PN theory: Far-zone physics

Recall the wave-zone solution to $\Box\psi = -4\pi\mu$

$$\frac{\mu(t - |\boldsymbol{x} - \boldsymbol{x'}|/c, \boldsymbol{y})}{|\boldsymbol{x} - \boldsymbol{x'}|} = \sum_{\ell=0}^{\infty} \frac{(-1)^\ell}{\ell!} x'^L \partial_L \frac{\mu(t - r/c, \boldsymbol{y})}{r}.$$

$$\psi_{\mathcal{N}}(t, \boldsymbol{x}) = \sum_{\ell=0}^{\infty} \frac{(-1)^\ell}{\ell!} \partial_L \left[\frac{1}{r} \int_{\mathcal{M}} \mu(\tau, \boldsymbol{x'}) x'^L \, d^3x' \right]$$

Must add the integral over the wave zone $\psi_{\mathcal{W}}$

For the field $h^{\alpha\beta}$:

$$h^{\alpha\beta}_{\mathcal{N}}(t, \boldsymbol{x}) = \frac{4G}{c^4} \sum_{\ell=0}^{\infty} \frac{(-1)^\ell}{\ell!} \partial_L \left[\frac{1}{r} \int_{\mathcal{M}} \tau^{\alpha\beta}(\tau, \boldsymbol{x'}) x'^L \, d^3x' \right]$$

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General form of wave-zone fields

M_0 $\qquad\qquad$ $M_0 X^k = 0$

$$h^{00}_{\mathcal{N}}(t,\boldsymbol{x}) = \frac{4G}{c^4}\left\{\frac{1}{r}\int_{\mathcal{M}}\tau^{00}d^3x' - \partial_k\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{00}(\tau,\boldsymbol{x'})x^k\,d^3x'\right]\right.$$
$$\left. + \sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{00}(\tau,\boldsymbol{x'})x'^L\,d^3x'\right]\right\}$$

$\mathcal{I}^L(\tau)$

$$\boxed{h^{00}_{\mathcal{N}} = \frac{4GM_0}{c^2 r} + \frac{4G}{c^2}\sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{\mathcal{I}^L(\tau)}{r}\right]}$$

General form of wave-zone fields

$$\tau^{0j}x^k = \frac{1}{2}\partial_0\left(\tau^{00}x^jx^k\right) + \tau^{0[j}x^{k]} + \frac{1}{2}\partial_p\left(\tau^{0p}x^jx^k\right)$$

$P^j = 0$

$$h^{0j}_{\mathcal{N}}(t,\boldsymbol{x}) = \frac{4G}{c^4}\left\{\frac{1}{r}\int_{\mathcal{M}}\tau^{0j}\,d^3x' - \partial_k\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{0j}(\tau,\boldsymbol{x'})x^k\,d^3x'\right]\right.$$
$$\left. + \sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{0j}(\tau,\boldsymbol{x'})x'^L\,d^3x'\right]\right\}$$

$$\boxed{\begin{aligned} h^{0j}_{\mathcal{N}} &= -\frac{2G}{c^3}\frac{(\boldsymbol{n}\times\boldsymbol{J}_0)^j}{r^2} - \frac{2G}{c^3}\partial_k\left[\frac{\dot{\mathcal{I}}^{jk}(\tau)}{r}\right] \\ &\quad + \frac{4G}{c^4}\sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{0j}(\tau,\boldsymbol{x'})x'^L\,d^3x'\right]\end{aligned}}$$

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General form of wave-zone fields

$$h^{jk}_{\mathcal{N}}(t,\boldsymbol{x}) = \frac{4G}{c^4}\sum_{\ell=0}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{jk}(\tau,\boldsymbol{x'})x'^L\,d^3x'\right]$$

$$\tau^{jk} = \frac{1}{2}\partial_{00}\left(\tau^{00}x^jx^k\right) + \frac{1}{2}\partial_p\left(2\tau^{p(j}x^{k)} - \partial_q\tau^{pq}x^jx^k\right)$$

$$\boxed{h^{jk}_{\mathcal{N}} = \frac{2G}{c^4}\frac{\ddot{\mathcal{I}}^{jk}(\tau)}{r} + \frac{4G}{c^4}\sum_{\ell=1}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{jk}(\tau,\boldsymbol{x'})x'^L\,d^3x'\right]}$$

General form of wave-zone fields

In the far-away wave-zone, keep only 1/r terms

$$\partial_k r = n_k$$
$$\partial_k r^{-1} = -\frac{n_k}{r^2}$$
$$\partial_j n_k = \frac{1}{r}(\delta_{jk} - n_j n_k)$$
$$\partial_k \tau = -\frac{1}{c} n_k$$

$$h^{00}_{\mathcal{N}} = \frac{4GM}{c^2 r} + \frac{4G}{c^2}\sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{\mathcal{I}^L(\tau)}{r}\right]$$

$$\Longrightarrow \frac{4GM}{c^2 r} + \frac{4G}{rc^2}\sum_{\ell=2}^{\infty}\frac{n^L}{c^\ell \ell!}\frac{d^\ell}{d\tau^\ell}\mathcal{I}^L(\tau)$$

$$h^{0j}_{\mathcal{N}} = -\frac{2G}{c^3}\frac{(\boldsymbol{n}\times\boldsymbol{J}_0)^j}{r^2} - \frac{2G}{c^3}\partial_k\left[\frac{\dot{\mathcal{I}}^{jk}(\tau)}{r}\right] + \frac{4G}{c^4}\sum_{\ell=2}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{0j}(\tau,\boldsymbol{x}')x'^L\, d^3x'\right]$$

$$\Longrightarrow \frac{2G}{rc^4} n_k \ddot{\mathcal{I}}^{jk}(\tau) + \frac{4G}{rc^4}\sum_{\ell=2}^{\infty}\frac{n^L}{c^\ell \ell!}\frac{d^\ell}{d\tau^\ell}\mathcal{M}^{0jL}(\tau)$$

$$h^{jk}_{\mathcal{N}} = \frac{2G}{c^4}\frac{\ddot{\mathcal{I}}^{jk}(\tau)}{r} + \frac{4G}{c^4}\sum_{\ell=1}^{\infty}\frac{(-1)^\ell}{\ell!}\partial_L\left[\frac{1}{r}\int_{\mathcal{M}}\tau^{jk}(\tau,\boldsymbol{x}')x'^L\, d^3x'\right]$$

$$\Longrightarrow \frac{2G}{rc^4}\ddot{\mathcal{I}}^{jk}(\tau) + \frac{4G}{rc^4}\sum_{\ell=1}^{\infty}\frac{n^L}{c^\ell \ell!}\frac{d^\ell}{d\tau^\ell}\mathcal{M}^{jkL}(\tau)$$

$$h^{00} = \frac{4GM}{c^2 R} + \frac{G}{c^4 R}C(\tau,\boldsymbol{N})$$
$$h^{0j} = \frac{G}{c^4 R}D^j(\tau,\boldsymbol{N})$$
$$h^{jk} = \frac{G}{c^4 R}A^{jk}(\tau,\boldsymbol{N})$$

Far wave-zone fields & TT gauge

$$\partial_j h^{\alpha\beta} = -\frac{1}{c} N_j \partial_\tau h^{\alpha\beta} + O(R^{-2})$$

$$\boxed{\begin{aligned} h^{00} &= \frac{4GM}{c^2 R} + \frac{G}{c^4 R} C(\tau, \boldsymbol{N}) \\ h^{0j} &= \frac{G}{c^4 R} D^j(\tau, \boldsymbol{N}) \\ h^{jk} &= \frac{G}{c^4 R} A^{jk}(\tau, \boldsymbol{N}) \end{aligned}}$$

(from now on, r -> R, n^j -> N^j)

Harmonic gauge

$$\partial_\beta h^{\alpha\beta} = 0 = \frac{1}{c}\left(\partial_\tau h^{\alpha 0} - N_j \partial_\tau h^{\alpha j}\right) + O(R^{-2})$$

Integrating:

$$C = N_j D^j = N_j N_k A^{jk}$$

$$D^j = N_k A^{jk}$$

Gauge (coordinate) transformation

$$h^{\alpha\beta} \to h^{\alpha\beta} - \partial^\alpha \zeta^\beta - \partial^\beta \zeta^\alpha + \left(\partial_\mu \zeta^\mu\right)\eta^{\alpha\beta}$$

Stay within harmonic gauge as long as $\Box \zeta^\alpha = 0$

$$\zeta^0 = \frac{G}{c^3 R}\alpha(\tau, \boldsymbol{N}) + O(R^{-2})$$

$$\zeta^j = \frac{G}{c^3 R}\beta^j(\tau, \boldsymbol{N}) + O(R^{-2})$$

Far wave-zone fields & TT gauge

After a gauge transformation:

$$h^{00} \to \frac{4GM}{c^2 R} + \frac{G}{c^4 R}(C + \dot\alpha + N_j \dot\beta^j)$$

$$h^{0j} \to \frac{G}{c^4 R}(D^j + \dot\beta^j + N^j \dot\alpha)$$

$$h^{jk} \to \frac{G}{c^4 R}\left[A^{jk} + 2N^{(j}\dot\beta^{k)} + \delta^{jk}(\dot\alpha - N_m \dot\beta^m)\right]$$

To kill the h^{00} & h^{0j} terms:

$$\dot\beta^j + N^j \dot\alpha = -D^j = -N_m A^{jm}$$

$$N_j \dot\beta^j + \dot\alpha = -N_j D^j = -C$$

$$N_k h^{jk} = 0$$

Insert β^j

$$h^{jk} \to \frac{G}{c^4 R}\left[A^{jk} - 2\dot\alpha N^j N^k - 2N^{(j} N_n A^{k)n} + \delta^{jk}(2\dot\alpha + N_m N_n A^{mn})\right]$$

Note that $h = h^k_k = \frac{G}{c^4 R}\left[A + 4\dot\alpha + N_k N_n A^{kn}\right]$

Free to choose α so that h = 0: $\dot\alpha = -\frac{1}{4}(A + N_k N_n A^{kn})$

Final answer:

$$\boxed{\begin{aligned} h^{jk} &= \frac{G}{c^4 R} A_{mn}\left[P^{jm}P^{kn} - \frac{1}{2}P^{jk}P^{mn}\right] \\ &\equiv \frac{G}{c^4 R} A^{jk}_{\mathrm{TT}} \end{aligned}}$$

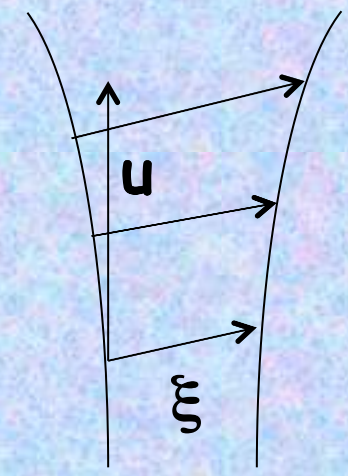
$$P^{jm} = \delta^{jm} - N^j N^m$$

$$P^{jm}P^{jn} = P^{mn}$$

$$P^{kk} = 2$$

Wave zone physics: Gravitational waves

Geodesic deviation: $$\frac{D^2\xi^\alpha}{ds^2} = -R^\alpha{}_{\beta\gamma\delta}u^\beta\xi^\gamma u^\delta$$



In the rest frame of an observer

$$\begin{aligned}\frac{d^2\xi^j}{dt^2} &= -c^2R_{0j0k}\xi^k \\ &= \frac{1}{2}\partial_{\tau\tau}h^{jk}_{TT}\xi^k \\ &= \frac{G}{2c^4R}\ddot{A}^{jk}_{\mathrm{TT}}\xi^k\end{aligned}$$

$$\xi^j(t) = \xi^j(0) + \frac{1}{2}h^{jk}_{\mathrm{TT}}(t-R/c)\xi_k(0)$$

Wave zone physics: Gravitational waves

Wave in the z-direction

$$A^{jk}_{\mathrm{TT}} = \begin{pmatrix} A_+ & A_\times & 0 \\ A_\times & -A_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

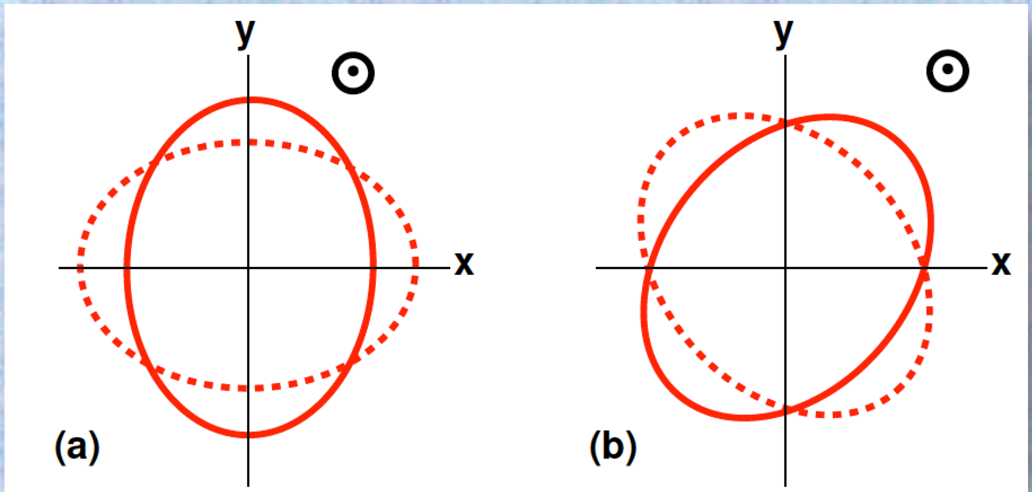
More generally: $\boldsymbol{e}_Z = \boldsymbol{N}$

$$A^{jk}_{\mathrm{TT}} = \left(e^j_X e^k_X - e^j_Y e^k_Y\right) A_+ + \left(e^j_X e^k_Y + e^j_Y e^k_X\right) A_\times$$

$$x(t) = x_0 + \frac{G}{2c^4 R}\Big(A_+ x_0 + A_\times y_0\Big)\,,$$

$$y(t) = y_0 + \frac{G}{2c^4 R}\Big(A_\times x_0 - A_+ y_0\Big)\,,$$

$$z(t) = z_0$$



Wave zone physics: The quadrupole formula

Requires **two** iterations of the relaxed Einstein equation:

$$
\begin{aligned}
h^{ij}_{2\mathcal{N}} &= \frac{4G}{c^4}\int \frac{\tau^{ij}(h_1)(t-|\boldsymbol{x}-\boldsymbol{x'}|/c,\boldsymbol{x'})}{|\boldsymbol{x}-\boldsymbol{x'}|} d^3x' \\
&= \frac{2G}{rc^4}\ddot{\mathcal{I}}^{jk}(h_1)(\tau) + \frac{4G}{rc^4}\sum_{\ell=1}^{\infty}\frac{n^L}{c^\ell \ell!}\frac{d^\ell}{d\tau^\ell}\mathcal{M}^{jkL}(h_1)(\tau) \\
&= \frac{2G}{rc^4}\ddot{\mathcal{I}}^{jk}(h_1)(\tau) + O(c^{-5})
\end{aligned}
$$

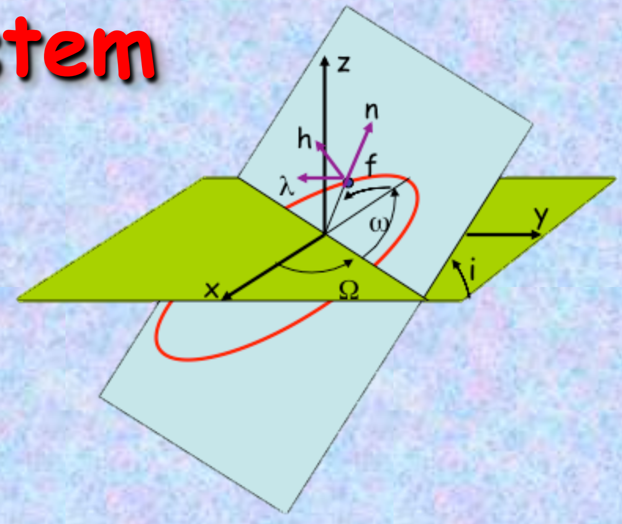
$$
\begin{aligned}
\mathcal{I}^{jk}(\tau) &:= \int_{\mathcal{M}} c^{-2}\tau^{00}(\tau,\boldsymbol{x'})x'^j x'^k \, d^3x' \\
&= \int_{\mathcal{M}} \rho^*(\tau,\boldsymbol{x'})x'^j x'^k \, d^3x' + O(c^{-2})
\end{aligned}
$$

For an N-body system

$$
\ddot{\mathcal{I}}^{ij} = 2\sum_A M_A v^{ij}_A - \sum_{A\neq B}\frac{GM_AM_B}{r_{AB}}n^{ij}_{AB}
$$

- By convention, the quadrupole formula is called the ``Newtonian”-order result
- Higher order PN corrections can be calculated by further iterating the relaxed equations
- 3 iterations needed for 1 & 1.5 PN order, 4 for 2PN order etc, but full details usually not needed

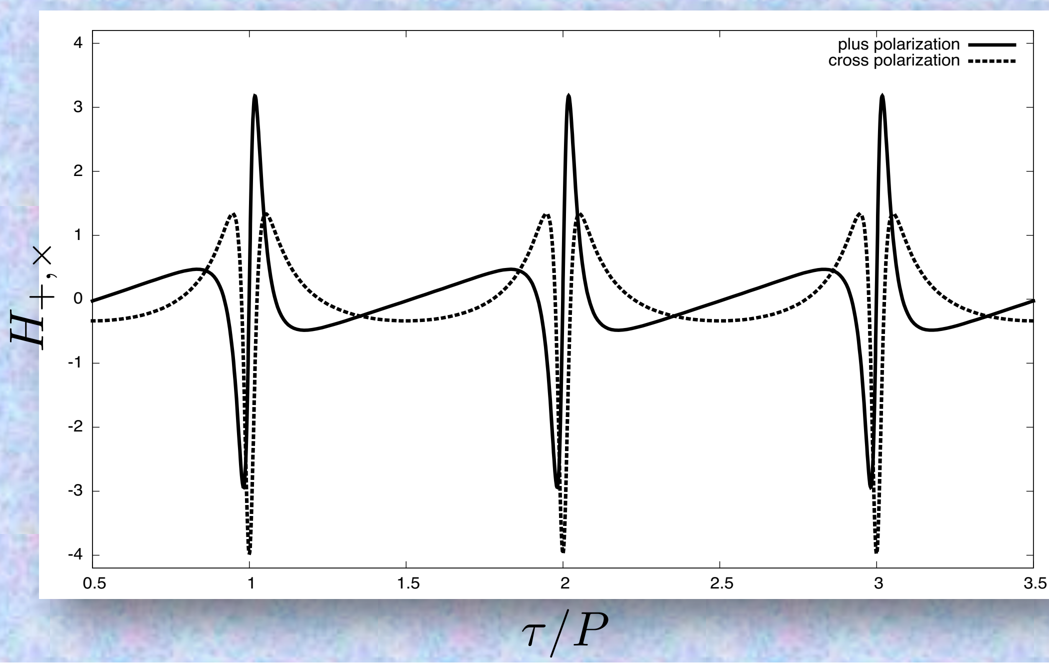
Waves from a binary system



$$h_{+(\times)} = \frac{2Gm\eta}{c^2 R}\left(\frac{Gm}{c^2 p}\right) H_{+(\times)}$$

$$H_+ = -(1+\cos^2\iota)\left[\cos(2\phi+2\omega) + \frac{5}{4}e\cos(\phi+2\omega) + \frac{1}{4}e\cos(3\phi+2\omega) + \frac{1}{2}e^2\cos 2\omega\right] + \frac{1}{2}e\sin^2\iota(\cos\phi + e),$$

$$H_\times = -2\cos\iota\left[\sin(2\phi+2\omega) + \frac{5}{4}e\sin(\phi+2\omega) + \frac{1}{4}e\sin(3\phi+2\omega) + \frac{1}{2}e^2\sin 2\omega\right]$$

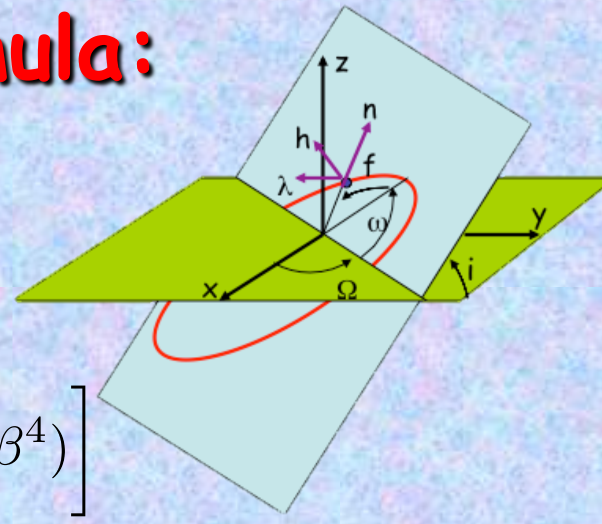


$e = 0.7$

$\iota = 30^{\circ}$

$\omega = 45^{\circ}$

Beyond the quadrupole formula:



For a binary system in a circular orbit:

$$h_{+,\times} = \frac{2\eta G m}{c^2 R}\beta^2\left[(1+2\pi\beta^3)H^{[0]}_{+,\times} + \Delta\beta H^{[1/2]}_{+,\times} + \beta^2 H^{[1]}_{+,\times} + \Delta\beta^3 H^{[3/2]}_{+,\times} + \beta^3 H^{\rm tail}_{+,\times} + O(\beta^4)\right]$$

$$\boxed{\begin{aligned}
H^{[0]}_\times &= -2C\sin 2\Psi, \\
H^{[1/2]}_\times &= -\frac{3}{4}SC\sin\Psi + \frac{9}{4}SC\sin 3\Psi, \\
H^{[1]}_\times &= \frac{1}{3}C\left[(17-4C^2)-(13-12C^2)\eta\right]\sin 2\Psi - \frac{8}{3}(1-3\eta)S^2C\sin 4\Psi, \\
H^{[3/2]}_\times &= \frac{1}{96}SC\left[(63-5C^2)-2(23-5C^2)\eta\right]\sin\Psi \\
&\quad - \frac{9}{64}SC\left[(67-15C^2)-2(19-15C^2)\eta\right]\sin 3\Psi + \frac{625}{192}(1-2\eta)S^3C\sin 5\Psi,
\end{aligned} \qquad \begin{aligned} C &= \cos\iota \\ S &= \sin\iota \end{aligned}}$$

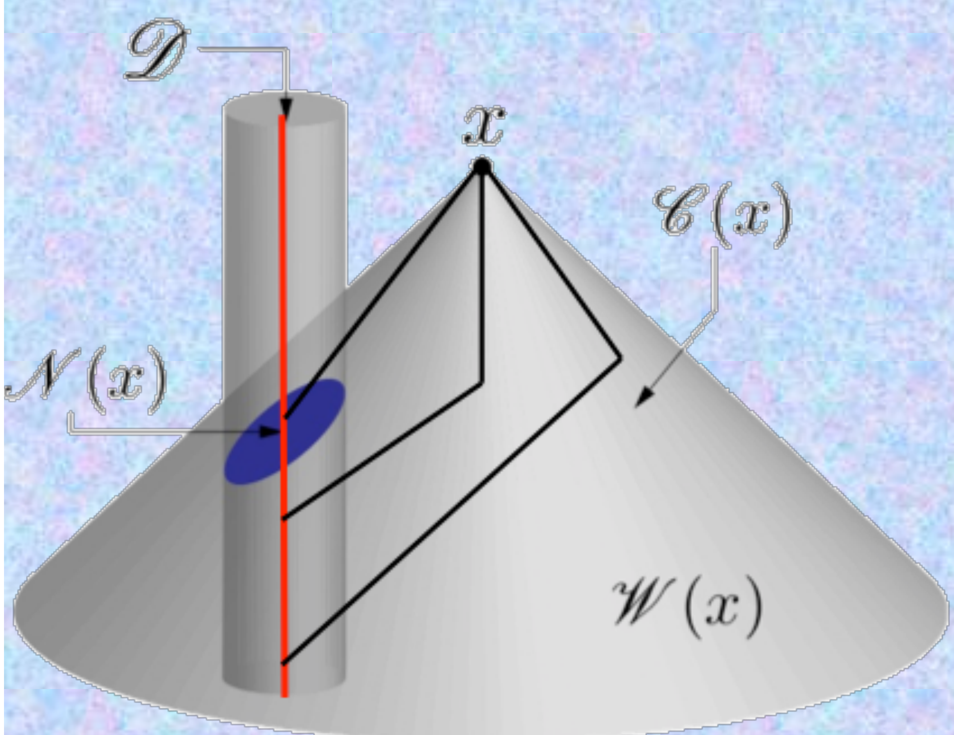
$$\beta = \left(\frac{Gm\Omega}{c^3}\right)^{1/3} \sim \frac{v}{c}, \quad m = M_1 + M_2\,,\ \eta = \frac{M_1 M_2}{(M_1+M_2)^2}\,,\ \Delta = \frac{M_1 - M_2}{M_1 + M_2}$$

Beyond the quadrupole formula:

$$h_{+,\times} = \frac{2\eta G m}{c^2 R}\beta^2\Big[(1+2\pi\beta^3)H^{[0]}_{+,\times} + \Delta\beta H^{[1/2]}_{+,\times} + \beta^2 H^{[1]}_{+,\times} + \Delta\beta^3 H^{[3/2]}_{+,\times} + \beta^3 H^{\rm tail}_{+,\times} + O(\beta^4)\Big]$$

$$\beta = \left(\frac{G m \Omega}{c^3}\right)^{1/3}$$

$$H^{[0]}_{\times} = -2C\sin 2\Psi \qquad H^{\rm tail}_{\times} = 8C\left[\gamma + \ln(4\Omega R/c)\right]\cos 2\Psi$$



Combine with the leading term:

$$\sin 2\Psi - 4\frac{Gm\Omega}{c^3}\ln(4\Omega R/c)\cos 2\Psi$$
$$= \sin\left[2\Omega\left(t - R/c - 2\frac{Gm}{c^3}\ln(4\Omega R/c)\right)\right]$$

Shapiro time delay

Gravitational-wave estimates

$$h^{jk}_{\mathrm{TT}} = \frac{2G}{c^4 R}\ddot{I}^{jk}_{\mathrm{TT}}$$
$$\sim \frac{GM}{c^2 R}(v_c/c)^2 \quad \sim 4.8 \times 10^{-19}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{1\,\mathrm{Mpc}}{R}\right)(v_c/c)^2$$

Binary system

$$(v_c/c)^2 \sim GM/c^2 a \sim (2\pi GM/c^3 P)^{2/3}$$

$$h_0 \simeq \frac{3.0 \times 10^{-21}}{1-e^2}\left(\frac{\mathcal{M}}{20\,M_\odot}\right)^{5/3}\left(\frac{10\,\mathrm{ms}}{P}\right)^{2/3}\left(\frac{100\,\mathrm{Mpc}}{R}\right)$$

Chirp mass

$$\mathcal{M} \equiv \eta^{3/5} m = \left(\frac{m_1^3 m_2^3}{m}\right)^{1/5}$$

Deformed neutron star

$$h_0 \simeq 6.8 \times 10^{-25}\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{I_3}{1.6 \times 10^{38}\ \mathrm{kg\,m^2}}\right)\left(\frac{10\ \mathrm{ms}}{P}\right)^2\left(\frac{1\ \mathrm{kpc}}{R}\right)$$

Supernova core collapse

$$h_0 \sim 4.8 \times 10^{-21}\left(\frac{\varepsilon}{10^{-3}}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{10\,\mathrm{kpc}}{R}\right)$$

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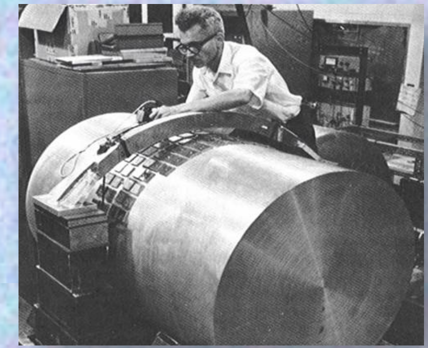
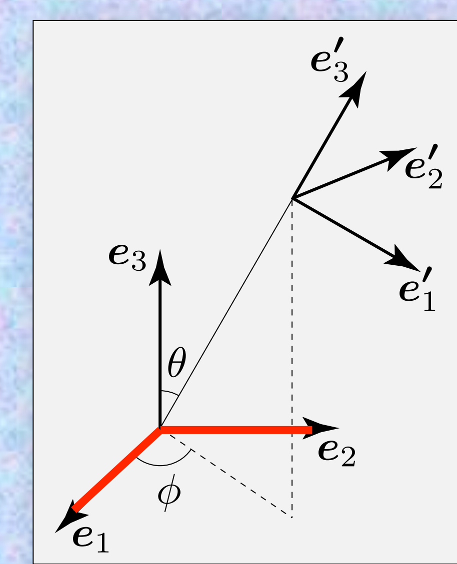
Joseph Weber & Gravitational Waves: Case History in How Science Works

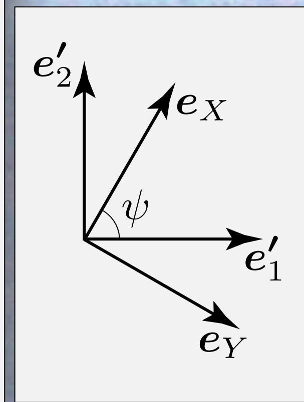


Joe Weber (1919-2000)

- pioneer in electronics, masers and lasers
- 1959 - learned GR, began building GW detectors
- 1969 - reported coincident events in detectors 1000 km apart
- 1971 - more events when bars were perpendicular to galactic center
- strength of signals 1000 times stronger than anybody expected
- 1970s - spurred theoretical work on black holes, neutron stars, supernovas
  - ✓ could not explain Weber's events
- 1970s - spurred other groups to build detectors of better sensitivity
  - ✓ no events detected
- 1980 - consensus developed - no GW seen directly by Weber
- 1980 - 2004 - work on advanced "Weber bars" continued
- mid 1980s - plans developed for large "laser interferometer" observatories
- 1994 - 1999 - construction of LIGO
- 2002 - LIGO's first science run
- 2003 - 2008 - Weber bar detectors phased out
- 2010 – 2015 - upgrade to advLIGO-advVIRGO
- 2015, Sept 14 – detection of waves from binary black hole inspiral

Laser interferometers





Phase difference between 2 arms:

$$\Delta\Phi = 2\pi\nu(2L_1/c - 2L_2/c)$$

Displacement due to the wave:

$$\xi_1^j = L_0\left(e_1^j + \frac{1}{2}h_{\mathrm{TT}}^{jk}e_1^k\right)$$

$$\xi_2^j = L_0\left(e_2^j + \frac{1}{2}h_{\mathrm{TT}}^{jk}e_2^k\right)$$

$$\Delta\Phi = \frac{4\pi\nu L_0}{c}\frac{1}{2}(e_1^j e_1^k - e_2^j e_2^k)h_{\mathrm{TT}}^{jk} = \frac{4\pi\nu G L_0}{c^5 R}S(t)$$

$$\begin{aligned} S(t) &= \frac{1}{2}(e_1^j e_1^k - e_2^j e_2^k)A_{\mathrm{TT}}^{jk}(\tau, \boldsymbol{N}) \\ &= F_+ A_+(t - R/c) + F_\times A_\times(t - R/c) \end{aligned}$$

$$\begin{aligned} A_{\mathrm{TT}}^{jk} &= (e_X^j e_X^k - e_Y^j e_Y^k)A_+ \\ &\quad + (e_X^j e_Y^k + e_Y^j e_X^k)A_\times \end{aligned}$$

Detector pattern functions

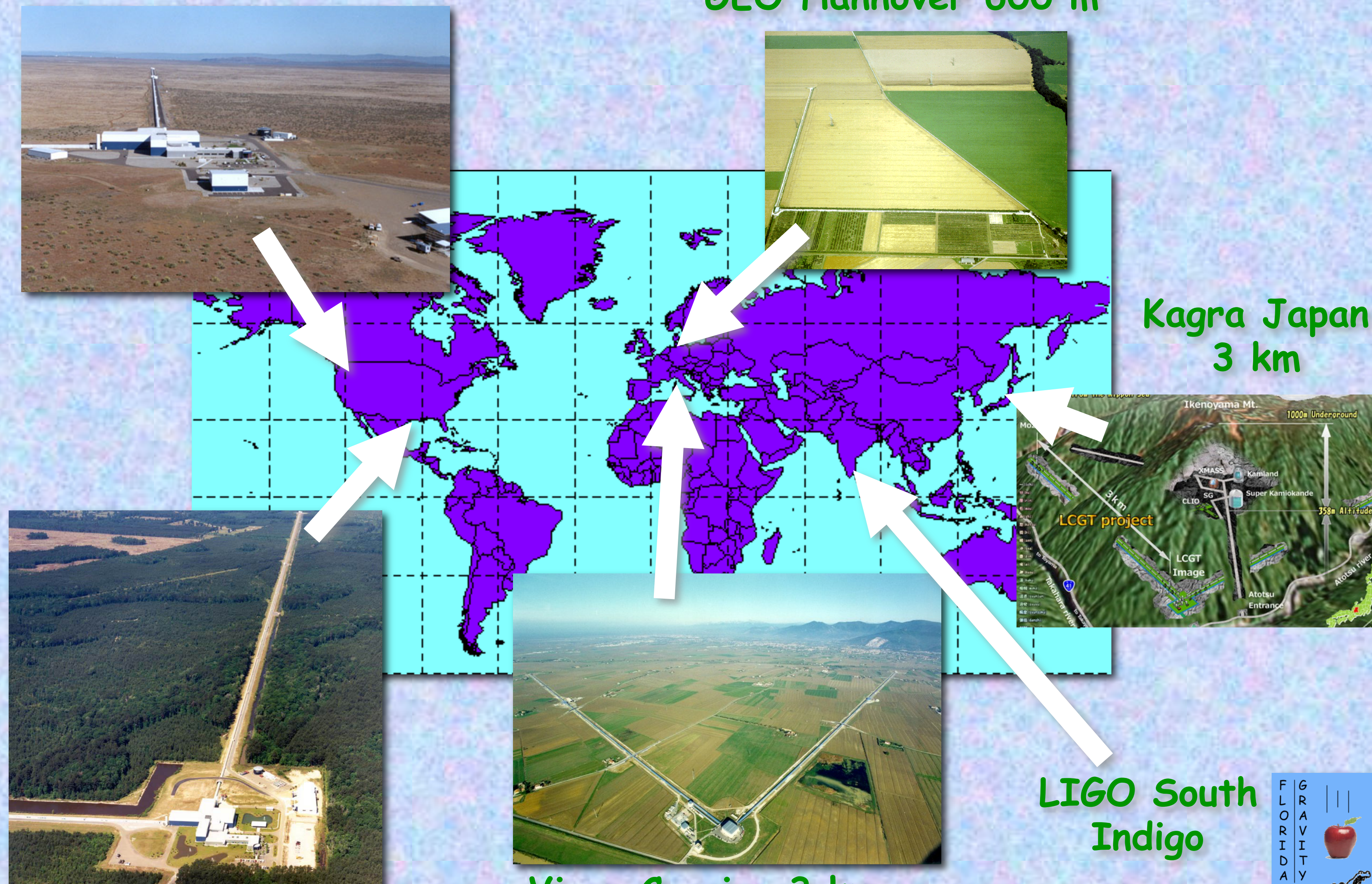
$$F_+ := \frac{1}{2}(e_1^j e_1^k - e_2^j e_2^k)(e_X^j e_X^k - e_Y^j e_Y^k) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \cos 2\psi - \cos\theta \sin 2\phi \sin 2\psi$$

$$F_\times := \frac{1}{2}(e_1^j e_1^k - e_2^j e_2^k)(e_X^j e_Y^k + e_Y^j e_X^k) = \frac{1}{2}(1 + \cos^2\theta)\cos 2\phi \sin 2\psi + \cos\theta \sin 2\phi \cos 2\psi$$

GW interferometers

LIGO Hanford 4&2 km

GEO Hannover 600 m



Kagra Japan
3 km

LIGO South
Indigo

LIGO Livingston 4 km

Virgo Cascina 3 km

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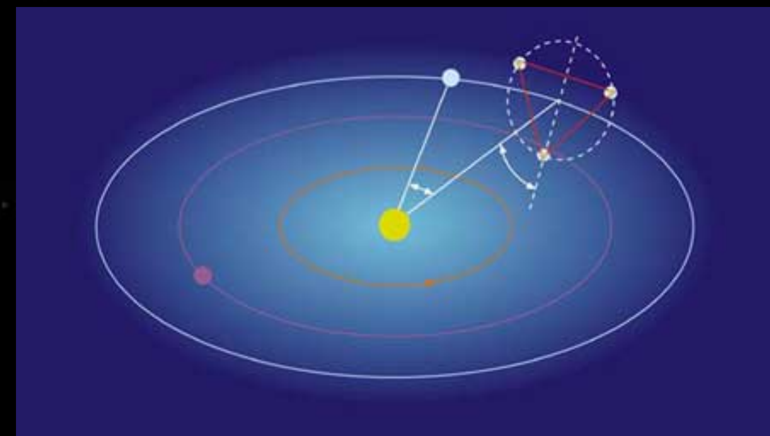
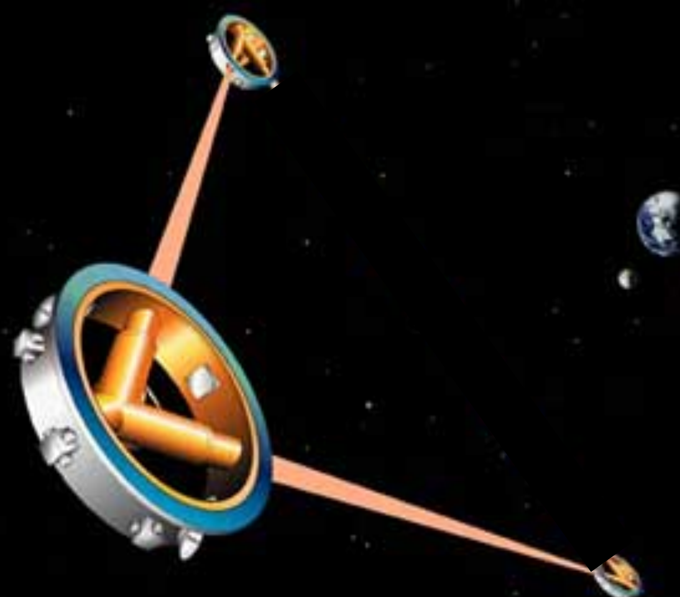
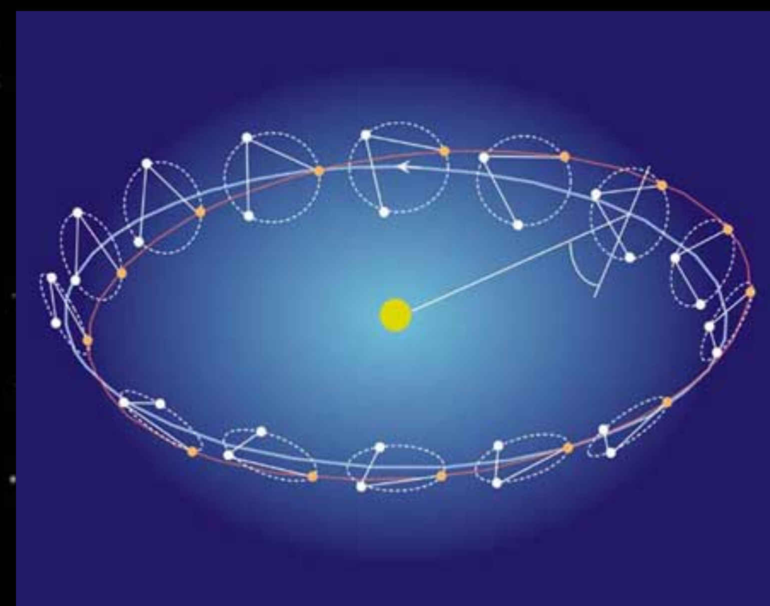
eLISA: a European space interferometer



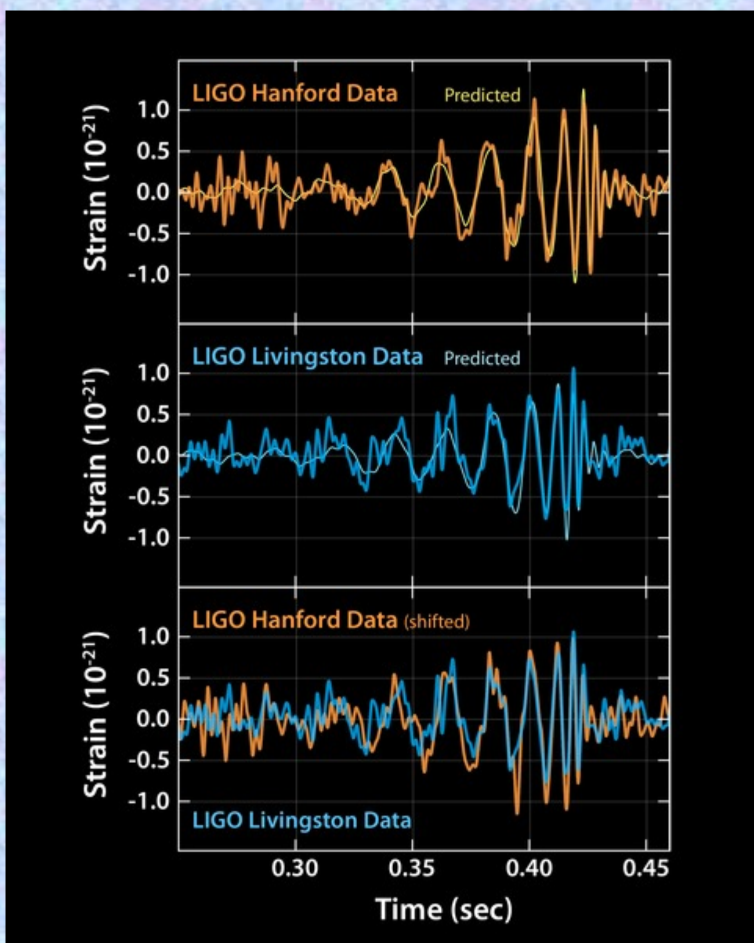




Pulsar Timing Arrays

LIGO detects gravitational waves!

- Advanced LIGO began operations in summer 2015
- 14 September, near the end of an "engineering run"
- Signals in both LIGO detectors, 7 milliseconds apart

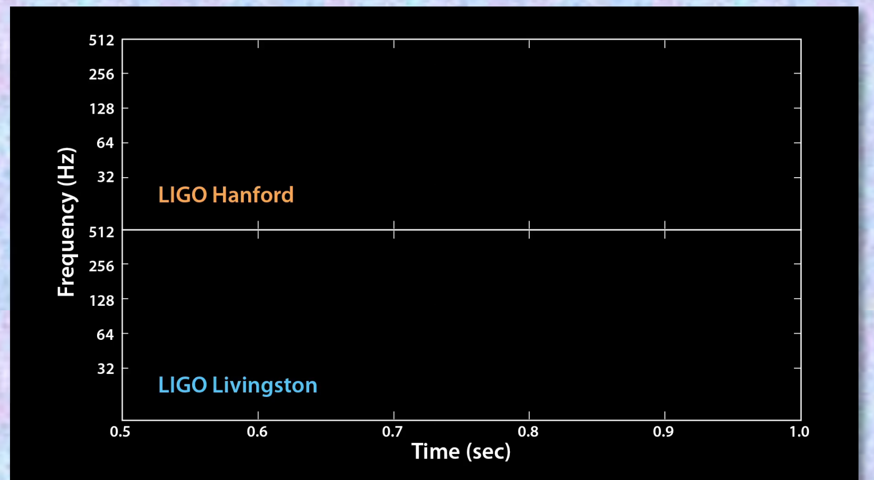


$$
\begin{aligned}
m_1 &= 36^{+5}_{-4}\, M_\odot \\
m_2 &= 29 \pm 4\, M_\odot \\
m_{\rm F} &= 62 \pm 4\, M_\odot \\
S_{\rm F}/m_{\rm F}^2 &= 0.67^{+0.05}_{-0.07} \\
D &= 1.3\,\text{bly} \\
L_{\max} &= 3.6 \times 10^{56}\,\text{erg/s}
\end{aligned}
$$

GW150914: a binary black hole merger

LIGO detects gravitational waves!

- Advanced LIGO began operations in summer 2015
- 14 September, near the end of an "engineering run"
- Signals in both LIGO detectors, 7 milliseconds apart



Audio Credit: Caltech/MIT/LIGO Lab

$$
\begin{aligned}
m_1 &= 36^{+5}_{-4}\, M_\odot \\
m_2 &= 29 \pm 4\, M_\odot \\
m_{\rm F} &= 62 \pm 4\, M_\odot \\
S_{\rm F}/m_{\rm F}^2 &= 0.67^{+0.05}_{-0.07} \\
D &= 1.3\,\text{bly} \\
L_{\max} &= 3.6 \times 10^{56}\,\text{erg/s}
\end{aligned}
$$

- SNR ~ 24, σ ~ 5.1, false alarm 1/203,000 yr
- 3 solar masses converted into energy in 0.2 sec
- More power than all the stars in the universe
- 1^{st} detection of a BBH, masses larger than expected
- Revised event rate 2 – 400 /Gpc^3/yr
- Data on GW150914 publicly available