Gravitational Waves Physics and Techniques

Part III: first results
& multimessenger connections

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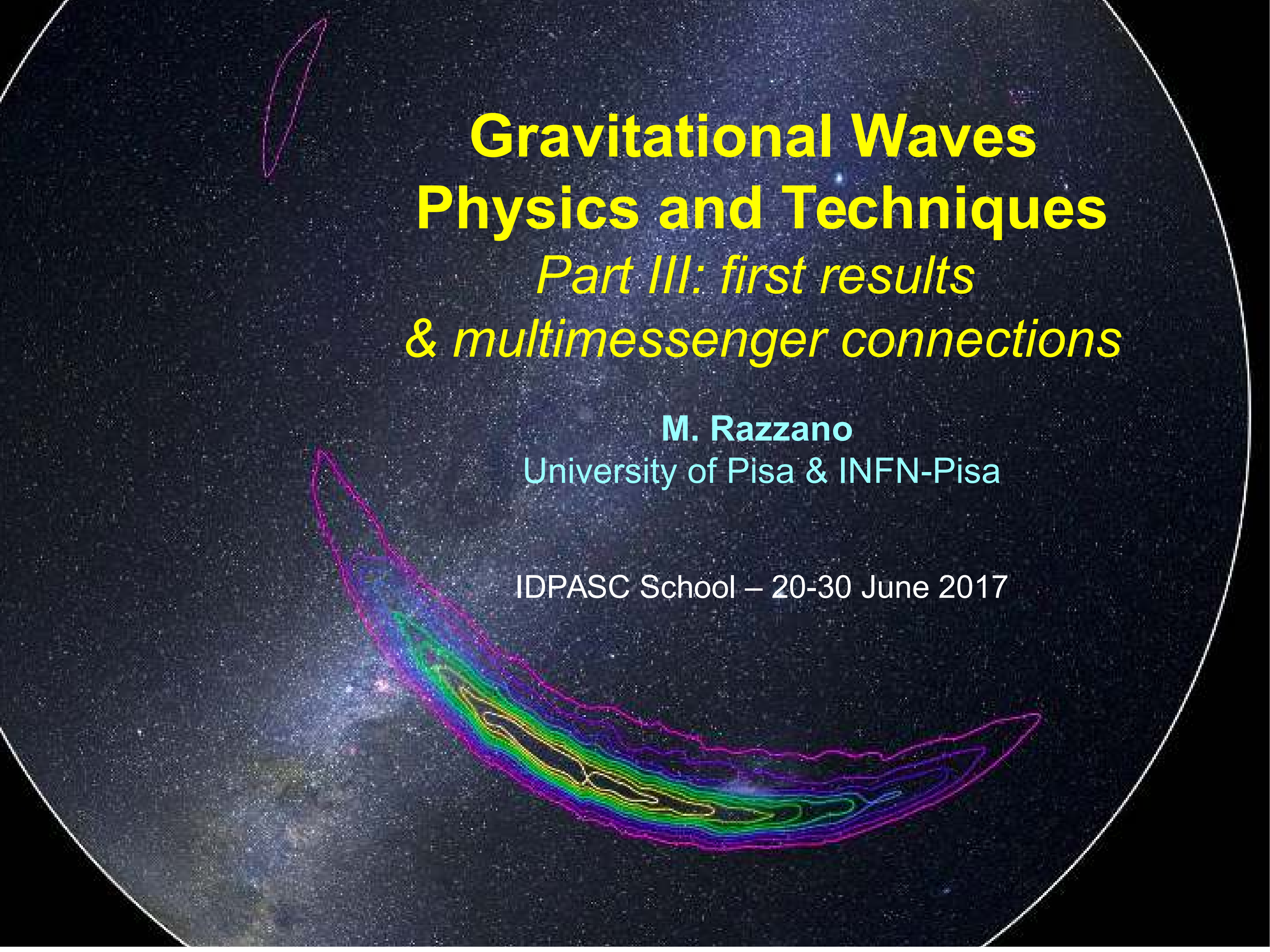
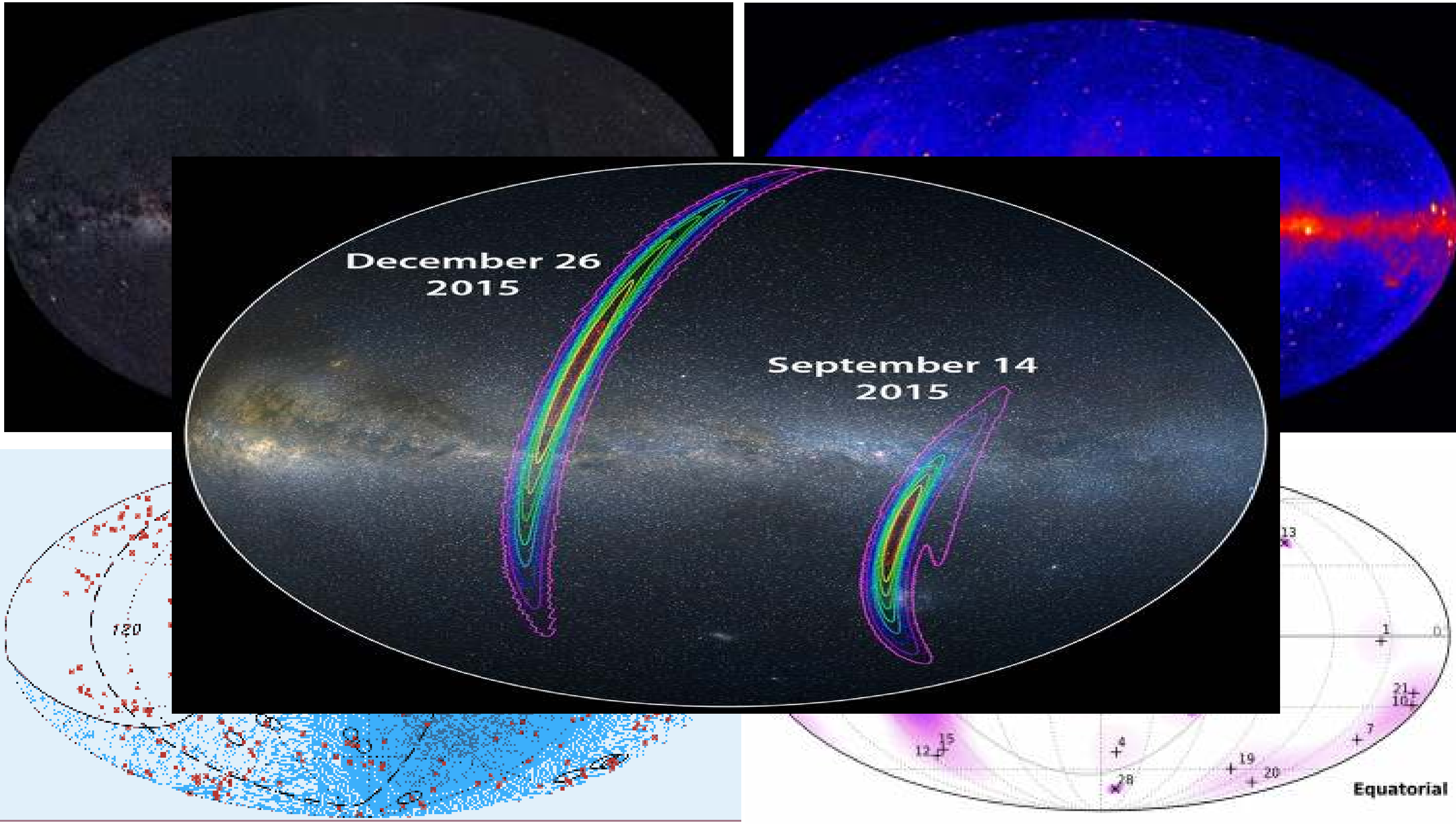
IDPASC School – 20-30 June 2017



The multi-messenger sky today

Optical (APOD)

Gamma rays > 0.1 GeV (Fermi-LAT, 2013)



Cosmic rays > 57 Eev (Auger, 2007)

Neutrinos > 30 Tev (Icecube, 2013)

*

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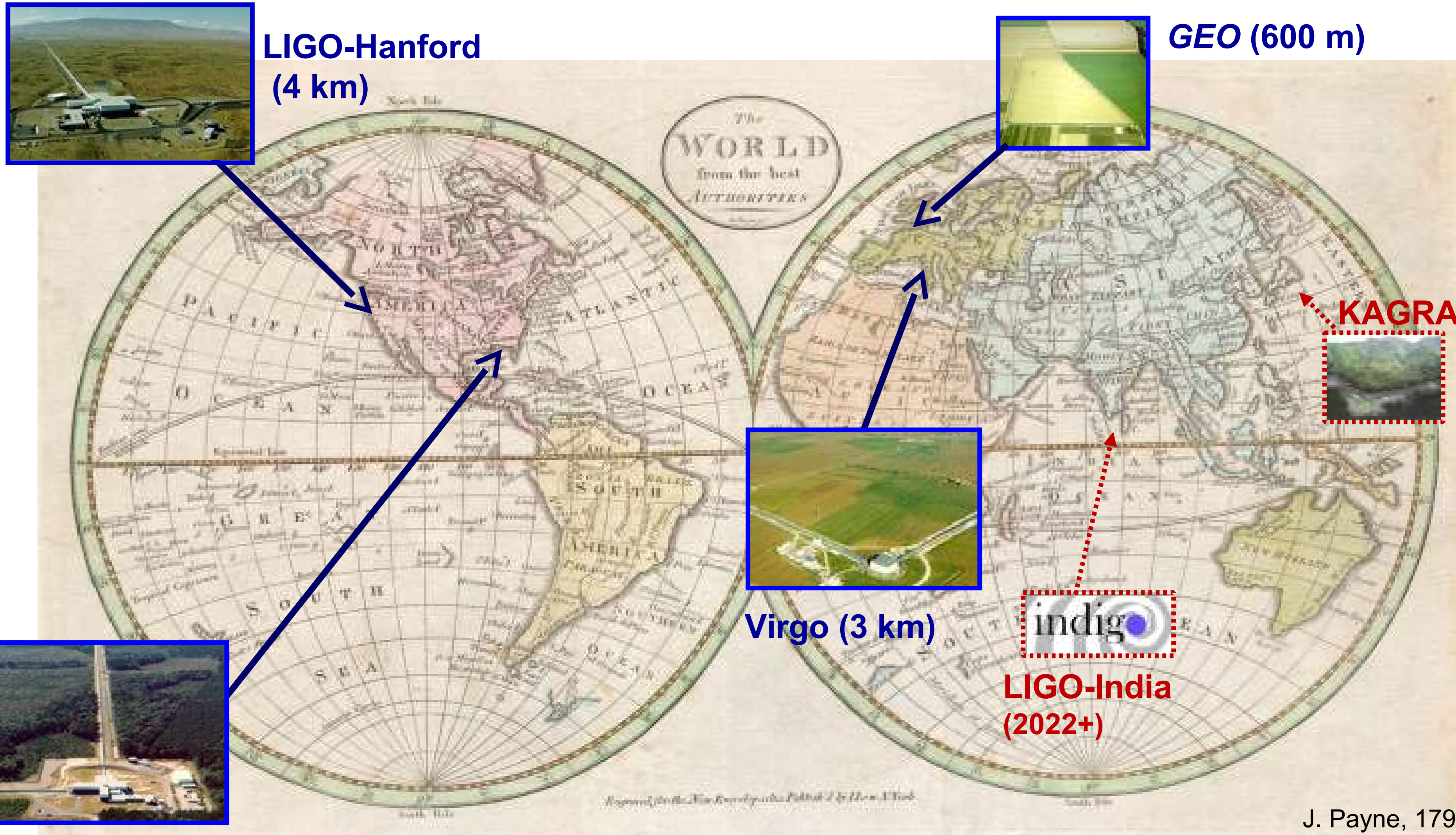
The era of Advanced GW detectors



LIGO-Livingston
(4 km)

Advanced LIGO now in its second observing run (O2)
Virgo planned to join soon

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The era of Advanced GW detectors

Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO and Advanced Virgo

Abbott, B. P. et al.
The LIGO Scientific Collaboration and the Virgo Collaboration
(The full author list and affiliations are given at the end of paper.)
email: lsc-spokesperson@ligo.org, virgo-spokesperson@ego-gw.it

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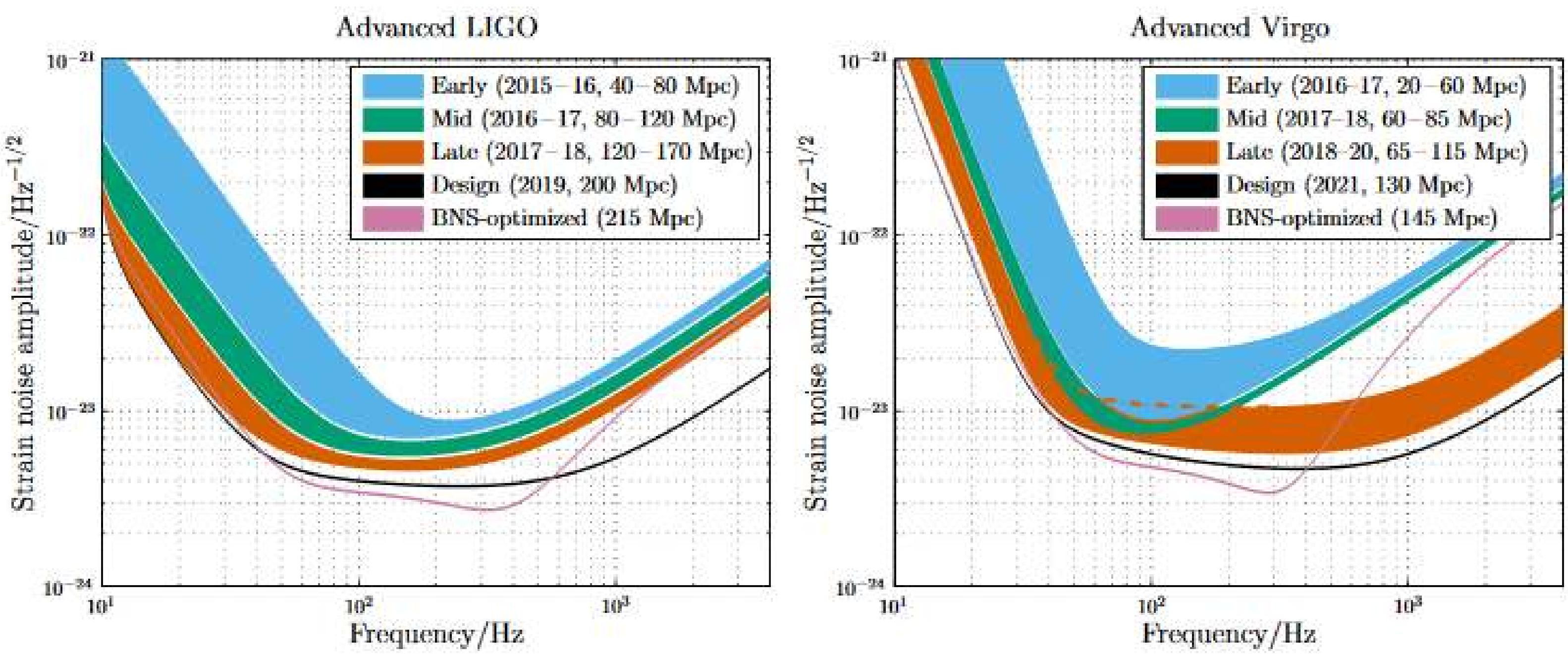

Abbott+16, LRR 19,1

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The frontier of multimessenger astronomy

LIGO

- Complementary information:
  - GWs: mass distribution
  - EM: emission processes, acceleration mechanisms, environment
  - Neutrinos: hadronic/nuclear processes, etc

- Give a precise (arcmin/arcsecond) localization
  - Localize host galaxy of a merger
  - Identify an EM counterpart with timing signature (e.g. pulsars)
  - EM follow-up to get simultaneous observations

- Provide a more complete insight into the most extreme events in the Universe

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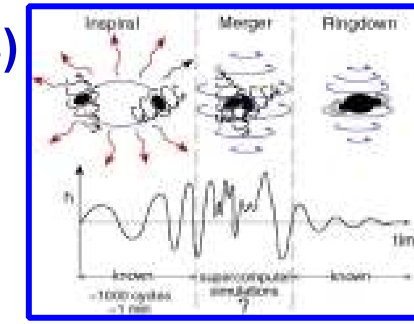
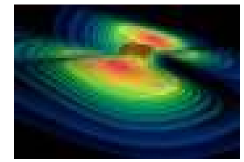
Expected multimessengers sources by Advanced LIGO/Virgo

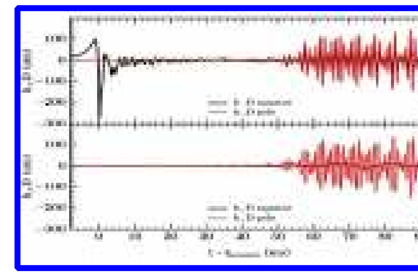
Transients

- **Coalescence of compact binary systems (NSs and/or BHs)**
  - Known waveforms (template banks)
  - $E_{gw} \sim 10^{-2}\ Mc^2$



- **Core-collapse of massive stars**
  - Uncertain waveforms
  - $E_{gw} \sim 10^{-8} - 10^{-4}\ Mc^2$



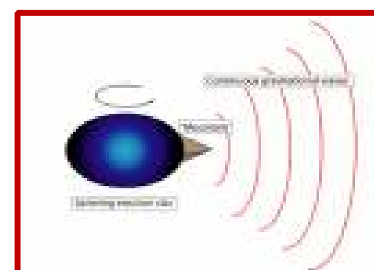


Ott, C. 2009

Non transients

- **Rotating neutron stars**
  - Quadrupole emission from star's asymmetry
  - Continuous and Periodic

- **Stochastic background**
  - Superposition of many signals (mergers, cosmological, etc)
  - Low frequency



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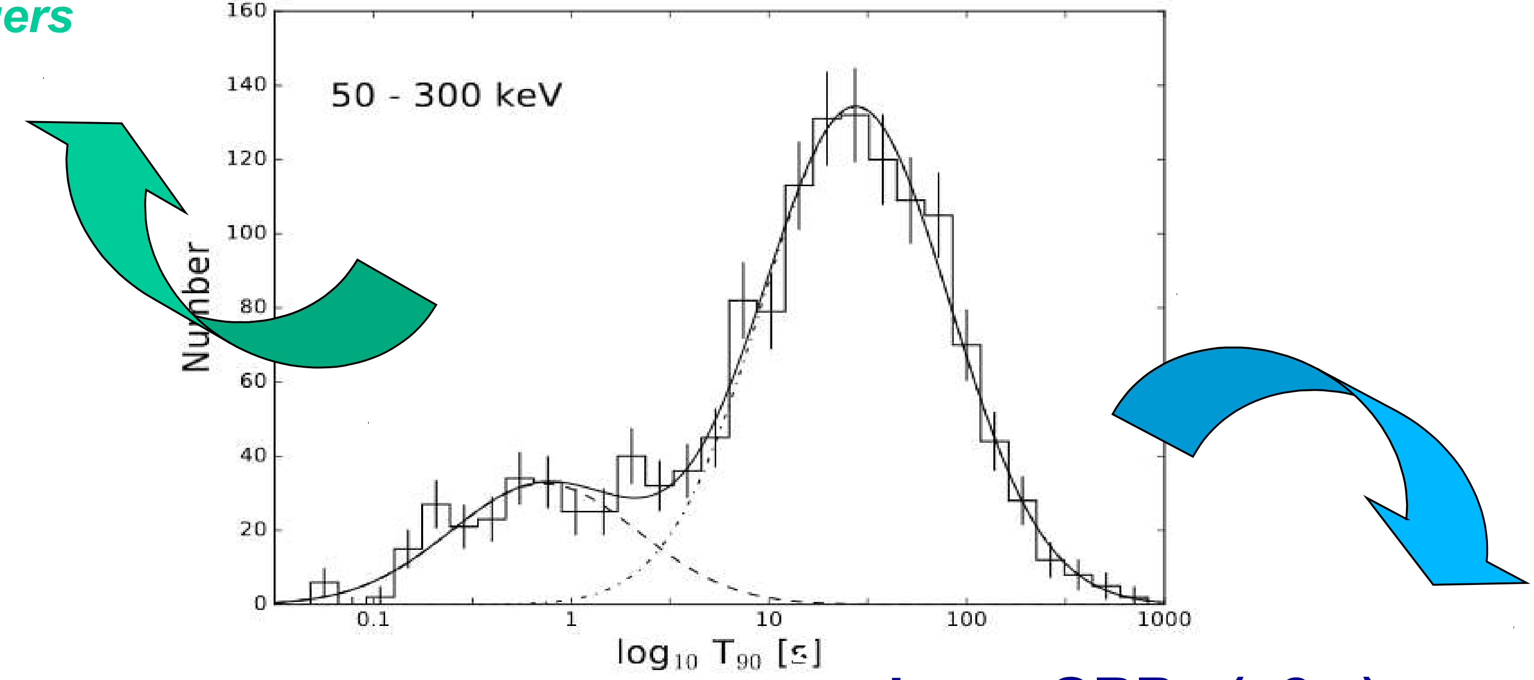
Science case for EM follow-up: the GRB connection

Short GRBs (<2 s)

believed to be associated with mergers

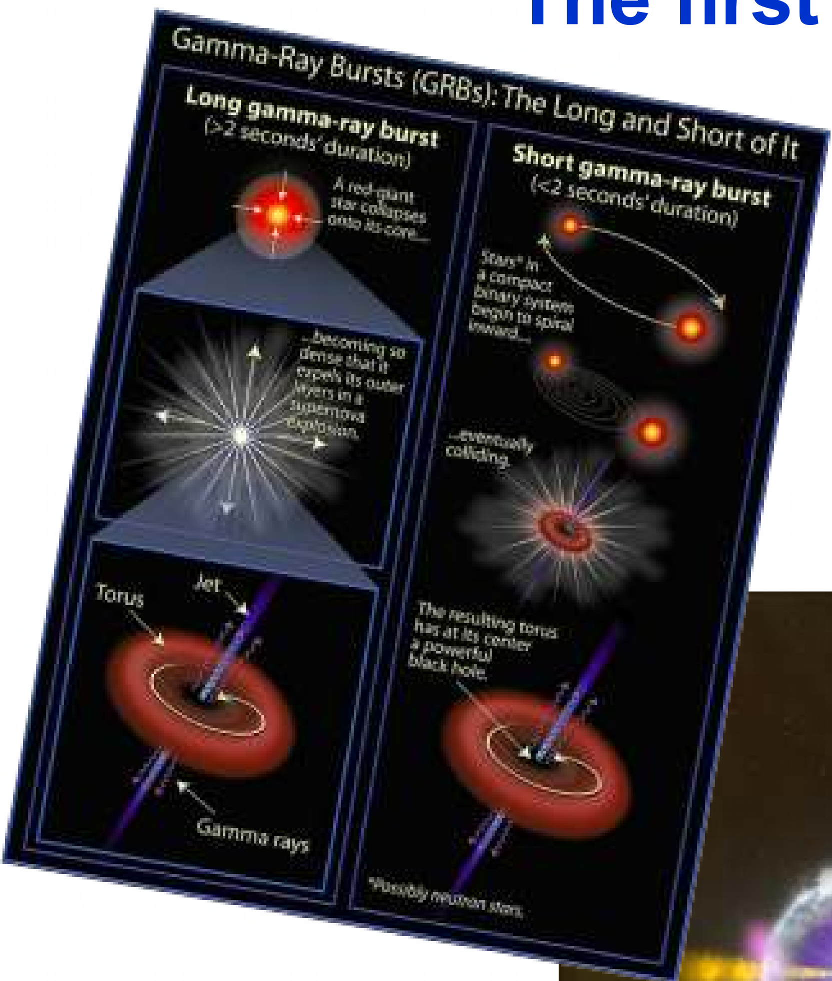


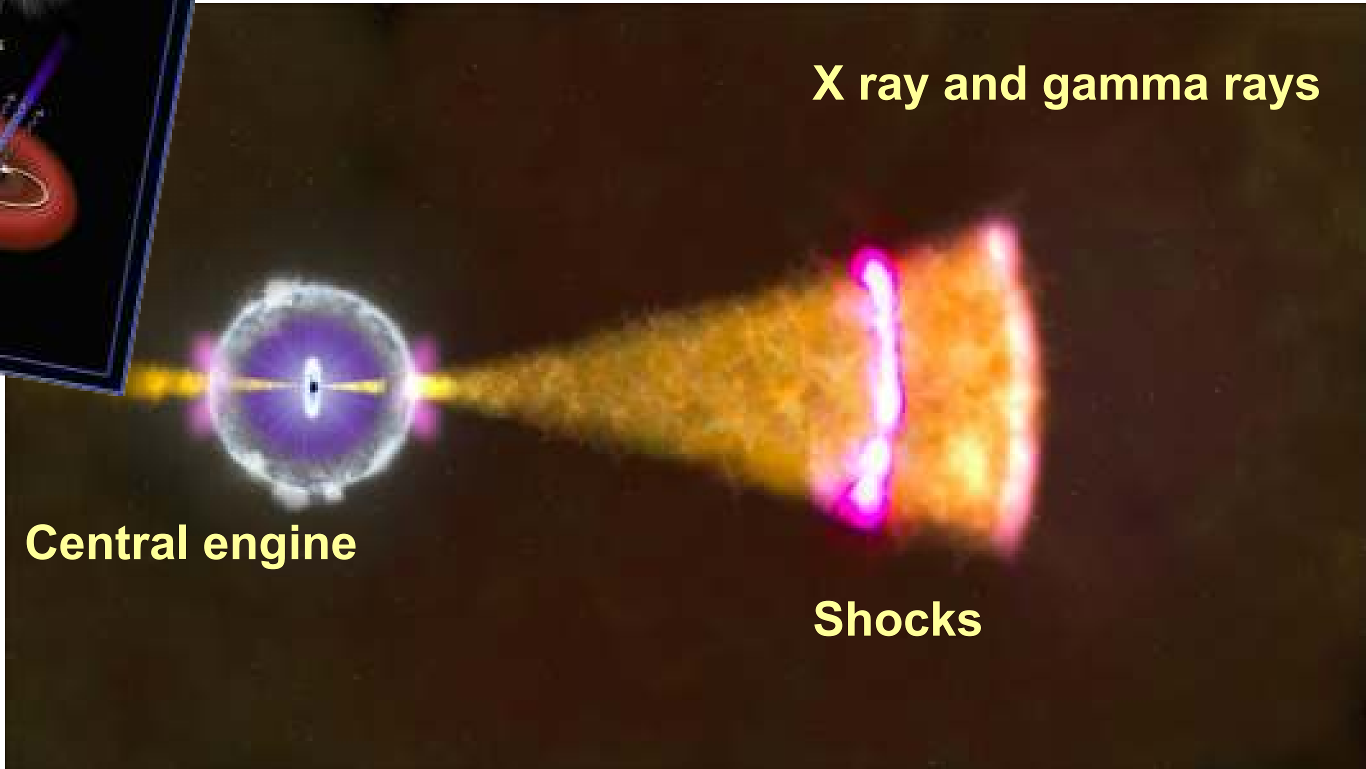
Long GRBs (>2 s)

Believed to be associated with core-collapse of massive stars

3rd GBM catalog
Narayana Bhat+, ApJS,223 (2016)

The first synergy: GRBs





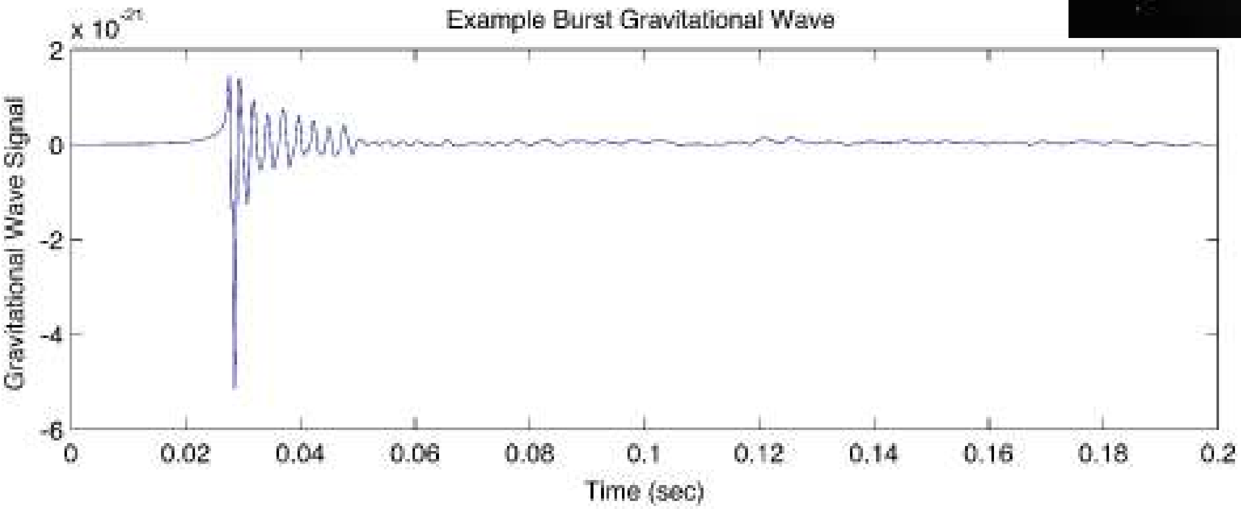
Credits: D. Darling (top), NASA (right)

Other transients – Supernovae

Stellar explosions

- What is the physical mechanisms behind Supernovae?
- What is the structure/asymmetry during collapse?
- Many inputs beyond GW are required
- X and MeV energies observations are very important

Credits: ESO/L. Calcada



Credits: A. Stuver/LIGO, using data from C. Ott, D. Burrows, et al

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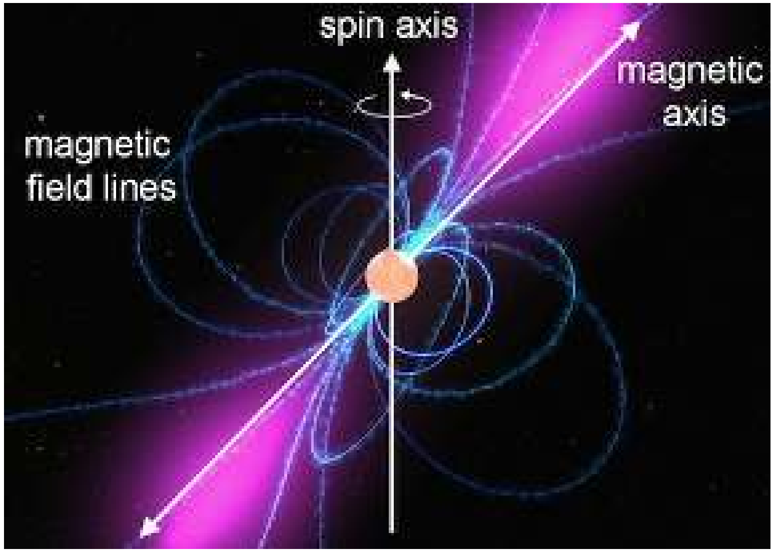
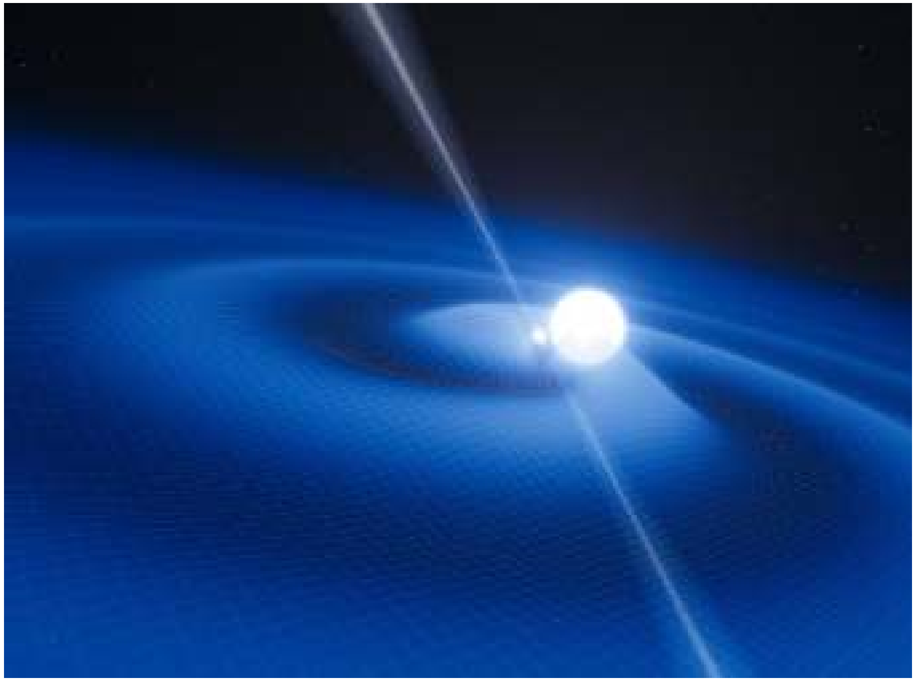
Continuous sources– Neutron Stars

Continuous Waves

- Non-linear instabilities and NS evolution
- Explore the nature of the NS crust
- Glitches
- Gamma-ray monitoring very useful to search for GWs from known pulsars



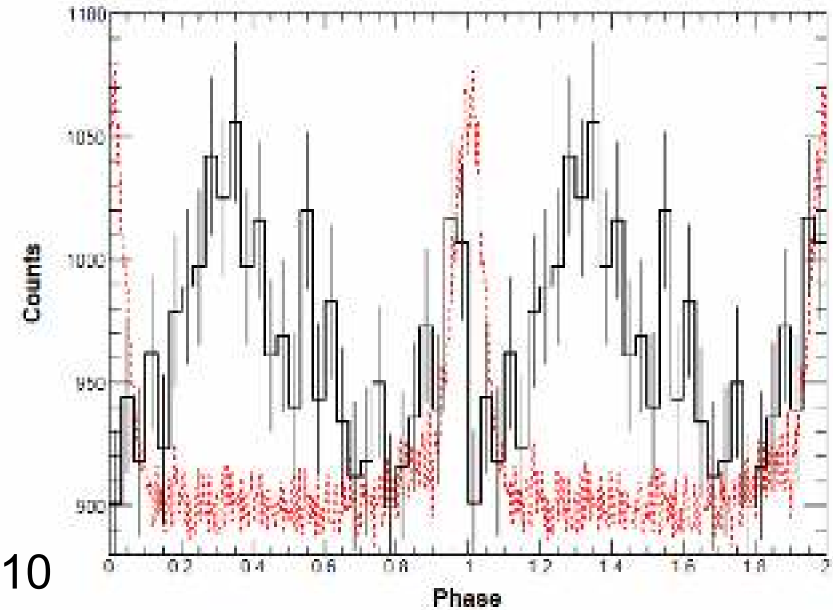
Credits: NASA



Credits: ESO/L. Calcada

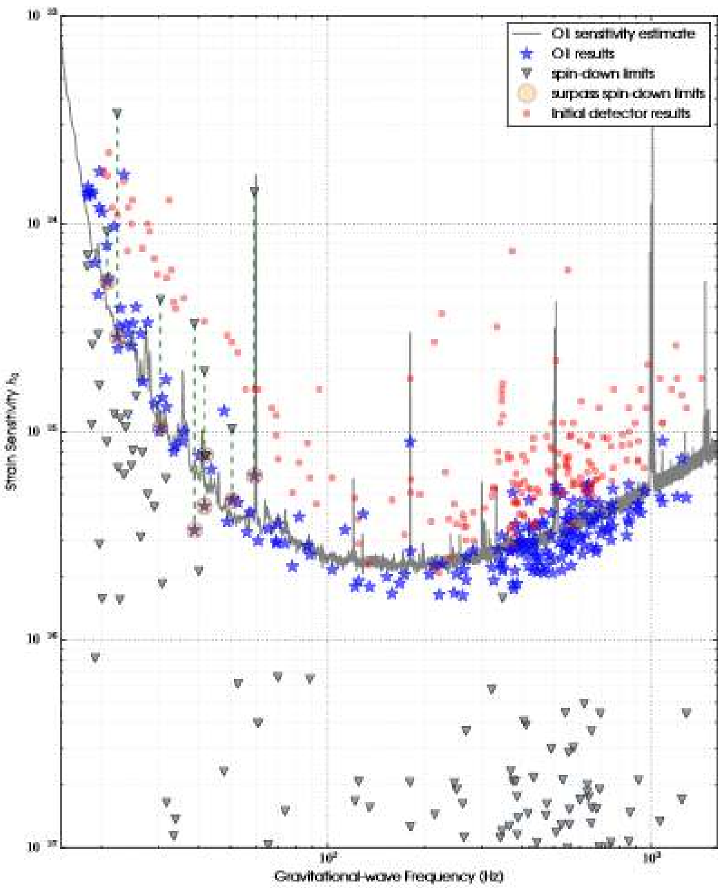
Continuous sources– Neutron Stars

- High-B pulsars at MeV energies
- PSR B1509-59 is one of the candidate

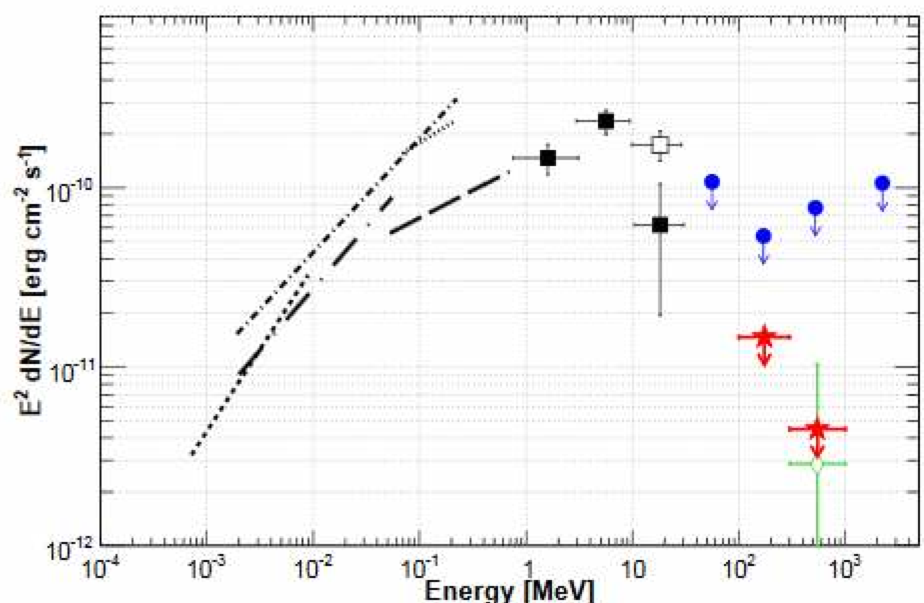


Abdo+2010

FIG. 1. — Light curve of the pulsar PSR B1509−58 above 30 MeV within an energy-dependent circular region, as described in Sec 3.1.3. The light curve profile is binned to 1/30 of pulsar phase. The radio profile (red dashed line) is overlaid in arbitrary units. The ... peak of the radio pulse seen at 1.4 GHz is at phase 0. Two cycles are shown.

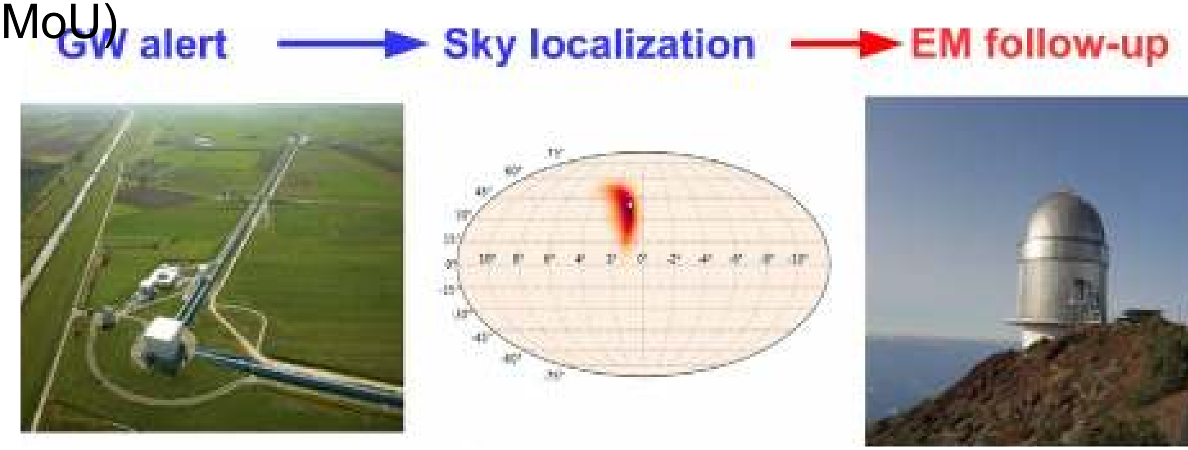


Abbot+17



Back to the EM follow-up…

- Past experiences (2009-2010)
  - ~30 min latency, optical telescopes+Swift
  - Centralized organization
- Now (2015-)
  - Few mins latency
  - GCN alerts for EM partners (MoU)
  - Broadband coverage



EM event	EM band	Timescale
Prompt emission	Gamma rays	<seconds
Afterglow	X-ray, optical, radio	Hours-days
Kilonova-macronova	Optical-near IR	Days-weeks
Radio blast wave	Radio	Months-years

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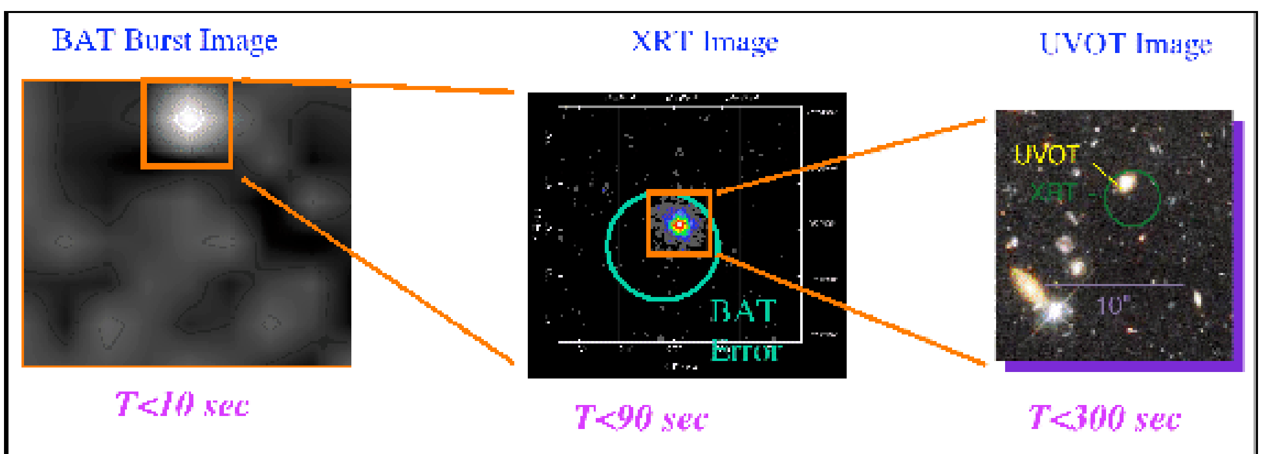
A needle in a haystack: an example from the past

Find a counterpart is not easy!

- **EM Transients might be**
  - **Fast**
  - **Faint**
  - **Too many**

- **Finding counterparts of GRBs was quite difficult**

- **For GWs, the situation is worse...**



Credits: NASA

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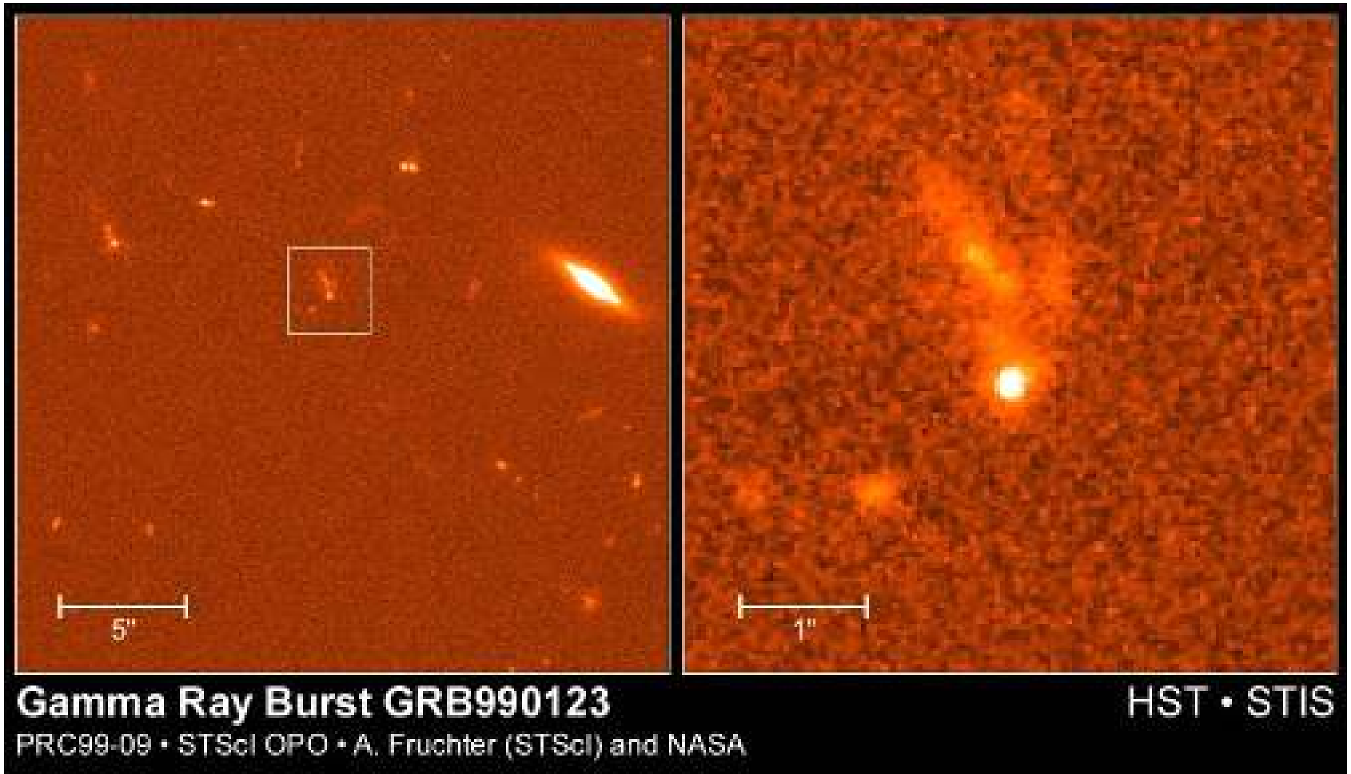
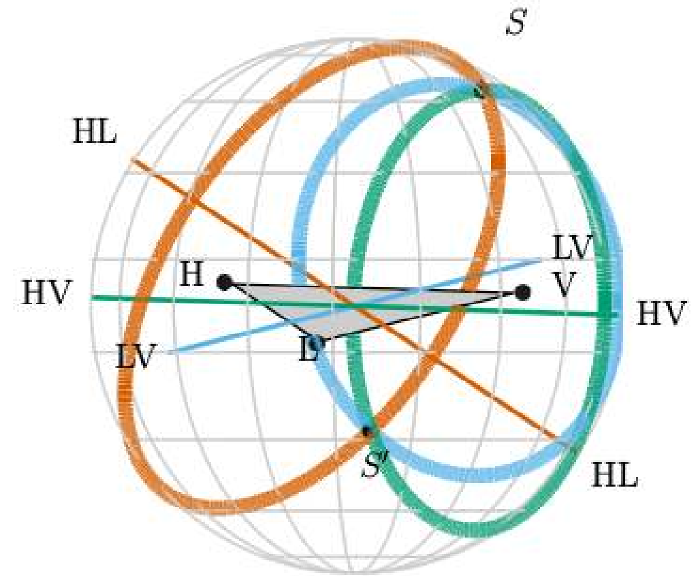
EM follow-up : key challenges

- What is the best observing strategy?
  - Scan the full error box?
  - Look only to specific regions (e.g. potential galaxy hosts?)
  - How to identify the potential host?
- If there is more than one candidate…
  - How can we uniquely identify it?
  - How can models help us?

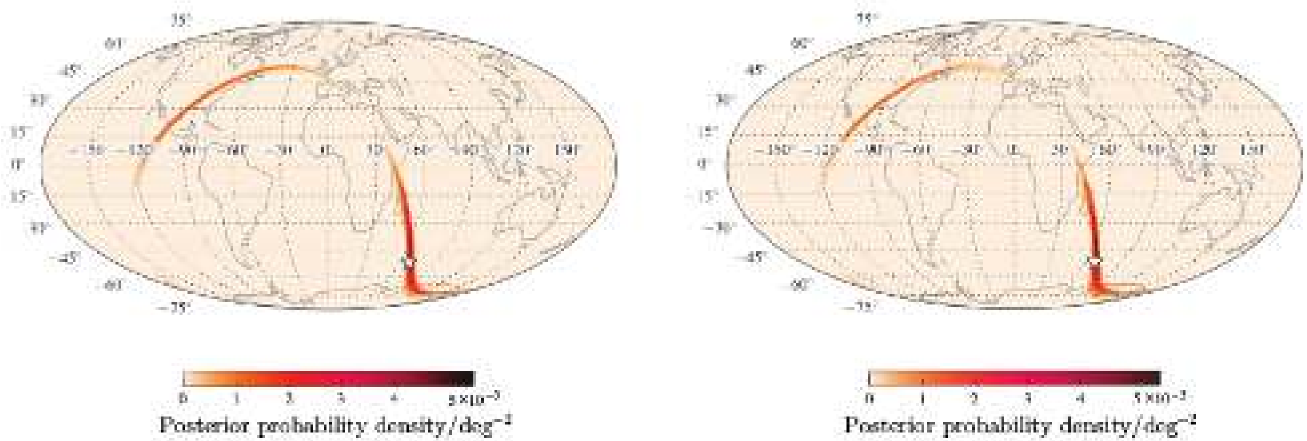


Sky Localization of GW transients

- “Triangulation” using temporal delays
- Depends on the SNR
- Low SNR → large error box (tens – hundreds sq deg)
- Wide-fov telescopes are required!



Abbott+16, LRR 19,1



Abbott+16, LRR 19,1

BNS system, SNR ~13.2
LALINFERENCE (left), BAYESTAR (right)

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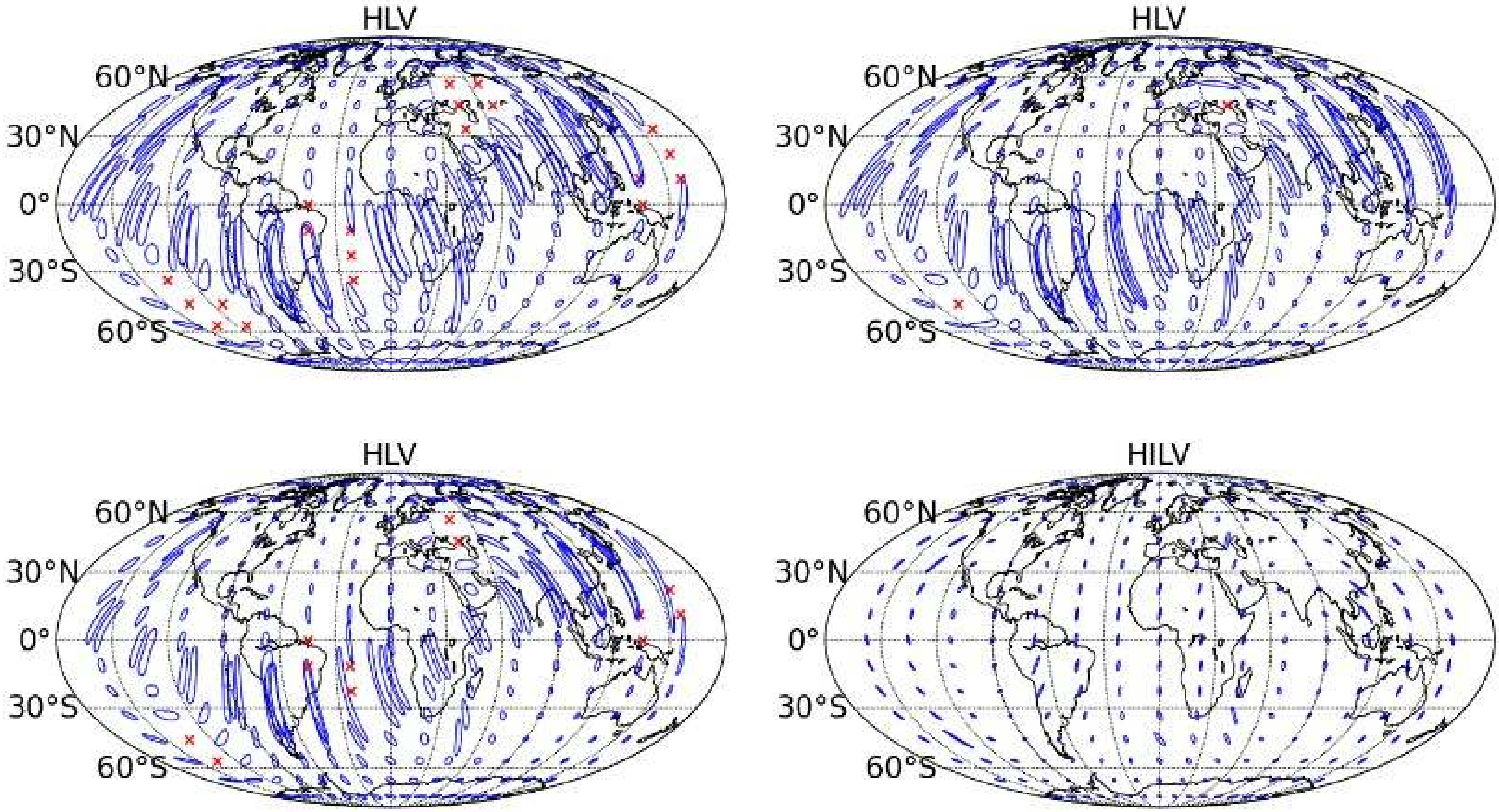
Sky Localization

BNS, 80 Mpc

2016-17

2017-18



2019+

2022+

BNS, 160 Mpc

90% CL

X

No detection

Abbott+16, LRR 19,1

EM follow-up: the role of gamma-ray telescopes

- GRBs are very energetic phenomena
  - Best candidates for GWs from NS/NS system
  - Clearly, strong HE emitters too

- Gamma-ray telescopes are very useful
  - Large FoV & good localization
  - Kev-MeV-GeV energy coverage
  - Gamma sky not so crowded as optical one
  - However, detection required jet alignment (cuts event rate) (e.g. Patricelli,MR+16)

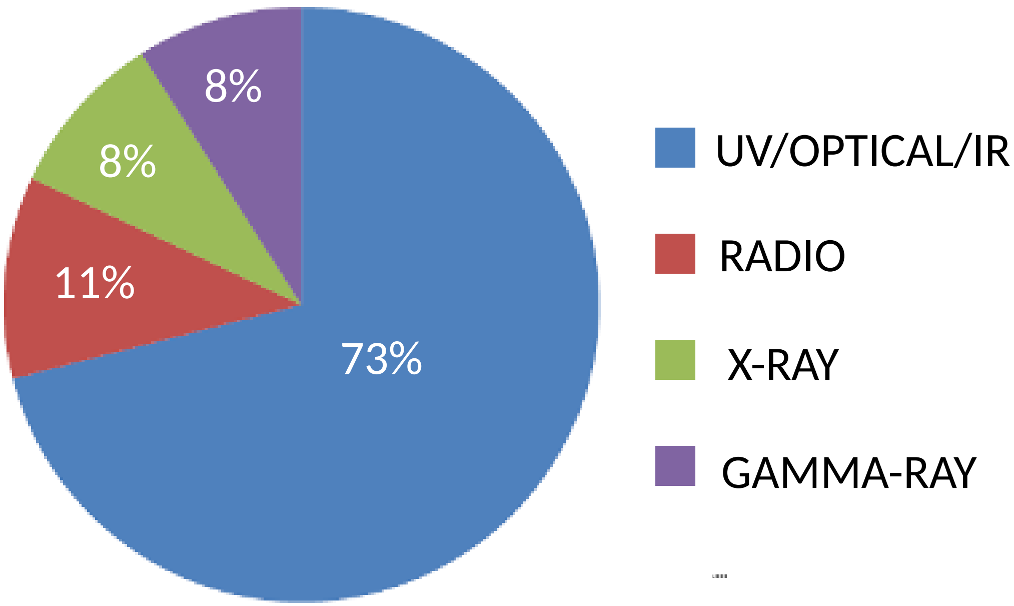
Why an EM follow-up program?

- EM follow-up is key to find counterparts (and do great science)
  - GW analysis and checks require time
  - Need to avoid misinformation/rumors
  - Encourage multiwavelength coverage

- LV-EM follow-up program
  - Standard MoU to share information promptly while maintaning confidentiality for event candidates
  - GW alerts sent to partners through private GCN notices/circulars
  - Once first few (>=4) detections, prompt alerts will be made public for high-significance detections (FAR<1/100 yrs)

- Status
  - 85 groups have signed MoU with LIGO & Virgo
  - From radio to gamma rays
  - Special LVC GCN Notices and Circulars with distribution limited to partners

LIGO and Virgo EM follow-up program



Now 85 MoUs involving

➢ **160 instruments**
(space and ground-based facilities)
Broadband, radio – VHE gamma rays

➢ **Astronomical institutions, agencies and large/small groups of astronomers** (20 countries)

In 2012, **LVC agreed policy on releasing GW alerts**

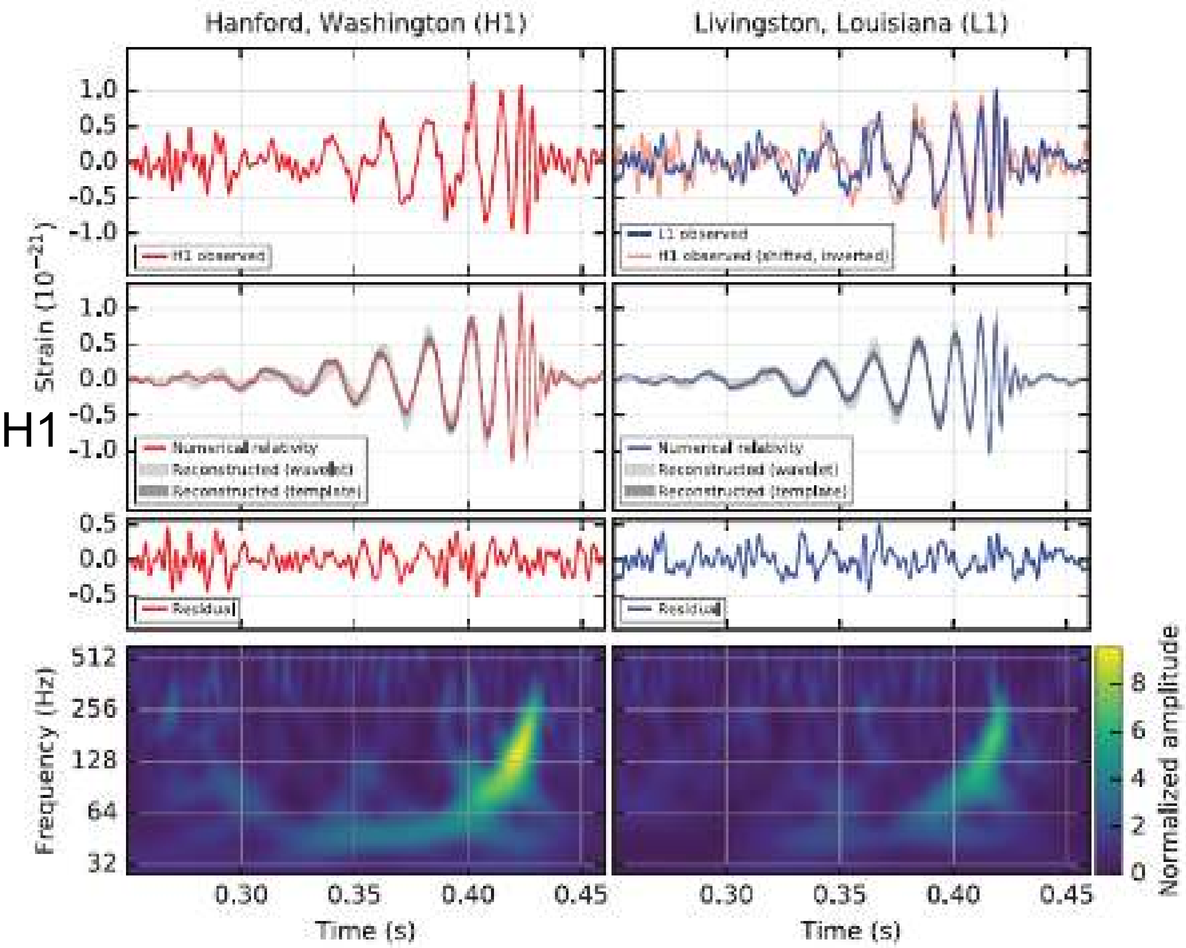
*“Initially, **triggers** (partially-validated event candidates) will be **shared promptly only with astronomy partners who have signed a Memorandum of Understanding** (MoU) with LVC involving an agreement on deliverables, publication policies, confidentiality, and reporting.*

***After four GW events have been published**, further event candidates with high confidence will be **shared immediately with the entire astronomy community**, while lower-significance candidates will continue to be shared promptly only with partners who have signed an MoU.”*

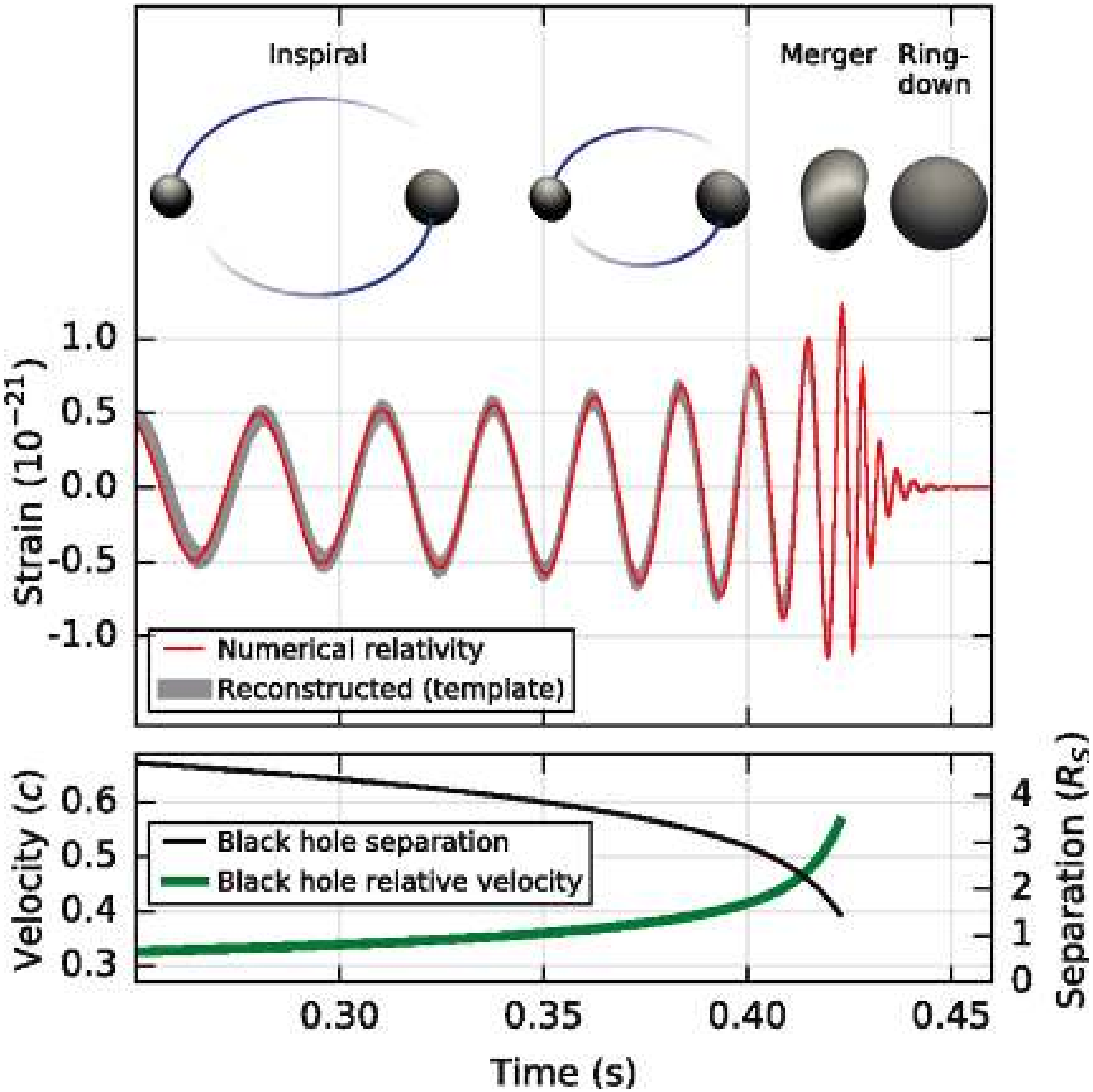
- First (2014), second (2015) and third (2016) open calls for participation in GW-EM follow-up program **85 MoUs signed**
- **http://www.ligo.org/scientists/GWEMalerts.php**

Opening the GW window

- GW150914
- Abbott+16, PRL116,6
- Sep 14, 2017 9:50 UTC
- Delay 7ms between L1 and H1
- Duration 0.2 s
- Freq: 35 -150 Hz
- $M_{chirp} \approx 30\ M_{sol}$

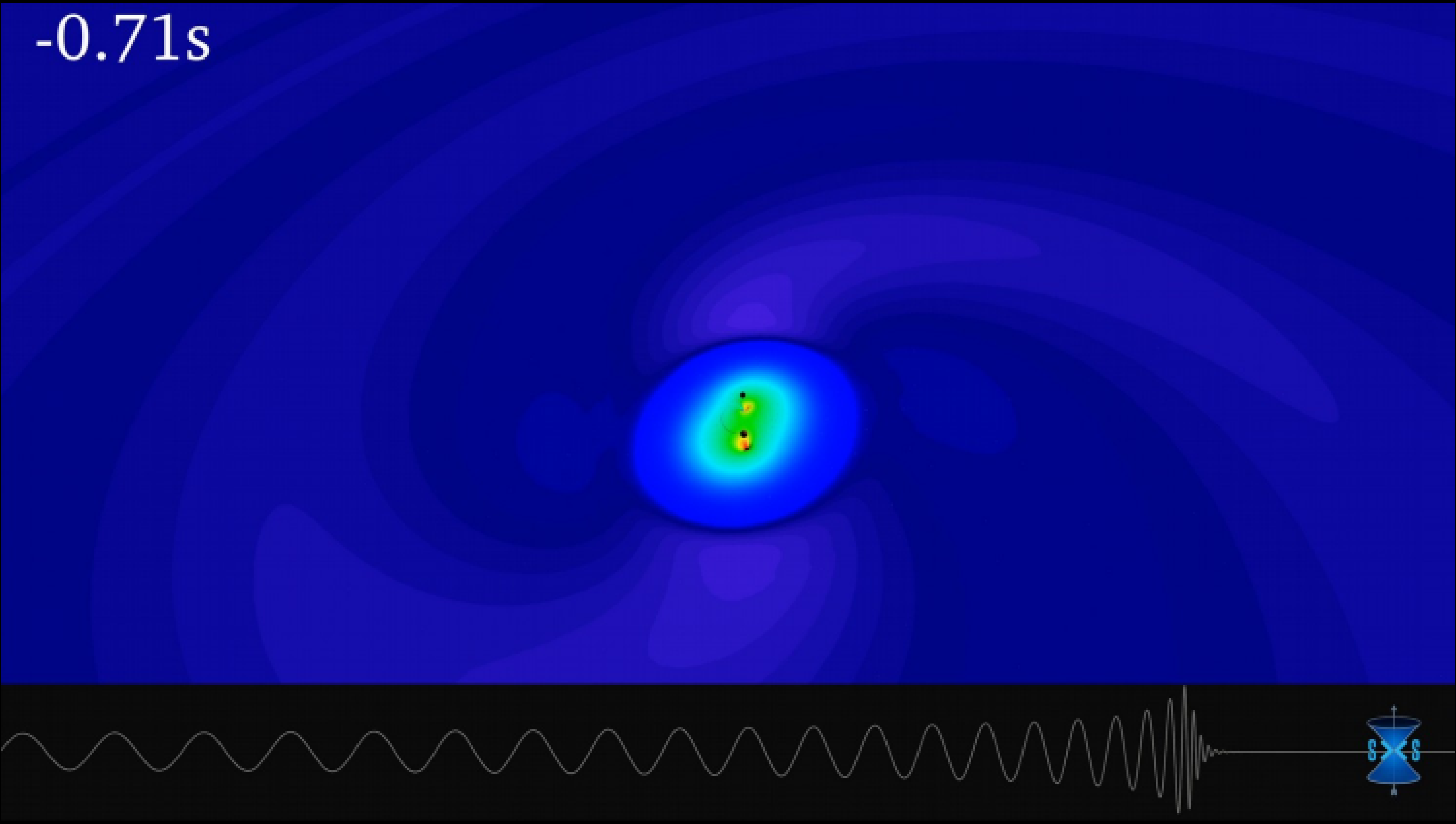


GW150914



GW150914
Abbott+16, PRL116,6

GW150914 simulation



Facts about GW150914

GW150914:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; SIMULATION OF BLACK HOLE HORIZONS (MIDDLE-TOP), BEST FIT WAVEFORM (MIDDLE-BOTTOM)

first direct detection of gravitational waves (GW) and first direct observation of a black hole binary

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	< 1 in 5 million
false alarm rate	< 1 in 200,000 yr
Source Masses	M⊙
total mass	60 to 70
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	58 to 67
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.57 to 0.72
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

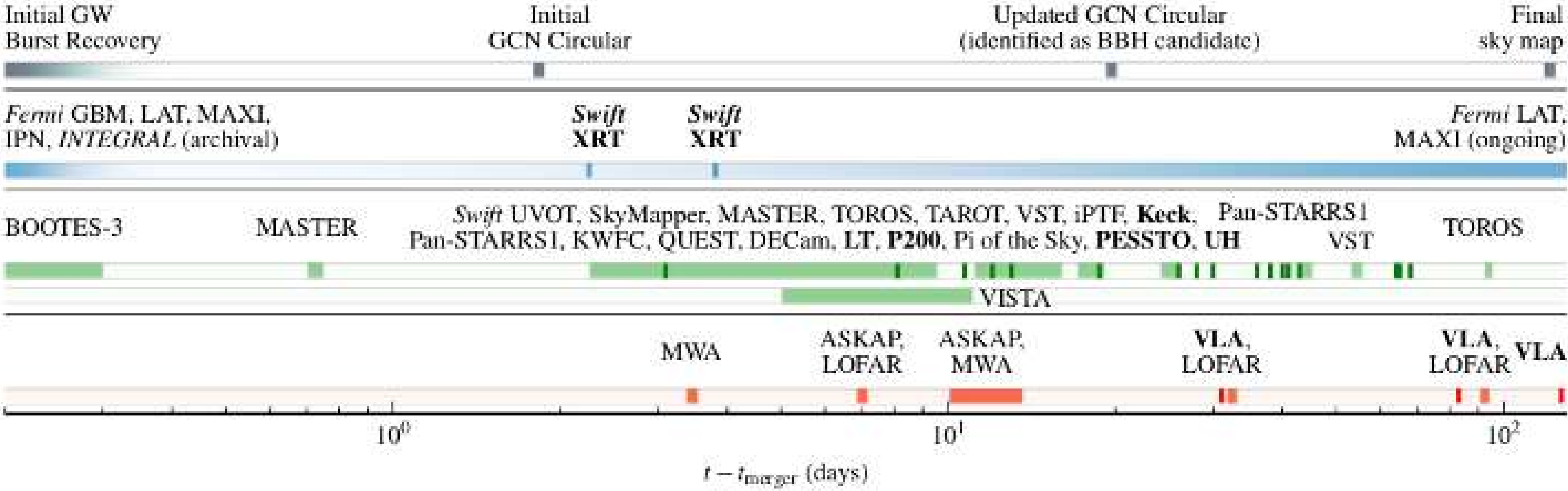
duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate of binary black holes	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameter ranges correspond to 90% credible bounds. Acronyms: L1=LIGO Livingston, H1=LIGO Hanford; Gly=giga lightyear=9.46×10^{12} km; Mpc=mega parsec=3.2 million lightyear, Gpc=10^3 Mpc, fm=femtometer=10^{-15} m, M⊙=1 solar mass=2×10^{30} kg

GW150914
Abbott+16, PRL116,6

The GW150914 follow-up

- t+few minutes: cWB & oLIB pipelines
  - T+17 min – 14 hr (skymaps)
    - T+2d: first alert (after many checks)
      - T+3w (Oct 3): BBH identification
        - T+4m (Oct 20) updated FAR (<1/100 yr)



Abbott+16, ApJ 826, 13

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GW150914 sky maps

Localization pipelines

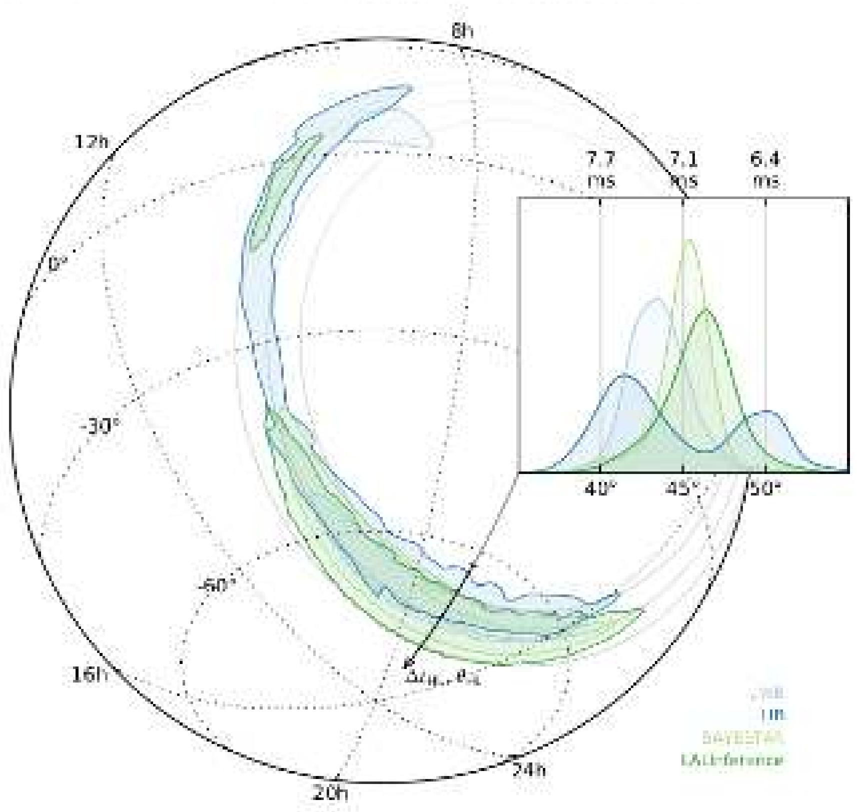
- cWB: constrained ML on sky grid
- LIB: bayesian inference
- BAYESTAR: triangulation (based on CBC pipelines, here offline)
- LALInference: full details

	Area[a]			θ_{HL}[b]	Comparison[c]			
	10%	50%	90%		cWB	LIB	BSTR	LALInf
cWB	10	100	310	43^{+2}_{-2}	—	190	180	230
LIB	30	210	750	45^{+6}_{-5}	0.55	—	220	270
BSTR	10	90	400	45^{+2}_{-2}	0.64	0.56	—	350
LALInf	20	150	620	46^{+3}_{-3}	0.59	0.55	0.90	—

[a] Area of credible level (deg^2). Note that the LALInference area is consistent with but not equal to the number reported in Abbott et al. (2016e) due to minor differences in sampling and interpolation.

[b] Mean and 10% and 90% percentiles of polar angle in degrees.

[c] Fidelity (below diagonal) and the intersection in deg^2 of the 90% confidence regions (above diagonal).



Abbott+16, ApJ 826, 13

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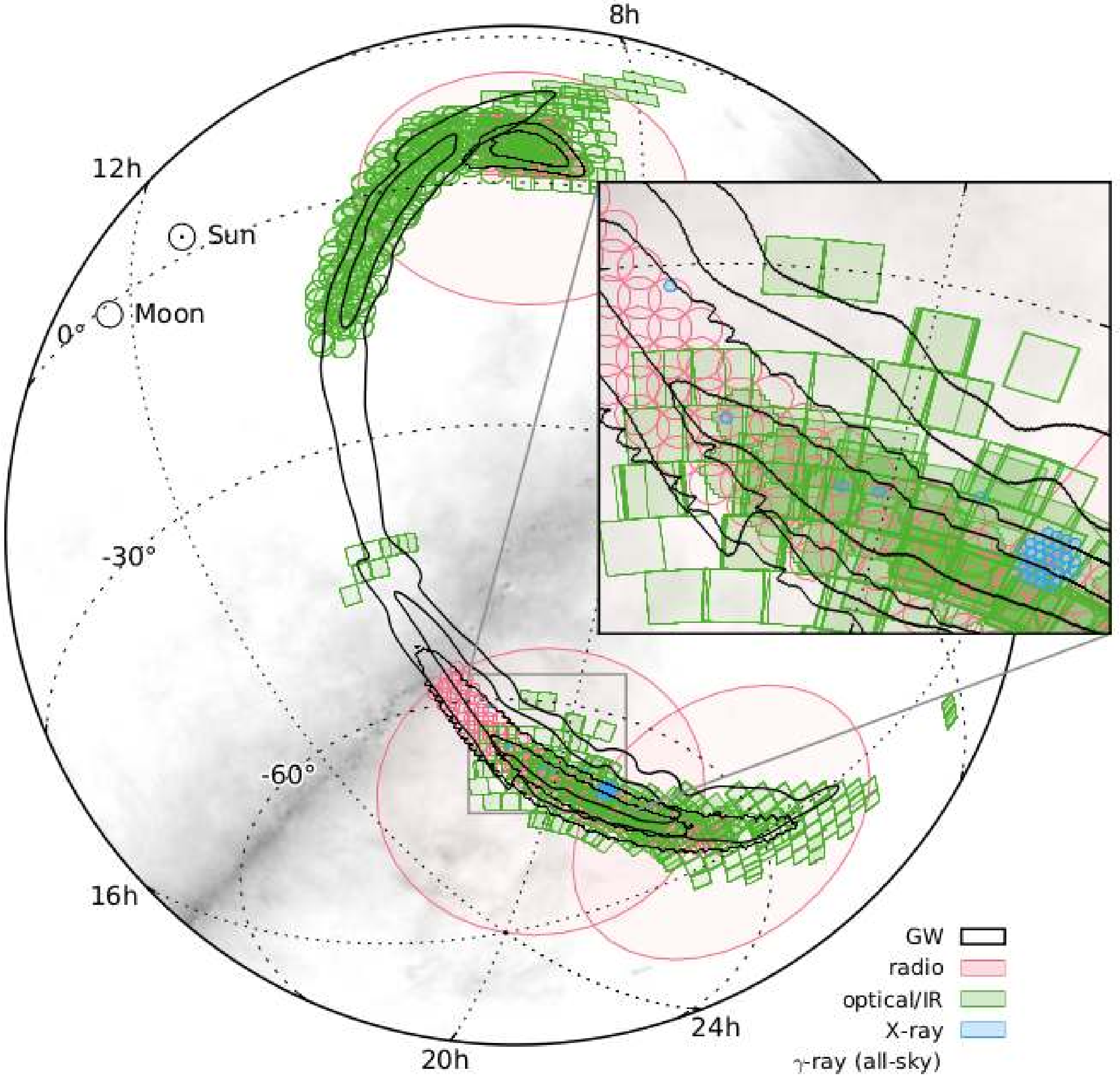
GW150914 coverage



- 25 teams involved
- 19 orders of magnitudes in wavelenghts
- Repointing (optical)
- Archival (X & gamma)
- Deep follow-up (optical/radio)

Abbott+16, ApJ 826, 13

X-rays and gamma rays

Facility/ Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained Probability (%) cWB	LIB	BSTR[d]	LALInf	GCN
Gamma-ray									
Fermi LAT	20 MeV–300 GeV	1.7×10^{-9}	(every 3 hr)	—	100	100	100	100	18709
Fermi GBM	8 keV–40 MeV	$0.7–5 \times 10^{-7}$ (0.1–1 MeV)	(archival)	—	100	100	100	100	18339
INTEGRAL	75 keV–1 MeV	1.3×10^{-7}	(archival)	—	100	100	100	100	18354
IPN	15 keV–10 MeV	1×10^{-7}	(archival)	—	100	100	100	100	—
X-ray									
MAXI/GSC	2–20 keV	1×10^{-9}	(archival)	17900	95	89	92	84	19013
Swift XRT	0.3–10 keV	5×10^{-13} (gal.)	2.3, 1, 1	0.6	0.03	0.18	0.04	0.05	18331
		$2–4 \times 10^{-12}$ (LMC)	3.4, 1, 1	4.1	1.2	1.9	0.16	0.26	18346

- Fermi GBM: 1 candidate ~1.9σ, ~0.4 s (Connaughton+16)
- Fermi LAT : no candidates (Ackermann+16)
- AGILE: no candidates (Tavani et al+16)
- INTEGRAL: no candidates (Sevechenko+16)
- Swift: candidates, but no new sources (Ewans+16)

Abbott+16, ApJ 826, 13

Optical, IR, radio

- Optical
  - Tiled and galaxy-oriented
  - Tens of candidates, later observed deeper
  - Candidates compatible with normal population of SNe, AGN, etc..
- Radio coverage up to t+4 months

Abbott+16, ApJ 826, 13

Facility/ Instrument	Band[a]	Depth[b]	Time[c]	Area (deg^2)	Contained Probability (%) cWB	LIB	BSTR[d]	LALInf	GCN
				Optical					
DECam	i, z	$i < 22.5$, $z < 21.5$	3.9, 5, 22	100	38	14	14	11	18344, 18350
iPTF	R	$R < 20.4$	3.1, 3, 1	140	3.1	2.9	0.0	0.2	18337
KWFC	i	$i < 18.8$	3.4, 1, 1	24	0.0	1.2	0.0	0.1	18361
MASTER	C	< 19.9	-1.1, 7, 7	590	56	35	55	49	18333, 18390, 18903, 19021
Pan-STARRS1	i	$i < 19.2 - 20.8$	3.2, 21, 42	430	28	29	2.0	4.2	18335, 18343, 18362, 18394
La Silla–QUEST	g, r	$r < 21$	3.8, 5, 0.1	80	23	16	6.2	5.7	18347
SkyMapper	i, v	$i < 19.1$, $v < 17.1$	2.4, 2, 3	30	9.1	7.9	1.5	1.9	18349
Swift UVOT	u	$u < 19.8$ (gal.)	2.3, 1, 1	3	0.7	1.0	0.1	0.1	18331
	u	$u < 18.8$ (LMC)	3.4, 1, 1						18346
TAROT	C	$R < 18$	2.8, 5, 14	30	15	3.5	1.6	1.9	18332, 18348
TOROS	C	$r < 21$	2.5, 7, 90	0.6	0.03	0.0	0.0	0.0	18338
VST	r	$r < 22.4$	2.9, 6, 50	90	29	10	14	10	18336, 18397
				Near Infrared					
VISTA	Y, J, K_S	$J < 20.7$	4.8, 1, 7	70	15	6.4	10	8.0	18353
				Radio					
ASKAP	863.5 MHz	5–15 mJy	7.5, 2, 6	270	82	28	44	27	18363, 18655
LOFAR	145 MHz	12.5 mJy	6.8, 3, 90	100	27	1.3	0.0	0.1	18364, 18424, 18690
MWA	118 MHz	200 mJy	3.5, 2, 8	2800	97	72	86	86	18345

Doing it again!

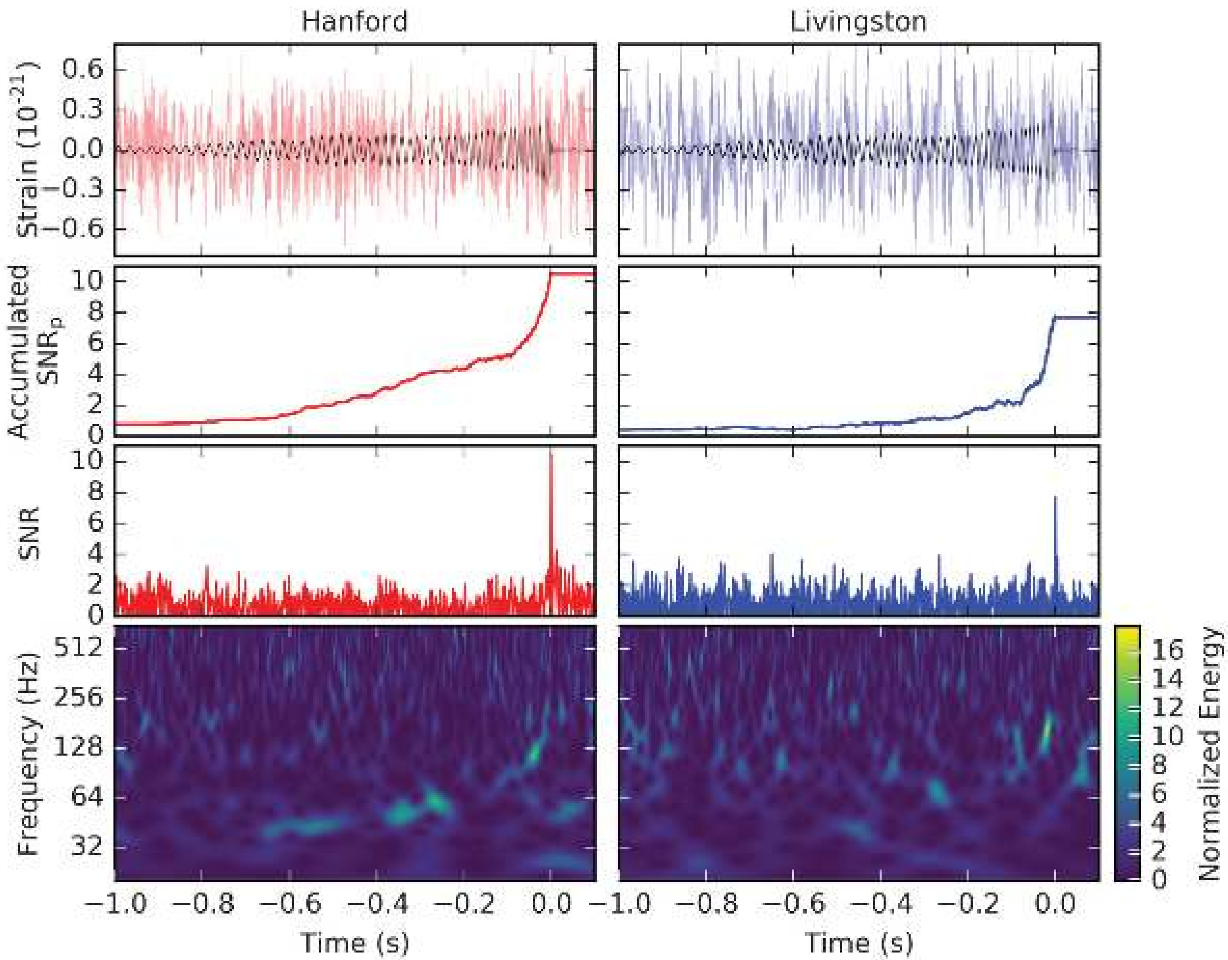
GW151226
Abbott+16, PRL116,24

Dec 26, 2017, 3:38 UTC

Delay 1.1 ms

Duration 1 s

From 35 to 450 Hz



Comparing GW150914 and GW151226

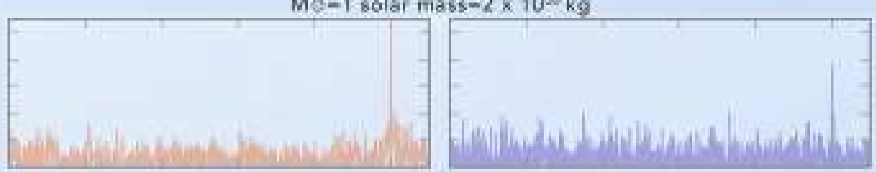
GW151226:FACTSHEET

BACKGROUND IMAGES: TIME-FREQUENCY TRACE (TOP) AND SIGNAL-TO-NOISE RATIO TIME-SERIES (BOTTOM) IN THE TWO LIGO DETECTORS; EXAMPLE WAVEFORM (MIDDLE)

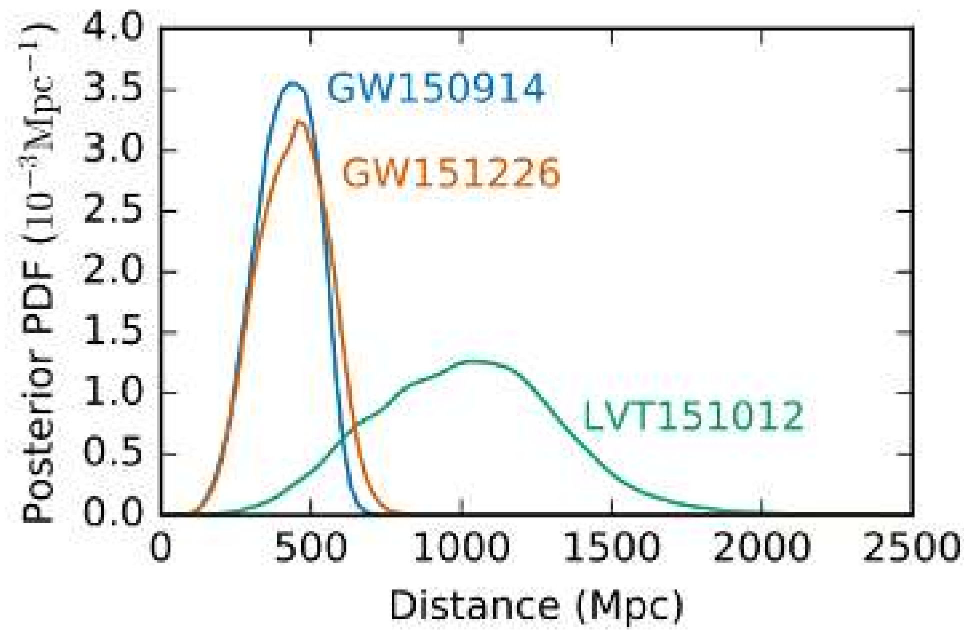
observed by	LIGO L1, H1
source type	black hole (BH) binary
date	26 Dec 2015
time	03:38:53 UTC
likely distance	250 to 620 Mpc
redshift	0.05 to 0.12
signal-to-noise ratio	13
false alarm prob.	~ 1 in 10 million
Source Masses	M⊙
total mass	20 to 28
primary BH	11 to 23
secondary BH	5 to 10
remnant BH	19 to 27
mass ratio	> 0.28
primary BH spin	> 0.2
remnant BH spin	0.7 to 0.8
resolved to	~850 sq. deg.

duration from 35 Hz	1.0 s
# cycles from 35 Hz	55
signal arrival time delay	arrived in H1 1 ms after L1
peak GW strain	3.5×10^{-22}
peak displacement of interferometers arms	±0.7 am
frequency/wavelength at peak GW strain	420 Hz, 710 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.3×10^{56} erg s^{-1}
radiated GW energy	0.8-1.1 M⊙
remnant ringdown freq.	~ 750 Hz
remnant damping time	~ 1.3 ms
remnant size, area	60 km, 3.5×10^{4} km^2
online trigger latency	~ 3 min
# offline analysis pipelines	2

Parameter ranges correspond to 90% credible bounds. Acronyms: L1/H1=LIGO Livingston/Hanford; Mpc=mega parsec=3.2 million lightyear, am=attometer=10^{-18} m, M⊙=1 solar mass=2×10^{30} kg



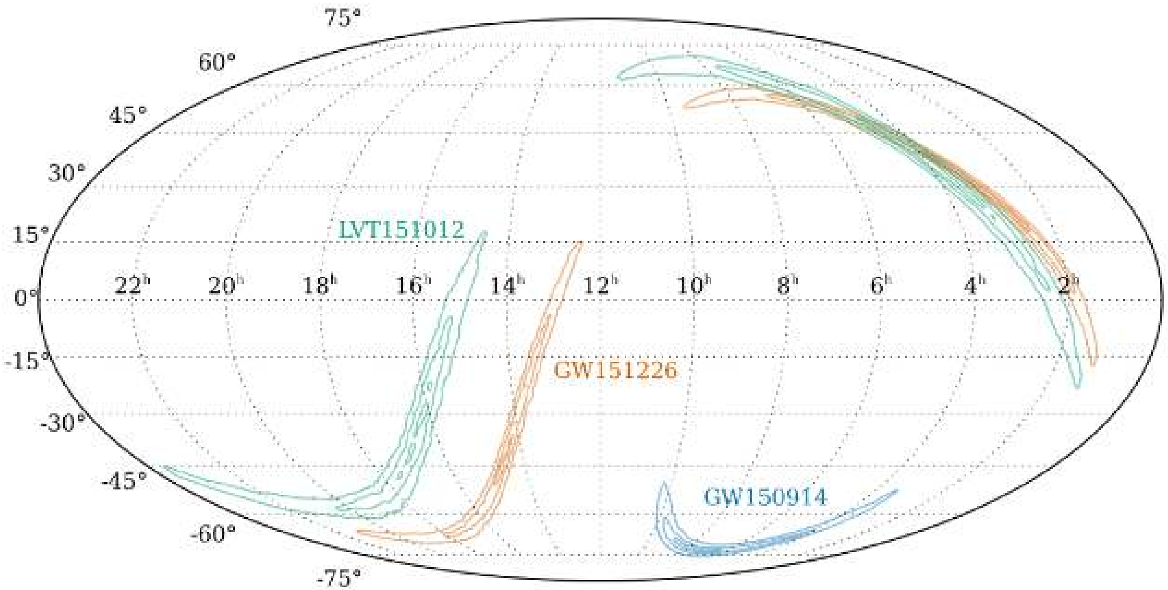
GW151226 & LVT151012

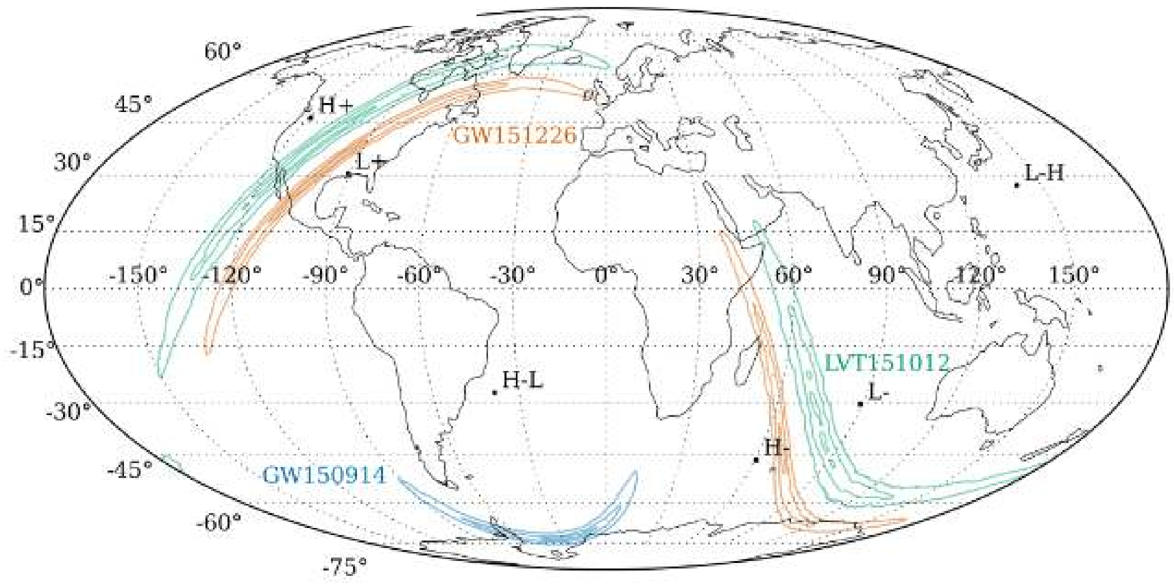


Abbot+16,PhysRevX,6,4

Event	Dt (HL, ms)	Area of 90% Prob (90%)	Distance (Mpc)
GW150914	~7	~630	~420
GW151226	~1.1	~850	~440
LVT151012	~-0.6	~1600	~1000

GW151226 & LVT151012

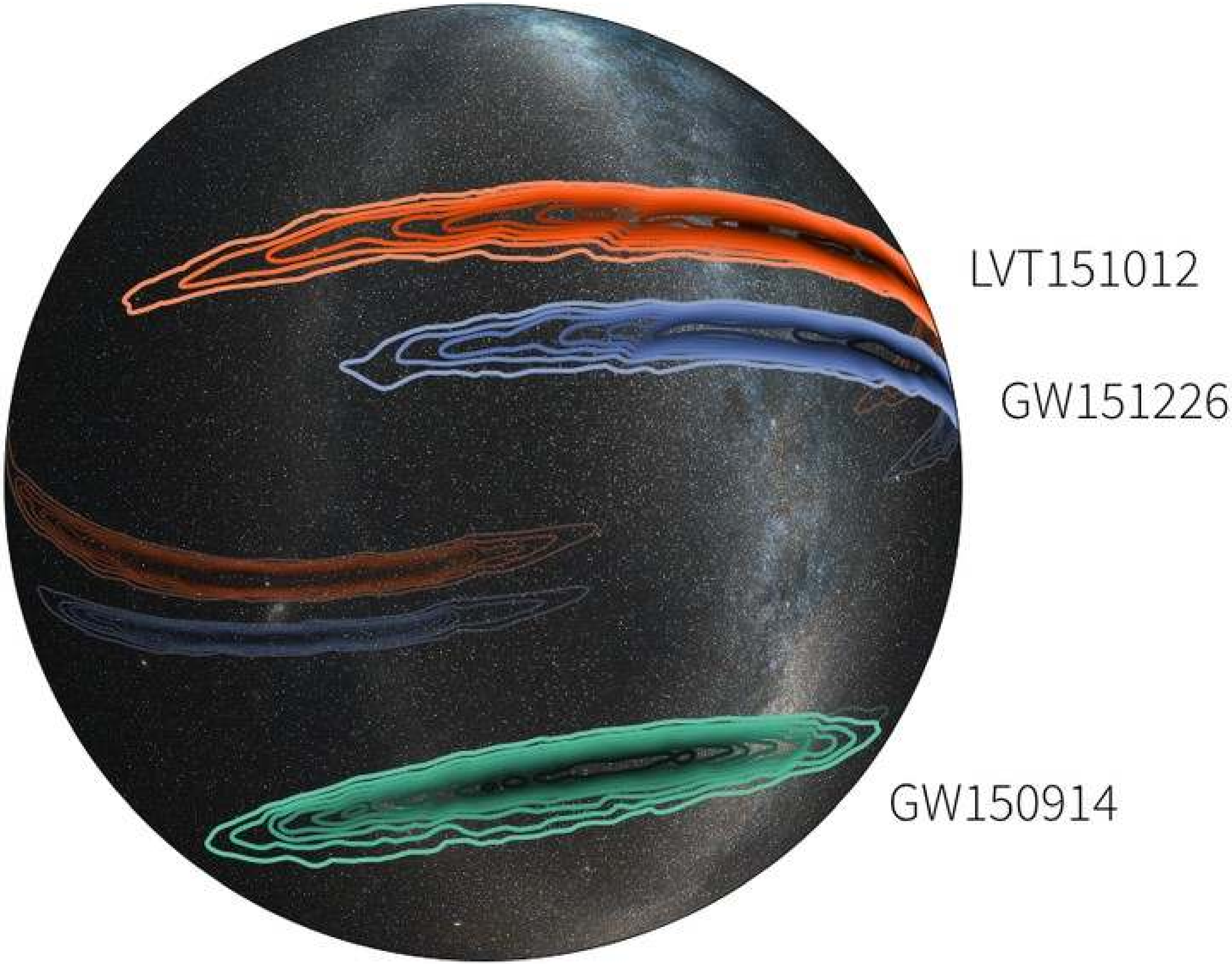




Abbot+16,PhysRevX,6,4

M. Razzano

Future perspectives: the role of Virgo



Credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

Future perspectives: the role of Virgo

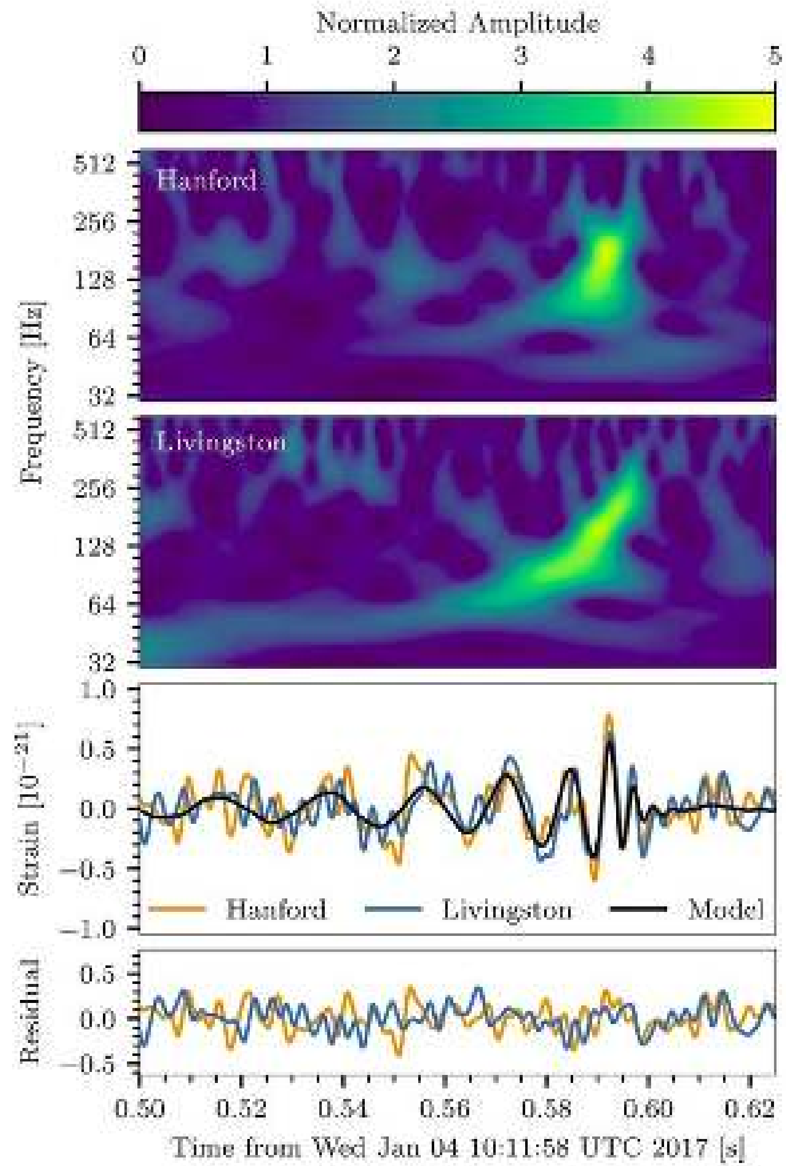
Assuming Virgo horizon 36 Mpc

Virgo will help in localization and parameter estimation

Credit: LIGO (Leo Singer) /Milky Way image (Axel Mellinger)

And a third one!

GW170104
Abbott+17, PRL118



GW170104
Abbott+17, PRL118

GW170104:FACTSHEET

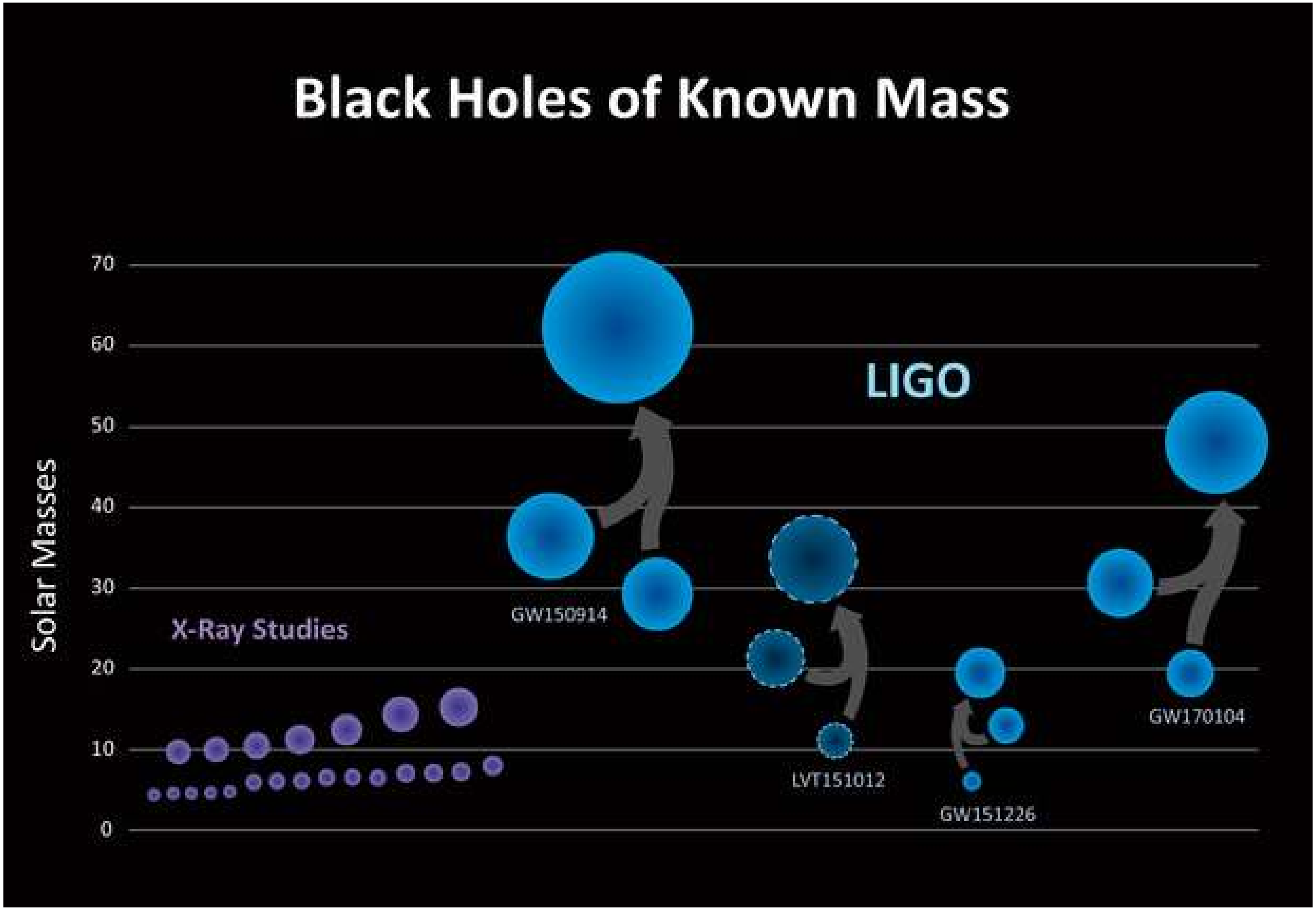
Background Images: time-frequency trace (top), H1 and L1 time series and maximum likelihood binary black hole model (middle top), residuals between data and best-fit model (middle bottom), reconstructed waveforms from wavelet and binary black hole analyses (bottom)

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	04 Jan 2017
time	10:11:58.6 UTC
signal-to-noise ratio	13
false alarm rate	< 1 in 70,000 years
probability of astrophysical origin	> 0.99997
distance	1.6 to 4.3 billion light-years
redshift	0.10 to 0.25
total mass	46 to 57 $M_\odot$
primary BH mass	25 to 40 $M_\odot$
secondary BH mass	13 to 25 $M_\odot$
mass ratio	0.36 to 0.94
remnant BH mass	44 to 54 $M_\odot$
remnant BH spin	0.39 to 0.7
remnant size (effective radius)	123 to 150 km
remnant area	1.9 to 2.8 x 10^5 km^2
effective spin parameter	-0.42 to 0.09
effective precession spin parameter	unconstrained

duration from 30 Hz	~ 0.30 to 0.48 s
# of cycles from 30 Hz	~ 13.8 to 16.3
signal arrival time delay	arrived at H1 3 ms before L1
credible region sky area	1200 sq. deg.
peak GW strain	~ 5 × 10^{-22}
peak displacement of interferometer arm	~ ± 1 am
frequency at peak GW strain	160 to 199 Hz
wavelength at peak GW strain	1510 to 1880 km
peak GW luminosity	1.8 to 3.8 × 10^{56} erg s^{-1}
radiated GW energy	1.3 to 2.6 $M_\odot$
remnant ringdown freq.	297 to 373 Hz
remnant damping time	2.5 to 3.2 ms
consistent with general relativity?	passes all tests performed
graviton mass combined bound	≤ 7.7 x 10^{-23} eV/c^2
evidence for dispersion of GWs	none

Parameter ranges correspond to 90% credible intervals.
Acronyms:
L1/H1=LIGO Livingston/Hanford, am=attometer=10^{-18} m, $M_\odot$=1 solar mass=2 x 10^{30} kg

And a third one!



GW150914
Abbott+17, PRL118

And a third one!

LIGO/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger)

GW150914
Abbott+17, PRL118

Conclusions

- GW and photons provide complementary information
  - Multimessenger observations extremely promising
- Multimessenger approach is key to study the most extreme objects in the Universe
  - Natural laboratories to probe fundamental physics
  - Transients (e.g. GRBs)
  - Also, other sources (e.g. neutron stars)
- First GW events provided first tests for EM follow-up campaign
  - Great synergy and coverage
  - No expected EM emission from BBHs, but new interesting models arising
- Gamma-ray telescopes are important
  - Emission from GRBs and other HE sources
  - Large FoV
- Present & Future
  - Not just BBH: what about BNS/NSBH?
  - Advanced LIGO O2 ongoing
  - Advanced Virgo in commissioning

Let’s get some pratice !

- Online Python tutorial provided by LIGO Open Science Data Center

https://losc.ligo.org/tutorials/

What do you need?

- A wifi connection
- Python installed (with the basic packages (numpy, scipy, etc)
- Jupyter Python notebooks

- Also, Azure and mybinder options are available!

Take your time and play a bit with one of these events!