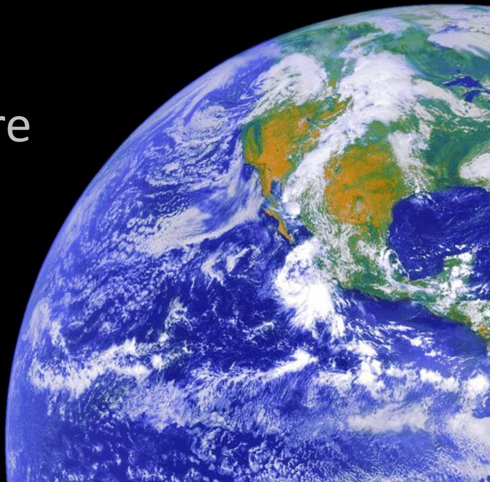
The Remarkable Story of LIGO's Detection of Gravitational Waves

Peter Shawhan

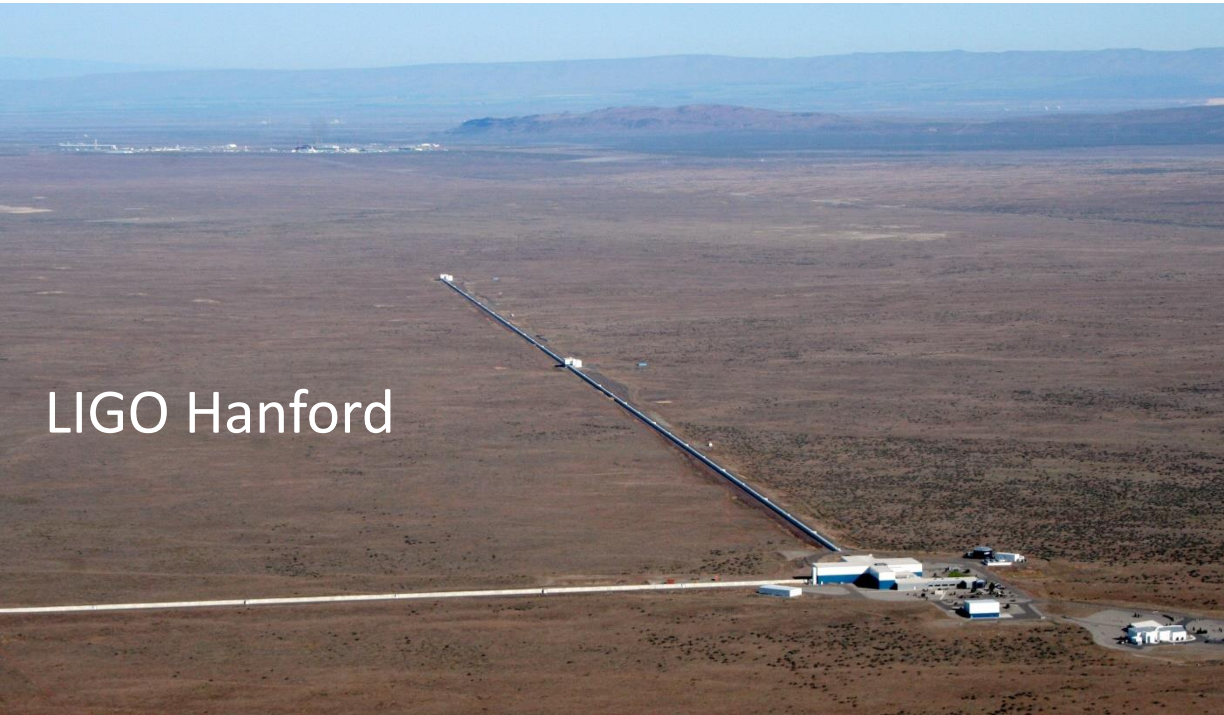
Virtual Institute of Astroparticle physics lecture
April 1, 2016

LIGO-G1600320-v3

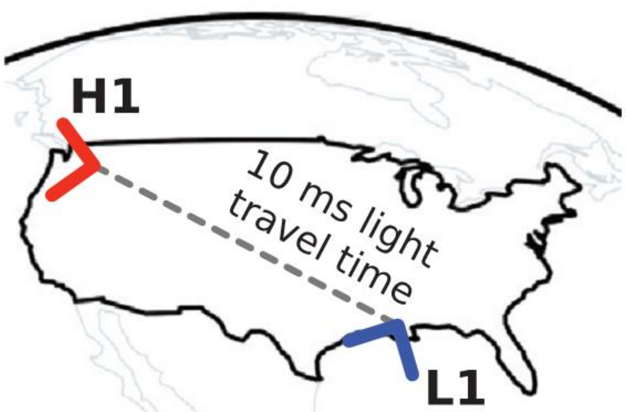


GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

The LIGO* Observatories



* LIGO = Laser Interferometer Gravitational-wave Observatory



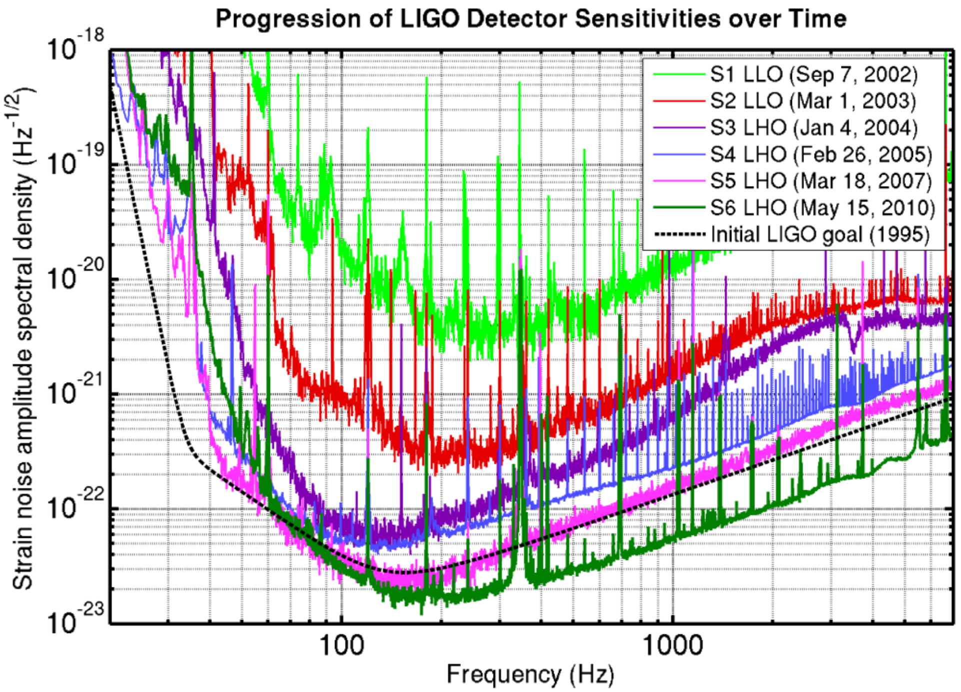
Science from Initial LIGO

~100 papers published by the LIGO Scientific Collaboration

Many meaningful (but generally unsurprising) upper limits

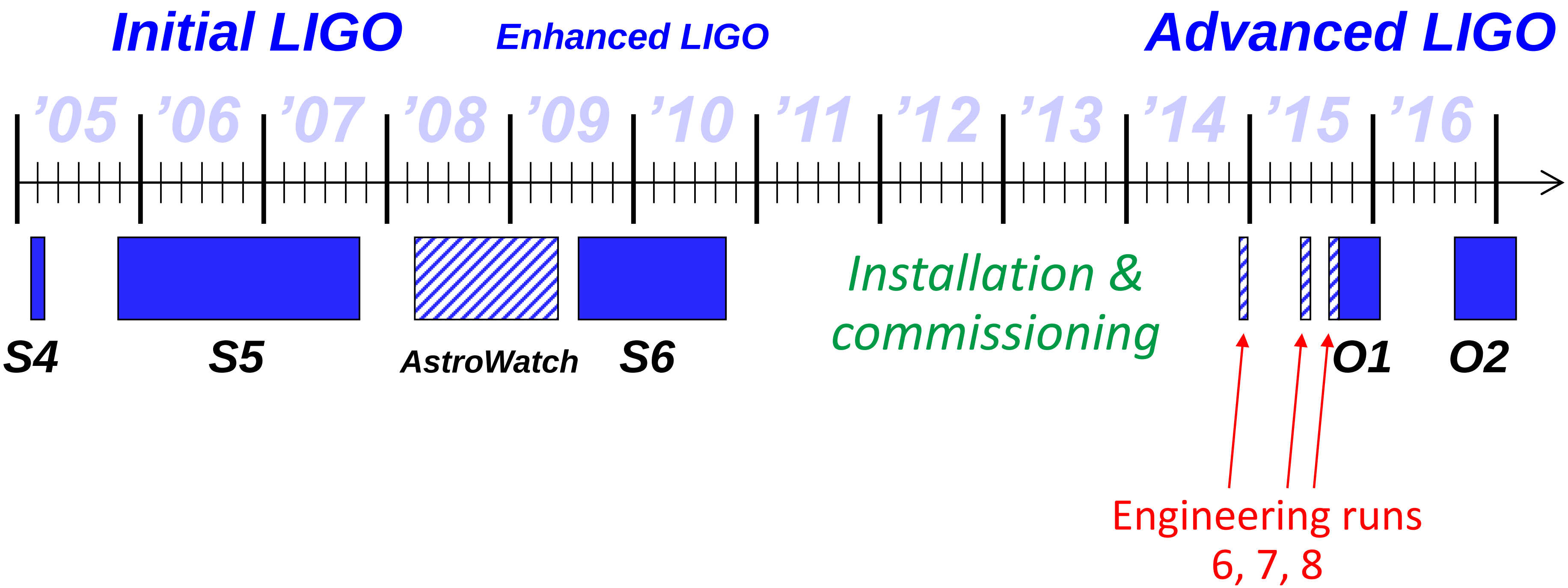
- Rates of binary coalescence events in the nearby universe
- Continuous emission from the Crab Pulsar and other spinning neutron stars
- Limits on stochastic gravitational-wave backgrounds over the sky
- GW emission from GRBs
- And more…

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



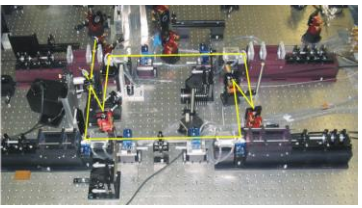
Summer 2015: Out of the "Dark Ages"

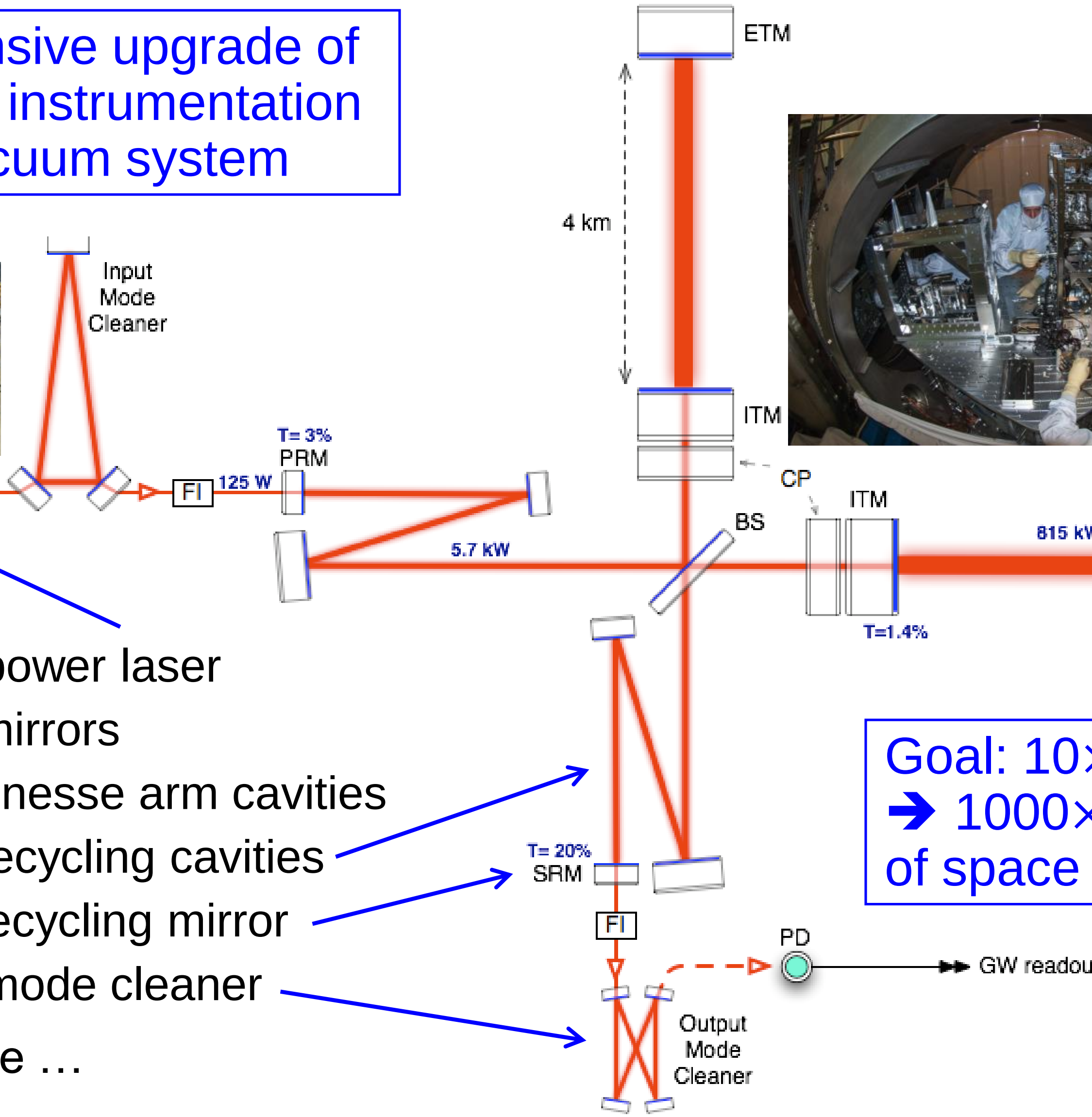
Focus: Transition the LIGO gravitational wave detectors back to observing operations after a 5-year shutdown to carry out the Advanced LIGO upgrade project

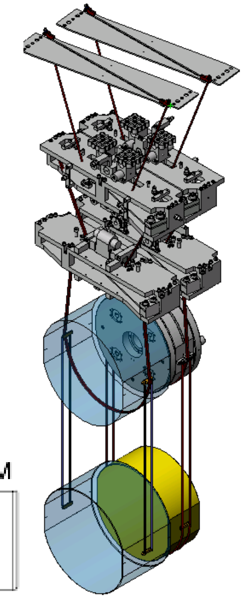


Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system





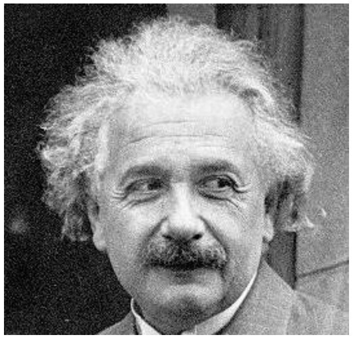


Improvements

- 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

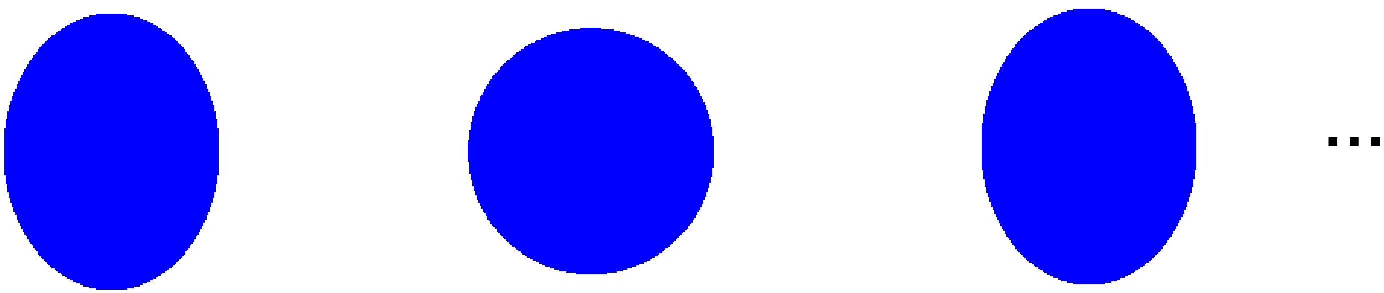
Gravitational Waves Primer



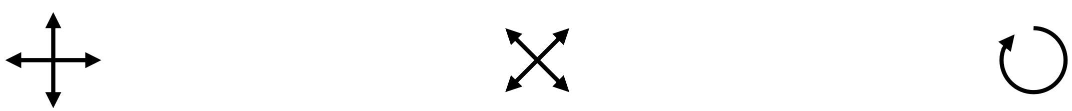
The Einstein field equations have wave solutions !

- 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

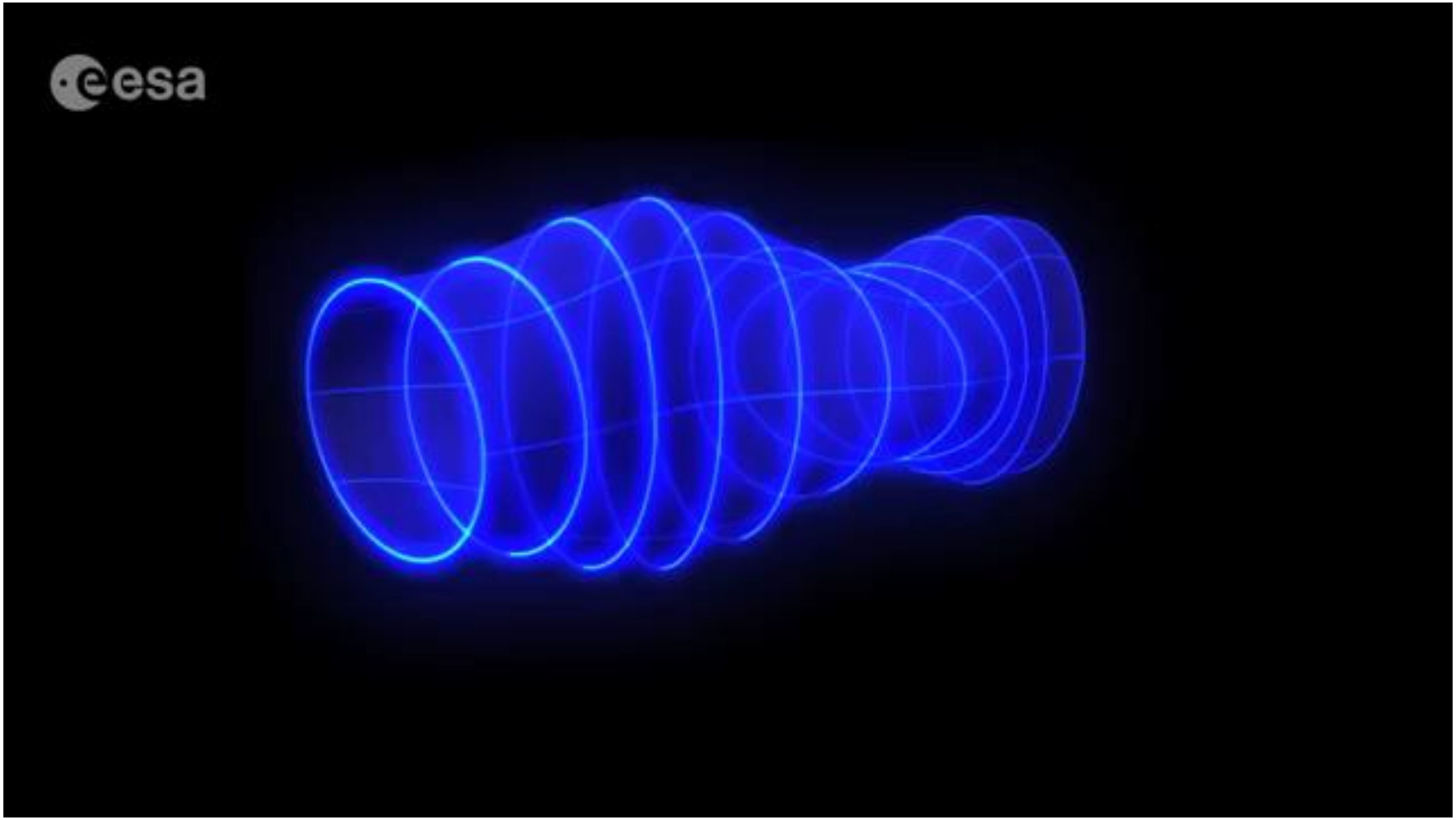
(Neutron stars or black holes)

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

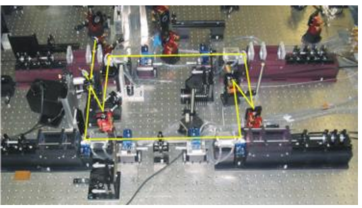
The stretching is described by a dimensionless strain, $h = \Delta L / L$

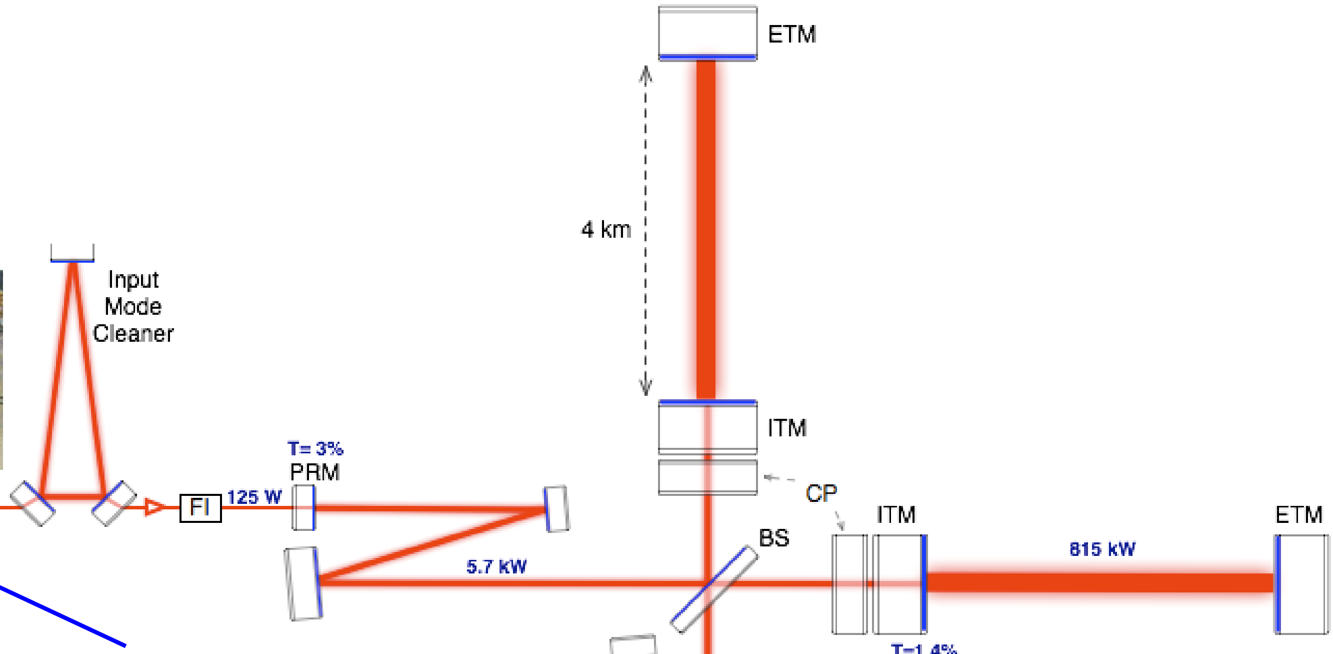
h is inversely proportional to the distance from the source

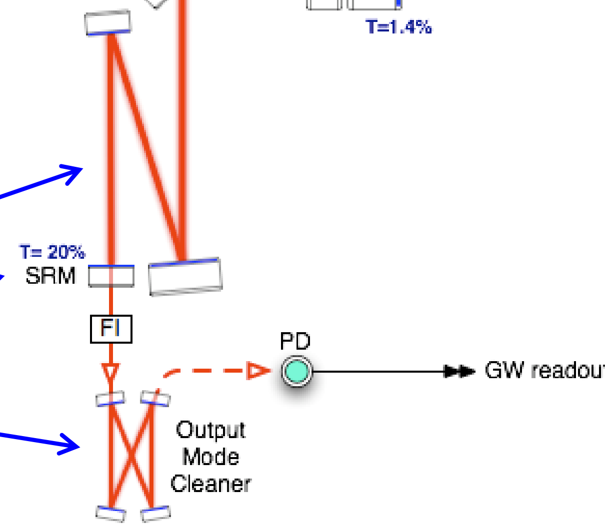
Gravitational Waves in Motion



Advanced LIGO Optical Layout







Improvements

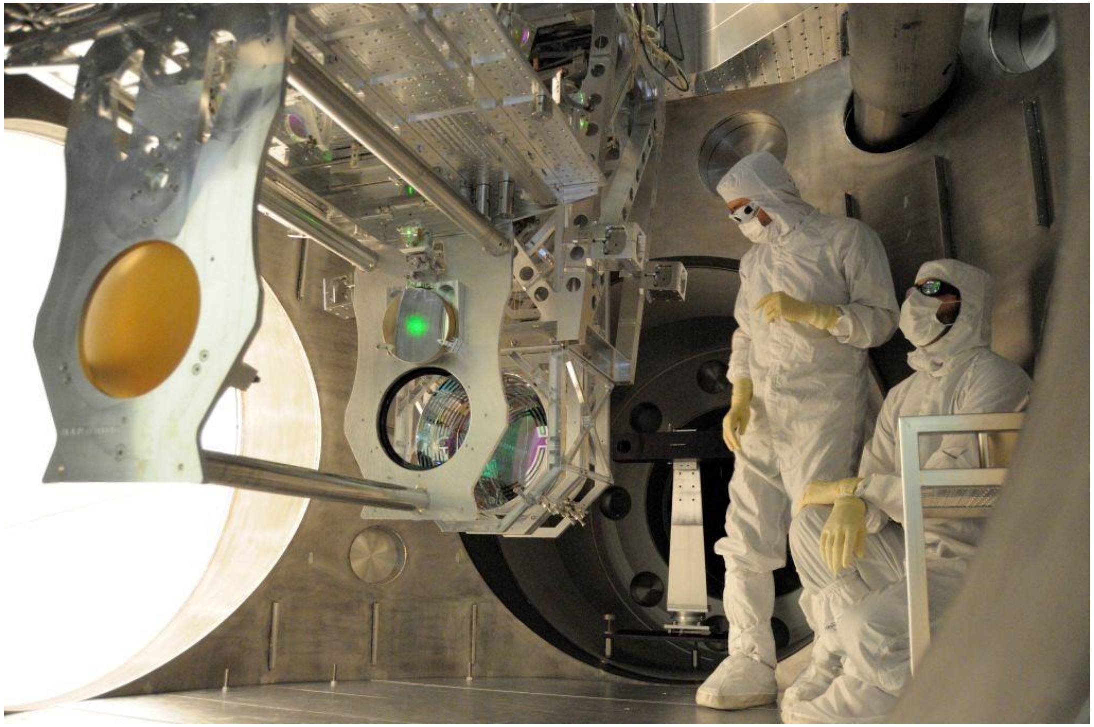
Higher-power laser
Larger mirrors
Higher finesse arm cavities
Stable recycling cavities
Signal recycling mirror
Output mode cleaner
and more …

Advanced LIGO Installation

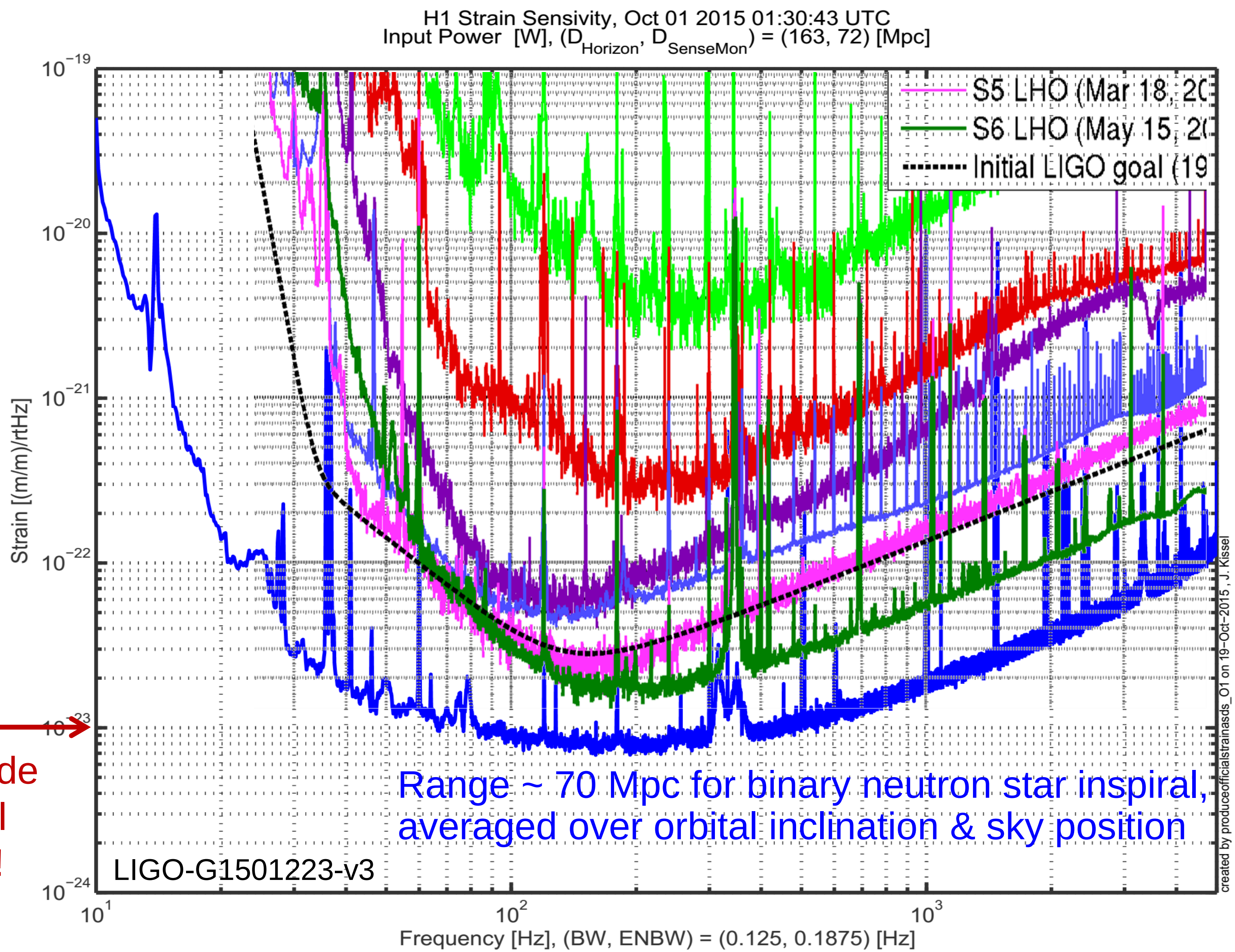
Installation went pretty smoothly at both LIGO observatories

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

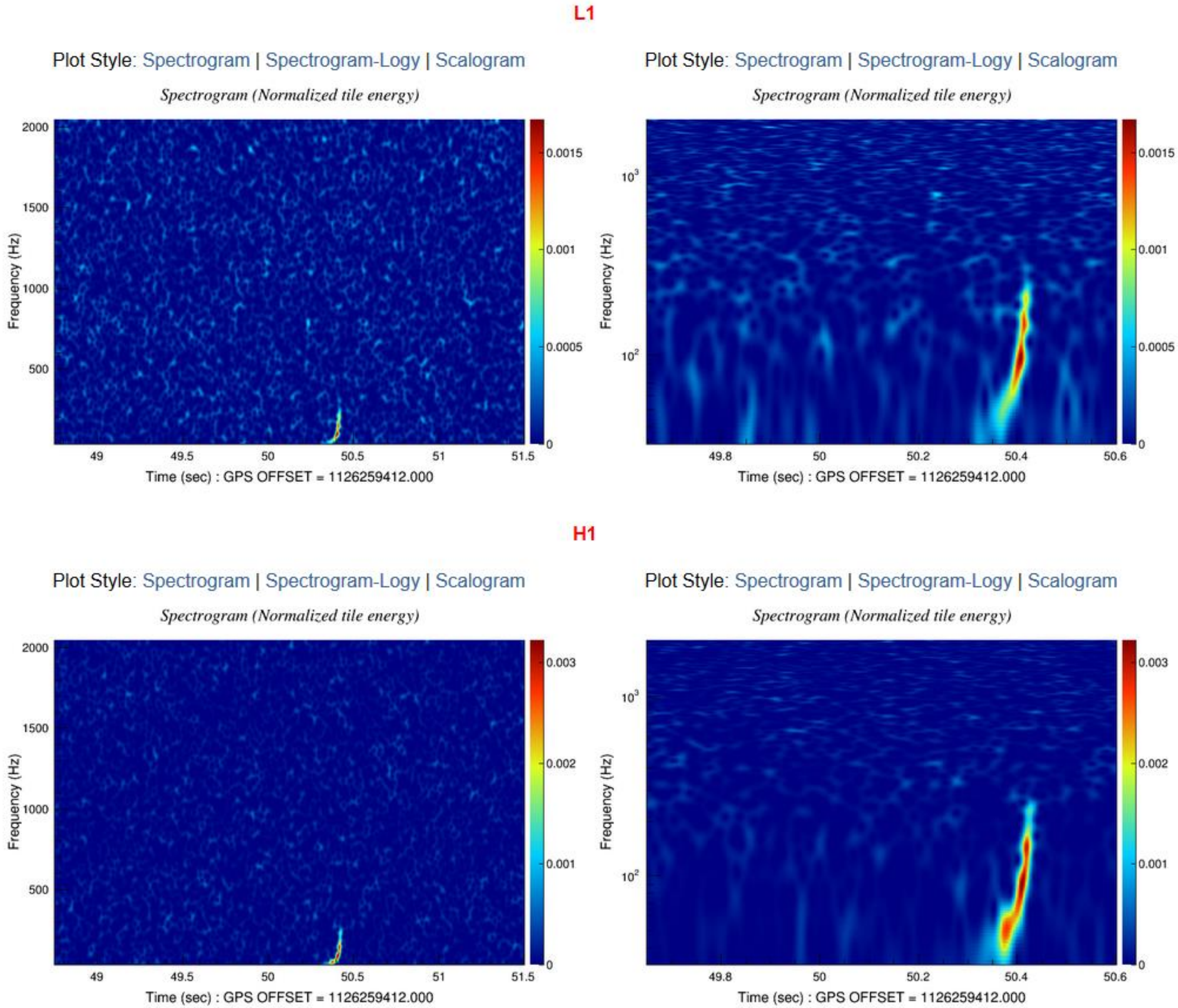
This is the CED:
https://ldas-jobs.ligo.caltech.edu/~waveburst/online/ER8_LH_ONLINE/JOBS/112625/1126259540-1126259600/OUTPUT_CED/ced_1126259420_180_1126259540-1126259600_slag0_lag0_1_job1/L1H1_1126259461.750_1126259461.750/

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/

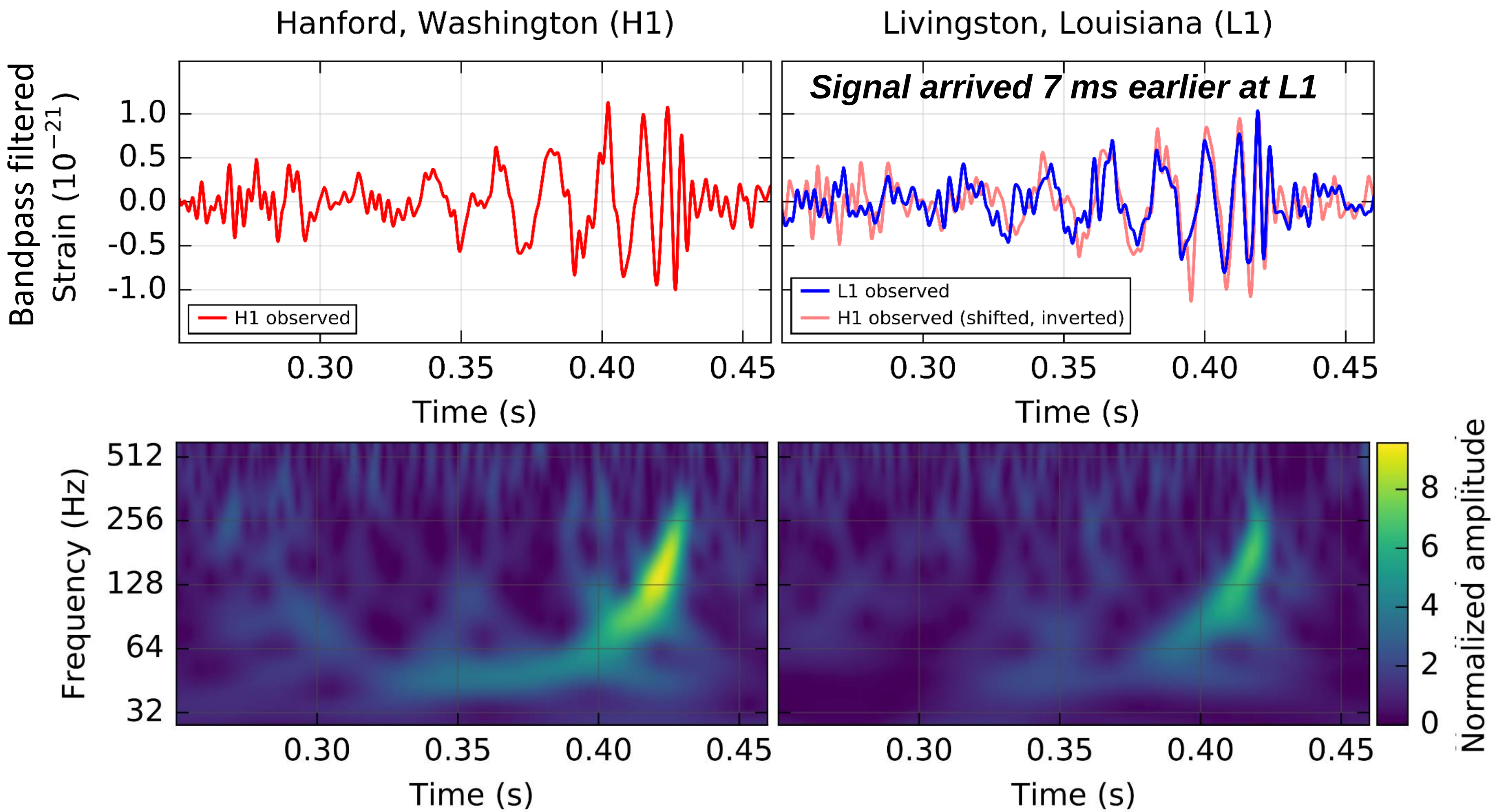
It is not flag as an hardware injection, as we understand after some
fast investigation. Someone can confirm that is not an hardware injection?

Marco

Coherent WaveBurst Event Display

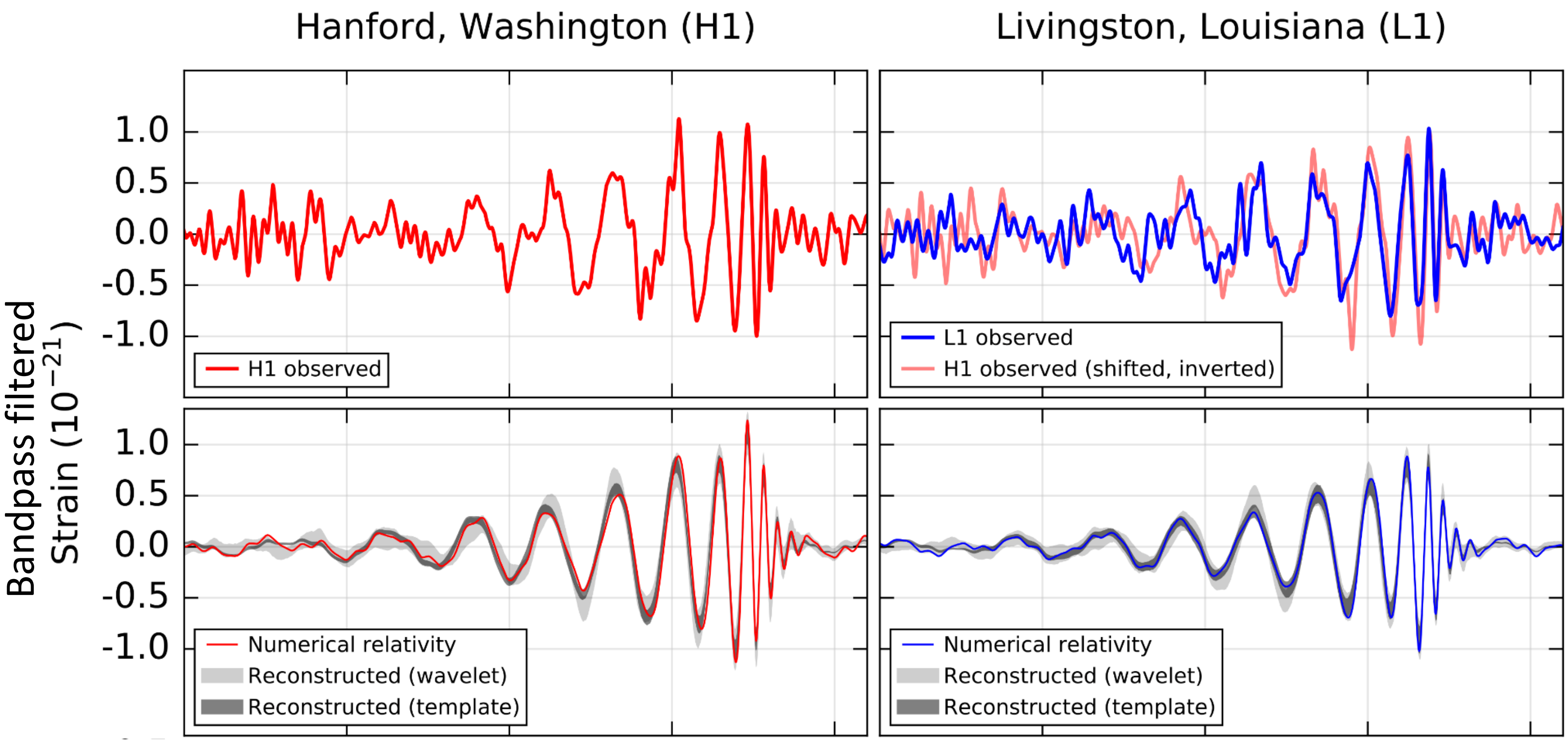


The Actual Waveforms



Looks like a binary black hole merger!

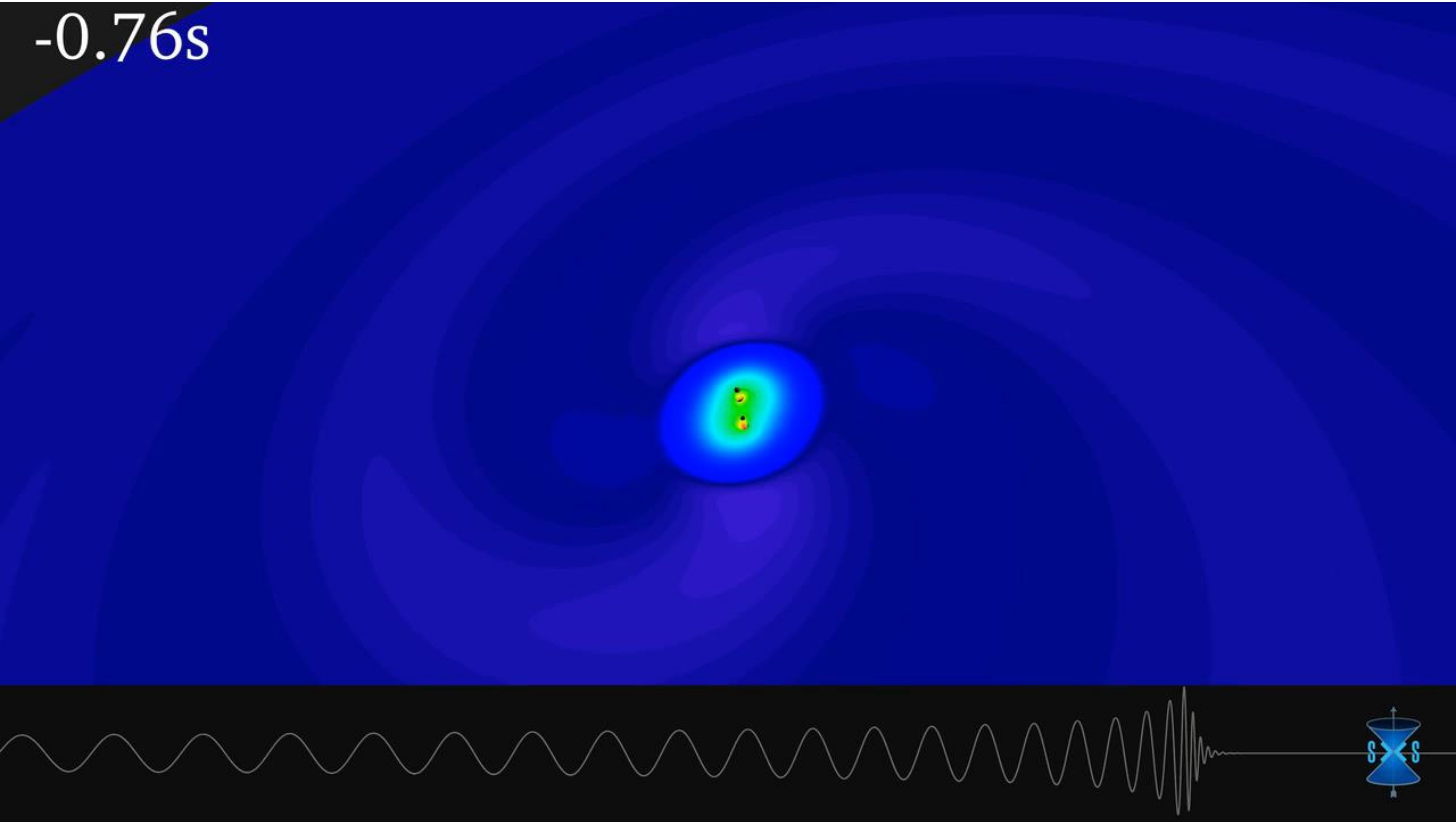
Matches well to BBH template with same filtering



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

Faster chirp ➔ Higher mass

Full Numerical Relativity Simulation



Credit: Simulating eXtreme Spacetimes team

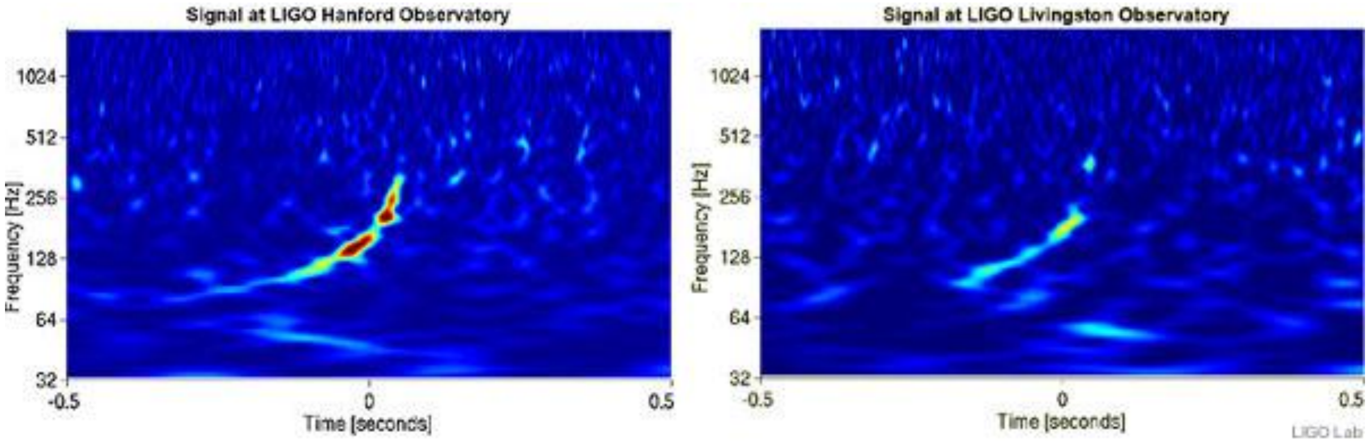
Could it be a blind injection?

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



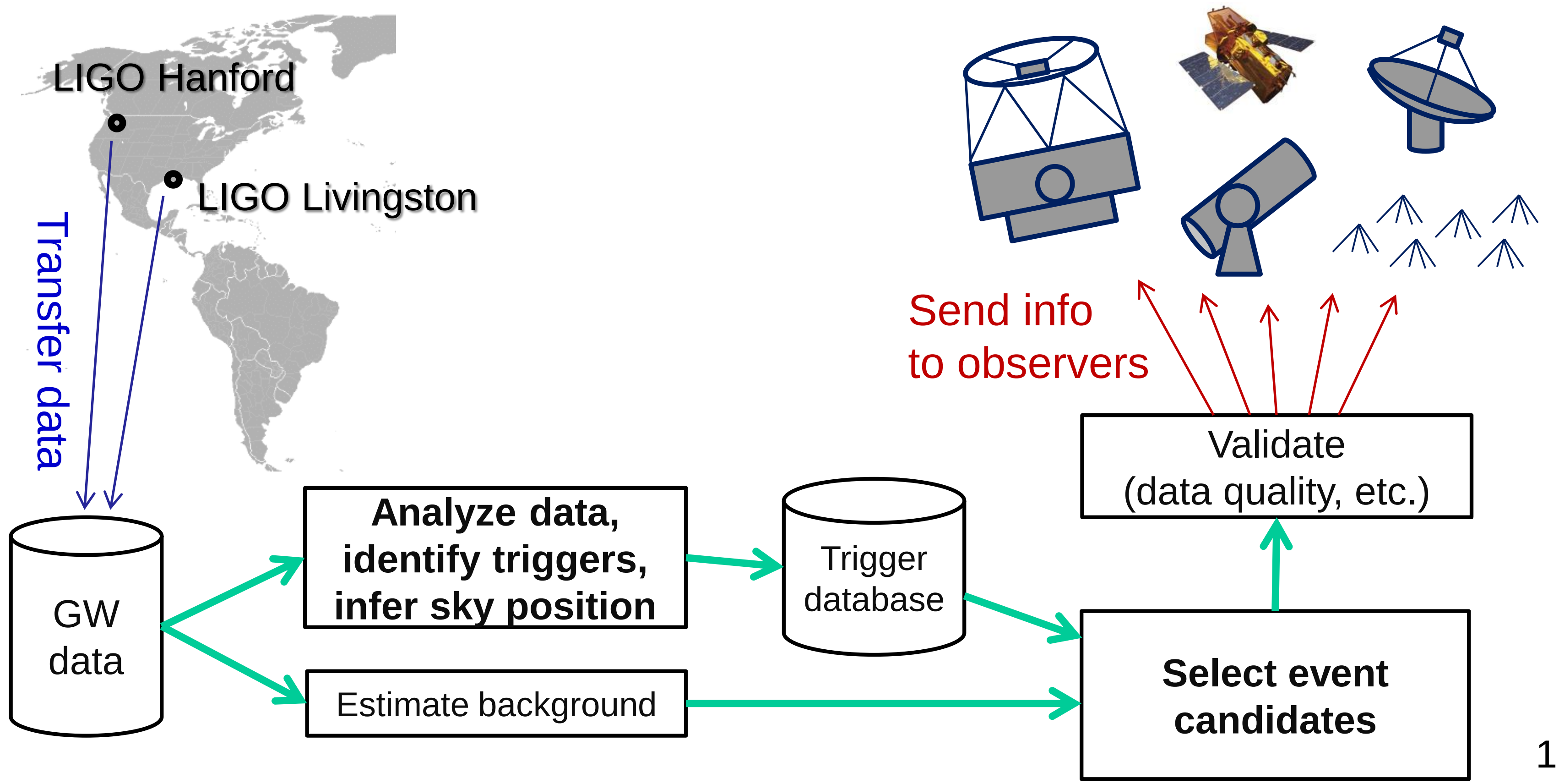
A blind injection exercise was authorized for O1

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

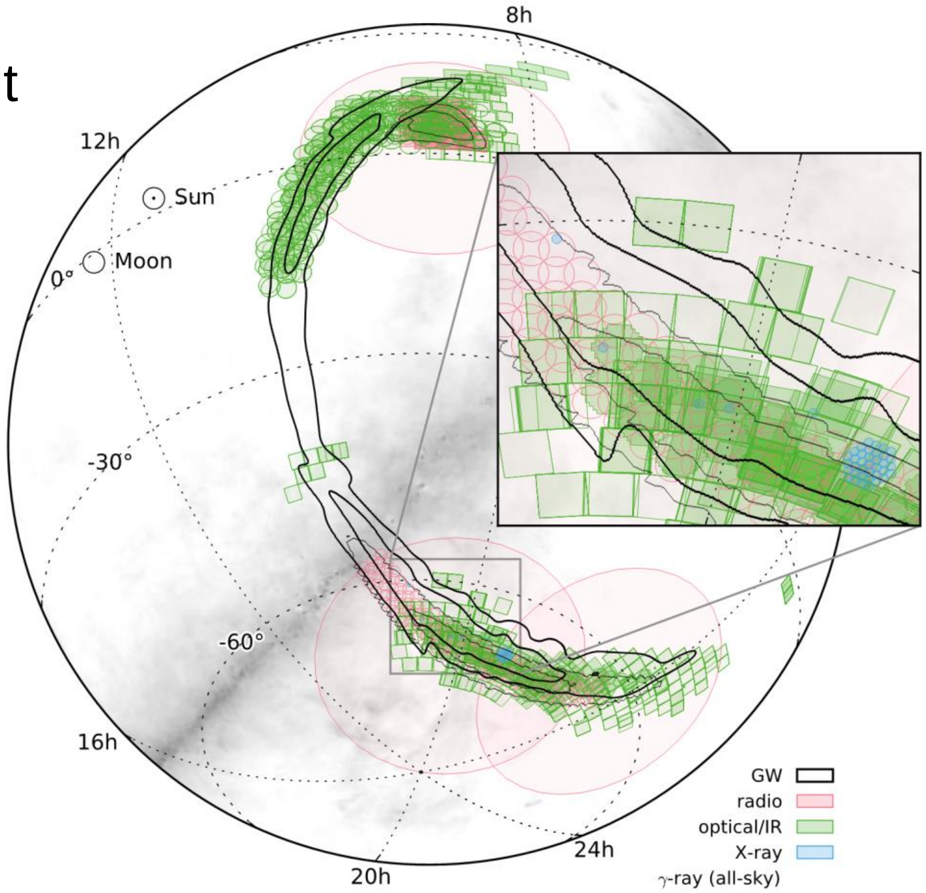
Alert Astronomer Partners!

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

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 arXiv:1602.08492

One Event, Many Names

G184098

The Rosh Hashanah Event

Dawn

Preemie

Hydra's Head

The Big Enchilada

Rainbow Unicorn

The Event

…

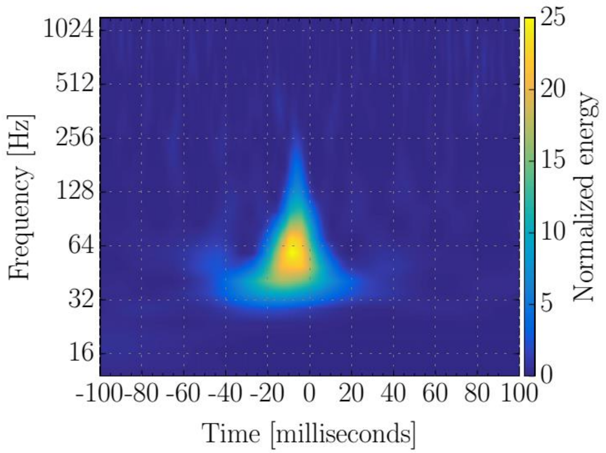
→ GW150914

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

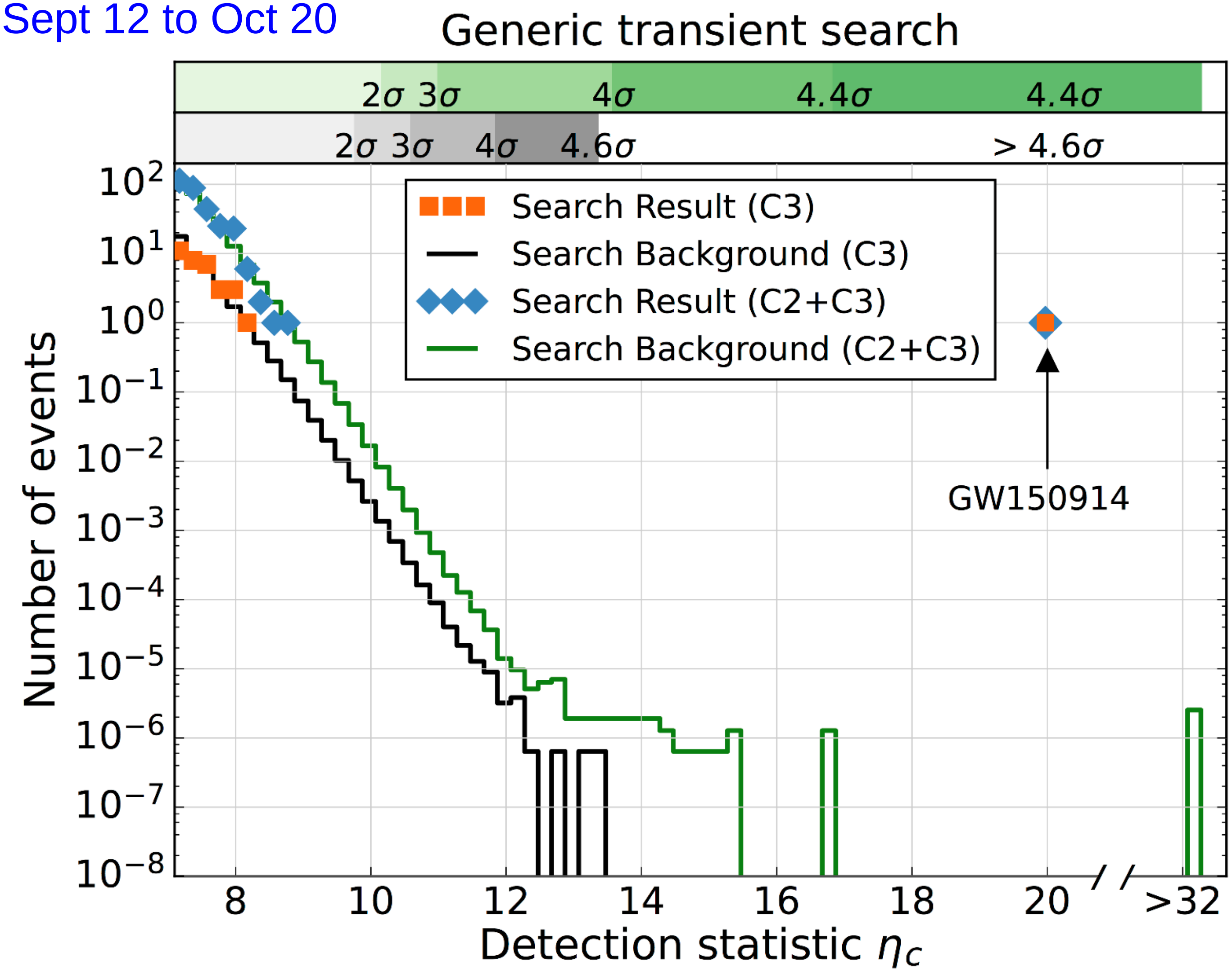
We can estimate the background (from random false coincidences) by analyzing time-shifted data

➔ 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

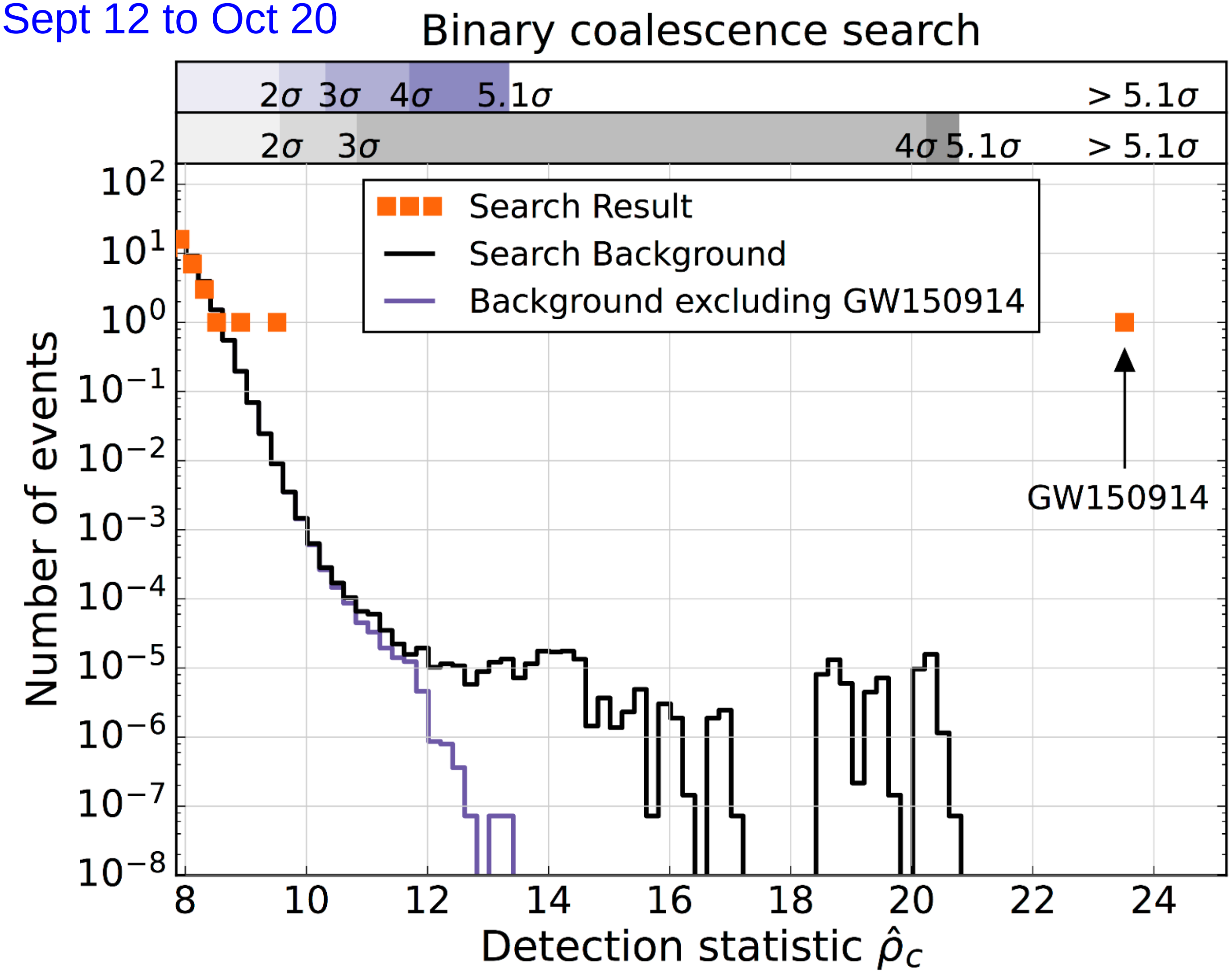
Final Analysis – Generic Transient Search

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

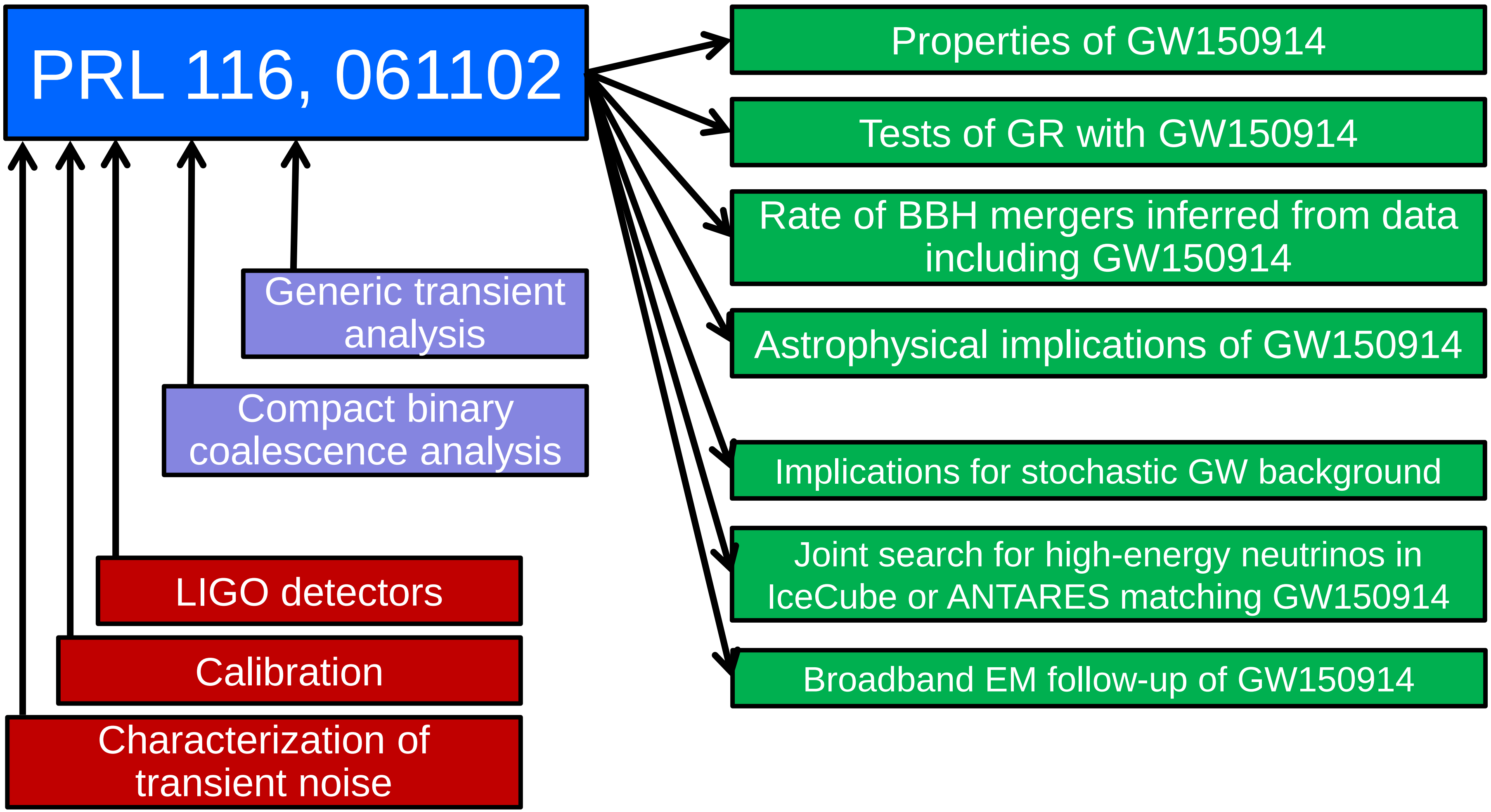
B. P. Abbott *et al.*[*]

(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



Available at https://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

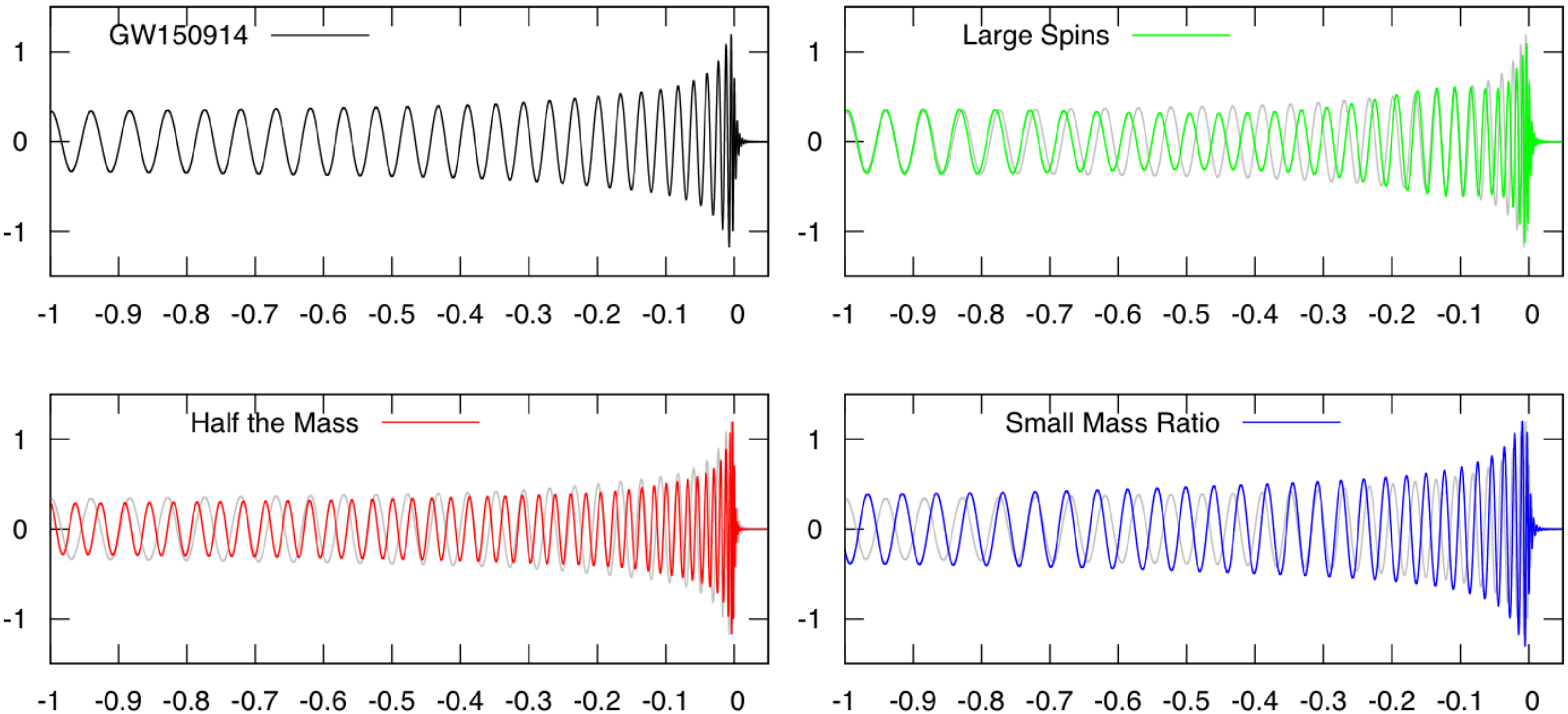


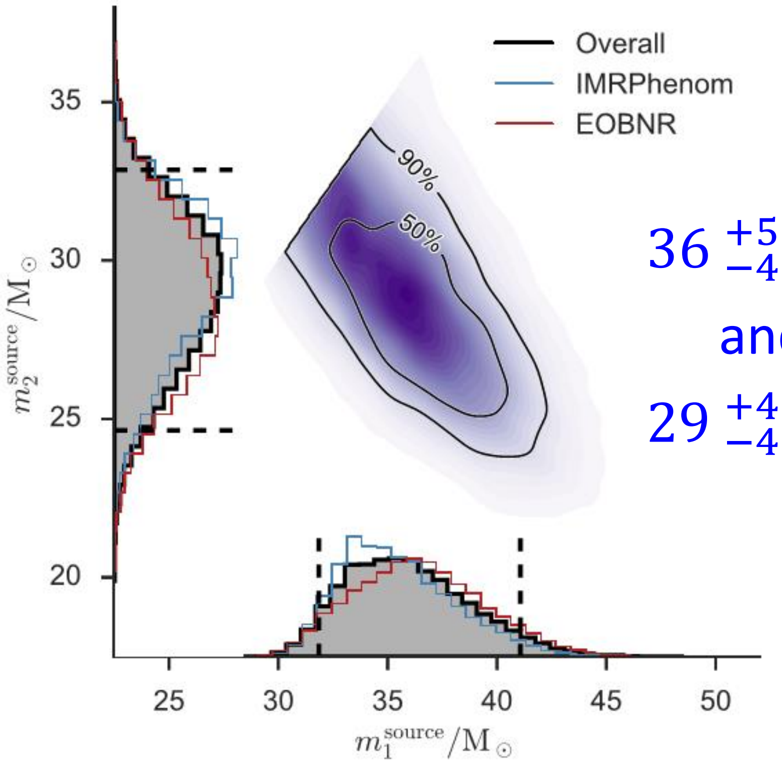
Illustration by N. Cornish and T. Littenberg

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

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: $0.67\,^{+0.05}_{-0.07}$

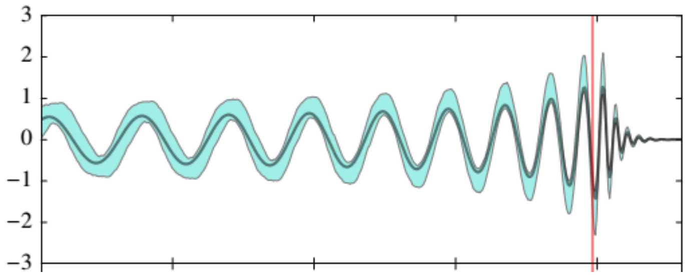
Abbott et al., arXiv:1602.03840

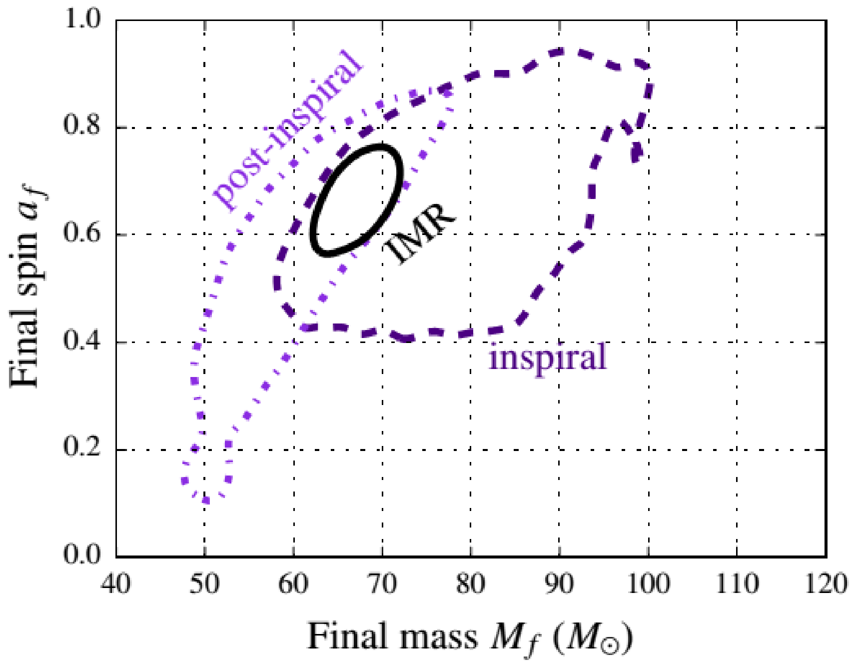
We examined the detailed waveform of GW150914 in several ways to see whether there is any deviation from the GR predictions

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





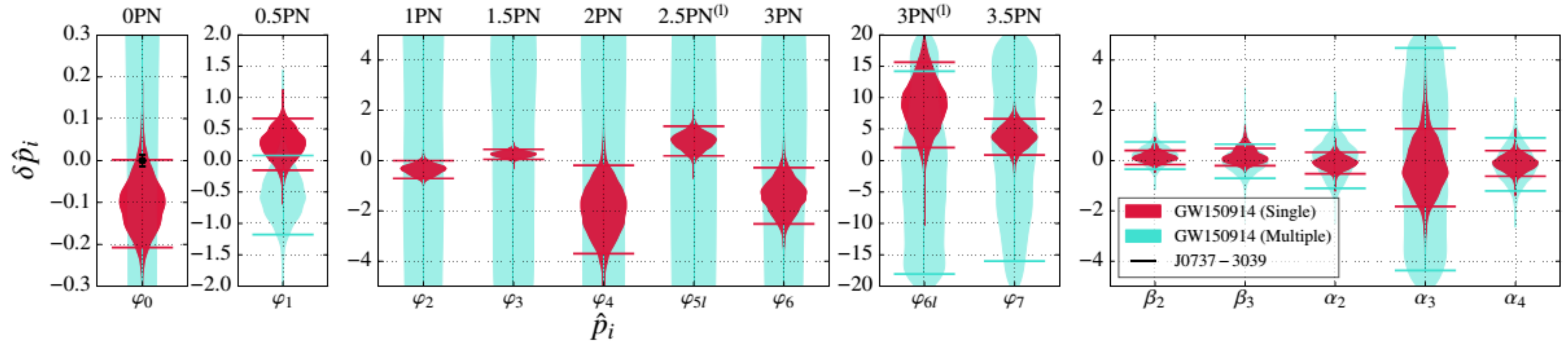
Pure ringdown of final BH?

Not clear in data, but consistent

Abbott et al., arXiv:1602.03841

Testing General Relativity

Allowing deviations in post-Newtonian waveform model



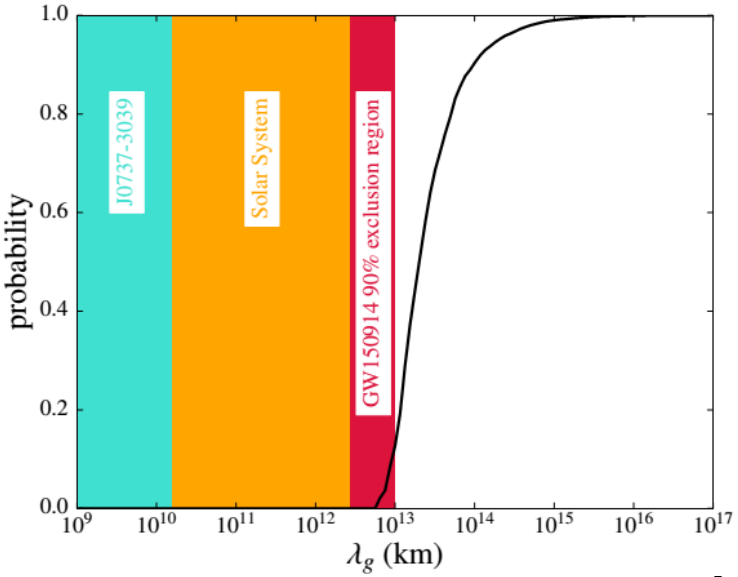
Parameter deviations are reasonably consistent with zero

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

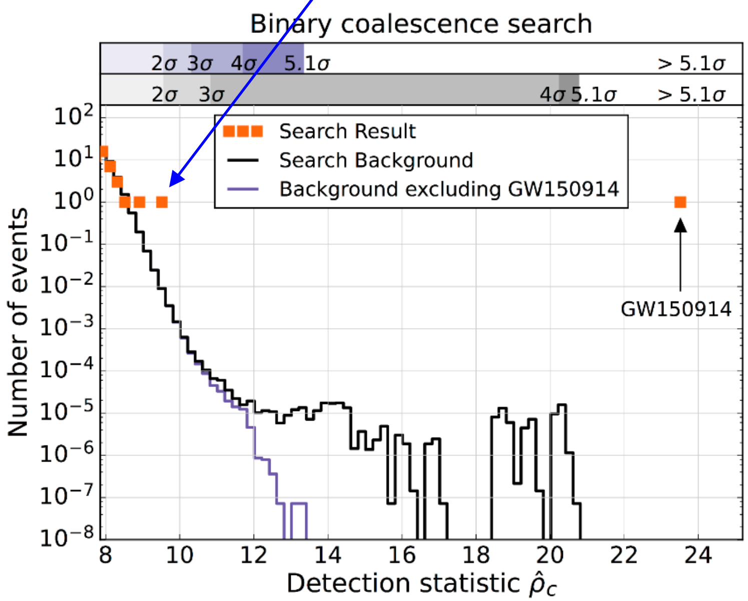
Abbott et al., ApJL **818**, L22 (2016)

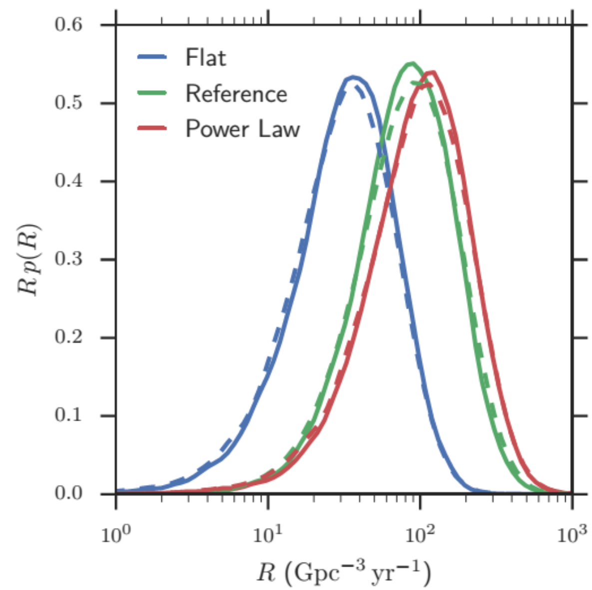
Inferring the Rate of BBH Mergers

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 weaker candidates which *could* be real, estimate (6 to 400) per year per Gpc^3





Abbott et al., arXiv:1602.03842

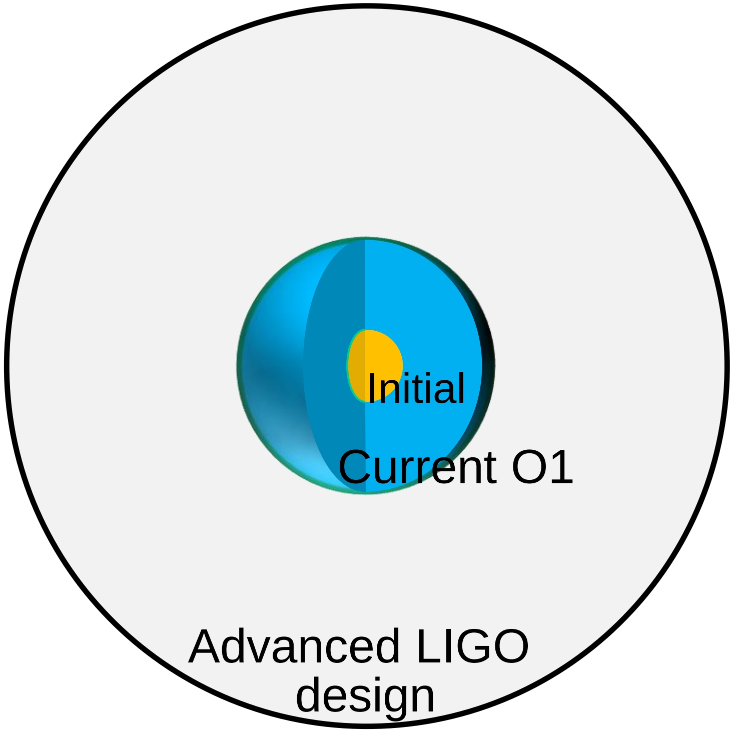
What's Next

Finish analyzing the rest of the O1 data

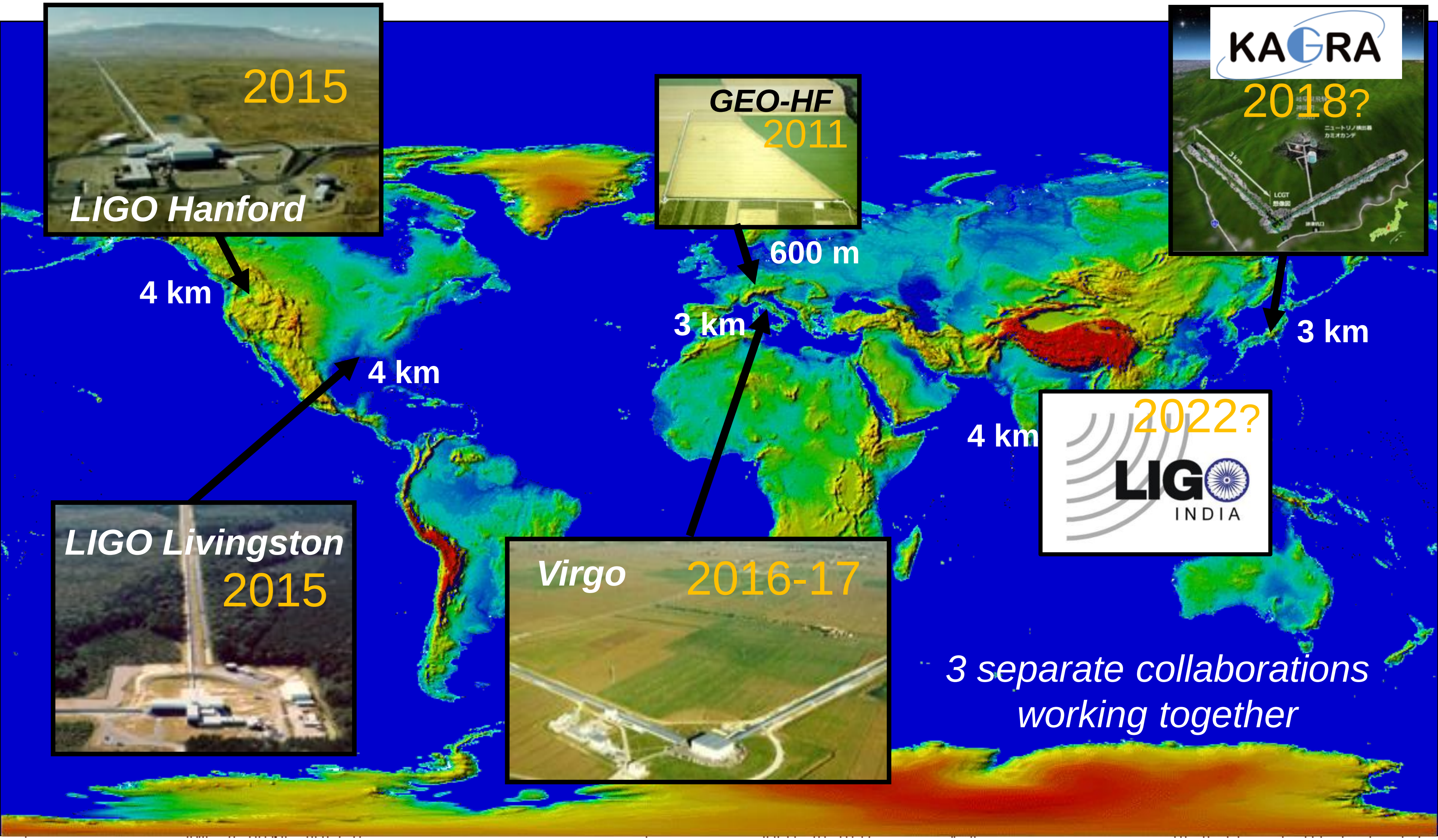
Complete our full suite of searches for various GW signals

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



Closing Remarks

Decades of patient work and faith finally paid off !

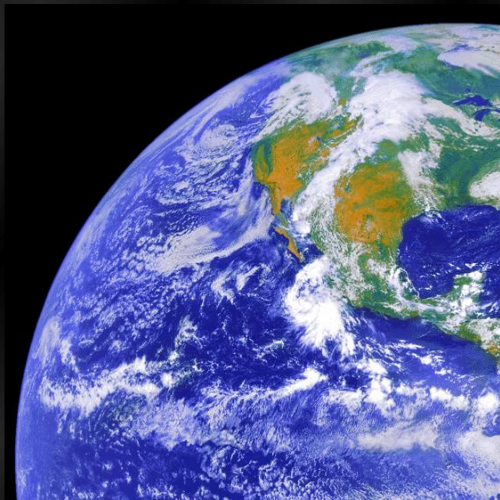
We were lucky that our first detected event was so spectacular

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

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!

Special Collections and University Archives, University of Maryland Libraries

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

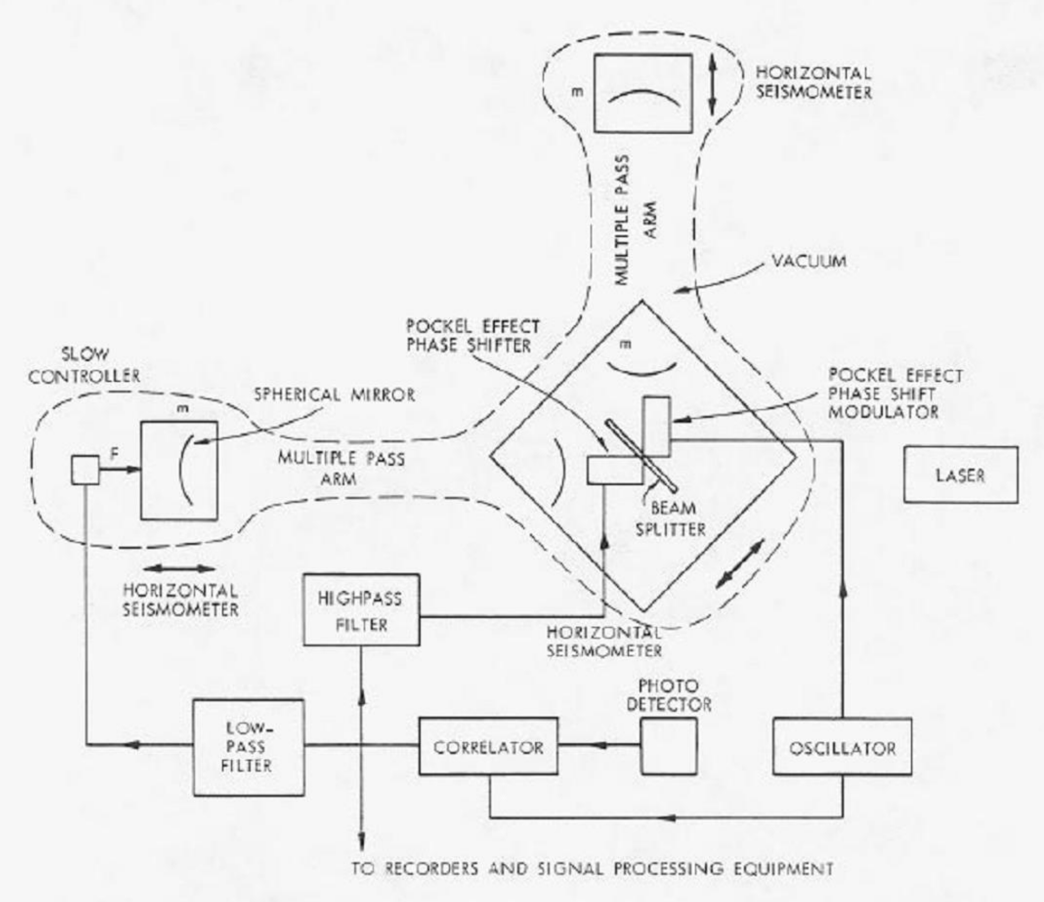
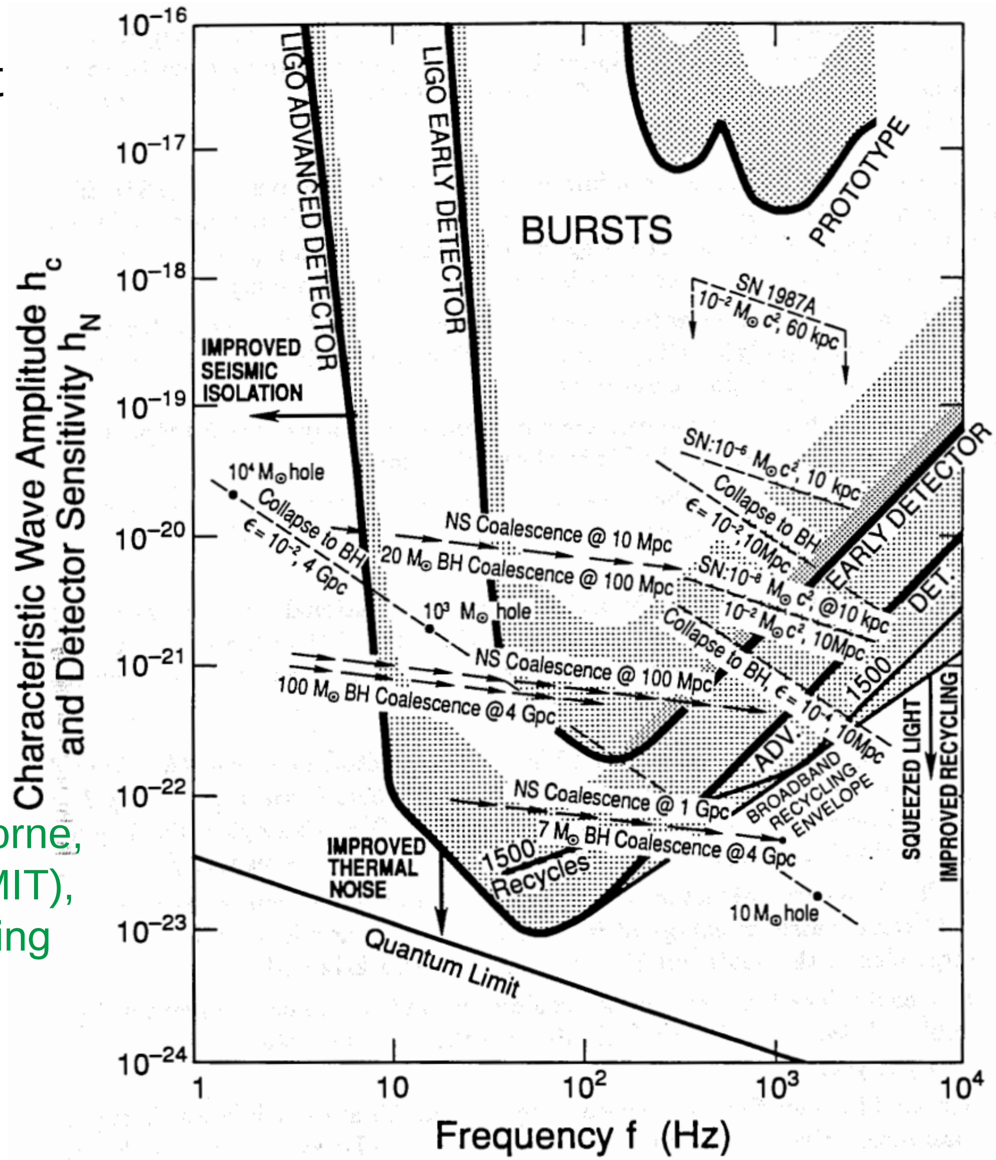


Fig. V-20. Proposed antenna.

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



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

Estimated Rates of Binary Coalescence

All over the board, really…

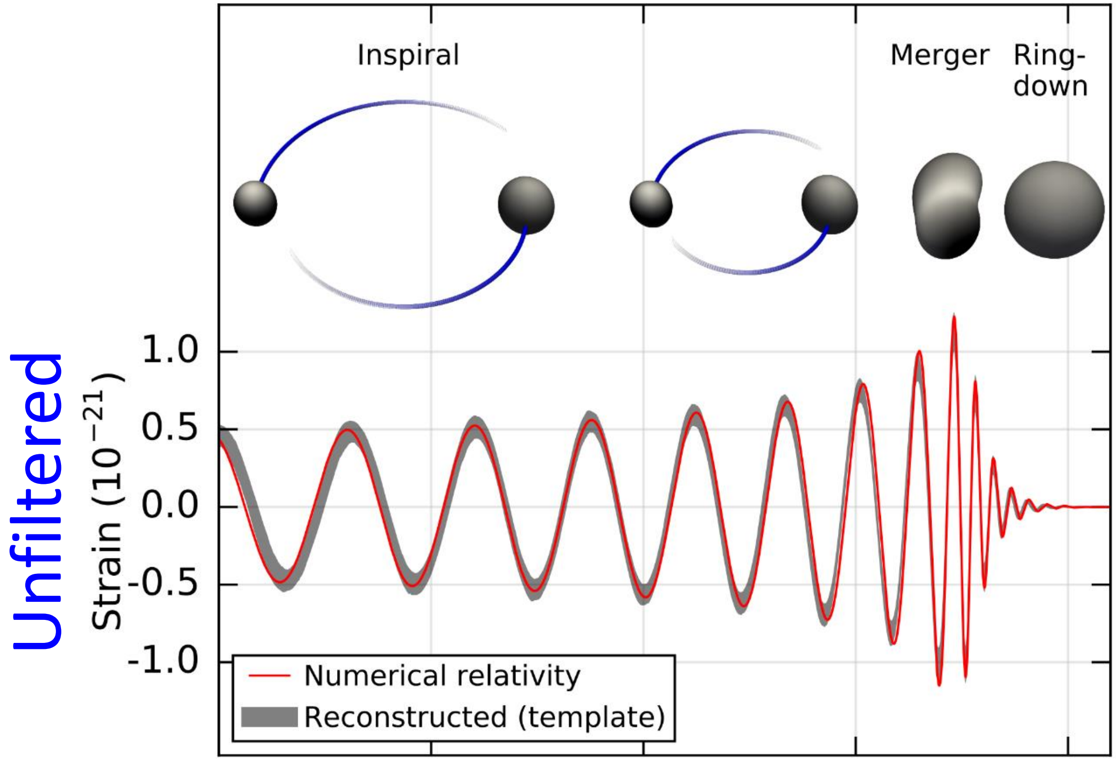
"Realistic" (??) estimated rates

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	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]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	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)

Form of a Binary Coalescence Signal

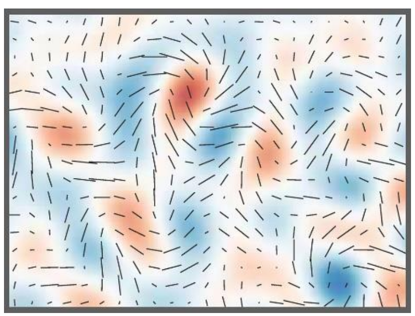
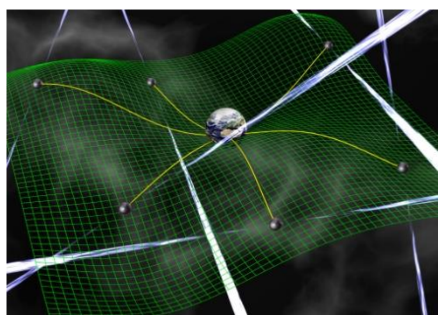
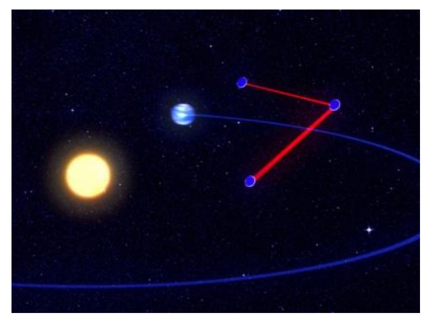


The rapidity of the “chirp” tells us about the masses of the objects

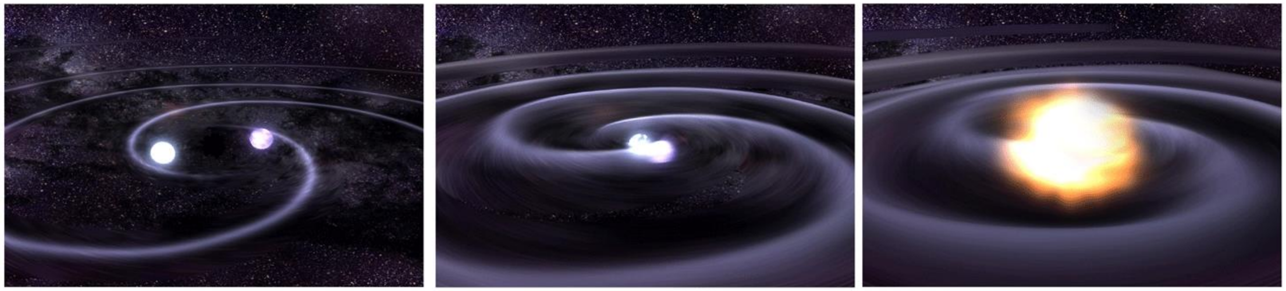
Faster chirp ➔ Higher mass

➔ This looks like a binary black hole coalescence!

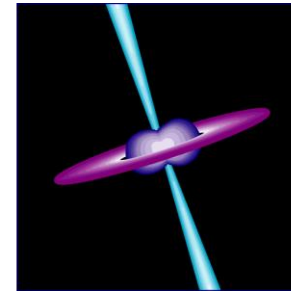
The Wide Spectrum of Gravitational Waves

	$\sim 10^{-17}$ 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 **Ultra-compact Galactic binaries**	Neutron stars, stellar-mass BHs **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 / 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

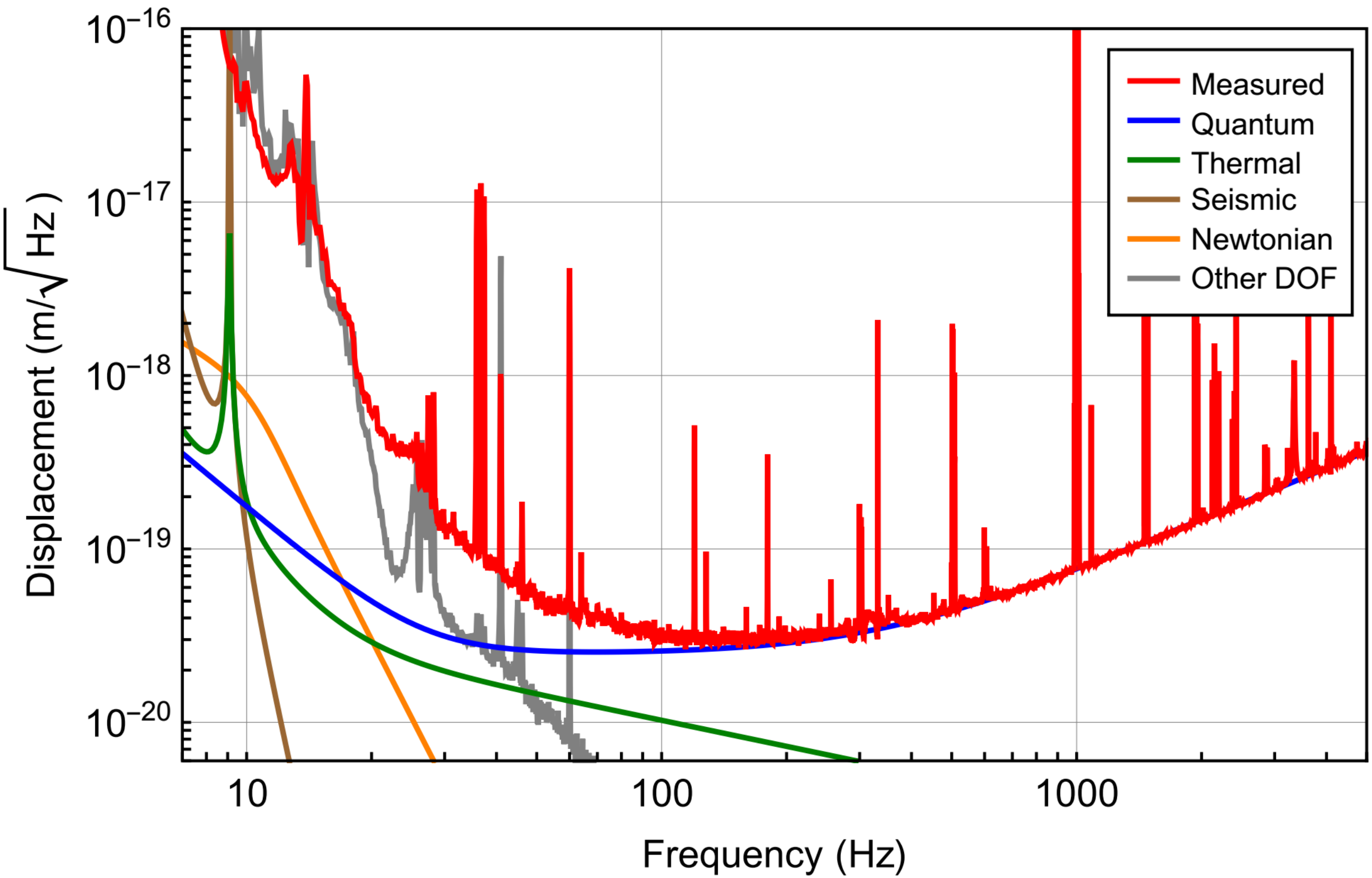
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400

Planning for Virgo to join late next year, then KAGRA in a few years

Still very uncertain when we'll detect the first GW signal(s)

Wide range of estimates from observed binary pulsars and population synthesis simulations – begs for observational truth!

LIGO Detector Noise Components



From Abbott et al., arXiv:1602.03838

Effect of Data Quality Cuts

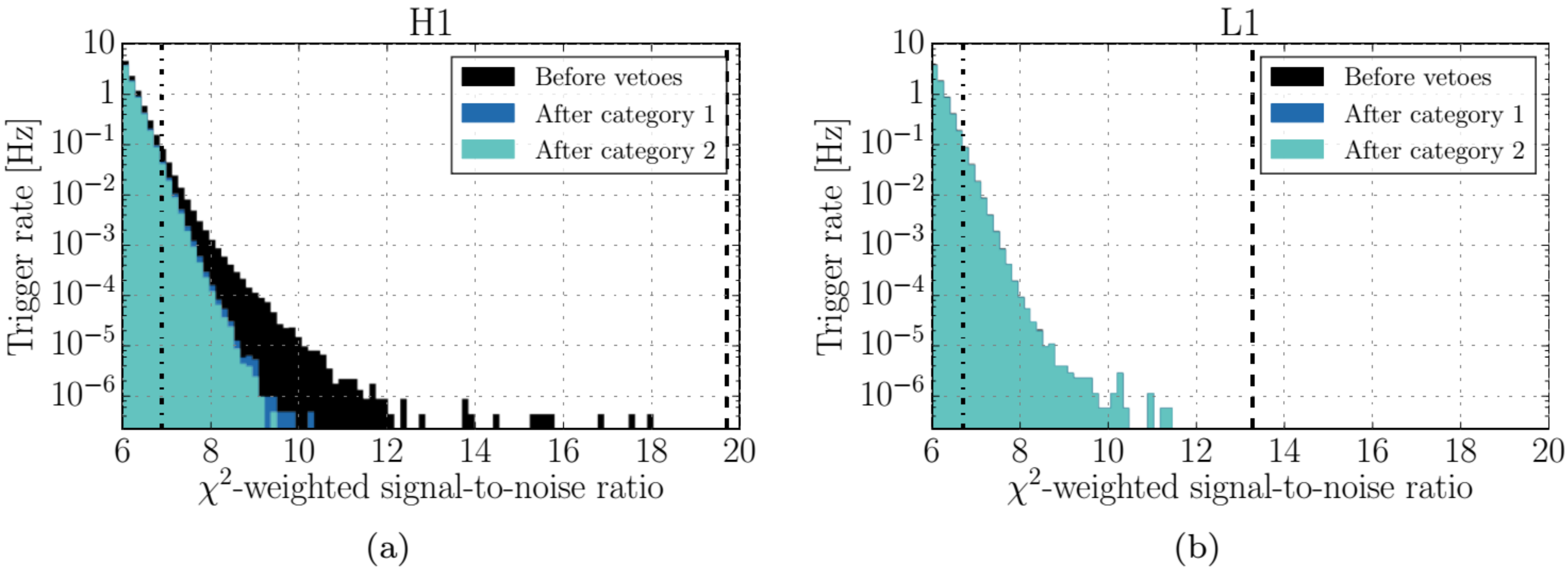
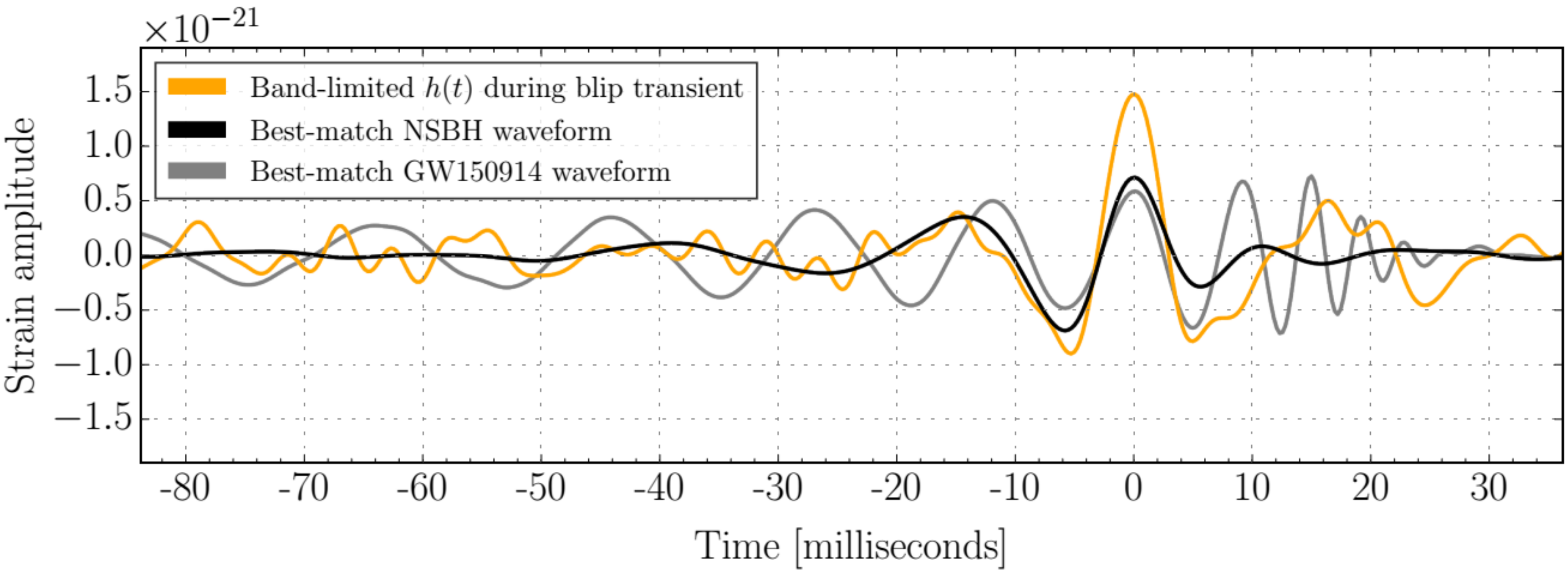


Figure 7: The impact of data-quality vetoes on the CBC background trigger distribution for (a) LIGO-Hanford and (b) LIGO-Livingston. The single-detector χ^2-weighted SNR of GW150914 is indicated for each detector with a dashed line (19.7 for Hanford and 13.3 for Livingston), and for event LVT151012 with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

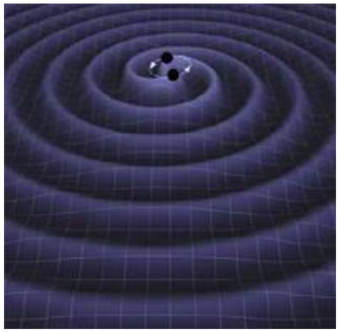
From Abbott et al., arXiv:1602.03844

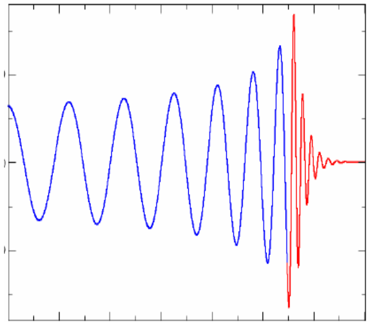
A Closer Look at a “Blip Transient”



From Abbott et al., arXiv:1602.03844

Searches for GW Transient Sources

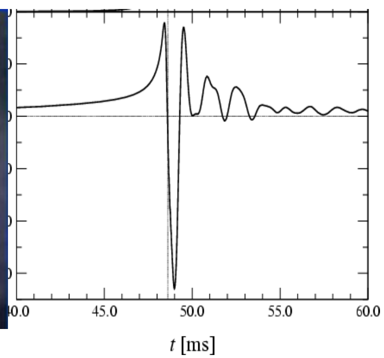




Compact Binary Coalescence (CBC)

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

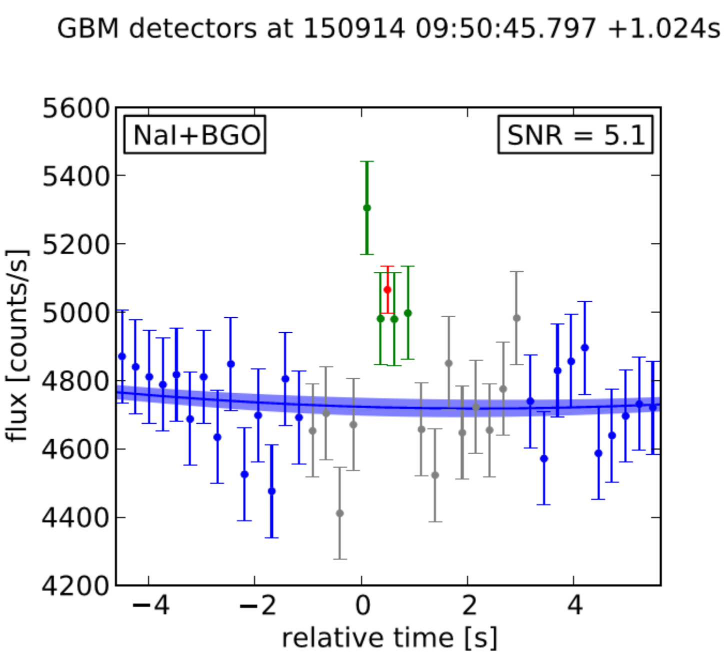
With coherent analysis, identify event candidates and generate preliminary sky position probability maps within a few minutes

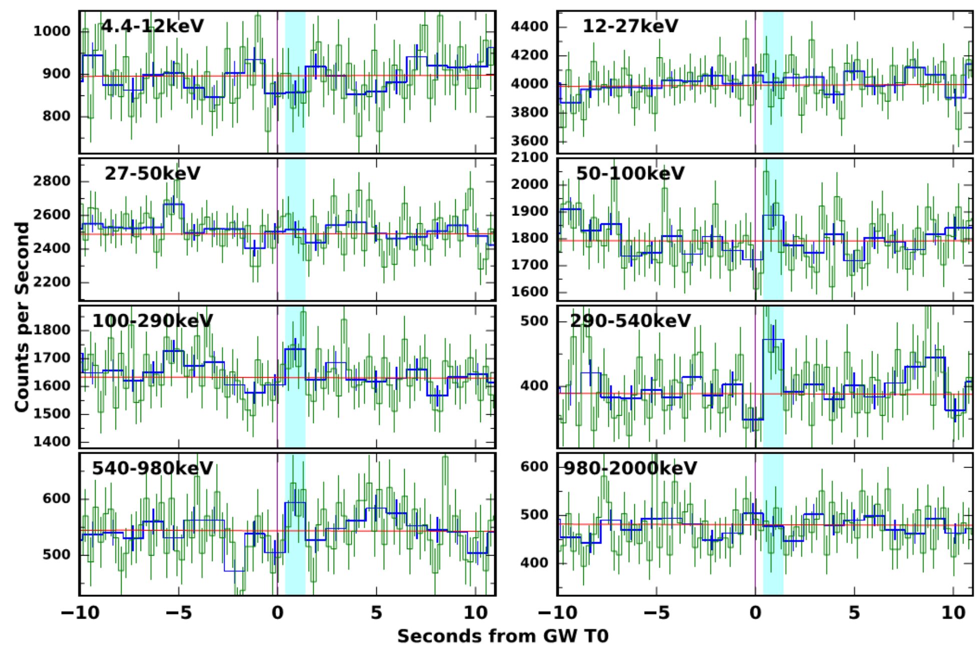
Possible Gamma-ray Counterpart??

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., arXiv:1602.03920

Post-trials false alarm prob ~ 0.0022





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