Laser Interferometer Gravitational-Wave Observatory
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Phenomenology & Detectability of Quantum Effects in BBH Mergers

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SURF 2020 Final Presentation

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GW150914

Presentation Outline

Background: Binary Black Hole Coalescence

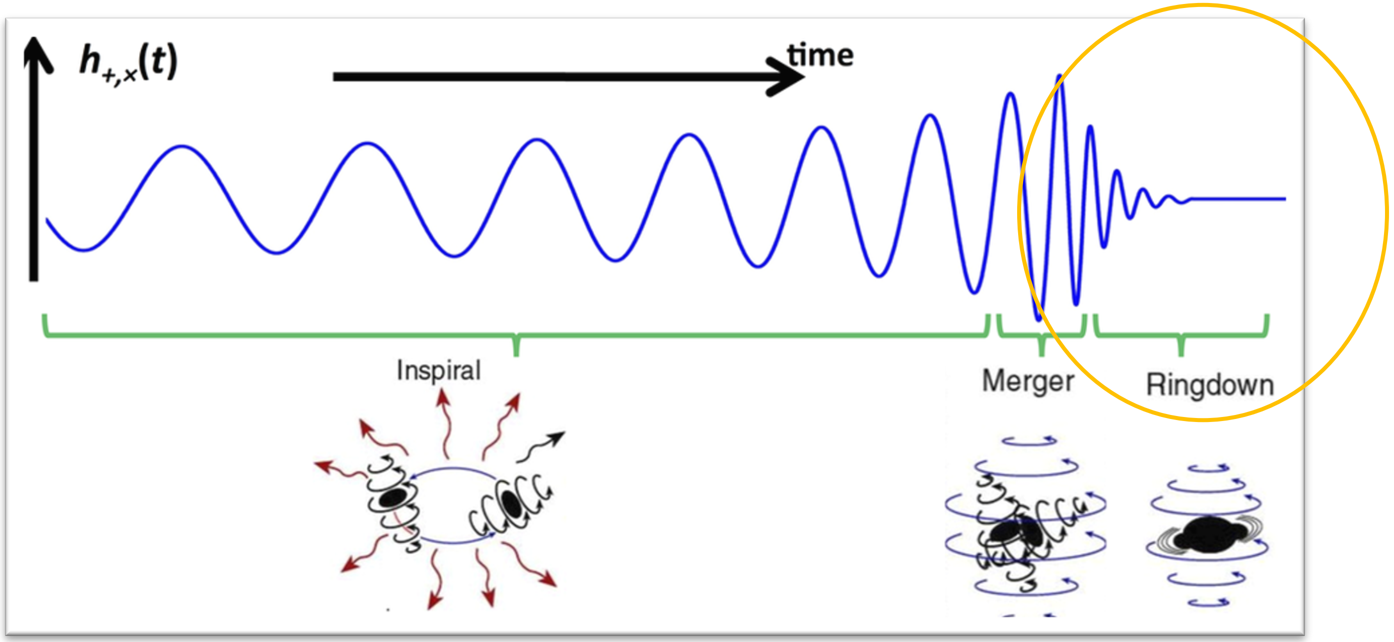

FIG 1. Inspiral, merger, and ringdown of Binary Black Hole (BBH) system [1]

1. Interesting physics!
2. Current detectors & models are at the cusp of detecting and analyzing ringdown components
3. Quantum effects in the ringdown!

Background: Ringdown

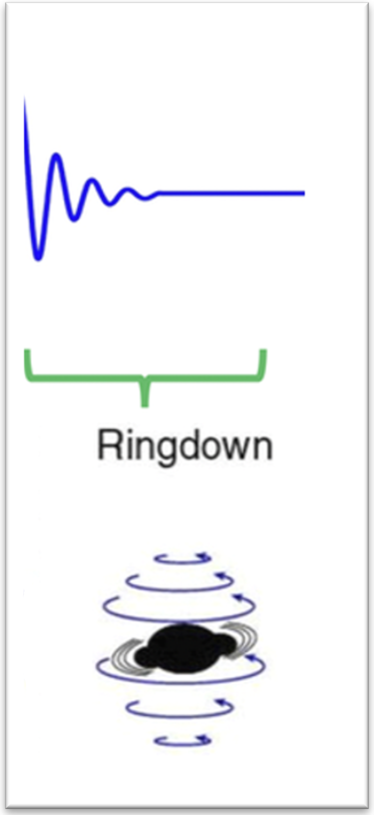

FIG 2. Ringdown BBH system [1]

$$h_+ = \sum_{lmn} \frac{M}{r} \Re(A^+_{lmn} e^{i(\omega_{lmn} t + \phi^+_{lmn})} e^{-t/\tau_{lmn}} S_{lmn}(\iota, \phi))$$
$$h_\times = \sum_{lmn} \frac{M}{r} \Im(A^\times_{lmn} e^{i(\omega_{lmn} t + \phi^\times_{lmn})} e^{-t/\tau_{lmn}} S_{lmn}(\iota, \phi))$$

Eq 1. Cross and plus polarization strain for quasi-normal mode (QNM) ringdown. Ringdown just looks like a linear superposition of damped-sinusoids! [2]

For a (l, m, n) mode where l, m, n are the quantum numbers:

- A_{lmn} is amplitude of a QNM
- ω_{lmn} is the (real) the angular frequency of a QNM
- ϕ_{lmn} is the phase
- τ_{lmn} is damping time, inverse of the imaginary angular frequency
- S_{lmn} is the spheroidal harmonics, a function of viewing angle

Background: Higher Order Modes

What's a higher order mode (HOM)?

For a quasi-circular binary, quadrupolar radiation dominates, (l, m) = (2, |2|) (green)!

- Ringdown has been assumed to be *just* the (2, 2) mode
- HOMs are hard to detect, but well-predicted by General Relativity (GR)

GW190412 & GW190814 show evidence of (3, 3) mode [3][4]

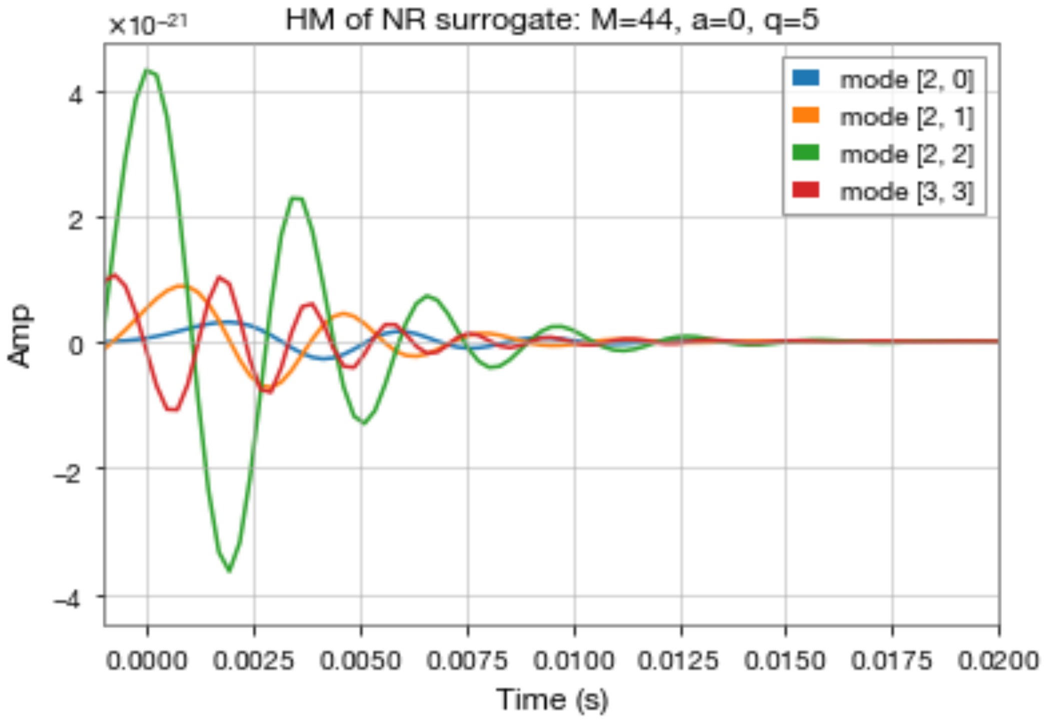

FIG 3. NRSurdq4 (M=44, a=0, q=5, ι=0, distance=235 Mpc) ringdown highlighting HOMs green is the dominant (2, 2) mode [8]

Background: Motivation

"Okay nice, but what's the big deal with HOMs?"

HOMs and the ringdown provide a *fine* test of GR

It's expected that quantum mechanical effects should *modify* GR

- QNM ringdown is a probe for BH interior

Background: Brustein *et al* "Toy" Polymer Model

The polymer model is just a general fluid mechanics problem involving …

- BH-copycat filled with *stringy quantum matter* rather than empty space that imitates GR ringdown
- A stringy quantum "fluid" with an index of refraction: $n_{ref} = c/v_{sound}$
- n_{ref} inversely depends on how frequently the string interact, or string coupling g_s

[5][6][7]

Relativistic limit: $v_{sound} \sim c/\sqrt{3}$

- Suppressed!

Sub-relativistic limit: $v_{sound} << c$

- Predicted frequency & damping time

Background: Brustein *et al* "Toy" Polymer Model

CLASSICAL GR

$$\omega = \frac{0.7474c}{R_s} \quad \tau = \frac{R_s}{0.178c}$$

Eq 3. Perturbed Schwarzschild BH (2, 2) QNM [2]

POLYMER

$$\omega = \frac{pc\pi}{2R_s n_{ref}} \quad \tau = \frac{R_s n_{ref}^2}{c}$$

Eq 2. Polymer Ringdown modes

For a particular (odd) mode, *p*, where:
R_s is the Schwarzschild radius (2GM)
n_{ref} is the refractive index [7]

Compared to the dominant (2, 2) mode for a perturbed Schwarzschild BH the quantum fundamental mode has a …

- Frequency which is ~ $1/n_{ref}$ lower
- Damping time (τ) is ~ $10\ n_{ref}^2$ longer

Project

Brustein *et al's* polymer model predicts a new mode that's distinct from GR's predictions which is the result of the BH being *being full of quantum stuff* [5][6][7]

1. How does the quantum mode look relative to GR modes?
2. Using *bilby,* which is a Bayesian inference software, is this mode within the frequency range for GW observation & and at what masses can you recover the quantum mode, varying n_{ref}
3. Can the quantum mode be recovered within a full ringdown & generally, under what conditions (varying Mass, amplitude, n_{ref}) is this mode *best* observable?

1. How does the quantum mode look relative to GR modes?

Increasing n_{ref}

Phenomenology of Model: Frequency

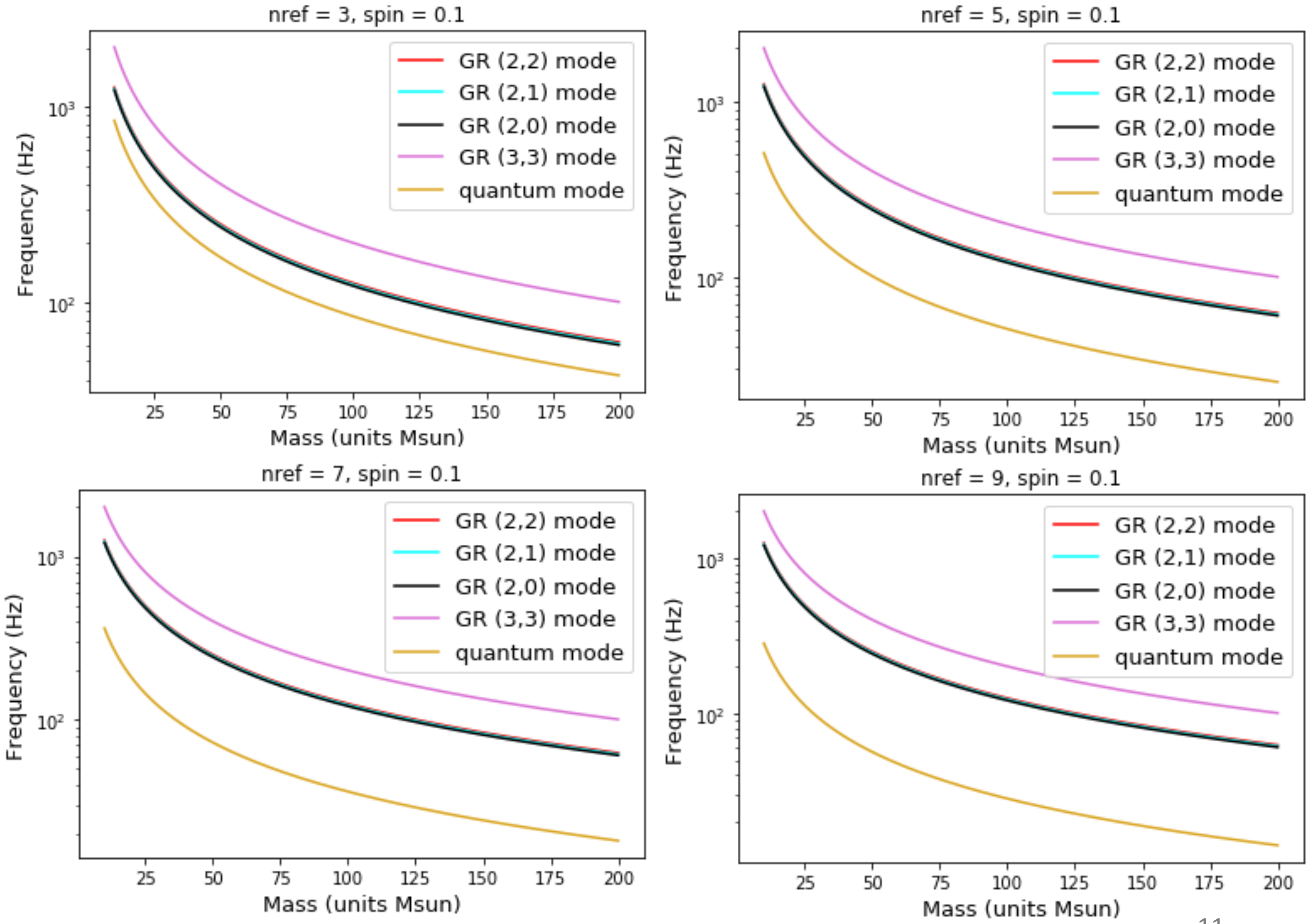

FIG 5. Plots of Mass (units Msun) versus Frequency (Hz) for n_{ref} between 3 and 9 for low spin. Quantum modes (yellow) are lower in frequency than GR modes. [10]

- Higher n_{ref} are further separated from GR modes

Phenomenology of Model: Damping Time

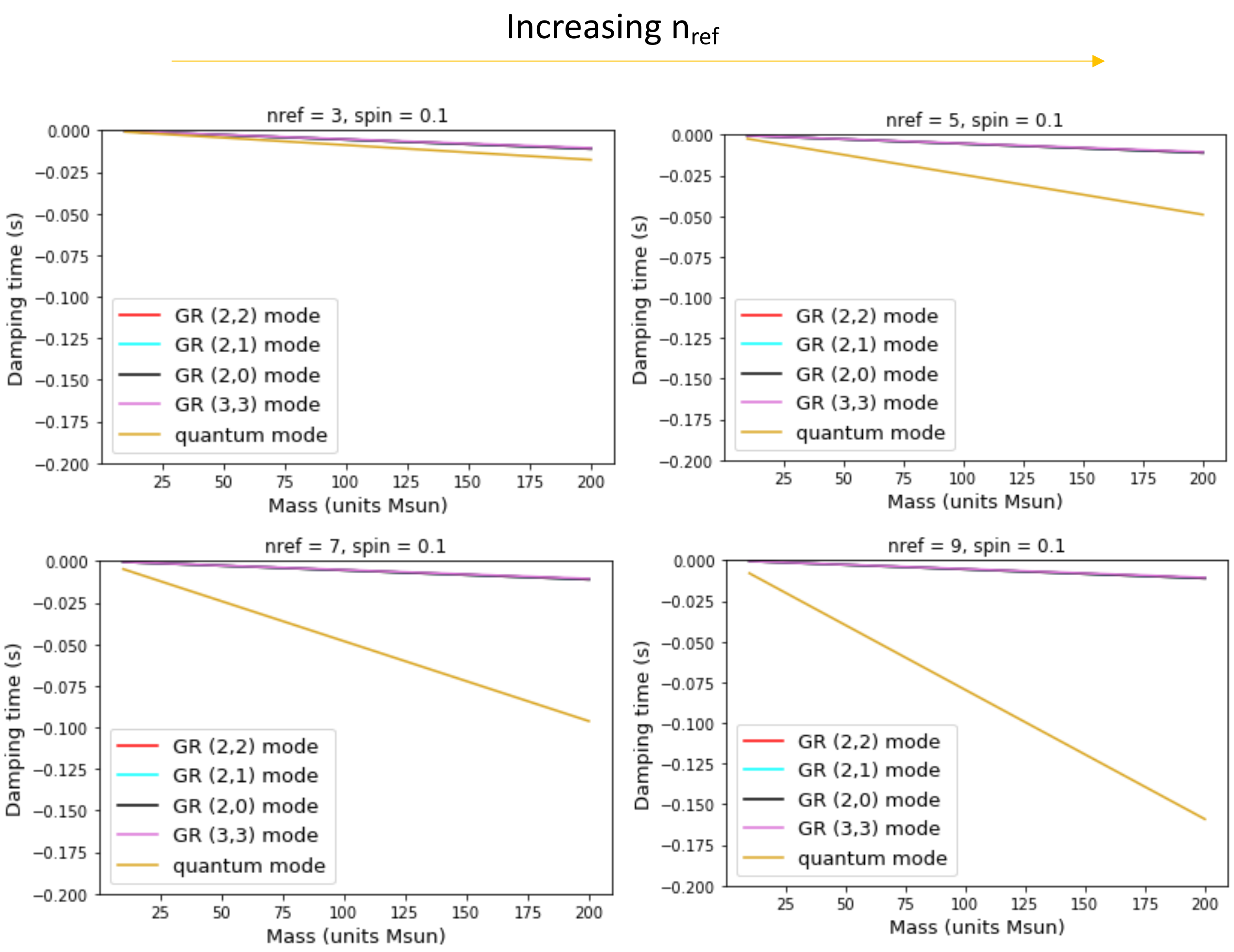

FIG 6. Plots of Mass (units Msun) versus Damping time (seconds) for n_{ref} between 3 and 9 for low spin. Quantum modes (yellow) are longer lasting than GR modes. [10]

- Higher n_{ref} are longer lasting

2. Are these quantum modes within the frequency range for GW observation? Given a n_{ref} value, what mass is optimal?

Looking at *just* the Quantum mode, we find the optimal mass for detection at various n_{ref} given the LIGO noise curves …

Use *bilby!*

The Log Bayes factor is a metric for how well a model with certain parameters matches the data [9]

A higher Log Bayes factor indicates a better fit

Results: Recovering Quantum Modes at High SNR

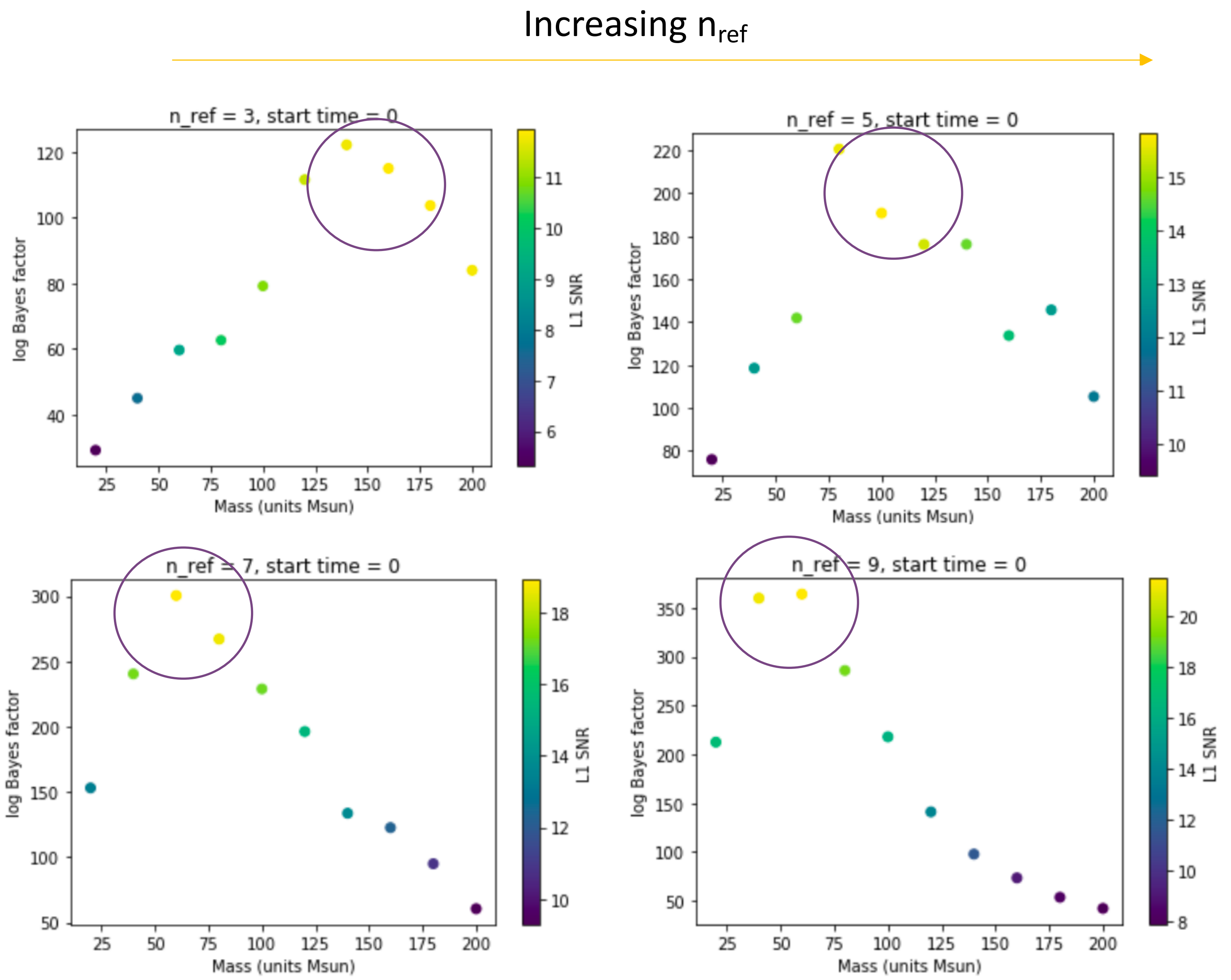

FIG 7. Plots of Mass (units Msun) versus Log Bayes factor for n_{ref} between 3 and 9, $\chi = 0$, and *fixed* amplitude. The color bar represents SNR: high SNR is in yellow.

- Higher n_{ref} peak at lower total mass, while smaller n_{ref} peak at higher total mass.
- LIGO sensitive to BBH mergers which are ~ 20 Msun to ~ 100 Msun

3. Can the quantum mode be recovered within a *full ringdown* & under what conditions (specifically Mass, n_{ref}) are they *best* observable?

Add Quantum mode (with a *fixed* amplitude) to NRSurdq4 including HOMs using peak masses we found (for each n_{ref})!

Results: Recovering NRsurdq4 + Quantum Model

$n_{ref} = 3$

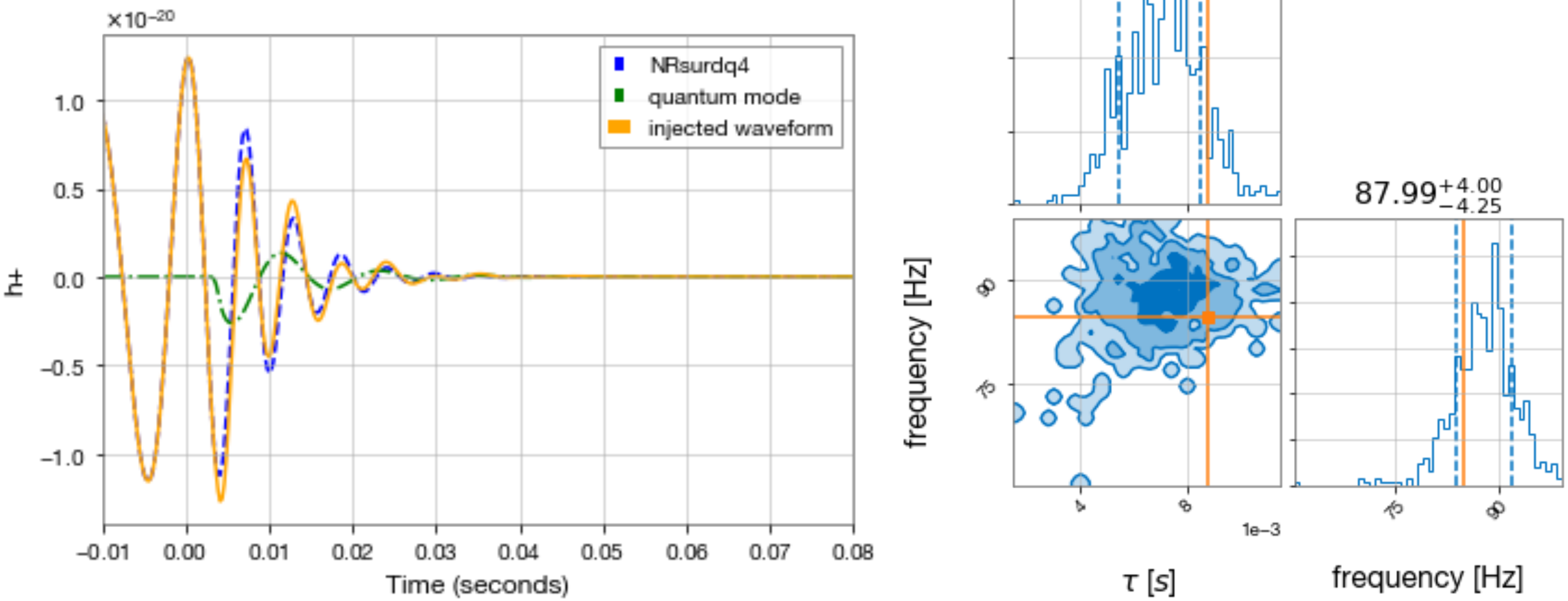

FIG 8. (Left) Plot of NRsurdq4 (blue), quantum mode (green) and the final injected waveform (orange) with $n_{ref} = 3$, Amplitude = 5e-22, Mass = 100 Msun
(Right) Recovered parameters with *bilby*, injected are marked in orange

Results: Recovering NRsurdq4 + Quantum Model

$n_{ref} = 9$

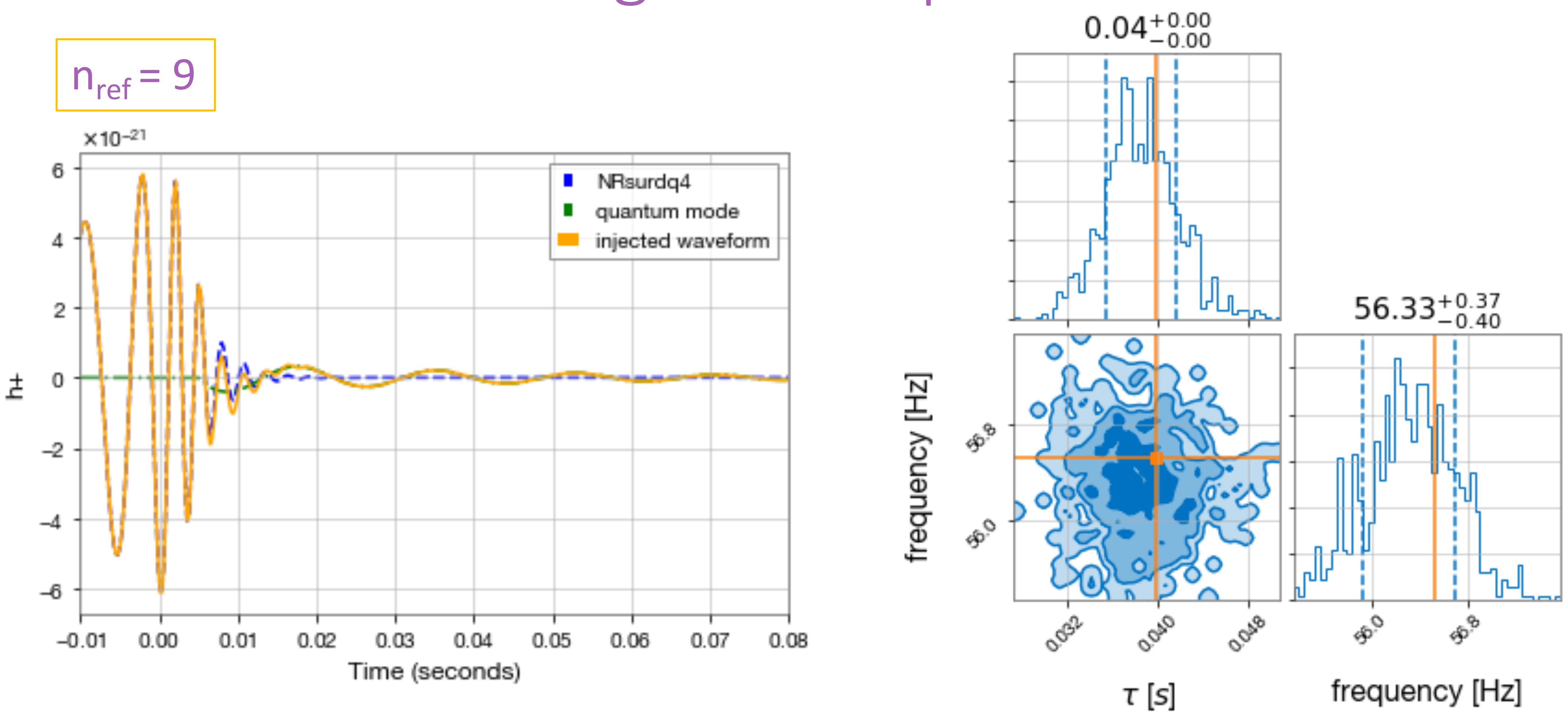

FIG 9. (Left) Plot of NRsurdq4 (blue), quantum mode (green) and the final injected waveform (orange) with $n_{ref} = 9$, Amplitude = 5e-22, Mass = 50 Msun

(Right) Recovered parameters with *bilby*, injected are marked in orange

Conclusions: Summary

These quantum modes from the polymer model are:

- lower in frequency and longer in duration

In general, recovery is dependent on mass and $n_{ref,}$ but *slightly* better parameter recovery tends towards longer damping times

i.e. higher n_{ref} values & lower mass mergers

Conclusions: Future Work

In the near and nearer future …

1. Smaller signal strength

How about varying amplitude? Does the observed trend continue?

2. Is there actually more evidence for a more complicated model?

Compare the Log Bayes factor of the the model *with* the quantum mode & *without* at various Mass and n_{ref}

Acknowledgements

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References

[1] https://www.soundsofspacetime.org/the-basics-of-binary-coalescence.html

[2] https://www.arxiv-vanity.com/papers/0905.2975/#S4

[3] LIGO and VIRGO, Gw190412: Observation of a binary-black-hole coalescence with asymmetric masses, arXiv (2020)

[4] R. Abbott and et al, Gw190814: Gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object, arXiv (2020).

[5] R. Brustein and A. Medved, Non-singular black holes interiors need physics beyond the standard model, Progress of Physics 67 (2019).

[6] R. Brustein and Y. Sherf, Emission channels from perturbed quantum black holes, Phys. Rev. D 100 (2019).

[7] A. M. Ram Brustein and K. Yagi, When black holes collide: Probing the interior composition by the spectrum of ringdown modes and emitted gravitational waves, arXiv (2017).

[8] Scott Field, Chad Galley, Jan Hesthaven, Jason Kaye, and Manuel Tiglio. `"Fast prediction and evaluation of gravitational waveforms using surrogate models". Phys. Rev. X 4, 031006 (2014). arXiv: gr-qc:1308.3565

[9] https://lscsoft.docs.ligo.org/bilby/

[10] https://pypi.org/project/qnm/

Results: Recovering NRsurdq4 + Quantum Model

$n_{ref} = 5$

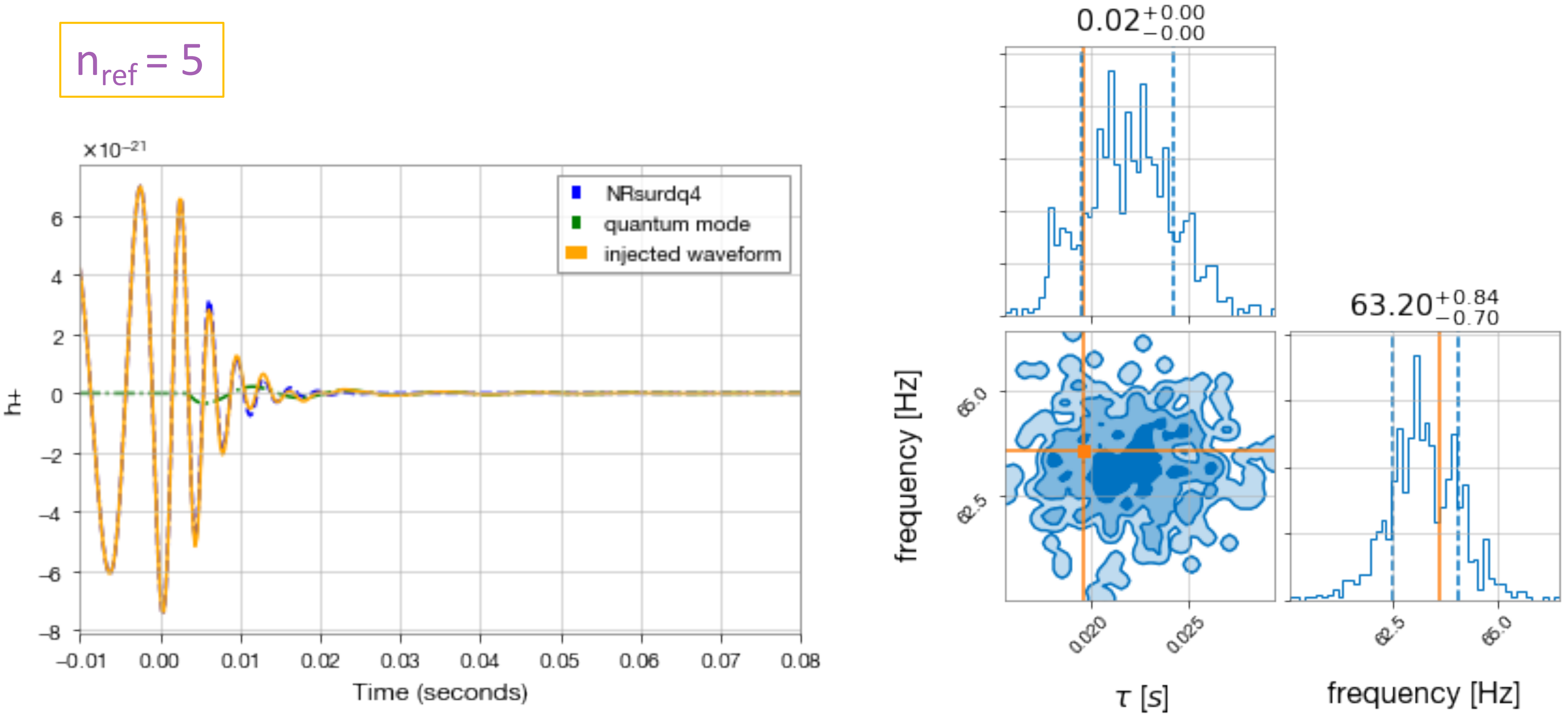
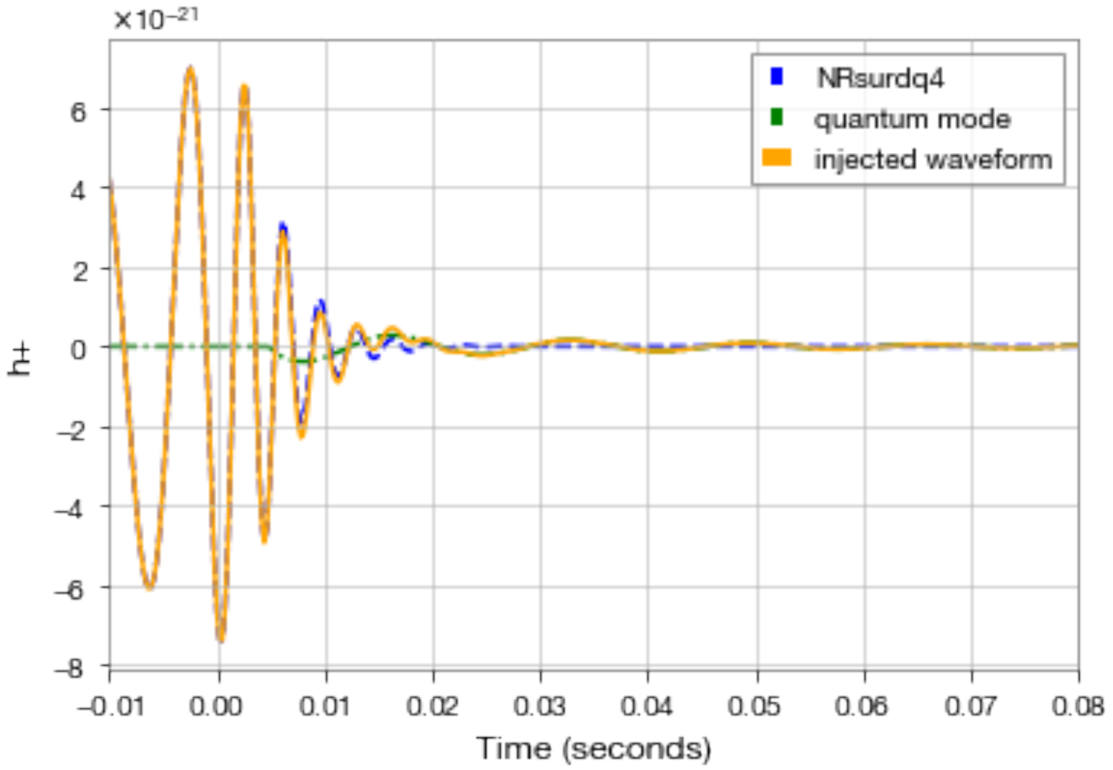


FIG 9. (Left) Plot of NRsurdq4 (blue), quantum mode (green) and the final injected waveform (orange) with $n_{ref} = 5$, Amplitude = 5e-22, Mass = 80 Msun
(Right) Recovered parameters with *bilby*, injected are marked in orange

Results: Recovering NRsurdq4 + Quantum Model

$n_{ref} = 7$



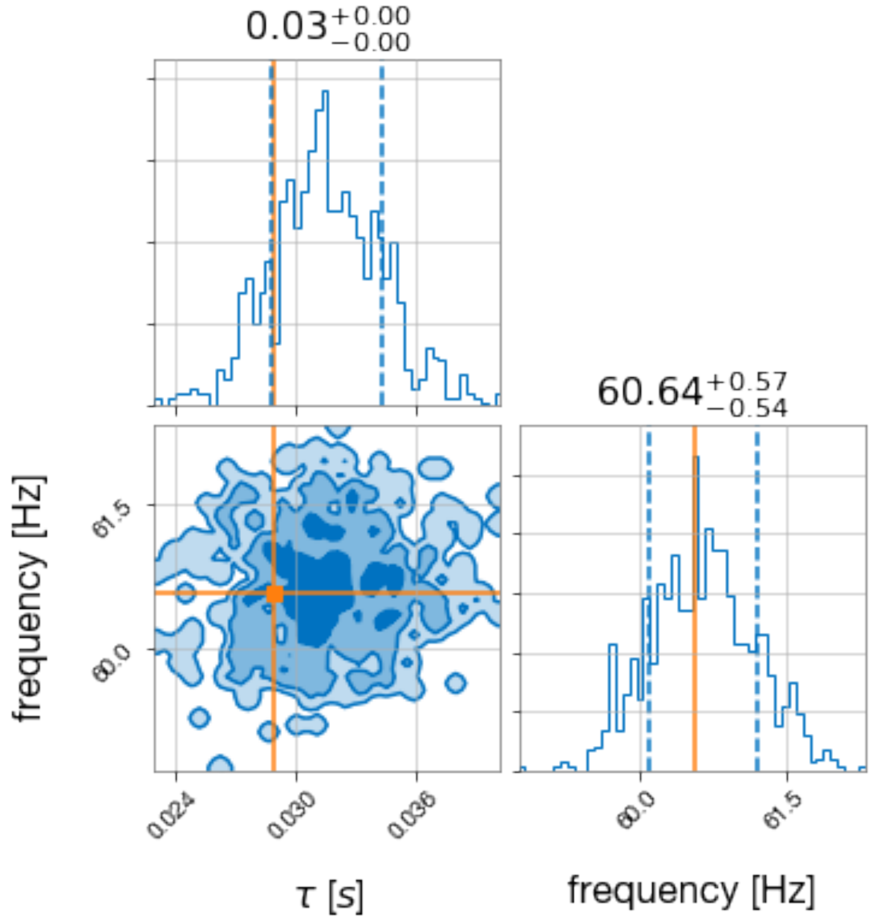
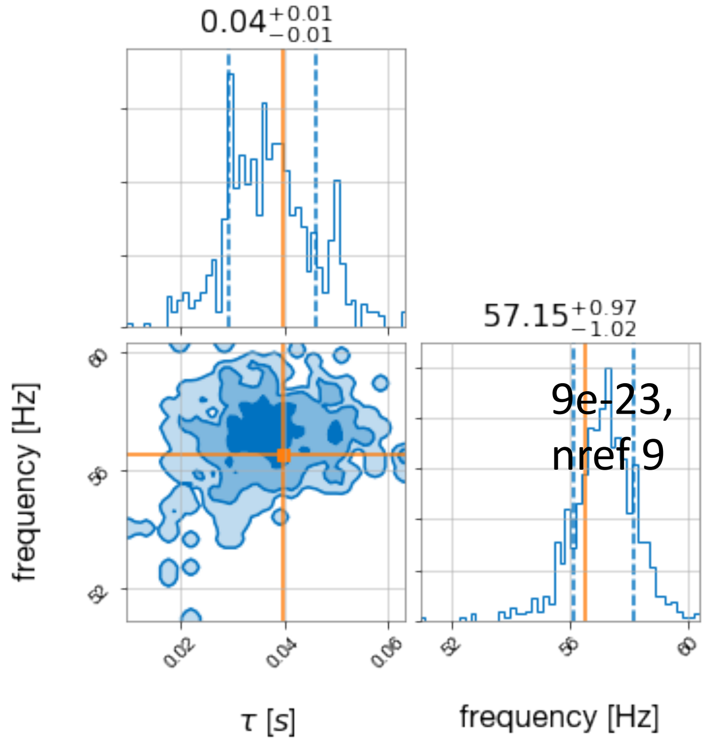
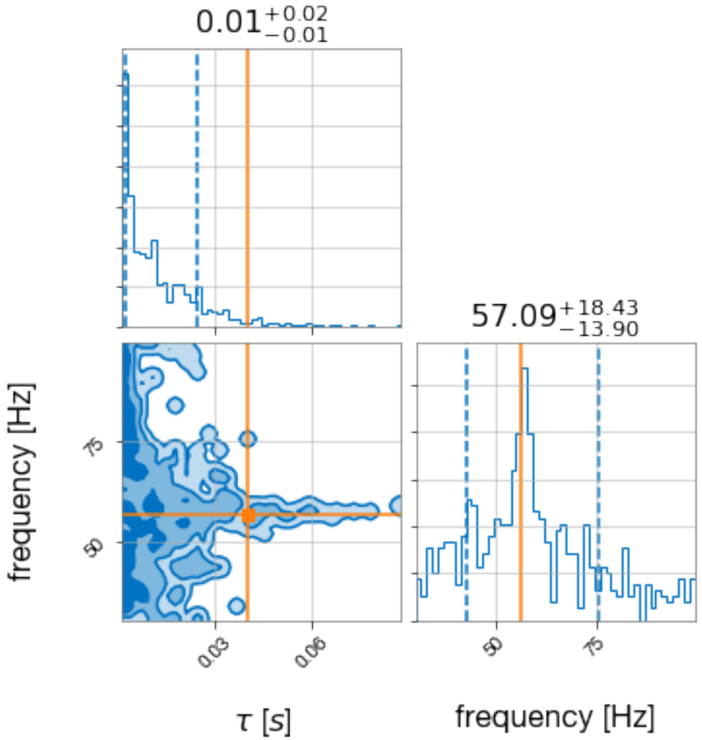


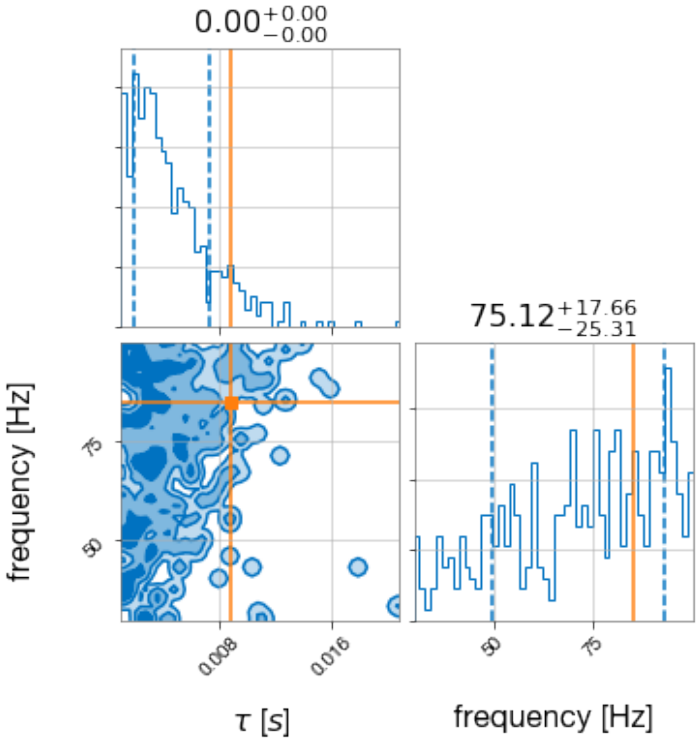
FIG 10. (Left) Plot of NRsurdq4 (blue), quantum mode (green) and the final injected waveform (orange) with $n_{ref} = 7$, Amplitude = 5e-22, Mass = 60 Msun
(Right) Recovered parameters with *bilby*, injected are marked in orange



2e-22,
nref 9



9e-23,
nref 9



2e-22,
nref 3