Significance of the detection of a gravitational wave signal from a binary black hole merger

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IMPAN and NCBJ

Contents

- Gravitational waves and black holes
- Gravitational wave detectors
- Gravitational wave data analysis
- Gravitational waves from a binary black hole merger
- Astrophysical significance
- Exotic scenarios (unlikely!)

Some references to contributions from Polish scientists scattered throughout the talk

Gravitational waves

(solutions of Einstein's equations)

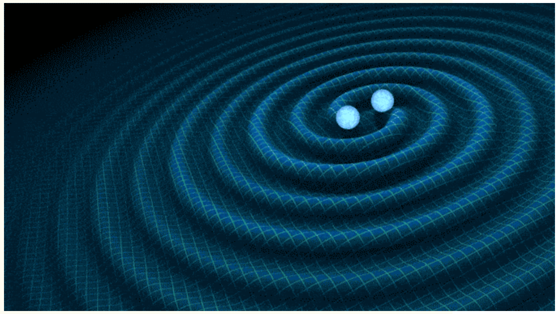
$$\boxed{G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}}$$

Linearized E. eqs. (Einstein 1916):
$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

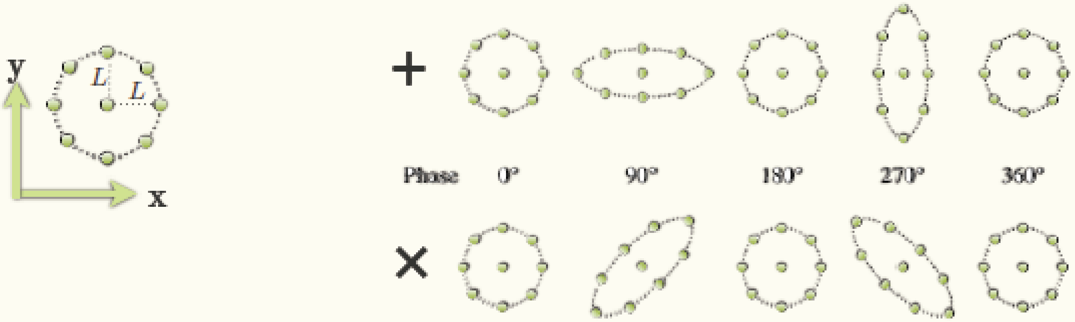
$$\Box \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} T_{\mu\nu}$$

Einstein equations are a set of quasilinear partial equations of the second order for metric components $g_{\mu\nu}$

- **General relativity predicts gravitational waves as propagating oscillations of spacetime:**
  - » Propagate at the speed of light.
  - » Generated by quadrupolar mass movements: $h_{jk} = \frac{G}{c^4}\frac{2}{r}\frac{\mathrm{d}^2}{\mathrm{d}t^2}Q_{jk}$
  - » Two transverse polarizations: "+" and "x".



- **Ring of free particles**
  - » Responding to GW propagating along z-axis:



» Gravitational wave acts as a strain: $h \approx 2\Delta L/L$

Gravitational waves in GR

„The Big Four”: H. Bondi, F. Pirani, R. Sachs, A. Trautman showed in the 50ties and 60ties that Einstein’s equations admit gravitational radiation.

A significant role in understanding of gravitatioanal radiation and its measurability played discussions at the conference in Chapel Hill, 18-23 January 1957 (**GR1**).

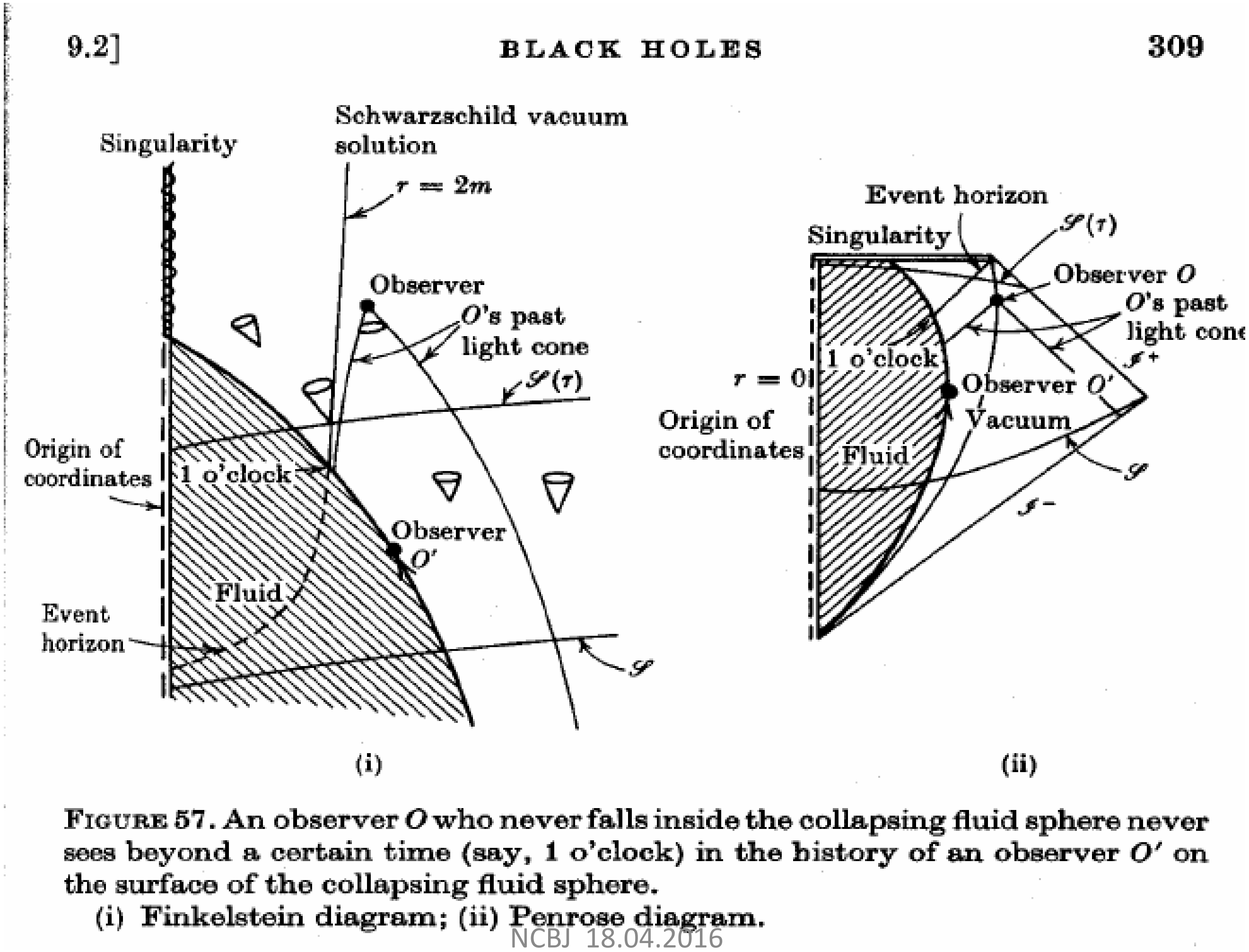
Pirani: *“By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor”.*

Pirani, F.A.E.: *On the physical significance of the Riemann tensor*. Acta Phys. Polon. 15, 389 (1956)

Gravitational collapse

Hawking & Ellis, *The large scale structure of space-time*, CUP, 1972

$\Omega^2 g$

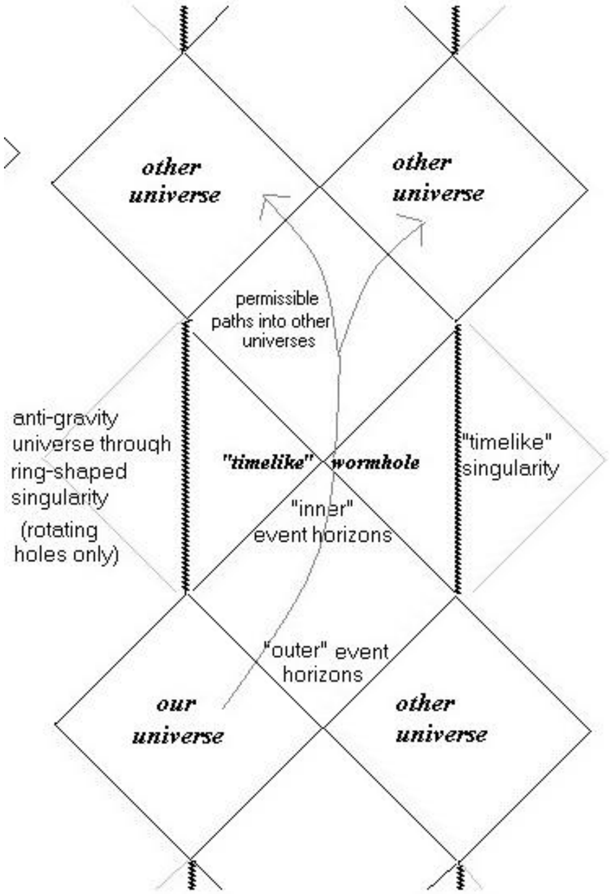


9.2] BLACK HOLES 309

FIGURE 57. An observer O who never falls inside the collapsing fluid sphere never sees beyond a certain time (say, 1 o'clock) in the history of an observer O' on the surface of the collapsing fluid sphere.
(i) Finkelstein diagram; (ii) Penrose diagram.

Black holes

ELECTRICALLY CHARGED
AND/OR ROTATING WORMHOLE



Black hole uniquenes and „no-hair" theorems (conjectures)

Kerr space time is the unique stationary black hole and black hole is characterized by only two parameters – mass (m) and spin (a)

BH merger and GWs

Area of the event horizon

$$\partial B = 8\pi m(m+(m^2-a^2)^{1/2})^{1/2}$$

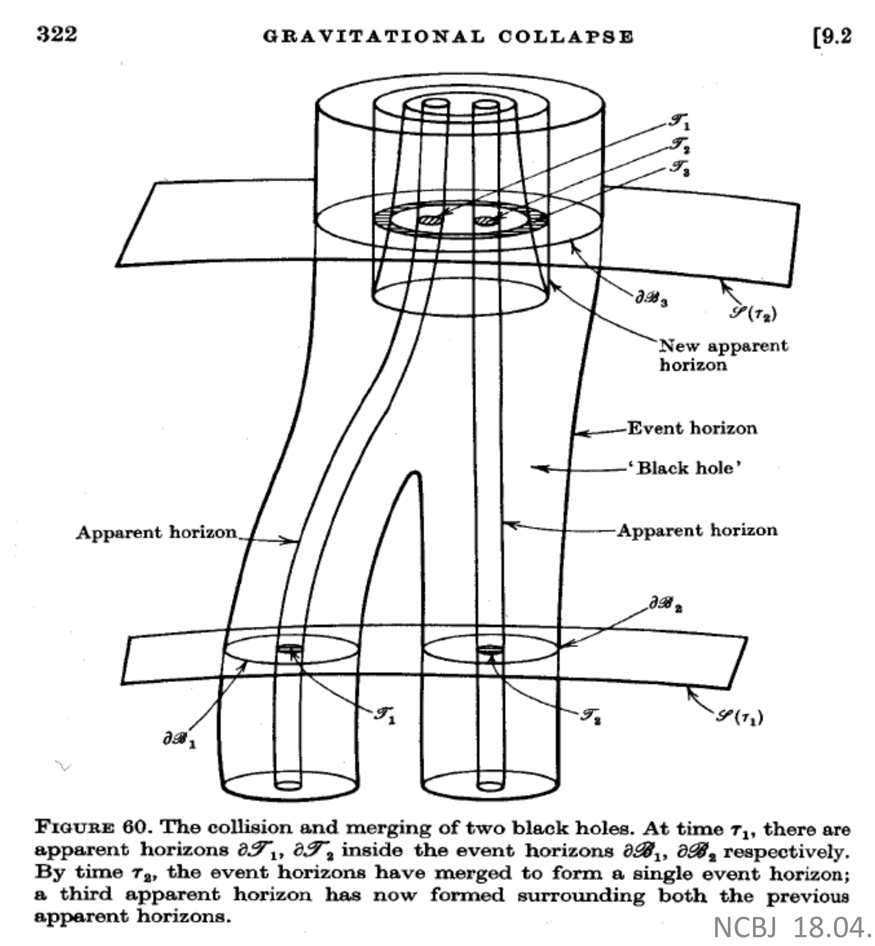


FIGURE 60. The collision and merging of two black holes. At time τ_1, there are apparent horizons $\partial\mathcal{T}_1$, $\partial\mathcal{T}_2$ inside the event horizons $\partial\mathcal{B}_1$, $\partial\mathcal{B}_2$ respectively. By time τ_2, the event horizons have merged to form a single event horizon; a third apparent horizon has now formed surrounding both the previous apparent horizons.

Efficiency for GW radiation using area theorem

$$\varepsilon_{GW} < 1/2$$

$$\varepsilon_{GW} < 1-1/\sqrt{2} \quad (\mathrm{dla\ a} = 0)$$

Back of envelope calculation

$$E_{GW} \approx (m_1+m_2)c^2 - Gm_1m_2/(2r),$$

$$r \approx 5GM/c^2$$

$$\varepsilon_{GW} \approx 1/30$$

Numerical relativity (inspiral + merger)

$$\varepsilon_{GW} \approx 1/20$$

Tests of GR using double pulsar PSR J0737–3039A/B

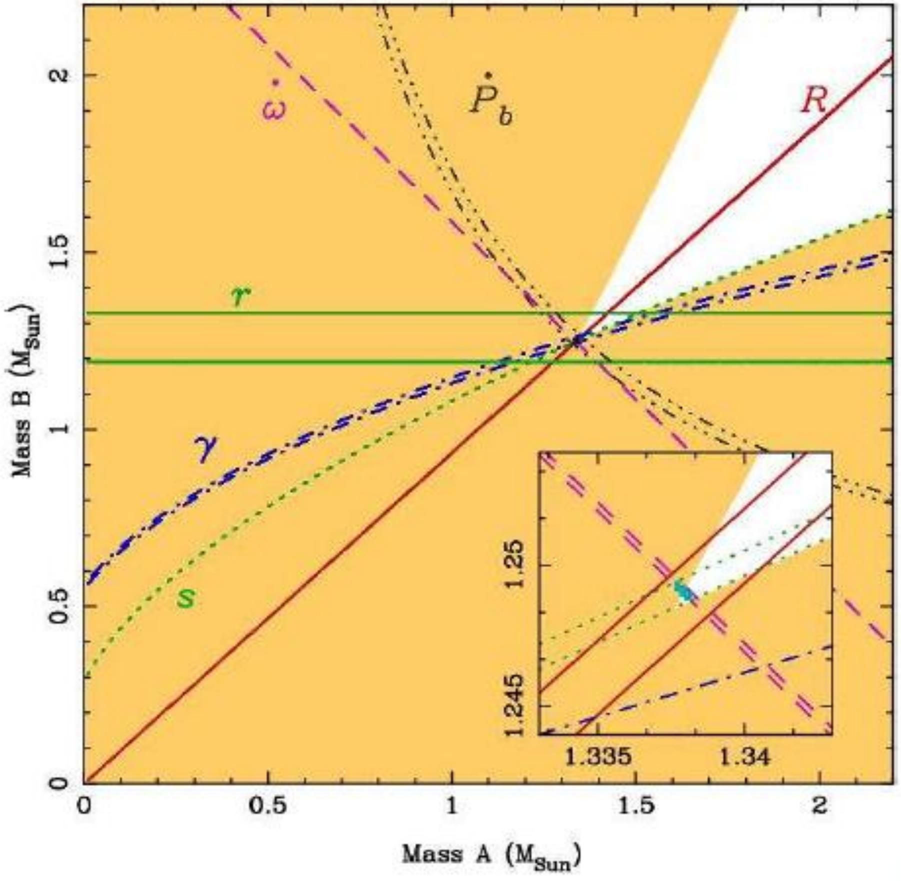


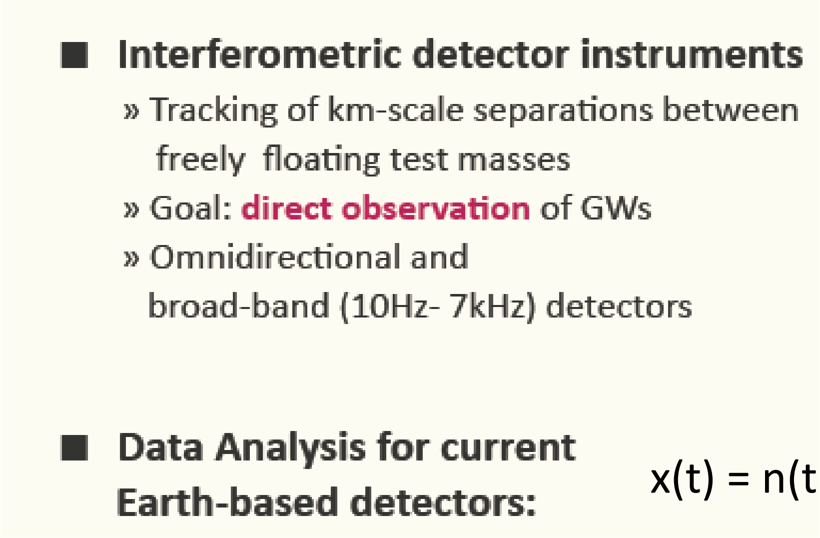
Fig. 1

Post-Keplerian (PK) parameters

ω˙ - relativistic precession of the orbit
γ - gravitational redshift and time dilation
˙Pb - decrease in orbital period due to the emission of gravitational waves.

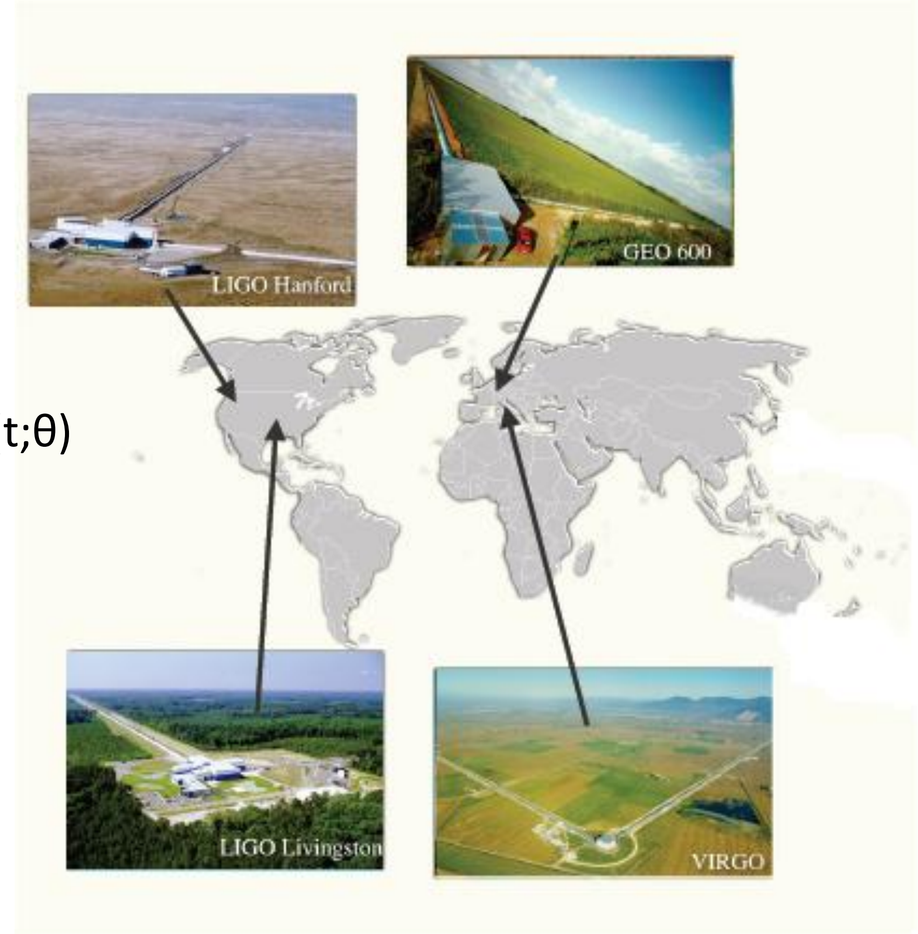
s and **r** - Shapiro delay
(delay that is added to the pulse arrival times when propagating
through the curved space-time near the companion)

Worldwide detector network



- **Interferometric detector instruments**
  - » Tracking of km-scale separations between freely floating test masses
  - » Goal: **direct observation** of GWs
  - » Omnidirectional and broad-band (10Hz- 7kHz) detectors
- **Data Analysis for current Earth-based detectors:**

$x(t) = n(t) + s(t;\theta)$



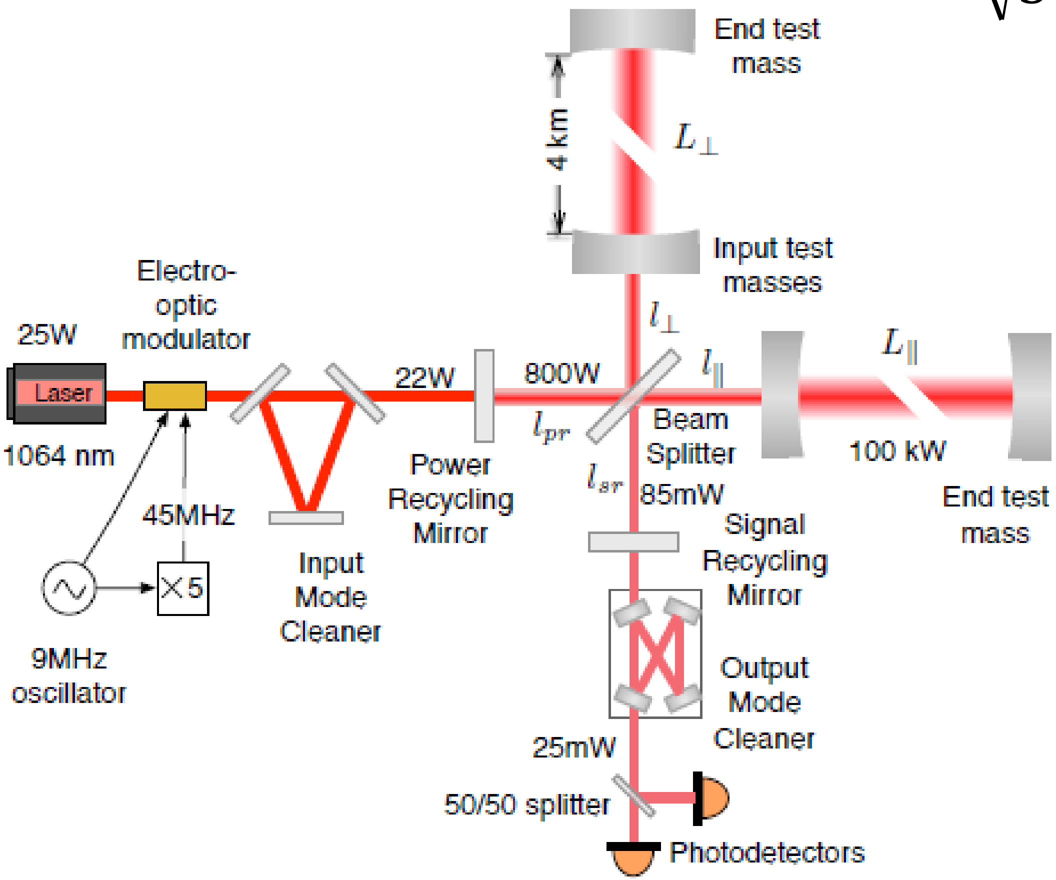
>>Impulse signals - Supernovae (SN)

>>Chirp signals - NSNS, NSBH, BHBH binaries

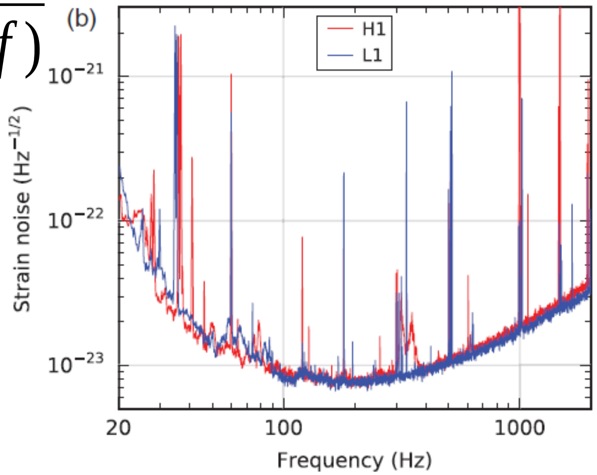
>>Stochastic signals – early Universe

>>Periodic signals – Neutron stars (NS)

Laser interferometric detector



$\sqrt{S(f)}$



Layout of an Advanced LIGO detector.
The annotations show the optical power in use during O1.

Signal detection in noise

Fundamental lemma of Neyman and Pearson:

Test that maximizes probability of detection subject to fixed false alarm probability is likelihood ratio test

J. Neyman & E. Pearson,
Phil. Trans. Roy. Soc. Ser. A, 231:289-337,1933

Likelihood ratio

N-P test: Compare $\Lambda = p_1(x)/p_0(x)$ to a threshold

additive noise: $x(t) = n(t) + s(t)$

Gaussianity: $\ln\Lambda = (x|s) - \frac{1}{2}(s|s)$

Matched filter

statationarity:

$$(x|s) = 4\Re\int_0^\infty \frac{\tilde{x}(f)\tilde{s}^*(f)}{S(f)}df$$

Spectral density of noise

Parameter estimation

Maximum likelihood estimation

$$\frac{\partial \log \Lambda(\theta | x)}{\partial \theta} = 0$$

→ Maximum likelihood estimators

Bayesian estimation

Posterior Prior

Bayes theorem

$$p(\theta | x) = \frac{p(x,\theta)}{p(x)} \pi(\theta)$$

A posteriori distribution of parameter θ_1

$$p(\theta_1 | x) = \iiint \frac{p(x,\theta_1,\theta_2,\theta_3,\theta_4)}{p(x)} \pi(\theta_1,\theta_2,\theta_3,\theta_4) d\,\theta_2\, d\,\theta_3\, d\,\theta_4$$

GW from a binary system in quadrupole appriximation

Chirp mass

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

$$h_{CB} = 1.0\times10^{-21}\left(\frac{M_c}{31.6Ms}\right)^{5/3}\left(\frac{f_{GW}}{100Hz}\right)^{2/3}\left(\frac{410Mpc}{r}\right)$$

Evolution time

$$\tau_{\mathrm{GW}} = 46.8\mathrm{ms}\left(\frac{M_c}{31.6Ms}\right)^{-5/3}\left(\frac{f_{GW}}{100Hz}\right)^{-8/3}$$

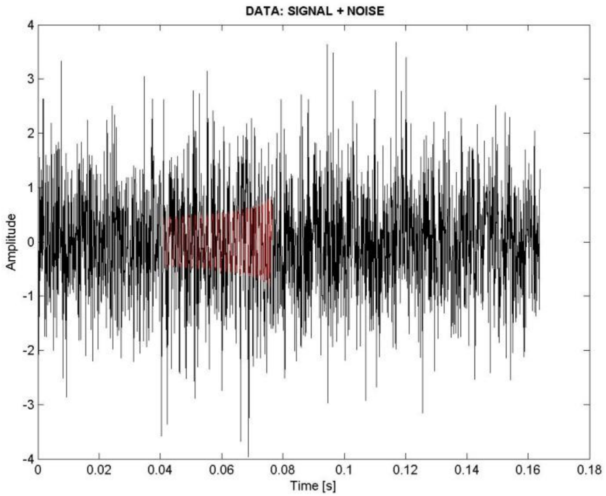
Fourier transform

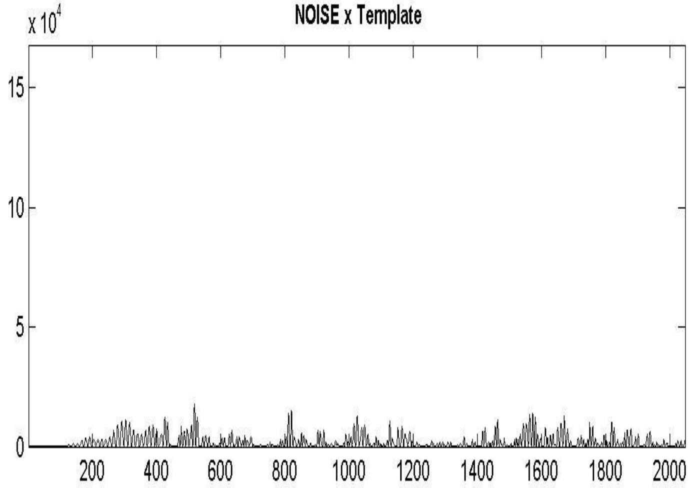
$$\overline{h}_{CB} = 1.4\times10^{-23}\left(\frac{M_c}{31.6Ms}\right)^{5/6}\left(\frac{f_{GW}}{100Hz}\right)^{-7/6}\left(\frac{410Mpc}{r}\right)$$

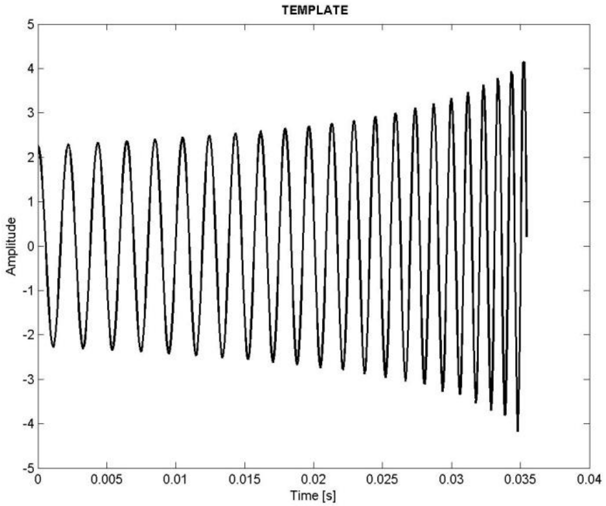
Innermost stable circular orbit

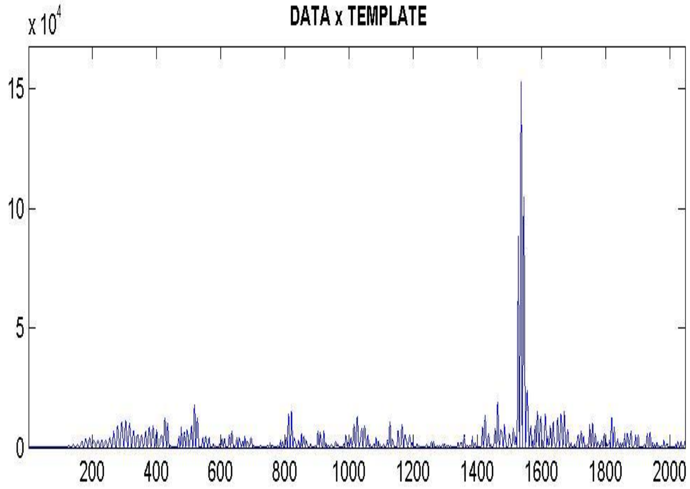
$$f_{\mathrm{isco}} = 116\mathrm{Hz}\left(\frac{m_1+m_2}{65\,Ms}\right)^{-1}$$

Matched Filter – the key





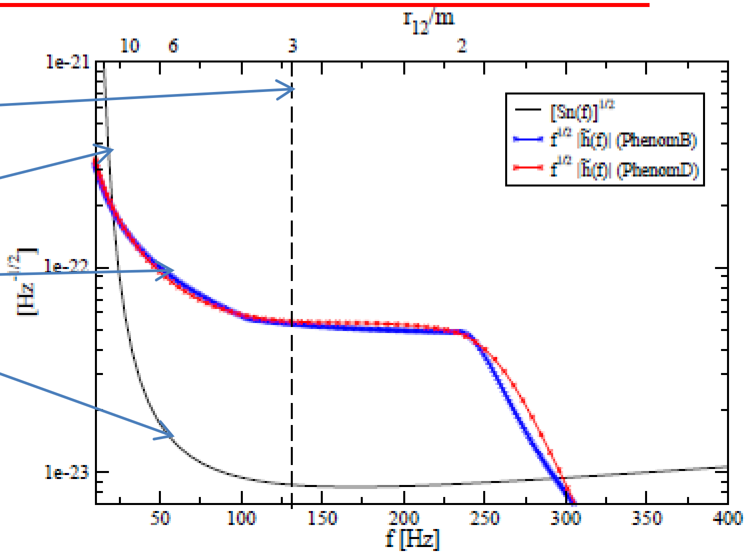




Signal-to-noise ratio and Fisher matrix

K.S. Thorne ~1985, unpublished notes: NS&BH binaries best detectable not SN !!!

$$SNR^2 \sim \frac{M_c^{5/3}}{r^2}\int_{fc}^{fisco}\frac{1}{f^{7/3}S(f)}df$$



arXiv:1603.08955

A. Krolak & B.F.Schutz (1987), A. Krolak (1989):
Postnewtonian (PN) corrections detectable

Fisher matrix

$$\Gamma_{ij} = E\left[\frac{\partial \ln \Lambda}{\partial \theta_i}\frac{\partial \ln \Lambda}{\partial \theta_j}\right]$$

Cramer-Rao bound states that for unbiased estimators the covariance matrix C≥Γ^{-1}

Introduced to GWDA: A. Krolak, GR12, 1989,
A.Krolak et al. 1990, unpublished

A. Krolak et al. 1996:
detctability of PN effects, eccentricity and alternative theories of gravity

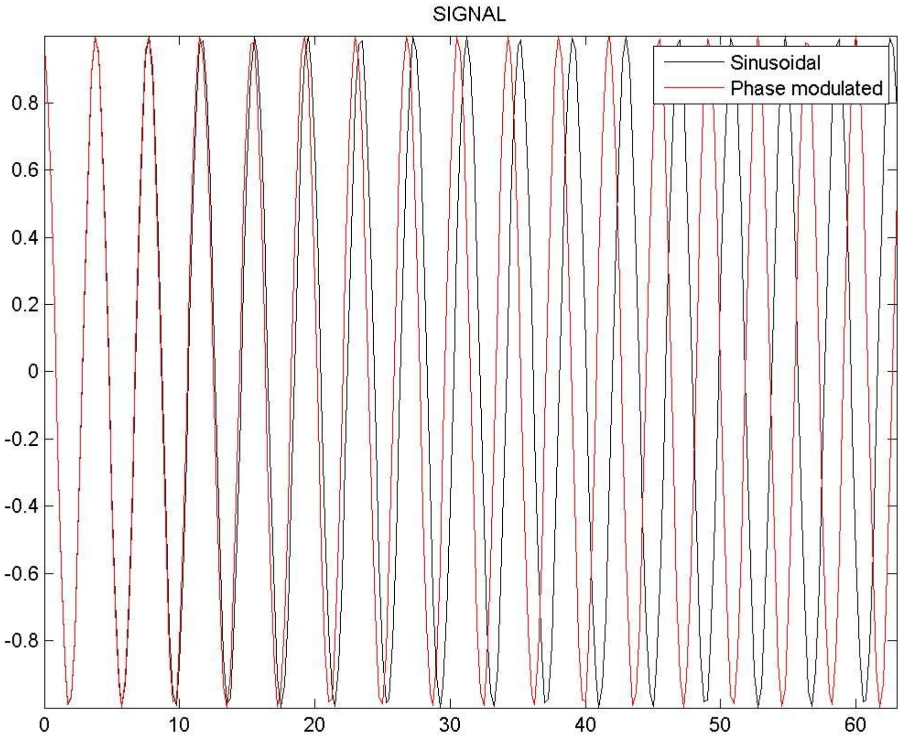
Matched filter sensitivity

Cutler, C., Apostolatos, T.A., Bildsten, L., Finn, L.S., Flanagan, ´E.´E., Kennefick, D., Markovic, D.M., Ori, A., Poisson, E., Sussman, G.J., and Thorne, K.S., *The last three minutes: Issues in gravitational-wave measurements of coalescing compact binaries*, *Phys. Rev. Lett.*, **70, 2984–2987, (1993).**

Matched filter sensitive to small effects in phase like post-Newtonian corrections

BH binaries maybe detected first:

Flanagan, E. E., & Hughes, S. A. 1998, Phys. Rev., D57, 4535



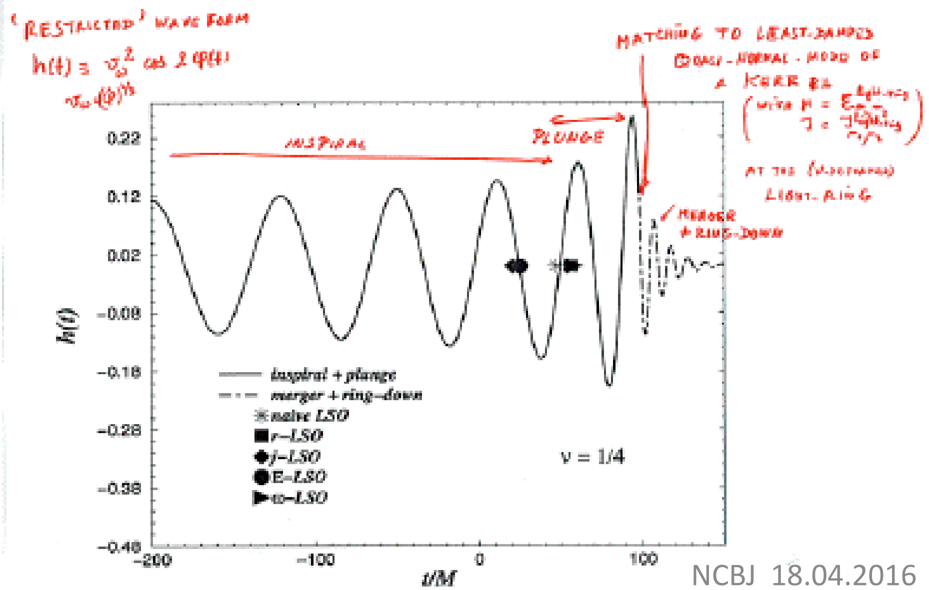
Modeling of the GW signal from a binary system: approximations

- **Postnewtonian corrections (in v/c)**

Wagoner & Will 76, Damour & Deruelle 81,82; Blanchet & Damour 86, Damour & Schafer 88, Blanchet & Damour 89; Blanchet, Damour, Iyer, Will, Wiseman 95
Blanchet 95, **Jaranowski** & Schafer 98, Damour, **Jaranowski**, Schafer 01, Blanchet, Damour, Esposito-Farese & Iyer 05, Kidder 07, Blanchet, Faye, Iyer & Sinha, 08

- **Effective one body approach (Buonanno &Damour)**

(Buonanno & Damour 2000)



Buonanno,Damour 99 (2 PN Hamiltonian)
Buonanno,Damour 00 (Rad.Reac. full waveform)
Damour, **Jaranowski,**Schäfer 00 (3 PN Hamiltonian)
Damour, 01 (spin)
Damour, Nagar 07, Damour, Iyer, Nagar 08 (factorized waveform)

Modeling of the GW signal from a binary system: numerical relativity

Accurate numerical models of inspiral and merger

- **Grand challenge initiated by NSF**:

A. M. Abrahams et al. (Binary Black Hole Grand Challenge Alliance), Phys. Rev. Lett. 80, 1812 (1998),

- **Breakthrough in 2005:**

1st approach ([1]) - *generalized harmonic coordinates, and excision of the black hole horizons*
2nd approach ([2],[3]) - *"moving punctures approach"*
used singularity avoiding slices of the black hole spacetimes

[1] F. Pretorius,
Phys. Rev. Lett. 95, 121101 (2005)
[2] M. Campanelli, C. O. Lousto, P. Marronetti, and Y. Zlochower,
Phys. Rev. Lett. 96, 111101 (2006)
[3] J. G. Baker, J. Centrella, D.-I. Choi, M. Koppitz, and J. van Meter,
Phys. Rev. Lett. 96, 111102 (2006)

GW150914

GW from a binary black hole merger

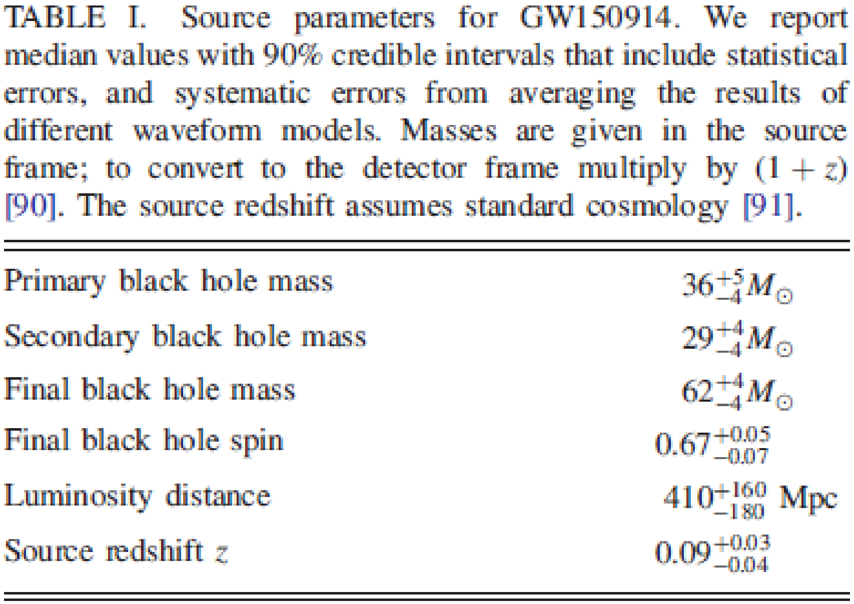
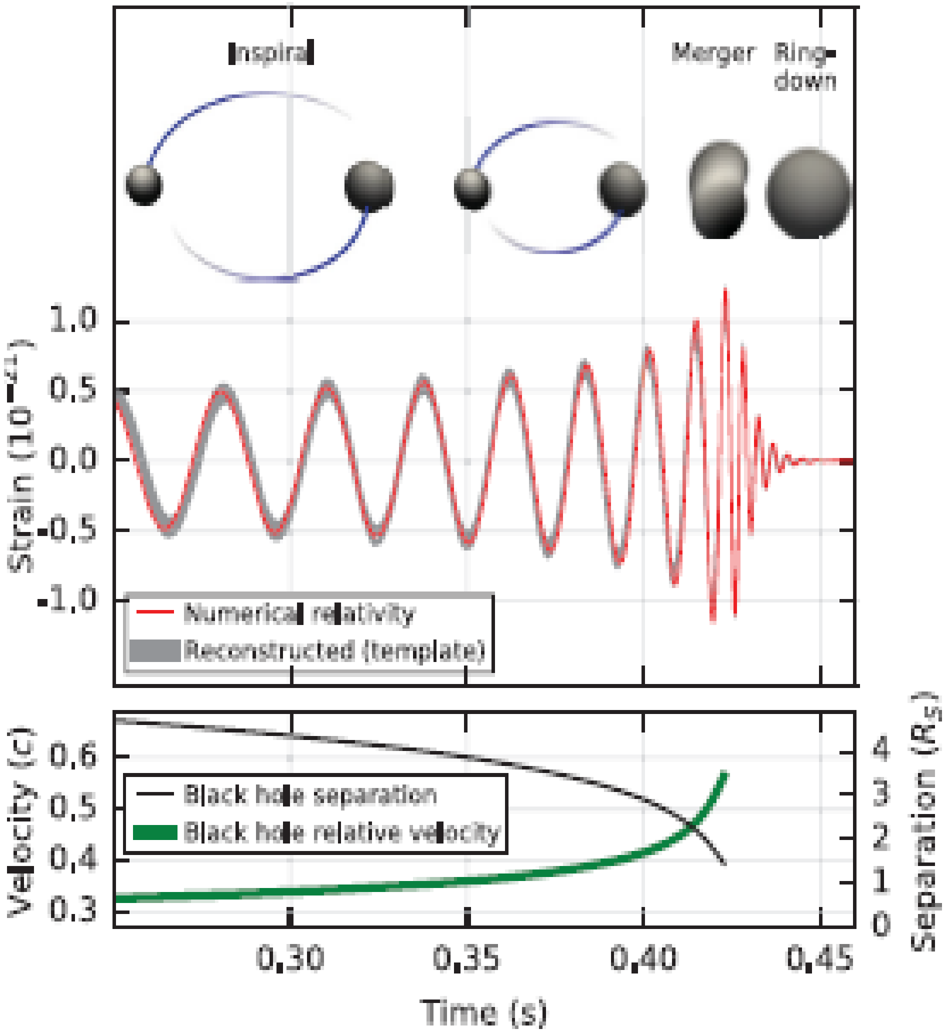


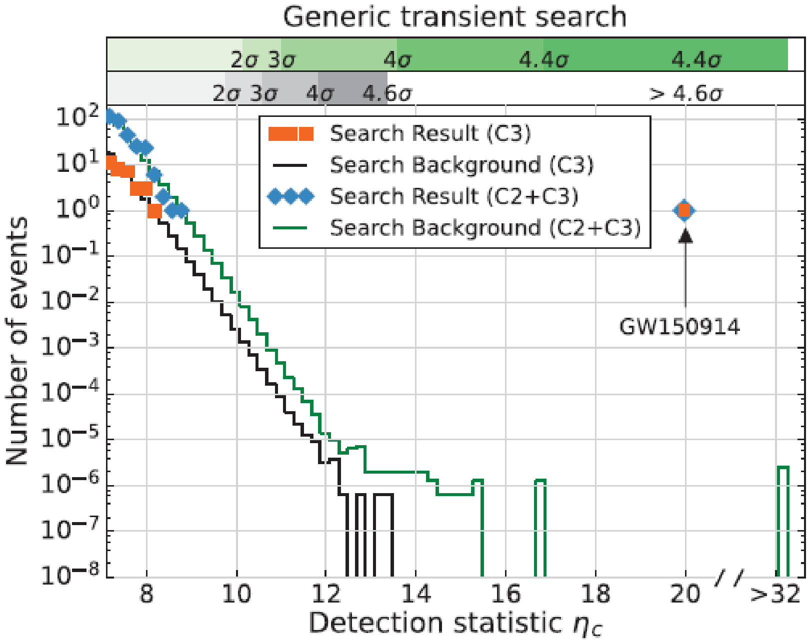
TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1 + z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$



Data analysis: detection

- GW150914 detected in real time by cWB pipeline: candidates identified by time-frequency analysis (wavelet transform) and reconstructed by maximum likelihood method



A. Krolak and P. Trzaskoma, *Application of the wavelet analysis to estimation of parameters of the gravitational-wave signal from a coalescing binary*, Classical and Quantum Gravity 13, 813-830 (1996).

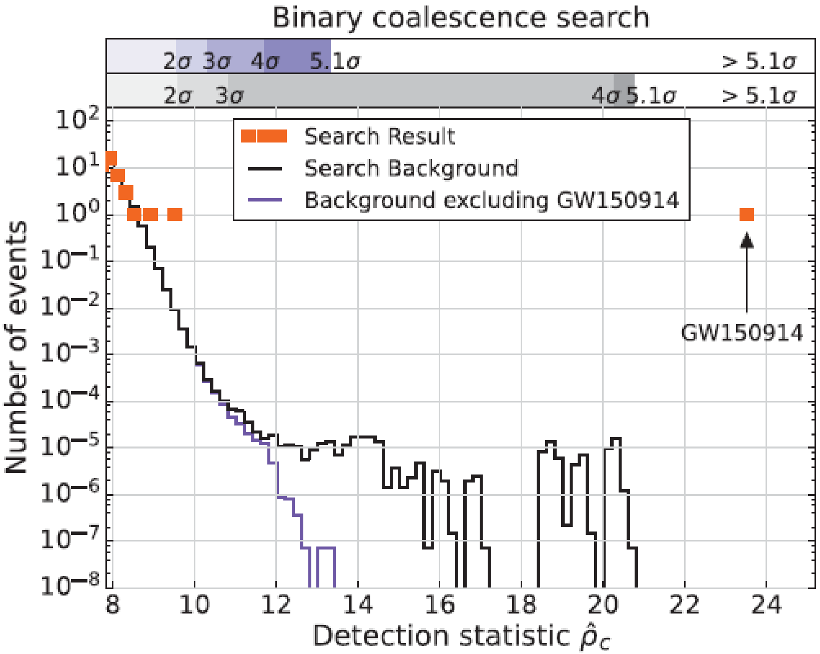
Statistical significance of signals obtained by shifting data by $\simeq 10\ \mathrm{ms}$ $1.6\text{x}10^{6}$ independent realizations of noise

Data analysis: confirmation

GW150914: First results from the search for binary black hole coalescence with Advanced LIGO (http://arxiv.org/abs/1602.03839)

- *PyCBC pipeline*: matched filter - effective one-body approach, template with 3.5PN corrections combined with numerical models

$$\rho^2(t) \equiv \frac{1}{\langle h|h\rangle}\left[\langle s|h_c\rangle^2(t) + \langle s|h_s\rangle^2(t)\right]$$



- *GstLAL pipeline*: confirmation of PyCBC by independent method – efficient construction of filters using SVD method.

False alarm probability < 1 event per 203000 years

Astrophysical origin of GW150914

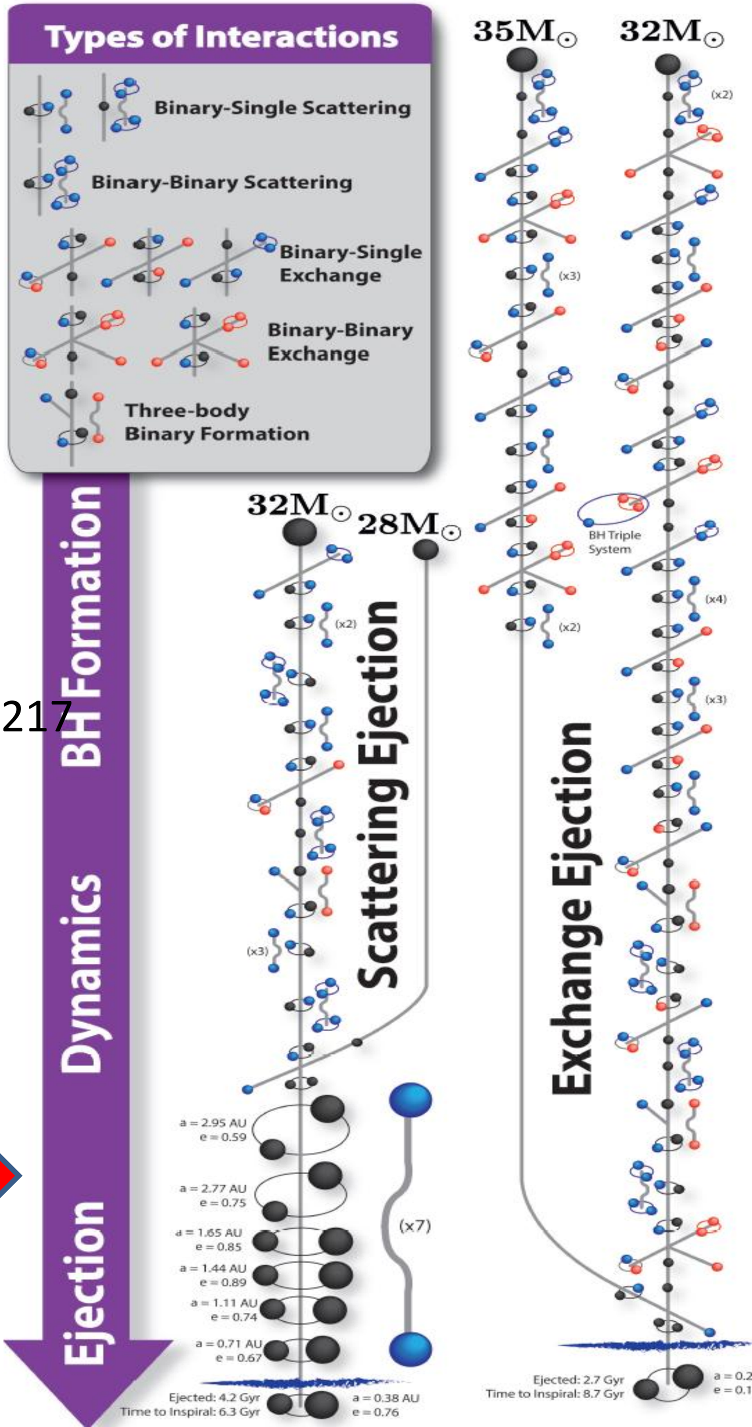
LSC-Virgo, [ASTROPHYSICAL IMPLICATIONS OF THE BINARY BLACK-HOLE MERGER GW150914, ApJL, 818, L22, 2016 (http://arxiv.org/abs/1602.03846)](http://arxiv.org/abs/1602.03846)

The surprisingly large masses of the individual BH components (36M and 29M) strongly suggest that the binary BH (BBH) progenitor of GW150914 was formed in a low-metallicity environment

Belczynski, K., Bulik, T., Fryer, C. L., et al. 2010a, ApJ, 714, 1217

1. In the galactic field with Z_s < ½ , < ¼

2. After ejection from the globular cluster with low Z_s



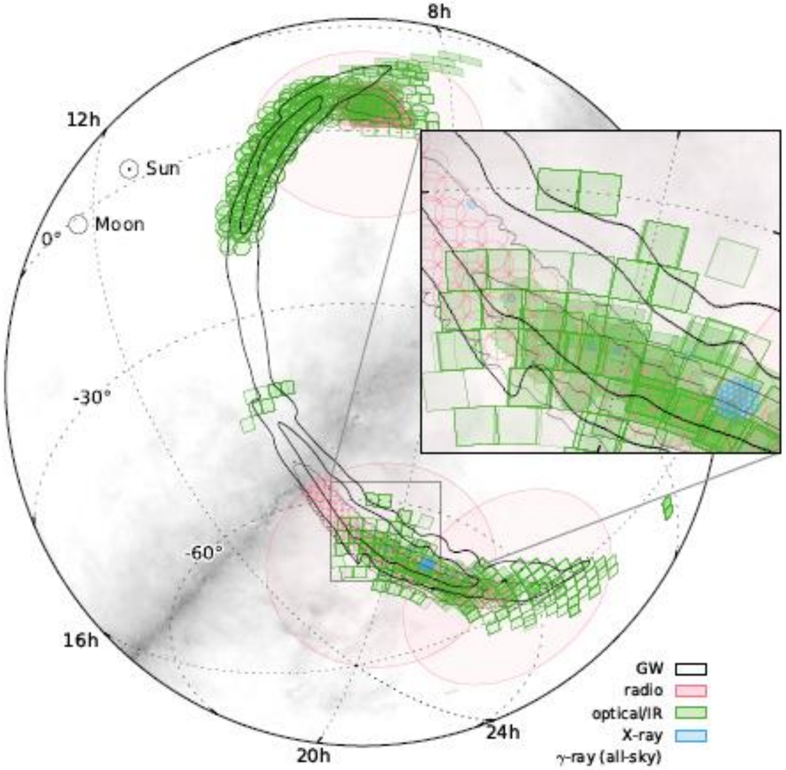
[arXiv:1604.04254](https://arxiv.org/abs/1604.04254)

Coincidences with EM observations

- There are > 70 EM observational projects with MoA with LVC to do joint observations .
- G184098 -> GW150914 followed by 25 teams including Pi-of-the-Sky.
- Alerts sent 2 days after detection (goal - 10 minutes)
- In a standard scenario we do not expect EM radiation from stellar BH merger

arXiv:1602.08492
Localization and broadband follow-up of the gravitational-wave transient GW150914
LIGO Scientific Collaboration, Virgo Collaboration and EM partners

Jaranowski & **Krolak** , Optimal solution to the inverse problem for the gravitational wave signal of a coalescing compact binary, *Phys. Rev. D*, ***49, 1723–1739, (1994)***



EM observations results

- High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with **ANTARES** and **IceCube** (http://arxiv.org/abs/1602.05411)
- **Swift** follow-up of the Gravitational Wave source GW150914 (http://arxiv.org/abs/1602.03868)
- **Pan-STARRS** and **PESSTO** search for the optical counterpart to the LIGO gravitational wave source GW150914 (http://arxiv.org/abs/1602.04156)
- **INTEGRAL** upper limits on gamma-ray emission associated with the gravitational wave event GW150914 (http://arxiv.org/abs/1602.04180)
- Fermi-LAT Observations of the LIGO event GW150914 (http://arxiv.org/abs/1602.04488)
- A **Dark Energy Camera** Search for Missing Supergiants in the LMC After the Advanced LIGO Gravitational Wave Event GW150914 (arXiv:1602.04199)
- **iPTF** Search for an Optical Counterpart to Gravitational Wave Trigger GW150914 **(arXiv:1602.08764)**
- **XMM-Newton** Slew Survey observations of the gravitational wave event GW150914 **(arXiv:1603.06585)**
- **AGILE** Observations of the Gravitational Wave Event GW150914 **(arXiv:1604.00955)**

ALL negative except …

Fermi GBM „observation”

- **Fermi GBM Observations of LIGO Gravitational Wave event GW150914** http://arxiv.org/abs/1602.03920

„weak transient source above 50 keV, 0.4 s after the GW event detected” !?

- Many experts doubt significance of this event
- Other GRB observations (Swift, INTEGRAL, Agile) did not see this event

An unlikely association …

arXiv:1602.05140
Short Gamma-Ray Bursts from the Merger of Two Black Holes
Rosalba Perna, Davide Lazzati, Bruno Giacomazzo

arXiv:1602.05529 Modeling the Afterglow of GW150914-GBM
Brian J. Morsony, Jared C. Workman, Dominic M. Ryan

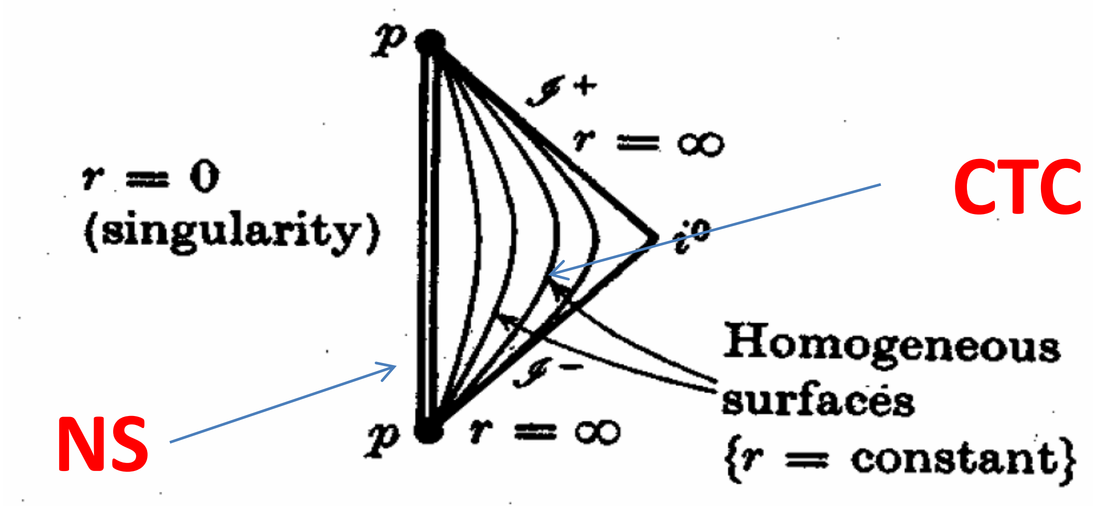
arXiv:1602.06526 Size of Shell Universe in Light of FERMI GBM Transient Associated with GW150914
Merab Gogberashvili, Alexander Sakharov, Edward Sarkisyan-Grinbaum

arXiv:1602.07352 Fermi GBM signal contemporaneous with GW150914 - an unlikely association
Maxim Lyutikov

arXiv:1602.08436 High Energy Neutrinos from the Gravitational Wave event GW150914 possibly associated with a short Gamma-Ray Burst
Reetanjali Moharana, Soebur Razzaque, Nayantara Gupta, Peter Meszaros

Cosmic censorship (CC) and chronology protection conjecture (CPC)

Black hole is not the only possibility for Kerr solution:
Fo a>1 there is no event horizon only the timelike singularity (NS) and closed timelike curves (CTCs)



CTC

NS

In physically realistic situations:

- CC (Penrose 1969) – **no naked singularities**
- CPC (Hawking 1992) - **no time travel**

Cosmic censorship

Attempts to prove CC failed so far:

A. Krolak, Towards the proof of cosmic censorship hypothesis, Classical and Quantum Gravity Vol.3 (1986), 267

Try to verify CC observationally (measure prameter **a** of observed BHs):

A. Krolak, Nature of singularities in gravitational collapse, Progress of Theoretical Physics Suplement, No.136, pp. 45-56, 1999.

Exotic scenarios

- arXiv:1603.02848 **Electromagnetic counterparts to gravitational waves from black hole mergers and naked singularities,** D. Malafarina, P. S. Joshi

Naked singularities can arise from topology change. Naked singularity can be a source of an observable EM signal

- arXiv:1603.07830 **The electromagnetic afterglows of gravitational waves as a test for Quantum Gravity,** M. A. Abramowicz, T. Bulik, G. F. R. Ellis, K. A. Meissner, M. Wielgus

If particularly powerful electromagnetic afterglows of the gravitational waves bursts will be observed in the future, this could be used as a strong observational support for some suggested quantum alternatives for black holes (e.g., firewalls and gravastars)

Mazur & Motolla

- A. Janiuk, M. Bejger, Sz. Charzynski, and P. Sukova

We speculate on the possible scenario for the formation of a gamma-ray burst accompanied by the GW signal. Our model invokes a close binary system consisting of a massive star and a black hole, which leads to triggering of a collapse of the star's nucleus, formation of a second black hole, and finally to the binary black hole merger

Meaning of the discovery

1. For the first time gravitational wave signal was registered by a detector on Earth
2. For the first time merger of two black holes into a single black hole was observed.

The end product of a black hole binary coalescence is perfectly consistent with Kerr black hole as described by Einstein's general relativity

Significance of the dicovery

- General relativity has been tested in extreme gravity regime where the gravitational field is strong and dynamical
- A new field – gravitational wave astronomy has been opened.