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Gravitational-wave events and modern population synthesis

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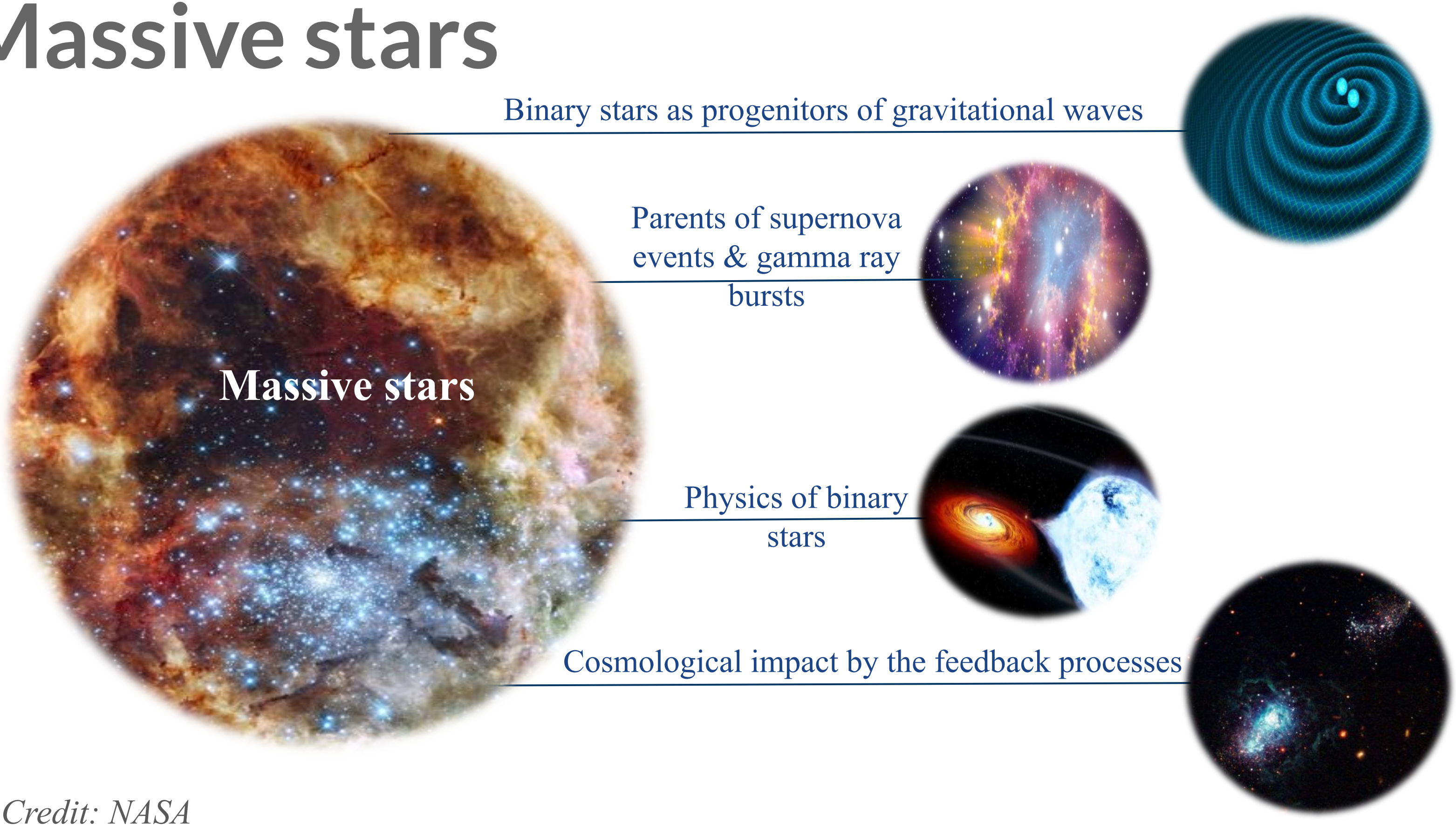
Figure Credit: NASA

Massive stars



Massive stars

Binary stars as progenitors of gravitational waves

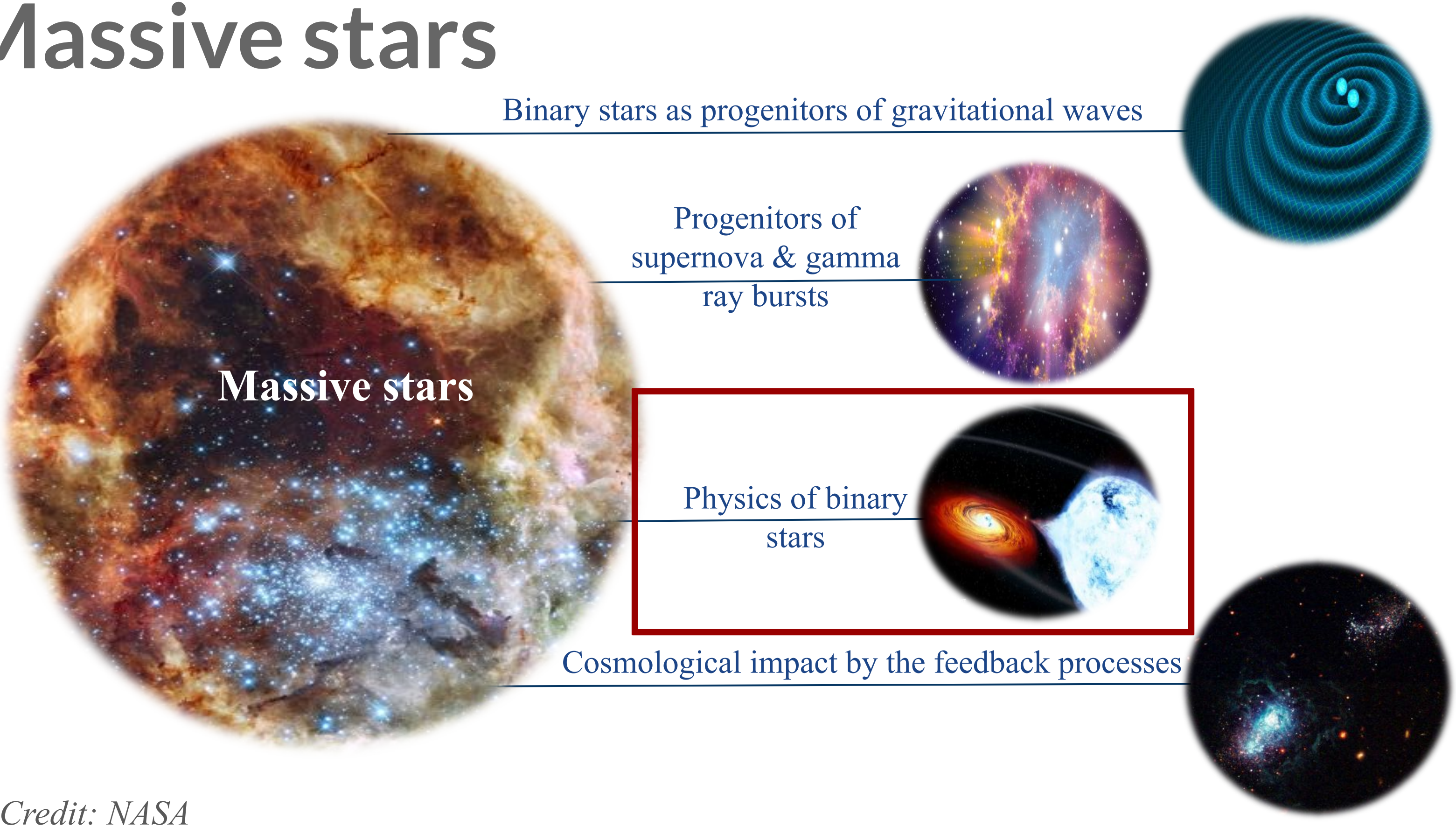
Parents of supernova events & gamma ray bursts

Physics of binary stars

Cosmological impact by the feedback processes

Figure Credit: NASA

Massive stars



Binary stars as progenitors of gravitational waves

Progenitors of supernova & gamma ray bursts

Physics of binary stars

Cosmological impact by the feedback processes

Figure Credit: NASA

Evolution of massive binary stars

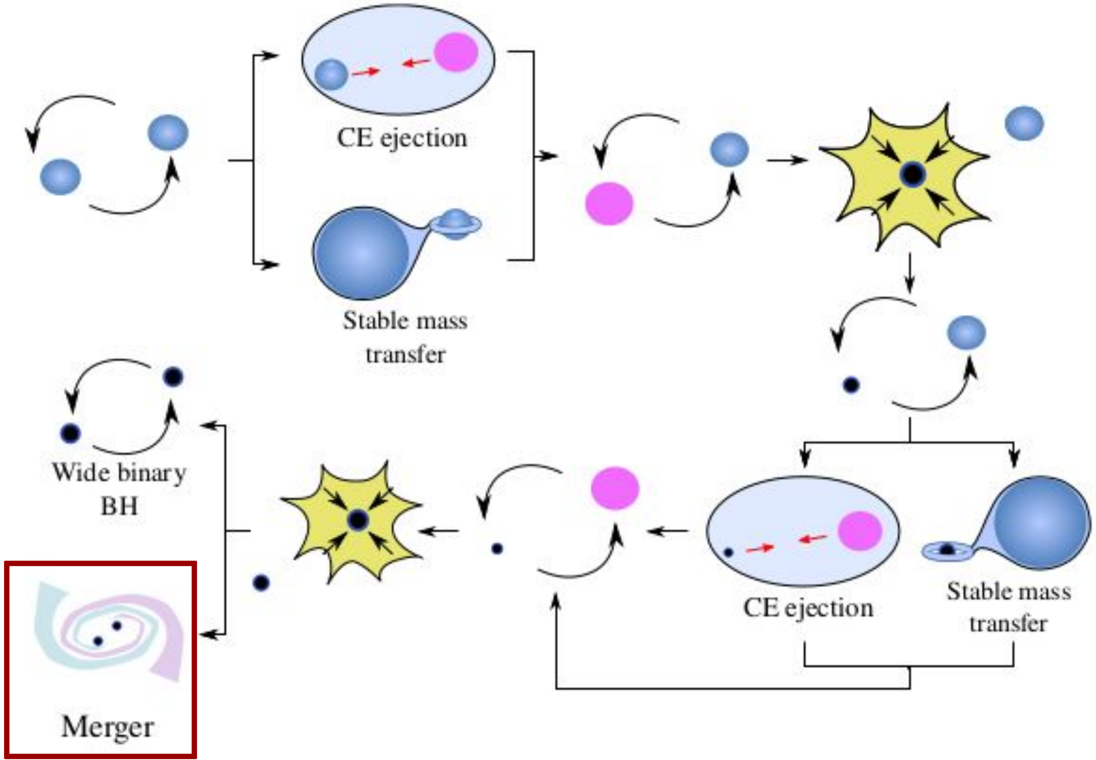
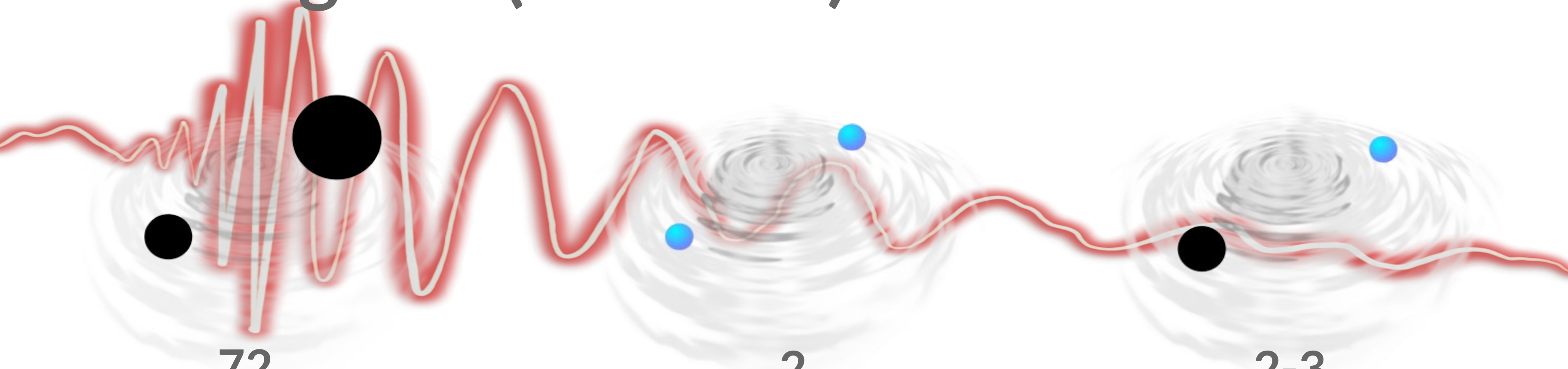


Figure Credit: Pablo Marchant

The Gravitational-Wave Transient Catalogue 3 (GWTC-3)



72
Binary black holes

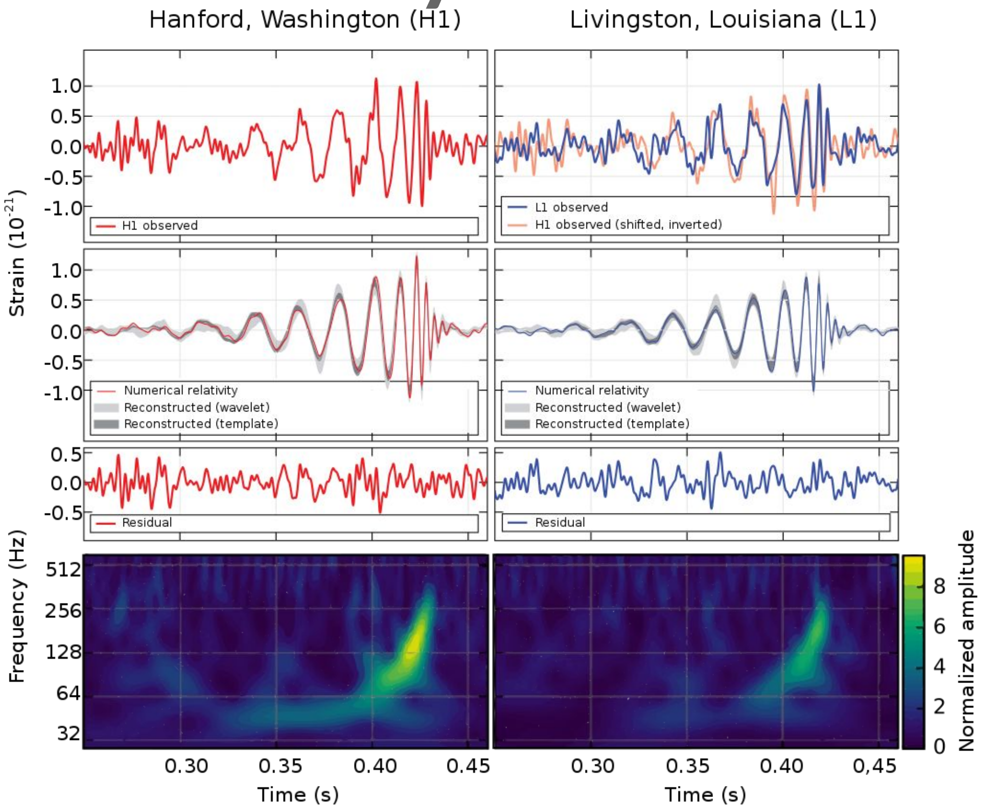
2
Binary neutron star

2-3
Black hole-neutron star

Abbot et al. arXiv:2111.03606 (2021)

Challenges in GW Data Analysis

- Event GW150914
  - On September 14th, 2015: GWs from two ~30 solar mass black holes (BHs), merging ~400Mpc from Earth (z~0.1), crossed the two LIGO detectors displacing their test masses by a small fraction of the radius of a ***proton***.
  - Measuring intervals must be smaller than 0.01 seconds.



Challenges in GW Data Analysis

- Matched-filtering Technique
    - It is an optimal linear filter for weak signals buried in Gaussian and stationary noise ***n(t)***.
    - Works by ***correlating*** a known signal model ***h(t)*** (template) with the data.
    - Starting with data: ***d(t) = h(t) + n(t)***.
    - Defining the matched-filtering SNR ***ρ(t)***:

$$\rho^2[h] = (\tilde{h}(f)|\tilde{h}(f)) = 4\Re\left\{ \int_0^\infty \frac{\tilde{h}^*(f)\ \tilde{h}(f)}{S_n(f)}\ df \right\}$$

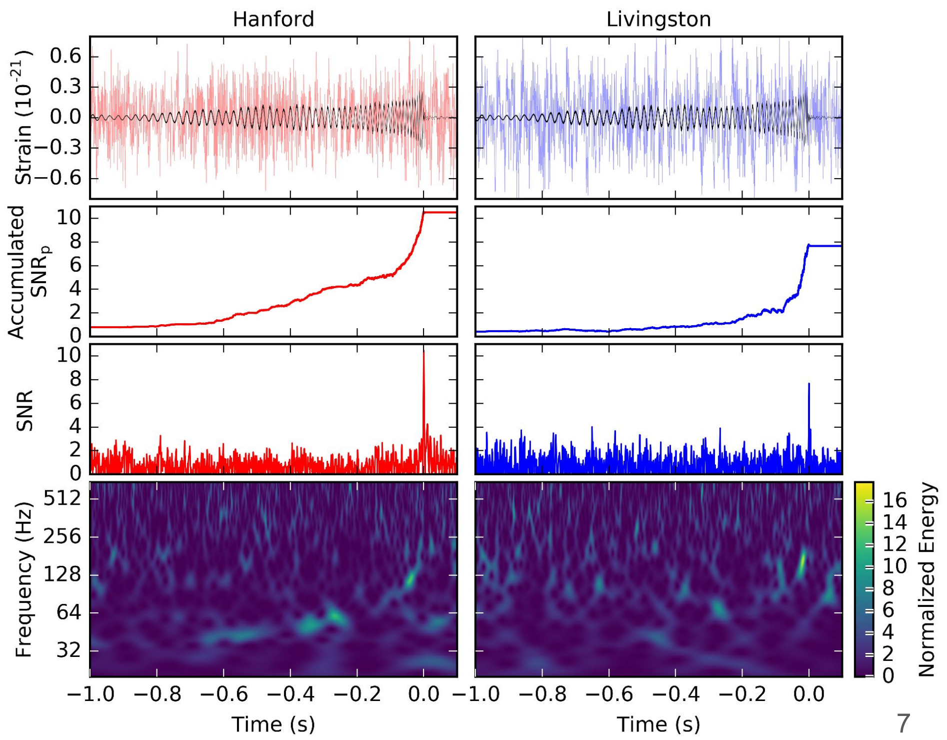
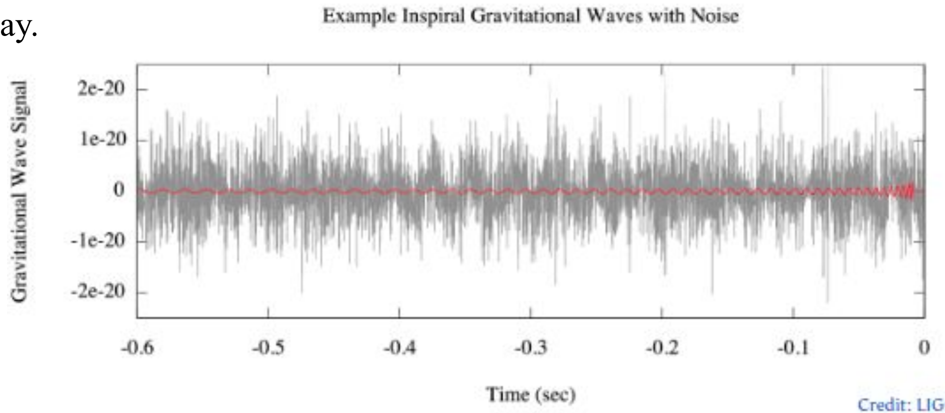


Figure Credit: LIGO-VIRGO collaboration

Challenges in GW Data Analysis

- Noise in the detector
    - The ***actual data*** from the detector is shown in gray.
    - The noise is much ***louder (~100x)*** than the expected signals in red. (BHs with spinning/non-spining and two neutron stars)
    - It's ***non-Gaussian*** and ***non-stationary*** that containing anomalous non-Gaussian transients, known as ***glitches***.



Credit: LIGO

Deep learning, Convolutional neural networks and AI methods:

- When ***machine & deep learning*** meets GW astronomy:
  - Covering more parameter-space (***Interpolation***)
  - Automatic generalization to new sources (***Extrapolation***)
  - Resilience to real non-Gaussian noise (***Robustness***)
  - Acceleration of existing pipelines (***Speed, <0.1ms***)

Milestones

Proof-of-principle studies

Phys.Rev.D 97 (2018) 4, 044039
Phys.Rev.Lett 120 (2019) 14, 141103

Production search studies

Phys.Rev.D 100 (2019) 6, 063015
Phys.Rev.D 101 (2020) 10, 104003
Phys. Rev. D 105 (2022), 024024
For more related links:
https://iphysresearch.github.io/Survey4GWML/

Accelerated, scalable and reproducible AI-driven GW detection

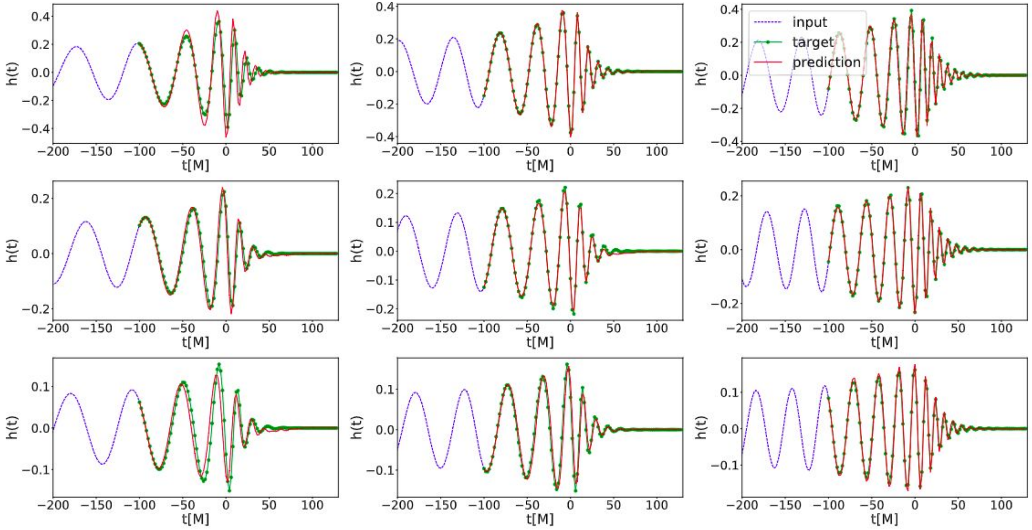
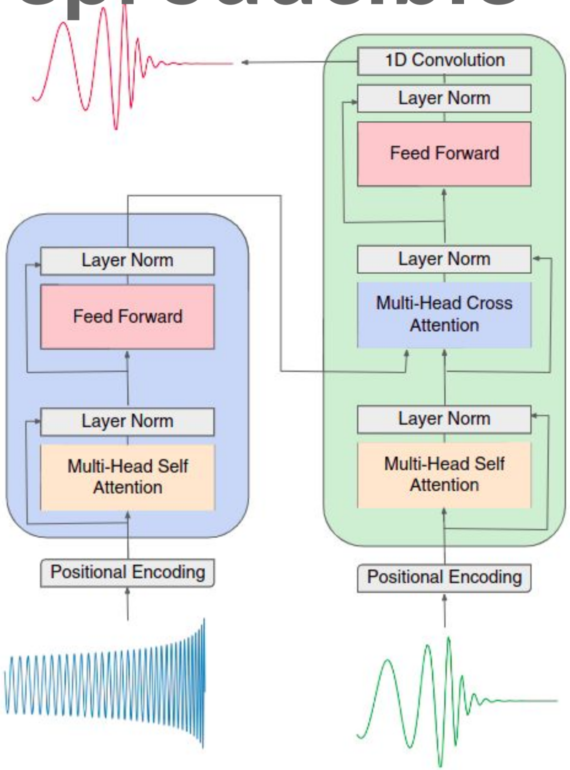


FIG. 4. Gallery of results. Sample input, target and predicted waveforms for binary black holes with mass ratios $q = \{1.04, 4.24, 6.80\}$, from top to bottom; and spins $s_1^z = s_2^z = \{-0.7, 0.0, 0.7\}$, from left to right. Notice the impact of individual spins in the dynamics of the systems, encompassing rapid (left column) and delayed plunges (right column). The model predicts the waveform evolution in the range $-100\ \mathrm{M} \leq t \leq 130\ \mathrm{M}$.



1D Convolution

Layer Norm

Feed Forward

Layer Norm

Multi-Head Cross Attention

Layer Norm

Multi-Head Self Attention

Positional Encoding

Layer Norm

Feed Forward

Layer Norm

Multi-Head Self Attention

Positional Encoding

https://doi.org/10.1038/s41550-021-01405-0

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Thank you...

Figure Credit: NASA