



Towards gravitational-wave astronomy

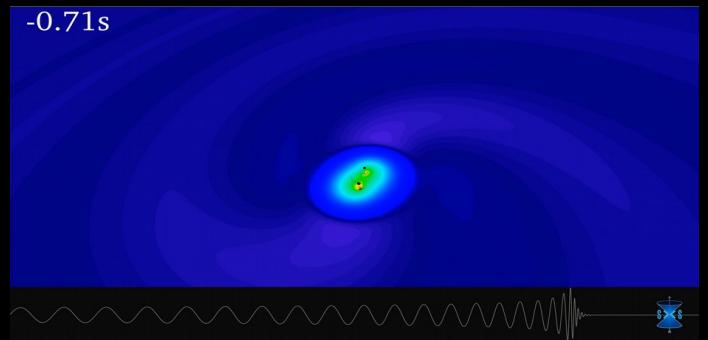
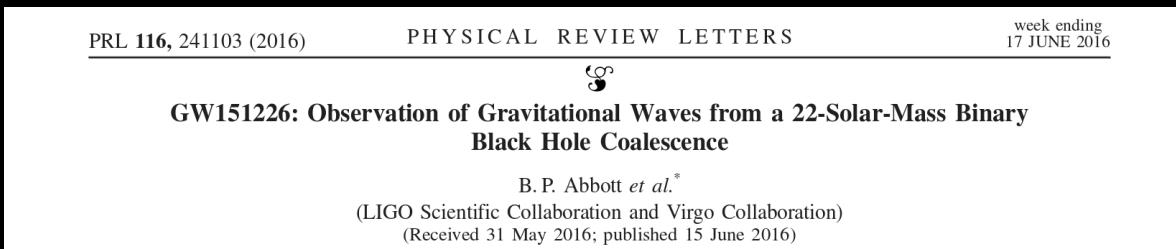
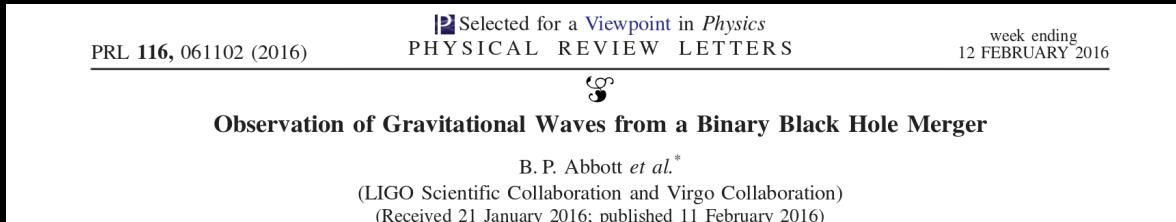
Florent Robinet

For the LIGO scientific collaboration and the Virgo collaboration
IPA Sep. 2016

In case, you missed the news...²

100 years after Einstein's prediction:

"We have detected gravitational waves... We did it!" Dave Reitze, LIGO director



Phys. Rev. D 93, 122004:

arXiv:1602.03839:

Phys. Rev. Lett. 116, 241102:

arXiv:1602.03842:

ApJL. 818, 2:

Phys. Rev. Lett. 116, 221101:

Phys. Rev. Lett. 116, 131102:

arXiv:1602.03845:

Class. Quantum Grav. 33, 13:

ApJL. 826, 1:

Phys. Rev. D 93, 122010:

Phys. Rev. Lett. 116, 131103:

arXiv:1606.04856:

Observing gravitational-wave transient GW150914 with minimal assumptions

GW150914: First results from the search for binary black hole coalescence with Advanced LIGO

Properties of the binary black hole merger GW150914

The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914

Astrophysical Implications of the Binary Black-Hole Merger GW150914

Tests of general relativity with GW150914

GW150914: Implications for the stochastic gravitational-wave background from binary black holes

Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914

Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914

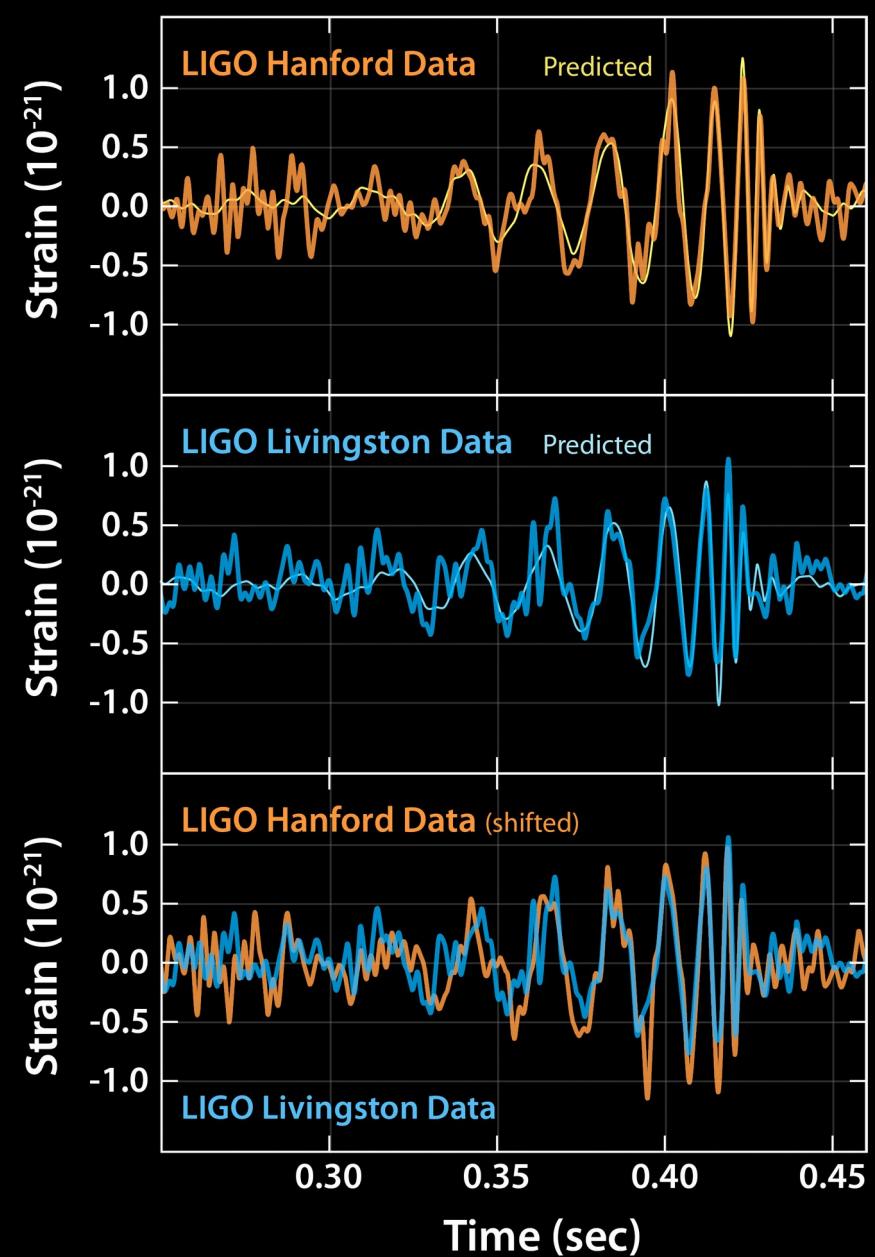
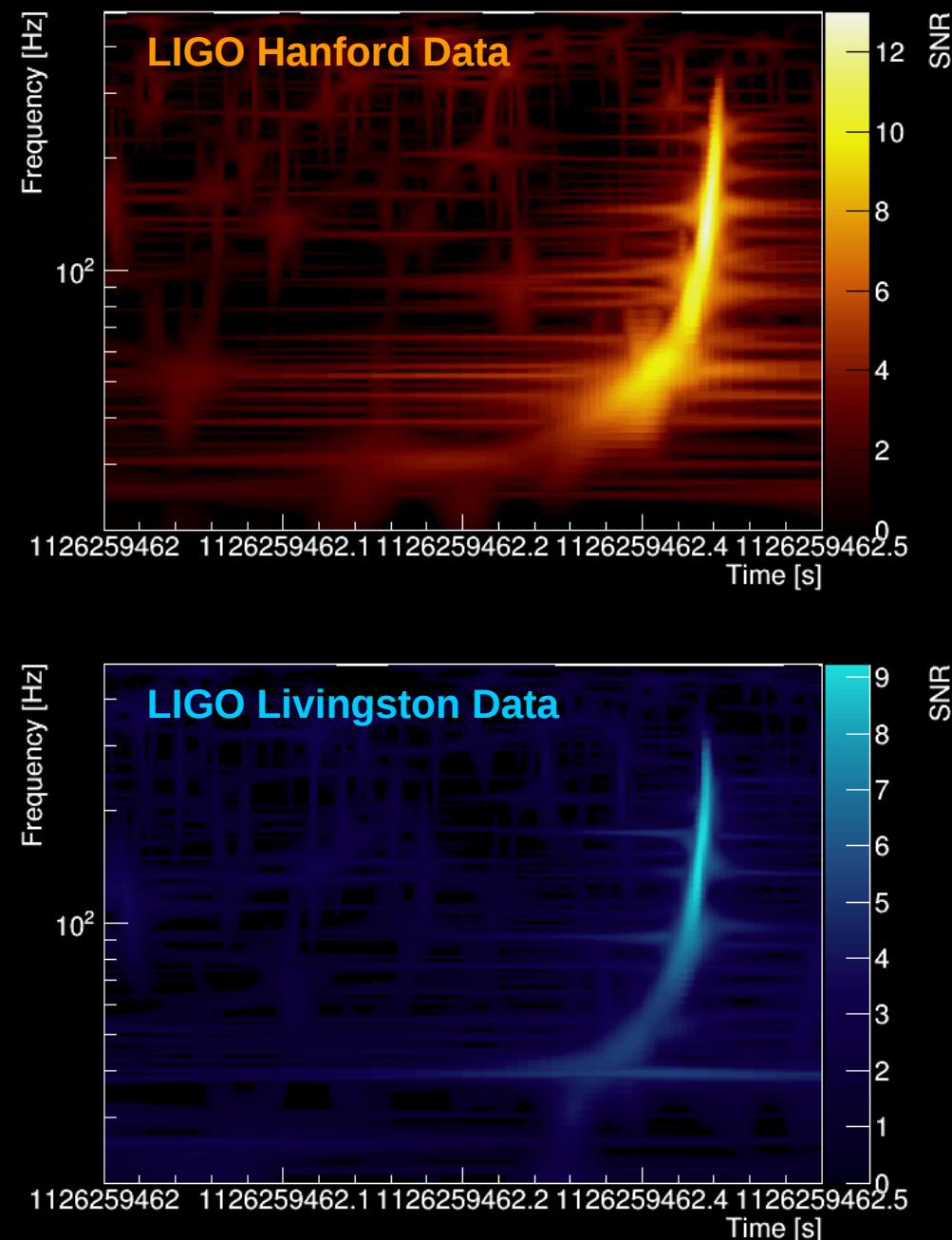
Localization and broadband follow-up of the gravitational-wave transient GW150914

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES

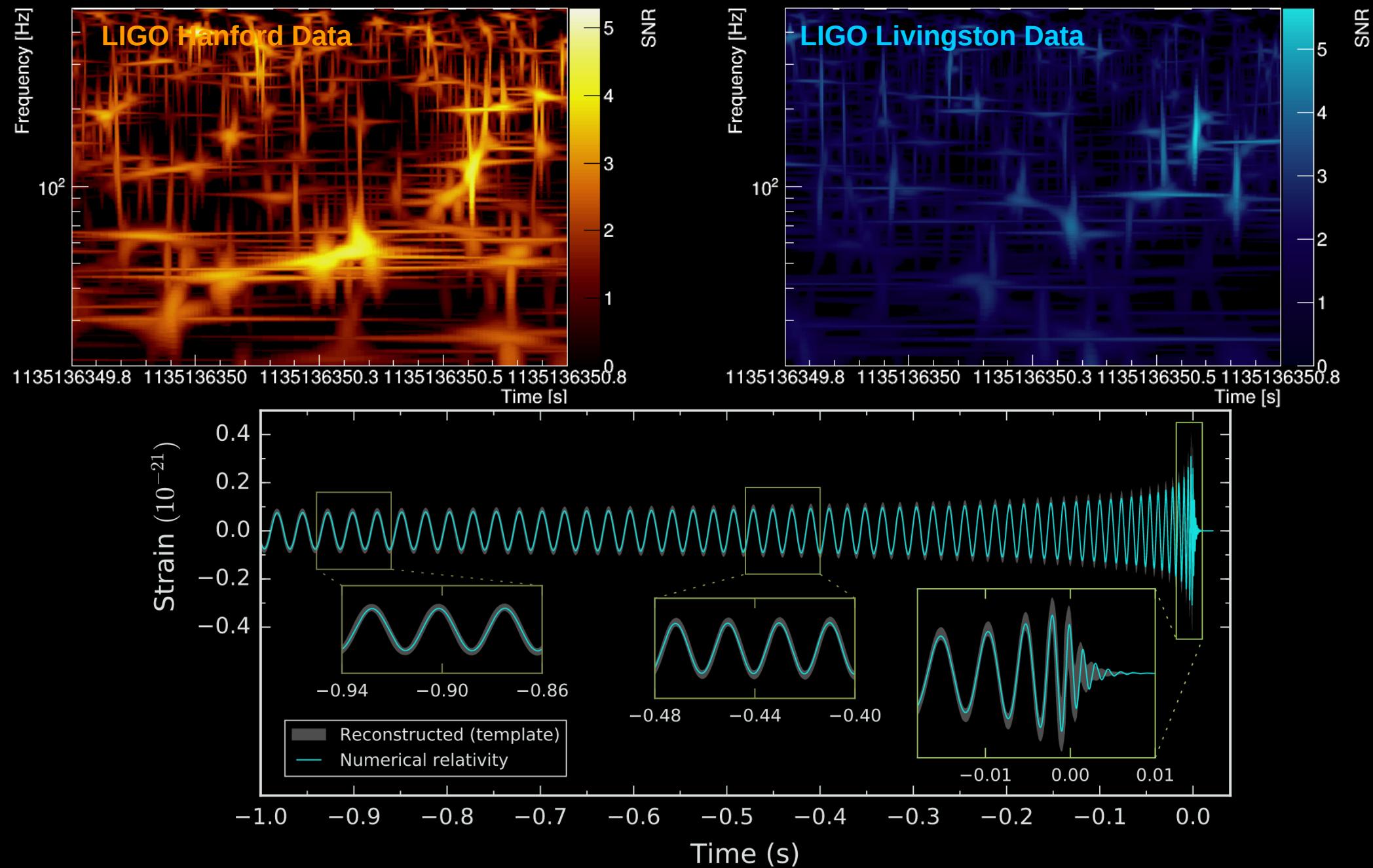
GW150914: The Advanced LIGO Detectors in the Era of First Discoveries

Binary Black Hole Mergers in the first Advanced LIGO Observing Run

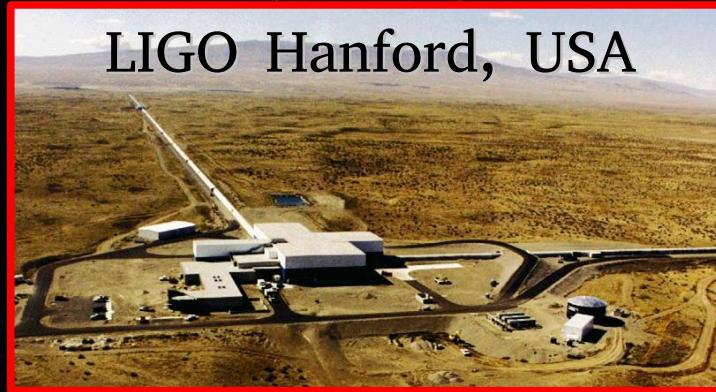
GW150914



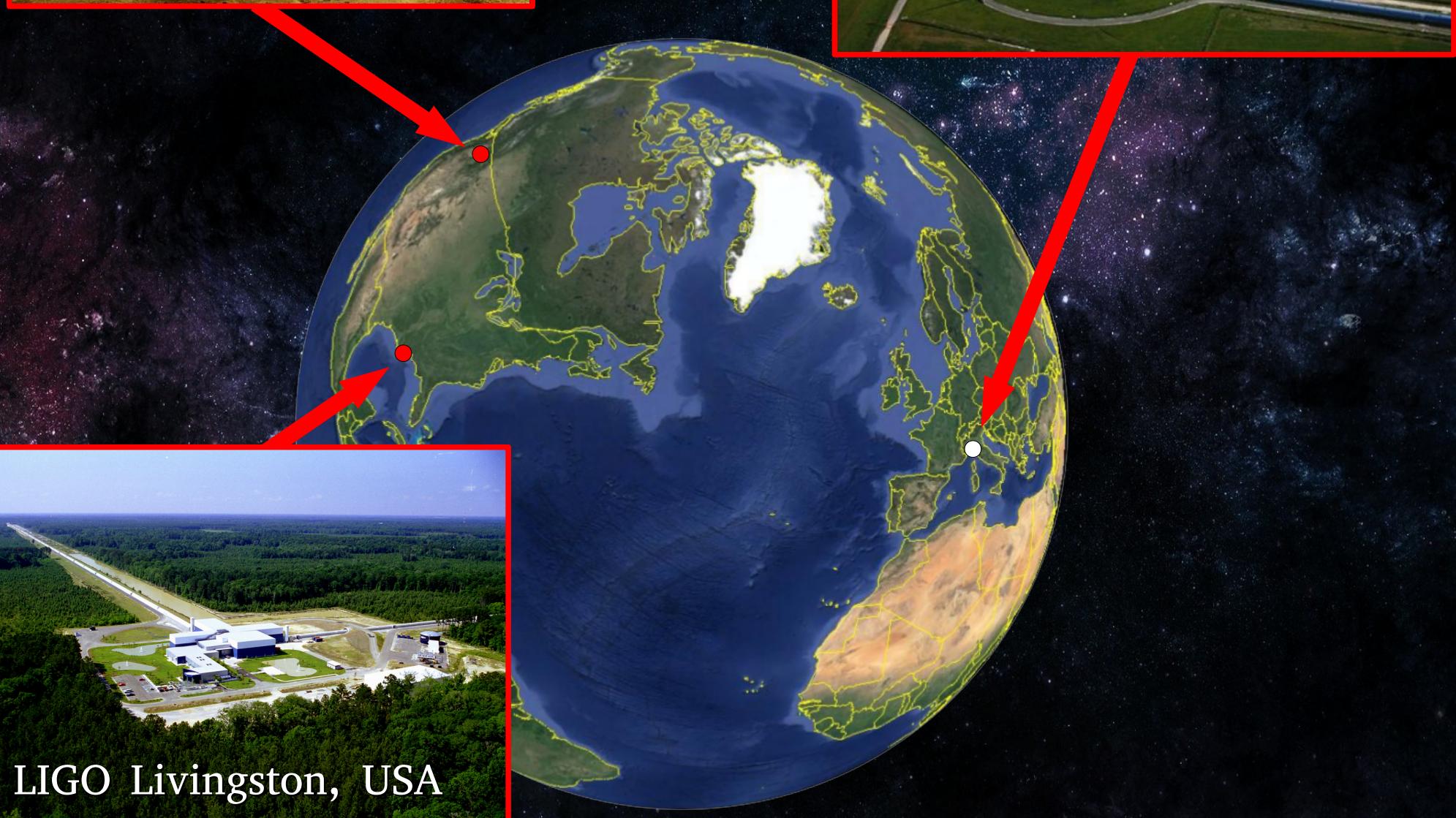
GW151226



LIGO Hanford, USA



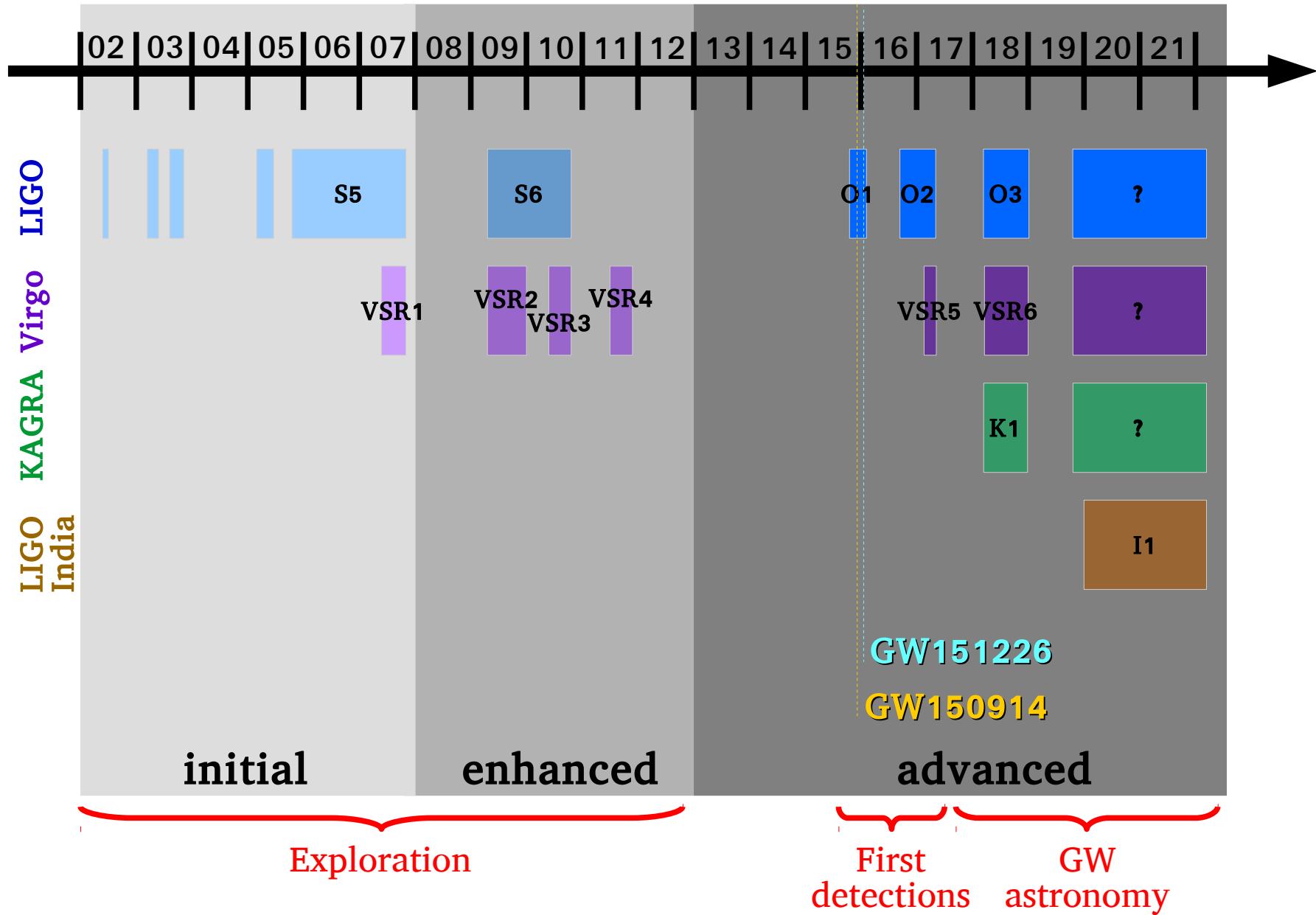
Virgo Pisa, Italy



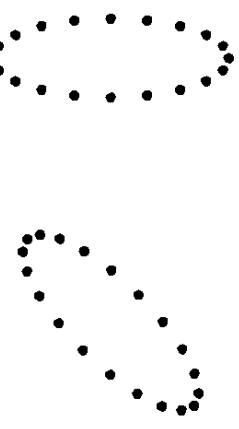
LIGO Livingston, USA



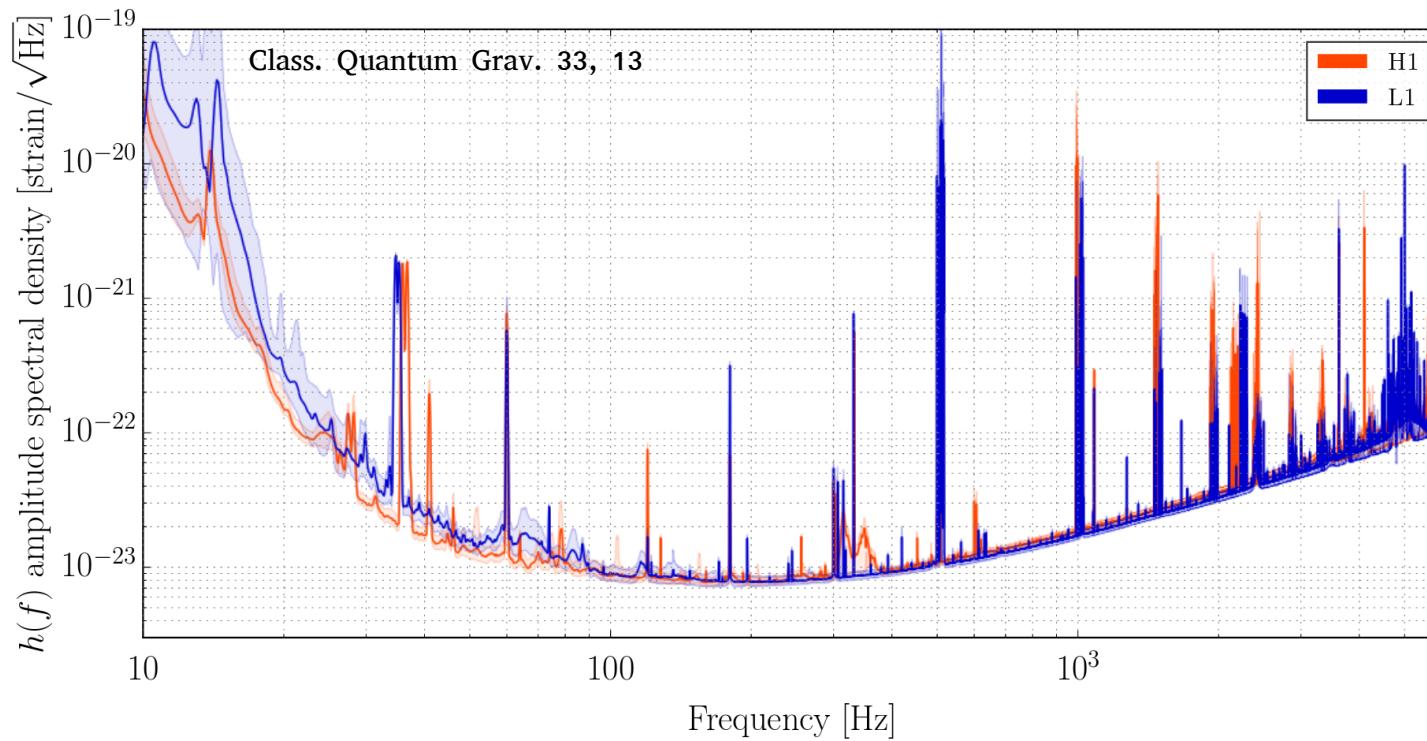
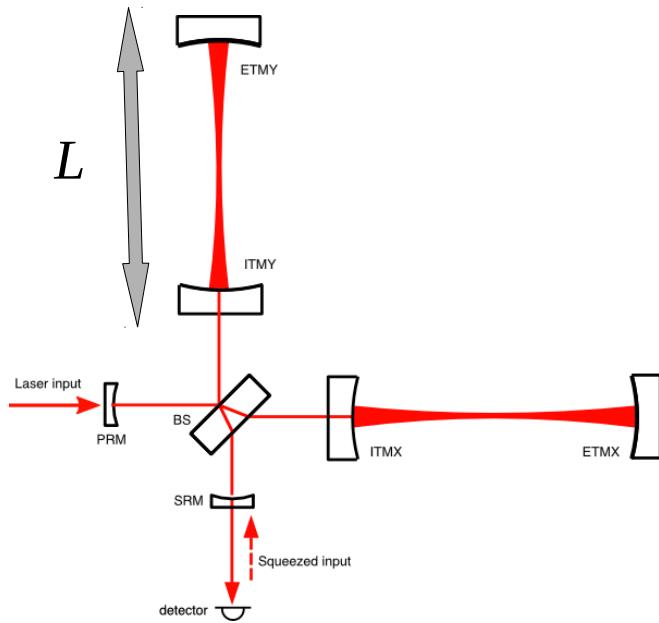
Scientific runs⁶



The detectors⁷



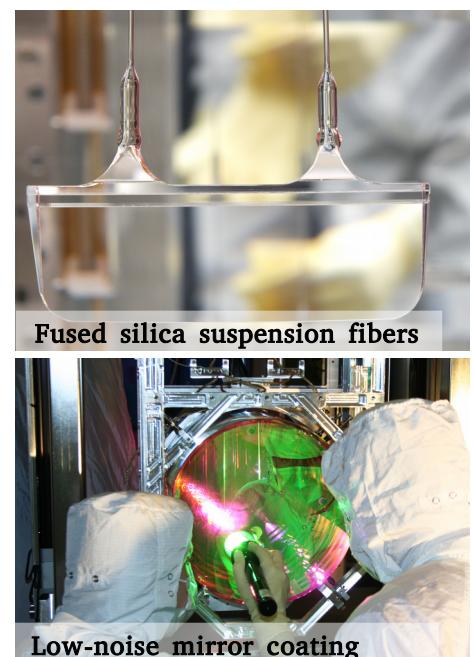
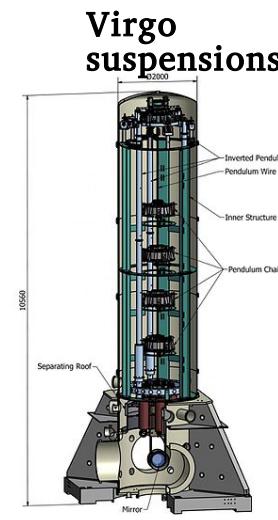
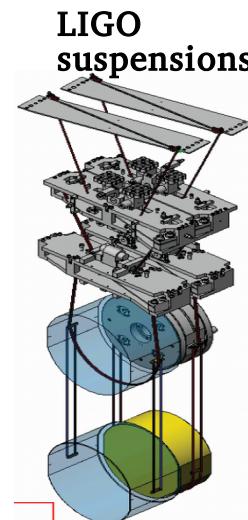
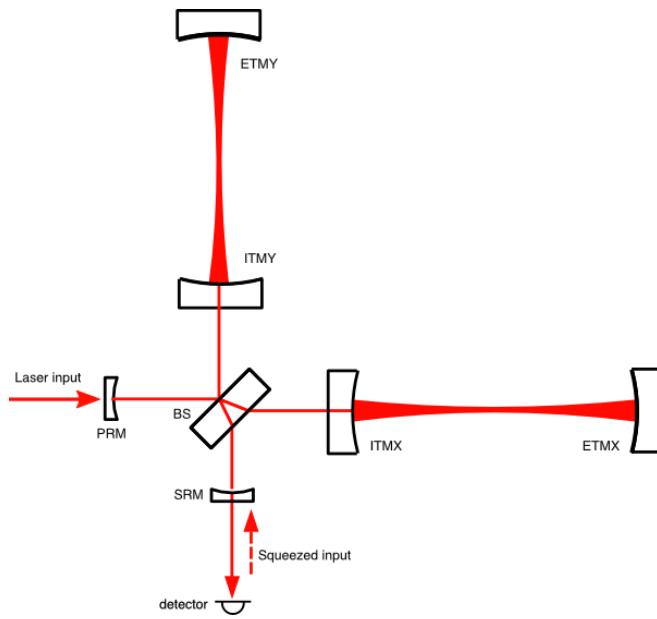
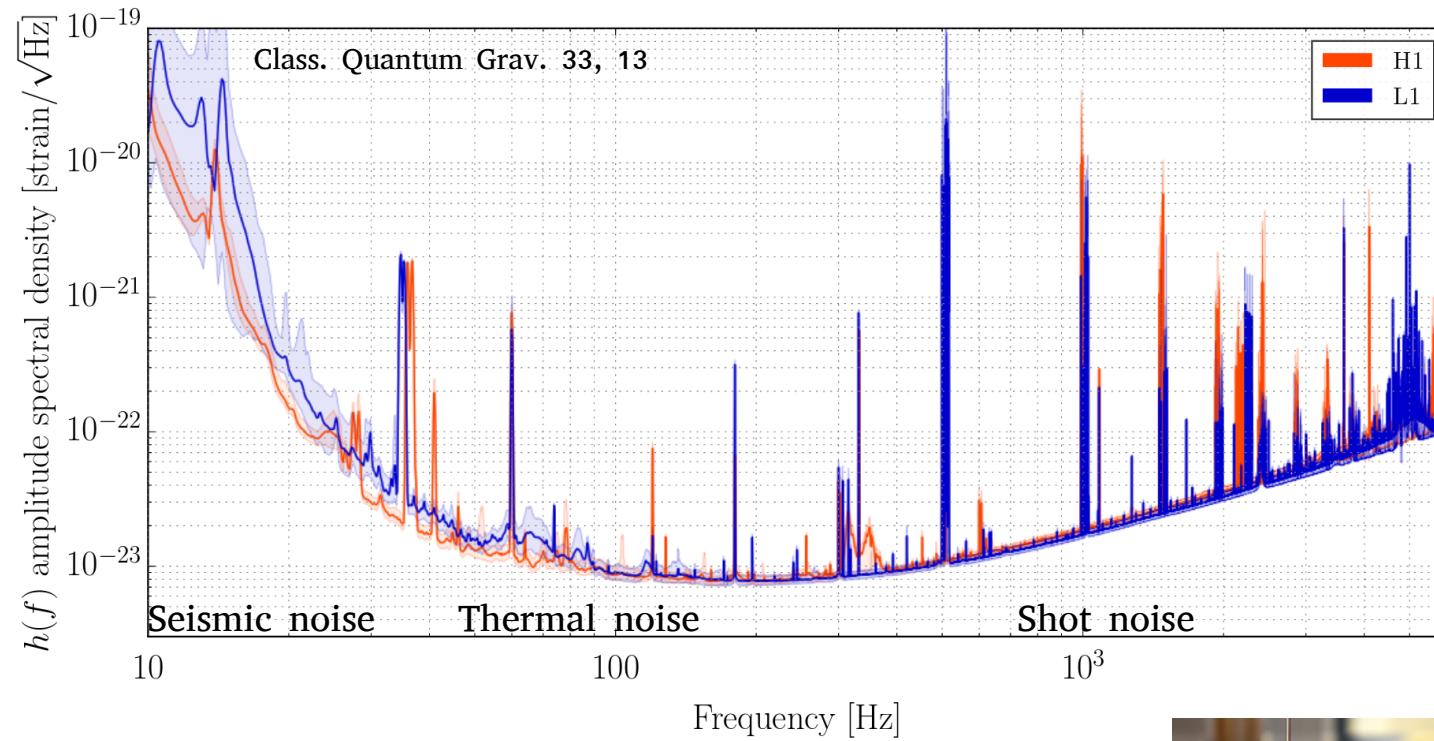
$$h = 2 \frac{\Delta L}{L}$$



To reach the desired sensitivity ($h \sim 10^{-21}$), Michelson interferometers were built:

- Kilometer-scale arms
- High-power laser
- Fabry-Perot cavities
- Power and signal recycling
- Power and frequency stabilized laser
- Heavy mirrors
- Seismic attenuators
- Ultra-high vacuum
- High-quality optics

The detectors⁸



The strain amplitude is measured over time: $h(t)$
 $h(t)$ data are transferred to computing centers (< 1 s)



The strain amplitude is measured over time: $h(t)$
 $h(t)$ data are transferred to computing centers (< 1 s)
where low-latency searches are conducted

Caltech:

- CBC modeled search (*gstlal*)
- unmodeled burst search (*olib*)

Hannover:

- unmodeled burst search (*cWB*)

Virgo:

- CBC-modeled search (*MBTA*)



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Compact binary coalescence
- black holes or neutron stars -

Hannover:
modeled burst search (*cWB*)

Virgo:

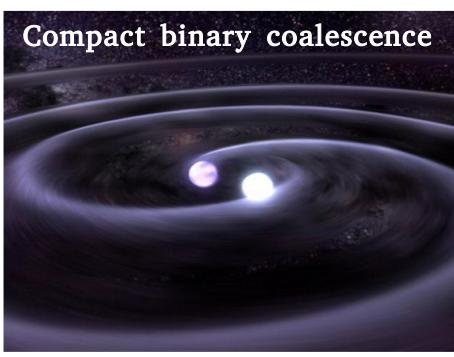
- CBC-modeled search (*MBTA*)

The strain amplitude is measured over time: $h(t)$
 $h(t)$ data are transferred to computing centers (< 1 s)
where low-latency searches are conducted

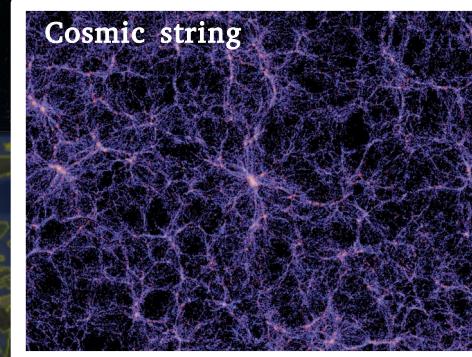
Burst sources

Caltech:

- CBC modeled search
- unmodeled burst search



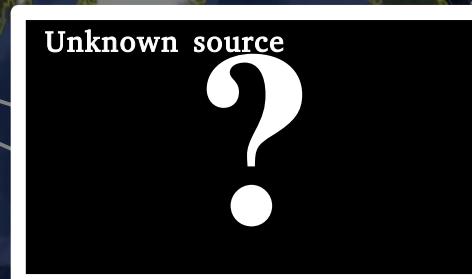
Compact binary coalescence



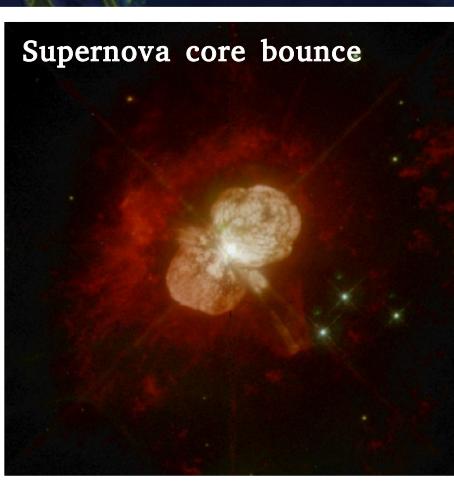
Cosmic string



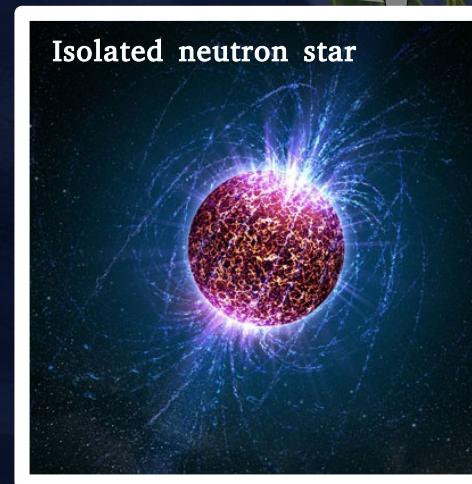
Newly-formed black hole



Unknown source



Supernova core bounce



Isolated neutron star

Hannover:

Unmodeled burst search (*cWB*)

Virgo:

CBC-modeled search (*MBTA*)

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where low-latency searches are conducted

Caltech:

- CBC modeled search (*gstlal*)
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Hannover:

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- CBC-modeled search (*MBTA*)



Online event database¹⁴

GraceDB — Gravitational Wave Candidate Event Database

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

UID	Labels	Group	Pipeline	Search	Instruments	Event Time	FAR (Hz)	Links	Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	2015-09-14 09:50:45 UTC	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	Event Time	Agptime	FAR (Hz)	Links	Submitted
G184147		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	6.338e-09	Data	2015-09-14 13:19:12 UTC
G184149		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	6.338e-09	Data	2015-09-14 13:24:04 UTC
G184201		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	3.169e-09	Data	2015-09-14 18:14:45 UTC
G190047		CBC	gstlal	HighMass	H1,L1	1126259462.4264	0.035435	2.754e-36	Data	2015-10-05 22:55:52 UTC
G190276		CBC	pycbc	AllSky	H1,L1	1126259462.4275	0.036490	2.965e-12	Data	2015-10-06 13:48:42 UTC

GWT150914

Online event database¹⁵

GraceDB — Gravitational Wave Candidate Event Database

Basic Info

GW150914

UID	Labels	Group	Pipeline	Search	Instruments	Event Time	FAR (Hz)	Links	Submitted
G150914	H1OK L1OK	Burst	CWB	AllSky	H1,L1	2015-09-14 09:50:45 UTC	1.178e-08	Data	2015-09-14 09:53:51 UTC

unmodeled search

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

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G184149		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	6.338e-09	Data	2015-09-14 13:24:04 UTC
G184201		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	3.169e-09	Data	2015-09-14 18:14:45 UTC
G190047		CBC	gstlal	HighMass	H1,L1	1126259462.4264	0.035435	2.754e-36	Data	2015-10-05 22:55:52 UTC
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unmodeled search

+3 min

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
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GW150914

Online event database¹⁷

GraceDB — Gravitational Wave Candidate Event Database

Basic Info

unmodeled search

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
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Neighbors [-5,+5]

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G184147		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	6.338e-09	Data	2015-09-14 13:19:12 UTC
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Online event database¹⁸

GraceDB — Gravitational Wave Candidate Event Database

Basic Info

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

Event ID: G184098 Labels: H1OK L1OK Group: Burst Pipeline: CWB Search: AllSky Instruments: H1,L1 Event Time: 2015-09-14 09:50:45 UTC FAR (Hz): 1.178e-08 Links: Data Submitted: 2015-09-14 09:53:51 UTC

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start_time	1126259461
start_time_ns	750000000
duration	2.477e-02
peak_time	None
peak_time_ns	None

central_freq	123.8285
bandwidth	51.8386
amplitude	1.410e+01
snr	23.4521
confidence	

false_alarm_rate	130.9219
ligo_axis_ra	4.4808
ligo_axis_dec	None
ligo_angle	None
ligo_angle_sig	None

Neighbors [-5,+5]

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Online event database¹⁹

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unmodeled search

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peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

+3 min

Signal parameters (preliminary)

Neighbors [-5,+5]

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G184147		Burst	LIB	AllSky	H1,L1	1126259462.4200	0.029000	6.338e-09	Data	2015-09-14 13:19:12 UTC
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G190276		CBC	pycbc	AllSky	H1,L1	1126259462.4275	0.036490	2.965e-12	Data	2015-10-06 13:48:42 UTC

multiple detections (different searches)

Online event database²⁰

GraceDB — Gravitational Wave Candidate Event Database

Basic Info

HOME	SEARCH	CREATE	REPORTS	RSS	LATEST	OPTIONS	DOCUMENTATION	AUTHENTICATED AS: FLORENT ROBINET
UID	Labels	Group	Pipeline	Search	Instruments	Event Time	FAR (Hz)	Submitted
211117	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 _⊙
Chirp Mass	9.5548 M _⊙
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 _⊙	19.924686 M _⊙
Mass 2	6.4254546 M _⊙	6.4254546 M _⊙
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	Event Time	Dgptime	FAR (Hz)	Links	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

multiple detections over time

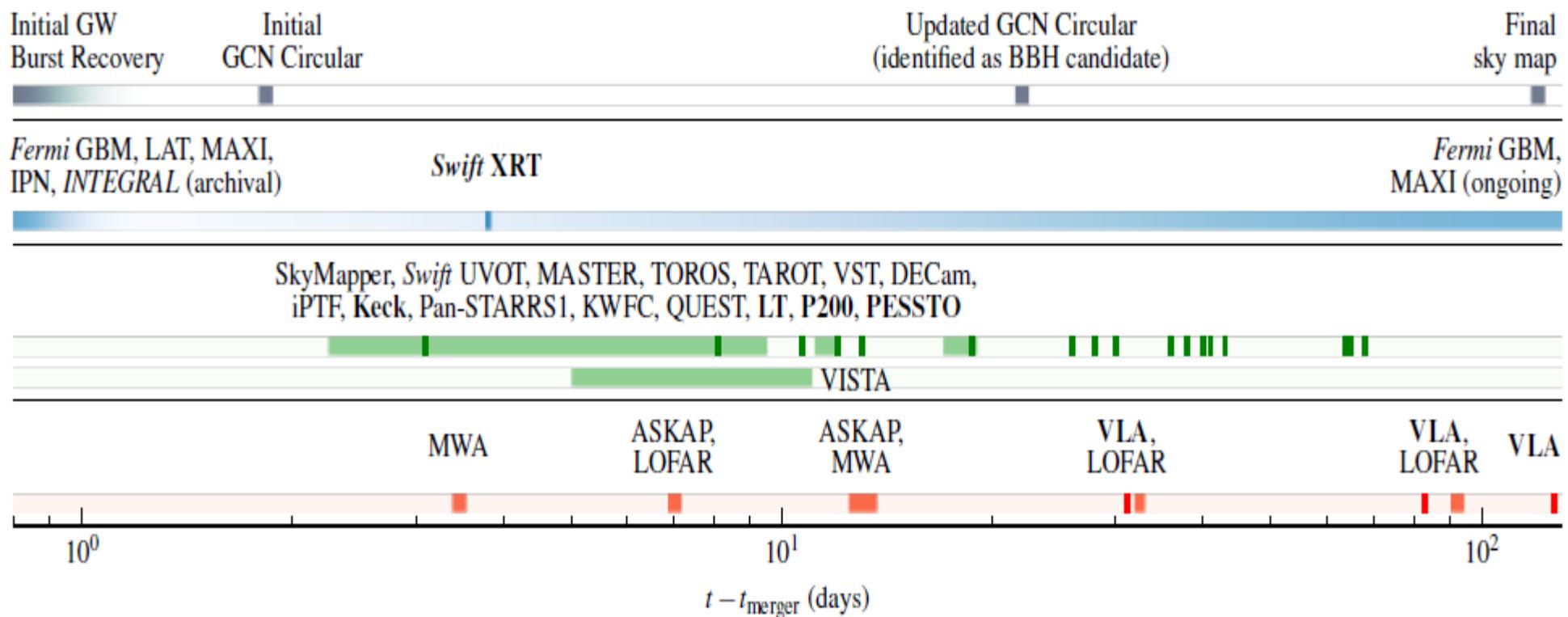
GW151226

EM follow-up²¹

ApJL. 826, 1

- 62 MOUs (radio, optical, IR, X-ray and γ -ray)
- GW150914 followed up by 21 teams (private GCN circulars)

Timeline of observations (/band)



The EM follow-up program will intensify → multi-messenger astronomy

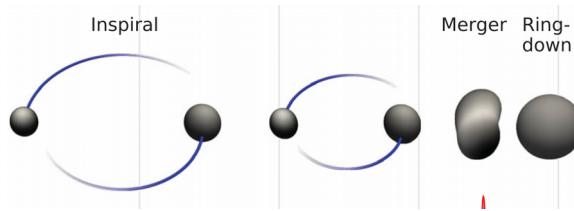
Modeled search (offline)²²

arXiv:1602.03839

arXiv:1606.04856

Theoretical input:

- 90s: CBC PN waveforms (Blanchet, Iyer, Damour, Deruelle, Will, Wiseman, ...)
- 00s: CBC Effective One Body “EOB” (Damour, Buonanno)
- 06: BBH numerical simulation (Pretorius, Baker, Lousto, Campanelli)



The intrinsic waveform parameters:

- Masses:

$$M_{tot} = M_1 + M_2$$

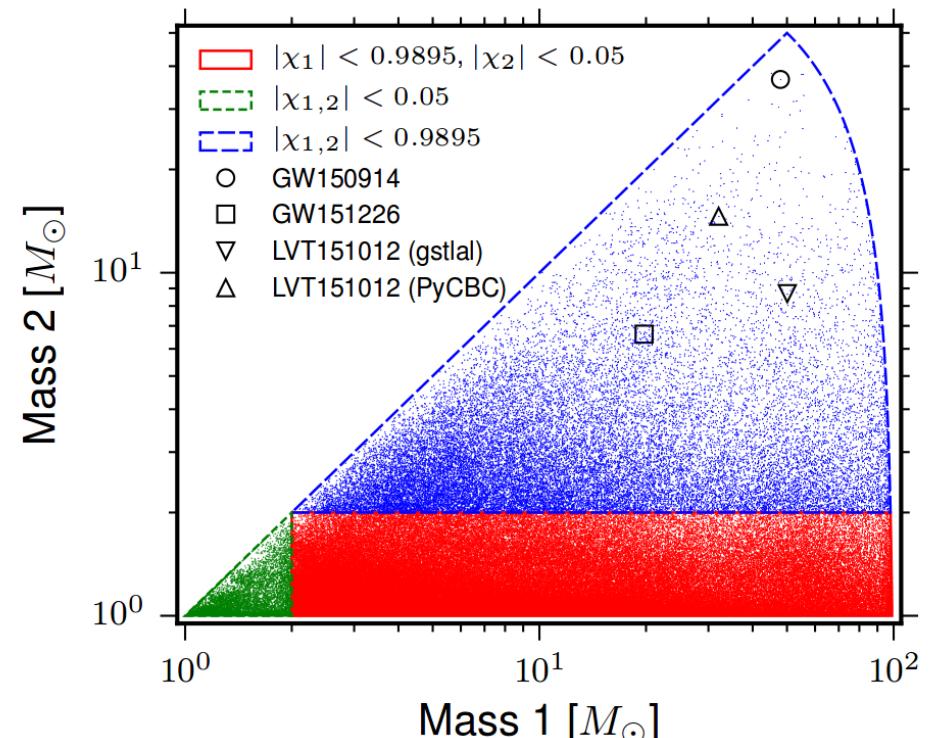
- Spins and orbital angular momentum:

$$\vec{S}_{tot} = \vec{S}_1 + \vec{S}_2 + \vec{J}$$

The waveform models used for the search:

- Inspiral, PN3.5 for $M_{tot} < 4 M_{sun}$
- Inspiral/Merger/Ringdown EOB + numerical relativity for $M_{tot} > 4 M_{sun}$
- Spins and orbital angular momentum are aligned

Template bank → match-filtering technique

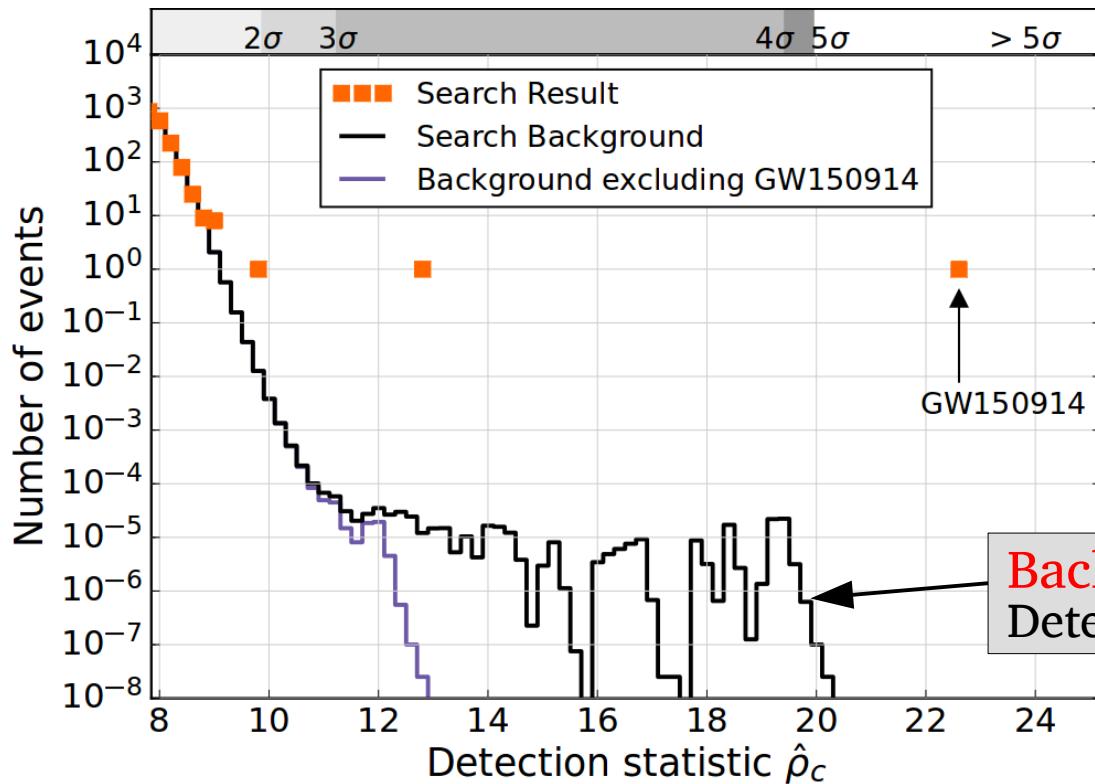


Modeled search (pyCBC offline)²³

arXiv:1602.03839

arXiv:1606.04856

Full O1 analysis, final calibration



GW150914

- SNR = 23.7
- False-alarm rate $< 6.0 \times 10^{-7} \text{ yr}^{-1}$
- Significance $> 5.3 \sigma$

Iterative process

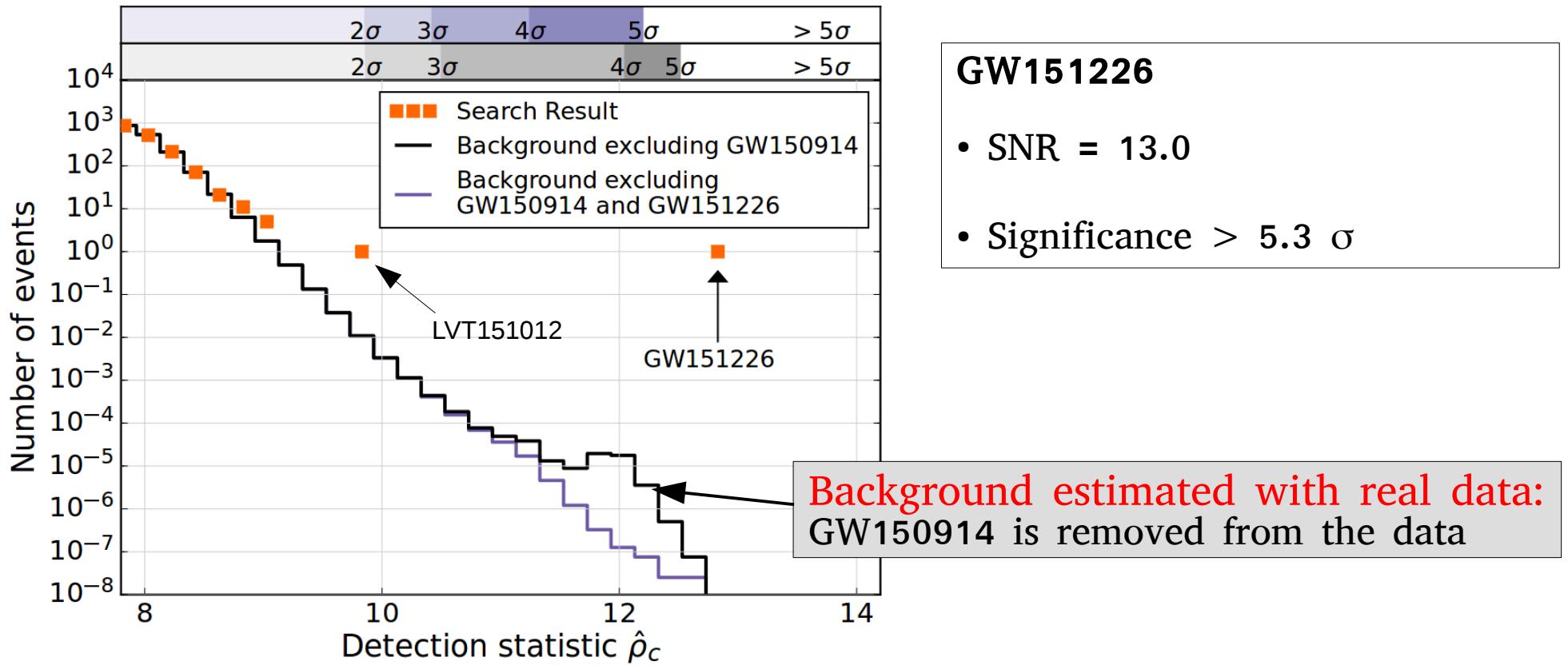
→ remove the highest-ranked event from background before estimating the next event significance

Modeled search (pyCBC offline)²⁴

arXiv:1602.03839

arXiv:1606.04856

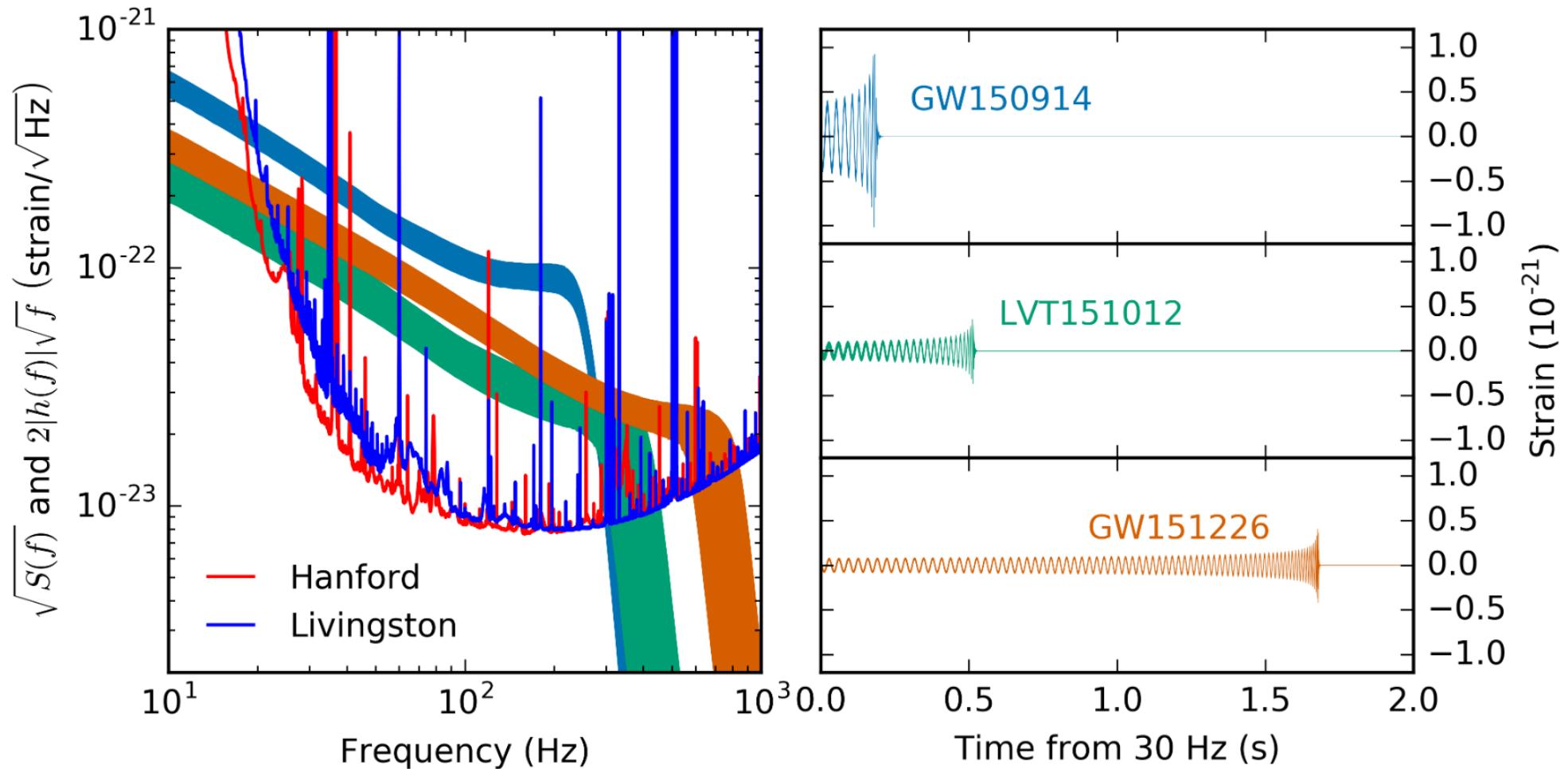
Full O1 analysis, final calibration



O1 gravitational-wave events²⁵

arXiv:1606.04856

Full O1 analysis, final calibration



Parameter estimation²⁶

arXiv:1606.04856

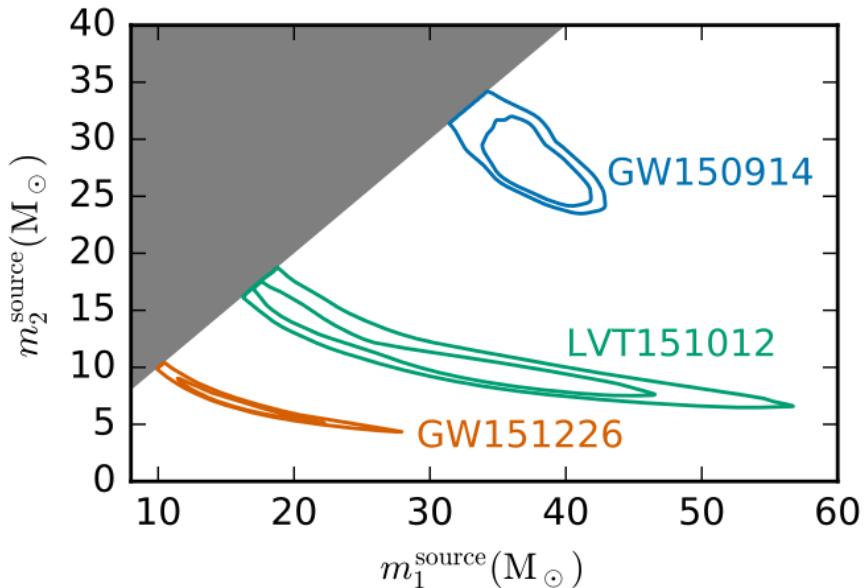
- Markov-Chain Monte Carlo + nested sampling techniques
- Evaluate likelihood over a multi-dimensional parameter space
- Search results used as prior

Event	GW150914	GW151226
Signal-to-noise ratio ρ	23.7	13.0
False alarm rate FAR/yr ⁻¹	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$
p-value	7.5×10^{-8}	7.5×10^{-8}
Significance	$> 5.3 \sigma$	$> 5.3 \sigma$
Primary mass $m_1^{\text{source}}/\text{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$
Secondary mass $m_2^{\text{source}}/\text{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$
Chirp mass $\mathcal{M}^{\text{source}}/\text{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$
Total mass $M^{\text{source}}/\text{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$

Event	GW150914	GW151226
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$
Final mass $M_f^{\text{source}}/\text{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$
Final spin a_f	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$
Radiated energy $E_{\text{rad}}/(\text{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$
Peak luminosity $\ell_{\text{peak}}/(\text{erg s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$
Luminosity distance D_L/Mpc	420^{+150}_{-180}	440^{+180}_{-190}
Source redshift z	$0.09^{+0.03}_{-0.04}$	$0.09^{+0.03}_{-0.04}$
Sky localization $\Delta\Omega/\text{deg}^2$	230	850

Component masses²⁷

arXiv:1606.04856



Mostly sensitive to the chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

→ m_1, m_2 degeneracy

GW150914

$$m_1 = 36.2^{+5.2}_{-3.2} M_{\text{sun}}$$

$$m_2 = 29.1^{+3.7}_{-4.4} M_{\text{sun}}$$

GW151226

$$m_1 = 14.2^{+8.3}_{-3.7} M_{\text{sun}}$$

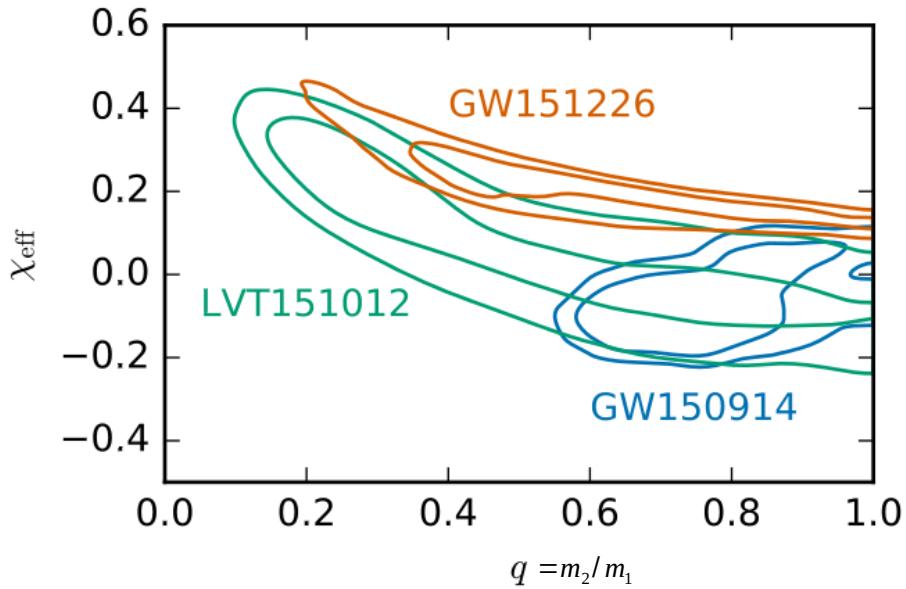
$$m_2 = 7.5^{+2.3}_{-2.3} M_{\text{sun}}$$

→ All the components are black holes

→ GW150914: heavy black holes ($m > 20 M_{\text{sun}}$)

Component spins²⁸

arXiv:1606.04856



$$\chi_{\text{eff}} = \frac{m_1 s_{1z} + m_2 s_{2z}}{m_1 + m_2}$$

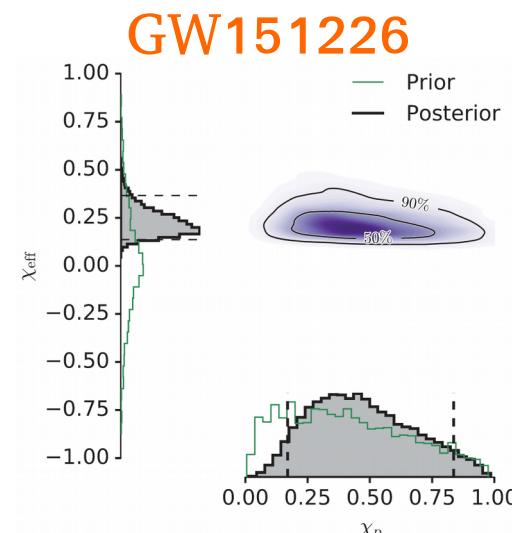
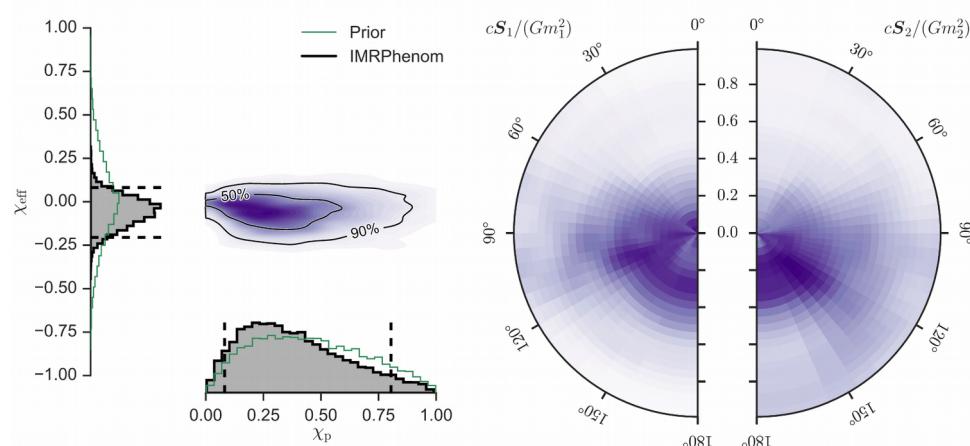
→ not well constrained

→ Maximal spin is excluded

→ GW151226: at least one black hole is a Kerr black hole
spin >0.2

Uninformative about precession

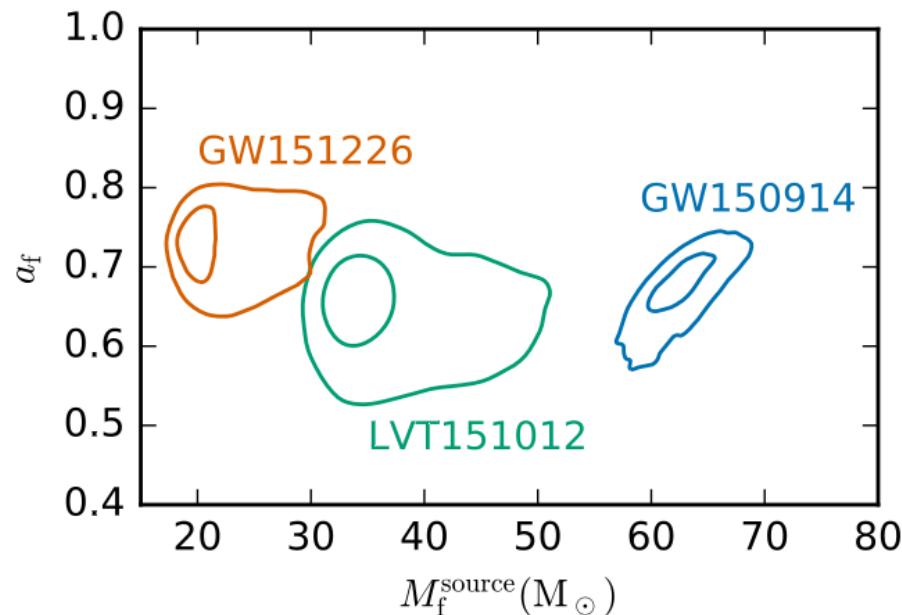
GW150914



Final mass & spins²⁹

arXiv:1606.04856

Final mass & spin



GW150914
 $M_f = 62.3^{+3.7}_{-3.1} M_{\text{sun}}$

$$a_f = 0.68^{+0.05}_{-0.06}$$

$\rightarrow \sim 3 M_{\text{sun}}$
radiated in GW

GW151226
 $M_f = 20.8^{+6.1}_{-1.7} M_{\text{sun}}$

$$a_f = 0.74^{+0.06}_{-0.06}$$

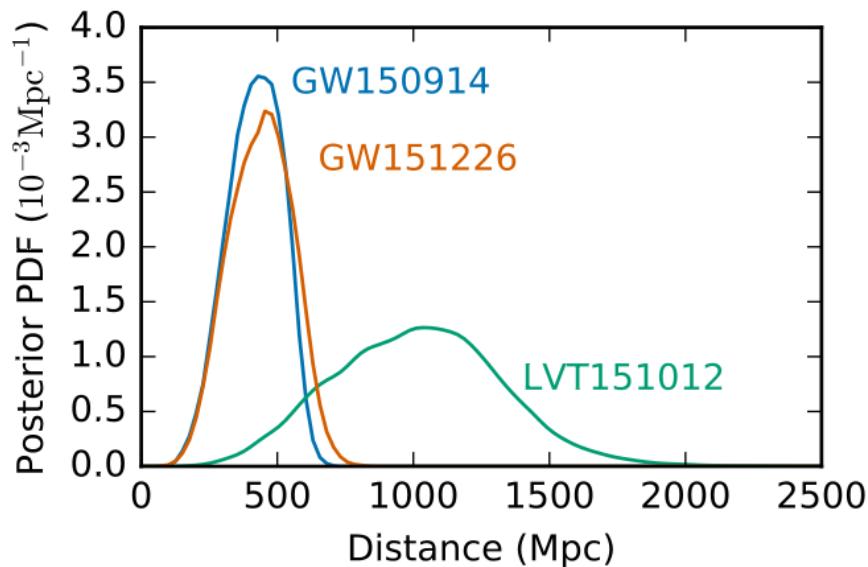
$\rightarrow \sim 1 M_{\text{sun}}$
radiated in GW

The ringdown phase is primarily governed by the mass and spin of the final black hole (quasi-normal modes)

Source position³⁰

arXiv:1606.04856

$$A_{GW} \propto 1/D_L$$



GW150914

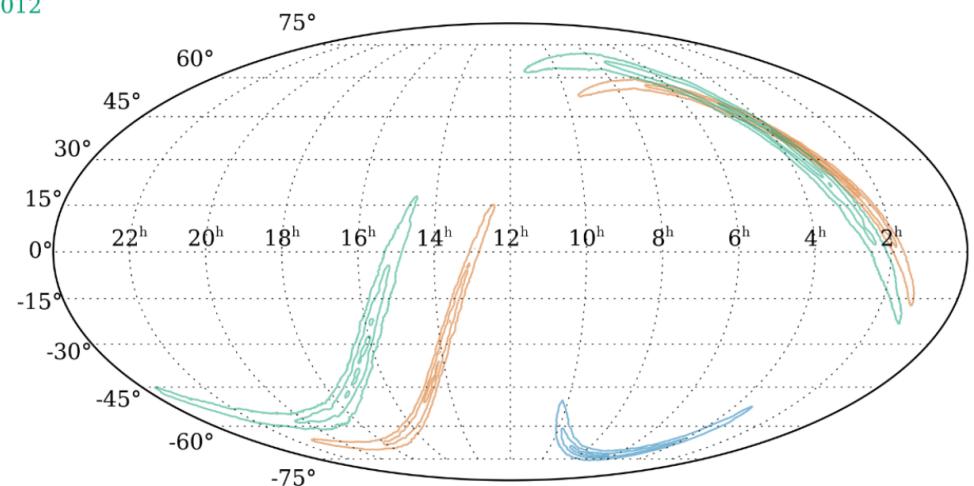
$$D_L = 420^{+150}_{-180} \text{Mpc} \quad z = 0.09^{+0.03}_{-0.04}$$

GW151226

$$D_L = 440^{+180}_{-190} \text{Mpc} \quad z = 0.09^{+0.03}_{-0.04}$$

(Lambda-CDM cosmology)

GW150914
GW151226
LVT151012



90% credible region for sky location:

$$\rightarrow \text{GW150914} = 230 \text{ deg}^2$$

$$\rightarrow \text{GW151226} = 850 \text{ deg}^2$$

Limited accuracy with 2 detectors
→ will be improved with a 3rd detector (a few deg²)

Testing the general relativity³¹

Phys. Rev. Lett. 116, 221101

arXiv:1606.04856

First opportunity to study GR in a strong-field regime

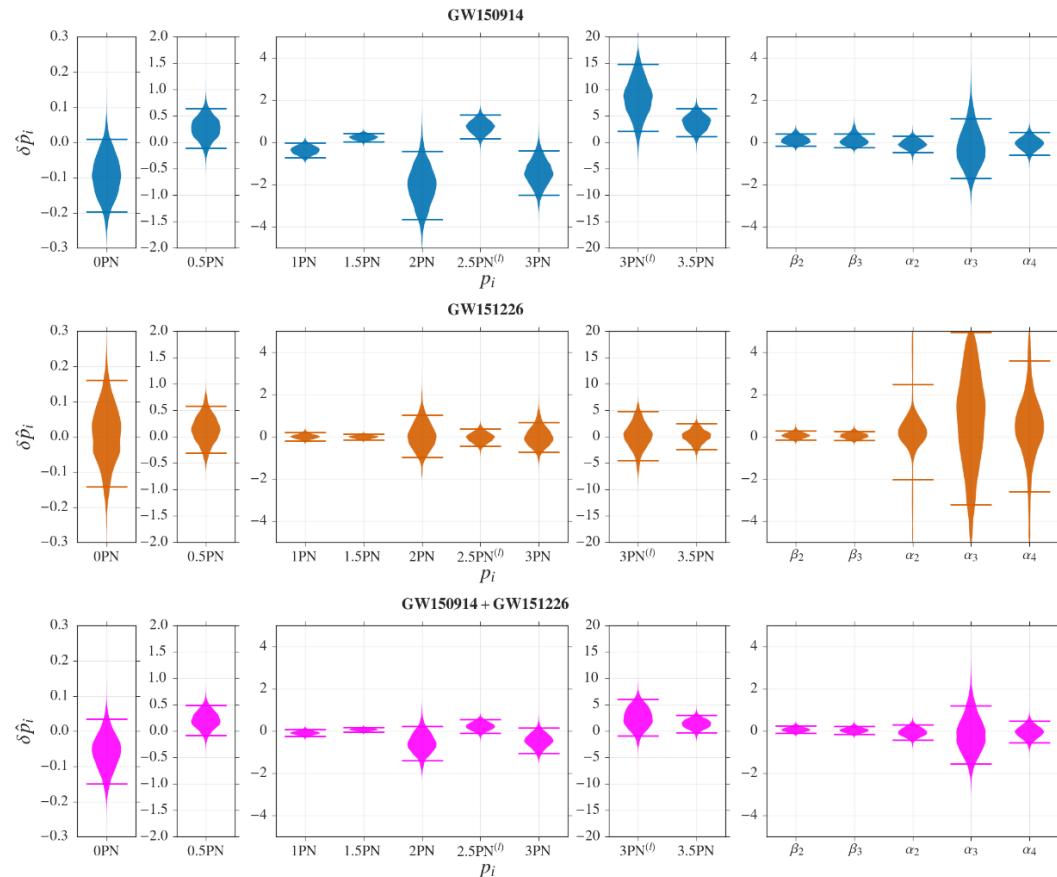
Test #1 → signal waveform/GR consistency: residual compatible with noise

Test #2 → BBH parameter consistency before/after merger: excellent

Test #3 → deviation from PN waveforms: constraints on PN coefficients

Test #4 → consistency with the least-damped quasi-normal-mode of the remnant black hole

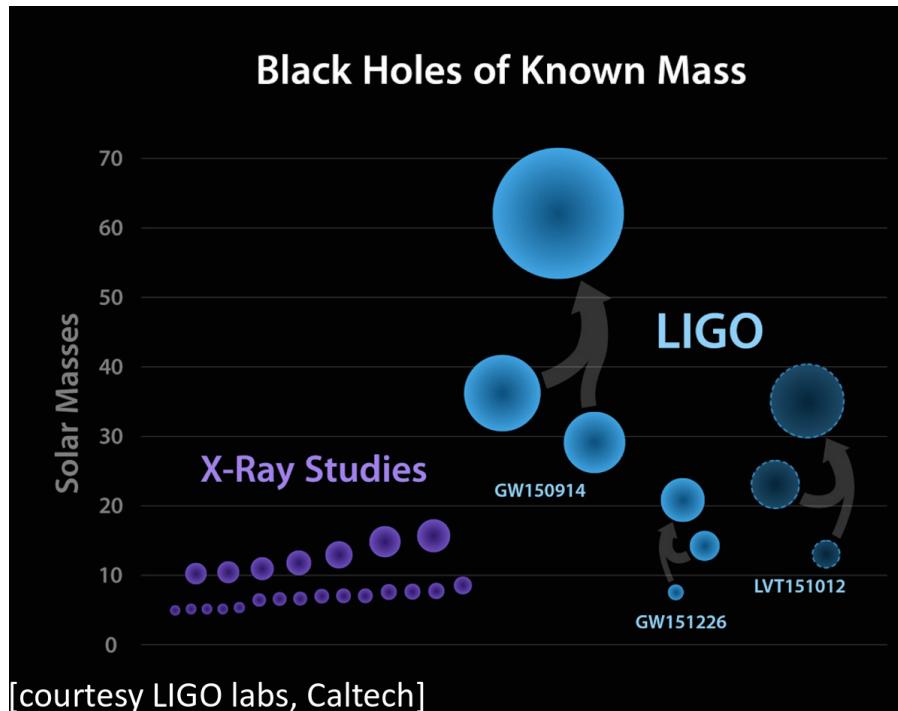
Test #5 → theory with massive graviton: best constraints on the graviton mass



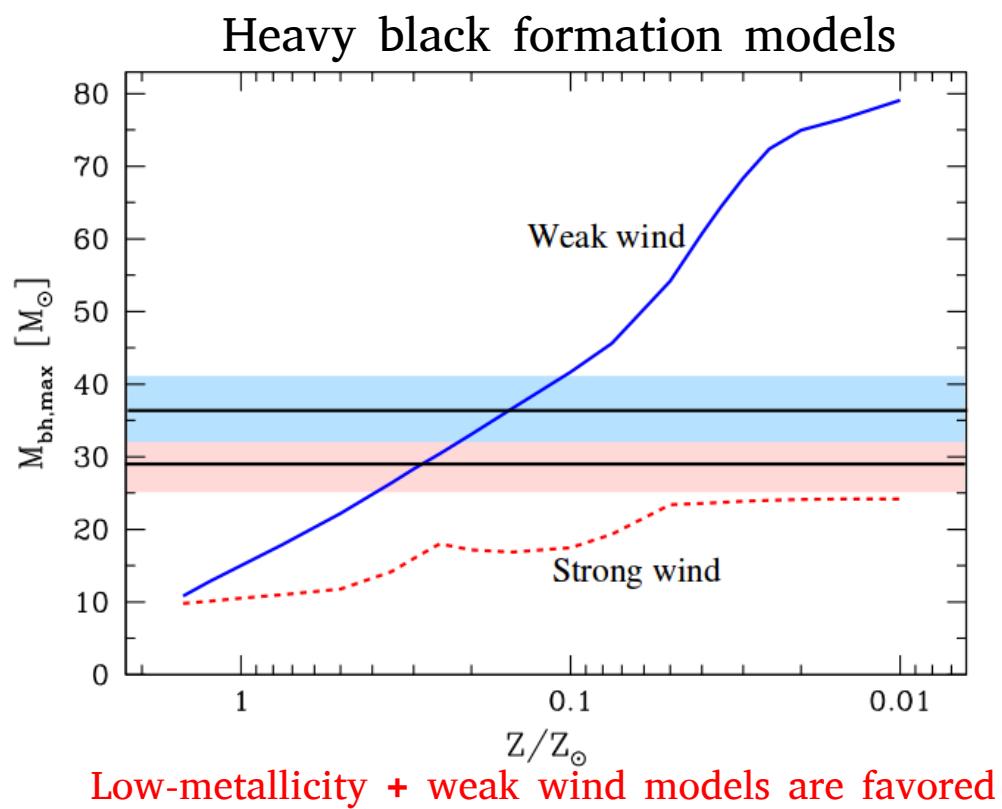
Waveform parameterization:
IMRPhenom phase is parameterized by
a set of coefficients
→ search for deviations:
 $p_i \rightarrow p_i \times (1 + \delta \hat{p}_i)$

Astrophysical implications³²

ApJL. 818, 2

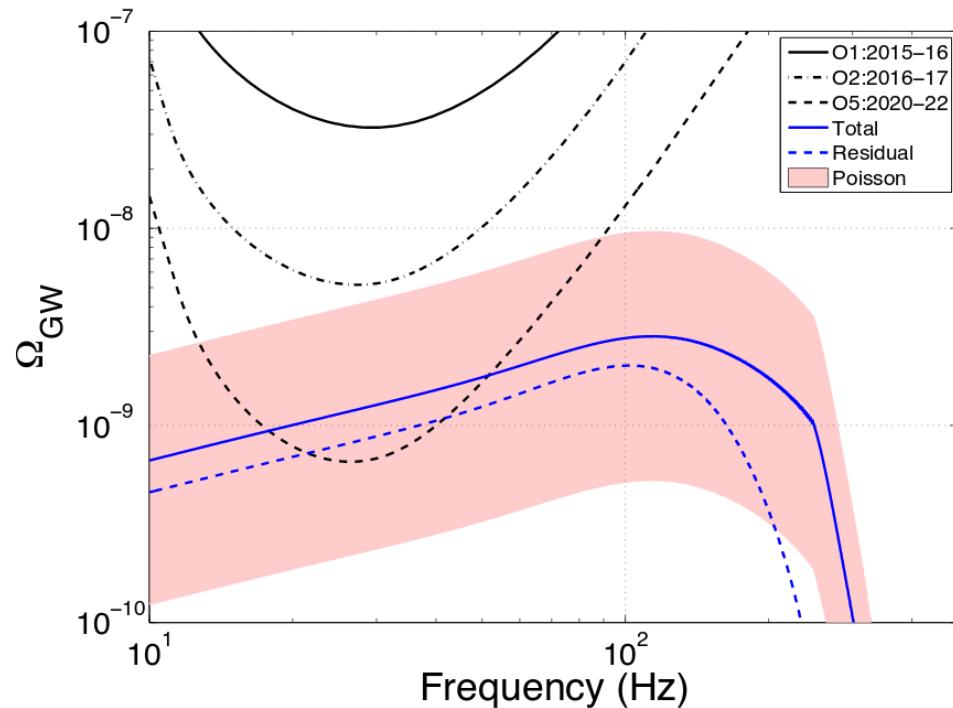


- binary black hole systems can form in nature (how?)
- binary black hole systems can merge in a Hubble time
- heavy stellar black holes can form in nature (how?)



Stochastic background³³

Phys. Rev. Lett. 116, 13110



Properties of GW150914 → robust estimate for the energy density of gravitational-wave background from binary black holes

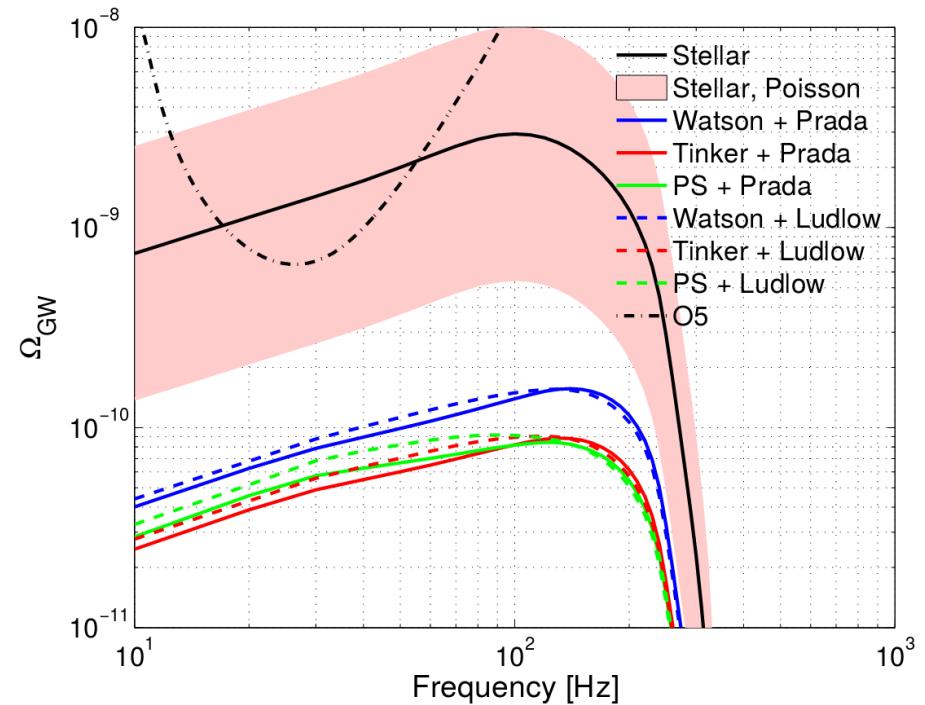
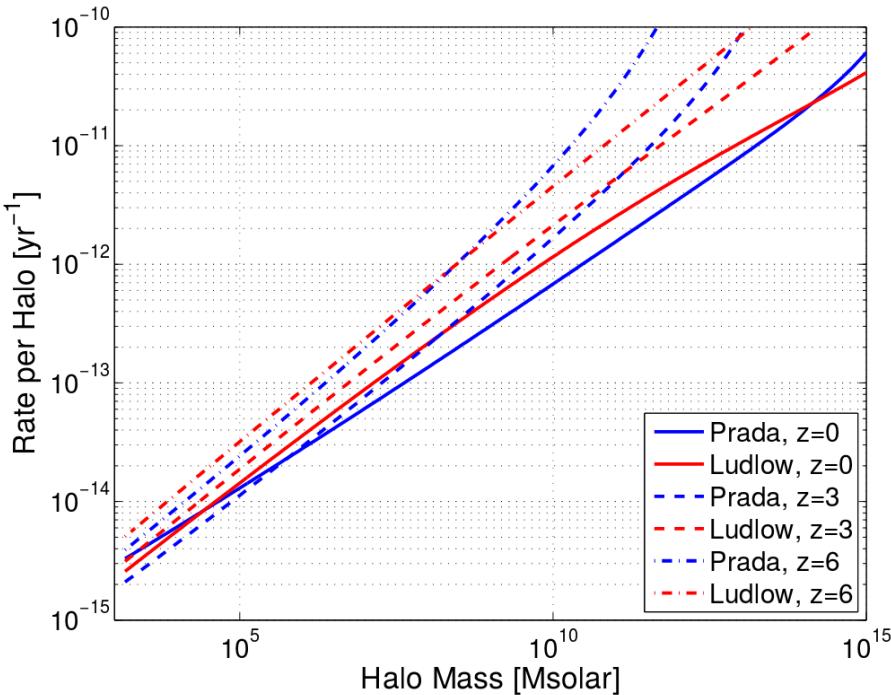
→ The design sensitivity of Advanced detectors is required to access such a signal
(but it is going to be tough!)

Hint for dark matter? ³⁴

Mandic et al. arXiv:160806699

GW150914: heavy black holes → could be of primordial origin and contribute to the dark matter content of the Universe

Model to compute the merger rate per dark matter halo → Stochastic background



→ Unlikely to detect primordial black holes with LIGO and Virgo detectors

Event rates³⁵

arXiv:1602.03842
arXiv:1606.04856

- Simulated signals with parameters drawn from astrophysical populations
- Noise distribution from CBC searches

Mass distribution	$R/(Gpc^{-3}yr^{-1})$		
	PyCBC	GstLAL	Combined
Event based			
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
Astrophysical			
Flat	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}

$p(m_1, m_2) \propto m_1^{-1} m_2^{-1}$
~underestimates the rate

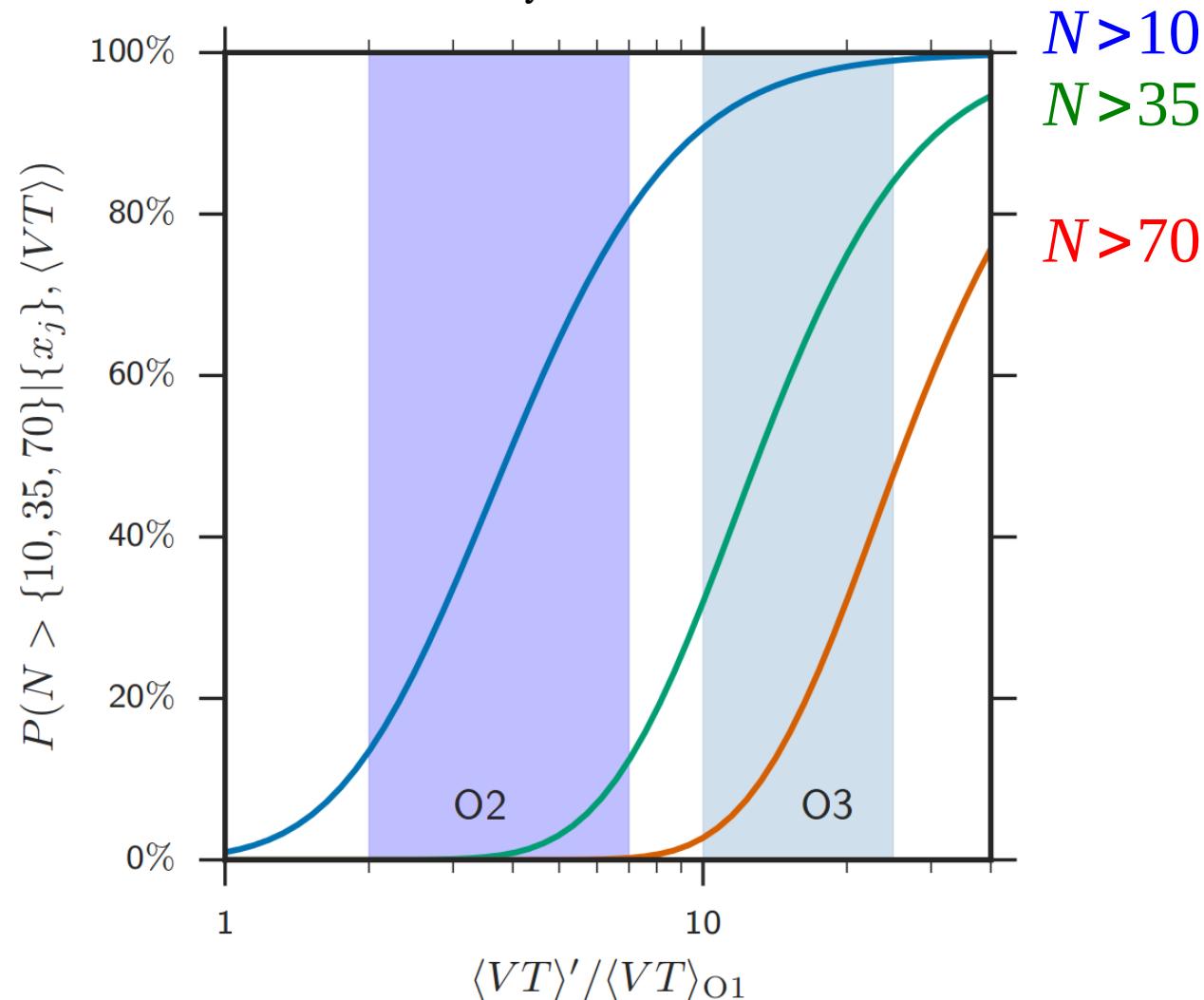
$p(m_1) \propto m_1^{-2.35}$
 $p(m_2) = cte$
~overestimates the rate

$$R = 9 - 240 Gpc^{-3} yr^{-1}$$

Detection rates³⁶

arXiv:1606.04856

False-alarm rate = 1 / 100 years



Conclusions & outlook³⁷

- This discovery is threefold:
 - first direct detection of a gravitational wave
 - first observation of a binary black hole system
 - first evidence of stellar mass $> 20 M_{\text{sun}}$
- Many experimental results obtained with only 2 events
- Gravitational-wave events can be detected with a low latency (<3min): first step in GW astronomy

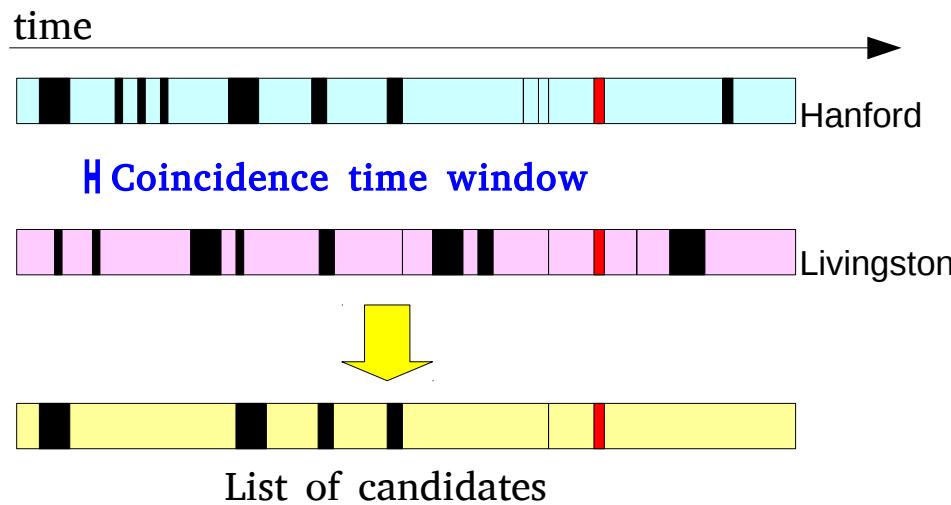
The future is promising

- More O1 results will be released soon
- A new data run is about to begin (O2), with improved detector sensitivity
- More events could be detected: population, new types of sources (supernovae, neutron stars)
- New instruments will join the network

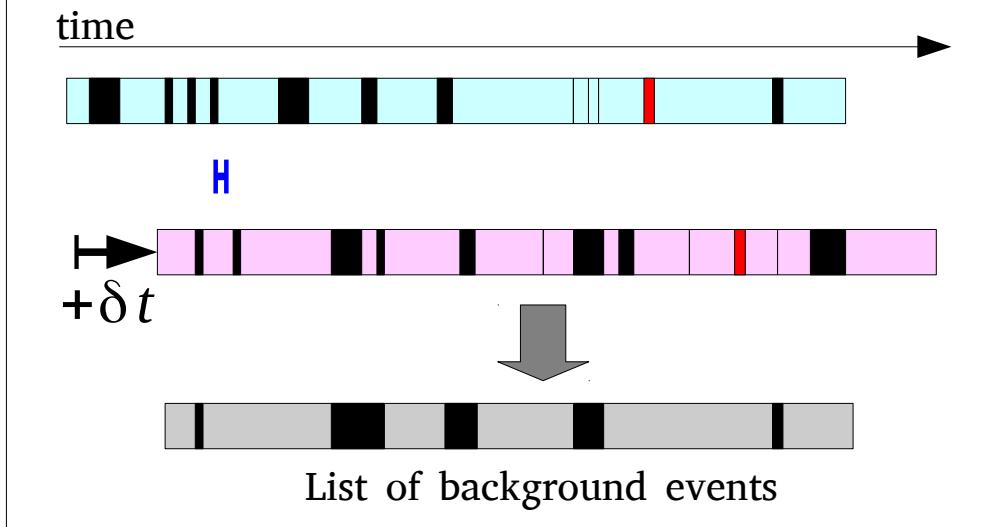
Event significance

The background of a gravitational-wave search is estimated using the time-slide technique
Assumption = uncorrelated noise between detectors

True experiment = noise + **signal**



Fake experiment = noise only



A very large number of fake experiments can be simulated using multiple offsets

GW150914 offline analysis:

- 16 days of coincident data
- $O(10^6)$ time offsets

→ **background estimated using a fake experiment of $O(100,000$ years)**

Binary neutron stars

Merger rate upper limits

