Title: The astrophysics we can do with LIGO - exploring the apparent black hole mass gap and hunting for electromagnetic counterparts

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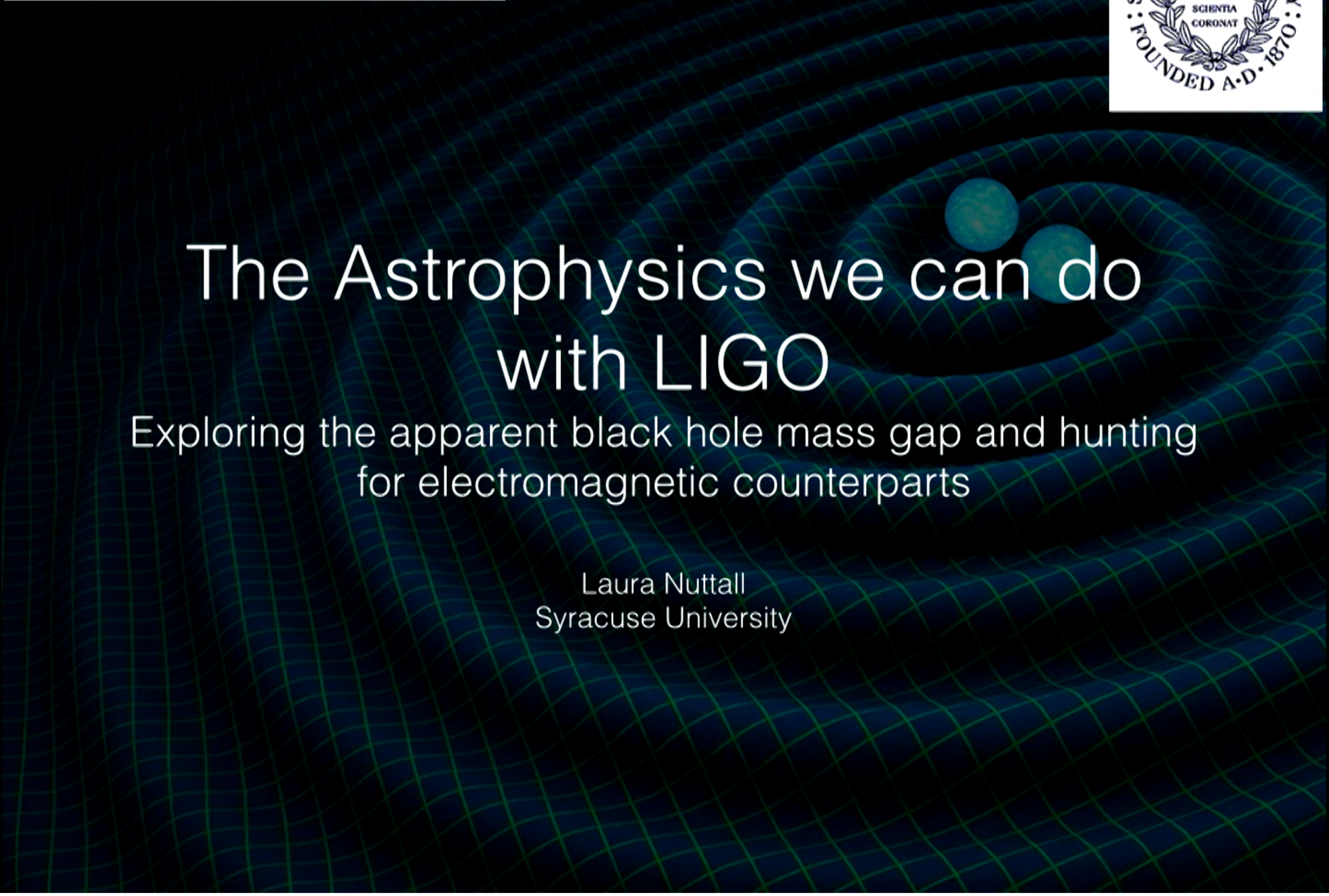
Abstract: <p>In 2015 the LIGO detectors observed gravitational waves from two distinct stellar-mass binary black hole mergers. This long awaited feat now opens avenues to explore astrophysical questions which cannot, or are difficult to, be answered purely by electromagnetic means. Massive stars which end their lives in a pair-instability supernova are not thought to leave a remnant behind, meaning there should exist a gap in the black hole mass spectrum. In this talk I will discuss whether LIGO observations can tell us something about this apparent mass gap. </p>

<p>LIGO is currently operating in its second science run, and like its first, alerts are sent to electromagnetic partners whenever a candidate event is identified. I will also discuss the efforts being made to capture the signature of an electromagnetic counterpart, some of the facilities involved and the hurdles which need to be overcome to make a confident association between a gravitational-wave signal and an electromagnetic transient.</p>



The Astrophysics we can do with LIGO

Exploring the apparent black hole mass gap and hunting for electromagnetic counterparts

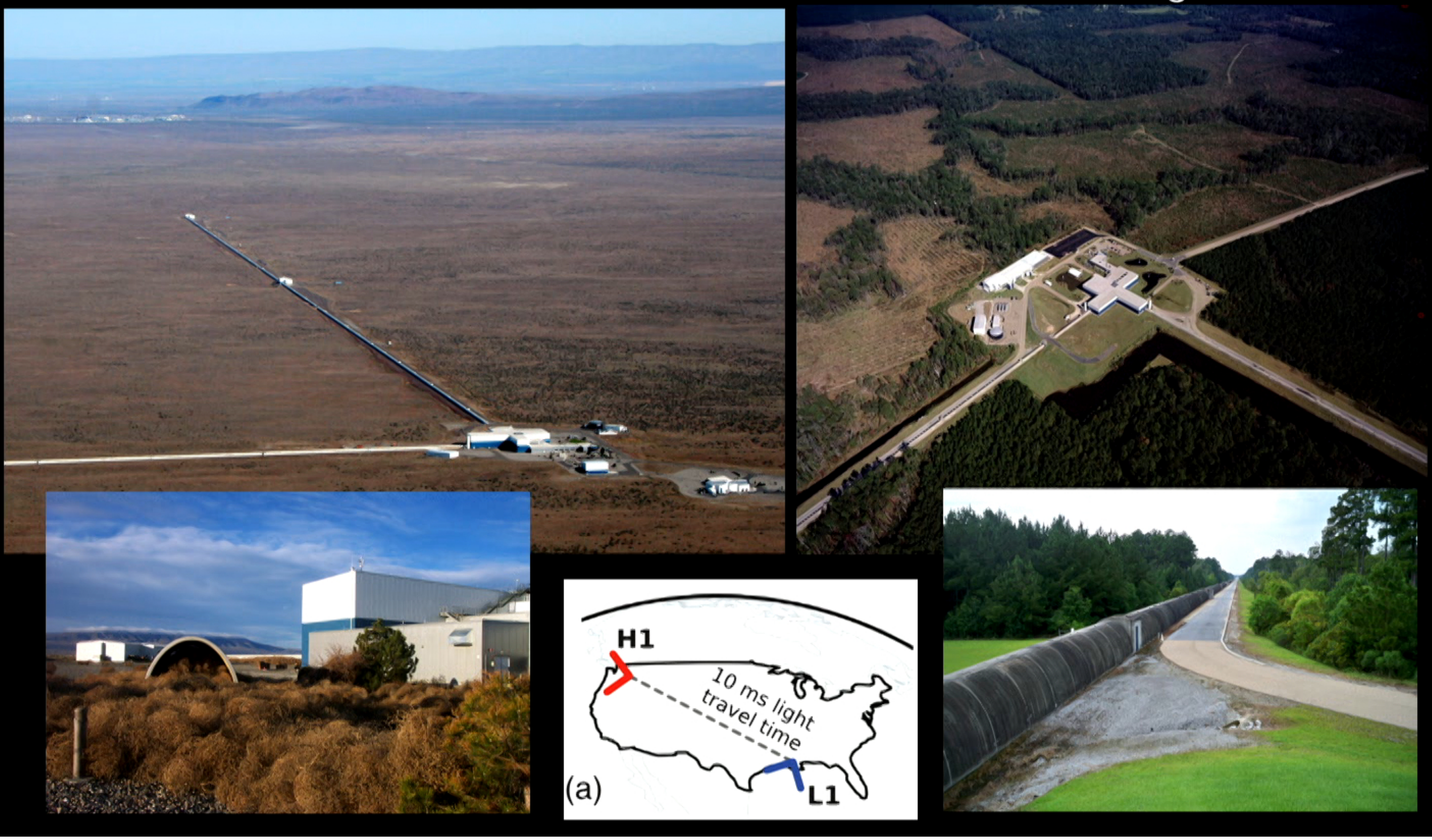
Laura Nuttall
Syracuse University

LIGO

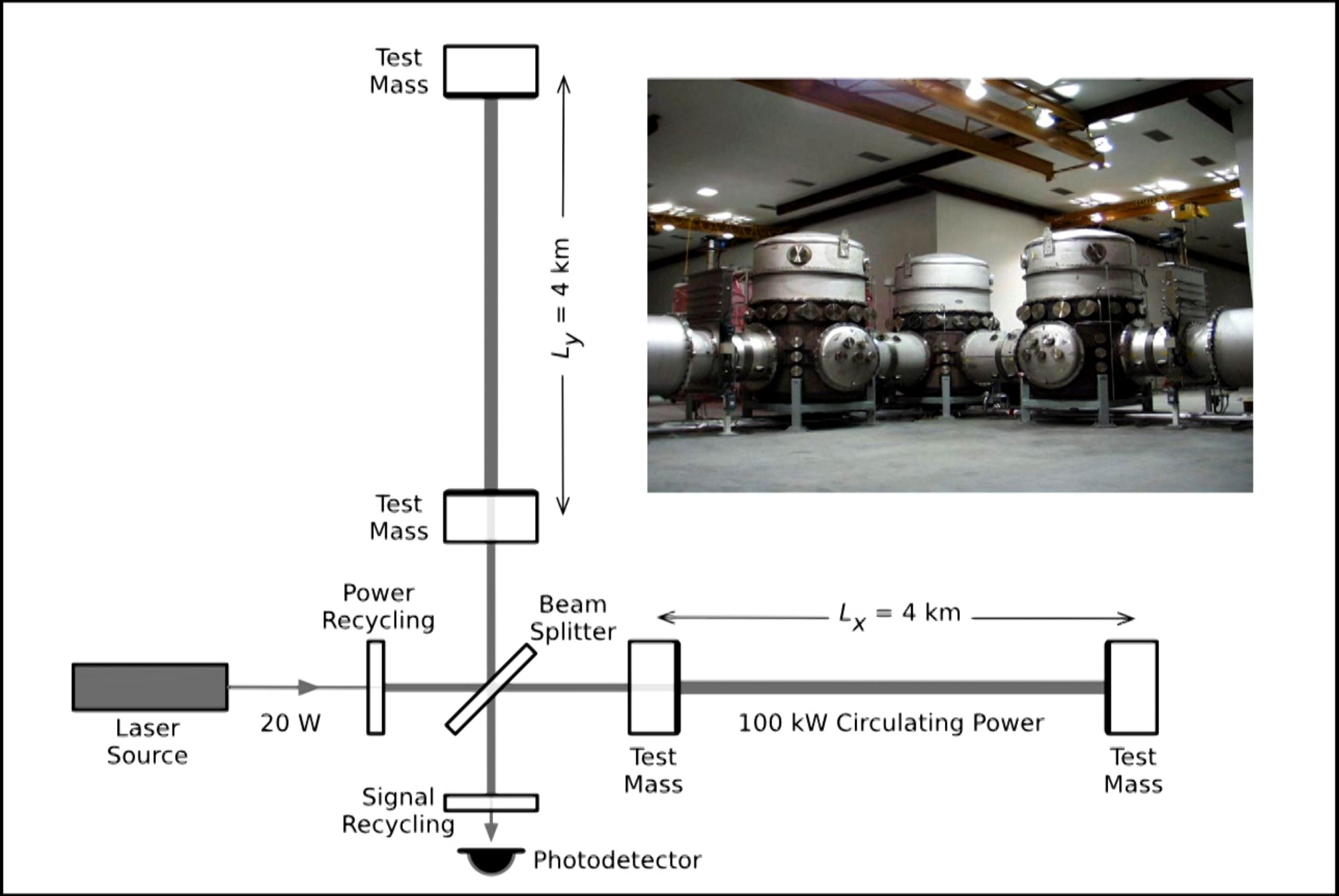
Laser Interferometer Gravitational-wave Observatory

LIGO-Hanford

LIGO-Livingston

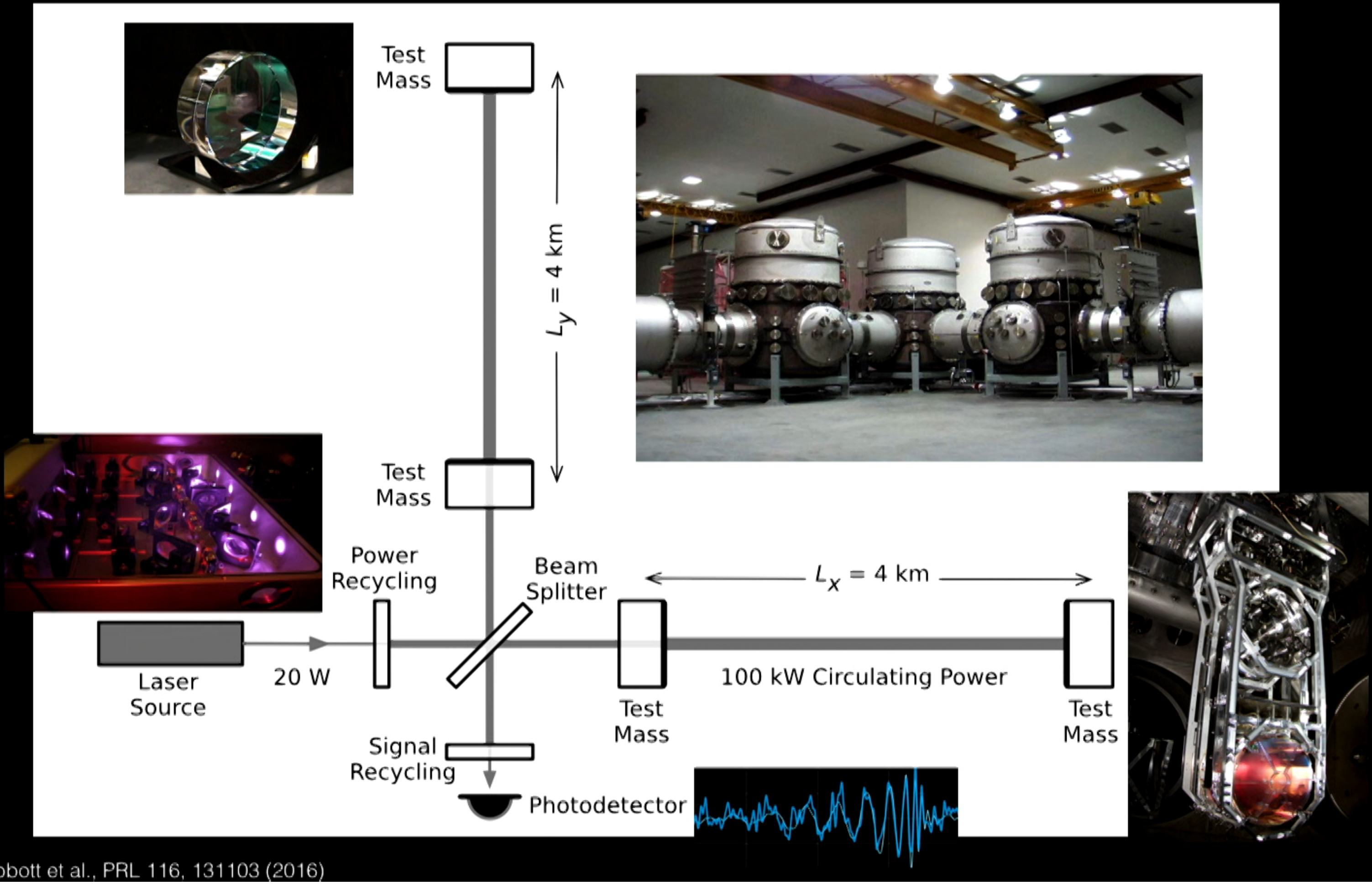


The Design



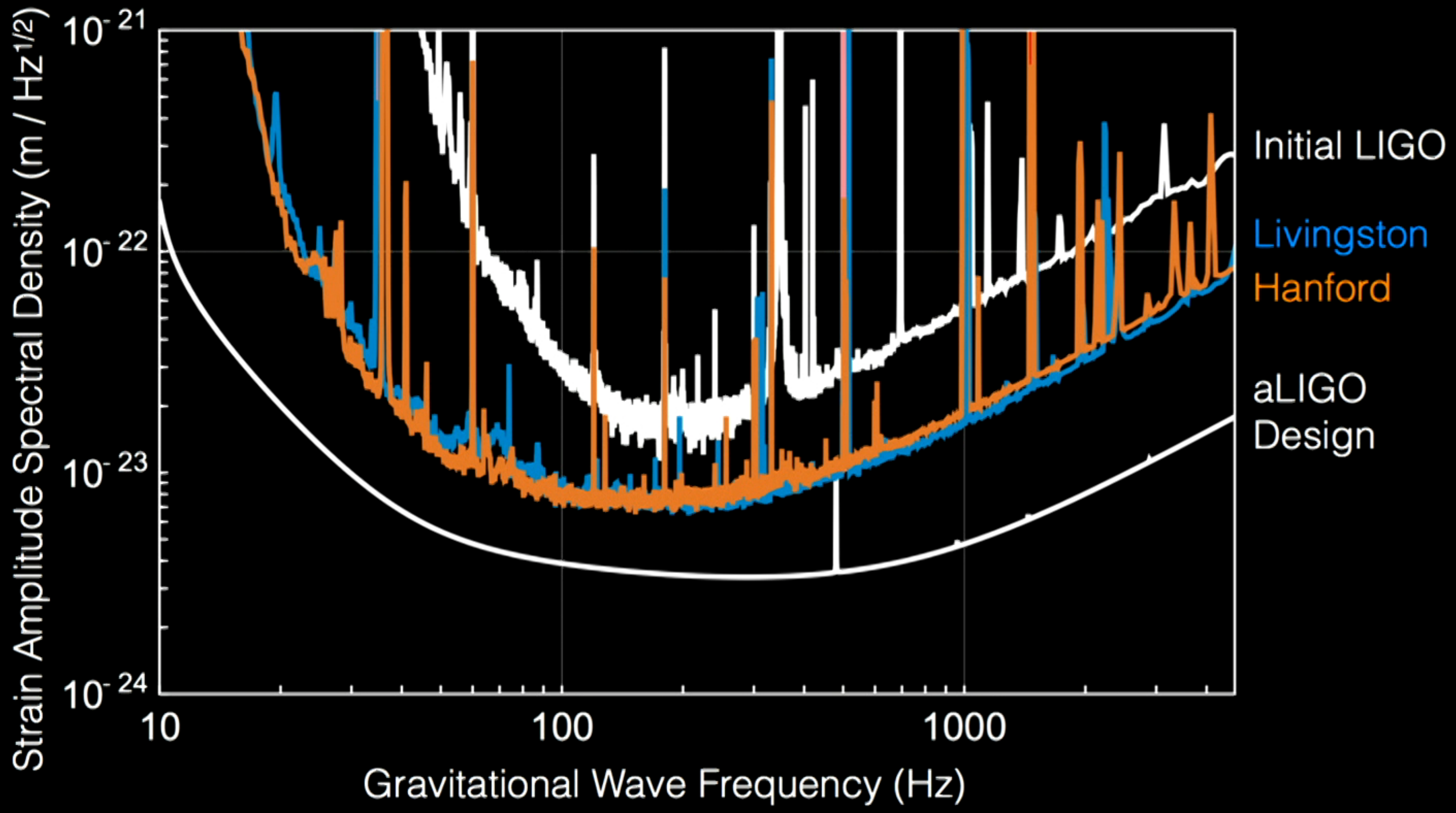
Abbott et al., PRL 116, 131103 (2016)

The Design



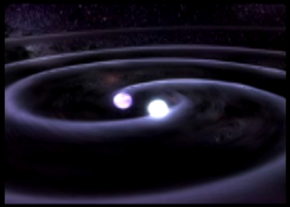
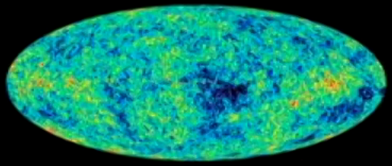
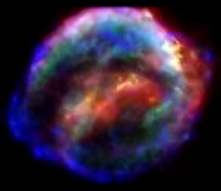
Abbott et al., PRL 116, 131103 (2016)

Sensitivity: past, present and future

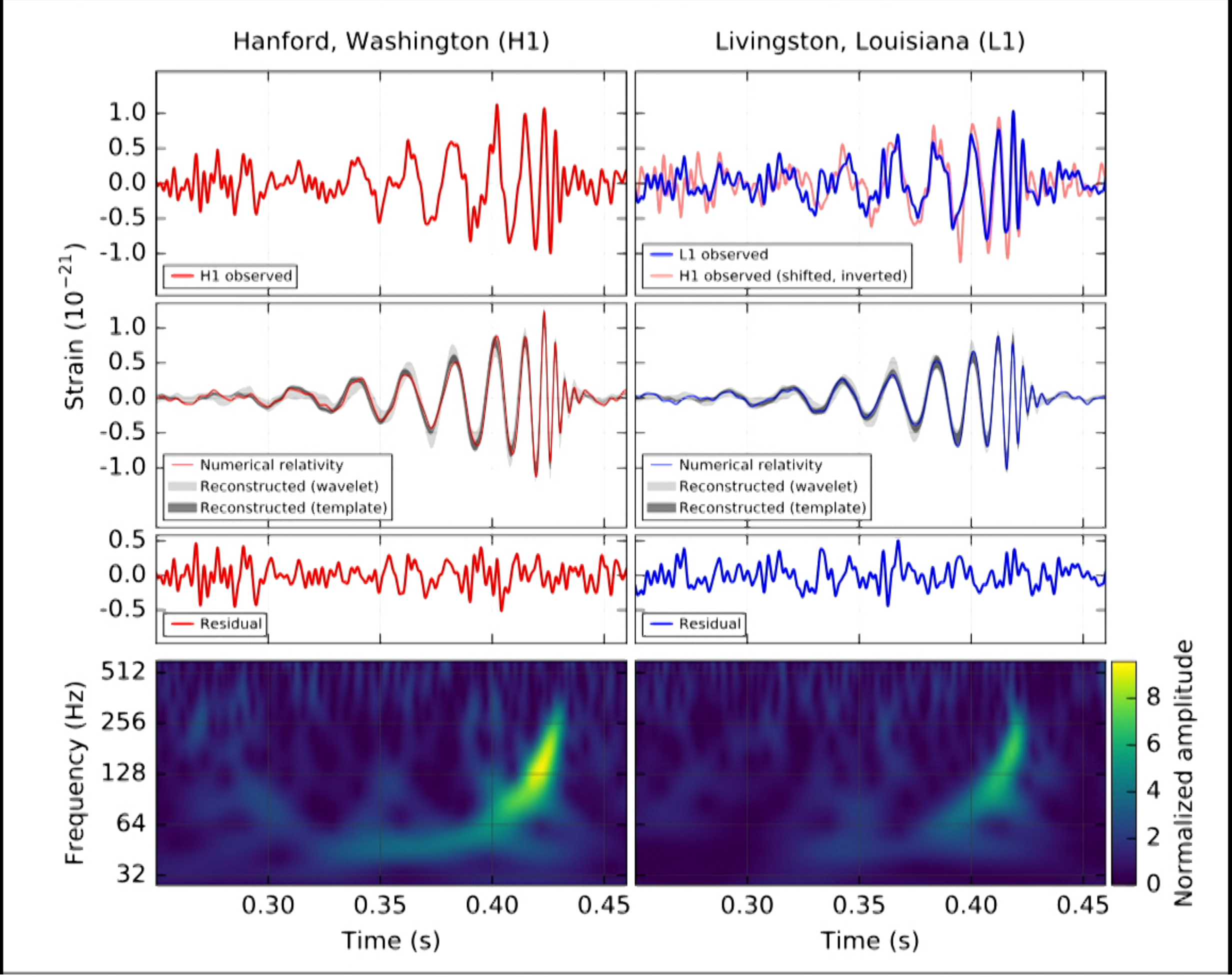


B. P. Abbott, …, LKN et al., PRL 116, 131103 (2016)

Sources And Methods

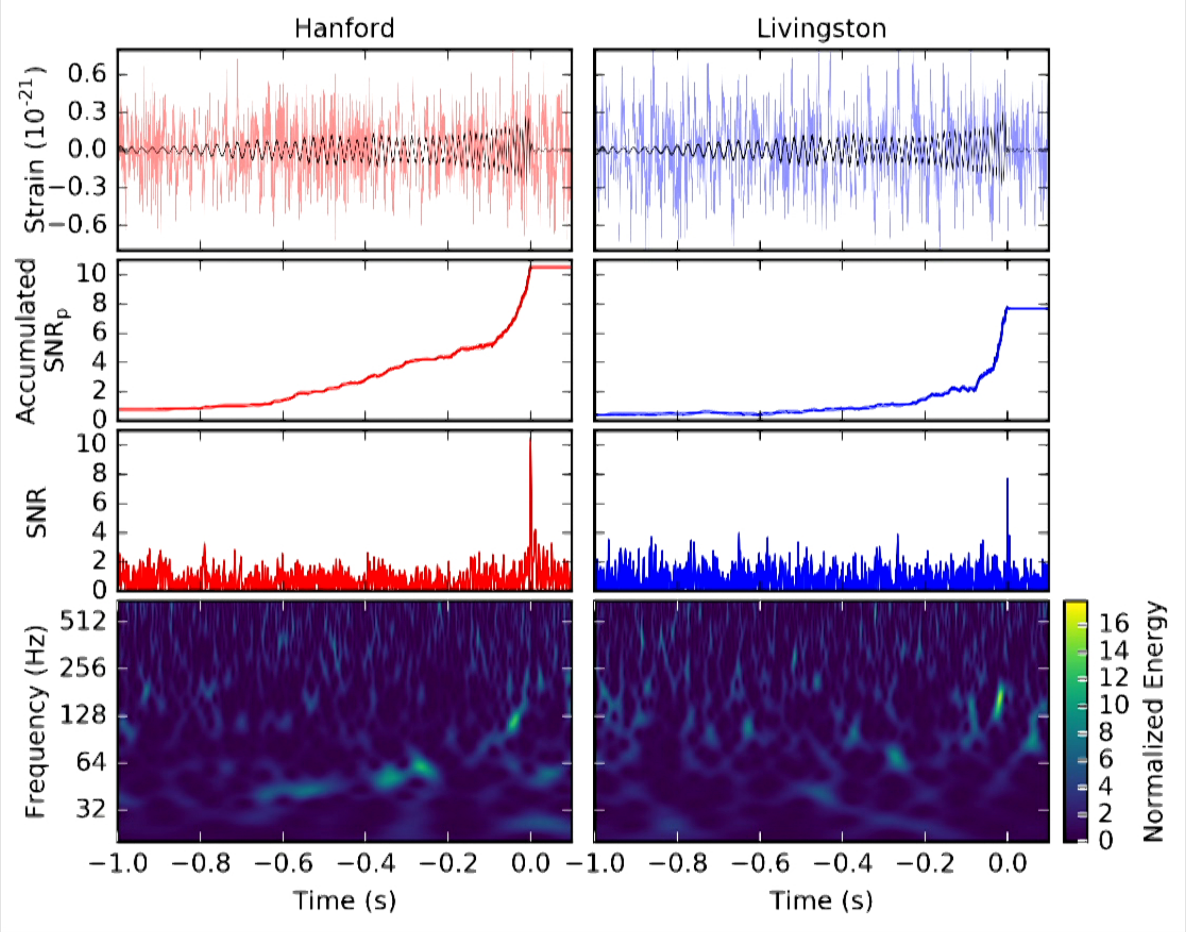
	Long duration	Short duration
Known Signal (matched filter search)	 Pulsars	 Compact Binary Inspirals
Unknown Signal (template-less methods)	 Stochastic Background	 Bursts

GW150914



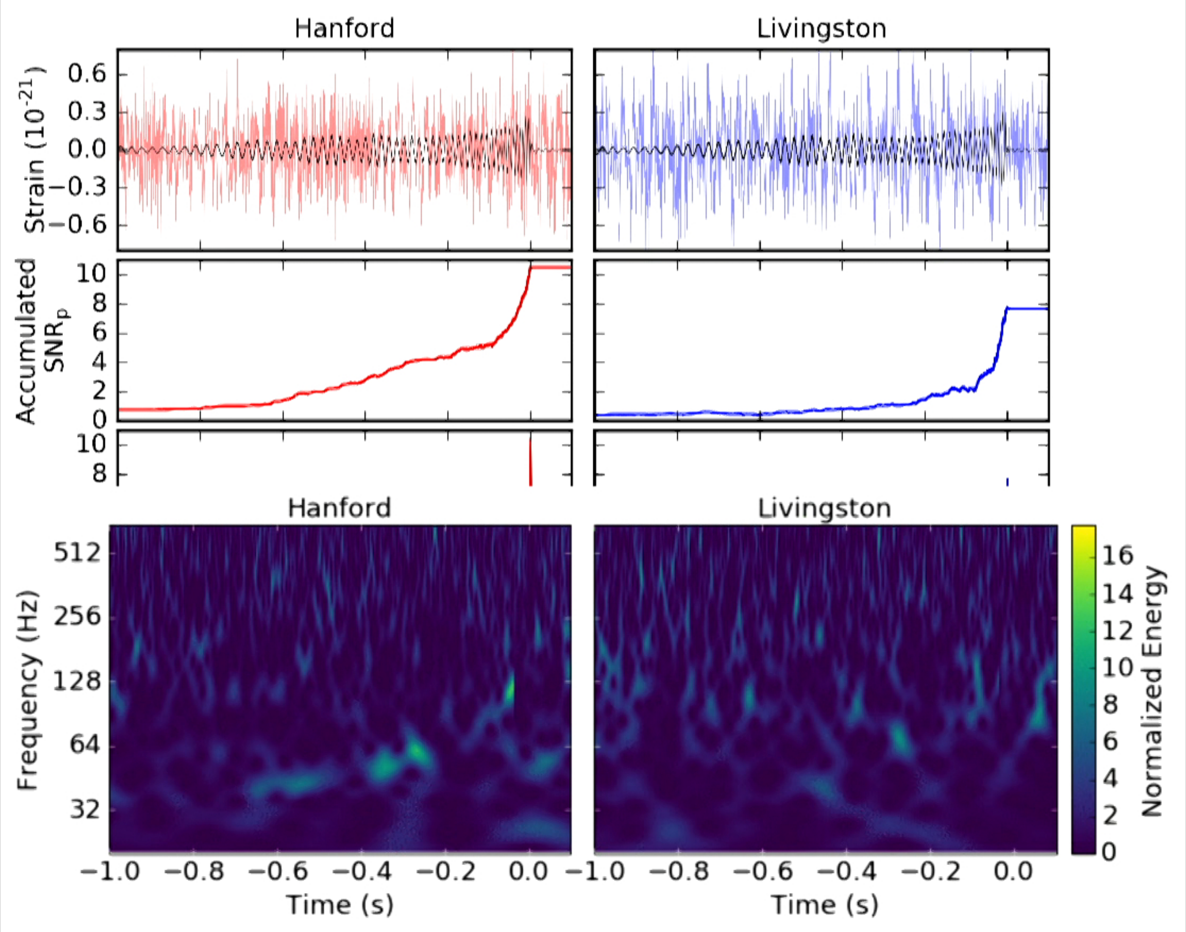
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
Normalized amplitude
0
2
4
6
8

GW151226



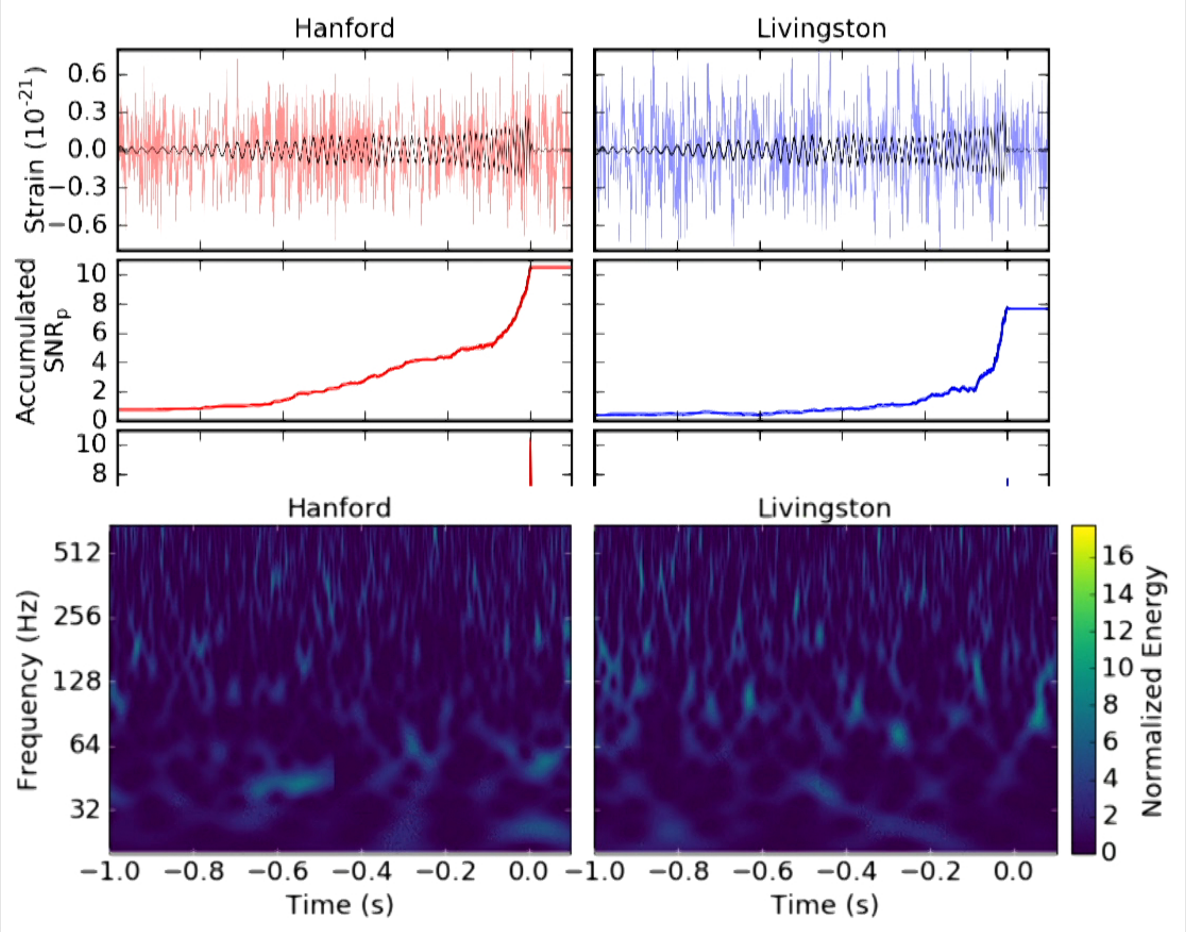
Abbott et al., PRL 116, 241103 (2016)

GW151226



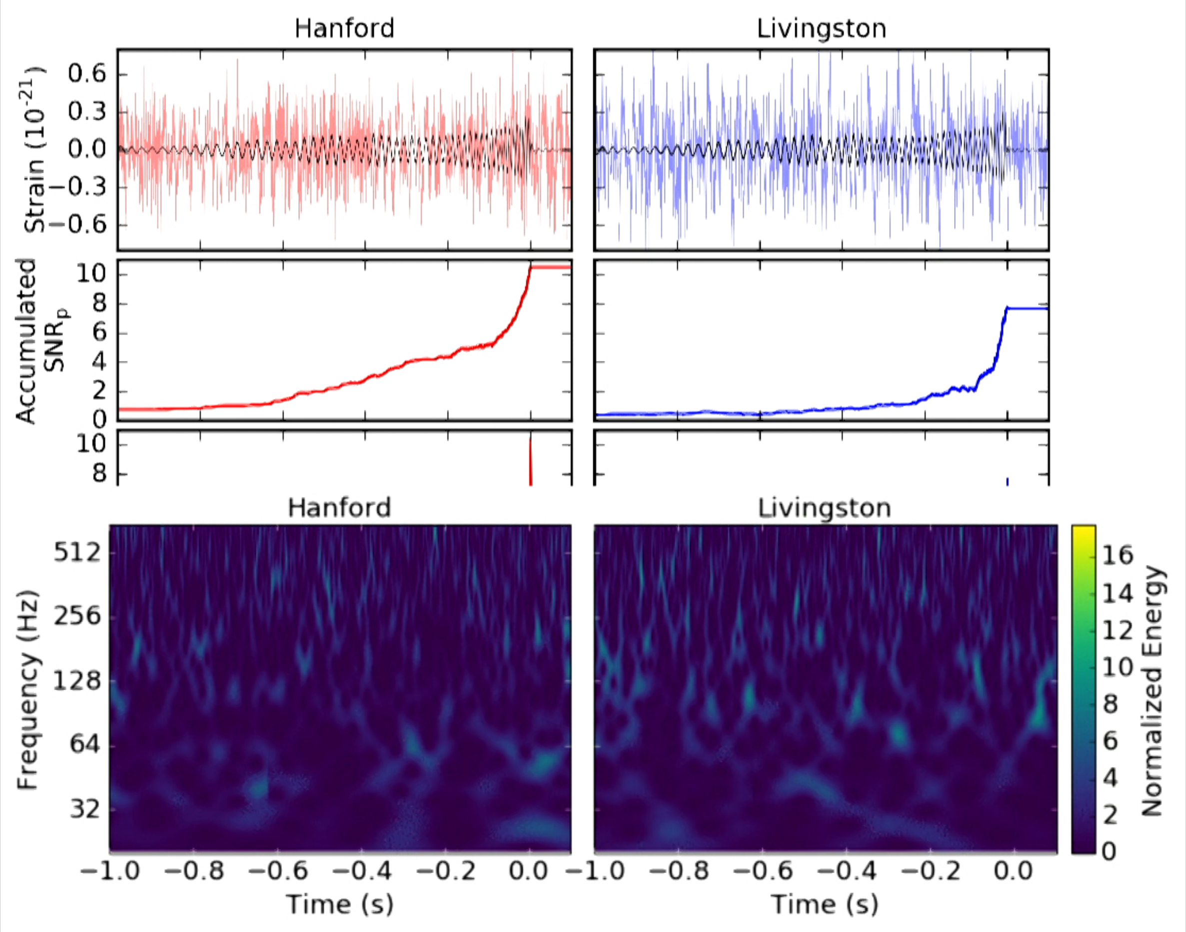
Abbott et al., PRL 116, 241103 (2016)

GW151226



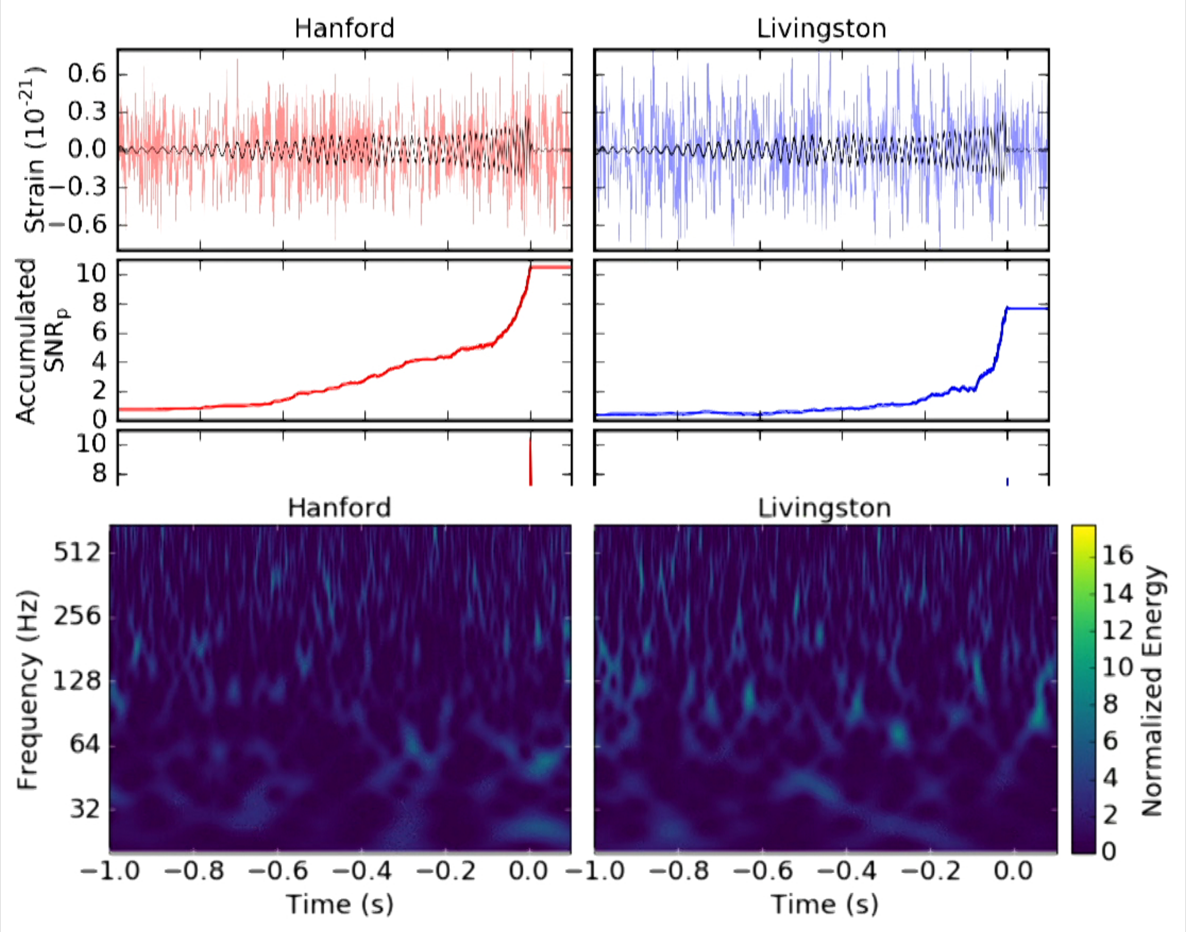
Abbott et al., PRL 116, 241103 (2016)

GW151226



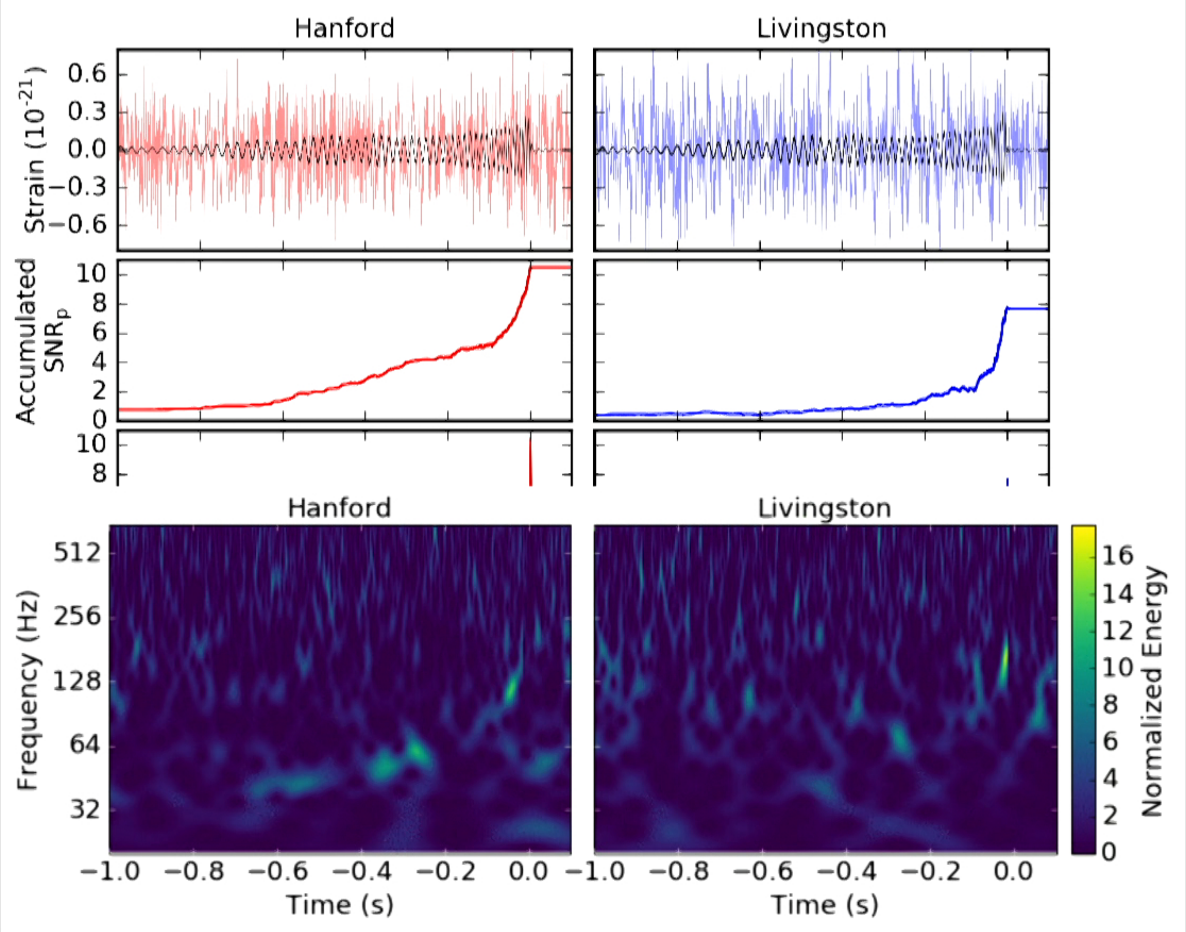
Abbott et al., PRL 116, 241103 (2016)

GW151226



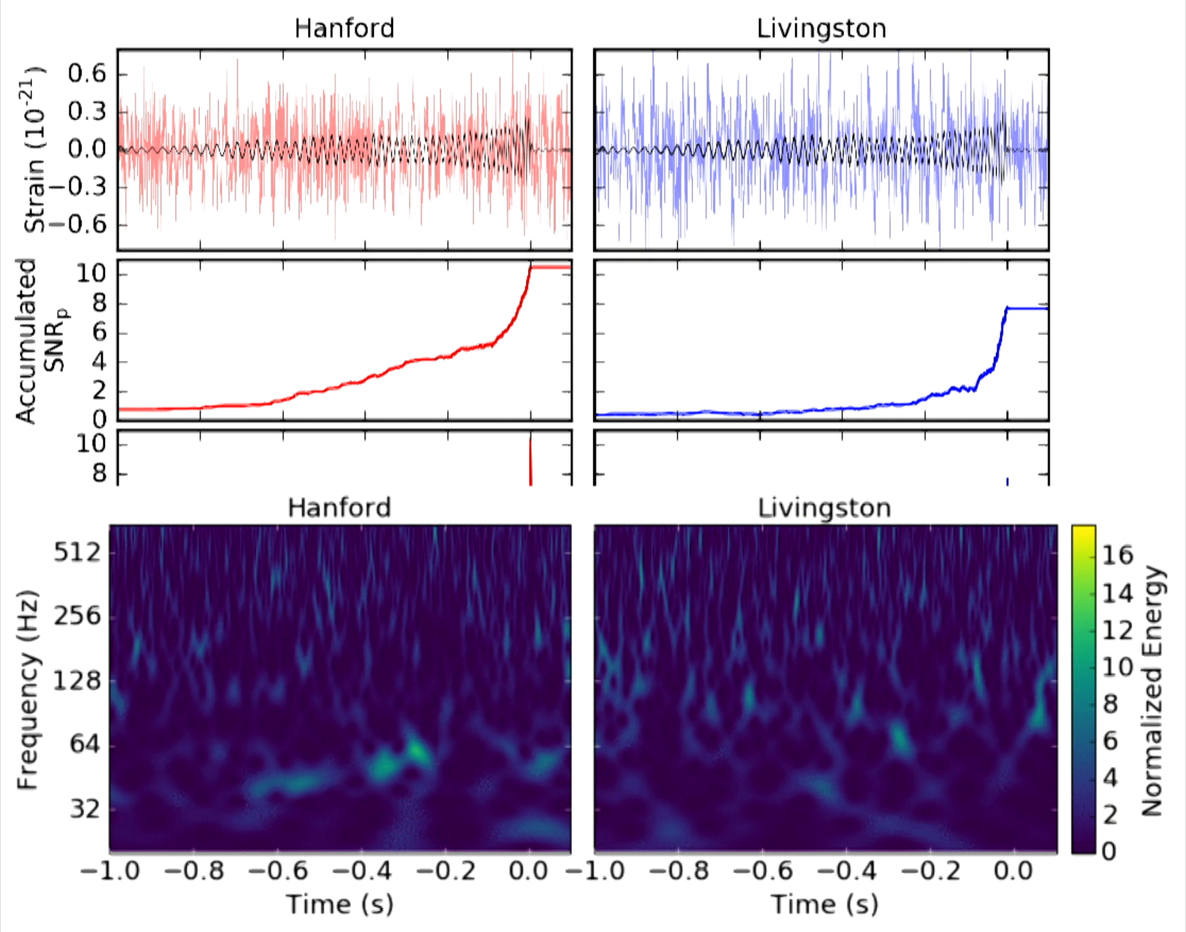
Abbott et al., PRL 116, 241103 (2016)

GW151226



Abbott et al., PRL 116, 241103 (2016)

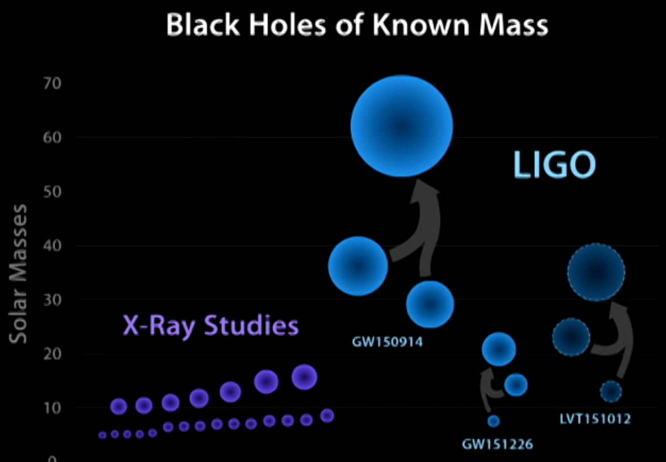
GW151226



Abbott et al., PRL 116, 241103 (2016)

Key facts from the detections

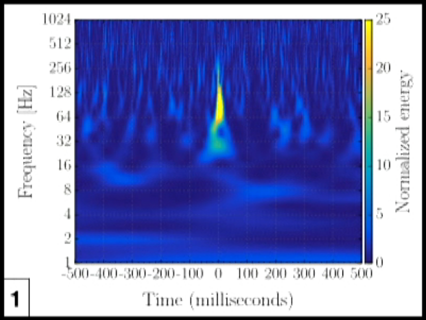
- GW150914 is the first observation of a binary black hole merger
- Black hole binaries exist and merge in Hubble time
- Black holes larger than 25 solar masses exist
- Black holes like those that resulted in GW150914 are likely formed in low-metallicity environment (< half solar metallicity)
- Best testing of GR in the strong field, nonlinear regime -> no evidence to doubt GR
- Merger rates implied from data: 9-240 Gpc^{-3} yr^{-1}



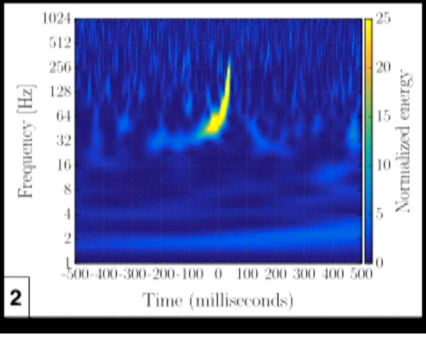
Data Quality

The quality of the data can change on an hourly timescale due to, for example, the weather, human traffic, hiccups in the electronics…

All of these things can create noise transients or glitches in the data

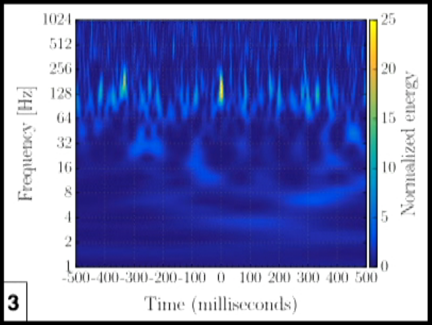


1

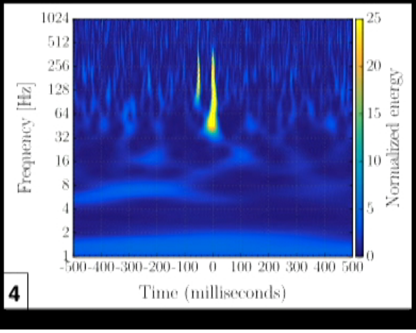


2

Glitches can mimic a gravitational wave signal -> makes it harder for the search algorithms to distinguish true signal from noise



3



4

Mitigating noise sources

- We analyse all data which were collected when the detectors are in their observation state
- When a noise source is identified, the instrument hardware/software is modified to remove/reduce the effect of the noise
- We sometimes wish to remove egregious data from the search which was collected during a time of a known instrumental problems
- This is only done by systematically identifying and removing troublesome data

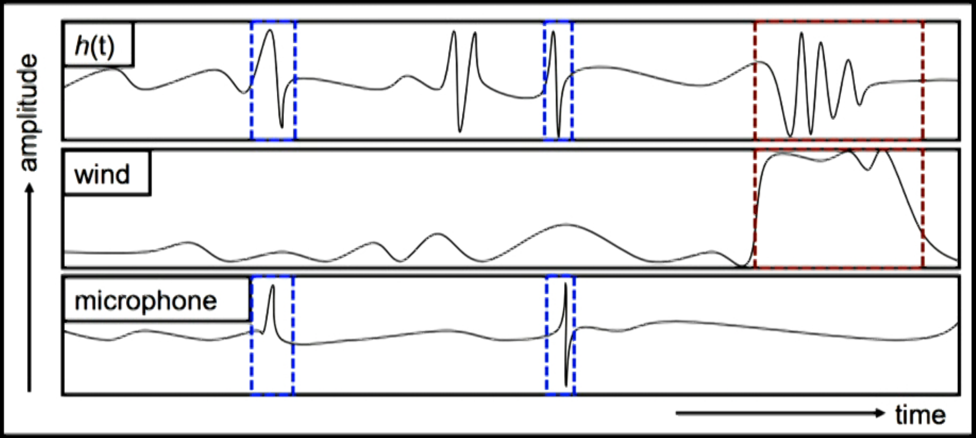
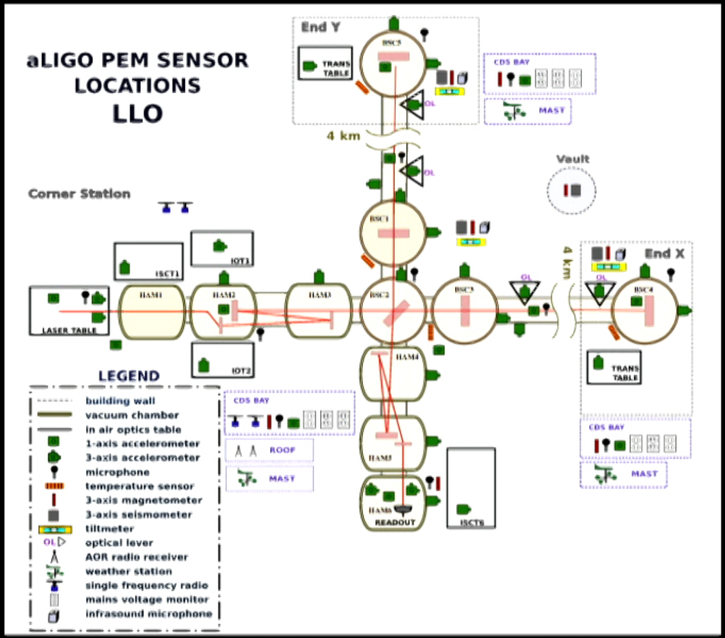


Figure: J. R. Smith et al., CQG 28 235005 (2011)

Detector Monitoring

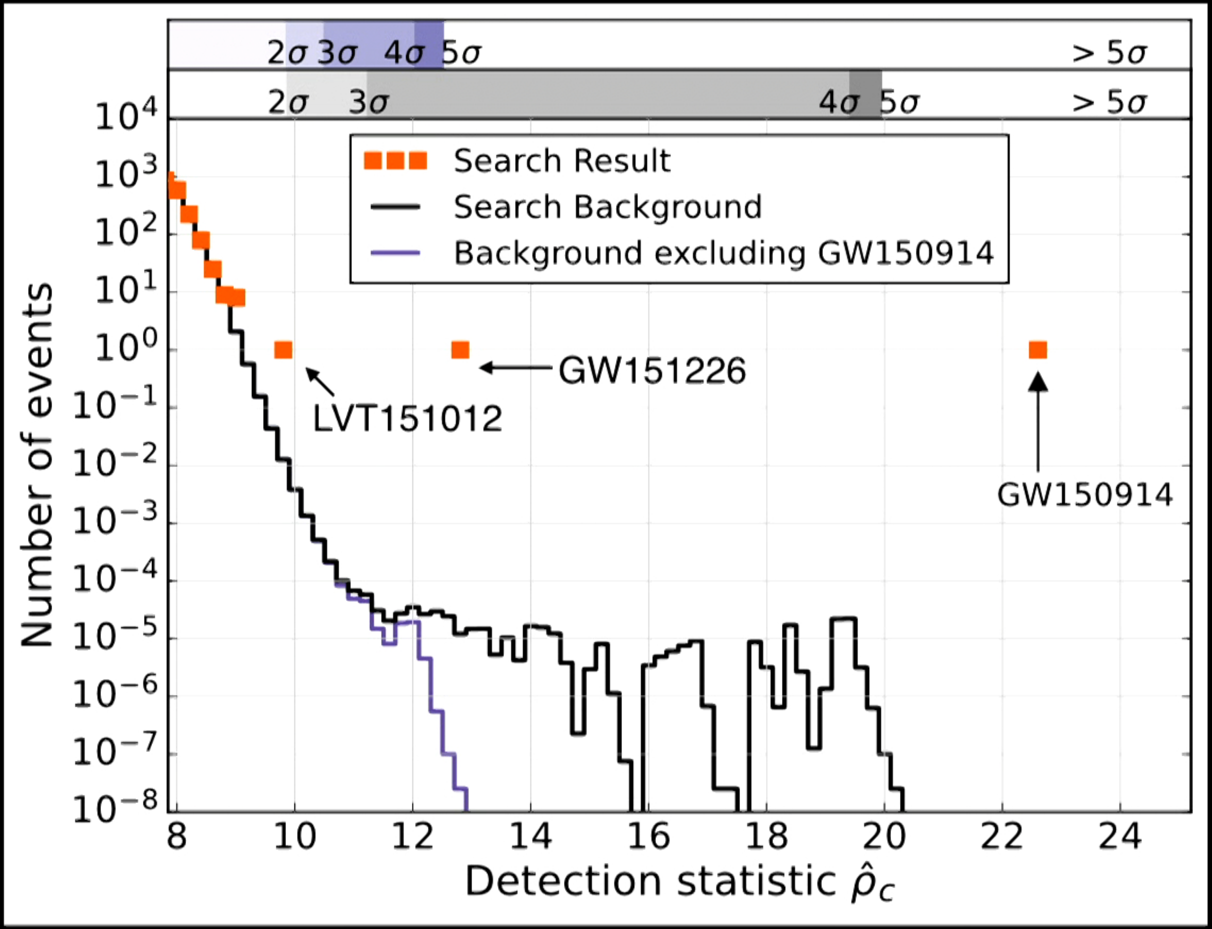
There are over 200,000 channels which monitor instrument behaviour and environmental conditions



- These channels witness a broad spectrum of potential coupling mechanisms
- We look for correlations between data in the gravitational wave channel and these auxiliary channels to identify times of bad data
- Efforts have been made to improve the data quality prior to the observing run
  (L. K. Nuttall et al., Class. Quant. Grav., 32, 2015)

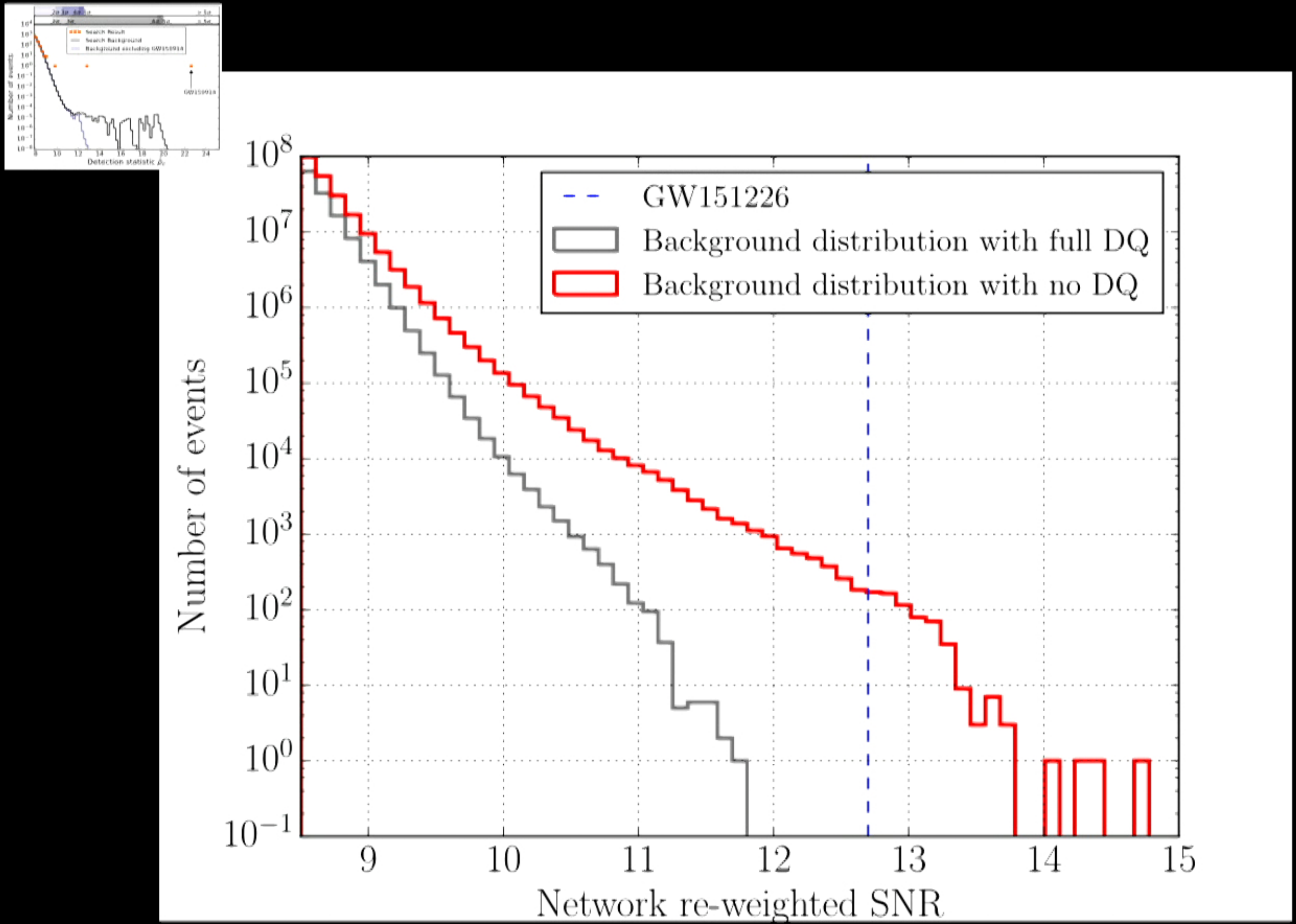
B. P. Abbott, …, LKN et al., Class. Quant. Grav. 33, 134001 (2016)

Benefits of performing Data Quality Studies



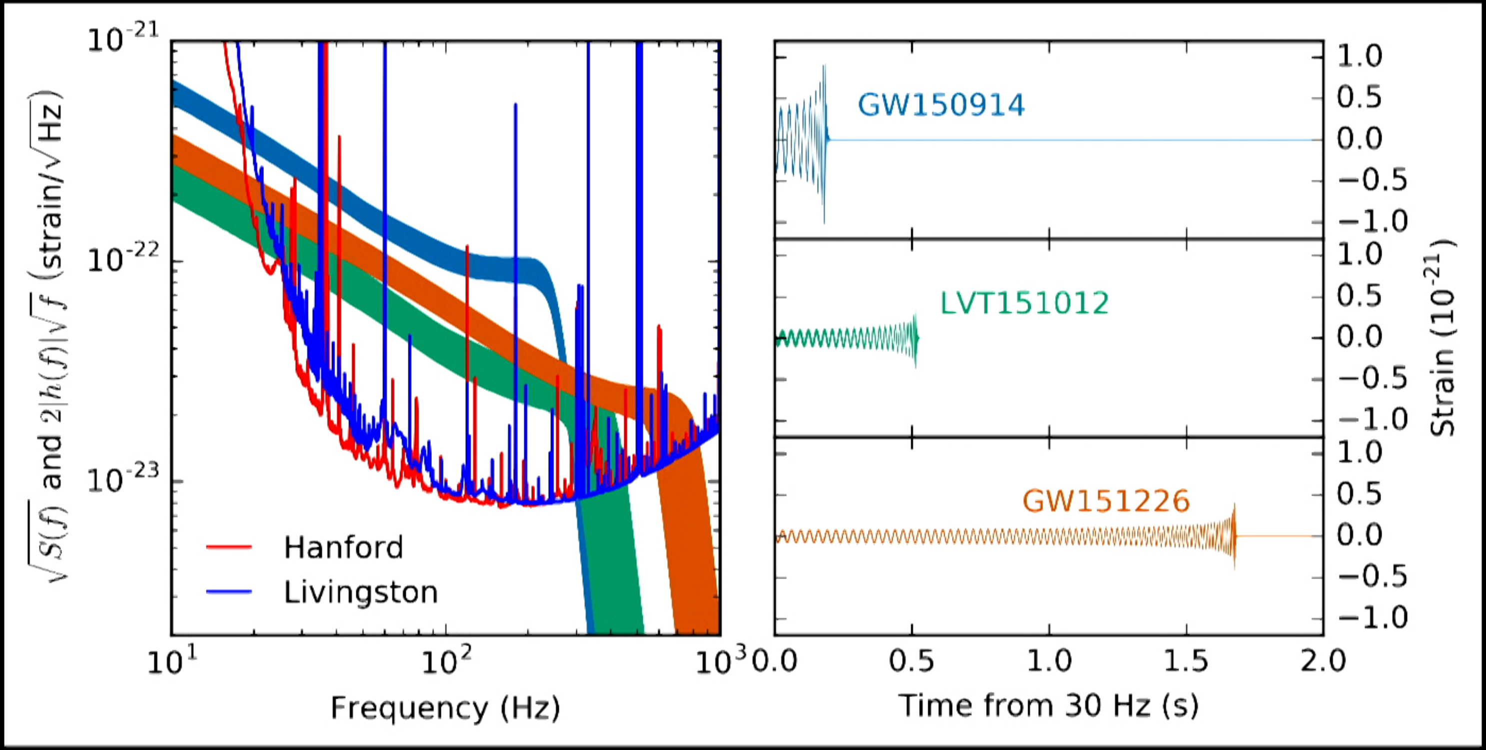
B. P. Abbott, …, LKN et al., In Prep (2017)

Benefits of performing Data Quality Studies



B. P. Abbott, …, LKN et al., In Prep (2017)

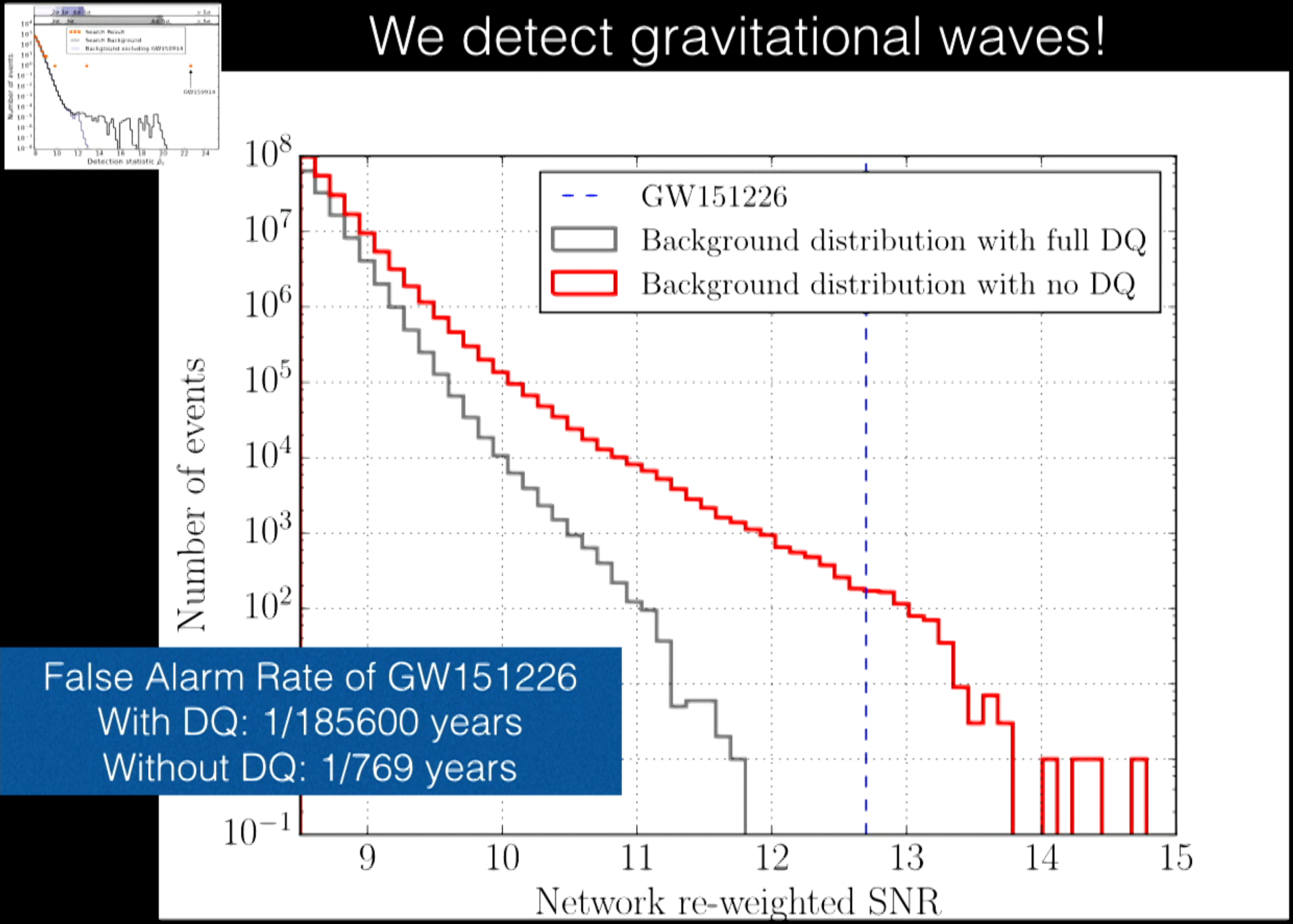
Results from the first observing run: September 12th 2015 - January 19th 2016



B. P. Abbott, …, LKN et al., Phys. Rev. X 6, 041015 (2016)

Benefits of performing Data Quality Studies

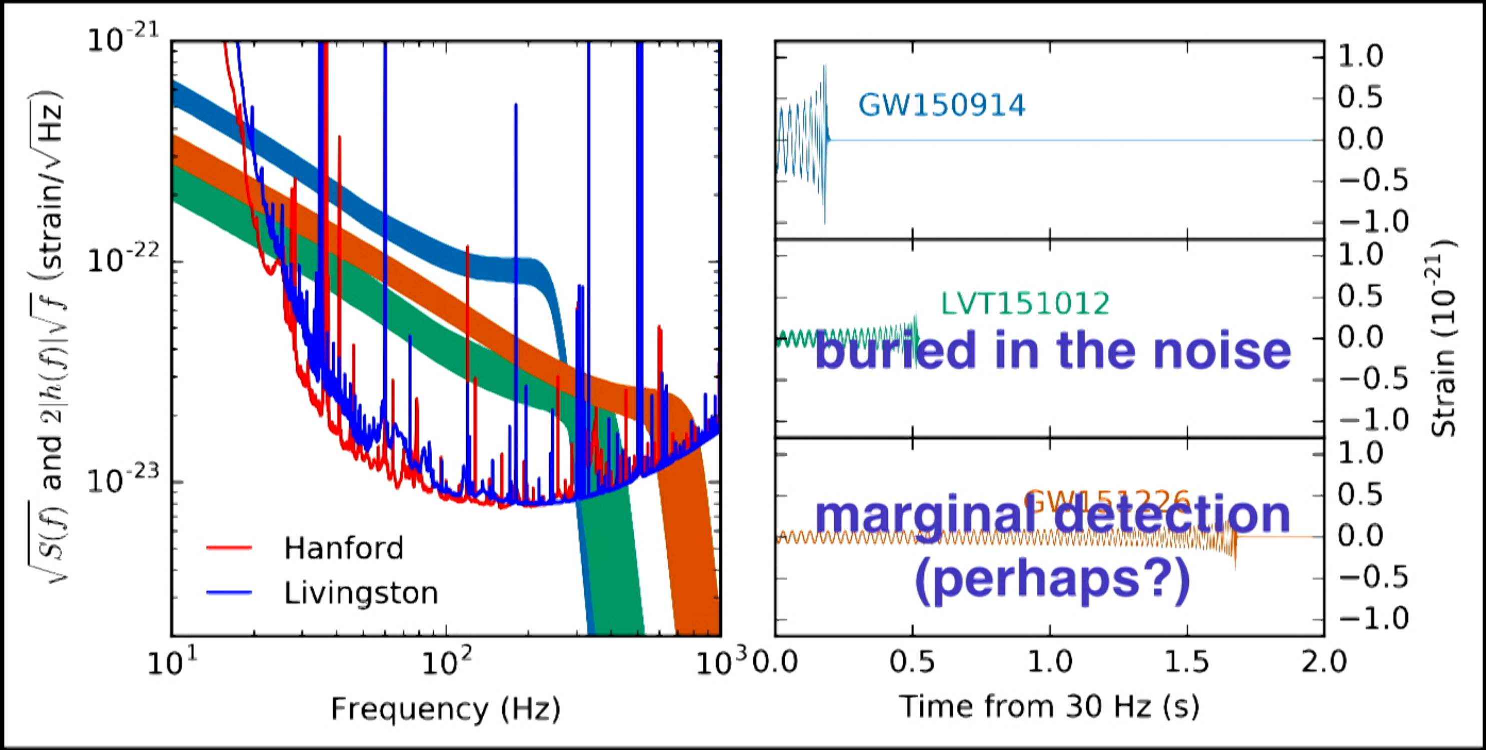
We detect gravitational waves!



False Alarm Rate of GW151226
With DQ: 1/185600 years
Without DQ: 1/769 years

B. P. Abbott, …, LKN et al., In Prep (2017)

Results from the first observing run:
September 12th 2015 - January 19th 2016



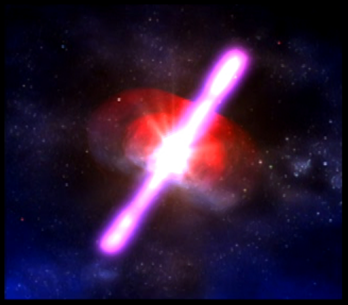
buried in the noise

marginal detection (perhaps?)

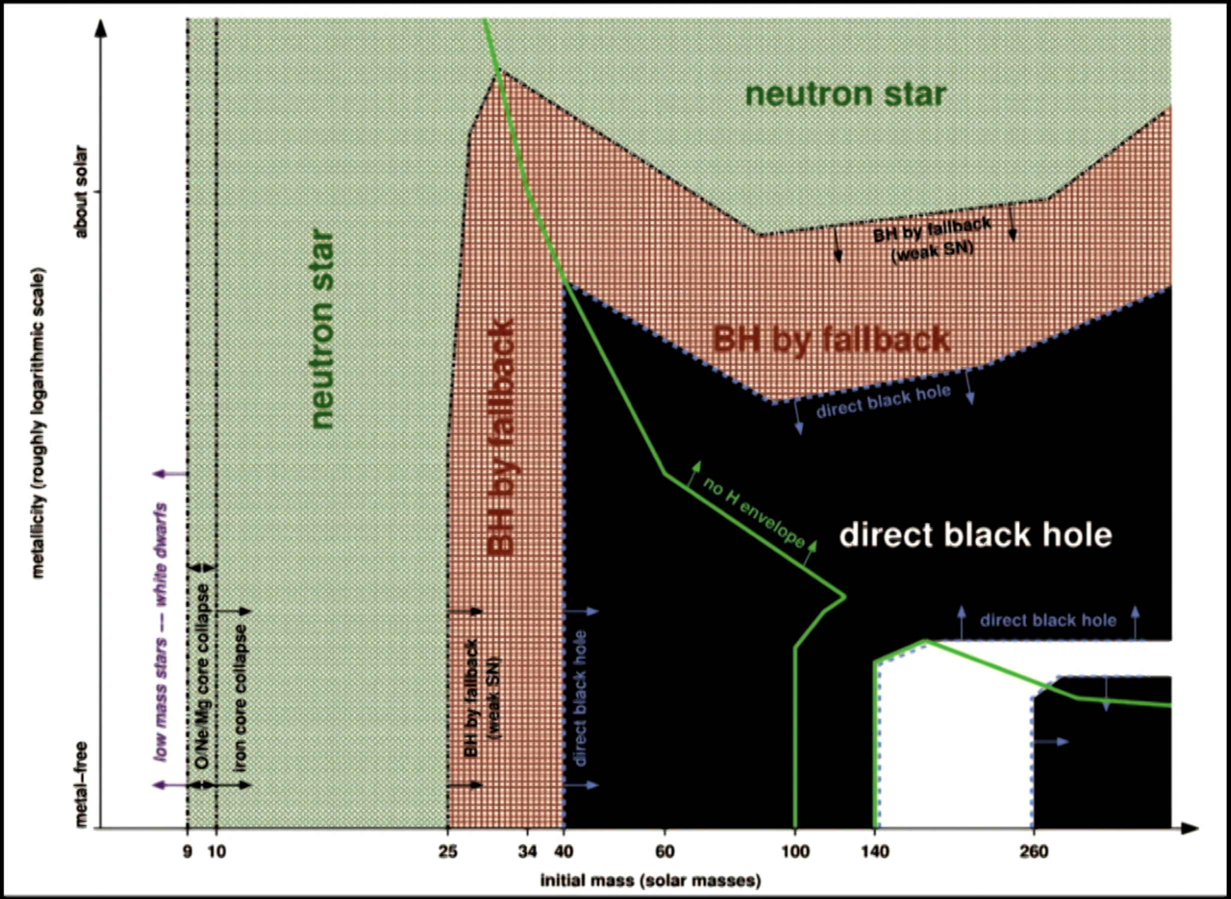
B. P. Abbott, …, LKN et al., Phys. Rev. X 6, 041015 (2016)

More Detections = More Astrophysics

- How many black holes are there in the universe?
- What happens when two black holes collide?
- What is the maximum mass of a neutron star?
- How do the first generations of stars live and die?
- Is there a gap in the black hole mass spectrum due to pair instability supernovae
- What is the engine that powers a short hard gamma ray burst?

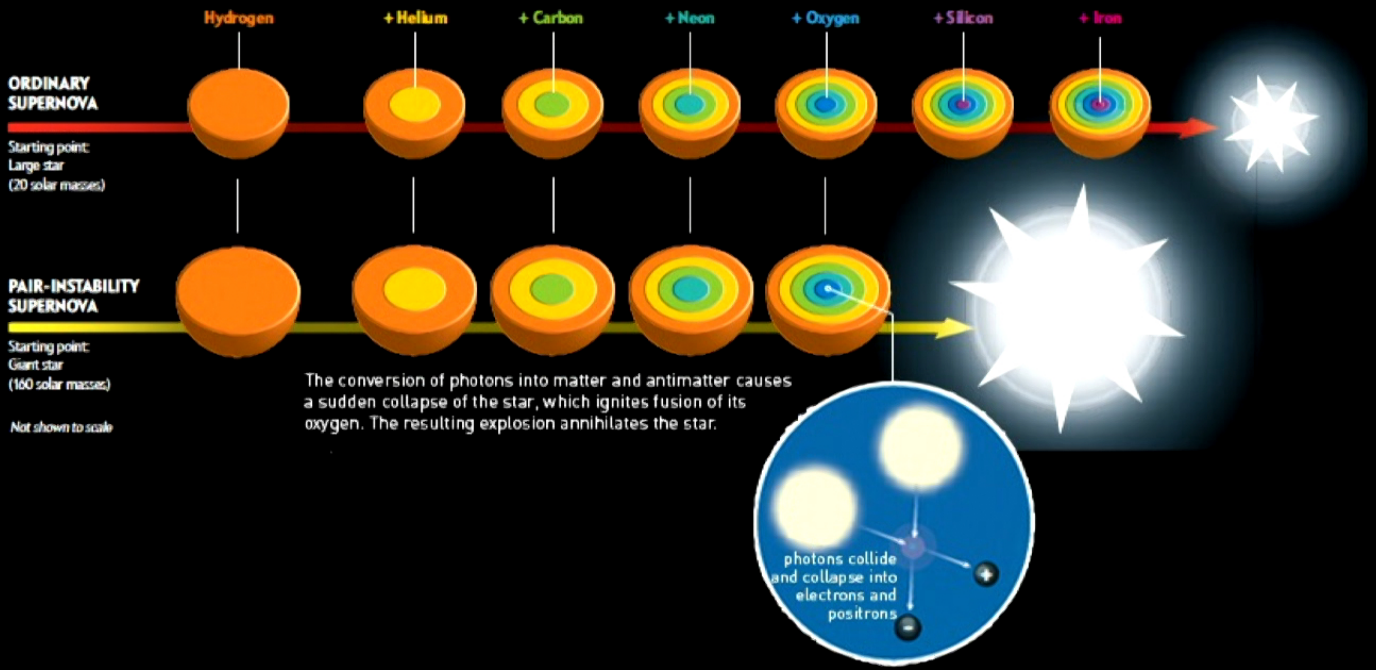


What happens at the end of a massive star's life?



A. Heger et al., ApJ, 591:288-300 (2003)

Pair-Instability Supernovae (PISN)



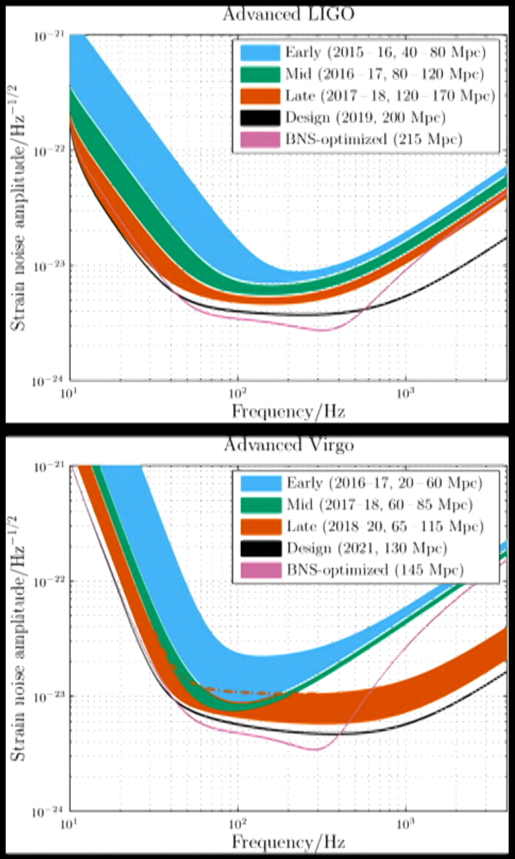
The conversion of photons into matter and antimatter causes a sudden collapse of the star, which ignites fusion of its oxygen. The resulting explosion annihilates the star.

Expect there to be a gap in the black hole mass spectrum between ~60-130 $M_\odot$

Can we use Advanced LIGO to tell if there is a mass gap?

Injecting gravitational waveforms from the merger of two black holes in to Advanced LIGO and Virgo at design sensitivity:

- Injections are scaled in the source frame and then transformed to detector frame
- Waveforms are injected in to the data
- MCMC recovers the parameters of the waveform in the detector frame
- One MCMC are finished (~20,000 iterations) we transform back to the source frame



B. P. Abbott et al., Living Rev. Relativity 19 (2016), 1

Biwer, Nuttall et al., In Prep

Can we use Advanced LIGO to tell if there is a mass gap?

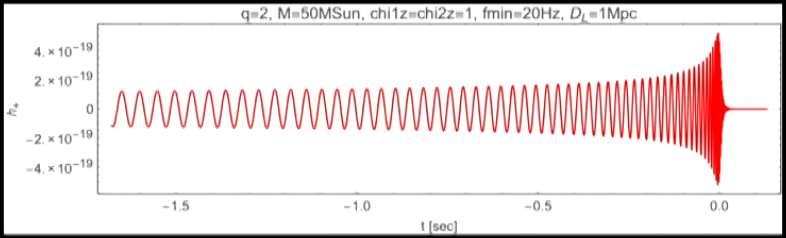
The Injections:

SEOBNRv4 waveforms (A. Bohe et al., Phys. Rev. D 95, 044028 (2017)):
- Effective one body
- Spinning, non-precessing black holes
- Calibrated to 141 NR waveforms

Distance scaled so that coherent SNR of waveform is ~25

Sampled uniformly:
- $15 < m_1\ (M_\odot) < 250$
- $15 < m_2\ (M_\odot) < 130$

Aligned spin, uniform distribution between -0.7 to 0.7



http://friendshao.github.io/news/2016/11/14/seobnrv4-waveforms-for-aligo.html

Biwer, Nuttall et al., In Prep

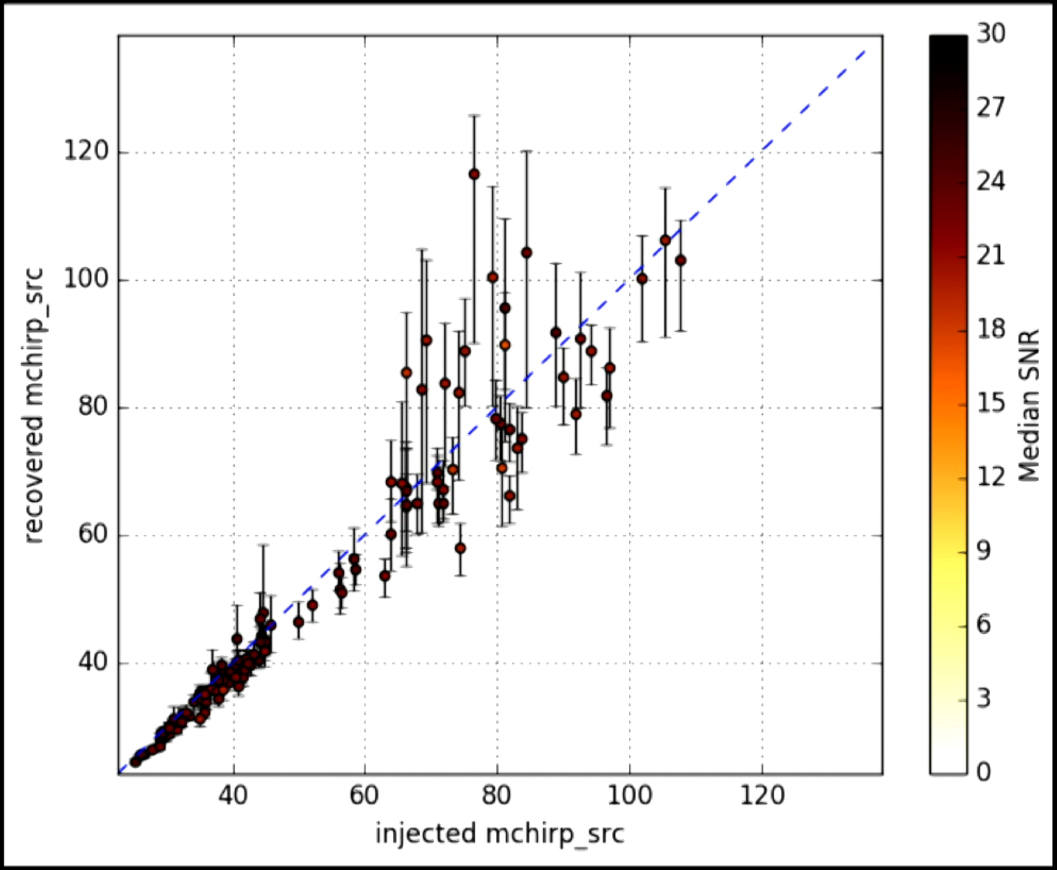
Can we use Advanced LIGO to tell if there is a mass gap?

Sampling:

- Start at 10Hz
- Priors uniform over:
  - m_1 and m_2, but sampled in Mchirp = $(m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$ and mass ratio $q = m_1/m_2$
  - spin1z
  - spin2z
  - Inclination angle
  - Polarization angle
  - Coalescence phase
  - RA
  - Distance (Mpc)
- Dec prior is cosine distribution

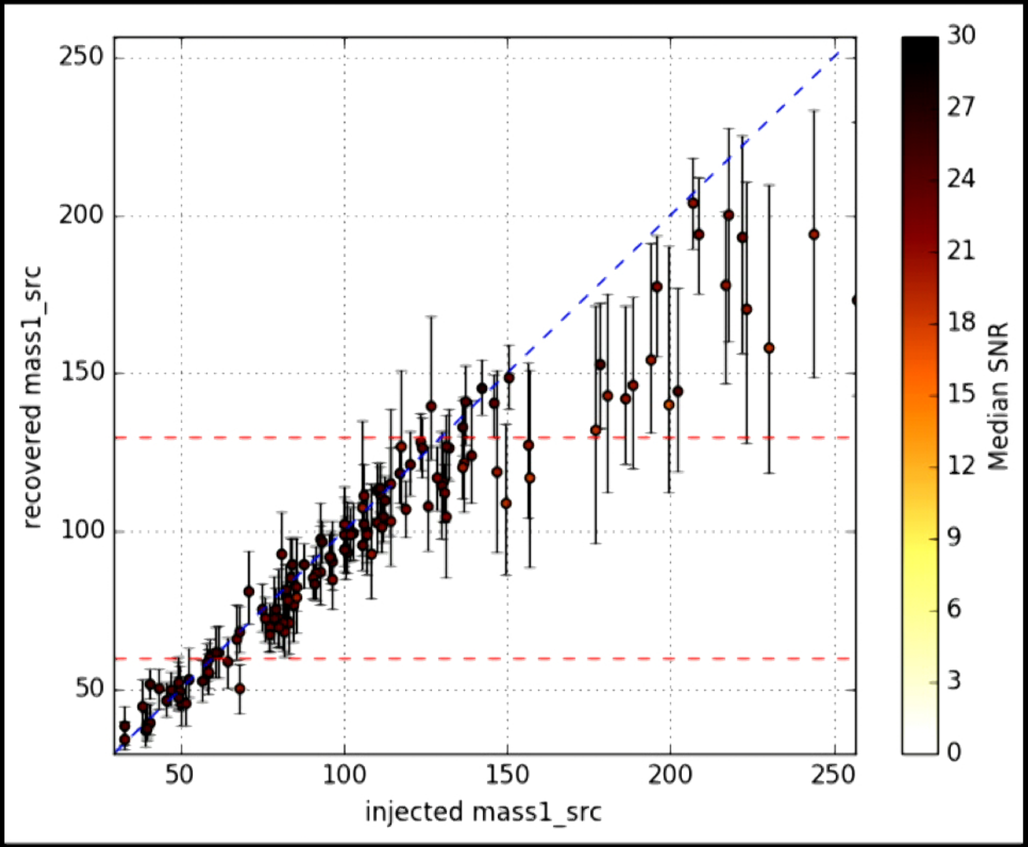
Biwer, Nuttall et al., In Prep

Can we use Advanced LIGO to tell if there is a mass gap?



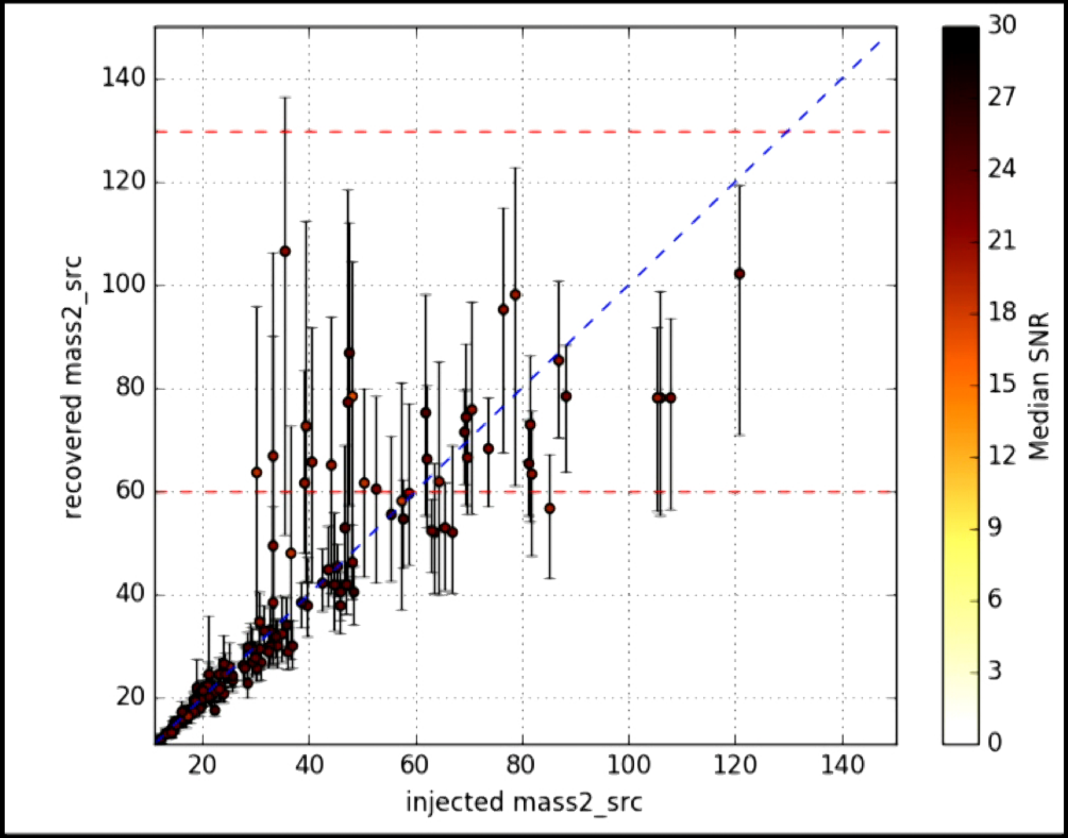
Biwer, Nuttall et al., In Prep

Can we use Advanced LIGO to tell if there is a mass gap?

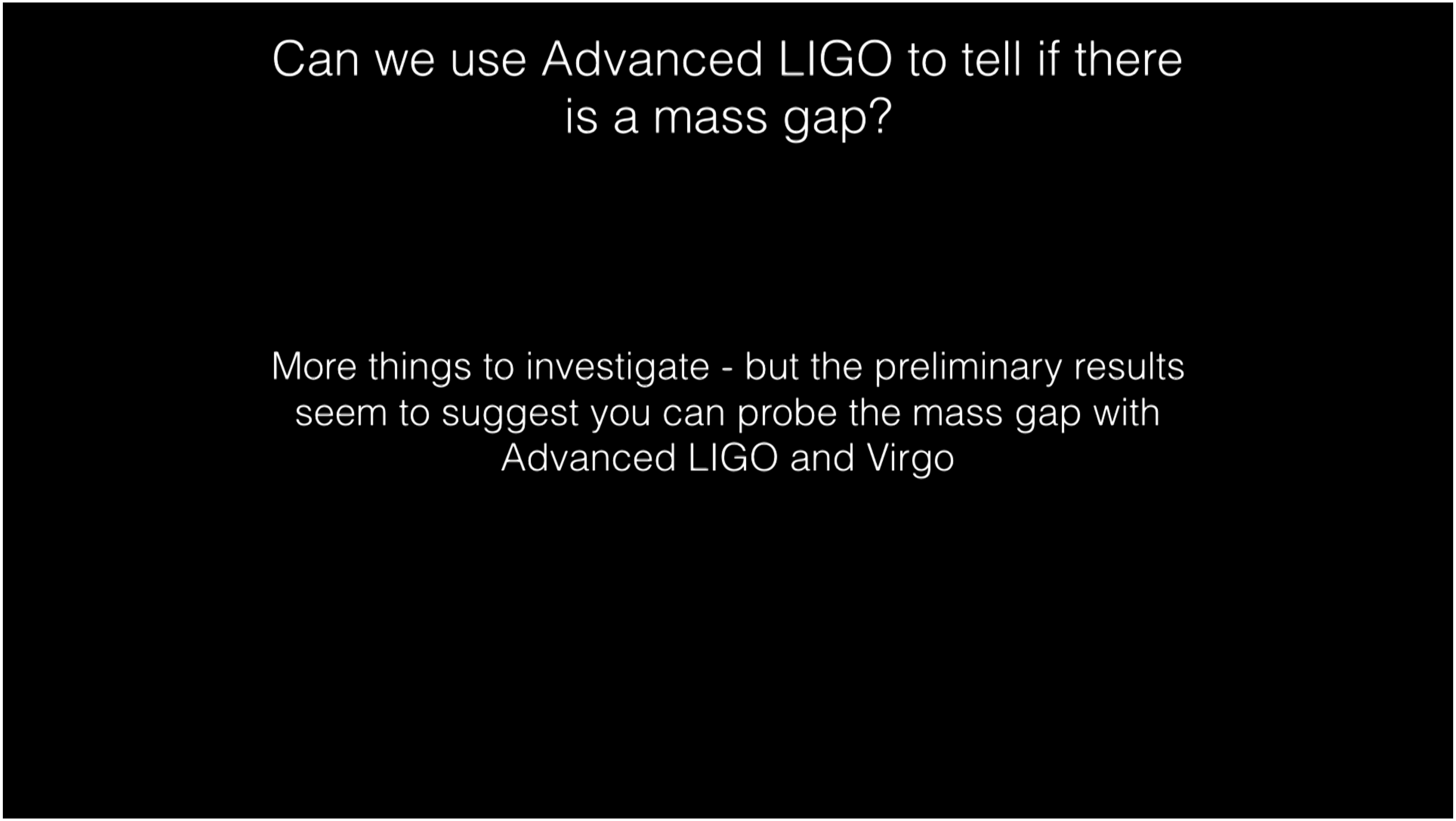


Biwer, Nuttall et al., In Prep

Can we use Advanced LIGO to tell if there is a mass gap?



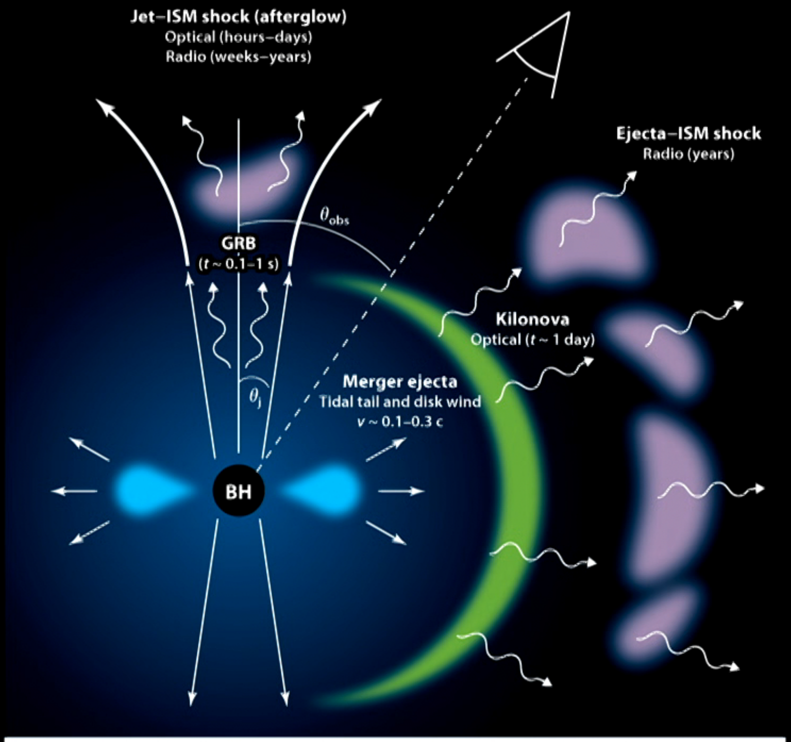
Biwer, Nuttall et al., In Prep



Can we use Advanced LIGO to tell if there is a mass gap?

More things to investigate - but the preliminary results seem to suggest you can probe the mass gap with Advanced LIGO and Virgo

EM+GW Observations



Berger E. 2014.
Annu. Rev. Astron. Astrophys. 52:43–105

Just a few examples:

- Central engine + Ejecta
- Pinpoint host galaxy - formation environment
- Explain nature of SGRBs
- Standard sirens - independent measure of cosmological parameters
- Explain abundance of heavy elements

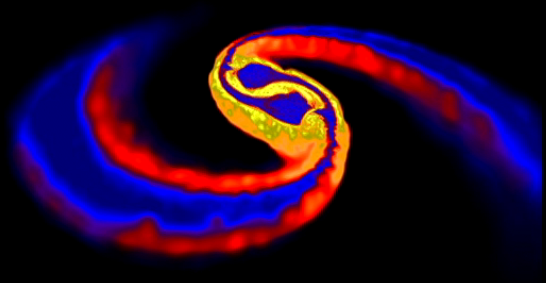
Source example: compact merger

High Energy Photons (X-ray / Gamma Ray):
- Gamma ray burst (seconds)
- Gamma ray burst afterglow (hours)
- Ejecta from a magnetar (10s of minutes)

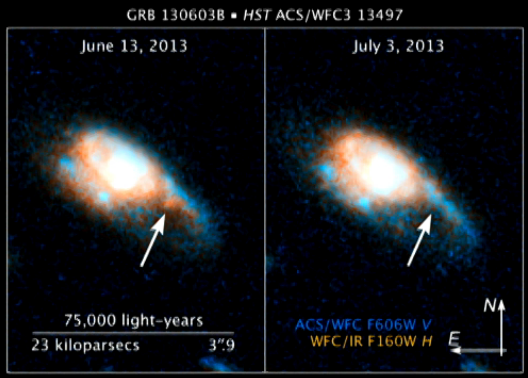
UV / Optical / IR
- Gamma ray burst afterglow (hours)
- Kilonova (days)

Radio
- Gamma ray burst afterglow (weeks to months)
- Prompt, coherent emission (seconds)

Lots of models! Lots of uncertainty!



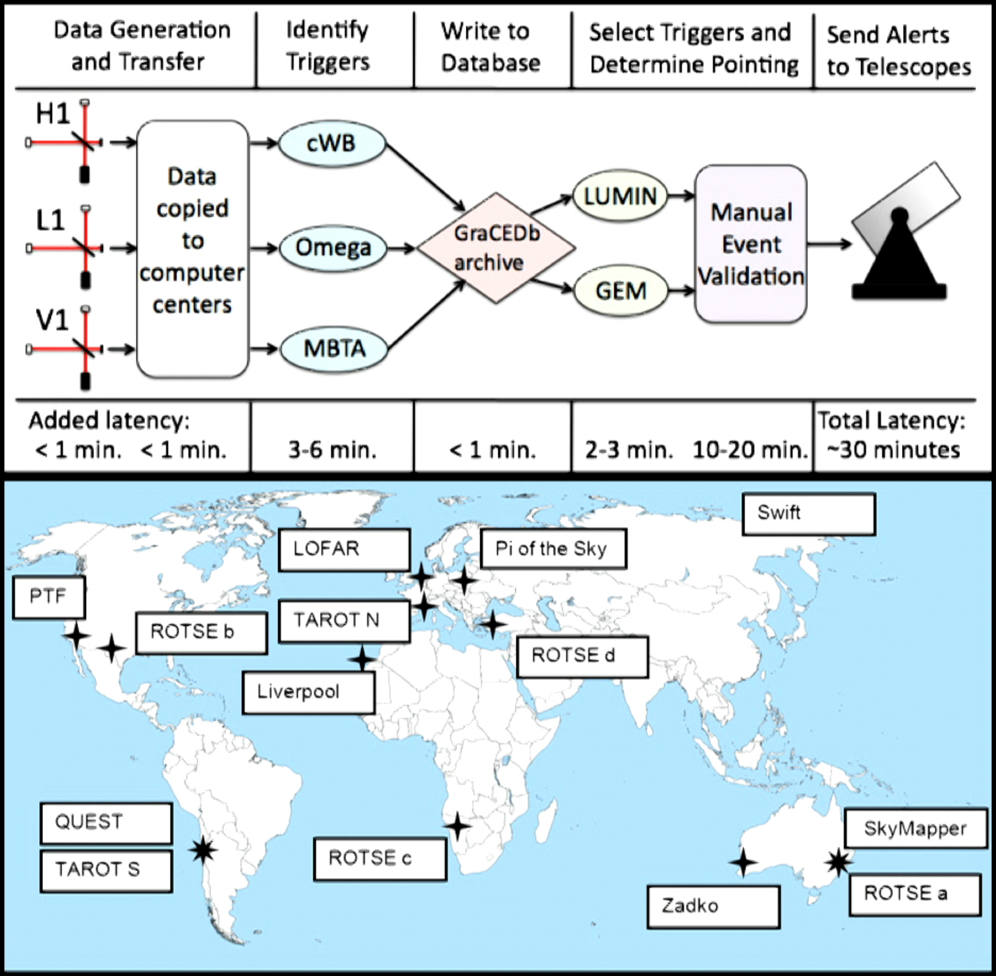
D. Price, S. Rosswog



NASA

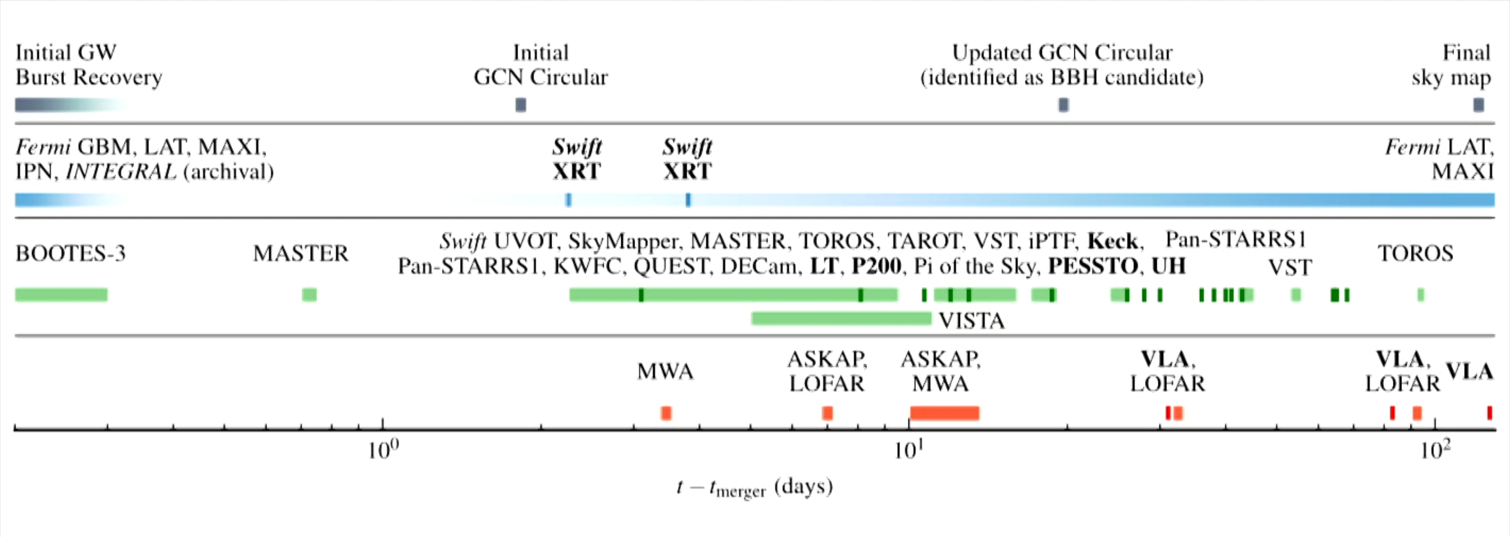
Possible GWs also from: Supernovae, Long GRBs, etc…

Something similar in the last science run of Initial LIGO



J. Abadie,..., LKN et al., 2011, A&A, 539, A124 / J. Aasi, ..., LKN et al., 2014, ApJS, 211, 7

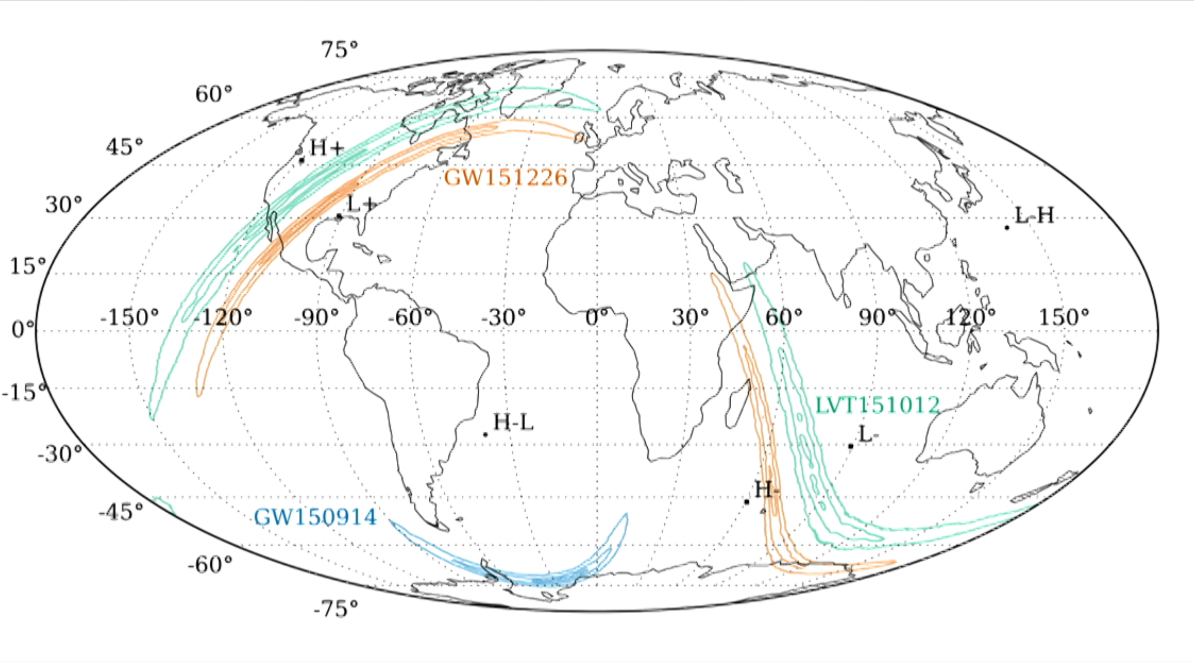
Electromagnetic Follow-Up



Timeline of observations of GW150914, separated by band and relative to the time of the gravitational wave event

B. P. Abbott et al. ApJ 826, L13 (2016)

Localisation



Sky localization inferred from triangulation of times, phases and amplitudes of signals on arrival

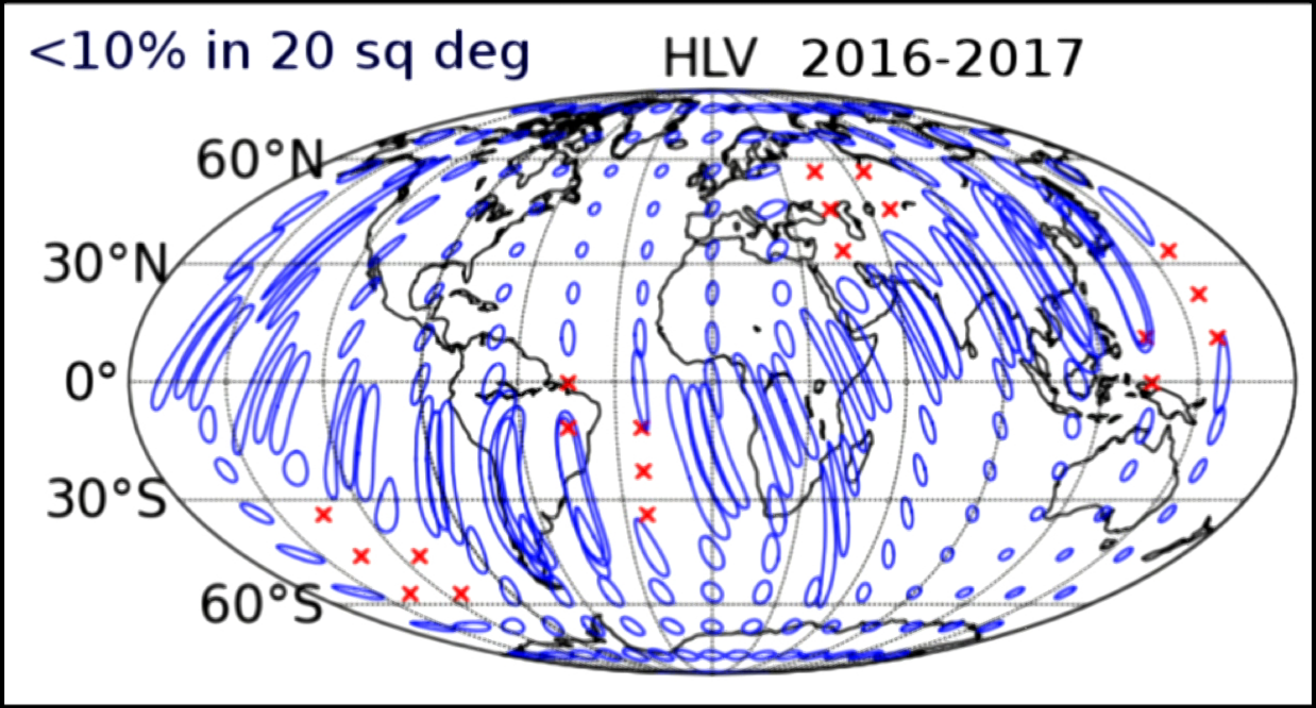
Distance inferred by signal amplitude and directional antenna patterns of the detectors

B. P. Abbott, …, LKN et al., Phys. Rev. X 6, 041015 (2016)

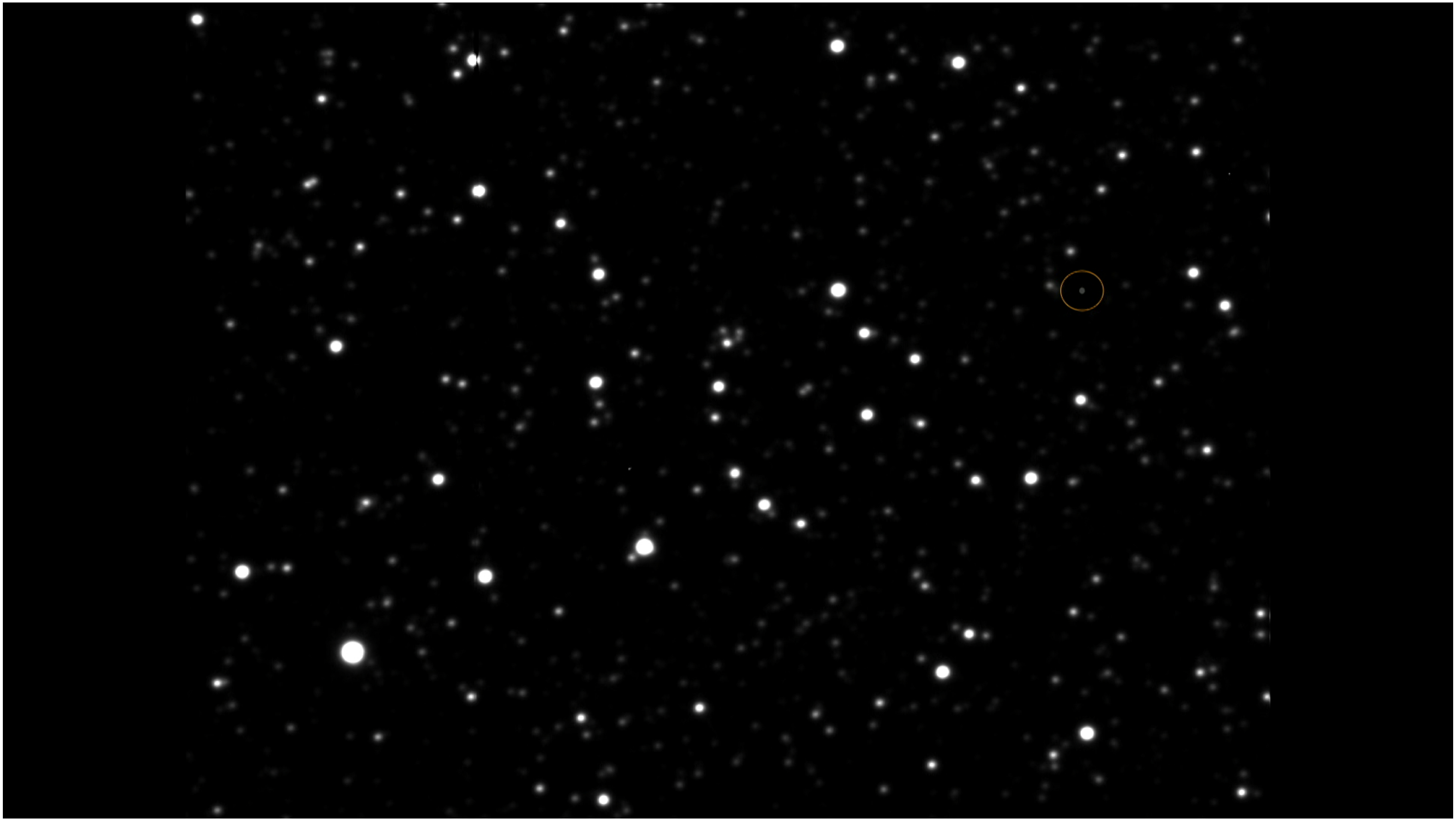
Localisation - this year

3 detectors (add Virgo)

~1-2 signals per month of observation



B. P. Abbott et al., Living Rev. Relativity 19 (2016)



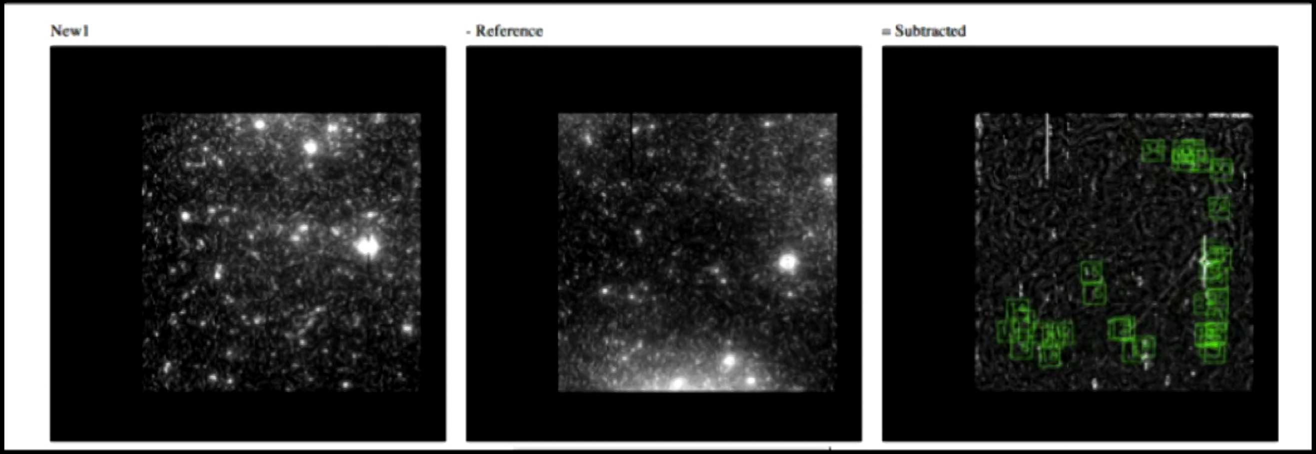
Challenge is to associate an electromagnetic transient with a gravitational wave event

Very similar problem as for GW data:

- Lots of varying objects in an EM image not caused by an event which also produced a detectable GW signal

Subtract the image of interest with an image of the same region of sky taken months apart

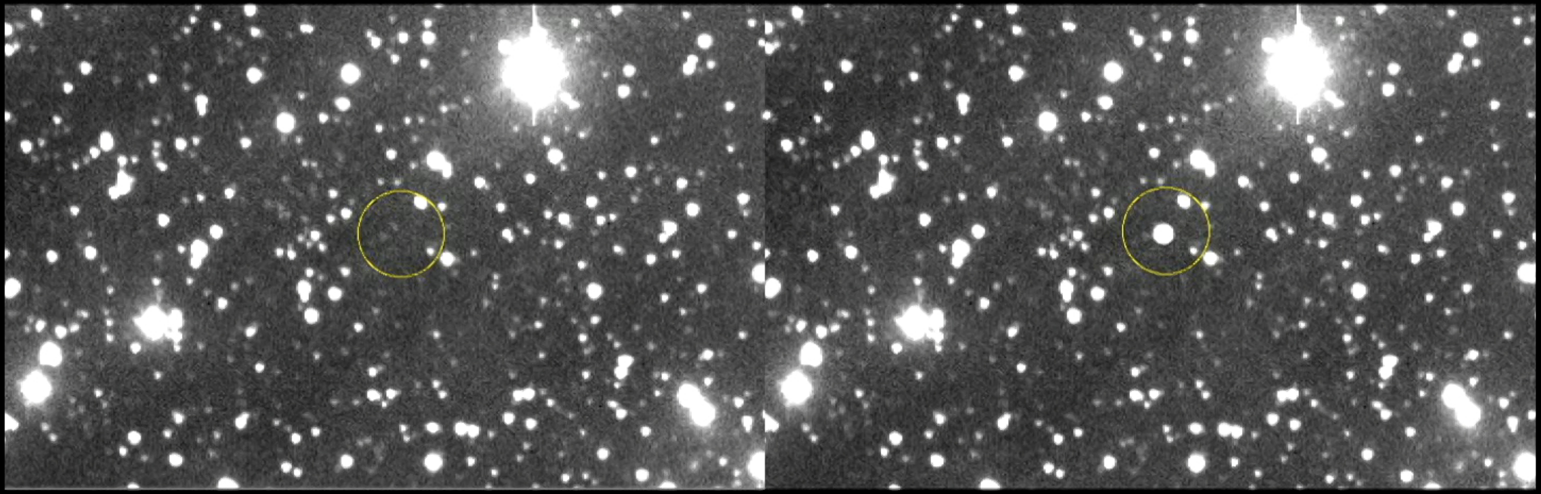
- Can get bad subtractions



L. K. Nuttall, 2012, J. Phys.: Conf. Ser. 363 012033 / L. K. Nuttall et al., 2013, ApJS, 209, 24 / J. Aasi, …, LKN et al., 2014, ApJS, 211, 7

Challenge is to associate an electromagnetic transient with a gravitational wave event

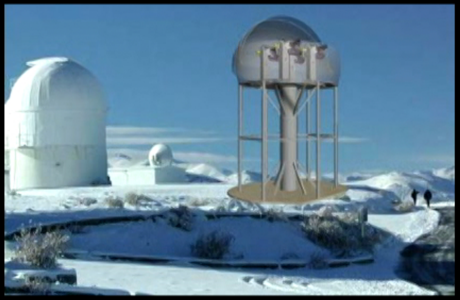
- Perform a background study to assess the statistical significance of any transient found in images taken in response to GW candidate
- Simulated false transients consistent with target theoretical light curves (kilonova (Metzger et al. MNRAS (2010) 406), short/long gamma-ray bursts (Kann et al., Astrophys.J., 720:1513–1558, 2010, Kann et al. Astrophys.J., 734:96, 2011)



L. K. Nuttall, 2012, J. Phys.: Conf. Ser. 363 012033 / L. K. Nuttall et al., 2013, ApJS, 209, 24 / J. Aasi, …, LKN et al., 2014, ApJS, 211, 7

BlackGEM

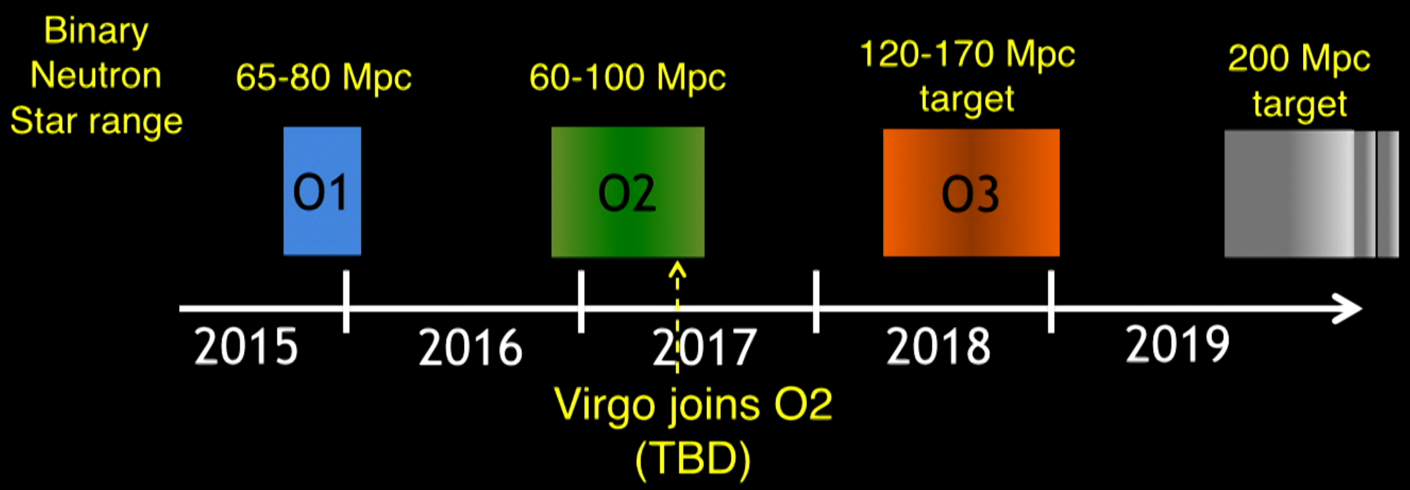
- Dedicated to measure the optical emission from pairs of merging neutron stars and black holes
- Will comprise of 15 telescopes - each telescope is $2.7\mathrm{deg}^2$ in size
- BlackGEMs configuration can change to better map an elongated GW skymap
- Will be capable of reaching a limiting magnitude of 23 in 5 minutes
- Operational by the end of 2017



https://astro.ru.nl/blackgem/

Plausible Observing Timeline

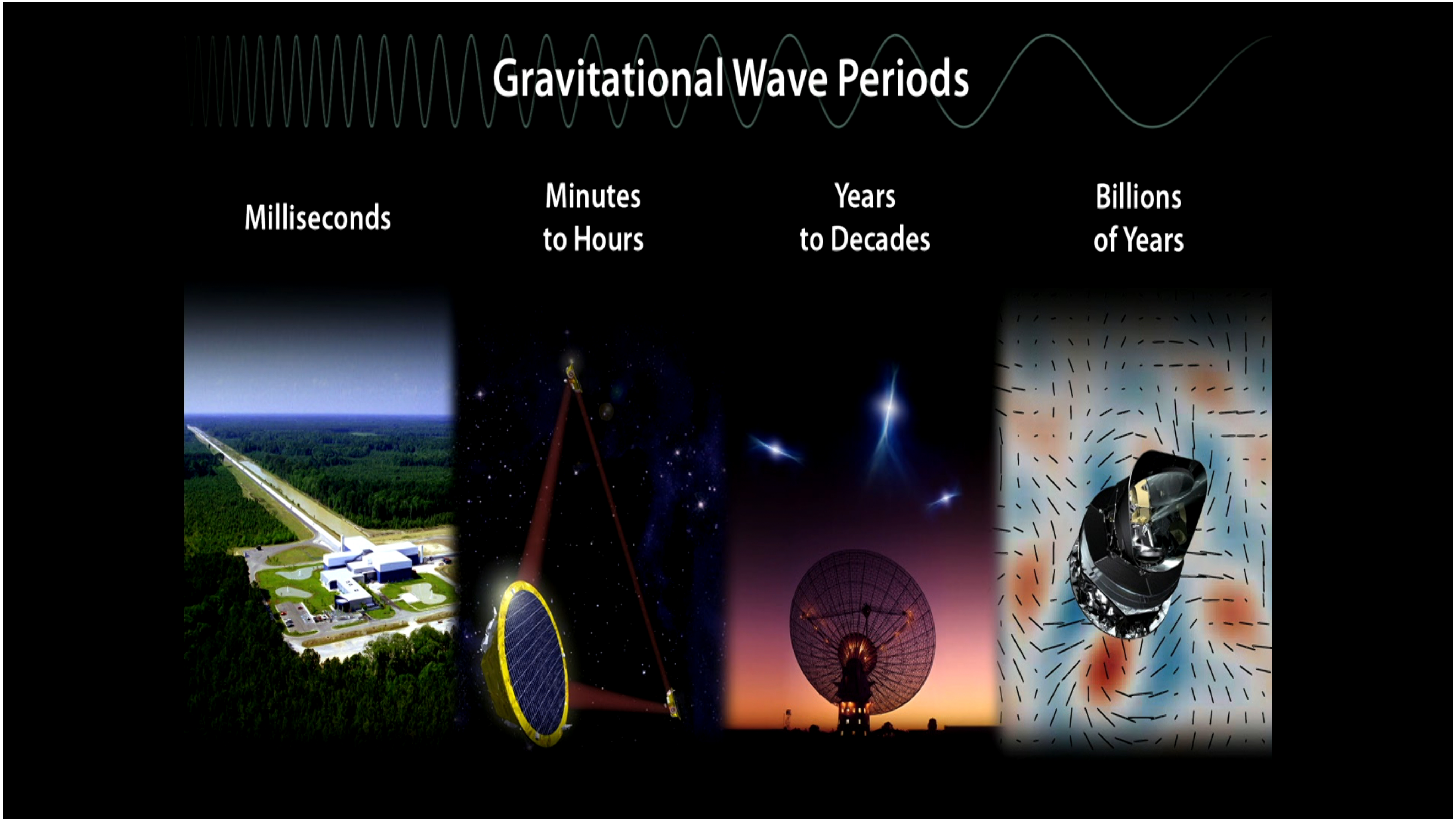
(Plans still under development within the LIGO and Virgo Collaborations)



Second Observing Run (O2)

- Started November 30th 2016 and currently underway
- Scheduled break: December 22nd 2016 - January 4th 2017
- Approximately 12 days of coincident data has been collected as of January 23rd 2017
- Average reach of the LIGO network for binary merger events is ~ 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun
- So far, 2 event candidates, identified by online analysis using a *loose false-alarm-rate threshold of one per month* and shared with astronomer partners
- A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

http://www.ligo.org/news/index.php#O2Jan2017update



Gravitational Wave Periods

Milliseconds

Minutes
to Hours

Years
to Decades

Billions
of Years