On the Hunt for Counterparts to Gravitational-Wave Events

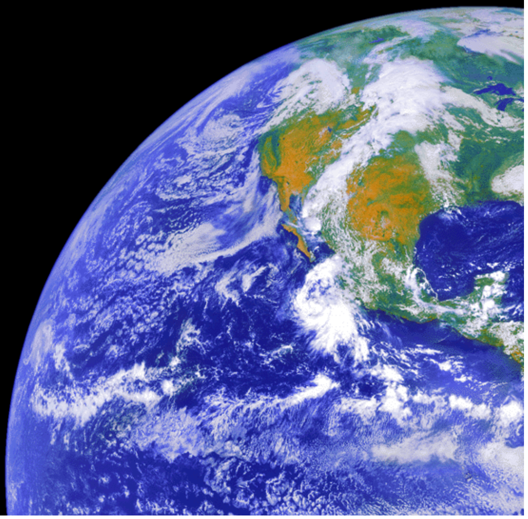
Peter Shawhan

U. of Maryland / Joint Space-Science Institute

LUVOIR Seminar

December 7, 2016

LIGO-G1602298-v1



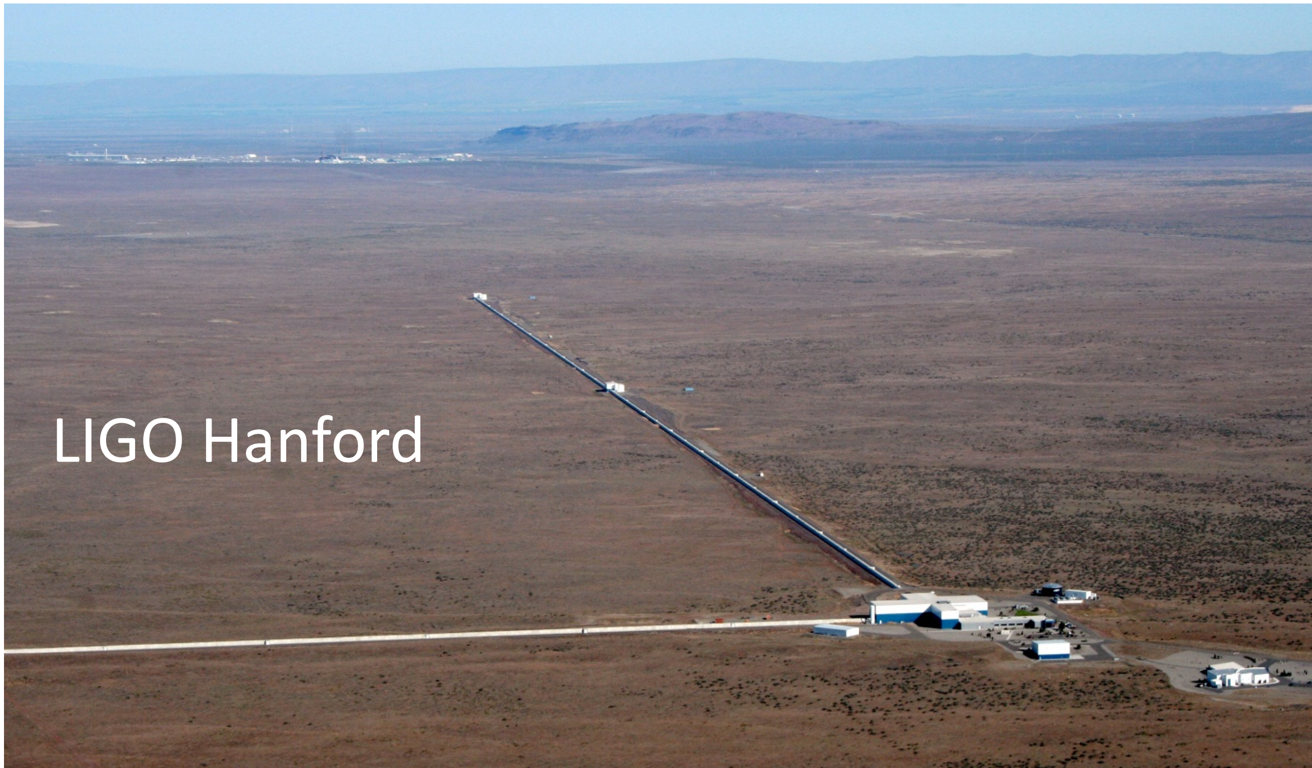
GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

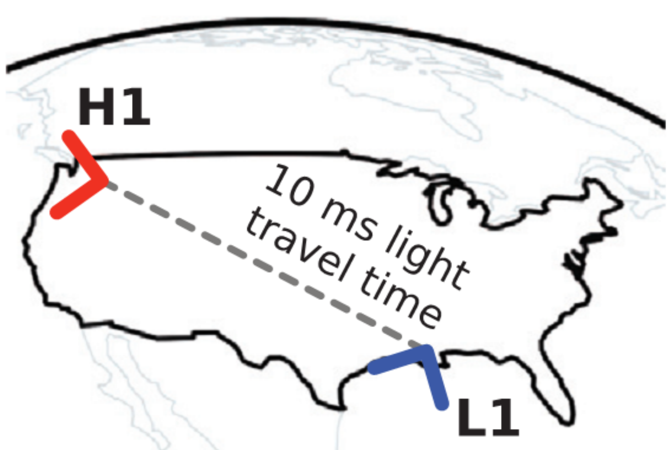
NEWS FLASH:
We detected gravitational waves

We = the LIGO Scientific Collaboration together with the Virgo Collaboration

… using the LIGO* Observatories

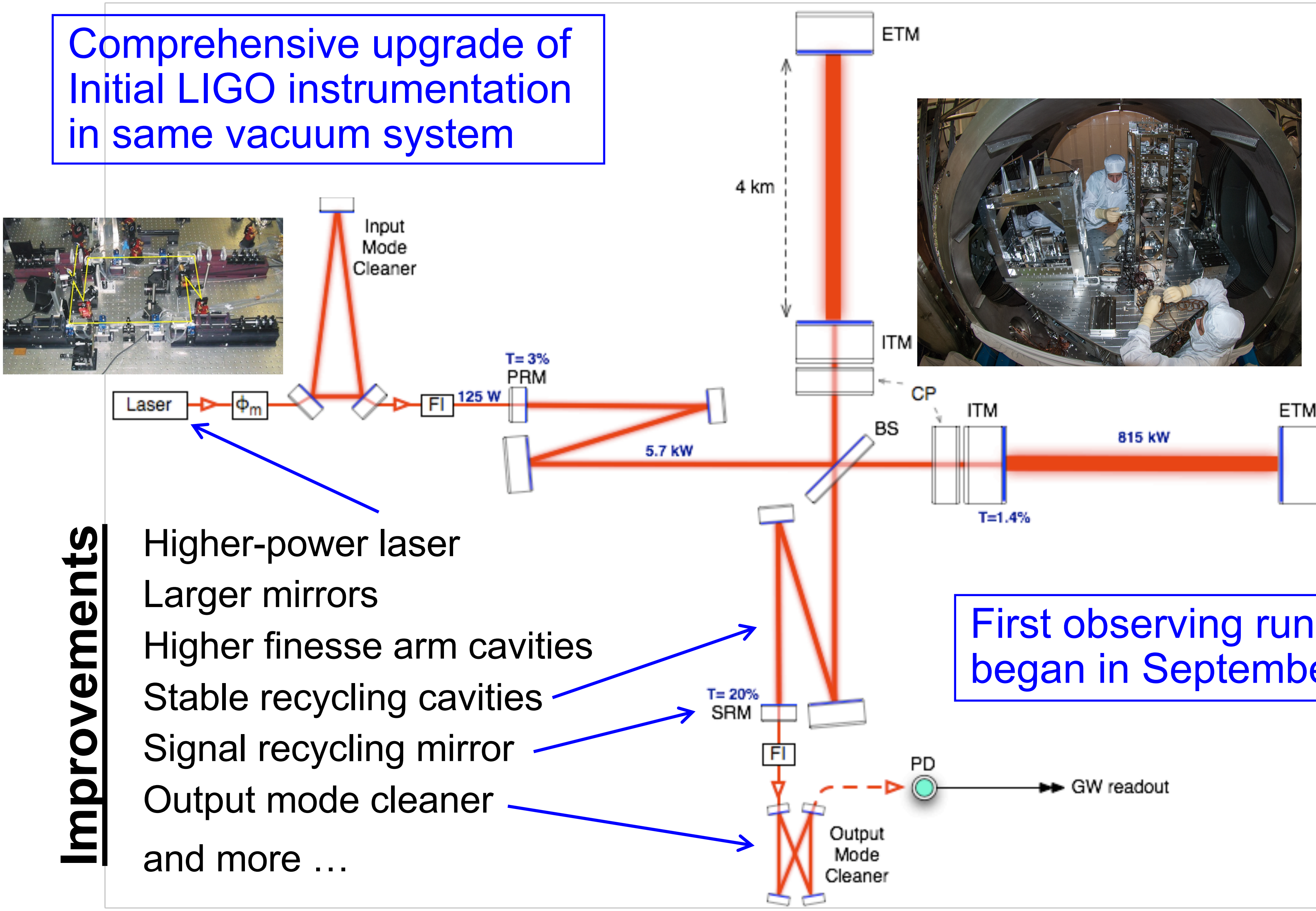
* LIGO = Laser Interferometer Gravitational-wave Observatory

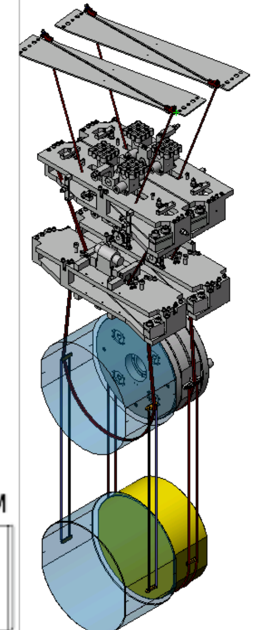




… after the *Advanced LIGO* Upgrade

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system





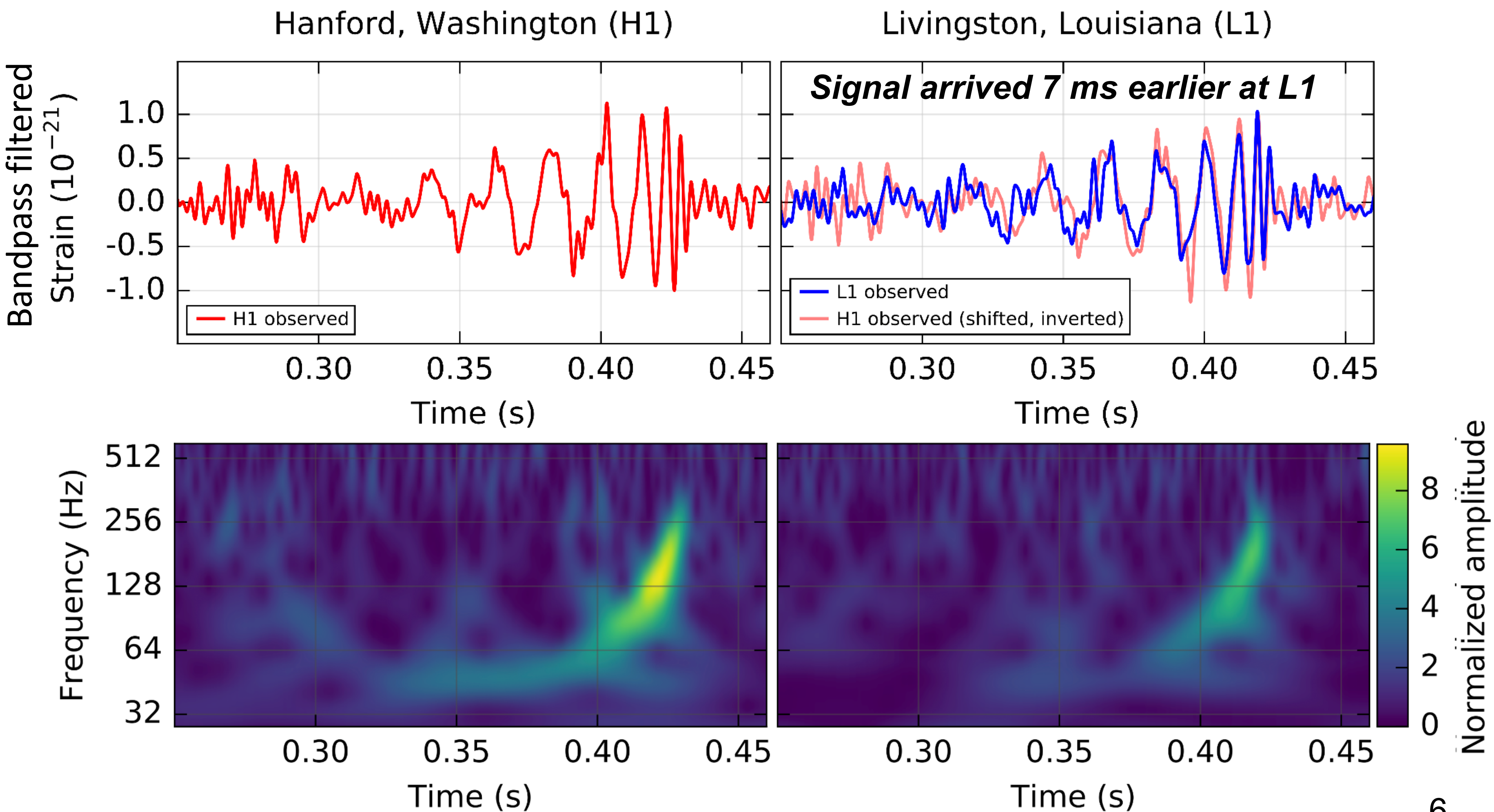
Improvements

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

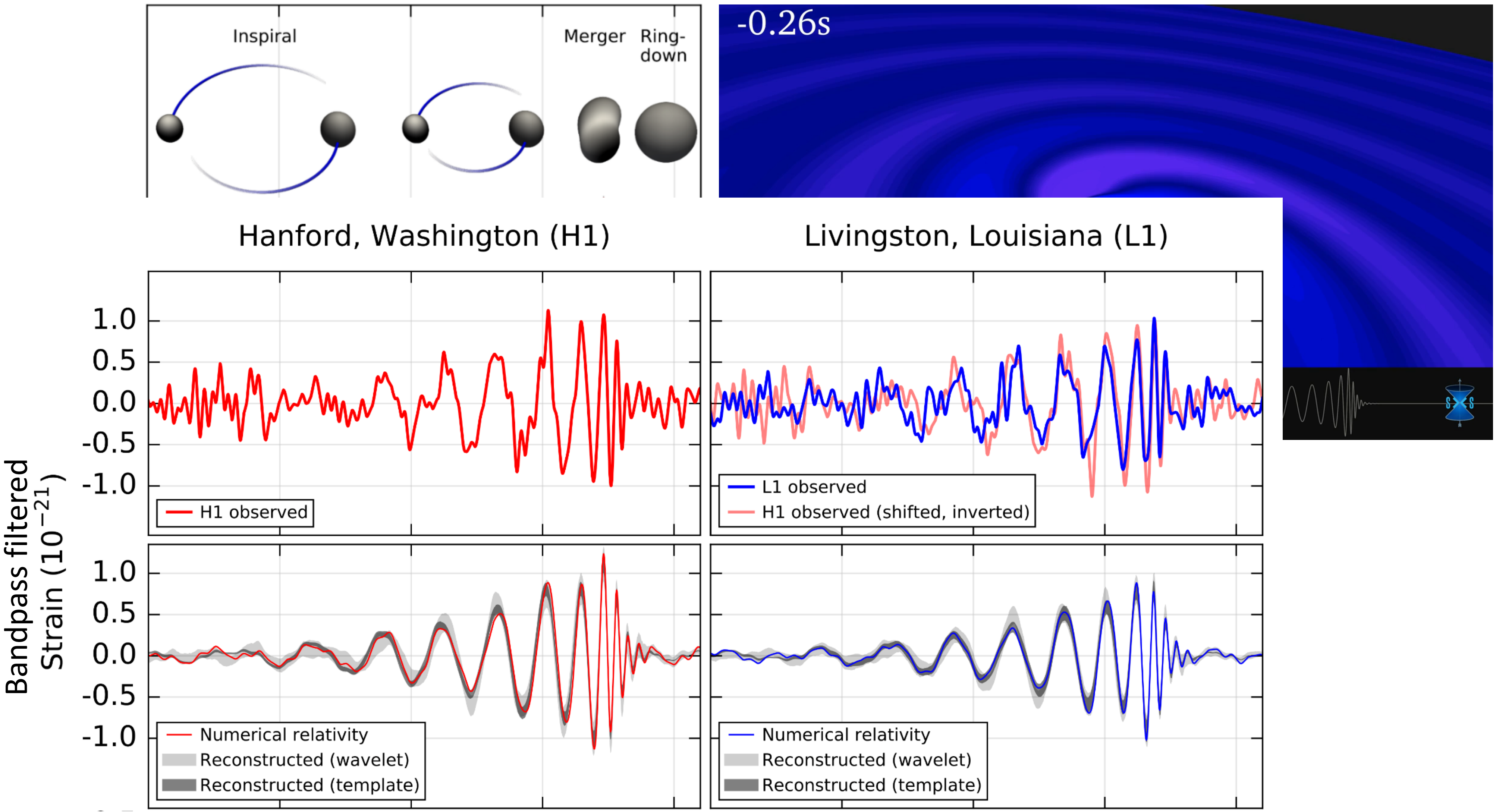
First observing run (O1) began in September 2015

GW150914

Arrived a couple of days *before* the official start of the first Advanced LIGO observing run (O1) !



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

4645

LIGO Retweeted

President Obama @POTUS · Feb 11

Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.

9.3K 22K

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

The New York Times

Late Edition

Today, some sunshine giving way to times of clouds, cold, high 28. **Tonight,** a flurry or heavier squall late, low 15. **Tomorrow,** windy, frigid, high 21. Weather map, Page A19.

© 2016 The New York Times — NEW YORK, FRIDAY, FEBRUARY 12, 2016 — $2.50

CALTECH-M.I.T.-LIGO LABORATORY

…010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

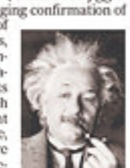
A RIPPLE IN SPACE-TIME

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

…eran: Hillary Clinton."

But that was late January. Interviewed again Tuesday as Mrs. Clinton's rival, Senator Bernie Sanders of Vermont, was surging toward an overwhelming victory in the New Hampshire Demo-… candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an undecided voter and planned to do some homework on Mr. Sanders.

Mrs. Clinton has long looked forward to the Feb. 27 Democratic contest in South Carolina, the first state where blacks will make up a dominant part of the primary vote. African-Americans accounted for more than half the voters in the 2008 Democratic primary, and she has been count-…

Last Occupier In Rural Oregon Is Coaxed Out

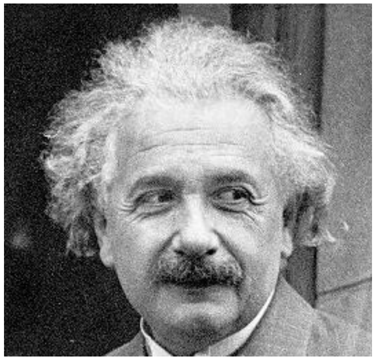
*This article is by **Dave Seminara, Richard Pérez-Peña** and **Kirk Johnson.***

PRINCETON, Ore. — They implored the last holdout in the armed occupation of a wildlife refuge here to think about the Holy Spirit. They explained that the First Amendment was about…

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

Encoded in the *Einstein field equations*

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

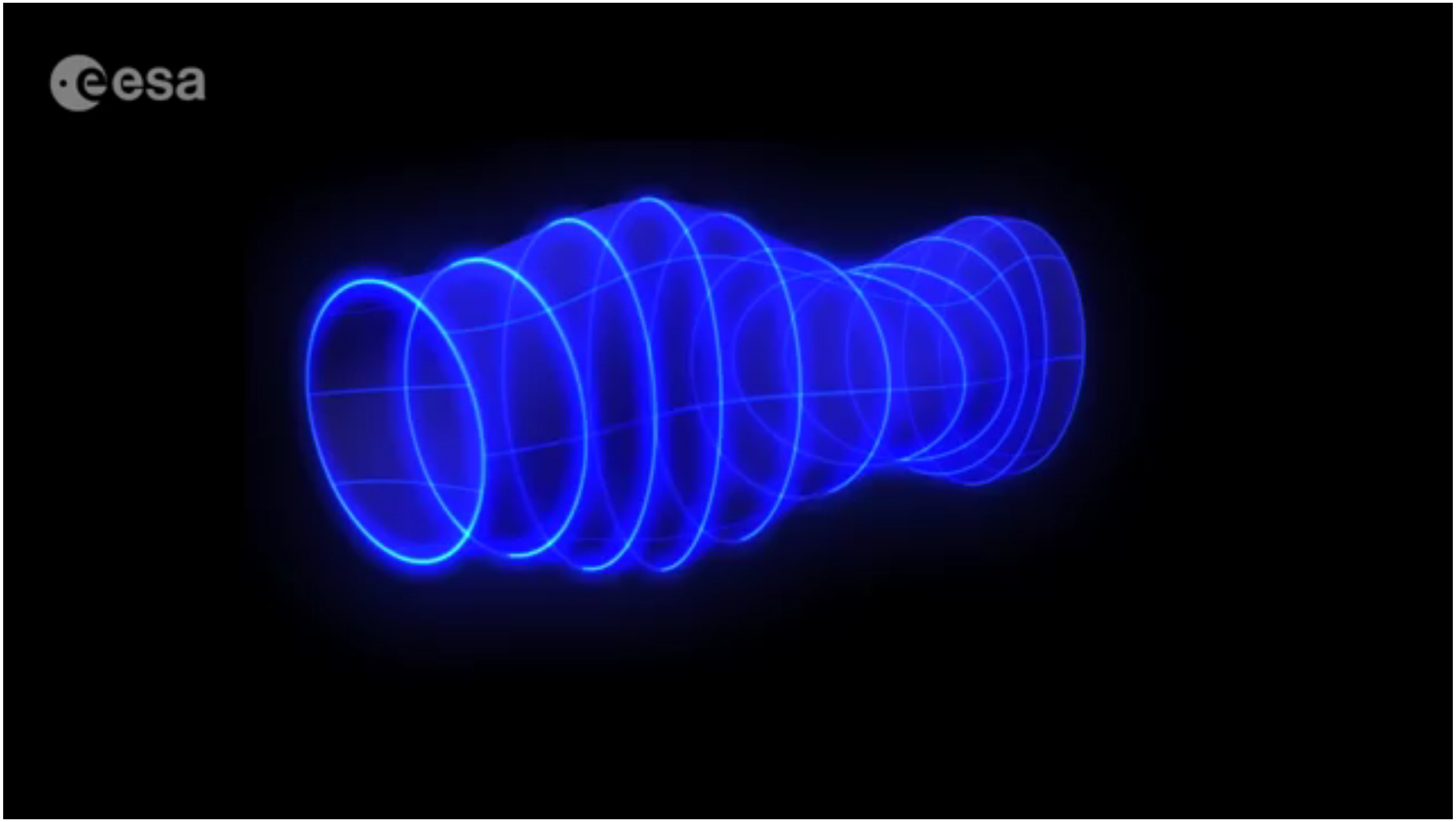
These waves are perturbations of the *spacetime metric* —
the effective distance between points in space and time

$$g_{\mu\nu}$$

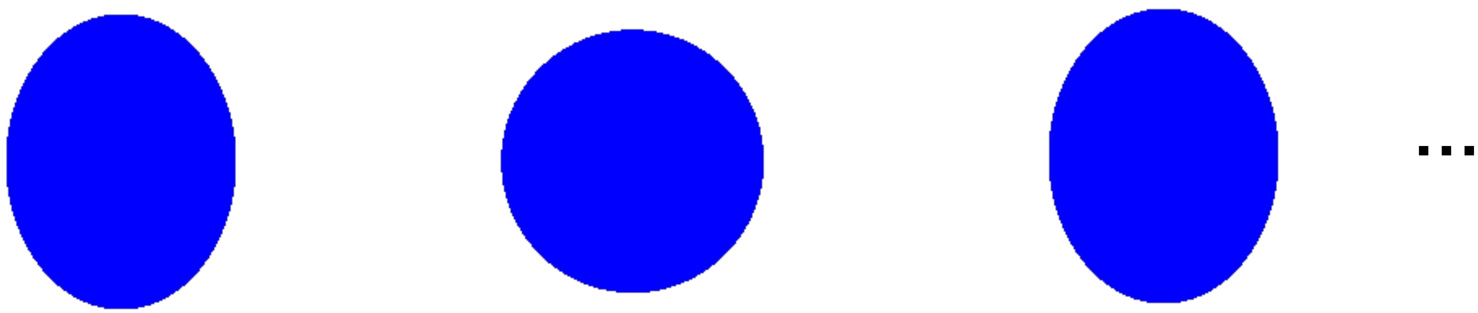
➔**The geometry of space-time is dynamic, not fixed!**

It alternately *s t r e t c h e s* and *shrinks* with a characteristic *strain*

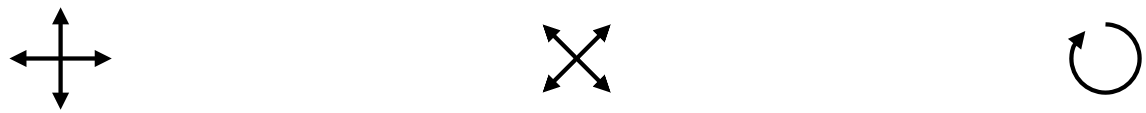
Gravitational Waves in Motion



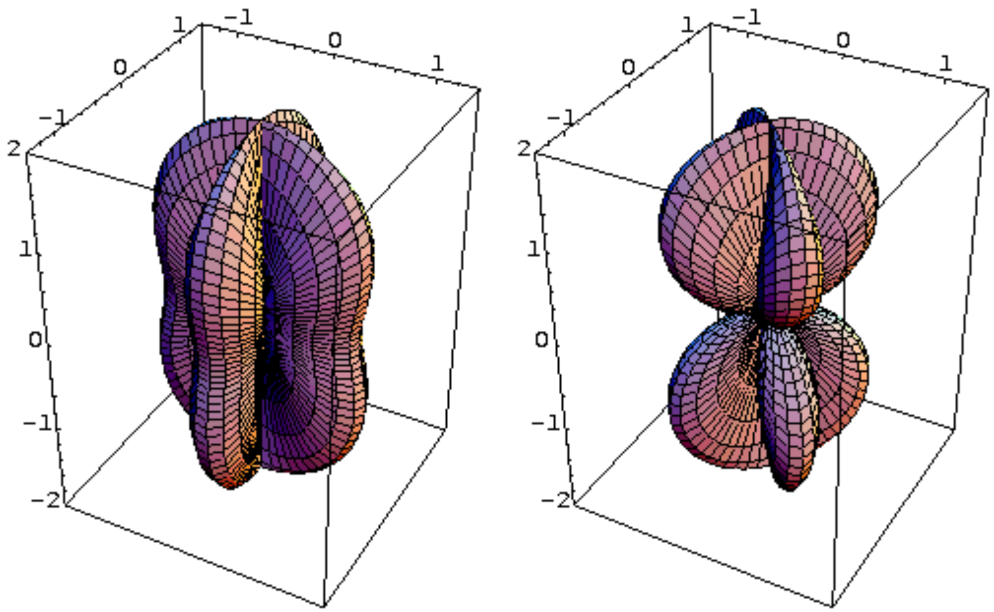
Gravitational Wave Polarizations



“Plus” polarization　　“Cross” polarization　　Circular polarization



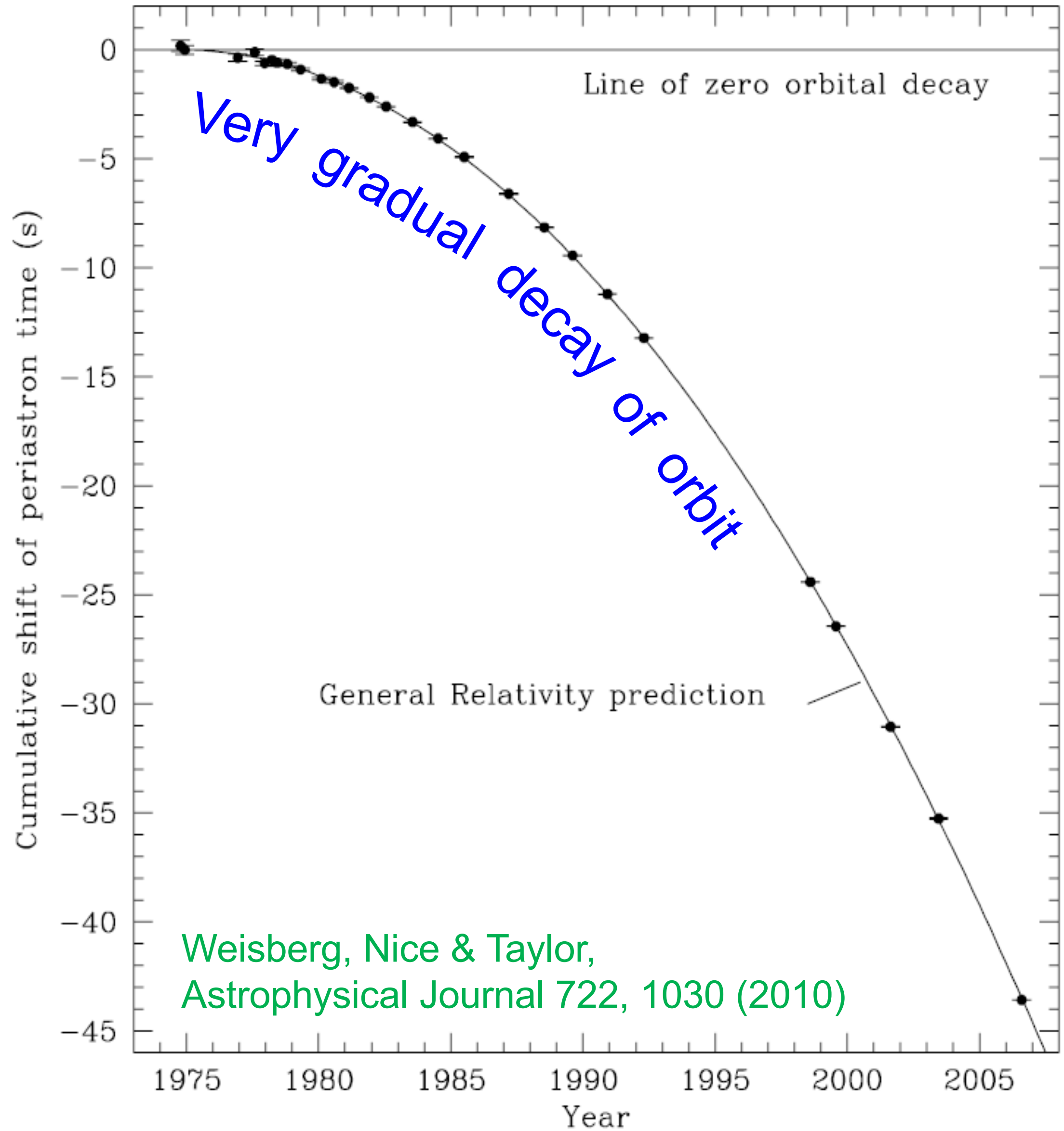
Directional sensitivity of detector depends on polarization of waves



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

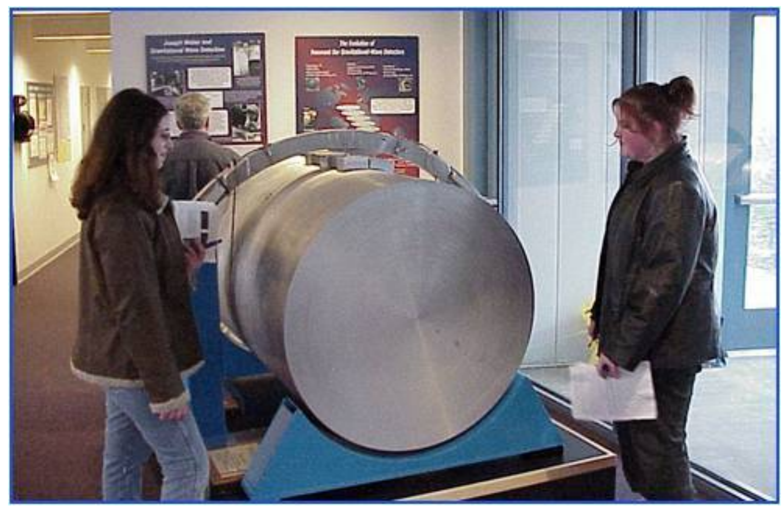
This binary neutron star system is changing, just as general relativity predicts!
Very strong <u>indirect</u> evidence for gravitational radiation



Joe Weber's Fearless Idea!

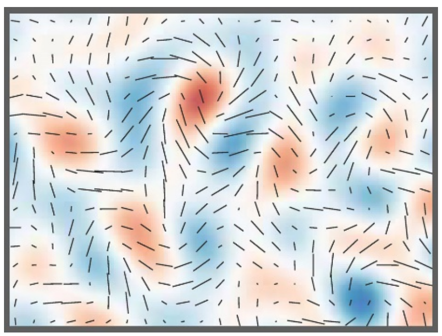
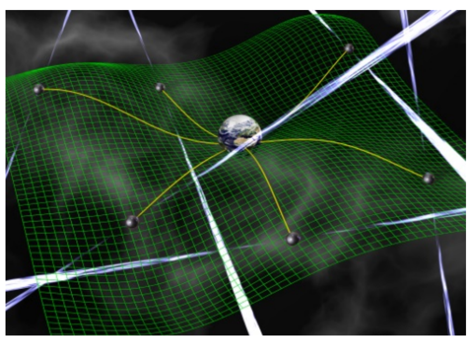
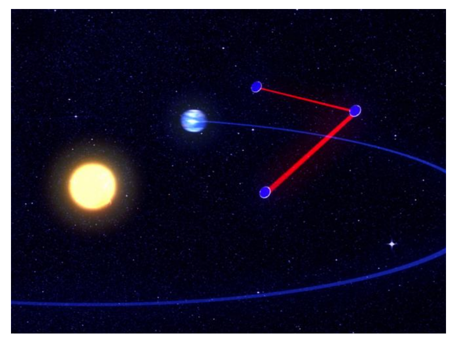
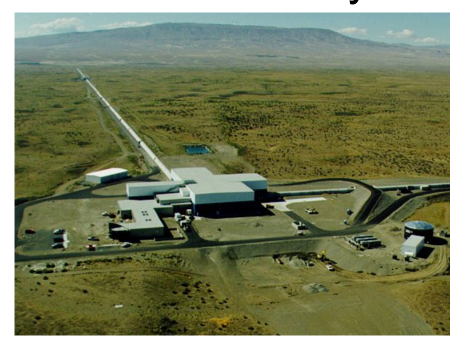
Special Collections and University Archives, University of Maryland Libraries

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



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	Planck, BICEP/Keck, ABS, POLARBEAR, SPTpol, SPIDER, …	NANOGrav, European PTA, Parkes PTA	eLISA, DECIGO	LIGO, GEO 600, Virgo, KAGRA

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

Exploring the Properties of GW150914

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

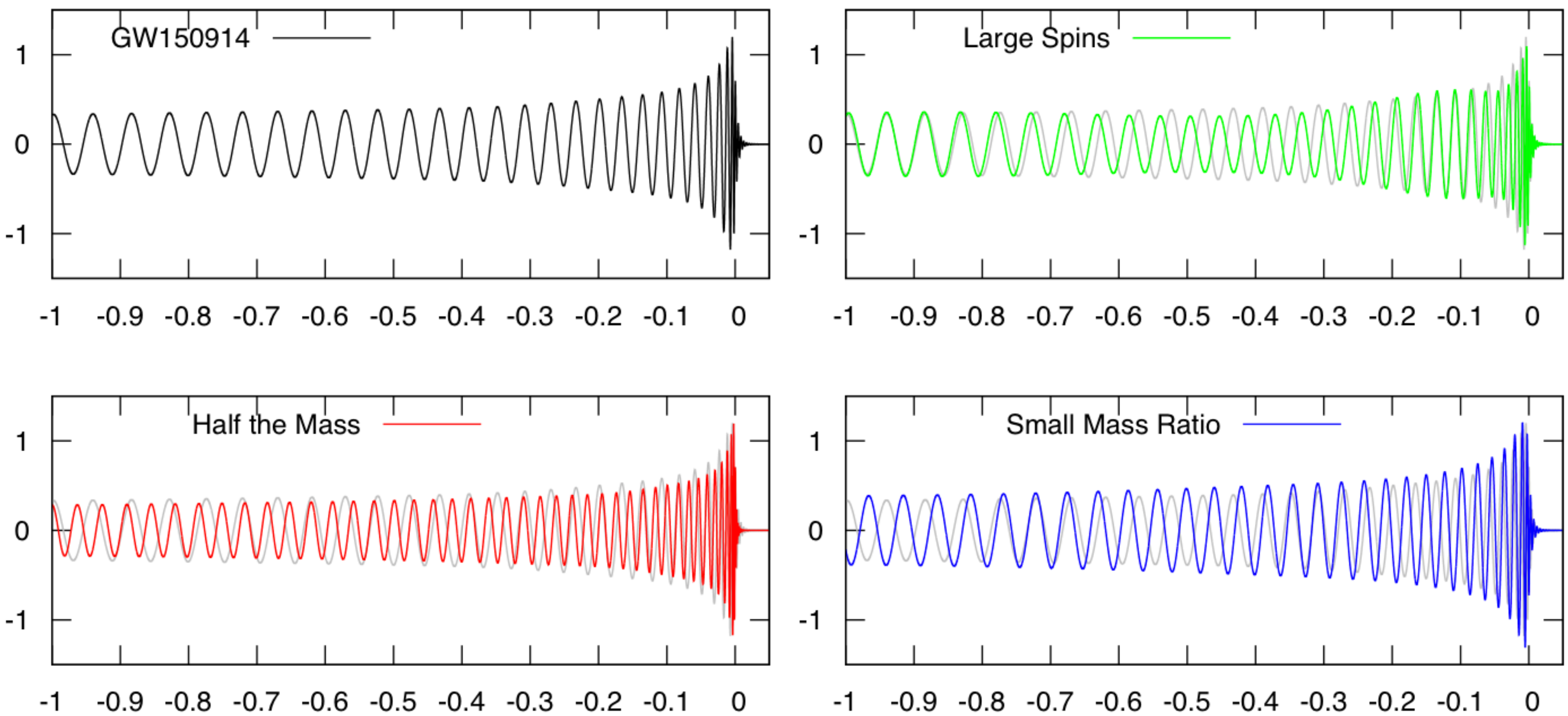


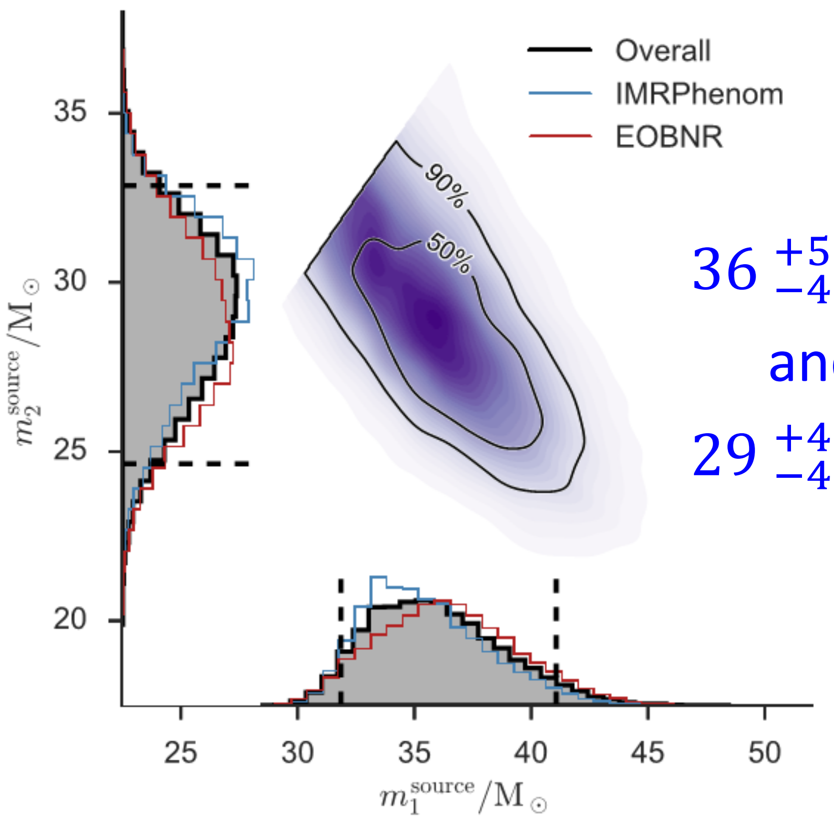
Illustration by N. Cornish and T. Littenberg

➔ **Get ranges of likely ("credible") parameter values**

Properties of GW150914

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 6, 041014) 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, $\frac{Gm^2}{c}$)

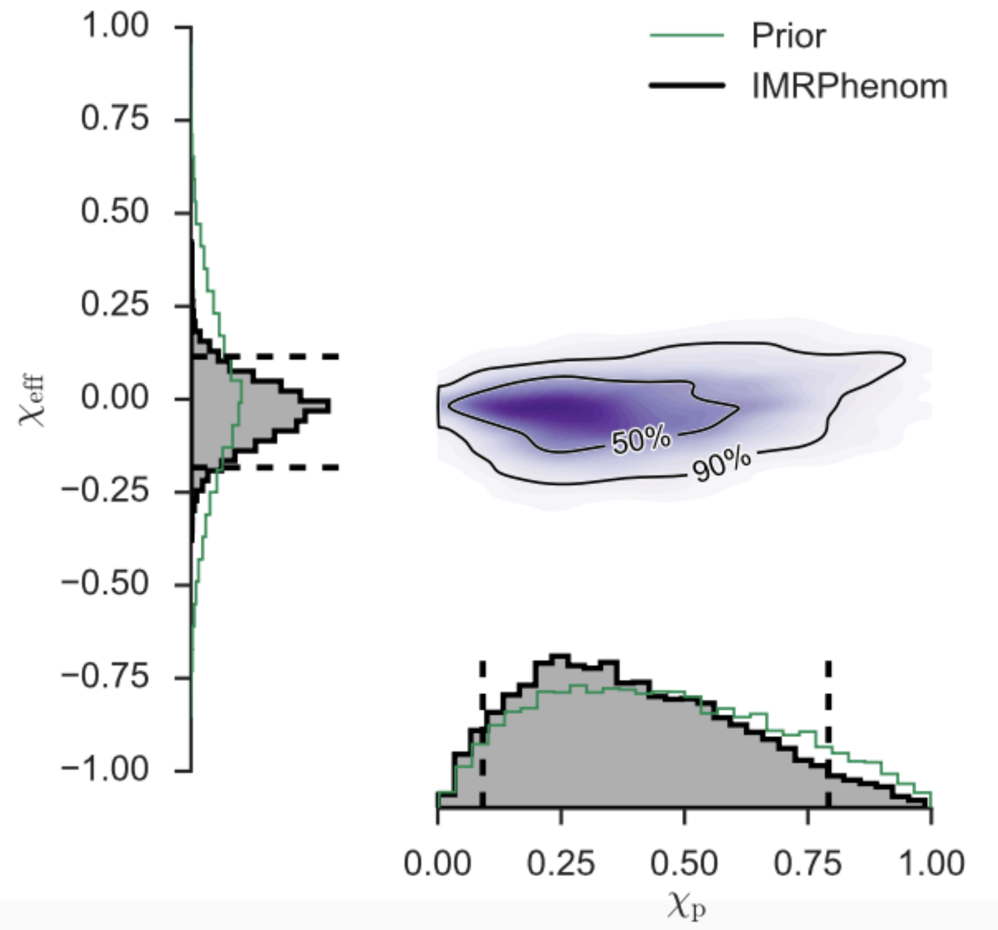
We don't find evidence for spin of the initial component black holes (and only weak limits)

From parameters that influence the waveform:

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

affects how the signal "chirps"

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

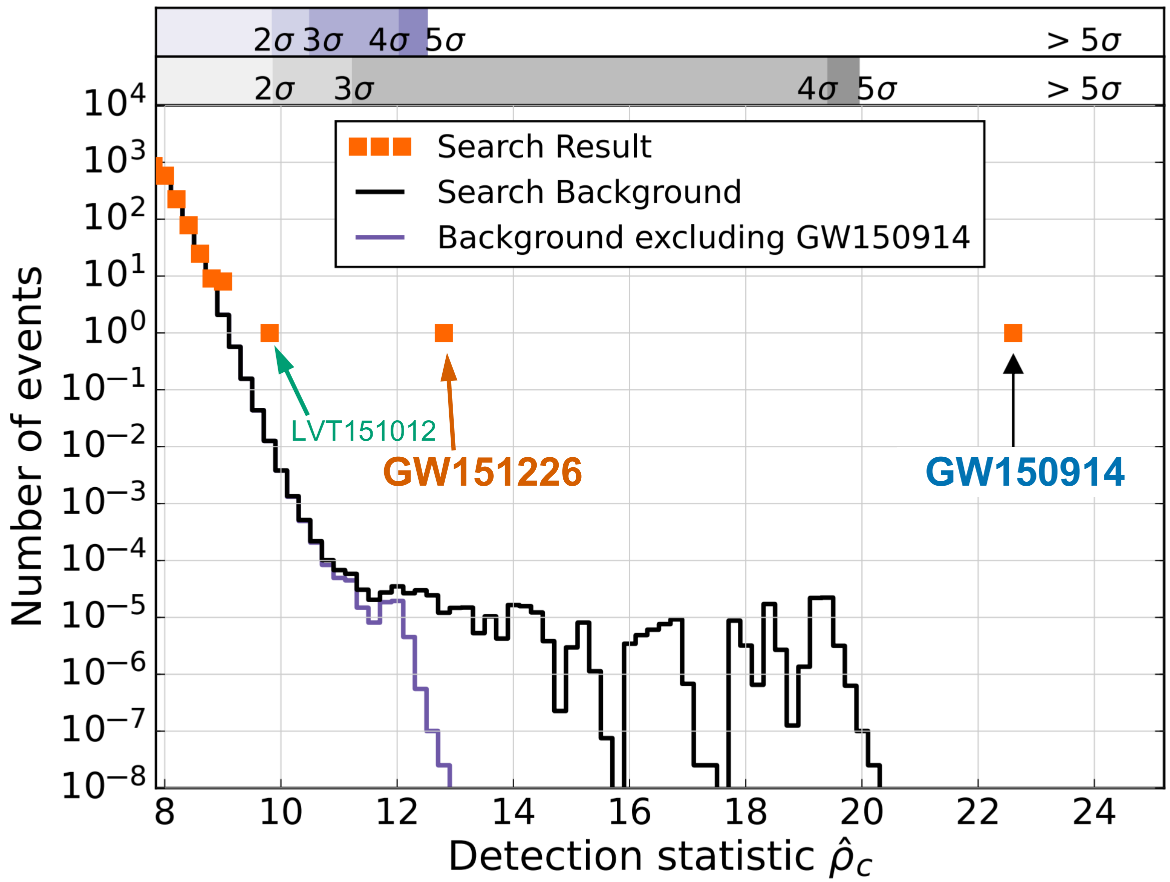


Abbott et al., PRL 116, 241102

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

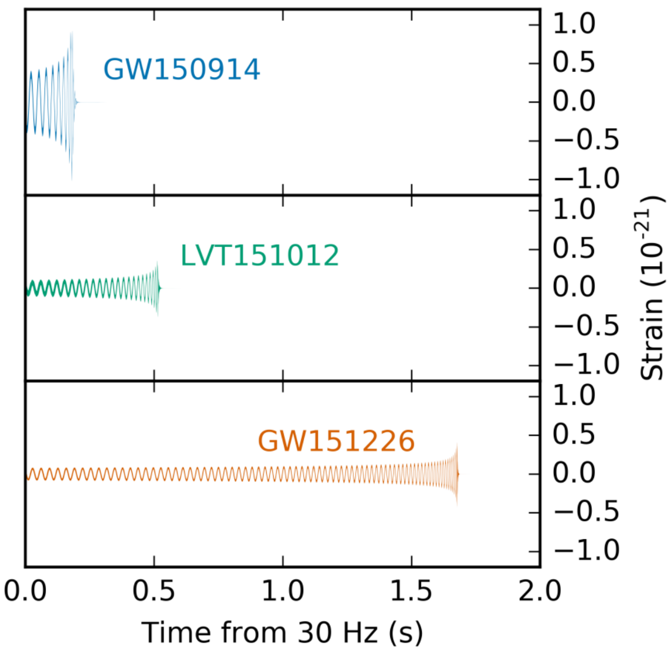
Weaker than GW150914, but still detected with $> 5\sigma$ significance

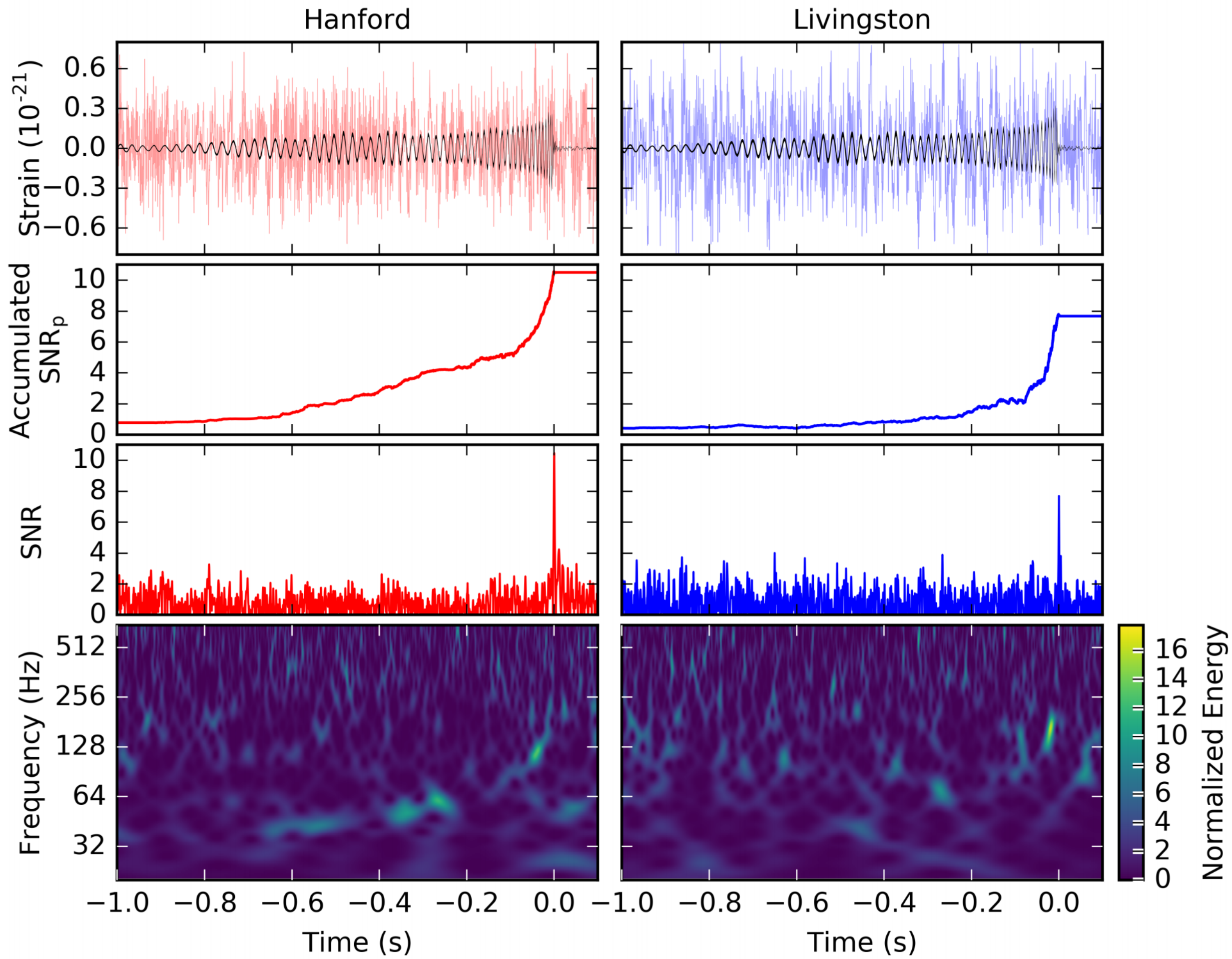
And there's also a marginally significant candidate, LVT151012

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

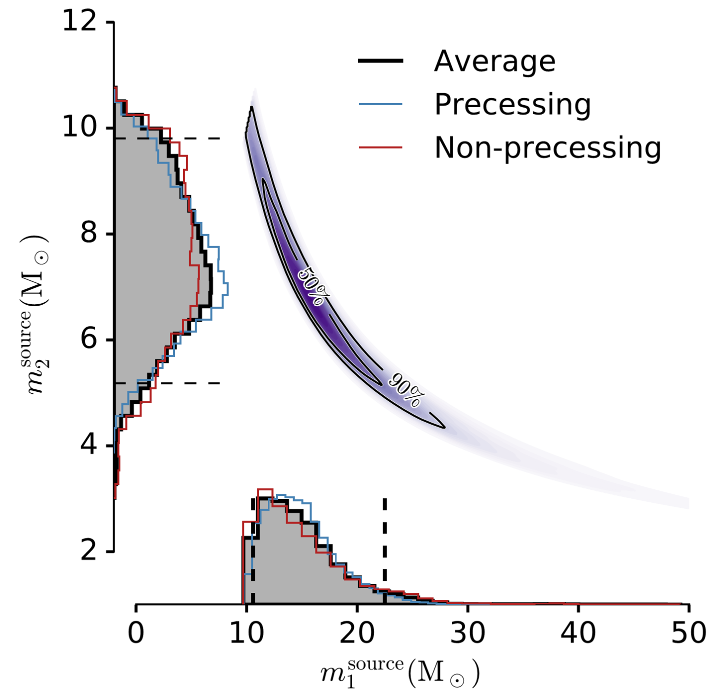
GW151226 has lower mass than GW150914

Initial masses: $14.2^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$

Final BH mass: $20.8^{+6.1}_{-1.7}\ M_\odot$

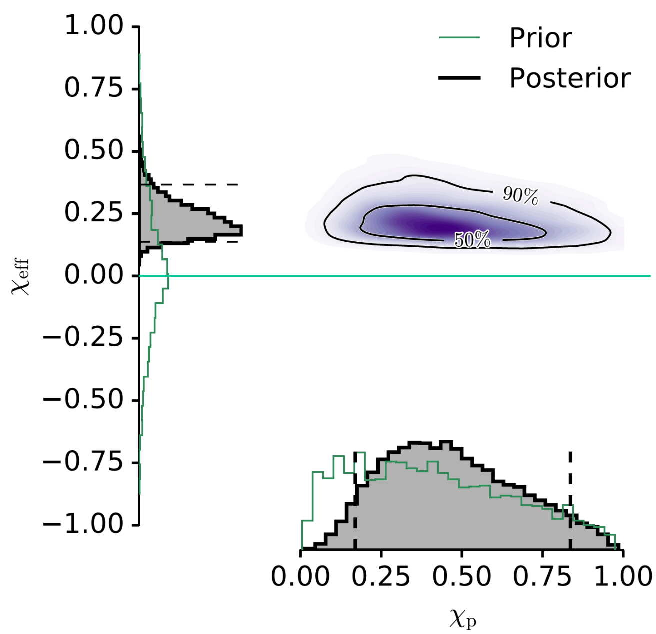
Energy radiated: $1.0^{+0.1}_{-0.2}\ M_\odot c^2$

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



Abbott et al., PRL 116, 241103

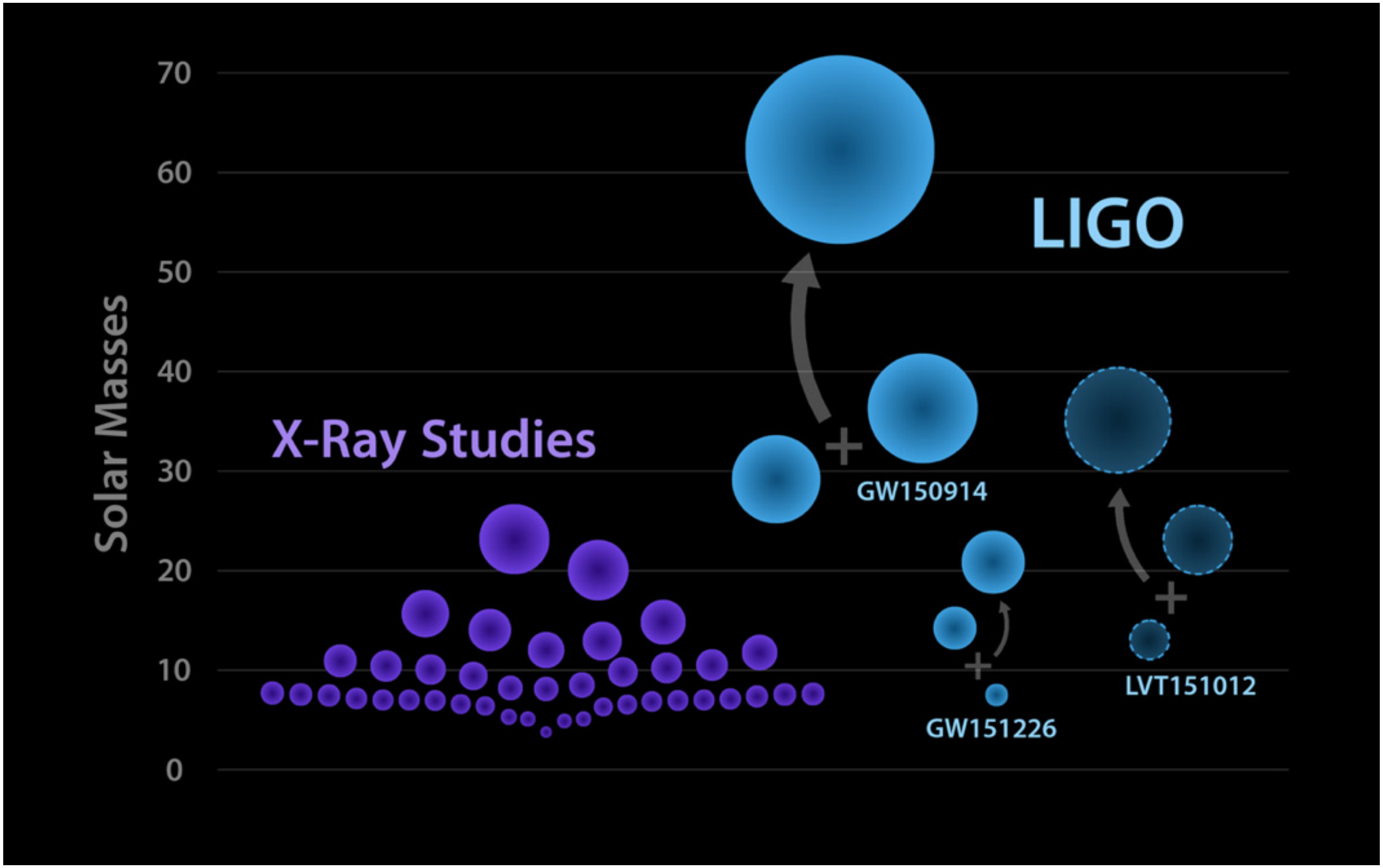
… and nonzero spin !



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)

Comparison of Black Hole Masses

GW150914 is *heavy!* That has implications for how it was formed



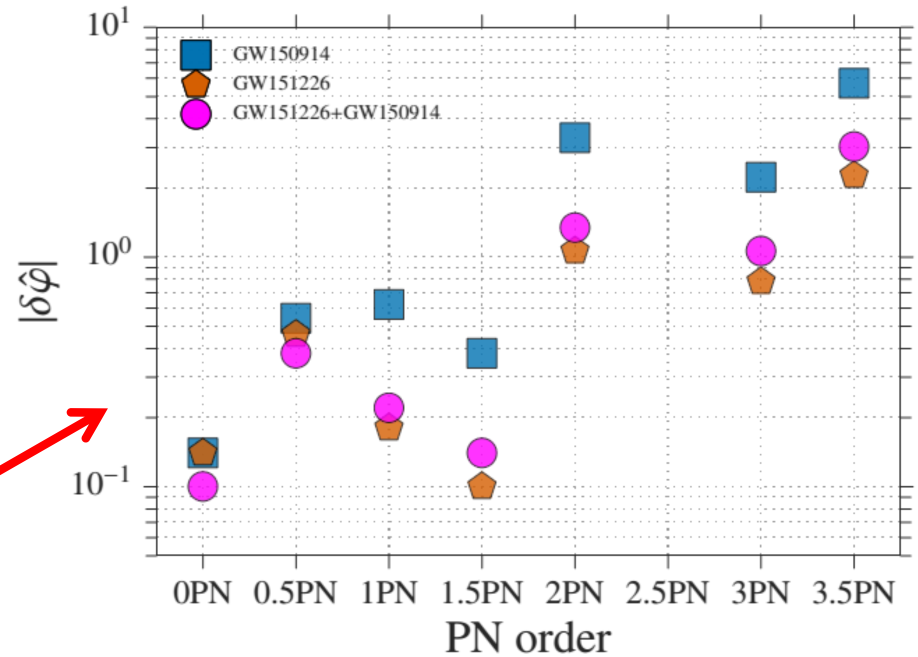
Testing GR as the Theory of Gravity

Check consistency of inspiral / merger / ringdown

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

GW151226, with more cycles, permits more stringent tests

Abbott et al., PRX 6, 041015



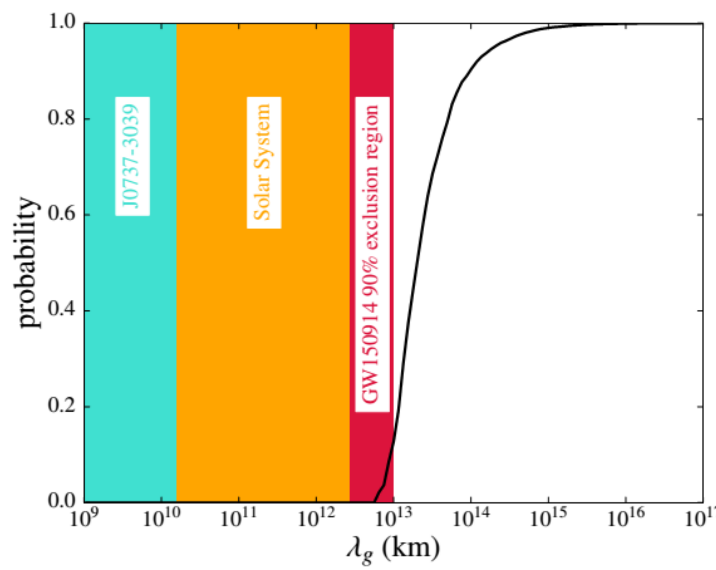
Allow for a massive graviton

Would distort waveform due to dispersion

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

➔ $m_g < 1.2\times10^{-22}\ \mathrm{eV}/c^2$

Abbott et al., PRL 116, 221101



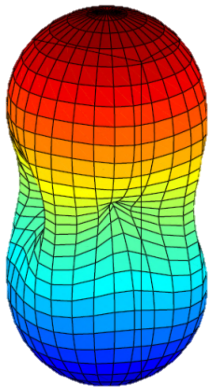
Multi-messenger astronomy
and the hunt for counterparts

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

Motivation from Energetics

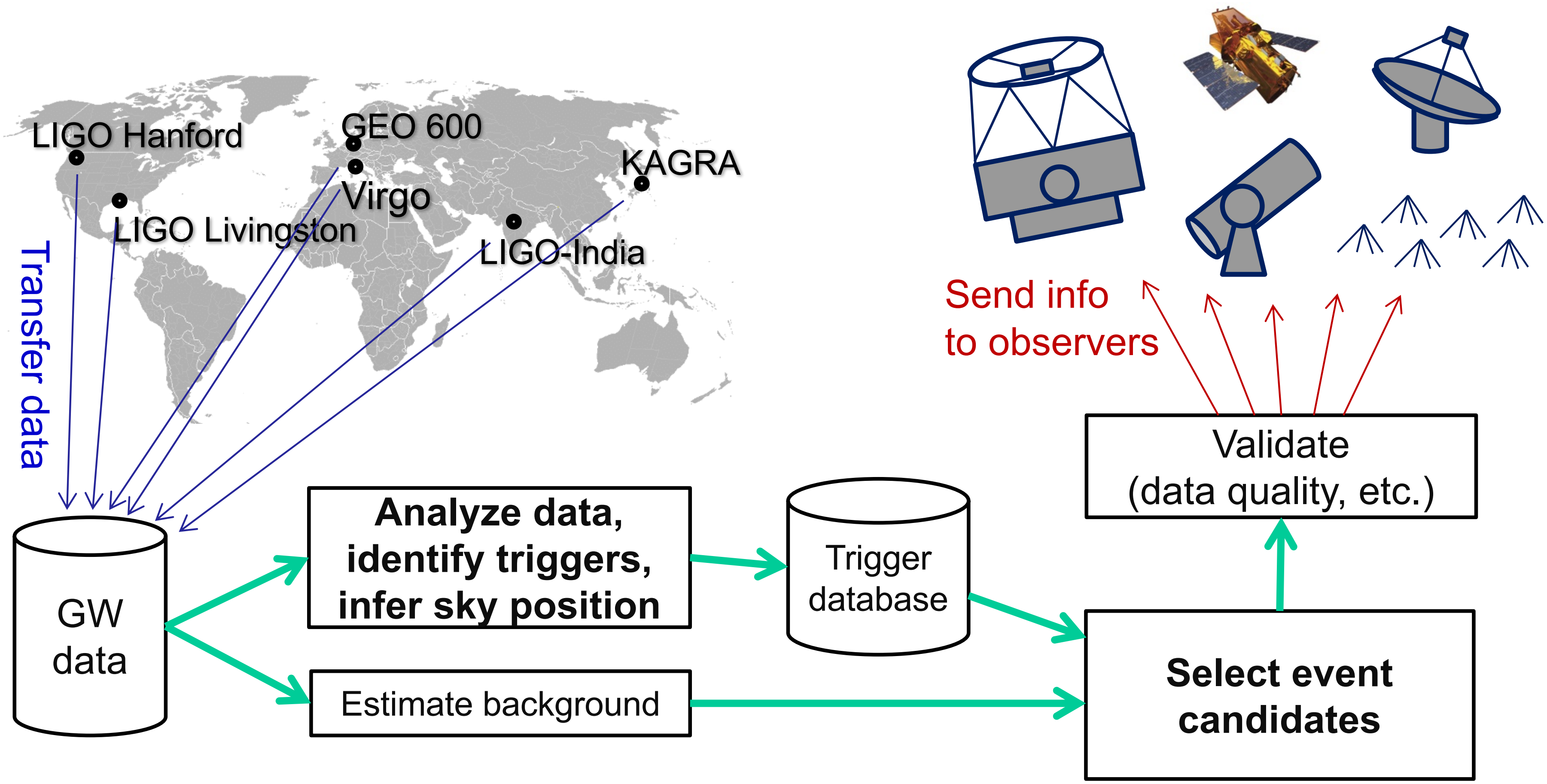
For any GW event detected by LIGO/Virgo, the energy emitted in GWs is enormous

e.g. for GW150914: ~5e54 erg in a fraction of a second!

One can imagine many ways for some of that energy to be reprocessed, directly or indirectly, into electromagnetic emission that can be detected by astronomers as a transient "counterpart"

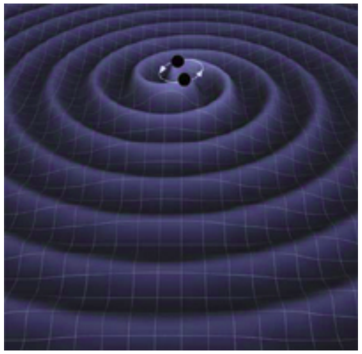
→ Our general philosophy is that it is worth looking for counterparts over as many EM bands and timescales as possible

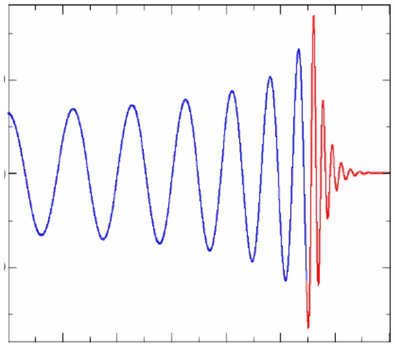
Outline of the “EM Follow-up” Project



Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

Searches for GW Transient Sources

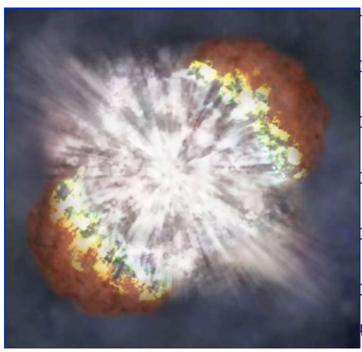


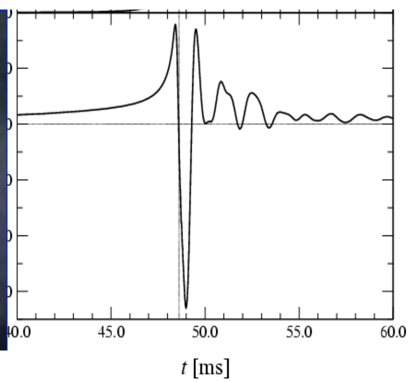


Compact Binary Coalescence (CBC)

Known waveform ➔ Matched filtering

Templates for a range of component masses
(spin affects waveforms too, but not so important for initial detection)





Unmodelled GW Burst (< ~1 sec duration)

e.g. from stellar core collapse

Arbitrary waveform ➔ Excess power

Require coherent signals in detectors,
using direction-dependent antenna response

Low-latency searches run continuously as data is collected

Whenever two or more detectors are operating normally

With coherent analysis, identify event candidates and generate preliminary sky position probability maps within a few minutes

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 a few hundred 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**

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

- Broad spectrum of transient astronomy researchers and instruments
- Optical, Radio, X-ray, gamma-ray, VHE
- Set up to distribute GCN "notices" and "circulars" to partners

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

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

Response by Observers During O1

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

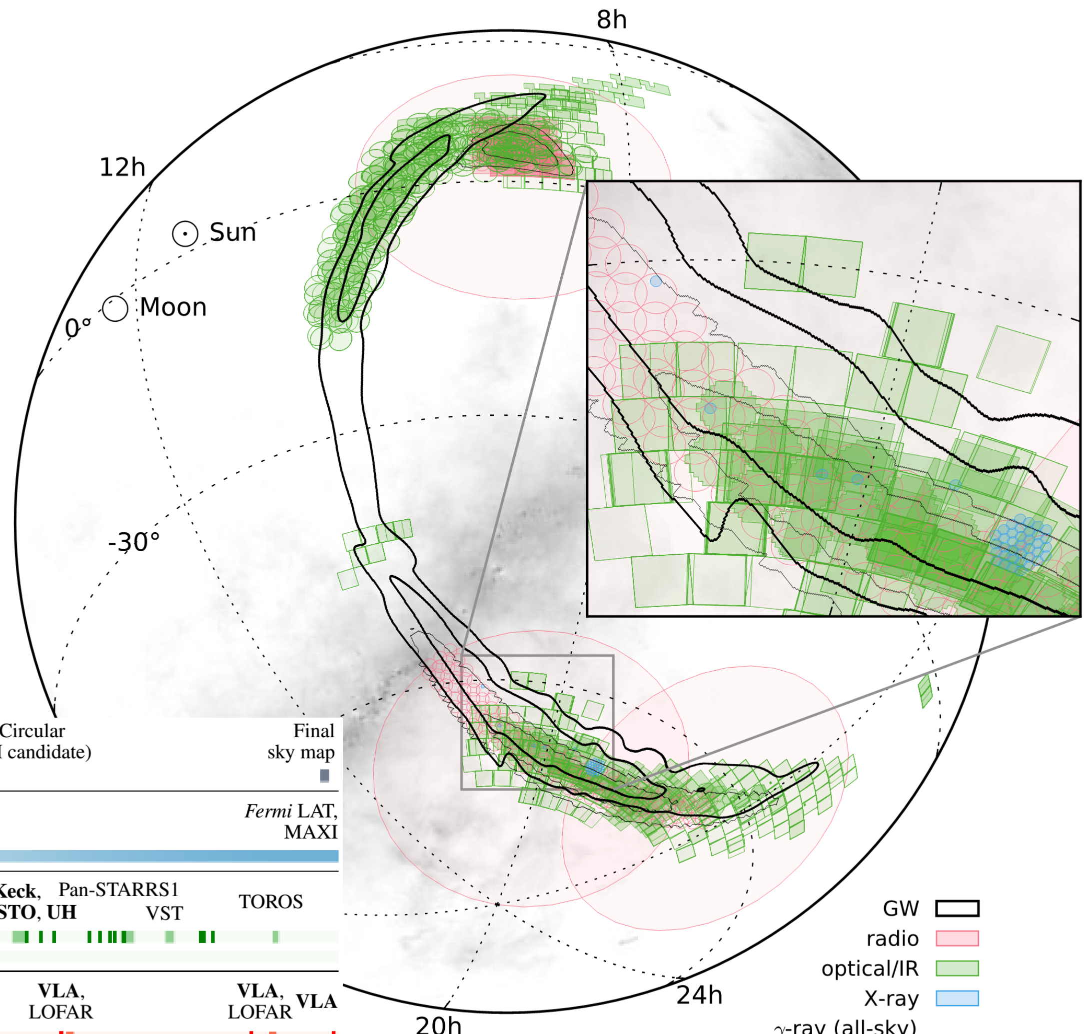
For GW150914:

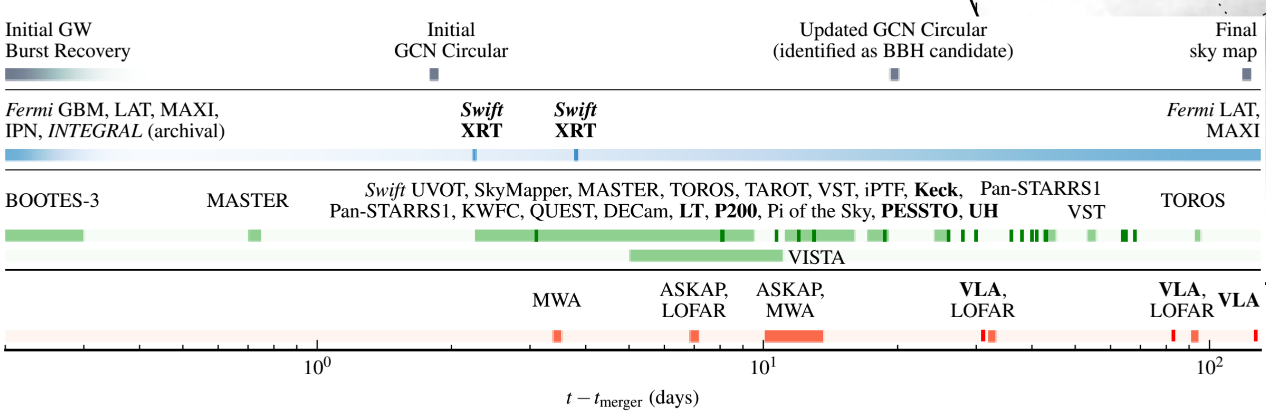
Covered most of skymap area at a wide range of wavelengths starting within a few hours

~50 GCN Circulars, ~12 papers

Also strong response for GW151226

Figures from Abbott++, ApJL 826, L13



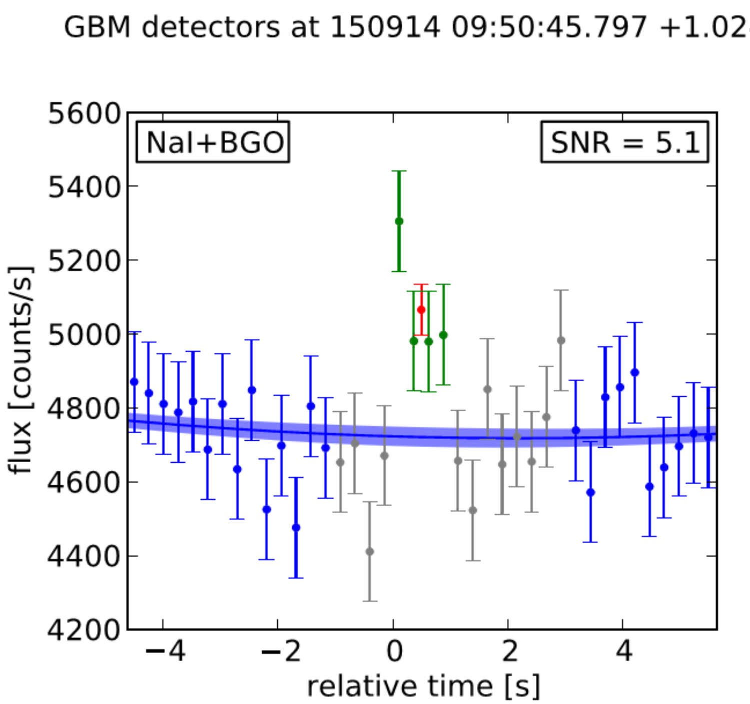


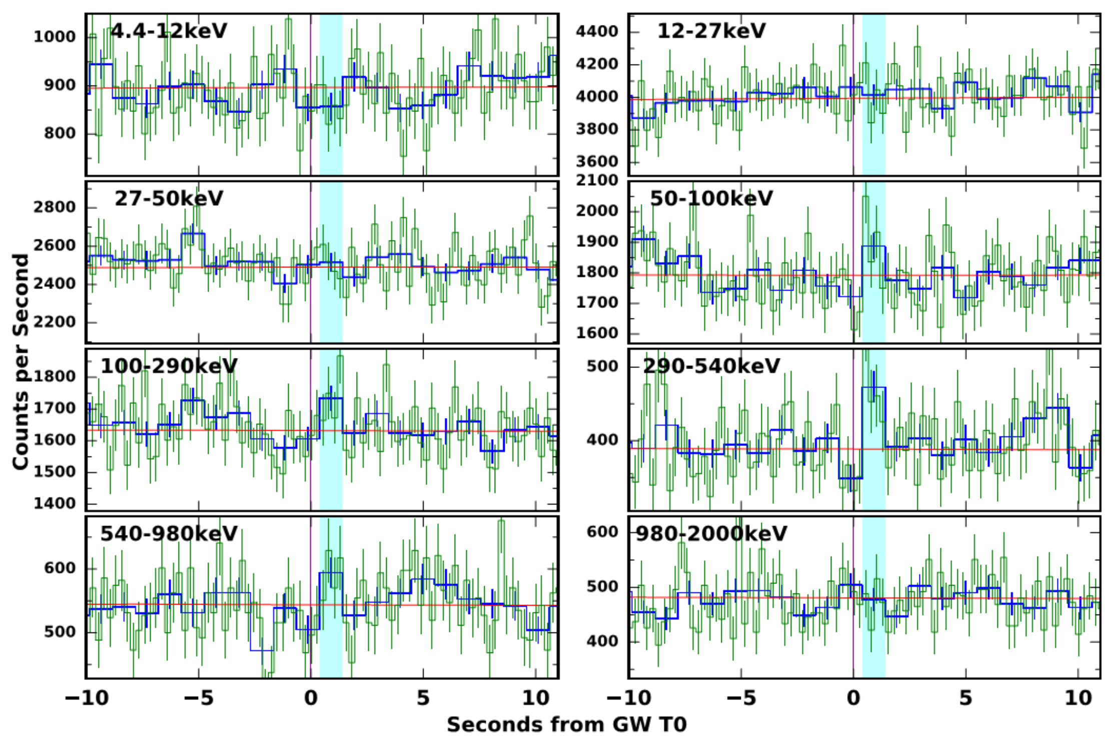
A Possible Gamma-ray Counterpart?

A weak signal was detected by the Gamma-ray Burst Monitor (GBM) on board the Fermi satellite about 0.4 second after the time of GW150914

Connaughton et al., ApJL 826, 13

Fermi: NASA E/PO, Sonoma State U., Aurore Simonnet





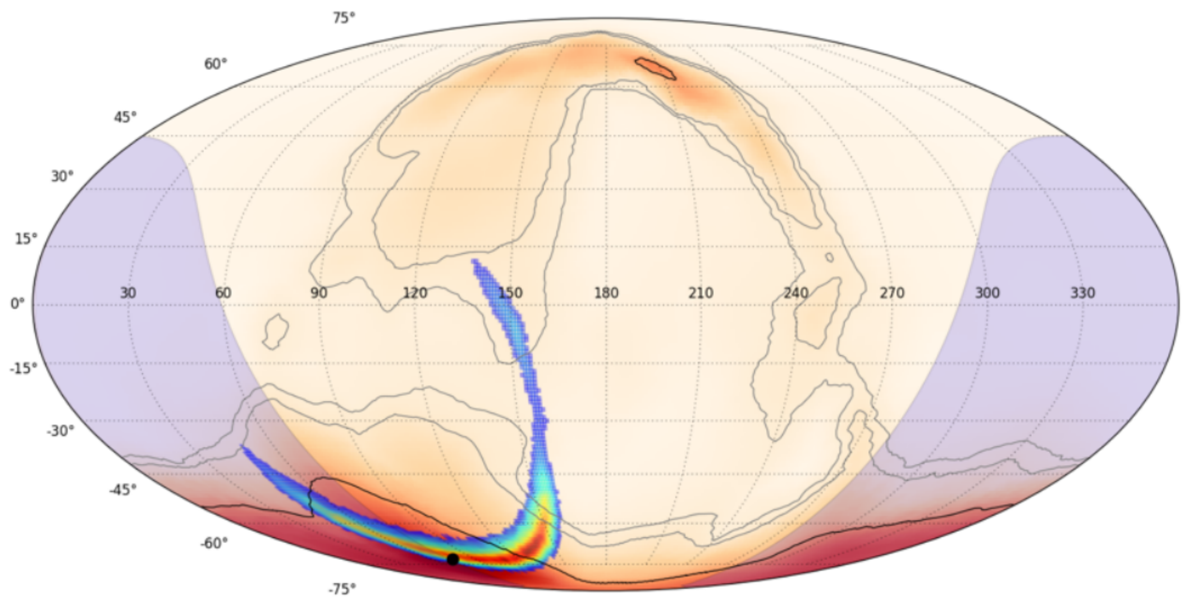
Post-trials false alarm prob ~ 0.0022

GBM Transient Localization

High-probability GBM region is consistent with LIGO region

Near the limb of the Earth from GBM's viewpoint

But doesn't match any known type of terrestrial signal



A real counterpart, or just a chance coincidence?

Inconclusive – we'll have to wait for more comparable events!

No GBM signal seen for GW151226 – but that had lower energy and LIGO skymap region was partly occulted by Earth (Racusin et al., arXiv:1606.04901)

Can a binary black hole merger produce a detectable EM transient?

We don't expect a stellar-mass binary black hole system to have enough matter around for the final BH to accrete and form a relativistic jet *[e.g., Lyutikov, arXiv:1602.07352]* — or can it? **Various models have been proposed:**

Single star: collapse of a *very* massive, rapidly rotating stellar core, which fissions into a pair of black holes which then merge *[Fryer+ 2001; Reisswig+ 2013; Loeb 2016, ApJL 819]*; but see Woosley, arXiv:1603.00511v2 for modeling that does not support this idea

Instant BBH: massive star-BH binary triggers collapse of star to BH, then immediate inspiral and merger; final BH can be kicked into circumbinary disk and accrete from it *[Janiuk+ 2013, A&A 560; arXiv:1604.07132]*

BBH with fossil disk: activates and accretes long-lived cool disk *[Perna+ 2016, ApJL 821]*

BBH embedded in AGN disk: binary merger assisted by gas drag and/or 3-body interactions in AGN disk, which provides material to accrete *[Bartos+, arXiv:1602.03831; Stone+ 2016, MNRAS]*

Third body: tidal disruption of a star in a hierarchical triple with the BBH at time of merger *[Seto&Muto 2011, cited in Murase+ 2016, ApJL 822]*

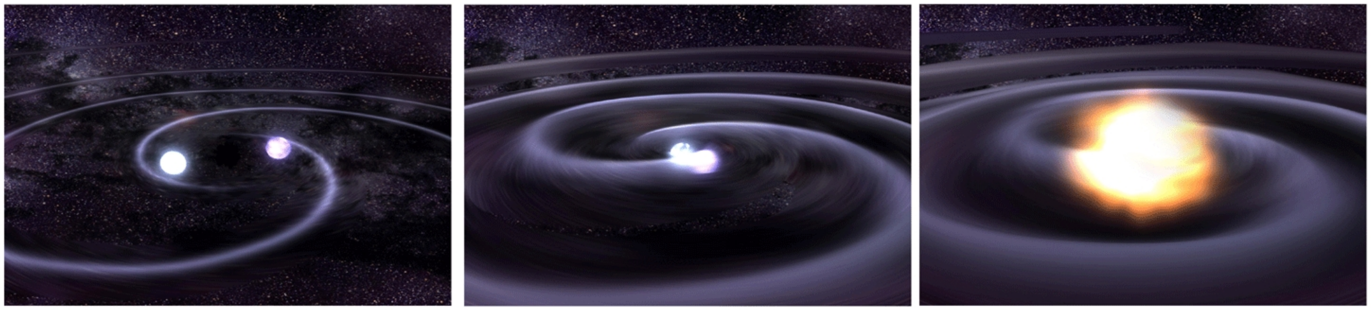
Charged BHs: Merging BHs with electric (or magnetic monopole!) charge could produce a detectable EM transient *[Zhang 2016, ApJL 827; Liebling&Palenzuela 2016, PRD 84]*

Magnetic reconnection *[Fraschetti, arXiv:1603.01950]*

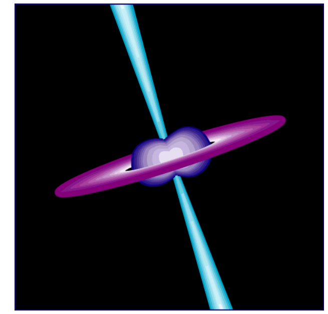
Also models for high-energy neutrino and ultra-high energy cosmic ray emission

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

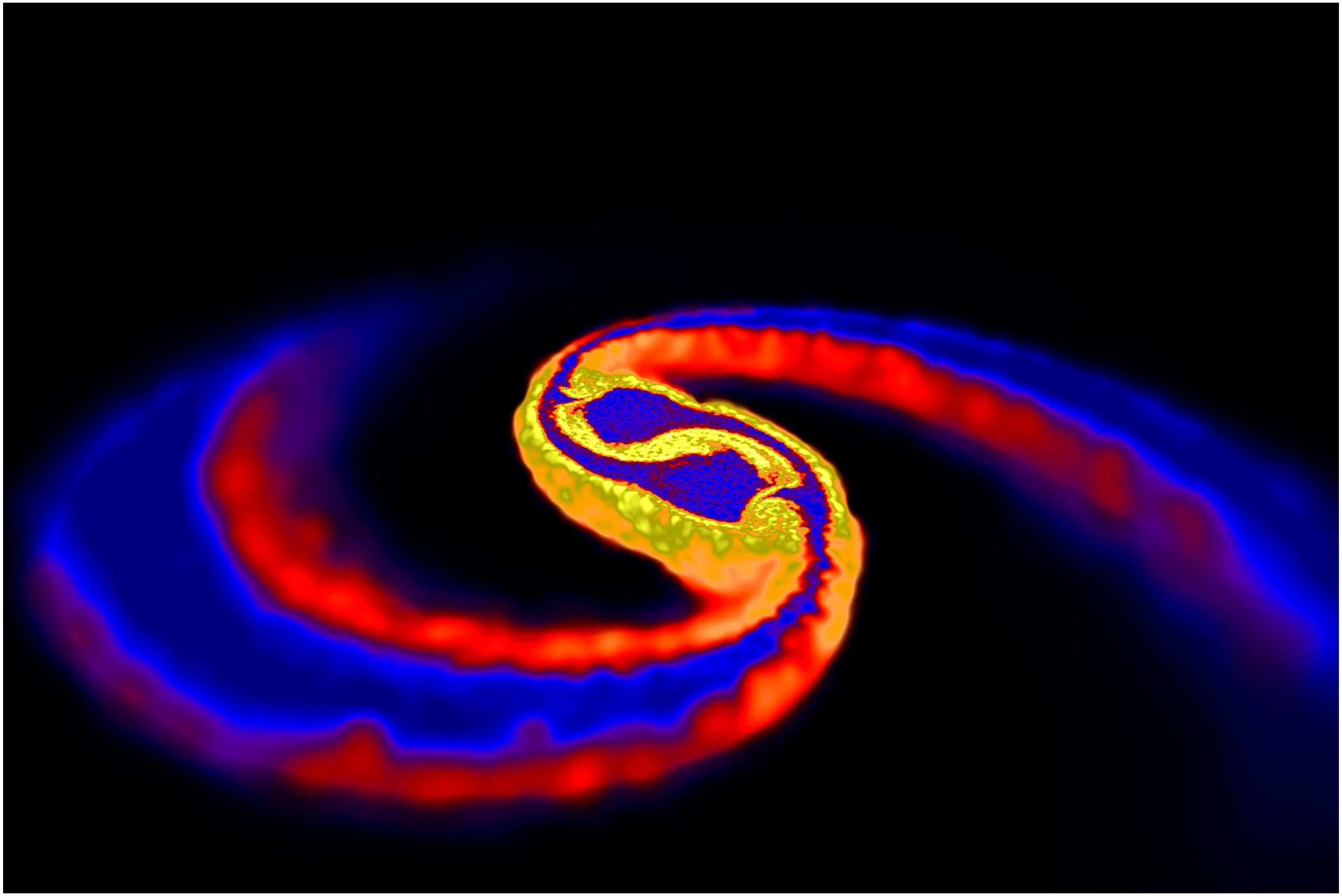
Beamed gamma-ray emission → many more mergers than GRBs

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")

IR/Visible/UV (?) emission powered by radioactive decay of r-process elements produced in neutron-rich ejecta [e.g., Barnes & Kasen, ApJ 775, 18]

Roughly isotropic, though varies due to geometric effects

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]

Kilonova Promise and Challenges

Great reference: Brian Metzger's "Kilonova Handbook", arXiv:1610.09381

Expected signature is unclear due to complicated astrophysics!

Different remnant scenarios

- Direct collapse to black hole (with some amount of spin)
- Hypermassive neutron star collapsing to black hole after a delay
- Stable, magnetized heavy neutron star

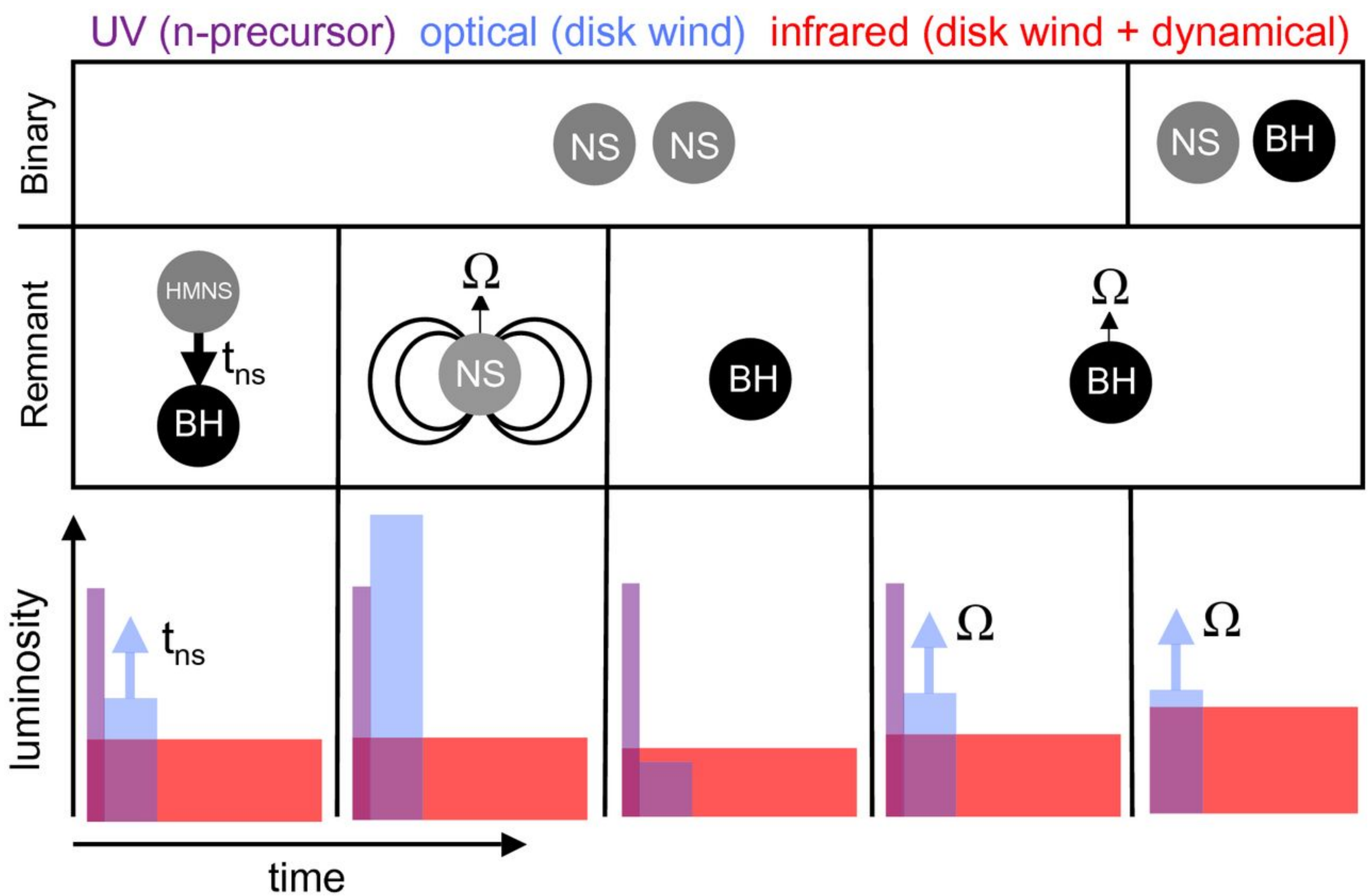
Different types of ejecta ➔ EM emission signatures

- Dynamical ejection of tidally disrupted mass (lanthanide-dense → IR)
- Decay of free neutrons in surface layer (faster heating → UV)
- Wind from remnant accretion disk (lanthanide-free → visible)

Uncertain ejecta mass and opacity ➔ brightness & time scales

- Likely faint, requiring 8+ meter scopes, especial as GW detectors improve
- ➔ An opportunity for LUVOIR !

Dependence on Progenitor & Remnant



Kasen, Fernández & Metzger, MNRAS 450, 1777

Colors and Light Curves

These are AB magnitudes for a source at **200 Mpc**

Dynamical ejecta:

IR, peaking after several days

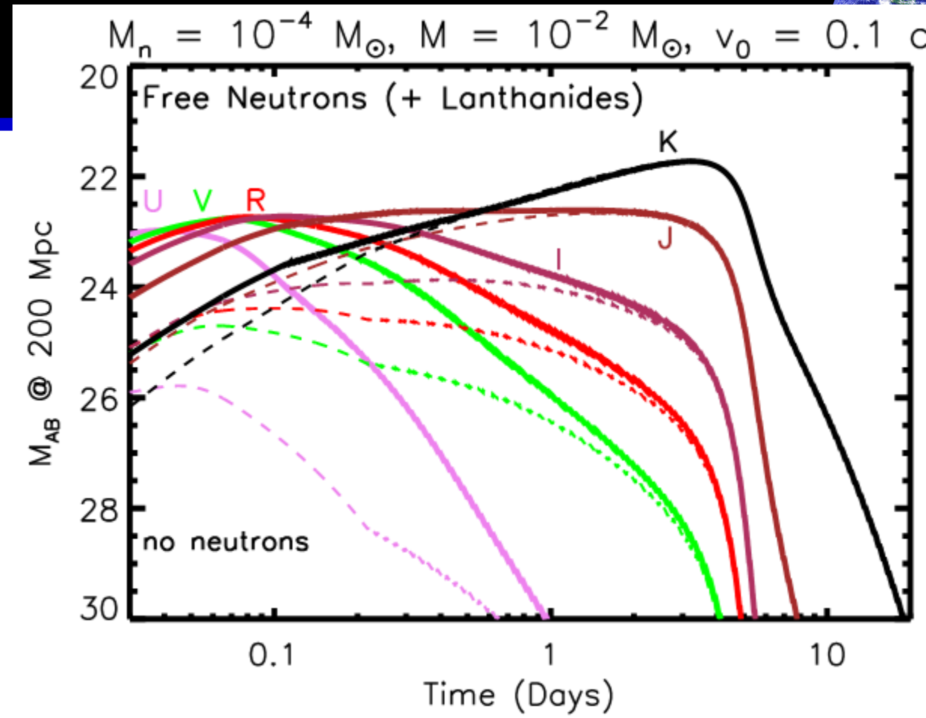
Thermal pulse from decay of free neutrons:

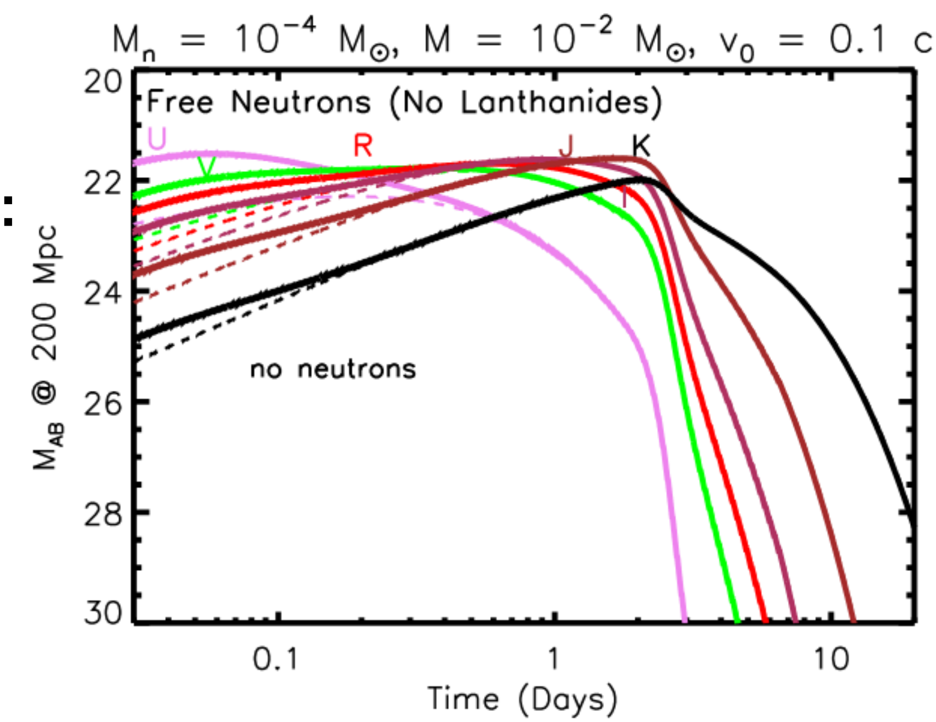
UV, peaking in ~1 hour

Wind from remnant accretion disk:

Visible/IR, peaking in ~1 day

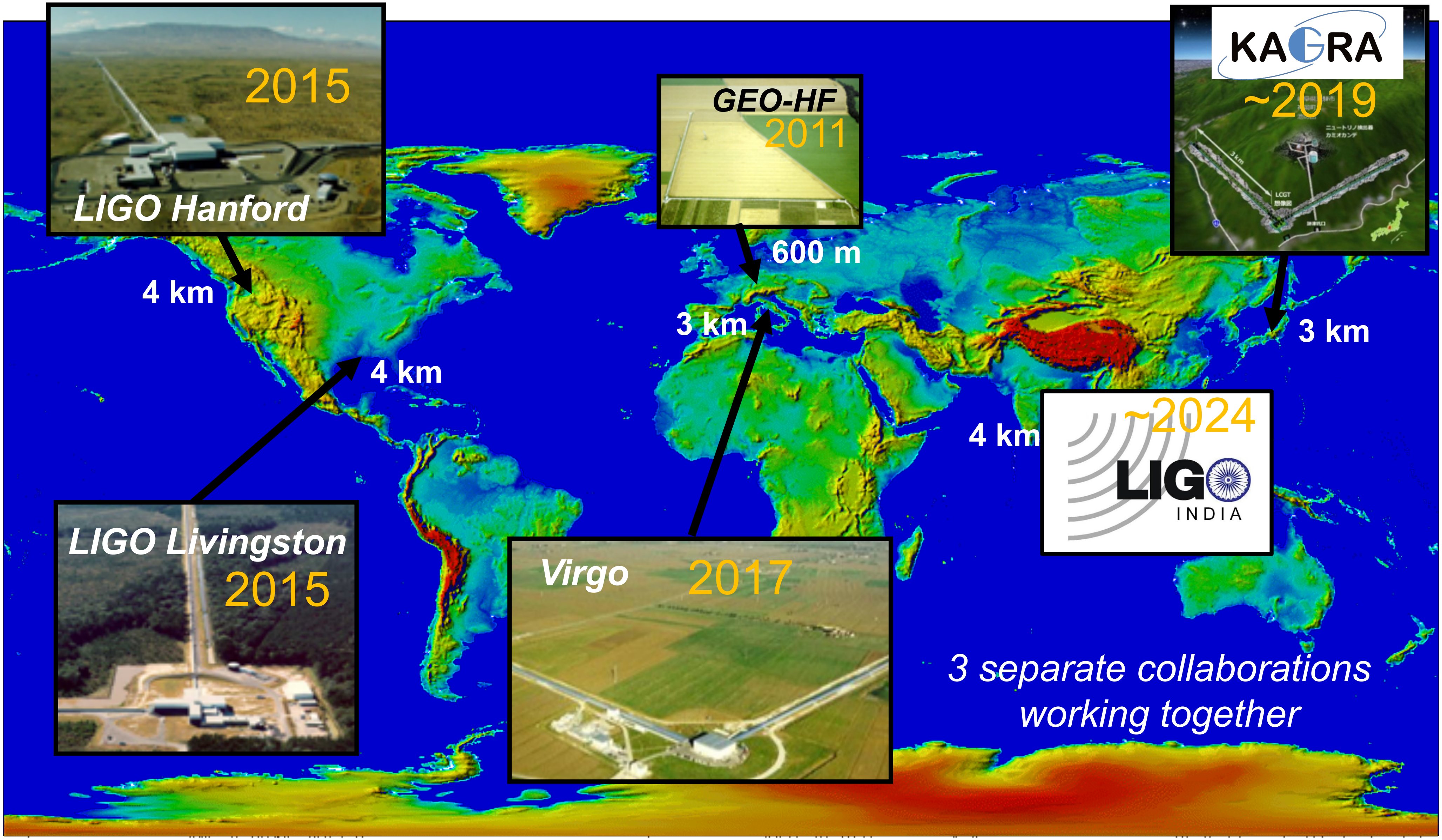
From Metzger, arXiv:1610.09381





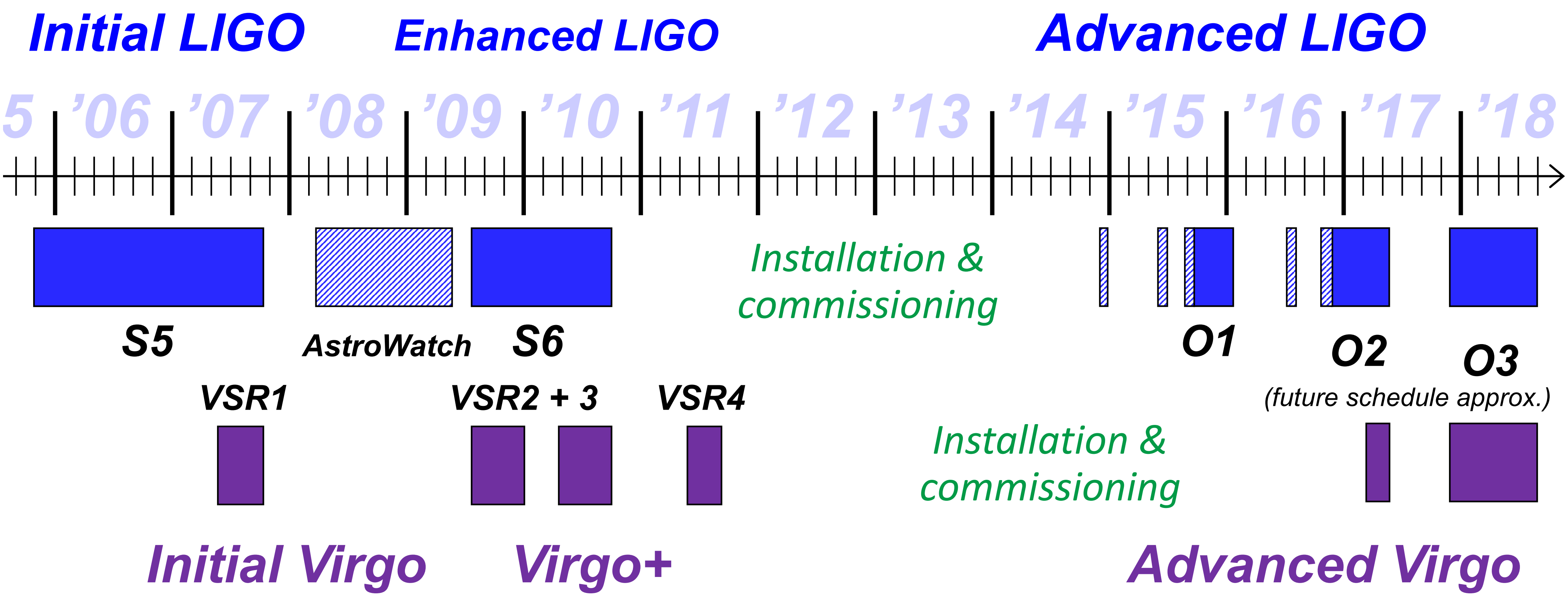
Looking ahead

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/

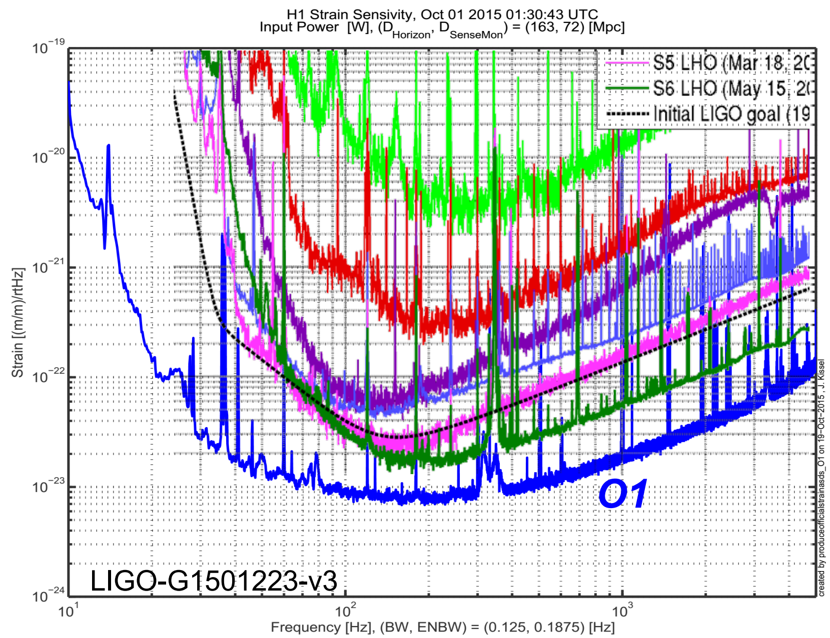
How will the GW detector network improve?

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

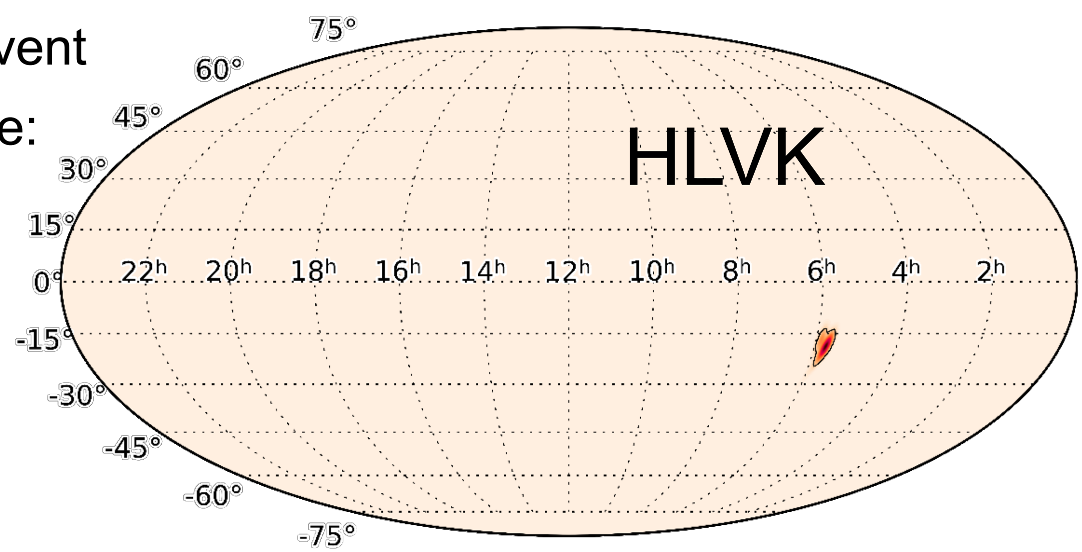
Further incremental upgrades and new facilities are being studied



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 GW 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?

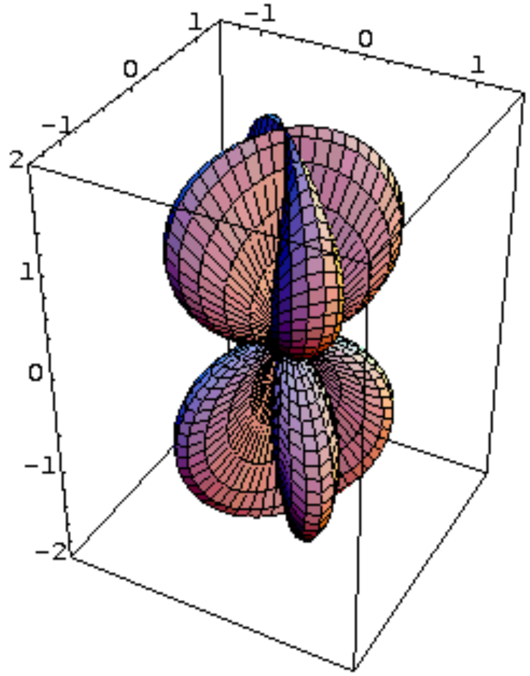
➔ Opportunities for multi-messenger astronomy

Backup slides

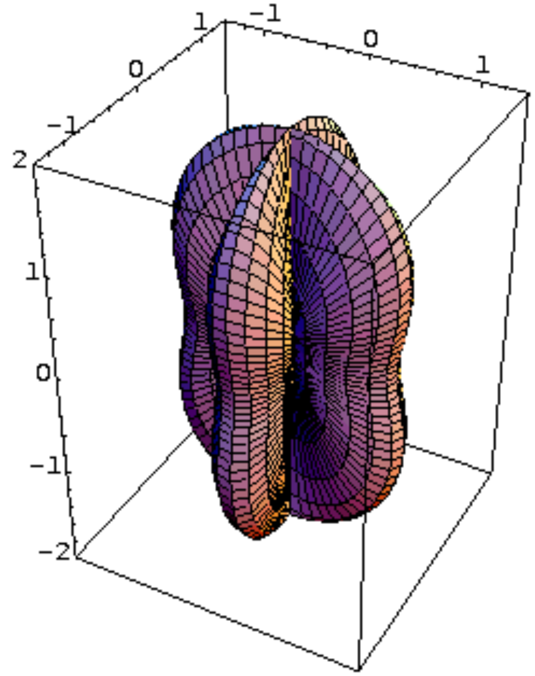
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

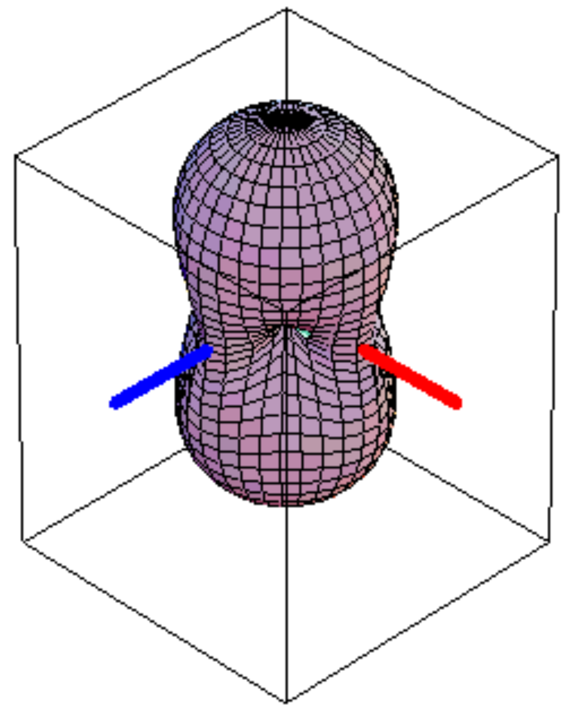
“×” polarization



“+” polarization



RMS sensitivity



A broad antenna pattern

⇒ **More like a radio receiver than a telescope**

Gravitational Wave Strain

Two massive, compact objects in a tight orbit deform space (and any object in it) with a frequency which is twice the orbital frequency

(Neutron stars or black holes)

The stretching is described by a dimensionless strain, $h = \Delta L / L$

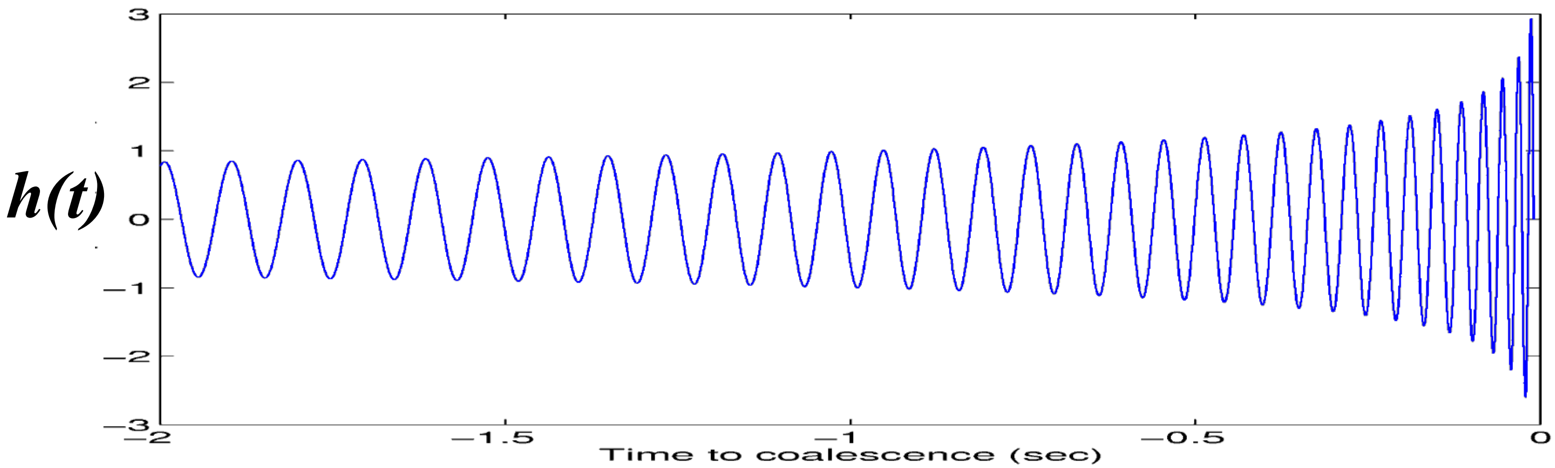
h is inversely proportional to the distance from the source

Challenge: only expect $h \sim 10^{-21}$ at Earth!

The Fate of B1913+16

Gravitational waves carry away energy and angular momentum

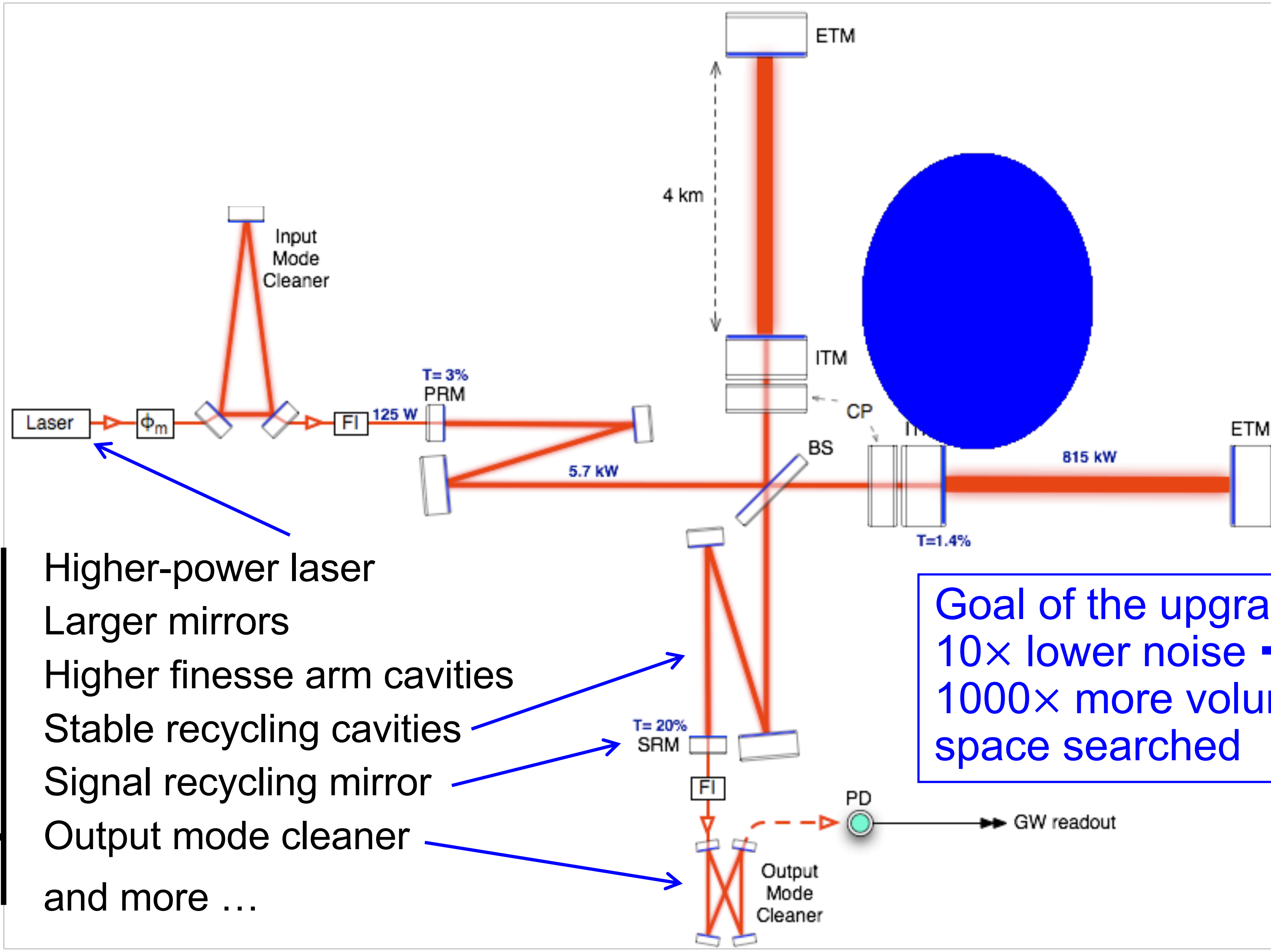
Orbit will continue to decay—“inspiral”—over the next ~300 million years, until…



The neutron stars will merge !

- And probably collapse to form a black hole
- Final ~minute will be in audio frequency band

Advanced LIGO Optical Layout



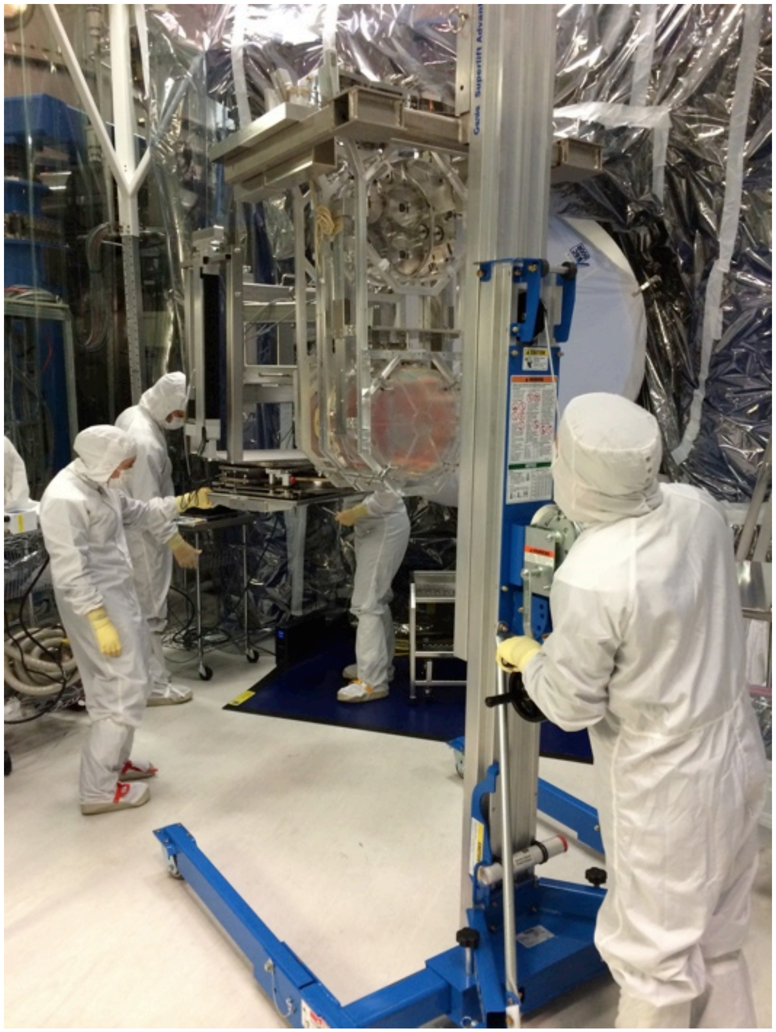
Improvements

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

Goal of the upgrade:
10× lower noise ➔
1000× more volume of
space searched

Advanced LIGO Installation

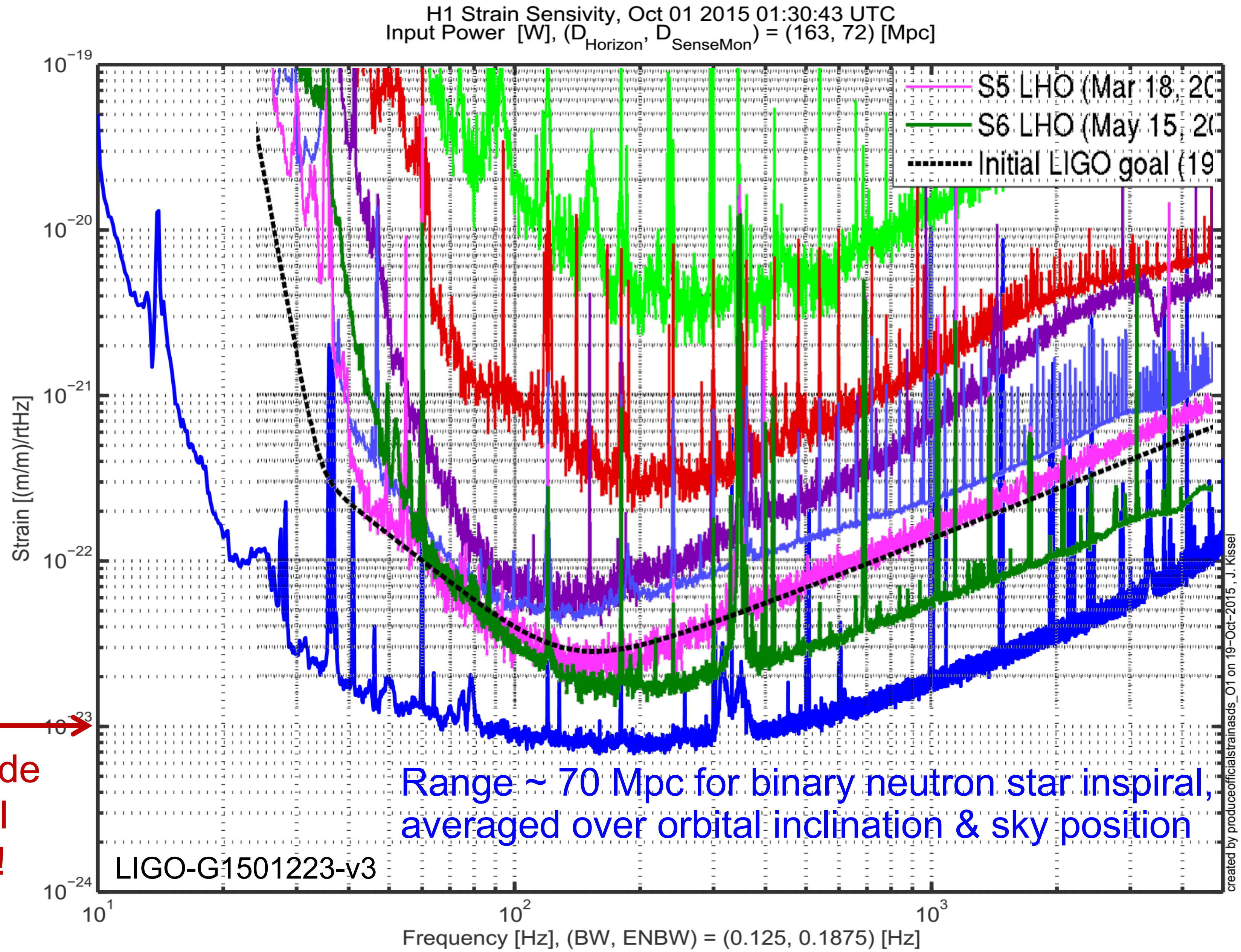
Installation went pretty smoothly at both LIGO observatories



Achieved full interferometer lock in 2014, first at LIGO Livingston, then at LIGO Hanford

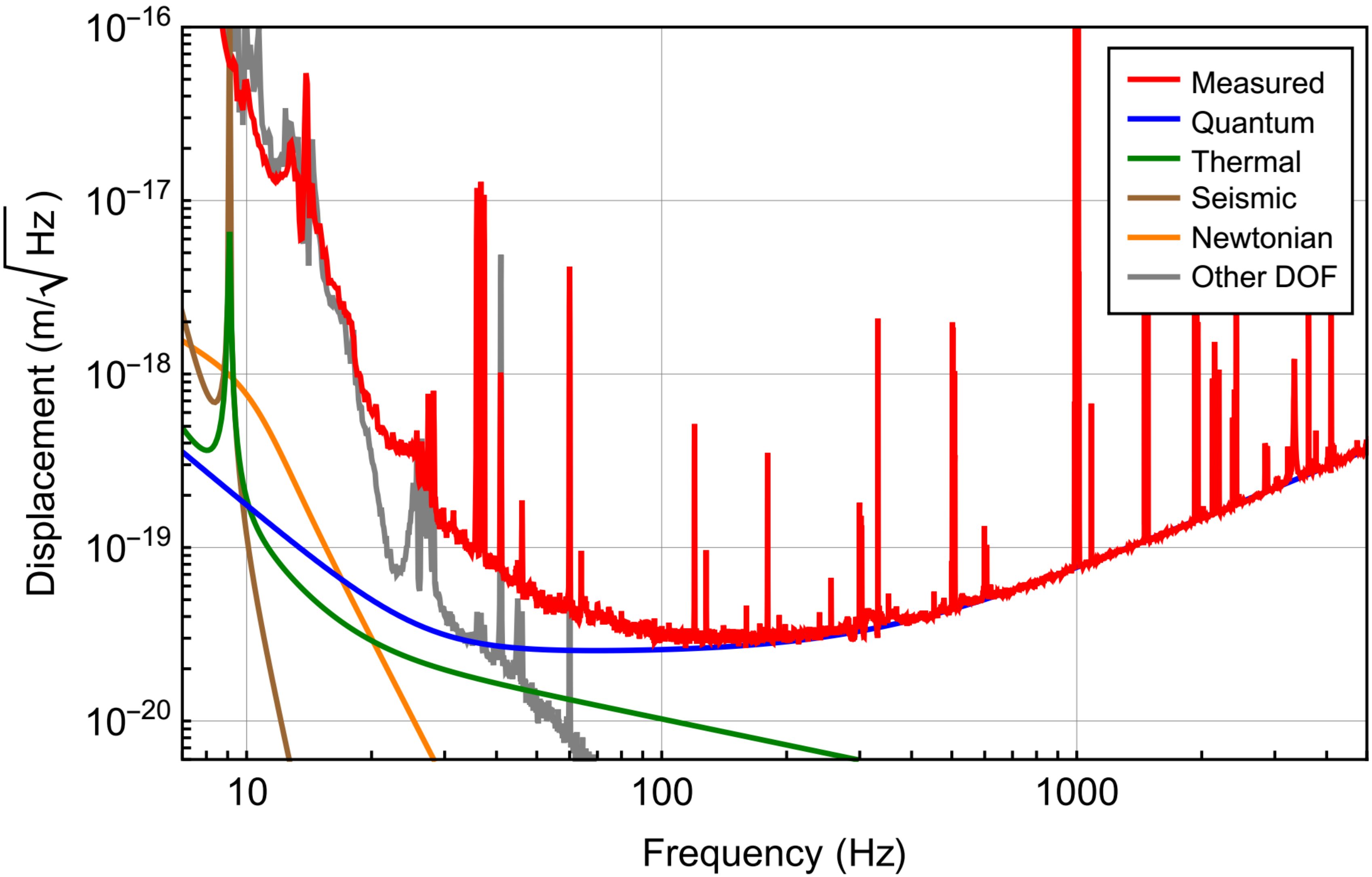
Commissioning: lots of work, lots of progress

LIGO GW Strain Sensitivity for O1



10^{-23} amplitude spectral density!

LIGO Detector Noise Components



From Abbott et al., arXiv:1602.03838

Could it be an instrumental noise artifact?

Would have to have been (nearly) coincident at the two sites

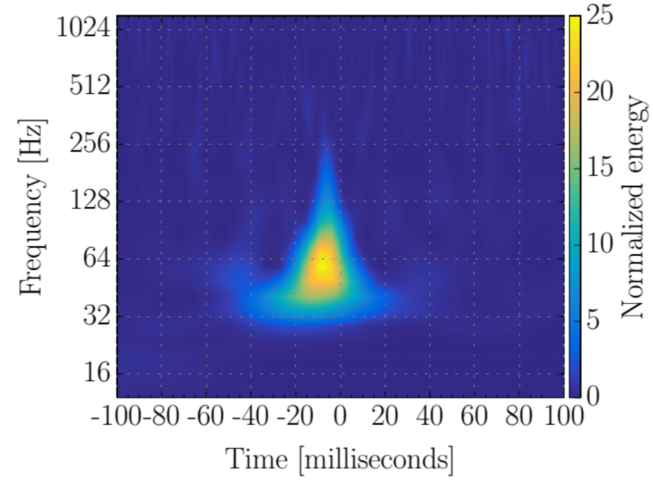
We checked for possible *correlated* noise in the detectors

No significant signals found in magnetometers, etc.

There are also uncorrelated "glitches" in the data

Some can be rejected with data quality cuts on monitoring channels

Still have "blip transients" with unknown origin, though they don't look much like "The Event"

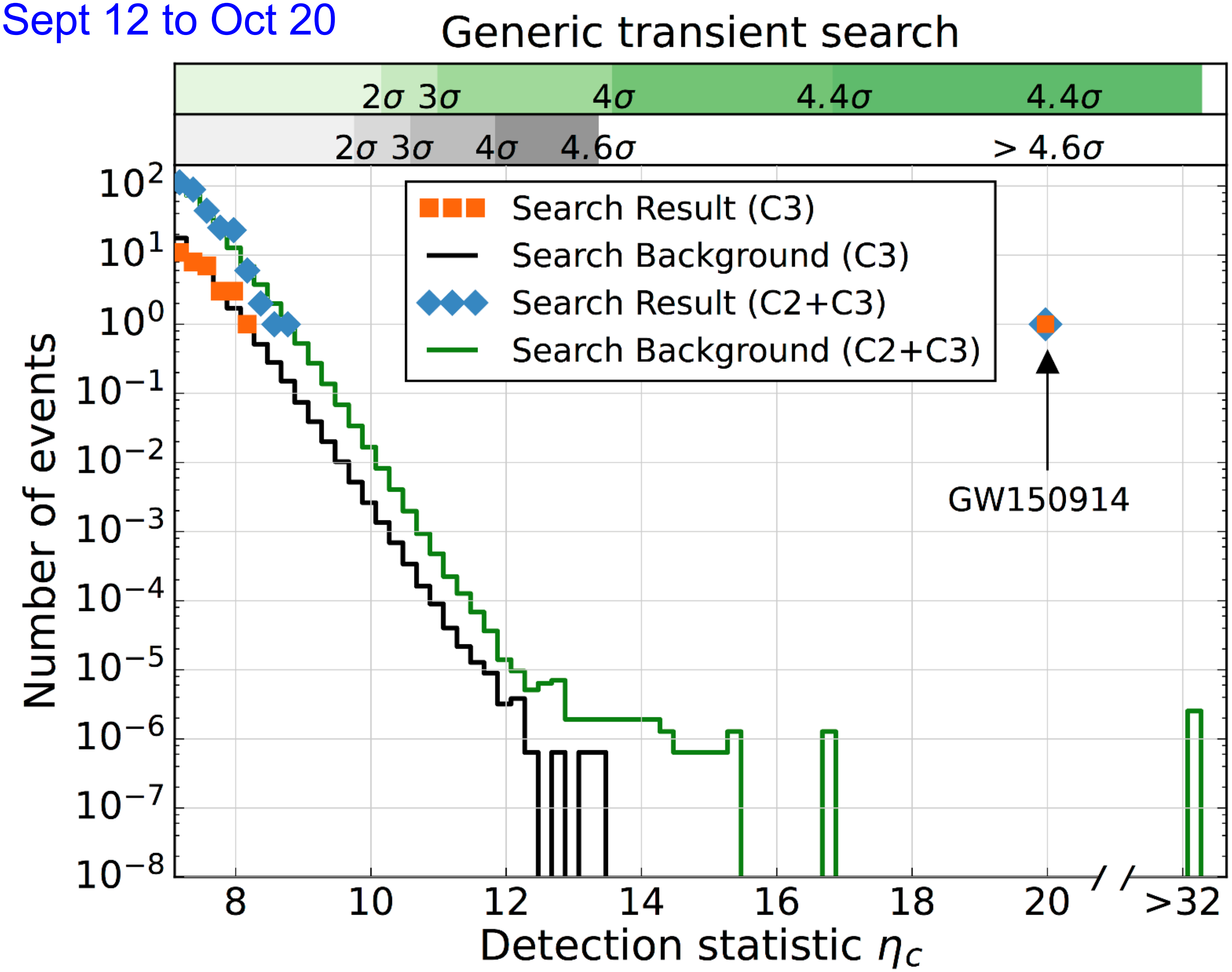


We can estimate the background (from random false coincidences) by analyzing time-shifted data

➔ We calculated that we would need **16 days of data** (livetime) to check for background similar to the The Event **at the "5σ" level**

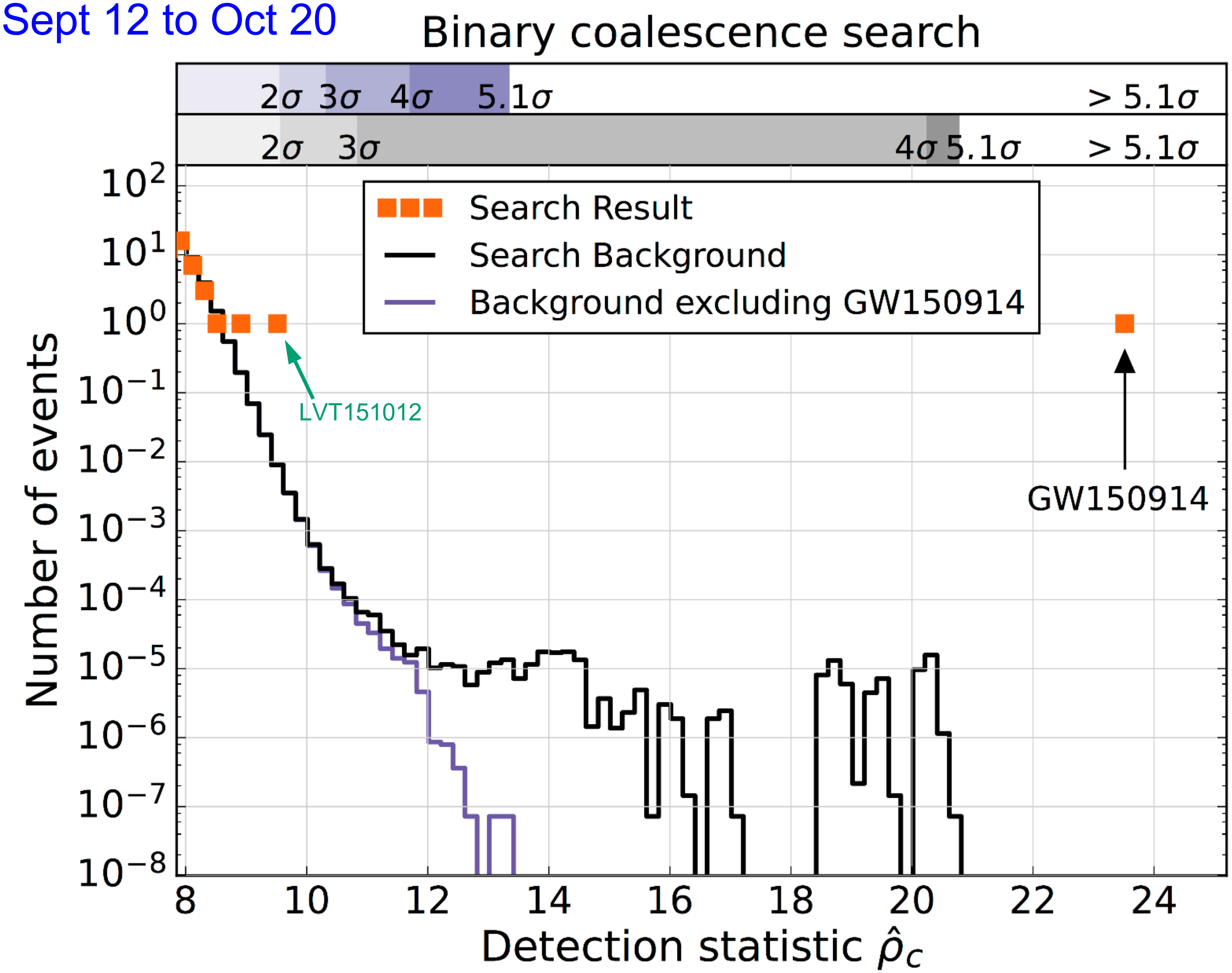
Final Analysis – Generic Transient Search

Data set: Sept 12 to Oct 20

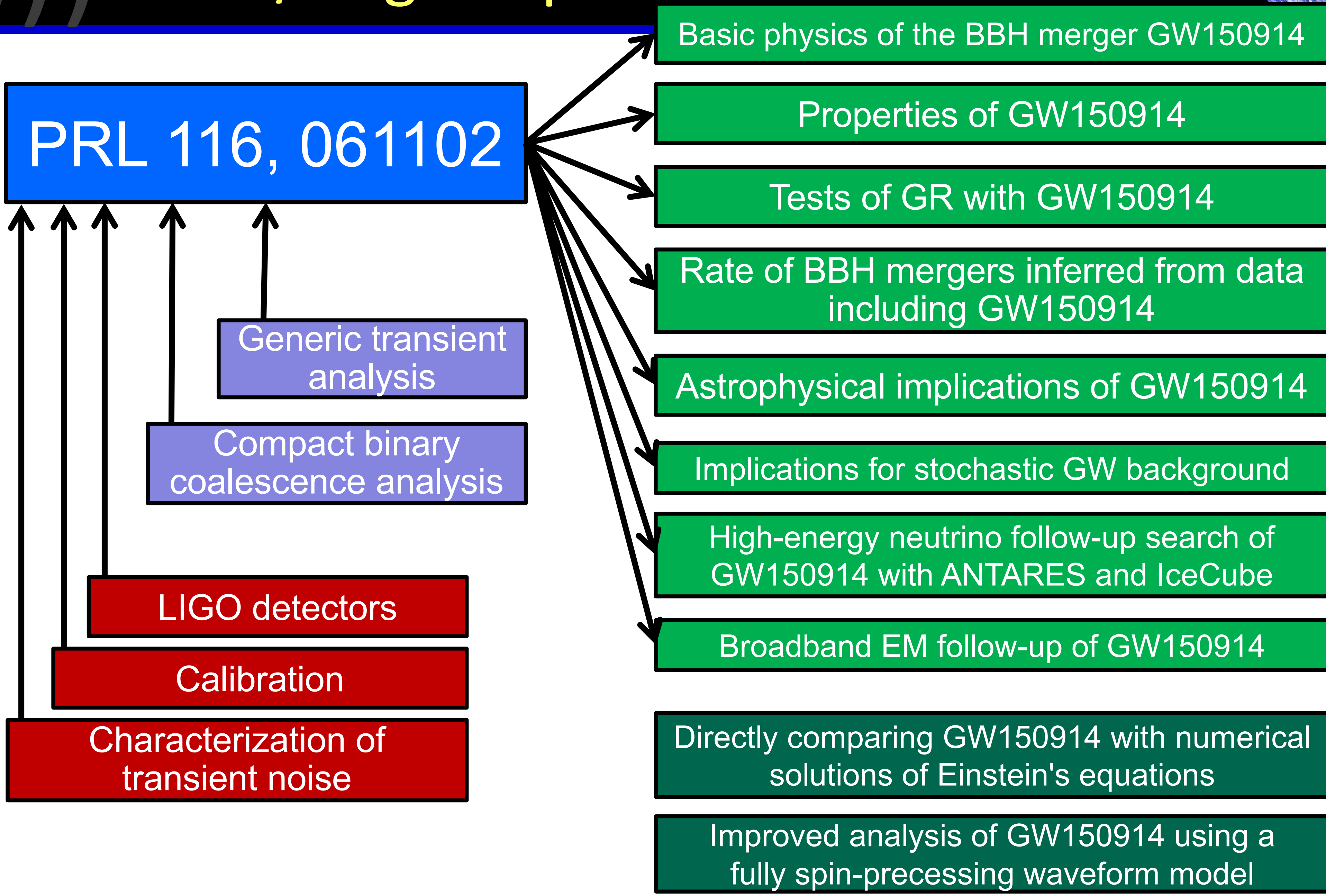


Final Analysis – Binary Coalescence Search

Data set: Sept 12 to Oct 20



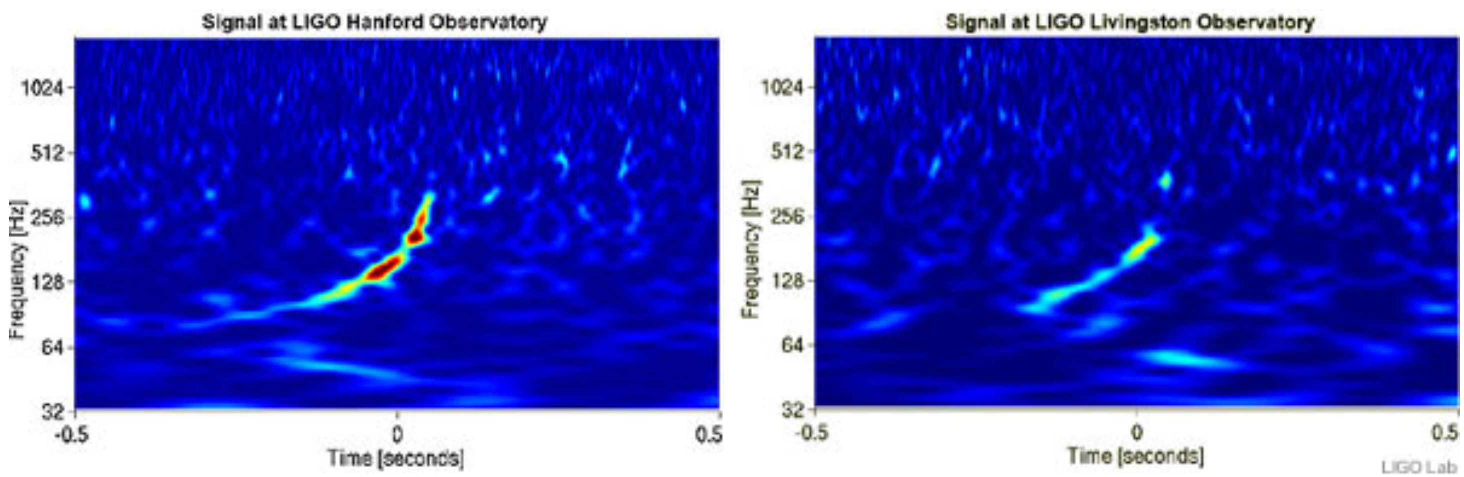
LIGO/Virgo Papers About GW150914



Could it be a blind injection?

LIGO and Virgo have done blind injections in the past

- A few people authorized to secretly insert a signal into the detectors
- Truly end-to-end test of the detectors, data analysis, and interpretation
- Including the “Equinox event” in Sept 2007 and “Big Dog” in Sept 2010



A blind injection exercise was authorized for O1

But it had not started as of September 14 !

Effect of Data Quality Cuts

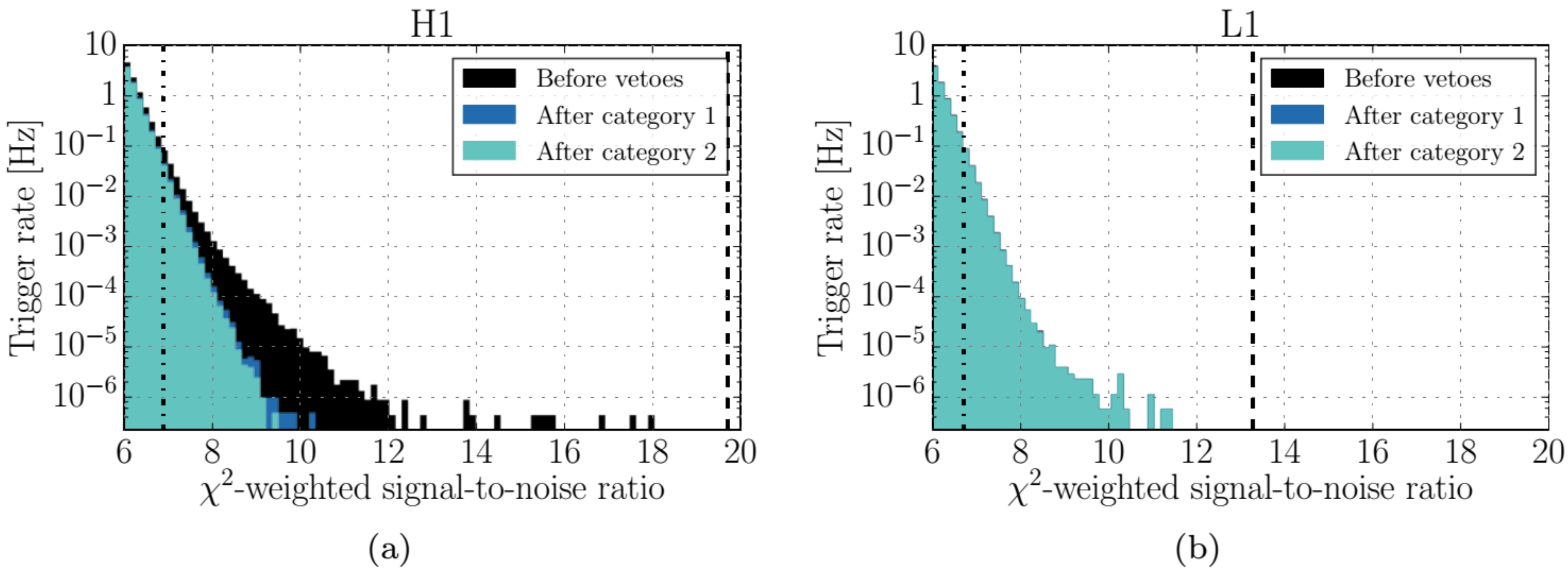
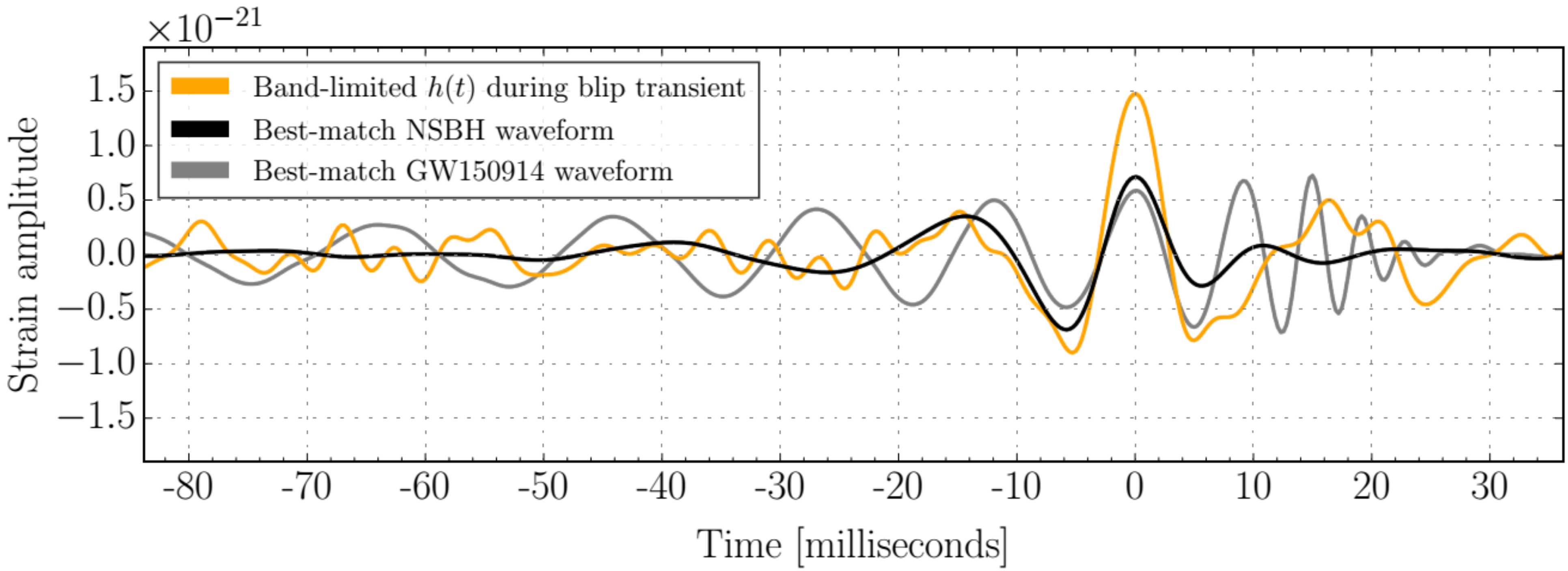


Figure 7: The impact of data-quality vetoes on the CBC background trigger distribution for (a) LIGO-Hanford and (b) LIGO-Livingston. The single-detector χ^2-weighted SNR of GW150914 is indicated for each detector with a dashed line (19.7 for Hanford and 13.3 for Livingston), and for event LVT151012 with a dot-dashed line (6.9 for Hanford and 6.7 for Livingston).

From Abbott et al., arXiv:1602.03844

A Closer Look at a "Blip Transient"



From Abbott et al., arXiv:1602.03844

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)

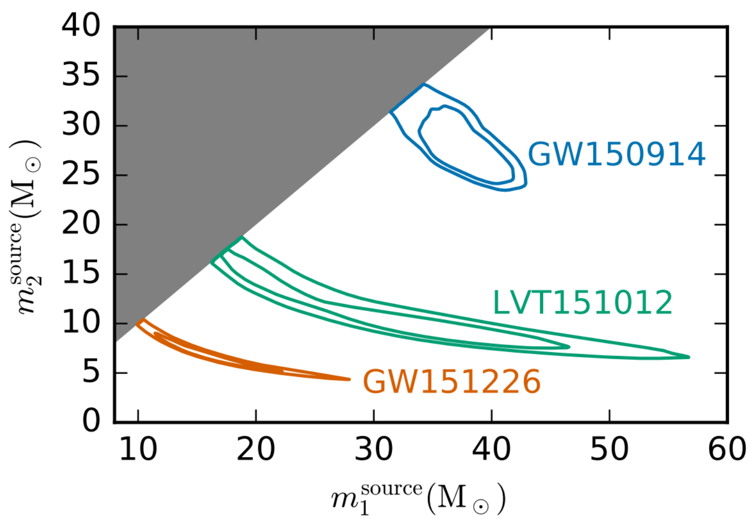
Over two dozen papers…

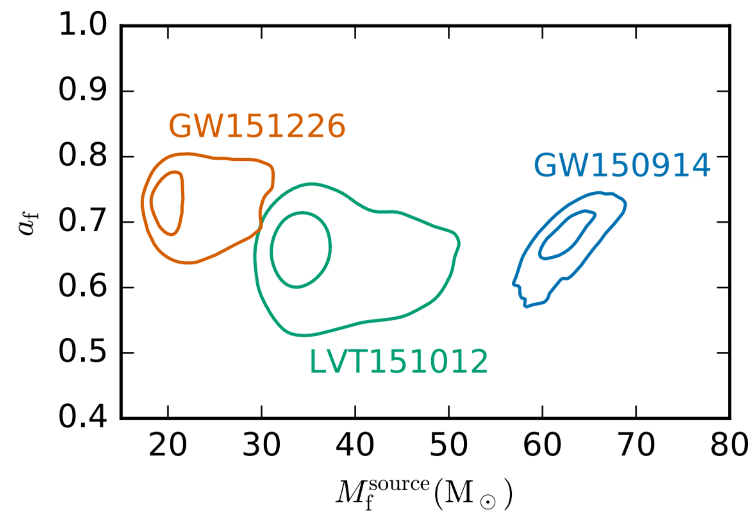
CBC, Burst	GRBs	– using public (GCN) and	private info
CW	Known pulsars	public	private
Burst	SGR/magnetar flares	public	private
	Pulsar glitch (Vela)		private
	High-energy neutrinos		private
	Radio transients		private
	Supernovae	public (CBET, etc.)	
CBC	Offline follow-up with satellite	public γ/X-ray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

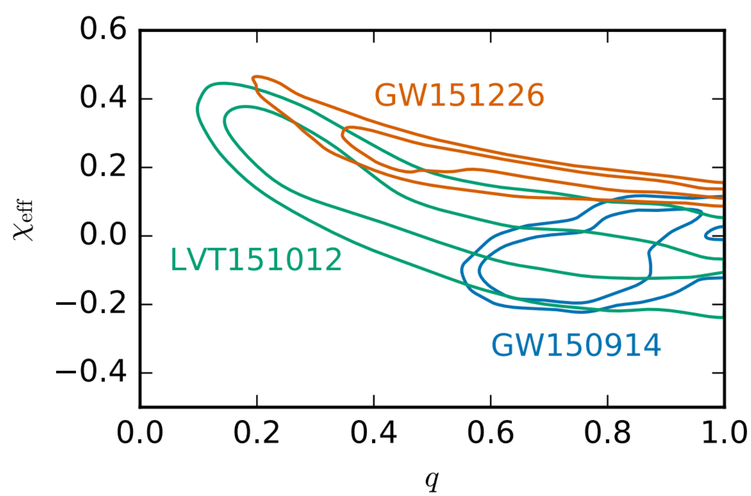
Also initiated an *EM follow-up program*, distributing GW event candidates to observers to enable them to search for counterparts

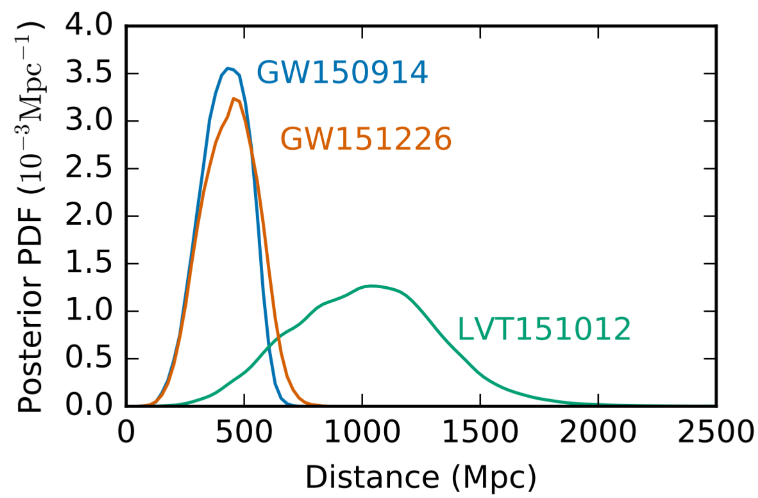
Starting to see the population…

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









Astrophysical Implications

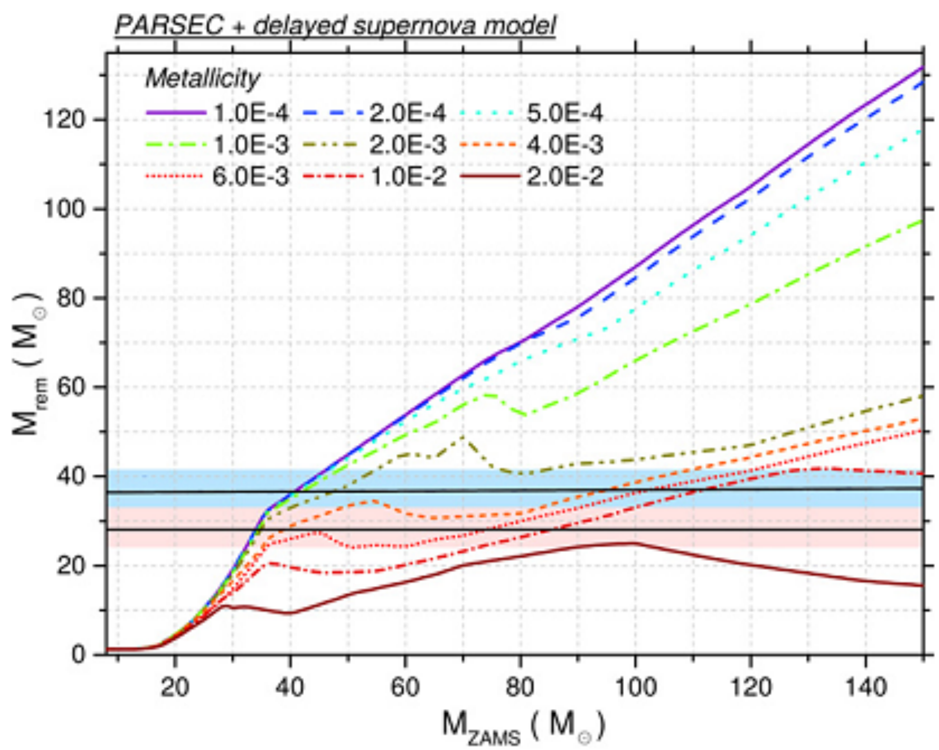
GW150914 proves that there are black hole binaries out there, orbiting closely enough to merge, and *heavy !*

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?

The First Alert – September 16, 2015

We weren't really ready, but scrambled to package the event information, update software and send GCN notices and a "circular" out to our observing partners…

//

TITLE: GCN CIRCULAR
NUMBER: 18330
SUBJECT: LIGO/Virgo G184098: Burst candidate in LIGO engineering run data
DATE: 15/09/20 00:53:16 GMT
FROM: Leo Singer at NASA/GSFC <leo.p.singer@nasa.gov>

Dear colleagues,

We would like to bring to your attention a trigger identified by the online Burst analysis during the ongoing Engineering Run 8 (ER8). Normally, we would send this in the form of a private GCN Circular, but the LIGO/Virgo GCN Circular list is not ready yet.

The LIGO Scientific Collaboration and Virgo report that the cWB unmodeled burst analysis identified candidate G184098 during real-time processing of data from LIGO Hanford Observatory (H1) and LIGO Livingston Observatory (L1) at 2015-09-14 09:50:45 UTC (GPS time: 1126259462.3910). Alerts were not sent in real-time because the candidate occurred in ER8 data; however, we have now sent GCN notices through our normal channel.

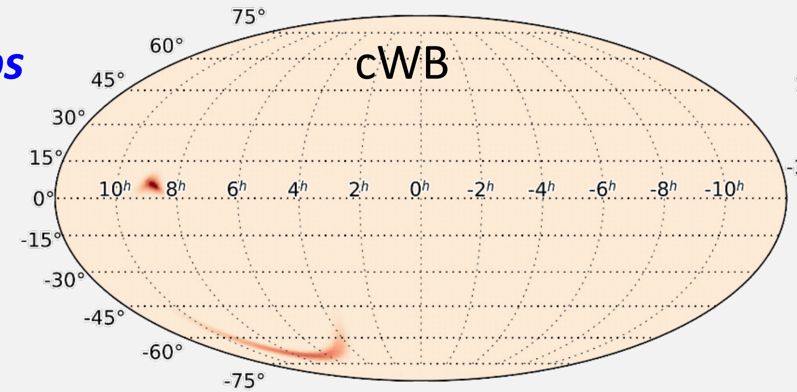
G184098 is an unvetted event of interest, as the false alarm rate (FAR) determined by the online analysis would have passed our stated alert threshold of ~1/month. The event's properties can be found at this URL: https://gracedb.ligo.org/events/G184098
…

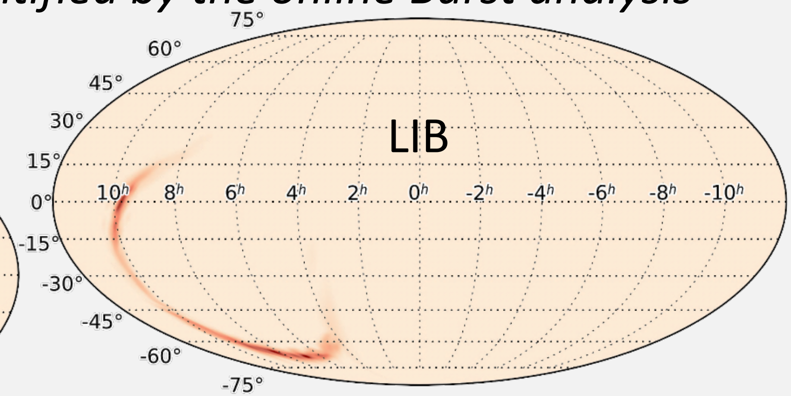
Now archived publicly at http://gcn.gsfc.nasa.gov/other/G184098.gcn3

GW150914 – What LIGO/Virgo Sent to Partners

- **16 Sept 05:39** ***UTC*** *notification about the trigger identified by the online Burst analysis during ER8 (GCN 18330)*

Burst sky maps



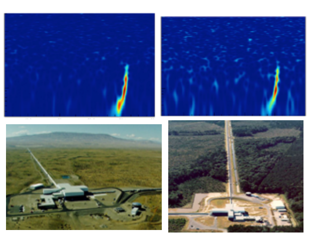


Event time *2015-09-14 09:50:45 UTC* ***FAR*** *1.178e-08 Hz 1/2.7 yr*

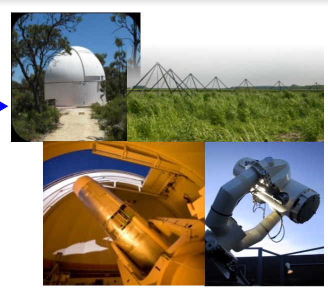
The 50% credible region spans about 200 deg^2 and the 90% region about 750 deg^2

- **03 Oct 2015** *update → waveform reconstruction appears consistent with expectations for a* ***binary black hole coalescence*** *(GCN 18388)*

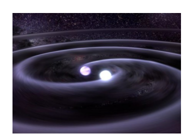
- **11 Jan 2016** *update* → offline calibration and re-analysis ***FAR < 1/100 yr*** *(GCN 18851)*
- **13 Jan** *update* → **Refined localizations** from CBC parameter estimation *(GCN 18858)*



2 days



19 days



4 months