Probing Physics and Astrophysics with Gravitational Wave Observations

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Mid-Atlantic Senior Physicists' Group
January 18, 2017

GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

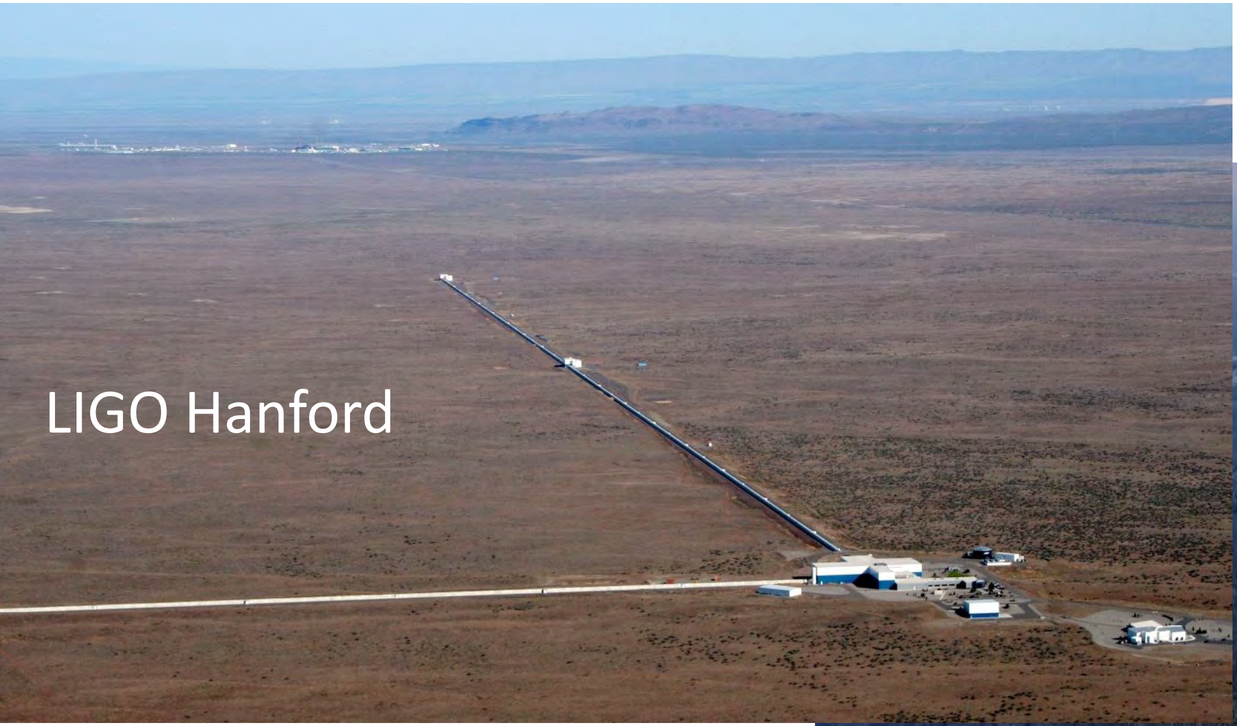
NEWS FLASH:
We detected gravitational waves

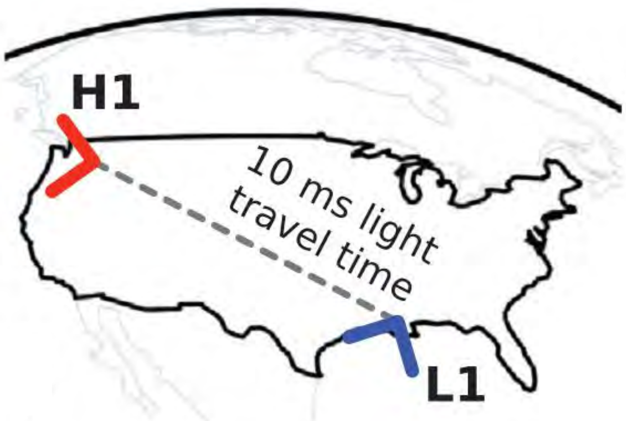
We = the LIGO Scientific Collaboration together with the Virgo Collaboration

Trinity University
University of Maryland
Andrews University
Washington State University
California State University Fullerton
The University of Alabama in Huntsville
Whitman College
Sonoma State University
indigo
Montclair State University
University of Glasgow
Australian National University
American University
University of the West of Scotland UWS
Texas Tech University
Tsinghua University
R·I·T
Max Planck Institute for Gravitational Physics Albert Einstein Institute
University of Strathclyde
Michigan
Università degli Studi del Sannio
CITA ICAT
NASA Goddard Space Flight Center
ICTP SAIFR
The University of Western Australia
University of Cambridge
ACU
Monash University
Southern University Agricultural & Mechanical College
Columbia University in the City of New York
The University of Chicago
Montana State University
The University of Mississippi
The University of Adelaide Australia
Caltech
University of Minnesota
University of Birmingham
The University of Melbourne
Universitat de les Illes Balears
University of Washington
GEO 600
UTRGV
University of Wisconsin Milwaukee
Syracuse University
Cardiff University Prifysgol Caerdydd
Northwestern
Monash University
INPE
UF University of Florida
Georgia Institute of Technology
Korean Gravitational Wave Group
LSU Louisiana State University
ACIGA
University of Southampton
Charles Sturt University
Embry-Riddle Aeronautical University
Leibniz Universität Hannover
PennState
Science & Technology Facilities Council Rutherford Appleton Laboratory

… using the LIGO* Observatories

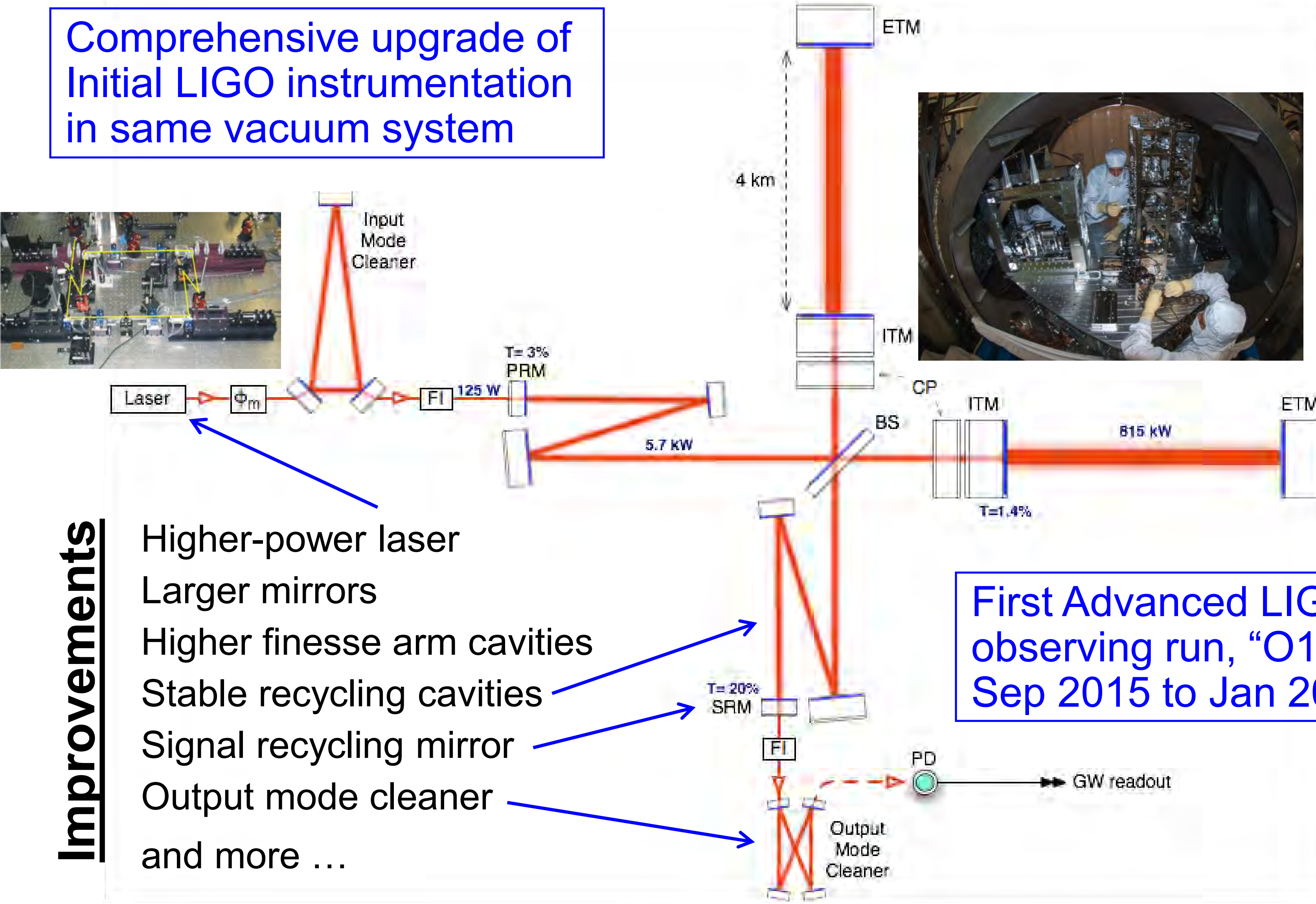
* LIGO = Laser Interferometer Gravitational-wave Observatory

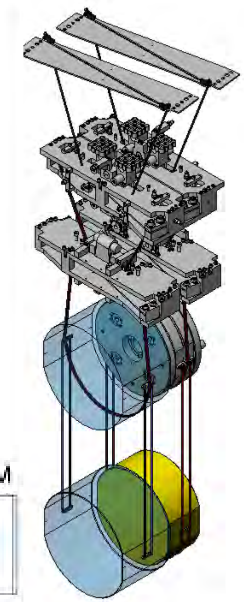




… after the *Advanced LIGO* Upgrade

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system



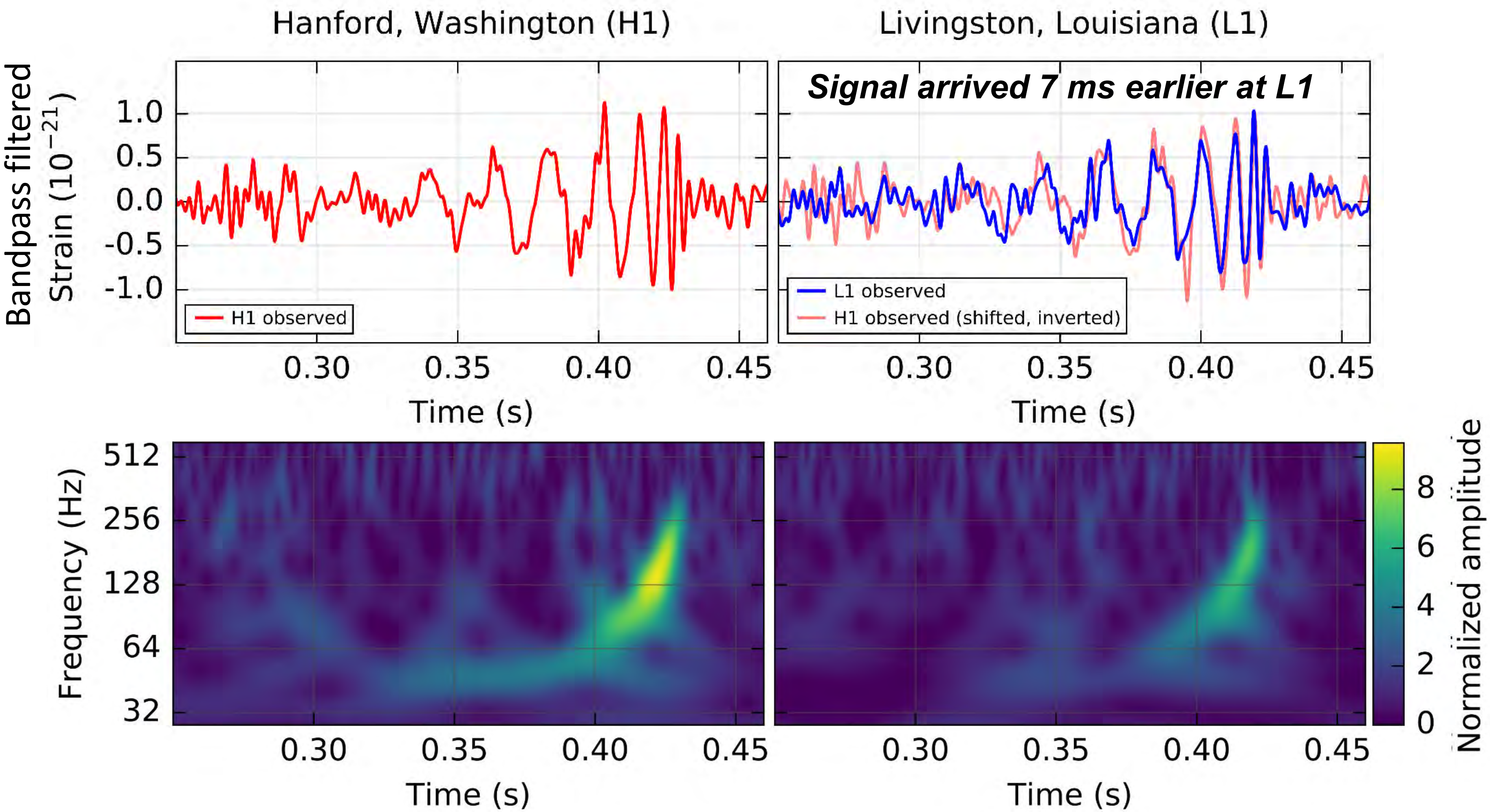


Improvements

- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and more …

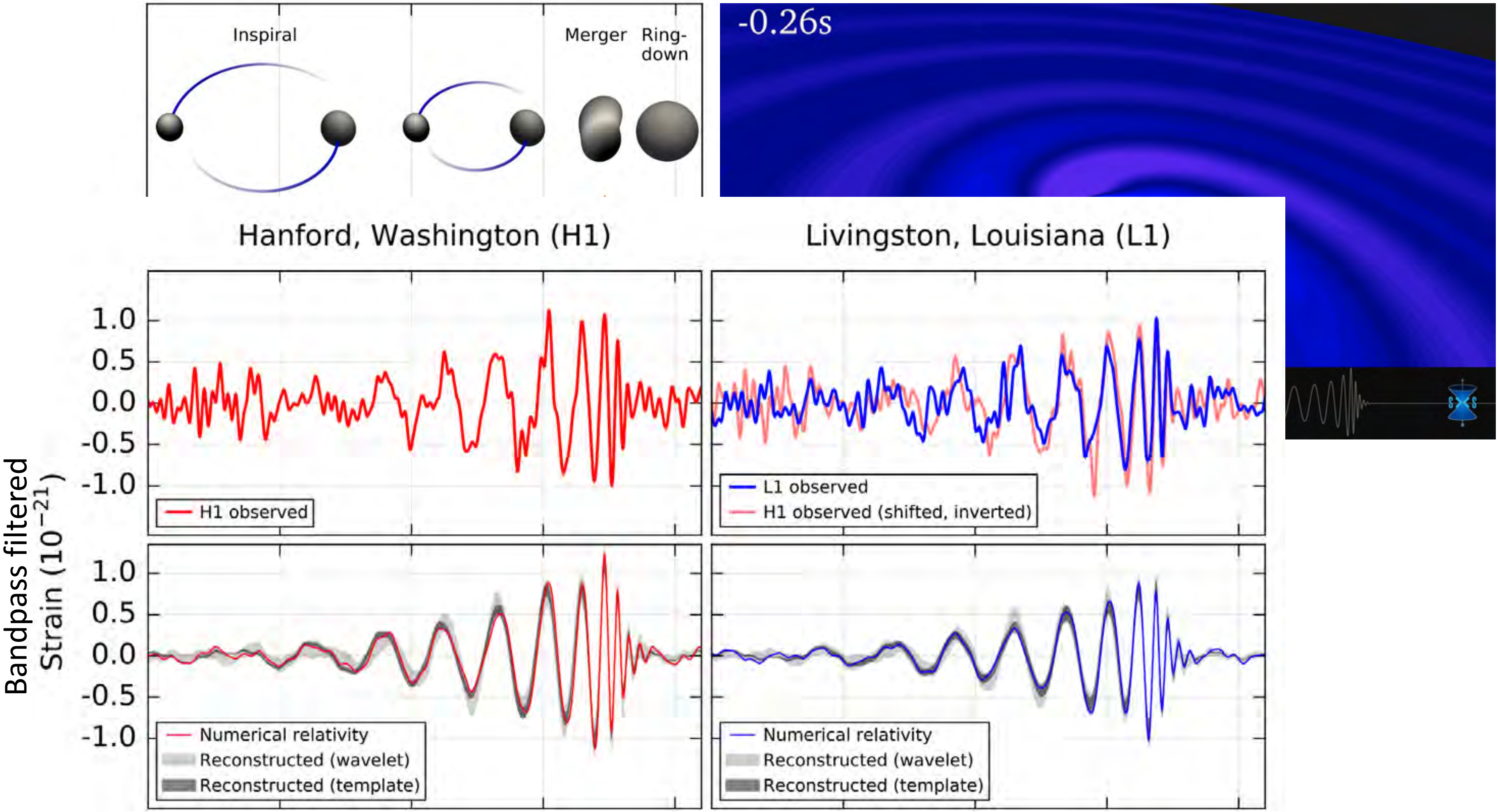
First Advanced LIGO observing run, “O1”, was Sep 2015 to Jan 2016

GW150914



Hanford, Washington (H1)
Livingston, Louisiana (L1)
Signal arrived 7 ms earlier at L1
Bandpass filtered Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
0.30
0.35
0.40
0.45
Time (s)
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
8
6
4
2
0

Looks just like a binary black hole merger!



Matches well to BBH template when filtered the same way

Announcing the Detection

Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

A Big Splash in February

with both the scientific community and the general public!

- Press conference
- PRL web site
- Twitter

- Facebook
- Newspapers & magazines
- YouTube videos
- The Late Show, SNL, …

The New York Times

Late Edition

NEW YORK, FRIDAY, FEBRUARY 12, 2016

$2.50

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.

More generally, it means that a century of innovation, testing, questioning and plain hard work after Einstein imagined it on paper, scientists have tapped into the deepest register of physical reality, where the weirdest and wildest implications of Einstein's universe become manifest.

…'s Corner, Blacks Notice Sanders

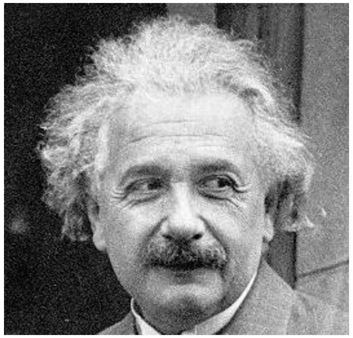
Courted Hard in South Carolina, Loyalists Listen Closely

Last Occupier In Rural Oregon Is Coaxed Out

A long-awaited confirmation

Gravitational Waves

Predicted to exist by Einstein's general theory of relativity



… which says that gravity is really an effect of "curvature" in the geometry of space-time, caused by the presence of any object with mass

Expressed mathematically by the Einstein field equations

Solutions describe the regular (static) gravitational field,
but also wave solutions which travel at the speed of light

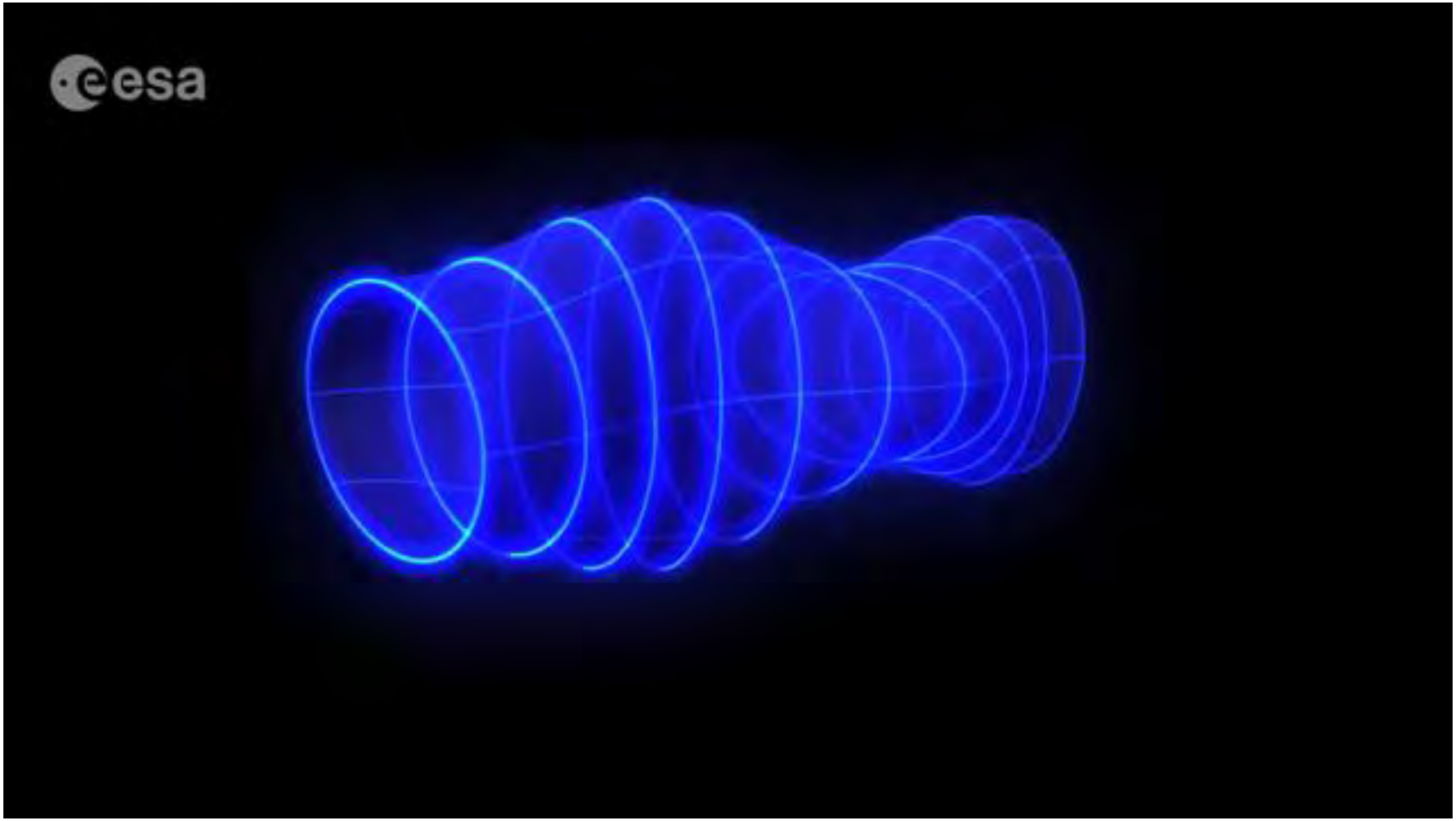
These waves are perturbations of the *spacetime metric* —
the effective distance between points in space and time

$$g_{\mu\nu}$$

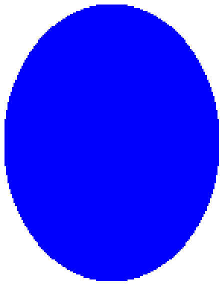
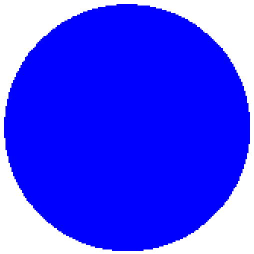
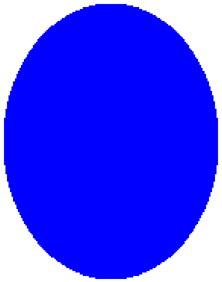
➔The geometry of space-time is dynamic, not fixed!

It alternately *stretches* and *shrinks* with a characteristic *strain*

Gravitational Waves in Motion

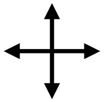


Gravitational Wave Polarizations

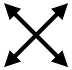




…

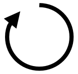
“Plus” polarization



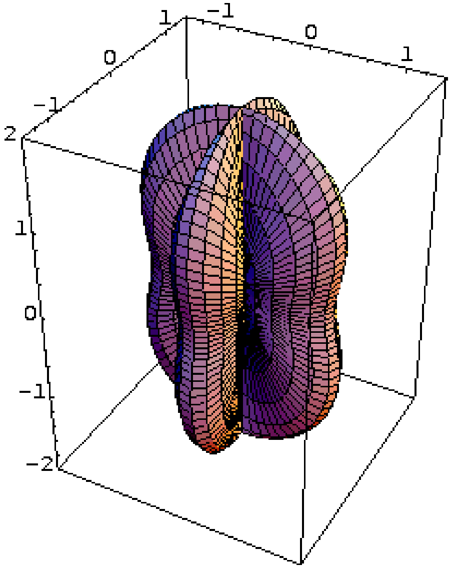
“Cross” polarization

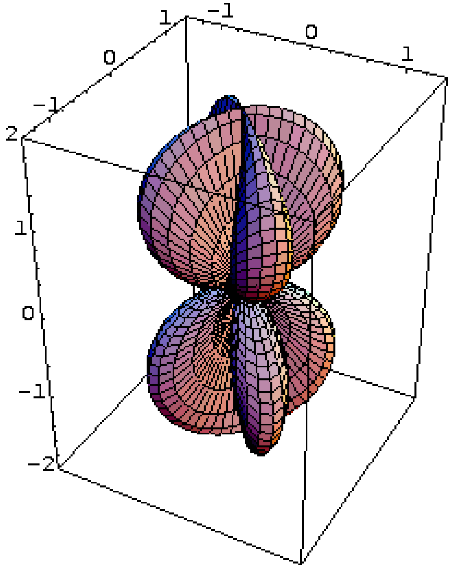


Circular polarization



Directional sensitivity of detector depends on polarization of waves

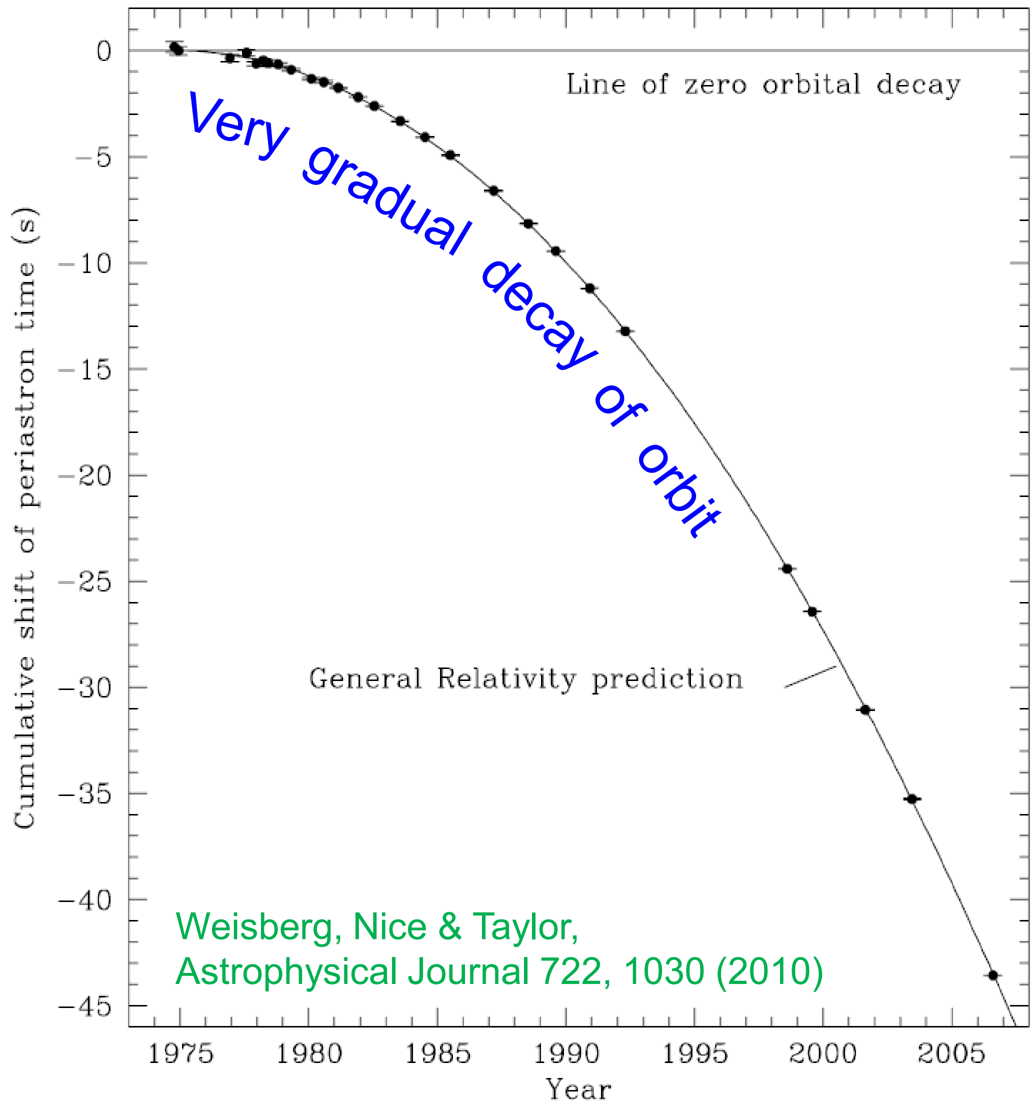




Earlier Evidence for Gravitational Radiation

Arecibo radio telescope observations of the binary pulsar B1913+16 give us the masses (1.44 and 1.39 $M_\odot$) and orbital parameters

This binary neutron star system is changing, just as general relativity predicts! Very strong <u>indirect</u> evidence for gravitational radiation



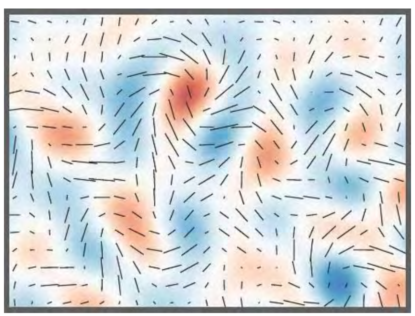
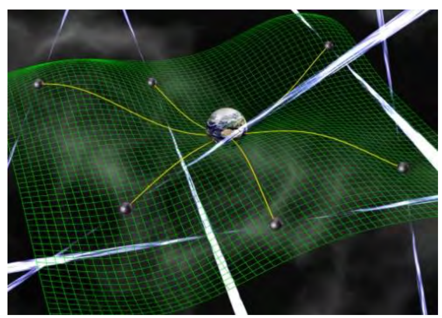
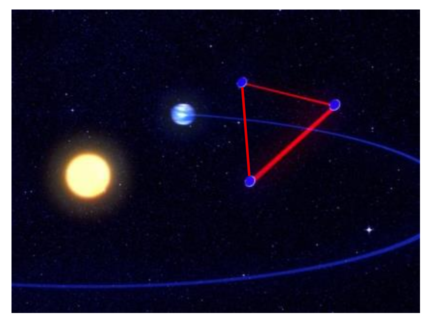
Joe Weber's Fearless Idea!

LIGO and other gravitational wave detectors have built on Weber's pioneering efforts using resonant "bar" detectors, first constructed on the UMD campus in the 1960s

1969 claim of evidence for discovery of gravitational radiation could not be confirmed by others

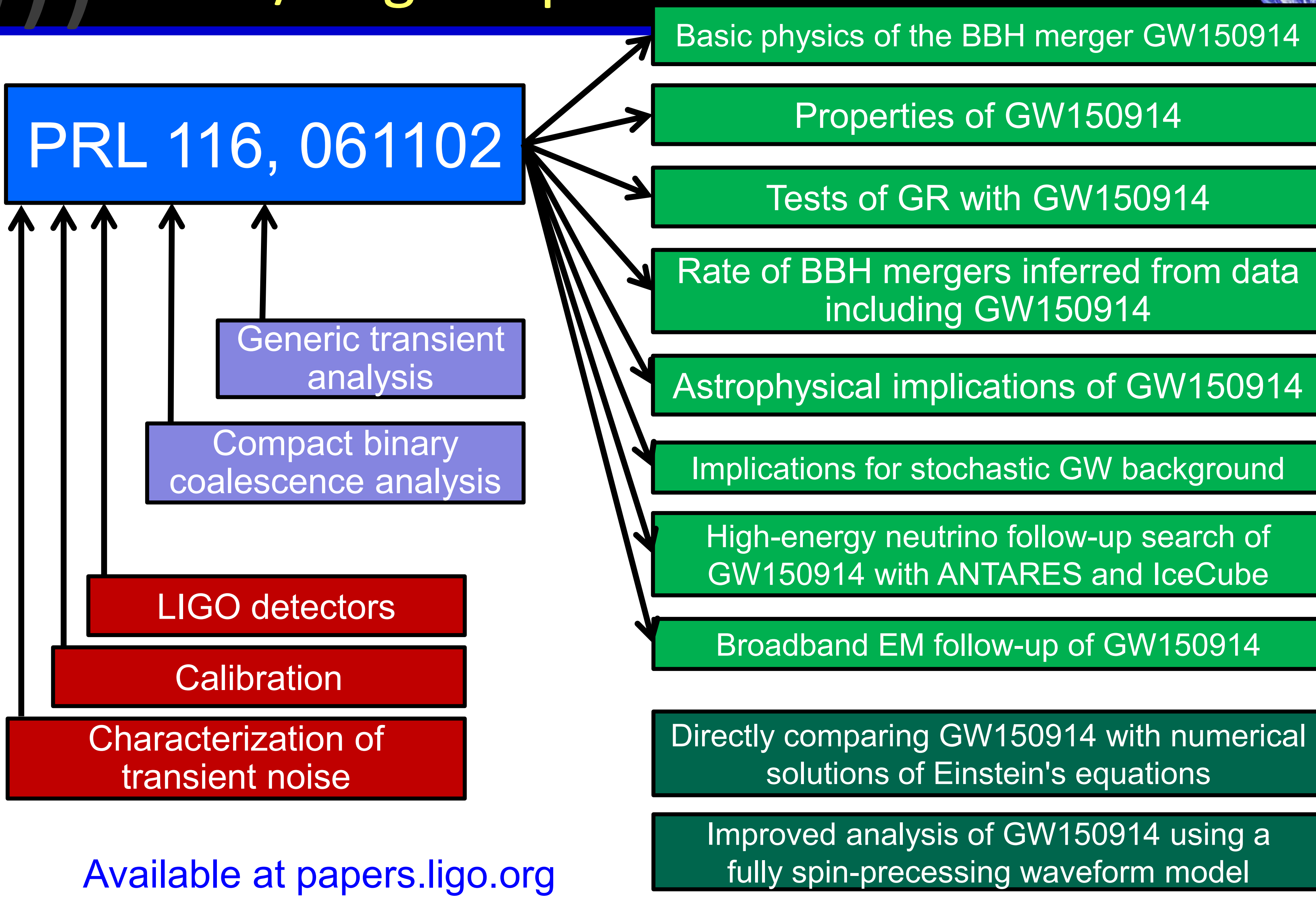
Weber bar on permanent display at LIGO Hanford Observatory

The Wide Spectrum of Gravitational Waves

	$\sim 10^{-17}$ Hz	$\sim 10^{-8}$ Hz	$\sim 10^{-2}$ Hz	~ 100 Hz
Likely sources	**Primordial GWs from inflation era**	***Gravitational radiation driven Binary Inspiral + Merger***		
		Supermassive BHs	Massive BHs, extreme mass ratios	Neutron stars, stellar-mass BHs
		Cosmic strings?	**Ultra-compact Galactic binaries**	**Spinning NSs** **Stellar core collapse** Cosmic strings?
Detection method	B-mode polarization patterns in cosmic microwave background	Pulsar Timing Array (PTA) campaigns	Interferometry between spacecraft	Ground-based interferometry
	 BICEP2	 David Champion	 AEI/MM/exozet	 LIGO Laboratory
Projects	BICEP2/Keck, ACT, EBEX, POLARBEAR, SPTpol, SPIDER, …	NANOGrav, European PTA, Parkes PTA	LISA, DECIGO	LIGO, GEO 600, Virgo, KAGRA

But what exactly did we detect?
And what is significant about it?

LIGO/Virgo Papers About GW150914



Available at papers.ligo.org

Exploring the Properties of GW150914

Bayesian parameter estimation: Adjust physical parameters of waveform model to see what fits the data from both detectors well

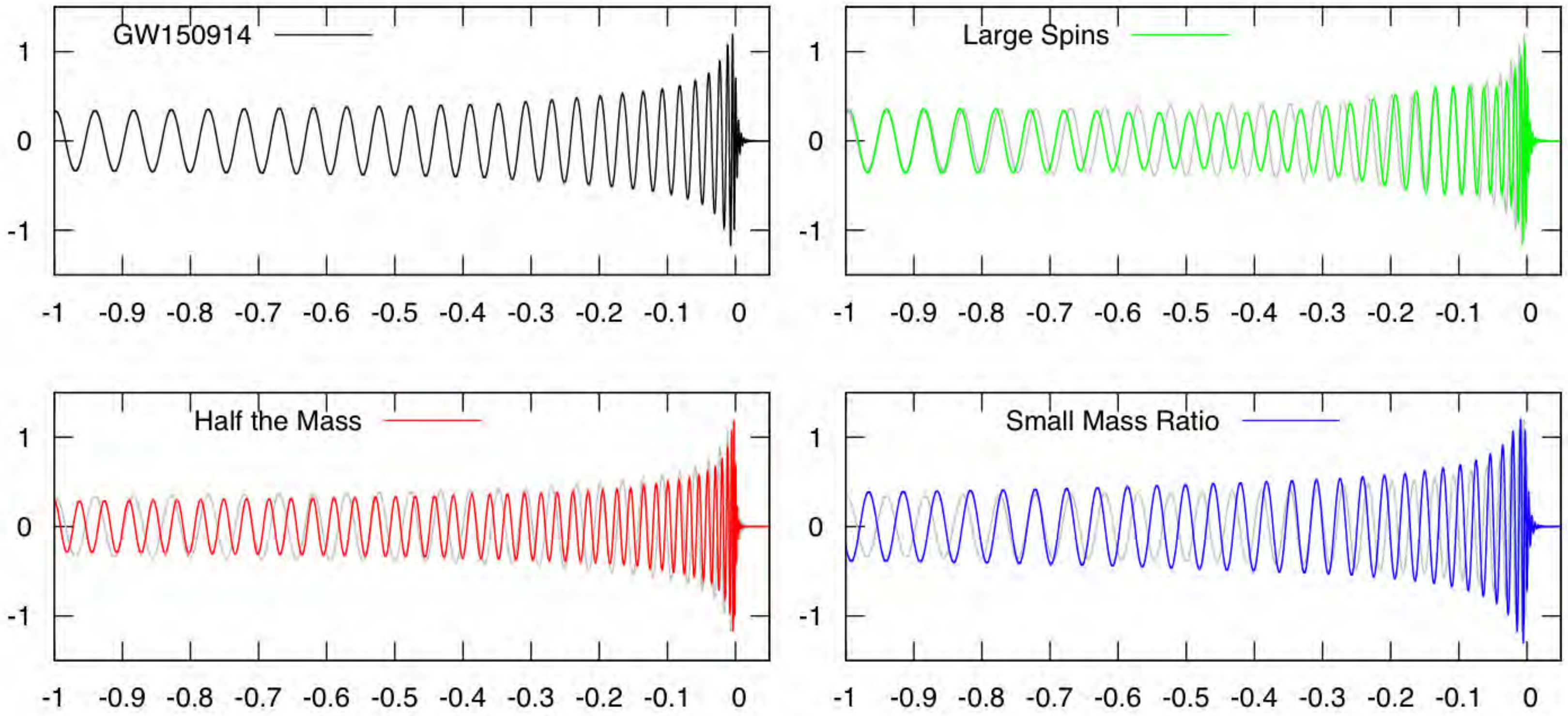
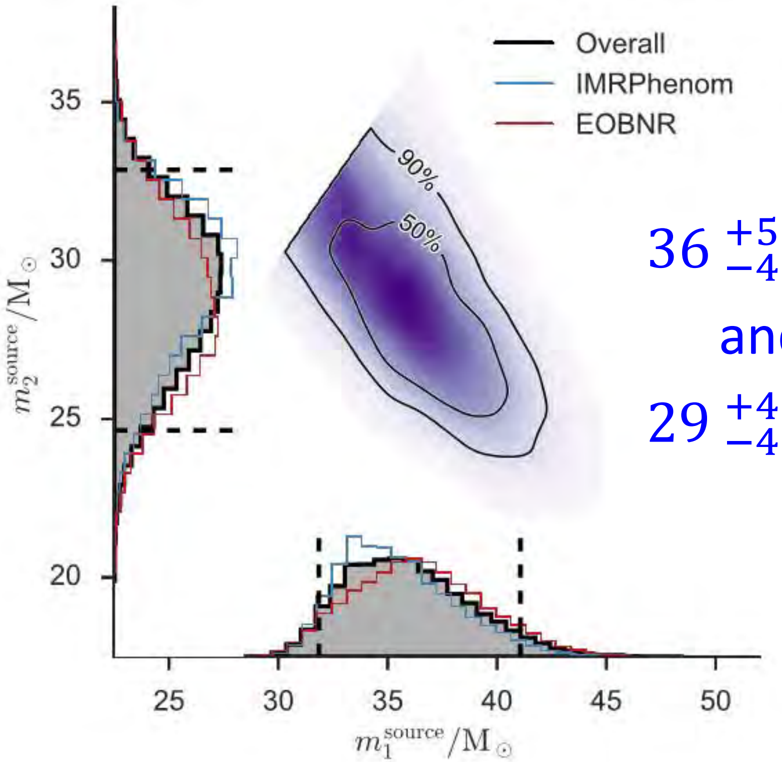


Illustration by N. Cornish and T. Littenberg

➔ Get ranges of likely (“credible”) parameter values

Use waveform models which include black hole spin, but no orbital precession

Masses:



$36^{+5}_{-4}\ M_\odot$

and

$29^{+4}_{-4}\ M_\odot$

Abbott et al., PRL 116, 241102

Reanalysis with fully precessing waveform model (PRX in press, arXiv:1606.01210) is consistent, with slightly smaller errors

Final BH mass: $62 \pm 4\ M_\odot$

Energy radiated: $3.0 \pm 0.5\ M_\odot c^2$

Peak power $\sim 200\ M_\odot c^2/s$!

Luminosity distance

(from absolute amplitude of signal):

410^{+160}_{-180} Mpc

(~1.3 billion light-years!)

➔ Redshift $z \approx 0.09$

Frequency shift of signal is taken into account when inferring masses

Properties of GW150914

The spin of the final black hole is inferred to be $\mathbf{0.67^{+0.05}_{-0.07}}$
(as a fraction of the maximum spin allowed by GR, $\frac{Gm^2}{c}$)

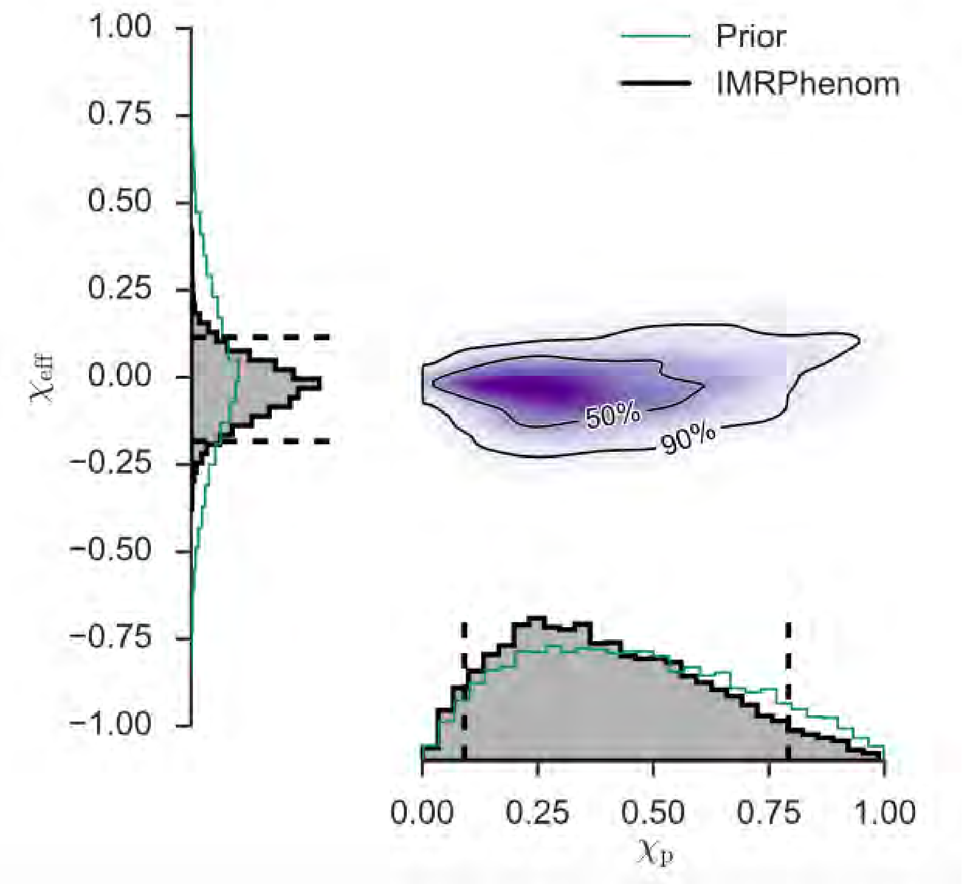
We don't find evidence for spin of the initial component black holes (and only weak limits)

From parameters that influence the waveform:

$$\chi_{\text{eff}} = \frac{c}{G}\left(\frac{\vec{S}_1}{m_1} + \frac{\vec{S}_2}{m_2}\right) \cdot \frac{\hat{L}}{(m_1+m_2)}$$

affects how the signal "chirps"

χ_{p} quantifies the expected precession of the orbital plane

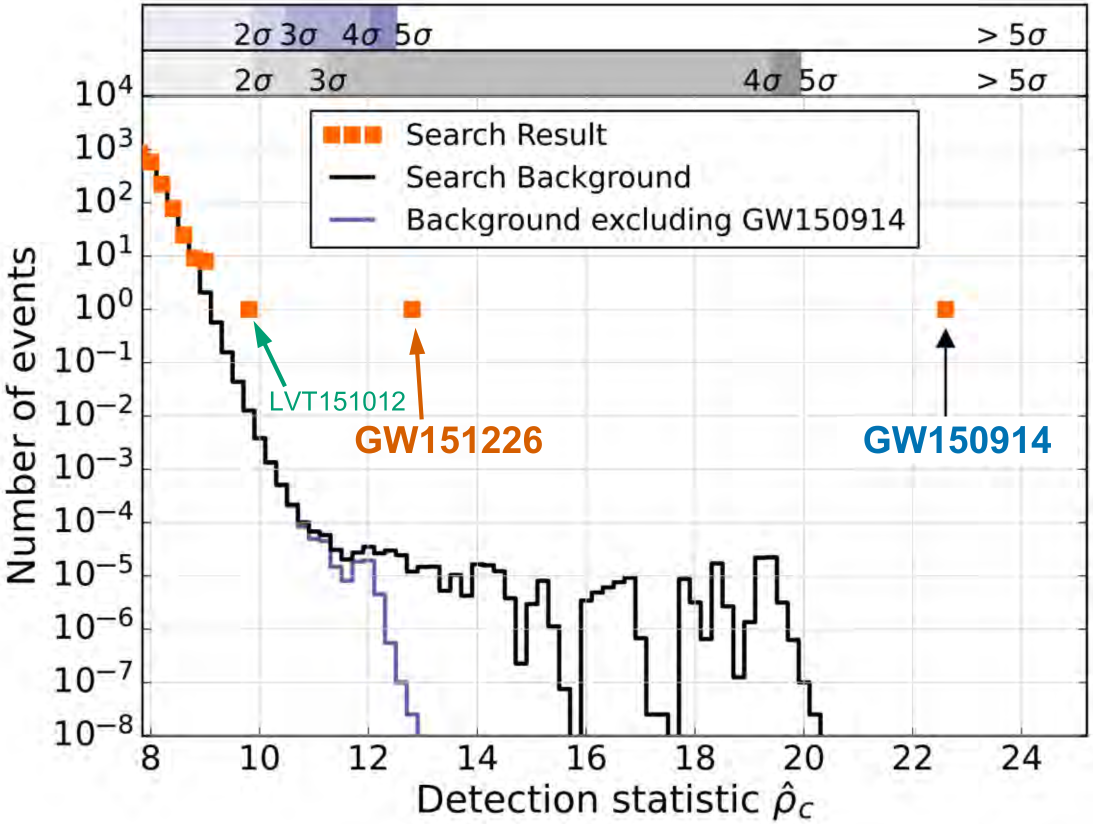


Abbott et al., PRL 116, 241102

But wait, there’s more!

The Boxing Day Event

Analysis of the complete O1 run data revealed one additional significant binary black hole coalescence signal, GW151226



Data set:
Sept 12 to Jan 9

Abbott et al.,
PRL 116, 241103

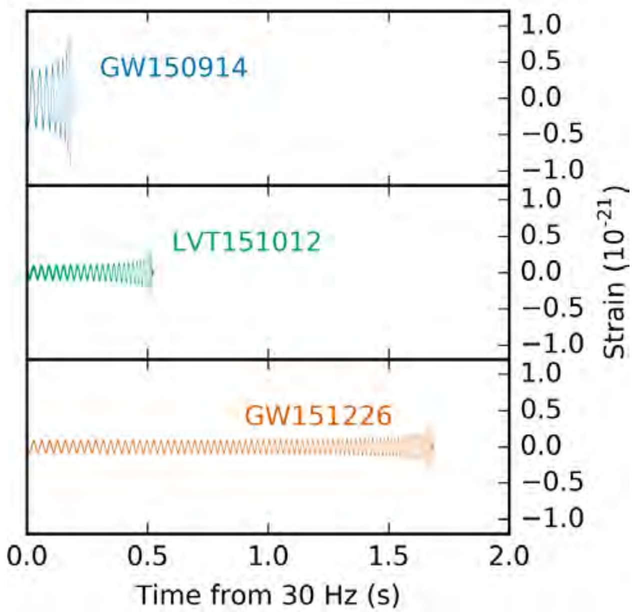
Weaker than GW150914, but still detected with $> 5\sigma$ significance

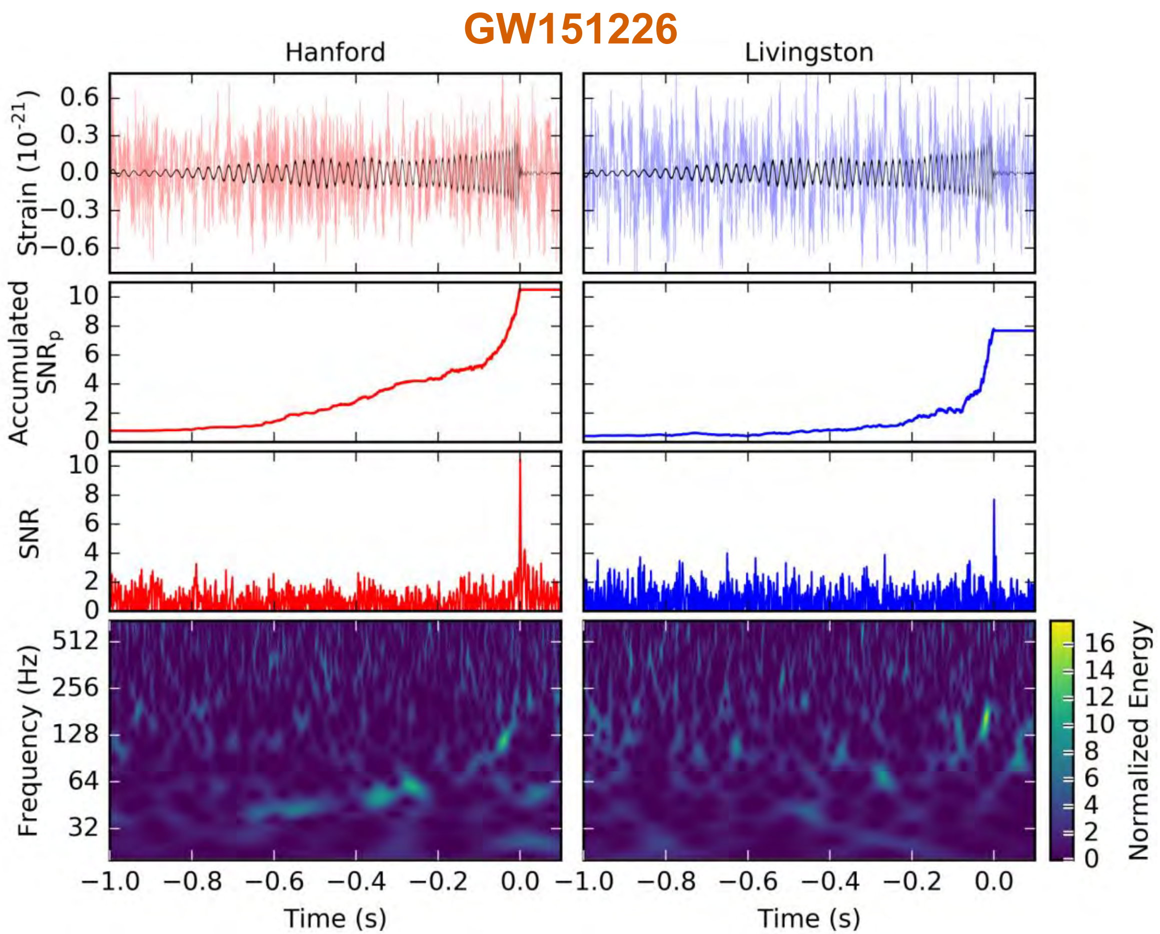
And there's also a marginally significant candidate, LVT151012

Not so visible in the data…

Another signal consistent with GR, but qualitatively different

Longer duration,
lower amplitude,
more “cycles” in band





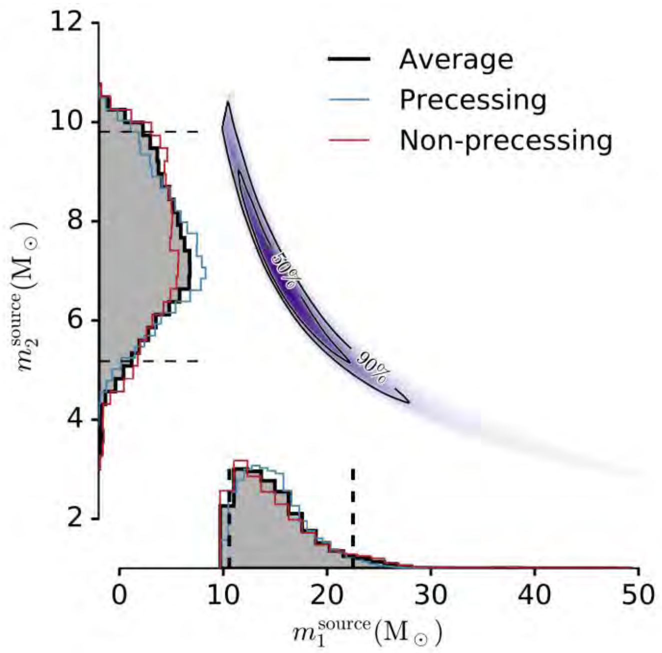
➔ *Matched filtering* was essential for detecting GW151226

Properties of GW151226

GW151226 has lower mass than GW150914

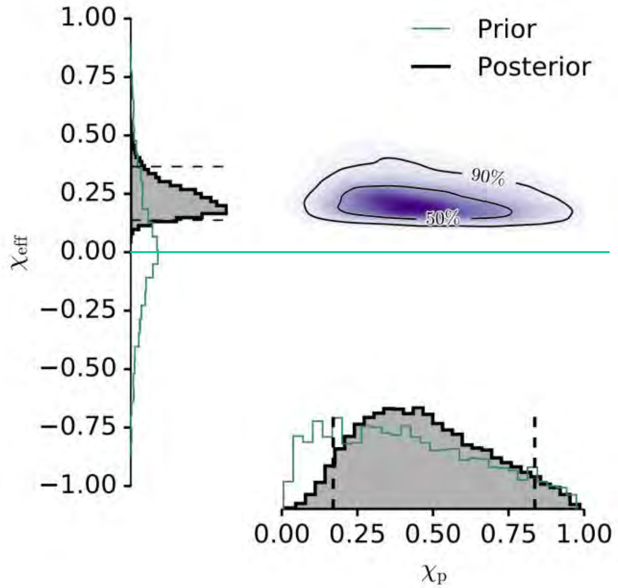
Initial masses: $14.2^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$
Final BH mass: $20.8^{+6.1}_{-1.7}\ M_\odot$
Energy radiated: $1.0^{+0.1}_{-0.2}\ M_\odot c^2$

Luminosity distance: 440^{+180}_{-190} Mpc



Abbott et al., PRL 116, 241103

… and nonzero spin !



Effective signed spin combination definitely positive
⇒ at least one of the initial BHs had nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)

https://losc.ligo.org/start/

LVmtg Petitions LV-EM Traffic Phys Dept Classes ELMS MP Burst telecons Home email AY login Handbook

LIGO Open Science Center

LIGO is operated by California Institute of Technology and Massachusetts Institute of Technology and supported by the U.S. National Science Foundation.

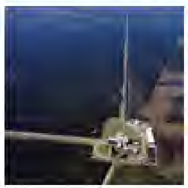
losc.ligo.org

- Getting Started
- Tutorials
- Data
  - Events
  - Bulk Data
- Timelines
- My Sources
- Software
- GPS ↔ UTC
- About LIGO
- Data Analysis Projects
- Acknowledgement

Getting Started

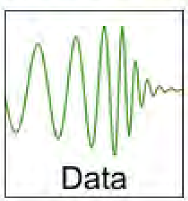
Welcome! The LIGO Open Science Center (LOSC) provides access to LIGO data, as well as documentation, tutorials, and online tools for finding and viewing data.

What's LIGO!?



The LIGO Scientific Collaboration Home Page provides a general introduction to LIGO.

Where's the data?

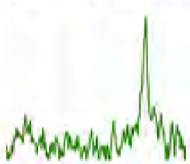


The Data Page allows you to download LIGO data.

The main data are a time series sampled at 4096 Hz.

Data are calibrated so that gravitational wave signals have units of dimensionless strain (ΔL / L).

How do I work with LIGO data?

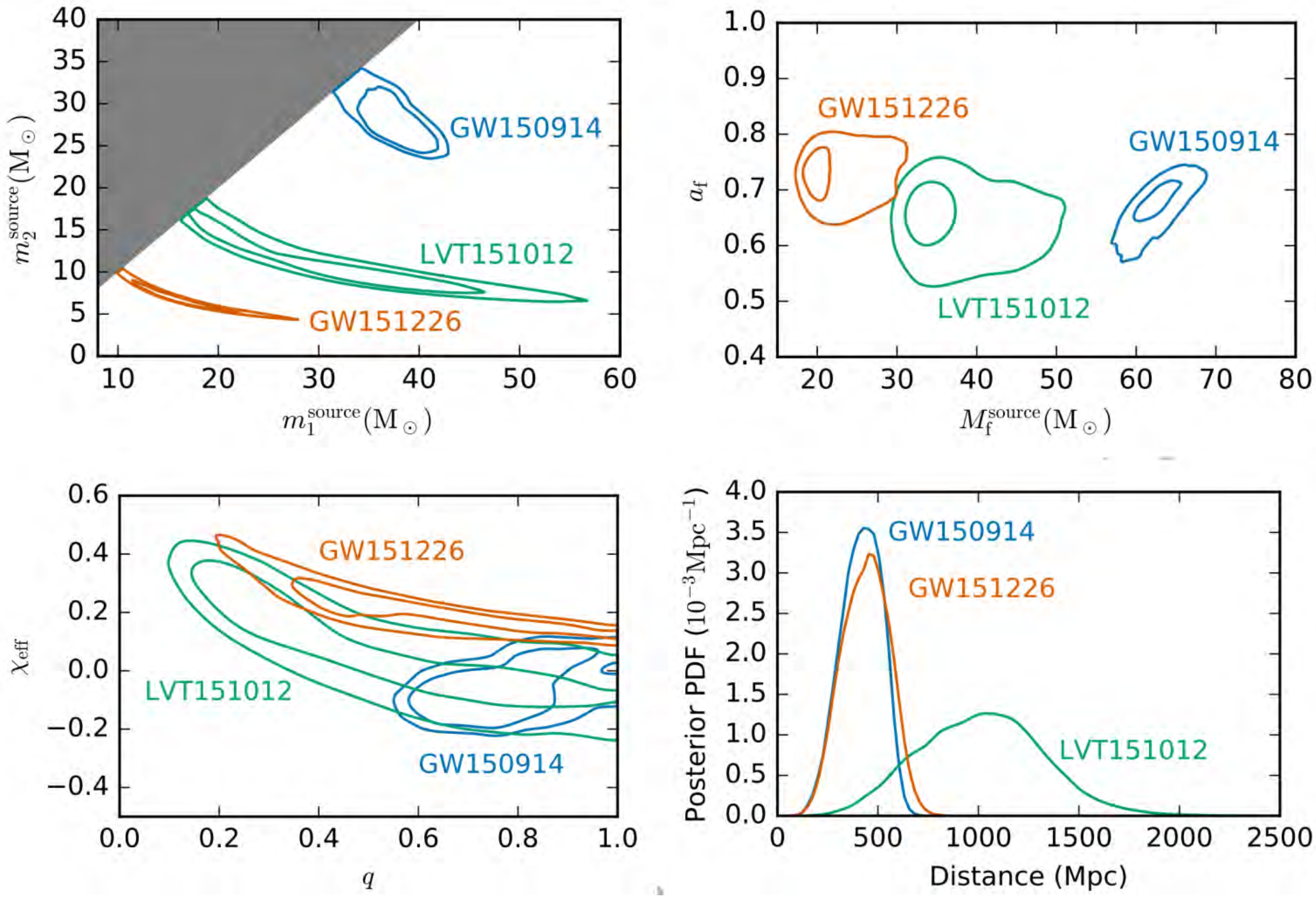


The Tutorials Page gives examples of how to work with LIGO data. If you are a student, this is a great place to start.

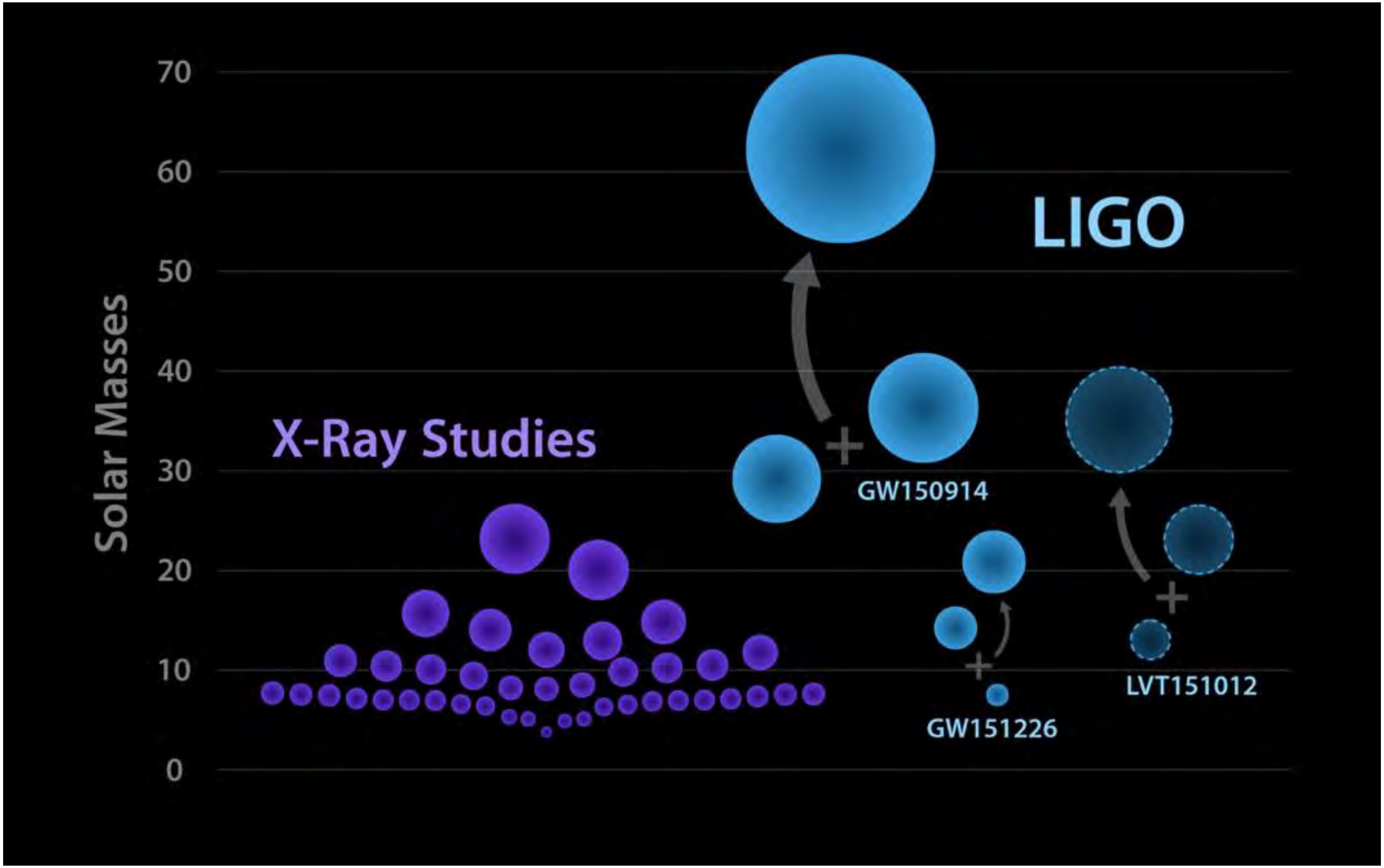
Astrophysical implications

Starting to see the population…

We include LVT151012 here because it is *probably* a real signal; our analysis estimates ~87% chance of it being real



Comparison of Black Hole Masses



Astrophysical Implications

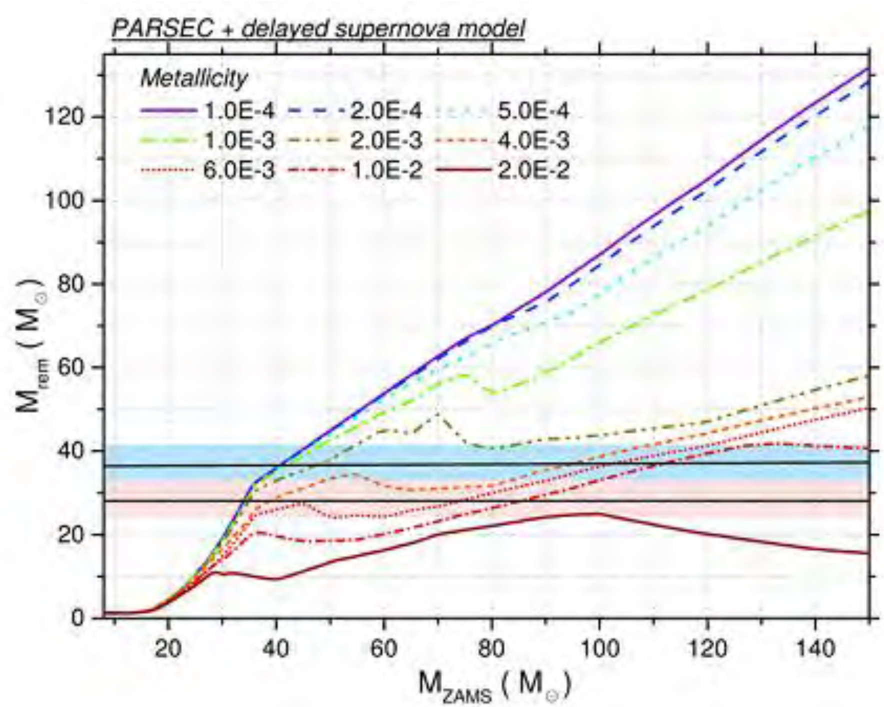
GW150914 proves that there are black hole binaries out there, orbiting closely enough to merge, and *heavy !*

For comparison, reliable BH masses in X-ray binaries are typically $\sim 10\ M_{\odot}$

We presume that each of our BHs formed directly from a star

➔ Low metallicity is required to get such large masses

Otherwise, strong stellar winds limit the final BH mass



Spera et al., MNRAS 451, 4086

Abbott et al., ApJL 818, L22

Astrophysical Implications

We can't tell *when* the binary was formed

The merger may have followed billions of years of gradual inspiral

Different formation pathways have been considered:

- A massive binary star system with sequential core-collapses
- Chemically homogeneous evolution of a pair of massive stars in close orbit
- Dynamical formation of binary from two BHs in a dense star cluster
- Or, from a population of primordial black holes?

Is GR really the correct theory of gravity?

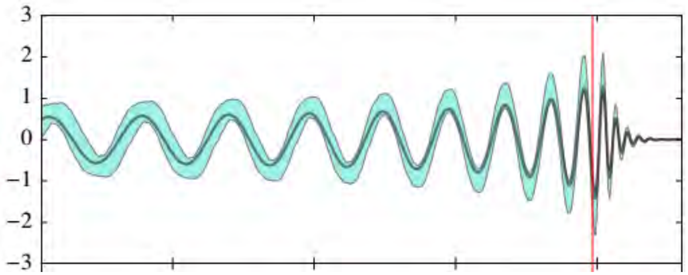
Detailed waveform comparisons

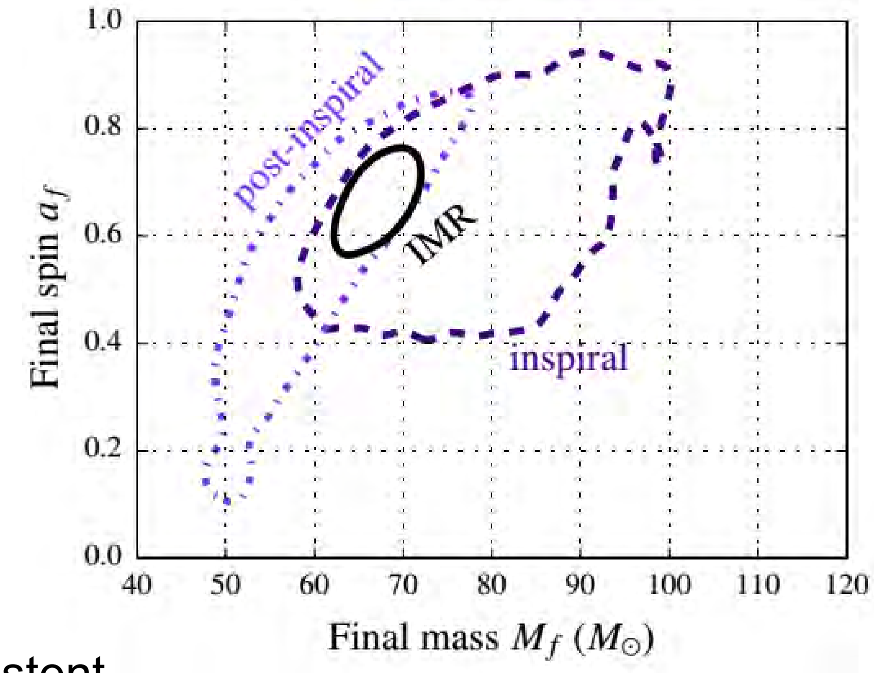
We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions

Known through post-Newtonian (analytical expansion) and numerical relativity

Inspiral / merger / ringdown consistency test

Compare estimates of mass and spin from before vs. after merger





Pure ringdown of final black hole?

Not clear in data, but consistent

C. V. Vishveshwara (1938-2017)

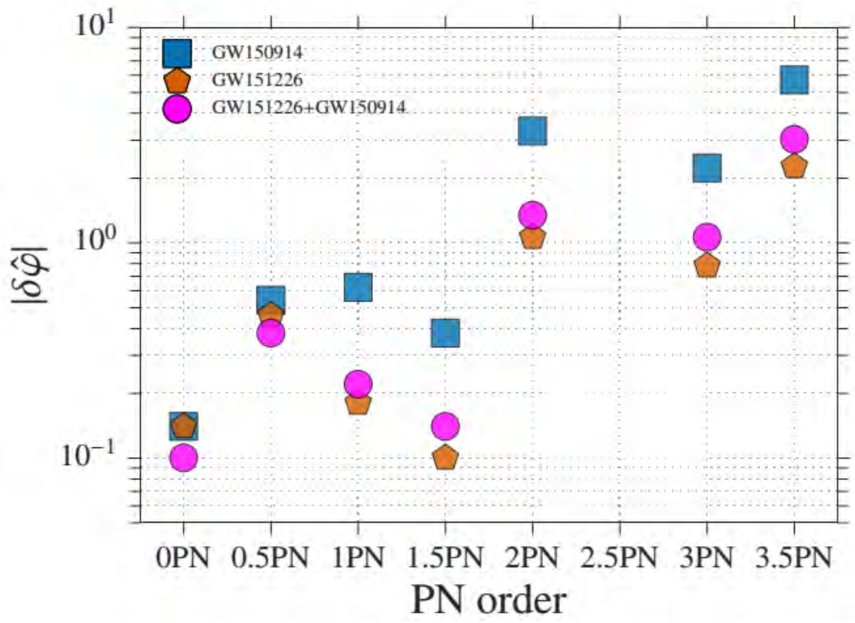
Abbott et al., PRL 116, 221101

Detailed waveform comparisons

Allow deviations from GR in the post-Newtonian parameters of the "chirp"

GW151226, with more cycles in its waveform, permits more stringent tests

Abbott et al., PRX in press, arXiv:1606.04856



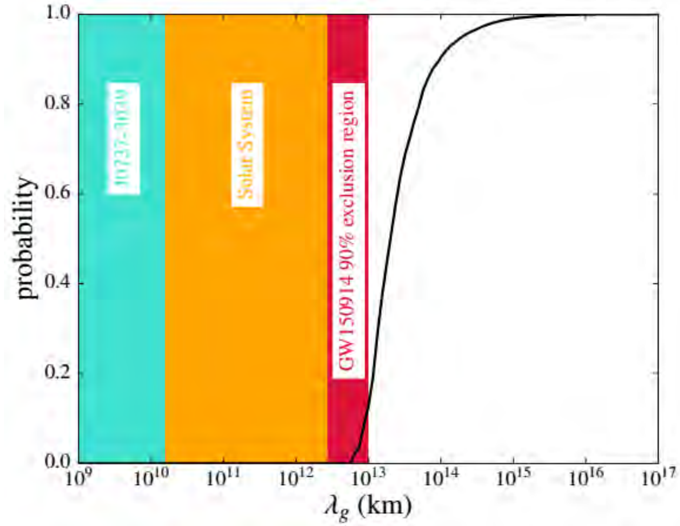
Allow for a massive graviton

Would distort waveform due to dispersion

We can place a limit on graviton Compton wavelength: $> 10^{13}$ km

➔ $m_g < 1.2 \times 10^{-22}\ \mathrm{eV}/c^2$

Abbott et al., PRL 116, 221101

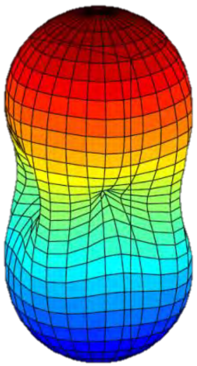


Multi-messenger astronomy and astrophysics

Gravitational Waves: A Unique Messenger

Oscillating spacetime distortions from massive objects in motion

- Caused by rapid motion or flow of mass or energy, in particular from a time-varying quadrupole moment
- Direction-dependent polarization content



GW emissions are only weakly beamed, and GW detectors are only weakly directional

➔ Monitor the whole sky for sources with all orientations

➔ Not dependent on being within the cone of a jet

GWs come directly from the central engine of astrophysical objects

Not significantly attenuated or scattered by material

➔ Complements photon (& neutrino?) diagnostics of photosphere, outflows, circumburst medium, …

Bill Saxton, NRAO/AUI/NSF

Multi-Messenger Searches with GWs

LIGO/Virgo have done many *externally triggered* GW searches

(deep analysis of GW data around the time and/or sky position of reported EM event)

and have collaborated on *joint* searches

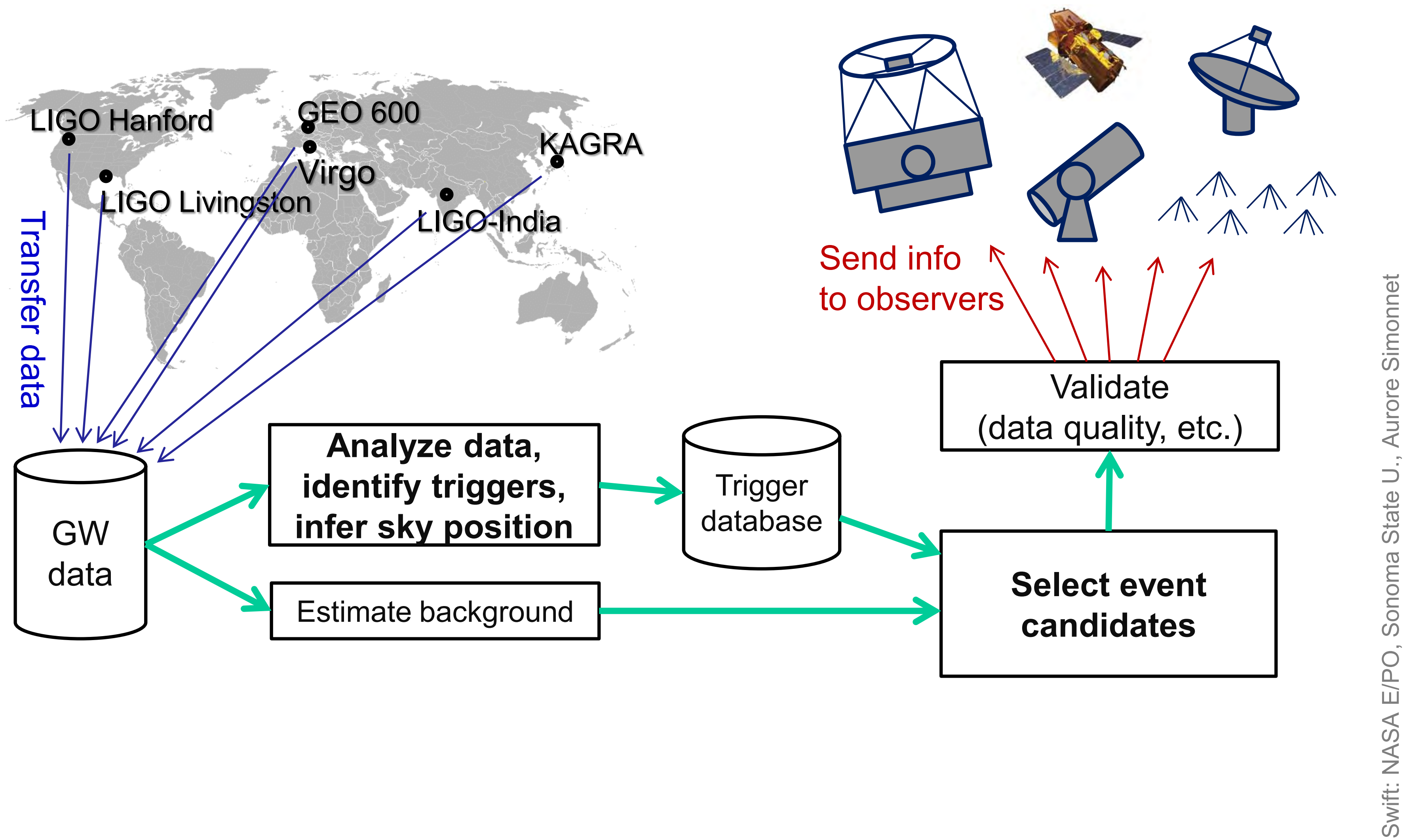
(compare sets of candidate events)

Over two dozen papers…

CBC, Burst	GRBs	– using	public (GCN) and	private info
CW	Known pulsars		public	private
Burst	SGR/magnetar flares		public	private
Burst	Pulsar glitch (Vela)			private
Burst	High-energy neutrinos			private
Burst	Radio transients			private
Burst	Supernovae		public (CBET, etc.)	
CBC	Offline follow-up with satellite		public γ/X-ray data [methods paper only]	

Also initiated an *EM follow-up program*, distributing GW event candidates to observers to enable them to search for counterparts

Generating and Distributing Prompt Alerts



Goals of the EM Follow-up Project

Identify GW event candidates as quickly as possible

With basic event parameters and an estimate of confidence

Provide rapid alerts to other observers

Allow quick correlation with other transient survey events or candidates

Trigger follow-up observations (prompt and/or delayed)

What this can enable:

Pick out interesting (strong or marginal) events from GW and other surveys

Prioritize follow-up observing resources

Maybe catch a counterpart that would have been missed,
or detected only later

Identify host galaxy → provide astronomical context

Obtain multi-wavelength (and multi-messenger!) data for remarkable events

Challenge: GW reconstructed sky regions are large !

With just the two LIGO detectors: typically hundreds of square degrees

With LIGO+Virgo: typically tens of square degrees

Partnerships for Follow-up Observing

Confident detection of first few GW signals requires time and care—need to avoid misinformation / rumors / media circus

➔ **Established a standard MOU framework to share information promptly while maintaining confidentiality for event candidates**

Once GW detections become routine (≥4 published), there will be prompt public alerts of *high-confidence* detections

LIGO & Virgo have signed MOUs with >80 groups so far

Broad spectrum of transient astronomy researchers and instruments

Optical, Radio, X-ray, gamma-ray, air-shower, neutrino

Set up to distribute GCN “notices” and “circulars” to partners

Encourage free communication among all “inside the bubble” for multi-wavelength follow-up

Follow-up Observations During O1

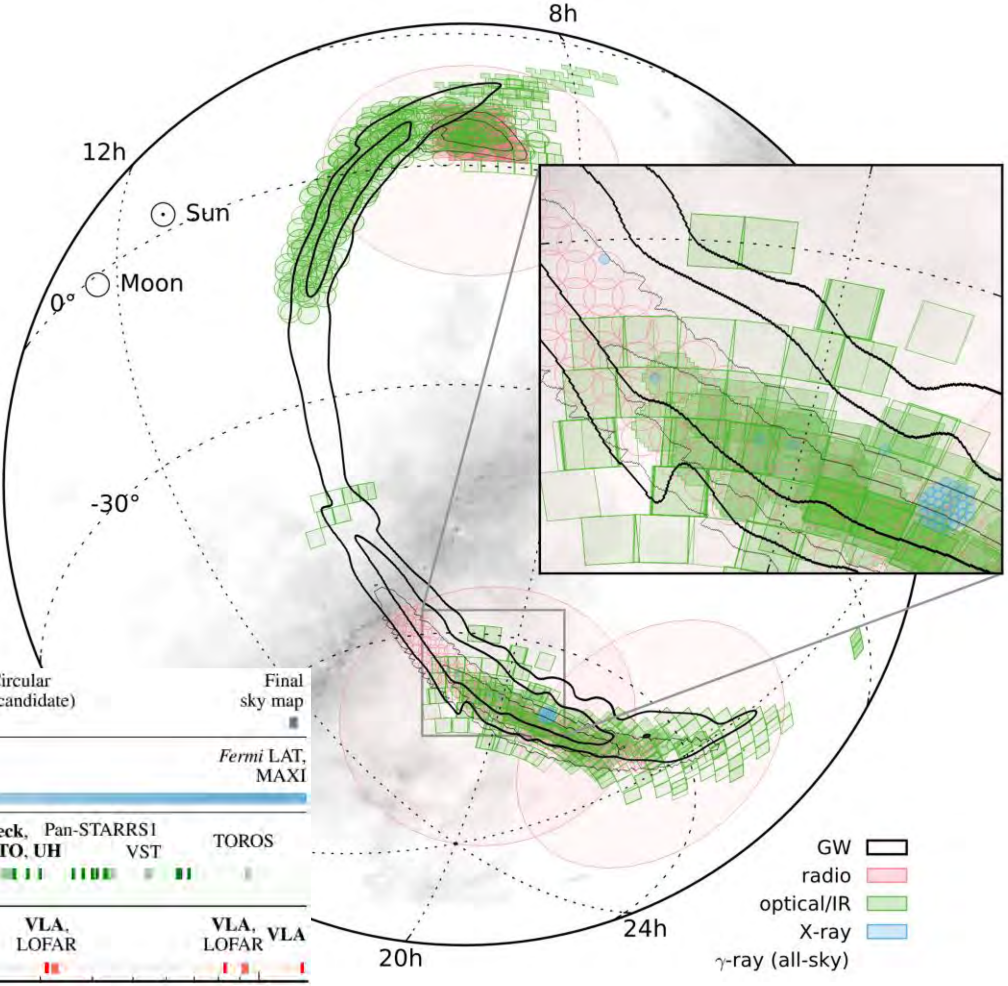
About half of those with observing capability during O1 responded to at least one of the 3 alerts during the run

For GW150914:

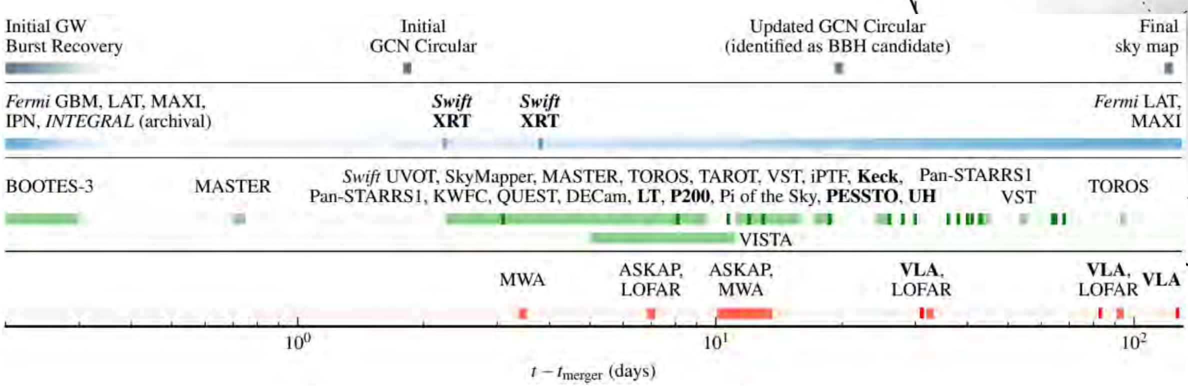
Covered most of skymap area at a wide range of wavelengths starting within a few hours

~50 GCN Circulars, ~12 papers

Also strong response for GW151226

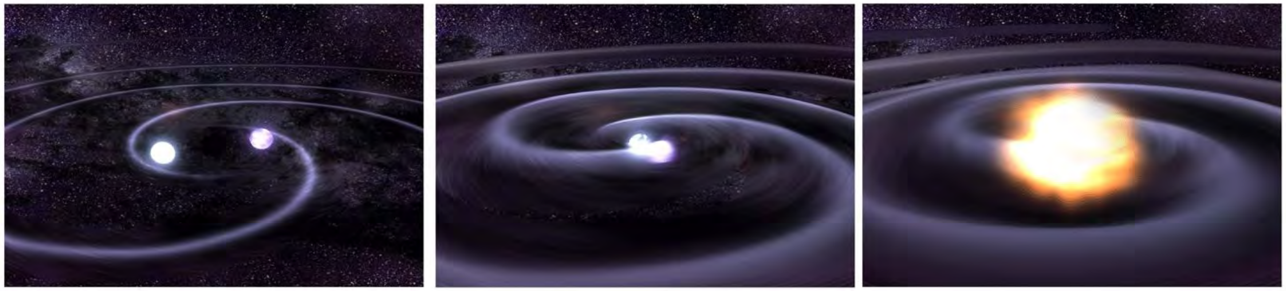


Figures from Abbott++, ApJL 826, L13

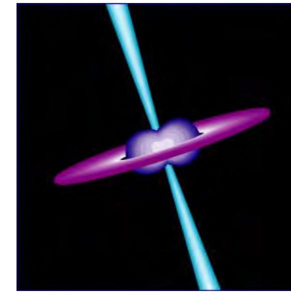


The special promise of neutron star binary mergers

Short Gamma-ray Bursts = Mergers?



NASA



P.J.T. Leonard (NASA/GSFC)

Compact binary mergers are thought to cause most short GRBs

- Strong evidence from host galaxy types and typical offsets [Fong & Berger, ApJ 776, 18]
- Could be NS-NS or NS-BH, with post-merger accretion producing a jet

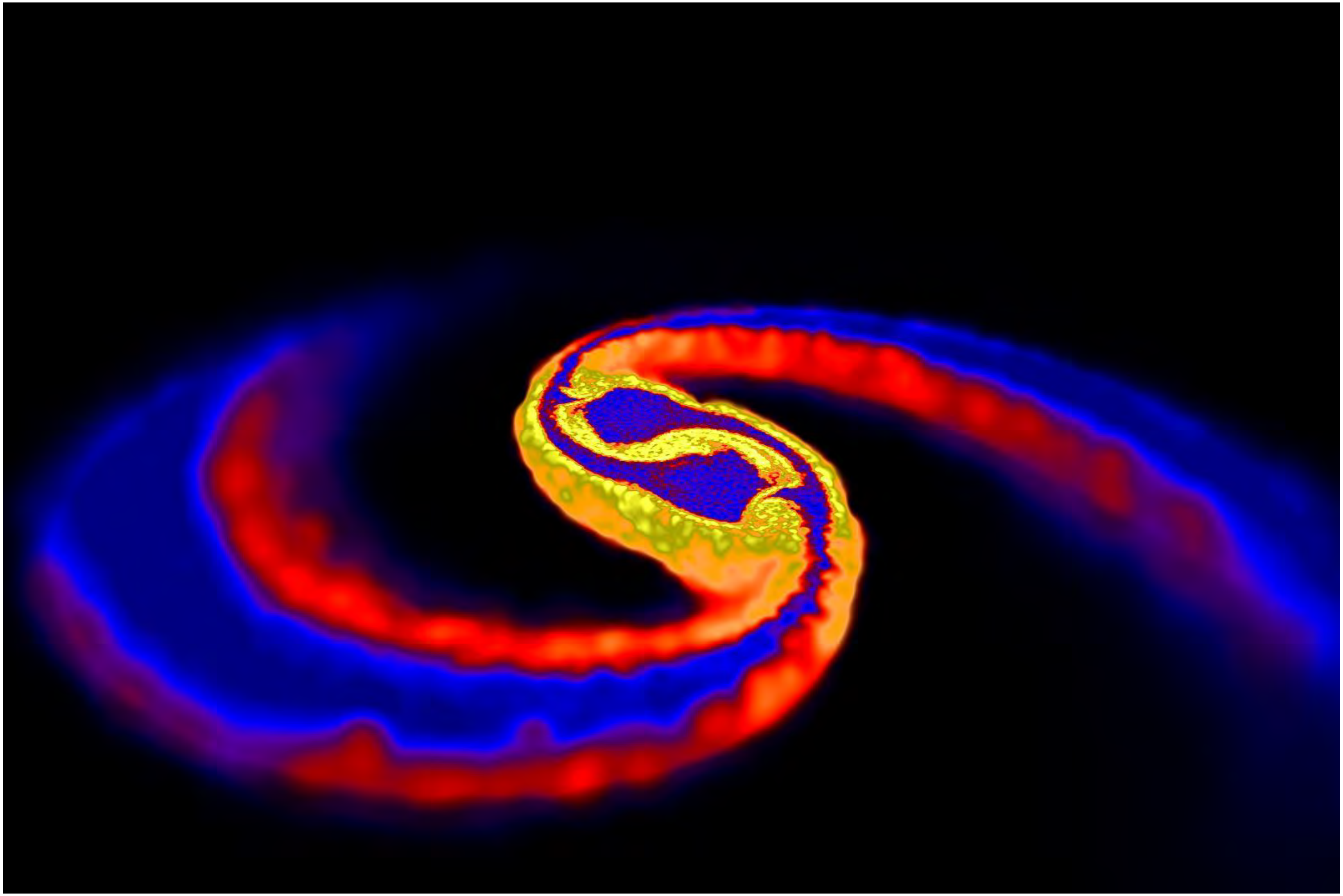
Beamed gamma-ray emission → many more mergers than GRBs

- Some opening angles measured, e.g. $16 \pm 10°$ [Fong+ 2016, ApJ 815, 102]

Exciting possibility to confirm the merger-GRB association!

But are we stuck with the beaming limitation for the EM emission?

Tidal Disruption of Neutron Stars



Price/Rosswog/Press

Other Signatures of Neutron Star Mergers

X-ray afterglow

May be detectable if gamma-ray emission is missed, or if off-axis

➔ We're proposing to put a wide-field X-ray imager into orbit

Kilonova (aka "macronova")

Visible/IR emission powered by radioactive decay of heavy elements produced in the neutron-rich ejecta [e.g., Barnes & Kasen, ApJ 775, 18]

Roughly isotropic, though varies due to geometric effects

Can have disk (red, slow) and wind (bluer, faster?) components

Already seen for GRB 130603B? [Berger et al., ApJ 765, 121; Tanvir et al., Nature 500, 547] and possibly one or two other past GRBs

Radio transients

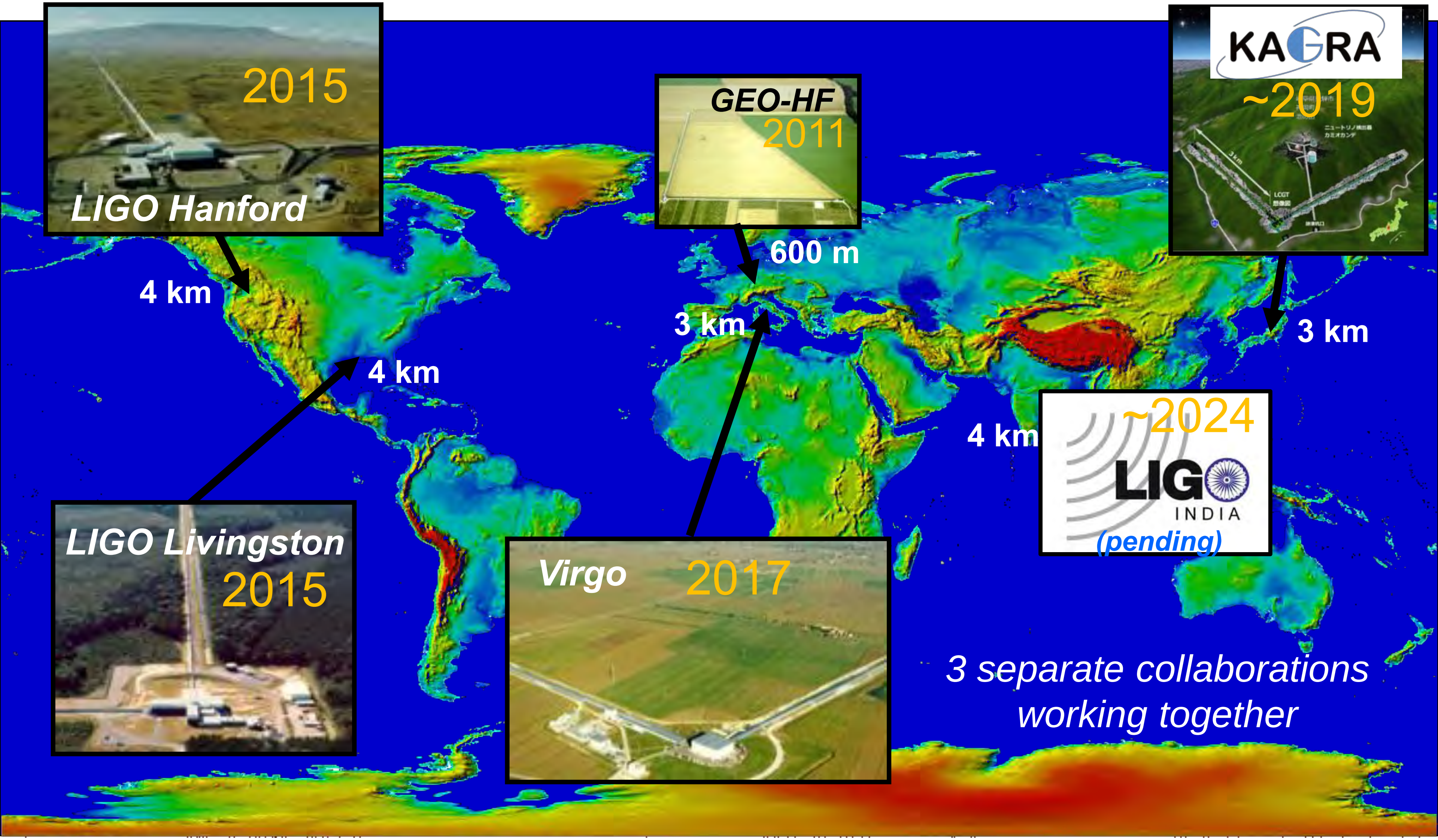
Pulsar-like emission from transfer of energy to magnetic field [Pshirkov&Postnov, 2010] or MHD conversion [Moortgat&Kuijpers 2004]

Late-time radio afterglow

Synchrotron radiation [Nakar&Piran 2011, Nature; Hotokezaka+, arXiv:1605.09395]

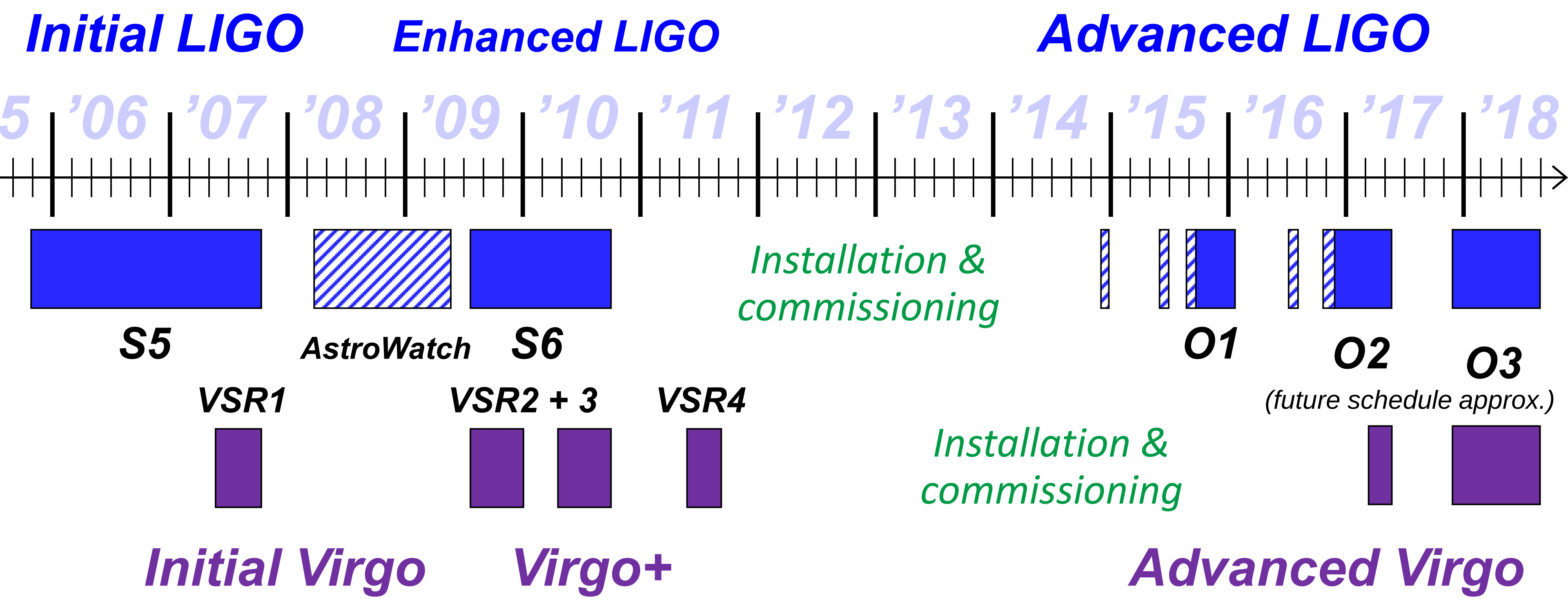
Looking ahead

Advanced GW Detector Network: Under Construction → Operating



Observing Run History and Outlook

The LIGO detectors resumed observing operations in 2015 after the Advanced LIGO upgrade project – and Virgo will join soon



Meanwhile, GEO has run more-or-less continuously to demonstrate advanced technologies and to maintain "AstroWatch" vigil

KAGRA ~2019
LIGO-India ~2024

See Abbott et al., Liv. Rev. Rel. 19, 1: http://relativity.livingreviews.org/Articles/lrr-2016-1/

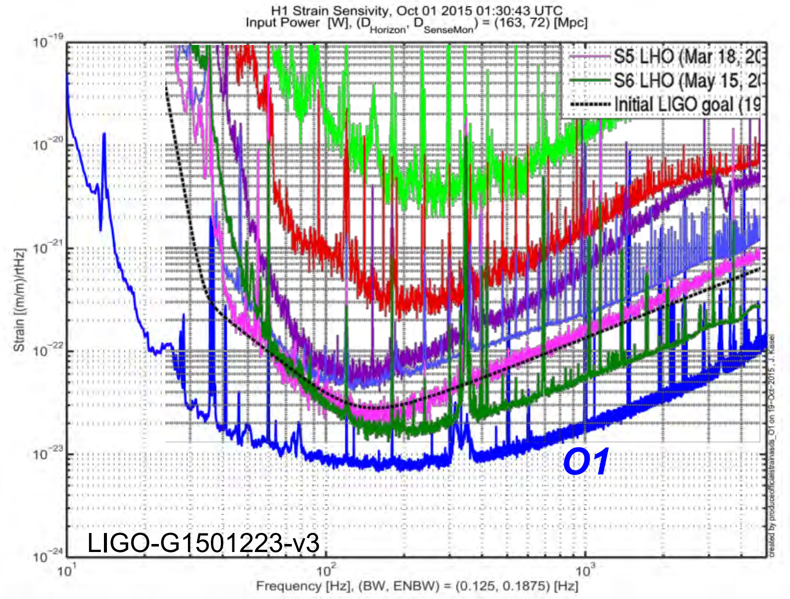
How will the GW detector network improve?

Sensitivity → Distance reach

O1 amplitude noise level was ~3 times above Advanced LIGO design; commissioning continues

Virgo will likely begin with modest sensitivity, and improve over time

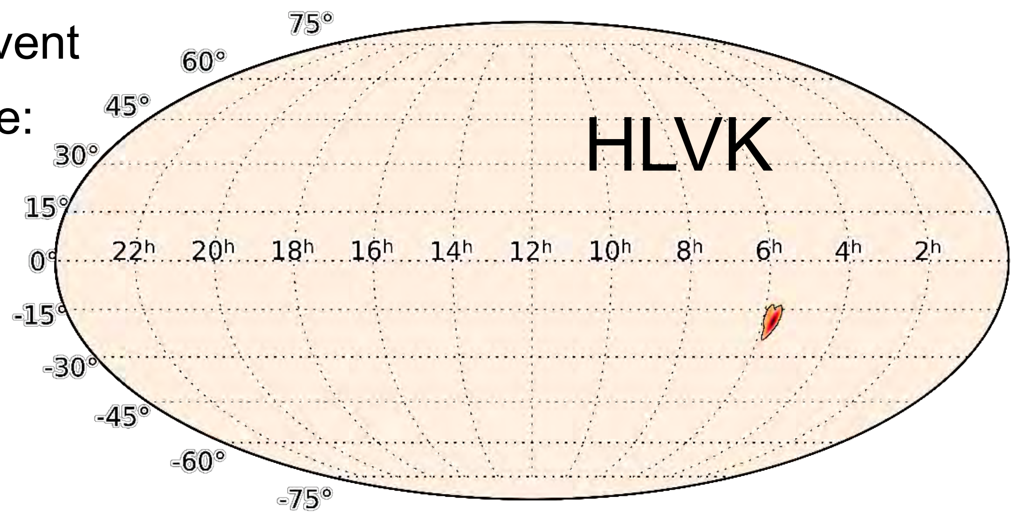
Further incremental upgrades and new facilities are being studied



More detectors → Better localization

Varies event-by-event

One example:



Summary

We're already testing the predictions of GR in various ways and learning about the astrophysical source population

We have a full-scale EM follow-up program in place to try to catch and identify any counterpart

The second Advanced LIGO observing run began on Nov. 30, and Virgo will join sometime this Spring. The detector network will grow and improve over the next several years.

What will we detect next?

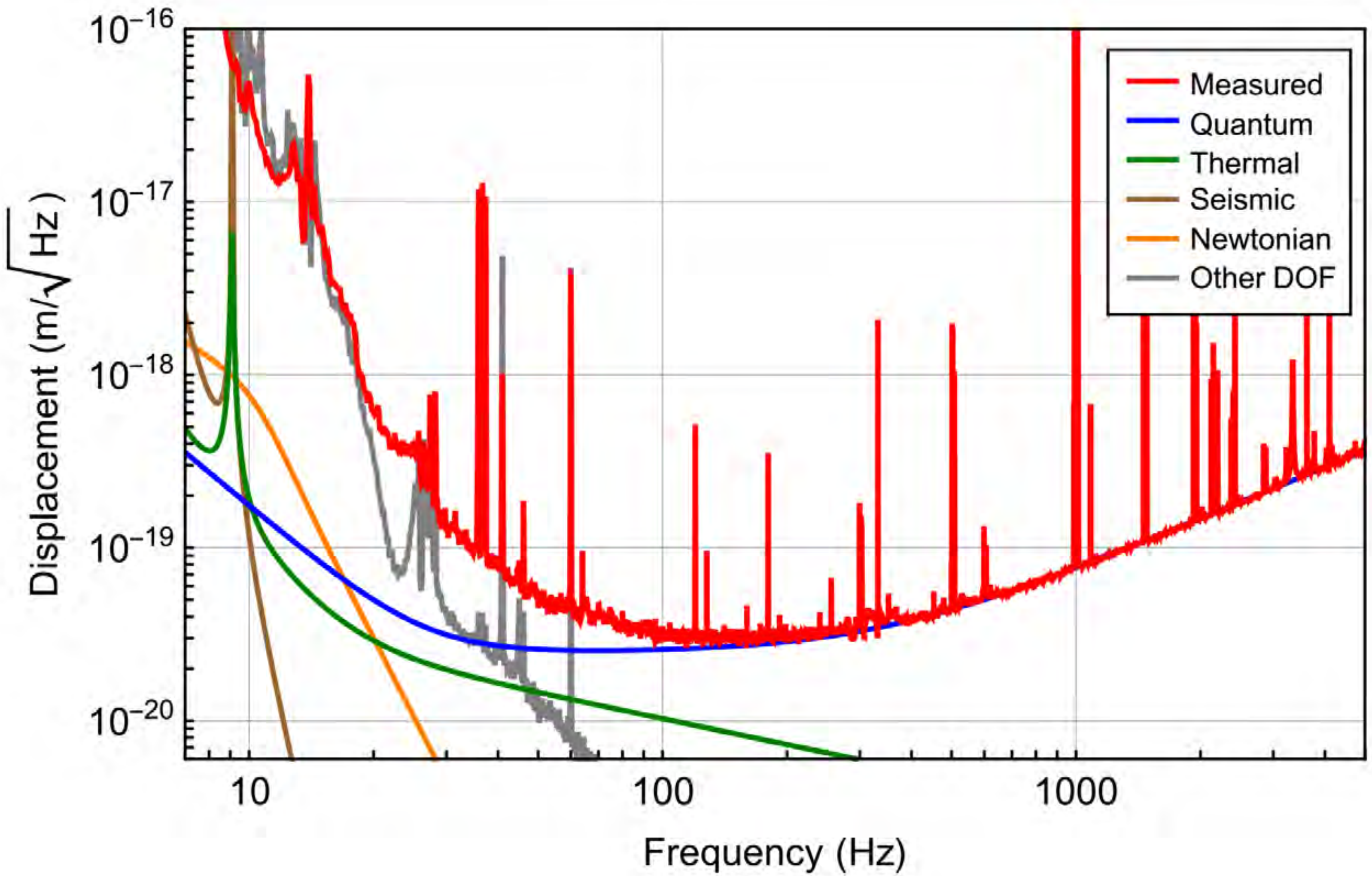
More binary black hole mergers! What can we learn from them?

Binary neutron star mergers? How else will we see them?

Other gravitational-wave sources?

Backup slides

LIGO Detector Noise Components



From Abbott et al., arXiv:1602.03838