LIGO Update and Future Prospects

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Astronomy and Astrophysics Advisory Committee
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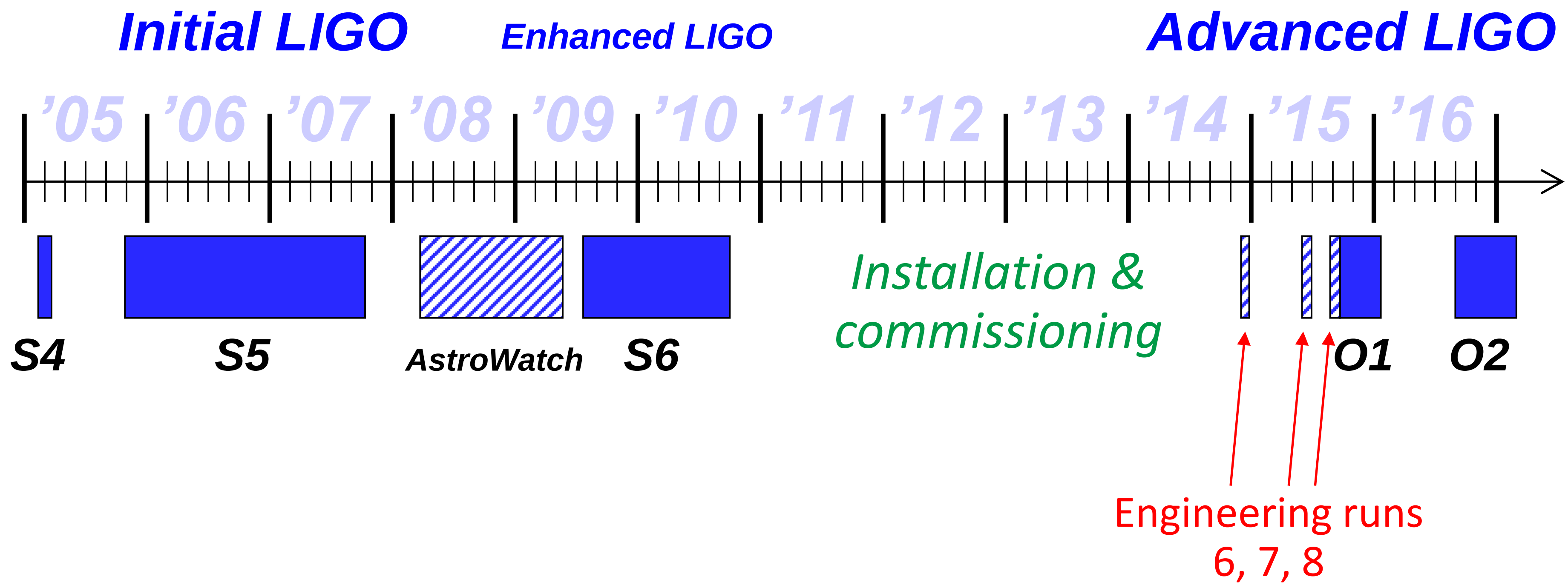
LIGO-G1600335-v1

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

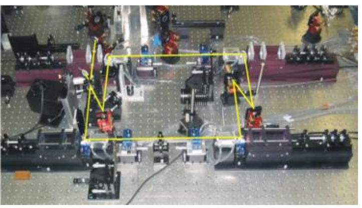
Summer 2015: Out of the "Dark Ages"

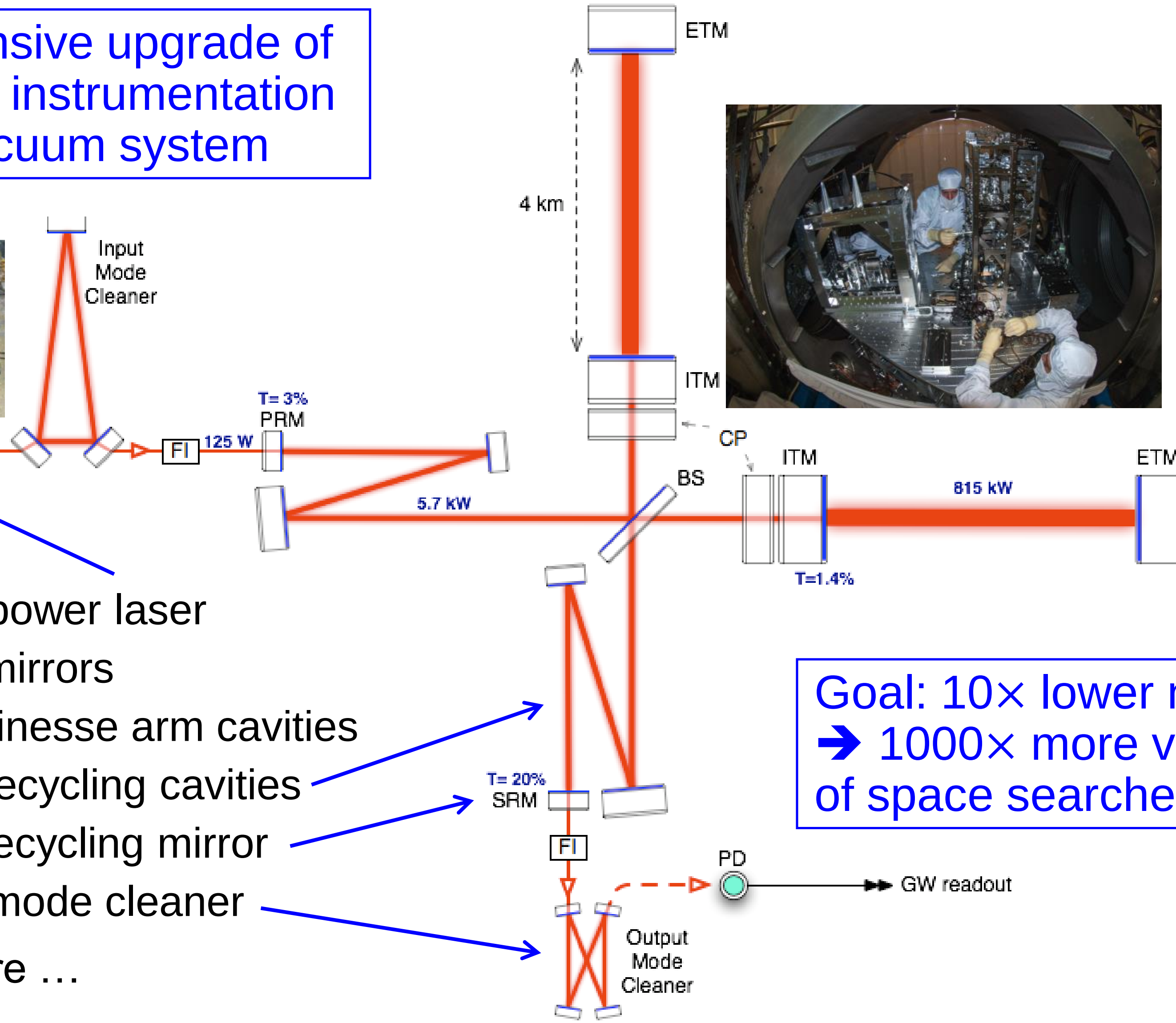
Focus: Transition the LIGO gravitational wave detectors back to observing operations after a 5-year shutdown to carry out the Advanced LIGO upgrade project

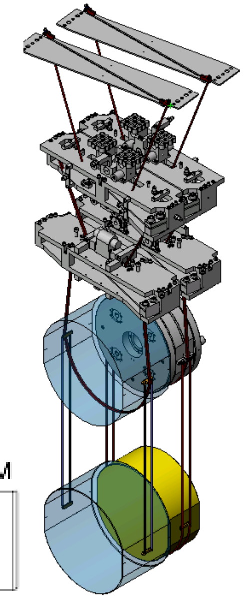


Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system





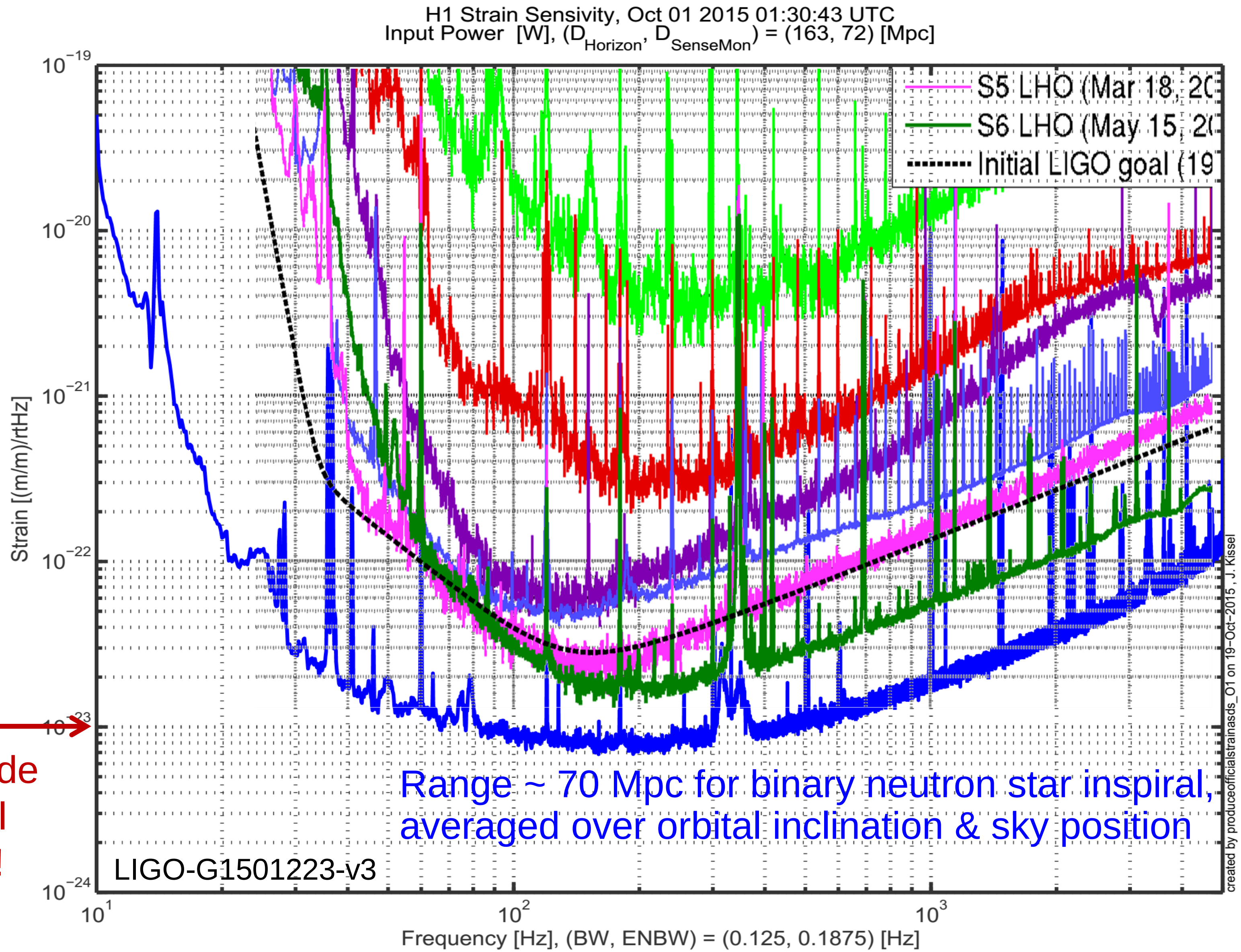


Improvements

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

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

LIGO GW Strain Sensitivity for O1



10^{-23} amplitude spectral density!

Scrambling in September

Both LIGO detectors were operating pretty well by late August, when Engineering Run 8 began

Observing run O1 was scheduled to begin on Sept 14 at 15:00 UTC

Still lots of details to transition to observing:

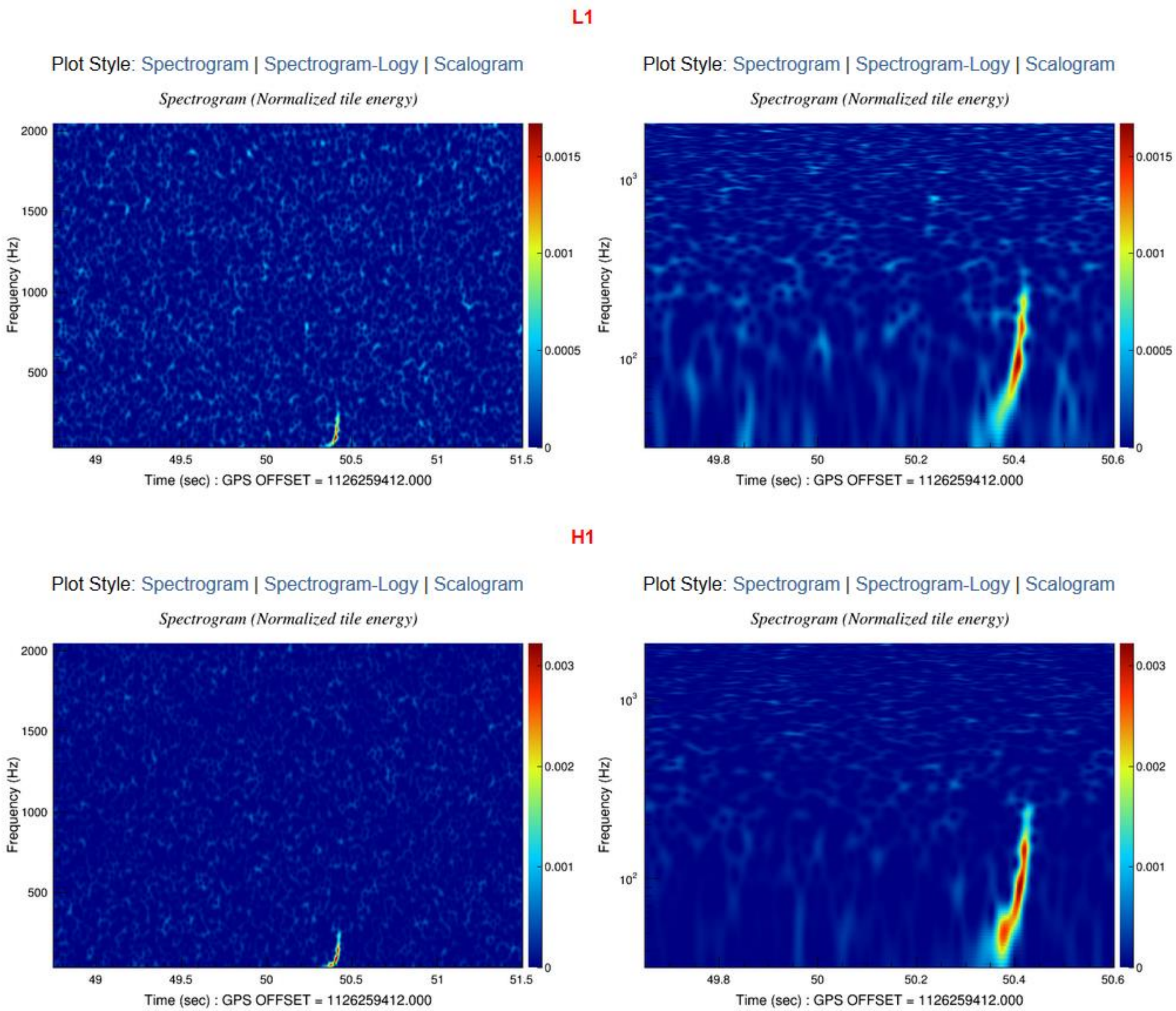
- Calibration studies
- Real-time $h(t)$ data stream production
- Hardware signal injection tests
- Low-latency data analysis automation and testing
- Event candidate alerts and rapid response procedures
- Environmental noise coupling studies

On Sept 11, start of O1 was delayed to Sept 18

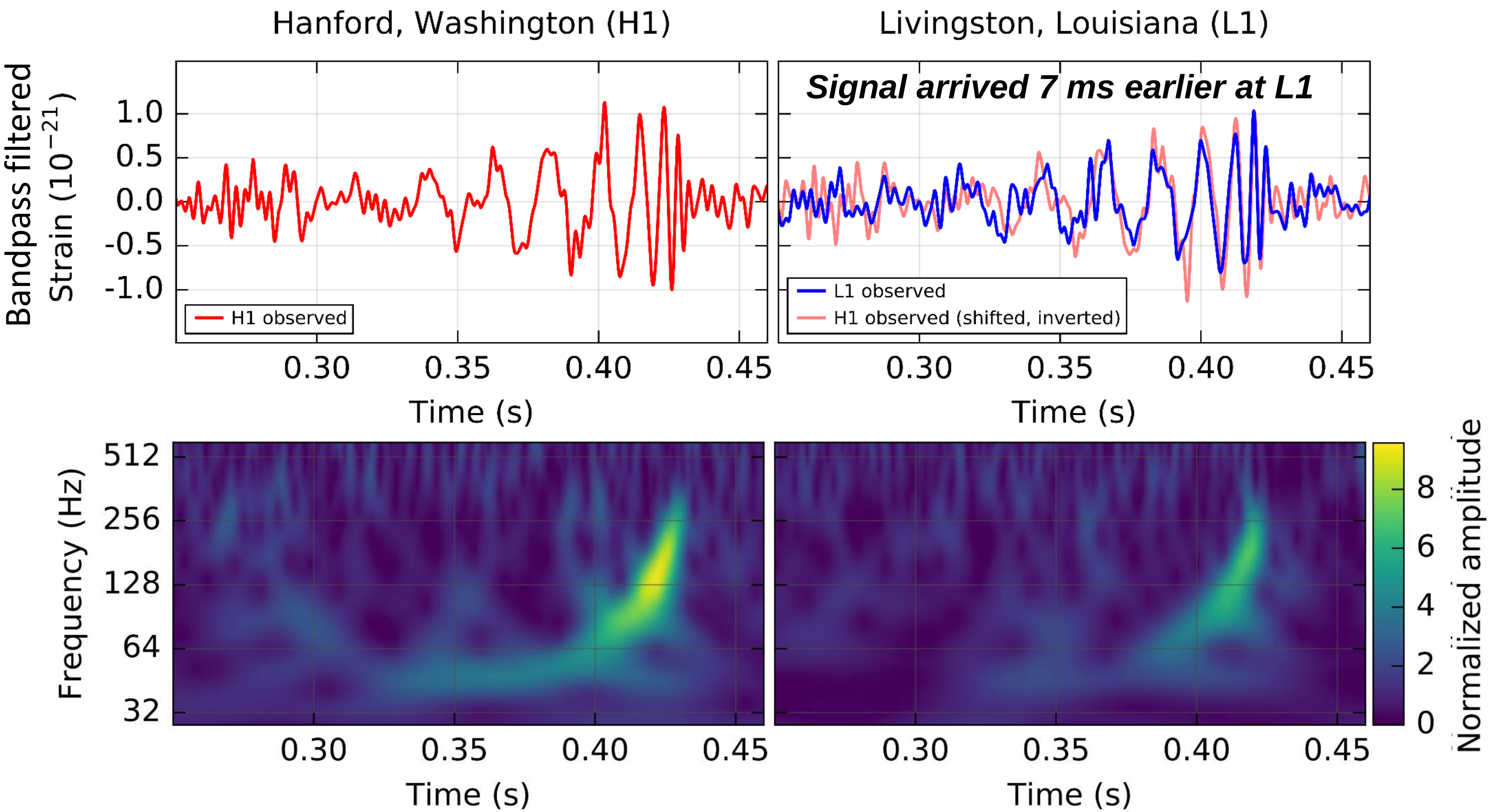
Calibration stable and well-measured by Sept 12, still working on some of the other things…

Event Candidate on Sept. 14 !

Identified within minutes by the Coherent WaveBurst algorithm

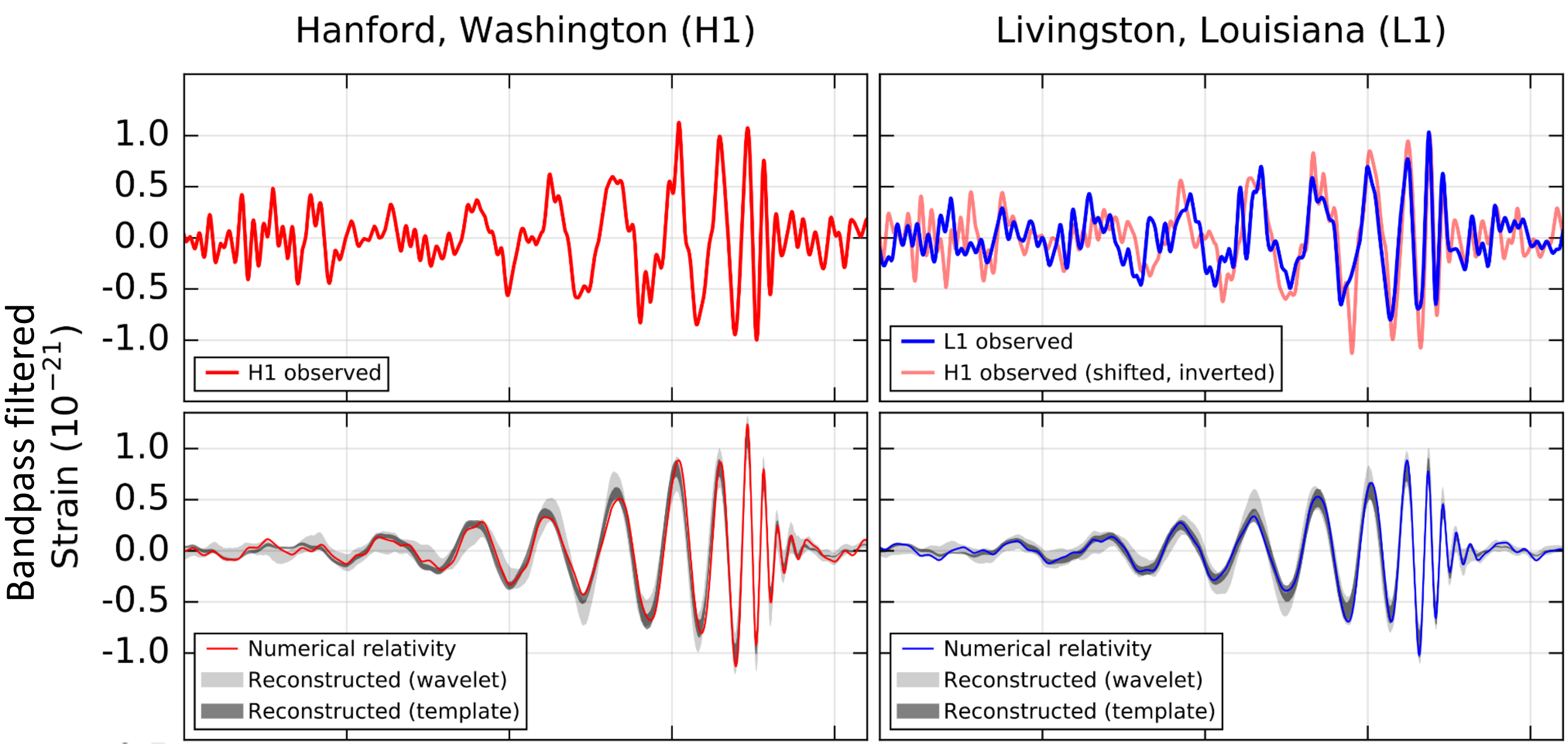


The Actual Waveforms



Looks like a Binary Black Hole Merger!

Matches well to BBH template with same filtering



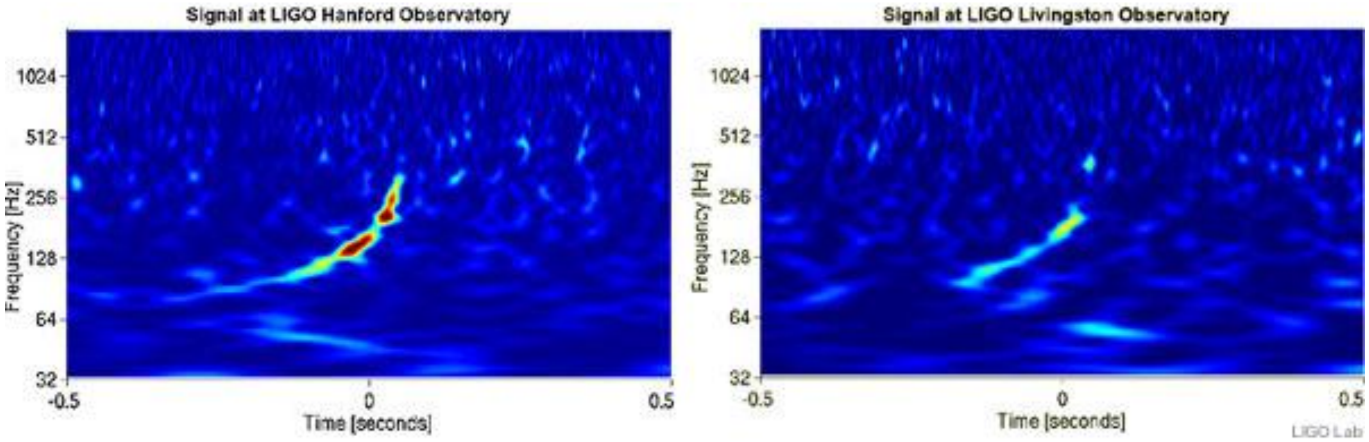
Could it be a blind injection?

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 !

Alerted observing partners

Had made prior arrangements with 62 teams of astronomers using a wide variety of instruments (gamma-ray, X-ray, optical, IR, radio)

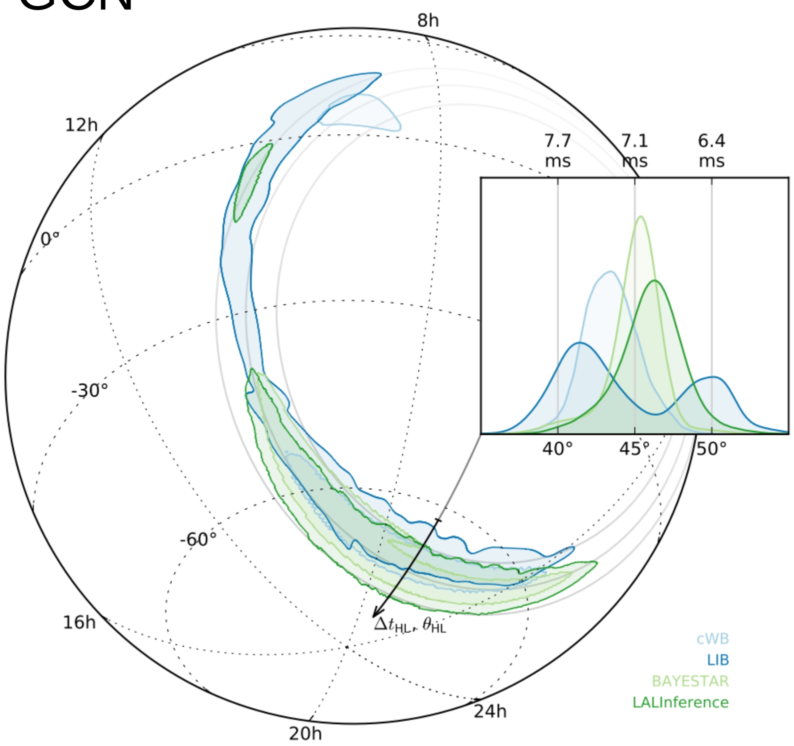
Developed software to rapidly select promising event candidates and send alerts over a private channel of the GCN

But that software wasn't fully set up yet !

Manually prepared and sent out an alert, ~44 hours after the event

Many observations were made, and are being reported separately by the observers

Fermi/GBM team have reported a weak *potential* counterpart (arXiv:1602.03920)



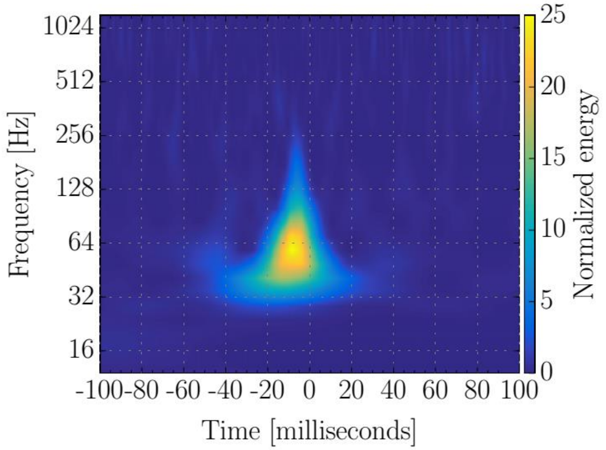
From https://dcc.ligo.org/P1500227/public

Could it be an instrumental noise artifact?

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

There are glitches in the data, but not like The Event

- Some suppressed with data quality cuts on monitoring channels
- Still have "blip transients" with unknown origin



Also checked for possible sources of correlated noise in the two detectors

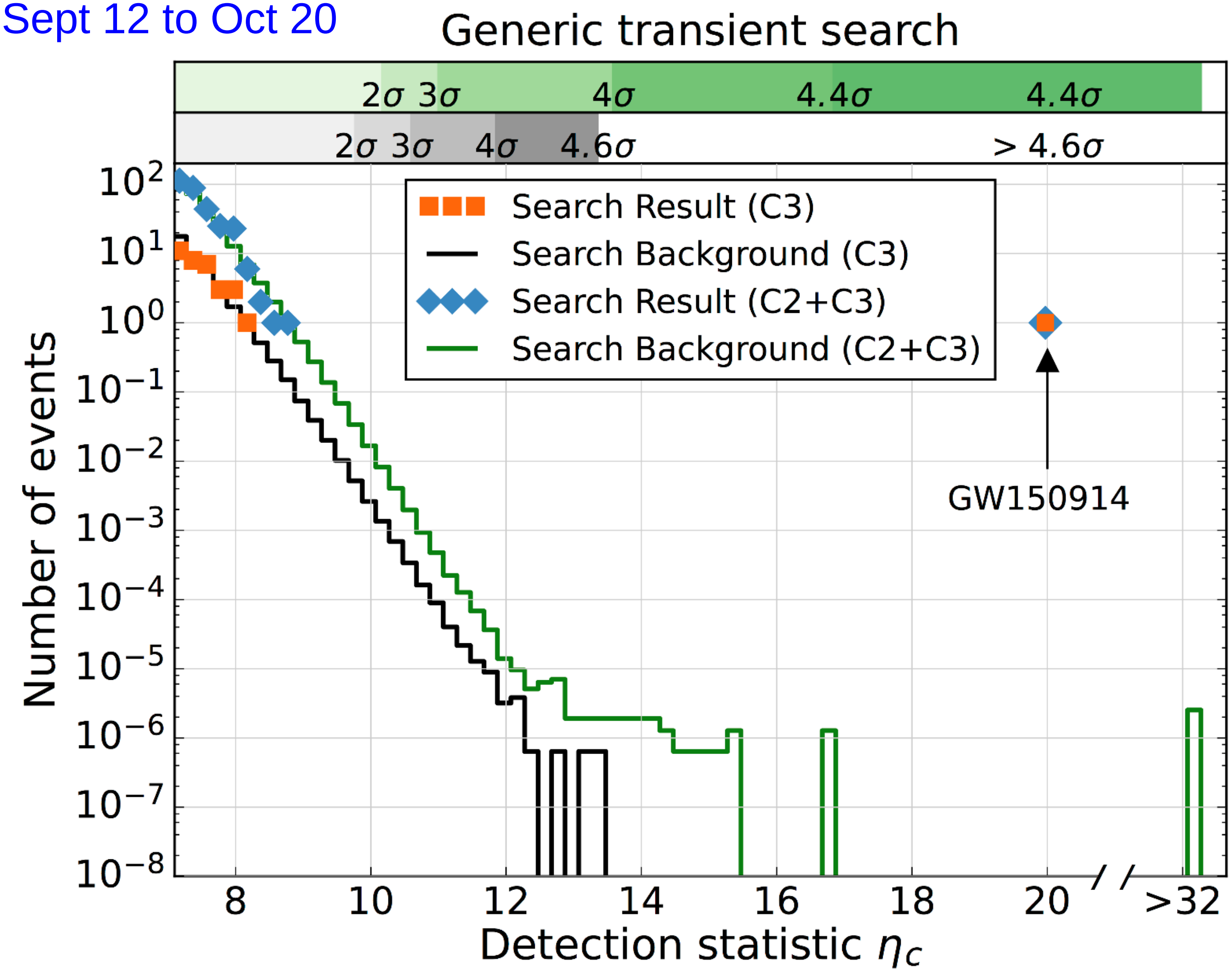
We can estimate the background (from random false coincidences) by analyzing time-shifted data

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

➔ Froze detector configuration, curtailed non-critical activities

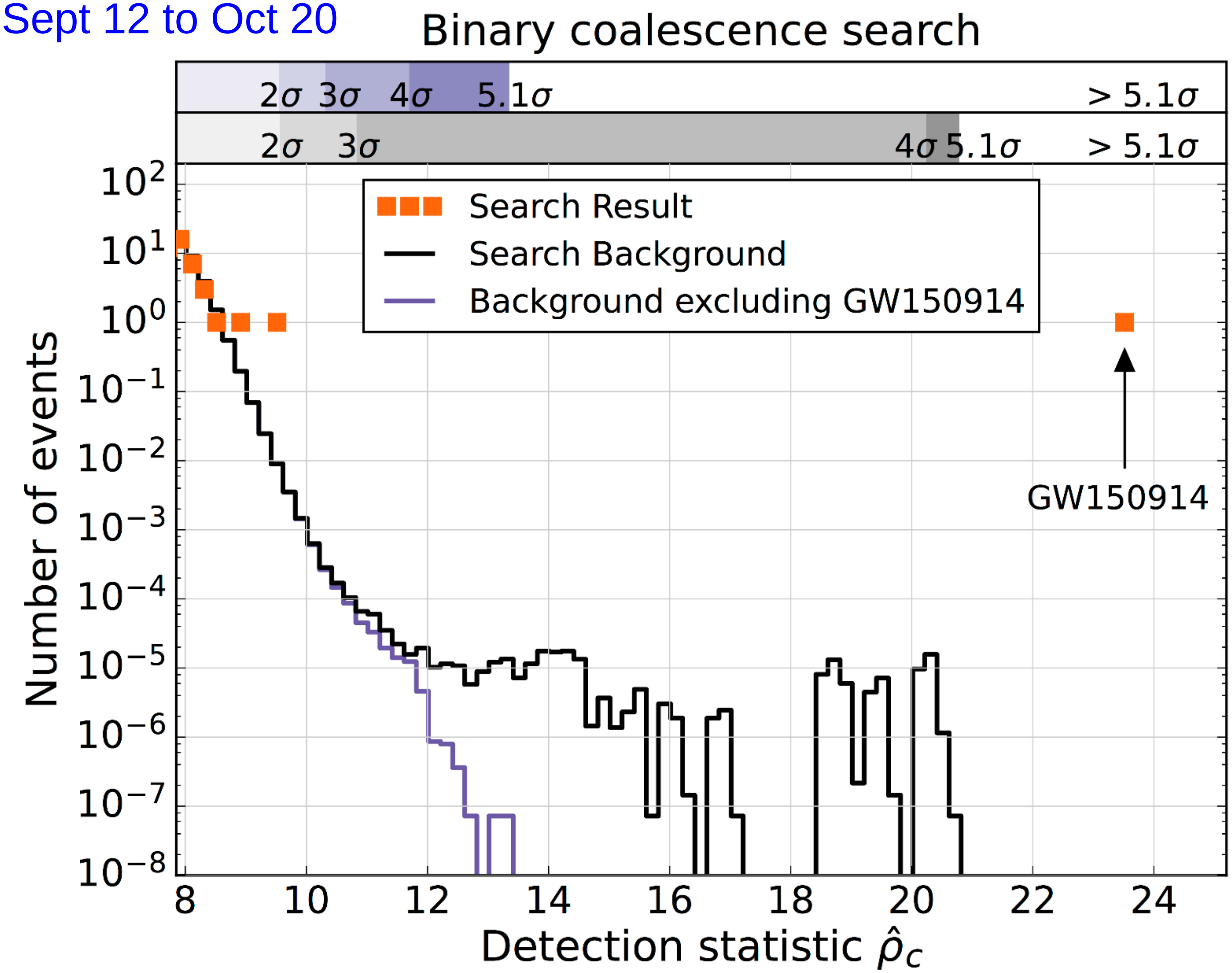
Final Analysis – Generic Transient Search

Data set: Sept 12 to Oct 20

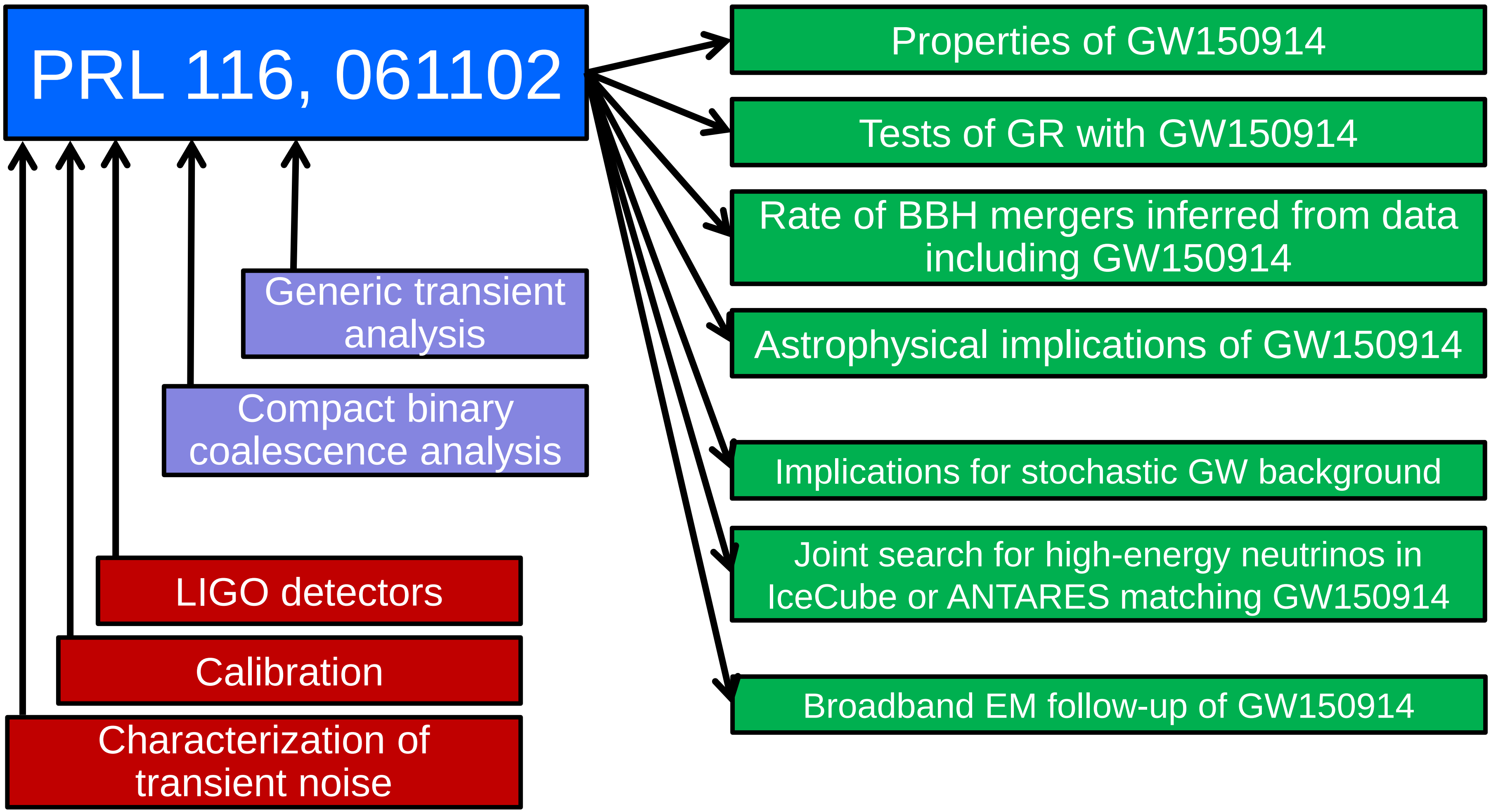


Final Analysis – Binary Coalescence Search

Data set: Sept 12 to Oct 20



Papers About GW150914

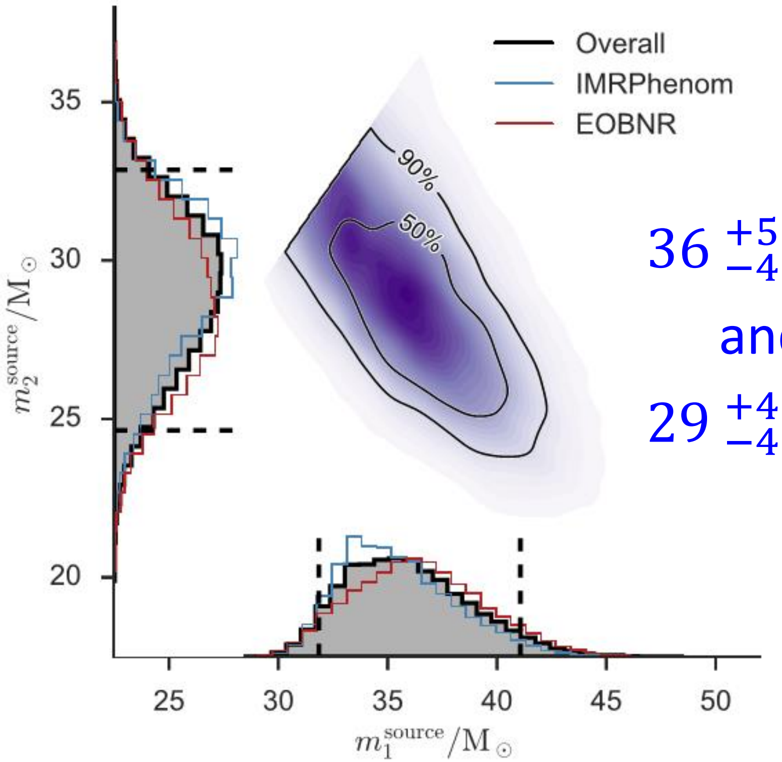


Available at https://papers.ligo.org/

Properties of GW150914

From Bayesian parameter estimation, using 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., arXiv:1602.03840

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

Black Hole Spins

Express as a fraction of the maximum spin permitted by GR: $\frac{Gm^2}{c}$

Spins of initial black holes are hardly constrained

Heavier BH: spin < 0.7

Lighter BH: spin < 0.9

Spin of final black hole: $0.67\,^{+0.05}_{-0.07}$

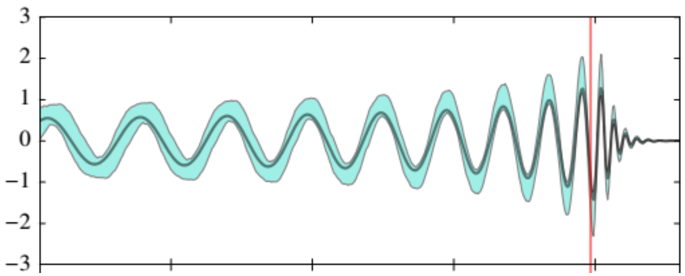
Abbott et al., arXiv:1602.03840

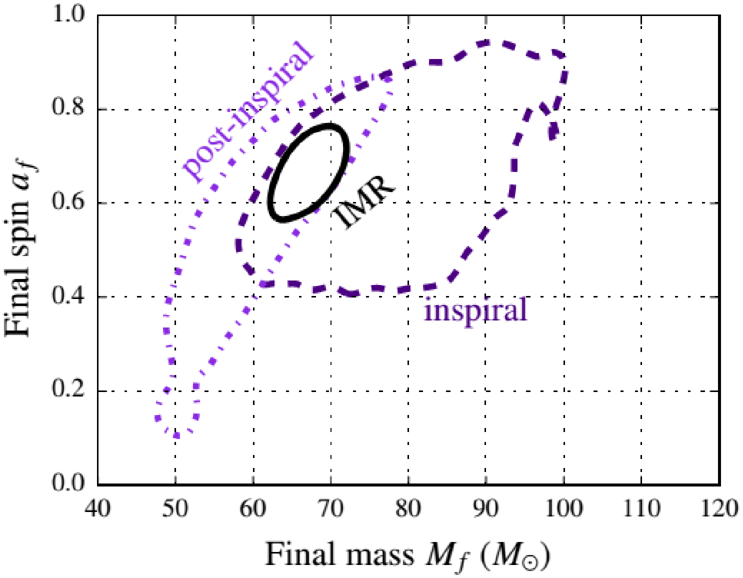
Testing General Relativity

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

Inspiral / merger / ringdown consistency test

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





Pure ringdown of final BH?

Not clear in data, but consistent

Test for deviations from post-Newtonian expansion of waveform

Place upper limit on graviton mass: $m_g < 1.2 \times 10^{-22}\ \mathrm{eV}/c^2$

Abbott et al., arXiv:1602.03841

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

The BBH system could have been formed either by:

A massive binary star system with sequential core-collapses; or

Dynamical formation of a binary from two BHs in a dense star cluster

Can't tell *when* the binary was formed, but we can say that the "kicks" of core-collapse supernova remnants can't be very large

Also can estimate volume rate of mergers

Broad range, depending on assumptions about population: (2 to 400) per year per Gpc^3

Abbott et al., ApJL **818**, L22 (2016) and arXiv:1602.03842

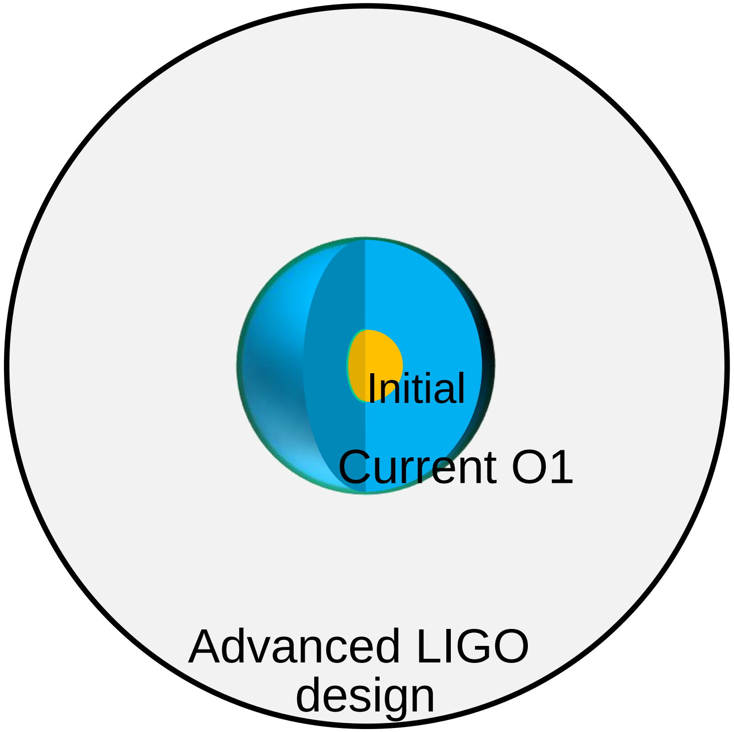
What's Next

Finish analyzing the rest of the O1 data

Complete our full suite of searches for various GW signals

Prepare for the O2 run starting this summer

Should be twice as long, hopefully with somewhat better sensitivity



LIGO / Virgo Observing Run Schedule

Projection made in 2013 (arXiv:1304.0670) still seems on target

Was based on guesses at how fast commissioning would progress

New version published as http://relativity.livingreviews.org/Articles/lrr-2016-1/

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections
		LIGO	Virgo	LIGO	Virgo	
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400

O2 run may begin by late summer 2016

Virgo may join around the end of 2016 (during the O2 run)

Closing Remarks

Decades of patient work and faith finally paid off !

We were lucky that our first detected event was so spectacular

The outpouring of interest from scientists and the public has been wonderful

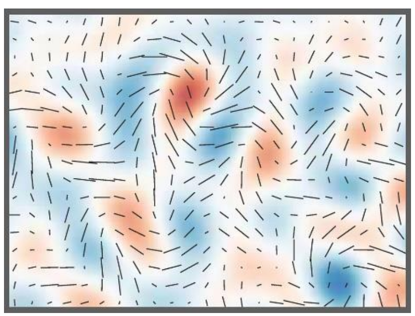
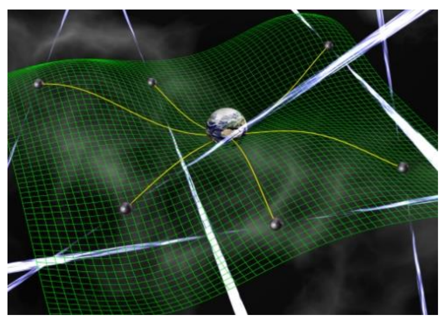
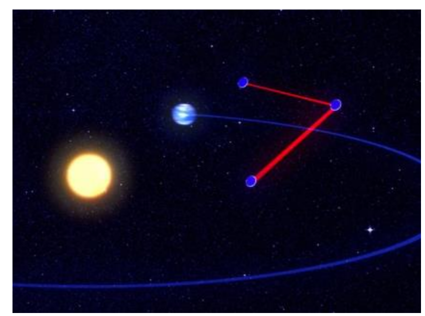
We're now finishing the analysis of O1 and gearing up for O2 – very soon!

How many more BBH mergers will we detect?

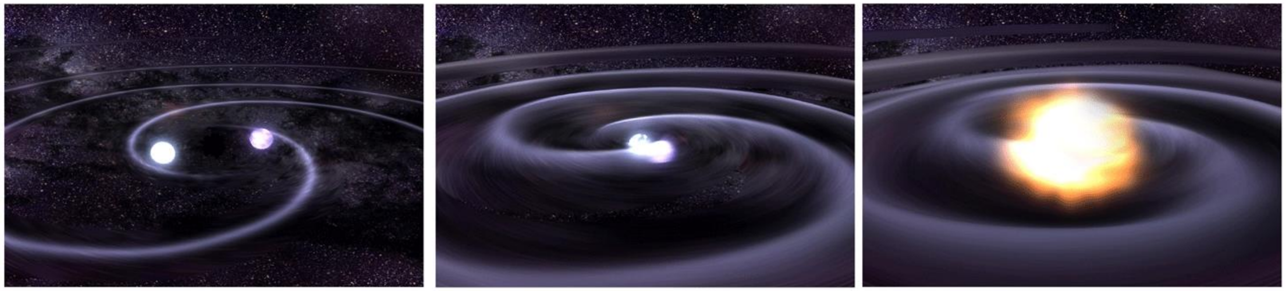
Will we detect NS-NS coalescence events too?
How many? What about other types of signals?

Backup slides

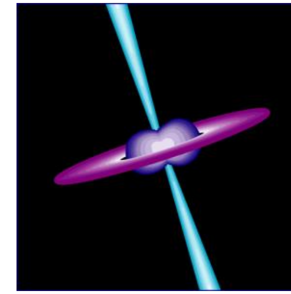
The Wide Spectrum of Gravitational Waves

	$\sim 10^{-17}$ Hz	$\sim 10^{-8}$ Hz	$\sim 10^{-2}$ Hz	~ 100 Hz
Likely sources	**Primordial GWs from inflation**	***Grav. radiation driven Binary Inspiral + Merger*** Supermassive BHs	Massive BHs, extreme mass ratios	Neutron stars, stellar-mass BHs
			Ultra-compact Galactic binaries	**Spinning NSs** **Stellar core collapse**
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

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

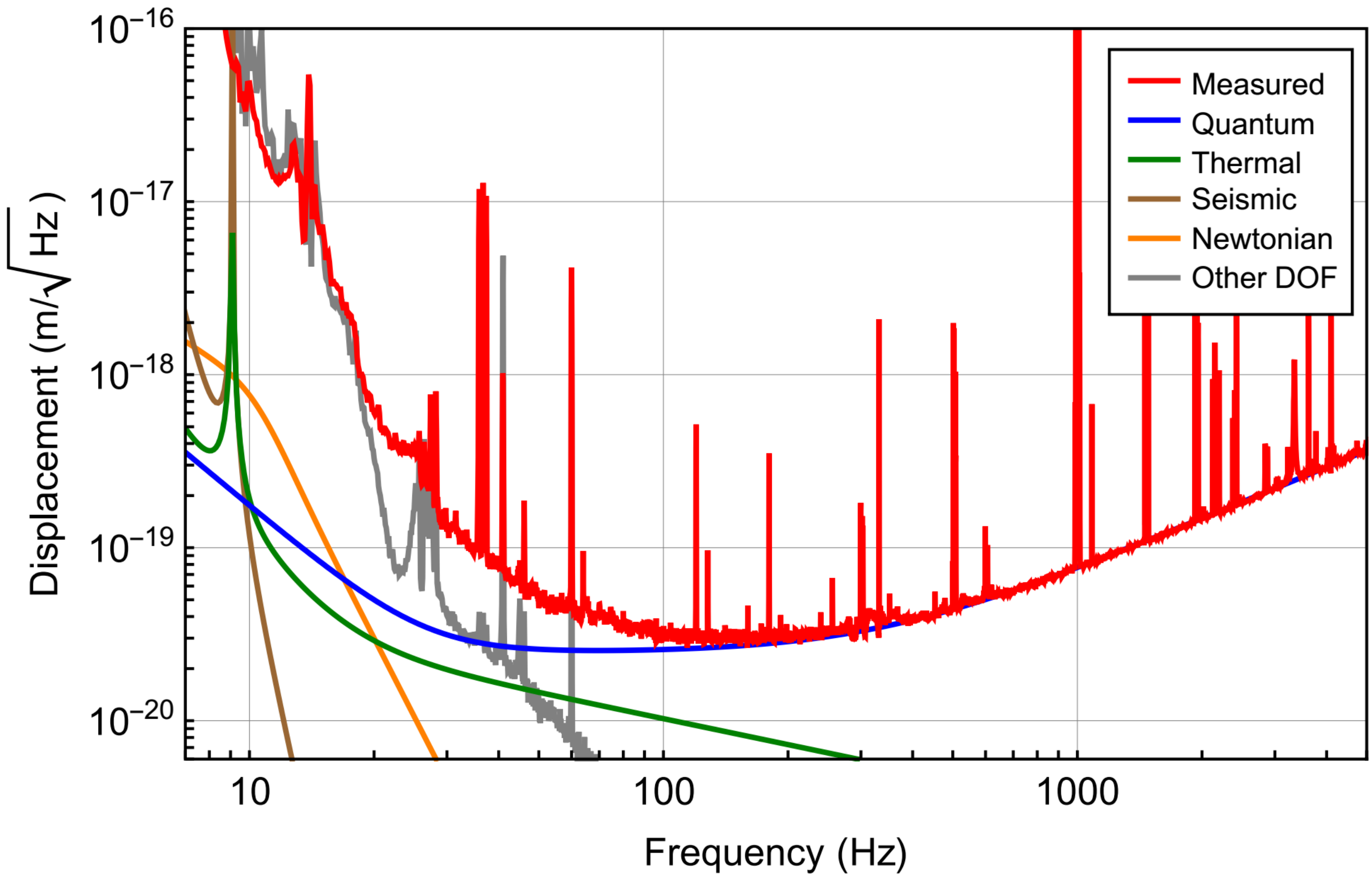
Some opening angles measured, e.g. $16 \pm 10°$ *[Fong et al., arXiv:1509.02922]*

Also may get detectable isotropic emission from nearby GRBs, such as infrared "kilonova" peak after several days, *[e.g. Barnes & Kasen, ApJ 775, 18]* seen for GRB 130603B? *[Berger et al., ApJ 765, 121; Tanvir et al., Nature 500, 547]*

Possible to detect X-ray afterglow from a somewhat off-axis nearby GRB ?

Exciting possibility to confirm the merger-GRB association!

LIGO Detector Noise Components



From Abbott et al., arXiv:1602.03838

Effect of Data Quality Cuts

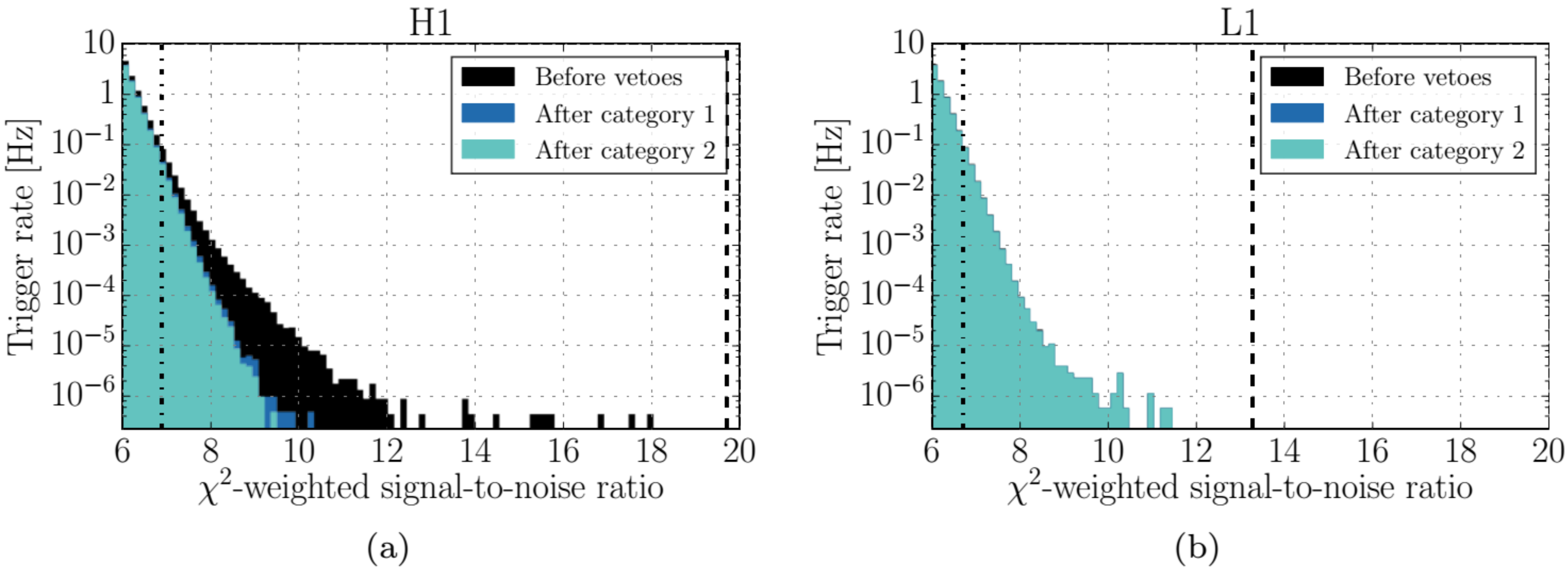
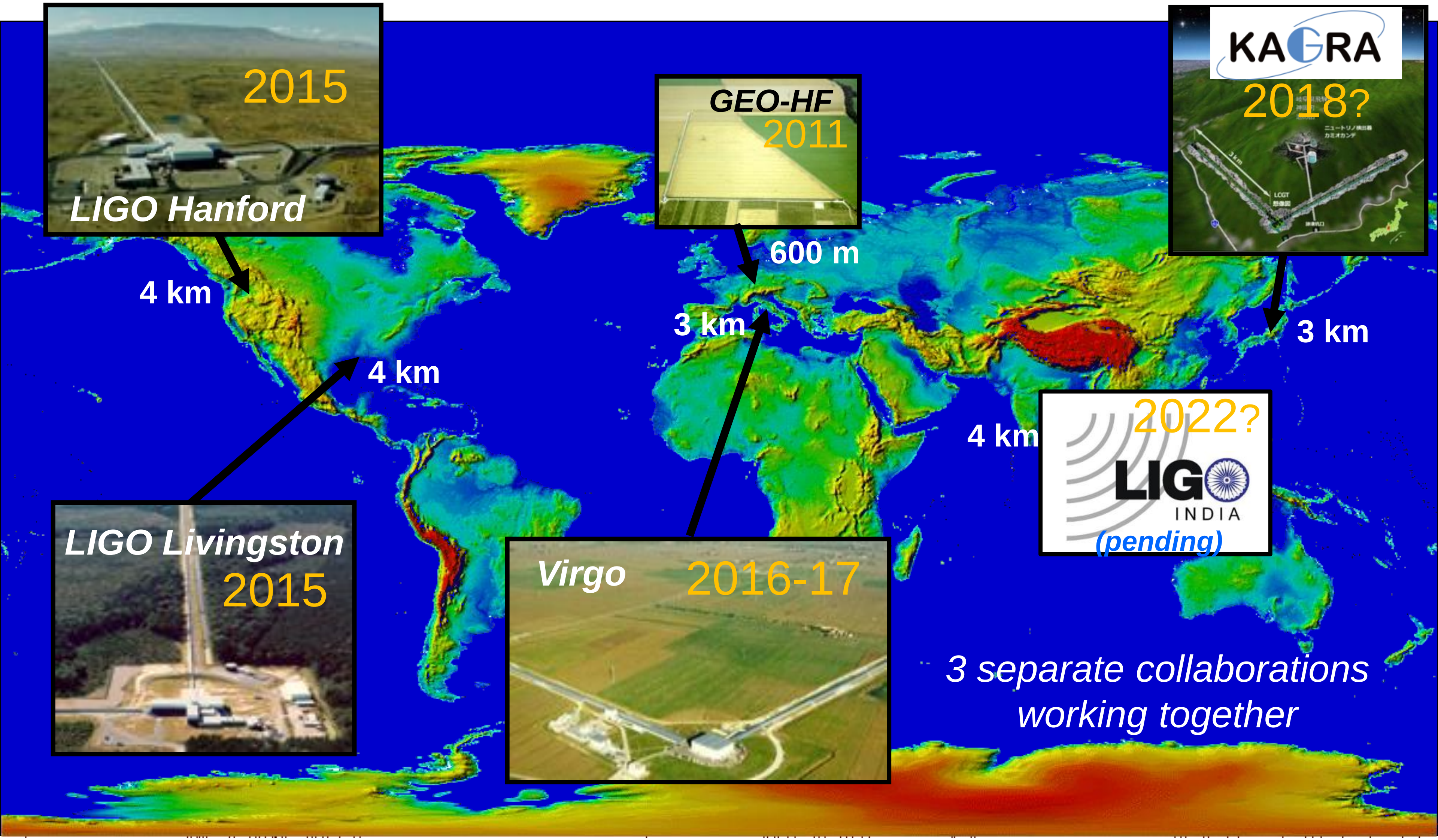


Figure 7: The impact of data-quality vetoes on the CBC background trigger distribution for (a) LIGO-Hanford and (b) LIGO-Livingston. The single-detector χ^2-weighted SNR of GW150914 is indicated for each detector with a dashed line (19.7 for Hanford and 13.3 for Livingston), and for event LVT151012 with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

From Abbott et al., arXiv:1602.03844

Advanced GW Detector Network: Under Construction → Operating

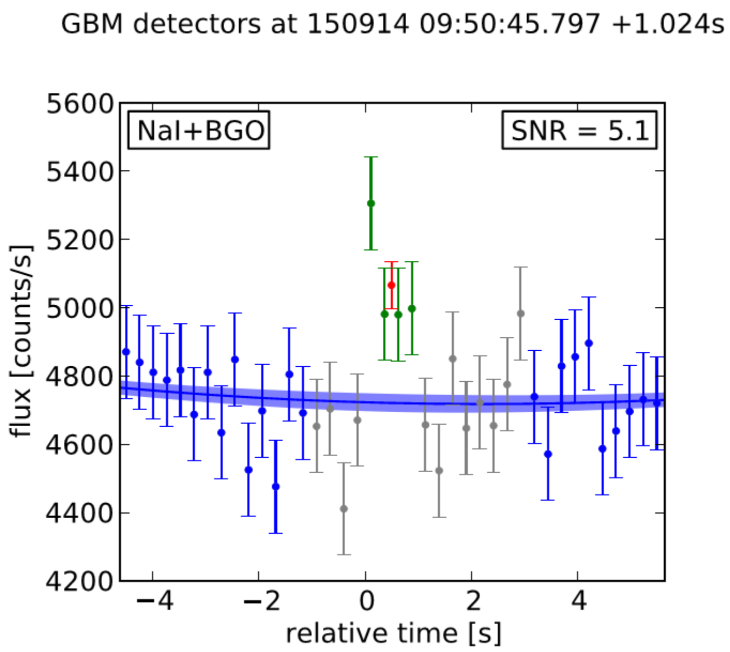


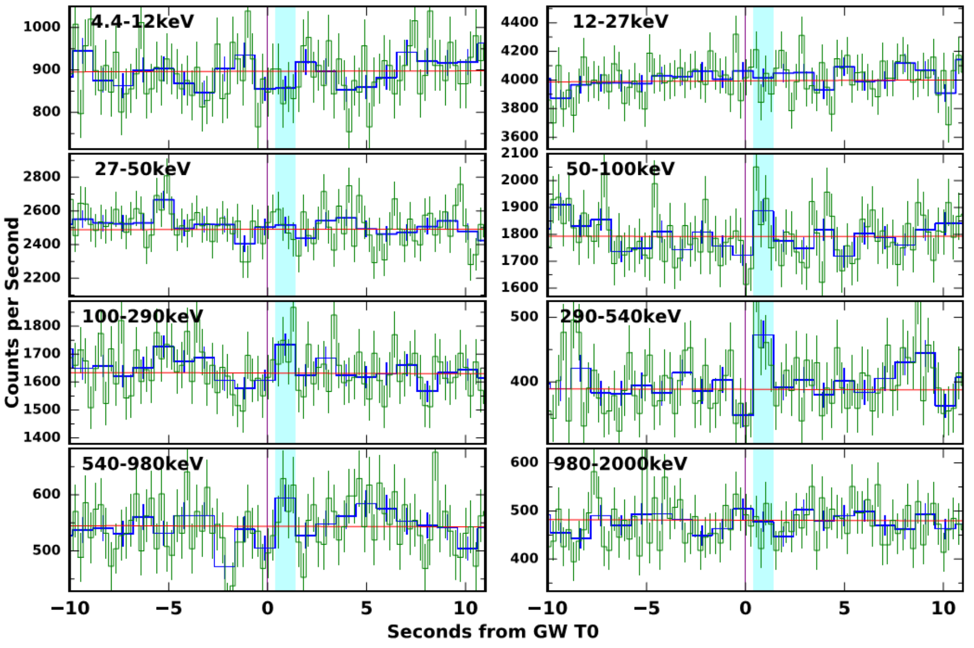
Possible Gamma-ray Counterpart??

A weak signal was identified in data from Fermi/GBM about 0.4 second after the time of GW150914

Connaughton et al., arXiv:1602.03920

Post-trials false alarm prob ~ 0.0022





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