The Remarkable Story of LIGO’s Detection of Gravitational Waves

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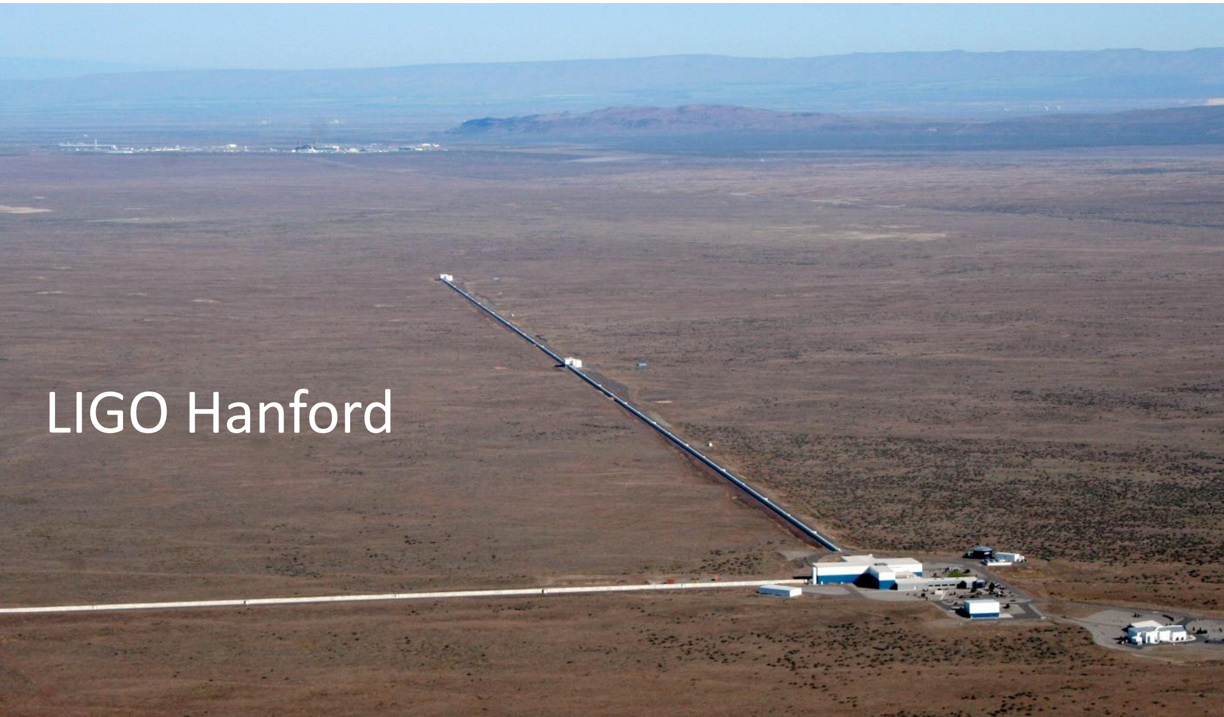
University of Maryland Physics Colloquium
February 23, 2016

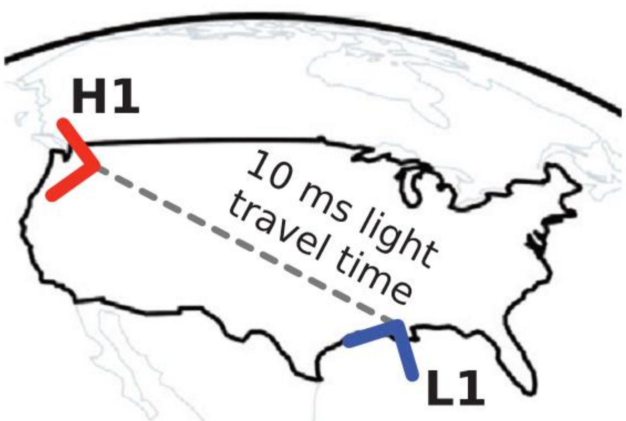
LIGO-G1600320-v2

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

The LIGO* Observatories

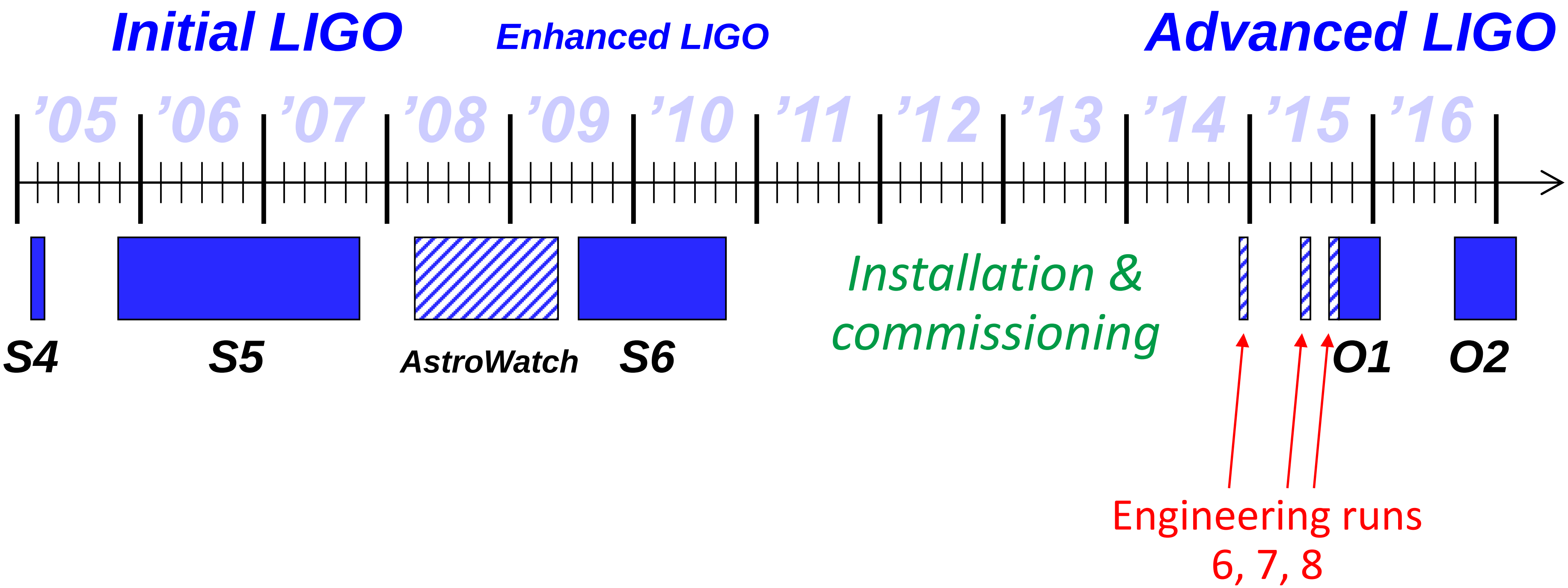
* LIGO = Laser Interferometer Gravitational-wave Observatory





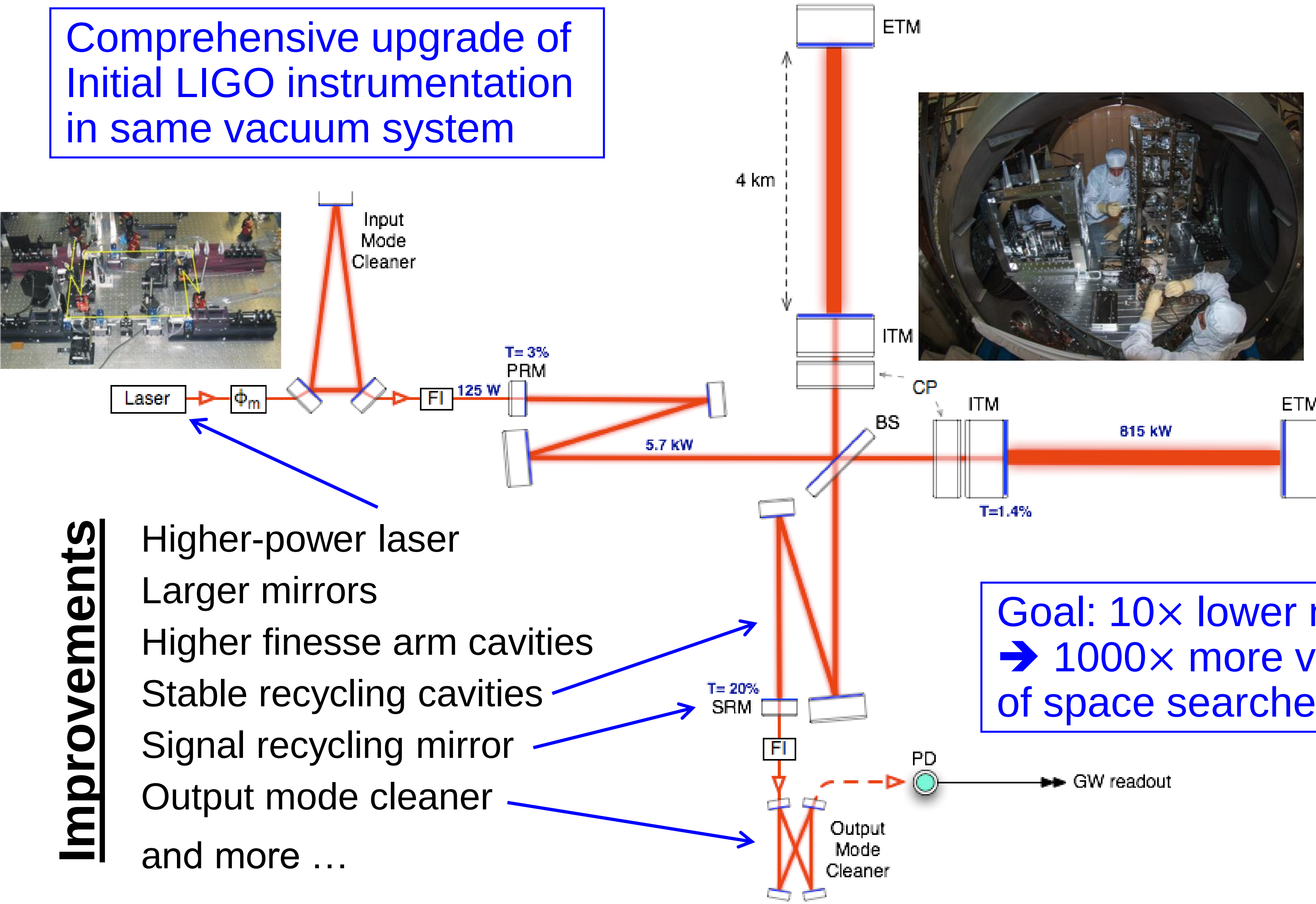
Summer 2015: Out of the "Dark Ages"

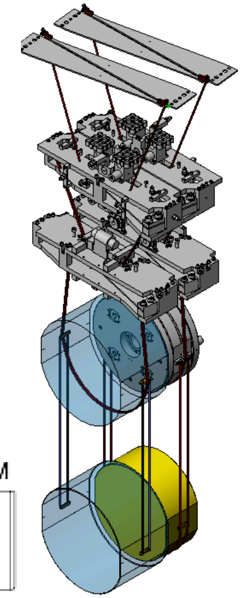
Focus: Transition the LIGO gravitational wave detectors back to observing operations after a 5-year shutdown to carry out the Advanced LIGO upgrade project



Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system



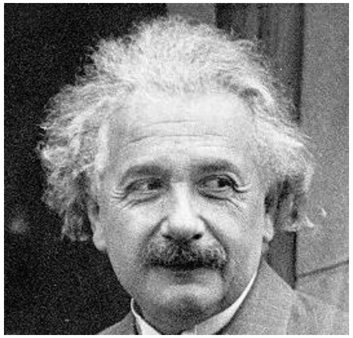


Improvements

- 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

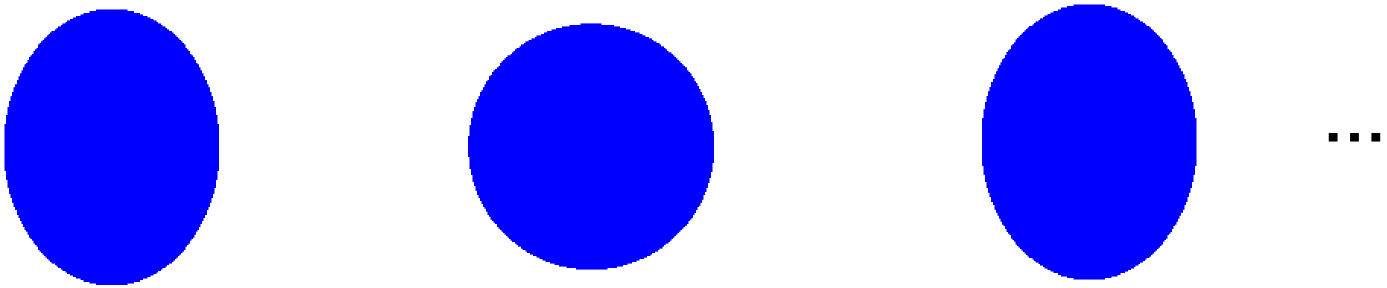
Gravitational Waves Primer



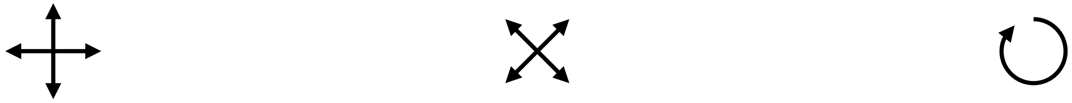
The Einstein field equations have wave solutions !

- ► Sourced by changing mass quadrupole (or higher) moment
- ► Waves travel away from the source at the speed of light
- ► Are variations in the spacetime metric —
  i.e., the effective distance between locally inertial points

Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* space and anything in it



"Plus" polarization — "Cross" polarization — Circular polarization



Gravitational Waves in Action

Two massive, compact objects in a tight orbit

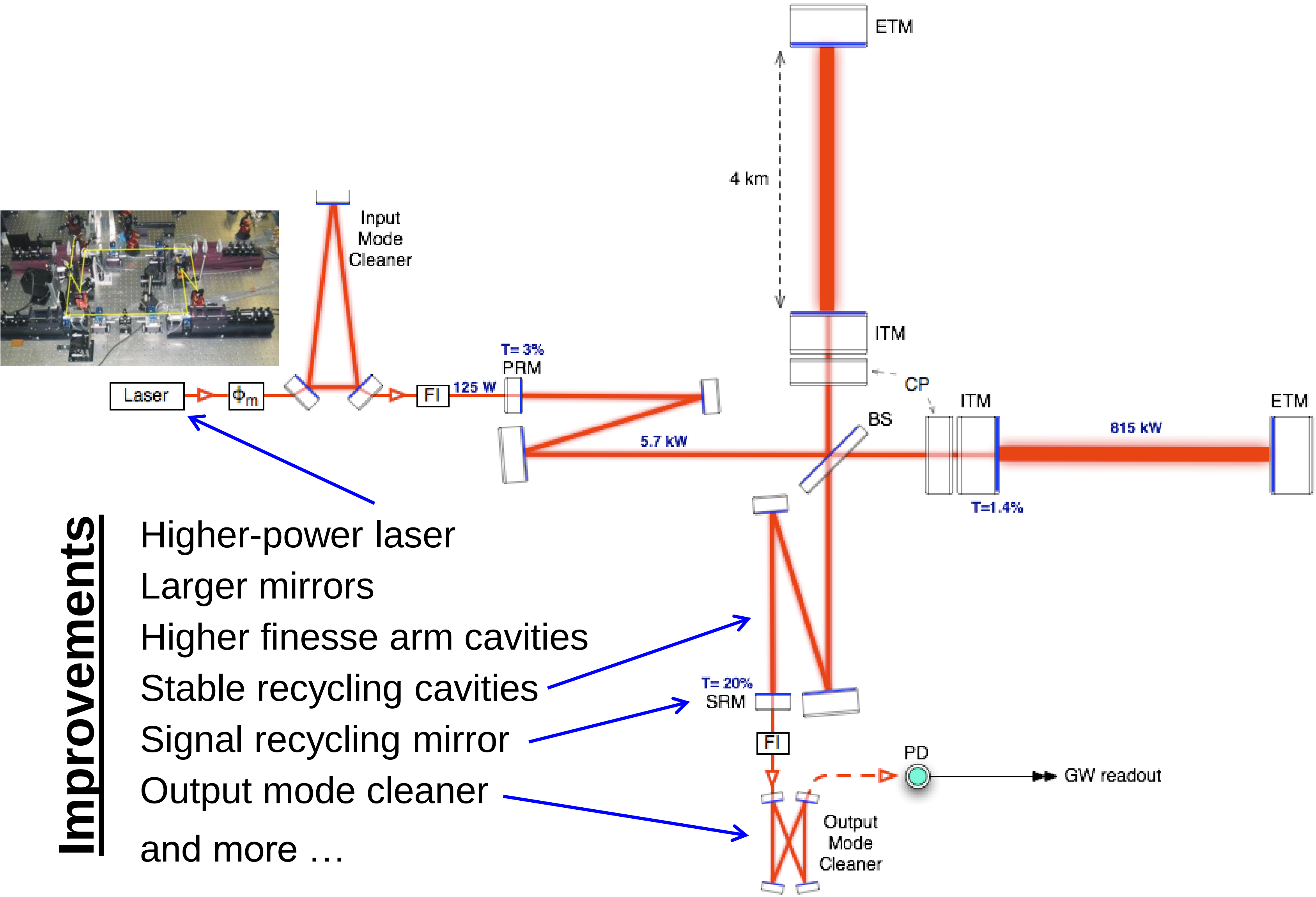
(Neutron stars or black holes)

deform space (and any object in it) with a frequency which is twice the orbital frequency

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

h is inversely proportional to the distance from the source

Advanced LIGO Optical Layout



Improvements

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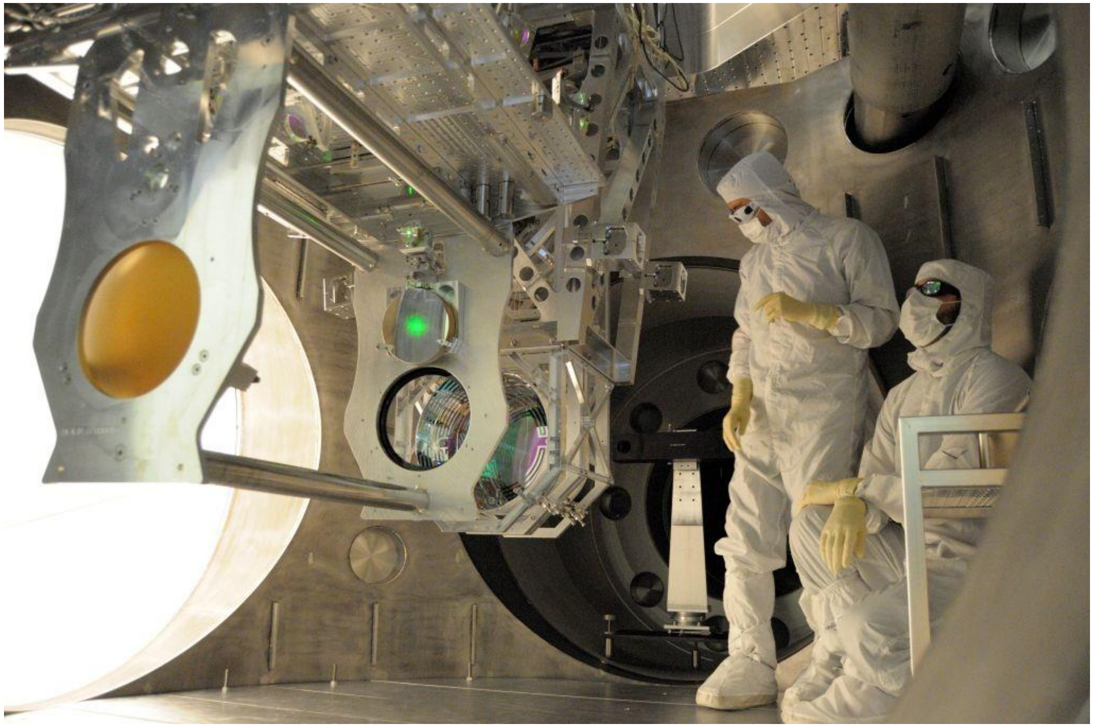
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and more …

Advanced LIGO Installation

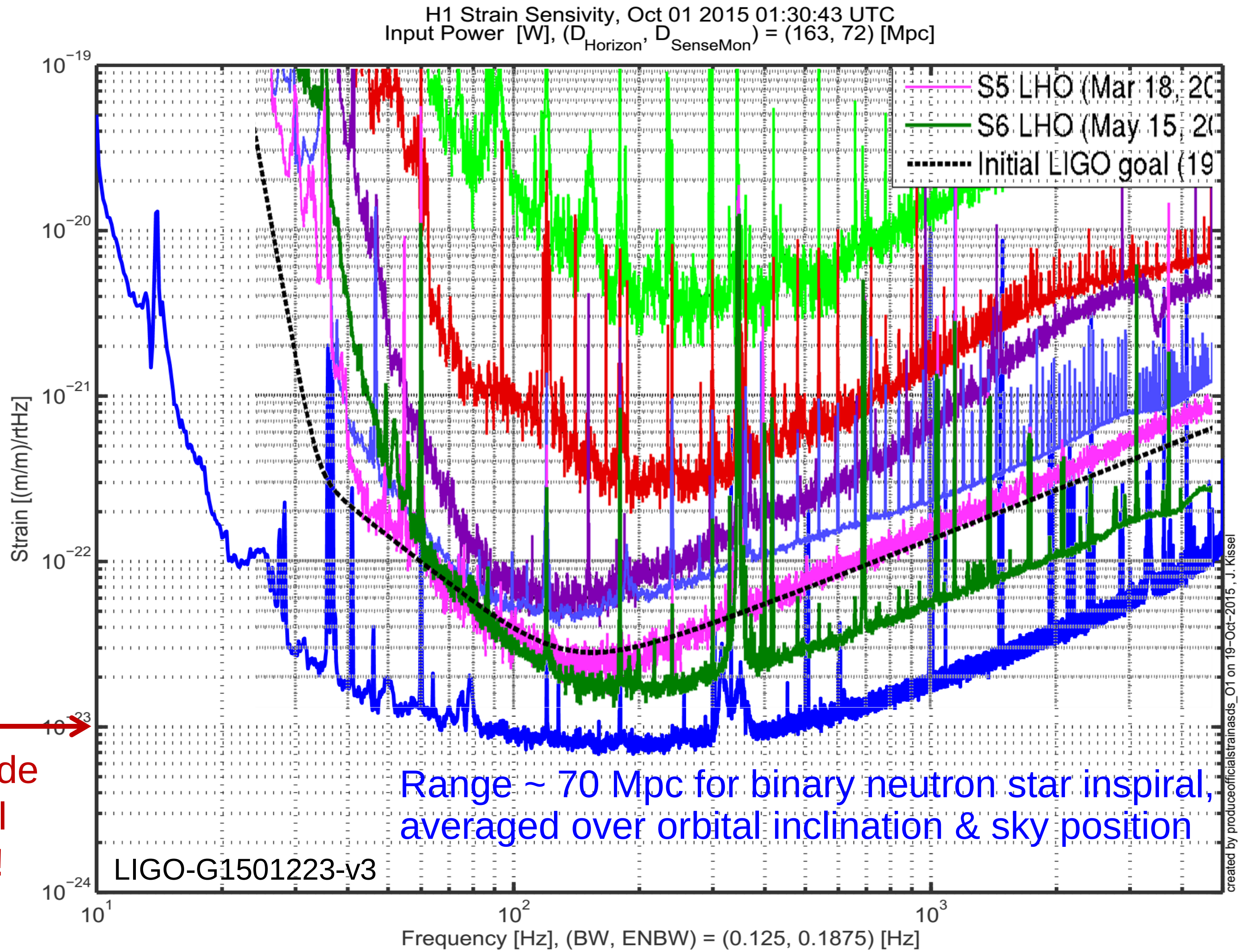
Installation went pretty smoothly at both LIGO observatories

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!

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…

Email on Monday morning, Sept 14

Date	9/14/2015 6:55 AM EDT
From	Marco Drago
Subject	Very interesting event on ER8

Hi all,
cWB has put on gracedb a very interesting event in the last hour.
https://gracedb.ligo.org/events/view/G184098

This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

Qscan made by Andy:
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/L1_1126259462.3910/
https://ldas-jobs.ligo.caltech.edu/~lundgren/wdq/H1_1126259462.3910/

It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

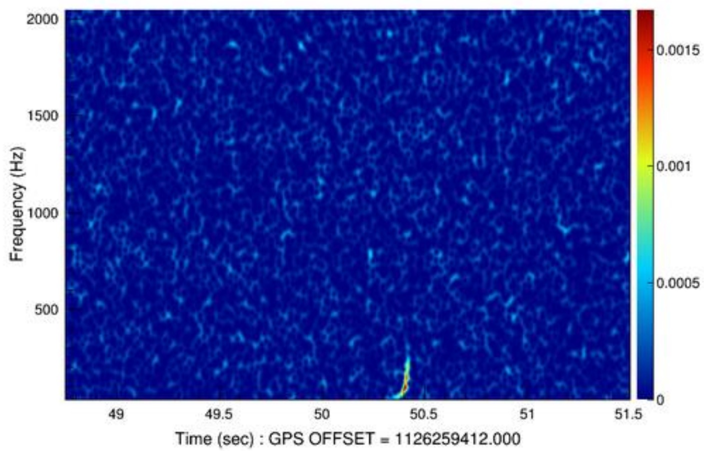
Marco

Coherent WaveBurst Event Display

L1

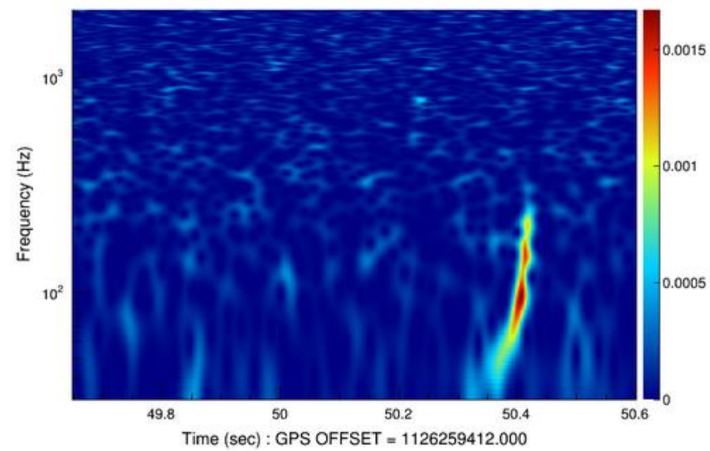
Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

Spectrogram (Normalized tile energy)



Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

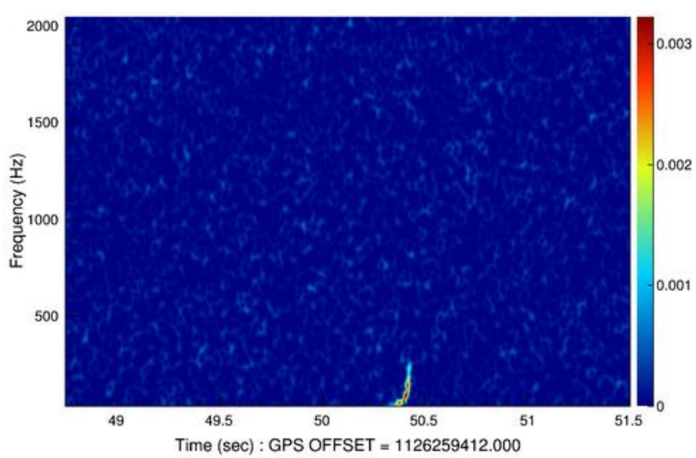
Spectrogram (Normalized tile energy)



H1

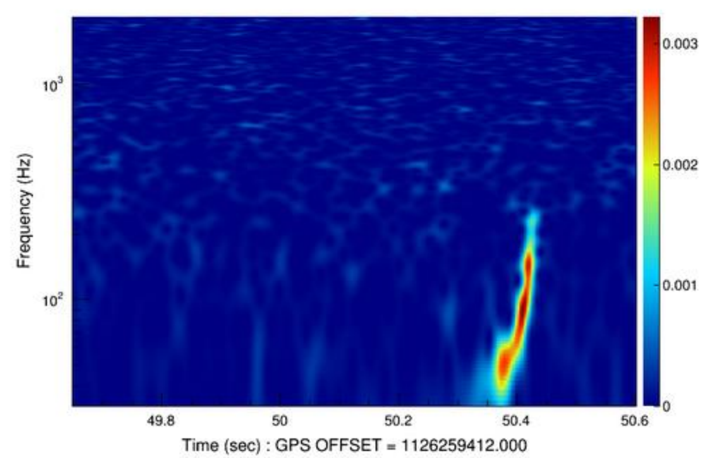
Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

Spectrogram (Normalized tile energy)



Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

Spectrogram (Normalized tile energy)



How we got to September 14, 2015

Early History

Einstein had predicted the existence of gravitational waves beginning with a 1916 paper, and he and others developed the full linearized theory over the following years

Einstein believed that the waves would be far too weak to detect

And, decades later, there was still doubt about whether gravitational waves were physically real, able to carry energy and influence matter

The reality of gravitational waves was finally given a firm footing by Felix Pirani in a talk at the 1957 Chapel Hill Conference

Peter Saulson has observed that **"*there is a very real possibility that the program to build actual detectors of gravitational waves was born at that very moment at the Chapel Hill Conference*"** [1]**,** out of Joseph Weber's discussions with Bondi, Pirani and others

[1] P. Saulson, General Relativity and Gravitation **43**, 3289 (2011)

Joe Weber's Fearless Idea!

Weber constructed resonant "bar" detectors on the UMD campus in the 1960s and collected data to search for GW signals

He even claimed to have detected coincident signals in widely separated bars…
but others could not reproduce that

J. Weber & J. Wheeler, "Reality of the cylindrical gravitational waves of Einstein and Rosen", Rev. Mod. Phys. **29**, 209 (1957)

J. Weber, "Detection and generation of gravitational waves", Phys. Rev. **117**, 306 (1960)

J. Weber, "Evidence for discovery of gravitational radiation", Phys. Rev. Lett. **22**, 1320 (1969)

Pushing the Limits

Resonant bars eventually are limited by thermal noise

Detectors using laser interferometry were suggested in the 1960s

Advantages:

- Broad frequency response
- Different (lower) fundamental noise limits

Initial sketch for a LIGO-like detector:

R. Weiss, "Electromagnetically Coupled Broadband Gravitational Antenna", in MIT Research Lab of Electronics Quarterly Progress Report no. 105, April 1972

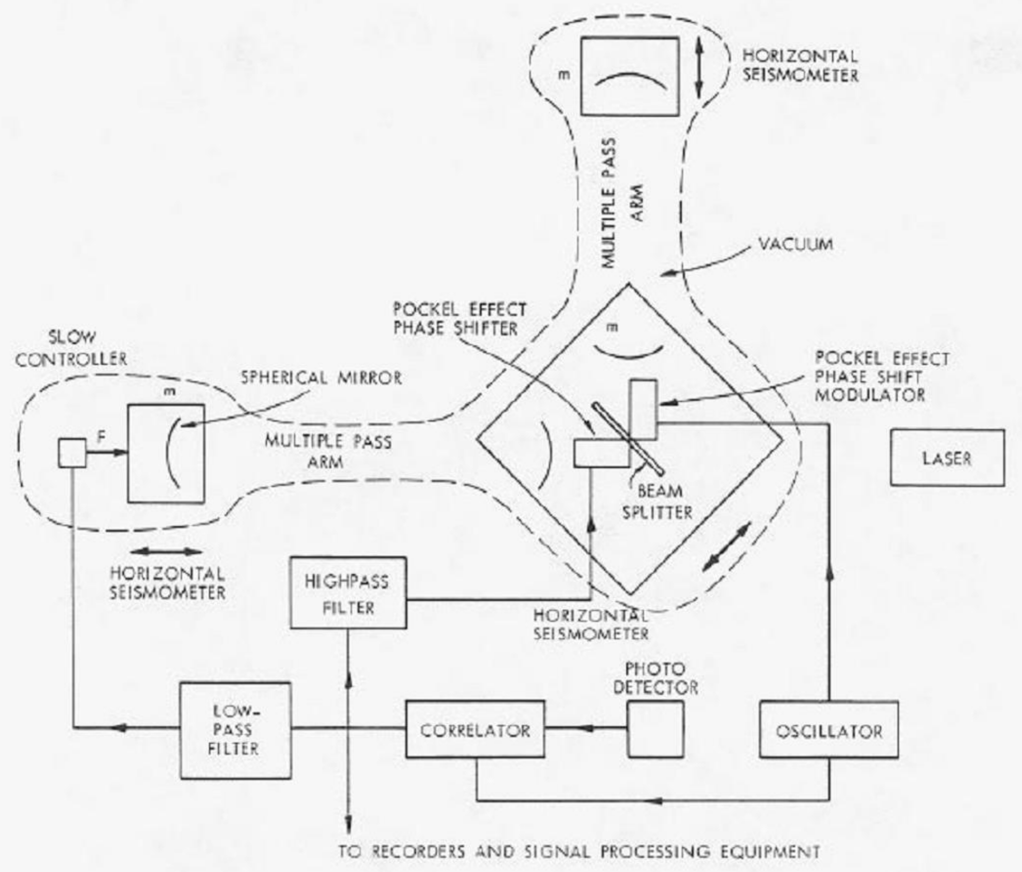


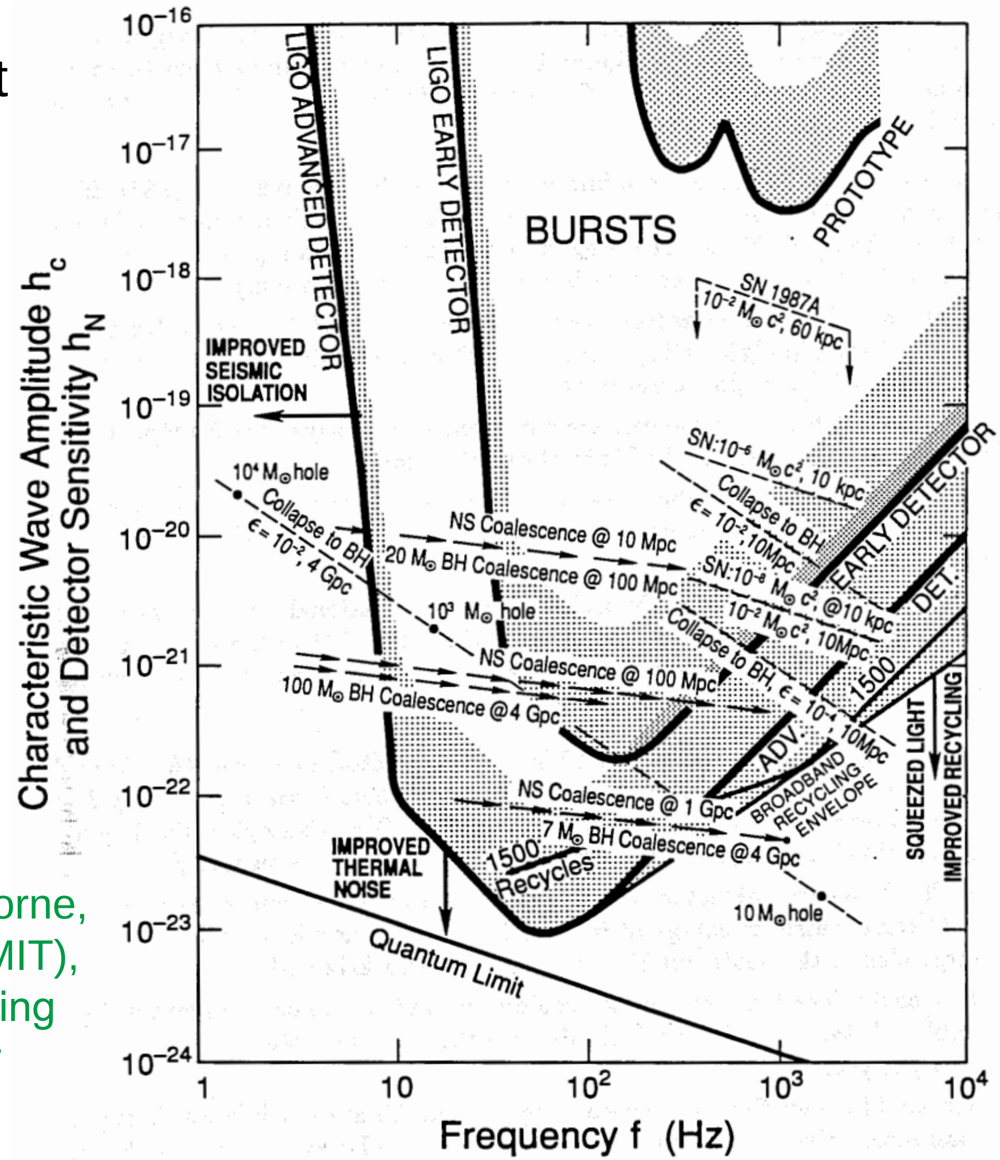
Fig. V-20. Proposed antenna.

Thanks, NSF!

NSF supported early development work, then funded the LIGO construction project beginning in 1992

Also many years of operations & the Advanced LIGO upgrade

LIGO / gravity NSF program officers with UMD connections:
Rich Isaacson,
David Berley, Beverly Berger



R. E. Vogt, R. W. P. Drever, K. S. Thorne, F. J. Raab and R. Weiss (Caltech & MIT), “Construction, operation, and supporting research and development of a Laser Interferometer Gravitational-wave Observatory”, proposal to NSF, 1989

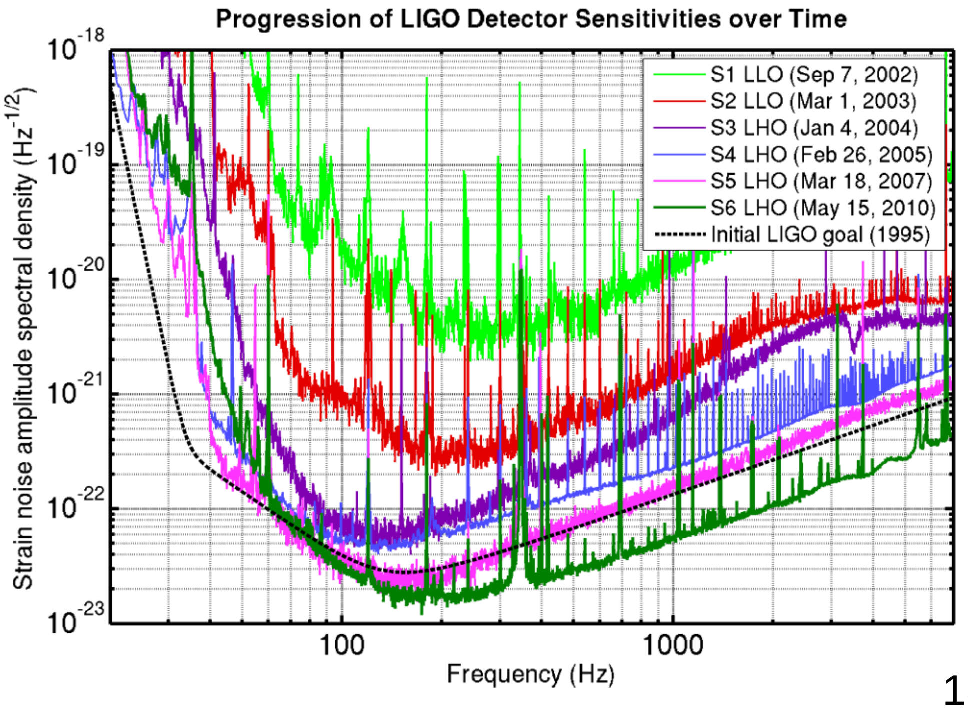
Science from Initial LIGO

~100 papers published by the LIGO Scientific Collaboration

Many meaningful (but generally unsurprising) upper limits

- Rates of binary coalescence events in the nearby universe
- Continuous emission from the Crab Pulsar and other spinning neutron stars
- Limits on stochastic gravitational-wave backgrounds over the sky
- GW emission from GRBs
- And more…

… but no detection of a GW signal, despite reaching sensitivity goal



Estimated Rates of Binary Coalescence

All over the board, really…

"Realistic" (??) estimated rates

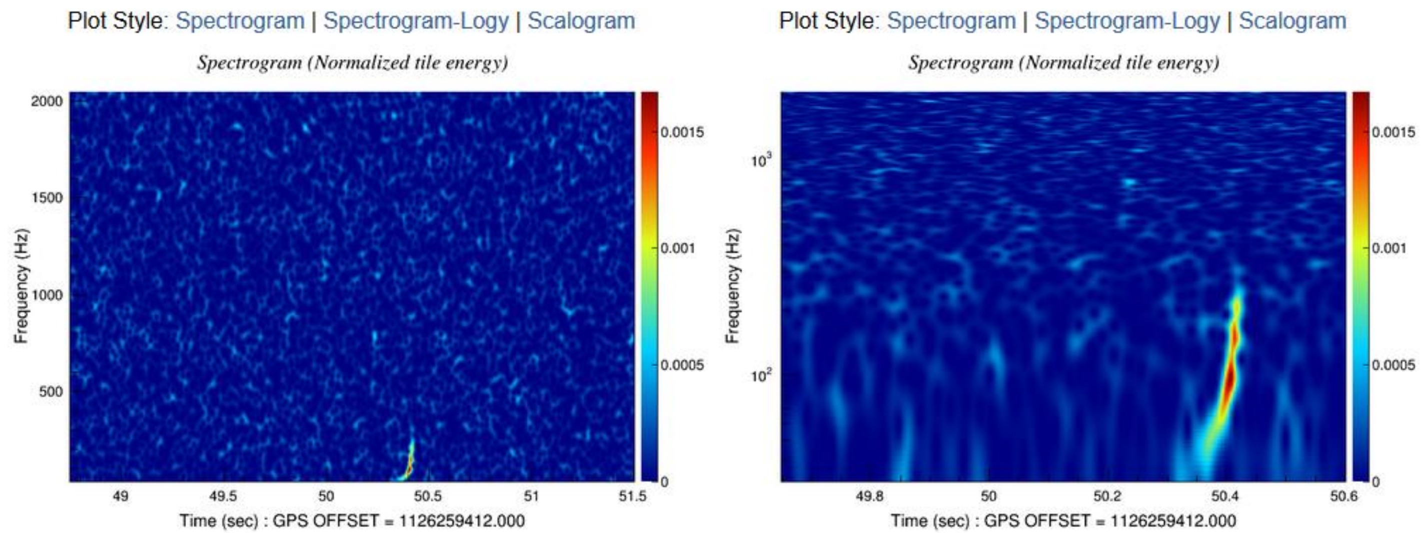
Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

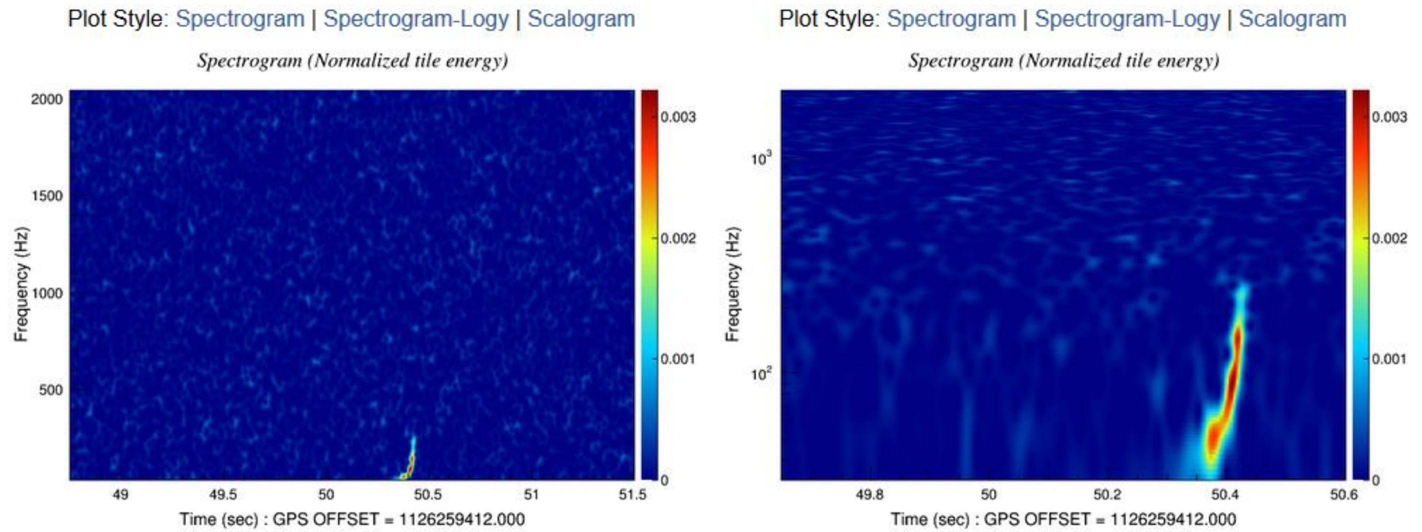
J. Abadie et al., Classical and Quantum Gravity 27, 173001 (2010)

Coherent WaveBurst Event Display

L1

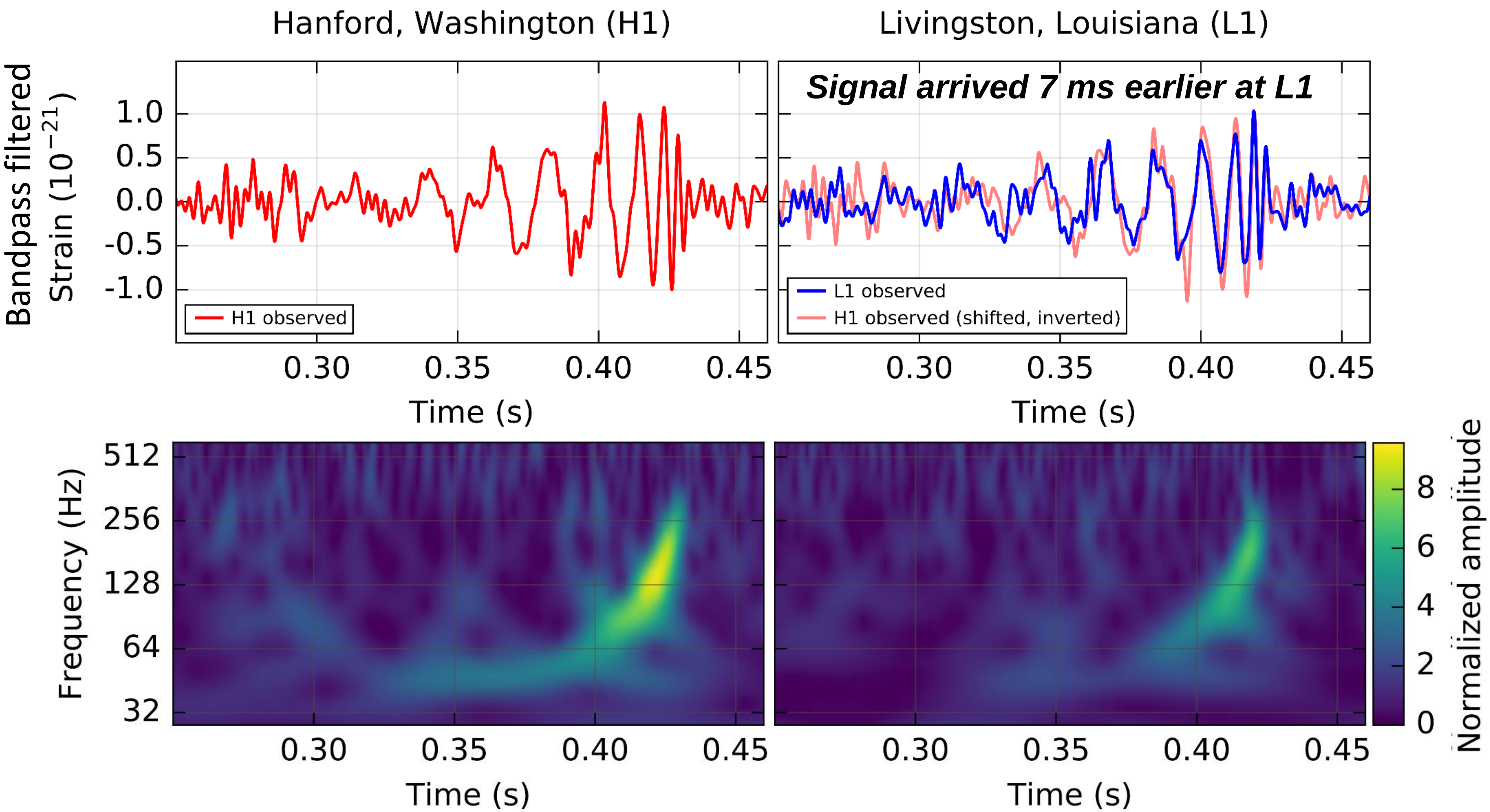


H1

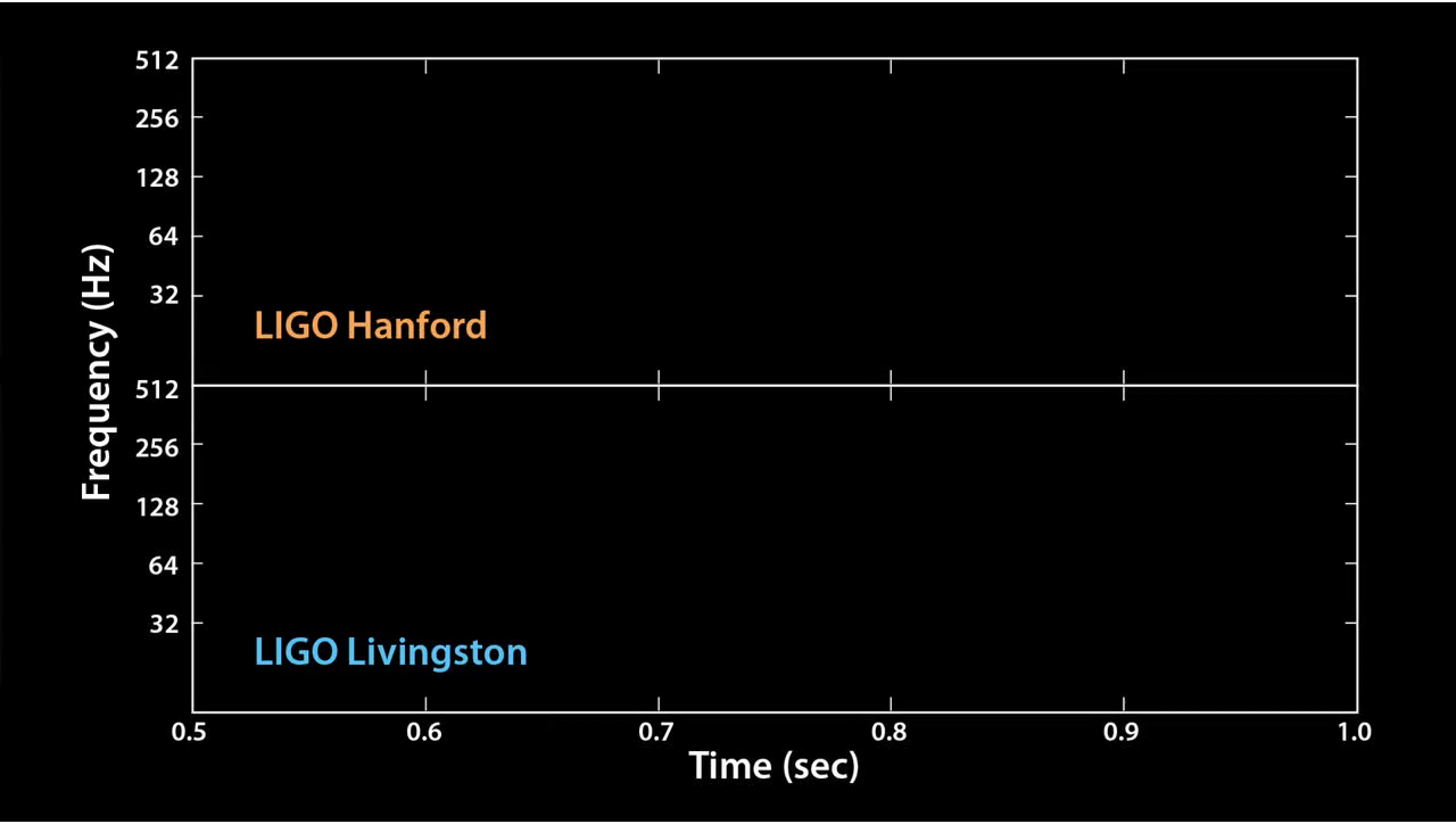


A closer look at the September 14 event candidate

The Actual Waveforms

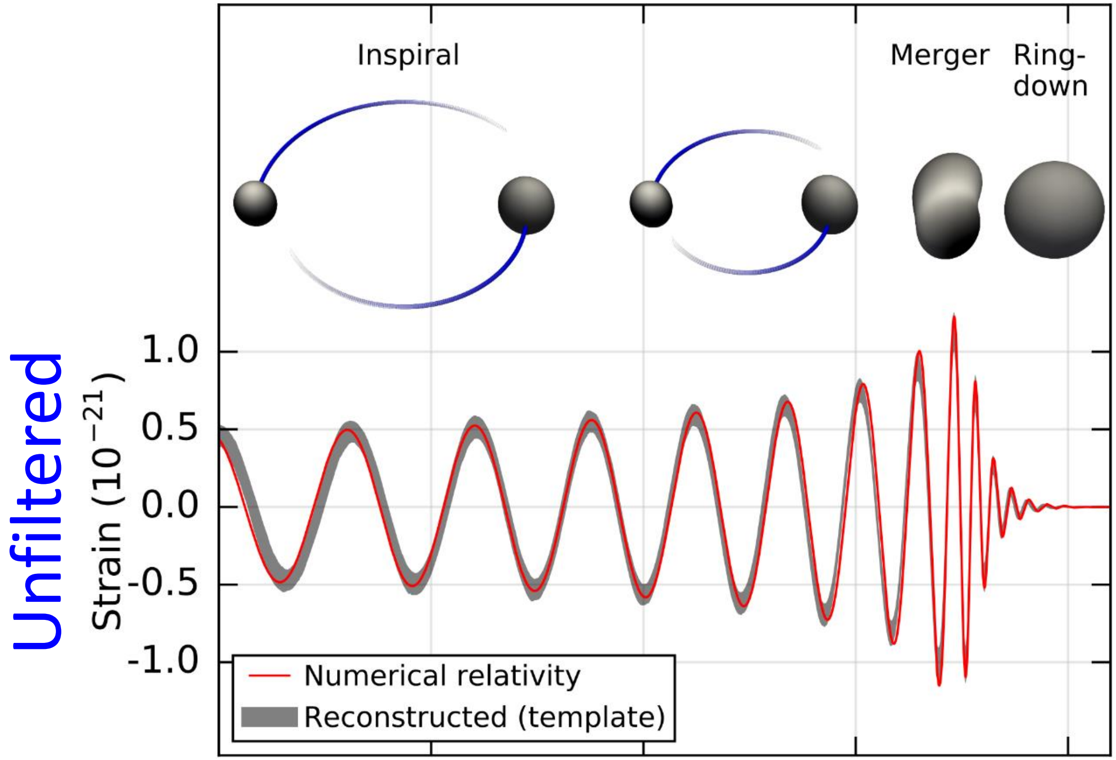


What it Sounds Like



Credit: LIGO

Form of a Binary Coalescence Signal



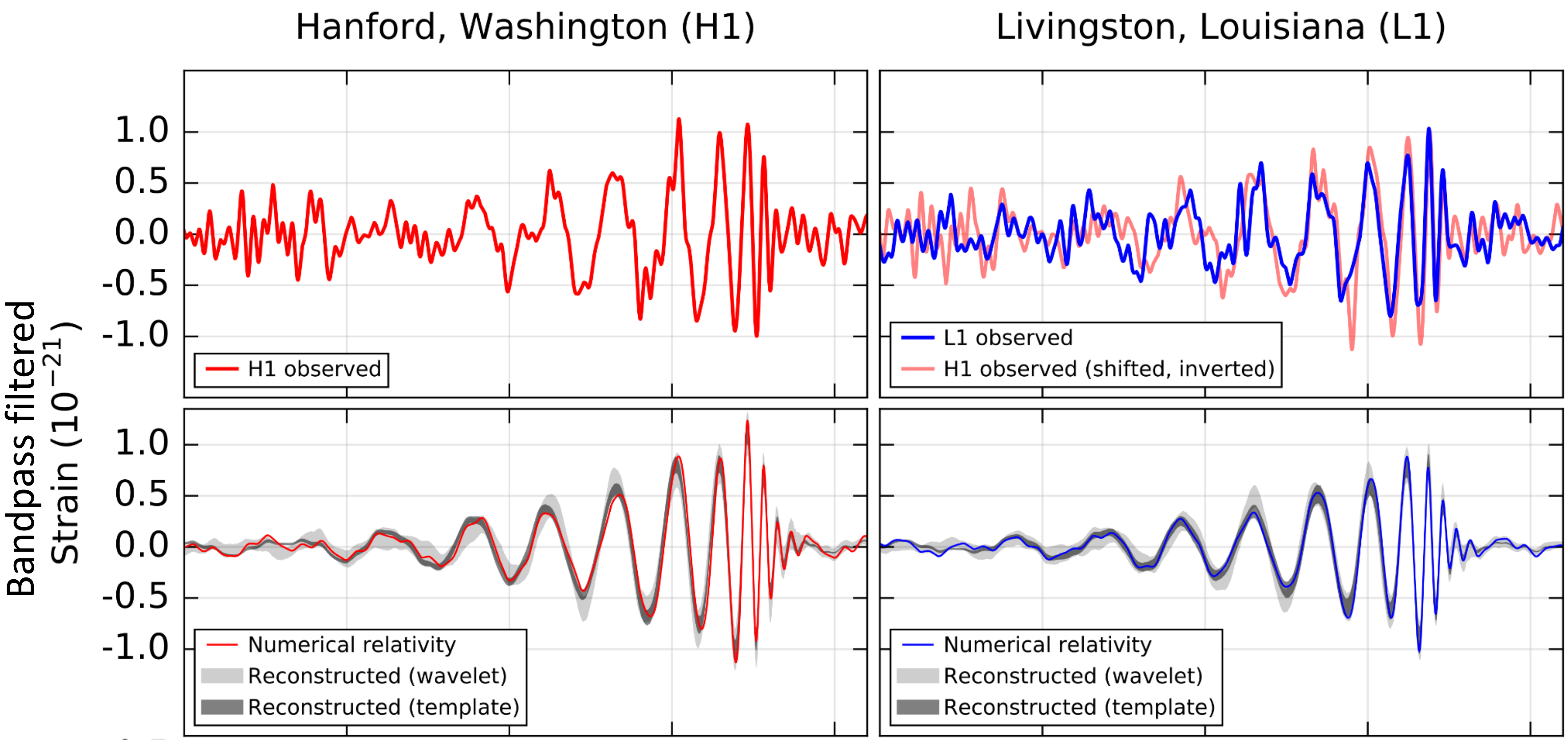
The rapidity of the "chirp" tells us about the masses of the objects

Faster chirp ➔ Higher mass

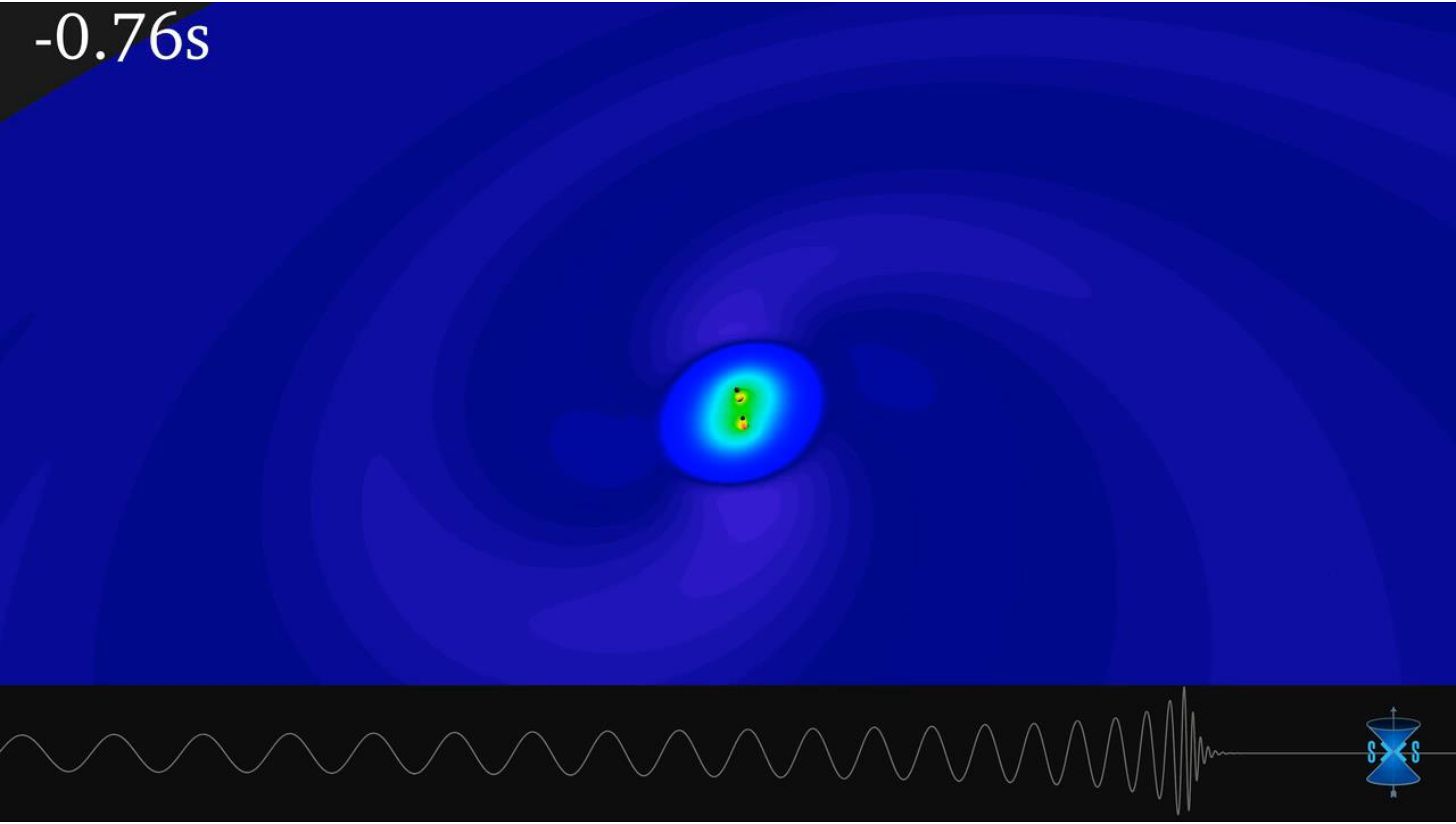
➔ This looks like a binary black hole coalescence!

Does it really look like a BBH ?

Yes – Matches well to BBH template with same filtering



Full Numerical Relativity Simulation



Credit: Simulating eXtreme Spacetimes team

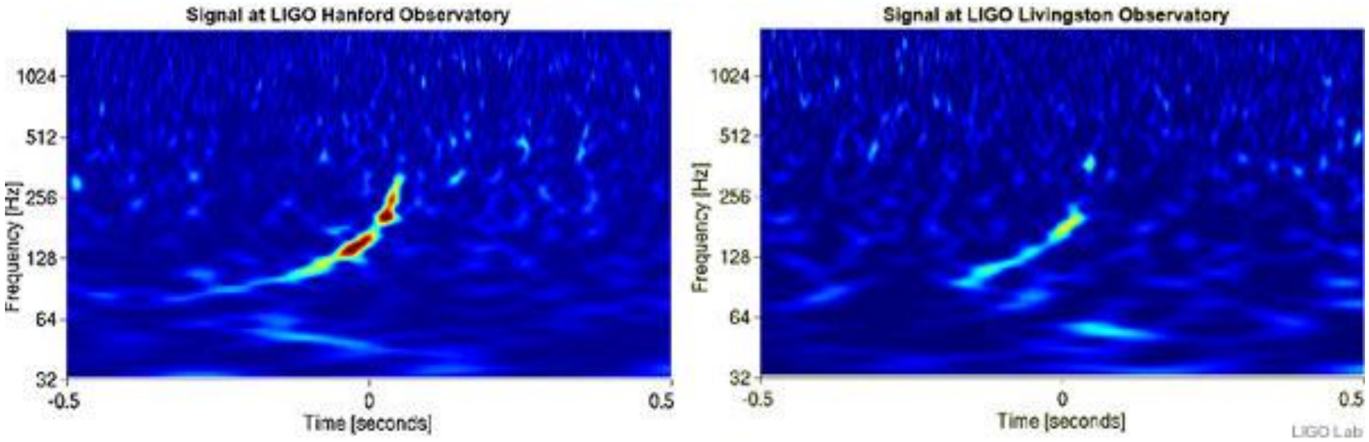
Could it be a blind injection?

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



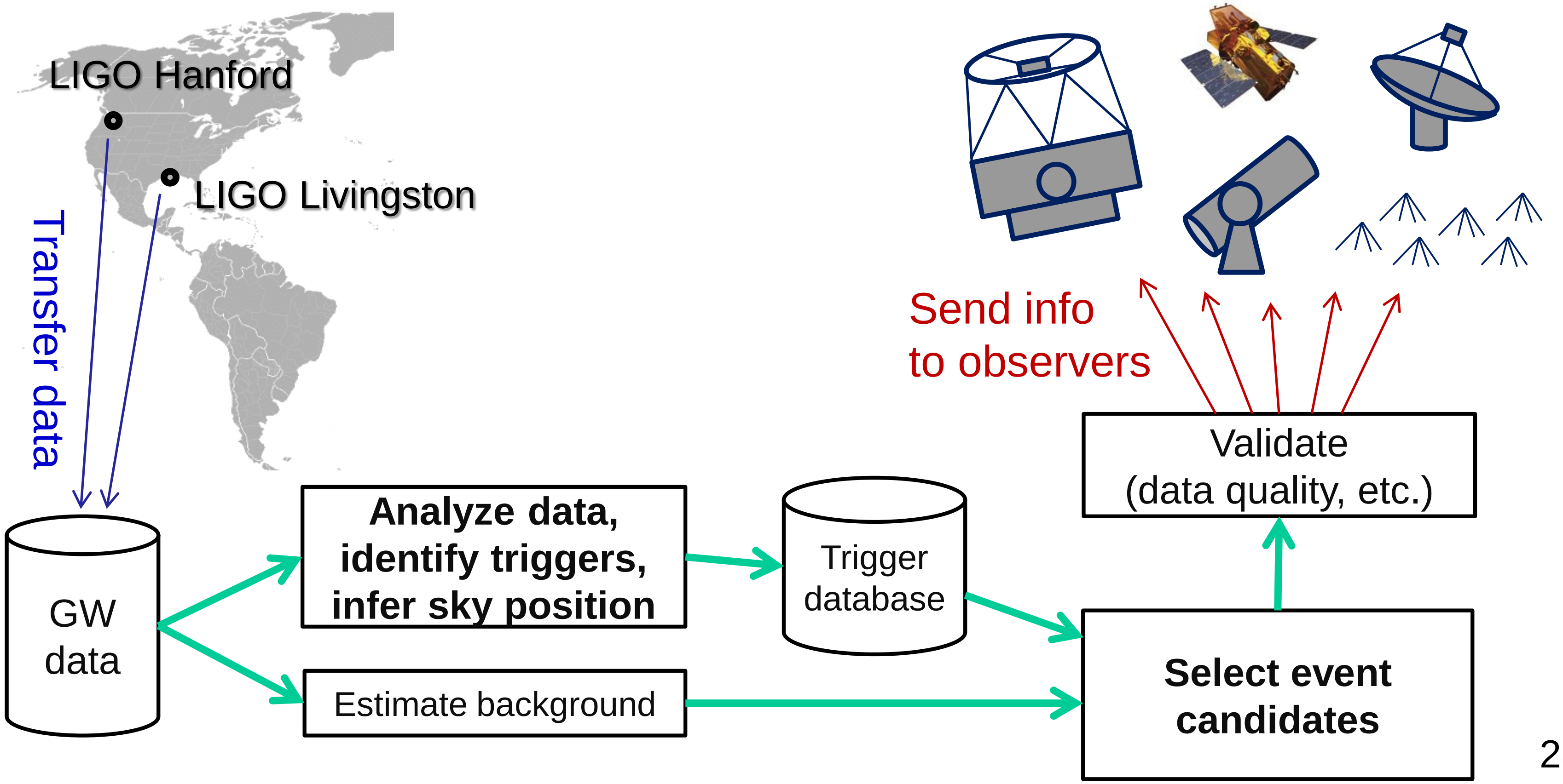
A blind injection exercise was authorized for O1

But it had not started as of September 14 !

Alert Astronomer 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 subset of the system used for GRBs



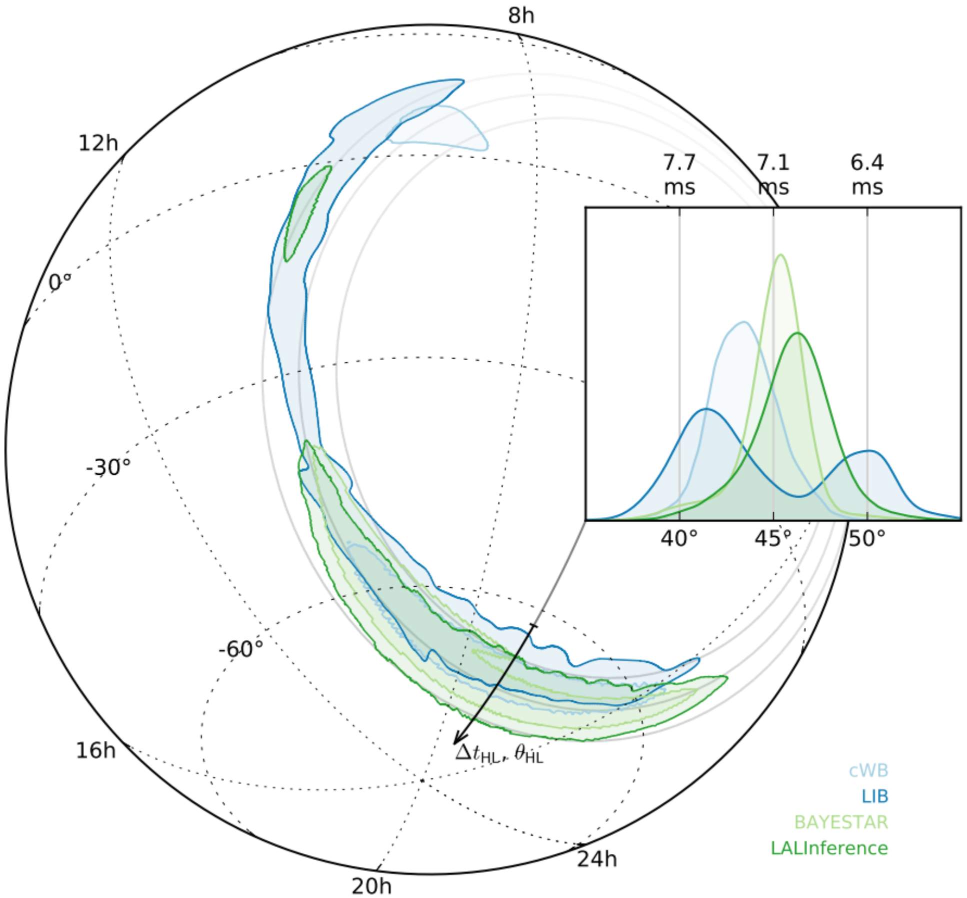
Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

Alert Astronomer Partners!

Problem: that software wasn't fully set up yet !

So a handful of us spent the evening of Sept 15 updating the software and sending out an alert

Many observations were made… are being reported separately by the observers



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

One Event, Many Names

G184098

The Rosh Hashanah Event

Dawn

Preemie

Hydra’s Head

The Big Enchilada

Rainbow Unicorn

The Event

…

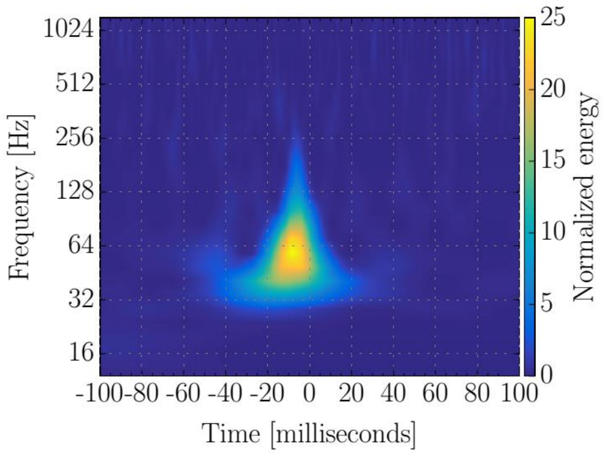
→ GW150914

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

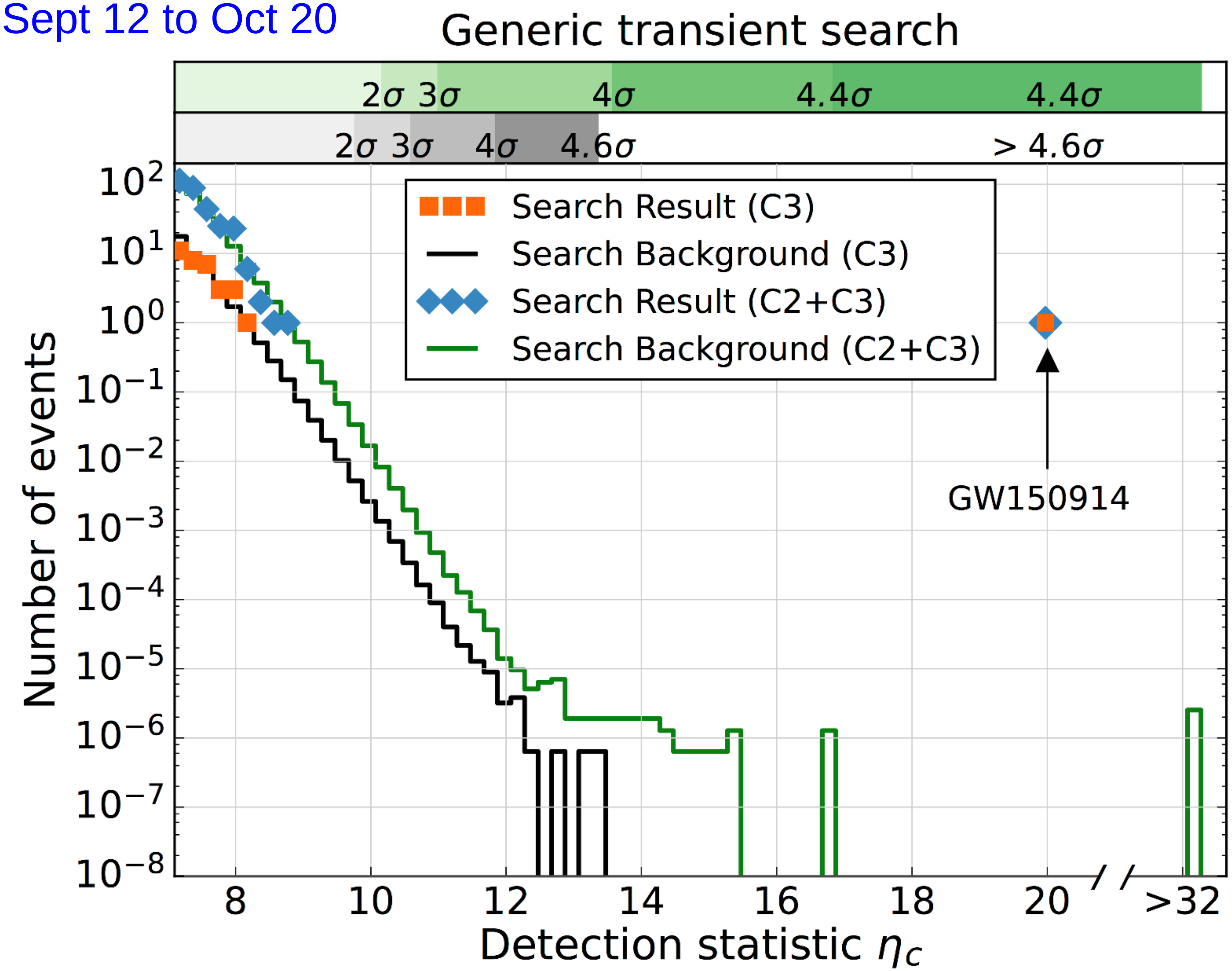
We can estimate the background (from random false coincidences) by analyzing time-shifted data

➔ 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

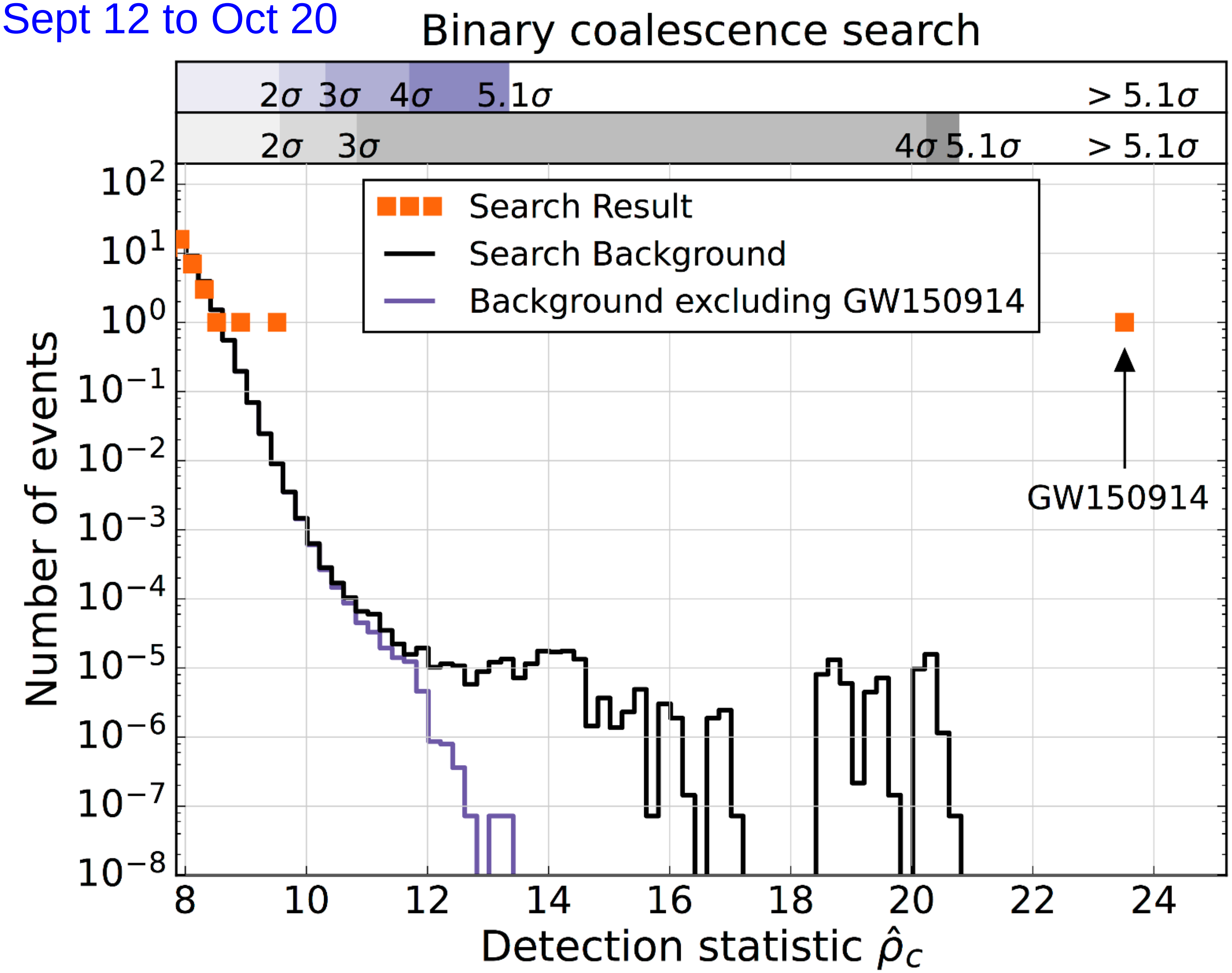
Final Analysis – Generic Transient Search

Data set: Sept 12 to Oct 20



Final Analysis – Binary Coalescence Search

Data set: Sept 12 to Oct 20



The Detection Paper

A huge undertaking to write and refine!

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

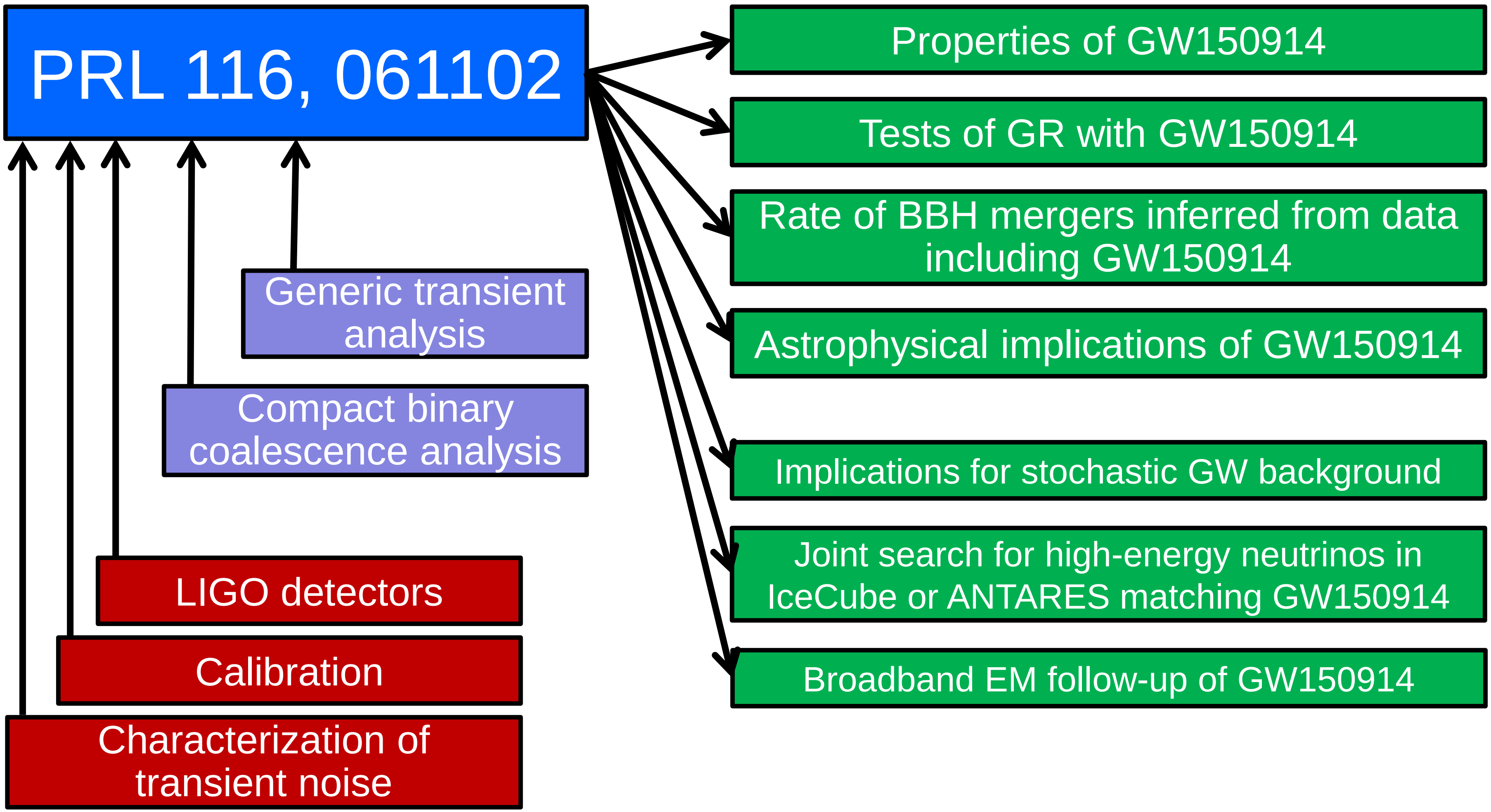
B. P. Abbott *et al.*[*]

(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.

Papers About GW150914



Exploring the Properties of GW150914

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

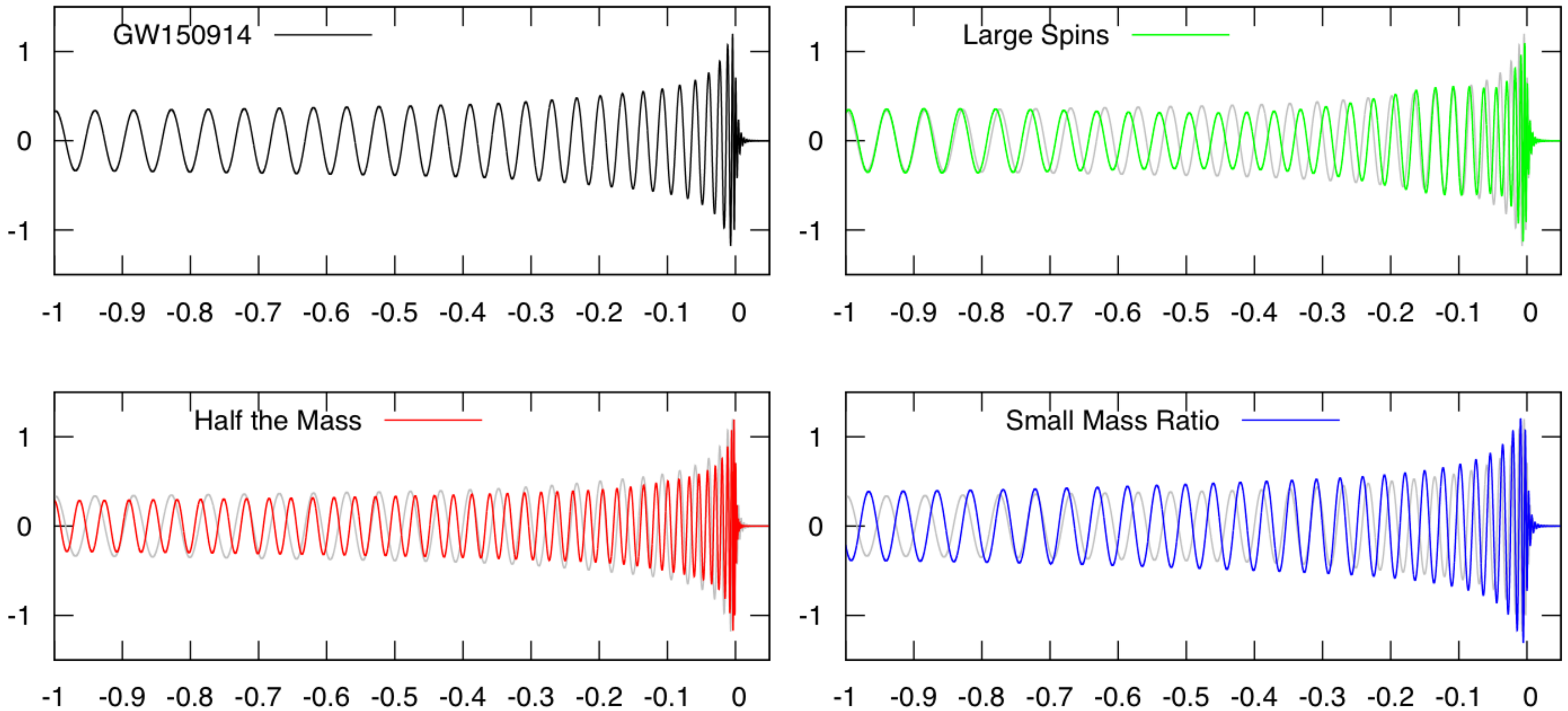


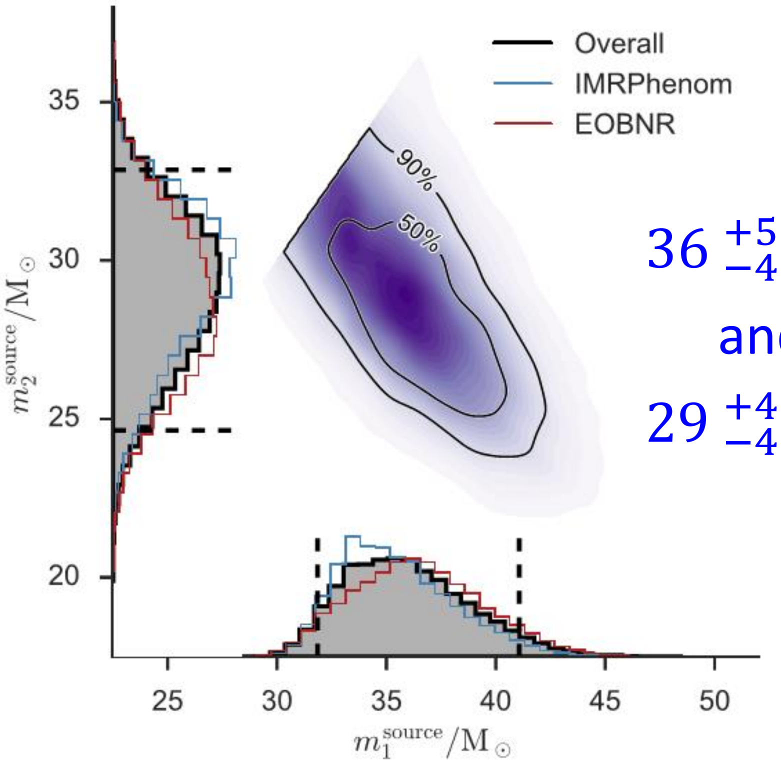
Illustration by N. Cornish and T. Littenberg

➔ **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., 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

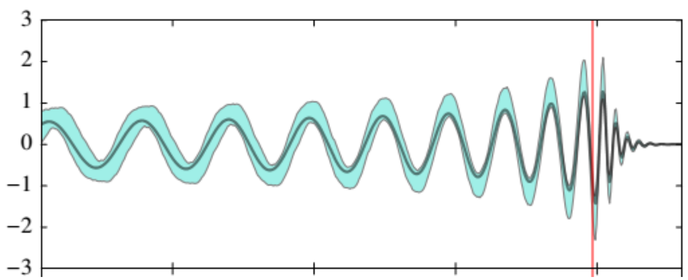
Testing General Relativity

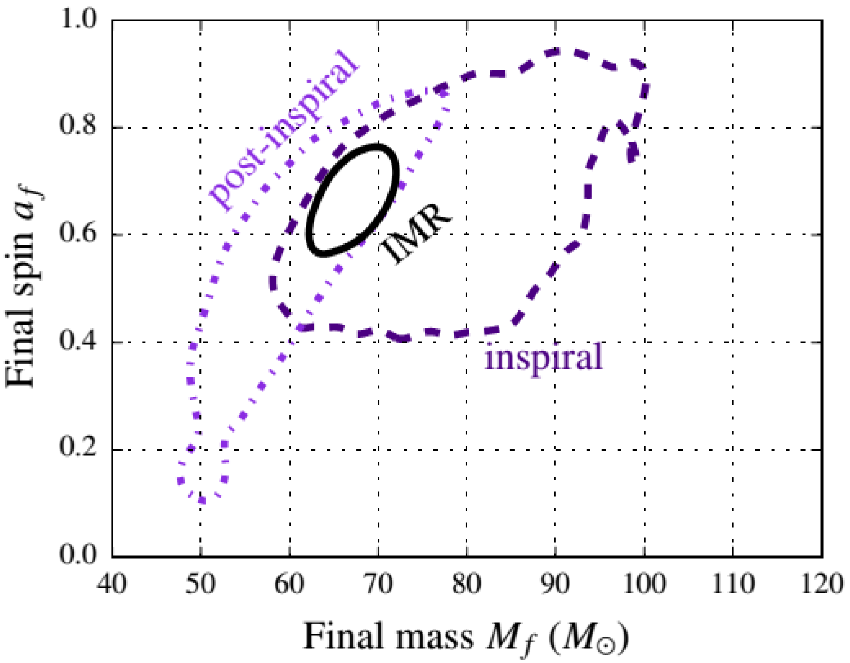
We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions

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





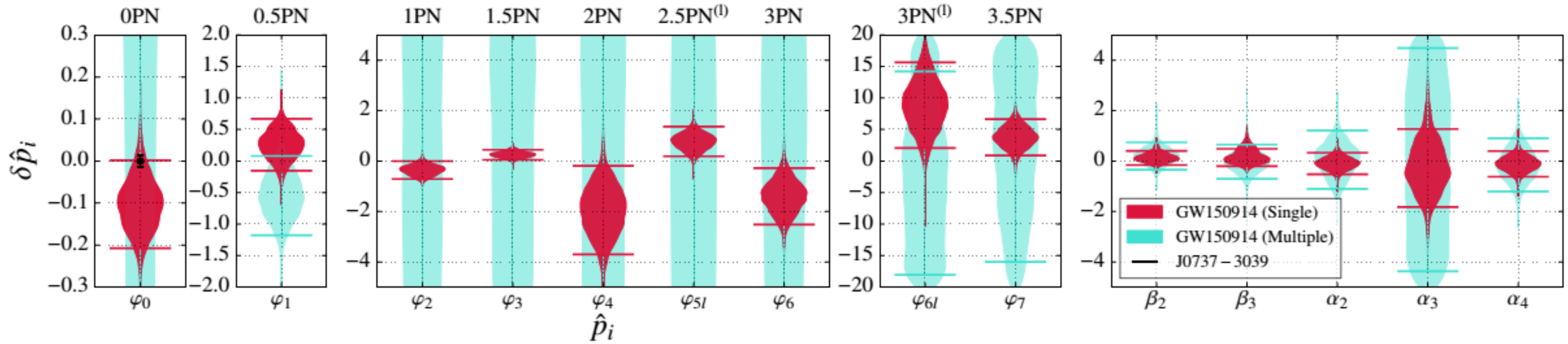
Pure ringdown of final BH?

Not clear in data, but consistent

Abbott et al., arXiv:1602.03841

Testing General Relativity

Allowing deviations in post-Newtonian waveform model



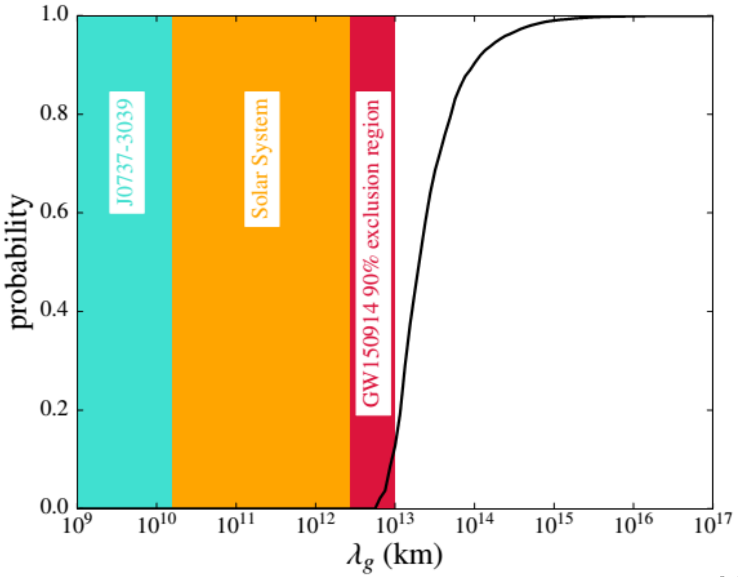
Parameter deviations are reasonably consistent with zero

Allowing 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., 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

Abbott et al., ApJL **818**, L22 (2016)

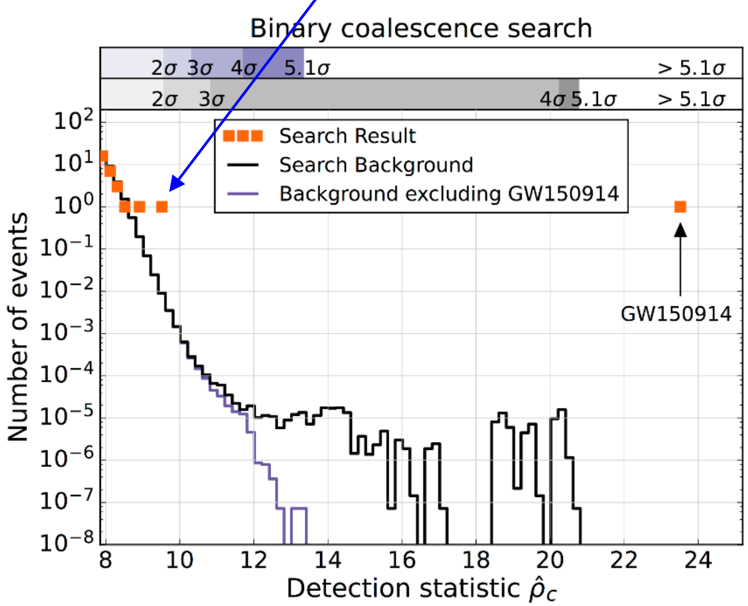
Inferring the Rate of BBH Mergers

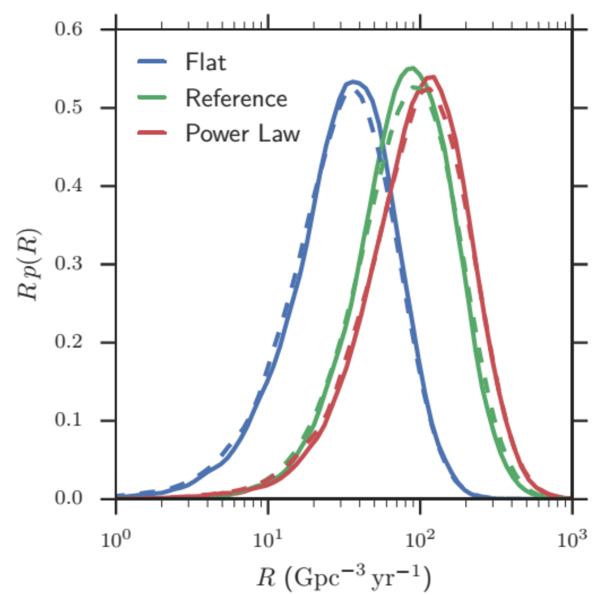
Considering GW150914 only, determine the volume of space in which a GW150914-like BBH could be detected

➔ (2 to 53) per year per Gpc^3

But wait, there's more!

Considering LVT151012 (masses ~23 and ~13 $M_\odot$) and other candidates which *might* be real, estimate (6 to 400) per year per Gpc^3





Abbott et al., arXiv:1602.03842

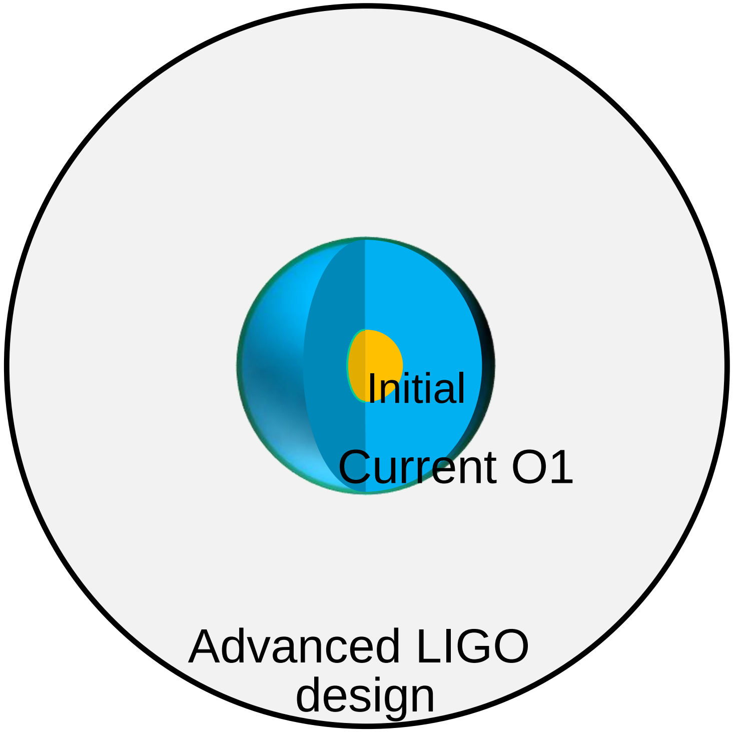
What's Next

Finish analyzing the rest of the O1 data

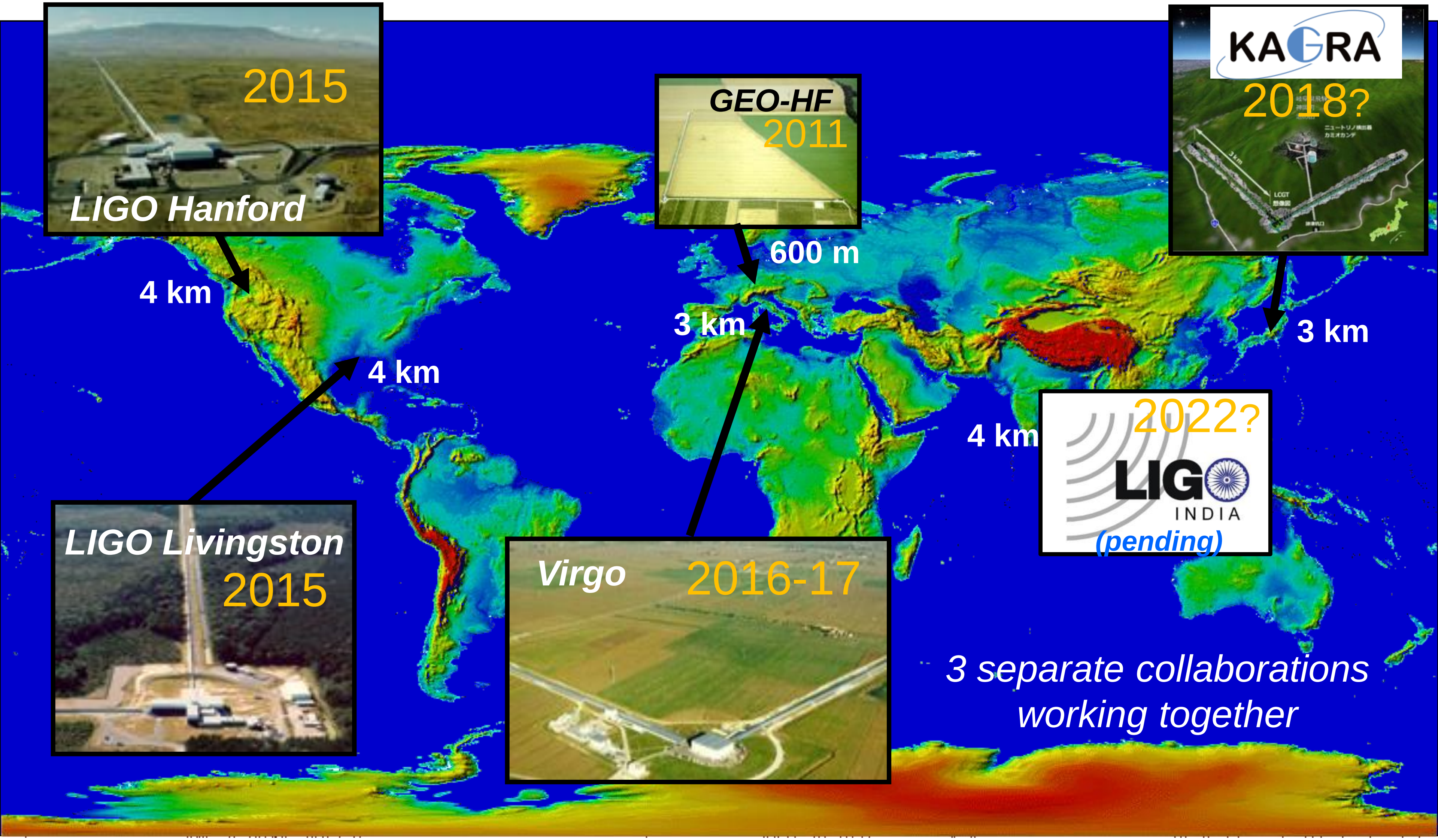
Complete our full suite of searches for various GW signals

Prepare for the O2 run starting this summer

Should be twice as long, hopefully with somewhat better sensitivity



Advanced GW Detector Network: Under Construction → Operating



3 separate collaborations working together

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 now have a concrete example of strong gravitational dynamics at work – and Einstein seems to be right

Resource web page: http://ter.ps/GW150914