Gravitational Waves and How to Detect Them

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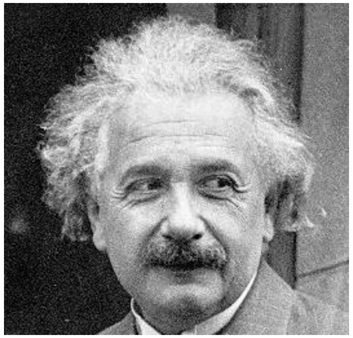
GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

Gravitational Waves

Predicted to exist by Einstein's general theory of relativity



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

Expressed mathematically by the Einstein field equations

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

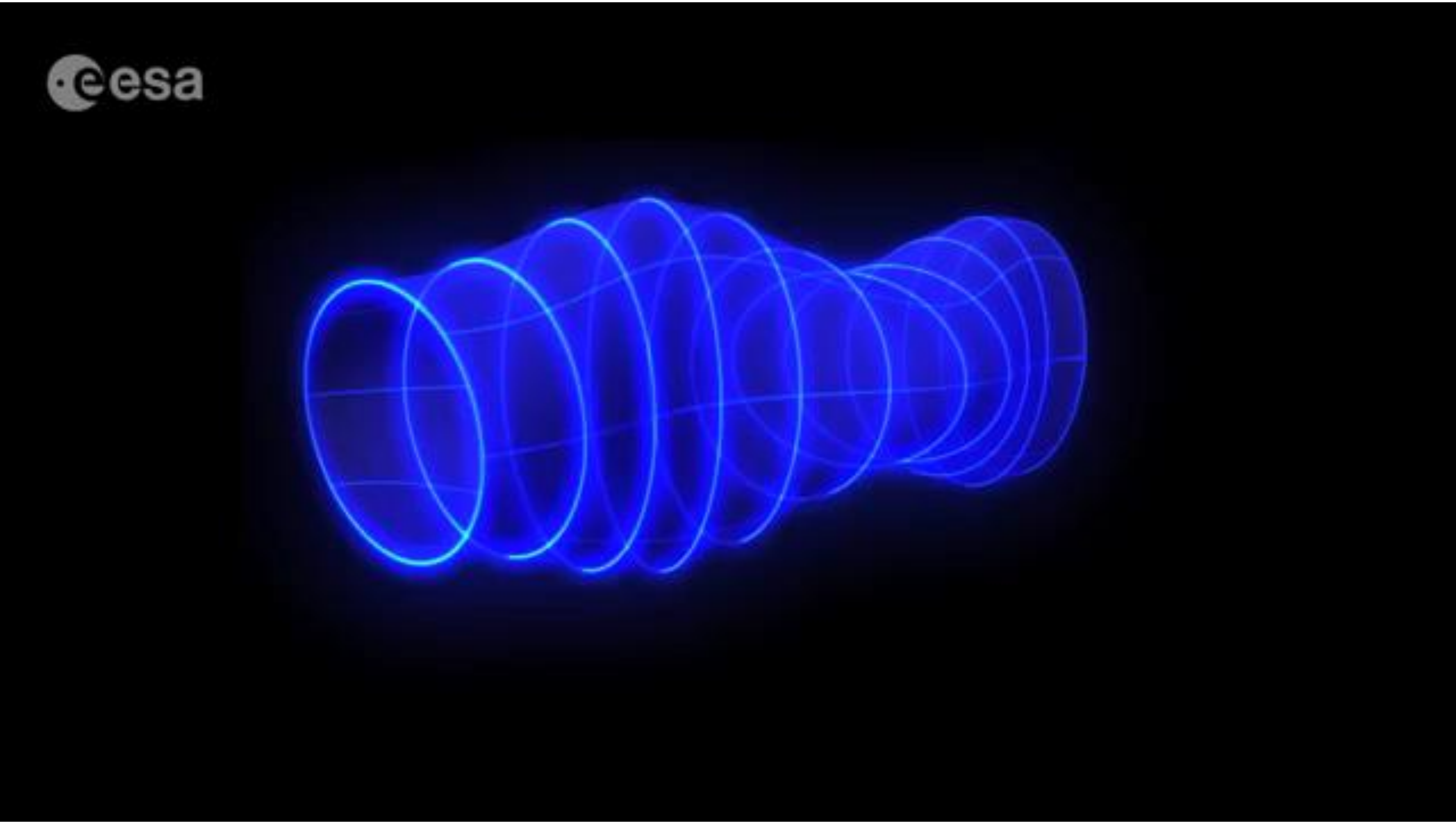
These waves are *perturbations of the spacetime metric* —
the effective distance between points in space and time

$$g_{\mu\nu}$$

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

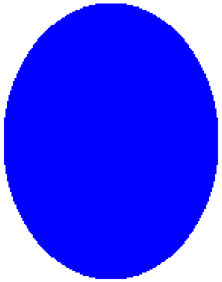
It alternately *stretches* and *shrinks* in a characteristic way

Gravitational Waves in Motion

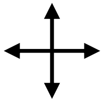


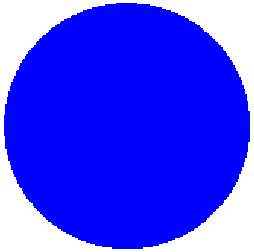
Gravitational Wave Polarizations

One convenient basis:

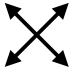


“Plus” polarization



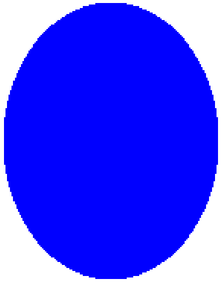


“Cross” polarization

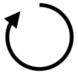


Any linear combination of these is a solution

Including, but not limited to:



Circular polarization



Gravitational Wave Strain

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

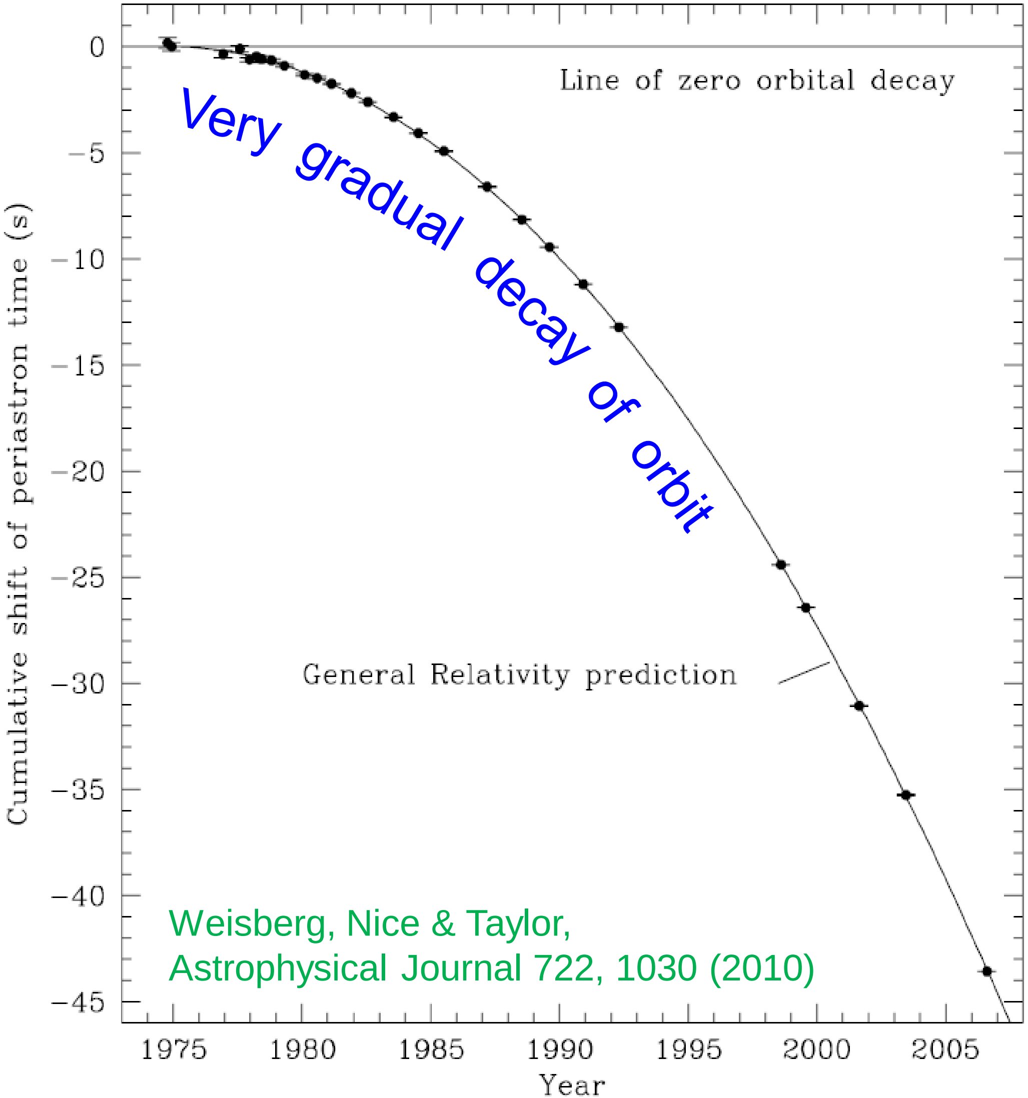
The stretching is described by a dimensionless strain, $h = \Delta L / L$

h is inversely proportional to the distance from the source

First Evidence for Gravitational Waves

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

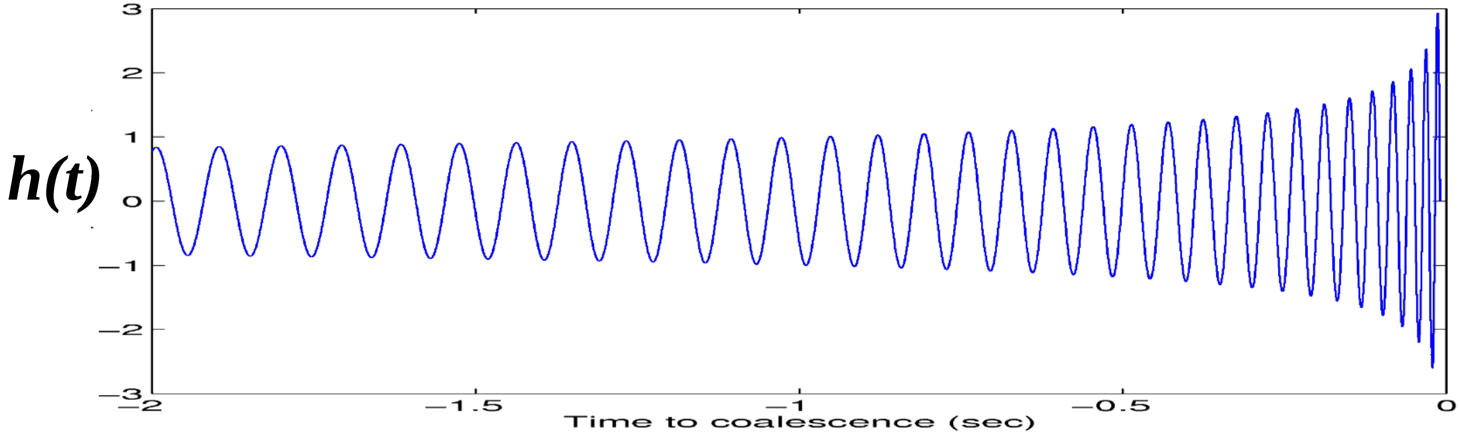
This binary neutron star system is changing, just as general relativity predicts!
Very strong <u>indirect</u> evidence for gravitational radiation



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

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

How can we possibly hope to measure such small length changes?

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)

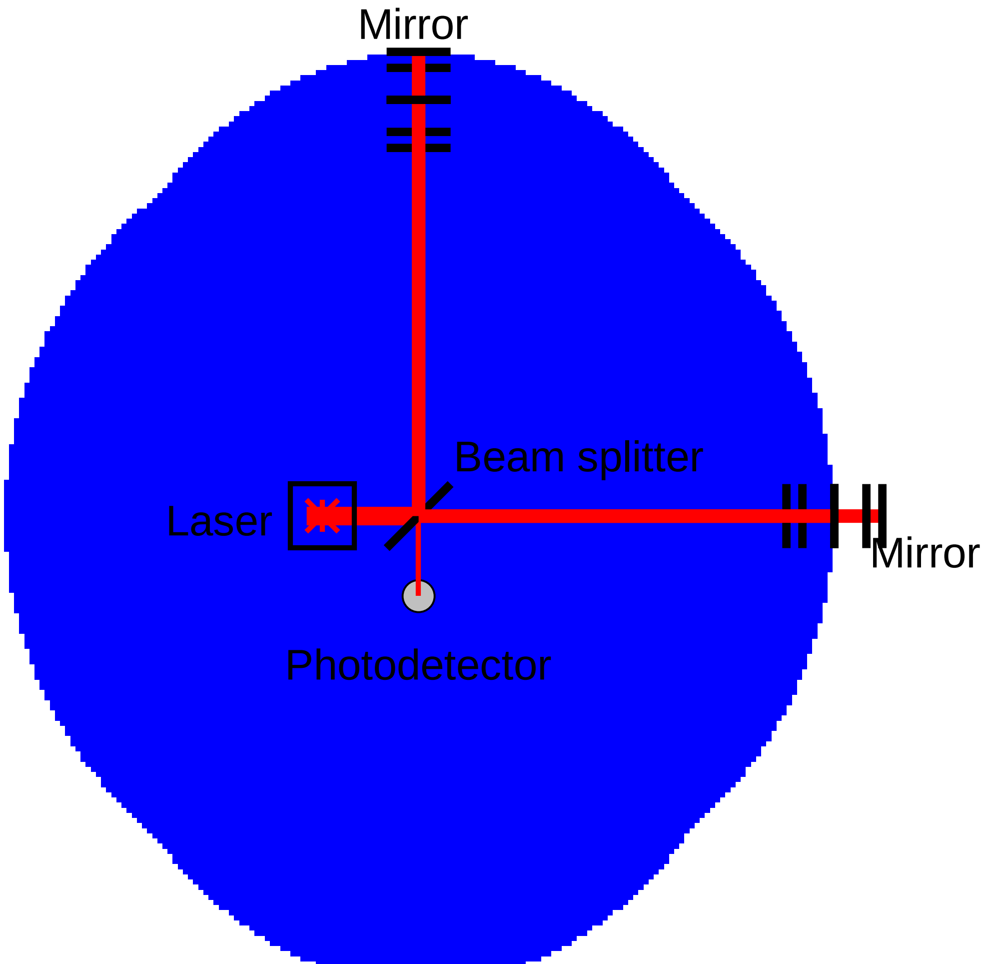
J. Weber, "Detection and generation of gravitational waves", Phys. Rev. **117**, 306 (1960)

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

A Laser Interferometer as a GW Detector

Variations on basic Michelson design, with two long arms

Measure *difference* in arm lengths to a fraction of a wavelength

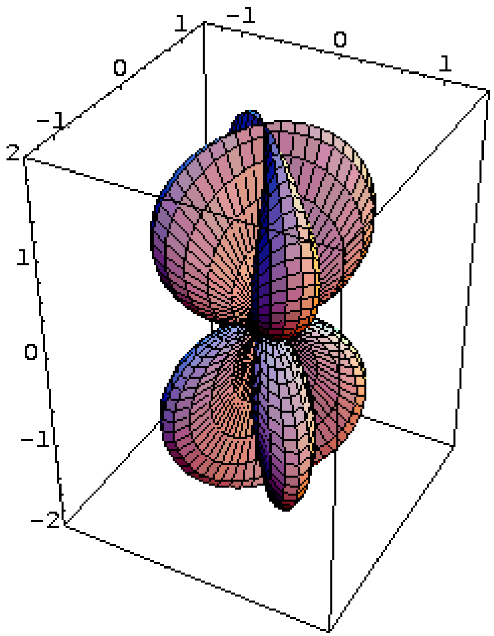


Response depends on the polarization of the wave

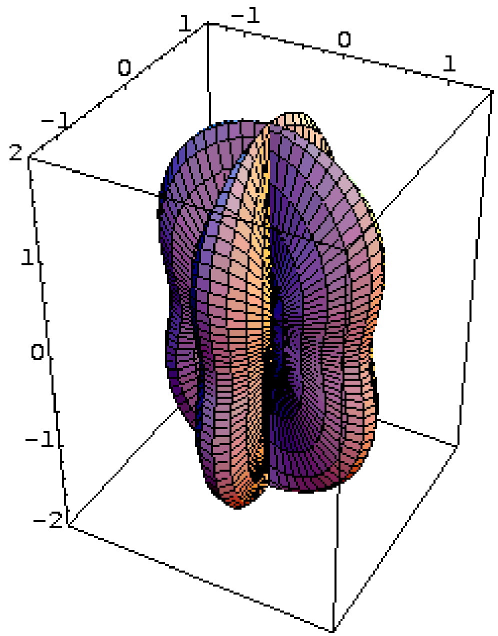
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

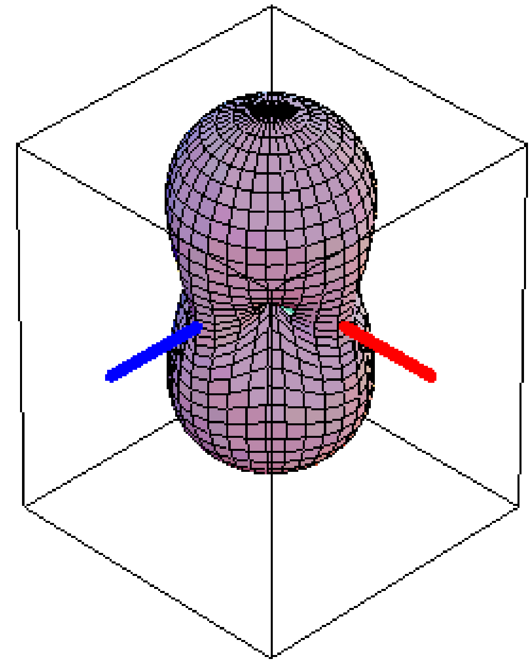
“×” polarization



“+” polarization



RMS sensitivity



A broad antenna pattern

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

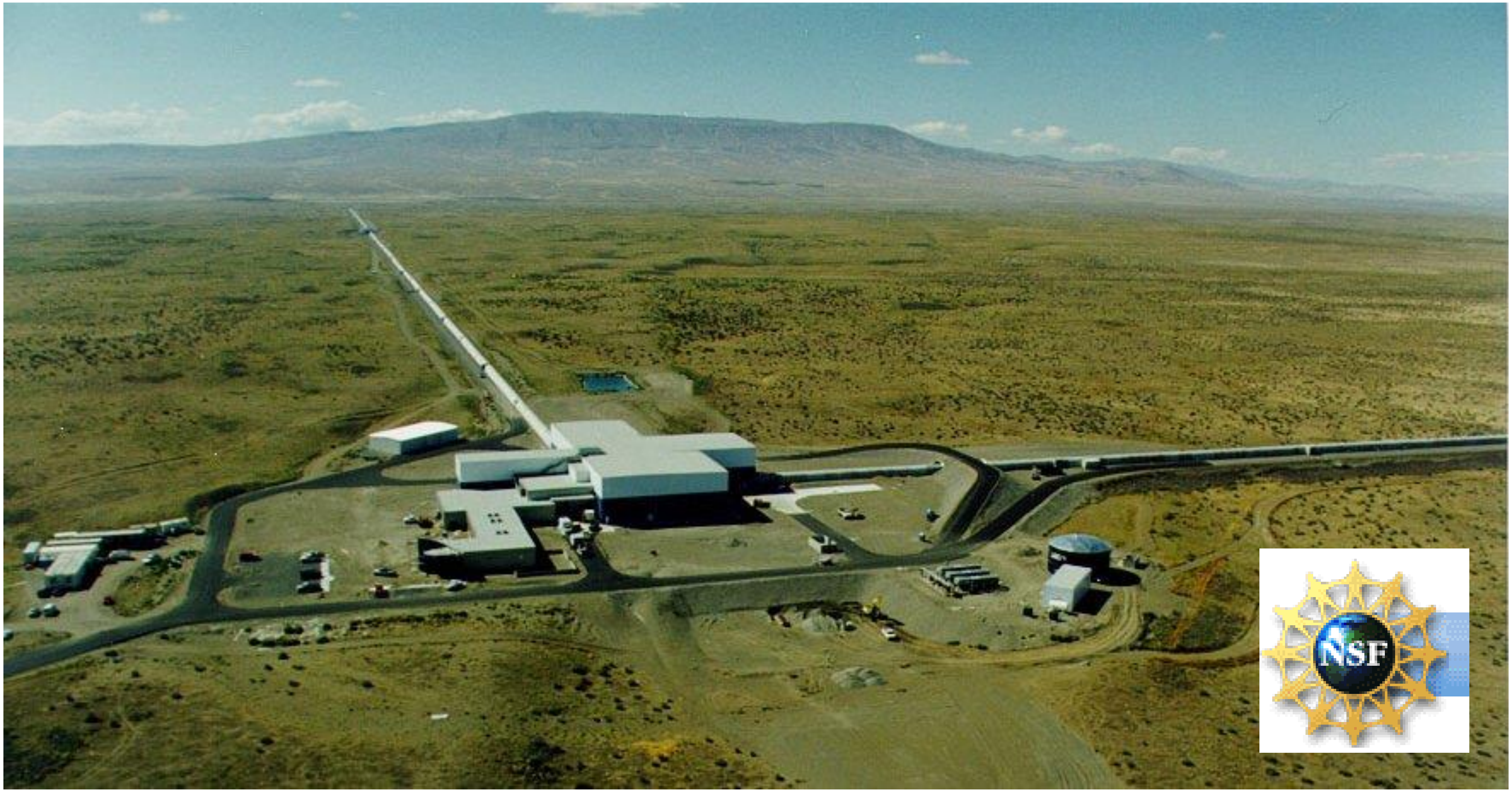
LIGO: Laser Interferometer Gravitational-wave Observatory

Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov

NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

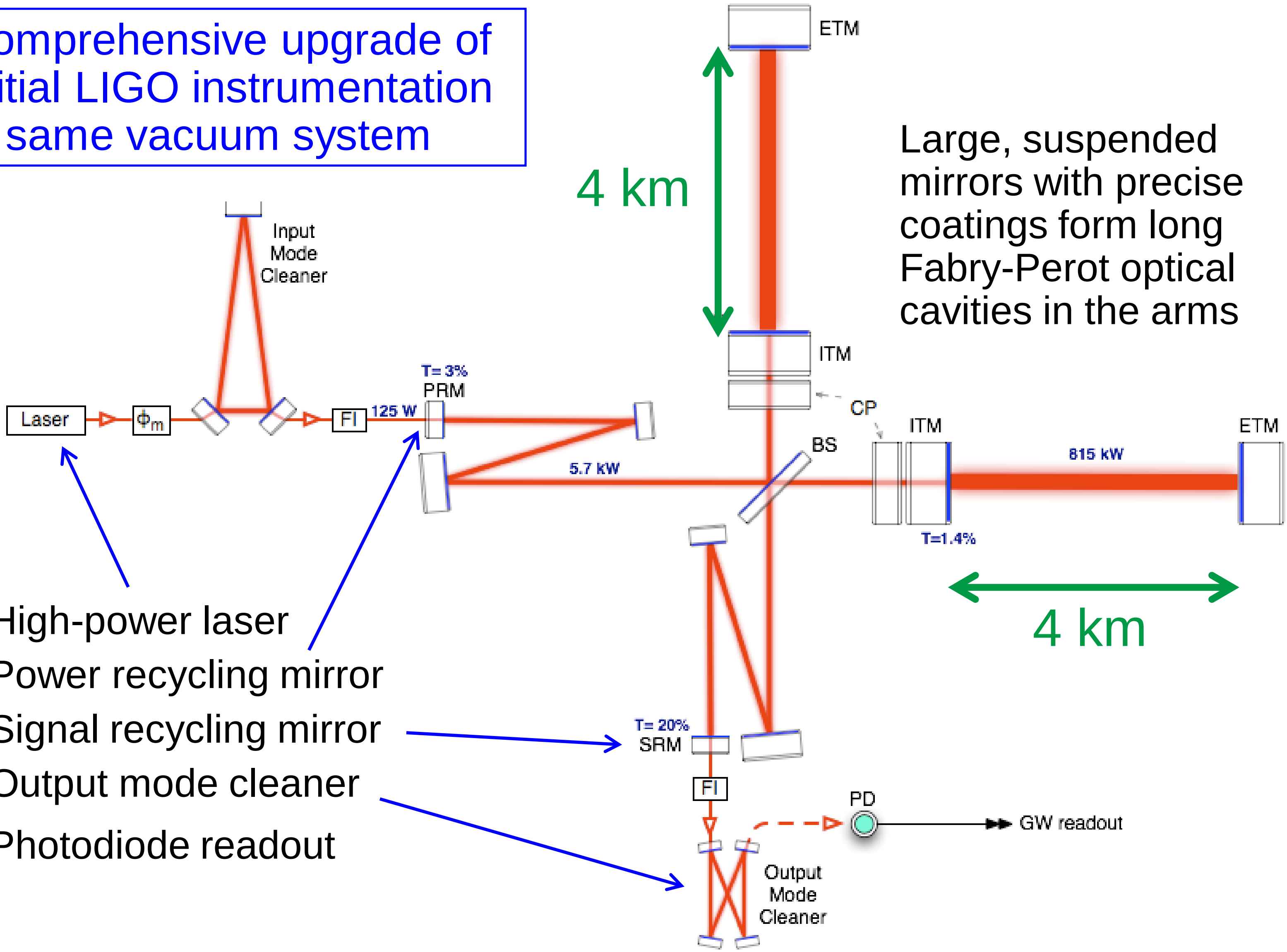
Beam Tube

Stainless steel, ~1 m in diameter, welded into 2 km lengths

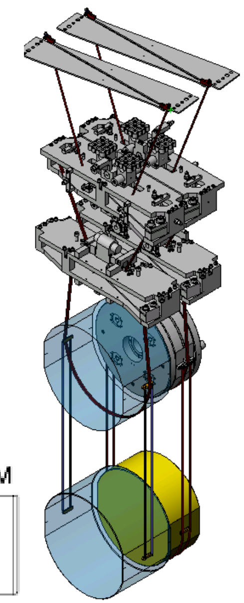
Baked to drive off adsorbed water vapor

Advanced LIGO Optical Layout

Comprehensive upgrade of Initial LIGO instrumentation in same vacuum system



Large, suspended mirrors with precise coatings form long Fabry-Perot optical cavities in the arms

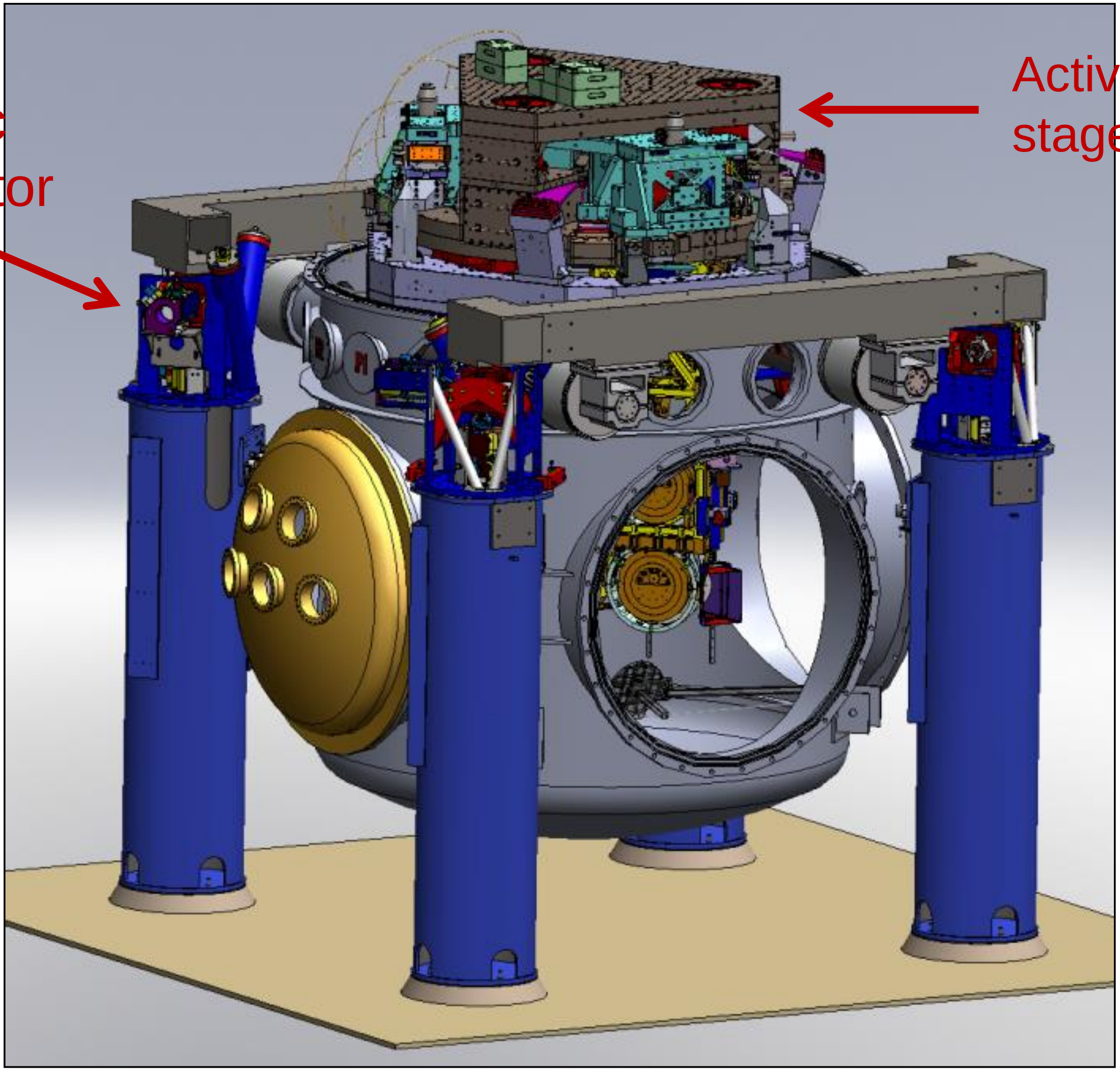


- High-power laser
- Power recycling mirror
- Signal recycling mirror
- Output mode cleaner
- Photodiode readout

Vacuum System in Corner Station

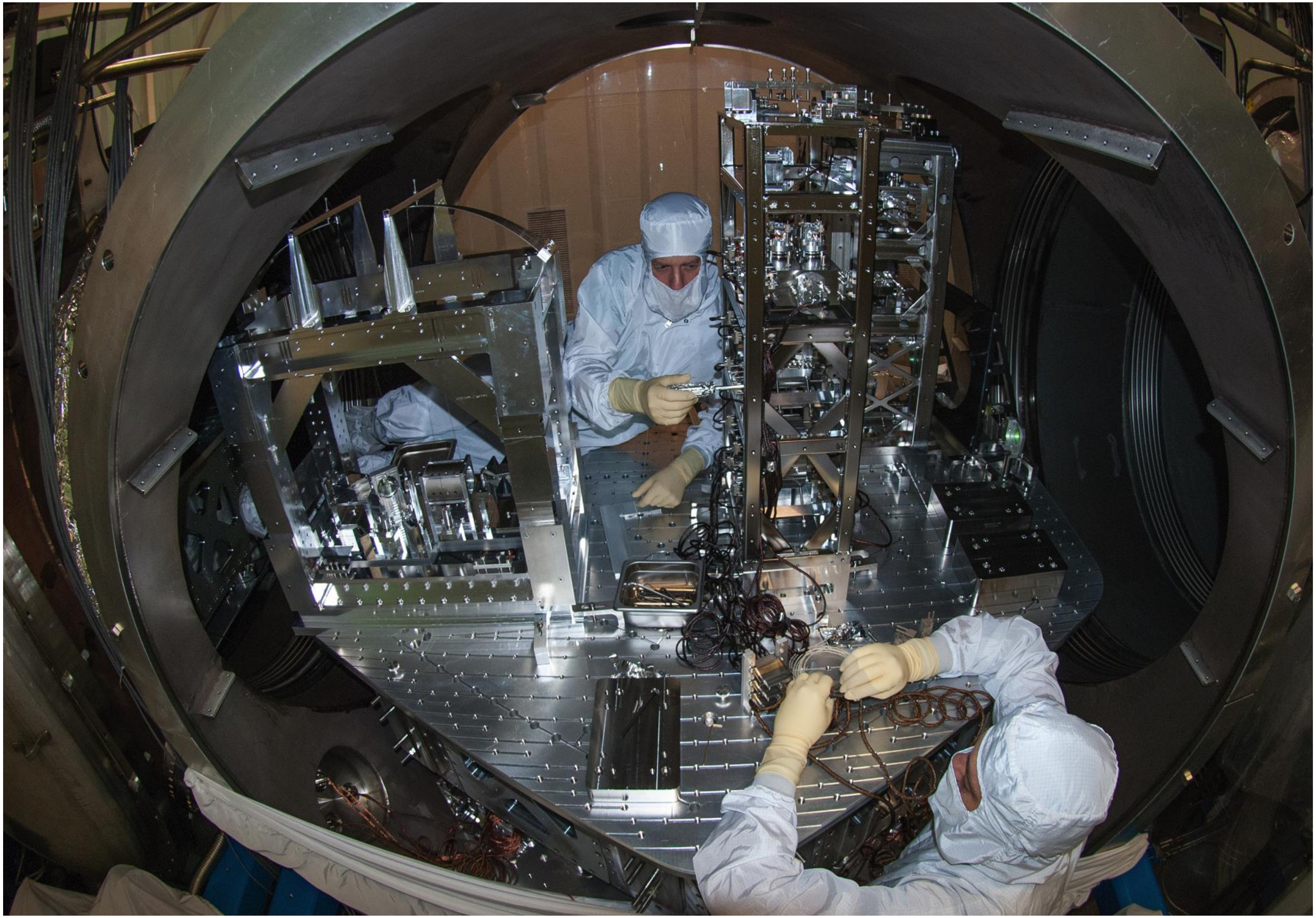
Suspension System (dome removed)

Hydraulic pre-isolator



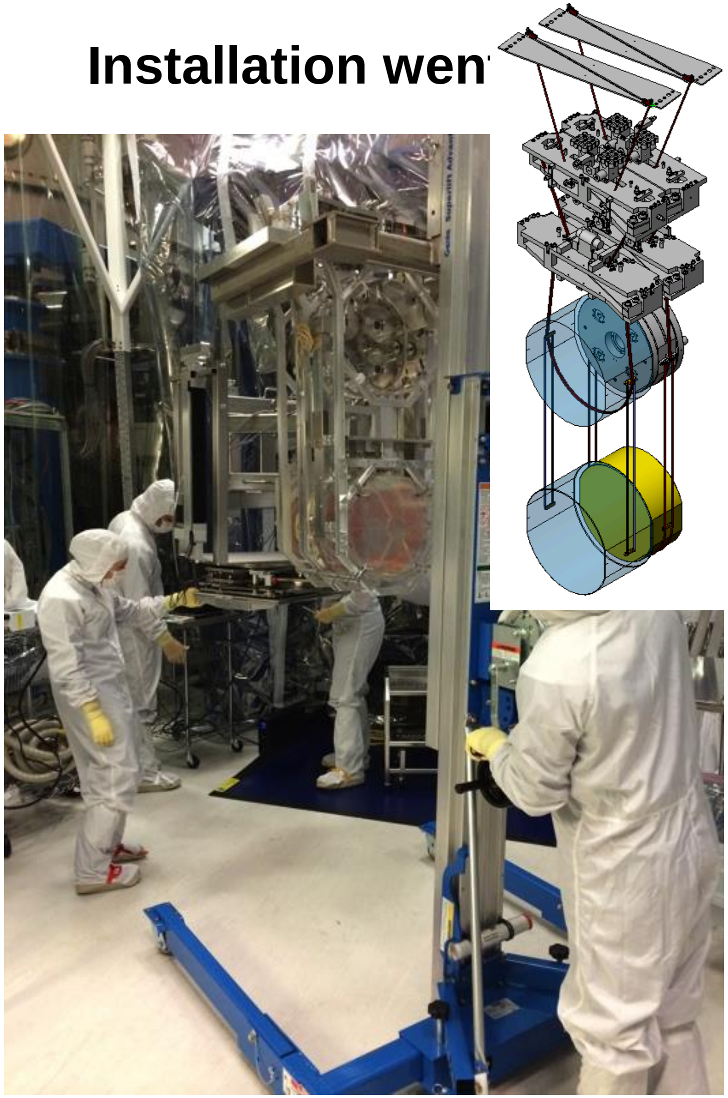
Active isolation stage (in vacuum)

Inside a Vacuum Chamber

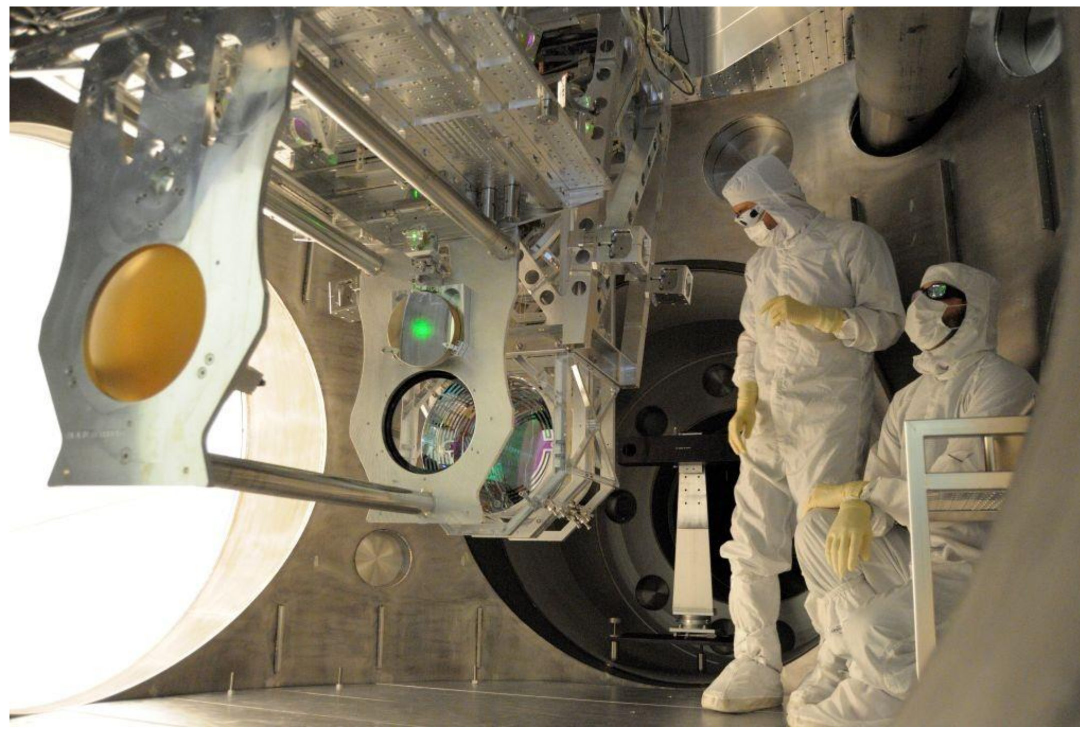


Advanced LIGO Installation

Installation wen noothly at both LIGO observatories



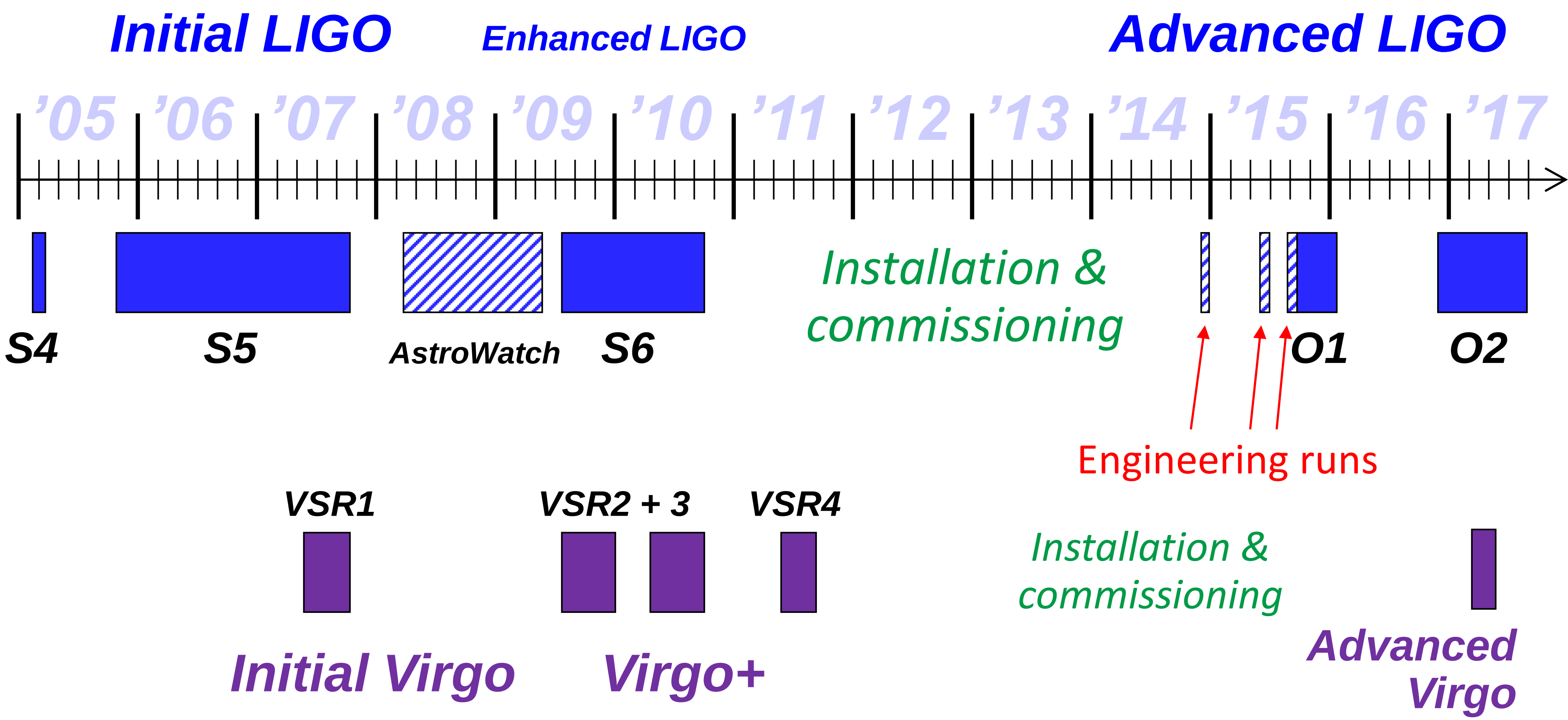
Achieved full interferometer lock in 2014, first at LIGO Livingston, then at LIGO Hanford



LIGO Detector Sensitivities

Past Observing Runs

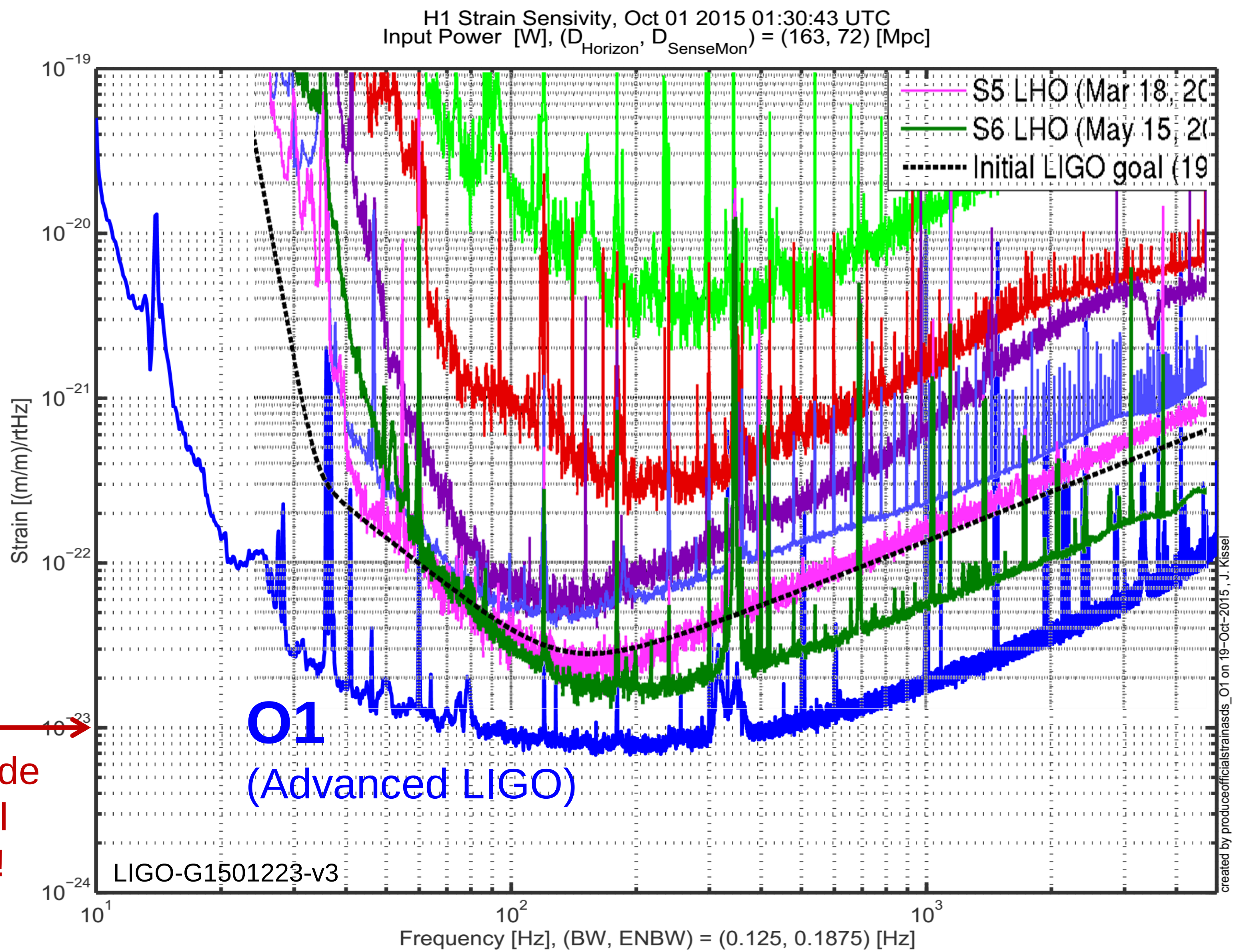
In 2015, completed (basically) a 5-year upgrade to Advanced LIGO



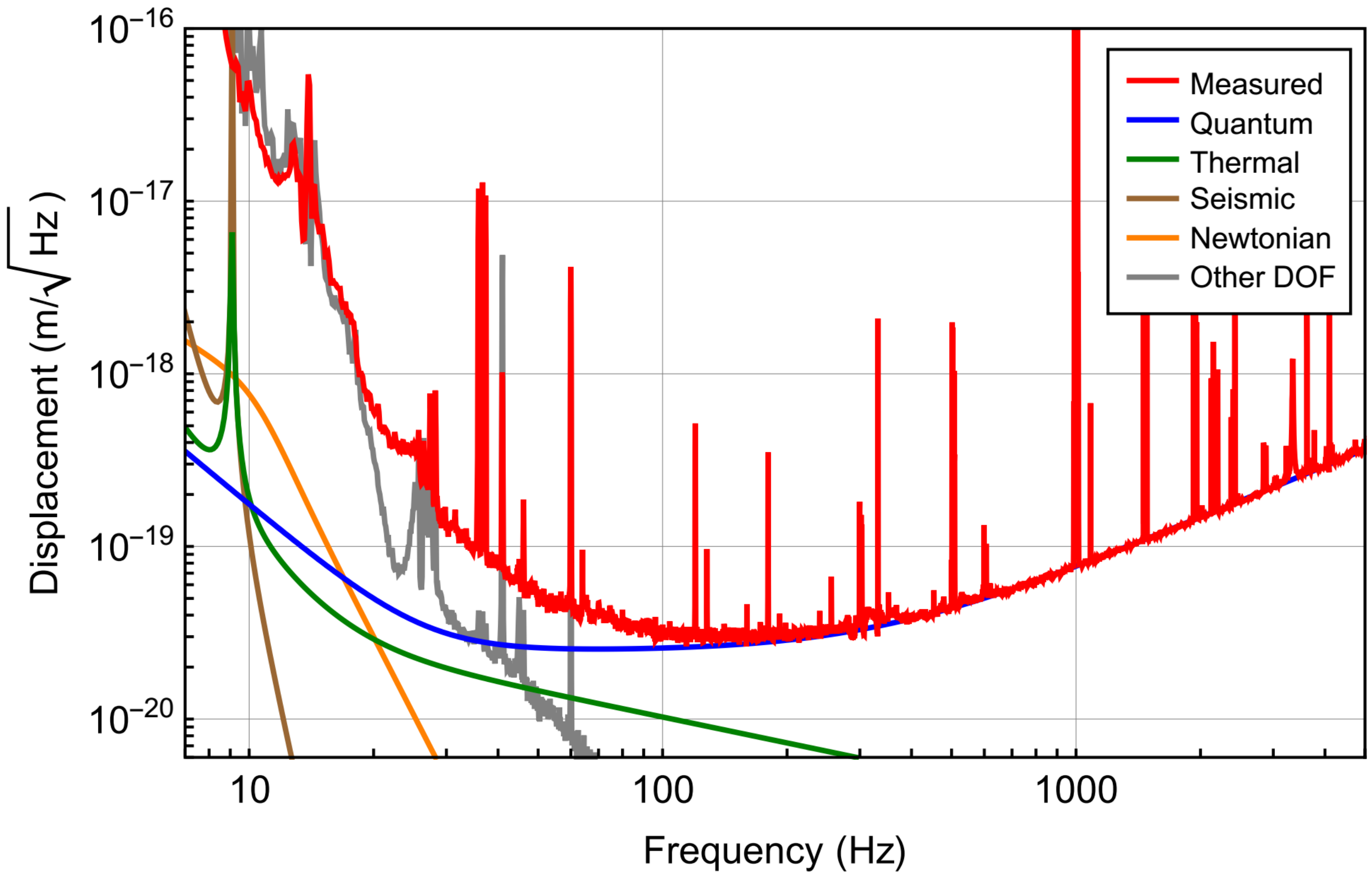
Meanwhile, GEO600 has run more-or-less continuously to demonstrate advanced technologies and to maintain "AstroWatch" vigil

Evolution of LIGO GW Strain Sensitivity

10^{-23} amplitude spectral density!

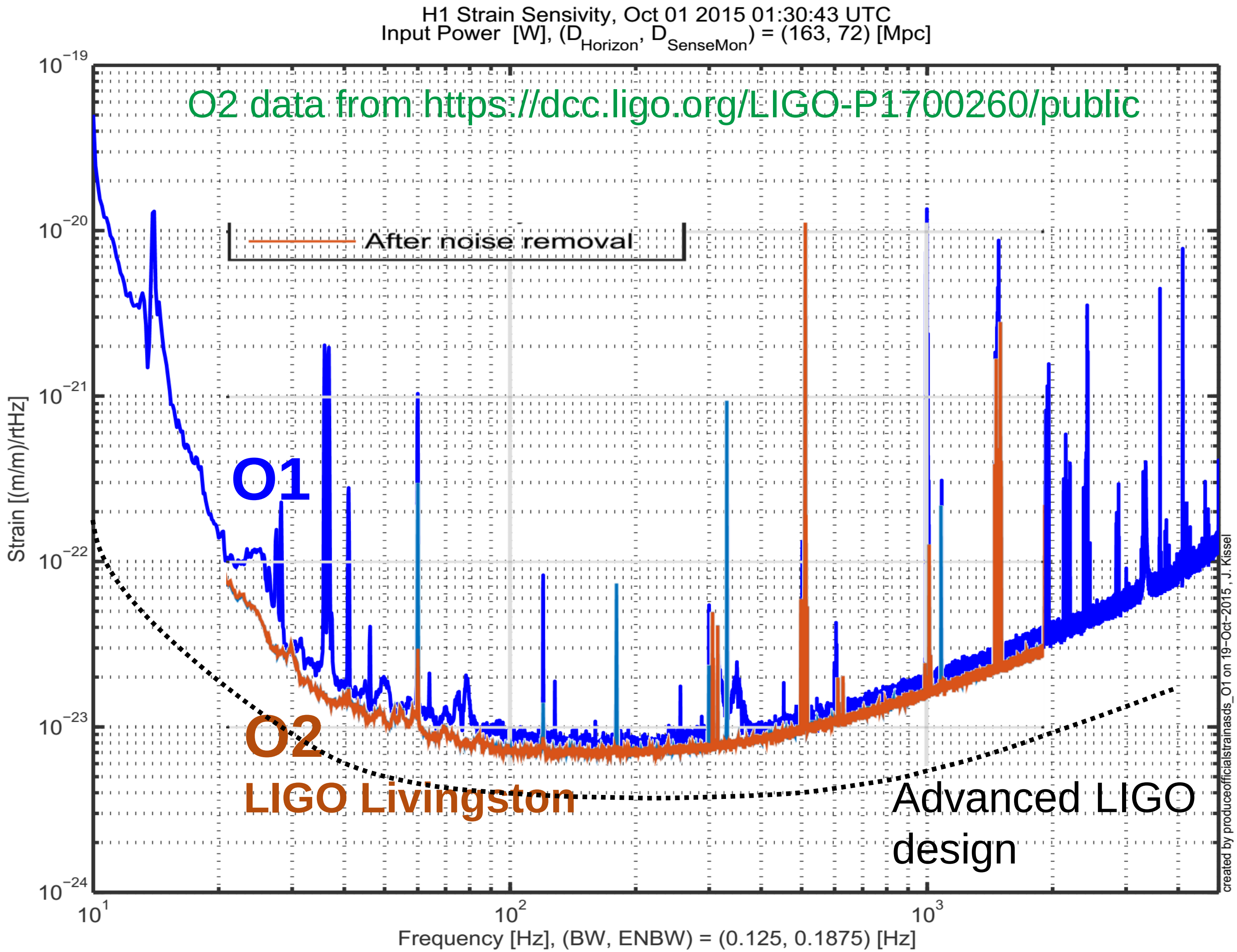


LIGO Detector Noise Components

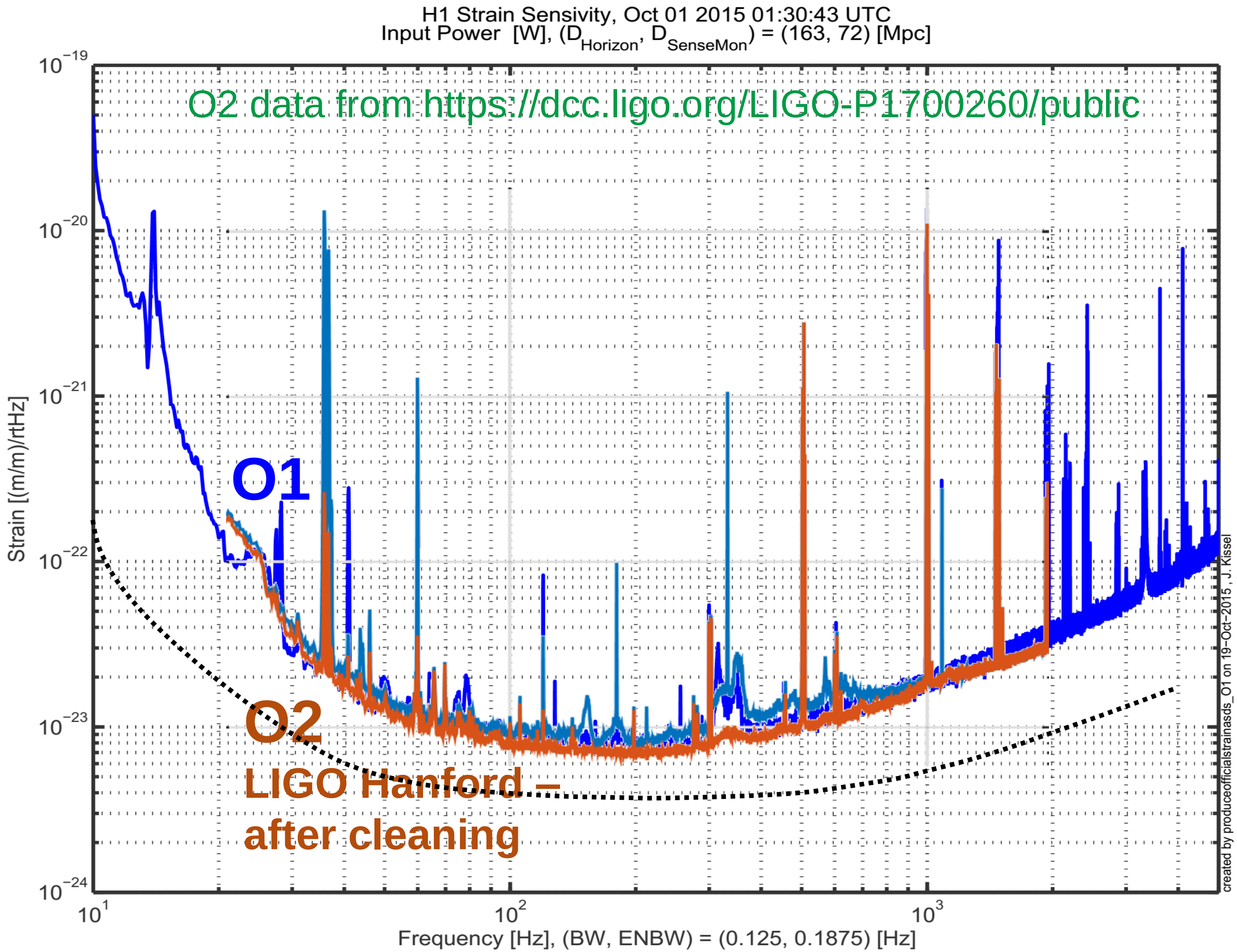


From Abbott et al., PRL 116, 131103 (2016) / arXiv:1602.03838

Sensitivites during O2 run (2016–17)



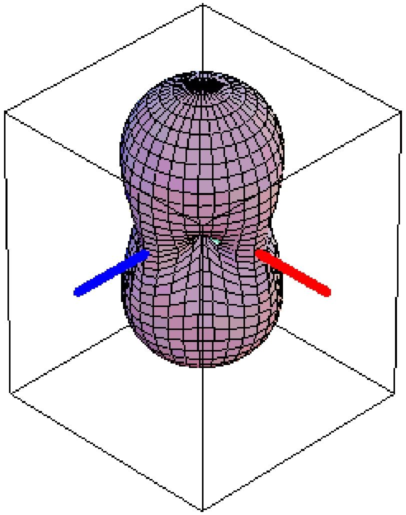
Sensitivites during O2 run (2016–17)



Summaries of Sensitivity

The *range* of a GW detector is defined as the distance at which a NS-NS binary ($1.4 + 1.4\ \mathrm{M}_{\odot}$) would be detected with S/N=8, averaged over all sky positions and orientations of the binary orbit

The *horizon* of a GW detector is defined as the distance at which a NS-NS binary ($1.4 + 1.4\ \mathrm{M}_{\odot}$) would be detected with S/N=8, for an optimal sky position and orbit (face-on)



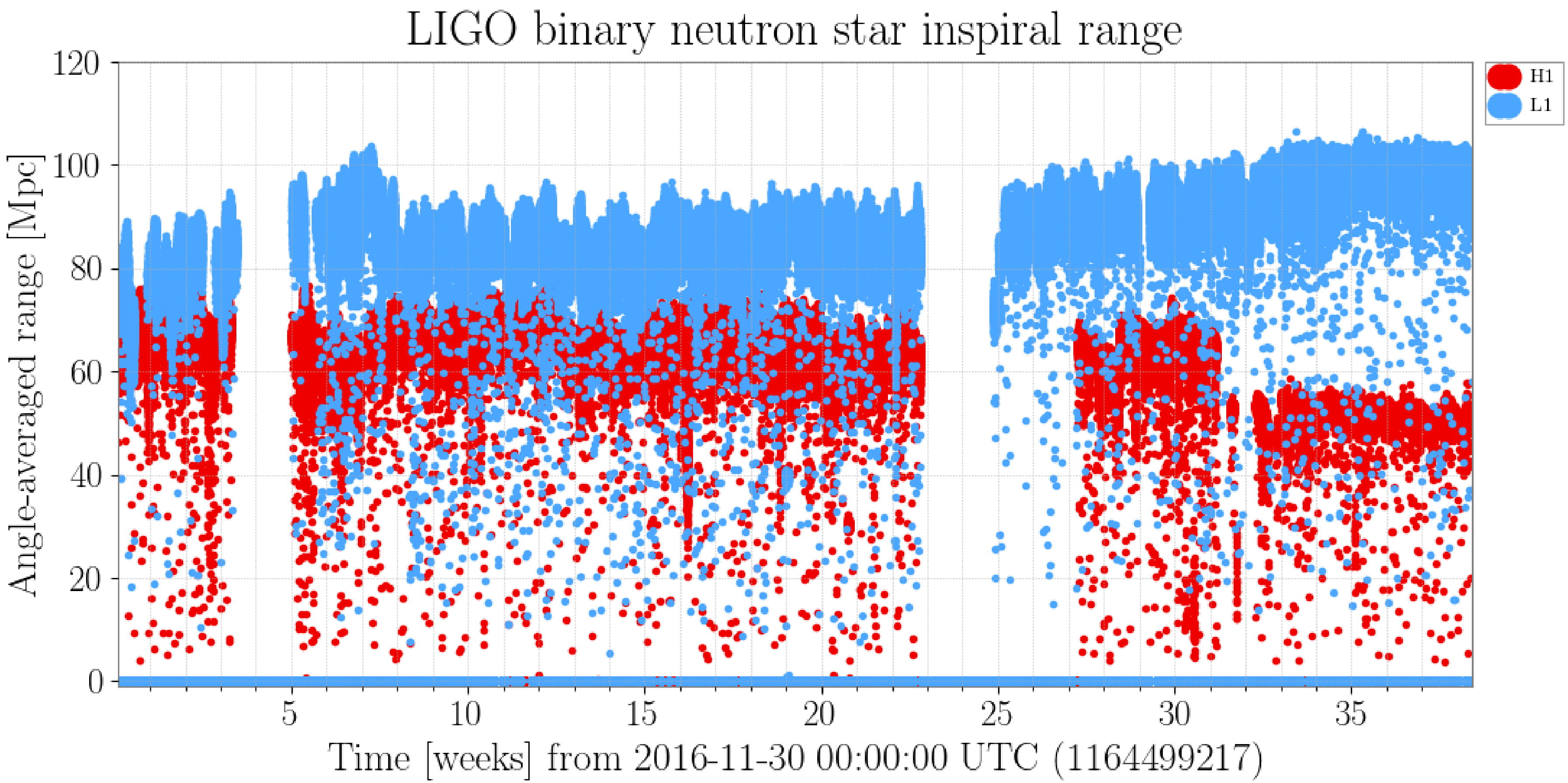
Notes:

Horizon = $2.26 \times$ Range

Range & horizon are *roughly* proportional to masses

Sensitivities for other masses are not strictly proportional

Ranges during O2



September 14, 2015…

Monday morning email

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/

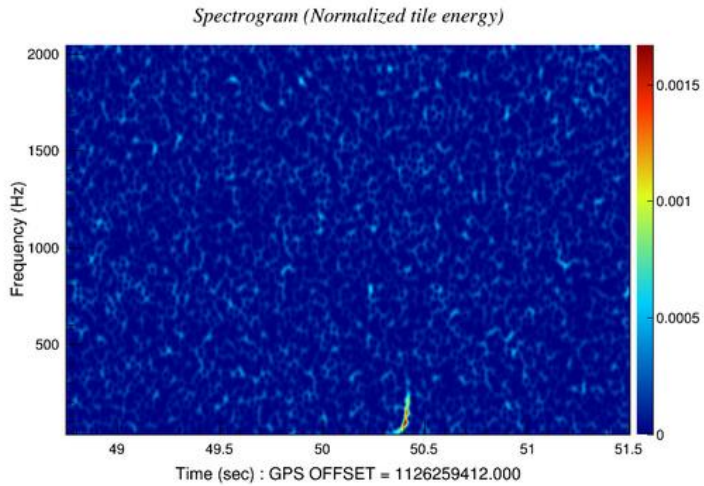
It is not flag as an hardware injection, as we understand after some fast investigation. Someone can confirm that is not an hardware injection?

Marco

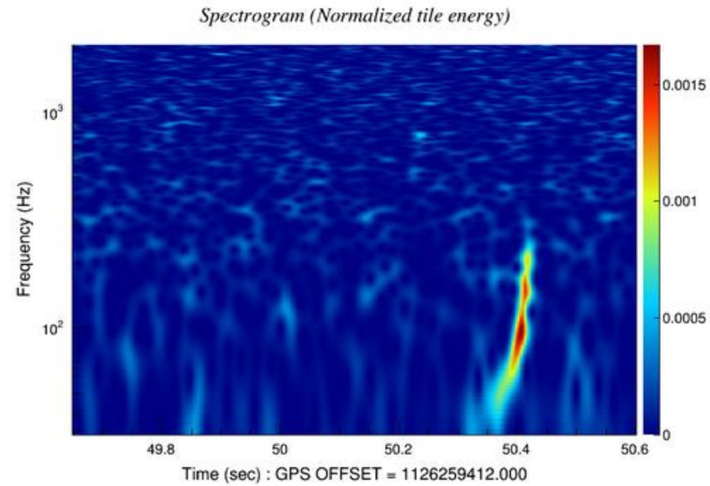
Coherent WaveBurst Event Display

L1

Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

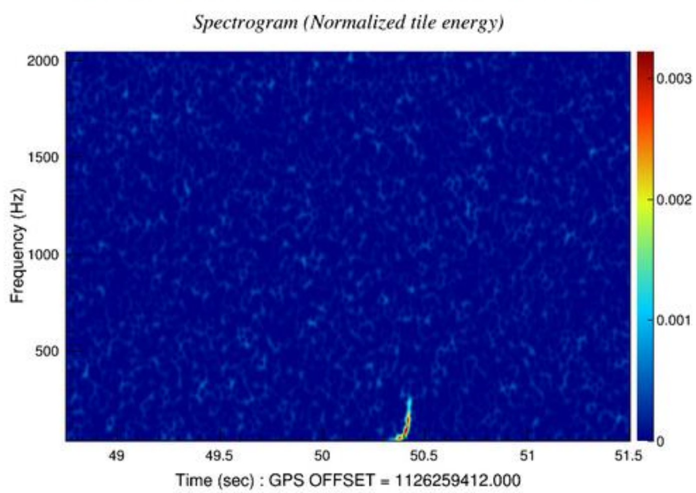


Plot Style: Spectrogram | Spectrogram-Logy | Scalogram

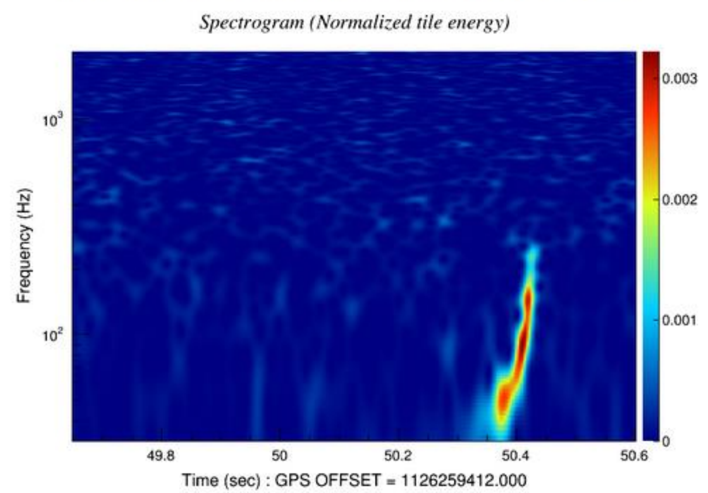


H1

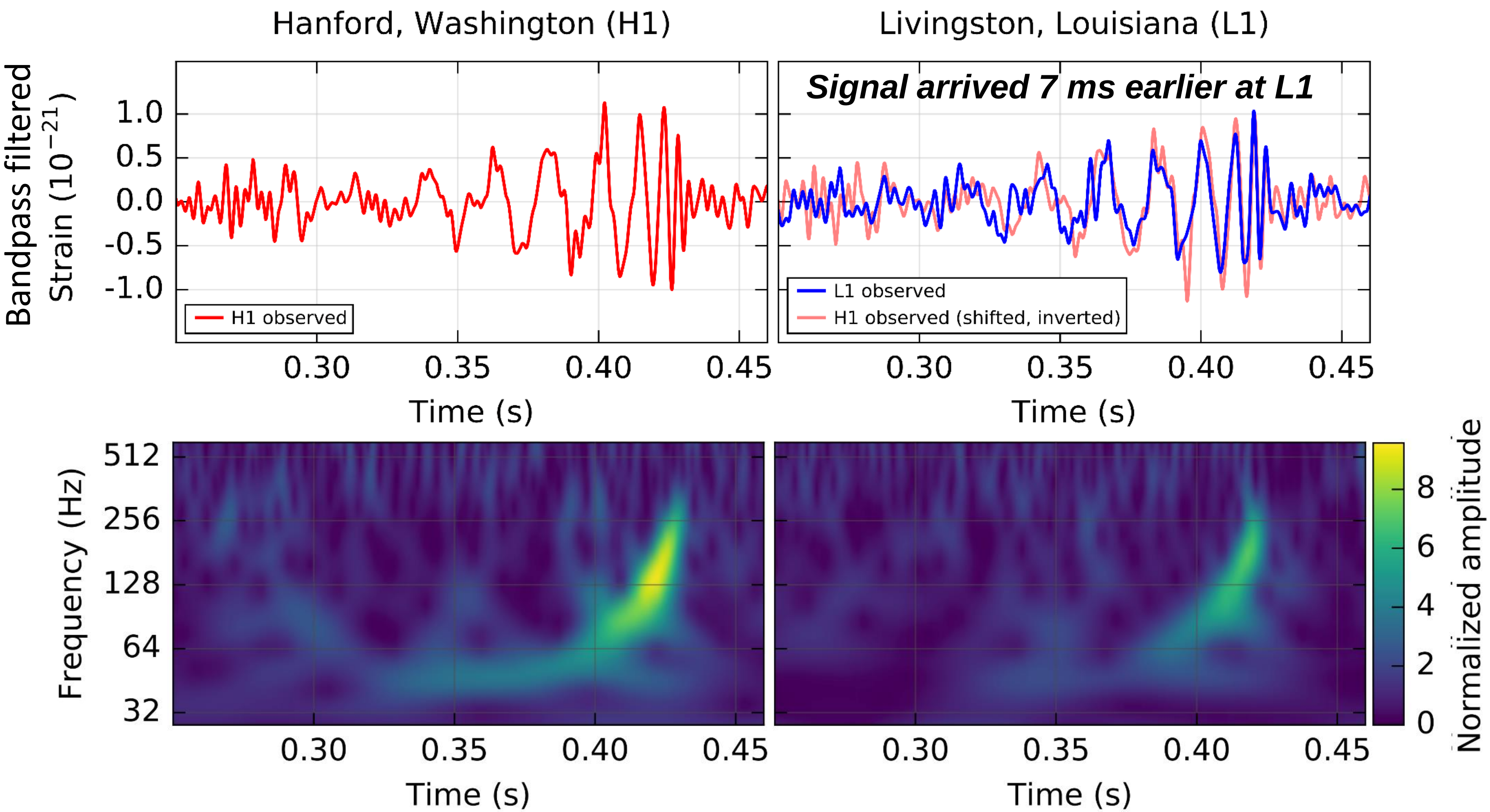
Plot Style: Spectrogram | Spectrogram-Logy | Scalogram



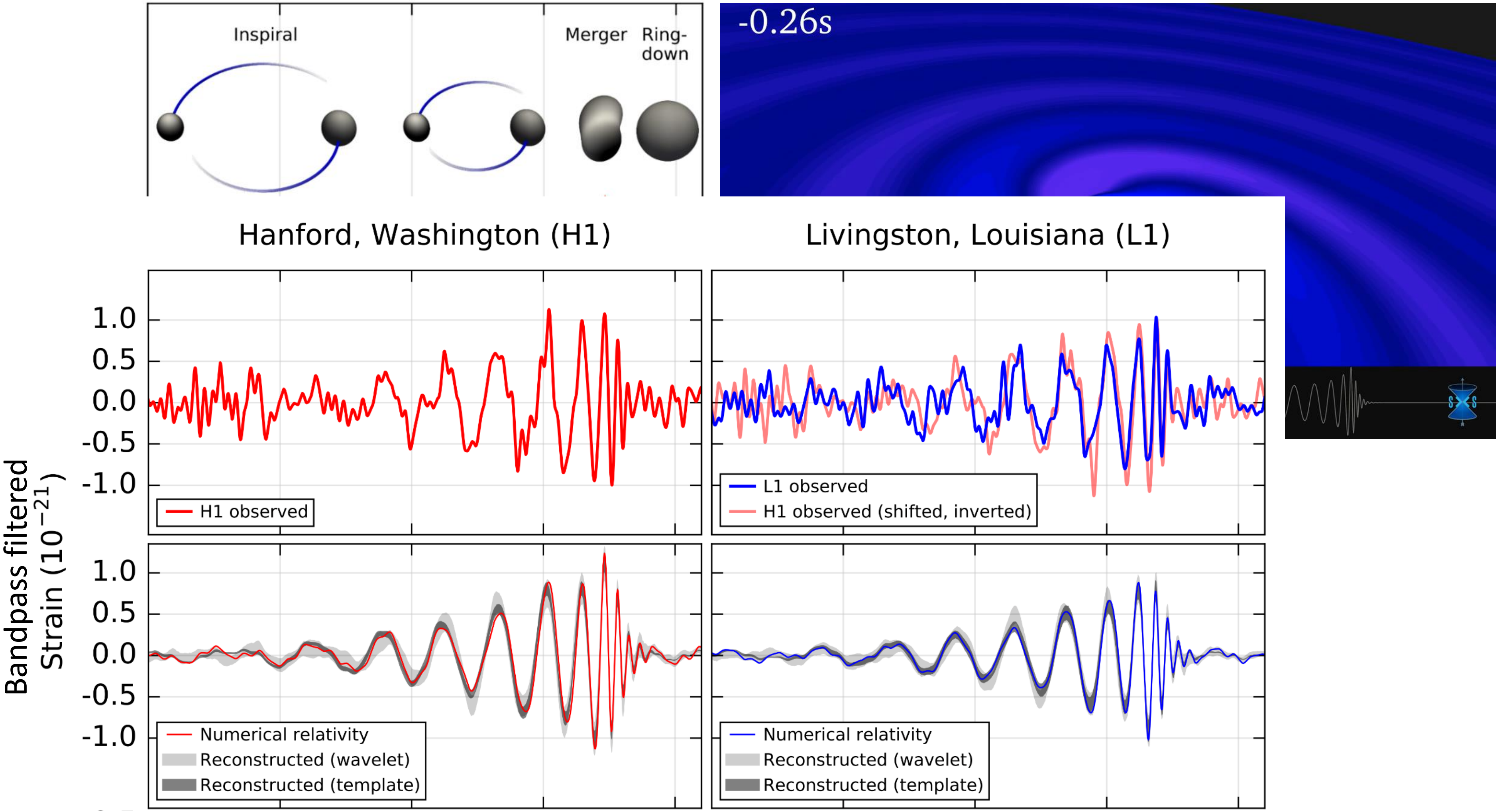
Plot Style: Spectrogram | Spectrogram-Logy | Scalogram



GW150914

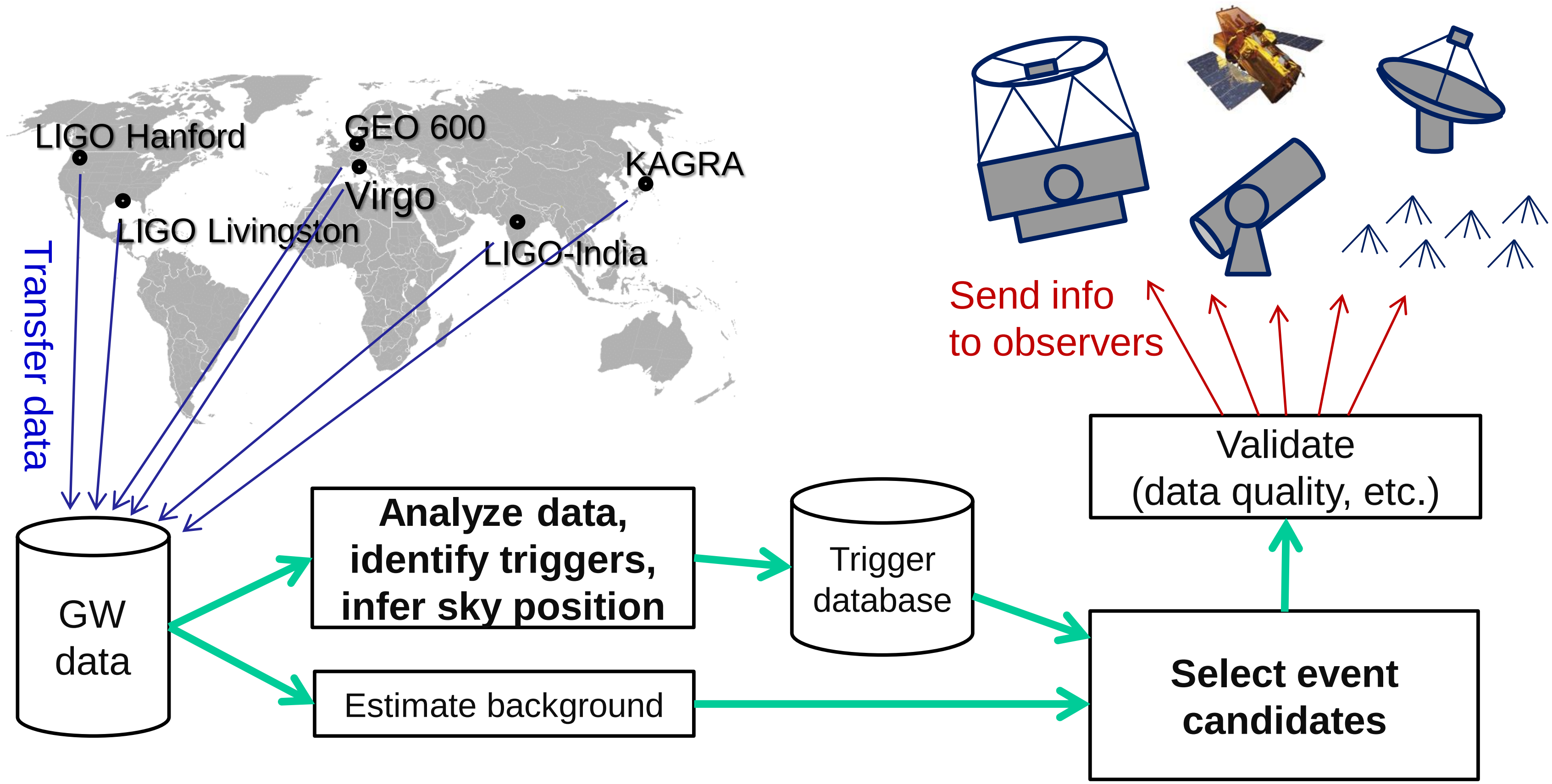

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Signal arrived 7 ms earlier at L1
Bandpass filtered Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
0.30
0.35
0.40
0.45
Time (s)
Frequency (Hz)
512
256
128
64
32
Normalized amplitude
8
6
4
2
0

Looks just like a binary black hole merger!



Matches well to BBH template when filtered the same way

Generating and Distributing Prompt Alerts



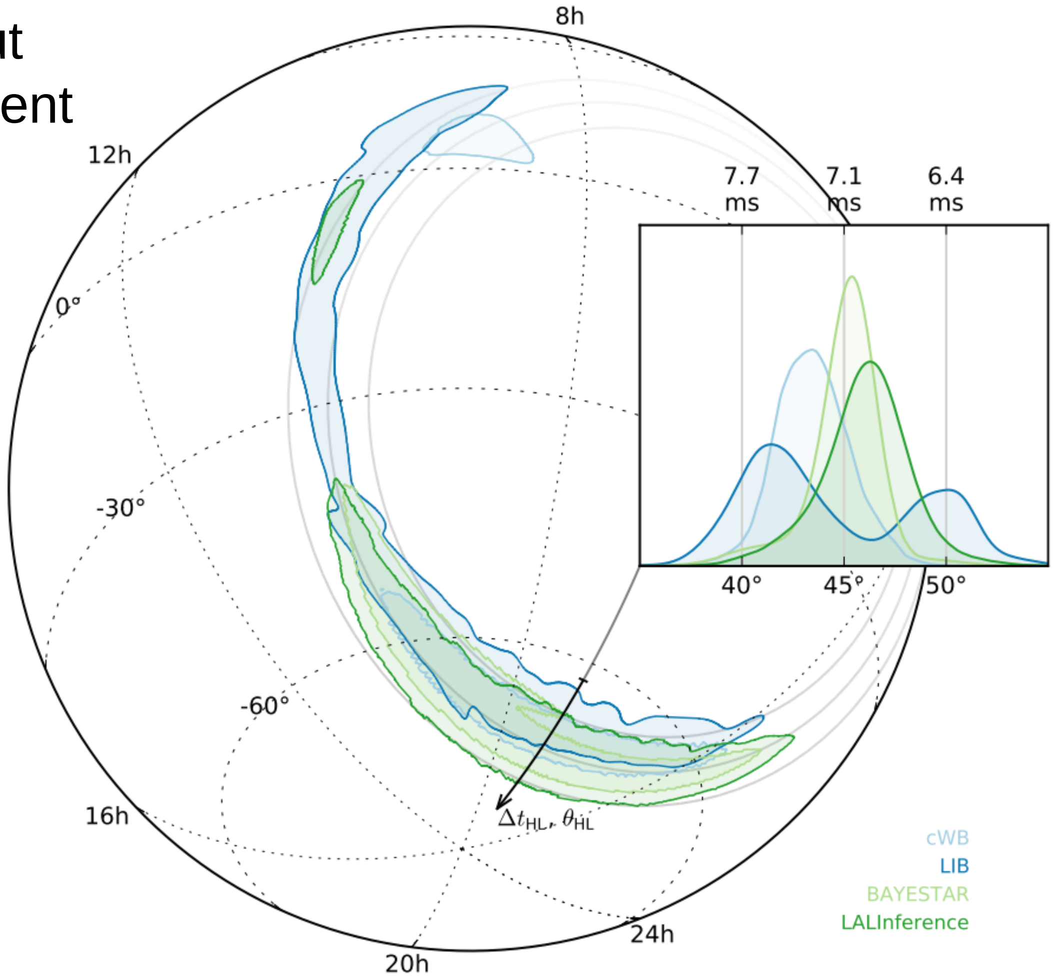
For the O1 run, LIGO+Virgo had signed memoranda of understanding (MOUs) with over 70 teams of observers to share information about GW event candidates

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

Alert Astronomer Partners!

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

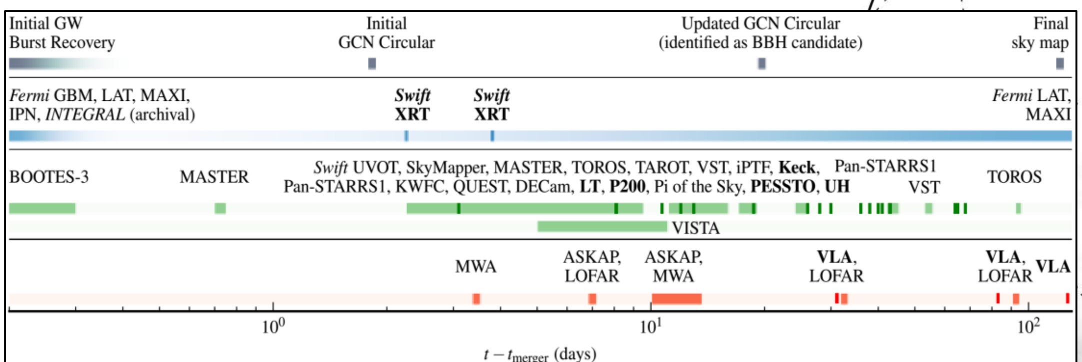
Manually prepared and sent out an alert, ~44 hours after the event

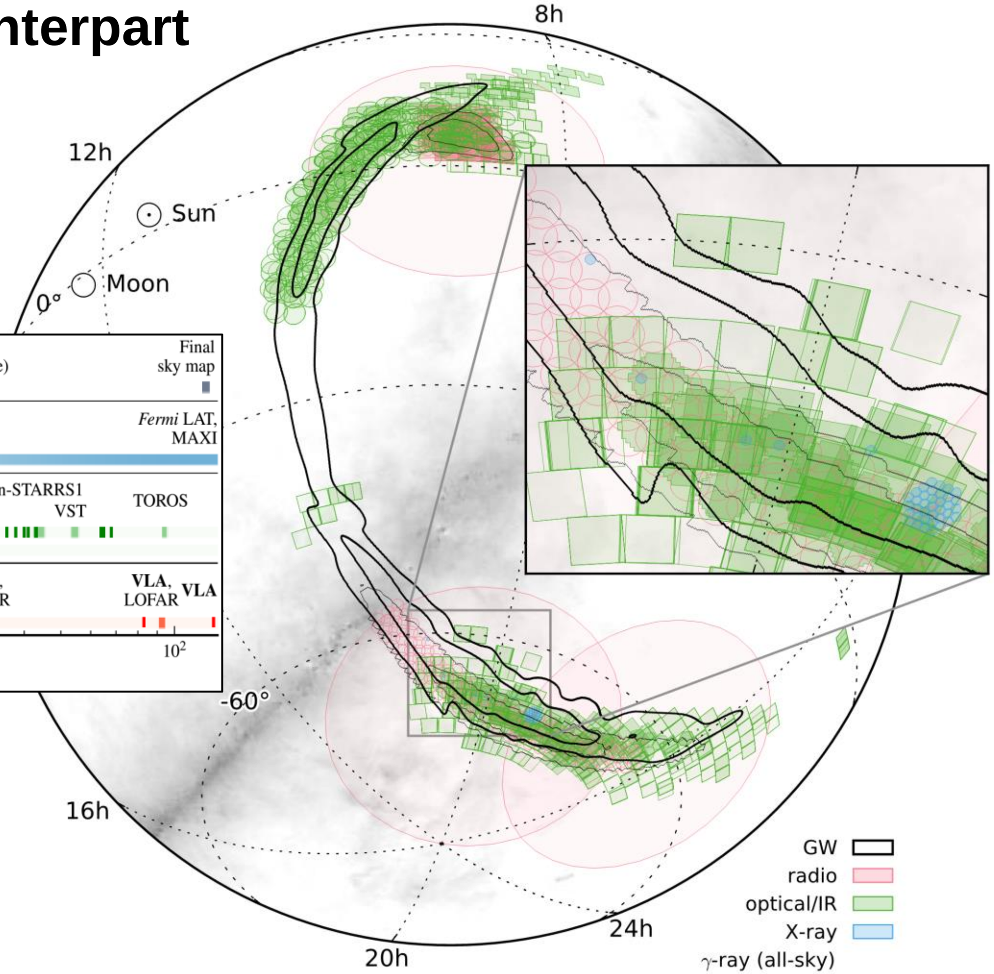


The Astronomers Responded!

25 teams used their telescopes / instruments to try to find a counterpart

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

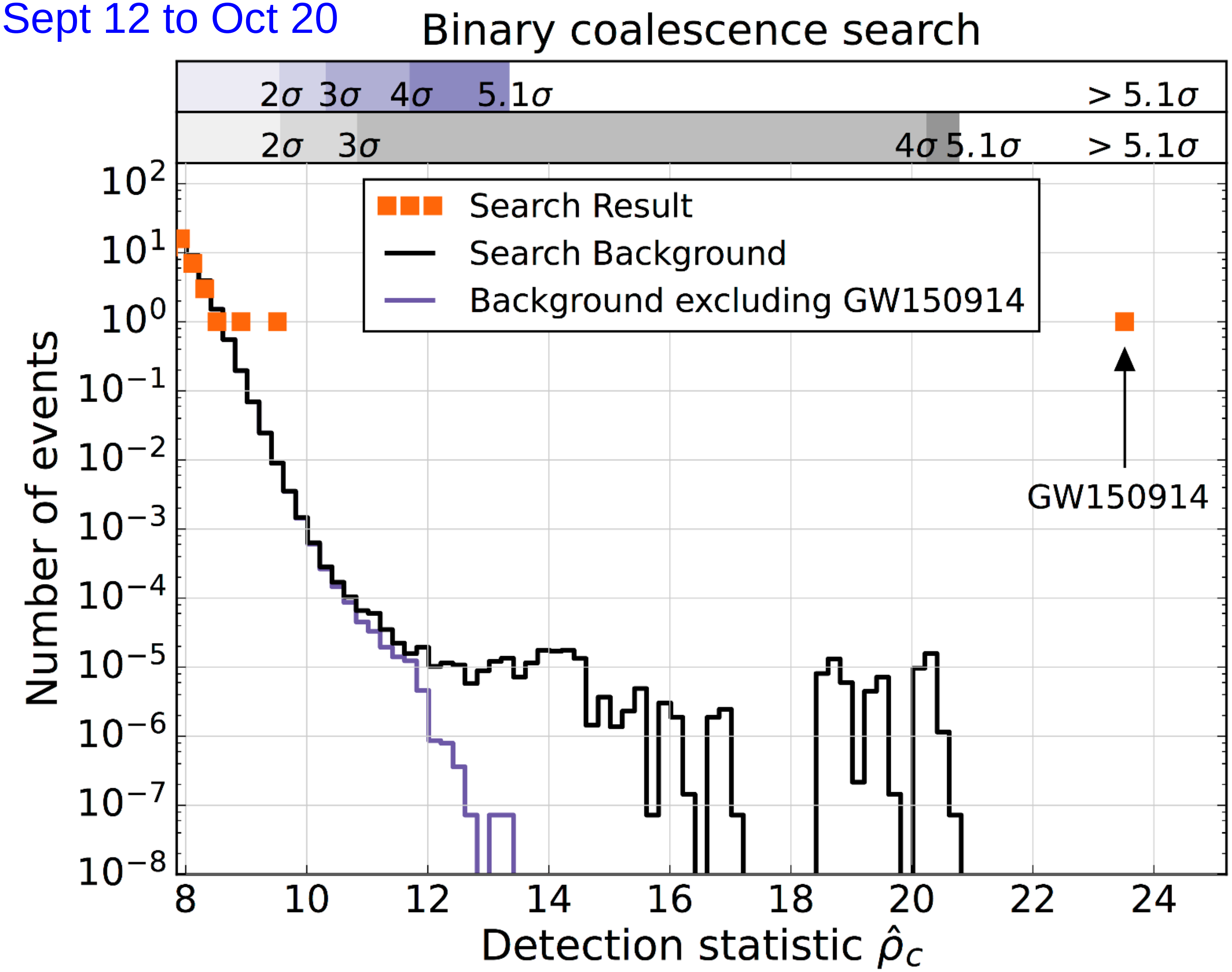




[Abbott et al. 2016, ApJL 826, L13]

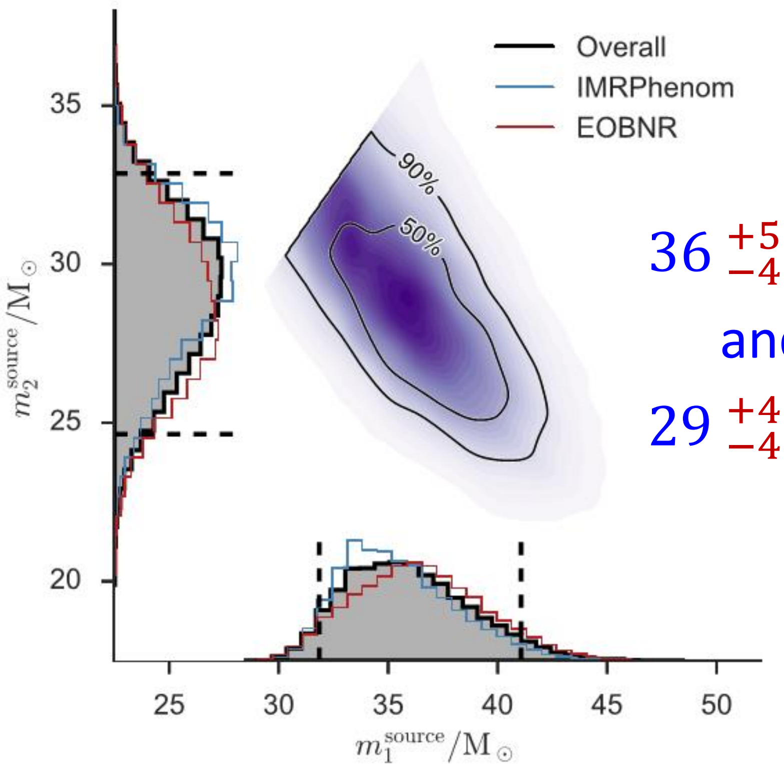
Final Analysis – Binary Coalescence Search

Data set: Sept 12 to Oct 20



Some Properties of GW150914

Masses:



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

and

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

These are surprisingly *heavy* for stellar-mass black holes !

It's telling us something about how stars are born and die

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

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

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

Distance: $410\ ^{+160}_{-180}$ Mpc

$= 1.3 \pm 0.5$ billion light-years

➔ Redshift $z \approx 0.09$

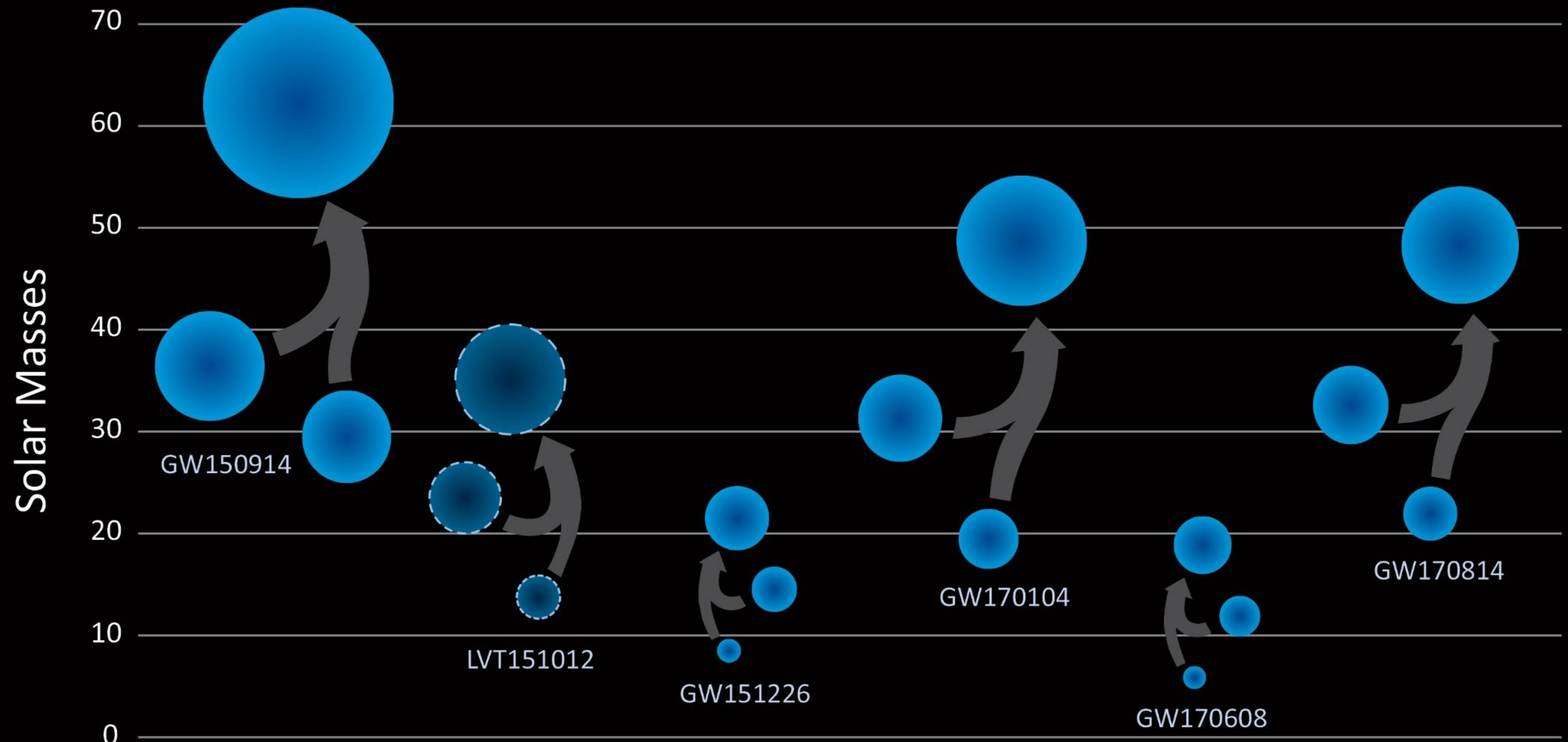
Couldn't tell if the initial black holes had any intrinsic "spin", but the spin of the final BH is

$0.67\ ^{+0.05}_{-0.07}$ of maximal spin allowed by GR

$\left(\frac{Gm^2}{c}\right)$

But wait, there's more!

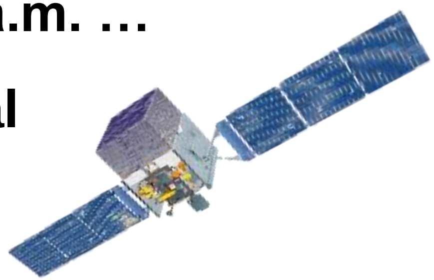
More Binary Black Hole Mergers



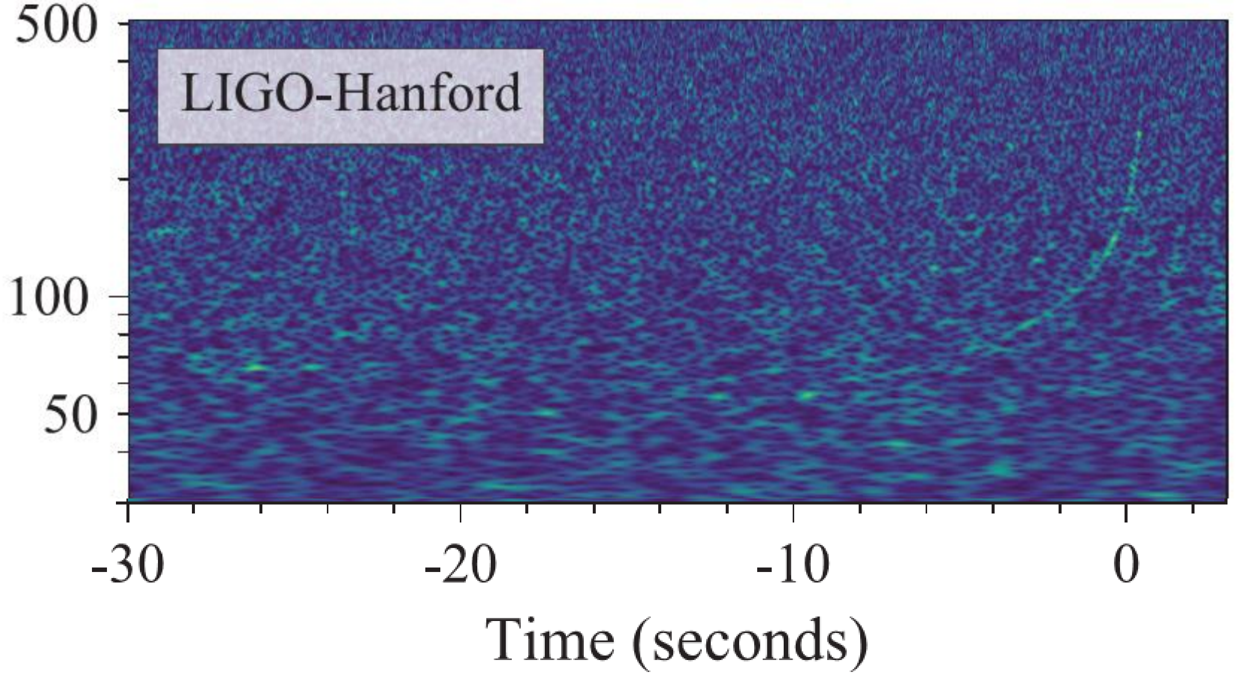
LIGO/Caltech/Sonoma State (Aurore Simonnet)

I get a few automated phone calls shortly after 8:42 a.m. …

LIGO-Virgo software has identified a candidate signal in the LIGO Hanford detector, at nearly the same time as a GRB reported by Fermi-GBM



Matches a template for a compact binary coalescence (CBC) with masses ~ 1.5 and $\sim 1.24\ M_{\odot}$ — and it is a *strong* signal



[Abbott et al. 2017, PRL 119, 161101]

Why only LIGO-Hanford?

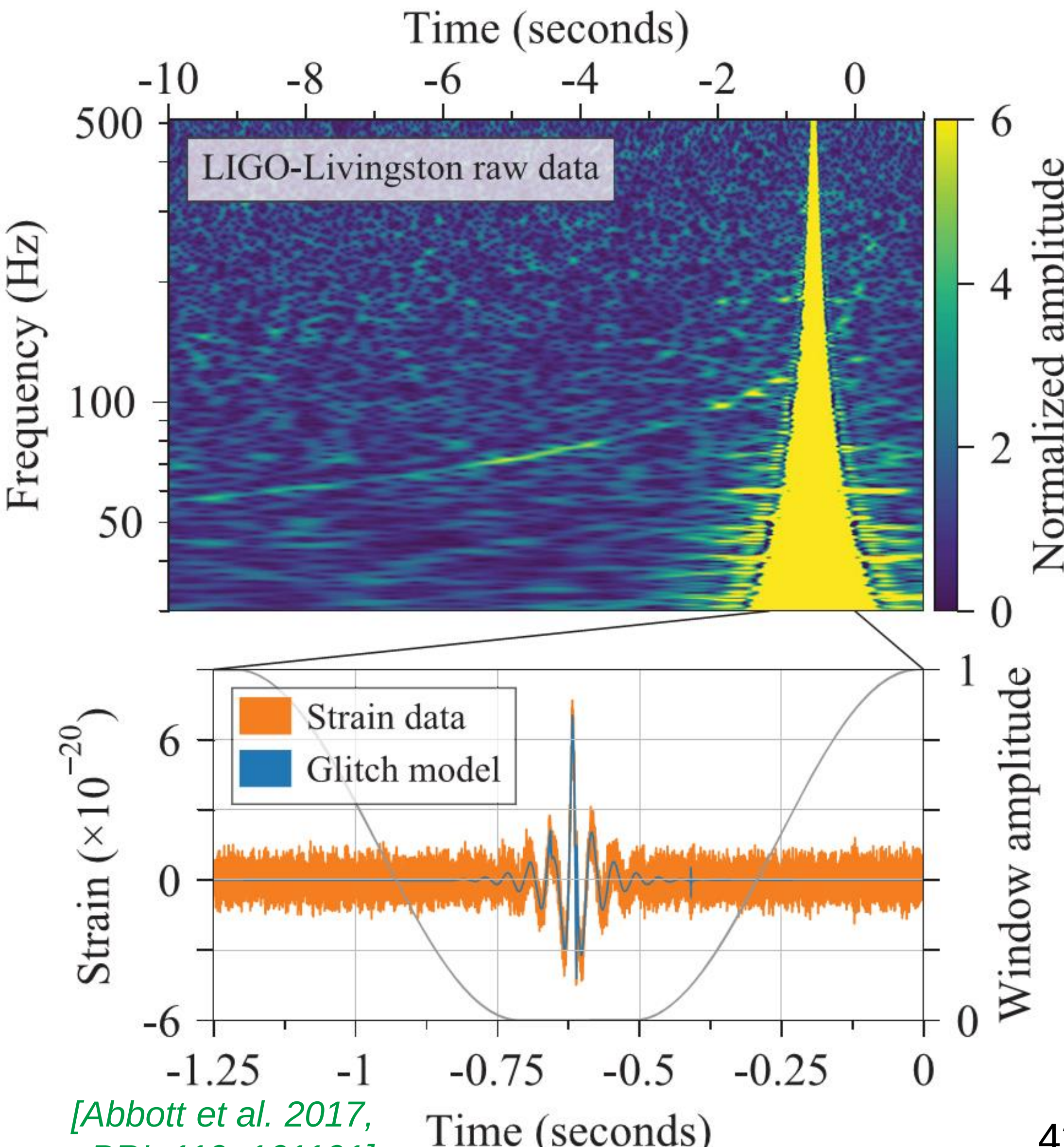
There was a big glitch in LIGO-Livingston data !

Caused the low-latency analysis pipeline to skip that section of LIGO-Livingston data

Virgo was collecting science data too

But there was a delay in transferring Virgo data to Caltech for analysis

So we knew we had a real binary neutron star (BNS) signal, but couldn't say at first where in the sky it was coming from



[Abbott et al. 2017, PRL 119, 161101]

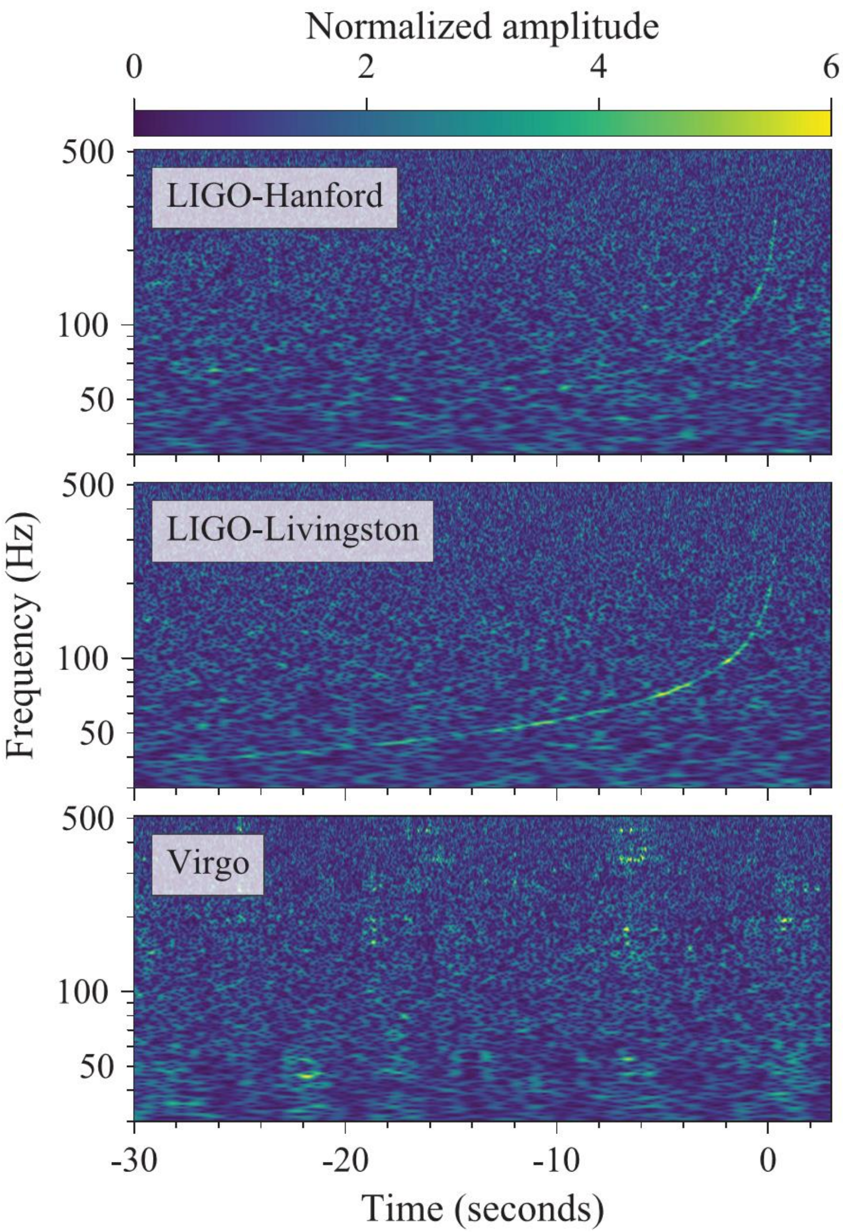
Working around the glitch

Within a few hours, LIGO-Virgo data analysts adapted the code to zero out the data around the glitch

Later, a method was developed to *subtract* the glitch

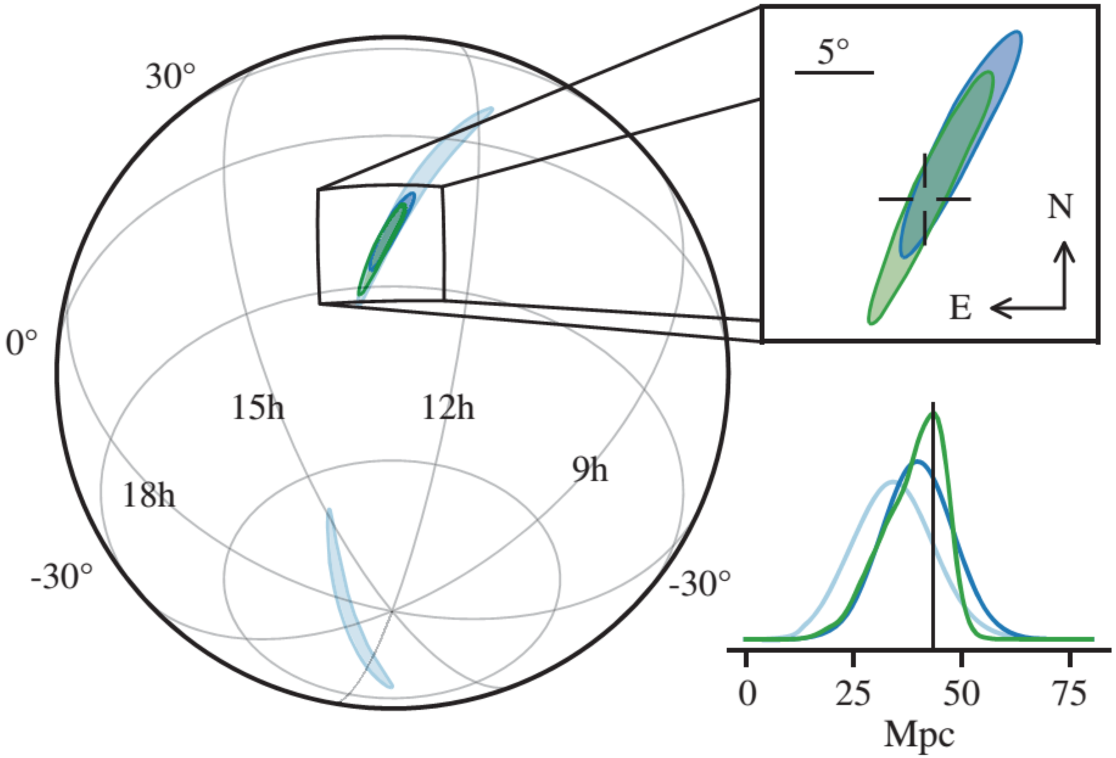
Checked to make sure that wouldn't bias parameter estimation analyses

[Abbott et al. 2017, PRL 119, 161101]



Able to tell the astronomers where to look!

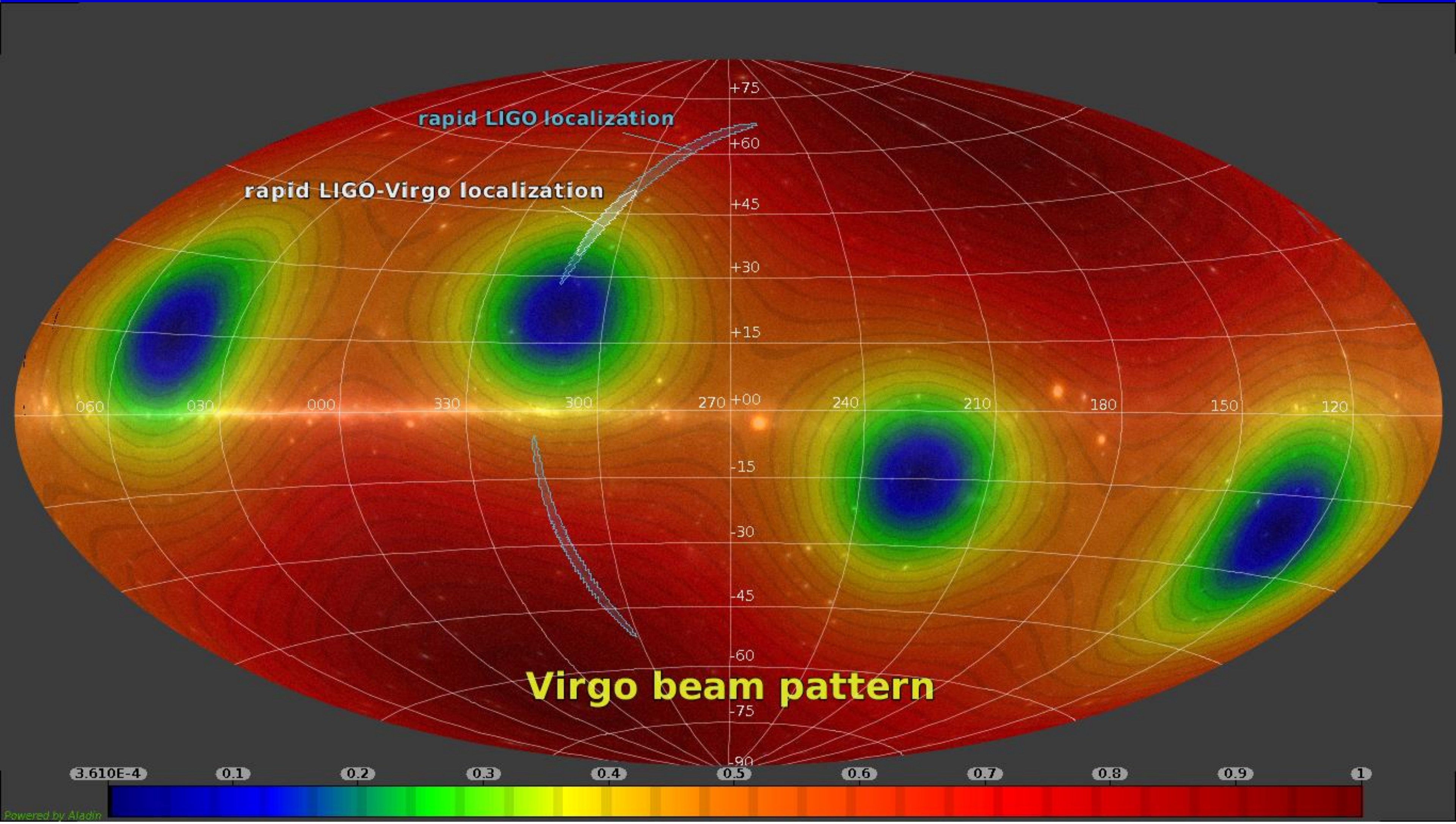
Sent a sky map after at T+5.25 hours with 3-detector sky map, area ~31 square degrees (90% probability region)



[Abbott et al. 2017, PRL 119, 161101]

Distance estimate
~30 – 50 Mpc

Virgo helped with localization

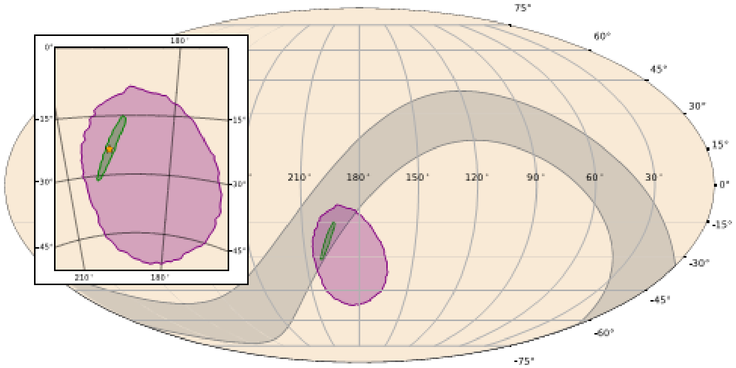


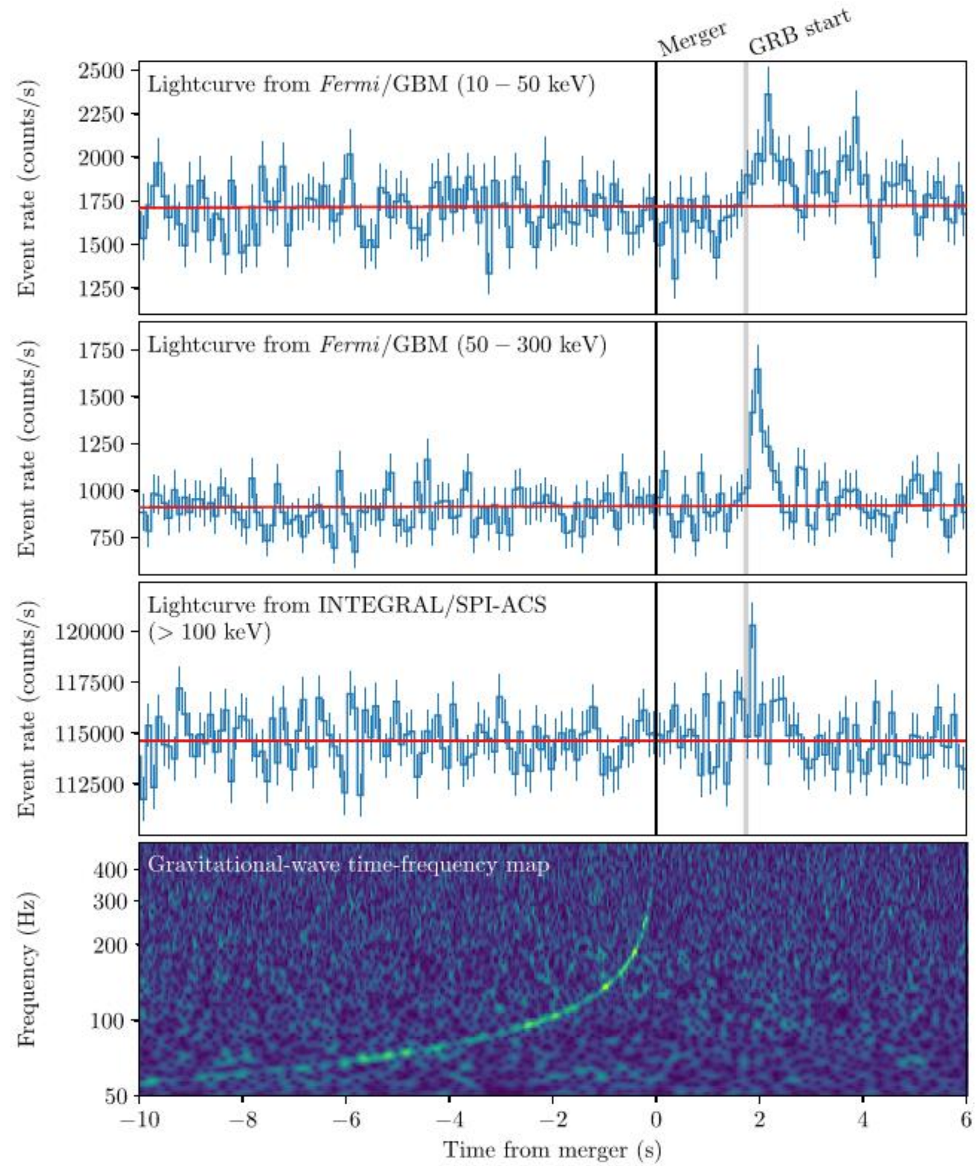
Galactic coordinates; Background image credit: Fermi gamma-ray sky map (HEASARC/Skyview)

Connecting the GW and the GRB

The GRB began $\mathbf{1.74 \pm 0.05}$ s after the merger

With consistent sky location!





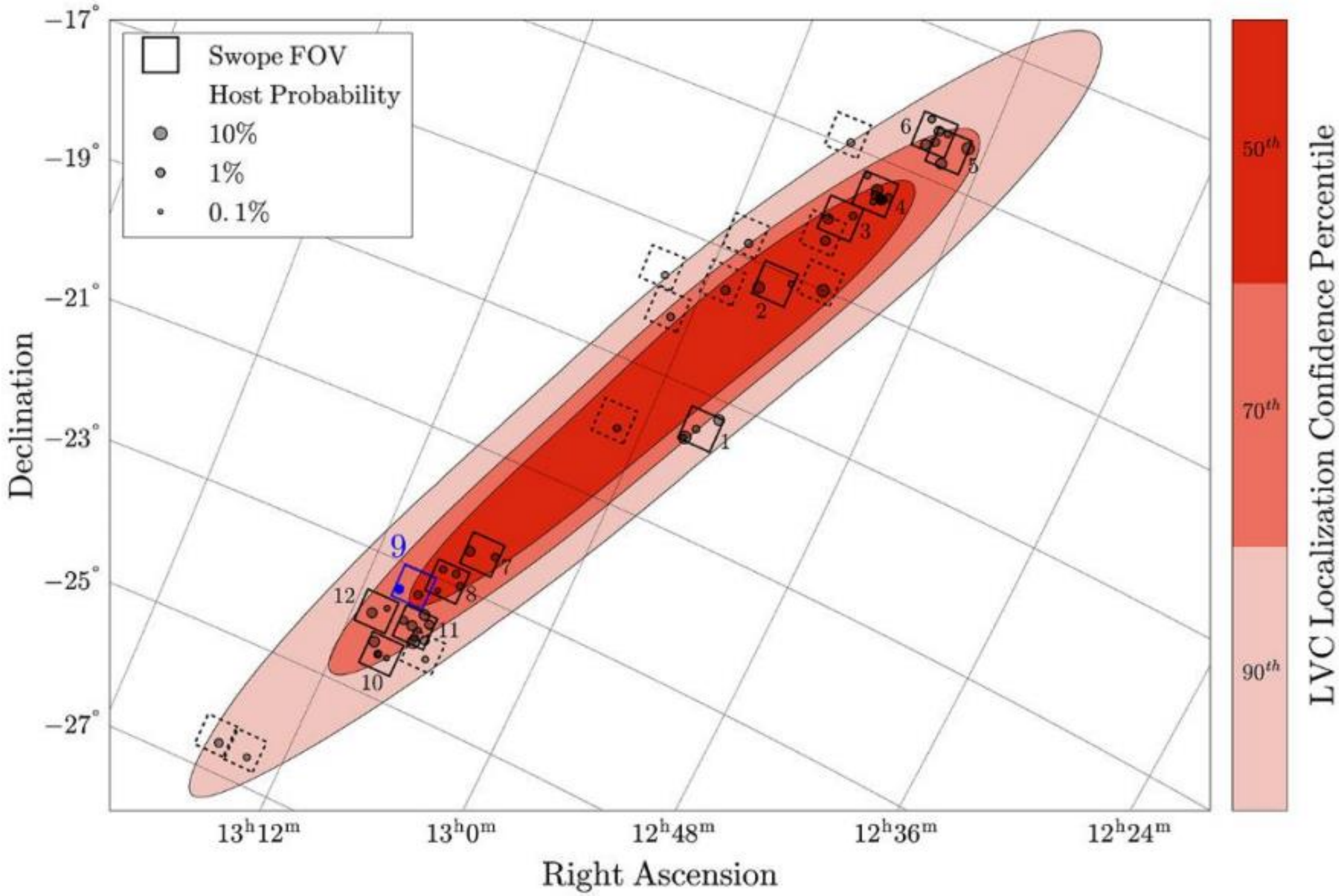
➔ **Speed of GWs is just about equal to speed of light**

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\mathrm{EM}}} \leqslant +7 \times 10^{-16}$$

[LSC, Fermi-GBM and INTEGRAL 2017, ApJL 848, L13]

Finding the optical counterpart

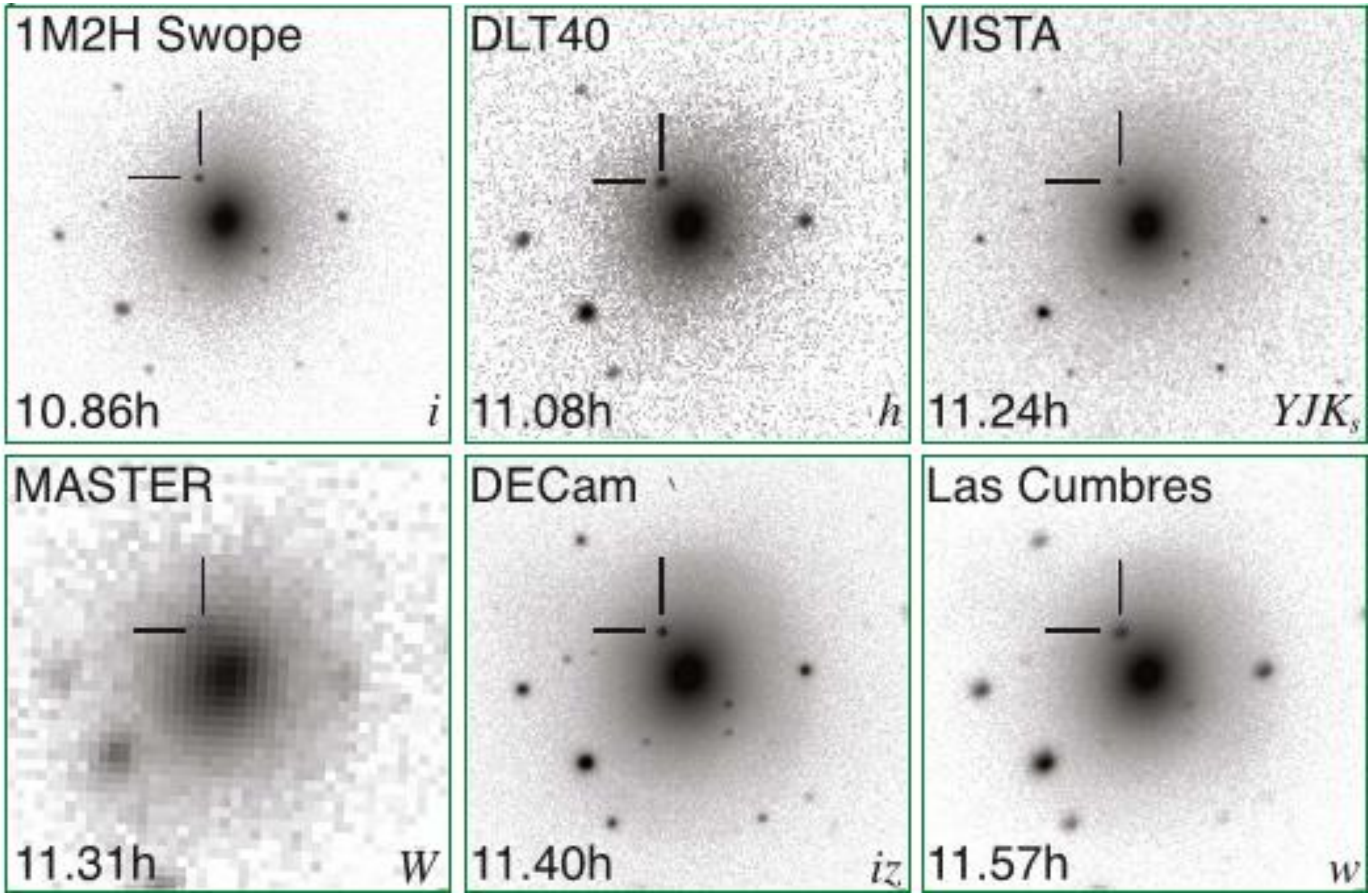
First found and reported by Coulter et al. 10.86 hours after the time of the GW event, in the galaxy NGC 4993



[Coulter et al. 2017, Science 10.1126/science.aap9811]

Finding the optical counterpart

Independently found by 5 other teams within the next 45 minutes



GW170817

GRB 170817A

SSS17a

DLT17ck

MASTER J130948.10-232253.3

→ AT 2017gfo

[Abbott and many others 2017, ApJL 848, L12]

A monumental joint paper

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

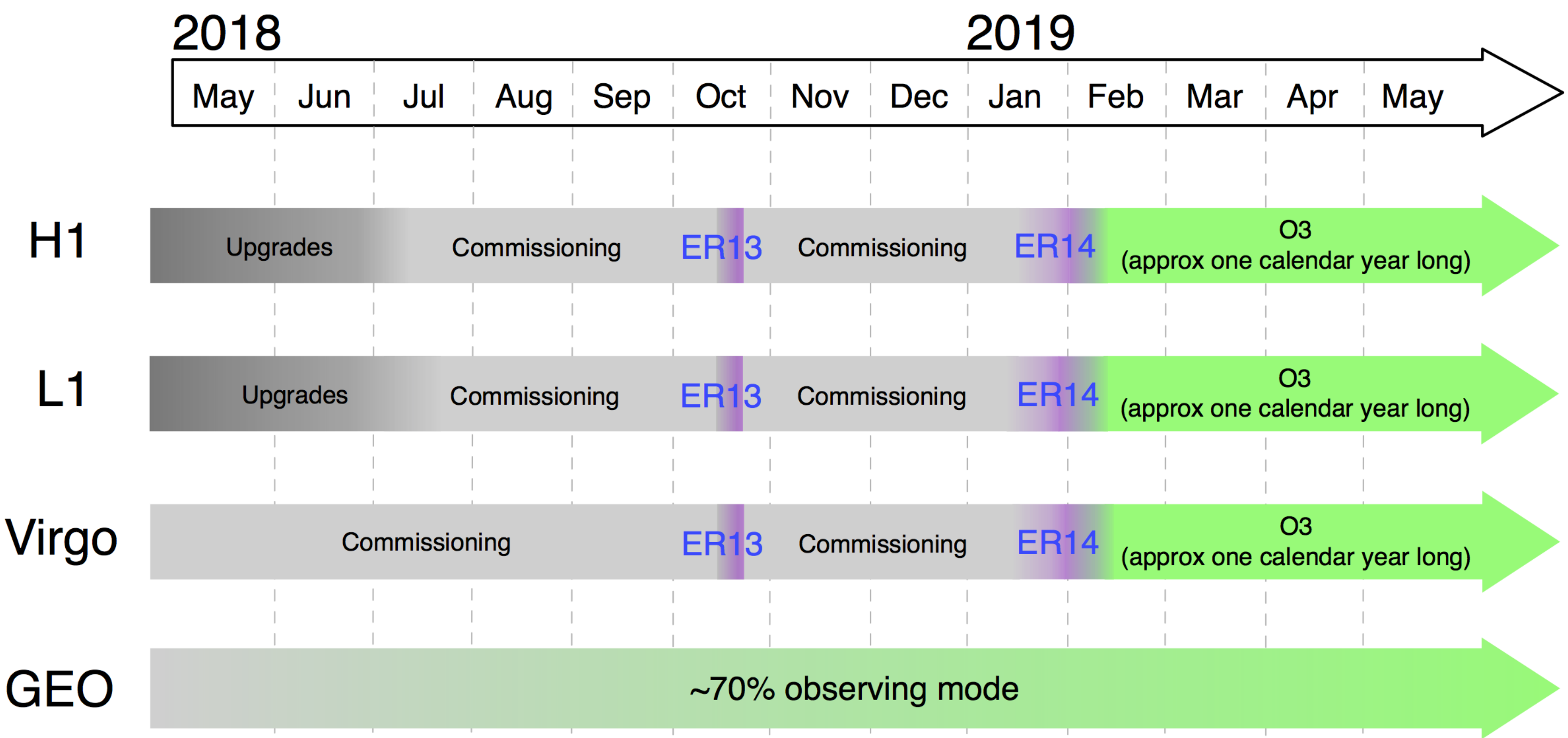
Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

~3600 authors !

Basically an overview of *many* results published separately

The evolving detector network

Coming in 2019: the O3 run

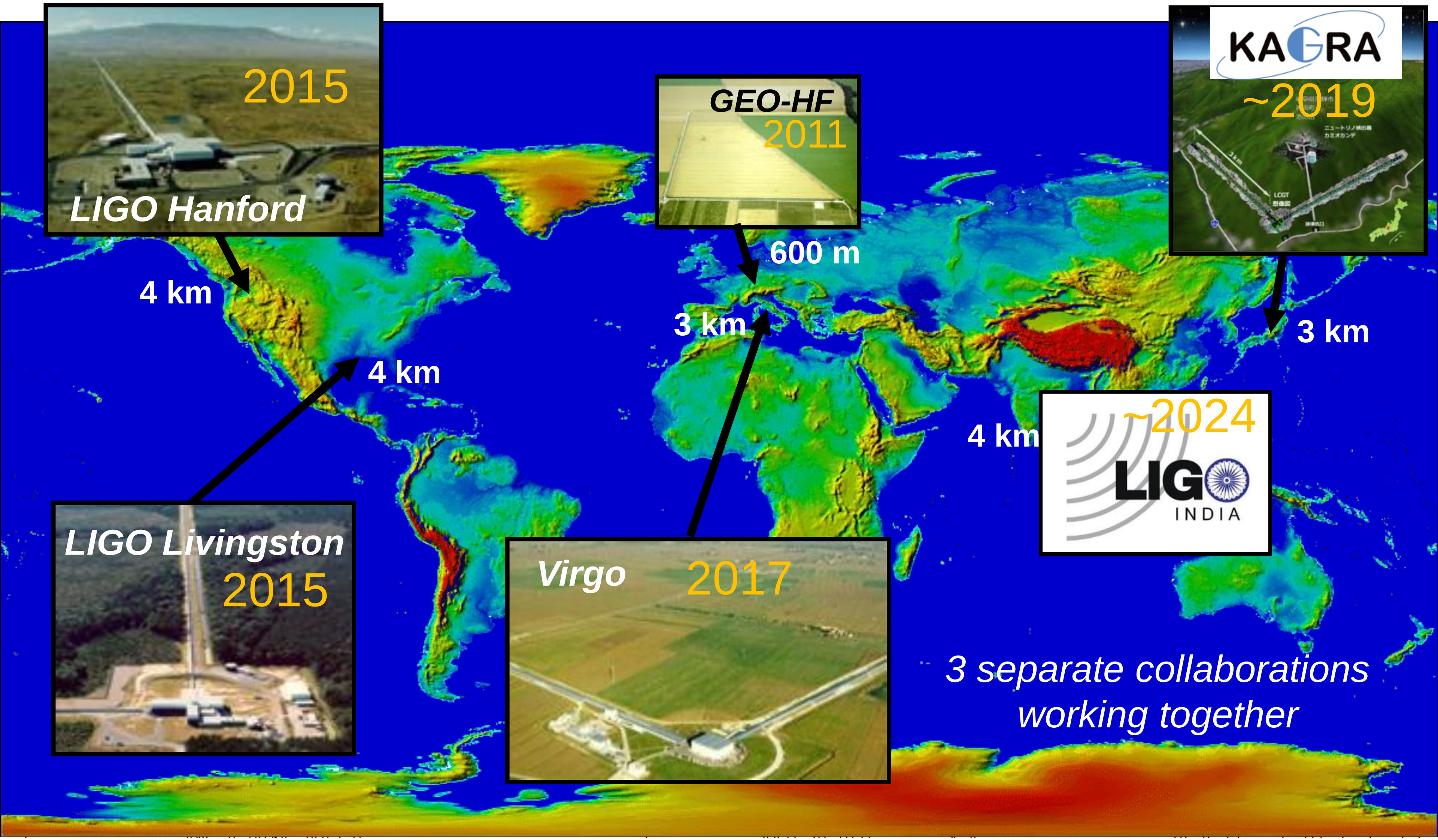


Projected timeline from https://www.ligo.org/scientists/GWEMalerts.php

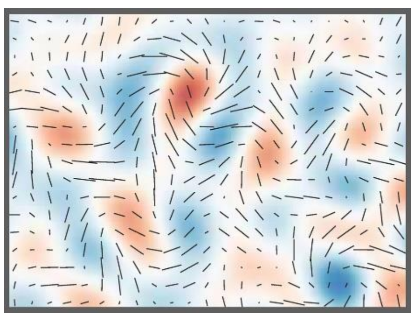
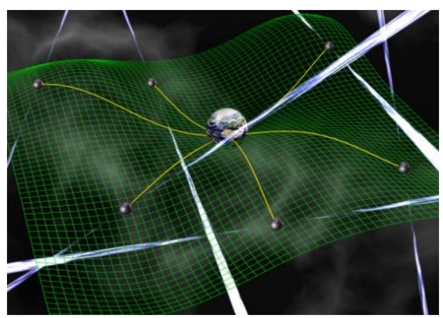
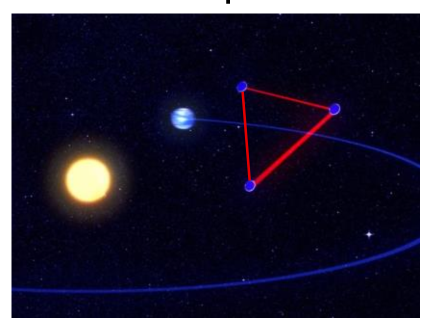
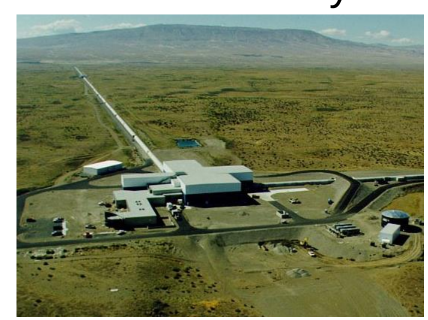
New for O3: **Open Public Alerts**

All decent GW event candidates will be shared publicly ASAP

Advanced GW Detector Network: Under Construction → Operating



The Wide Spectrum of Gravitational Waves

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

Where we are and where we're going

After decades of patient work, we've tested Einstein's prediction and launched a new kind of astronomy!

Black holes seem a bit more tangible now

We were lucky that our first detected event was *so* spectacular

The second observing run, including Advanced Virgo at the end, yielded more BBH events plus a binary neutron star merger

Another really spectacular event!

We're looking forward to detecting more GW events in O3 and beyond