The impact of the detected gravitational waves on fundamental physics

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Outline

- The detected GWs
- BH spacetimes
- Binary dynamics
- Impact on fundamental physics

The detected GWs

GW150914 from BBH (36/29)$M_\odot$ @420 Mpc; LIGO SNR 24, FAR $6/10^7$yrs

LVT151012 from BBH (23/13)$M_\odot$ @1000 Mpc; LIGO SNR 10, $37/10^2$yrs (1.7 σ)

GW151226 from BBH (14/08)$M_\odot$ @440 Mpc; LIGO SNR 13, $6/10^7$yrs (5.3 σ)

GW170104 from BBH (31/19)$M_\odot$ @880 Mpc (0.18); LIGO SNR 13, 1/70,000yrs

GW170814 from BBH (31/25)$M_\odot$ @540 Mpc; LIGO/Virgo SNR 18, 1/27,000yrs

GW170817 from BNS (1.5/1.3)*$M_\odot$ @40 Mpc; LIGO/Virgo SNR 32, 1/80,000yrs

GRB 170817A detected by Fermi-GBM 1.7 s after GW170817 near NGC 4993**
optical SSS17a/AT 2017gfo: less than 11 hours after merger with two week long Kilonova

*(1.36-1.60/1.17-1.36) Low-spin priors, (1.36-2.26/0.86-1.36) High-spin priors
Chirp mass 1.188 $M_\odot$

**$z = 0.008$: Hubble constant $H_0 = 70$ (67.90 from Planck) km/sMpc tidal deformability (significant above 600 Hz):

$$\Lambda = \frac{2}{3} k_2 \left(\frac{c^2}{G} \frac{R}{M} \right)^5$$

stellar radius: R

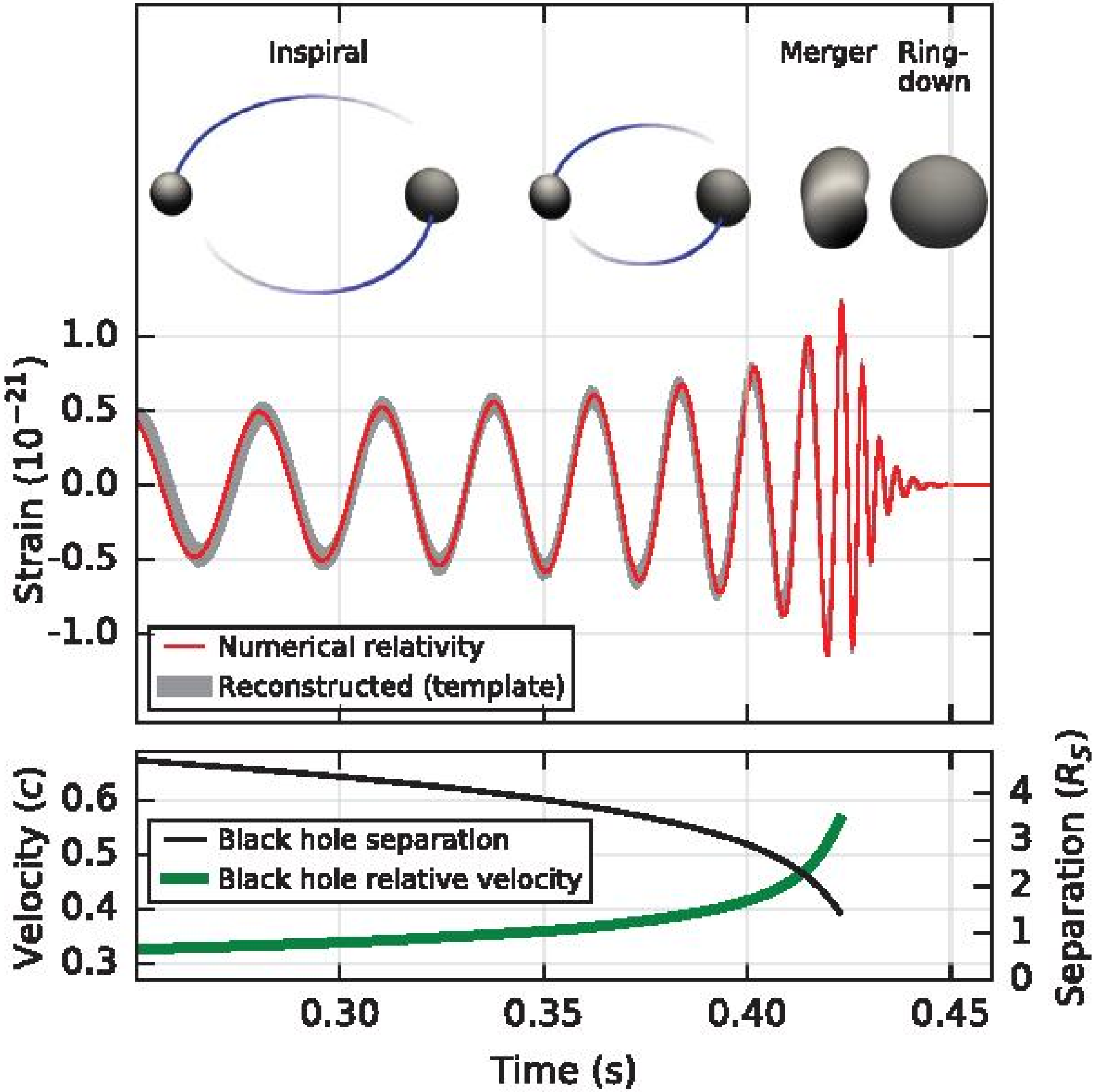
second Love number:

$k_2 = 0.05 - 0.15$ (NS)

$k_2 = 0$ (BH)

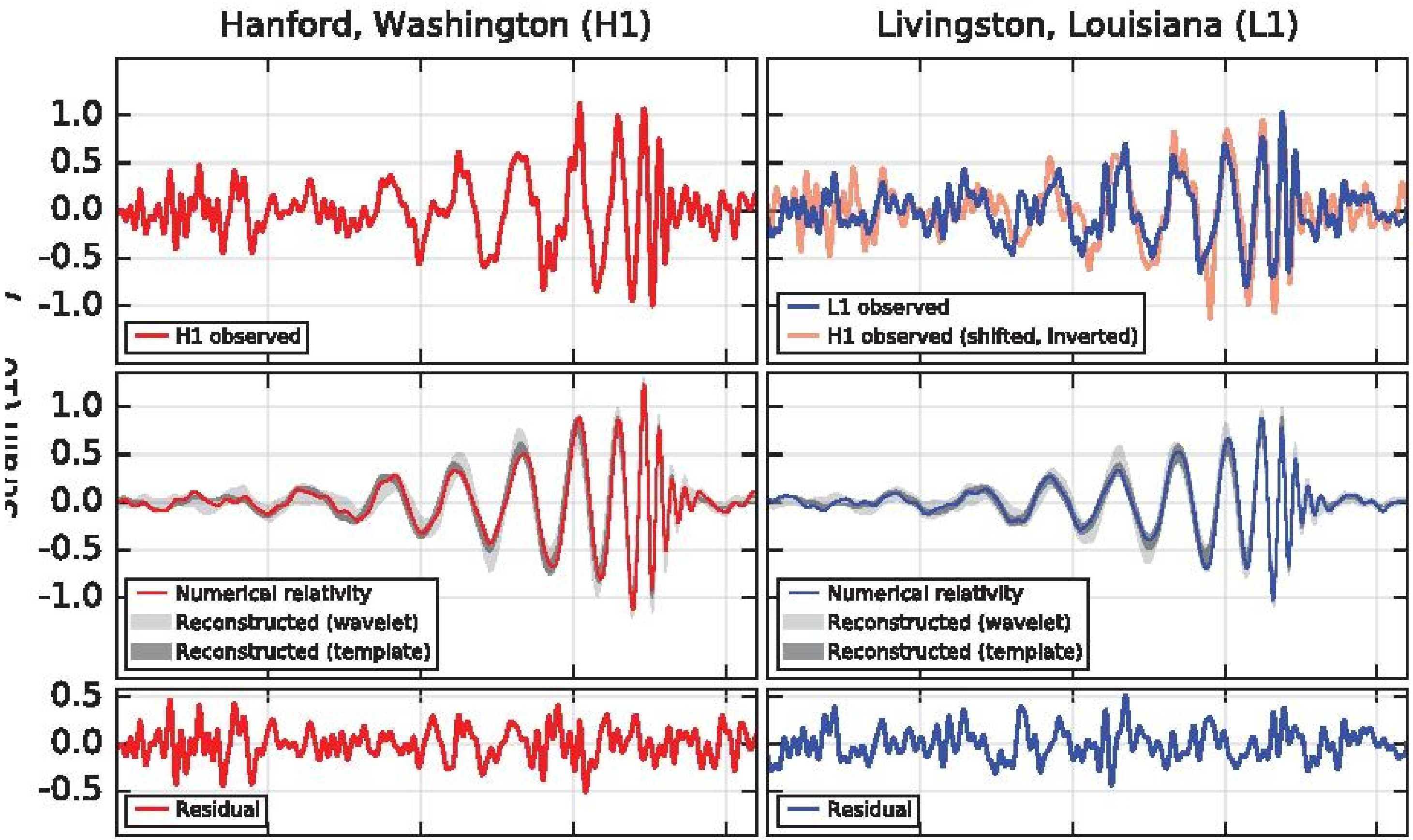
$\Lambda(1.4 M_\odot) \; \leq 800$ for Low-spin priors and $\leq 1,400$ for High-spin priors

GW150914



$$h(t)L = \Delta L(t) = \delta L_x - \delta L_y$$

GW150914



Hanford, Washington (H1)
Livingston, Louisiana (L1)
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

source power (3 solar masses radiated away in 0.2 seconds)

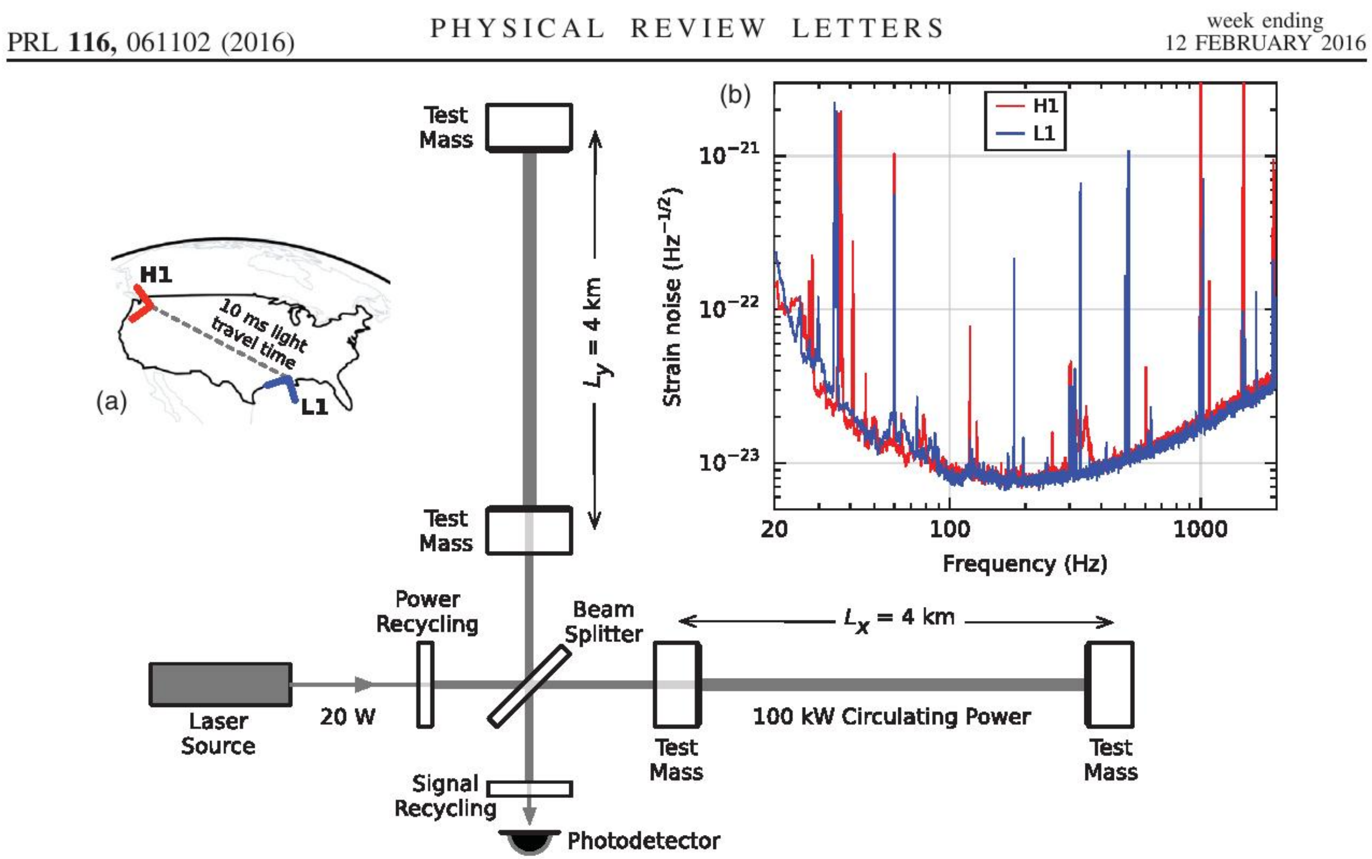
(3/1/2/2.7/0.025)

$$(6 \times 10^{30}\text{kg})\ 9 \times 10^{16} \left(\frac{\text{m}}{\text{sec}}\right)^2 /200\text{ms} = 2.7 \times 10^{48}\text{Watt} = 3 \times 10^{-4}\,\frac{c^5}{4G}$$

maximum power of a single process (Dyson luminosity)

$$\frac{c^5}{4G} = \frac{Mc^2}{(4GM/c^2)/c} = 0.9 \times 10^{52}\text{Watt}$$

Interferometric detection of GWs

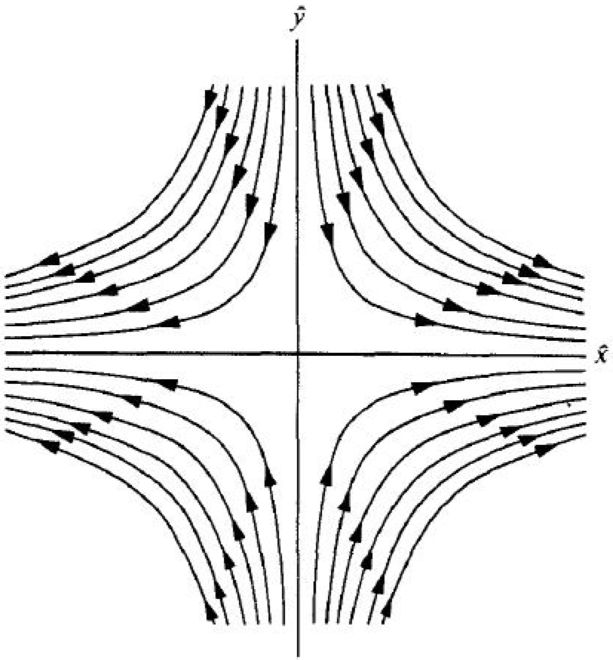


line element $$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

gravitational wave $$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + h_{ij}^{\mathrm{TT}} dx^i dx^j$$

Fermi normal coordinates

$$ds^2 = -(1 - \frac{1}{2c^2} \ddot{h}_{ij}^{\mathrm{TT}} \hat{x}^i \hat{x}^j) c^2 d\hat{t}^2 + d\hat{x}^i d\hat{x}^i \qquad (|\hat{\mathbf{x}}| << c/f)$$



(a) Force lines for $\ddot{A}_\times = 0$, $\ddot{A}_+ > 0$

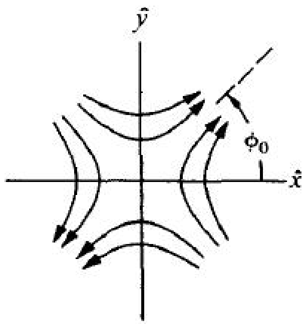
gravitational quadrupole wave

propagating in $\hat{z}$-direction

$$d^2\hat{x}/d\hat{t}^2 = \tfrac{1}{2}(\ddot{A}_+\hat{x} + \ddot{A}_\times\hat{y})$$

$$d^2\hat{y}/d\hat{t}^2 = \tfrac{1}{2}(-\ddot{A}_+\hat{y} + \ddot{A}_\times\hat{x})$$

$$d^2\hat{z}/d\hat{t}^2 = 0$$



(b)

MTW: Gravitation (1973)

chirp mass $$\mathcal{M} := \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left(\frac{5}{96}\frac{\dot{f}}{\pi^{8/3} f^{11/3}}\right)^{3/5}$$

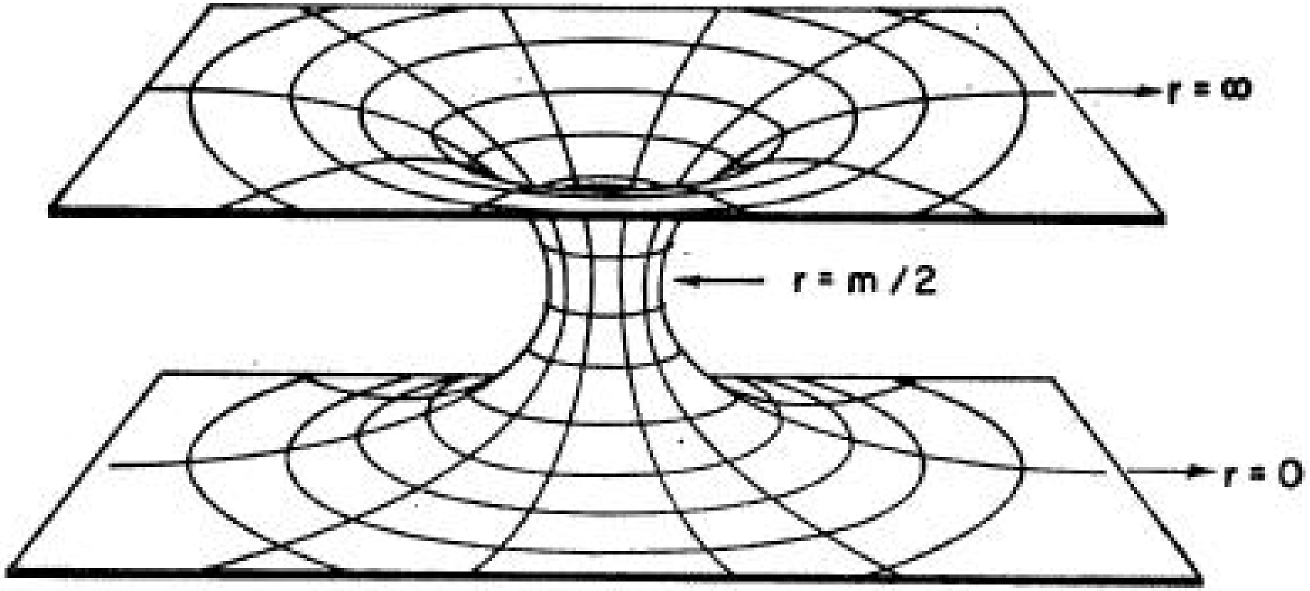
velocity $$\frac{v}{c} = \left(\frac{GM\pi f}{c^3}\right)^{1/3}$$

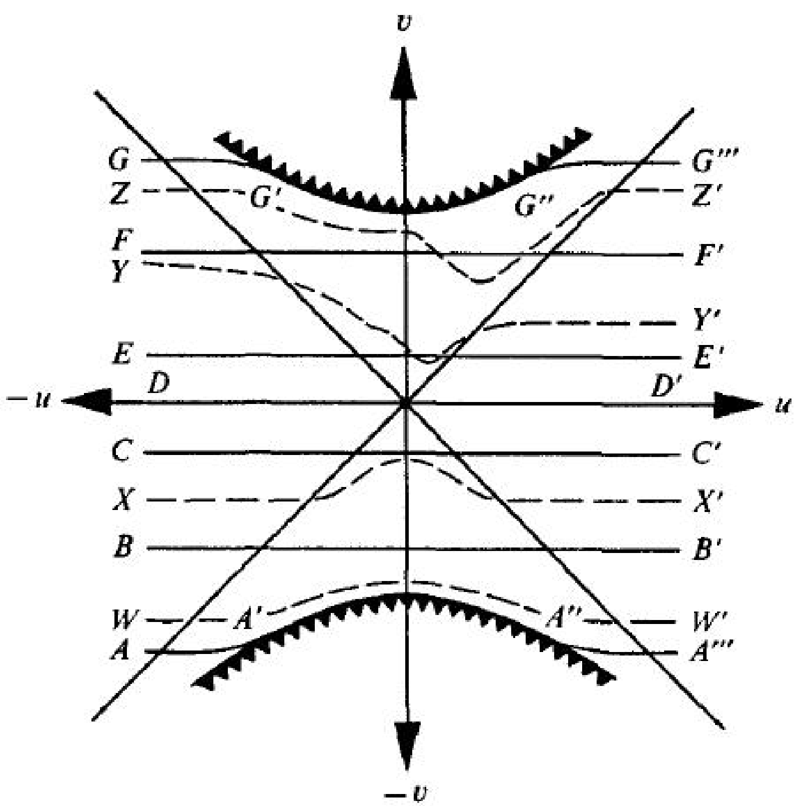
gravitational quadrupole wave

$$h_{ij}^{\mathrm{TT}}(t,\mathbf{x}) = \frac{2}{r}\frac{G}{c^4}P_{ijkm}(\mathbf{n})\ddot{Q}_{km}\left(t-\frac{r}{c}\right)$$

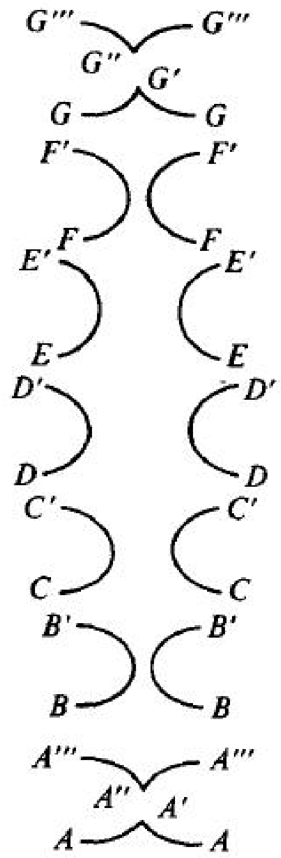
$$Q_{km} = \sum_a m_a(x_k^a x_m^a - \frac{1}{3}\delta_{km}x_l^a x_l^a)$$

BH spacetimes (non-rotating)

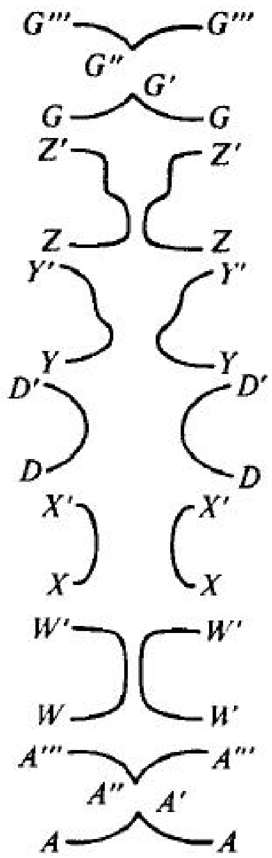




Spacelike slices

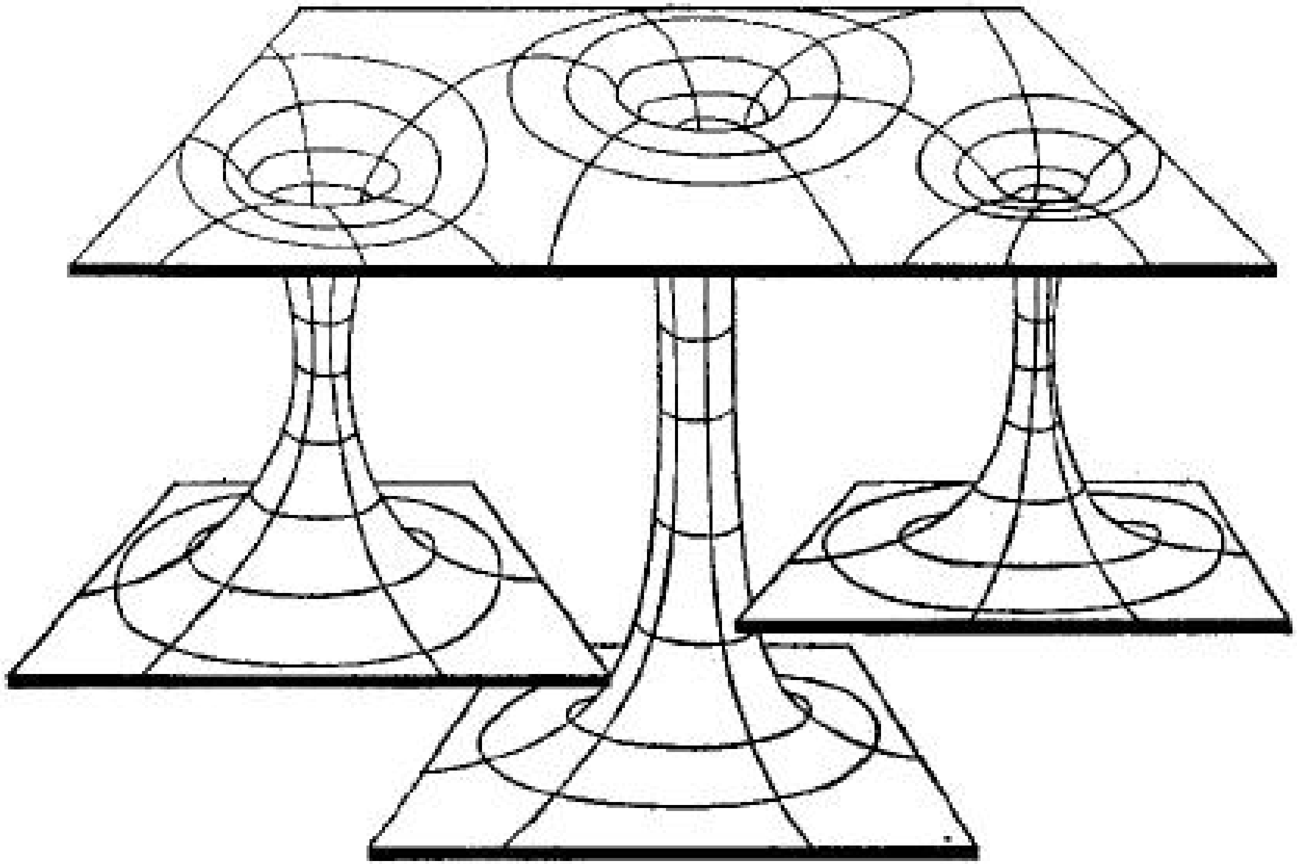


History
A-B-C-D-E-F-G

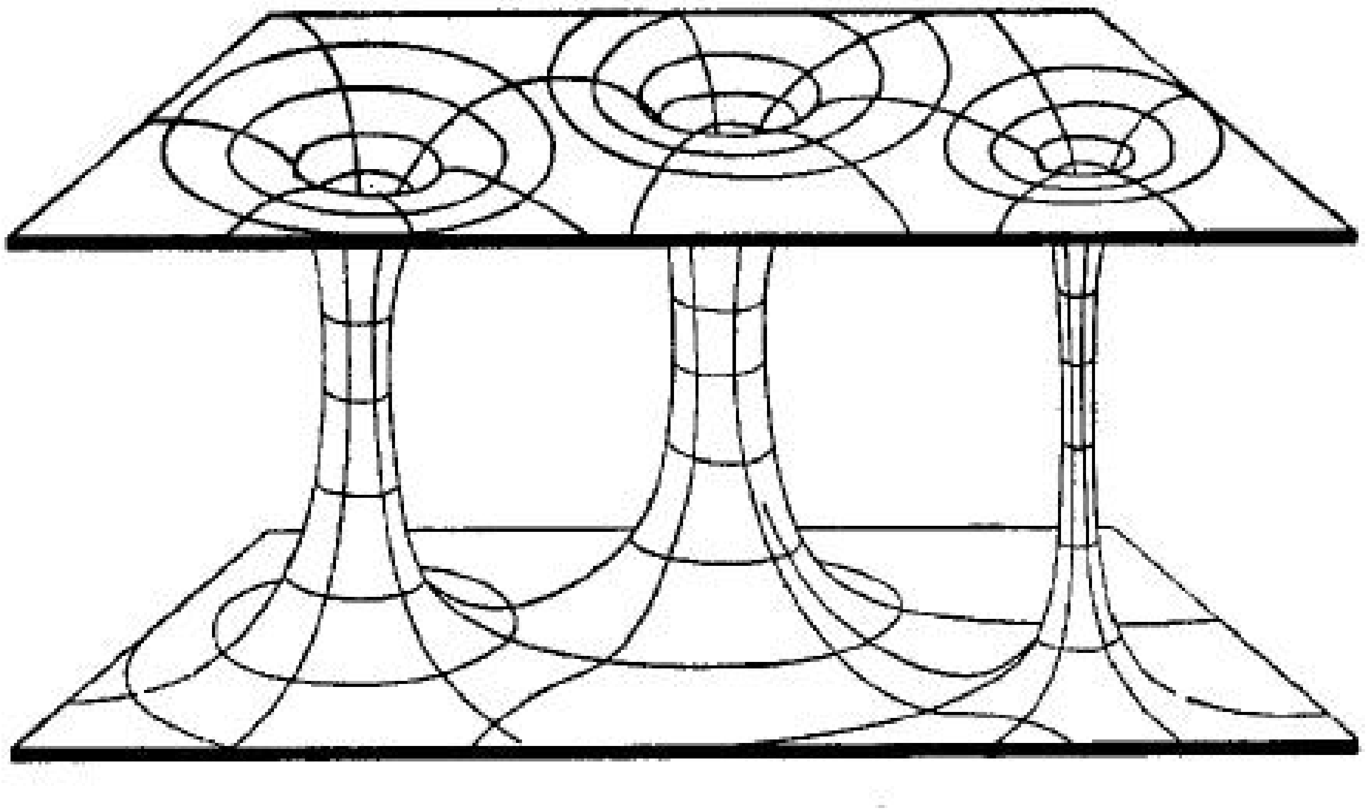


History
A-W-X-D-Y-Z-G

MTW: Gravitation (1973)



Brill-Lindquist BHs



Misner-Lindquist BHs

Binary dynamics

Test particle in Schwarzschild field

$r = 6\ GM/c^2 = 3\ R_S$ $(x = 1/6)$: ISCO

$r = 3\ GM/c^2 = 3/2\ R_S$ $(x = 1/3)$: light ring or light sphere

$r = 2\ GM/c^2 = R_S$ $(x = 1/2)$: event horizon

$r = 2.25\ GM/c^2 = 9/8\ R_S$: Buchdahl limit (most compact star)

Innermost Stable Circular Orbit (ISCO)

$H = H(\mathbf{p}, \mathbf{r}), \qquad p^2 = p_r^2 + j^2/r^2, \qquad p_r = (\mathbf{p} \cdot \mathbf{r})/r$

circular orbits: $p_r = 0, \qquad p^2 = j^2/r^2, \qquad H = H(j, r)$

circular motion: $\frac{\partial}{\partial r} H(j, r) = 0 \rightarrow H(j)$

orbital frequency: $\omega = \frac{dH(j)}{dj} \rightarrow H(\omega)$

ISCO: $\frac{\partial^2}{\partial r^2} H(j, r) = 0$ or alternatively $\frac{dH(\omega)}{d\omega} = 0$

$$E(x) \equiv \frac{H(x)}{\mu c^2}, \qquad x = \frac{(GM\omega)^{2/3}}{c^2}$$

SBH:
$$E(x) = \frac{1 - 2x}{\sqrt{1 - 3x}} = \sqrt{1 - x\frac{1 - 4x}{1 - 3x}}$$
$$= 1 - \frac{1}{2}x + \frac{3}{8}x^2 + \frac{27}{16}x^3 + \frac{675}{128}x^4 + \frac{3969}{256}x^5 + \ldots$$

Binaries at 4PN approximation:

Jaranowski/GS 2013, Damour/Jaranowski/GS 2014 (see PRD or arXiv)

$$E_{4PN}(x) = 1 - \frac{x}{2} + \left(\frac{3}{8} + \frac{1}{24}\nu\right)x^2 + \left(\frac{27}{16} - \frac{19}{16}\nu + \frac{1}{48}\nu^2\right)x^3$$

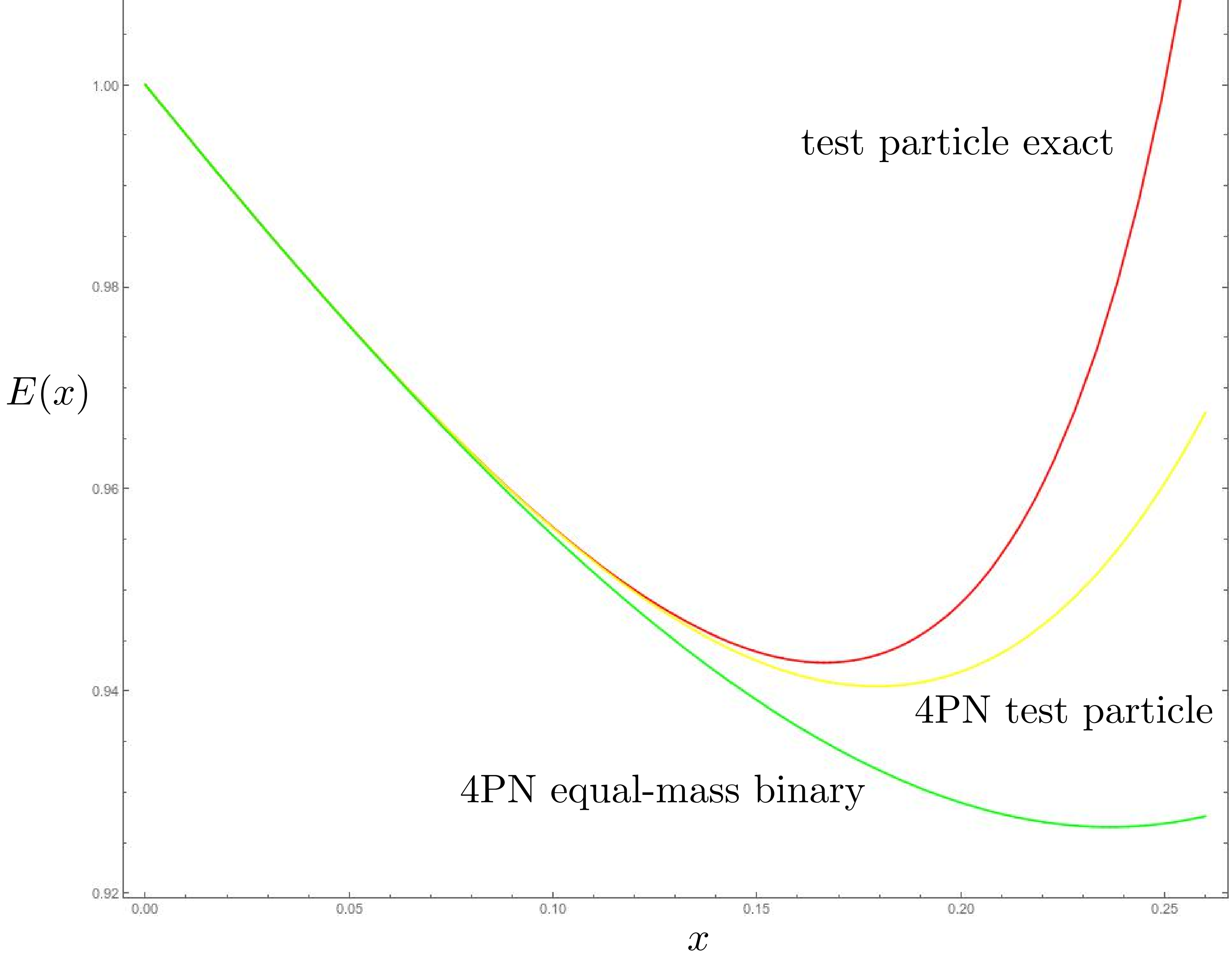
$$+ \left(\frac{675}{128} + \left(-\frac{34445}{1152} + \frac{205}{192}\pi^2\right)\nu + \frac{155}{192}\nu^2 + \frac{35}{10368}\nu^3\right)x^4$$

$$-\tfrac{1}{2}\left(-\tfrac{3960}{128} + (c_1 + \tfrac{448}{15}\ln x)\nu + \left(-\tfrac{498449}{3456} + \tfrac{3157}{576}\pi^2\right)\nu^2 + \tfrac{301}{1728}\nu^3 + \tfrac{77}{31104}\nu^4\right)x^5$$

$$c_1 = -\tfrac{123671}{5760} + \tfrac{9037}{1536}\pi^2 + \tfrac{1792}{15}\ln 2 + \tfrac{896}{15}\gamma_E$$

$$\nu = \tfrac{\mu}{M} = \tfrac{m_1 m_2}{M^2}, \quad M = m_1 + m_2, \quad \mu = \tfrac{m_1 m_2}{M}$$

$0 \leq \nu \leq \frac{1}{4} = 0.25$, $\nu = 0$: test particle, $\nu = 0.25$: equal masses



test particle exact
4PN test particle
4PN equal-mass binary
$E(x)$
x
1.00
0.98
0.96
0.94
0.92
0.00
0.05
0.10
0.15
0.20
0.25

Matched Filtering

S. Finn: *Detection, measurement, and gravitational radiation*, PRD 46, 5236 (1992)

C. Cutler, E. Flanagan: *Gravitational waves from merging compact binaries: How accurately can one extract the binary's parameters from the inspiral waveform?*, PRD 49, 2658 (1994)

A. Królak, K. Kokkotas, G. Schäfer: *Estimation of the post-Newtonian parameters in the gravitational-wave emission of a coalescing binary*, PRD 52, 2089 (1995)

J. Creighton, W. Anderson: *Gravitational-Wave Physics and Astronomy*, WILEY-VCH Verlag, Weinheim 2011

data stream: $s(t;\theta) = n(t) + h(t;\tilde{\theta}), \quad \theta = (\theta_i),\ i = 1, ..., N$

$n(t)$: noise amplitude

$h_{te} = h(t;\hat{\theta})$: template wave form

inner product:

$$< h_{te}|h > \; = 2\int_0^\infty \frac{\tilde{h}^*_{te}(f)\tilde{h}(f) + \tilde{h}^*(f)\tilde{h}_{te}(f)}{S_n(f)} df = 4\mathrm{Re}\int_0^\infty \frac{\tilde{h}^*_{te}(f)\tilde{h}(f)}{S_n(f)} df$$

$S_n(f)$: spectral noise density, $\quad S_n(f) = \lim_{T\to\infty} \frac{1}{T}|\tilde{n}(f;T)|^2$

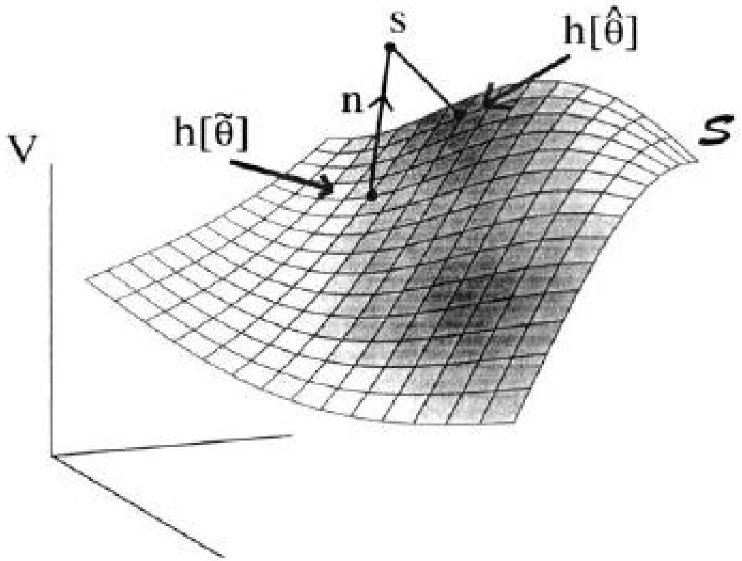


FIG. 1. Gravitational waveforms from coalescing compact binaries are completely specified by a finite number of parameters $\theta = (\theta^1, \ldots, \theta^k)$, and so form a surface $\mathcal{S}$ in the vector space V of all possible measured detector outputs $s = s(t)$. The statistical properties of the detector noise endow V with the structure of an infinite-dimensional Euclidean space. This figure illustrates the relationships between the true gravitational wave signal $h(\tilde{\theta})$, the measured signal s, and the "best-fit" signal $h(\hat{\theta})$. Given a measured detector output $s = h(\tilde{\theta}) + n$, where $n = n(t)$ is the detector noise, the most likely values $\hat{\theta}$ of the binaries parameters are just those that correspond to the point $h(\hat{\theta})$ on the surface $\mathcal{S}$ which is closest [in the Euclidean distance $(s - h \,|\, s - h)$] to y.

$$\text{SNR}: \quad \frac{S}{N}[h_{te}] = \frac{< h_{te}|h_{te} >}{\text{rms} < h_{te}|n >} = < h_{te}|h_{te} >^{1/2}$$

1.5PN wave form (including tail from back scattering) in Fourier domain above ISCO ($c = G = 1$):

$$\tilde{h}_{te}(f) = \frac{Q}{r}\mathcal{M}^{5/6} f^{-7/6} \exp[i\Psi(f)] \qquad 0 < f < (6^{3/2}\pi M)^{-1}$$

$$\Psi(f, \hat{\theta}) =$$

$$2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{4}(8\pi\mathcal{M}f)^{-5/3}\left[1 + \frac{20}{9}\left(\frac{743}{336} + \frac{11}{4}\nu\right)x - 16\pi x^{3/2}\right]$$

+ spin-orbit + spin1-spin2 + rotational quadrupole (spin^2) + tidal quadrupole

Impact on fundamental physics

1 - GW do exist! a la Einstein? longtime observations through BNS!

2 - BH do exist! a la Einstein? multipole structure? alternatives?

3 - NS-components likely! proper rotations? EOS? alternatives?