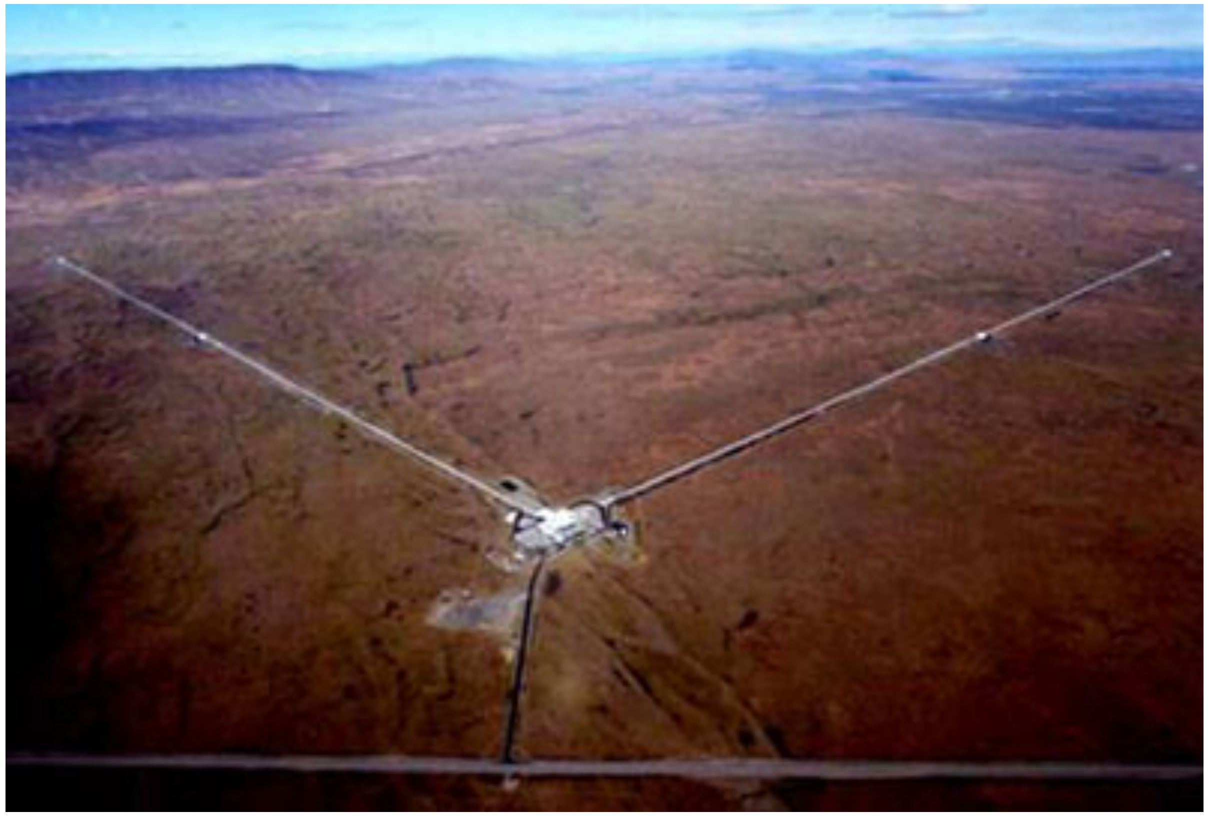
GW150914 RESULTS

Sudarshan Ghonge, Chandra Kant Mishra, Archisman Ghosh, Abhirup Ghosh, Nathan Johnson-McDaniel, and Arunava Mukherjee

CHARACTERISATION OF TRANSIENT NOISE IN THE ADVANCED LIGO DETECTORS DURING GW150914

- How do we know that GW150914 was not caused by noise?
  - What is the detector sensitive to?
  - What are the possible noise sources?
  - How do we deal with them?

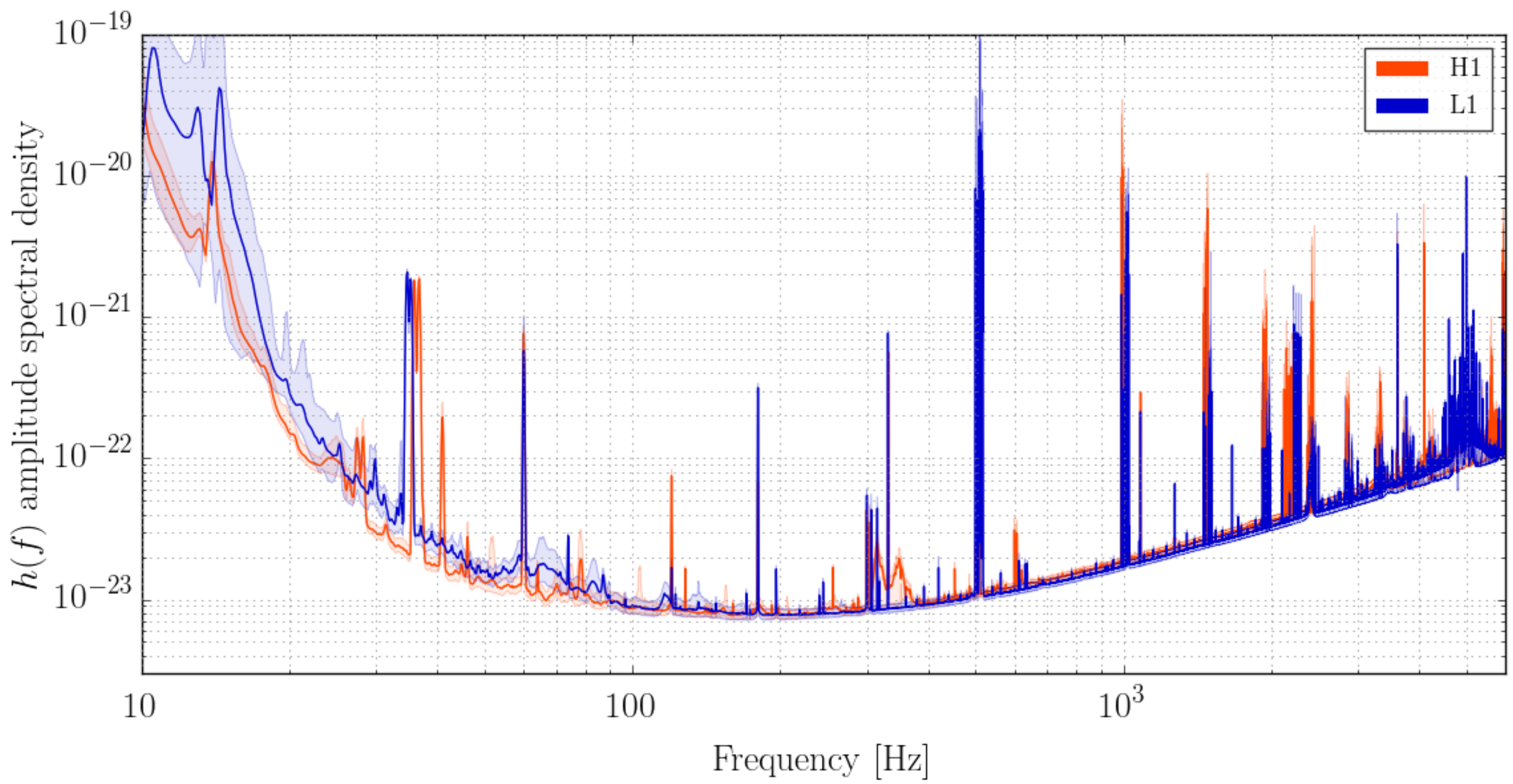
THE DETECTORS:



LIGO Hanford, Washington

LIGO Livingston, Louisiana

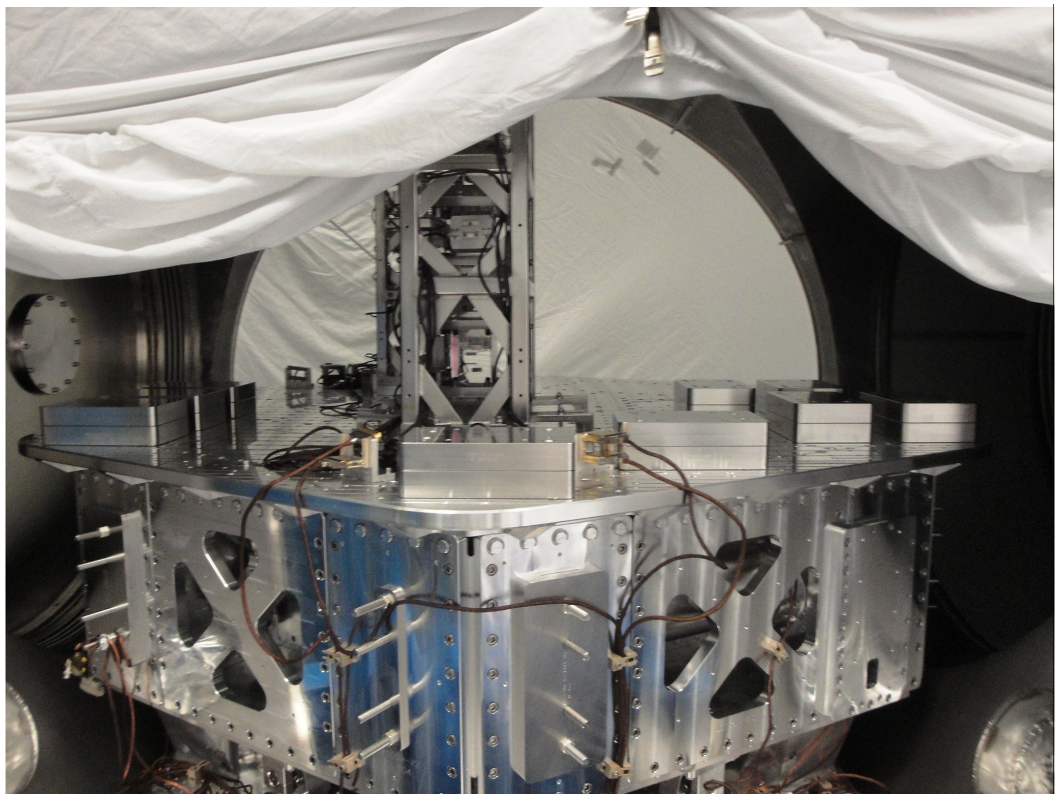
DETECTOR SENSITIVITY



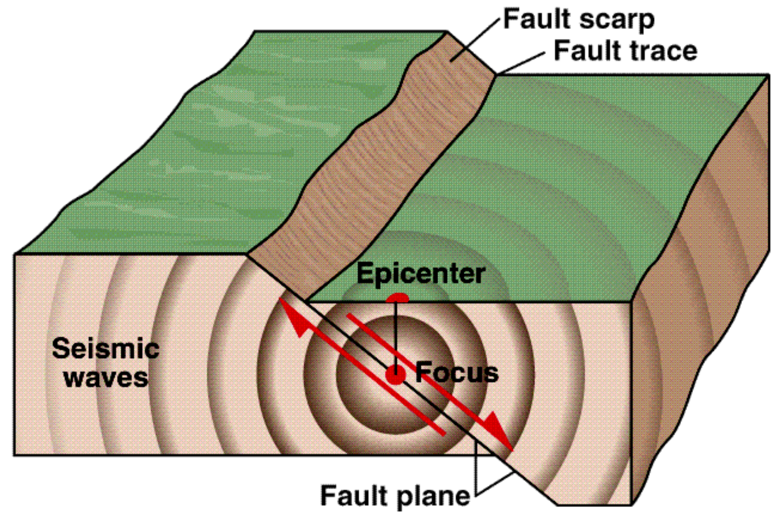
Spikes:

- Mechanical resonances
- Mains power

Sensitive to signals in the frequency range of 30 to 500 Hz - the "sweet spot."



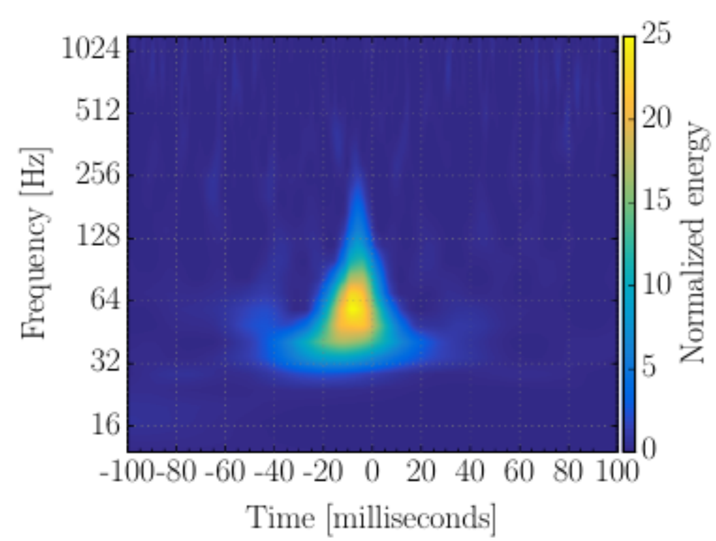
POSSIBLE NOISE SOURCES



Source: www.ykonline.yksd.com

- **Earthquakes:** can produce ground motion at the detectors with frequencies from approximately 0.03 to 0.1 Hz or higher if the epicenter is nearby. There are other sources such as sea waves hitting the coast of Washington and Louisiana.

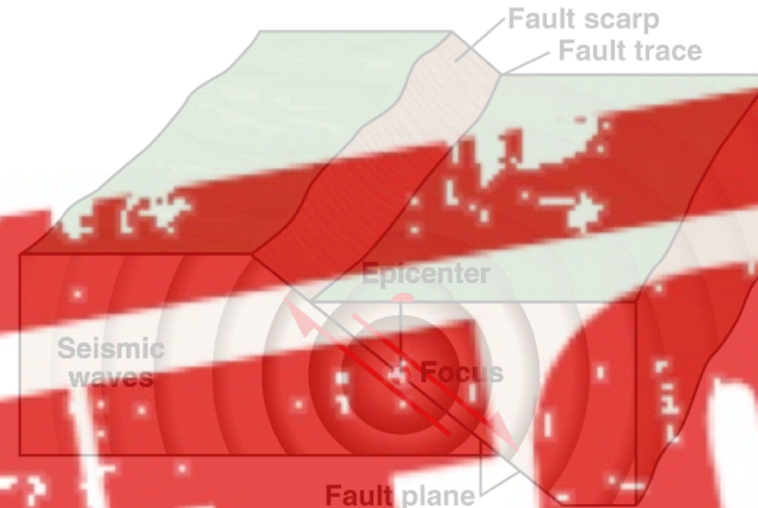
- **Anthropogenic Sources:** short duration transients in the data, such as human activity within one of the rooms that houses the vacuum chambers or infrequent strong ground motion or noise from other nearby locations. This is monitored by an array of accelerometers, seismometers, and microphones.



- **Blips** are short noise transients that appear in the gravitational wave strain channel h(t) as a symmetric 'teardrop' shape in time-frequency space, typically between 30 and 250 Hz, with the majority of the power appearing at the lowest frequencies. They contribute to some of the most significant background triggers in both the unmodeled burst and modeled CBC searches.

POSSIBLE NOISE SOURCES

VETO!



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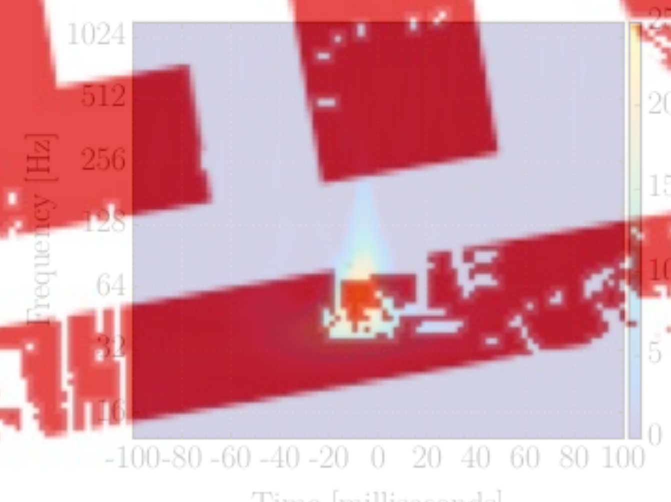

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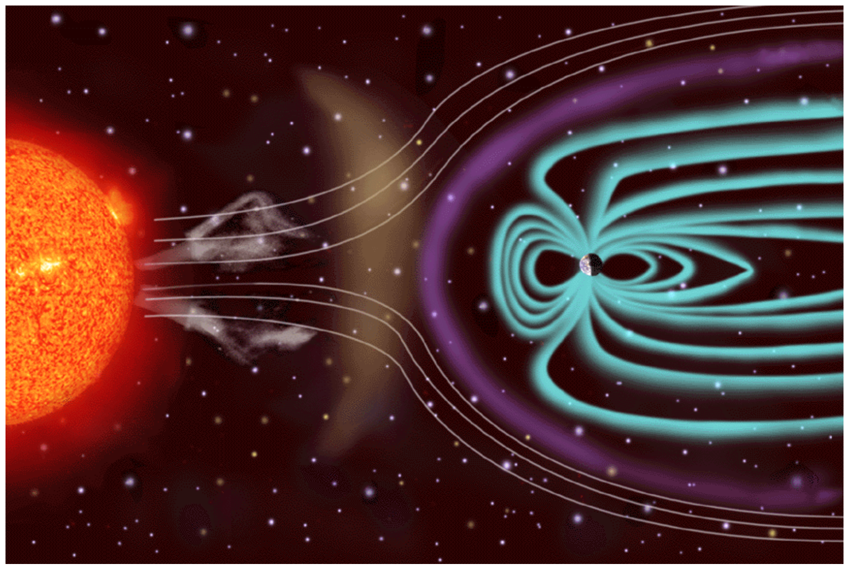
OTHER POSSIBLE NOISE SOURCES

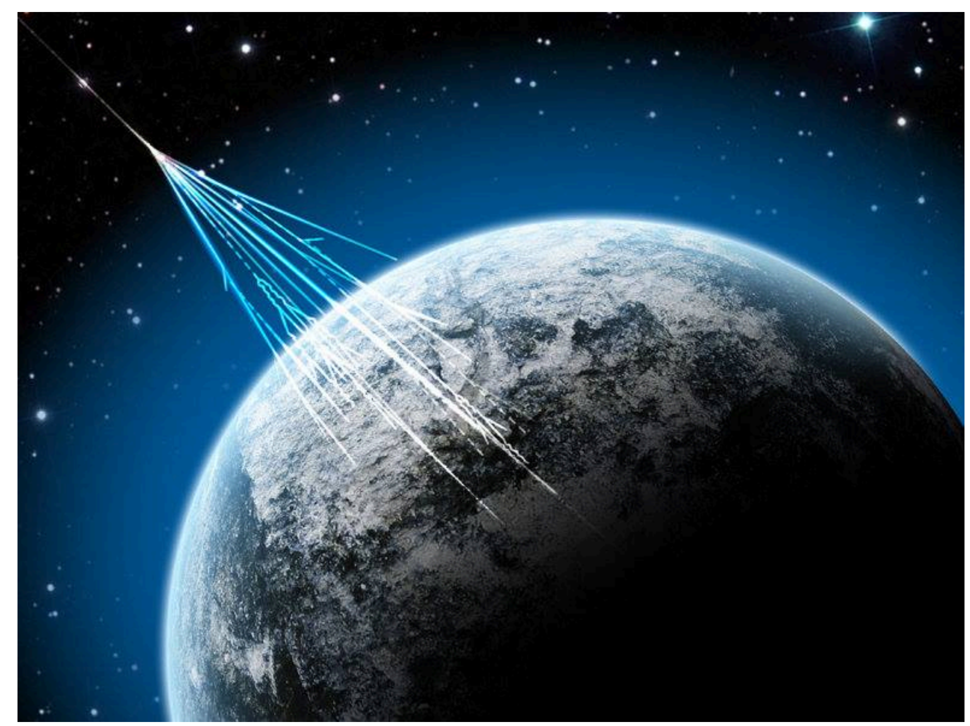


Solar wind

Radio frequency disturbances

Terrestrial lightning

Cosmic ray showers



CONCLUSIONS

- GW150914 occurred on September 14th, 2015, 3:21 PM IST.
- The data was collected over 39 calendar days from September 12th, 2015 to October 20th, 2015.
- ~18 days of coincident data was collected, out of which 16 days remain after data quality checks.
- The detectors were in perfect operational state during GW150914.
- The vetoed out segments did not include GW150914.
- Other noisy events within a few minutes of GW150914 were not so loud that they could have caused it.
- GW150914 is indeed a gravitational wave signal

FROM ALERTS TO A CONFIDENT DETECTION OF GW150914

Summary of:

- Observing Gravitational-Wave Transient GW150914 with Minimal Assumptions
- GW150914: First Results from the Search for Binary Black Hole Coalescence with Advanced LIGO

ONLINE BURST SEARCH

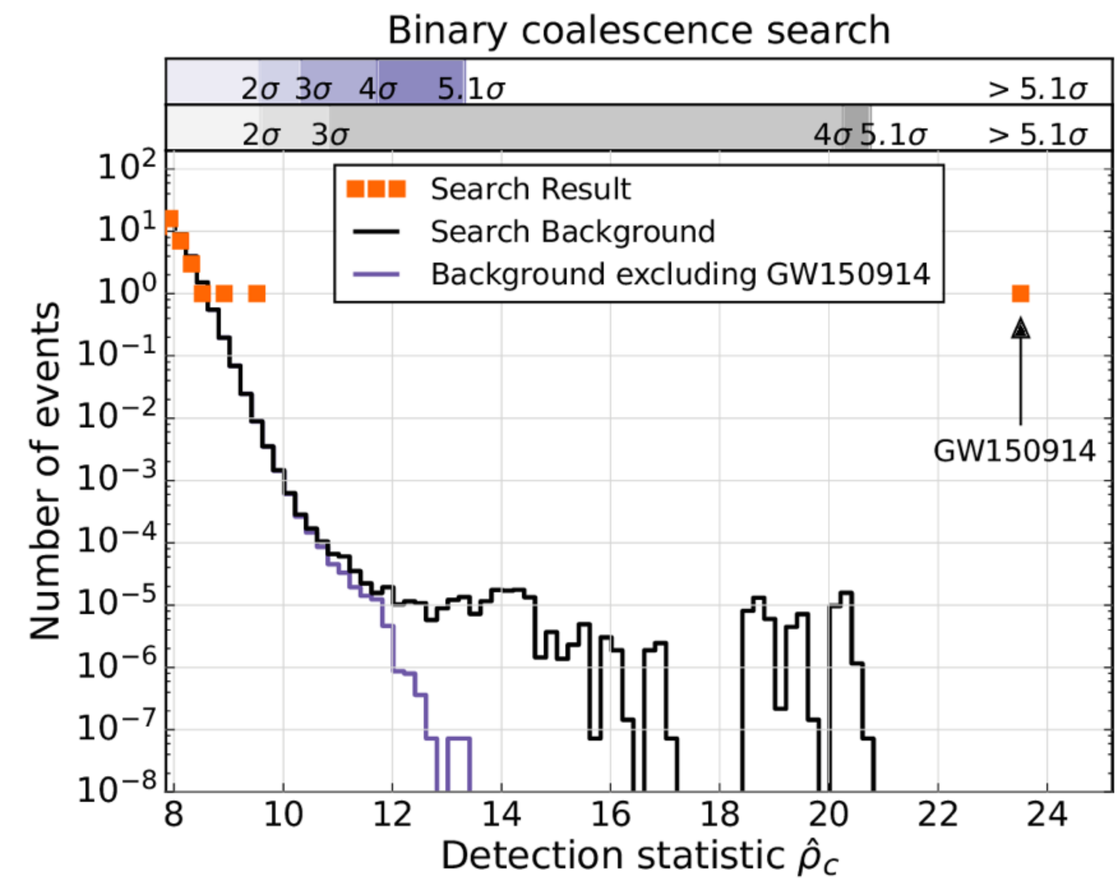
- On 14 September 2015 an online burst search (cWB) reported the detection of a transient signal that stood well above the detector's noise background at the two LIGO sites.
- The alerts were reported merely 3 minutes after the event time-stamp of 09:50:45 Greenwich Mean Time (about 03:20PM IST).
- Another burst search pipeline (oLIB) independently confirmed the detection with a latency of a few hours enhancing the confidence in the detection.
- Detailed followup analyses of the data collected around the time of the event was then carried out by two high latency versions of the burst pipelines cWB and oLIB as well as by two template based search pipelines, GstLAL and PyCBC.

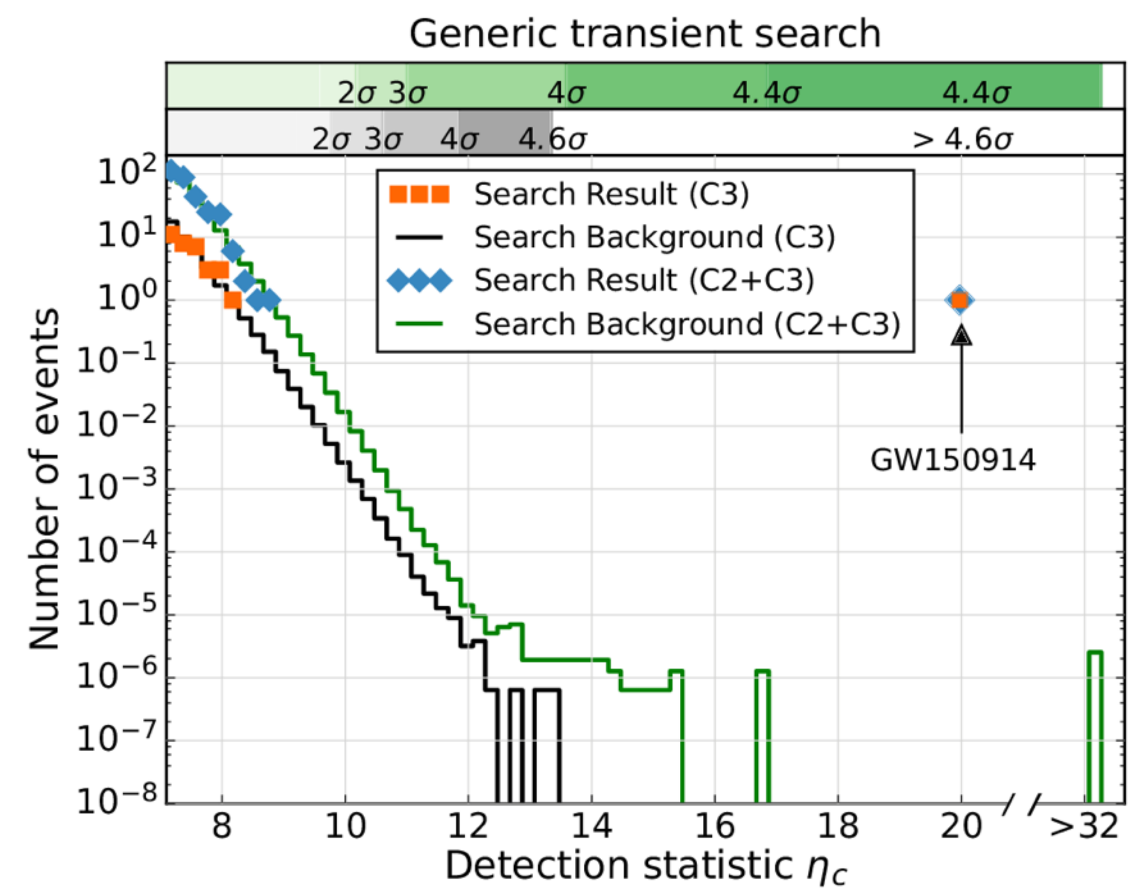
OFFLINE SEARCHES

- Based on the analyses of 16 days of coincident observations between the two LIGO detectors from 12 September 2015 to 20 October 2015, the trigger was declared to be a GW event of high significance, which we now know as GW150914.

- The template based searches observed the signal with a SNR of 24 and a false alarm rate (FAR) smaller than once in 203,000 years, suggesting a significance > 5.1 sigma.

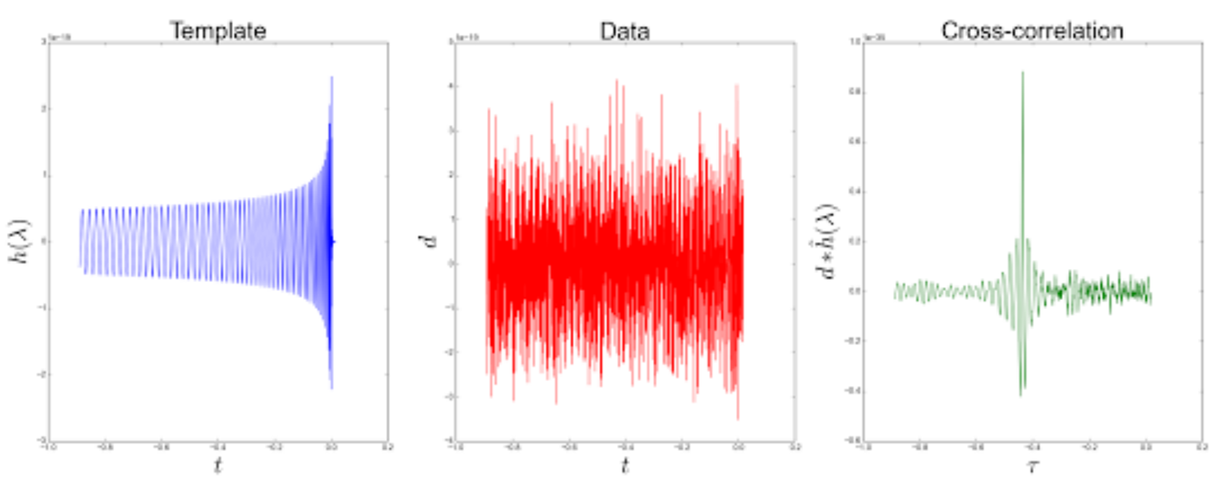
- The burst search suggested the FAR smaller than 1 in 22,500 years, equivalent to a significance > 4.6 sigma.

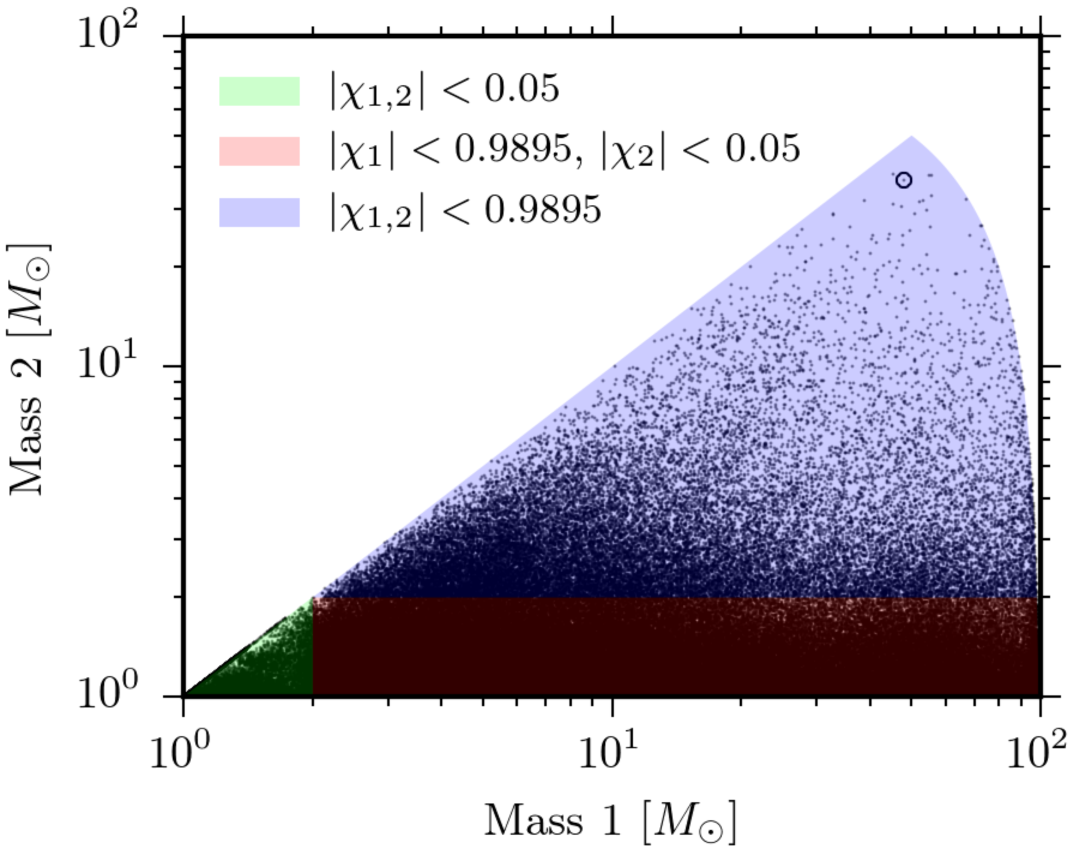


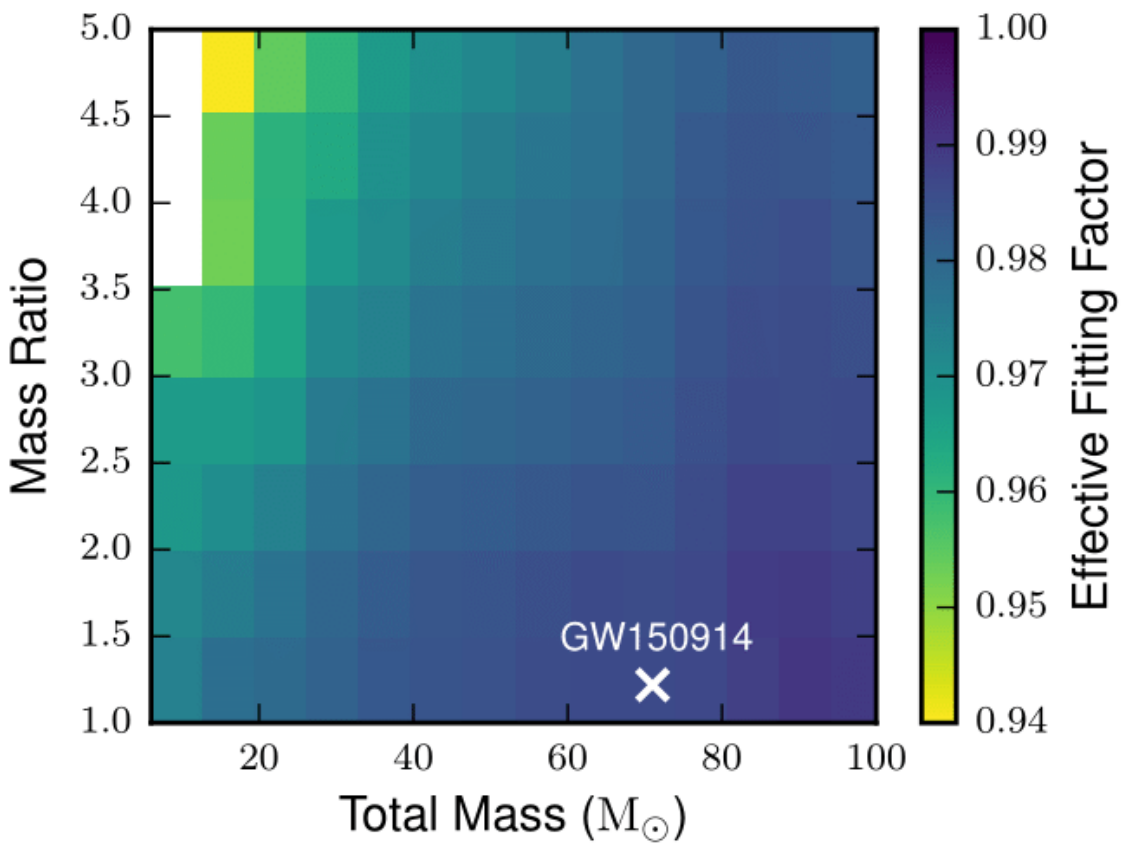


BINARY COALESCENCE SEARCH

- Recovers signals from the coalescences of compact objects, using optimal matched filtering of the data with a bank of waveforms predicted by General Relativity.
- A template bank with about 250, 000 waveforms were used in analysing the data using both search pipelines, GstLAL and PyCBC.
- Both pipelines reported the event with identical parameters and a significance greater than 5.1 sigma.

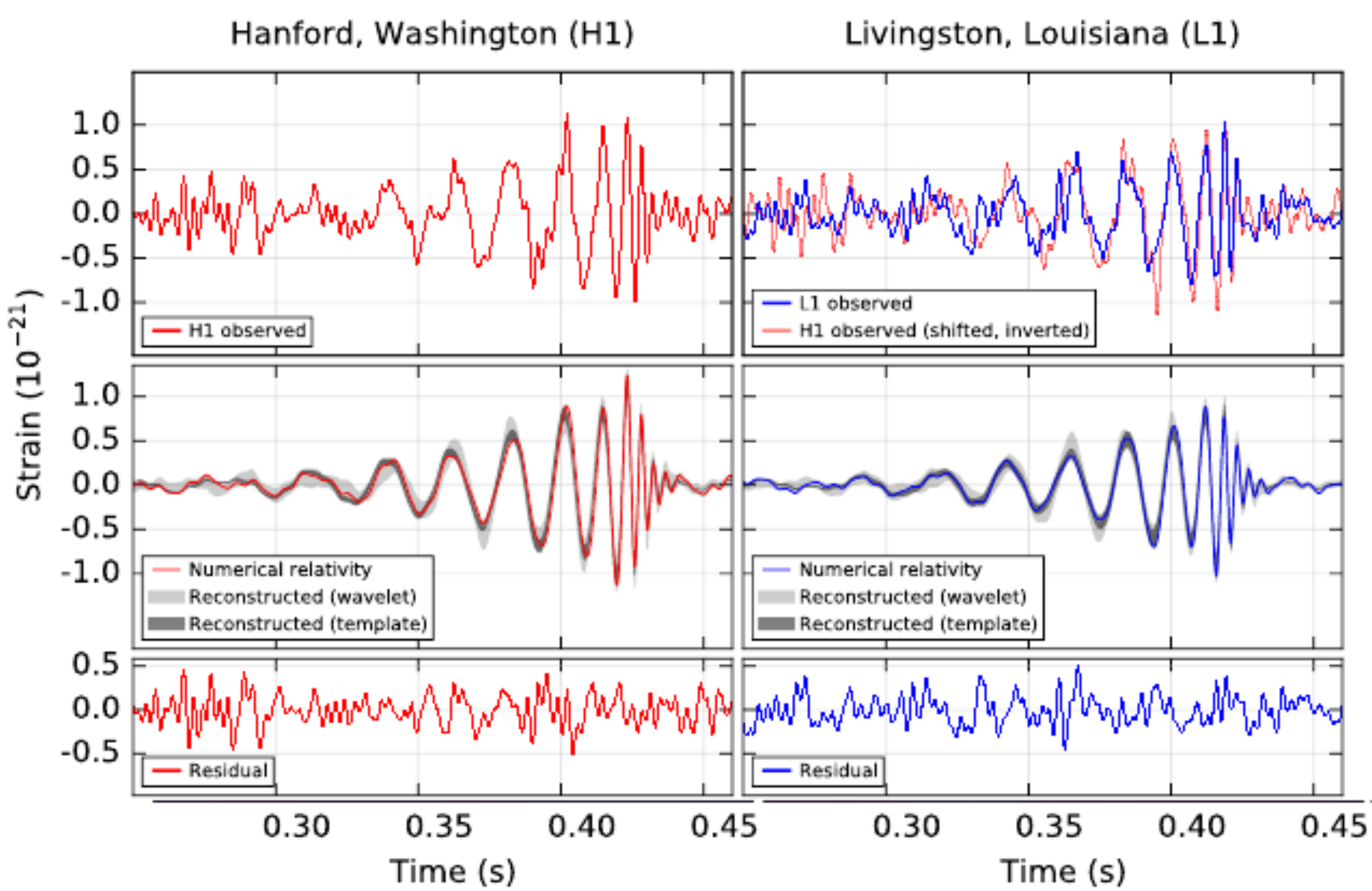






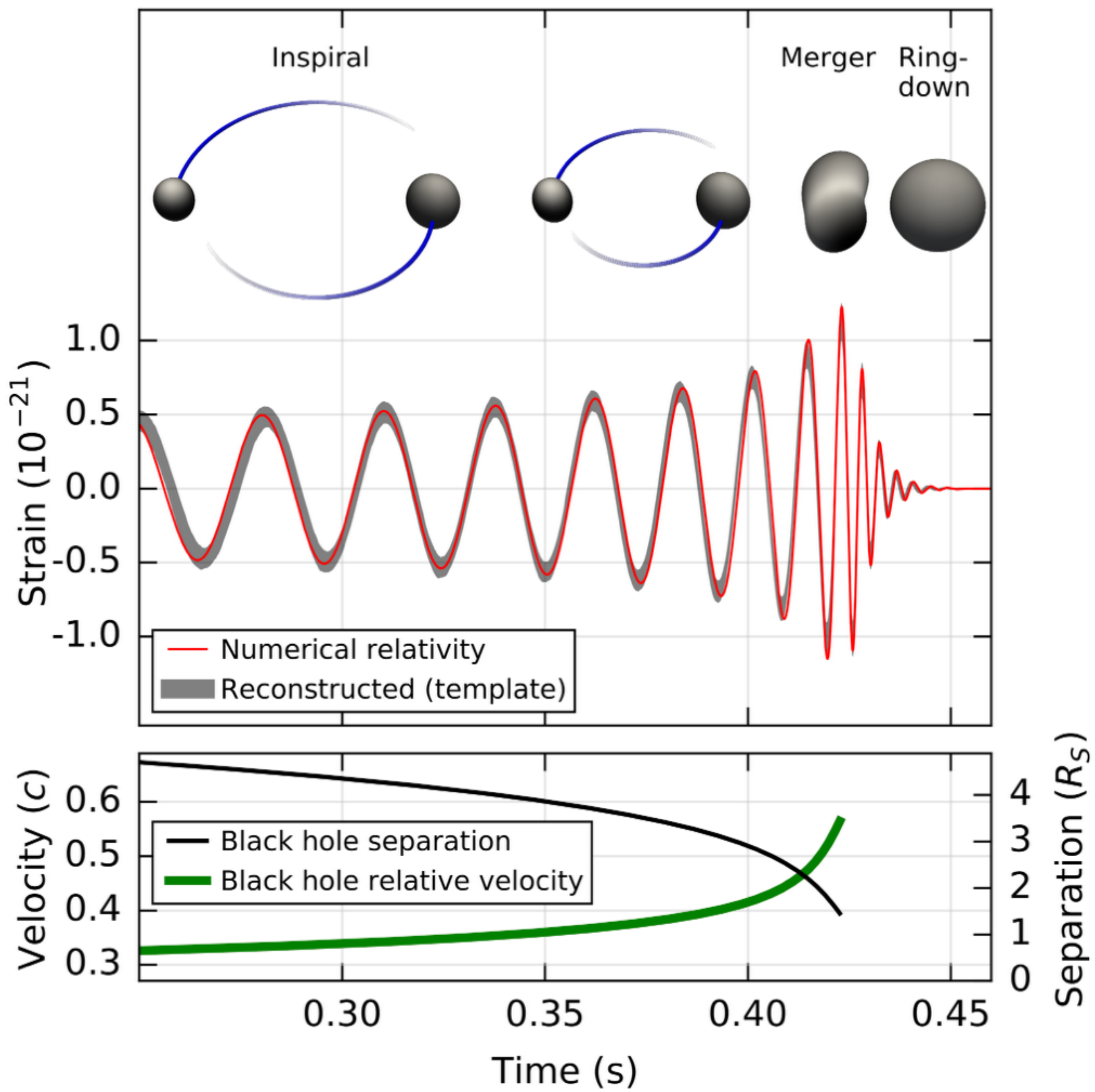
GENERIC TRANSIENT SEARCH

- Targets broad range of generic transient signals with minimal assumptions of signal morphology.
- Can identify signals with frequencies up to 1 kHz and durations up to a few seconds.
- Ranks events according to the detection statistic which quantifies the SNR of the event and the consistency of the data between the two detectors.



GW150914 : SEARCH SUMMARY

- A GW event consistent with the observations of the Inspiral, Merger and Ringdown of a system of two BHs in two independent searches.
- The waveforms reconstructed using best fit model parameters show excellent agreements with Numerical Relativity simulations.
- The system is highly relativistic, ideal for testing predictions of the theory in strong field regime (Abhirup's presentation).



PROPERTIES OF BINARY BLACK HOLE MERGER GW150914

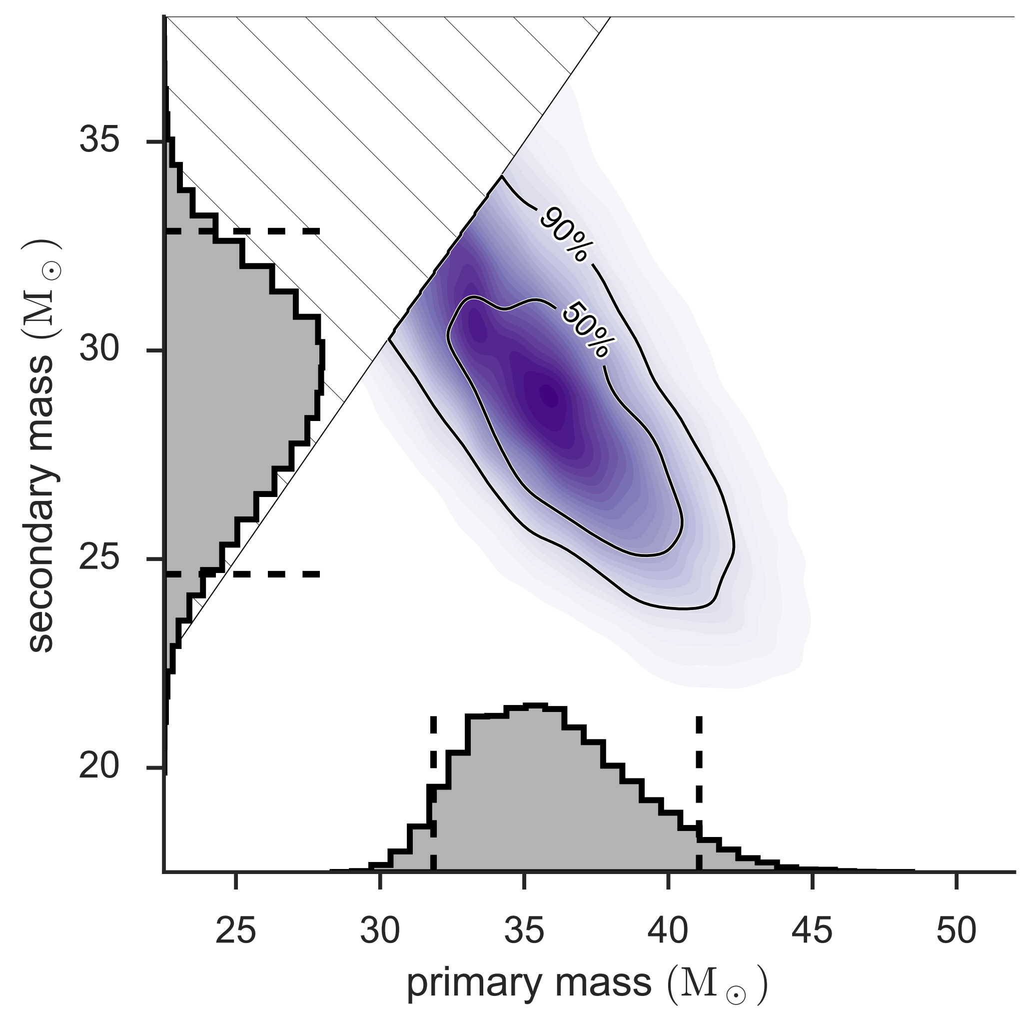
Summary of:

- Parameters estimated and numbers reported

PARAMETER ESTIMATION

- Measure the "parameters" that describe the binary BH merger — masses, spin angular momenta, distance and location, orientation.
- Crucial for extracting any information: astrophysics (formation, rates) or fundamental physics (consistency with theory).

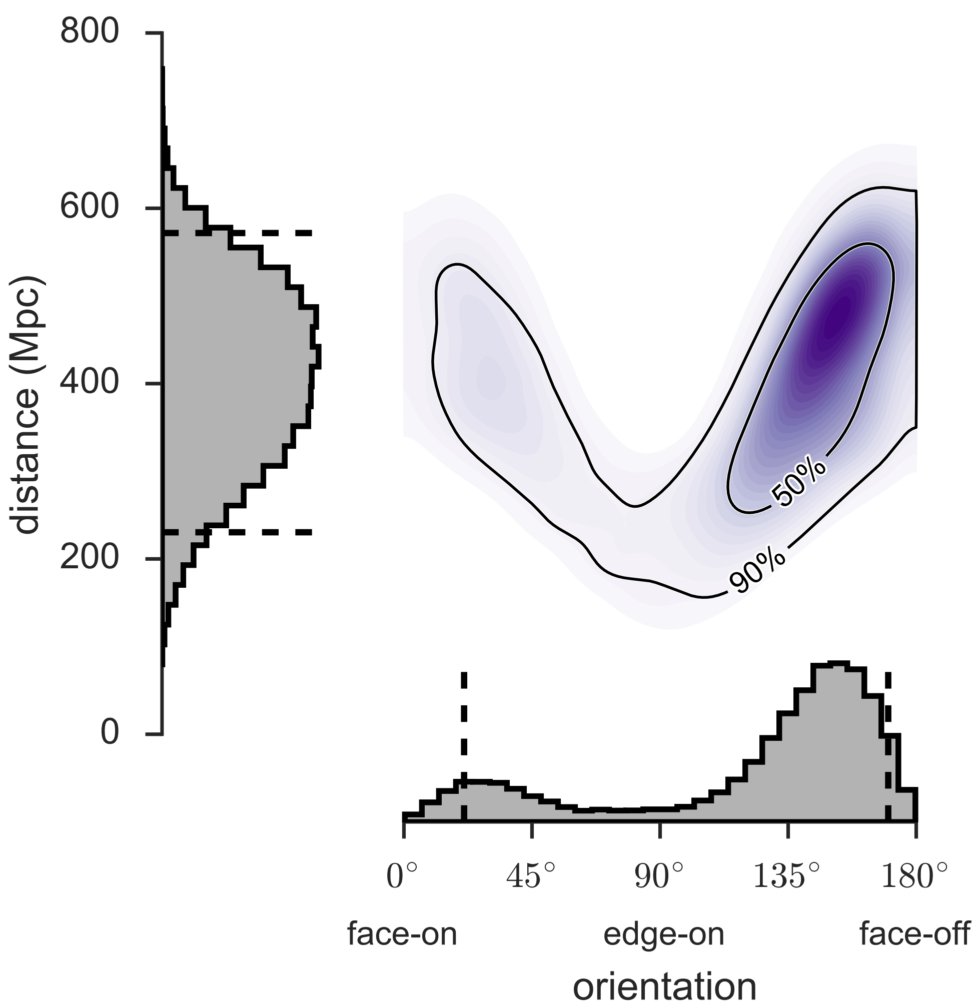
  Astrophysics: Arunava, Testing GR: Abhirup
- Uncertainties in estimating parameters – probability distribution of measured parameters!



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

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

WHERE DID THE MERGER TAKE PLACE?

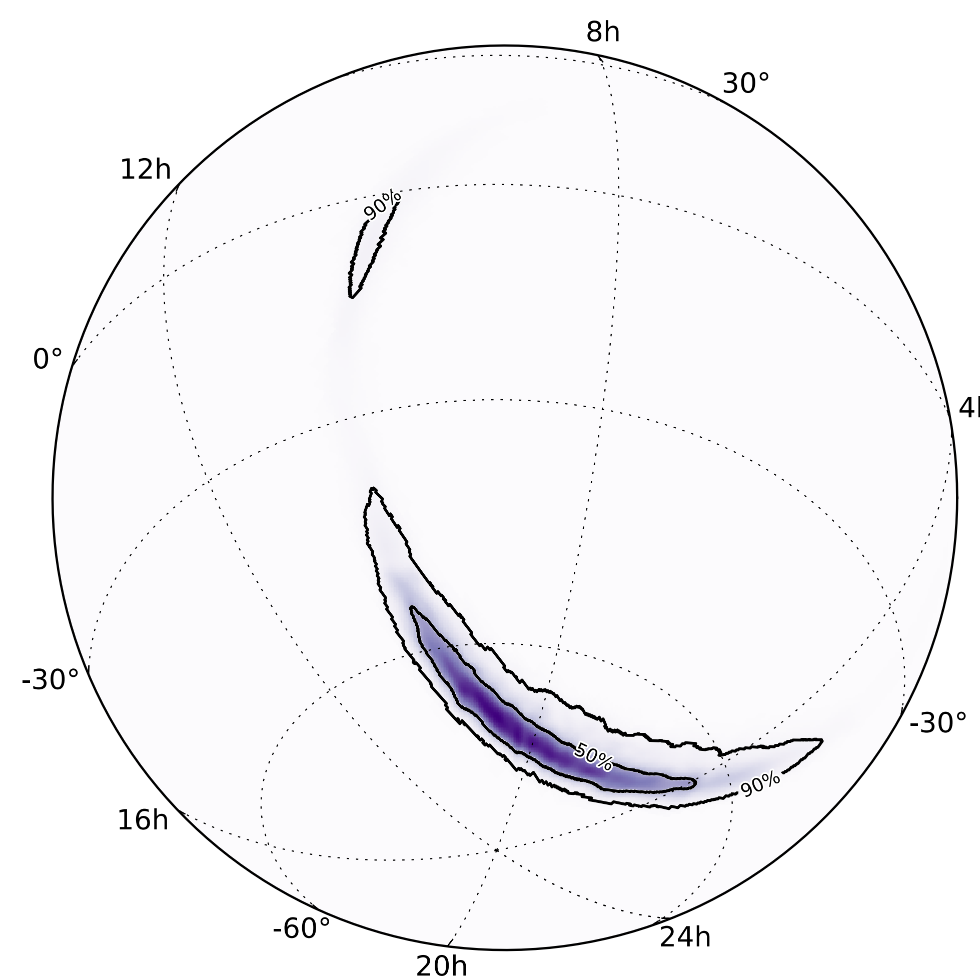


Distance: 410^{+160}_{-180} Mpc

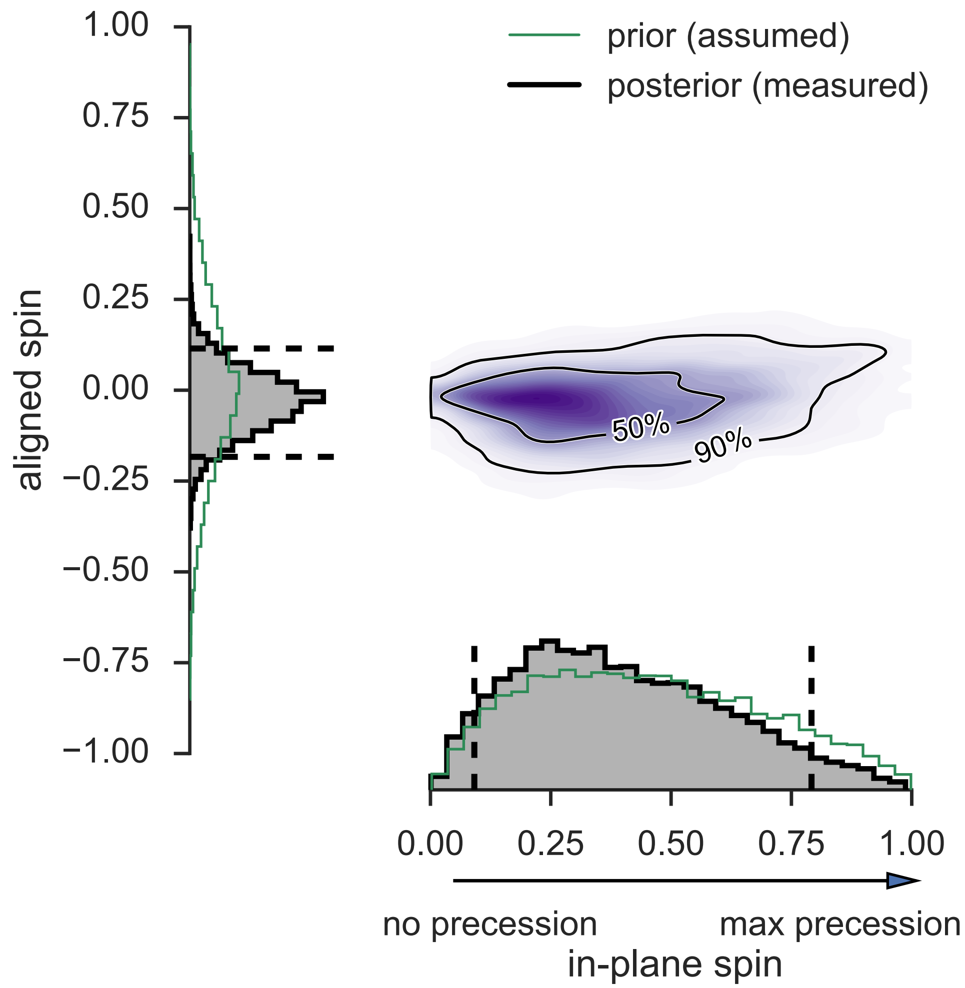
~1.3 billion light years

Location in the sky:
Patch in the Southern Hemisphere

Follow-up searches: Nathan



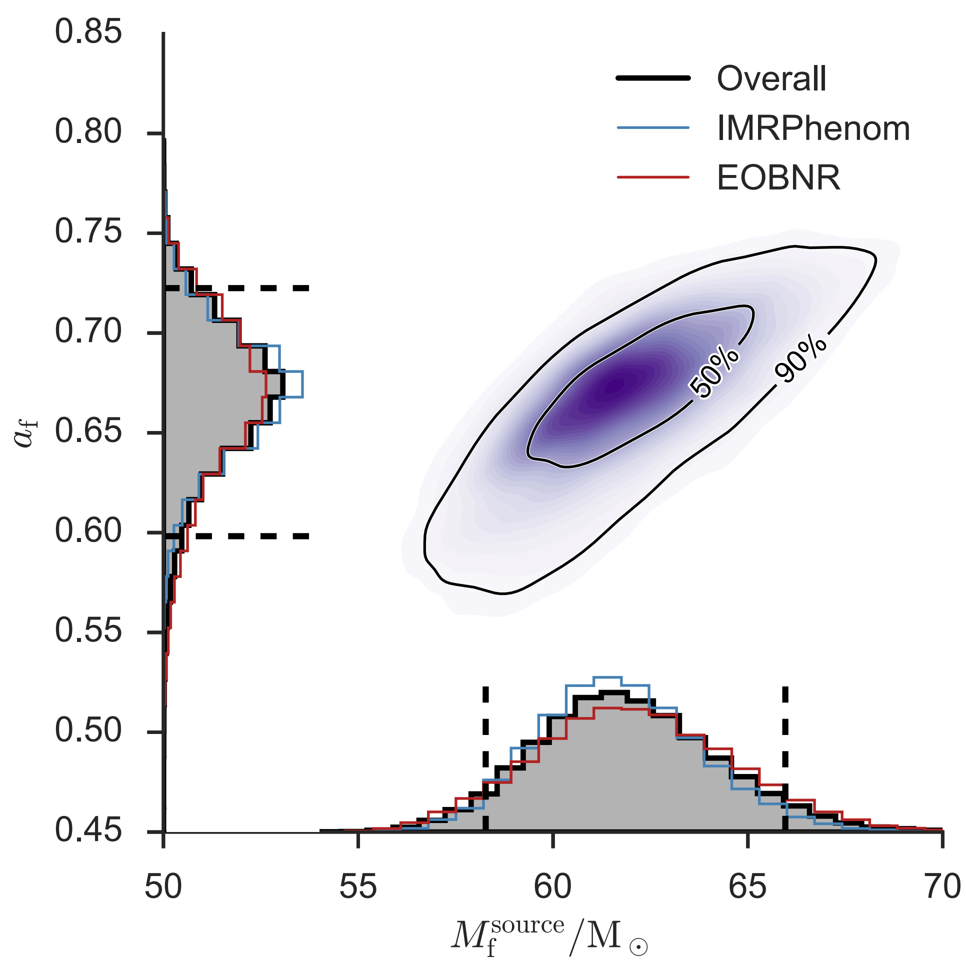
HOST OF OTHER PARAMETERS



Spin angular momenta of initial black holes not fully measured.

Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}
Source redshift z	$0.083^{+0.033}_{-0.036}$
Upper bound on primary spin magnitude a_1	0.65
Upper bound on secondary spin magnitude a_2	0.93
Lower bound on mass ratio q	0.64

PROPERTIES OF THE MERGER AND ITS REMNANT



Final mass: $62^{+4}_{-4}\,M_\odot$

Final spin: $0.67^{+0.05}_{-0.07}$

Archisman, Ajith

- One of the first accurate measurements of the spin angular momentum of a rotating black hole.
- The total amount of energy radiated in GW is about 3 times the entire mass of the Sun all converted into energy.
- Most of this takes place in a fraction of a second around the merger.
- A peak luminosity of ~3.6 × 10^{49} Watts.

Nathan

TESTS OF GENERAL RELATIVITY WITH GW150914

IMPORTANCE OF TESTING GENERAL RELATIVITY (GR) WITH GW150914

GENERAL RELATIVITY

DEPENDENCIES:

The detection paper as well as all remaining companion papers assume that GW150914 is consistent with general relativity

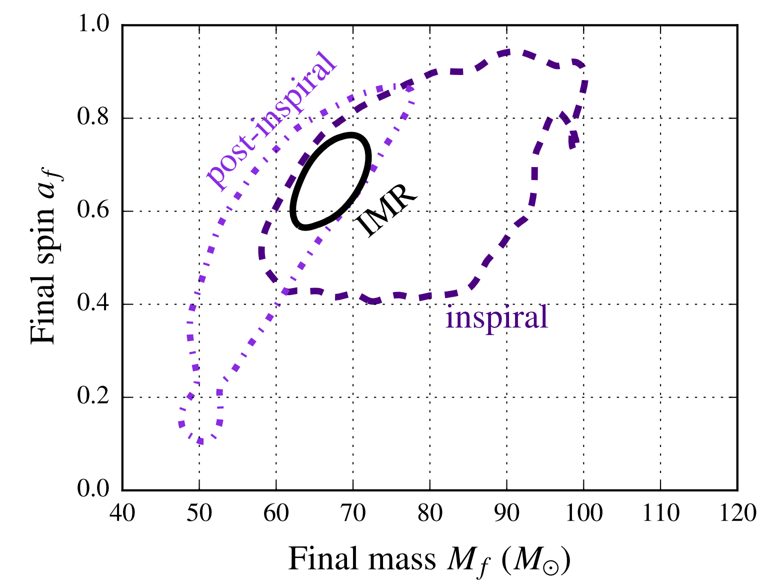
GW150914 represents the first ever genuine probe of the dynamics of space-time

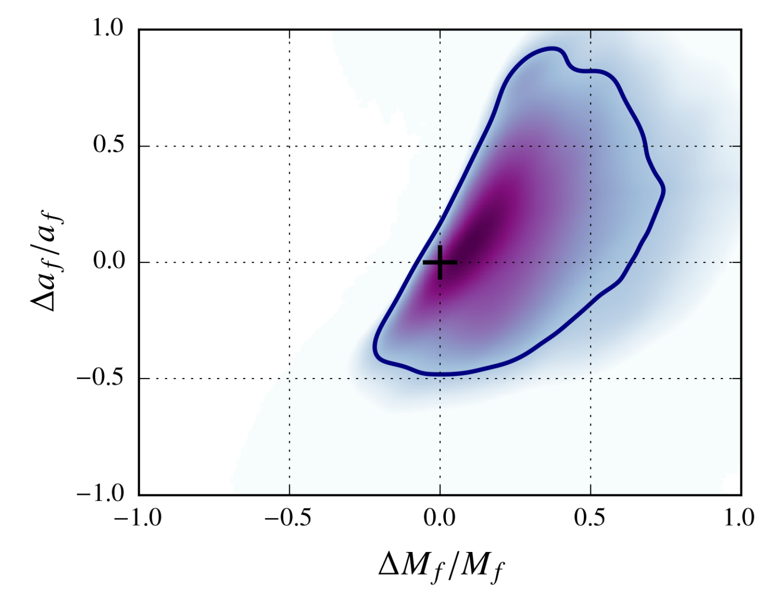
GRAVITATIONAL WAVE SCIENCE

- We perform several studies of GW150914 aimed at detecting deviations from the predictions of GR

IS GW150914 INDEED A BINARY BLACK HOLE MERGER DESCRIBED BY GR?

- **Inspiral, merger and ringdown consistency**
  - Compare the estimates of the mass and spin of the remnant obtained from different parts of the waveform, using the relations between the binary's components and final masses and spins provided by NR.
  - Our inspiral-merger-ringdown test shows no evidence of discrepancies with the predictions of GR.

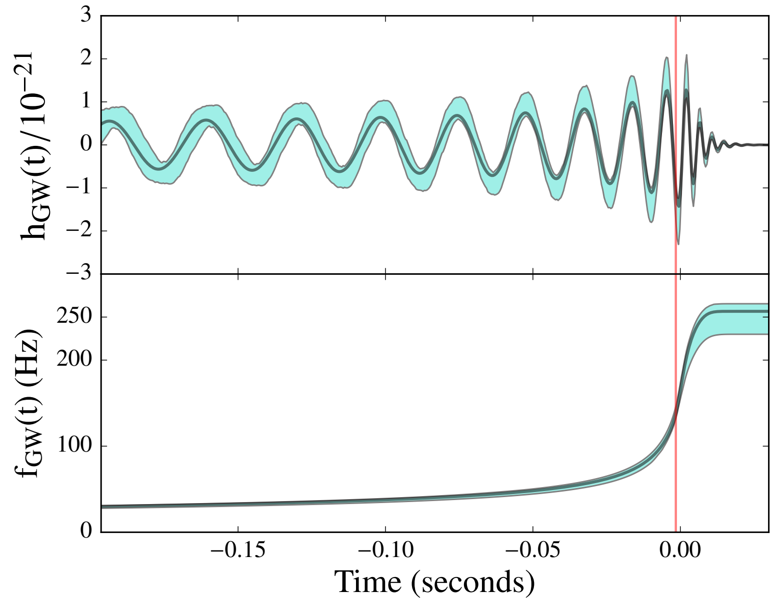


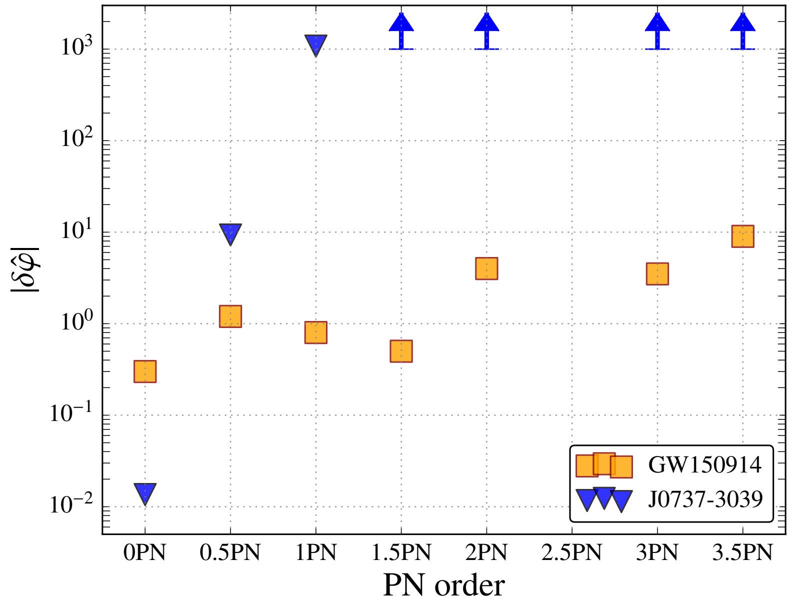


Abhirup, Archisman, Nathan, Chandra, Ajith

IS GW150914 INDEED A BINARY BLACK HOLE MERGER DESCRIBED BY GR?

- **Residuals test**
    - Subtract the best fit waveform from the observed data, and find that what remains is completely consistent with detector noise at other times when there is no signal.
- **Constraining parametrized deformations**
    - The parameters in the waveform that models GW150914 are consistent with Numerical Relativity (GR) predictions, within statistical uncertainties.
    - Also provide much stronger bounds on theoretical values than earlier observations



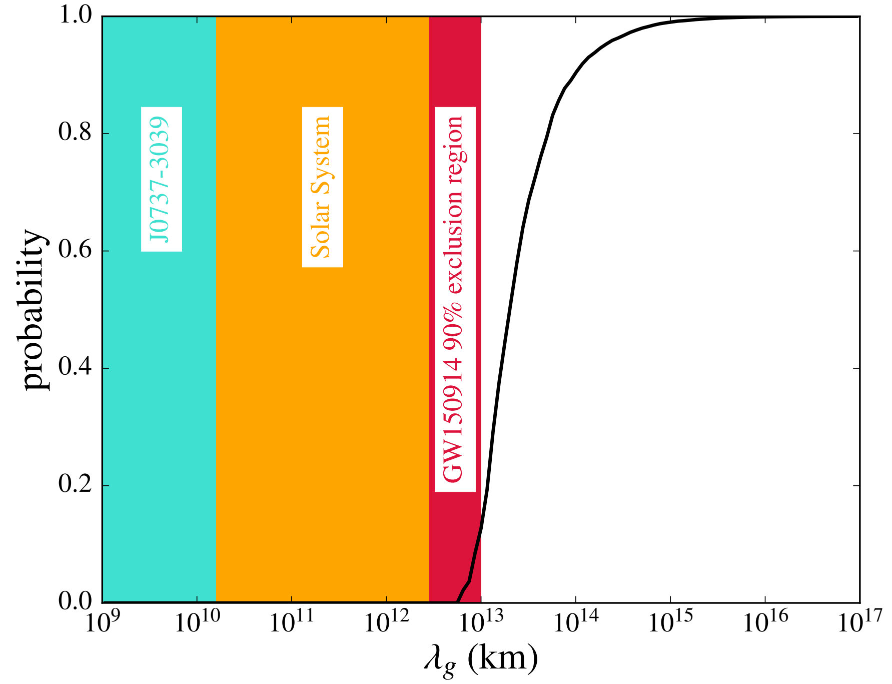


Anuradha S, Saleem, Archana

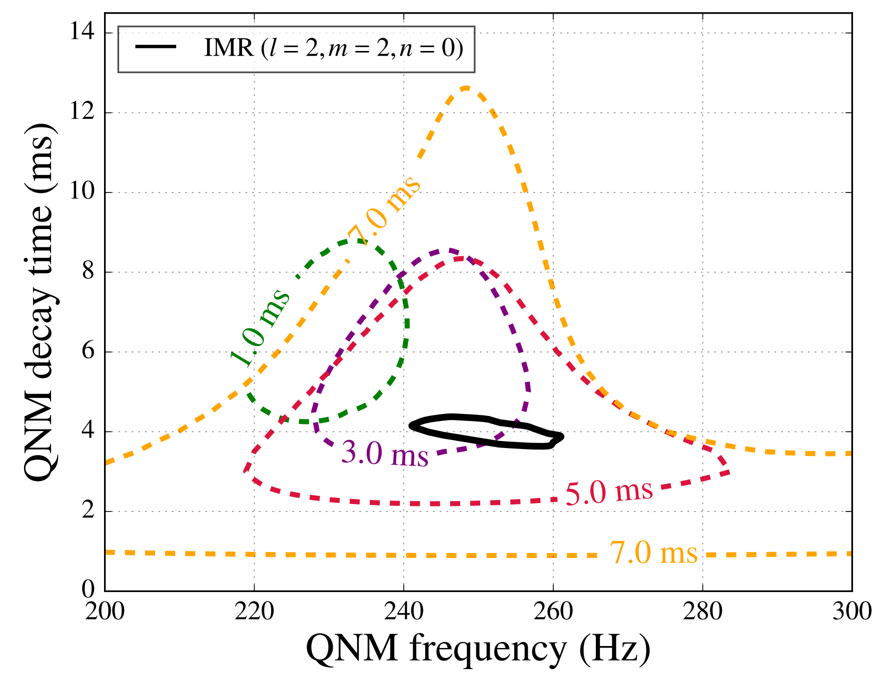
IS GW150914 INDEED A BINARY BLACK HOLE MERGER DESCRIBED BY GR?

- **Bounds on mass of graviton**
  - Although a fully consistent massive graviton theory has not been worked out yet, our analysis does put a bound on the possible mass of the graviton, by constraining the graviton Compton wavelength.

K G Arun



- **Least damped quasi-normal mode in the data**
  - The final BH shakes away its asymmetries through exponentially damped emission of GWs as it settles down to a final stable Kerr BH.
  - We find that the frequency and damping time of the least damped mode are consistent with those of a black hole with the final mass and spin we infer from the data.



MULTIMESSENGER ASTRONOMY AND GW150914

Overview of:

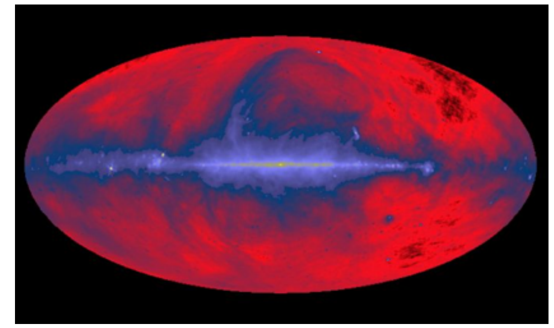
- EM follow-up observations

Summary of:

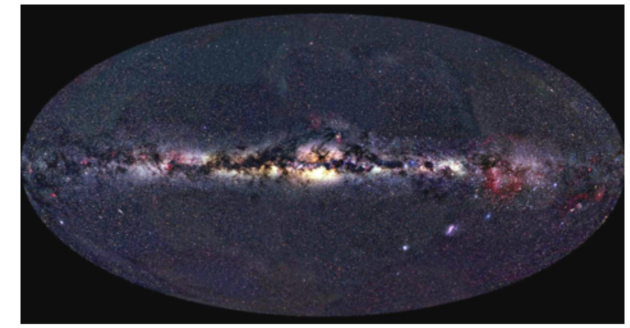
- High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES

MULTIMESSENGER ASTRONOMY: WHAT AND WHY

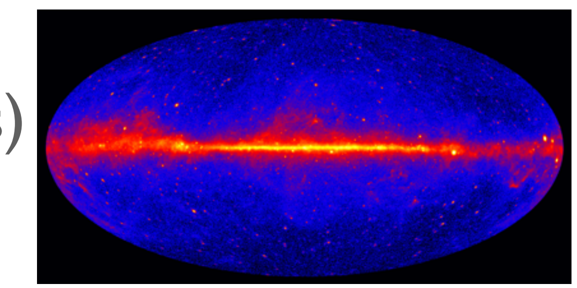
- Multiwavelength electromagnetic observations — now common and important for understanding sources (e.g., gamma-ray bursts)
- Multimessenger observations — use the other three fundamental forces: gravity (GWs), strong nuclear (cosmic rays), and weak nuclear (neutrinos)
- Coalescences of neutron stars with other neutron stars or black holes (of sufficiently small mass) will emit copious amounts of energy in photons and neutrinos, from, e.g., the ejecta, in addition to GWs.
- LIGO thus has MOUs with electromagnetic and neutrino astronomers to share triggers (for O1, 62 electromagnetic and 2 neutrino teams).



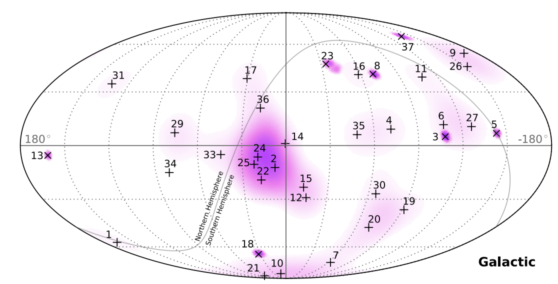
Radio



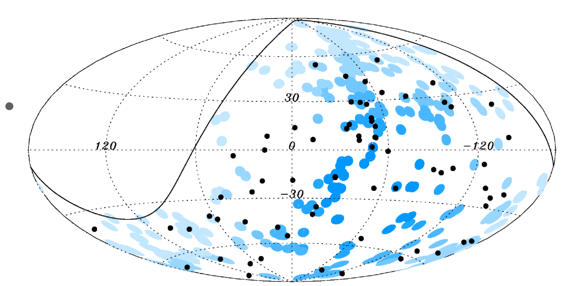
Optical



Gamma-ray (Fermi)



Neutrino (IceCube)



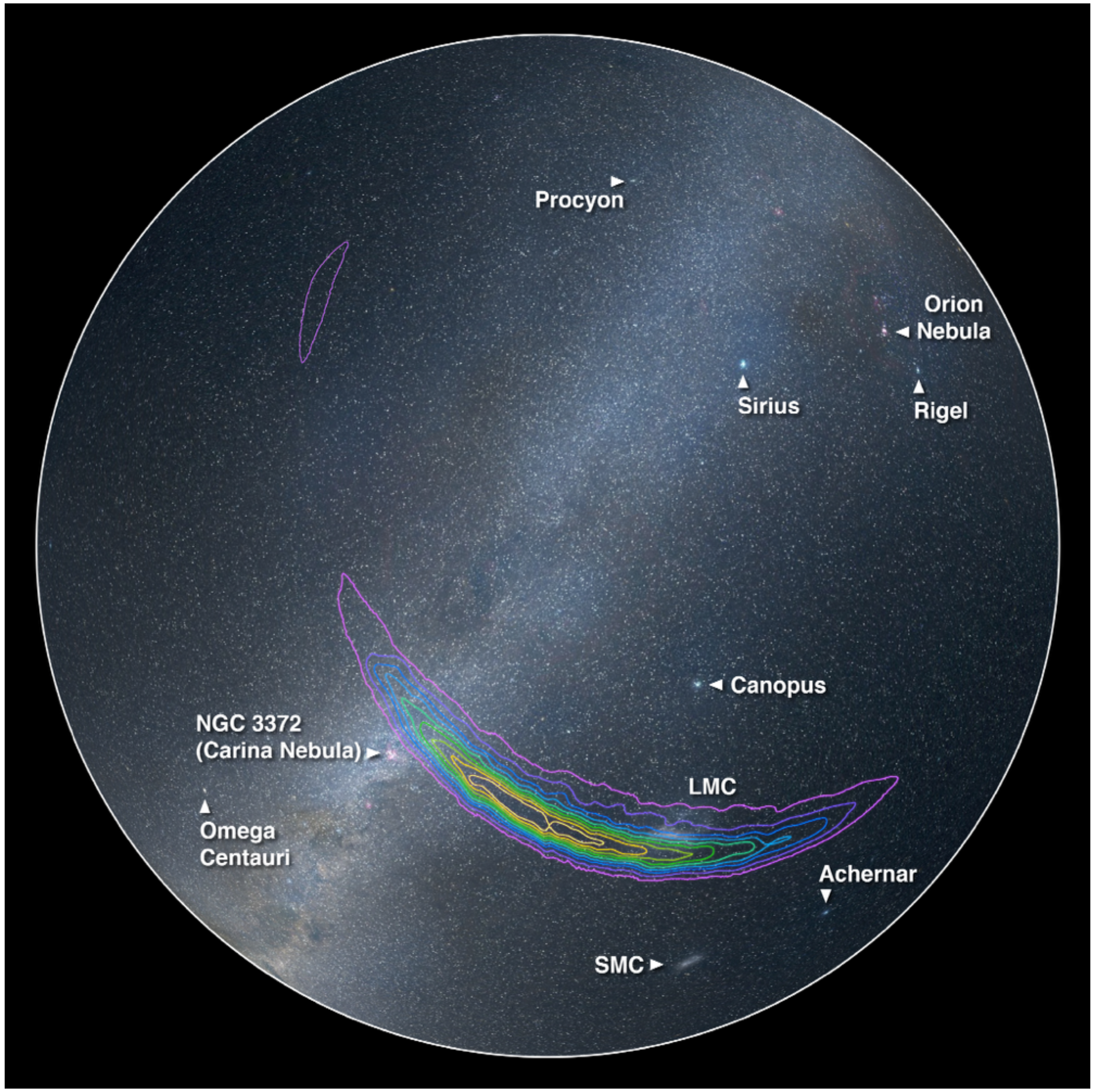
Cosmic ray (Auger)

?

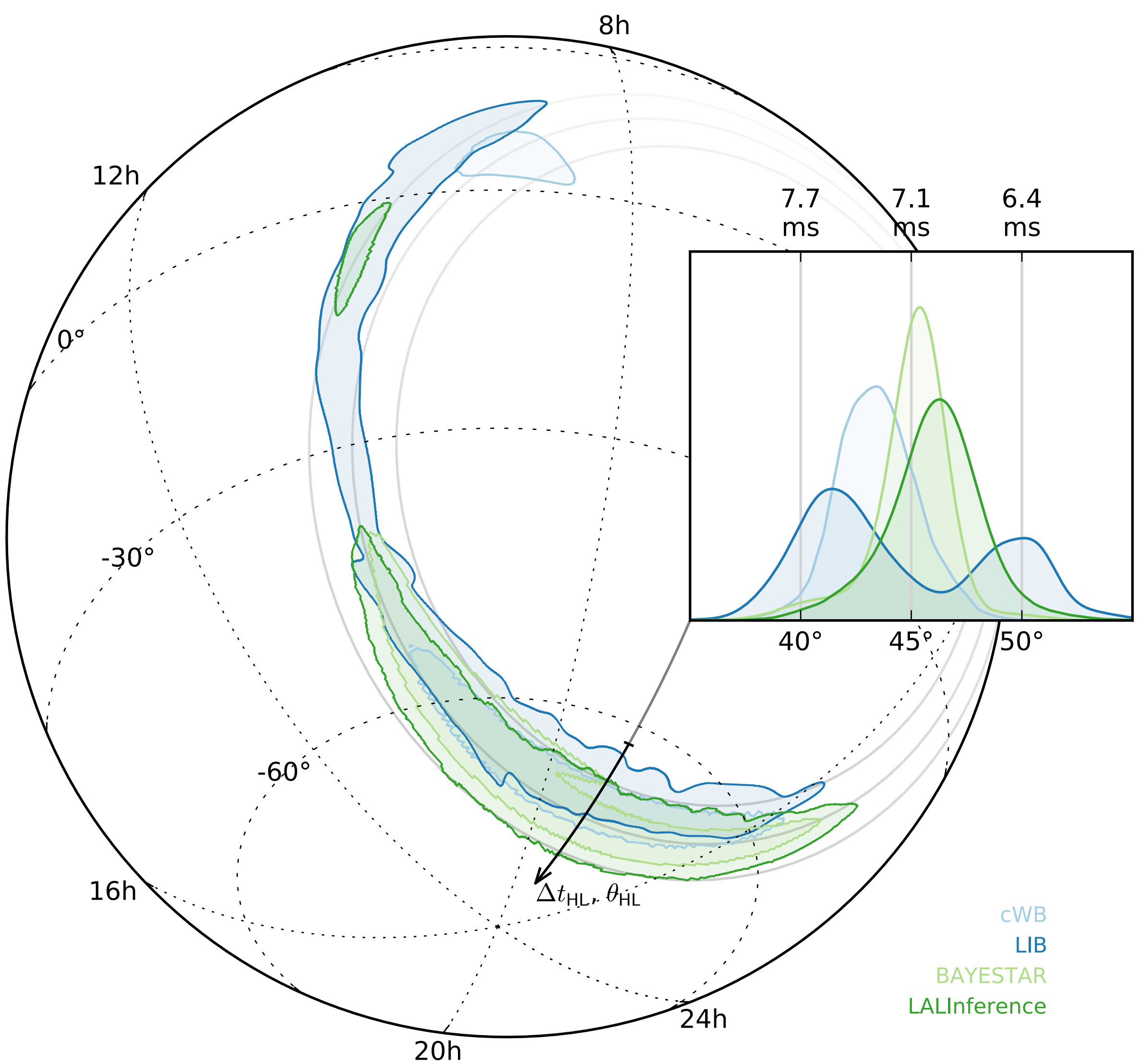
GWs

ELECTROMAGNETIC FOLLOWUP OF GW150914

- GW triggers below some false alarm rate (for O1 < 1/month) are communicated to EM partners via private GCN circulars.
- Stellar-mass BBH signals are not expected to have any detectable electromagnetic counterpart, but EM observers did not know about inferred source properties initially (BBH inference was not watertight at time of initial circular).
- Source was followed up by 21 teams, with both ground- and space-based instruments, across much of the electromagnetic spectrum, from radio to gamma-rays.



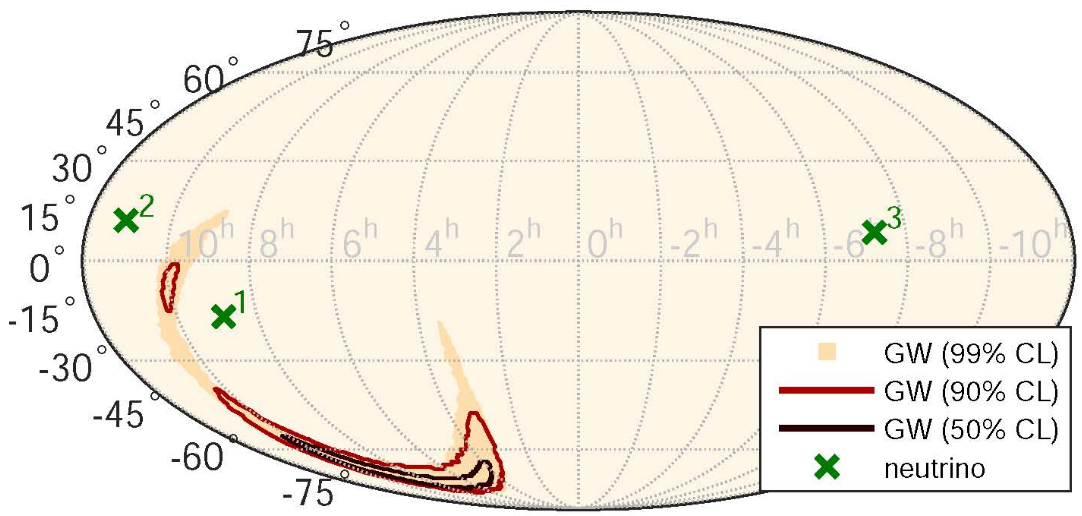
EM RESULTS



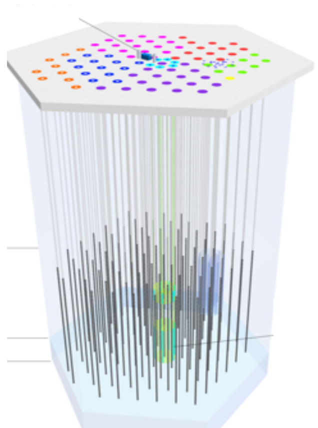
Evolution of the sky map from initial fast localization to final results

- The entire electromagnetic follow-up campaign will be described in a paper that is in the final stages of preparation and is expected to be released early this coming week.
- The Swift and Fermi Gamma-ray Burst Monitor teams have already posted their preprints online. We expect preprints from the remaining electromagnetic follow-up teams to appear very soon.
- Swift did not detect any counterpart (but GW150914 was not in the field of view of its wide-field instrument at the time, and its pointed follow-up two days later. was focussed on nearby galaxies).
- Fermi GBM detected a weak transient temporally coincident (within 0.4 s) of GW150914 and poorly localized, but consistent with the GW sky localization. It is unclear if this is a counterpart, which would be extremely unexpected and a major discovery. Note that these results still await review from the LIGO/Virgo side.

NEUTRINO RESULTS + OVERALL OUTLOOK



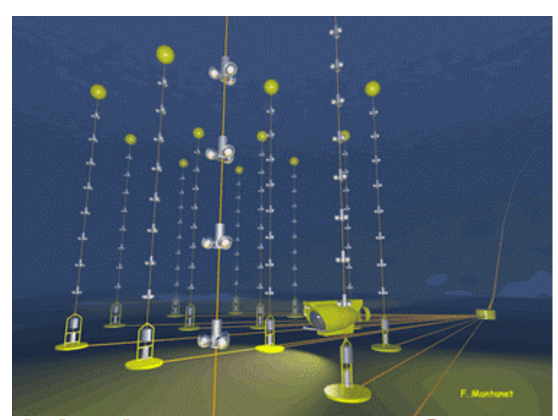
Three TeV neutrinos detected by IceCube in the 1000 seconds centred on the GW150914 trigger; all are consistent with atmospheric background. ANTARES did not detect any neutrinos during this period.



← IceCube

South Pole

ANTARES →



Mediterranean Sea

- Bound energy radiated in neutrinos to be < ~0.01 - ~1 solar mass (depending on sky location).
- Prospects for future multimessenger followup campaigns are good: Had GW150914 been a system containing a neutron star (at a distance to which such systems can be detected), this campaign would have provided constraints on various emission mechanisms.
- Note: After 4 GW detections have been published, LIGO triggers will be made publicly available promptly.

ASTROPHYSICAL BACKGROUND AND INTERPRETATION

Summary of:

- Astrophysical Implications of the Binary Black-Hole Merger GW150914

Overview:

- Formation Of (Stellar-Mass) Black Holes In Our Universe
- Formation And Evolution Of Binary Black Holes In Nature
- Inspiraling And Merging: Producing Gravitational Waves
- Predicting Such Events Observable In (Near) Future

FORMATION OF STELLAR-MASS BLACK HOLES IN NATURE

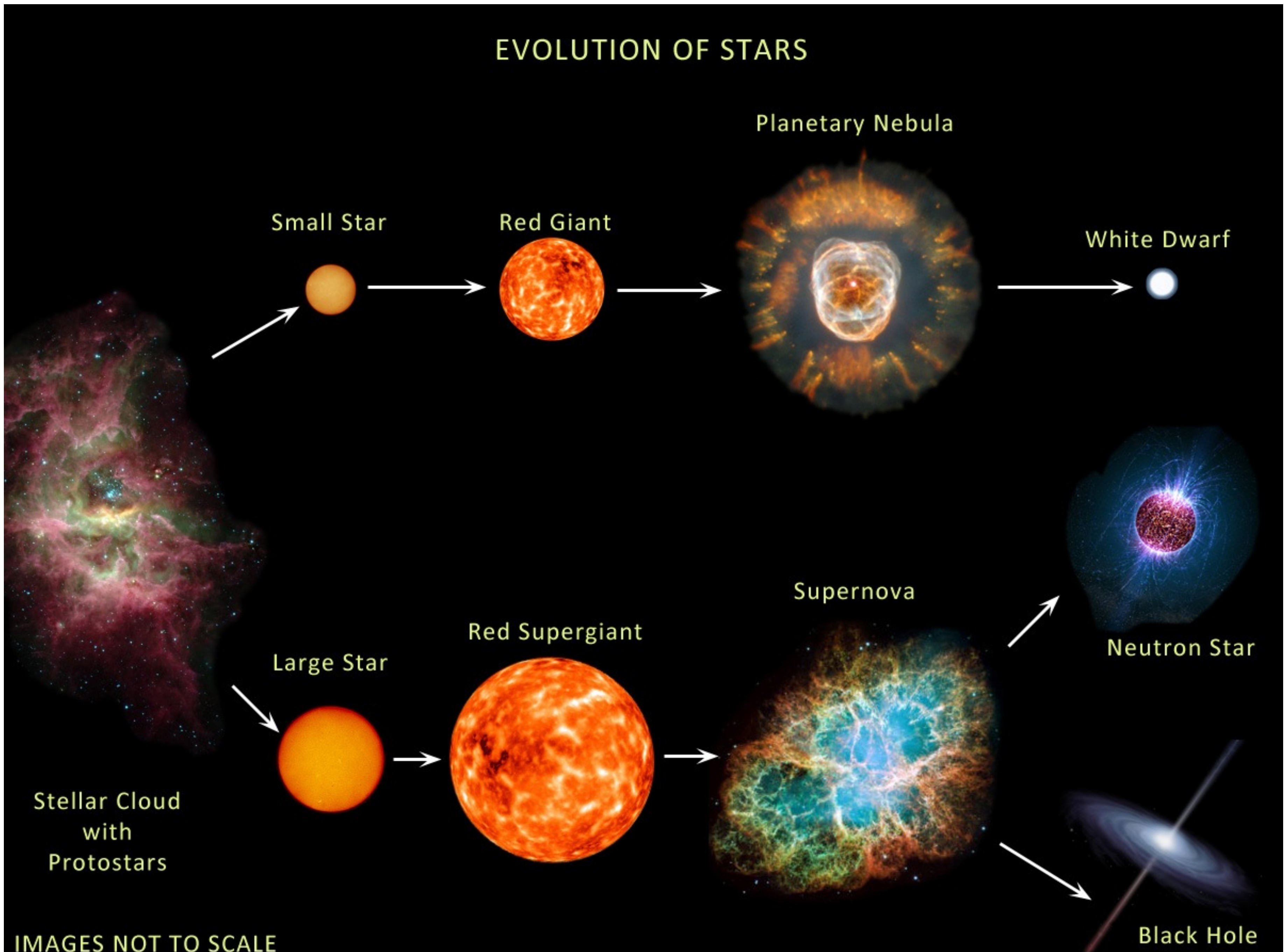
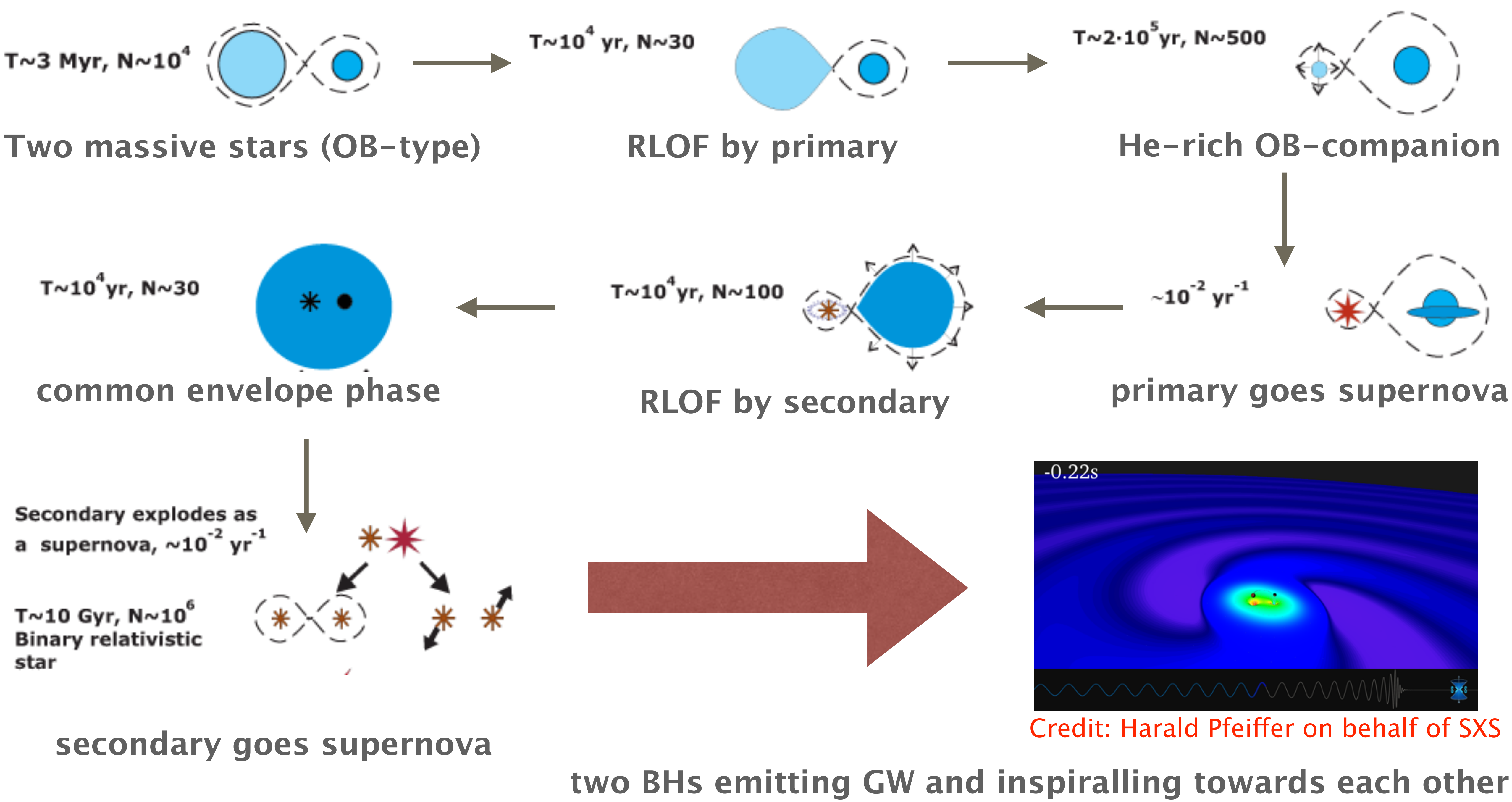


Illustration of stellar evolution of stars in our universe

Depicts the formation of stellar-mass black holes through the stellar evolution

Most massive stars, after running out of the fuel, explode in supernovae and become black holes!

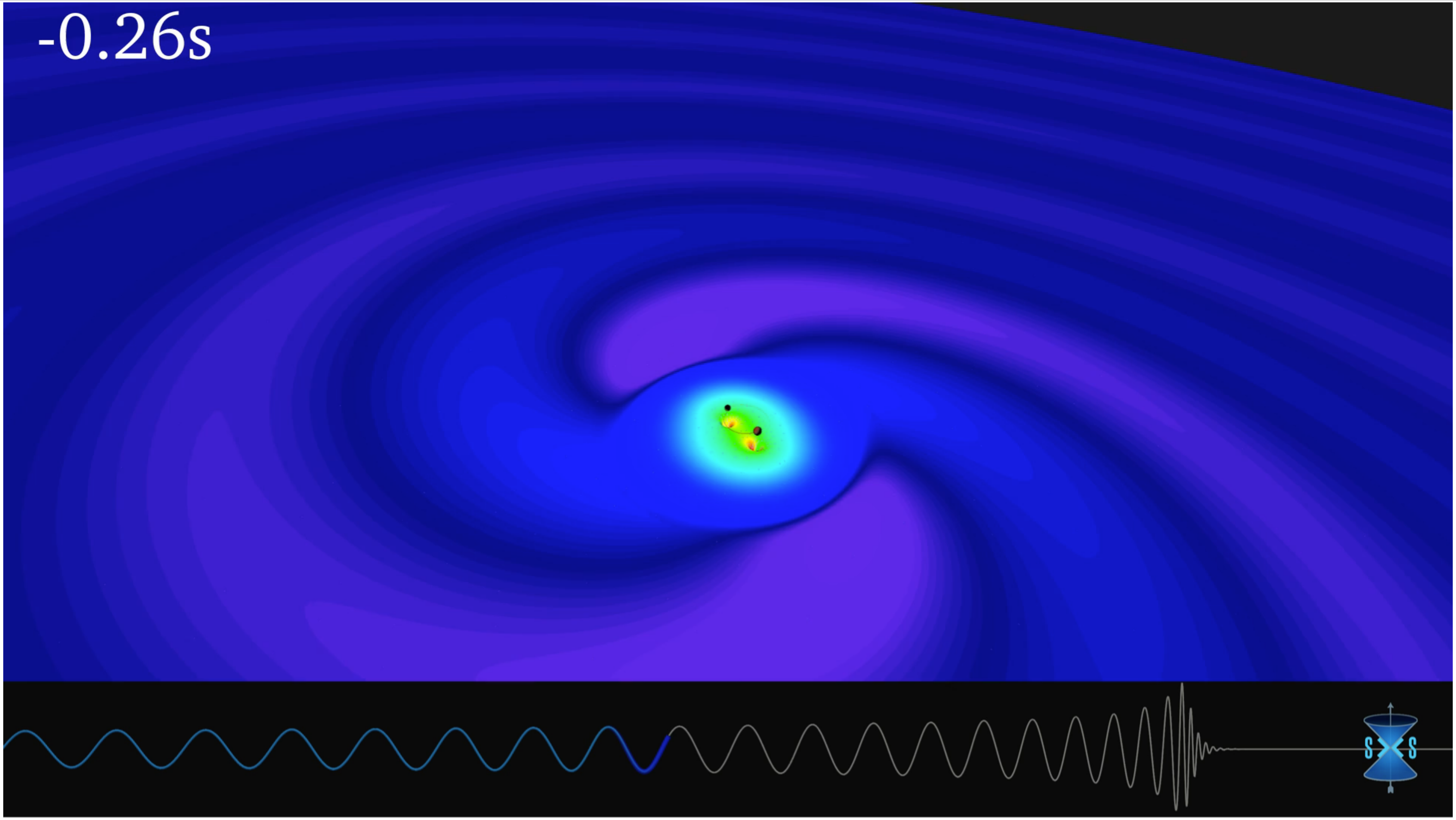
FORMATION OF A BINARY BLACK HOLE FROM AN ISOLATED BINARY



MERGER OF BINARY BLACK HOLES: A COMPUTER SIMULATION

Visualization available at https://www.black-holes.org/gw150914

Credit: Harald Pfeiffer on behalf of SXS



… and then these black holes inspiral towards each other and collide!

ASTROPHYSICAL BBH MERGER RATES AND SENSITIVITY FOR ADVANCED LIGO DETECTORS

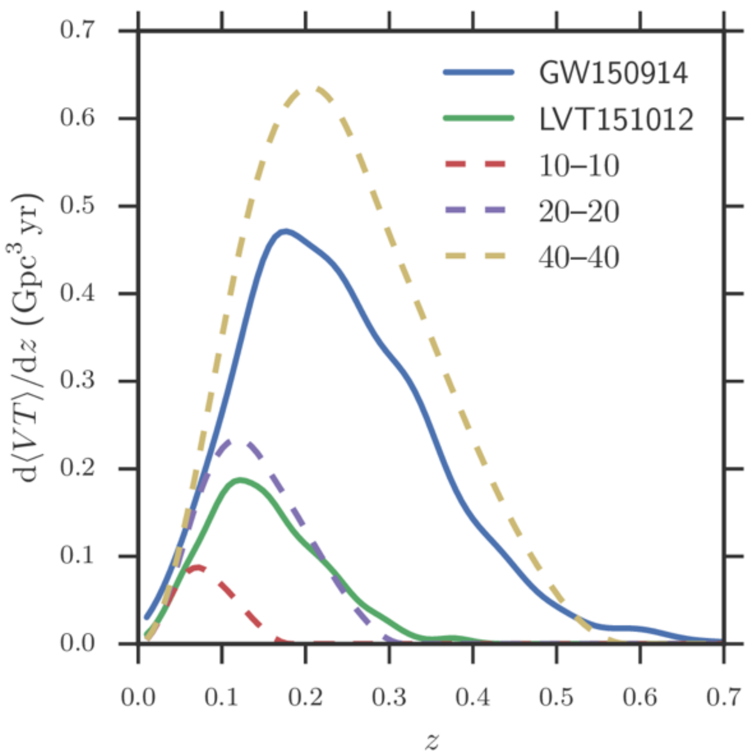


Figure above: The **rate** at which the **LIGO detectors accumulate time-volume** around this discovery, shown as a function of redshift. Curves for different component masses (in M⊙) are shown here, assuming sources with fixed masses in the comoving frame and without spin.

- **Left panel**: The median value and 90% credible interval for the **expected number of highly significant events**, as a function of surveyed time-volume. The **expected range** of values of ⟨VT⟩ for O2 and O3 are shown as vertical bands.

Figure below

- **Right panel**: The probability of observing N > 0 (blue), N > 5 (green), N > 10 (red), and N > 35 (purple) highly significant events. The vertical line and bands show, from left to right, the expected sensitive time-volume for the end of O1 (dashed line), O2, and O3.