Coalescing compact binaries and Gravitational wave astronomy

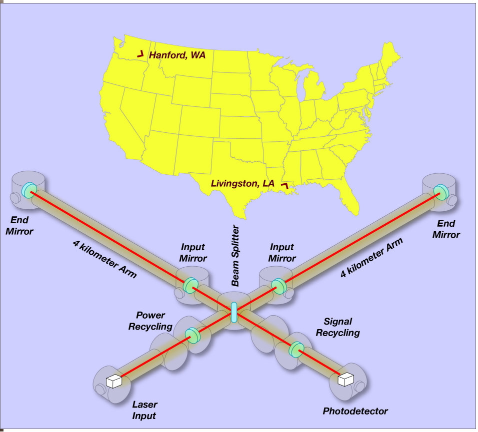
Archana Pai, IIT Bombay

Build-A-Detector Workshop **June 3, 2021**

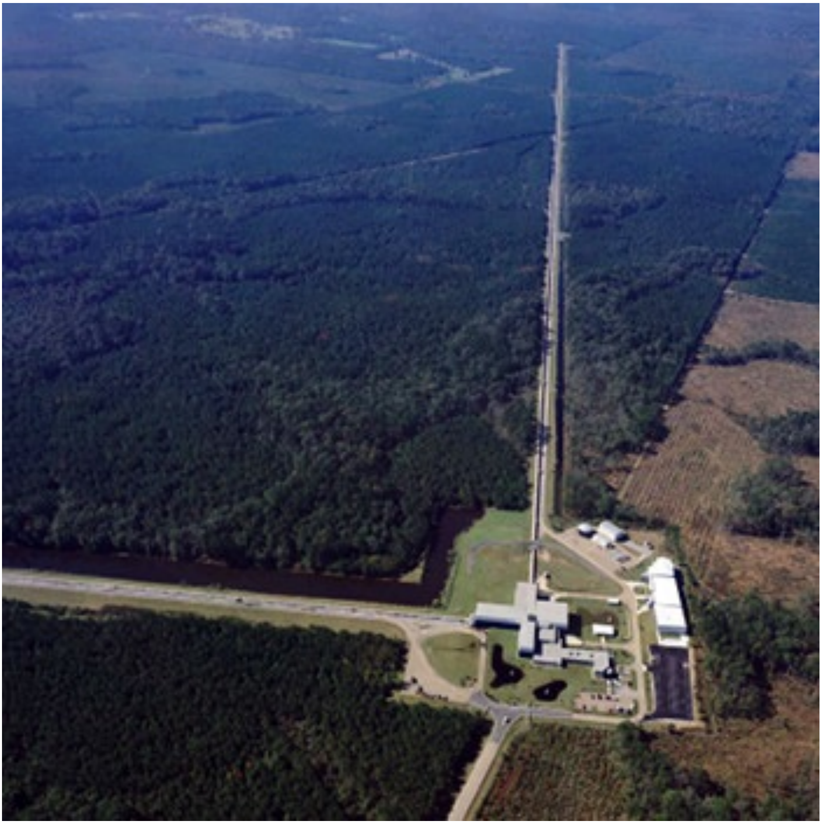
Beginning of Gravitational Wave Astronomy

Advanced LIGO detectors

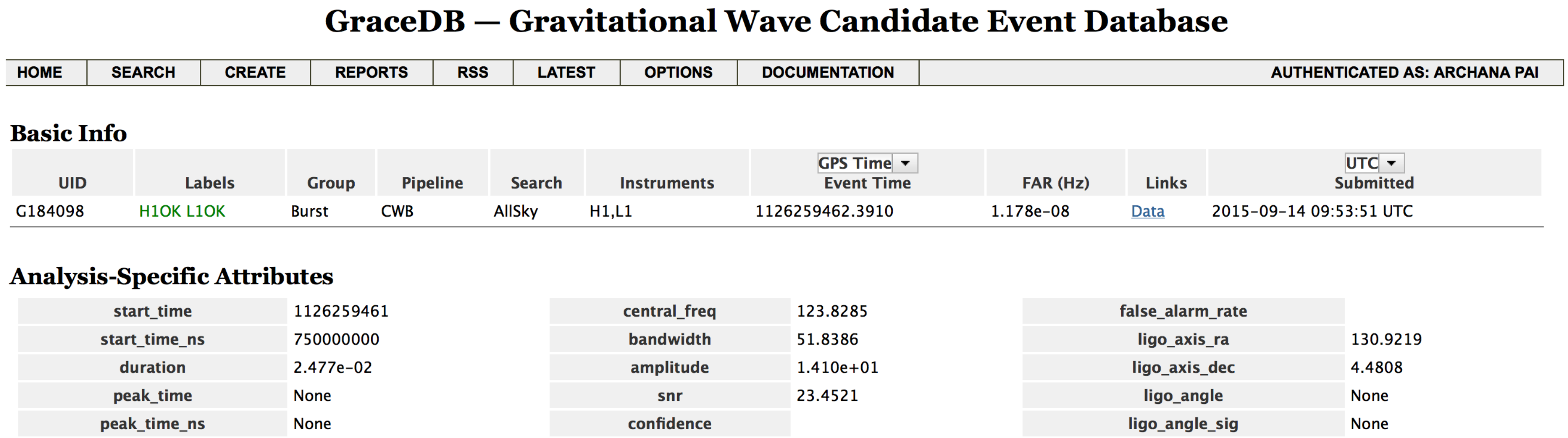
Hanford, Washington



Livingston, Lousiana



STORY BEGINS ON SEPTEMBER 14, 2015



GraceDB — Gravitational Wave Candidate Event Database

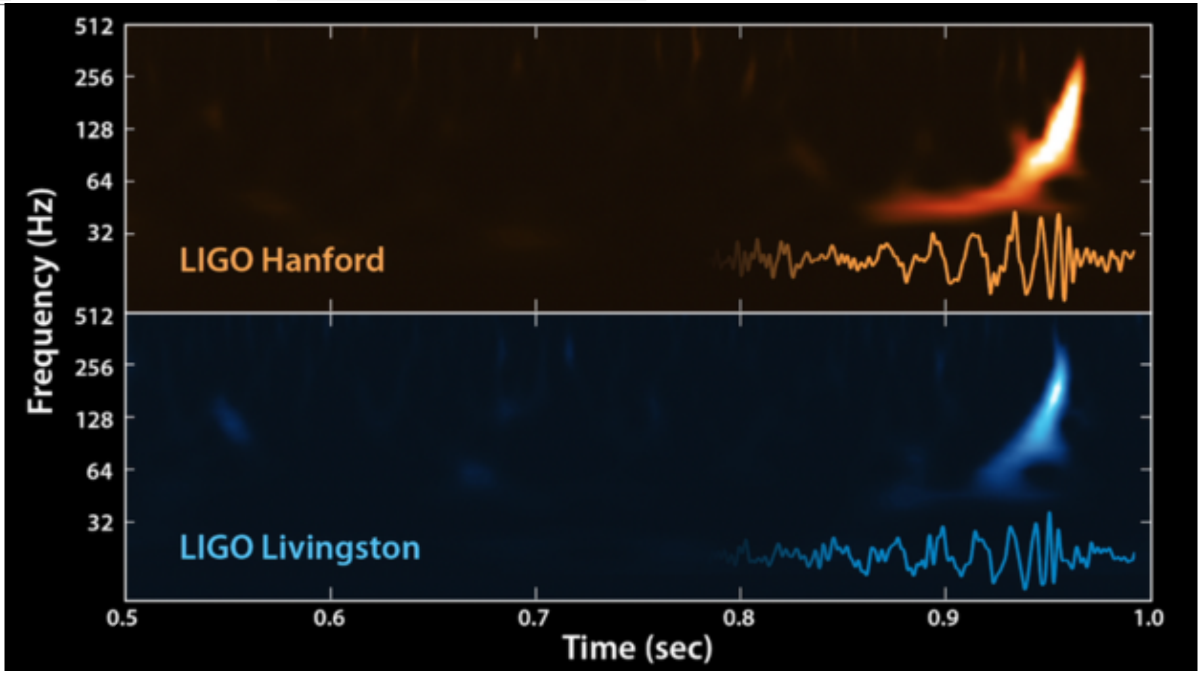
Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	1126259462.3910	1.178e-08	Data	2015-09-14 09:53:51 UTC

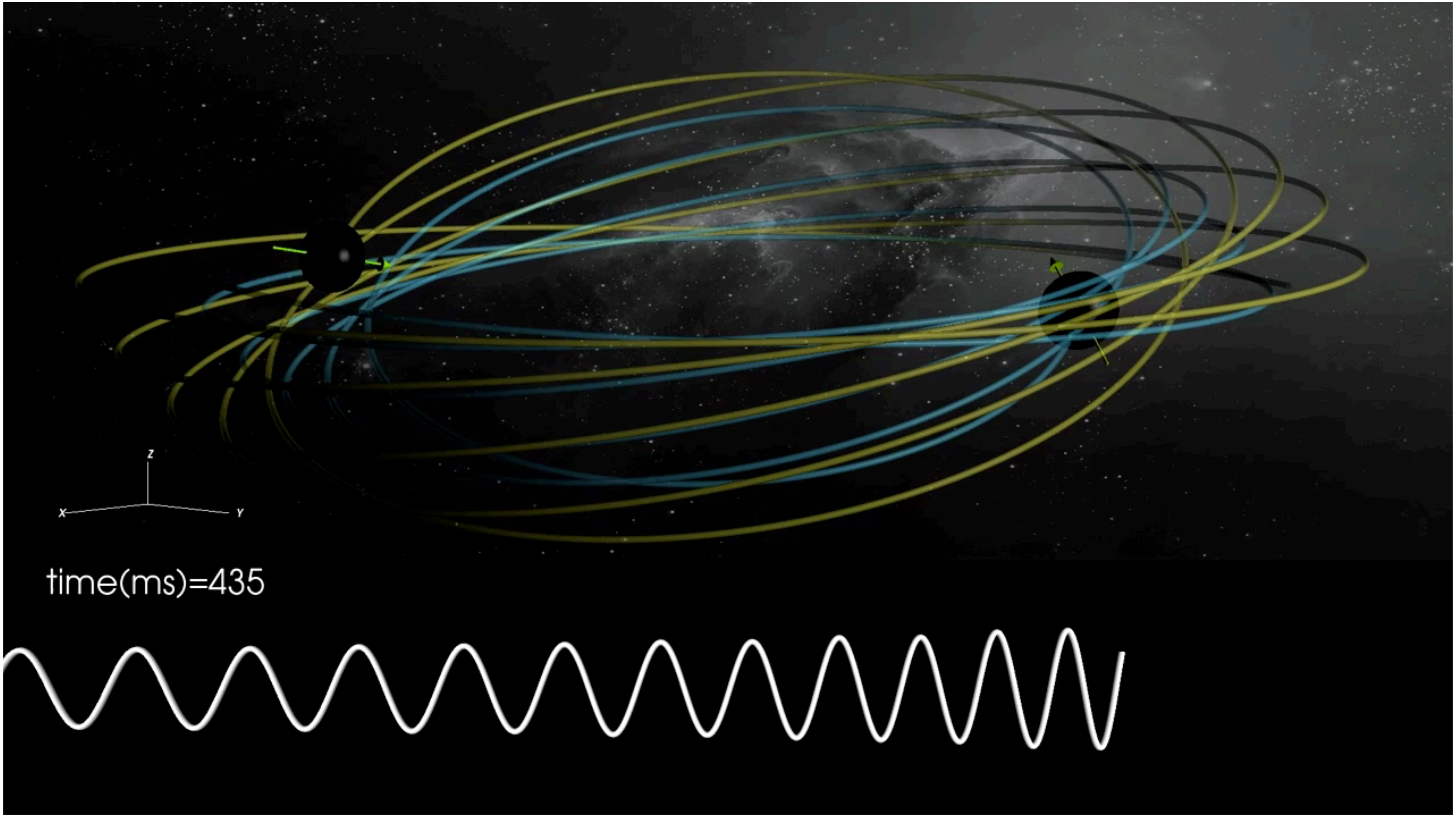
Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

A GENERIC GRAVITATIONAL WAVE SEARCH ALGORITHM SHOWS AN ALERT

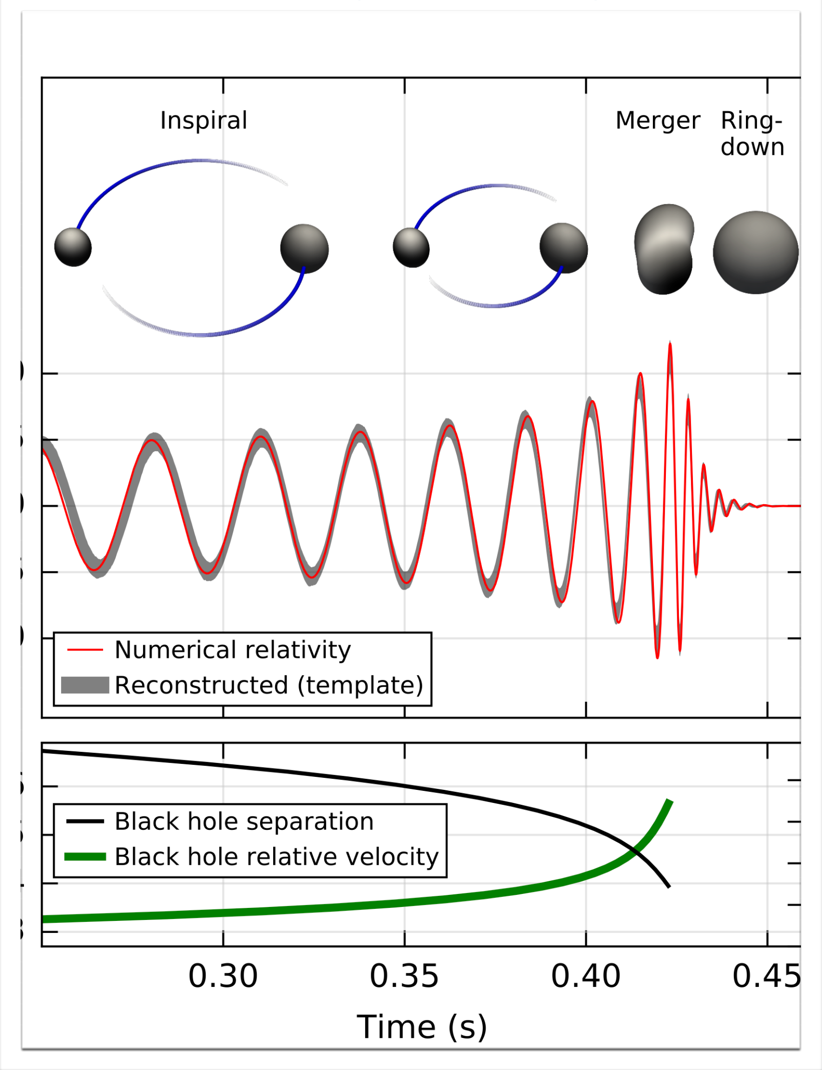


LVC, PRL 116, 061102 (2016)


Z
X
Y
time(ms)=435

GW150914: First black hole binary merger event

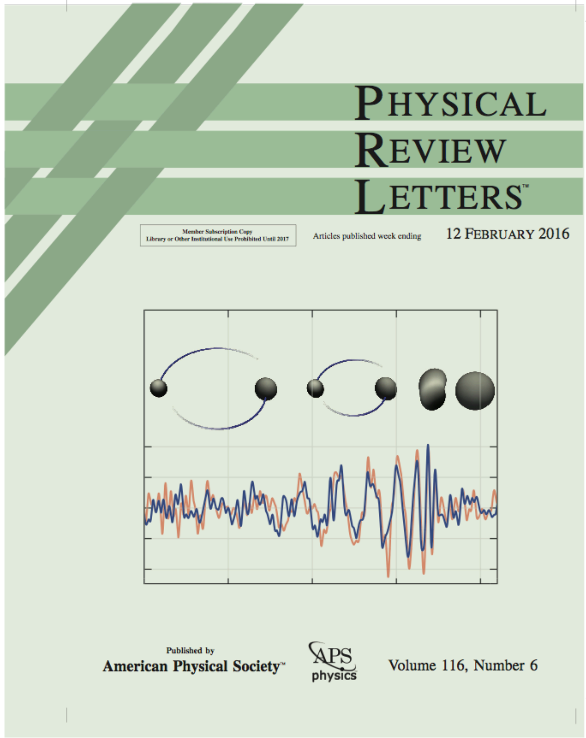
- Collision of two stellar mass black hole of masses 36-29 Msun into a kerr black hole.
- Located at the distance of 1.33 billion light years (450 Mpc)
- Signal duration of gravitational wave was 200 msec.
- Remnant black-hole of 62 Msun
- Highly relativistic system produced peak strain of $h \sim 10^{-21}$
- Power radiated in GW is equivalent to 3Msun.



LVC, PRL 116, 061102 (2016)

Four Firsts from the discovery

- **First** direct detection of gravitational waves
- **First** direct observation of stellar mass black holes in a binary system
- **First** direct evidence of collision of black holes in the binary system
- **First** direct evidence of existence of stellar mass black holes > 25 Msun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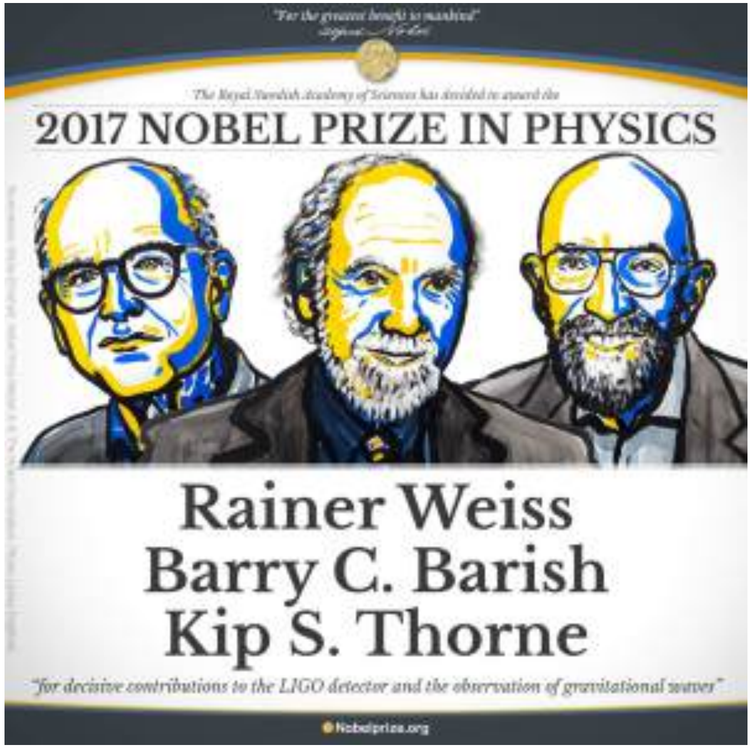
APS physics

Volume 116, Number 6


2017 NOBEL PRIZE IN PHYSICS

Rainer Weiss
Barry C. Barish
Kip S. Thorne

"for decisive contributions to the LIGO detector and the observation of gravitational waves"

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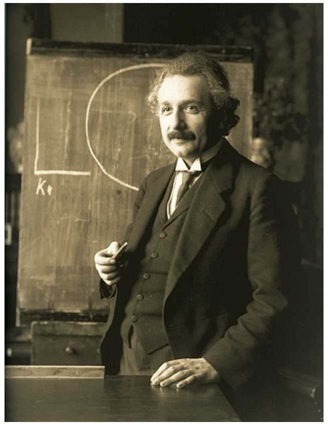
For decisive contributions to the LIGO And
The observation of gravitational waves
2017 Nobel Prize in Physics

Some background

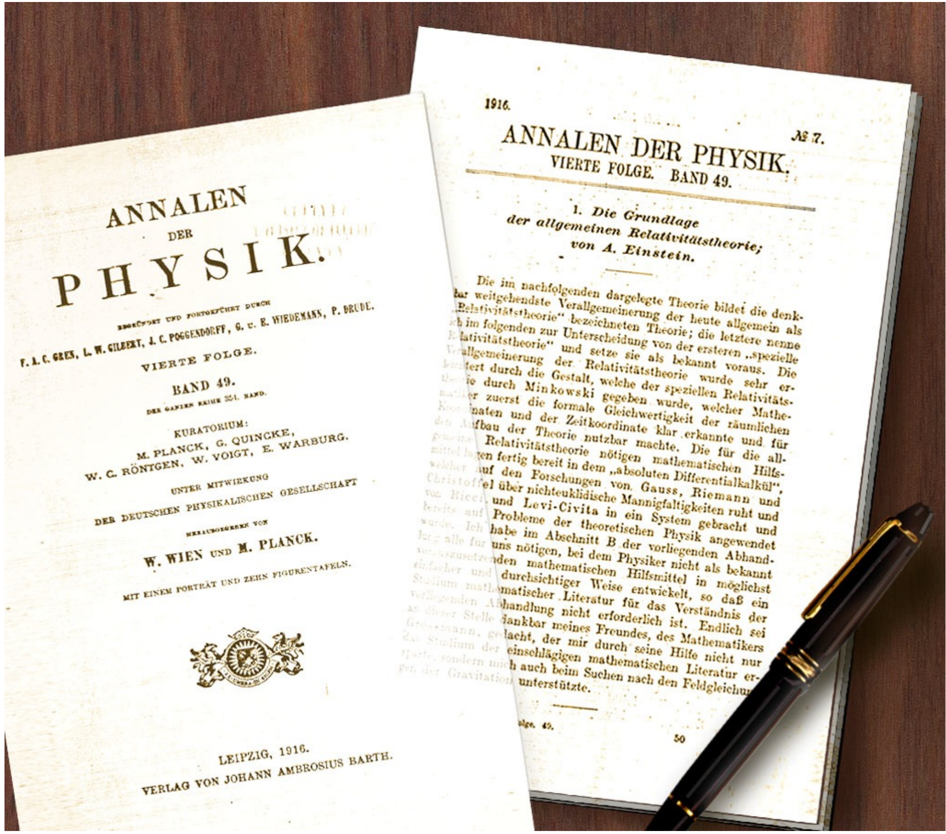


General Theory of Relativity (1916)

Equivalence Principle: Motion under gravity is a problem of geometry.

The matter defines the geometry. Geometry decides the trajectories

The weak field and slow motion limit
of the theory == Newtonian Gravity



ANNALEN
DER
PHYSIK.

BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. u. E. WIEDEMANN, P. DRUDE.

VIERTE FOLGE.

BAND 49.

DER GANZEN REIHE 354. BAND.

KURATORIUM:
M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, W. VOIGT, E. WARBURG.

UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT

HERAUSGEGEBEN VON
W. WIEN UND M. PLANCK.

MIT EINEM PORTRÄT UND ZEHN FIGURENTAFELN.

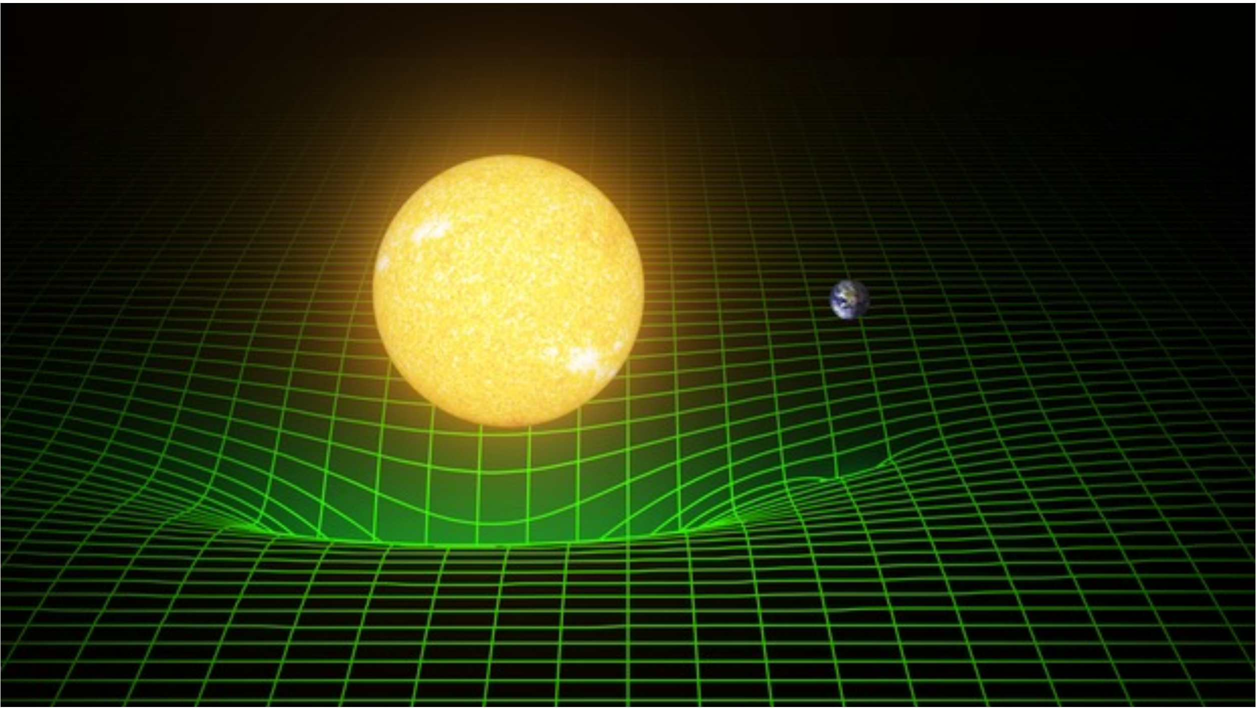
LEIPZIG, 1916.
VERLAG VON JOHANN AMBROSIUS BARTH.

1916. ANNALEN DER PHYSIK. № 7.
VIERTE FOLGE. BAND 49.

1. Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

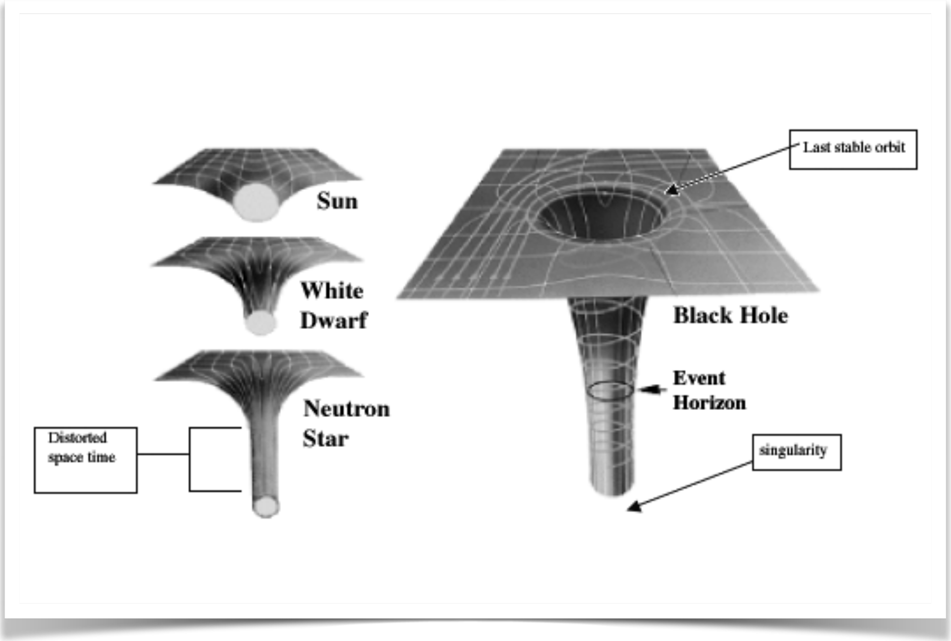
olge. 49. 50



Measure of strength of gravity

Compactness parameter :

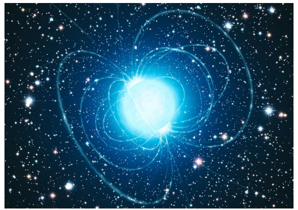
$$\alpha = \frac{2GM}{Rc^2}$$



Sun

Mass ~ 1e20 kg
Radius ~ 700,000 km

$\alpha \sim 0.000004$



Neutron Star (NS)

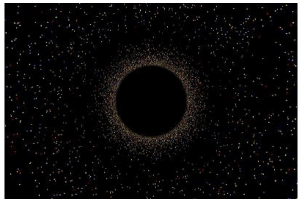
Mass ~ 1.4 Msun
Radius ~ 10 km

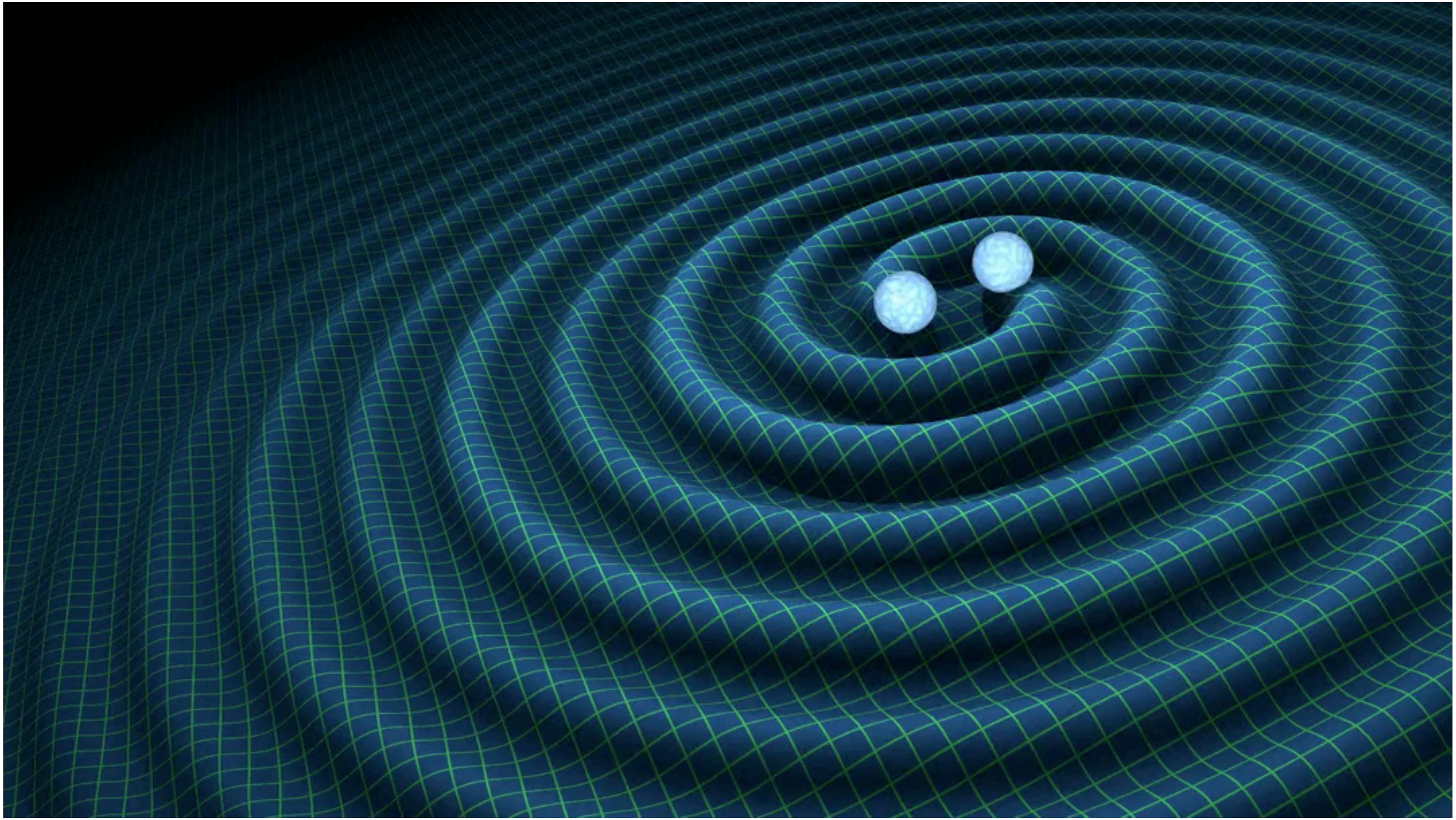
$\alpha \sim 0.4$

Black Hole (BH)

Mass ~ 3.0 Msun
Radius ~ 9.0 km

$\alpha \sim 1$





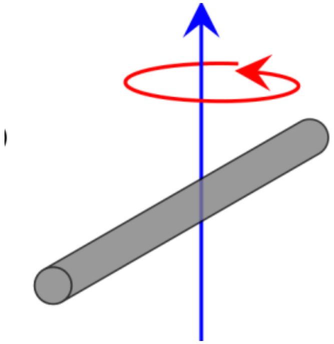
General Relativity and Gravitational Waves

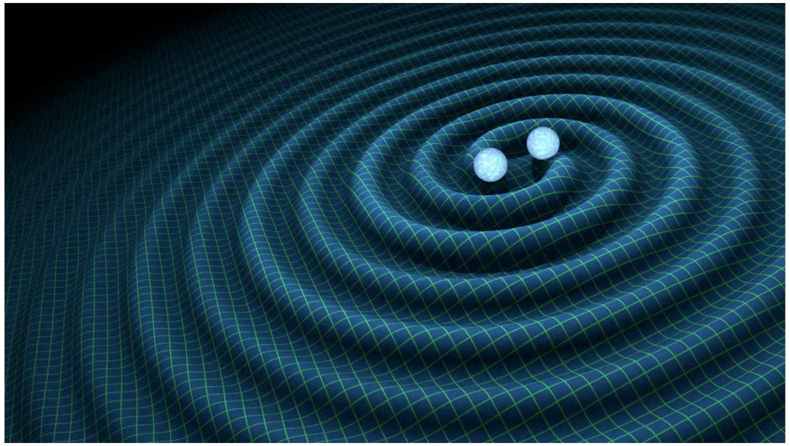
Estimate gravitational wave strain h

- Gravitational wave amplitude in terms of quadrupole moment Q

$$h = \frac{2G}{rc^4}\frac{d^2Q}{dt^2}$$

- Homework 1: Spinning rod of length 10 meters, spinning at 10Hz and mass of 1 ton located on Moon. Calculate the GW amplitude.

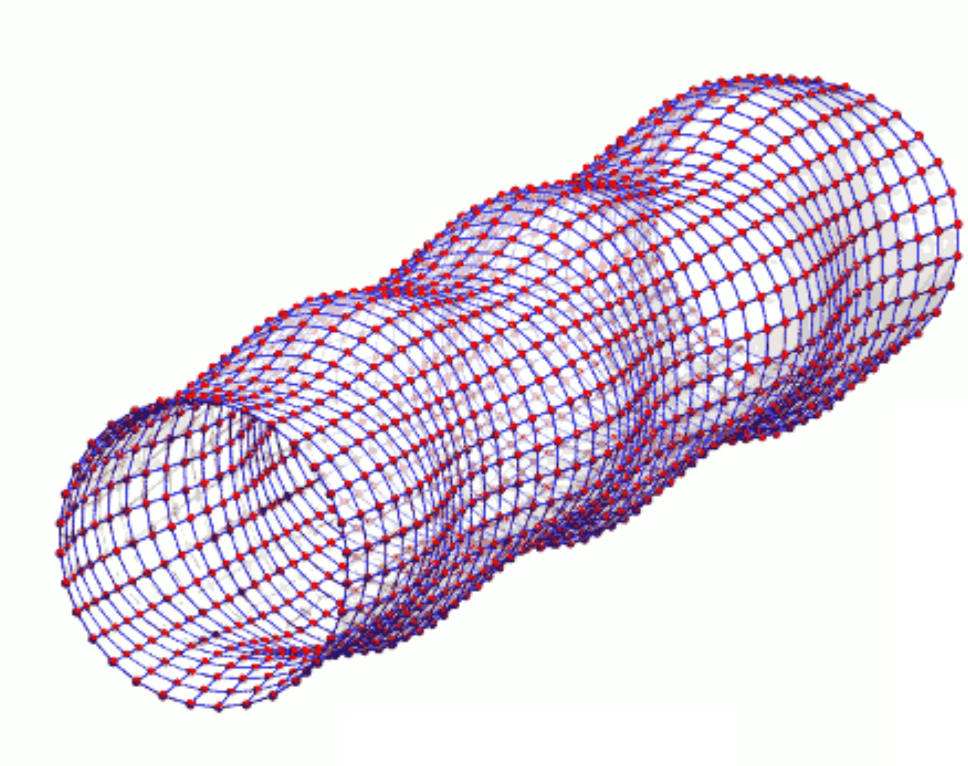




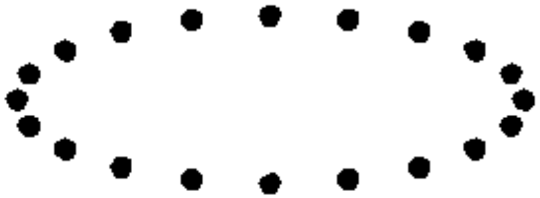
Coalescing compact binary in our galaxy:
NS Binary system located at 5kpc.
Orbital period: 7.7hrs
Orbital radius: 1 million km
GW dimensionless amplitude — $h \sim 10^{-23}$
GW frequency — 72 microHz

$$h_{\text{inspiral}} \sim \frac{M_c^{5/3} f^{2/3}}{r}$$

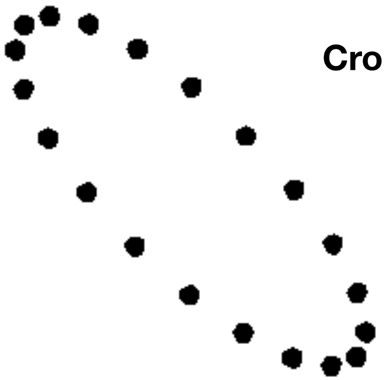
Gravitational Wave polarizations



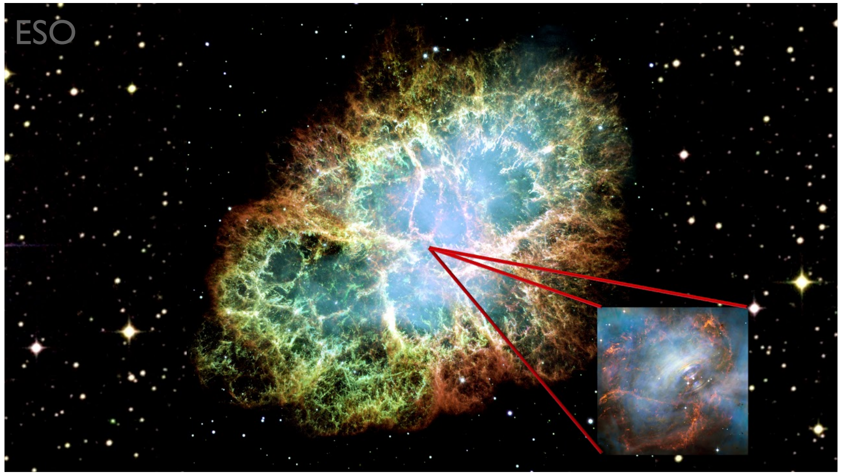
Plus +



Cross X

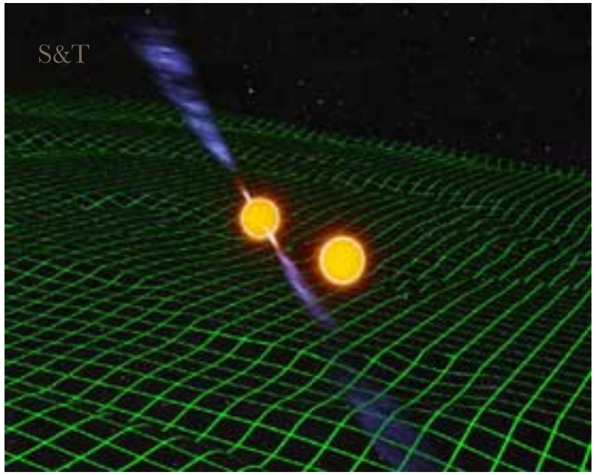


Astrophysical sources of gravitational waves

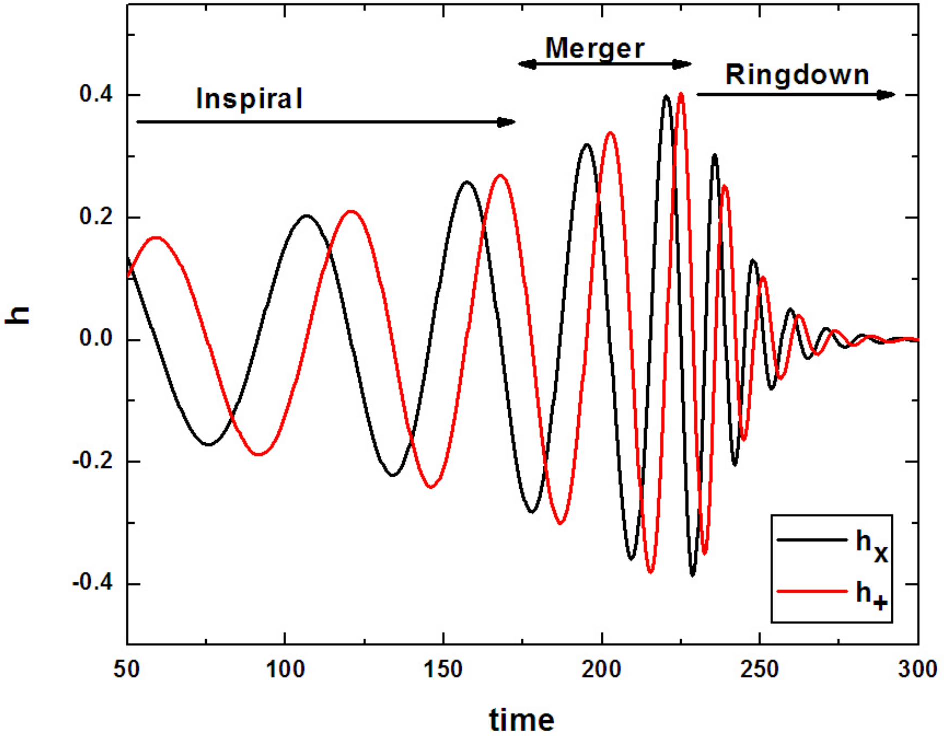

ESO

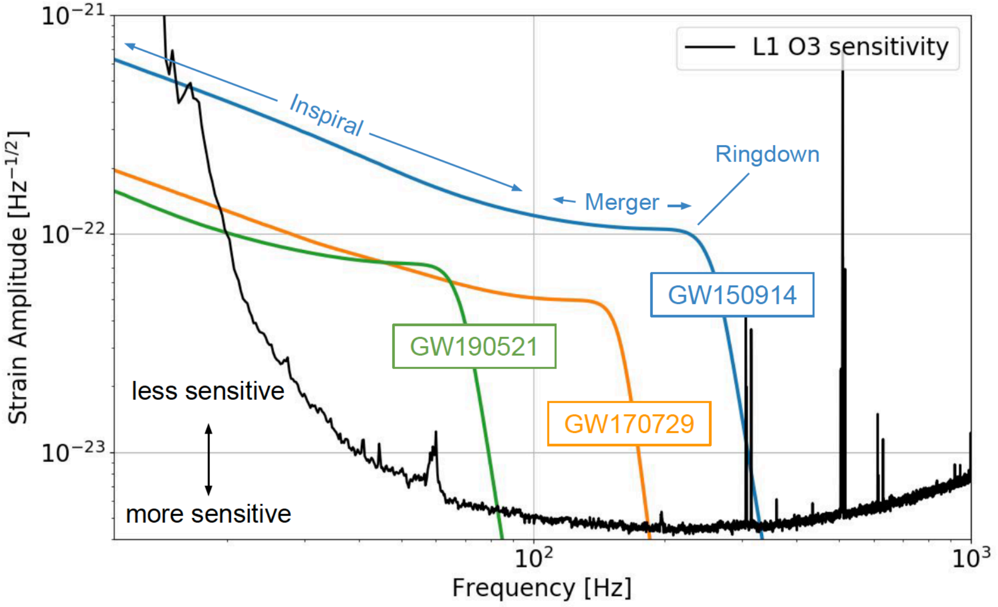

Hubble


NASA


S&T

Coalescing Compact binaries in GW detector

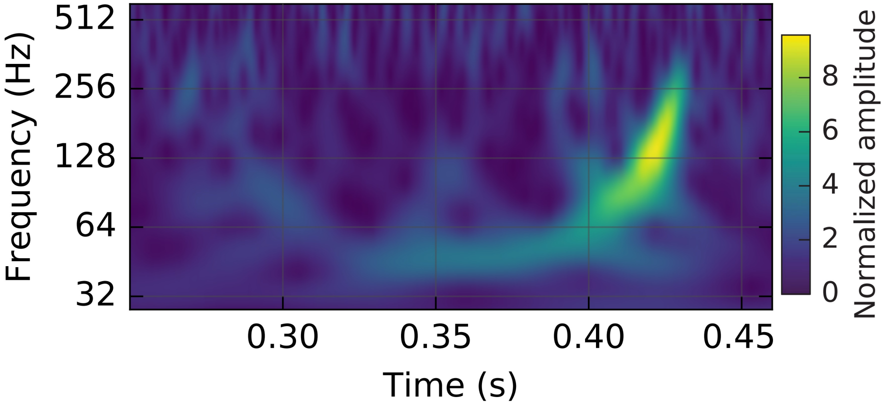




Coalescing binary and time frequency morphology

LVC, Annalen der Physik (2017)

GW150914 TF morphology



Inspiral phase is characterised by redshifted chirp mass:

$$M_c = \mu^{2/5} M^{2/5} (1+z)$$

Reduced mass **Total mass**

GW frequency evolution:

$$f_{GW}^{-8/3}(t) = \frac{(8\pi)^{8/3}}{5} \left(\frac{GM_c}{c^3} \right)^{5/3} (t_c - t)$$

- Signal duration of gravitational wave is 150 msec.
- Inspiral signal frequency: 30 — 150 Hz
- Inspiral phase gives chirp mass Mc ~ 30 Msun
- What if NS-BH system? With one NS, BH needs to be at least ~ 475 Msun
- Would have coalesced much faster and would not reach frequency as high 150Hz.
- Measurement of ringdown frequency gives

$$f_{GW|ringdown} \sim 260Hz \left(\frac{65M_\odot}{M} \right)$$

More detailed data analysis — John Veitch's talk

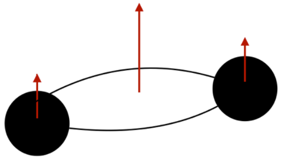
Homework 2:

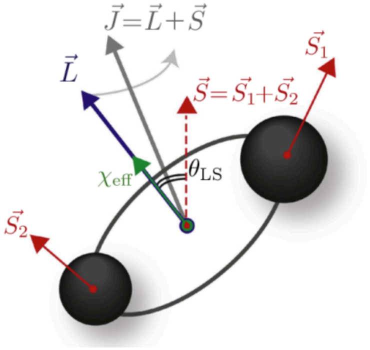
Plot the signal duration of the inspiral phase with respect to total mass.

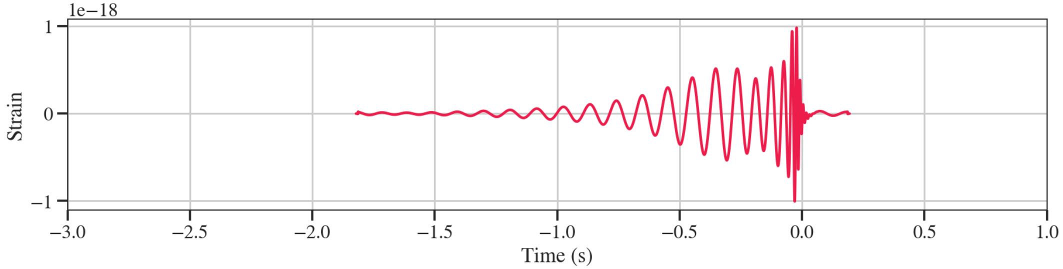
Assume equal mass binary system and consider the signal enters the detector at 15Hz.

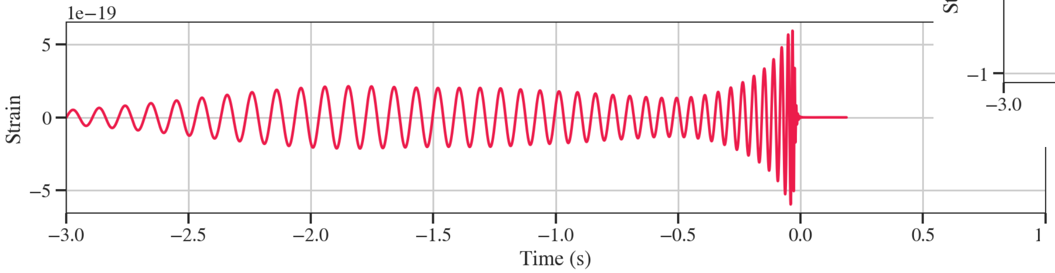
Compact binary gravitational wave signals

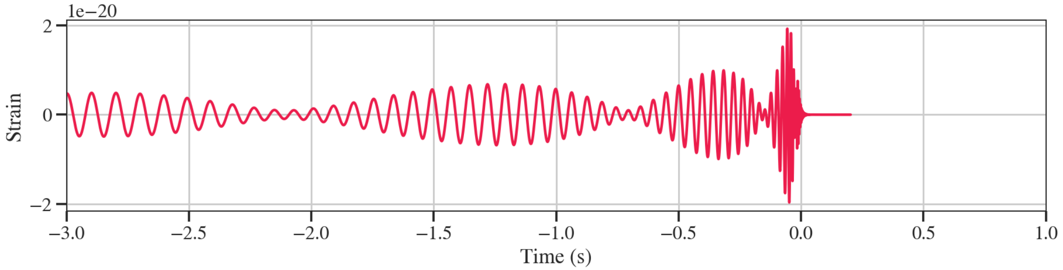
- Masses and spins
- Source location and orientation in the sky
- Spin orientation with respect to the binary orbit : mis-aligned spins give precession



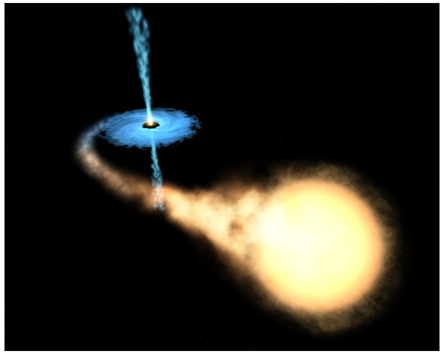








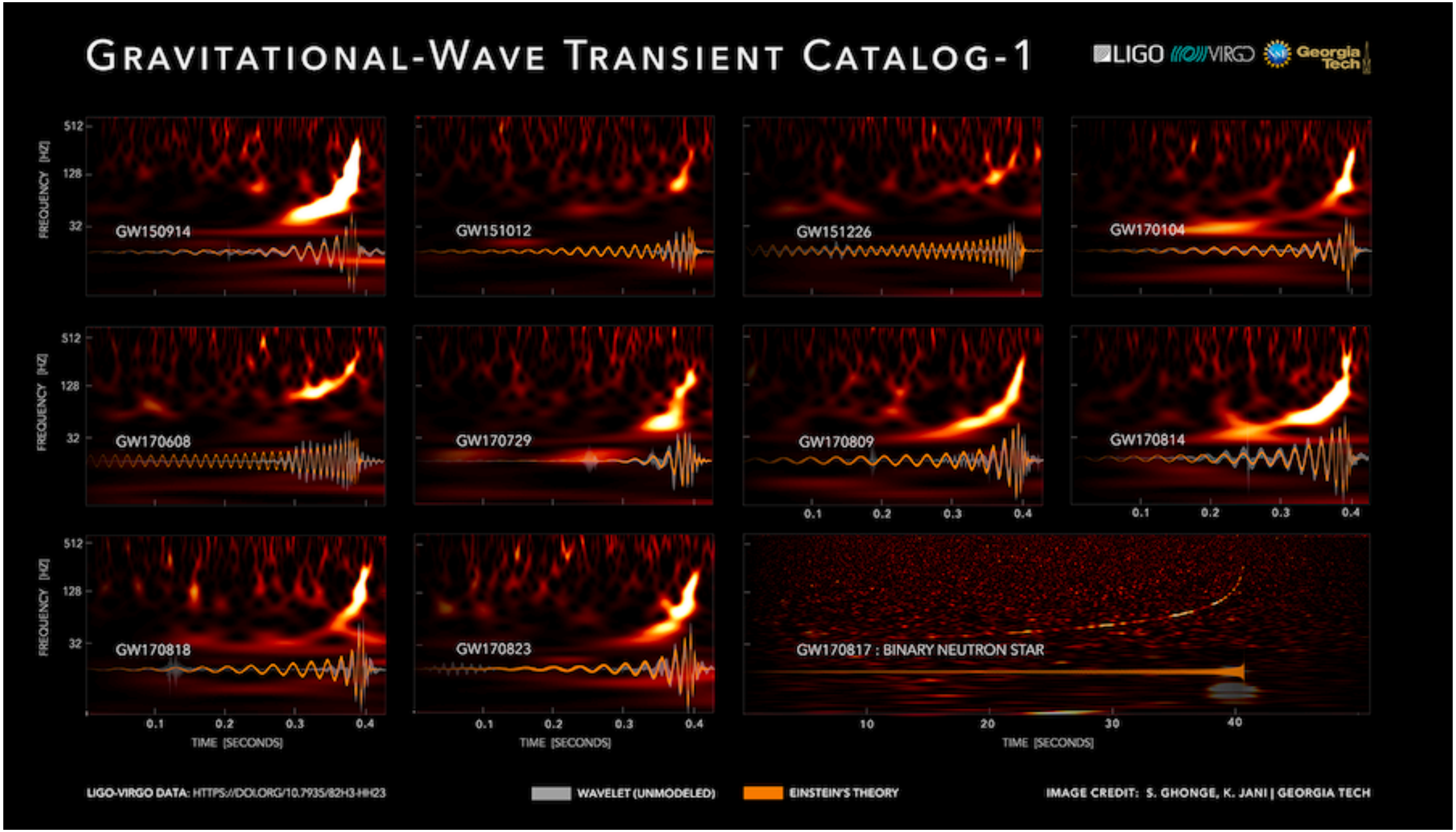
EM observations: Classification of Black holes



- Stellar-mass black holes: Black holes with mass < 100Msun
  - Produced due to supernova-core collapse of the massive star
  - Observed so far in X-ray, optical astronomy
- Supermassive mass black holes: Black holes with mass > 1 million Msun
  - Harbours at the centre of most of the galaxies and acts as engines of the galaxies
- Intermediate mass black holes: Black holes which fall in-between the two.
  - Indirect evidence of their existence in the EM astronomy
  - Direct observation of a black-hole with mass 142 Msun in GW window! **(Later in the talk)**

First two years of gravitational wave astronomy (Sept 2015- August 2017)

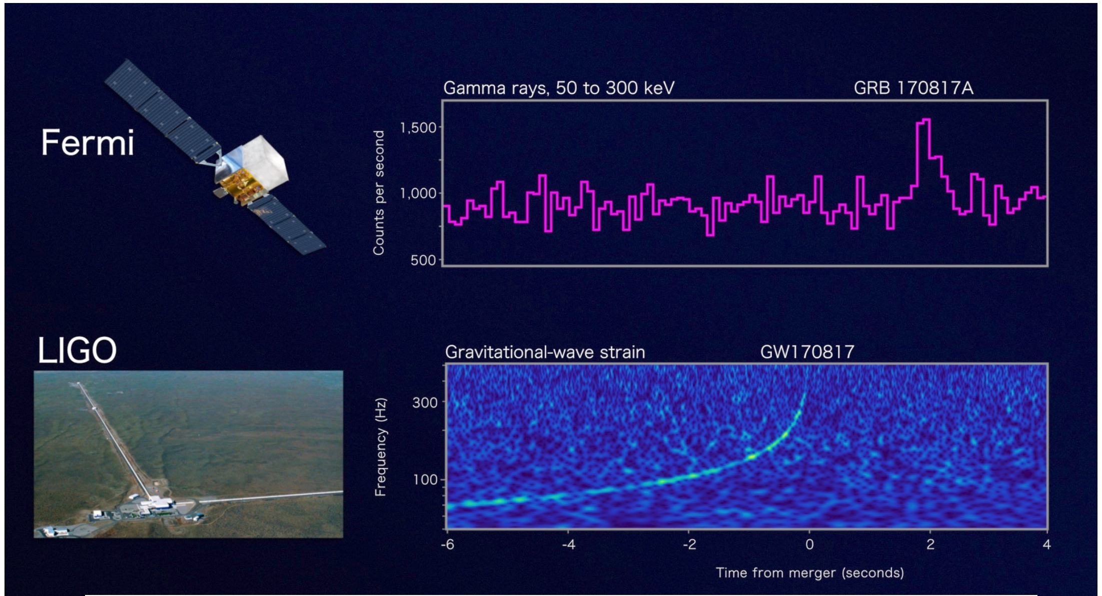
First two observing runs of Advanced LIGO and Virgo detectors

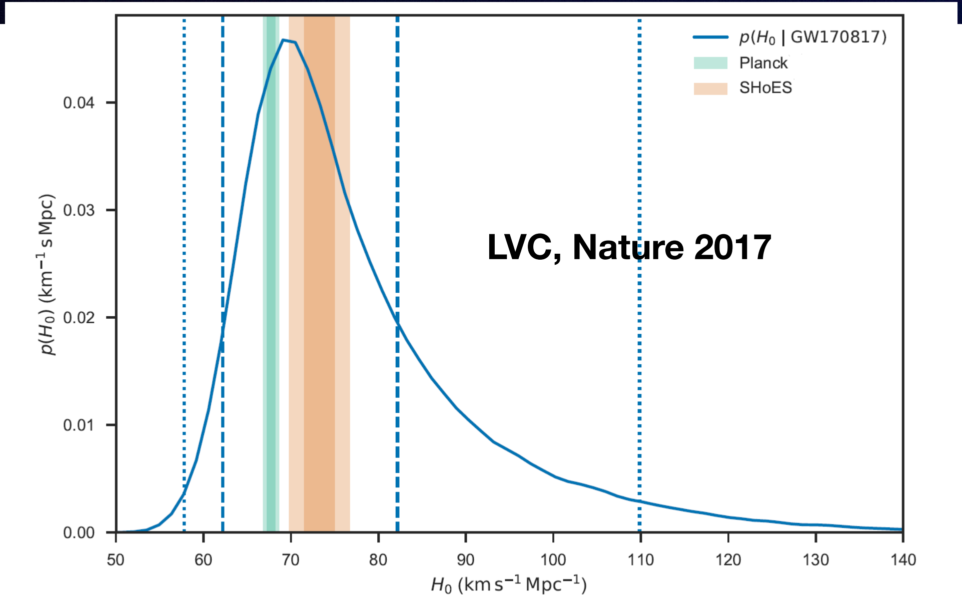


Result of first two observing runs of LIGO-Virgo detectors O1(Sept2015-Jan2016),O2(Nov2016-Aug2017):
Binary black holes 10 and Binary neutron star: 1

GW170817: the first binary NS merger

LVC, PRL 2017, LVC+EM, ApJL 2017





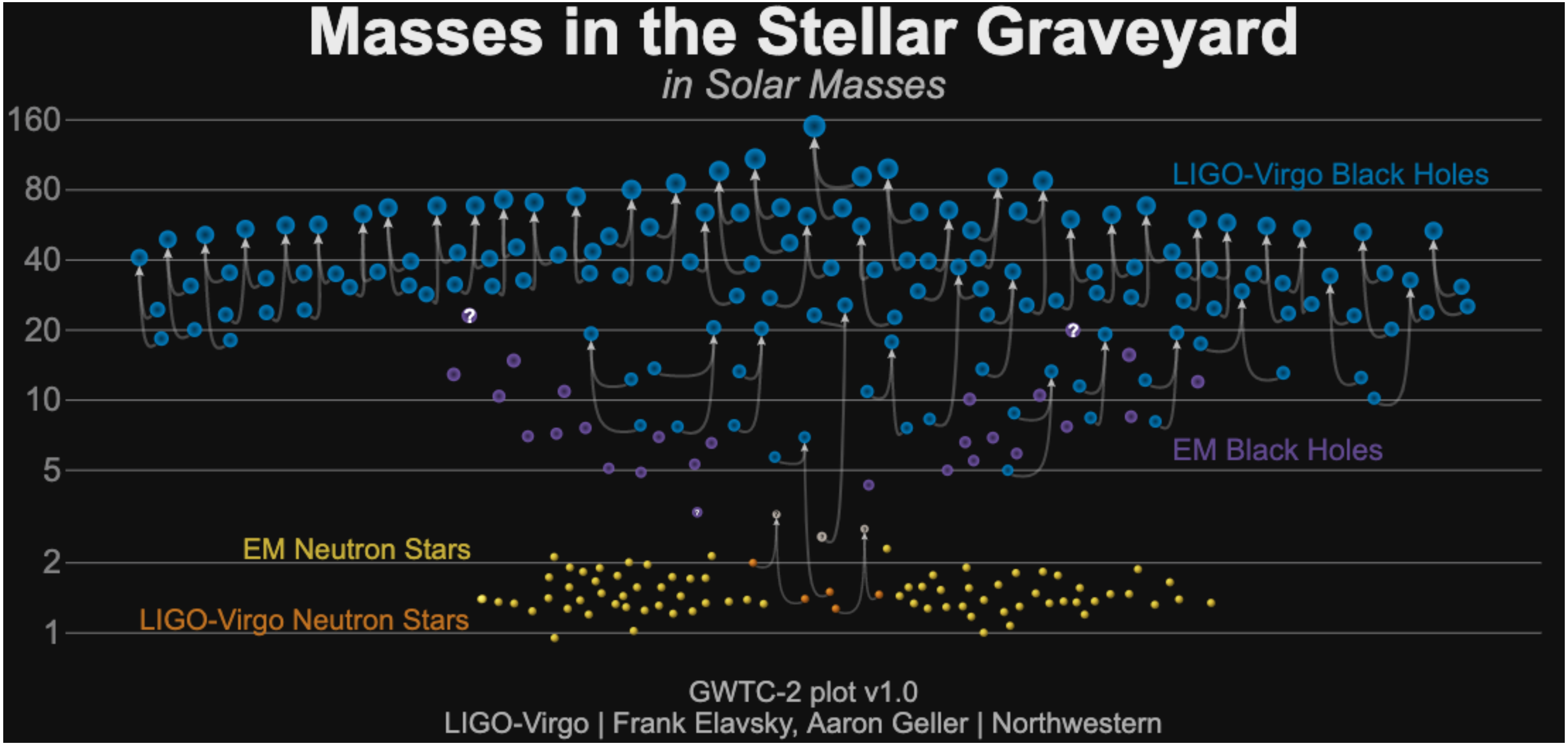
LVC, Nature 2017

- Jointly observed as binary NS merger event in GW window and short GRB in the EM telescopes
- Closest LIGO-Virgo compact binary merger event
- Closest observed short GRB event @40 Mpc
- Implications
    - Waveforms consistent with Einstein's GR
    - Equation of state constraints
    - Resolved short GRB progenitor puzzle
    - Independent estimation of Hubble's constant with the NGC4993 galaxy association
    - Constraint on the speed of gravitational waves

$$-3 \times 10^{-15} \leq \frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq 7 \times 10^{-16}$$

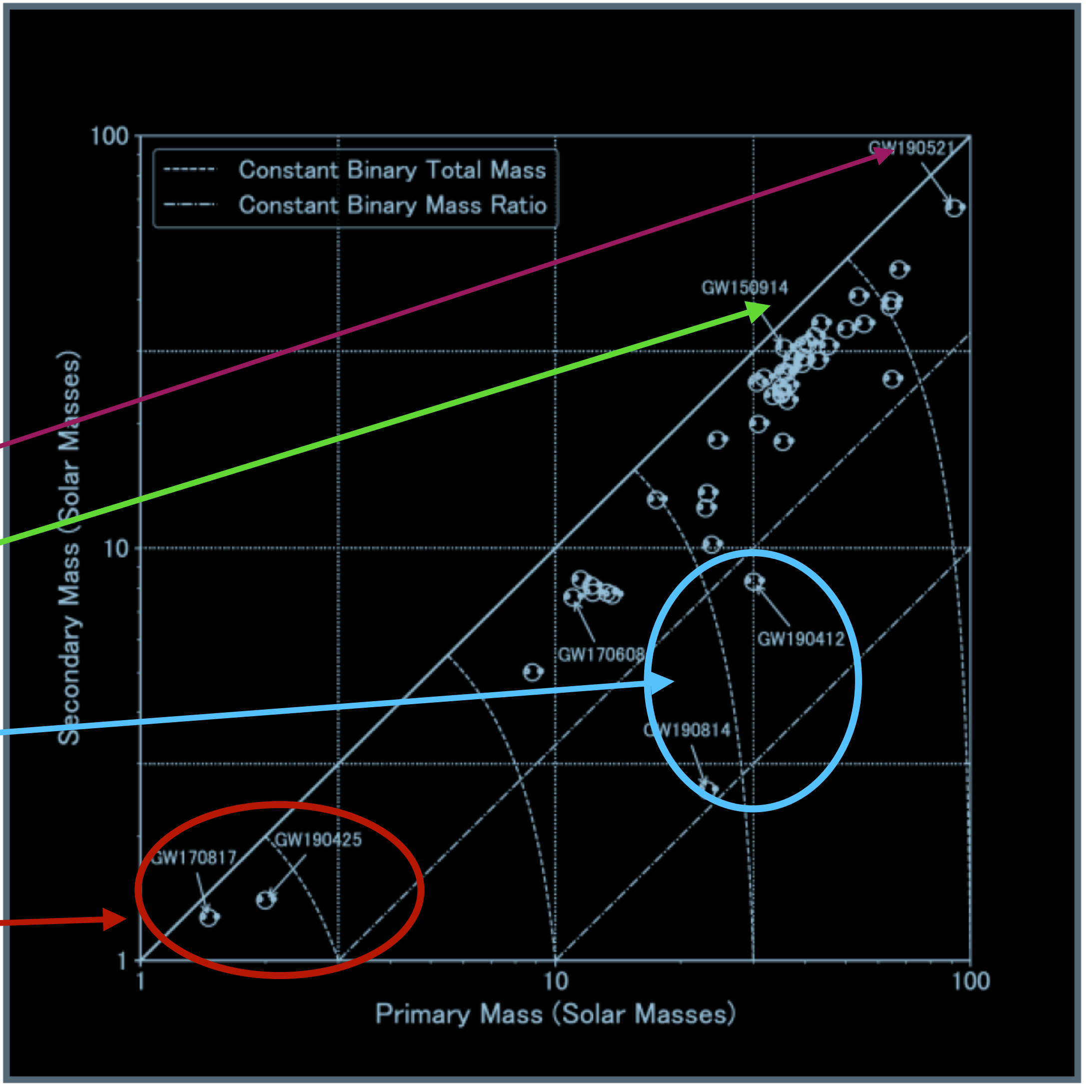
First Five years of gravitational wave astronomy!

Three observing runs of advanced detectors are complete


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Masses of the observed compact binaries

- Most of them are nearly equal mass systems.
- For a fixed total mass, GW signal from equal mass system is longer (louder) than un-equal mass systems.
- Most massive remnant: GW190521
- First GW detection : GW150914
- Two systems showed asymmetry : GW190814 and GW190412
- Binary NS : GW170817, GW190425



LVC, GWTC-2, PRL 2020,

LVC, ApJL 2020

GW190425: Heaviest NS observed so far

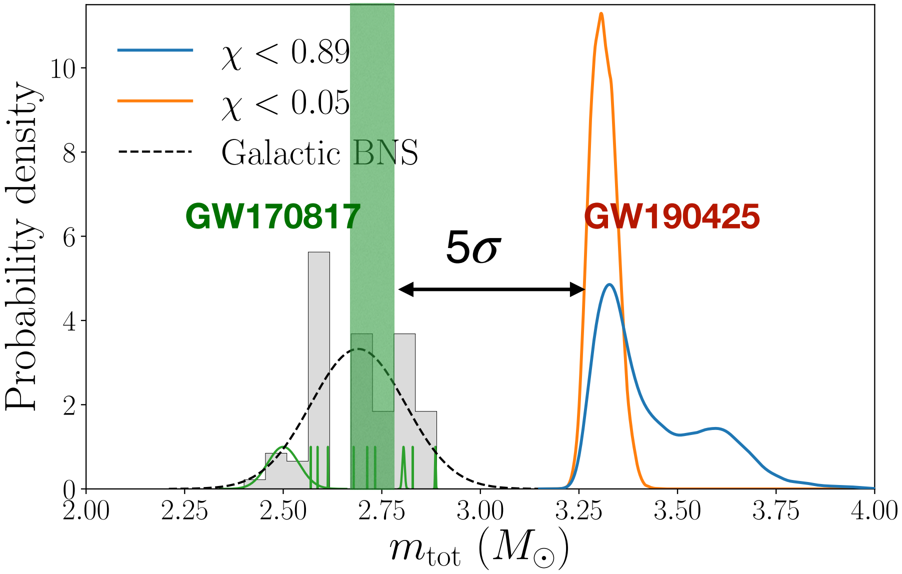
- Primary: 1.6-2.5 Msun — on the higher end. Most massive pulsar PSR 0740-6620 has mass 2.05-2.24 Msun

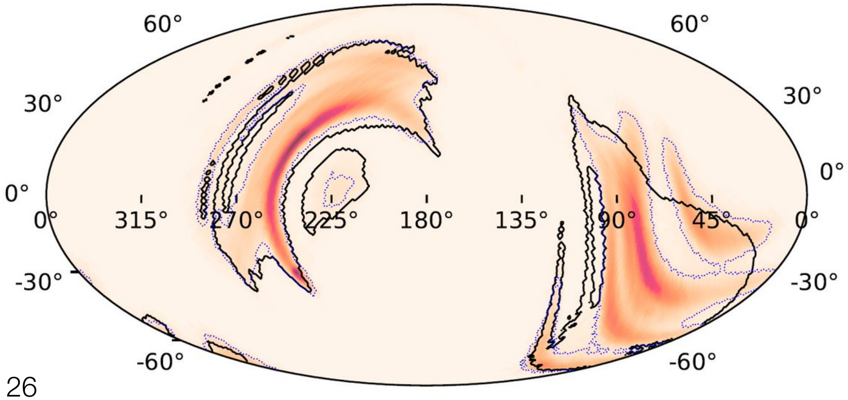
- Total mass: 3.3-3.7 Msun Heaviest system so far. Large deviation from the total mass distribution of the galactic NS binaries

- Large sky map 8000 sq. deg

- No confirmed EM and neutrinos detected, so far

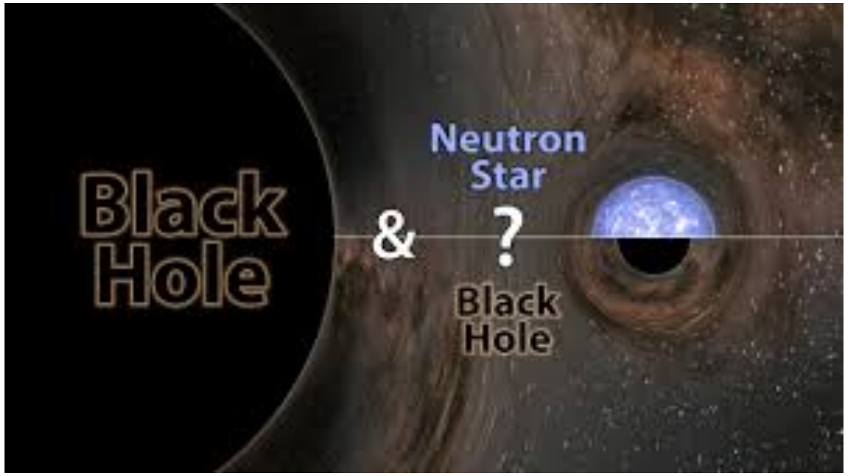
- Distance: 150 Mpc

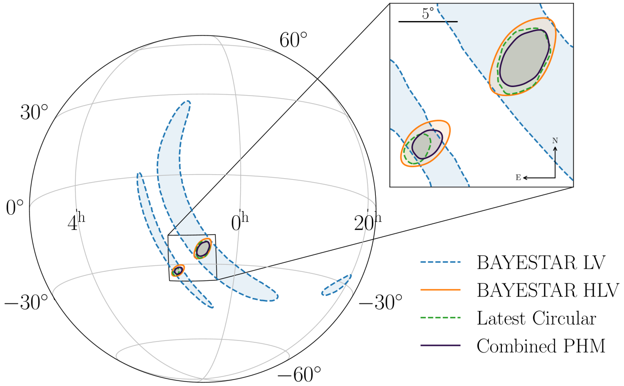




GW190814: Most asymmetric compact binary

- 23.2 Msun + 2.6Msun —> 25.6 Msun
- Secondary is either lightest BH/heaviest NS. Though no clear evidence of NS but can not be ruled out.
- Distance: 240 Mpc
- Raises important challenges on the compact binary formation scenarios
- Evidence of Higher order modes.
- Sky localisation of 20 square degrees — best sky-localised compact binary so far with no EM counterpart
- Implications: Obtain Hubble's constant using the galaxies in the sky-patch. Not so constraining given the single observation (More later)

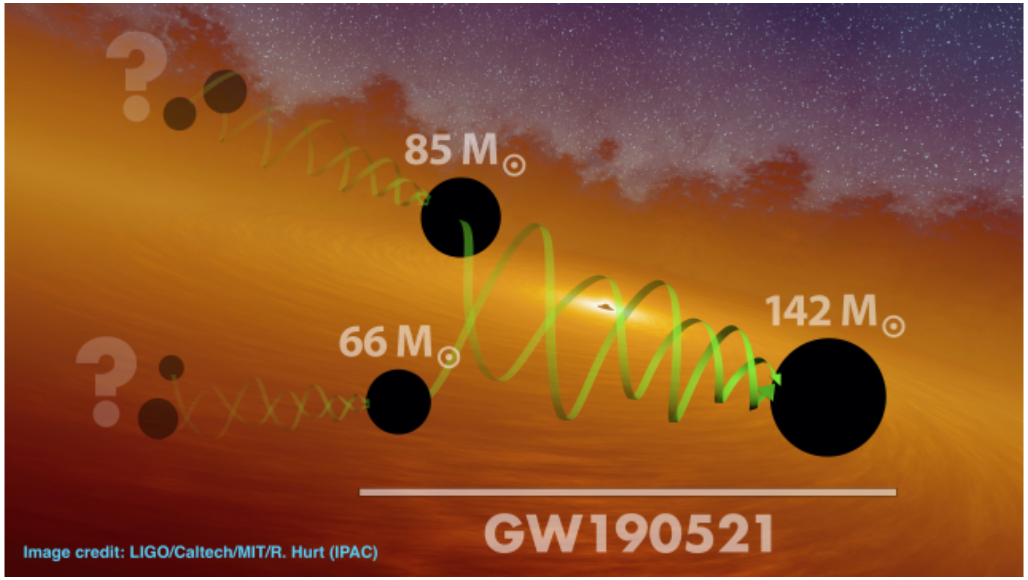




LVC, ApJ Lett. 896, 2 (2020)

GW190521: Most massive black hole binary so far!

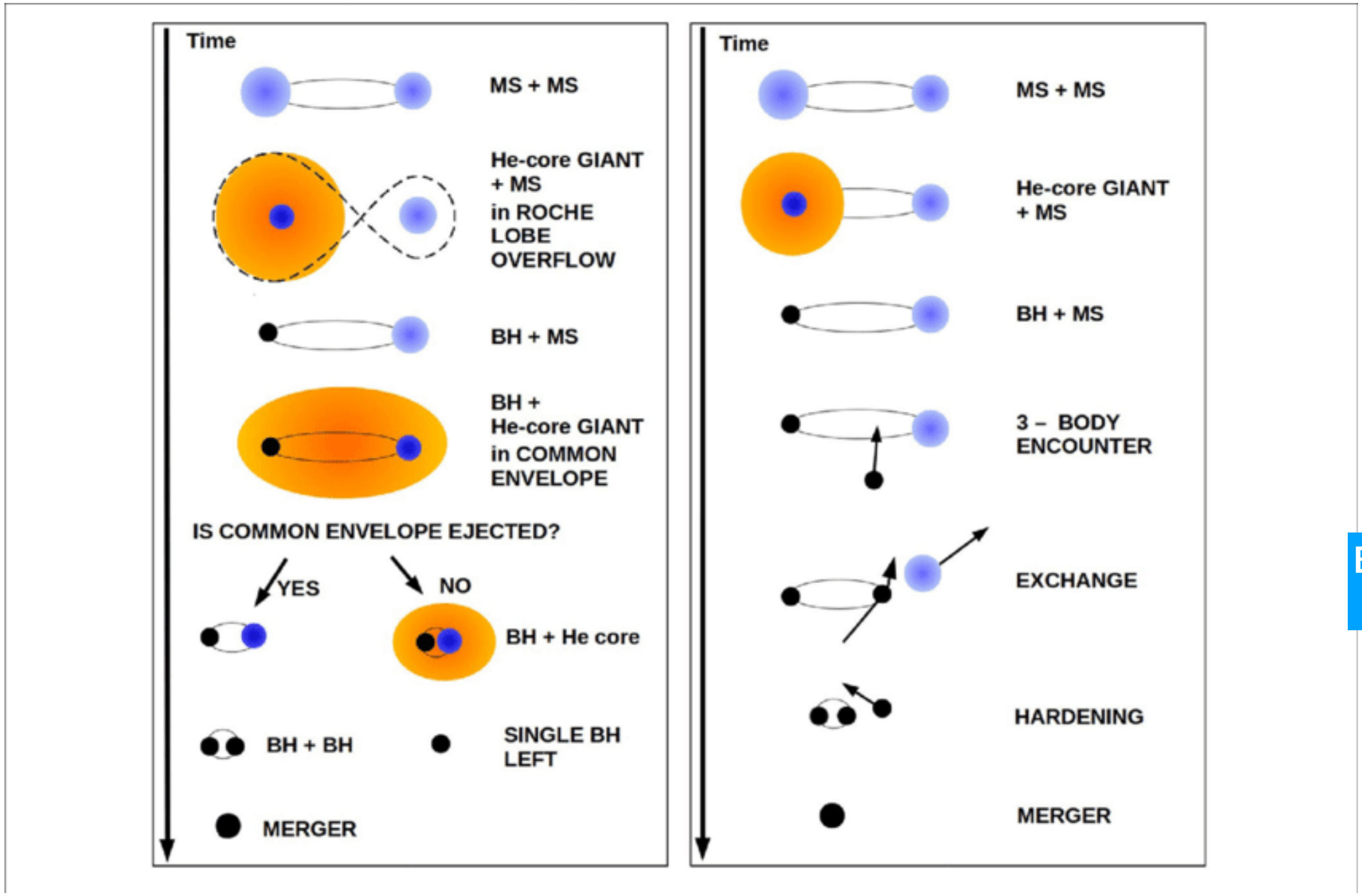
- Most massive stellar binary BBH system observed so far.
- Most distant GW source @ 5Gpc.
- Remnant mass is an IMBH (142 Msun).
- First direct evidence of existence of IMBH with mass below 1000 Msun.
- Possibility of massive black hole formation channel other than core collapse supernova

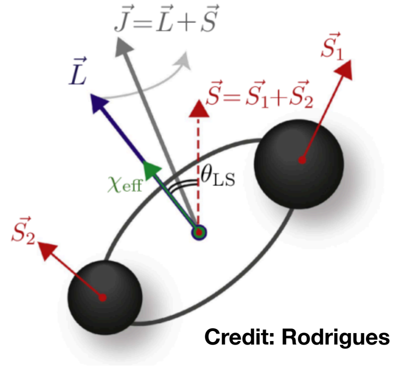


LVC, PRL 125, 101102(2020)

Black-hole binary formation

Isolated binary formation



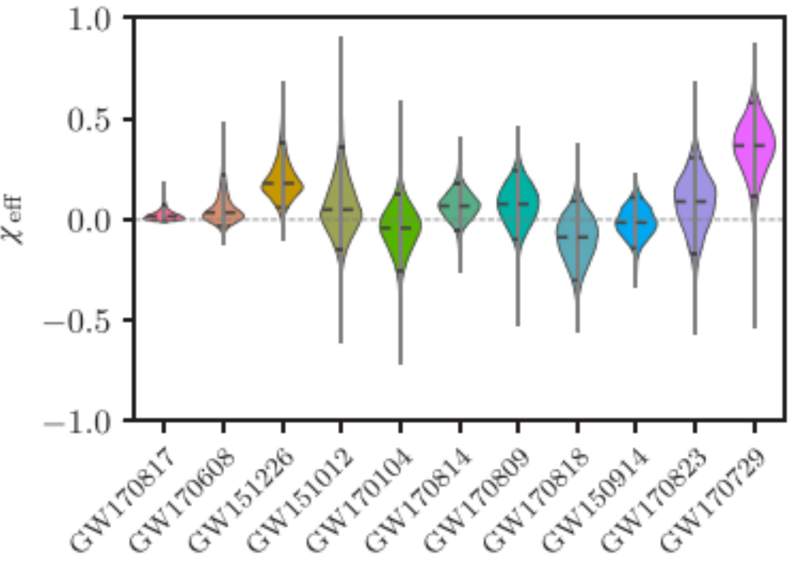


Credit: Rodrigues

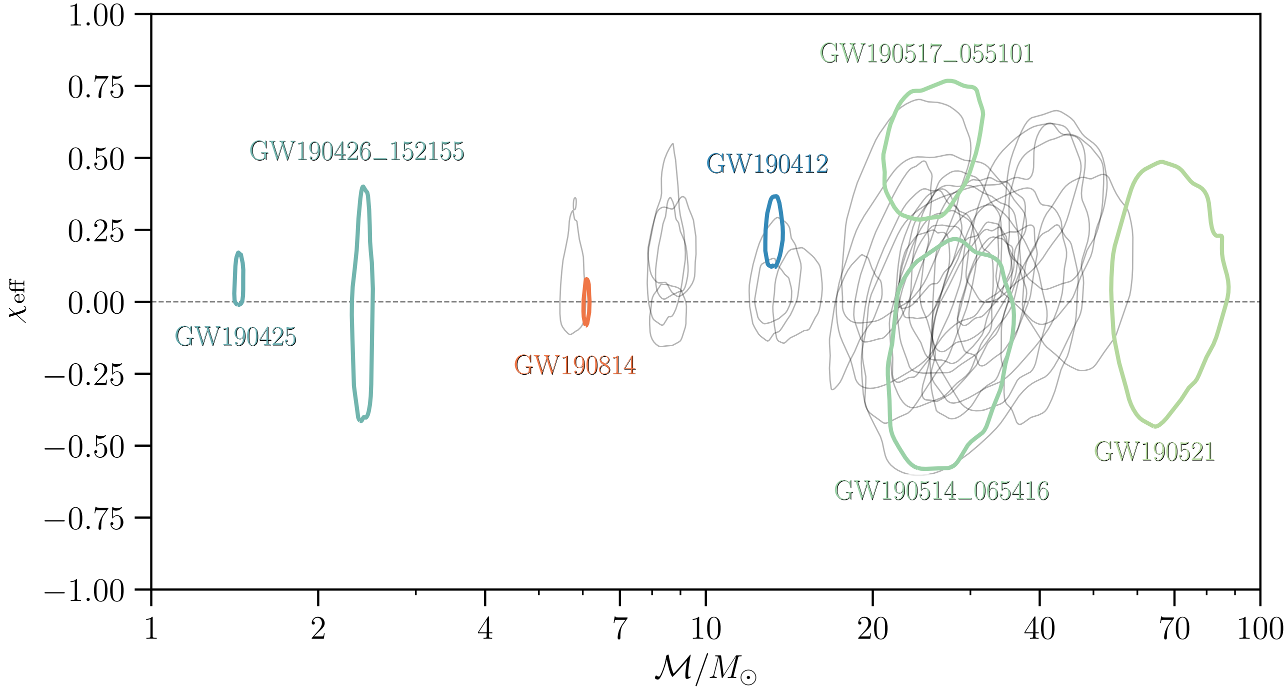
Binary in the crowded environment

Credit: Michela

Spins of the binary mergers



LVC, GWTC-1

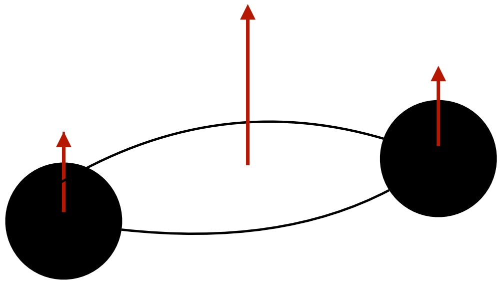


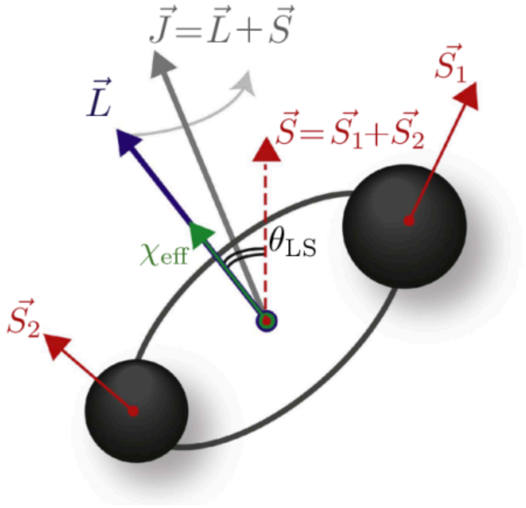
LVC, GWTC-2

- Most of them are nearly low spin, closed to small $\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M},$
- Few anti-aligned and some show precession e.g GW170729, GW190517_055101, GW190514_065416, GW190521

Observed black-hole binaries in GW astronomy

- Most of them are nearly equal mass systems.
- Most of them are aligned system.
- Isolated black-holes — Expected to be aligned
- Binaries formed in the crowded environment — Randomly oriented

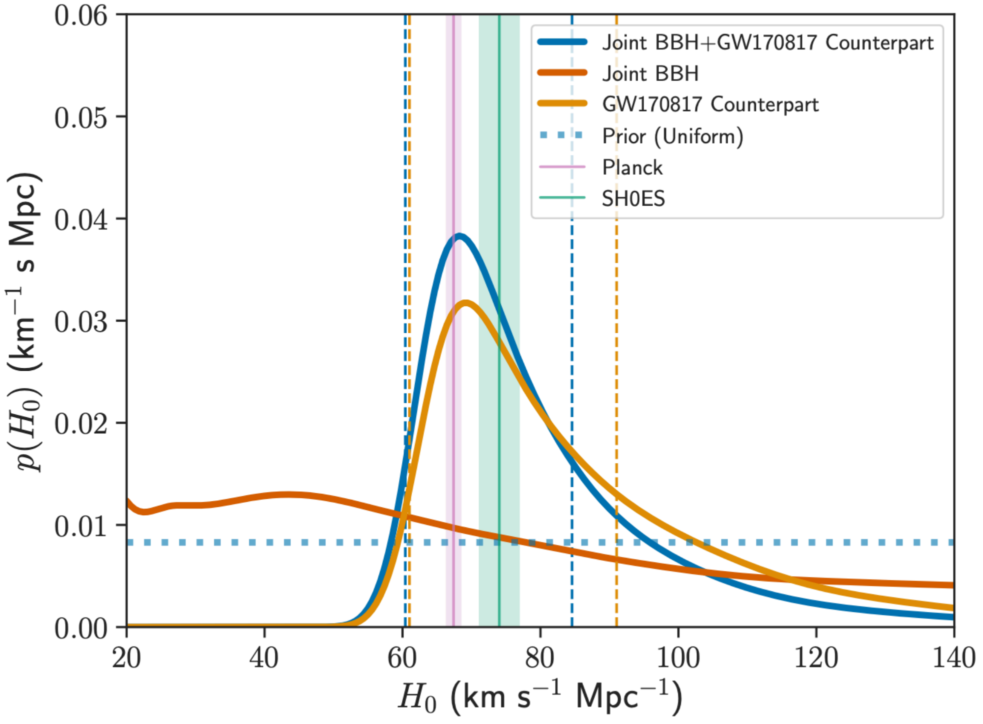




LVC, GWTC1, PRX 2019

Probing cosmology with GW observations

- Coalescing compact binary observations provide an independent measure of the Hubble's constant
- BNS observation in GW window (Luminosity distance measurement) + associated galaxy and redshift measurement —> Hubble's constant [Multi-messenger observation of GW170817]
- Improved sky location of binary BH system with the network + information of known galaxies in the sky-patch with redshift information —> Hubble constant estimate

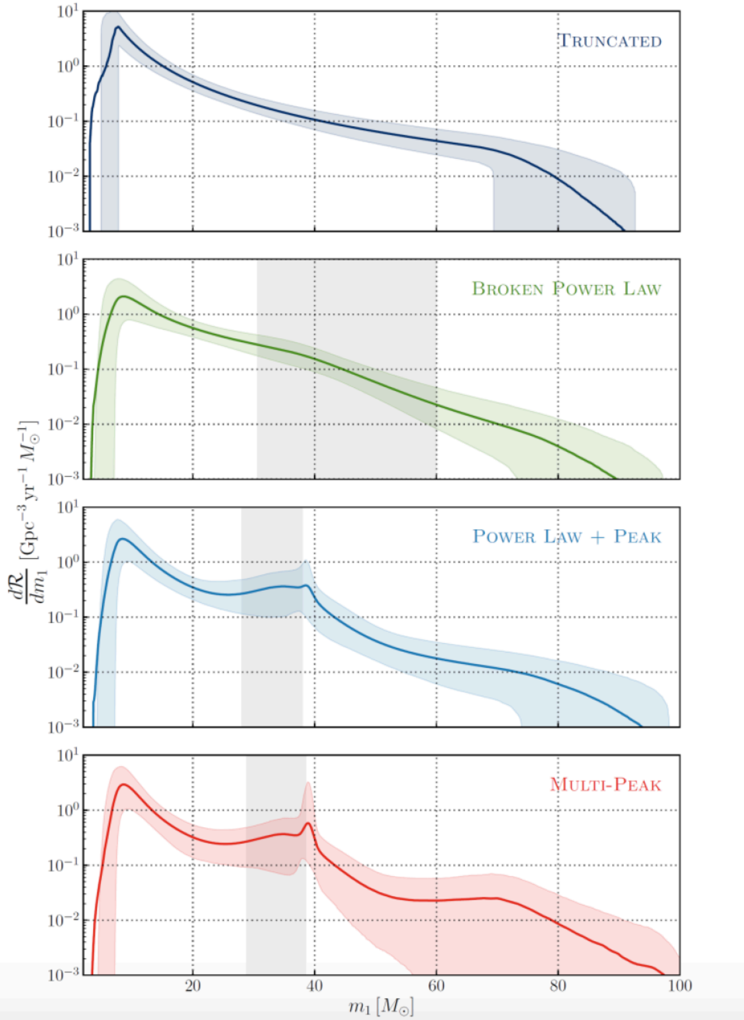


LVC, arXiv:1908.06060

Astrophysical merger rate estimates

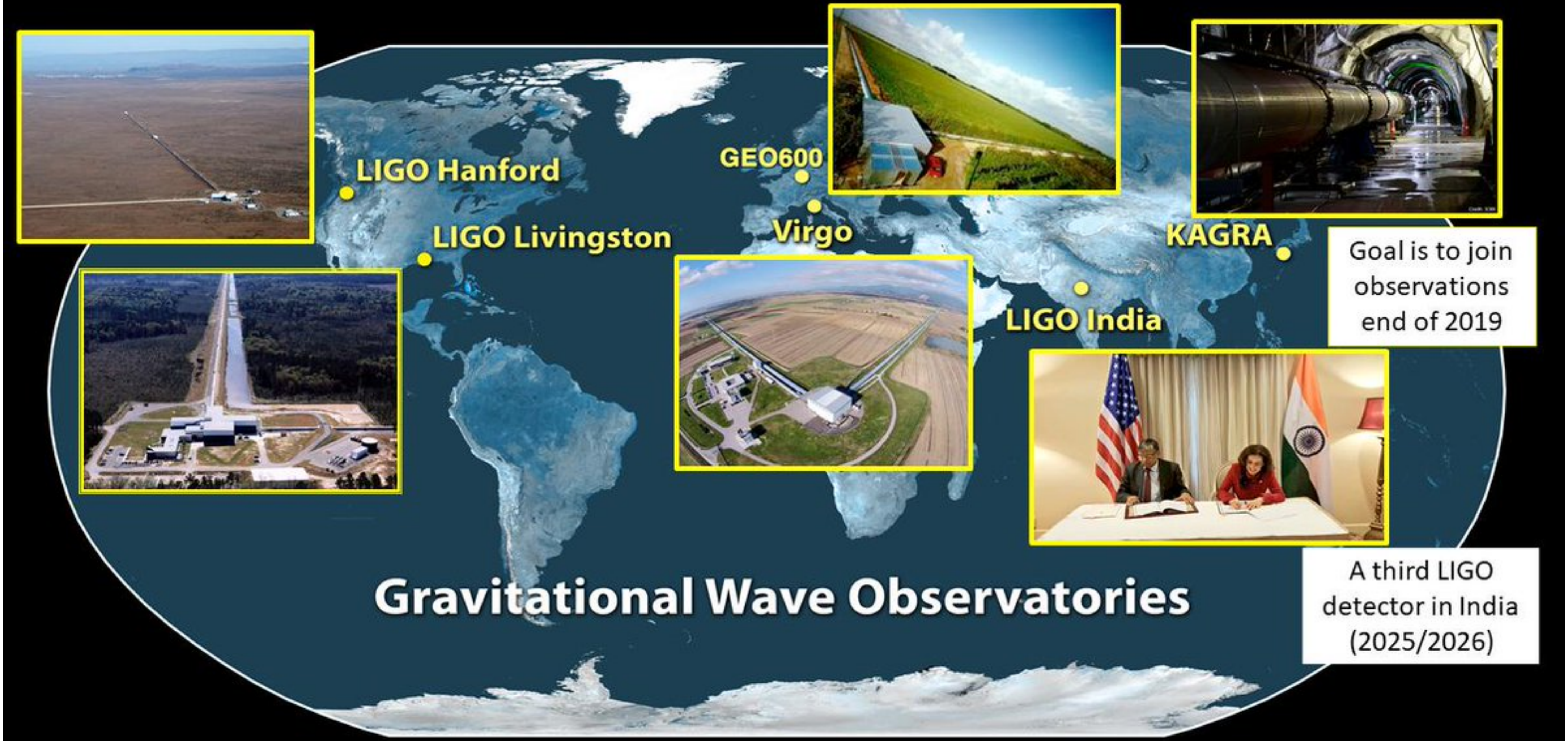
- Binary NS merger rate estimates $R_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- Consistent with the lower black hole mass gap of 2.6 Msun- 6 Msun
- The detections show evidence of distribution not following a simple power law — Need to account for massive black holes
- Models with peak in the distribution by incorporating Gaussian profile in addition to the power law is preferred by the data.
- Binary BH merger rate estimates

$$R_{\mathrm{BBH}} = 23.9^{+14.9}_{-8.6}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$



LVC, https://arxiv.org/abs/2010.14533

Gravitational Wave Observatories



Goal is to join
observations
end of 2019

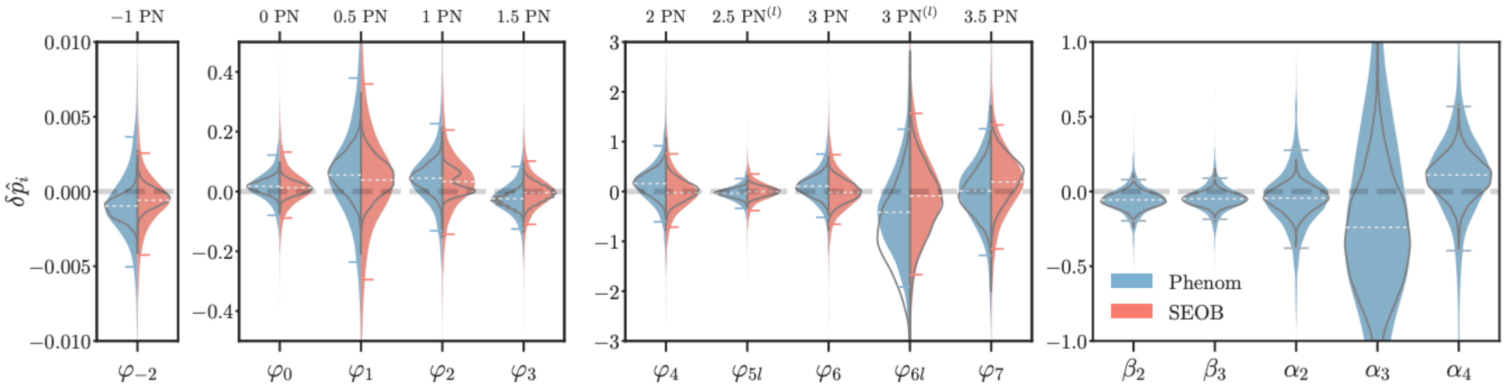
A third LIGO
detector in India
(2025/2026)

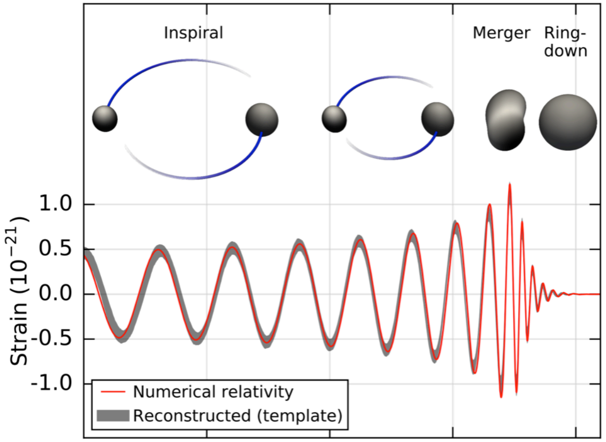
Thank you for attention

Stay tuned

List of resources:
Black hole hunter game — https://blackholehunter.org/
GW open science page —https://www.gw-openscience.org/about/
Open public alert: https://gracedb.ligo.org/superevents/public/O3/

Testing Einstein’s theory with observations





- Signatures of GR are embedded in the Gravitational wave signal.

- Deviations from GR can be captured by matching the data with the predicted GR signal.

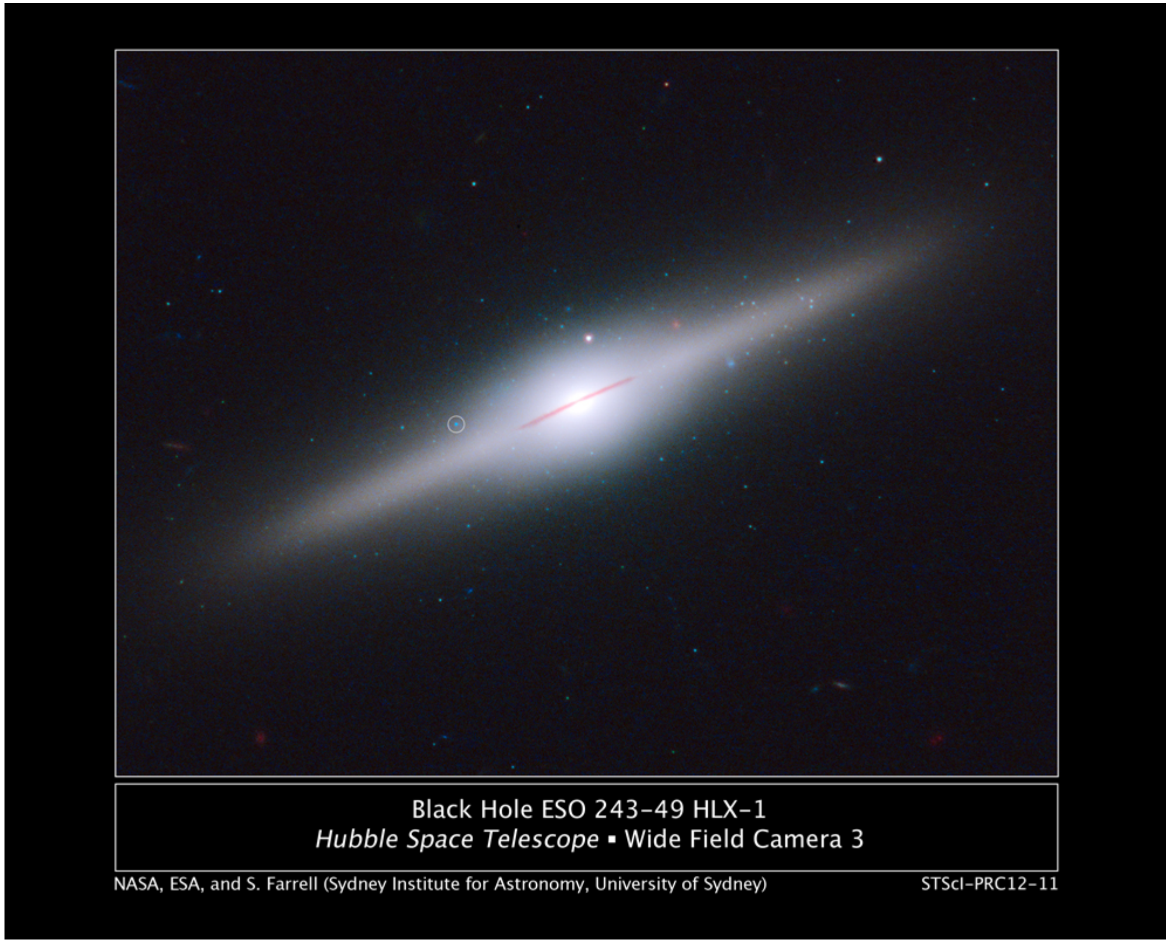
- Various parts of the signal are found to be consistent with GR.

- Observations are consistent with the Einstein’s GR.

LVC, PRD 100, 104036 (2019), LVC, ApJ Lett. (2017), LVC — GWTC-2

Intermediate mass black holes

- Black holes with mass > 100 Msun and mass below supermassive black holes
- IMBH candidates exists in X-ray astronomy
- HLX1: Most promising IMBH candidate
  - Power radiated $10^{32} Watts$ (million times that of our Sun)
  - Estimated mass ~ 100,000 Msun
- Direct observation of black hole with mass 142 Msun in gravitational wave window [Later in this talk]



Black Hole ESO 243-49 HLX-1

Hubble Space Telescope ▪ Wide Field Camera 3

NASA, ESA, and S. Farrell (Sydney Institute for Astronomy, University of Sydney)

STScI-PRC12-11