Merger-ringdown test

Based on work in arXiv:2101.07817
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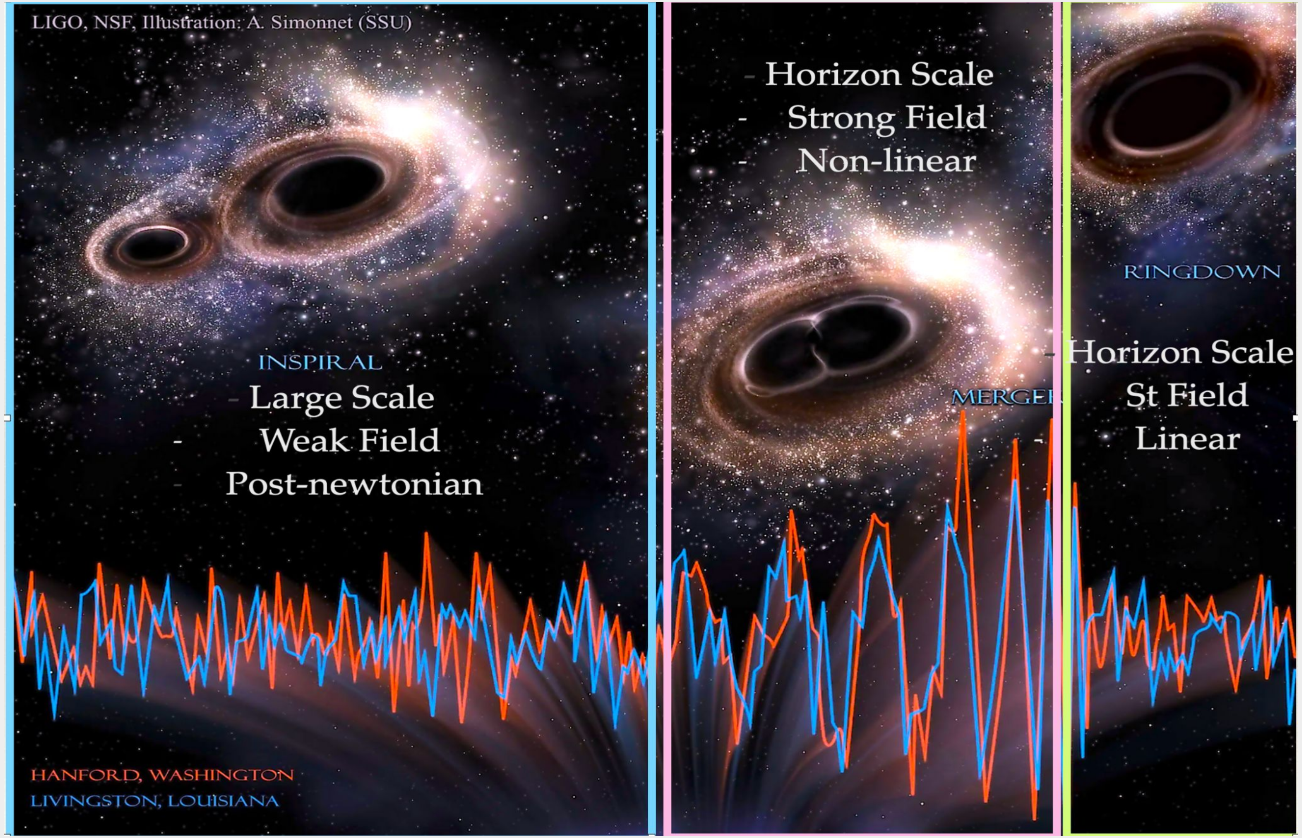
Overview of the talk

- Introduction to binary black hole ringdowns

- Traditional tests of gravity using ringdowns

- New test of GR using amplitude and phase information in ringdowns – Merger-ringdown test

Probing different regimes of gravity with BBH signals



Ringdown morphology

Superposition of damped sinusoids – Quasinormal modes

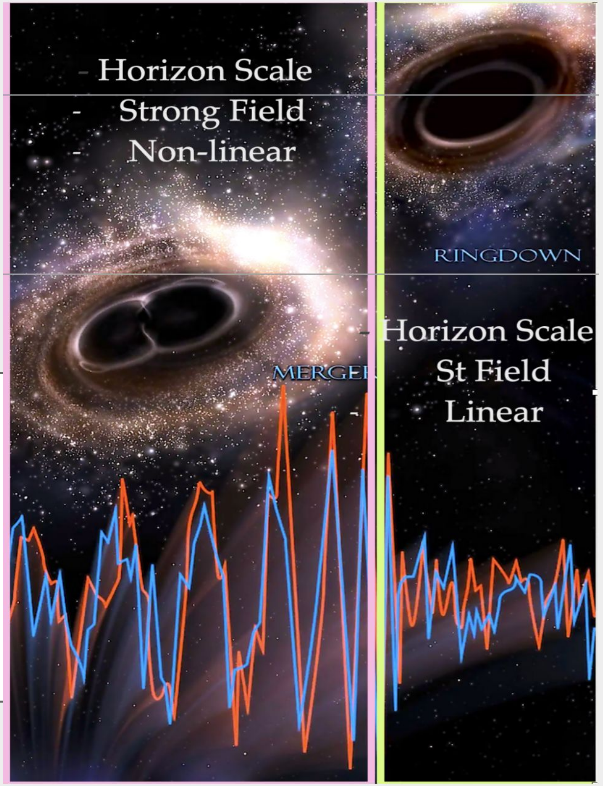
$$h_+ + i\,h_\times = A_{220}\sum_{lmn}\Big(e^{-i\frac{m}{2}\phi_{220}}\,A^R_{lmn}\,e^{i\delta\phi_{lmn}}\,S_{lmn}(\iota,\varphi) \times e^{i2\pi f_{lmn}t}\,e^{-t/\tau_{lmn}}\Big)$$

Dominant mode Amp

Amplitude ratio

Phase diff.

QNM spectra



DOMINANT QNM: (2,2,0)

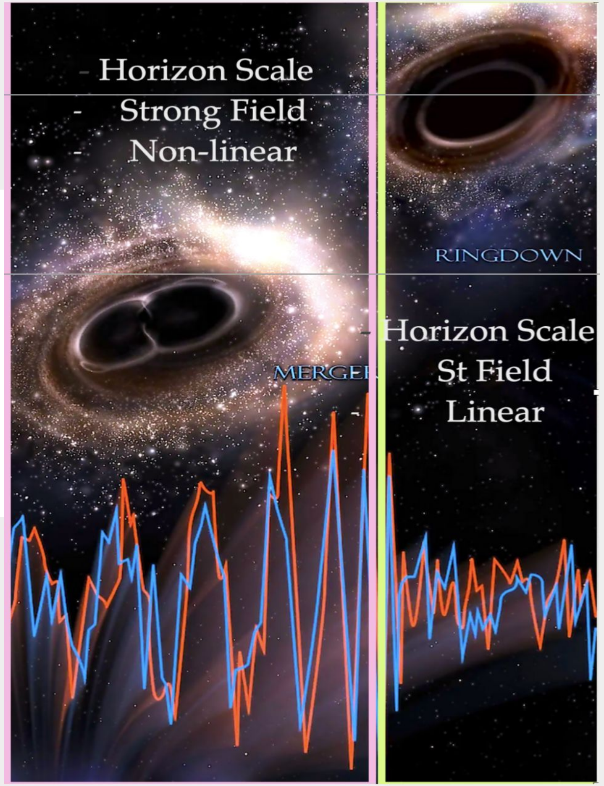
MOST PROMISING SUB-DOMINANT QNM: (3,3,0), (2,1,0) OR (4,4,0).

Traditional Tests of GR With Ringdown

BLACK HOLE SPECTROSCOPY - THE TRADITIONAL TEST

BLACK HOLE SPECTROSCOPY CONSTITUTES MEASURING THE FREQUENCIES AND DAMPING TIME OF MULTIPLE MODES

$$h_+ + i\,h_\times = A_{220} \sum_{lmn} \Big(e^{-i\frac{m}{2}\phi_{220}} A^R_{lmn} e^{i\delta\phi_{lmn}} S_{lmn}(\iota, \varphi) \times e^{i2\pi f_{lmn} t} e^{-t/\tau_{lmn}} \Big)$$



Validate the nature of the final remnant formed…

- no hair theorem test,
- area theorem test etc…

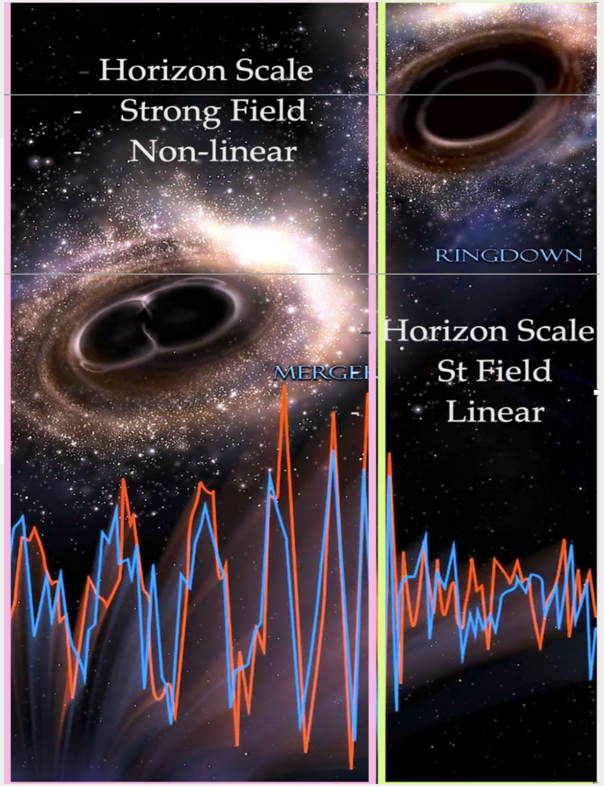
But... why not do checks using ringdown amplitudes and Phases?

Ringdown waveform - Amplitudes and phase

-linear superposition of quasi-normal modes

$$h_+ + i\,h_\times = A_{220} \sum_{lmn} \left(e^{-i\frac{m}{2}\phi_{220}} A^R_{lmn} e^{i\delta\phi_{lmn}} S_{lmn}(\iota, \varphi) \right.$$
$$\left. \times\, e^{i2\pi f_{lmn} t} e^{-t/\tau_{lmn}} \right)$$

Post-merger Pre-merger



Ringdown has 2 distinct information –

a) Amplitude and phase : Pre-merger dynamics
b) Frequency and damping time : Post-merger dynamics

Importance of using amplitude and phase information

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AMPLITUDES AND PHASES ⟺ PERTURBATION CONDITIONS ⟺ BBH PROPERTIES

Merger dynamics probes **the non-linear strong field dynamics**

MERGER-RINGDOWN CONSISTENCY TEST

The concept of merger-ringdown test

$$h_+ + i\,h_\times = A_{220} \sum_{lmn} \left(e^{-i\frac{m}{2}\phi_{220}} A^R_{lmn} e^{i\delta\phi_{lmn}} S_{lmn}(\iota, \varphi) \times e^{i2\pi f_{lmn} t} e^{-t/\tau_{lmn}} \right)$$

Step 1: parameterize ringdown as a function of {M, χ_f, q}

$$h_+(t) = h_+(t; M, \chi_f, q)\,, \quad h_\times(t) = h_\times(t; M, \chi_f, q)$$

Step 2: estimate {M, χ_f, q} from the ringdown data

MERGER-RINGDOWN TEST - CONSISTENCY BETWEEN MEASURED AND INFERRED SPINS

$$h_+(t) = h_+(t; M, \chi_f, q)\,, \quad h_\times(t) = h_\times(t; M, \chi_f, q)$$

Method 1 - Direct measurement of the set of parameters $\{M, \chi_f, q\}$ for each of the n events detected using PE.

Method 2 - Use GR relationship to related spin of the final BH and the mass ratio of the initial binary BH system.

$$\chi_f = 2\sqrt{3}\eta - 3.871\eta^2 + 4.028\eta^3 + \mathcal{O}(\eta^3)$$

where,

$$\eta = q/(1+q)^2$$

TECHNICAL DETAILS OF OUR PE SETUP

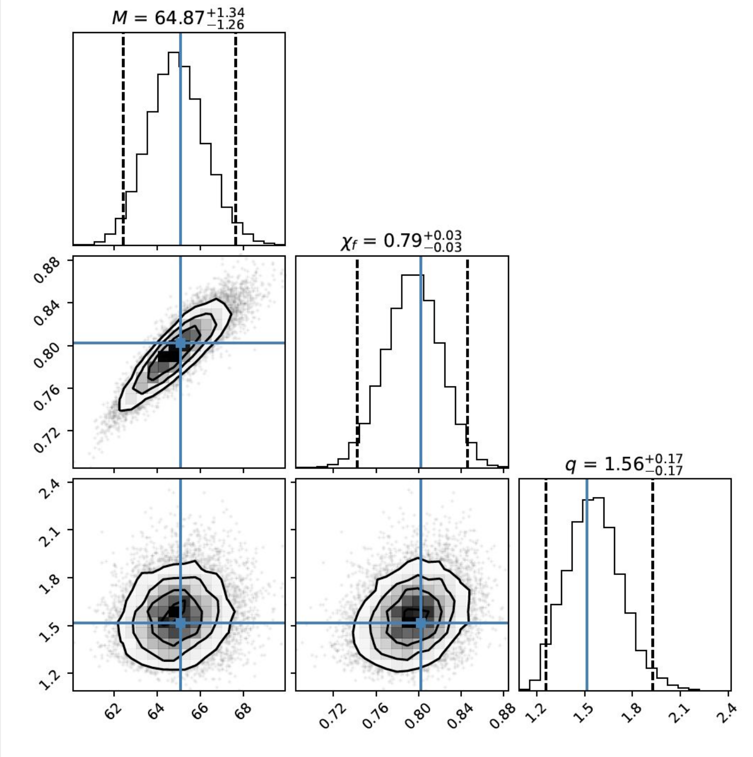
Parameter Estimation using Deep Learning

- **We use a deep learning framework.**
- **Neural Network Architecture: Conditional Variational Autoencoder (CVAE)**

A brief outline of the setup

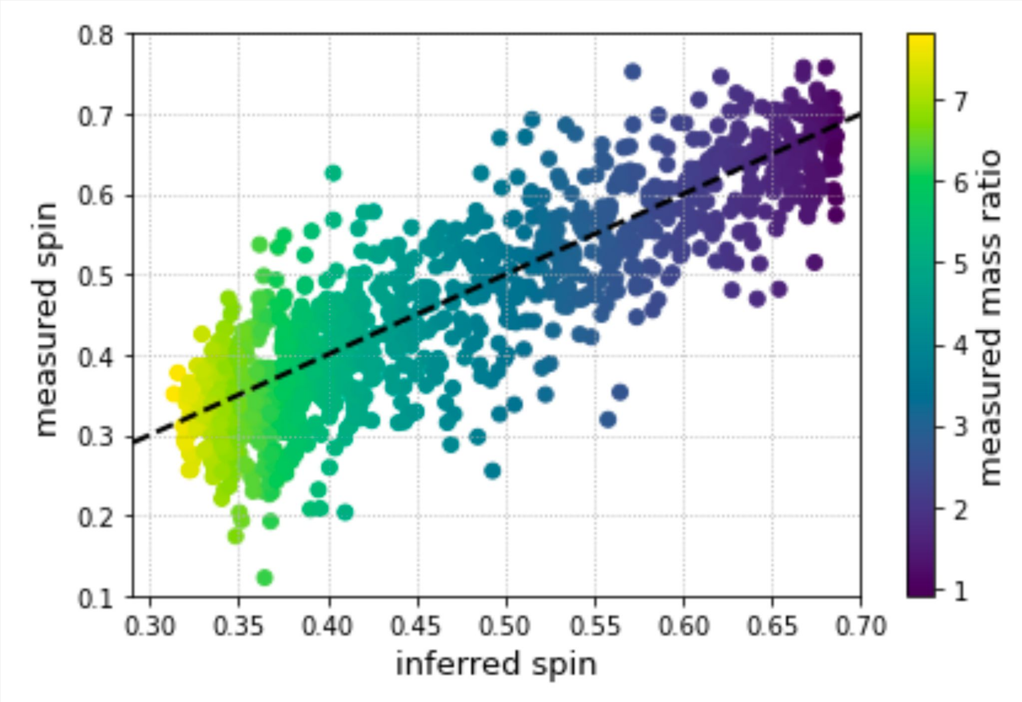
- We generate a dataset of 10^5 simulated ringdown waveforms
- The GW waveforms are embedded in simulated noise segments
- 90% dataset is used for training and 10% dataset used for validation.
- Our training takes 84 minutes on a single GPU.

- Then, we generate 10^3 simulated ringdowns to conduct our proof-of-concept study of merger-ringdown consistency test.
- PE with our network after training takes 40 ms per waveform
- We check the statistical accuracy of out PE setup using a P-P test.



Results of Merger-Ringdown test on 1000 ringdowns

Parameter	Symbol	Range
Final BH mass	M	$[25, 100]\ M_\odot$
Final BH spin	χ_f	$[0, 0.9]$
Binary mass ratio	q	$[1, 8]$
Phase of the (2,2) mode	ϕ_{22}	$[0, 2\pi]$ rad
Signal-to-noise ratio	SNR	$[40, 80]$



$$\chi_f^{\text{meas}} = a + b\,\chi_F^{\text{infer}}$$

Ringdown & Pre-merger

Ideally, for GR a=0 ; b=1

Result: $a \in [-0.014, 0.014]$ and $b \in [0.963, 1.013]$

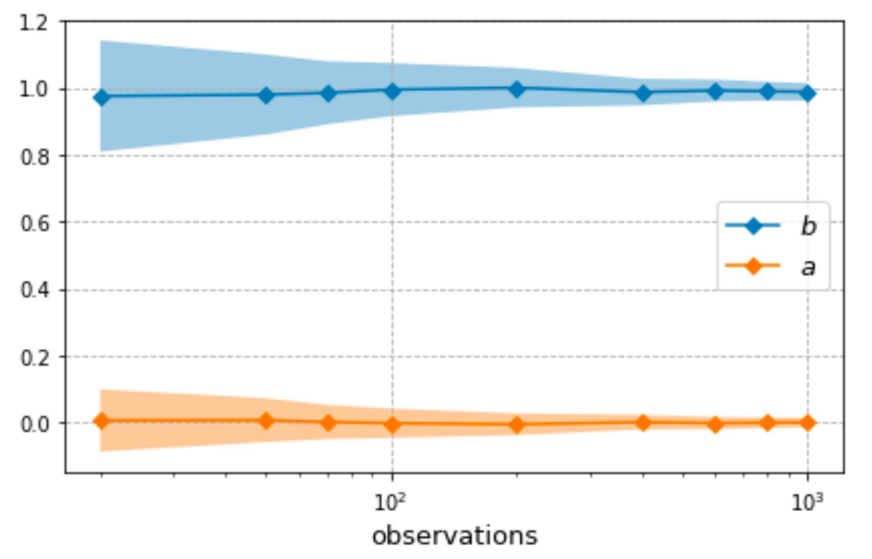
Efficiency of the test with number of observations

$$\chi_f^{\text{meas}} = a + b\,\chi_F^{\text{infer}}$$

Ringdown & Pre-merger

Ideally, for GR a=0 ; b=1

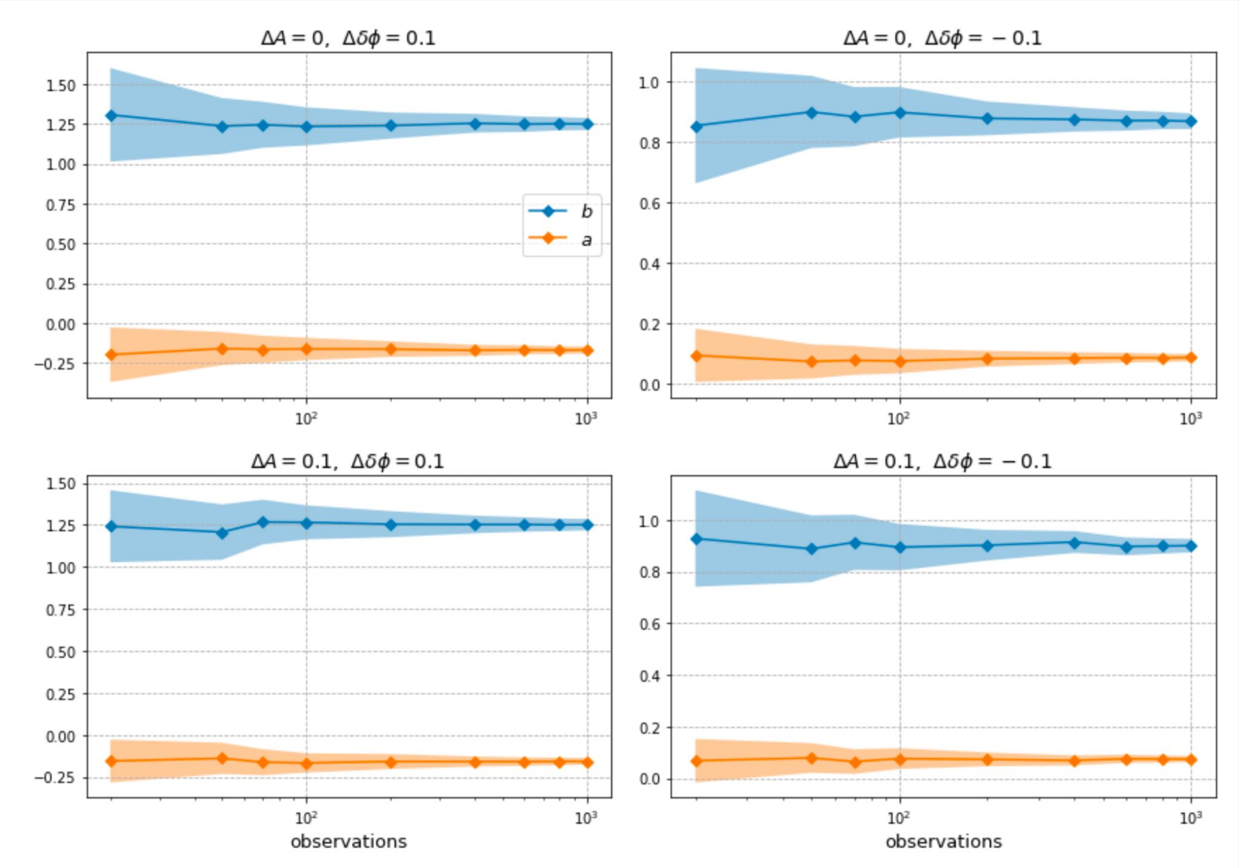
$$\sigma_a(n) = \frac{0.21}{\sqrt{n}}\,, \qquad \sigma_b(n) = \frac{0.41}{\sqrt{n}}$$



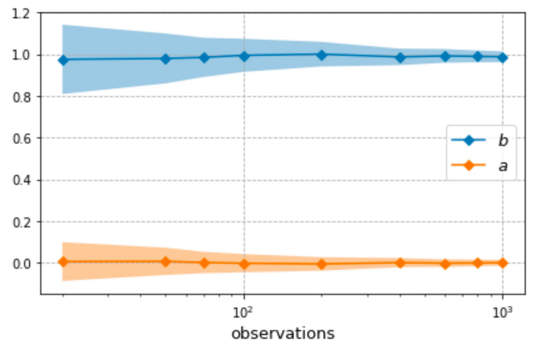
OK, SO THE NULL TEST WORKS!

BUT DOES THE TEST FAIL FOR NON-GR AMPLITUDE-PHASE??

Merger-ringdown test on NON-GR Ringdowns



Ideally,
for GR a=0 ; b=1

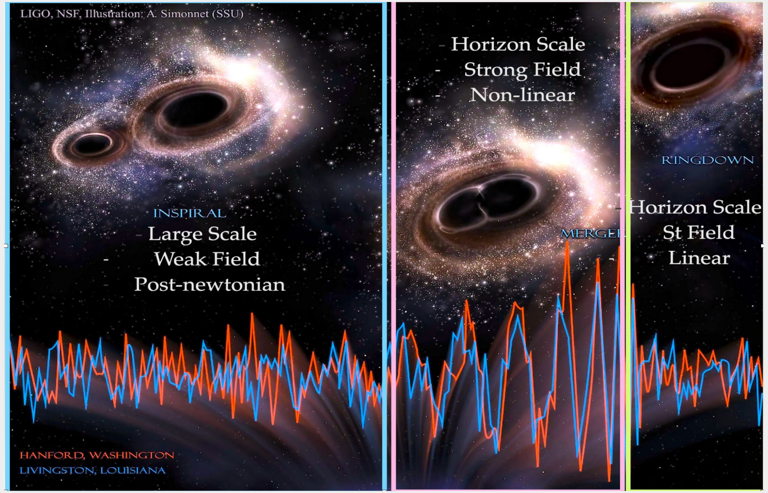


Conclusion

Conclusion and take away point

Amplitudes and phases in rindown contain a vital information –
They can tell us it the dynamics in the strong non-linear gravity regime Is consistent with GR predictions!

These tests are "complimentary" to black hole spectroscopy



Question/Comments?