FIRST CONSTRAINTS ON BINARY BLACK HOLE ENVIRONMENTS FROM LIGO-VIRGO OBSERVATIONS

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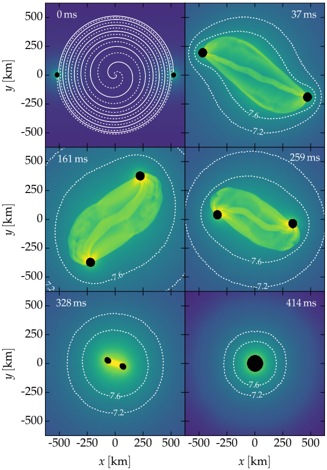
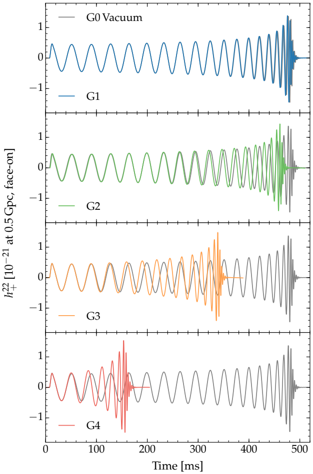
How empty is vacuum?

(Stellar-mass) binary black hole environments

- Several formation mechanisms involve environments
  (DF in AGN disks [Tagawa et al., 19], dynamical fragmentation [Loeb, 16], ...)
- EM counterparts (?)
  (GW150914 [Connaughton et al., 16], GW170104 [Verrecchia et al., 17])
- Environments are ubiquitous
  $\{\rho_{\rm DM} \sim (10^{-24}, 10^{-16}),\ \rho_{\rm disk} \sim (10^{-9}, 0.1),\ \rho_{\rm star} \gtrsim 10^{7}\}\ [{\rm g/cm^3}]$
- GW waveforms are modified
  (GR magneto-hydrodynamic simulations [Noble et al., 12; Fedrow et al., 17])

GR hydrodynamic simulations (GW150914)





Fedrow et al., 2017 [1704.07383]

Can we simplify the modeling?

Inspiral PN phase coefficients

$(G = c = 1)$

- Dynamical friction [Escala at al., 04] $F_j \approx -4\pi\rho \left(\frac{M_j}{v_j}\right)^2 \Lambda_j$ w/ $\Lambda_j \sim \mathcal{O}(1)$
- Adiabaticity $\dot{E}_{\rm orb} \approx -\dot{E}_{\rm GW} + \sum F_j v_j \implies \dot{f} \approx \frac{96\pi^{8/3}\nu}{5M^2}(Mf)^{\frac{11}{3}} + \frac{12\rho\Lambda}{\nu}$
- Stationary phase [Cutler et al., 94] $\tilde{h}(f) \propto e^{i\Psi(f)}$ w/ $\Psi \approx 2\pi f t - \phi - \frac{\pi}{4}$
- PN phase coefficients [Barausse et al., 14; Cardoso et al., 20]

  $\Psi \approx 2\pi f t_c - \phi_c - \frac{\pi}{4} + \Psi^{(0)}_{\rm GR}(1 + \psi_{\rm GR} + \psi_{\rm DF})$

  w/ $\Psi^{(0)}_{\rm GR} \approx \frac{3}{128\nu(\pi M f)^{5/3}}$ and $\psi_{\rm DF} \approx -\frac{25\rho M^2\Lambda}{304\pi^{8/3}\nu^2}(Mf)^{-\frac{11}{3}}$ [-5.5 PN]

What does the data tell us?

Environment (Bayesian) parameter estimation

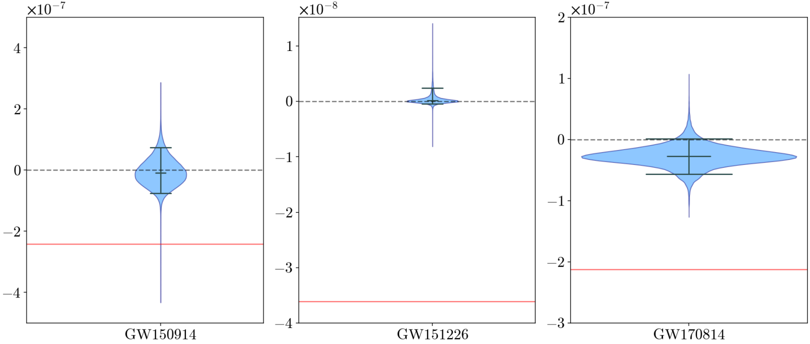
- Parametrized deviation to vacuum-GR at -5.5 PN:

  $\Psi = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \sum_{k=0}^{7} \left[\Phi_k + \Phi_{kl} \log(v^3)\right] v^{k-5} + \Phi_{-11} v^{-11}$
  w/ $v \equiv (\pi M f)^{\frac{1}{3}}$

- TIGER pipeline for Bayesian inference (same as 'tests of GR') with waveforms IMRPhenomPv2

- GW150914 ($M_1 \approx 35 M_\odot$, $M_2 \approx 30 M_\odot$, SNR ≈ 24)
- GW151226 ($M_1 \approx 14.2 M_\odot$, $M_2 \approx 7.5 M_\odot$, SNR ≈ 13)
- GW170814 ($M_1 \approx 30 M_\odot$, $M_2 \approx 25 M_\odot$, SNR ≈ 18)

Marginalized posteriors of Φ_{-11}

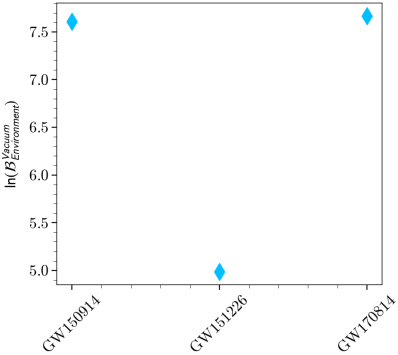


$$\Phi_{-11} \approx -2.4 \times 10^{-7} \frac{\Lambda}{(4\nu)^2} \left(\frac{\rho}{10^7\,\mathrm{g\,cm^{-3}}}\right) \left(\frac{M}{60 M_\odot}\right)^2$$

At radius ~ 1000 km a presupernova star has $\rho \sim (10^7, 10^9)\,\mathrm{g\,cm^3}$

Vacuum vs Environment (Bayes factor)

$$\mathcal{B}^{Vacuum}_{Environment} \equiv \frac{\Pr(D|Vacuum)}{\Pr(D|Environment)}$$



Final remarks

- Environment affects GW emission through DF (dephasing)
- Inspiral PN phase coefficients (-5.5 PN for DF) provide an efficient [and accurate(?)] model
- Bayesian inference to constrain the PN phase coefficients and, so, the evinronment parameters (as of now, we've applied it only for GWTC-1)
- At moment, data strongly favors vacuum over environment (and most events constraint $\rho \lesssim 10^7\,\mathrm{g\,cm^{-3}}$)
- What's the constraining power of LIGO-Virgo (at design sensitivity)?
- Impact of more informative prior?
- GW170817 (NS-NS) has very large # cycles and SNR... what's its constraint?

PN phase coefficients vs simulations [Fedrow et al., 2017]

$$\mathcal{M}(h_1, h_2) \equiv 1 - \max_{\{\chi_i\}} \frac{\langle h_1 | h_2 \rangle}{\sqrt{\langle h_1 | h_1 \rangle \langle h_2 | h_2 \rangle}}$$

$$\frac{1}{\mathrm{SNR}^2} \approx 1.7 \times 10^{-2}$$

$\rho\,[\mathrm{g\,cm^{-3}}]$	$\mathcal{M}_{\mathrm{num}}$	$\mathcal{M}_{\mathrm{PN}}$	Δt_{sim} [ms]	Δt_{PN} [ms]
1.72×10^4	8×10^{-5}	$(4, 440) \times 10^{-6}$	2	(0.1, 1)
1.72×10^5	6×10^{-3}	$(4, 345) \times 10^{-4}$	20	(1, 13)
1.72×10^6	2×10^{-1}	$(3, 28) \times 10^{-2}$	142	(13, 135)
1.72×10^7	4×10^{-1}	$(2, 4) \times 10^{-1}$	324	(135, 1349)