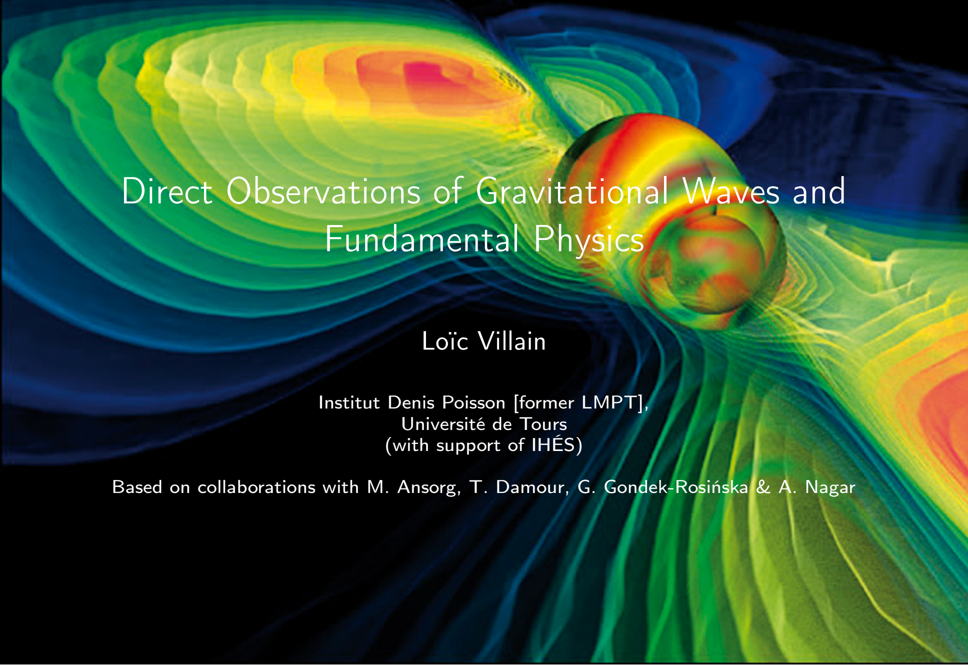

# Direct Observations of Gravitational Waves and Fundamental Physics

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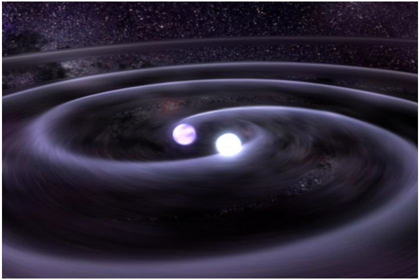
(with support of IHÉS)

Based on collaborations with M. Ansorg, T. Damour, G. Gondek-Rosińska & A. Nagar

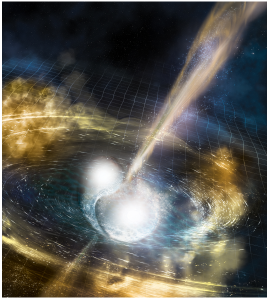
# GW150914

- Feb. 2016: announcement of the **detection** of gravitational waves (GW) by the **LIGO experiment**;
- **Some noticeable facts** :
  1. first **direct** detection (on **Sep. 14, 2015**);
  2. almost **100 yr** after their theoretical prediction by Einstein;
  3. advanced version of the detector still in **"engineering mode"**;
  4. in practice: measurement of **distances smaller than an atomic nucleus**;
  5. proof of the existence of binary black hole (BBH);
  6. first **direct** observation of black holes (BH).



# then...

- LIGO: **other detections** of GW from BBH;
- **Summer 2017**:
  - LIGO joined by **Virgo**;
  - first stereo detection of GW from a BBH;
  - first detection of GW from the merger of a binary neutron stars (BNS) system.
- **End 2017**: CNRS Gold Medal to Alain Brillet and Thibault Damour ; Nobel Prize in Physics to Rainer Weiss, Barry Barish & Kip Thorne;
- **30/11/2018**: announcement of 4 new detections (total: 10 BBH + 1 BNS) [all observed before 25/08/2017]



# Outline

# 1

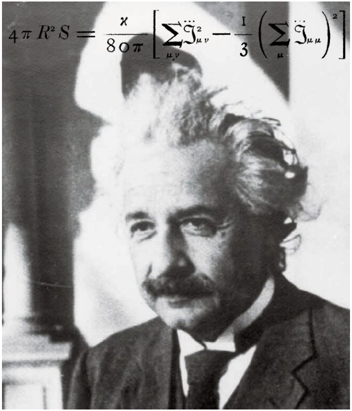
# Historical steps (incomplete story)

By. A. NAGAR

# Prediction of gravitational waves

## First mention

**1906, Poincaré**: any theory of gravitation with **Lorentz invariance** should contain some "ondes gravifiques" (but no valid/unique theory found)



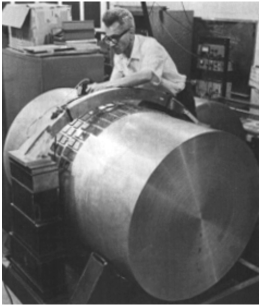

## Oscillations in general relativity (GR)

- **1916, Einstein**: "**gravitational waves**" in GR: progressive wave
- **1918, Einstein**: "**quadrupole formula**" ($\implies$ GW emissivity) for slow motions and weak gravitational field found in a fixed system of coordinates.

# Theoretical issues and evidences

- **Einstein & Rosen (1937)**: no physical plane GW in GR due to the presence of singularities in non-trivial solutions
- **Einstein, Droste, Eddington, Fock, Infeld, Dirac, Riesz, ... (1912-now)**: problem of motion (geodesics?, self-force, ...)
- **1957**: International Conference on Gravitation at **Chapell Hill** $\Longrightarrow$ beginning of a new era
- **Pirani (1956)**: "What would happen to my detector if a GW would go through my lab?" $\Longrightarrow$ **energy deposite** $\Longrightarrow$ physical detection possible [other important contributions: **Bondi, Robinson, Trautman, etc.**]
- **Bondi, Schoen, Yau, Witten (and others) (1962-1982)**: "What would happen to an objects emitting GW?" $\Longrightarrow$ **mass loss** until a positive value is reached $\Longrightarrow$ physical emission possible
- $\sim$ **1970-1980**: "quadrupole controversy" $\Longrightarrow$ is mathematical rigor (always) necessary?

# GW observation



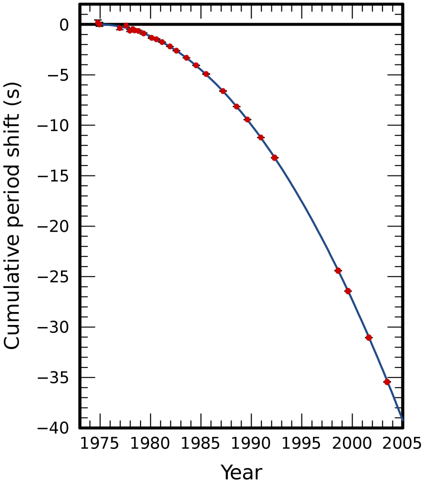
## First try of direct detection

**Weber (1965)**: first bar, no actual detection


## Observational proof

**Hulse & Taylor**: discovery in **1974** and precise observation of a **binary pulsar** $\Longrightarrow$ Nobel prize in 1993

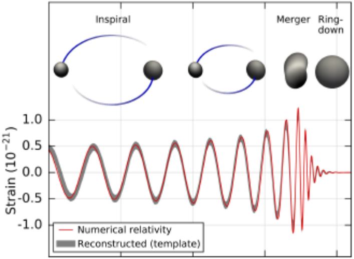
# Hulse & Taylor: indirect observation

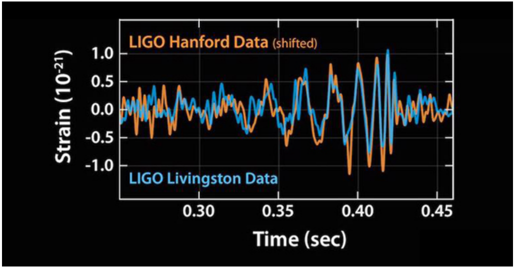



(from Weisberg & Taylor, 2004)

- indirect **experimental verification** of GW existence
- **very precise test of GR**: theoretical prediction versus observational data (red dots)
- current error bars due to uncertainty on astrophysical quantities (Earth-pulsar distance, etc.)
- made possible by **theoretical analysis** (Damour & Deruelle)

# GW150914

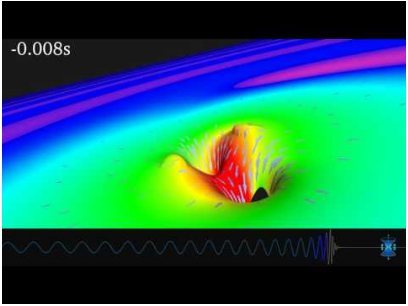



(Abbott et al. 2016/LIGO & Virgo Scientific collaborations)

- BBH (36 and 29 solar masses);
- $\sim$ 10 orbits in 0.2 s $\rightarrow v \sim 0.5\, c$ at merger;
- measured frequency: 35 Hz $\rightarrow$ 150 Hz;
- **observed relative distance variations** $\sim 10^{-21}$;
- source at 1.3 Gly from Earth.

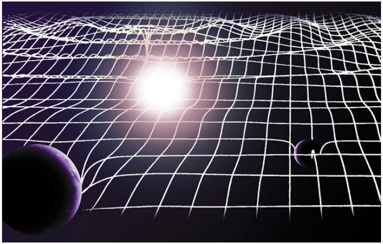
# Final BH




- **62 solar masses** $\rightarrow$ 3 $M_\odot$ emitted as GW;
- power at maximum $> 10^{49}$ W ($\sim 5 \times 10^{11}$ the EM power of the Milky Way; larger than the EM power of the observable Universe).

# 2

# GW in GR and beyond



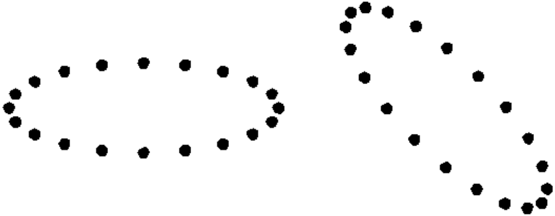
# GR: GW as a perturbation of the geometry

- rigorous **definition** in the full **non-linear** theory difficult to get (limited information from characteristic surfaces)
- **weak field description**:

$$\boldsymbol{g} = \boldsymbol{\eta} + \boldsymbol{h}$$

  with $\boldsymbol{g}$ = physical metric ($ds^2 = \boldsymbol{g}\, \boldsymbol{dx} \otimes \boldsymbol{dx}$), $\boldsymbol{\eta}$ = Minkowski and $\boldsymbol{h}$ = GW (**small oscillatory term**) $\Longrightarrow$ **Post-Minkowskian** decomposition, but not always natural;
- in **vacuum**, $\Box_\eta \boldsymbol{h} = 0$ (linearized equations);
- $\boldsymbol{h}$: symmetric second order tensor $\Longrightarrow$ **10 independant components**;
- **gauge (coordinates) fixing** $\Longrightarrow$ physical waves are transverse $\Longrightarrow$ **2 degrees of freedom** $\equiv$ **2 polarizations** [massless spin-2 field].
- **despite the non-linear equations of motion**: no dispersion of GW ($c_g = c$), but complicated **non-local** effects (**tail**, **memory**, etc.)

# GR: polarizations of GW



motion of **test masses** associated with the $+$ and $\times$ polarizations
(GW direction $\perp$ plane of the masses).

# Beyond GR

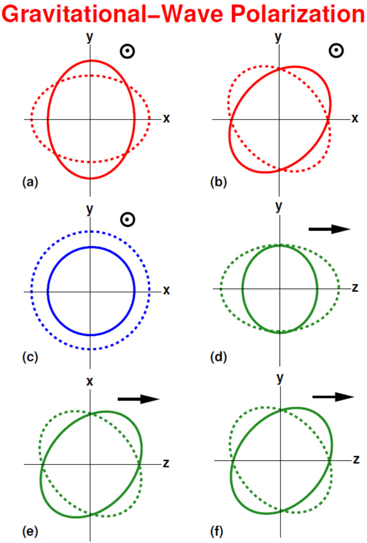
- **GR**: simplest relativistic theory of gravitation with "reasonable" properties

$$\text{Einstein-Hilbert Lagrangian :} \quad S = \int (R + 2\,\kappa\,\mathcal{L}_{\text{mat.}})\,\sqrt{g}\,d^4x$$

  with $R =$ Ricci scalar, $g =$ det. metric, and $\kappa = 8\pi G/c^4$;
- infinite number of other relativistic theories:
  - **tensor**: $f(R)$;
  - **scalar-tensor**: Brans-Dicke, Horndeski, degenerate higher-order scalar-tensor (DHOST) [Langlois, Noui, et al.]
  - **bimetric**: dRGT [ghost-free massive];
  - etc.
- some theories depend on several indeterminate **functions**
  $\Longrightarrow$ possibility of **extremely complicated equations of evolution**, **various types of GW**, etc.

# GW in metric theories

- **Assumptions**:
  1. ∃ metric;
  2. free fall = geodesic motion;
  3. in free fall, special relativity apply for non-gravitational interactions ( $\Longrightarrow$ equivalence principle).
- **Example**: scalar-tensor **without a direct coupling** between the scalar field and matter.
- **Modes:**
  - **GR**: (a) and (b);
  - **Massless** scalar-tensor theories: (a), (b) and (c);
  - **Massive** scalar-tensor theories: (a), (b), (c) and (d).




(from Will 2014)

# GWs emission and mass multipoles

## Electromagnetism

- at least time variations of electric **dipole** to emit electromagnetic waves
- breaking of spherical symmetry ($\sim$ massless spin 1 boson)
- also **magnetic emission**: variations of the distribution of electric currents

## Gravitation (GR)

- at least time variations of mass **quadrupole** to emit GWs in GR
- $\sim$ breaking of spherical and axial symmetries ($\sim$ massless spin 2 boson)
- also **gravito-magnetic emission**: variations of the distribution of mass currents

$\Longrightarrow$ the gravitational field (GW included) created by a **localized** source is uniquely described by a multipolar expansion (mass and current multipoles)

## Emissivity (Einstein 1918, Landau & Lifshitz 1949, etc.)

$$\frac{dE}{dt} \sim \frac{\mathcal{G}_\mathcal{N}}{c^5} s^2 \omega^6 M^2 R^4$$

- $s$ **breaking of symmetry**, $M$ mass, $R$ typical radius, $\omega$ typical frequency
- $\mathcal{G}_\mathcal{N}/c^5 \sim 3 \times 10^{-53}$ I.S. $\implies$ very weak emission
- no GWs in lab (current quadrupole: another $1/c$ factor)

## Astrophysical emissivity (Dyson 1963)

- trick: rewrite the formula with Schwarzschild radius, $R_s = 2M\mathcal{G}_\mathcal{N}/c^2$, typical velocity $v$, and $\omega \sim v/R$

$$\frac{dE}{dt} \sim \frac{c^5}{\mathcal{G}_\mathcal{N}} s^2 \left(\frac{R_s}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

- with astrophysical units the $10^{-53}$ factor has become a $10^{+53}$ factor...

## Typical amplitude in astrophysical units

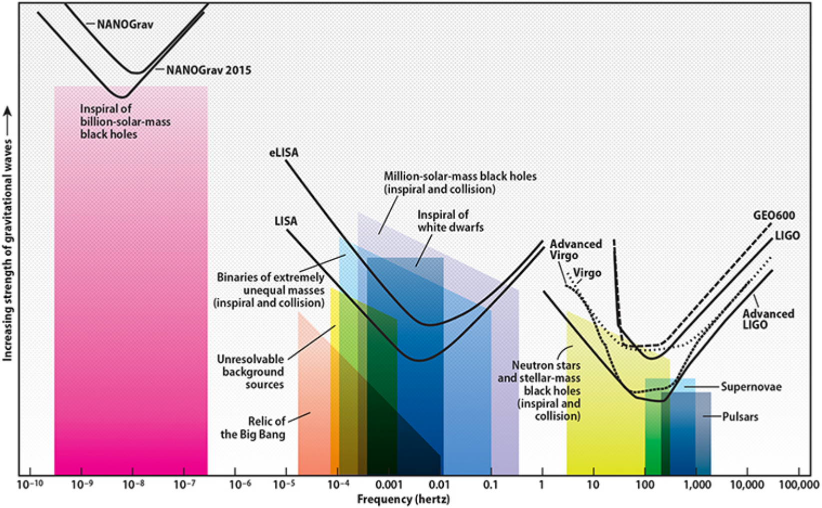
$$h \sim 2 \times 10^{-19} \left(\frac{M}{M_\odot}\right)^{1/2} \left(\frac{1\ \mathrm{Mpc}}{d}\right) \left(\frac{1\ \mathrm{kHz}}{f}\right) \left(\frac{1\ \mathrm{ms}}{\tau}\right)^{1/2} \epsilon^{1/2},$$

- $f$ frequency, $d$ distance to the source, $M_\odot$ solar mass, Mpc megaparsec ($\sim 3 \times 10^{22}$ m): Local group of galaxies, $\tau$ duration of the emission, $\epsilon$ efficacity (= ratio between emitted and mass energies)
- detection of $h$ and not $h^2$ $\rightarrow 1/d$ signal but weak...

## relevant (non-cosmological) sources

- relativistic ($v \sim c$) compact (high $M/R$) object with coherent internal motions (to avoid destructive interferences)
- compact binaries (black holes, neutron stars, strange stars) $+$ isolated compact object : oscillating, rotating (without axial symmetry) and/or accreting

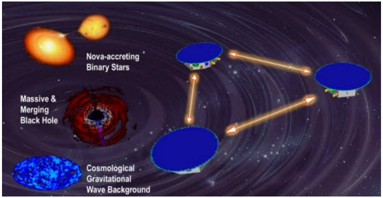
# Expected signals and detectability




(fig.: Kelly, after Moore, Cole, & Berry)

# 3

# Compact astrophysical objects



# Compact astrophysical objects

- central remnant ($\sim$ iron core) of core-collapse supernovæ;
- high **compactness parameter**: $\mathcal{C} = M/R$ in units $\mathcal{G}_{\mathcal{N}} = c = 1$ (Schwarzschild BH $= 0.5$; NS $\sim 0.3$; white dwarf $\sim 10^{-3}$; Sun $\sim 10^{-6}$)
- compactness $\neq$ density [an iron nucleus is dense but not compact]


- **NS**: $1 - 2M_{\odot}$ with $R \sim 10$ km $\Longrightarrow$ extreme conditions ($\rho \sim 10^{14}$ g/cm$^3$, superfluidity, etc.);
- **BH**: more compact; born from stars with $M_{\star} > 20\, M_{\odot}$ $\Longrightarrow$ no material surface
- **More exotic (?)**: black hole mimickers (gravastars), boson stars, preons stars, etc.

# BH in GR

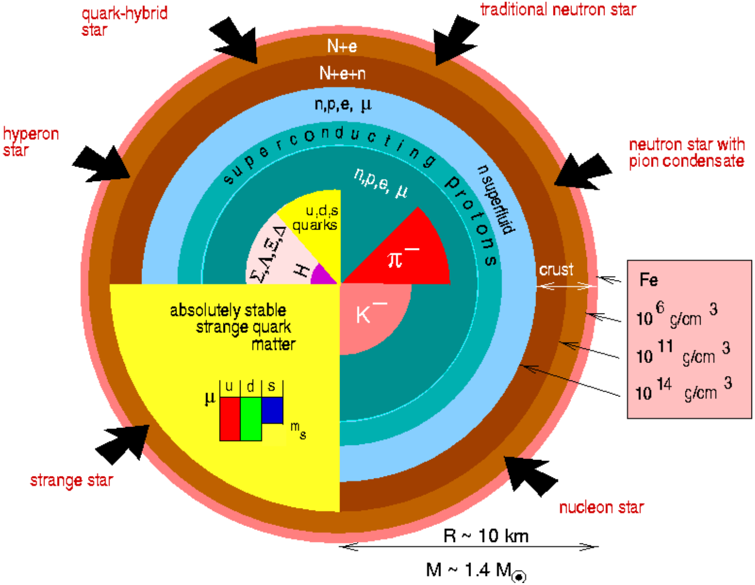
- **1916, Schwarzschild**: spherical solution of Einstein equations (characterized by its mass $M$);
- **1918, Reissner** $\&$ **Nordström**: spherical solution with electric charge $q$ $\implies$ irrelevant for astrophysical BH;
- **1923, Birkhoff**: Schwarzschild solution **unique** outside any **spherically symmetric** body;
- **1963, Kerr**: rotating BH with angular momentum $J$ $\implies$ Kerr-Newman (1965) with $q$ and $J$;
- **Wheeler**: no-hair theorem
  $\implies$ stationary BH **in GR** uniquely described by $M$, $J$ and $q$
  $\implies$ all **multipoles** (mass and current) of an astrophysical BH are **known functions** of $M$ and $J$

possibility to include $\Lambda \implies$ Schwarzschild-de Sitter spacetime, etc.

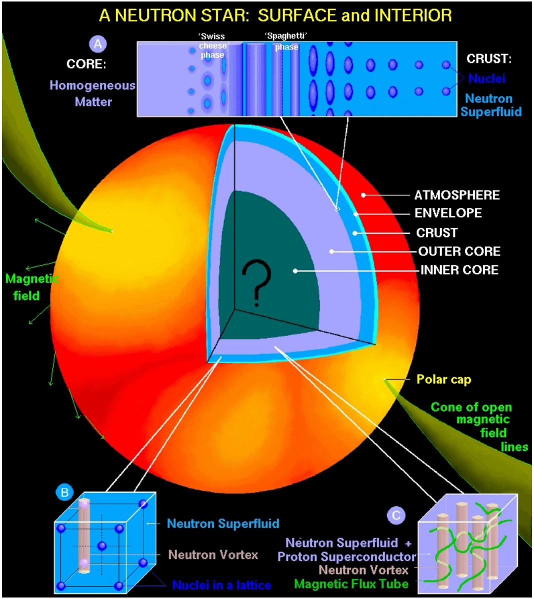
# NS and some of their exotic features

- **mass** of the Sun in a **10 km radius** ball: values depend on the equation of state (EOS) of the nuclear matter (not only neutrons!);
- magnetic flux conservation during core collapse
  $\Longrightarrow$ very high magnetic fields : $10^{8-9}$ G to $10^{13}$ G;
- (almost) conservation of angular momentum during core collapse
  $\Longrightarrow$ very high angular velocity (period $P \sim 1$ ms)
  $\Longrightarrow$ electromagnetic radiation (**lighthouse model of pulsars**);
- degenerate Fermi fluid of $n$, $p$ and $e$ in $\beta$-equilibrium
  (**at birth: opaque to** $\nu$);
- strong interaction
  $\Longrightarrow$ possible formation of nucleon Cooper paires
  $\Longrightarrow$ BCS superfluidity (for some densities since effective interaction):
  $T_F \sim 10^{11}$ K and $T \sim 10^9$ K;
- at very high densities: exotic particles and states? (pion condensate, hyperon crystal, deconfined quarks $\Longrightarrow$ strange star, etc.)

# Possible structures of an old compact star (fig. F. Weber)

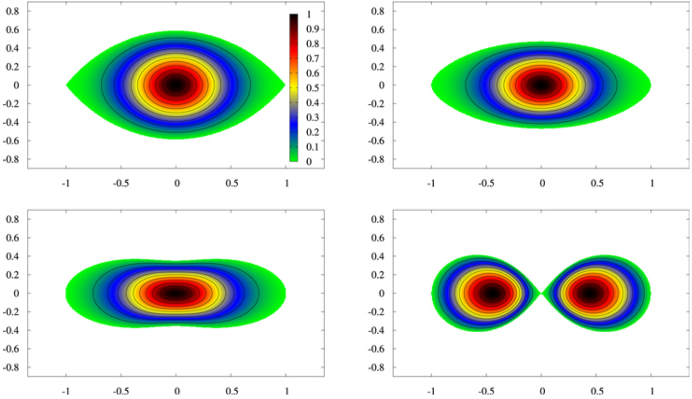


# Global view of a NS (fig. D. Page)



# Gravitational field and structure of a rotating compact star

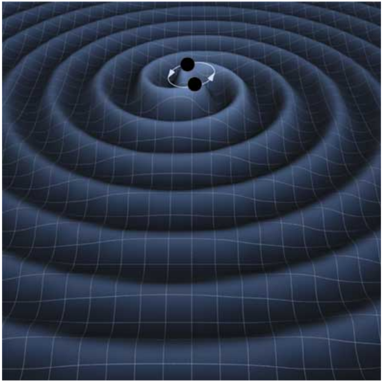
- the precise structure of a **stationary** NS depends on the equation of state
- a NS and its gravitational field are **not only** characterized by $M$ and $J$
  $\Longrightarrow$ multipoles depend on the EOS ($=$ microphysics)
- also strong influence of magnetic field and/or differential rotation



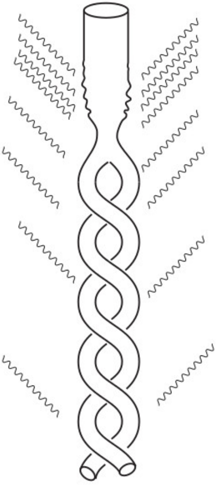
(from Gondek-Rosińska et al. 2016)

# 4

# GW from a compact binary

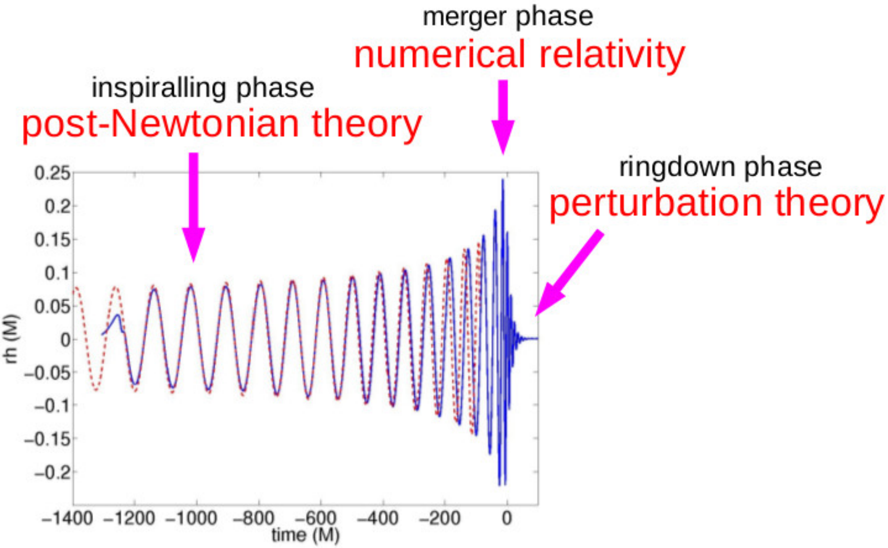


# Description of the merger of a compact binary



spacetime picture of the problem

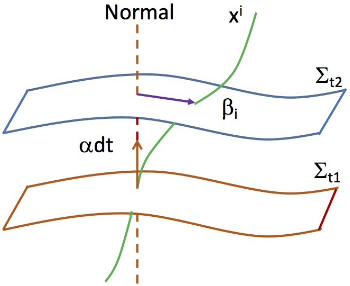
- **goal**: solving Einstein equations (+ equations for matter/EM field for BNS)
  $\Longrightarrow$ approximations required
- **early times**: weak field, slow motion
  $\Longrightarrow$ post-Newtonian (PN, powers of $v/c$) [Lorentz & Droste 1917, Einstein et al. 1918; Damour & Deruelle 1982; Blanchet, Faye, etc.]
- **late times**: perturbed BH
  $\Longrightarrow$ quasi-normal modes analysis (**if a BH is formed!**) [Regge & Wheeler 1957; Zerilli 1970; Thorne, etc.]
- **all times**: numerical relativity (breakthrough: Pretorius 2005, etc.)




usual complementary approaches (fig. Blanchet, cf. Brady, Craighton, Thorne 1998)

# Difficulties in numerical relativity

- $3+1$ **splitting** of the equation required ( $\Longrightarrow$ **evolution** and **constraints** equations, cf. Maxwell);
- choice of **gauge** (coordinates) but physical quantities have to be gauge independant;
- numerical errors (finite **resolution**, etc.);
- long duration of calculation (1 in several months);
- **finite** volume (space and time) of simulation but GW well defined at infinity;
- **horizon and singularities** (of BH) linked with divergences, etc.




(Fig. Eisenstein)

# Difficulties in the post-Newtonian formalism

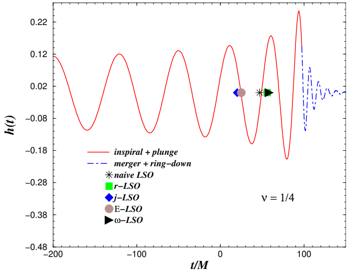
- complicated equations (number of terms increases with the order);
- need of matching between maps with **post-Minkowskian** far from the source and multipolar expansions (Blanchet-Damour approach);
- terms that are non-local in time (tail, memory);
- regularization of integrals needed;
- divergences when $v \sim c$ (light cylinder for rotating system, bad convergence of the expansion), etc.

$$
\begin{aligned}
\hat{H}_{4\mathrm{PN}}(\mathbf{r},\mathbf{p}) = {} & \left(\frac{7}{256} - \frac{63}{256}\nu + \frac{189}{256}\nu^2 - \frac{105}{128}\nu^3 + \frac{63}{256}\nu^4\right)(\mathbf{p}^2)^5 \\
& + \left\{\frac{45}{128}(\mathbf{p}^2)^4 - \frac{45}{16}(\mathbf{p}^2)^4\nu + \left(\frac{423}{64}(\mathbf{p}^2)^4 - \frac{3}{32}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^3 - \frac{9}{64}(\mathbf{n}\cdot\mathbf{p})^4(\mathbf{p}^2)^2\right)\nu^2\right. \\
& + \left(-\frac{1013}{256}(\mathbf{p}^2)^4 + \frac{23}{64}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^3 + \frac{69}{128}(\mathbf{n}\cdot\mathbf{p})^4(\mathbf{p}^2)^2 - \frac{5}{64}(\mathbf{n}\cdot\mathbf{p})^6\mathbf{p}^2 + \frac{35}{256}(\mathbf{n}\cdot\mathbf{p})^8\right)\nu^3 \\
& \left. + \left(-\frac{35}{128}(\mathbf{p}^2)^4 - \frac{5}{32}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^3 - \frac{9}{64}(\mathbf{n}\cdot\mathbf{p})^4(\mathbf{p}^2)^2 - \frac{5}{32}(\mathbf{n}\cdot\mathbf{p})^6\mathbf{p}^2 - \frac{35}{128}(\mathbf{n}\cdot\mathbf{p})^8\right)\nu^4\right\}\frac{1}{r} \\
& + \left\{\frac{13}{8}(\mathbf{p}^2)^3 + \left(-\frac{791}{64}(\mathbf{p}^2)^3 + \frac{49}{16}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^2 - \frac{889}{192}(\mathbf{n}\cdot\mathbf{p})^4\mathbf{p}^2 + \frac{369}{160}(\mathbf{n}\cdot\mathbf{p})^6\right)\nu\right. \\
& + \left(\frac{4857}{256}(\mathbf{p}^2)^3 - \frac{545}{64}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^2 + \frac{9475}{768}(\mathbf{n}\cdot\mathbf{p})^4\mathbf{p}^2 - \frac{1151}{128}(\mathbf{n}\cdot\mathbf{p})^6\right)\nu^2 \\
& \left. + \left(\frac{2335}{256}(\mathbf{p}^2)^3 + \frac{1135}{256}(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^2 - \frac{1649}{768}(\mathbf{n}\cdot\mathbf{p})^4\mathbf{p}^2 + \frac{10353}{1280}(\mathbf{n}\cdot\mathbf{p})^6\right)\nu^3\right\}\frac{1}{r^2} \\
& + \left\{\frac{105}{32}(\mathbf{p}^2)^2 + \left(\left(\frac{2749\pi^2}{8192} - \frac{589189}{19200}\right)(\mathbf{p}^2)^2 + \left(\frac{63347}{1600} - \frac{1059\pi^2}{1024}\right)(\mathbf{n}\cdot\mathbf{p})^2\mathbf{p}^2 + \left(\frac{375\pi^2}{8192} - \frac{23533}{1280}\right)(\mathbf{n}\cdot\mathbf{p})^4\right)\nu\right. \\
& + \left(\left(\frac{18491\pi^2}{16384} - \frac{1189789}{28800}\right)(\mathbf{p}^2)^2 + \left(-\frac{127}{3} - \frac{4035\pi^2}{2048}\right)(\mathbf{n}\cdot\mathbf{p})^2\mathbf{p}^2 + \left(\frac{57563}{1920} - \frac{38655\pi^2}{16384}\right)(\mathbf{n}\cdot\mathbf{p})^4\right)\nu^2 \\
& \left. + \left(-\frac{553}{128}(\mathbf{p}^2)^2 - \frac{225}{64}(\mathbf{n}\cdot\mathbf{p})^2\mathbf{p}^2 - \frac{381}{128}(\mathbf{n}\cdot\mathbf{p})^4\right)\nu^3\right\}\frac{1}{r^3} \\
& + \left\{\frac{105}{32}\mathbf{p}^2 + \left(\left(\frac{185761}{19200} - \frac{21837\pi^2}{8192}\right)\mathbf{p}^2 + \left(\frac{3401779}{57600} - \frac{28691\pi^2}{24576}\right)(\mathbf{n}\cdot\mathbf{p})^2\right)\nu\right. \\
& \left. + \left(\left(\frac{672811}{19200} - \frac{158177\pi^2}{49152}\right)\mathbf{p}^2 + \left(\frac{110099\pi^2}{49152} - \frac{21827}{3840}\right)(\mathbf{n}\cdot\mathbf{p})^2\right)\nu^2\right\}\frac{1}{r^4} \\
& + \left\{-\frac{1}{16} + \left(\frac{6237\pi^2}{1024} - \frac{169199}{2400}\right)\nu + \left(\frac{7403\pi^2}{3072} - \frac{1256}{45}\right)\nu^2\right\}\frac{1}{r^5} \\
& - \frac{1}{5}\frac{G^2M}{c^8} I_{ij}^{(3)}(t) \times \mathrm{Pf}_{2r_{12}/c}\int_{-\infty}^{+\infty}\frac{\mathrm{d}v}{|v|} I_{ij}^{(3)}(t+v)
\end{aligned}
$$

4PN term in the Hamiltonian (Damour et al. 2014)

# Effective One Body (EOB)

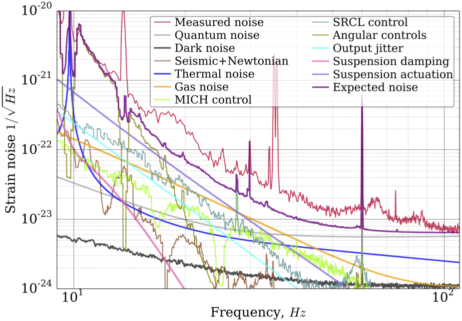
- **basic principle**: improved analytic description through a resummation of perturbative (PN) results [Buonanno & Damour 1999-2000, etc.]: point particle evolving in an effective metric (Schwarzschild or Kerr-like);
- **effective** Hamiltonian, energy flux, radiation-reaction force **calibrated** on NR and analytical results [based on **physical** processes: spin orbit coupling, etc.];
- blurred transition from inspiral to "plunge" (and then transition to ring-down) for BBH;
- possibility to include **tidal terms** for BNS (Damour & Nagar 2009)




GW signal for a BBH merger in the EOB approach (Buonanno & Damour 2000)

# Difficulties in all cases

- complicated and badly known microphysics (nuclear matter at high energy) with strong magnetic fields;
- gravitational equations already complicated in GR;
- determination of physical quantities only through the comparison with predicted signals $\Longrightarrow$ need of a huge bank of templates;
- expected signals with small amplitudes and drown in noise ( $\Longrightarrow$ match filtering, Bayesian inference, etc.).




Advanced LIGO noise budget (LIGO Scientific Collaboration)

# State of the art

- some preliminary results (**NR, PN, EOB**) for alternative theories of gravity (scalar-tensor mainly) [Cao et al. 2016, Okounkova et al 2017; Heffernan, Bernard, Will 2017; Julié & Deruelle 2017; etc.];
- PN and EOB results (often based on the **stationary phase approximation**) independent on the EOS at the lowest order (point-like sources), but exploration of EOS-dependent quantities started;
- in **all approaches**, need to better explore/understand spin effects;
- quite poor taking into account of **microphysics** in NR: dynamical situation $\Longrightarrow$ need to know out-of-equilibrium properties (transport coefficients, etc.) but few experimental data and in a different part of the phase diagram (heavy ions collisions, etc.);
- BNS: **LIGO-Virgo** only observe the inspiral phase (merger at higher frequency)
- BNS and BBH: limited part of the GW signal seen with unperfect resolution $\Longrightarrow$ **degeneracy in the parameter space** for the Bayesian inference...
- if one allows **beyond GR gravity**, as many free/unknown parameters in the gravitational sector as in the nuclear matter one...

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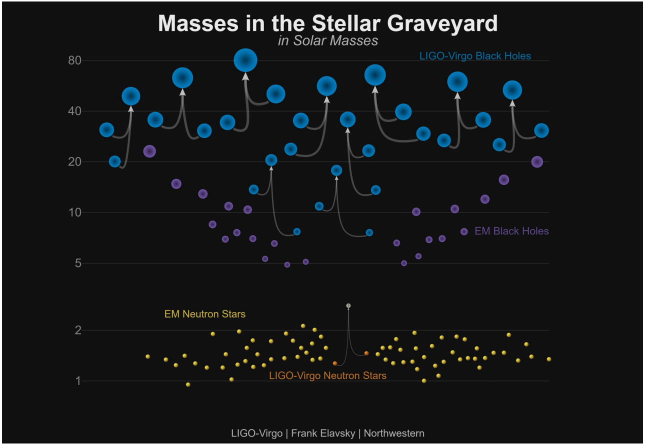
# Some results from direct observations

# Direct conclusions for stellar BBH

- **frequency** and its time derivative directly linked to the **chirp mass**, $\mathcal{M}^5 = (m_1 m_2)^3/(m_1+m_2)$;
- **amplitude** inversely proportional to the **luminosity distance**;
- position in the sky badly known if only 2 LIGO and no Virgo;
- uncertainties on distance linked with the inclination of the binary.

| Event | $m_1/\mathrm{M}_\odot$ | $m_2/\mathrm{M}_\odot$ | $\mathcal{M}/\mathrm{M}_\odot$ | $\chi_{\mathrm{eff}}$ | $M_{\mathrm{f}}/\mathrm{M}_\odot$ | $a_{\mathrm{f}}$ | $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$ | $\ell_{\mathrm{peak}}/(\mathrm{erg\,s^{-1}})$ | $d_L$/Mpc | $z$ | $\Delta\Omega/\mathrm{deg}^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| GW150914 | $35.6^{+4.8}_{-3.0}$ | $30.6^{+3.0}_{-4.4}$ | $28.6^{+1.6}_{-1.5}$ | $-0.01^{+0.12}_{-0.13}$ | $63.1^{+3.3}_{-3.0}$ | $0.69^{+0.05}_{-0.04}$ | $3.1^{+0.4}_{-0.4}$ | $3.6^{+0.4}_{-0.4}\times 10^{56}$ | $430^{+150}_{-170}$ | $0.09^{+0.03}_{-0.03}$ | 179 |
| GW151012 | $23.3^{+14.0}_{-5.5}$ | $13.6^{+4.1}_{-4.8}$ | $15.2^{+2.0}_{-1.1}$ | $0.04^{+0.28}_{-0.19}$ | $35.7^{+9.9}_{-3.8}$ | $0.67^{+0.13}_{-0.11}$ | $1.5^{+0.5}_{-0.5}$ | $3.2^{+0.8}_{-1.7}\times 10^{56}$ | $1060^{+540}_{-480}$ | $0.21^{+0.09}_{-0.09}$ | 1555 |
| GW151226 | $13.7^{+8.8}_{-3.2}$ | $7.7^{+2.2}_{-2.6}$ | $8.9^{+0.3}_{-0.3}$ | $0.18^{+0.20}_{-0.12}$ | $20.5^{+6.4}_{-1.5}$ | $0.74^{+0.07}_{-0.05}$ | $1.0^{+0.1}_{-0.2}$ | $3.4^{+0.7}_{-1.7}\times 10^{56}$ | $440^{+180}_{-190}$ | $0.09^{+0.04}_{-0.04}$ | 1033 |
| GW170104 | $31.0^{+7.2}_{-5.6}$ | $20.1^{+4.9}_{-4.5}$ | $21.5^{+2.1}_{-1.7}$ | $-0.04^{+0.17}_{-0.20}$ | $49.1^{+5.2}_{-3.9}$ | $0.66^{+0.08}_{-0.10}$ | $2.2^{+0.5}_{-0.5}$ | $3.3^{+0.6}_{-0.9}\times 10^{56}$ | $960^{+430}_{-410}$ | $0.19^{+0.07}_{-0.08}$ | 924 |
| GW170608 | $10.9^{+5.3}_{-1.7}$ | $7.6^{+1.3}_{-2.1}$ | $7.9^{+0.2}_{-0.2}$ | $0.03^{+0.19}_{-0.07}$ | $17.8^{+3.2}_{-0.7}$ | $0.69^{+0.04}_{-0.04}$ | $0.9^{+0.0}_{-0.1}$ | $3.5^{+0.4}_{-1.3}\times 10^{56}$ | $320^{+120}_{-110}$ | $0.07^{+0.02}_{-0.02}$ | 396 |
| GW170729 | $50.6^{+16.6}_{-10.2}$ | $34.3^{+9.1}_{-10.1}$ | $35.7^{+6.5}_{-4.7}$ | $0.36^{+0.21}_{-0.25}$ | $80.3^{+14.6}_{-10.2}$ | $0.81^{+0.07}_{-0.13}$ | $4.8^{+1.7}_{-1.7}$ | $4.2^{+0.9}_{-1.5}\times 10^{56}$ | $2750^{+1350}_{-1320}$ | $0.48^{+0.19}_{-0.20}$ | 1033 |
| GW170809 | $35.2^{+8.3}_{-6.0}$ | $23.8^{+5.2}_{-5.1}$ | $25.0^{+2.1}_{-1.6}$ | $0.07^{+0.16}_{-0.16}$ | $56.4^{+5.2}_{-3.7}$ | $0.70^{+0.08}_{-0.09}$ | $2.7^{+0.6}_{-0.6}$ | $3.5^{+0.6}_{-0.9}\times 10^{56}$ | $990^{+320}_{-380}$ | $0.20^{+0.05}_{-0.07}$ | 340 |
| GW170814 | $30.7^{+5.7}_{-3.0}$ | $25.3^{+2.9}_{-4.1}$ | $24.2^{+1.4}_{-1.1}$ | $0.07^{+0.12}_{-0.11}$ | $53.4^{+3.2}_{-2.4}$ | $0.72^{+0.07}_{-0.05}$ | $2.7^{+0.4}_{-0.3}$ | $3.7^{+0.4}_{-0.5}\times 10^{56}$ | $580^{+160}_{-210}$ | $0.12^{+0.03}_{-0.04}$ | 87 |
| GW170817 | $1.46^{+0.12}_{-0.10}$ | $1.27^{+0.09}_{-0.09}$ | $1.186^{+0.001}_{-0.001}$ | $0.00^{+0.02}_{-0.01}$ | $\leq 2.8$ | $\leq 0.89$ | $\geq 0.04$ | $\geq 0.1\times 10^{56}$ | $40^{+10}_{-10}$ | $0.01^{+0.00}_{-0.00}$ | 16 |
| GW170818 | $35.5^{+7.5}_{-4.7}$ | $26.8^{+4.3}_{-5.2}$ | $26.7^{+2.1}_{-1.7}$ | $-0.09^{+0.18}_{-0.21}$ | $59.8^{+4.8}_{-3.8}$ | $0.67^{+0.07}_{-0.08}$ | $2.7^{+0.5}_{-0.5}$ | $3.4^{+0.5}_{-0.7}\times 10^{56}$ | $1020^{+430}_{-360}$ | $0.20^{+0.07}_{-0.07}$ | 39 |
| GW170823 | $39.6^{+10.0}_{-6.6}$ | $29.4^{+6.3}_{-7.1}$ | $29.3^{+4.2}_{-3.2}$ | $0.08^{+0.20}_{-0.22}$ | $65.6^{+9.4}_{-6.6}$ | $0.71^{+0.08}_{-0.10}$ | $3.3^{+0.9}_{-0.8}$ | $3.6^{+0.6}_{-0.9}\times 10^{56}$ | $1850^{+840}_{-840}$ | $0.34^{+0.13}_{-0.14}$ | 1651 |

LIGO & Virgo collaborations, 1811.12907



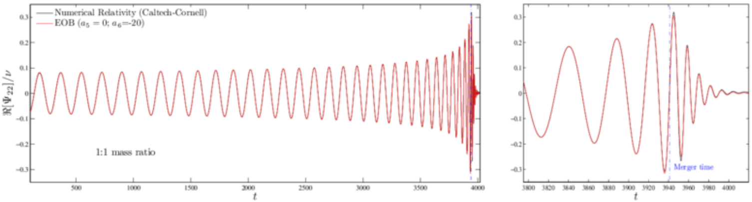

LIGO & Virgo collaborations, 1811.12907

- important population of massive stellar BH $\implies$ pop. III progenitors? primordial BH? dark matter?
- **mass gap** between NS and BH?
- small spins of BH $\implies$ contradiction with X-ray binaries observations?

# Spacetime properties from BBH and BNS

- possibility to **independently** analyze the ring-down and the inspiral phases $\Longrightarrow$ coherence between the GR predictions;
- constraint on some PN parameters from inspiral $\Longrightarrow$ **tail term**, etc.
- stronger bound on the **graviton mass** due to the absence of dispersion;
- for LIGO-Virgo observations: test of **polarization** (impossible with LIGO only);
- BNS allows Hubble constant measurement $\Longrightarrow$ precision of $2\%$ within 5 years (Chen et al., *Nature* 2018);
- delay between GW and GRB $\Longrightarrow$ $c_g = c$ at $10^{-15}$

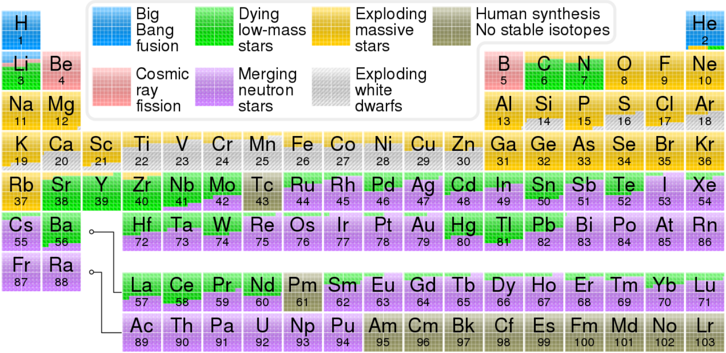
$\Longrightarrow$ elimination of many alternative to GR, but still many left...




(fig. Damour & Nagar 2009)

# Nuclear matter properties from BNS (GW170817)

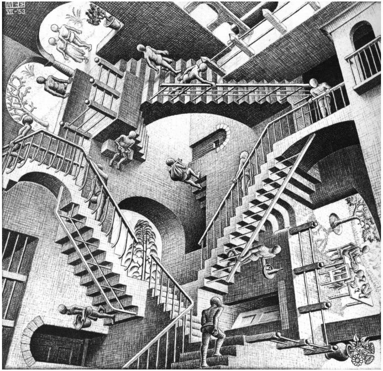
- estimation of the radii of the NS and their masses
  $\Longrightarrow$ constraints on the EOS;
- optical afterglow $\Longrightarrow$ proof of the formation of heavy elements;
- more BNS observation $\Longrightarrow$ observation of EOS dependent tidal effects (?) (Damour, Nagar & Villain 2012)




(fig. Wikipedia, based on data by J. Johnson)

# Conclusion

# The Future ?



# Listening to the Universe

- **GW** $\sim$ "Musica Universalis" $\implies$ we just left the time of silent astronomy;
- **few** detections $\implies$ already **a lot** of information $\implies$ many people joining the fieldS (theory, experiments);
- for the moment: GR works pretty well (as usual...)
- **Feb. 2019**: the **detectors are back** $\implies$ many more detections expected;
- Later: new interferometers (KAGRA, Japan; LIGO India; Einstein Telescope; LISA), new technics (**pulsar timing**), etc.;
- Also: **electromagnetic** observation of the neighbourhood of BH [GRAVITY (LESIA Meudon Observatory); Event Horizon Telescope]

$\implies$ new era for relativistic astrophysics (and not only)

# Links/References


- `http://www.black-holes.org/gw150914`: videos;
- `http://www.soundsofspacetime.org`: artificial sounds;
- D. Kennefick, *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves* (Princeton University Press, 2007);
- N. Deruelle & J-P. Lasota, *Les ondes gravitationnelles* (Odile Jacob, 2018).