Class. Quant. Grav. 36 (2019) no. 24, 245019

Inspiral-Merger-Ringdown Consistency Tests with Gravitational Signals from O2 catalog

Matteo Breschi

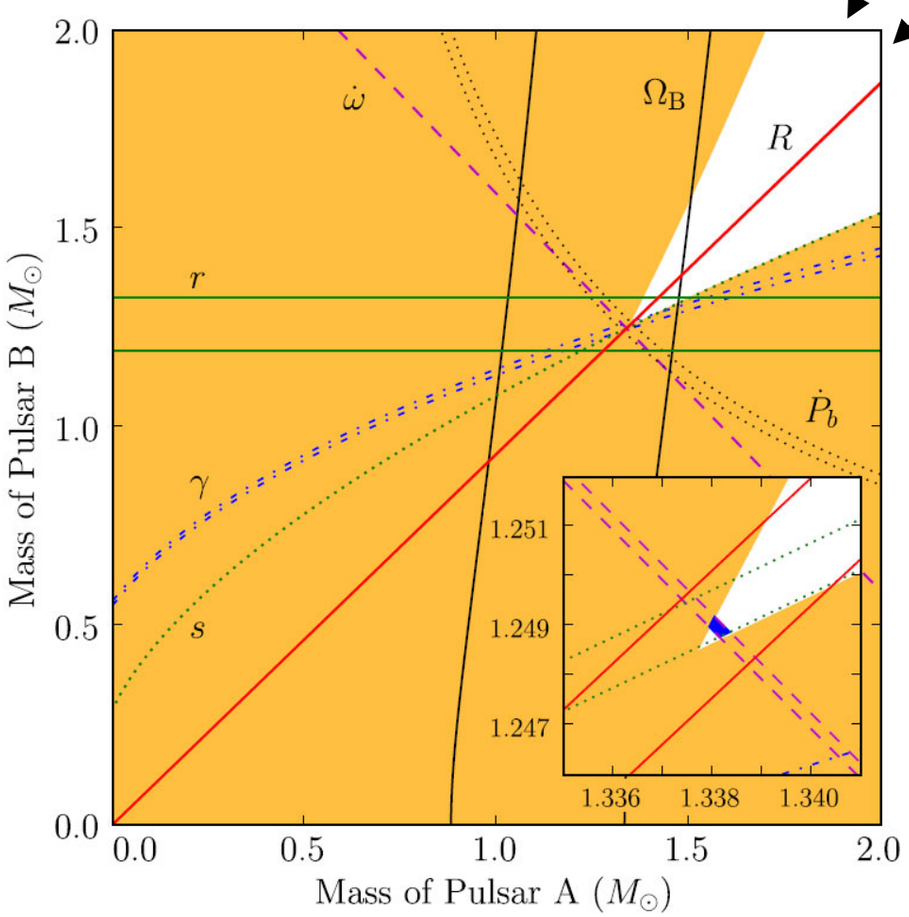
Collaborators:
Richard O'Shaugnessy, Jacob Lange, Ofek Birnholtz

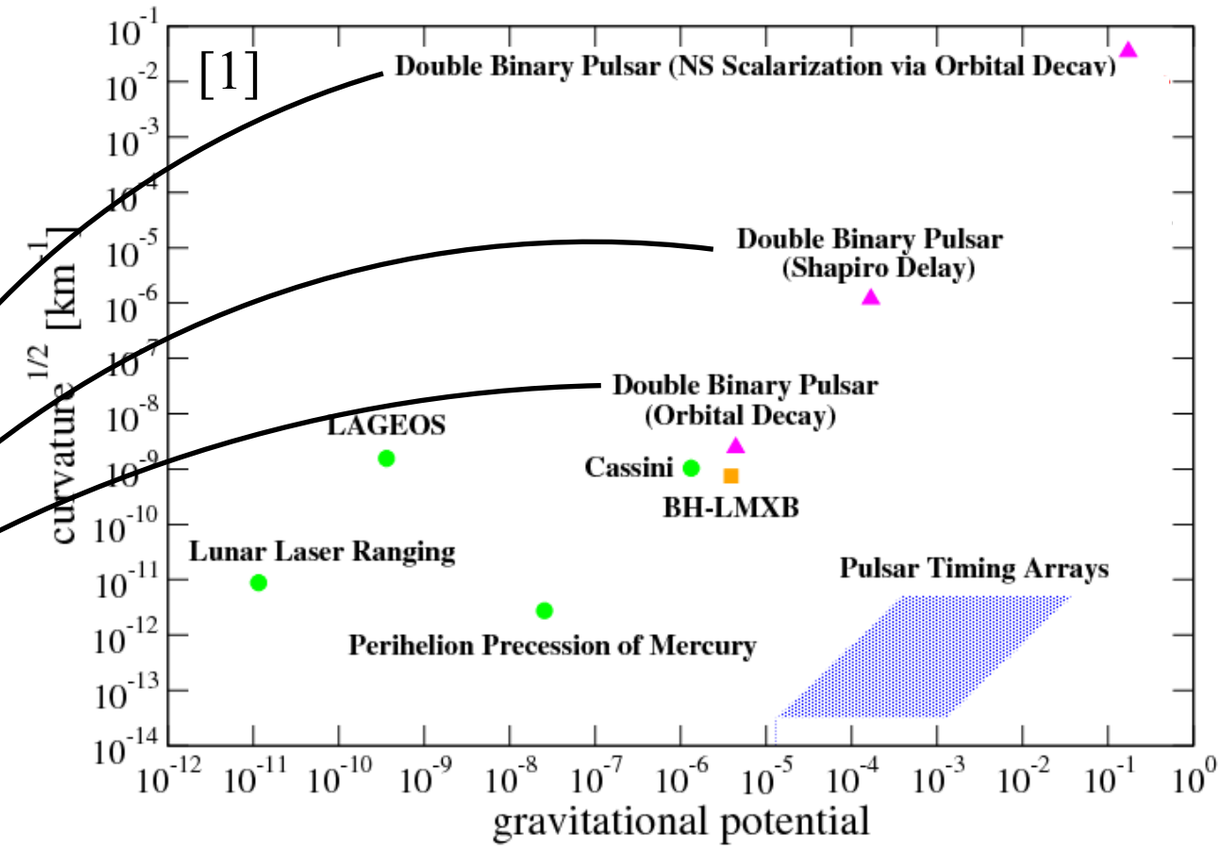
www.computational-relativity.org

Tests of General Relativity

Tests of General Relativity (GR) are crucial to understand the limits of our methods and verify their validity in different regimes

- Comparison between GR predictions and experimental data





PSR J0737-3039A/B (Double Pulsars) [2]

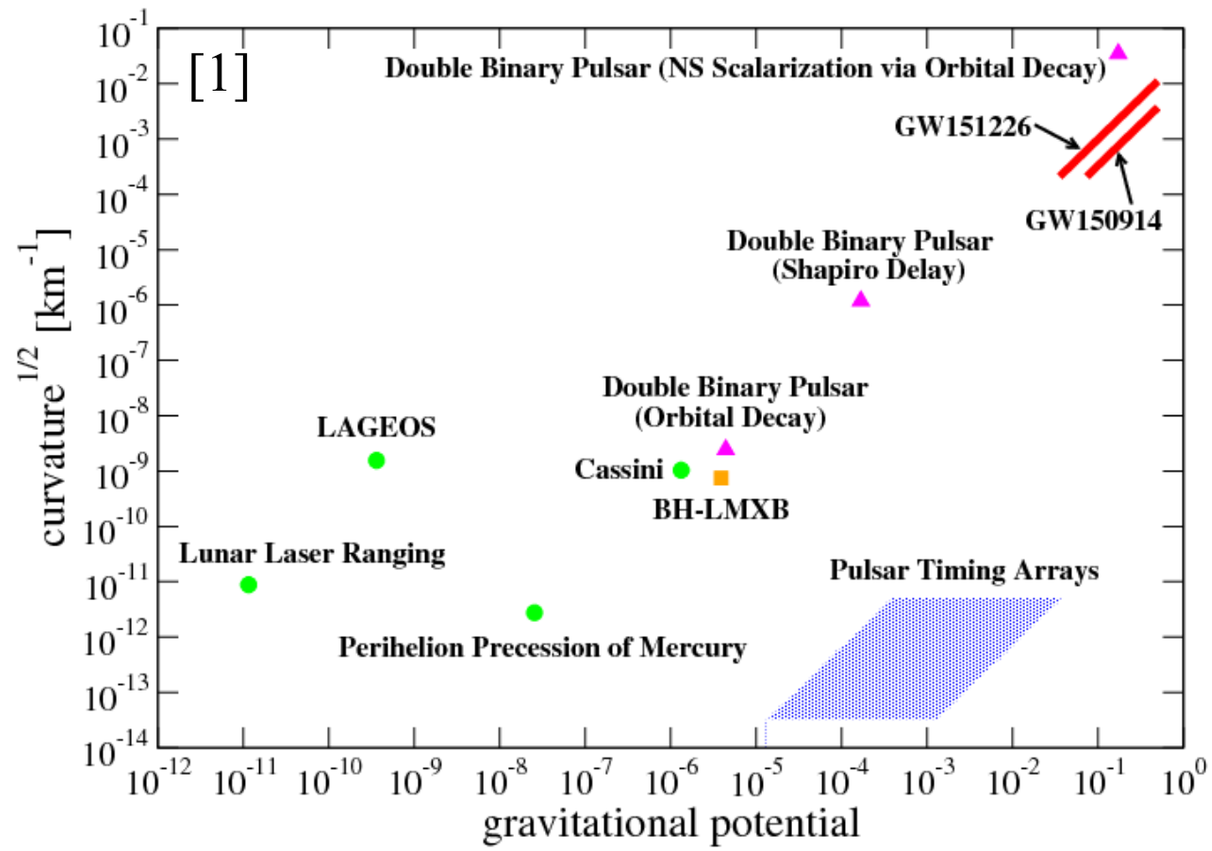
R = Mass ratio
r, s = Shapiro delay (shape and range)
$\dot{\omega}$ = Periastron advance rate
$\dot{P}_b$ = Orbital period decay
γ = Gravitational redshift
Ω_B = Spin precession rate

[1] Yagi *et al.* Phys. Rept. 681 (2017) 1-72
[2] Kramer *et al*. Science Vol. 314 (2006)
[3] LVC Phys.Rev. D100 (2019) no.10

Tests of General Relativity

Tests of General Relativity (GR) are crucial to understand the limits of our methods and verify their validity in different regimes

- Comparison between GR predictions and experimental data
- Gravitational Waves (GWs) observations allow us to test GR in very strong-field conditions



LIGO-Virgo Collaboration (LVC) has performed several tests of GR [3] on the observed events,

- Residual test
- Parametrized tests
- Inspiral-merger-ringdown consistency test
- Modified dispersion relation

[1] Yagi *et al.* Phys. Rept. 681 (2017) 1-72
[2] Kramer *et al*. Science Vol. 314 (2006)
[3] LVC Phys.Rev. D100 (2019) no.10

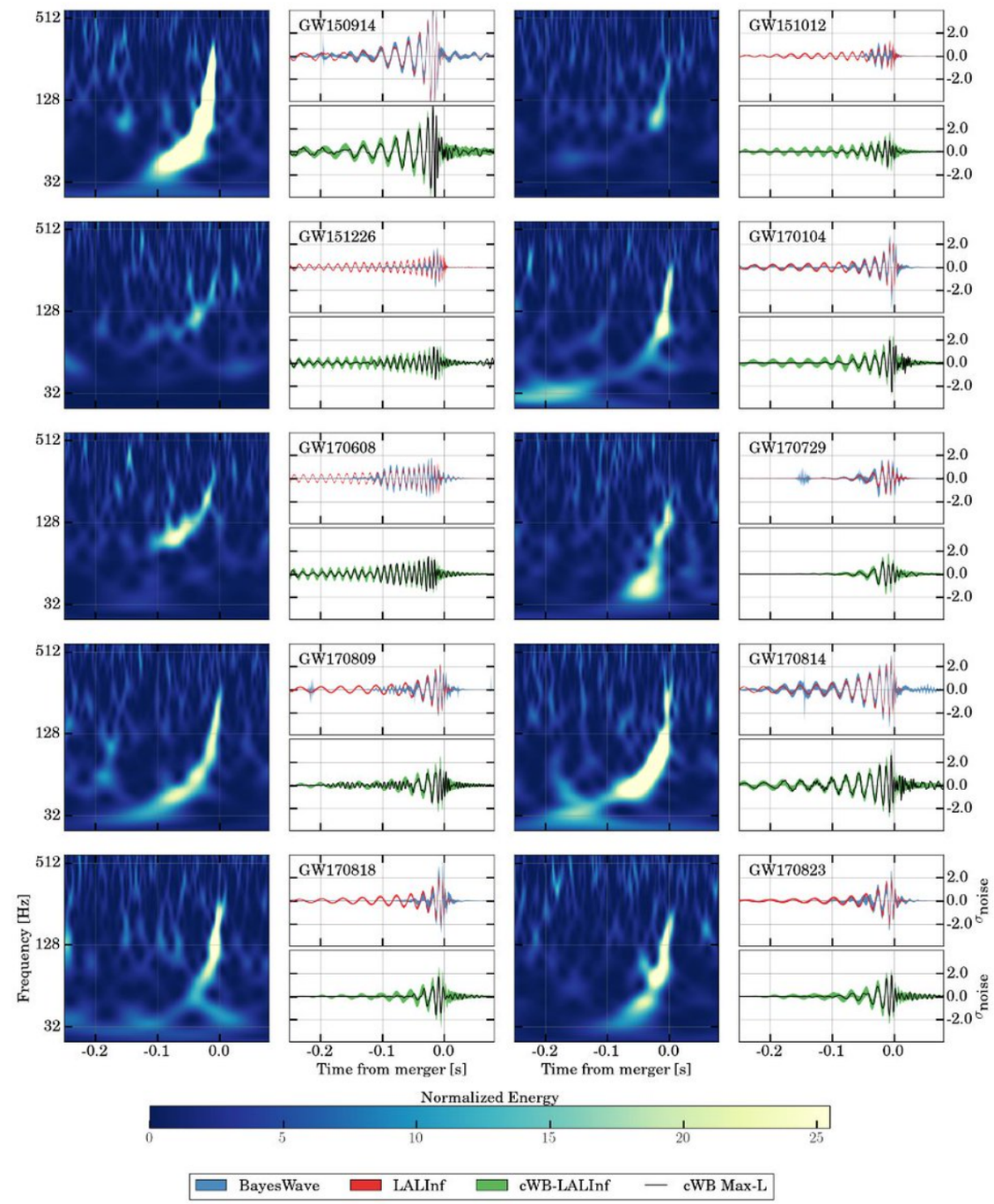
GWTC-1

In the first two observing runs (O1 and O2) [4], LIGO and Virgo detected 11 compact binary coalescences (CBCs):

- 10 binary black holes (BBH) →
- 1 binary neutron stars (BNS)

Currently, the third observing run O3 is ongoing,

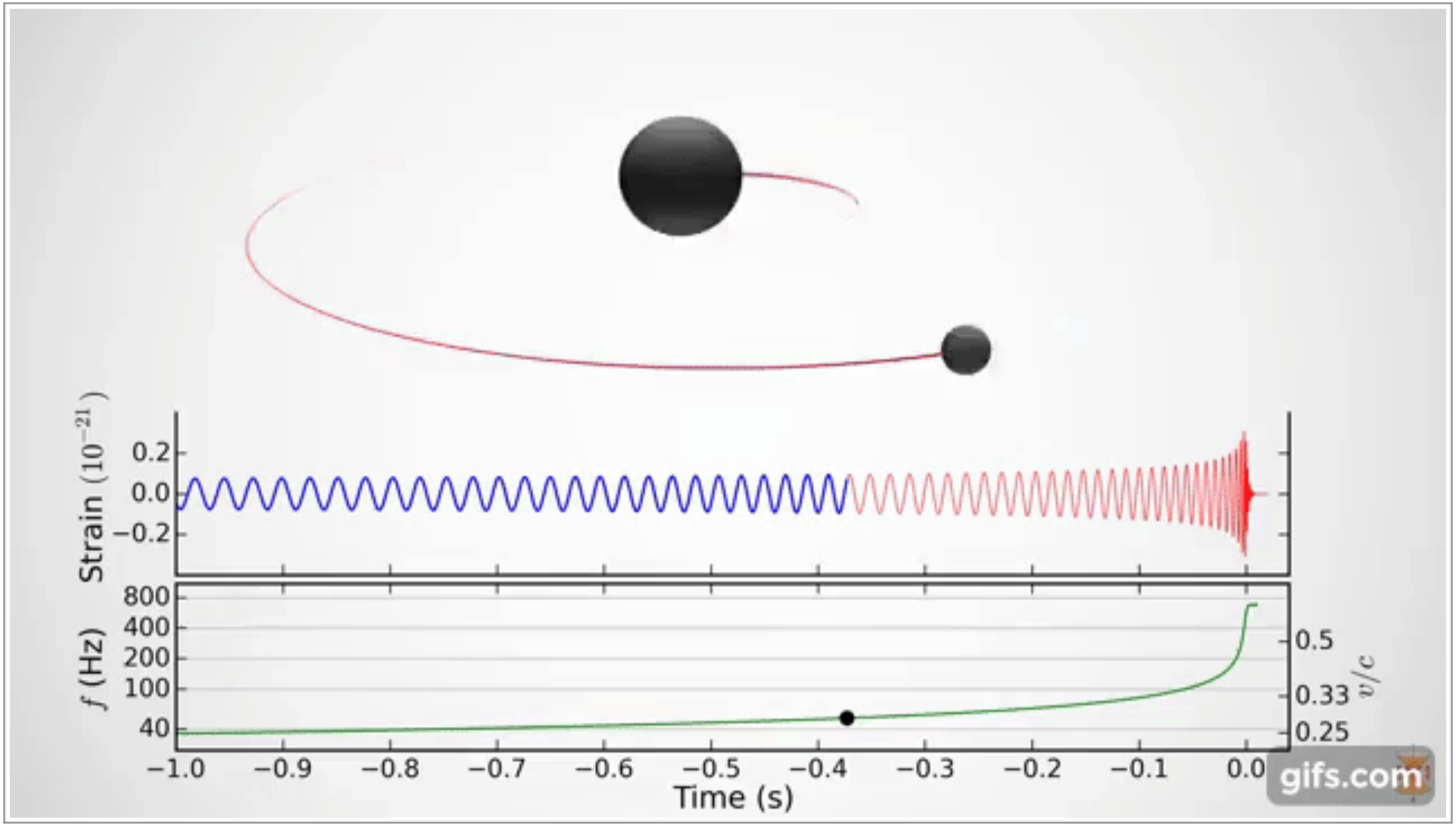
- In the first 6 months, we have ~33 candidates
- https://gracedb.ligo.org



[4] LVC, Phys.Rev. X9 (2019) no.3, 031040

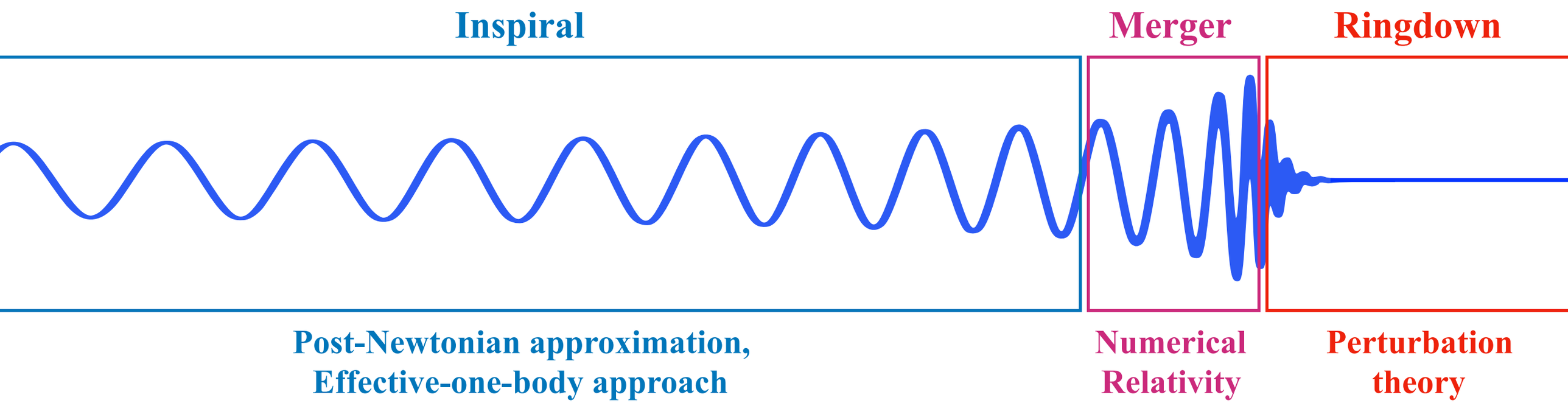
Binary Black Holes

Numerical Relativity (NR) simulation of the BBH merger GW151226, from SXS database [5]



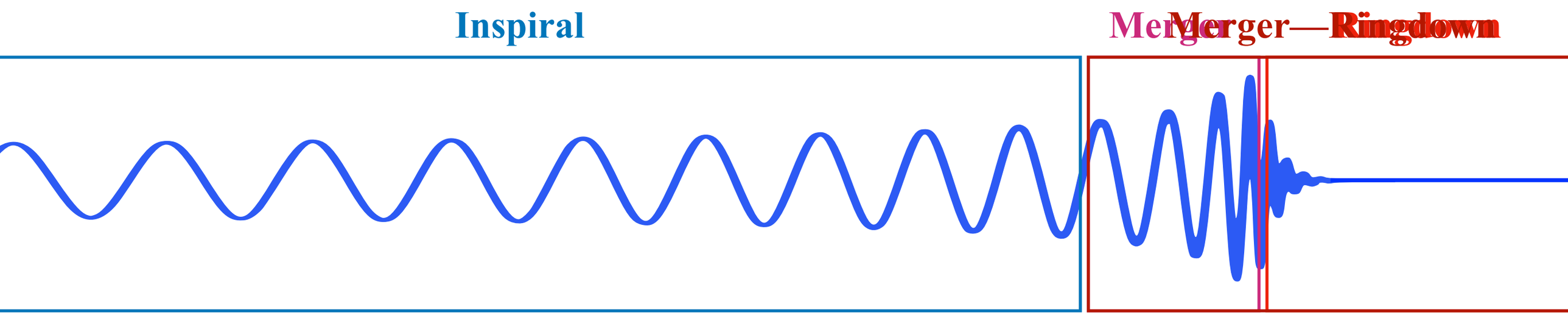
[5] https://www.youtube.com/watch?v=KwbXxzgAObU

Gravitational Waveform



Post-Newtonian approximation:
Low-velocity and weak-field expansion, current computations involve effective field theory techniques
Effective-one-body approach:
Hamiltonian formalism where the two-body dynamics is mapped to geodesic motion in an effective space-time
Numerical Relativity:
In the strong-field regime, the analytical approximations are not able to describe the dynamics, thus we resort to fully numerical methods to solve Einstein's field equations
Perturbation Theory:
Perturbation of the metric around a Schwarzschild or Kerr background, The computation is similar to a scattering problem, which gives the quasi-normal-mode (QNM) oscillations

Gravitational Waveform

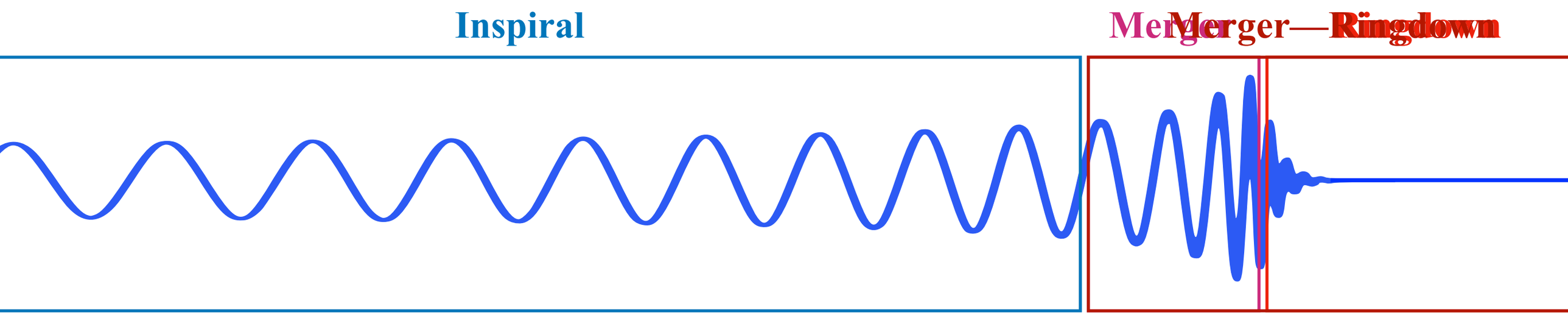


Matching the information coming from different methods and introducing coefficients calibrated to NR simulations, it is possible to build complete **waveform models** for BBH signals

- Fast and reliable GW templates, computed in ~10 ms (*CPU time*)
- The templates are used for Parameter Estimation (PE)
- For our analyzes, we use `NRSur7dq2` approximant [6]

[6] Blackman *et al.* Phys. Rev. D 96, 024058 (2017)

Gravitational Waveform



General idea of the IMR test: verify the consistency between the prediction coming from inspiral (low-frequency) and the ones from the post-inspiral (high-frequency)

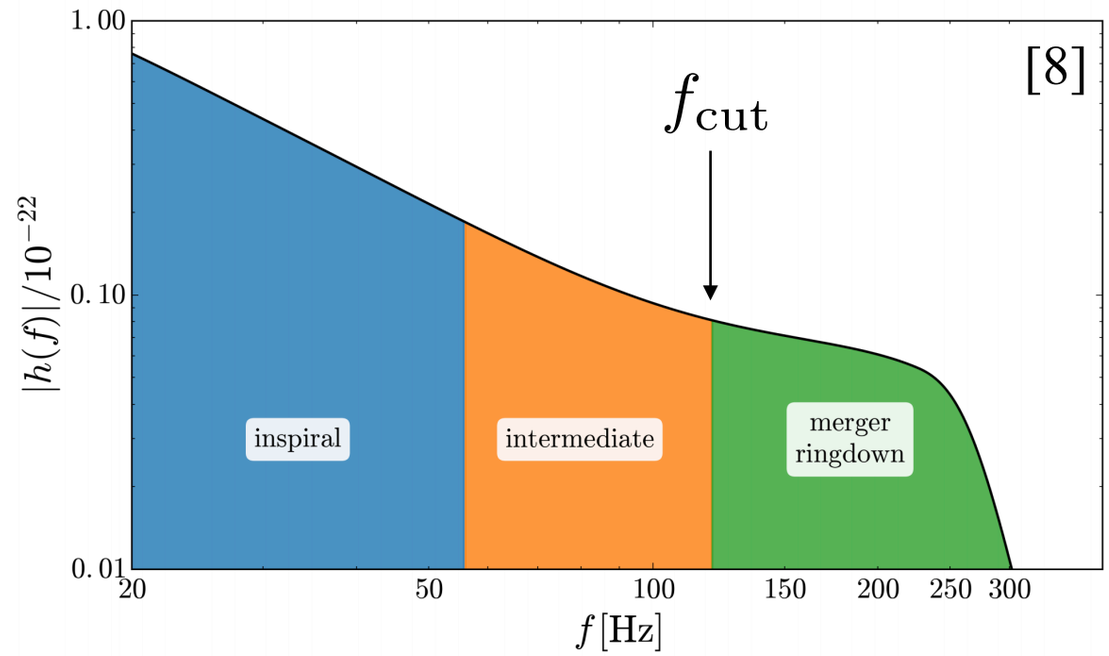
- Check the agreement between inspiral models and post-inspiral parametrization
- Modified theories of gravity are expected to give different post-merger signals
- In the frequency-domain, we can independently separate these portions since the frequency is a monotonic function of the time

[6] Blackman *et al.* Phys. Rev. D 96, 024058 (2017)

IMR Consistency Test

This test has been introduced by Abhirup Ghosh *et. al.* [7]

- For each event, we select a **cutoff frequency**, approximately the last stable orbit (LSO) frequency



- Perform independent PE analyzes on **low-frequency** (LF) and **high-frequency** (HF) segments

$$\Delta M_f = M_f^{\rm I} - M_f^{\rm MR} \quad , \quad \Delta\chi_f = \chi_f^{\rm I} - \chi_f^{\rm MR} \, ,$$

- Compute the **fractional deviation** between the two results, in particular the test focuses on the estimations of final mass and spin of the remnant BH

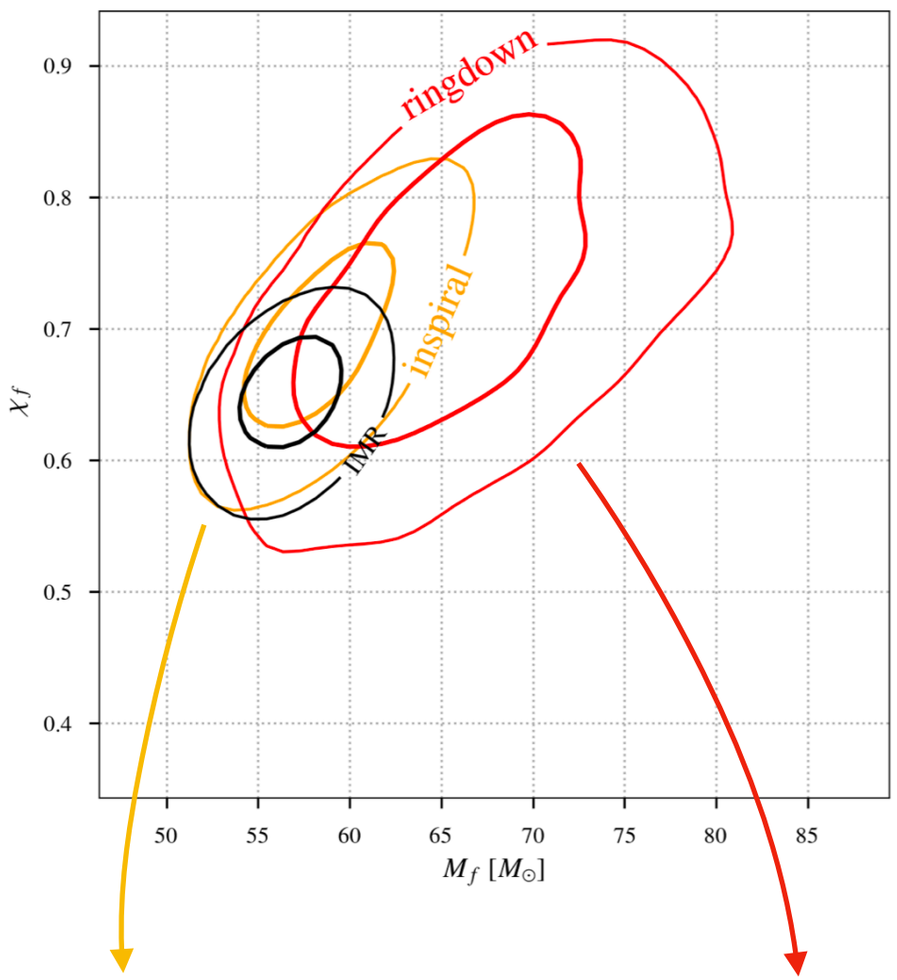
$$\bar{M}_f = \frac{M_f^{\rm I} + M_f^{\rm MR}}{2} \quad , \quad \bar{\chi}_f = \frac{\chi_f^{\rm I} + \chi_f^{\rm MR}}{2}$$

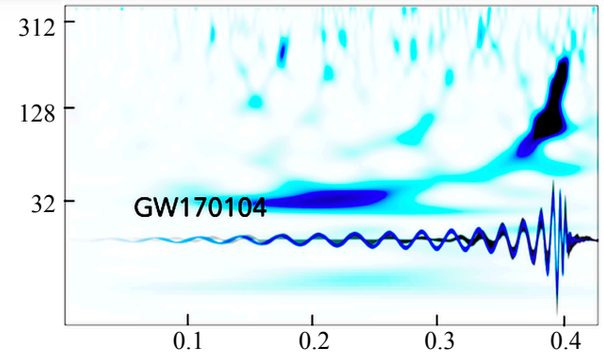
$$\Delta M_f / \bar{M}_f \quad , \quad \Delta\chi_f / \bar{\chi}_f$$

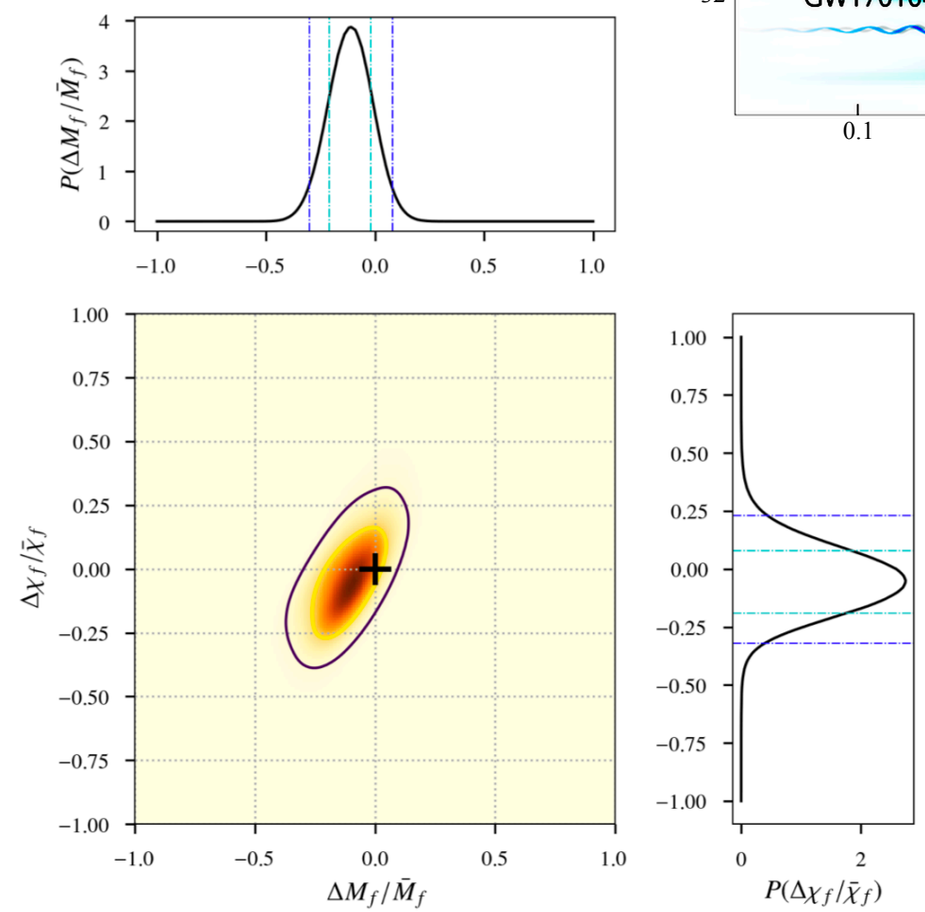
[7] Ghosh *et al.* Phys.Rev. D94 (2016) no.2
[8] Meidam *et al.* Phys.Rev. D97 (2018) no.4, 044033

GW170104

$f_{\mathrm{cut}} = 143$ Hz







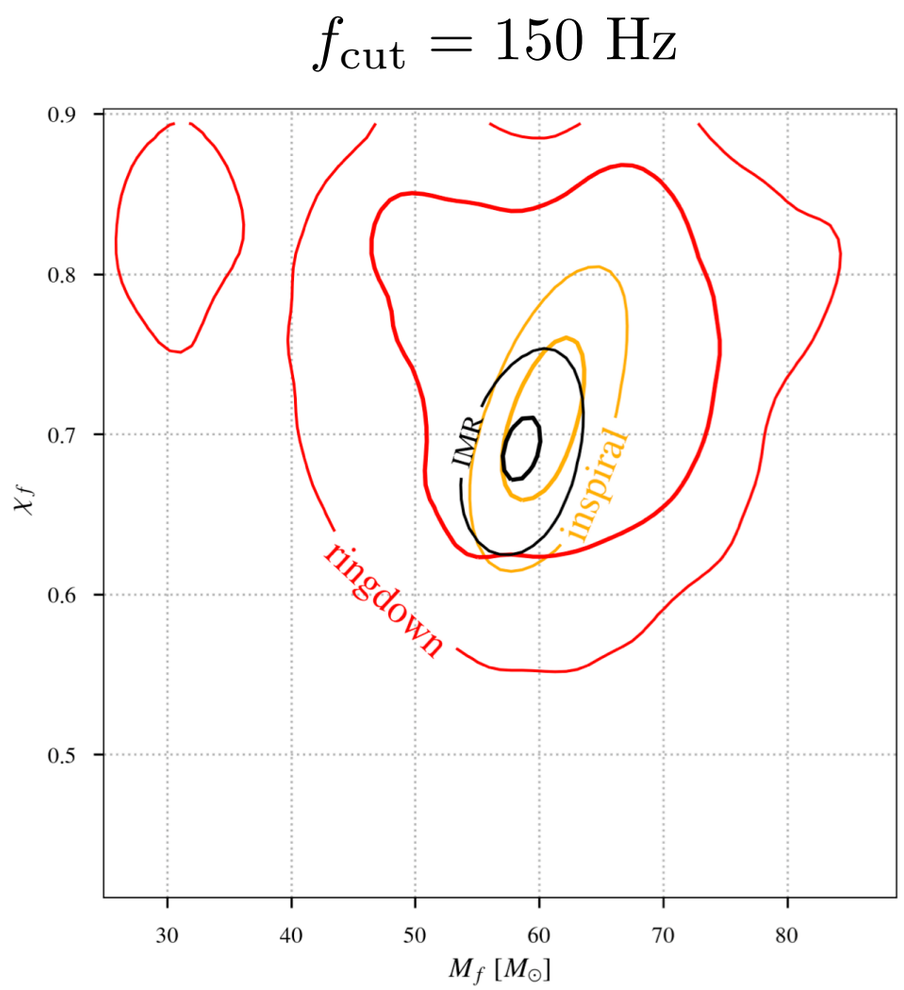
Low frequency
(Inspiral)

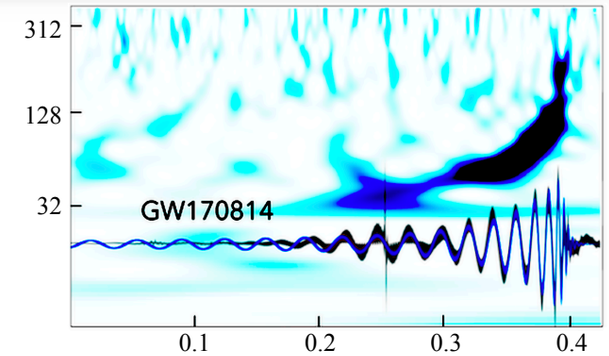
High frequency
(Post-inspiral)

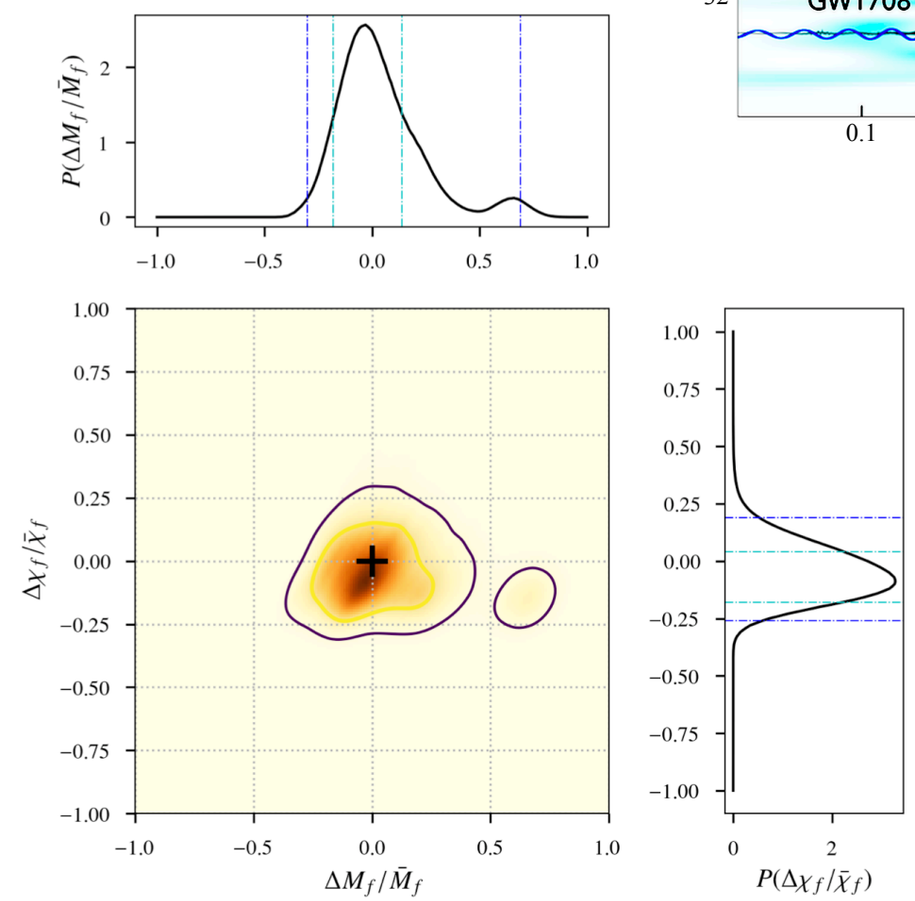
Maximum deviation from GR prediction: ~46%

[9] Breschi *et al.* Class. Quant. Grav. 36 (2019), 245019

GW170814







Uncertainties on single events are large

Maximum deviation from GR prediction: ~10%

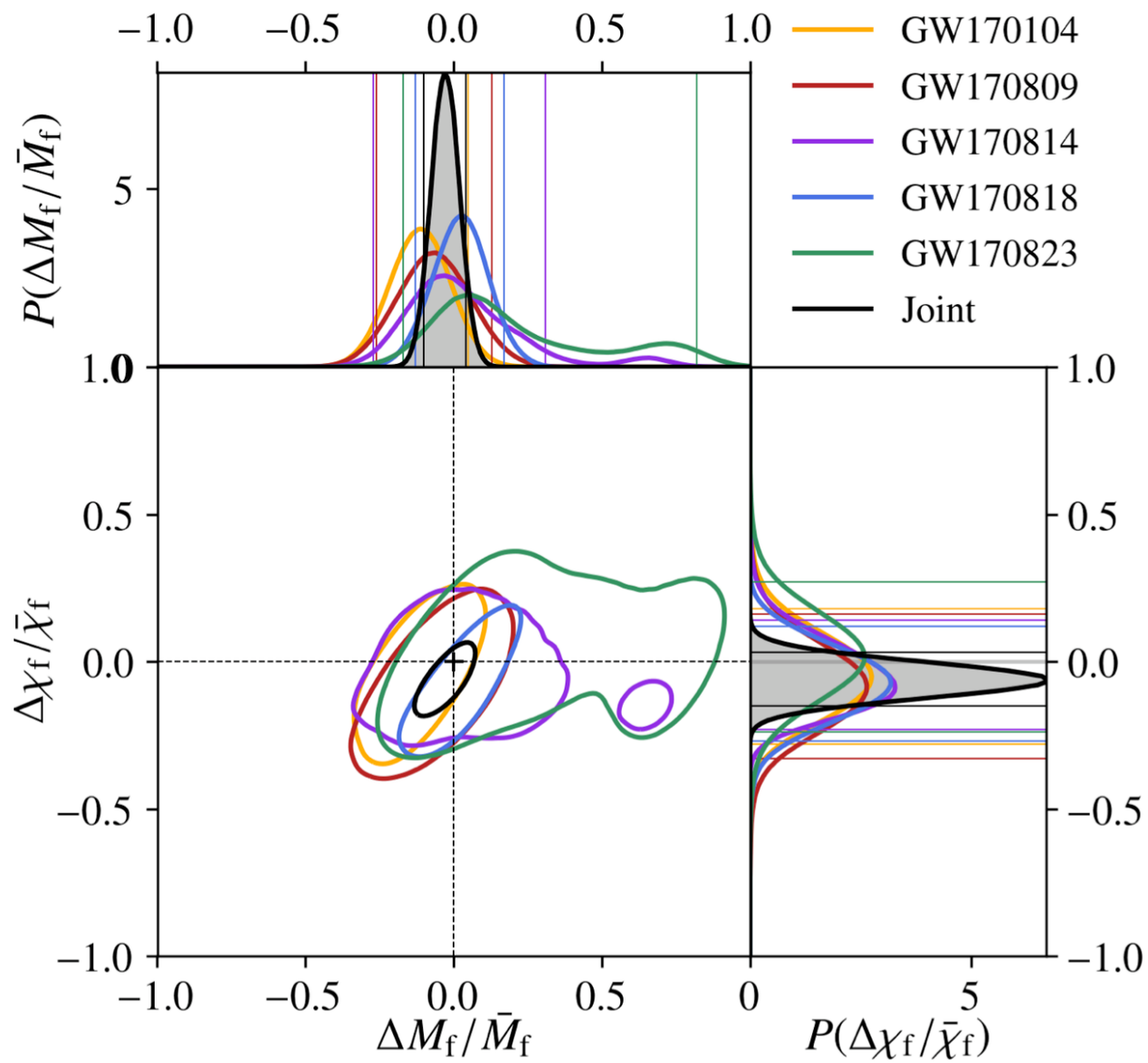
[9] Breschi *et al.* Class. Quant. Grav. 36 (2019), 245019

Combined Information

- Within the framework of Bayesian theory of probability, it is possible to combine information from different events, obtaining stronger constraints

- The O2 events do not show deviation from GR prediction above ~40% credible region, analogous to LVC results [4]

- O3 will be full of interesting news!



[9] Breschi *et al.* Class. Quant. Grav. 36 (2019), 245019

Thanks!

… questions ?