Tests of general relativity with the gravitational wave observations

Chennai Symposium on Gravitation and Cosmology

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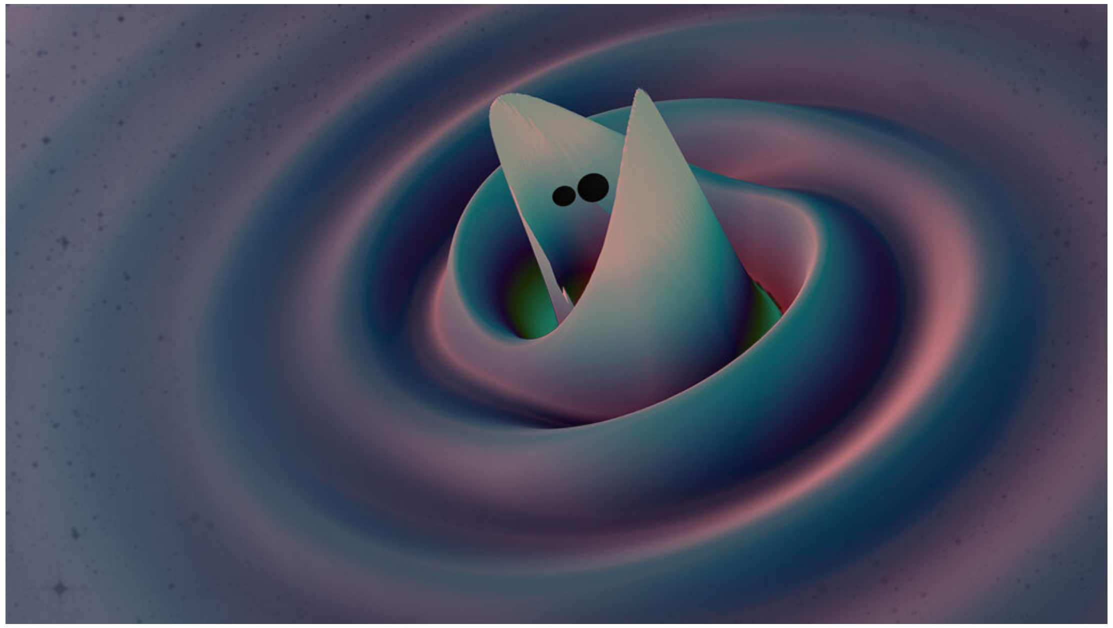
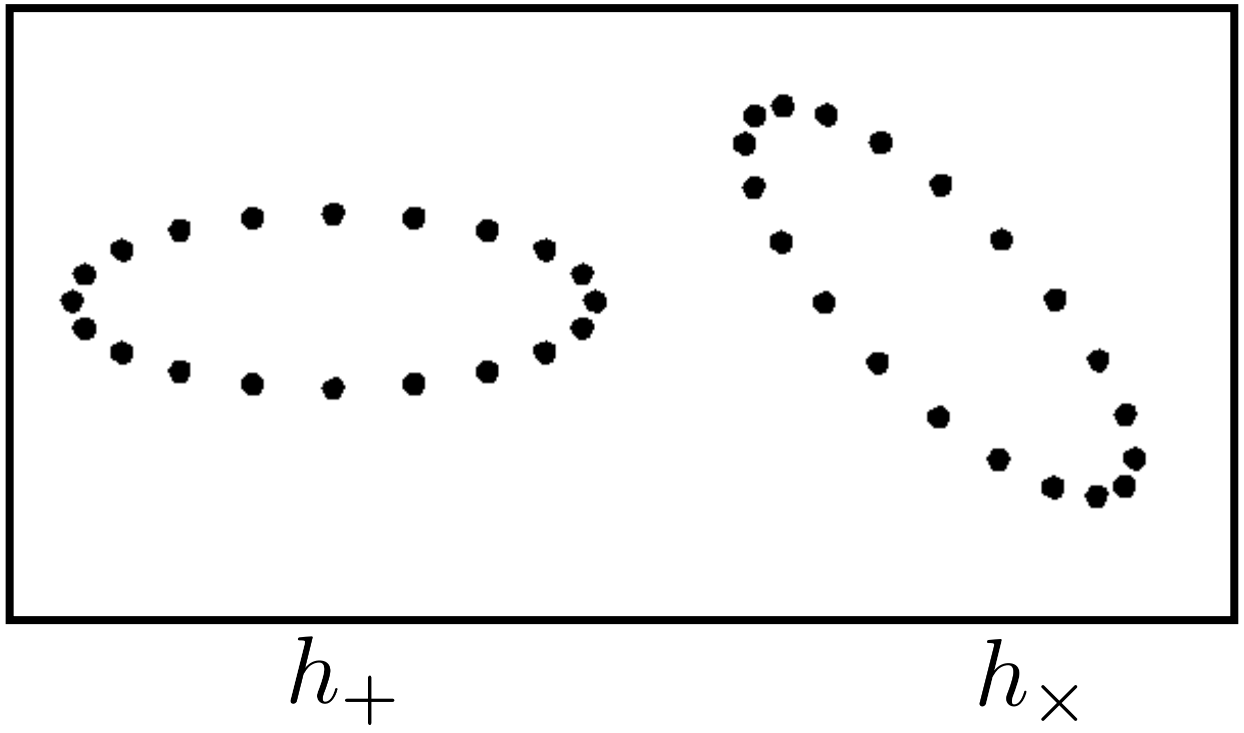
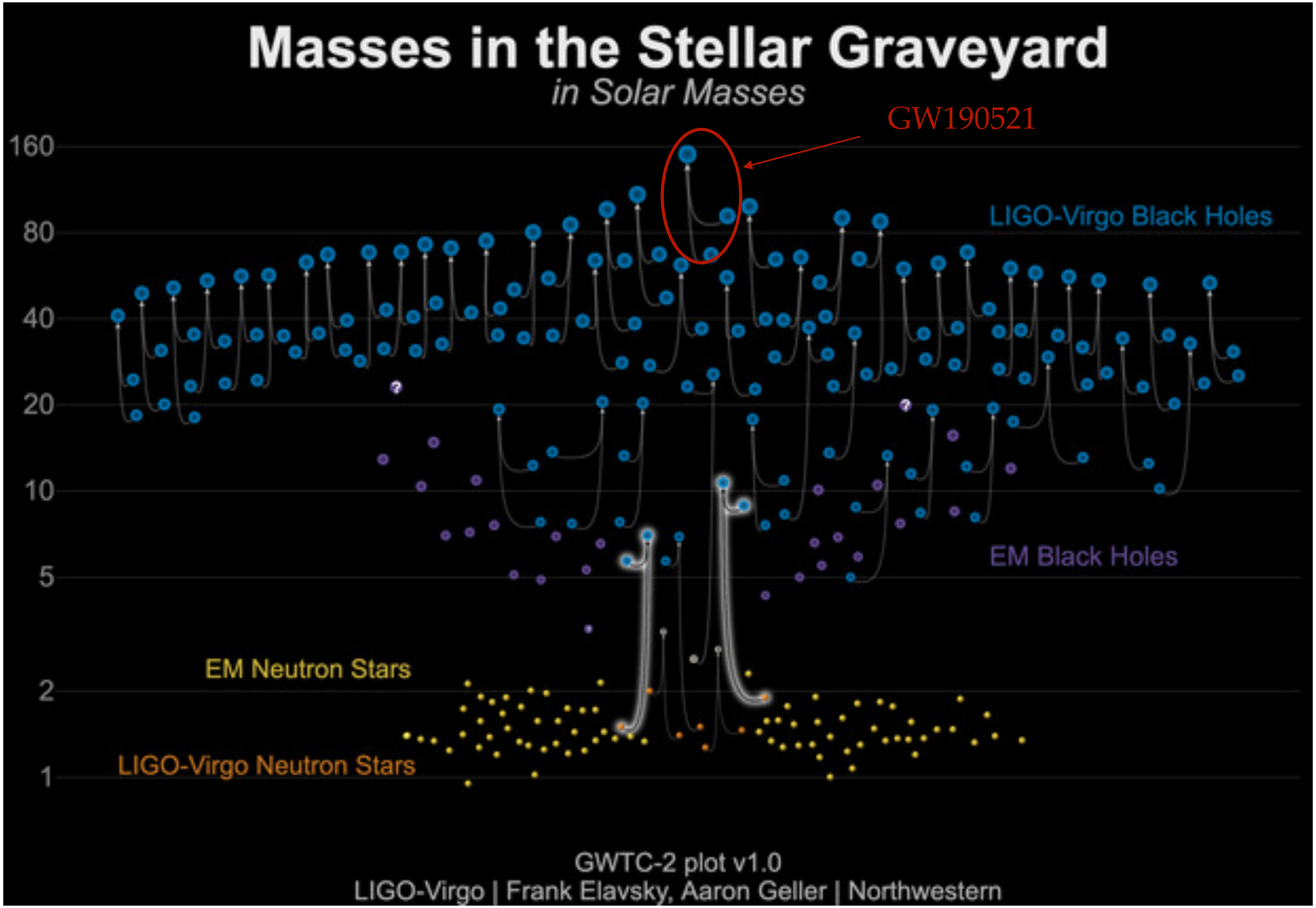
Gravitational waves

- One of the important predictions of Einstein’s General relativity
- Ripples in the fabric of space-time
- Travels at the speed of light
- Accelerated mass with time varying quadrupole moment radiates GWs.

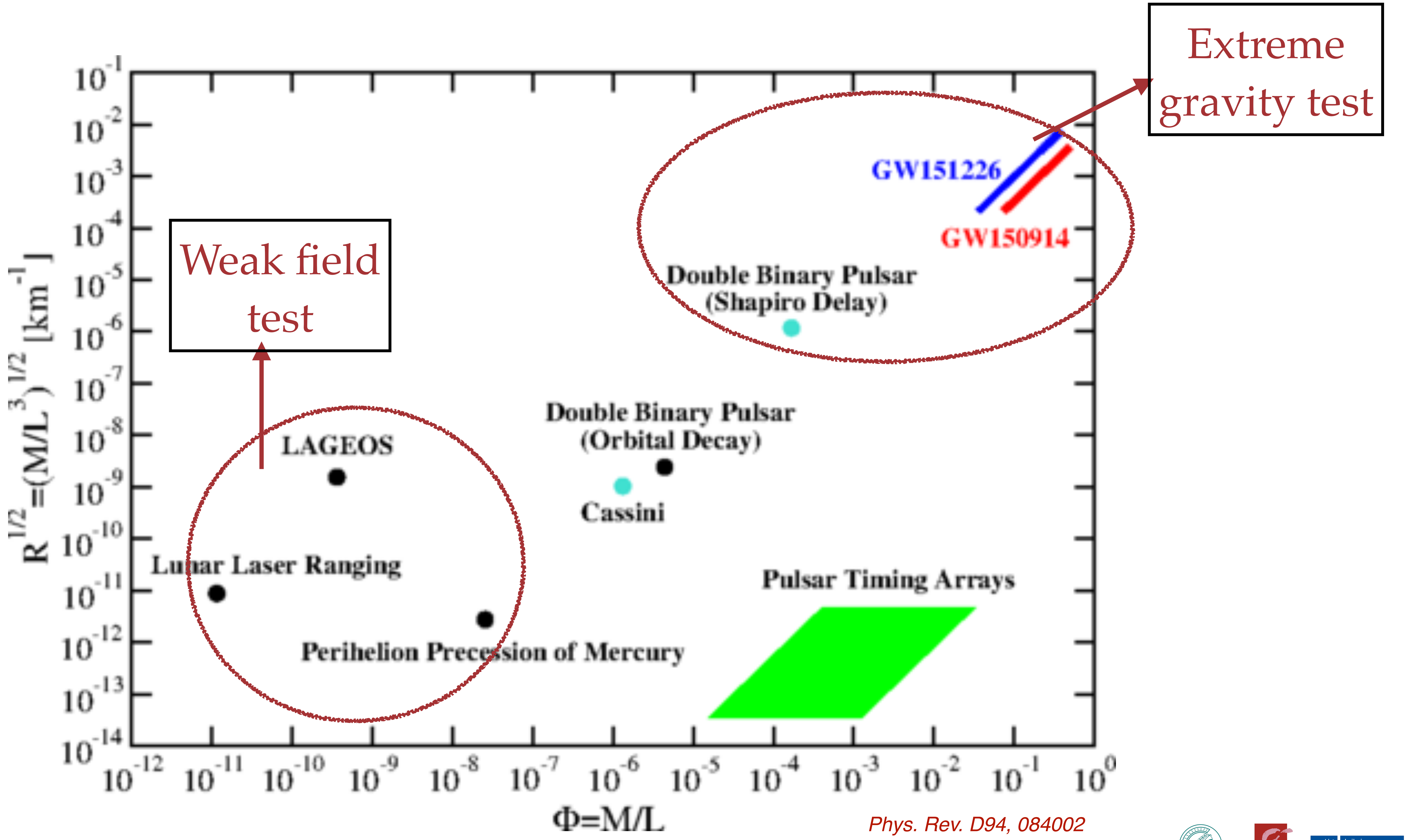




Masses of detected GW events



Tests of general relativity



Extreme gravity test

Weak field test

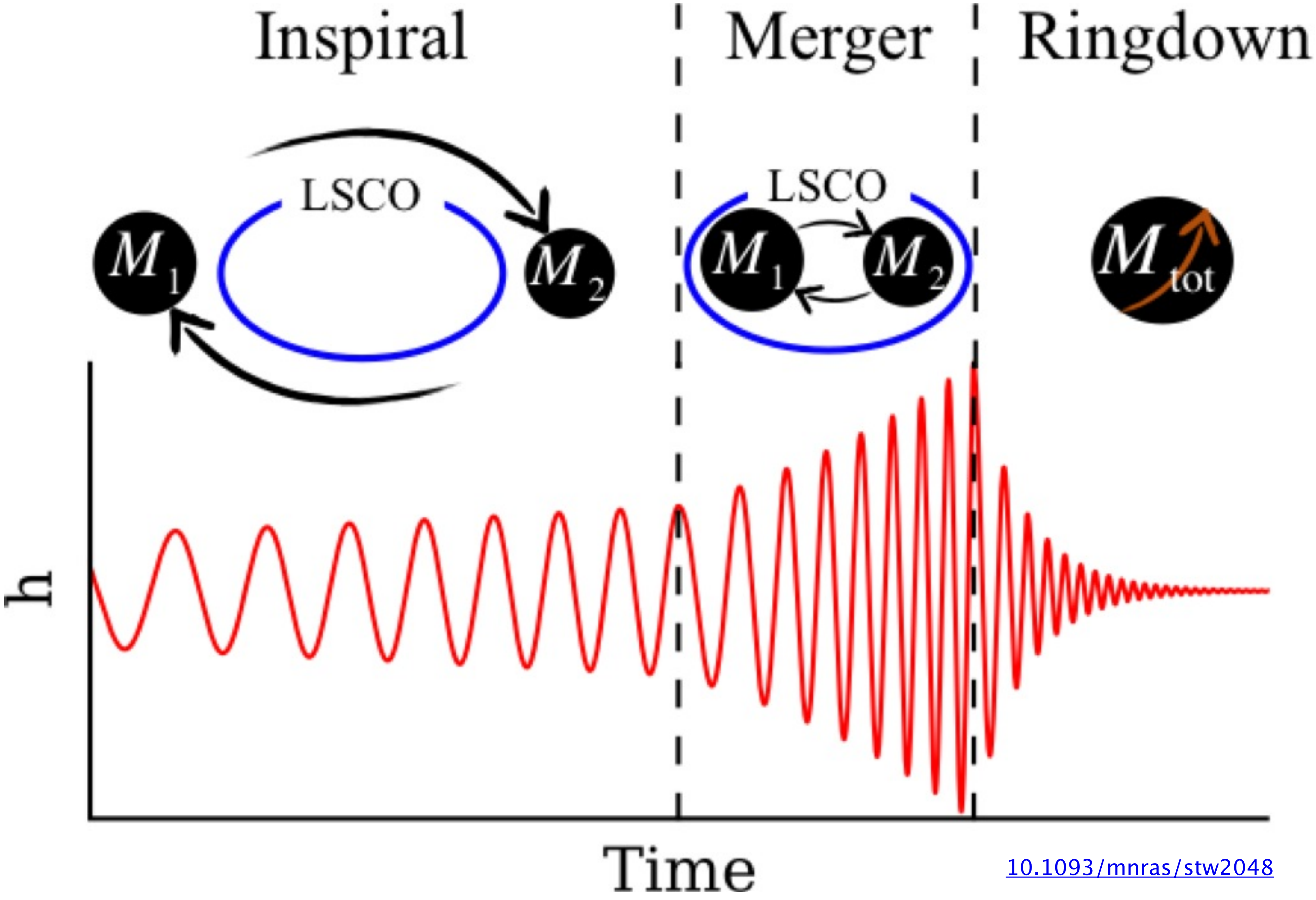
Phys. Rev. D94, 084002

Gravitational waveform modeling

Post Newtonian theory

Numerical Relativity

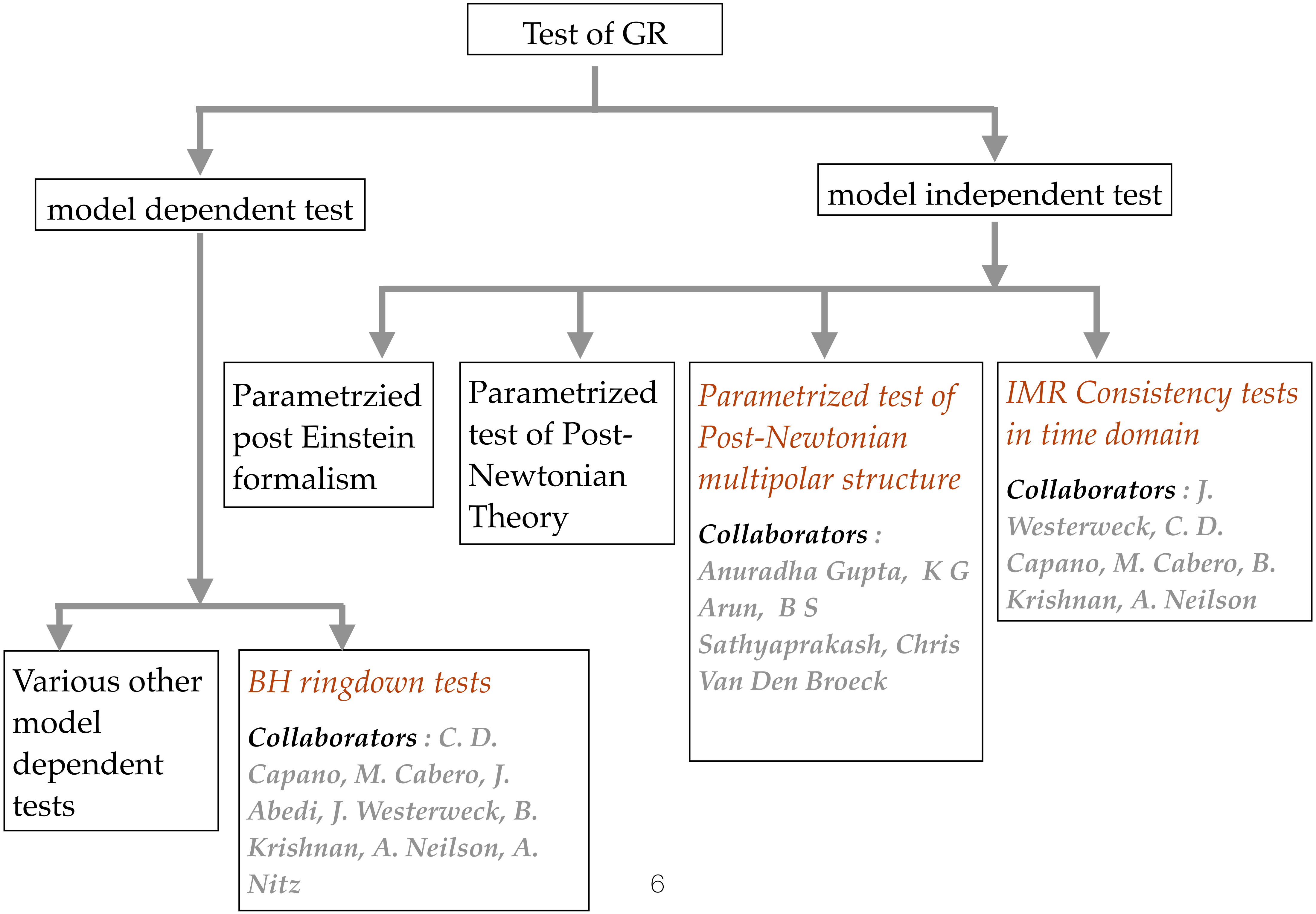
Perturbation theory



10.1093/mnras/stw2048

Test of GR with GW observations

GW observation provide a platform to test GR in the strong field regime.



Test of GR

model dependent test

model independent test

Parametrzied post Einstein formalism

Parametrized test of Post-Newtonian Theory

Parametrized test of Post-Newtonian multipolar structure

***Collaborators** : Anuradha Gupta, K G Arun, B S Sathyaprakash, Chris Van Den Broeck*

IMR Consistency tests in time domain

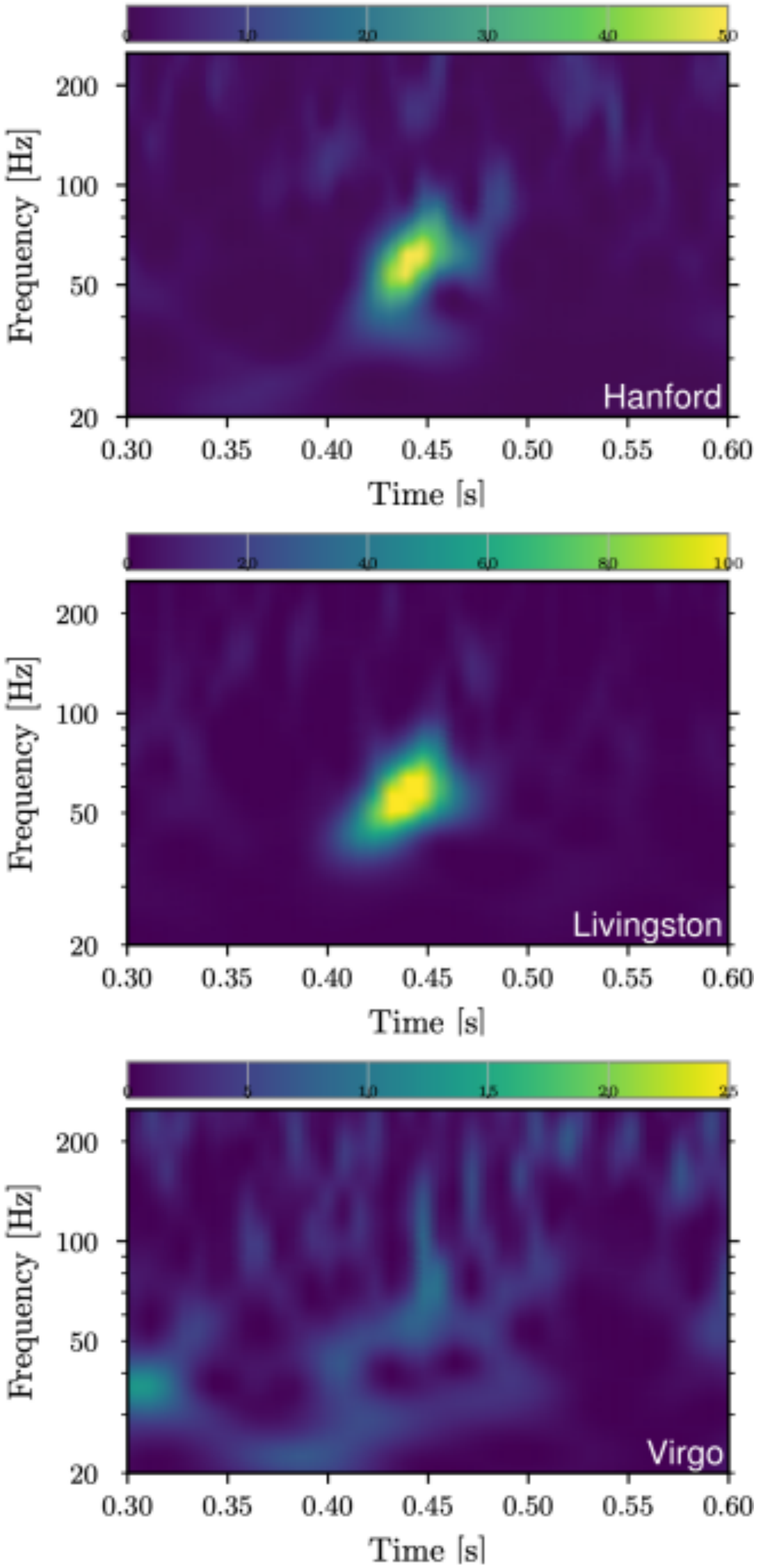
***Collaborators** : J. Westerweck, C. D. Capano, M. Cabero, B. Krishnan, A. Neilson*

Various other model dependent tests

BH ringdown tests

***Collaborators** : C. D. Capano, M. Cabero, J. Abedi, J. Westerweck, B. Krishnan, A. Neilson, A. Nitz*

GW190521



LIGO Scientific and Virgo Collaborations PRL 125 (2020), 101102

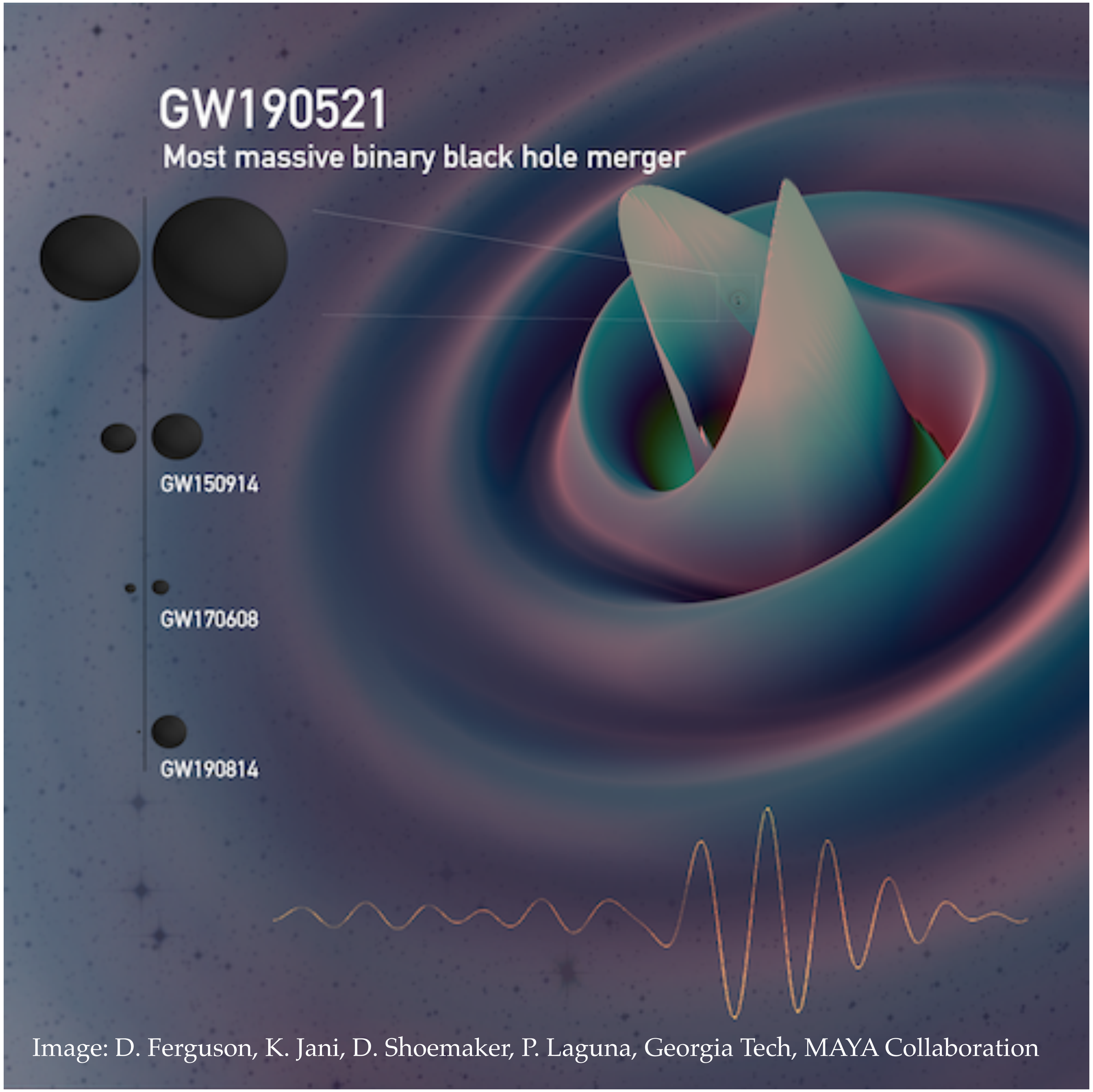
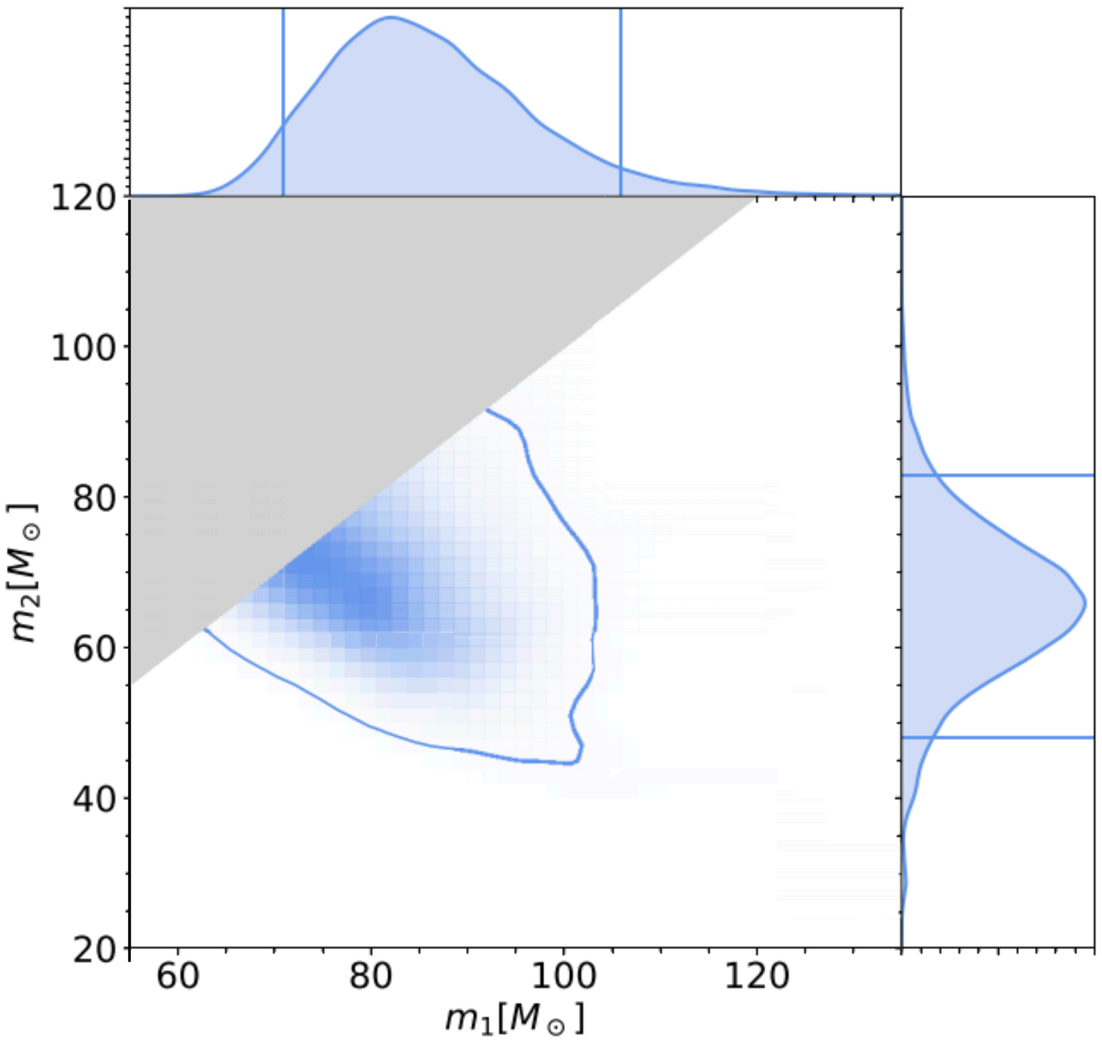


Image: D. Ferguson, K. Jani, D. Shoemaker, P. Laguna, Georgia Tech, MAYA Collaboration

GW190521



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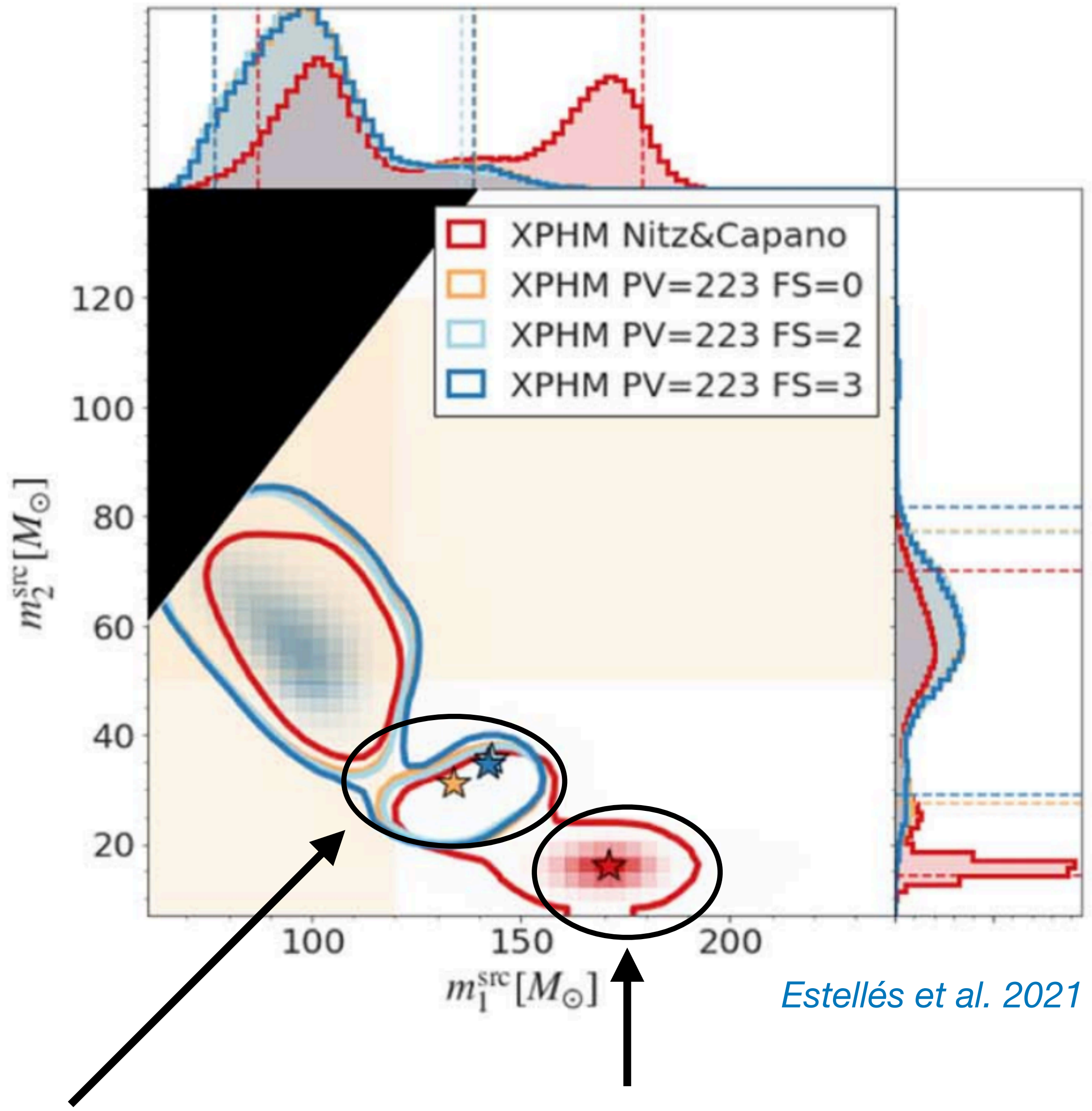
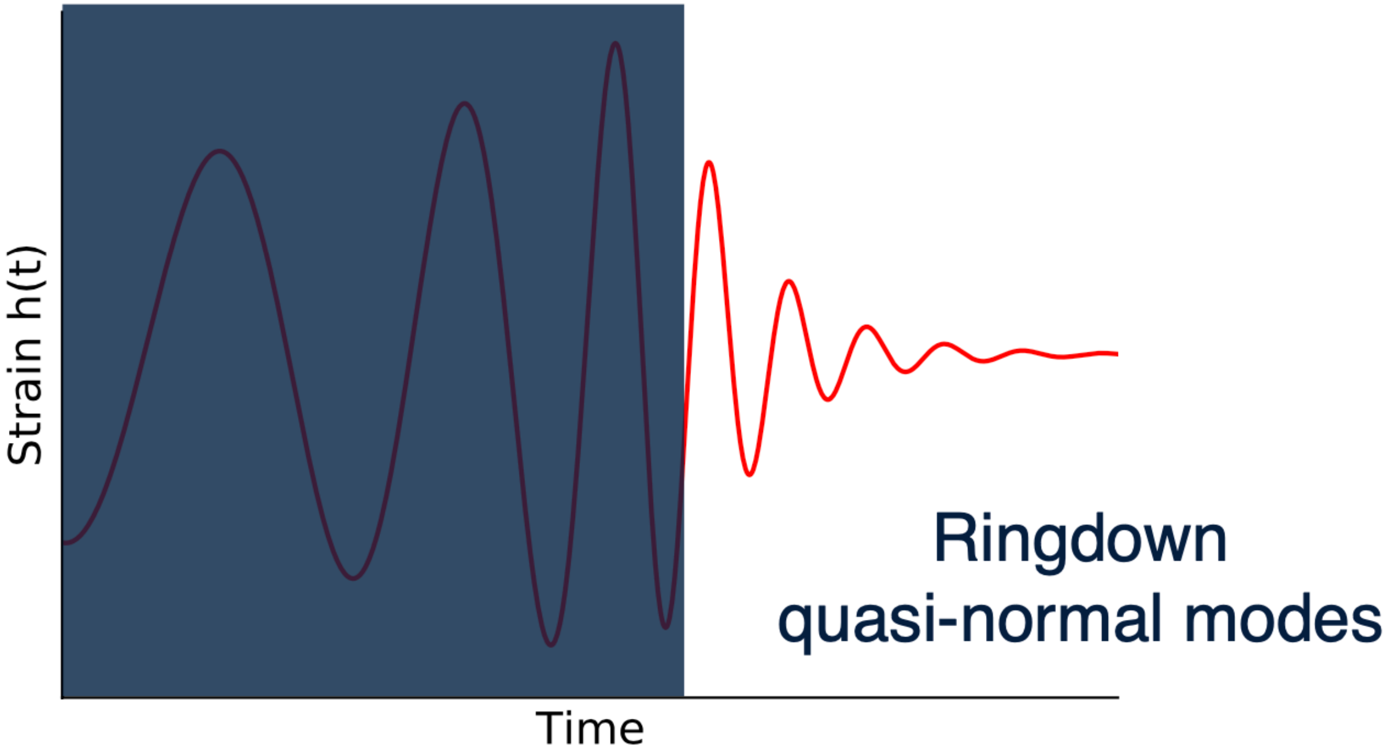


Estellés et al. 2021

High mass ratio region indicates existence of higher modes

With updated IMRPhenomXPHM no significant support for mass ratio ~10 (found in Nitz & Capano 2021a) mode is found

Blackhole spectroscopy



Amplitude *Phase*

$$h(t) = \frac{M}{D_L}\sum_{\ell mn} {}_{-2}S_{\ell m}(\iota,\varphi)\, A_{\ell mn}\, e^{i(\Omega_{\ell mn}t+\phi_{\ell mn})}$$

$$\Omega_{\ell mn} = 2\pi f_{\ell mn} + i/\tau_{\ell mn}$$

Complex frequency *Mode frequency* *Damping time*

- Independently vary

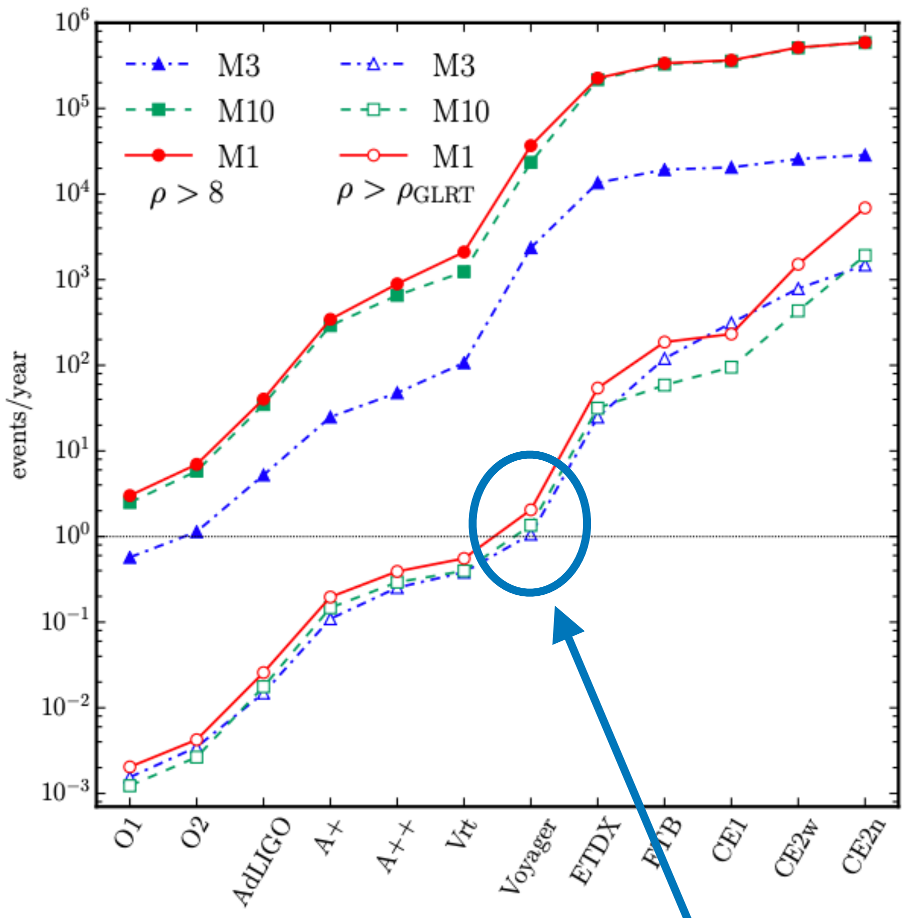
  $$A_{\ell mn}, \phi_{\ell mn}, M_f, \chi_f$$

- No hair theorem

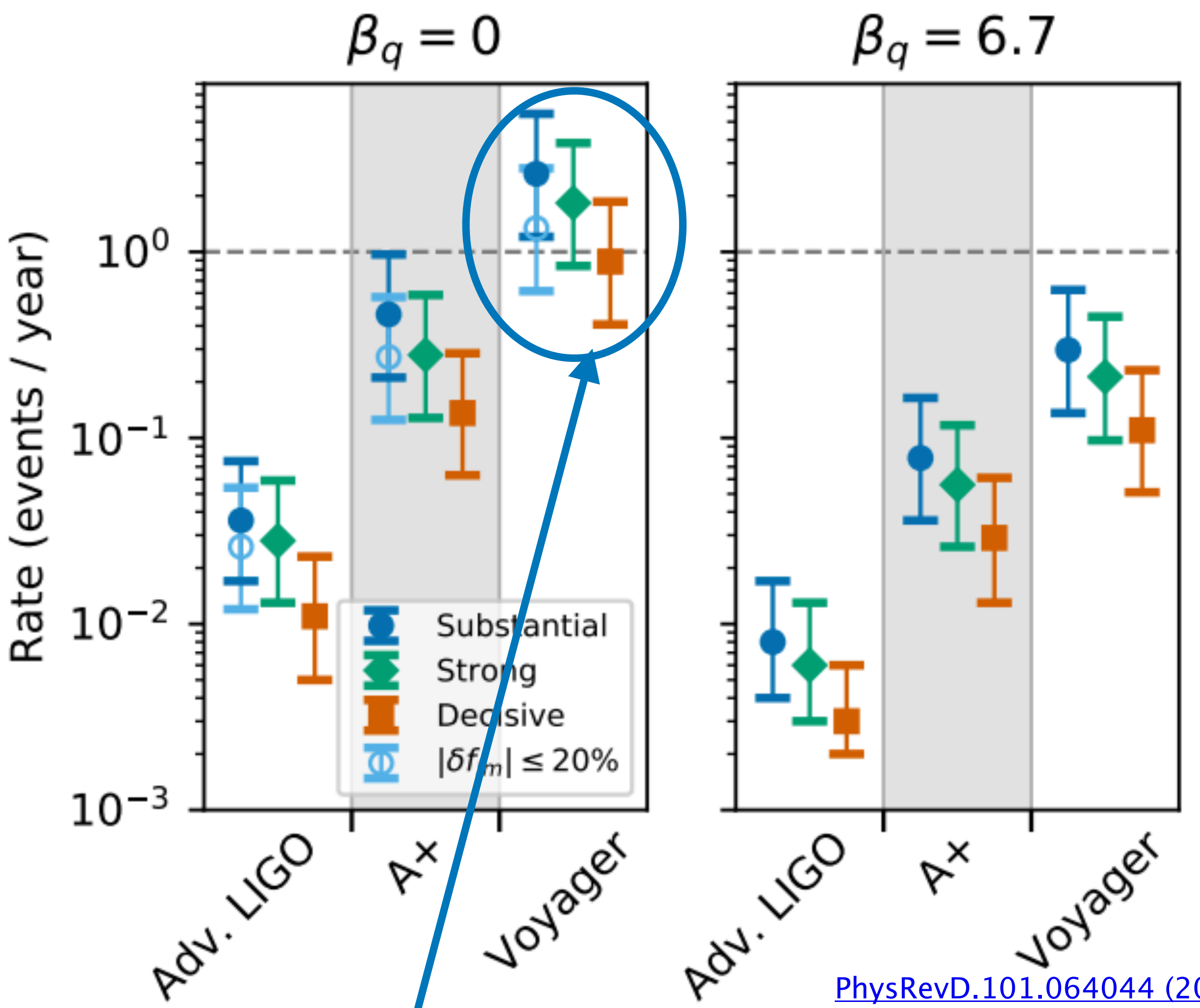
  $$f_{\ell mn} \equiv f_{\ell mn}(M_f, \chi_f),$$
  $$\tau_{\ell mn} \equiv \tau_{\ell mn}(M_f, \chi_f)$$

- Independent measurement of the mass and spin of the remnant blackhole.
- Measurement of multiple quasinormal mode frequencies enables blackhole spectroscopy.
- Facilitates a test of no hair theorem

Blackhole spectroscopy



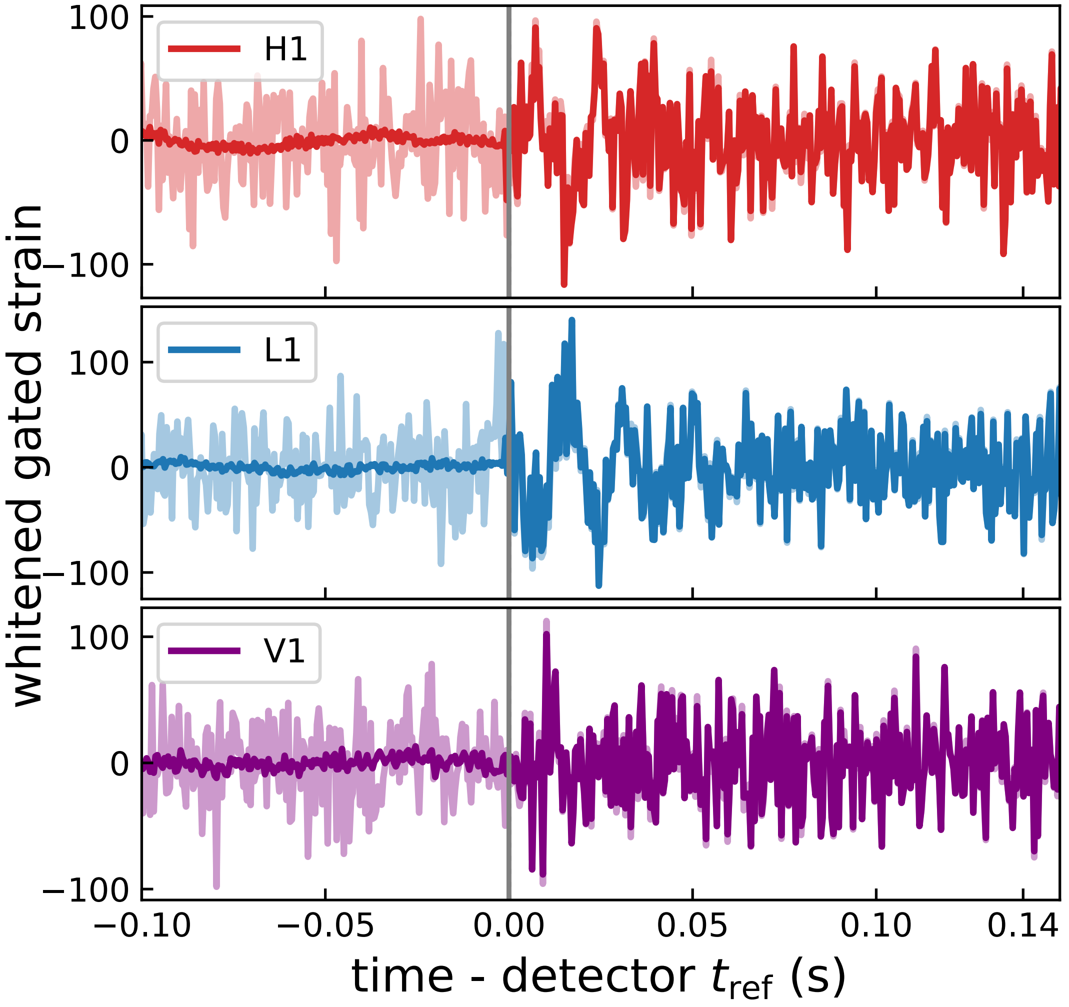
PhysRevLett.117.101102 (2016)

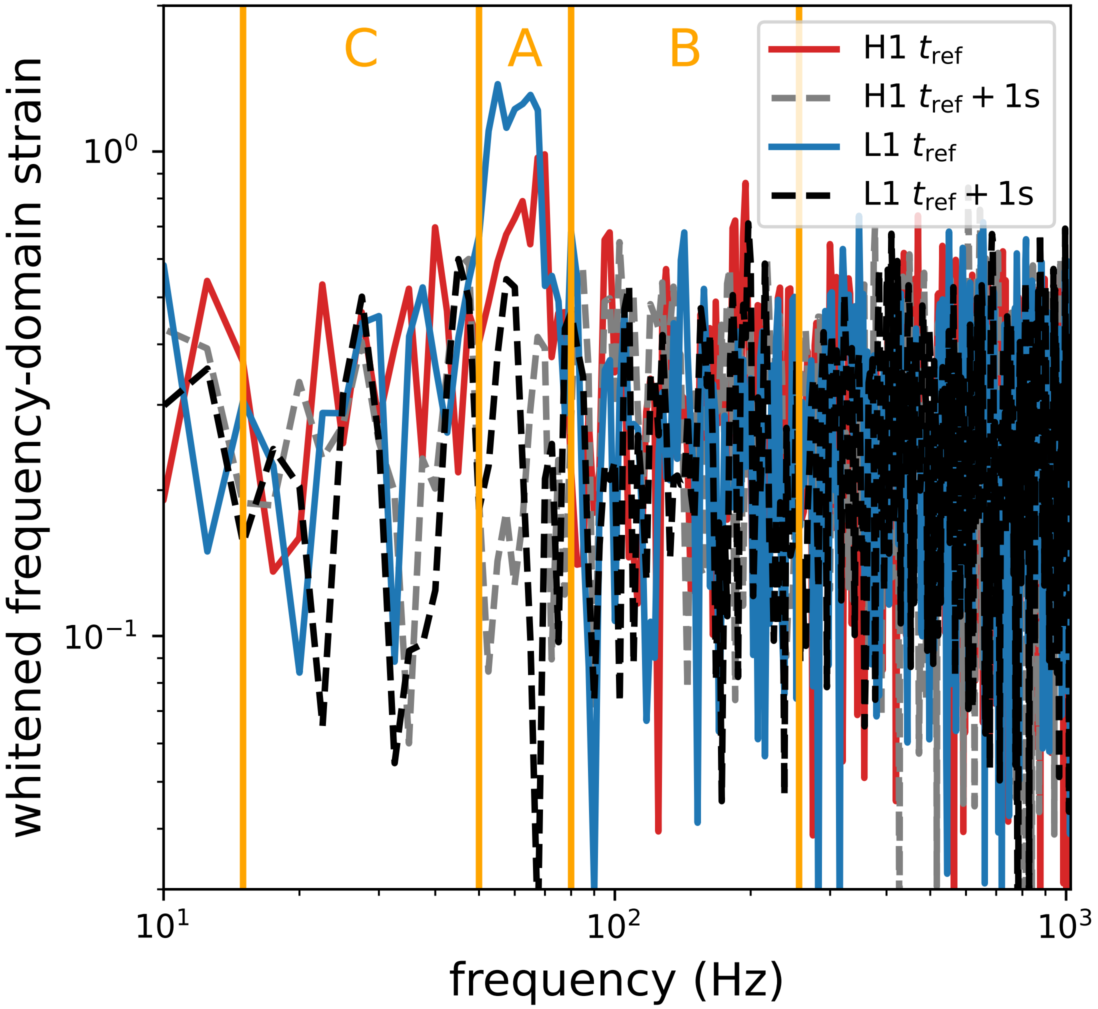


PhysRevD.101.064044 (2020)

Barely possible with Voyager like detector

Blackhole spectroscopy with GW190521

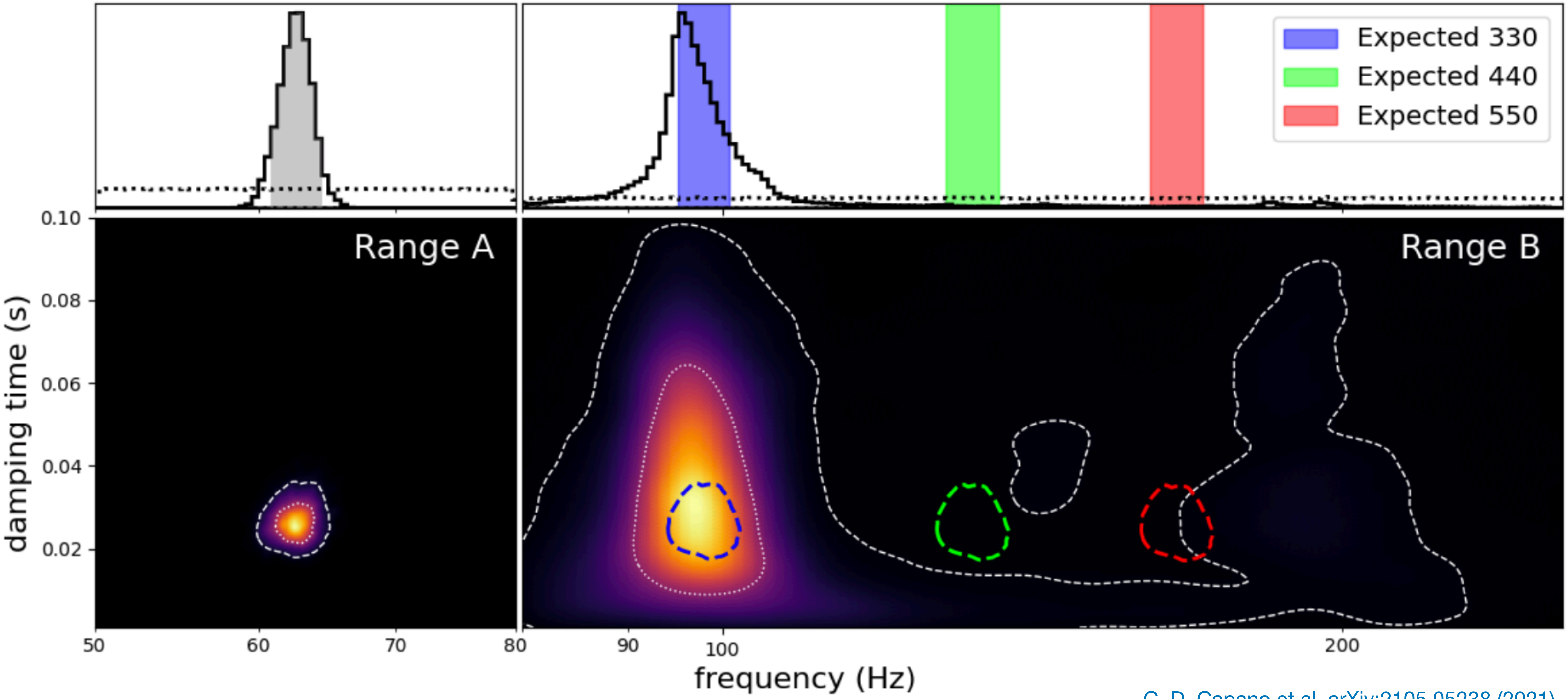




C. D. Capano et al. arXiv:2105.05238 (2021)

Blackhole spectroscopy with GW190521

Two arbitrary damped sinusoids (independent $\Omega_{\ell mn}$)



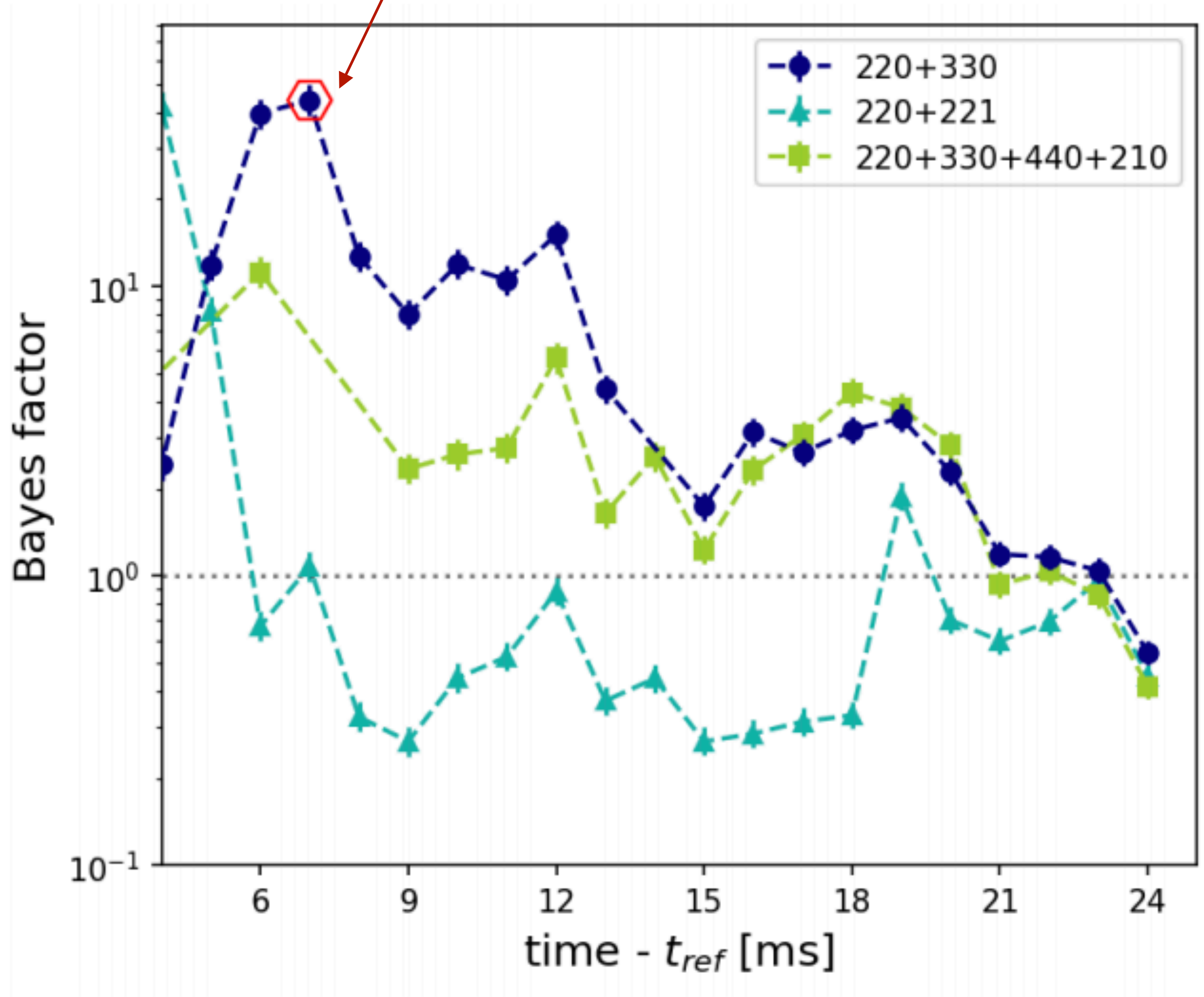
C. D. Capano et al. arXiv:2105.05238 (2021)

Blackhole spectroscopy with GW190521

- Ringdown of a Kerr blackhole is assumed
- We expect only a subset of the entire spectrum of quasi-normal modes to be visible above noise
- Bayes factor is used to compare between different combination of various modes and to identify the favoured model
- Comparison between three different model is shown in the figure
- Bayes factor ~ 40 implies a strong evidence
- GW190521 contains a loud measurable (3,3) ringdown quasi-normal mode.

We find strong evidence for a subdominant mode

$$(\ell, m) = (3, 3)$$



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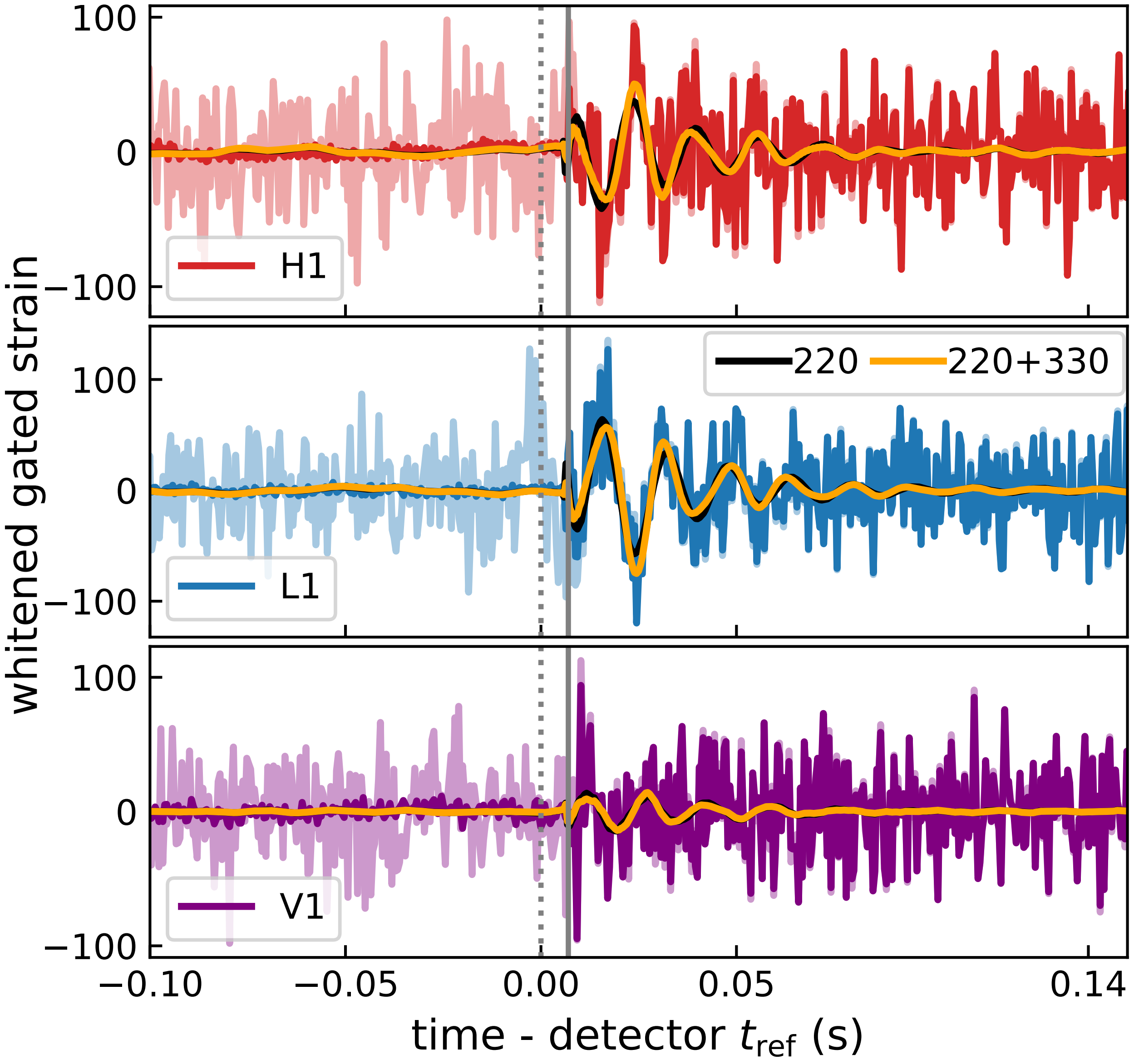
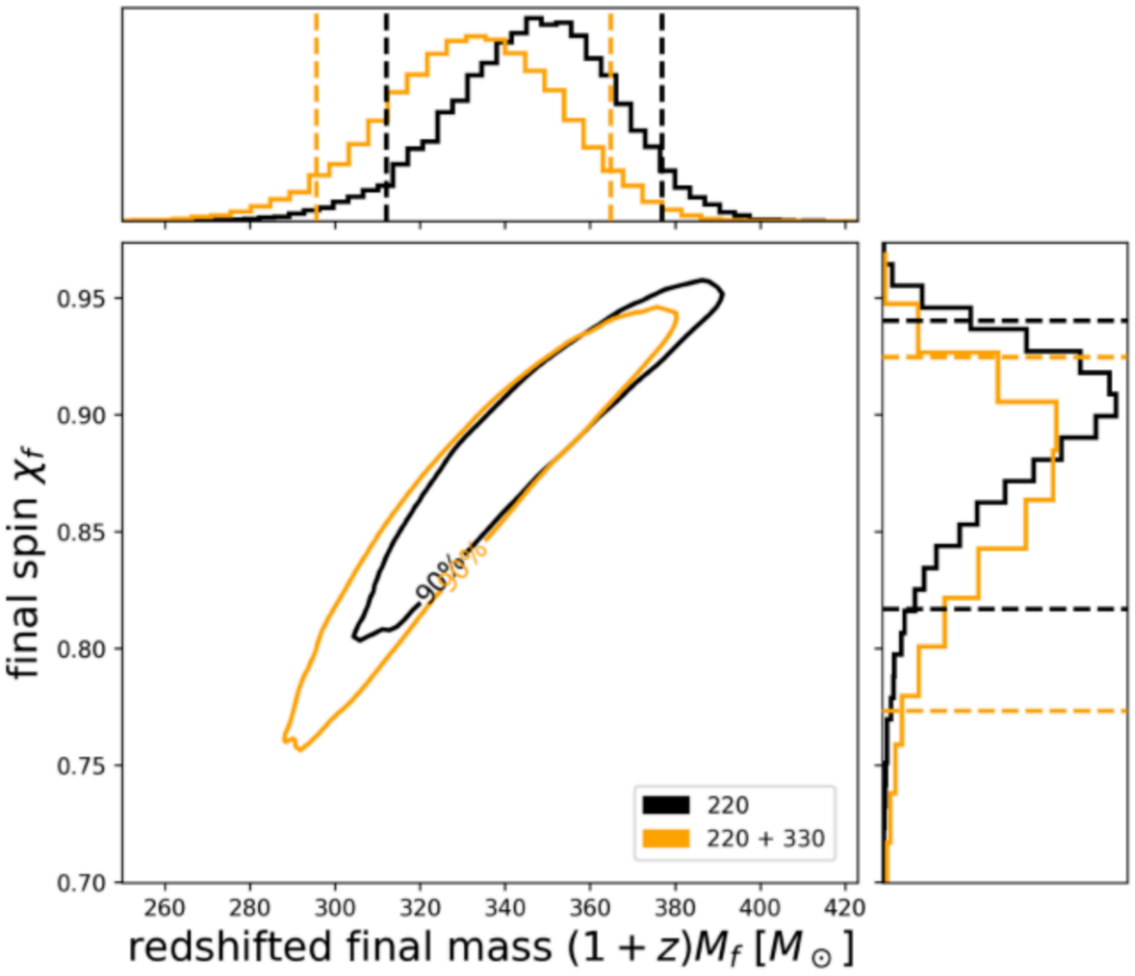
Blackhole spectroscopy with GW190521





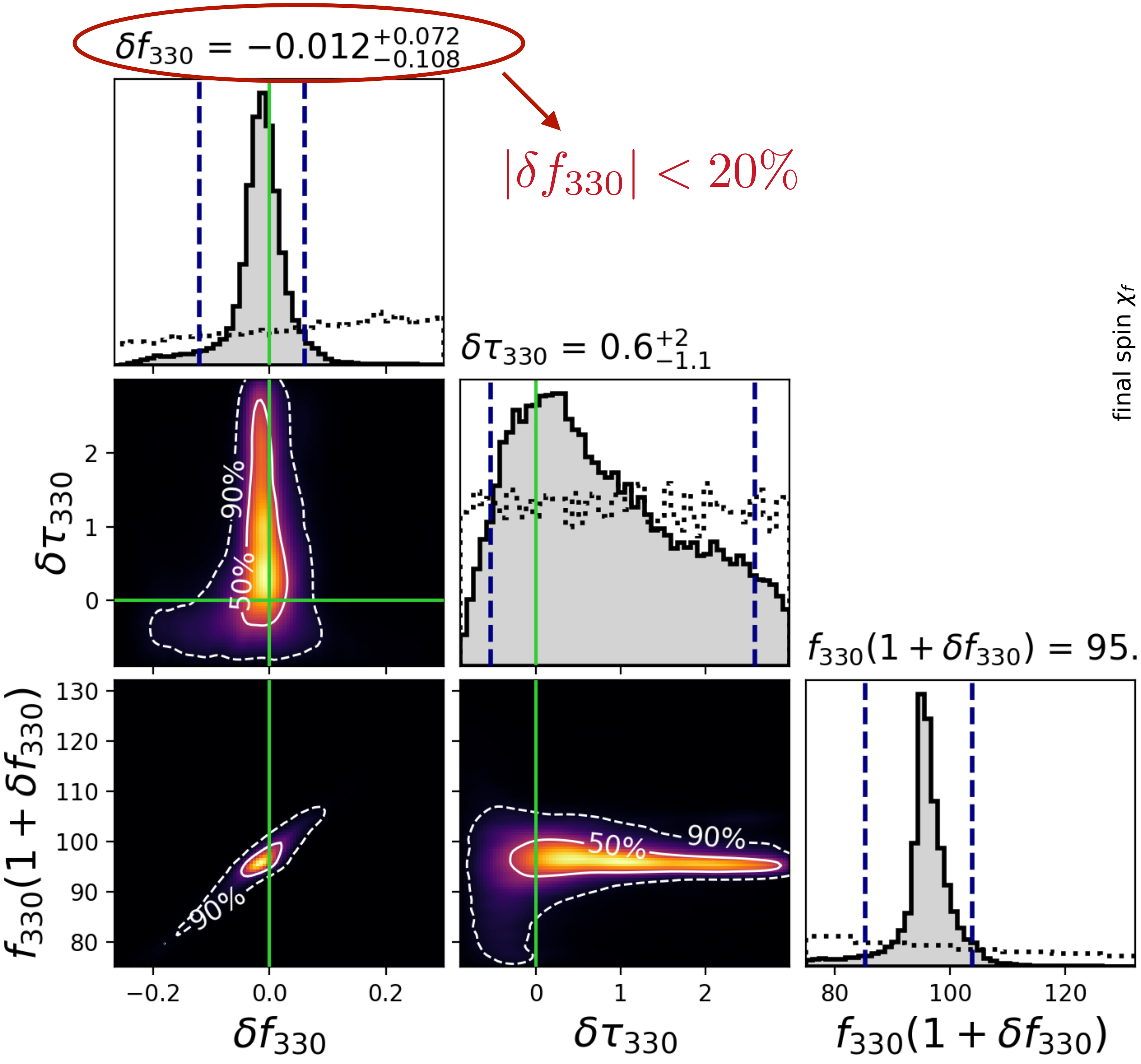
C. D. Capano et al. arXiv:2105.05238 (2021)

Independent measurement of the remnant black hole

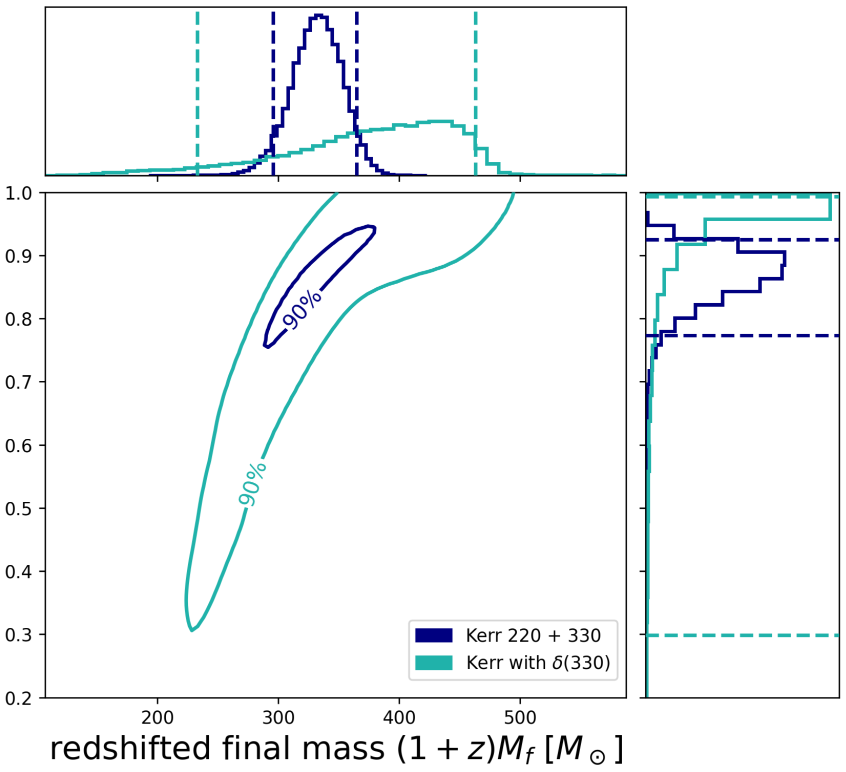
$$(1+z)M_f = 330^{+30}_{-40} M_\odot$$

$$\chi_f = 0.87^{+0.05}_{-0.10}$$

Deviations from General relativity



$|\delta f_{330}| < 20\%$



Remnant Blackhole is consistent with General relativity.

C. D. Capano et al. arXiv:2105.05238 (2021)

Summary

- GW190521 contains a loud measurable (3,3) ringdown quasi-normal mode.
- If GW190521 was a quasi-circular binary, the initial black holes had unequal masses.
- The remnant object is consistent with a Kerr black hole.
- We constrain deviations from the predicted (3,3) frequencies to be within 20%.
- Hand full of tests are being performed on every GW events having their own validity regime. Finding a mapping between different tests will establish the consistency of these tests and make any claim of a deviation from GR (if found) stronger.

Thank you !