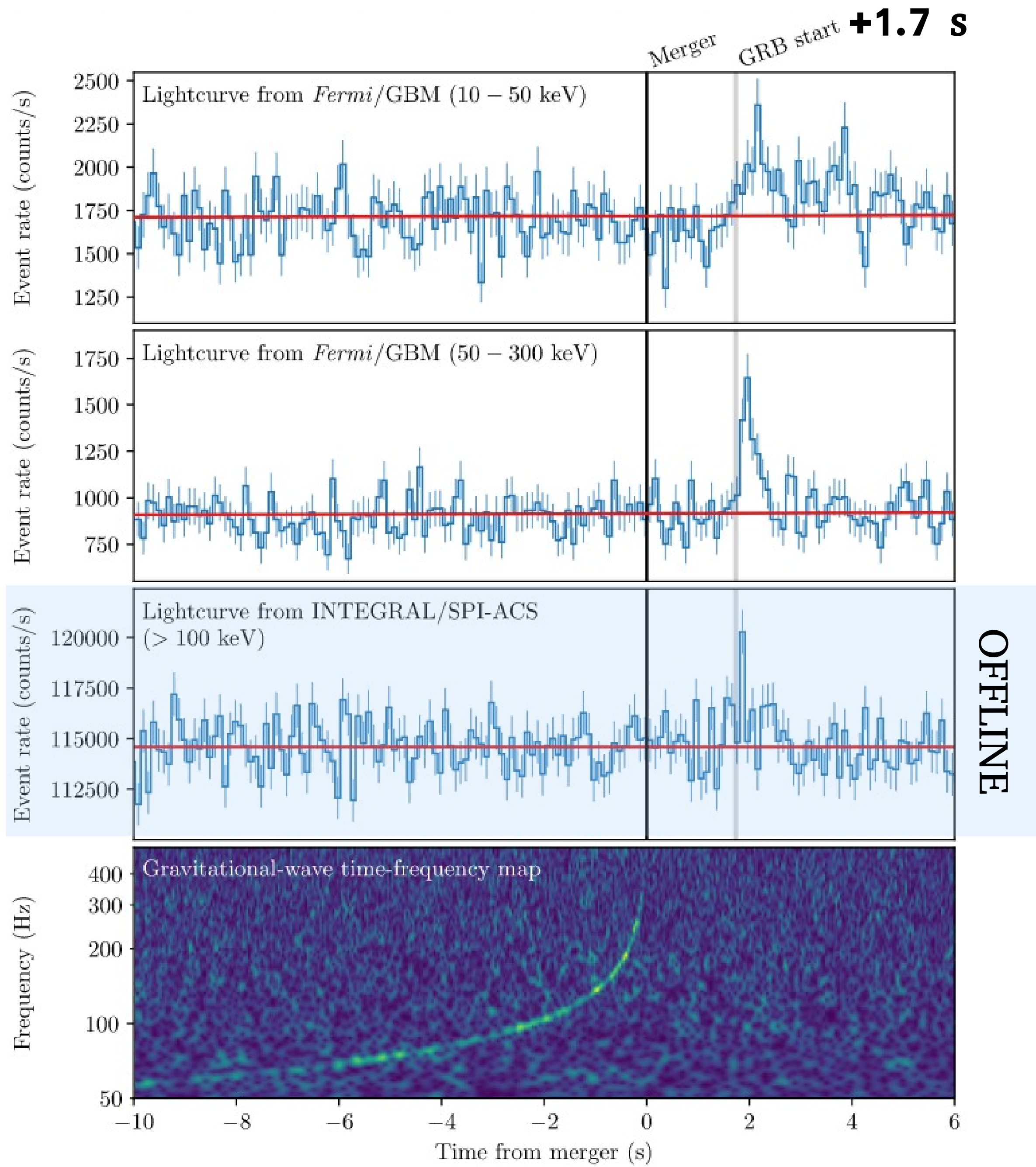
Single Inspiral Tables

IFO	H1
Channel	GDS-CALIB_STRAIN
End Time (GPS)	1187008882.445709865 s
Template Duration	360.338000866 s
Effective Distance	85.493584 Mpc
COA Phase	-2.0127285 rad
Mass 1	1.5270051 $M_\odot$
Mass 2	1.2422962 $M_\odot$
η	0.24735758
F Final	1024.0 Hz
SNR	14.452881
χ^2	1.8652176
χ^2 DOF	1
spin1z	-0.015901944
spin2z	-0.035747342

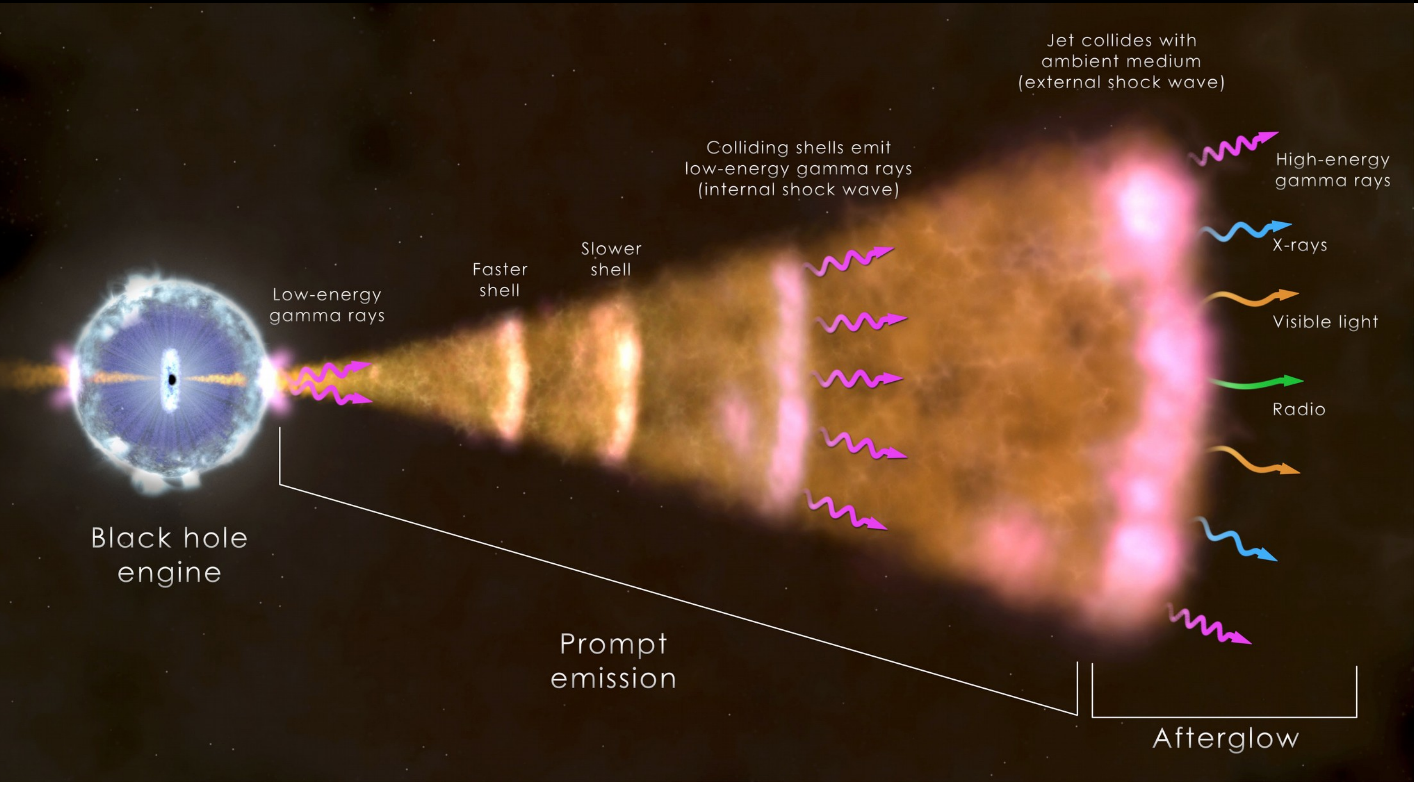
Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted
	gstlal	AllSky	H1,L1,V1	1187008882.4430	-0.002757	7.604e-59	Data	2018-09-06 16:50:51 UTC
	pycbc	AllSky	H1,L1,V1	1187008882.4434	-0.002351	1.291e-05	Data	2017-08-17 16:11:22 UTC
	pycbc	AllSky	H1,L1,V1	1187008882.4434	-0.002351	1.291e-05	Data	2017-08-19 01:47:59 UTC
rnal	Fermi	GRB		1187008884.4700	2.024290		Data	2017-08-17 12:41:45 UTC



2017, Aug. 17


+1.7 s
Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Lightcurve from Fermi/GBM (50 – 300 keV)
Lightcurve from INTEGRAL/SPI-ACS (> 100 keV)
OFFLINE
Gravitational-wave time-frequency map
Event rate (counts/s)
Frequency (Hz)
Time from merger (s)

Gamma ray burst

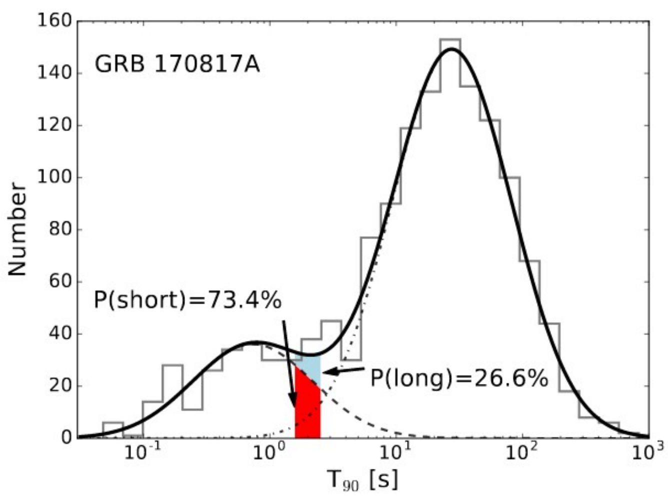


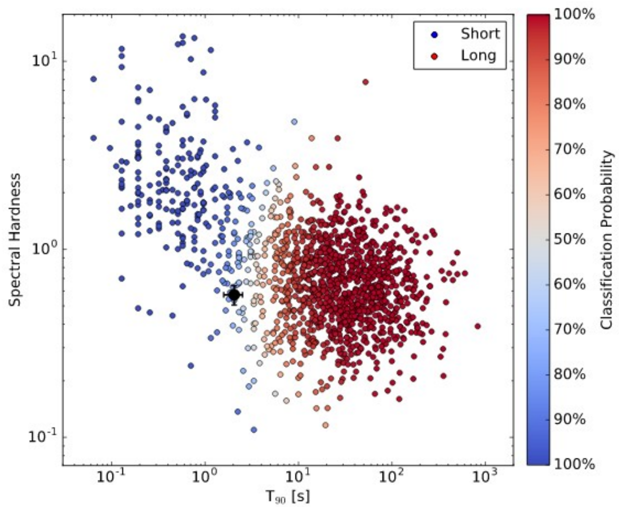
→ Brightest electromagnetic events in the Universe

→ 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)

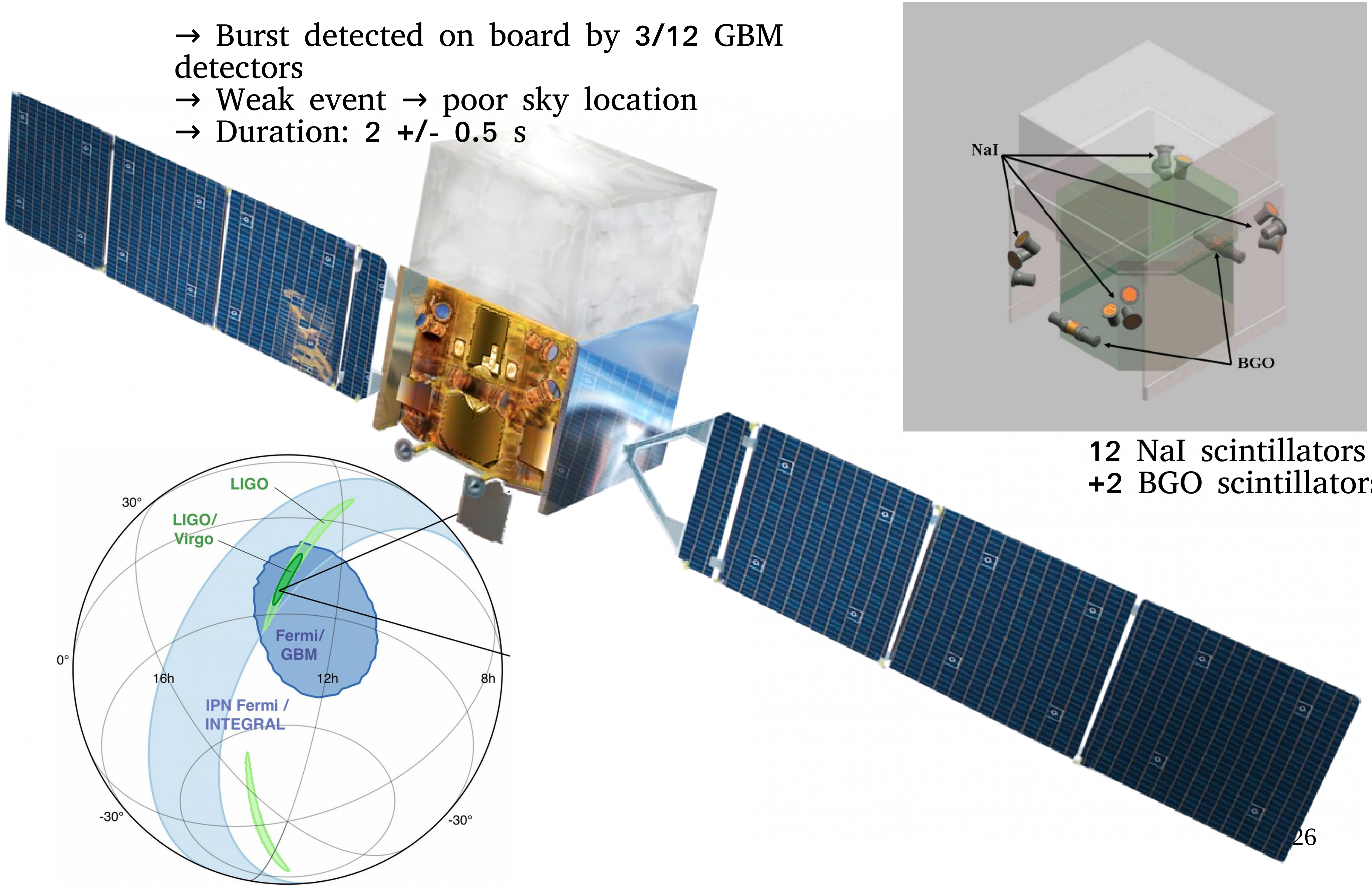
→ We detect ~**1** GRB every day





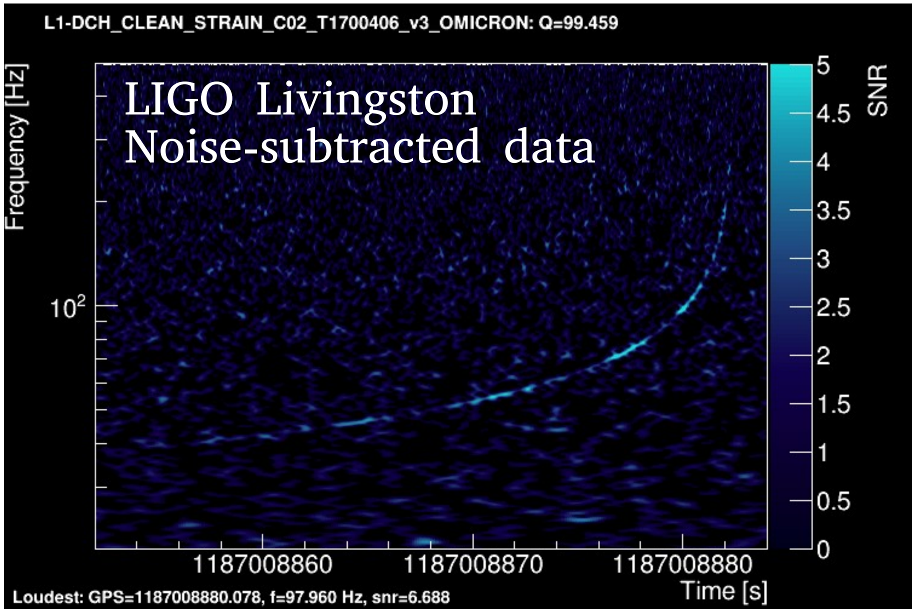
Fermi/GBM detection

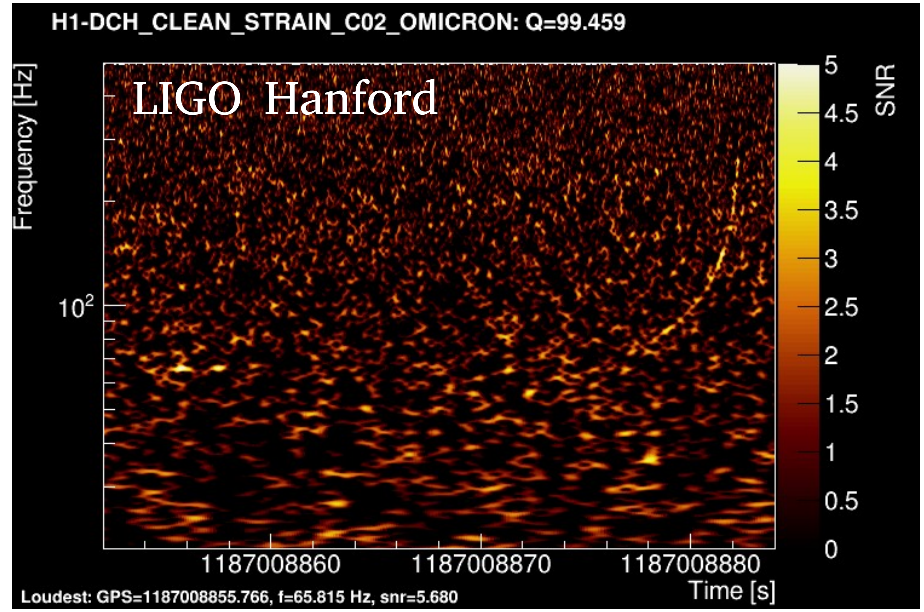
→ Burst detected on board by **3/12** GBM detectors
→ Weak event → poor sky location
→ Duration: **2 +/- 0.5** s

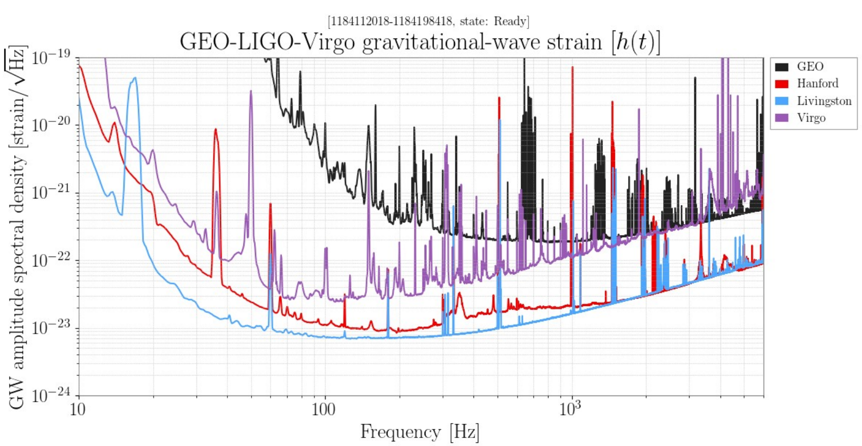


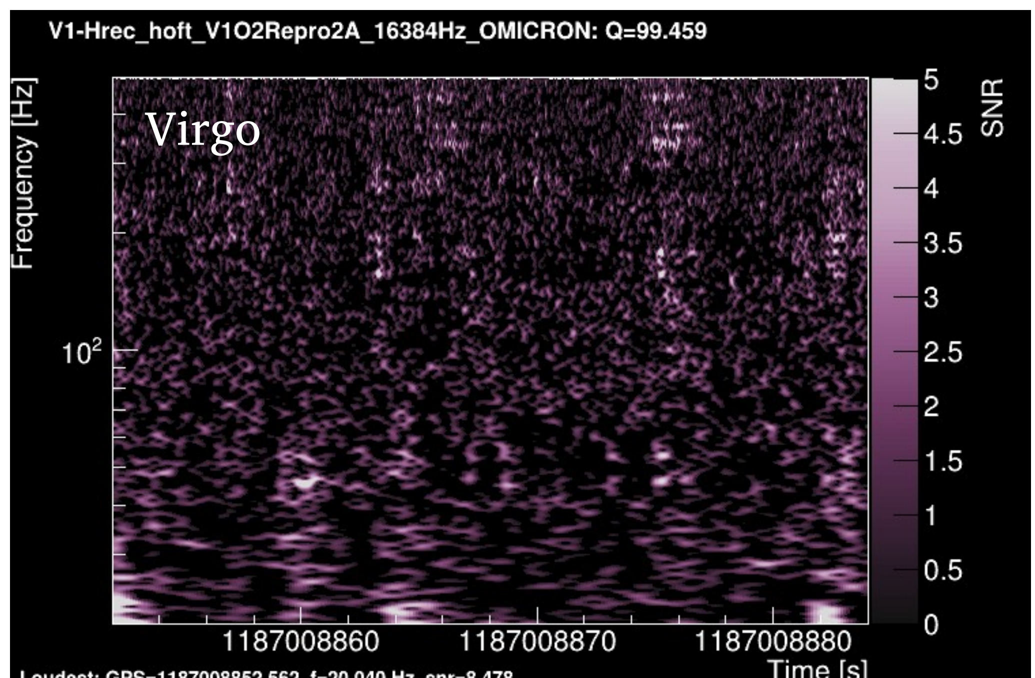
12 NaI scintillators
+2 BGO scintillators

GW detection

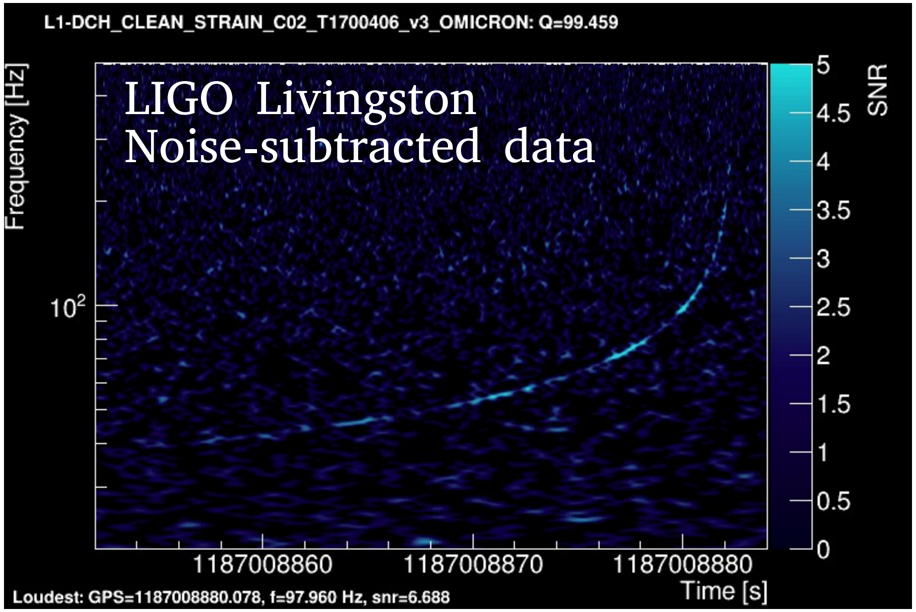


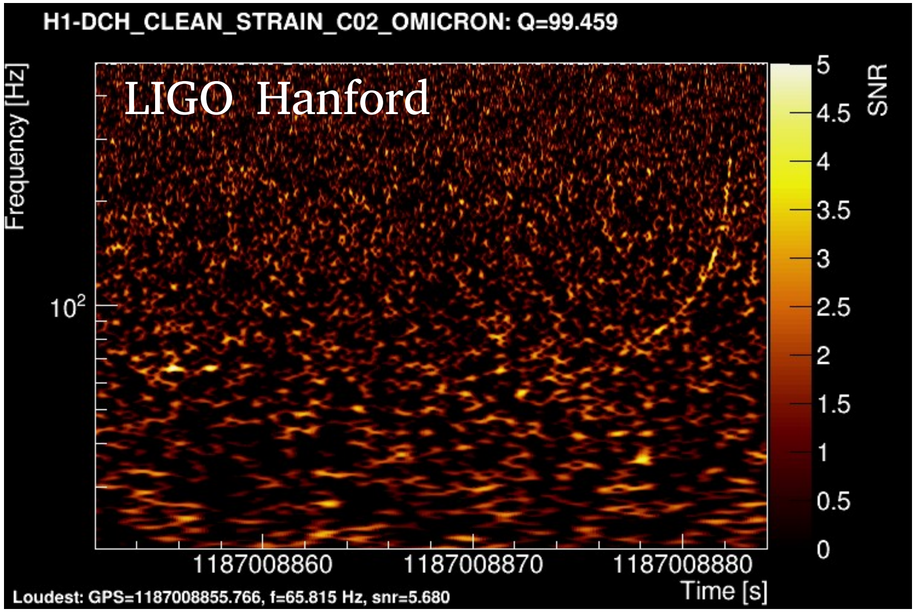






GW detection



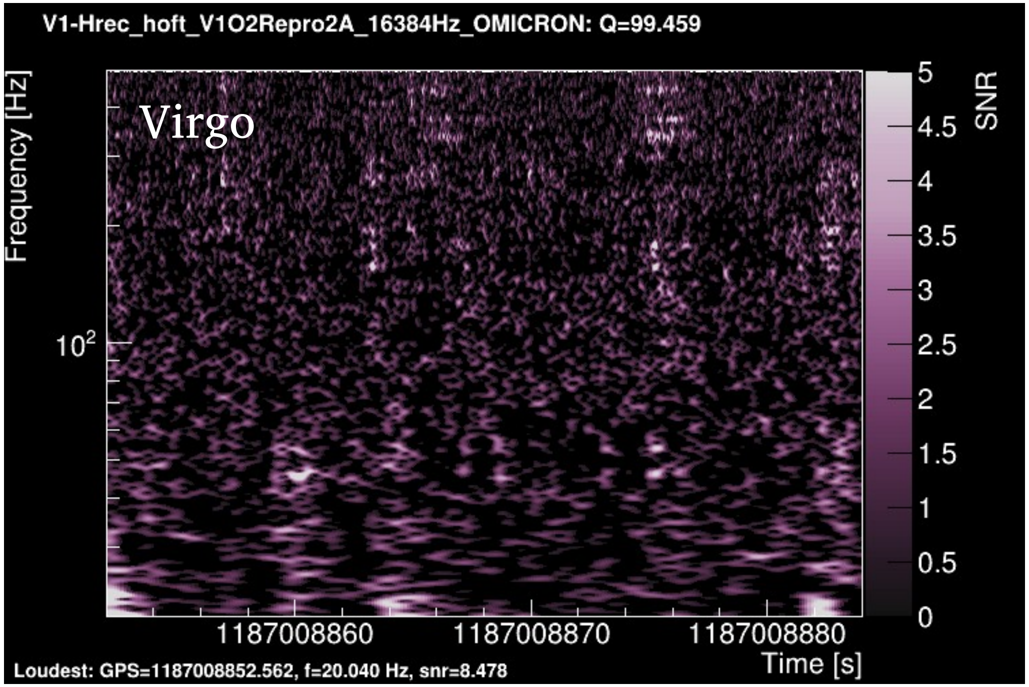


SNR
→ **26.4** (LIGO Livingston)
→ **18.8** (LIGO Hanford)
→ **2.0** (Virgo)

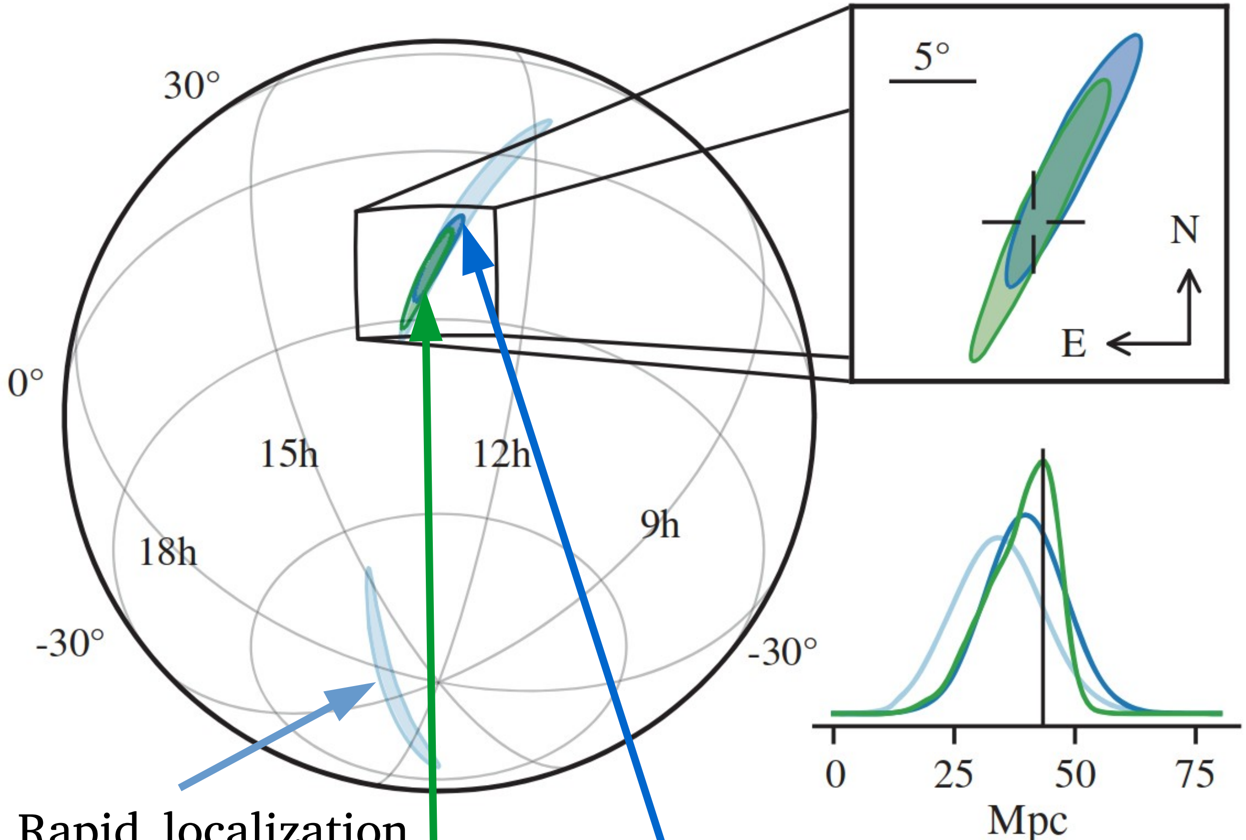
Combined SNR
32.4

False-alarm rate
10^-6/year

Long event in the data
~**100** s



GW sky localization



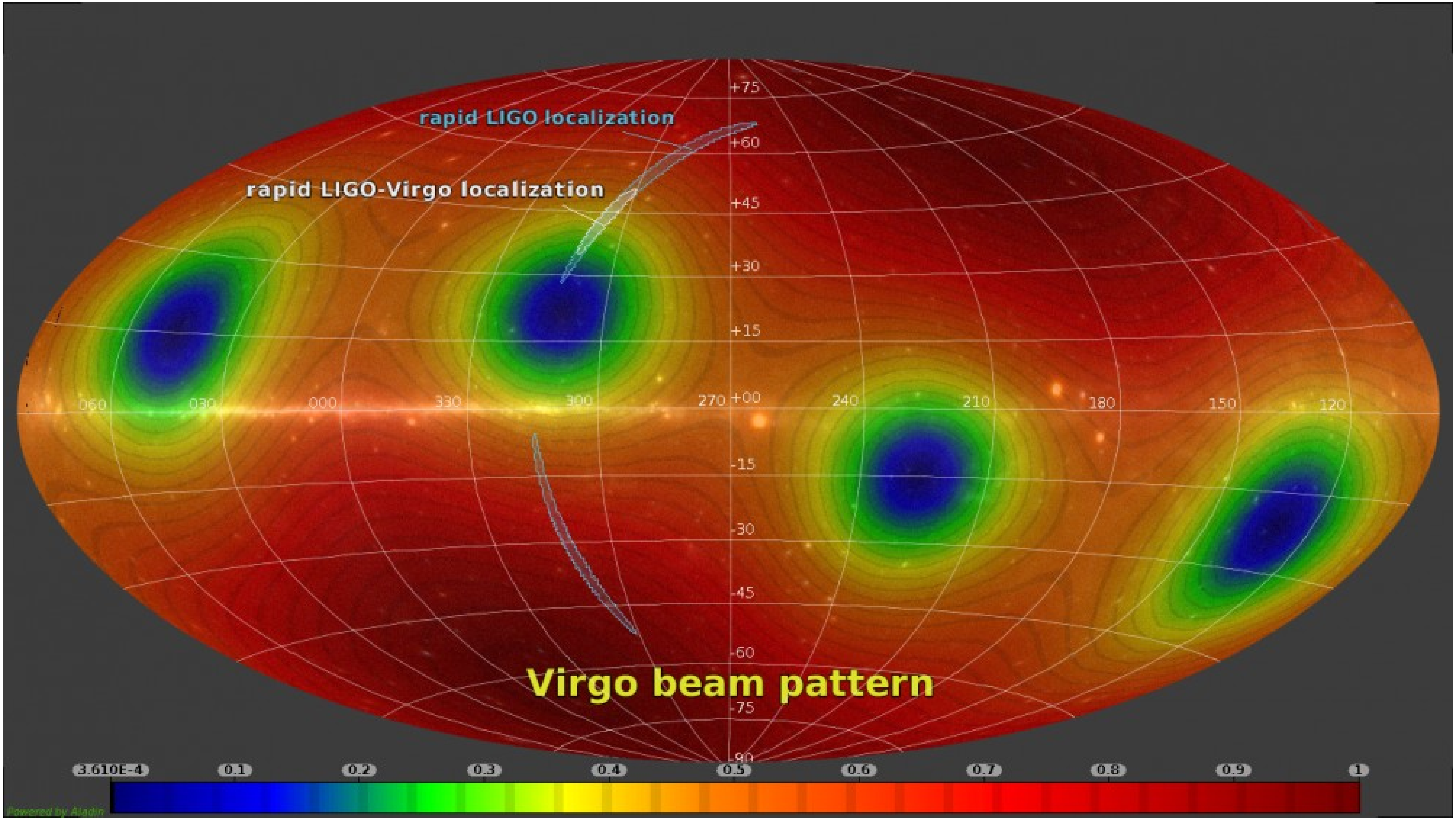
Rapid localization
LIGO only
190 deg²

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 ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
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

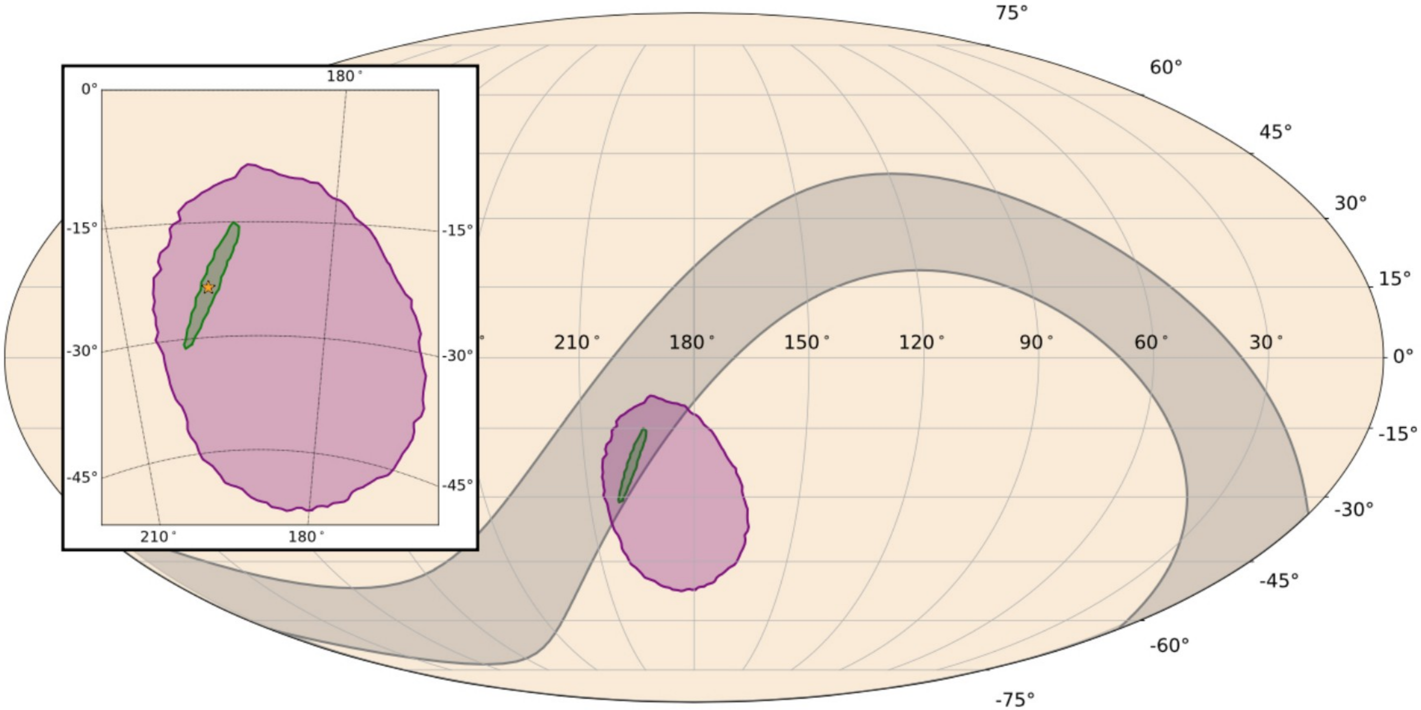
→ Can we claim we are dealing with **2** neutron stars**?**

→ Why **2** spin hypotheses**?**

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

→ Why is the distance $\sim$**1** order magnitude lower than for black holes**?**

GRB 170817A ↔ GW170817



90% Fermi-GBM sky localization (1100 deg^2)

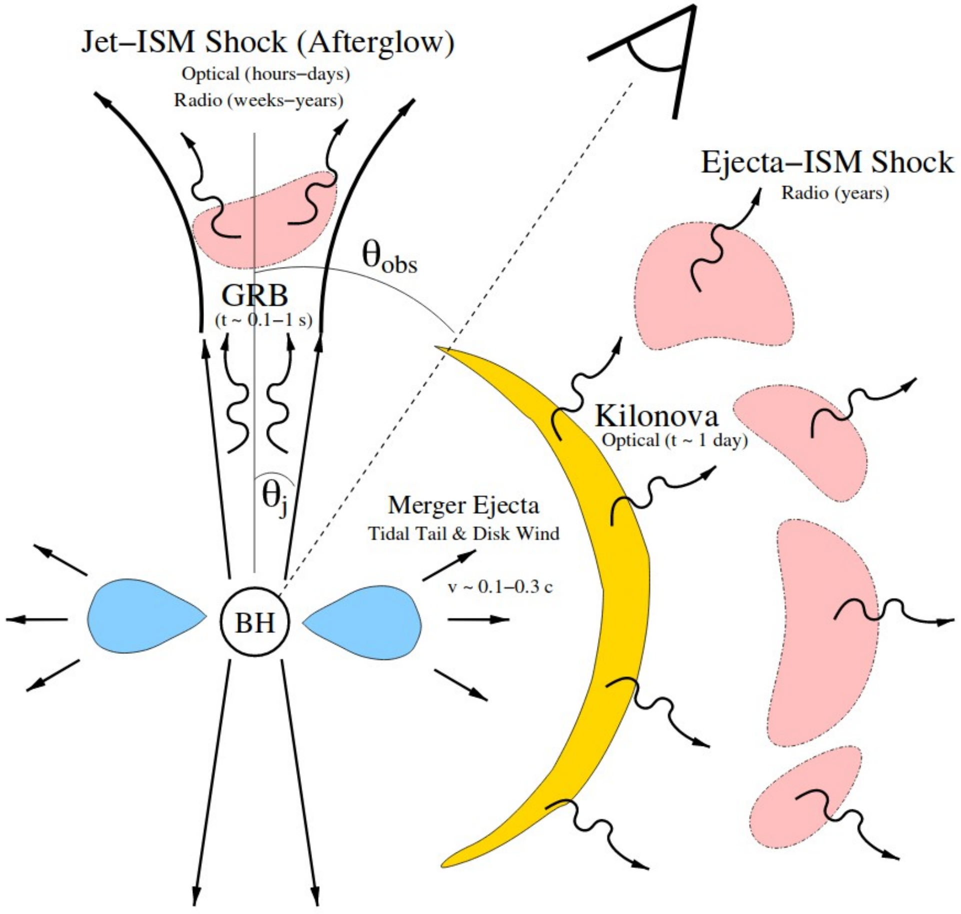
90% sky localization from Fermi and INTEGRAL timing

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!

EM emission

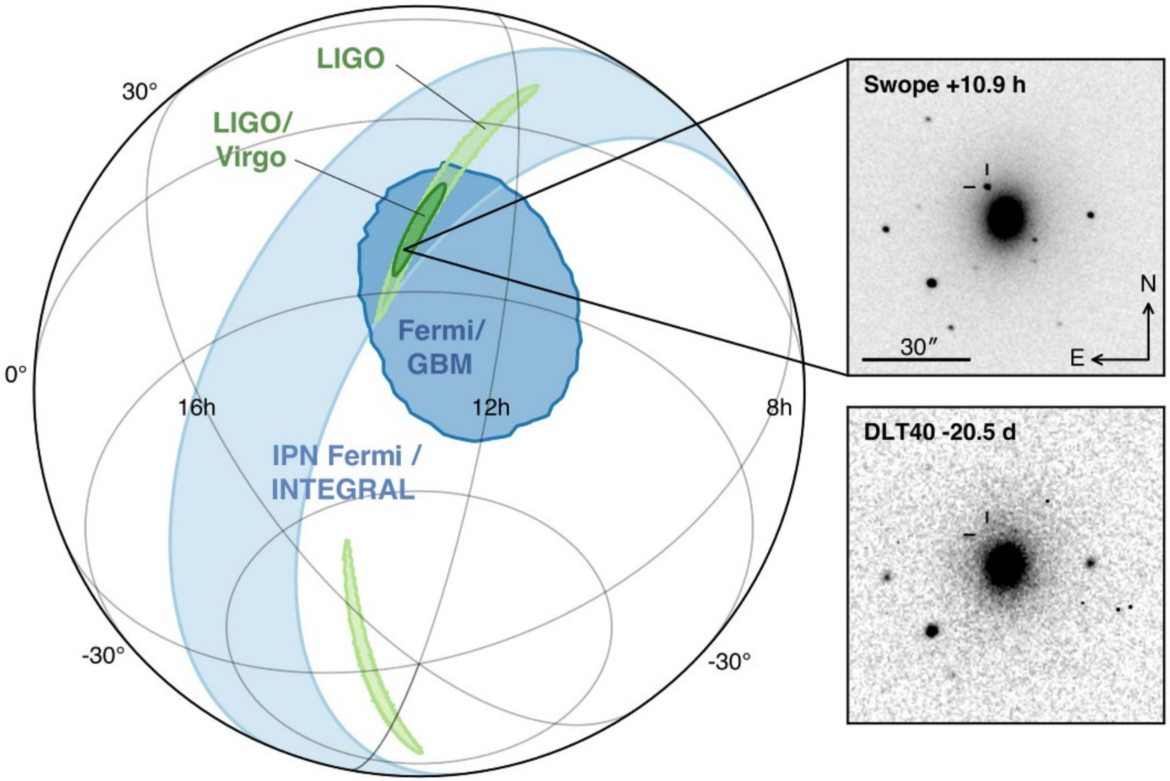


→ Merger (GW)
→ Rapid acretion (<1s)
→ Collimated relativistic jet
→ Short-duration GRB
→ Afterglow (interaction of the jet with circum-burst medium)
→ Kilonova

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

2017, Aug. 17

2017, Aug. 17

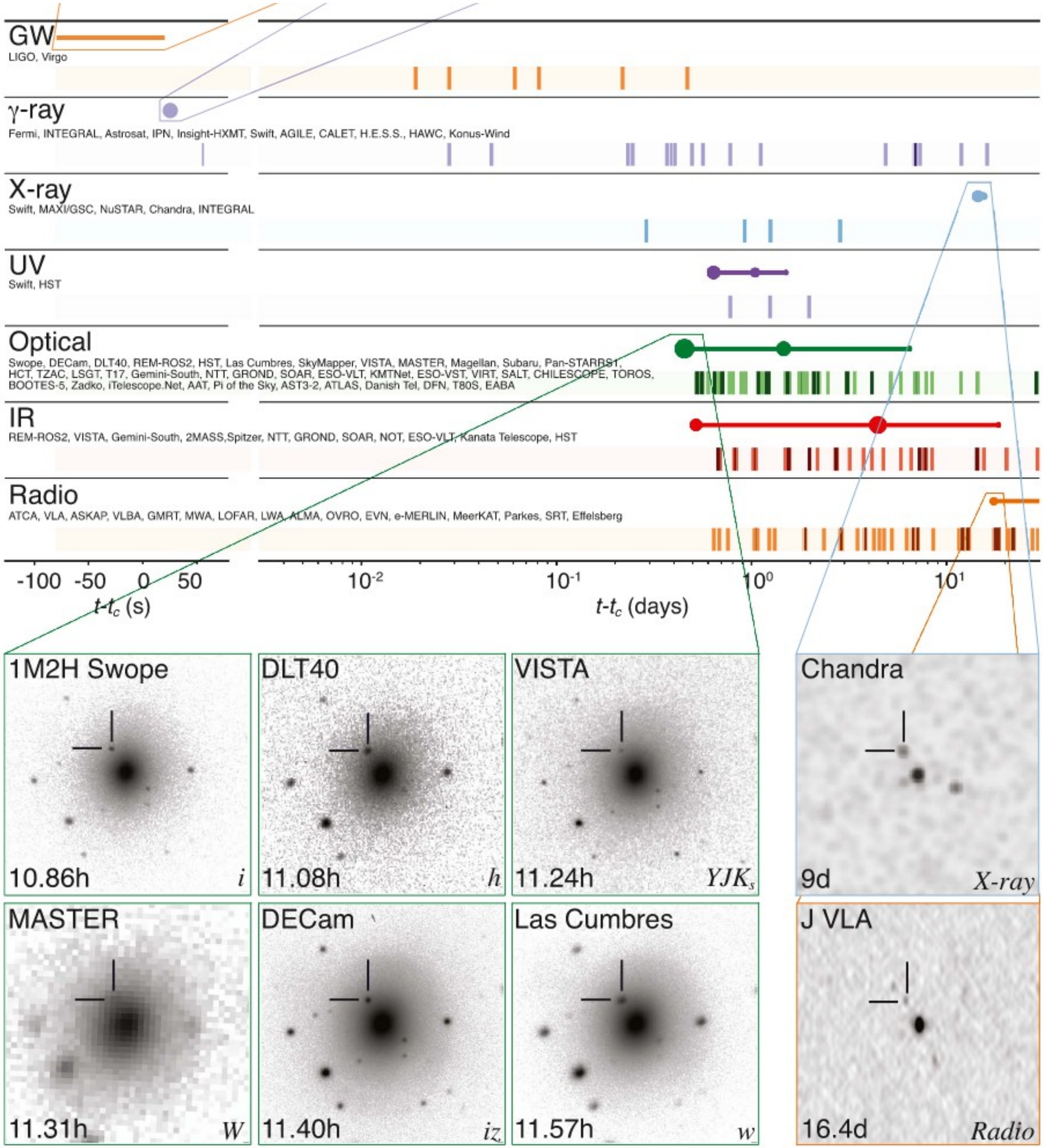


Host galaxy NGC 4993 in the Swope field of view

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

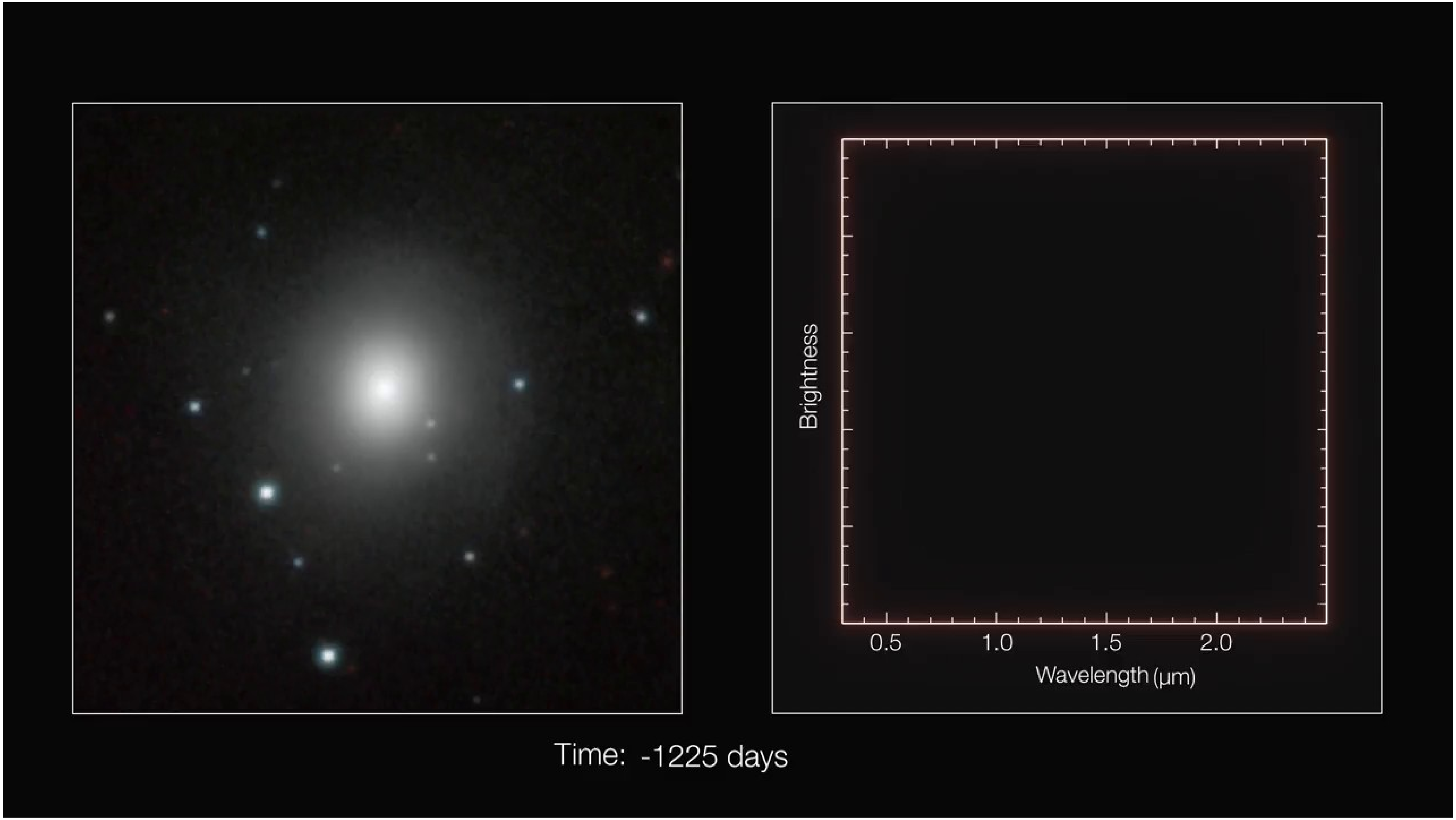


T0 = GW detection
+1.7s: Gamma ray burst detected by Fermi

+40 min: GW alert is sent

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

Spectrum measurement

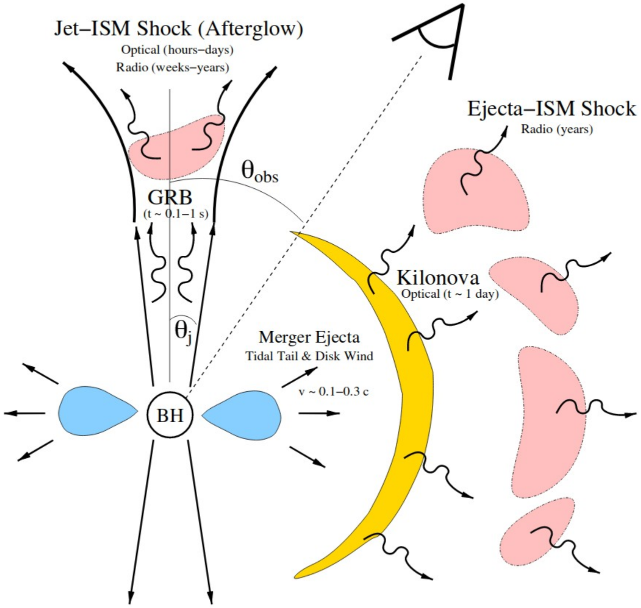


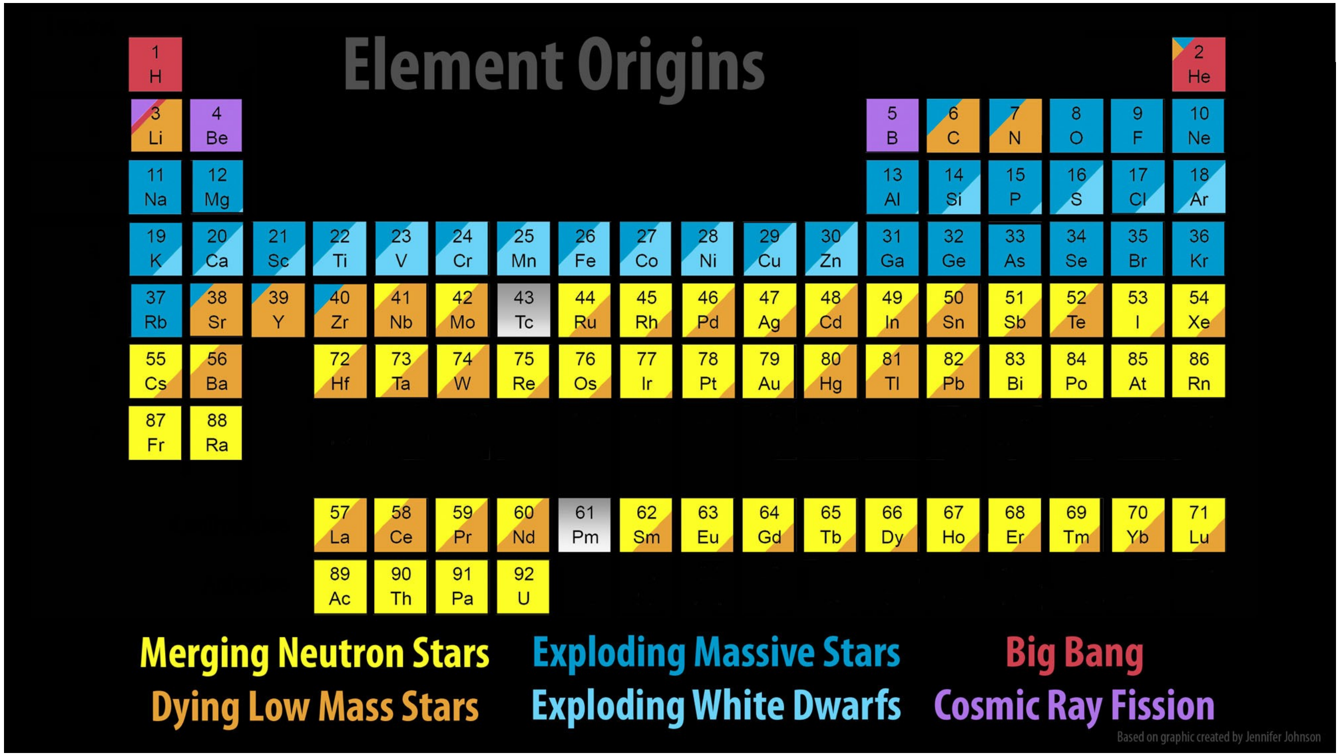
Kilonova

→ Concept introduced in 2010 by Metzger et al.

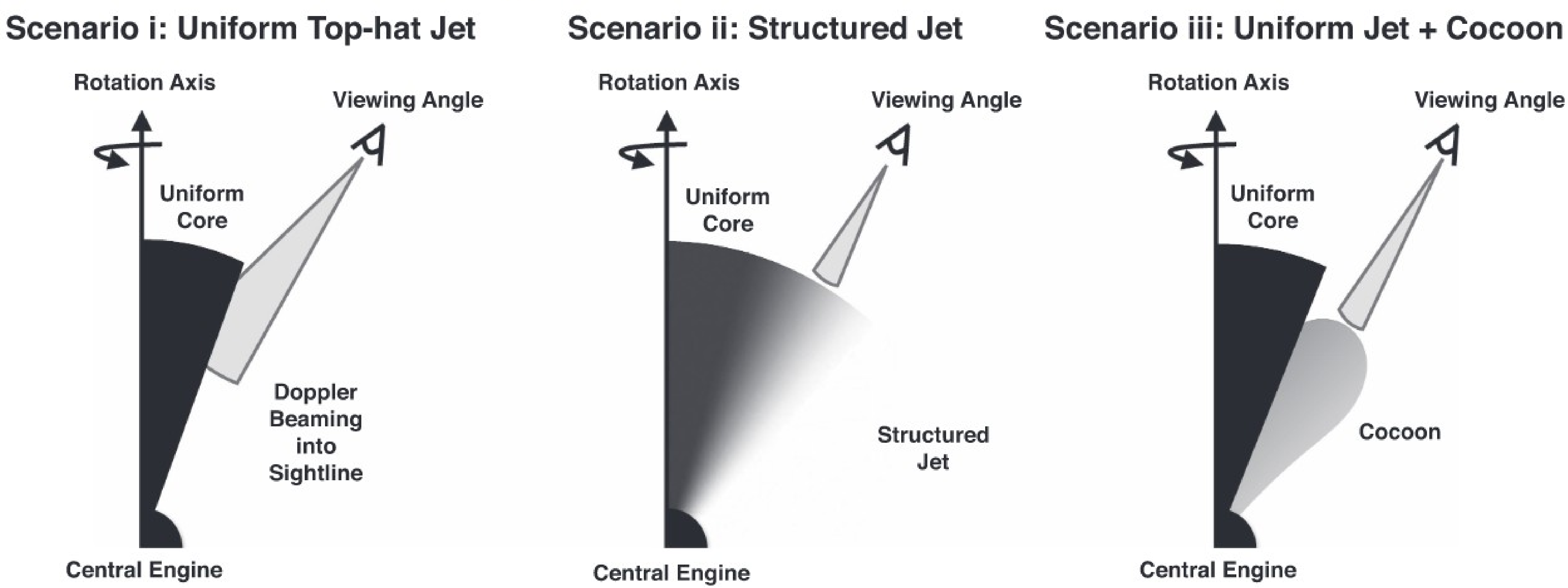
→ Main source of r-process nuclei (heavy elemen

→ First kilonova ever detected!

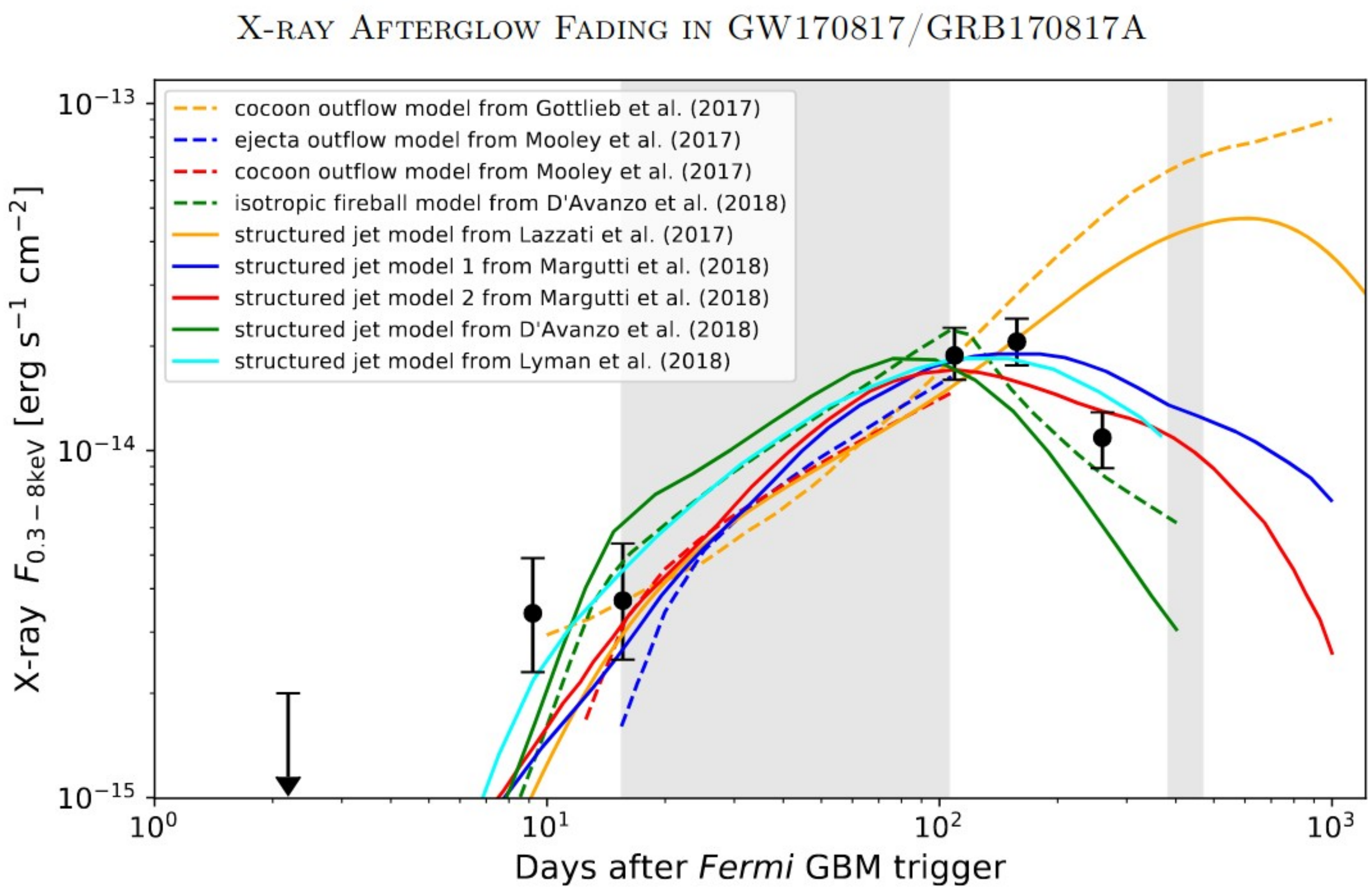




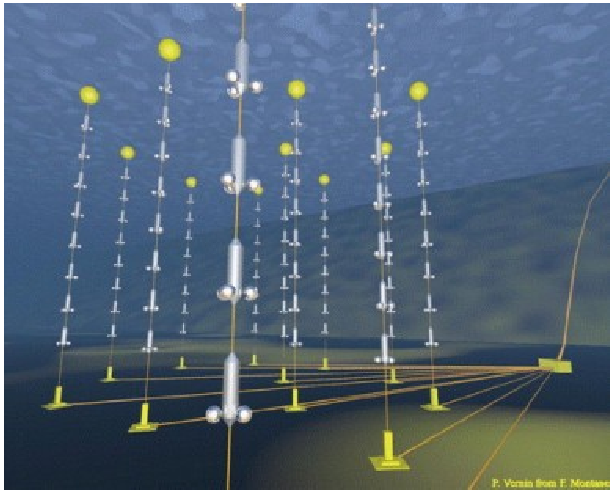
Jet geometry

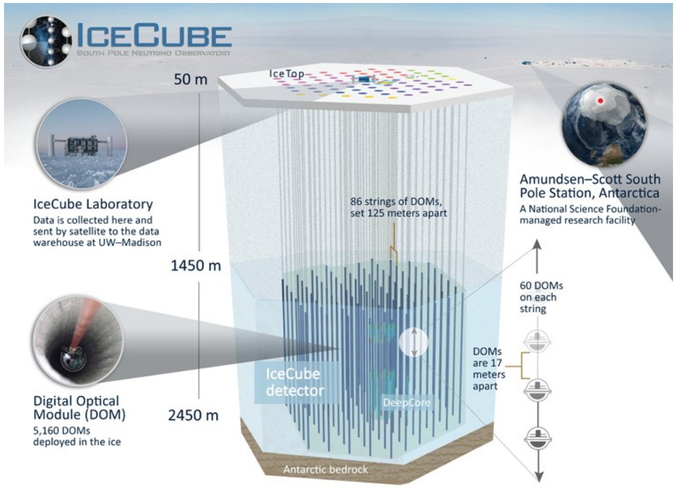


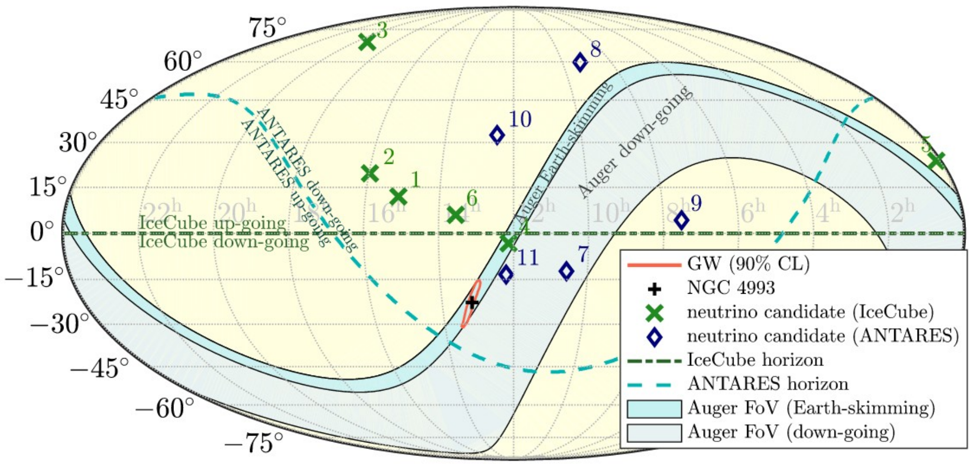
2017, Aug. 17


X-ray Afterglow Fading in GW170817/GRB170817A
cocoon outflow model from Gottlieb et al. (2017)
ejecta outflow model from Mooley et al. (2017)
cocoon outflow model from Mooley et al. (2017)
isotropic fireball model from D'Avanzo et al. (2018)
structured jet model from Lazzati et al. (2017)
structured jet model 1 from Margutti et al. (2018)
structured jet model 2 from Margutti et al. (2018)
structured jet model from D'Avanzo et al. (2018)
structured jet model from Lyman et al. (2018)
X-ray $F_{0.3-8keV}$ [erg s^{-1} cm^{-2}]
10^{-13}
10^{-14}
10^{-15}
10^0
10^1
10^2
10^3
Days after *Fermi* GBM trigger

The neutrinos

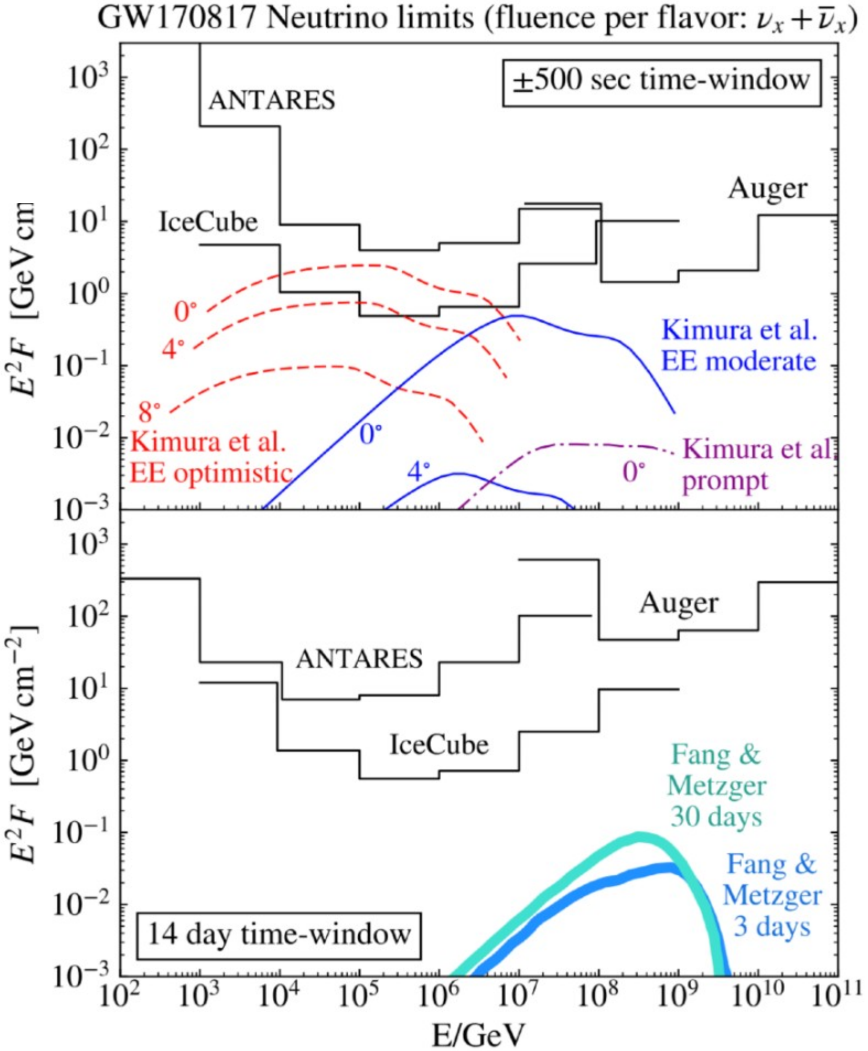






No neutrino counterparts were found by IceCube, ANTARES, and Pierre Auger within the [-500,500] second and the 14-days time window

The distance and the inclination angle of the binary neutron star merger are not expected to lead to a neutrino detection.



The neutrinos

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 will start early 2019 with improved sensitivities and will last ~1 year

- → BBH detection rate ~ 1/week
- → a few BNS events should be detected
- → population studies

→ 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)

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