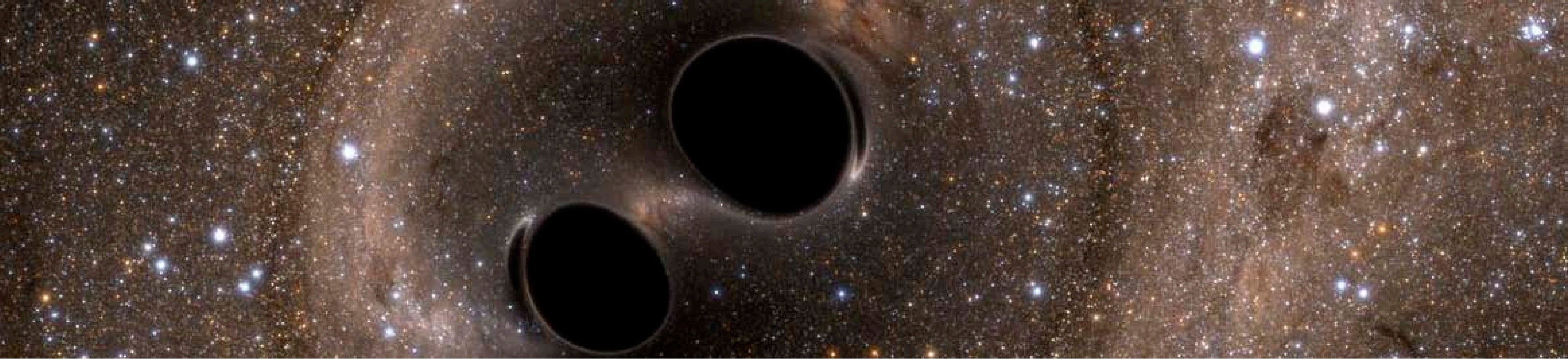

Summary: astrophysics from 1st LIGO events

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KITP, August 12, 2016

Binary Black Hole Mergers in the first Advanced LIGO Observing Run

Duncan Brown

The LIGO Scientific Collaboration and The Virgo Collaboration[a]
(23 JUNE 2016)

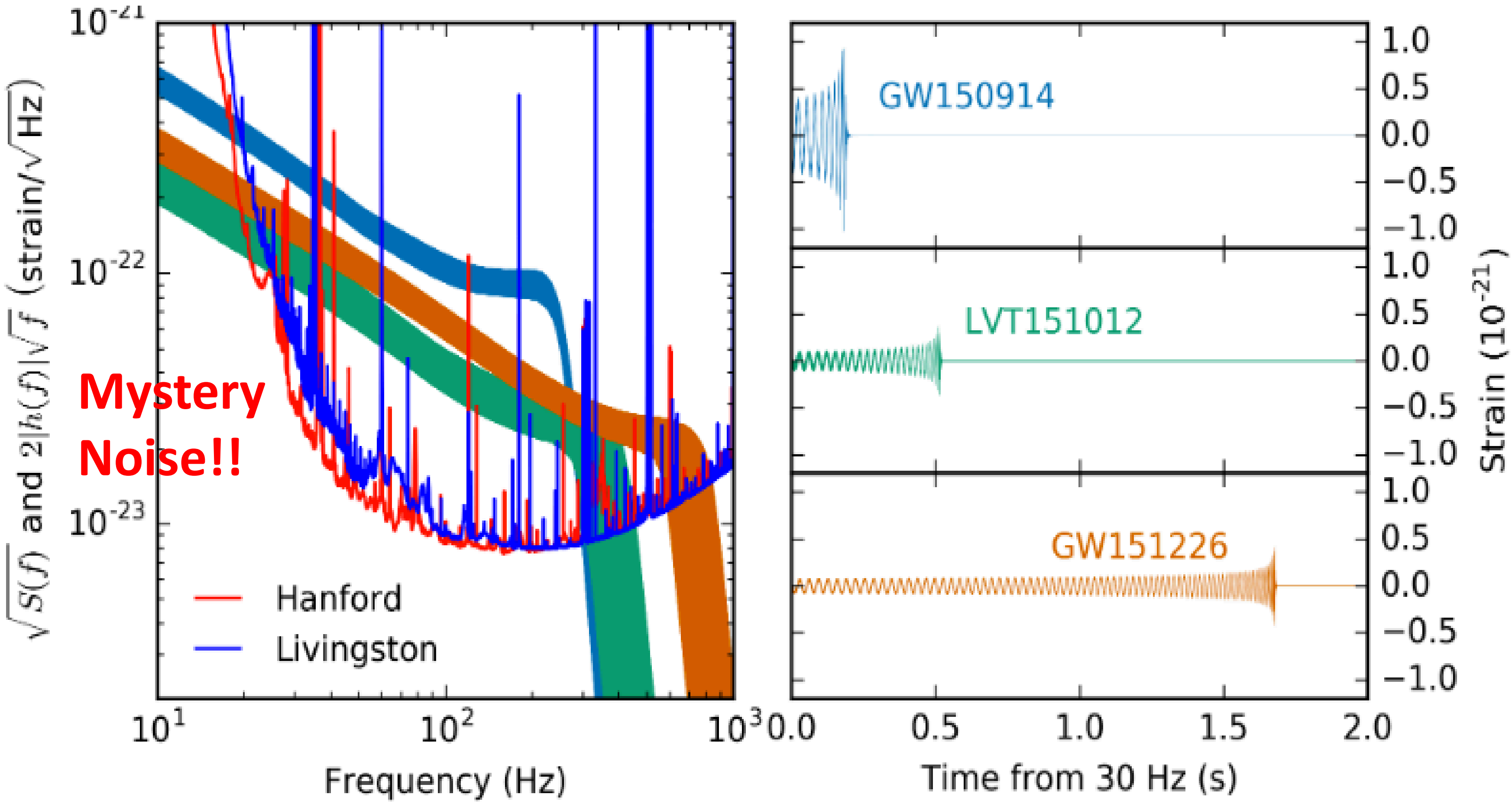
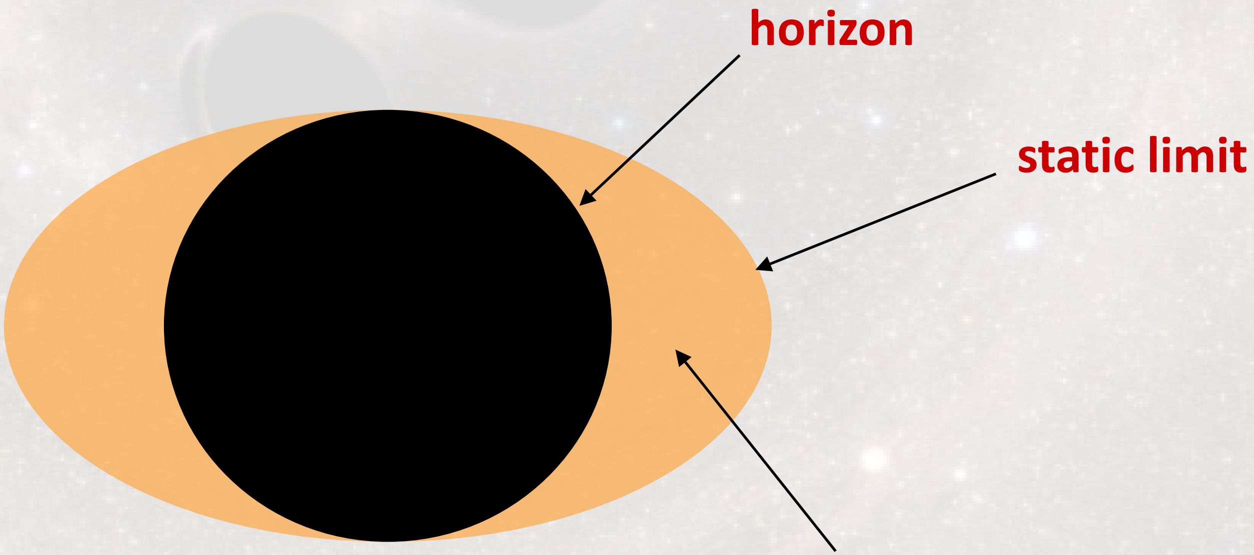


FIG. 1. Left: Amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226 and LVT151012 plotted so that the relative amplitudes can be related to the SNR of the signal (as described in the text). Right: Time evolution of the waveforms from when they enter the detectors' sensitive band at 30 Hz. All bands show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model [45].

Black hole is one of the simplest objects in the Universe (Dan Holtz)

Black hole mergers is the simplest dynamical process in the Universe



Spacetime described by the Kerr metric.

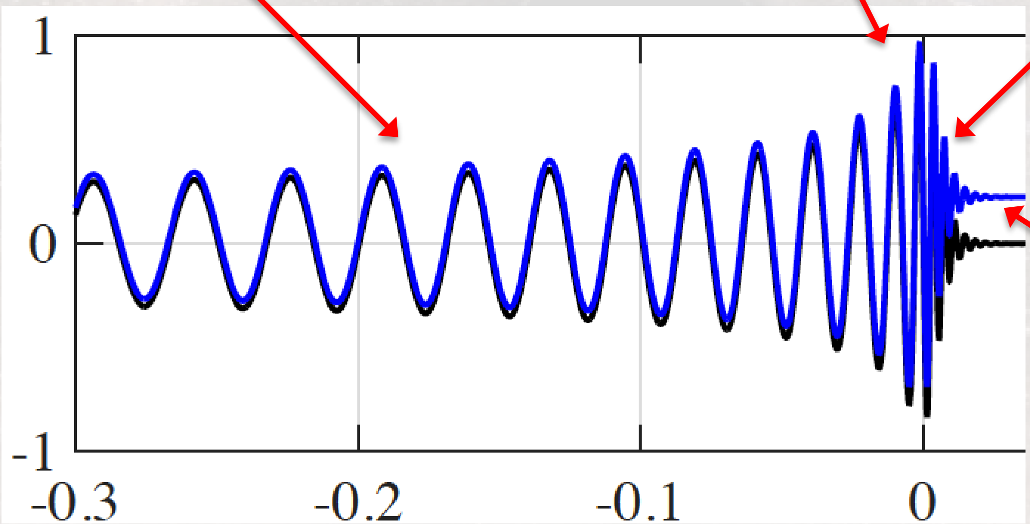
If relativity is correct.. (Alessandra Buonanno, Luis Lehner)

Chirp mass (easy)
Post-Newtonian coefficients (doable)
Mass ratio (more difficult)
Spins (hard)

Horizon area grows

Quasinormal modes
Tests of Kerr
Structure of the remnant. (Steve Gidding)
Hard, need next gen.

Figure credit: Paul Lasky



Christodoulou GW memory. Possible but need many mergers

A lot of astrophysical value to measure spins, but not easy. Ben Farr and Richard O'Shaugnessy.

LISA does not yet exist. Yet it has already helped in understanding galactic nuclei

- Mergers of supermassive black holes, last parsec “problem”, connection to hierarchical assembly of galaxies
- Non-resonant and resonant relaxation, relativistic loss cones, EMRIs and tidal disruptions, mass segregation and cusps of stellar black holes
- Self-gravitating accretion discs, BH binaries in discs, stellar disc in the Galactic Center, star and IMBH formation near big BH in the nuclei

LIGO brings into focus key questions of stellar astrophysics.

1. Mixing in stars due to non-sphericity (rotation, tides) and differential rotation (Selma de Mink, Pablo Marchant). Does it even happen (observations suggest so but theory is shaky)? If yes, how effective? Does it really lead to entirely homogeneous evolution?
2. Are Wolf-Rayet stars in the SMC produced by homogeneous evolution?? (Wolf-Rainer Hamann)
3. Are synthetic spectra generated from models in this scenario in agreement with any current scenario? (Lydia Oskinova).

LIGO brings into focus key questions of stellar astrophysics.

4. Angular momentum transport within stars (important for spins). Magnetic torques not understood, Spruit-Tayler dynamo predicts 10 times faster core spins for low-mass giants (Mateo Cantielo)
5. Mass loss not understood! Direct measurement difficult (clumping etc), extrapolations to low metalicity on thin ground (WR Hamann, Lydia Oskinova). Theory shaky or non-existent.

LIGO brings into focus key questions of stellar astrophysics.

6. Supernovae not understood (Stan Woosley). However one can classify stellar models by “explodability”, sharp delineation between explodable and unexplodable models, some ideas of BH mass range. BH mass gaps! How good are the models (some of them feature huge density gradients)? Is all the physics included? Does hydrogen envelope accrete onto a BH? (rotation, final mass and BH spin).

LIGO brings into focus key questions of stellar astrophysics.

7. Dynamical formation in globular and nuclear star clusters (Carl Rodriguez, Rainer Spurzem). Any evidence/constraints from detailed observations of clusters? Lack of pulsar accelerations near cluster cores (the data are exquisite)? Lack of BH-MS binaries predicted by the same simulations? Other exotic mergers?

LIGO brings into focus key questions of stellar astrophysics.

8. Common envelope!!! (Tomek Bulik, Enrico Ramirez-Ruiz, Tyrone Woods)

Not understood for compact objects inside envelopes.

No treatment with accretion feedback.

Not much on nearly equal masses.

For GW150914, might be neither common nor envelope.

Major effort needed.

EM counterparts

- General reluctance to talk about BH-BH counterparts (Andy MacFadyen?). What about exotic environment, e.g. discs (Barry "AGN disc" McKernan, Saavik Ford, Brian Metzger)
- Lots of theoretical effort on BH-NS and NS-NS (Francois Foucart). Ejecta? How much and how fast (need very high res. shock capturing GR simulations). Radiative transfer tricky! Observational appearance is still being worked out (Chris Fryer)
- Huge observational potential but very challenging (Shri Kulkarni, Greg Hallinan, Marcele Soares-Santos, Mansi Kasliwal). Many telescopes in all wavebands will be pointed at the same part of the sky at the same time. Any interesting extra science there ?
- Rapid development. Shri bets $1000 on radio astronomy. Any takers?

Phinney declaration

1. If LIGO finds M_1>30Msun binary black holes with a mass ratio q<0.5, then they are not a result of chemically homogeneous evolution of isolated binaries (i.e. in vacuum, no star cluster exchanges, triples or AGN disks).
2. If LIGO finds an 80-130Msun BH in a black hole binary (isolated: not in a star cluster, triple, or AGN disk), it will conclusively rule out the theory of pair instability supernovae, which is straightforward and has no major adjustable parameters.
3. If the spins of the black holes are both aligned with the orbital angular momentum, we all agree not to publish any papers proposing that the system was formed by dynamical interactions in a star cluster

Phinney declaration

4. If LIGO finds that the rate R of merger of M1+M2>100 Msun black hole binaries is greater than 1/4 the rate of merger of M1+M2>20 Msun black hole binaries, then the former cannot be a result of "conventional" (inhomogeneous, common-envelope) evolution, unless top-heavy IMFs are invoked.
5. If LIGO correlations with galaxy positions indicate that the typical BBH mergers are correlated with L* spiral galaxies, then the BBH mergers are not a result of Z<1/10 solar chemically homogeneous evolution.
6. If one or both black hole spins are always aligned with the orbital angular momentum, then dynamically (cluster exchange) formed binaries do not contribute significantly to the rate of BBH merger.

Phinney declaration

7. If in an approximately equal-mass BBH, both spins are large (a/M>0.5) and aligned with the orbital angular momentum, chemically homogenous evolution will be accepted as the origin.
8. If in an approximately equal-mass BBH, one spin is large (a/M >0.5) and aligned with the orbital angular momentum, but the other small (a/M<0.1), a wide orbit shrunk by common envelope evolution will be accepted as the origin.
9. If most spins in BBH mergers are found to be small (<0.2), and Wolf-Rayet mass loss is determined to be <10^{-6}Msun/y, with no late stage LBV mass loss, Z<1/10 solar chemically homogeneous evolution will be abandoned as an explanation for their origin.

Phinney declaration

10. If radial velocity measurements by integral-field spectrographs fail to find any binaries consisting of a massive black hole and a ~0.8Msun main sequence star in globular clusters of low enough density that most of their black hole binaries should not have been ejected, then globular clusters will be abandoned as a significant source of BBH mergers.
11. If no luminous red supergiants of >45Msun are found in galaxies of SMC or lower metal abundance, the standard (inhomogeneous, common-envelope) model for formation of 30+30Msun BBH will be abandoned.