Modéliser les signaux d'ondes gravitationnelles

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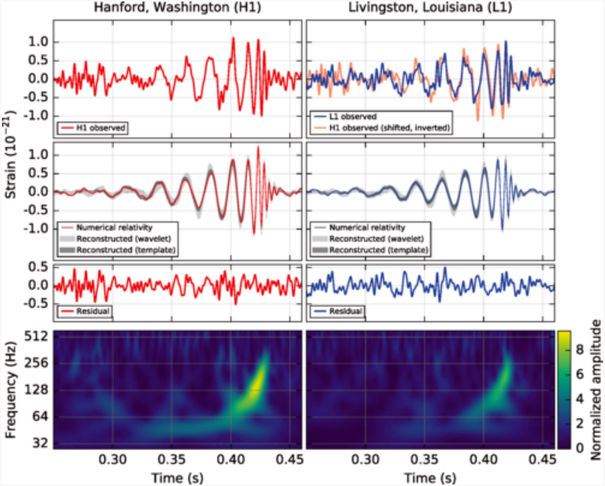
LUTH Observatoire de Paris | PSL cnrs

The first gravitational wave detection



LIGO-Virgo GW150914

Chirp: $\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3}f^{11/3}\,, \qquad \mathcal{M} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$

What I won't speak about...

$$
\begin{aligned}
L^{(4)}_{\mathrm{NNLO}} = {} & \frac{\alpha^4}{c^6 {r_{12}}^6}\frac{\zeta}{1-\zeta}\Bigg[\lambda_1^{(0)}\Bigg({m_1}^2{m_2}^2\Big(\bar\gamma(2+\bar\gamma)^2(\tfrac{4}{20}-\tfrac{3}{20}\bar\gamma)-\frac{\bar\delta_2\big(22\bar\gamma^2+12\bar\gamma^3+3\bar\gamma^4-160\bar\gamma\bar\beta_2+20\bar\gamma^2\bar\beta_2+160(\bar\beta_2)^2+80\bar\gamma\bar\chi_2\big)}{5\bar\gamma^2}\Big) \\
& + {m_2}^4\Big(-(\bar\delta_2)^2\frac{1}{(1-\zeta)\zeta}\big(4\zeta+21\zeta^2-58\zeta\lambda_1+40(\lambda_1)^2-8\lambda_2\big)+\bar\delta_2(2+\bar\gamma)^2\big(-\tfrac{13}{4}+\frac{3}{2(1-\zeta)}(5\zeta-4\lambda_1)(1-2s_2)\big)\Big) \\
& + m_1{m_2}^3\Big((\bar\delta_2)^2\frac{1}{(1-\zeta)\bar\gamma^2}6(\bar\gamma^2+8\bar\beta_2)(5\zeta-4\lambda_1)(1-2s_1)+\bar\delta_2\big(-\frac{79\bar\gamma^2+41\bar\gamma^3+8\bar\gamma^2\bar\beta_1-64\bar\gamma\bar\beta_2-24\bar\gamma^2\bar\beta_2+64\bar\beta_1\bar\beta_2}{\bar\gamma^2} \\
& + \frac{3}{2(1-\zeta)}(2+\bar\gamma)^2(5\zeta-4\lambda_1)(1-2s_2)\big)\Big)\Bigg) \\
& + \frac{\zeta}{1-\zeta}\bar\delta_2\phi_0\lambda_1^{(1)}\Bigg(-\frac{4{m_2}^4\bar\delta_2(6\zeta-5\lambda_1)}{\zeta}+3(2+\bar\gamma)^2{m_2}^4(1-2s_2)+\frac{6(2+\bar\gamma)m_1{m_2}^3(\bar\gamma-4\bar\beta_2)(1-2s_2)}{\bar\gamma}\Bigg) \\
& + \frac{-4\zeta}{1-\zeta}{m_2}^4(\bar\delta_2)^2{\phi_0}^2\lambda_1^{(2)}\Bigg]+[1\leftrightarrow 2]\,. \qquad (31e)
\end{aligned}
$$

LB, Dones, Mougiakakos '23

(A fraction of) the conservative Lagrangian at next-to-next-to-leading order in scalar-tensor theories

How to arrive at this result?

- Precise gravitational waveforms in general relativity
  - dynamics of compact objects
  - gravitational flux and waveform (phase & amplitude)
- Do the same for other theories of gravity

… and what I will say instead

Why do we need:

… and what I will say instead

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- to have a bank of extremely precise waveform templates?
  - data analysis: signal $h \sim \frac{\delta L}{L} \sim 10^{-18}$

… and what I will say instead

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  - ▷ GR highly non linear $\Longrightarrow$ numerical and analytical calculations

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Why do we need:

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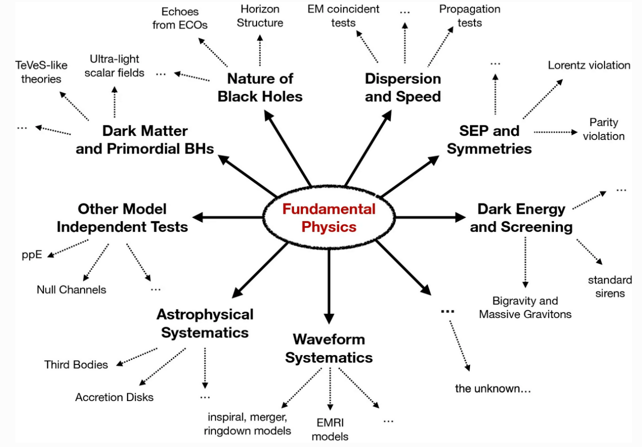
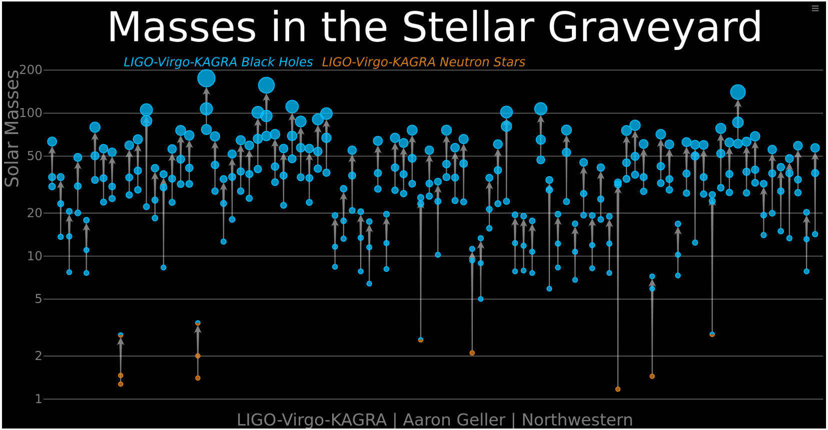
- to use different modeling techniques?
  - ▷ GR highly non linear $\Longrightarrow$ numerical and analytical calculations
- to go beyond GR?

Going beyond GR: why?

- high energy regime: quantum completion of GR
- low energy regime: dark sectors
  - dark energy $\longrightarrow$ cosmological constant and/or modified gravity?
  - dark matter $\longrightarrow$ new matter and/or modified gravity?

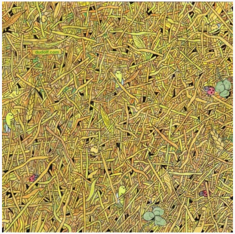


The current gravitational wave universe

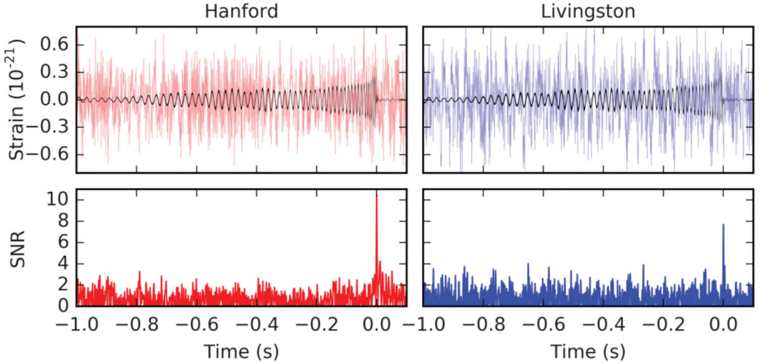


Chercher une aiguille dans une botte de foin *

* Looking for a needle in a haystack



LIGO-Virgo GW151226



Chercher une aiguille dans une botte de foin *

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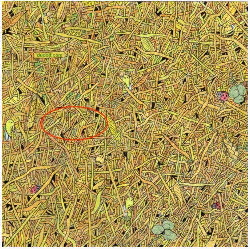
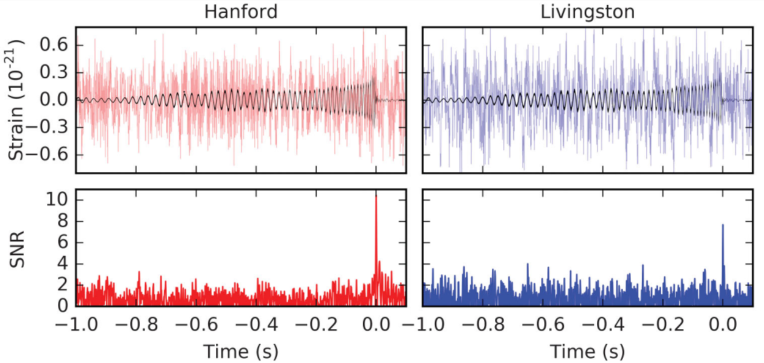
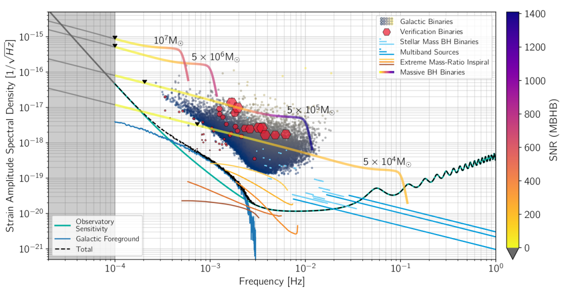
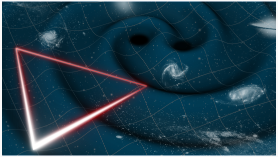


LIGO-Virgo GW151226



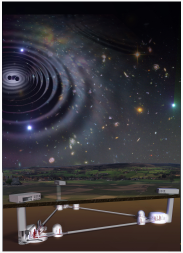
The future gravitational wave universe

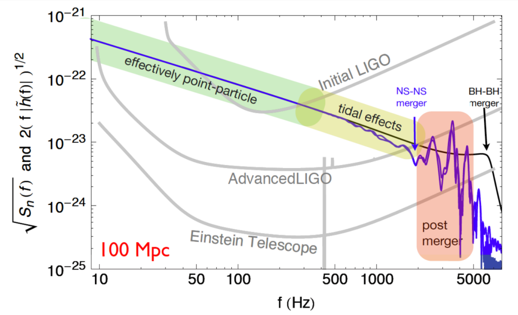




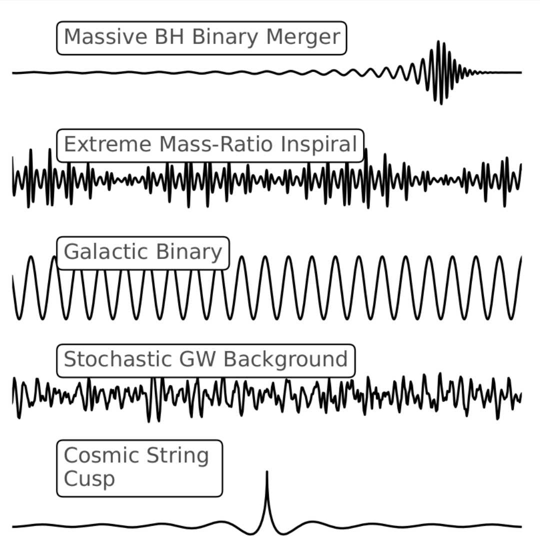
LISA definition study report (2023)

Einstein Telescope science case (2021)



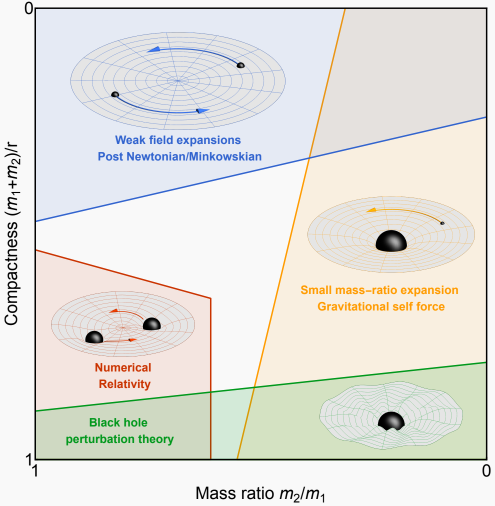


Gravitational waveforms



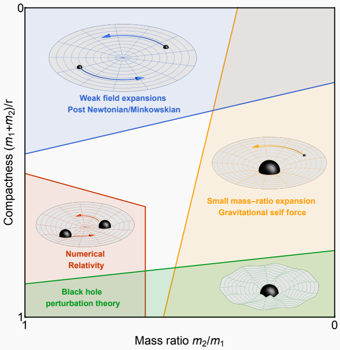
LISA definition study report 2023

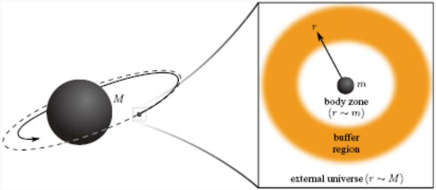
The different methods



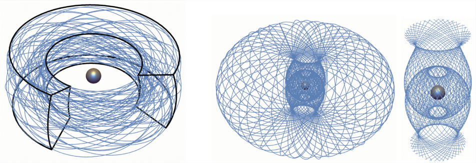
- ▷ Inspiral-Merger-Ringdown (IMR): *effective-one-body, phenomenological* & *surrogate models*

The different methods: gravitational self-force





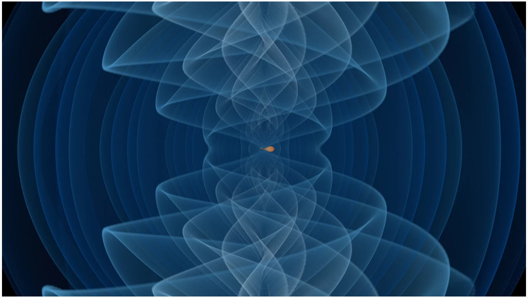
- ▷ extreme mass ratio inspiral
- ▷ expansion in $q = \frac{m_1}{m_2} \ll 1$
- ▷ resonances, par ex. 2:3



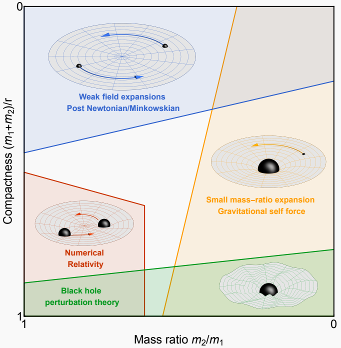
Barack & Pound '18

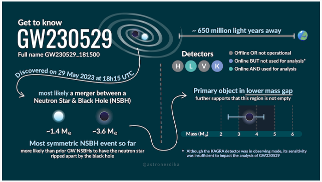
The different methods: numerical relativity

- solving the full Einstein equations
- computationally expensive
- add spins, eccentricity, *etc.*

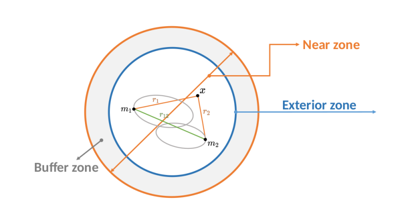


I. Markin, T. Dietrich, H. Pfeiffer, A. Buonanno (Potsdam University and Max Planck Institute for Gravitational Physics)

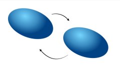




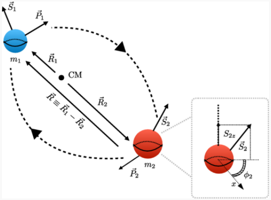
The different methods: post-Newtonian



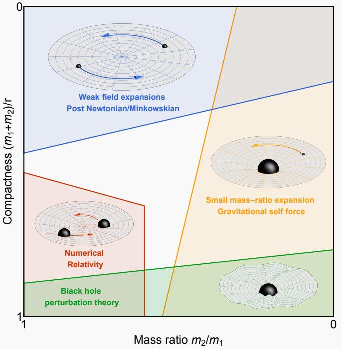
- ▷ expansion in $\epsilon = \frac{v_{12}^2}{c^2} \sim \frac{G(m_1)}{r_{12}c^2} \ll 1$
- ▷ point-particle approximation



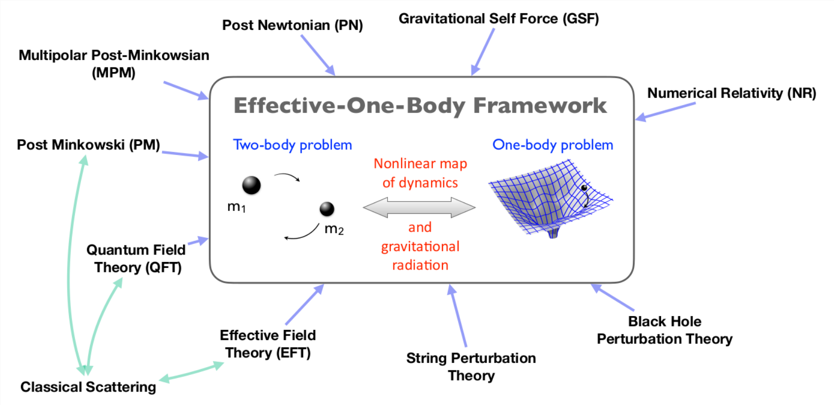
- ▷ add spins, tides, *etc.*



Tanay et al. '23



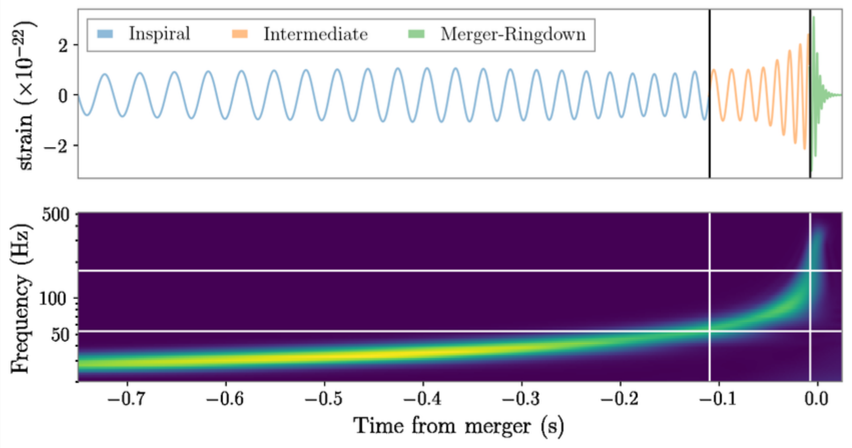
Full IMR waveform: the EOB class



LISA waveform white paper '23

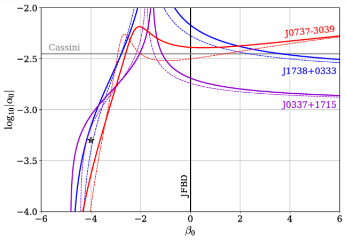
Full IMR waveform: the Phenom class

$$h(f) = \mathcal{A}(f)\, \mathrm{e}^{\psi_n(f)} \qquad \psi_n = \{\varphi_{0,..7},\ \sigma_{0..4},\ \beta_{1..3},\ \alpha_{0..5}\}$$



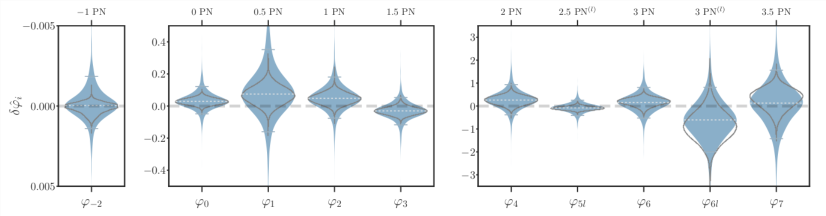
Kwok et al. '21

GR: a beautiful and successful theory



Kramer et al. '21

$$h(f) = \mathcal{A}(f)\ \mathrm{e}^{\psi_n(f)+\delta\psi_n(f)} \qquad \delta\psi_n = \{\delta\varphi_{-2,0,..7}\}$$



LIGO-Virgo '21

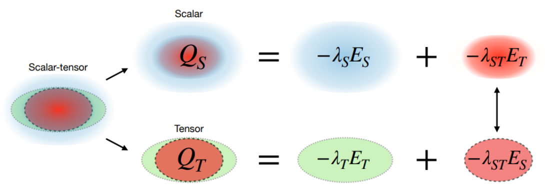
Focus on a specific effect: scalar tides

Reminder in GR

- electric and magnetic type Love numbers
- effacement principle: start at $5PN \sim \left(\frac{v}{c}\right)^{10}$

In scalar-tensor

- scalar dipole moment $\mathcal{E}_{ij} \propto \partial_{ij}\phi \Rightarrow$ scalar-induced tidal deformability



- enhanced effect wrt GR: $3PN$

Creci et al. '23

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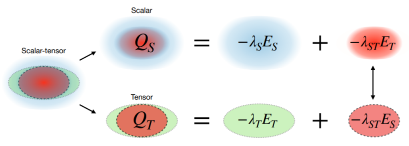
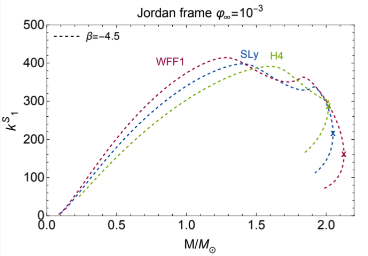
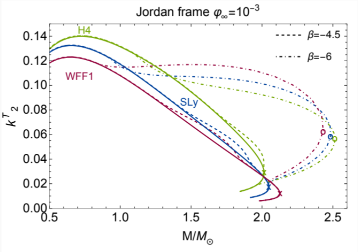


- ▷ enhanced effect wrt GR: $3PN$





Creci et al. '23

- ▷ more important at low frequency (LISA) or highly scalarized objects

Conclusion

Why?

- we need a bank of extremely precise waveform templates both in GR and beyond
  - ▷ to test all specific effects
  - ▷ include environmental effects
- we need to use different modeling techniques
  - ▷ analytical calculations are still required (LISA, ET)
  - ▷ include all effects spins, tides, *etc.*

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Merci !

Lac de Charpal (Lozère)