BLACK HOLE SPECTROSCOPY:

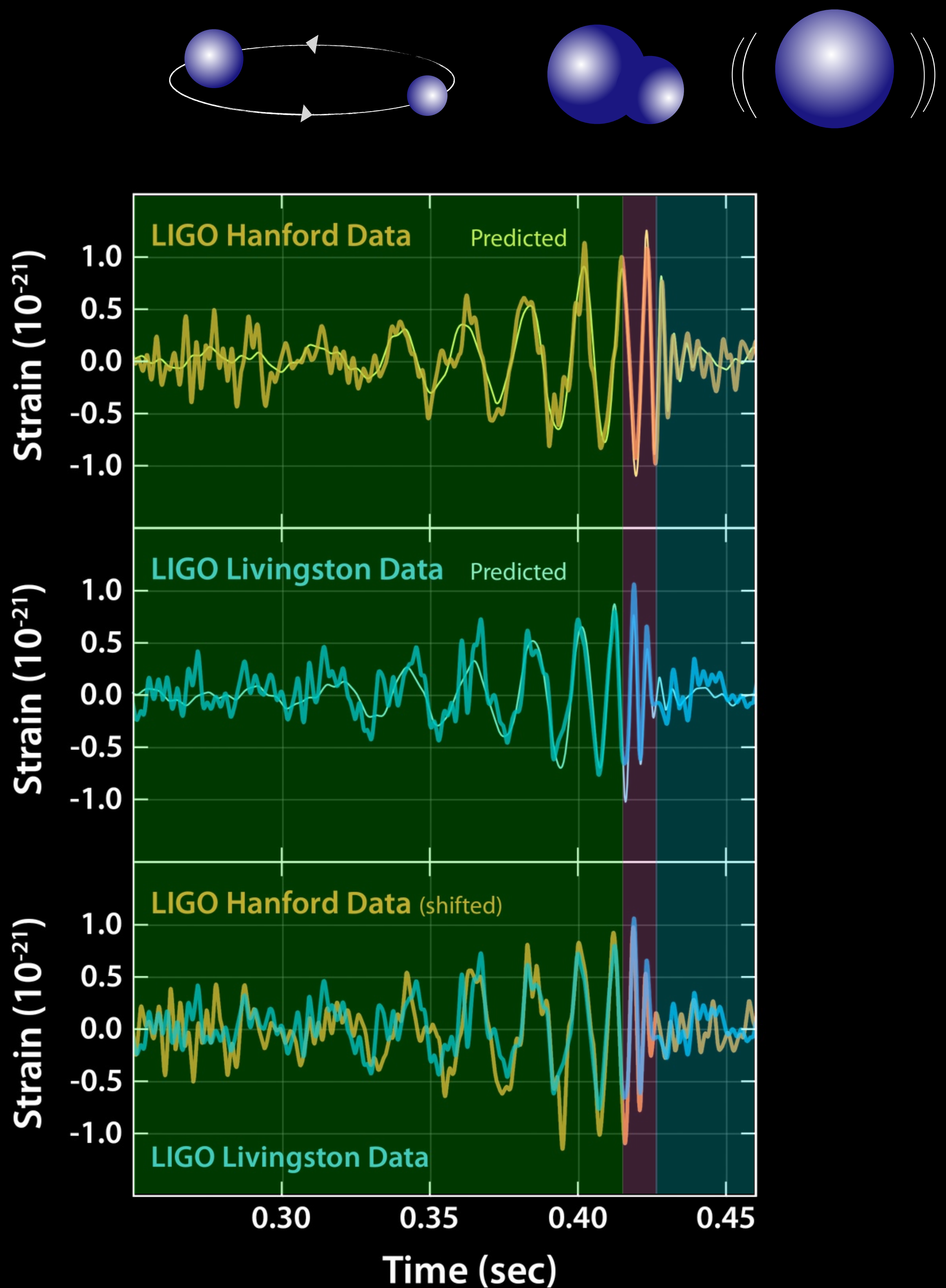
GR AND BEYOND

GIADA CANEVA SANTORO

IN COLLABORATION WITH ANIA LIU, NICOLA FRANCHINI, VASCO GENNARI, GREGORIO CARULLO

EPPG SEMINAR

Cosmic Dance

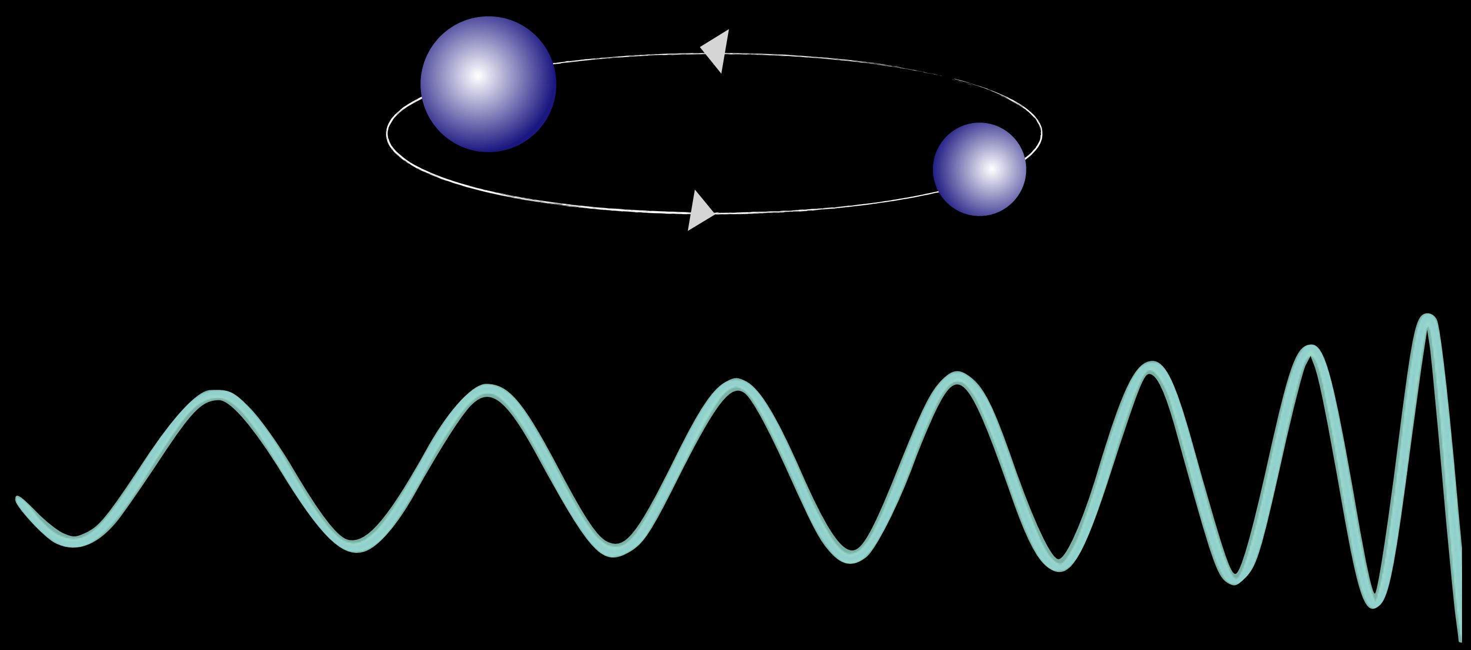


Caltech/MIT/LIGO Lab.

Inspiral

Bound orbits, shrinking and circularising due to the emission of GWs;

Post-Newtonian approximation (perturbative expansion in powers of v/c).



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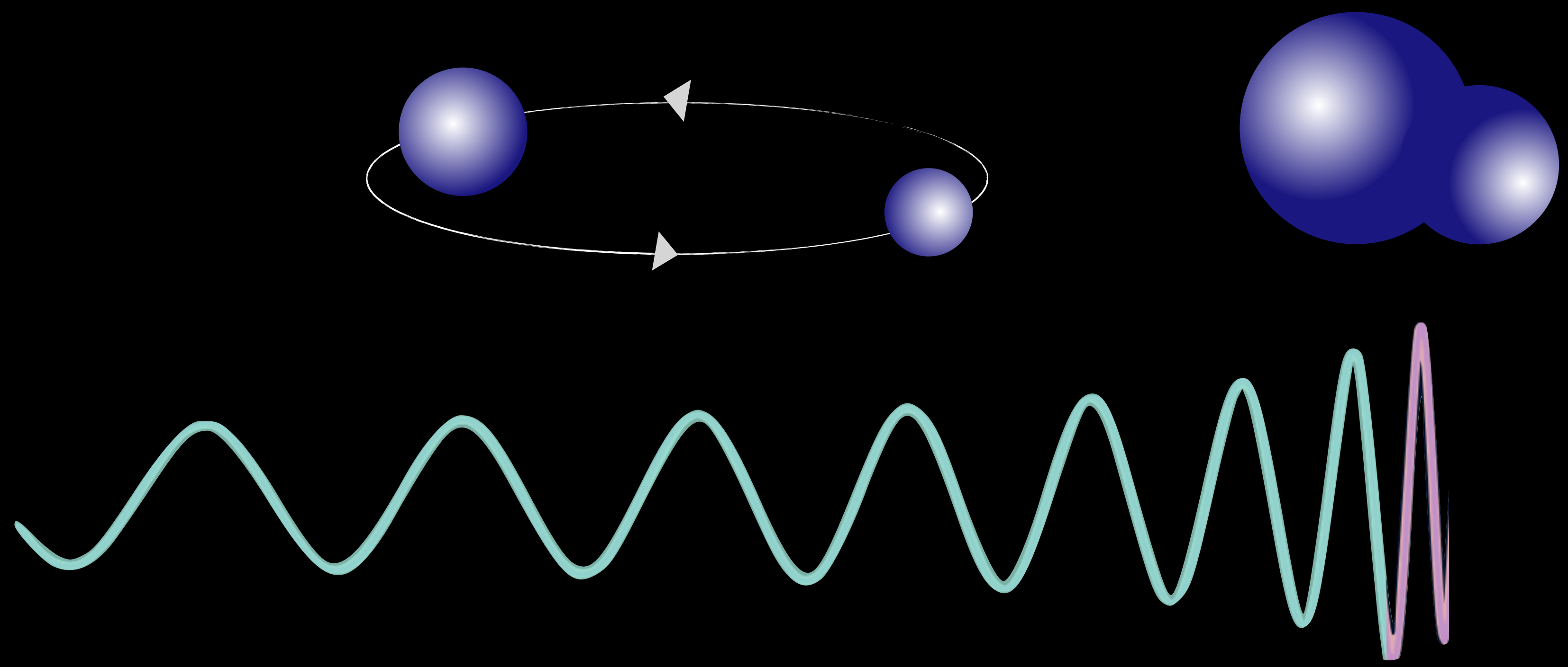
Merger

Plunge into each other due to energy and orbital angular momentum losses;

Formation of a common horizon, single final BH is formed;

Numerical relativity simulations.



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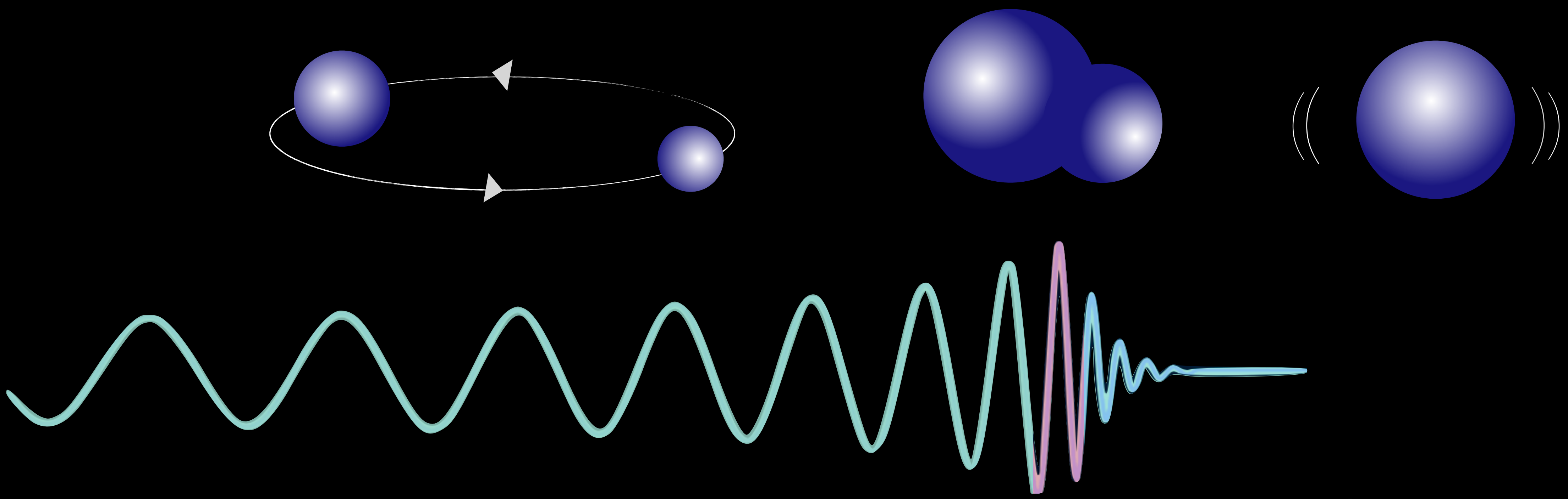
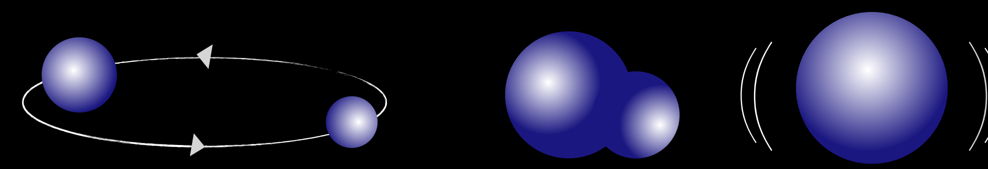


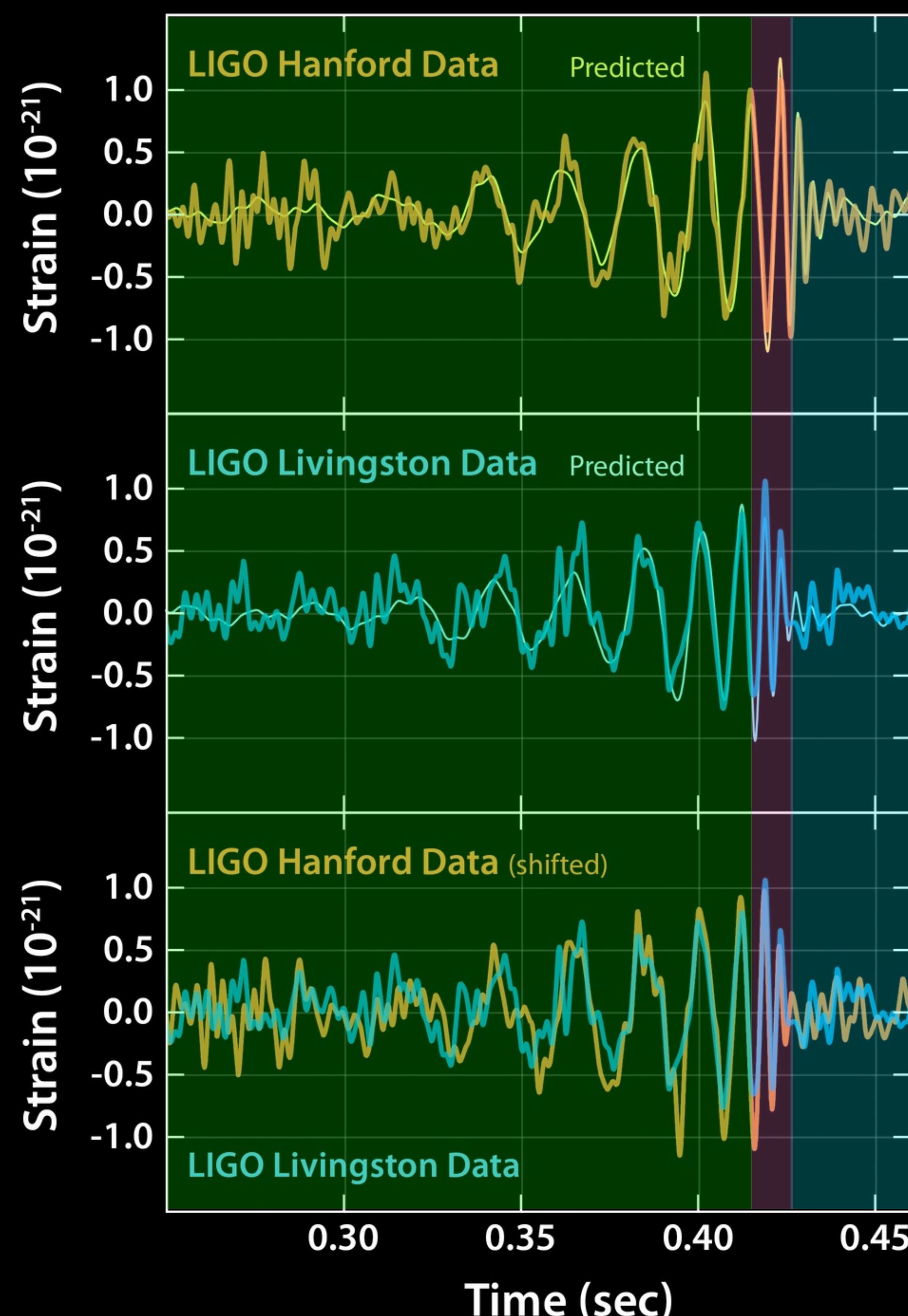
Ringdown

Highly asymmetric BH radiates away GWs to reach stable equilibrium state;

Perturbation theory.

Cosmic Dance

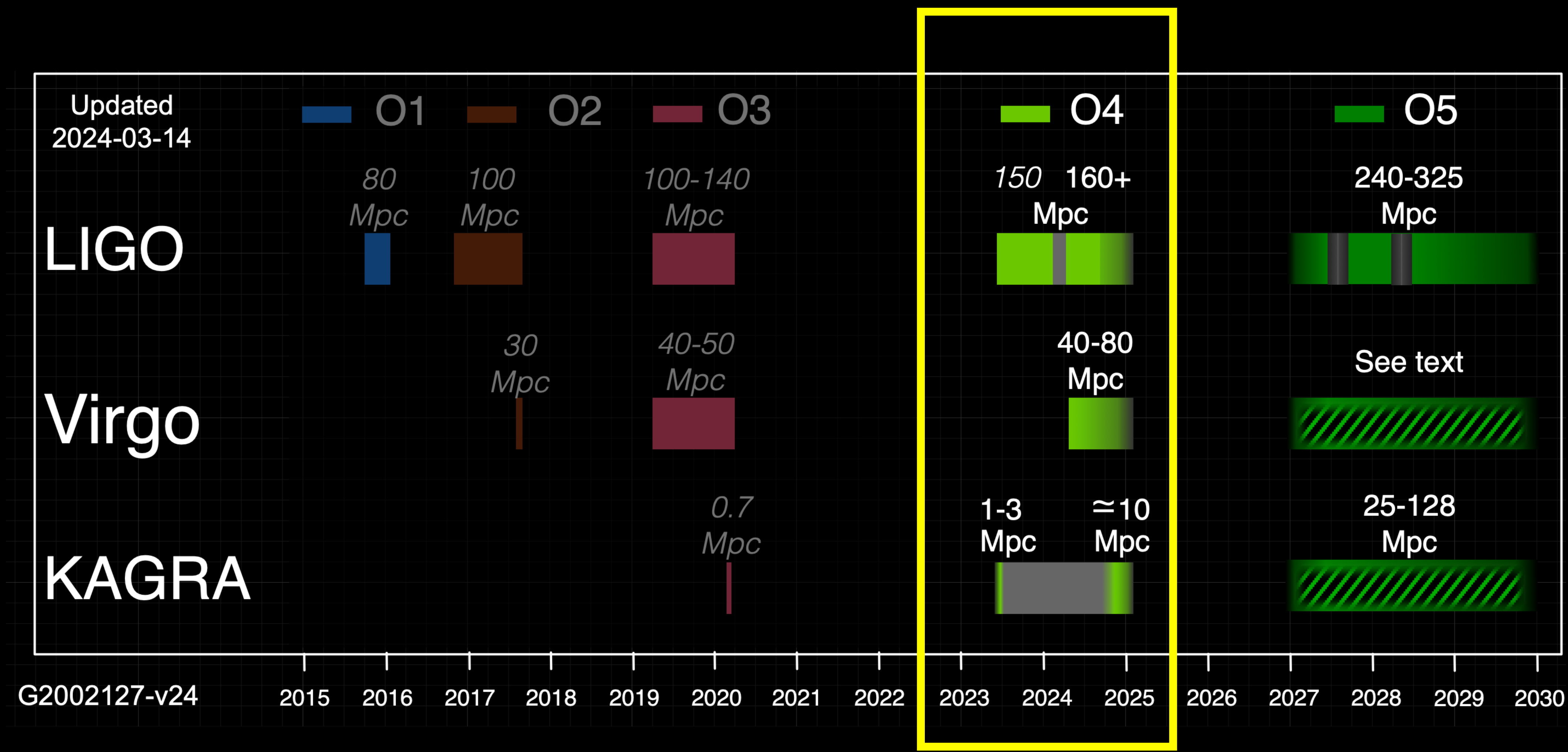




Caltech/MIT/LIGO Lab.

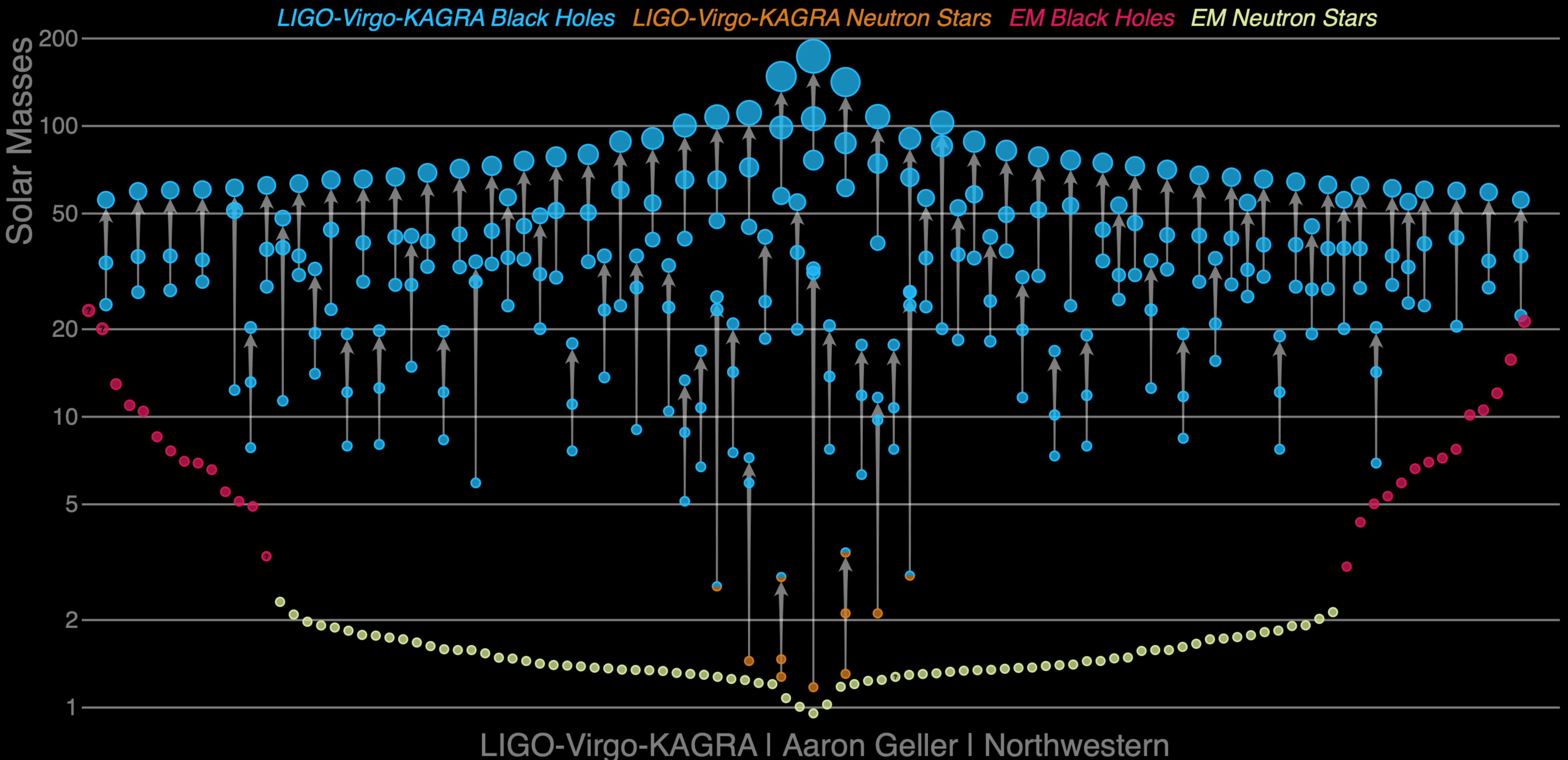
Courtesy of Cezary Turski

What is Happening now?



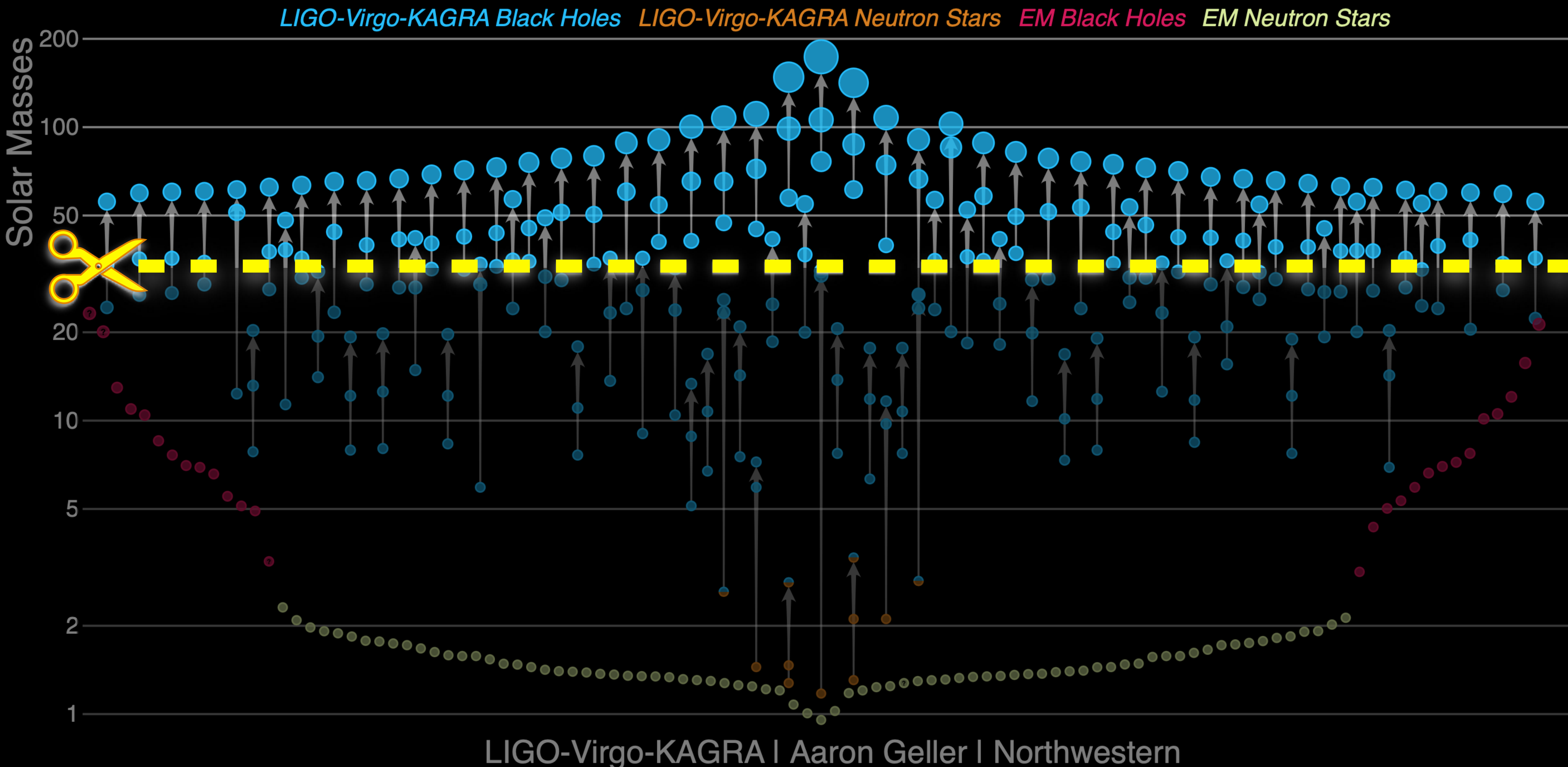
https://observing.docs.ligo.org/plan/

Stellar Necropolis



~90 compact binary mergers

RINGDOWN

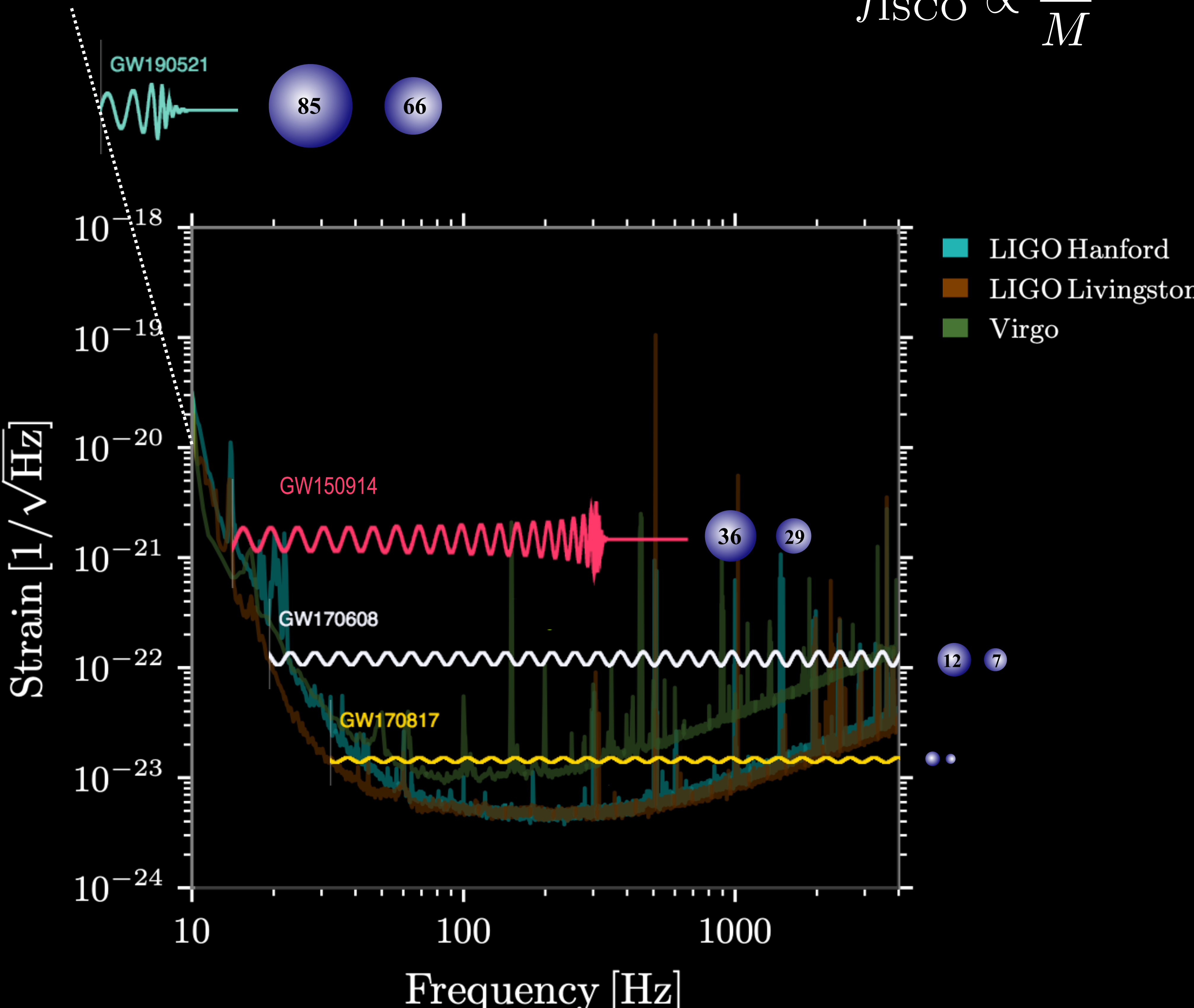


~90 compact binary mergers

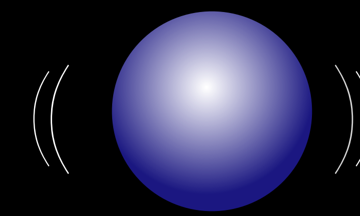
~49 events confident enough to test GR

~22 event with confident ringdown signatures

$$f_{\mathrm{ISCO}} \propto \frac{1}{M}$$



WHAT IS RINGDOWN?



Vibrates with many harmonic frequencies.

Vibrations give away energy through…

..sound waves.

…gravitational waves.

Harmonic oscillations can be described as…

…standing sine waves.

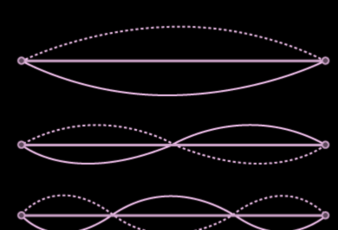
… QuasiNormal Modes (**QNMs**)

Fundamental mode

1st overtone

2nd overtone

…



Dynamical vs Perturbative

In a realistic scenario, right after merger:

Highly non-linear regime.

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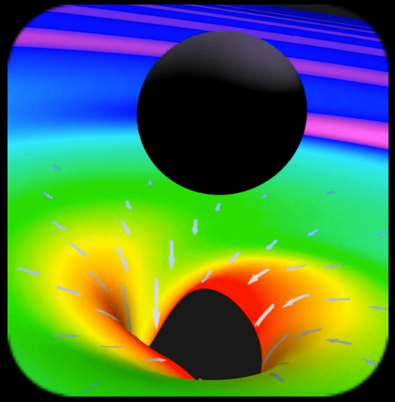

Dynamical horizon forming and…

DYNAMICAL VS PERTURBATIVE

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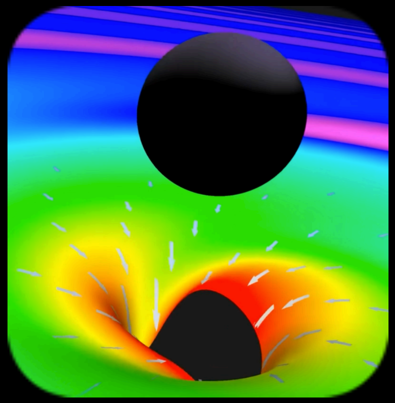

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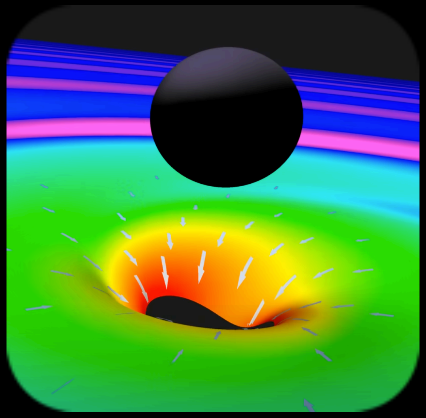

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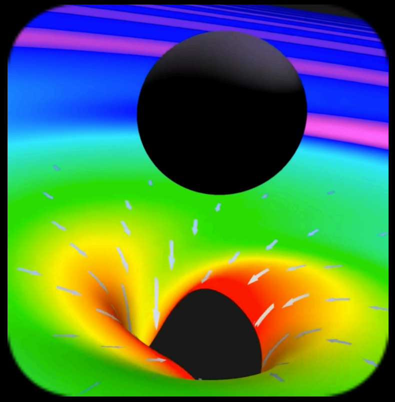

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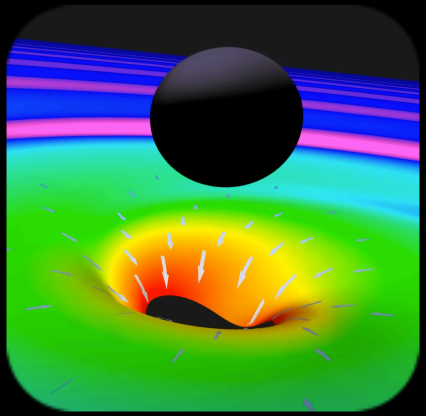

In perturbation theory:

1. Linearize Einstein field equation on a BH background metric:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

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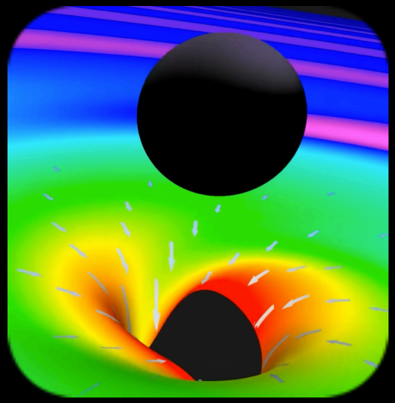

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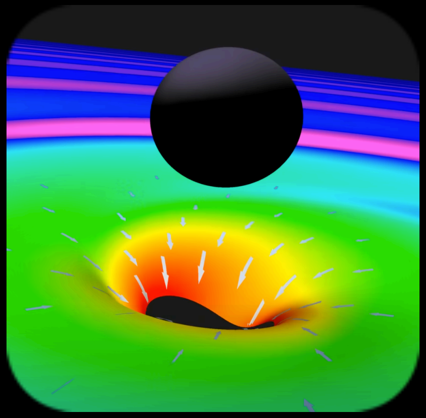

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$$\left(\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial x^2} - V(r_*)\right)\Psi = S$$

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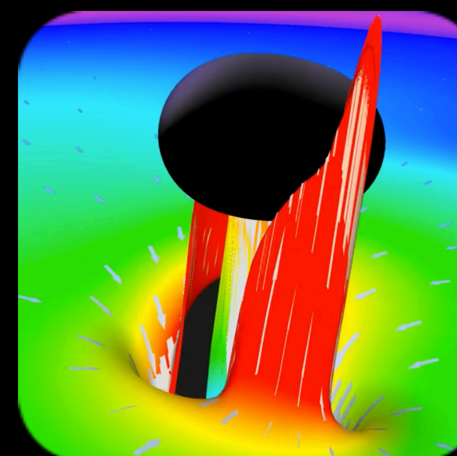

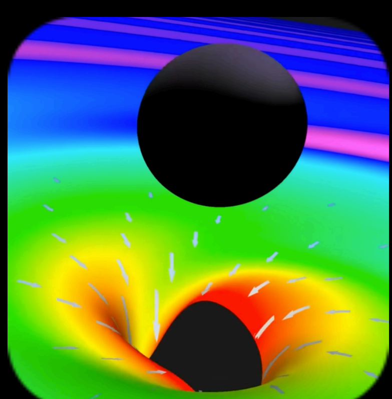

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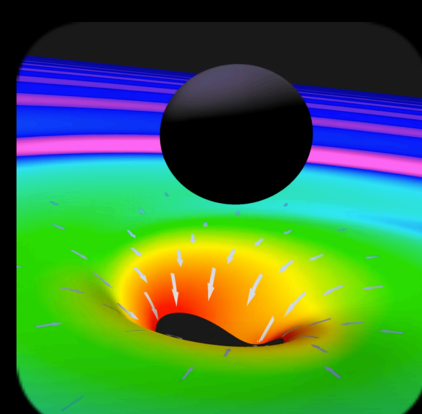

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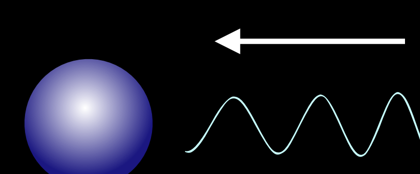

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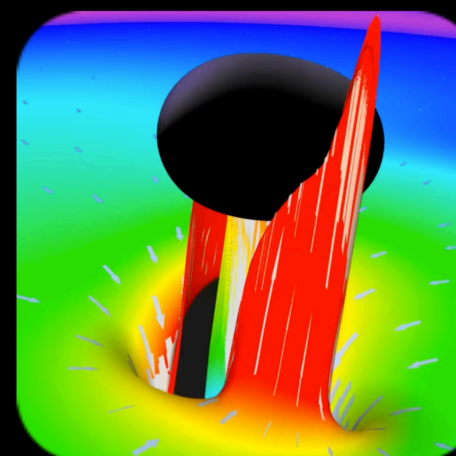

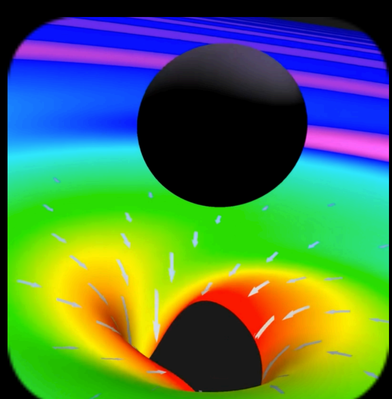

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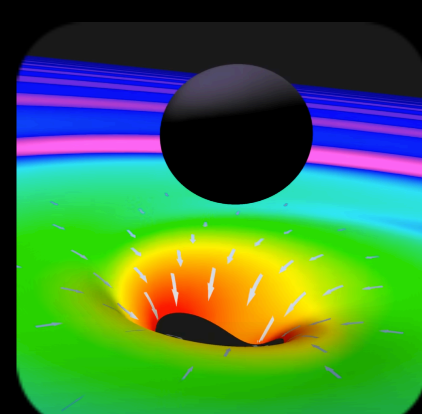

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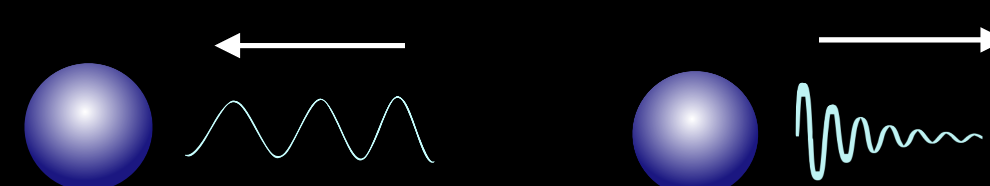

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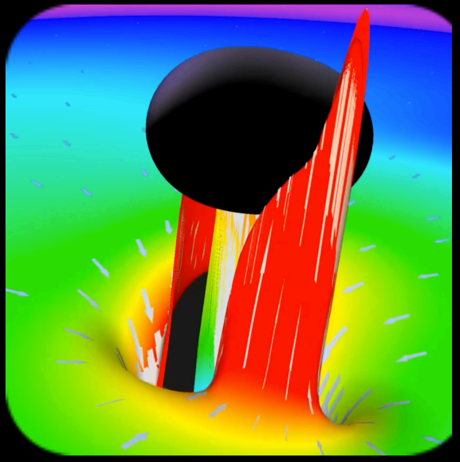

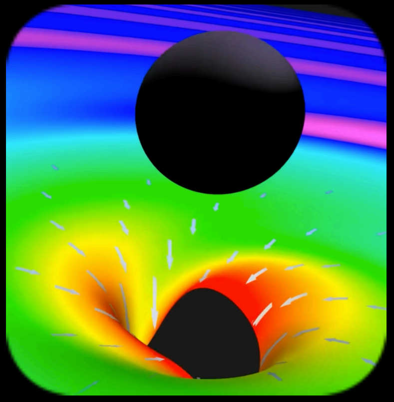

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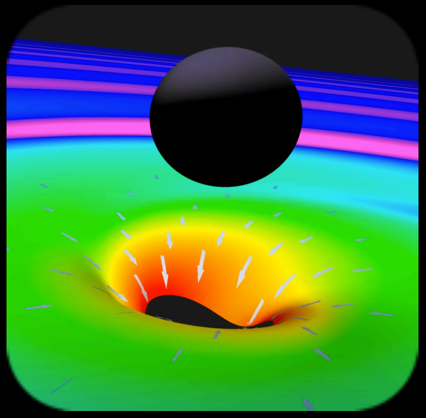

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$$h_+ - ih_\times = -\frac{M}{r}\sum_{lmn}\mathcal{A}_{lmn}S(\theta,\phi)e^{i\tilde{\omega}_{lmn}t}$$

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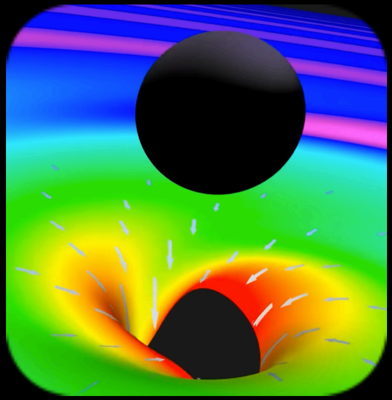

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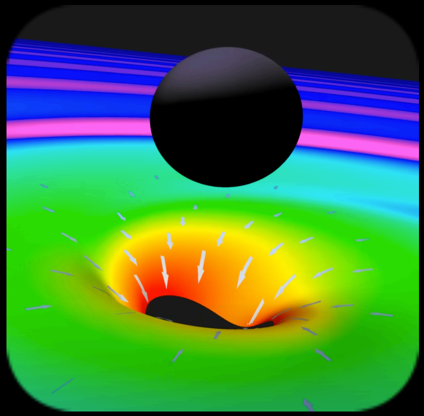

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$$\tilde{\omega}_{lmn} = \omega_{lmn} + \frac{i}{\tau_{lmn}}$$

BH vibrates

dissipative system

Where is the Non-linear description?

Why are BHs so cool?

1. "Black holes have no hair" - J. Wheeler

In standard Schwarzschild coordinates:

$$ds^2 = -c^2\left(1 - \frac{2GM}{c^2 r}\right)dt^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

fully characterized by a single parameter, the total gravitational mass M, can be generalised to include electric charge and rotation.

WHY IS RINGDOWN SO COOL?

2. The QNMs spectrum only depends on the mass and angular momentum of the Kerr BH:

$$\omega_{lmn}(M_f, a_f), \tau_{lmn}(M_f, a_f)$$

This allow to test the Kerr nature of a BH:

- measure the dominant mode $\omega_{220}(M_f, a_f), \tau_{220}(M_f, a_f)$;
- Infer the M_f and a_f;
- Measure the $\omega_{330}(M_f, a_f)$ and check it is consistent with the one predicted by perturbation theory.

Black hole spectroscopy: observational study of the QNMs spectrum.

Black hole Spectroscopy

In theory

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In reality…

- Analyse only post-merger signal;
- Time domain analysis avoids contamination of pre-merger frequencies when cutting the signal;
- Different models used to estimate remnant parameters and perform model selection.

pyRing

Black hole Spectroscopy

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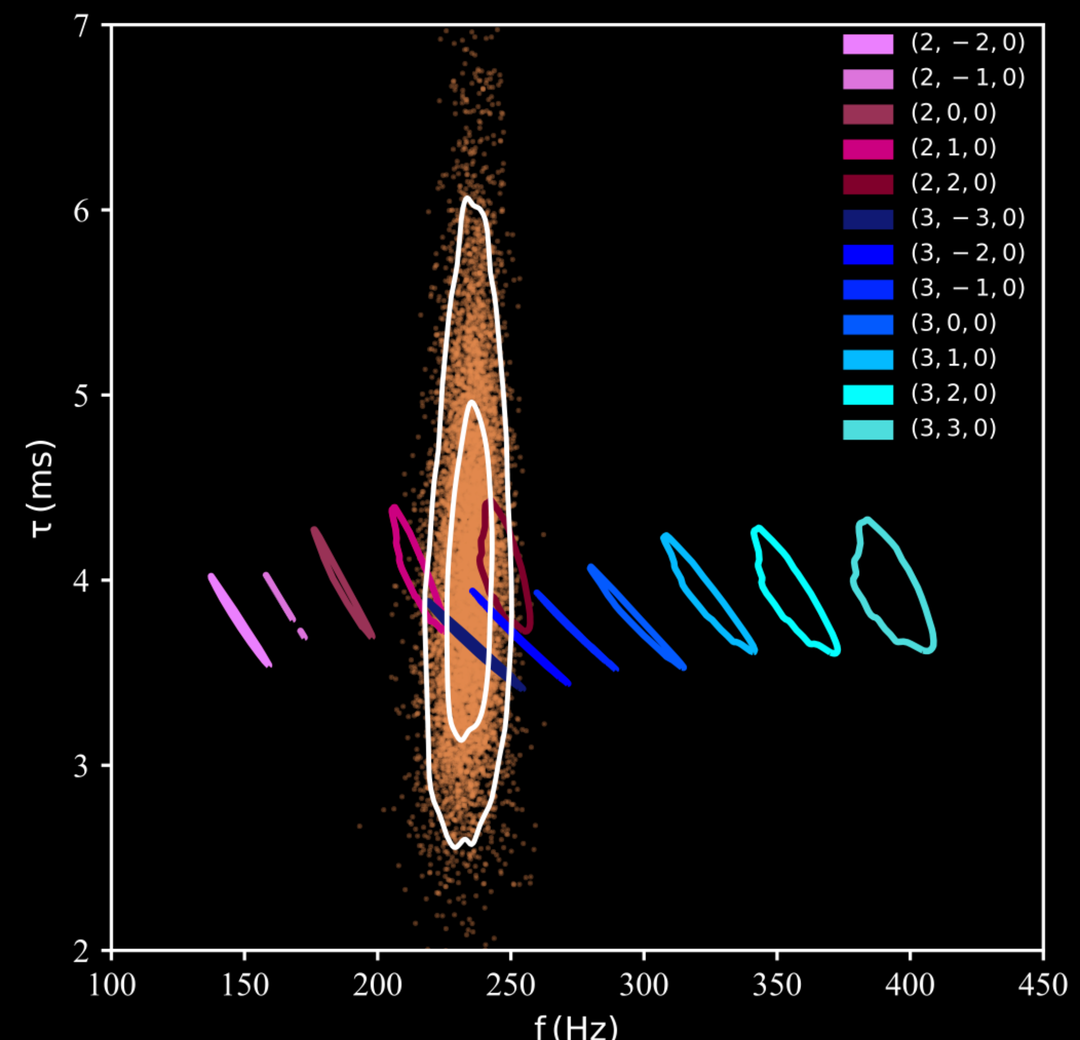

Carullo et al, PRD (2019)

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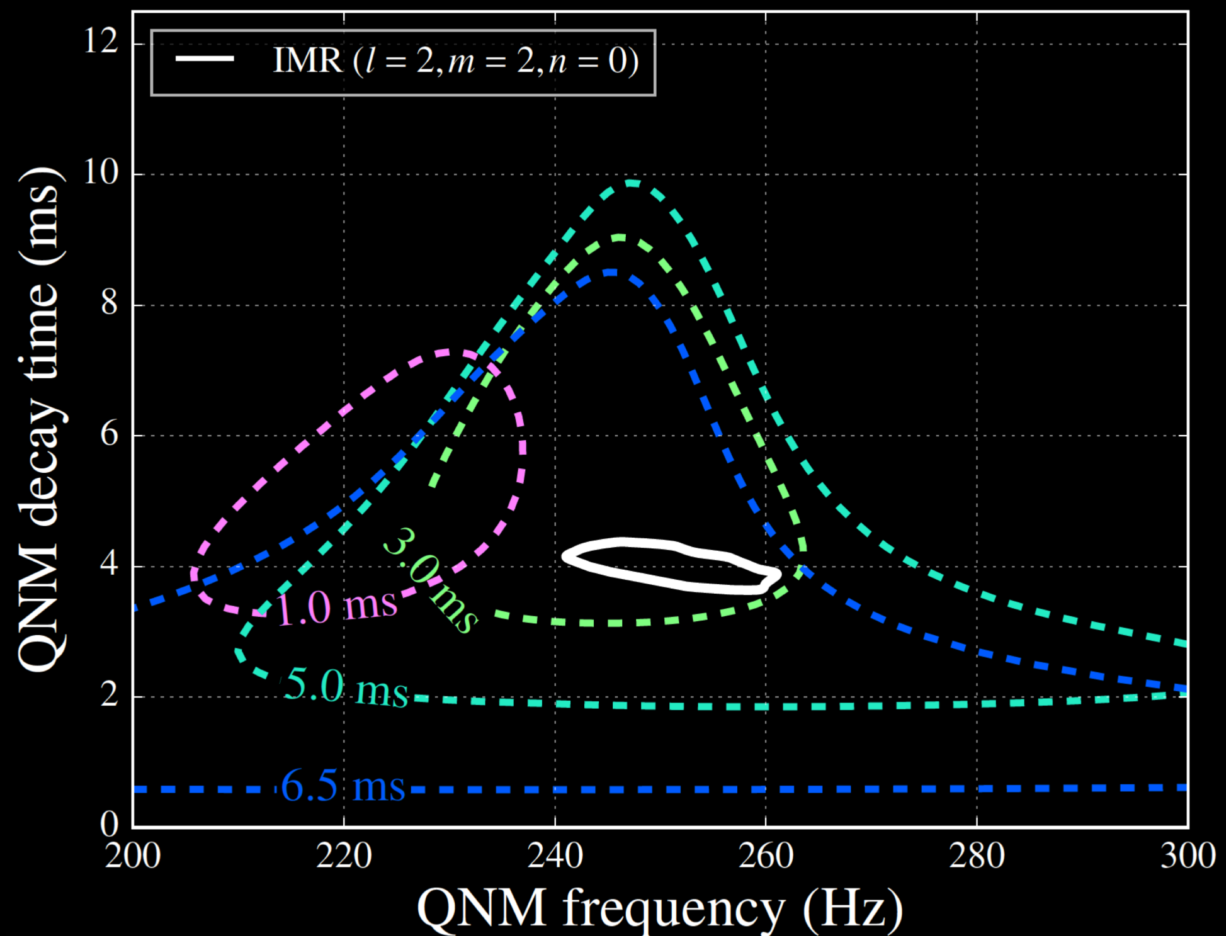

LVC, PRL 116, 221101 (2016)

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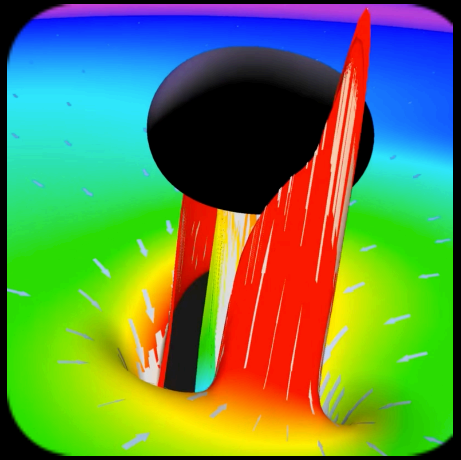

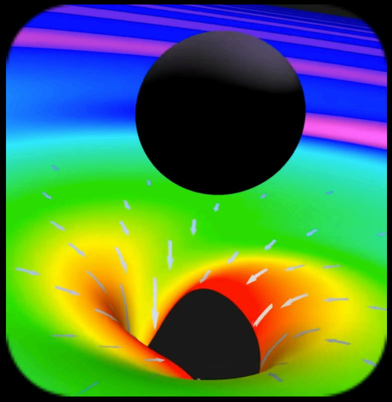

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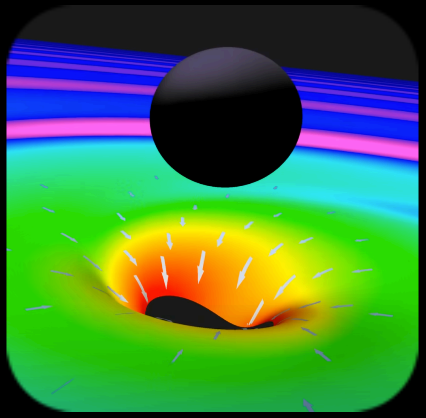
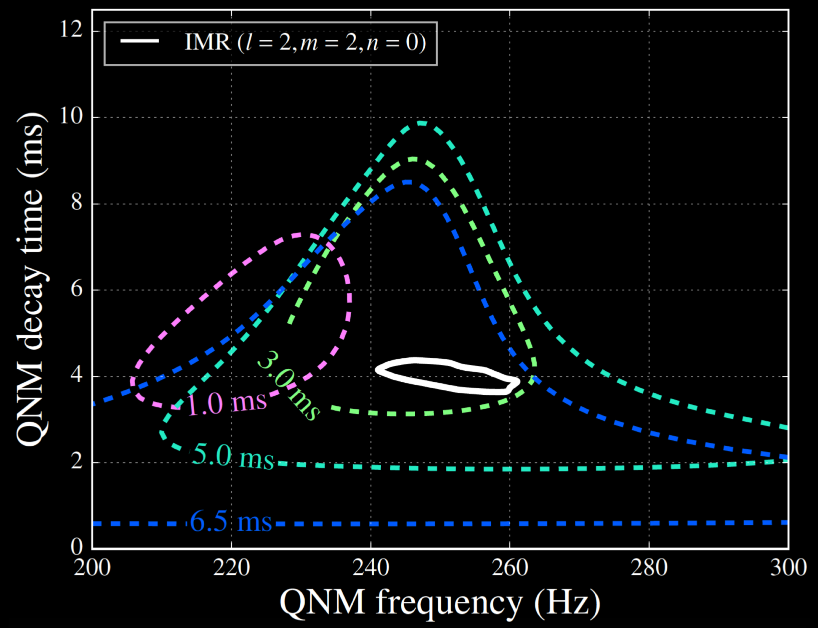


Where is the Non-linear description?



At *early times* non-linearities are non-negligible.

At *late times* QNMs description works better but SNR goes down.

THE DATA

GW150914-like aligned spins

- GR
- non-GR
  - Massive graviton dispersion
  - Charged BH Qf = 0.6, 0.7
  - EOB with modified energy flux $\alpha_2 = 100$
  - Scalar-tensor 0.2
  - Scaled BNS injections Mtot = 140 Msun

The Models

AGNOSTIC

INFORMED

GR

GR + deviation

$t_0 = [8\text{-}15]M_f$

Damped Sinusoids

- 1 mode
- 2 modes

Kerr (non precessing)

- 220
- 220+210
- 220+221
- 220+330

Free Amplitudes

Ordered Amplitudes

$+\delta\omega$

$+\delta\tau$

$+\delta\omega\delta\tau$

$t_0 = [13\text{-}20]M_f$

MMRDNP [London, 2020]

- 220
- HM (up to ℓ=4)

$t_0 = [-6,6]M_f$

TEOBPM [Damour & Nagar, 2014]

- 220
- 220+210
- 220+330
- 220+210+330

GR Systematics

Spin aligned

SYSTEMATICS

Agnostic superposition of damped sinusoids:

$$\boxed{h_s = \sum_j A_j^s \cos(\omega_j^s t + \phi_j^s)\, e^{-(t - t_j^{0,s})/\tau_j^s}}$$

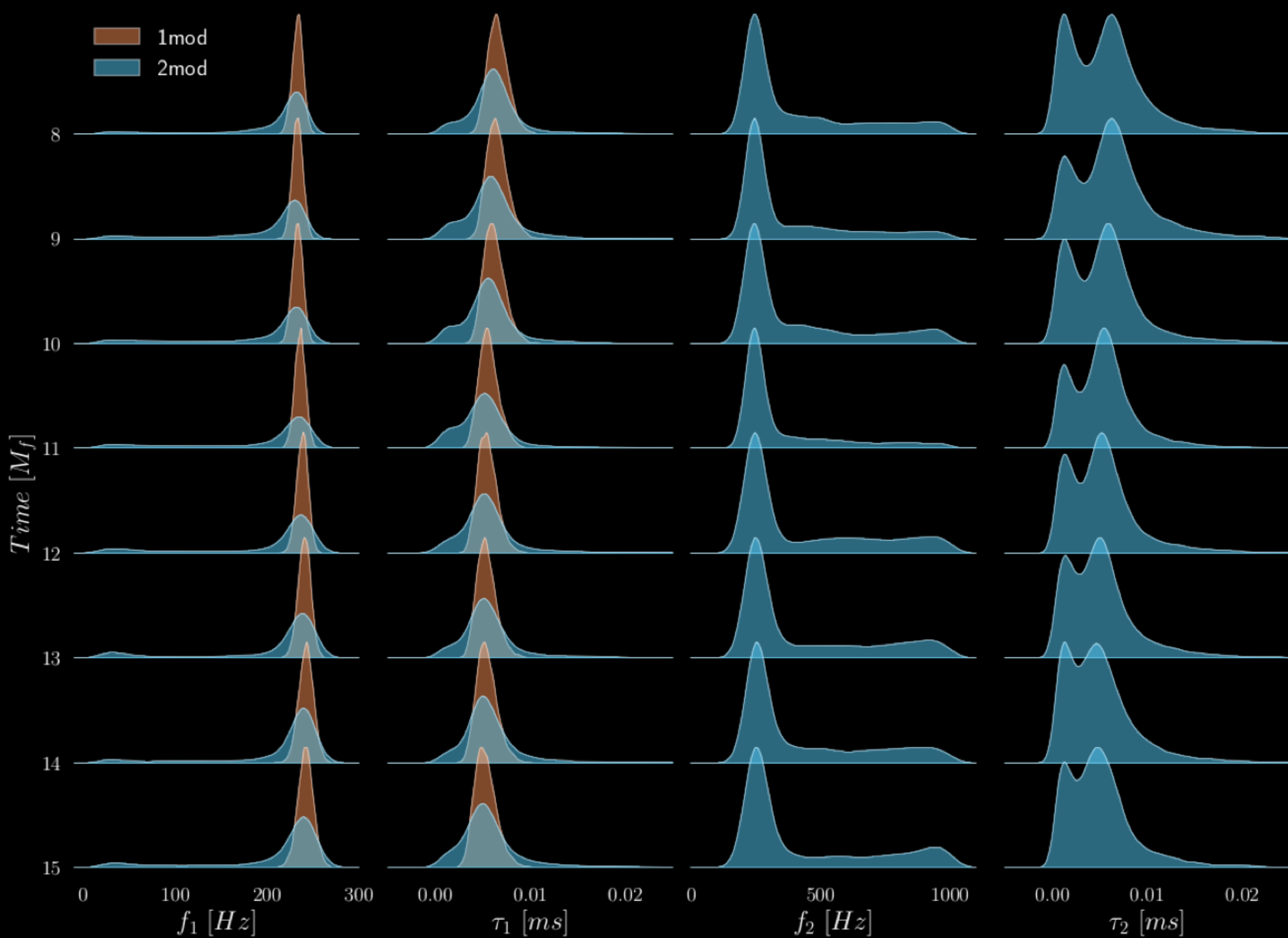
Each mode (fixed j,s) has $\{A, \phi, f, \tau\}$ are free to vary (assuming t^0 known).

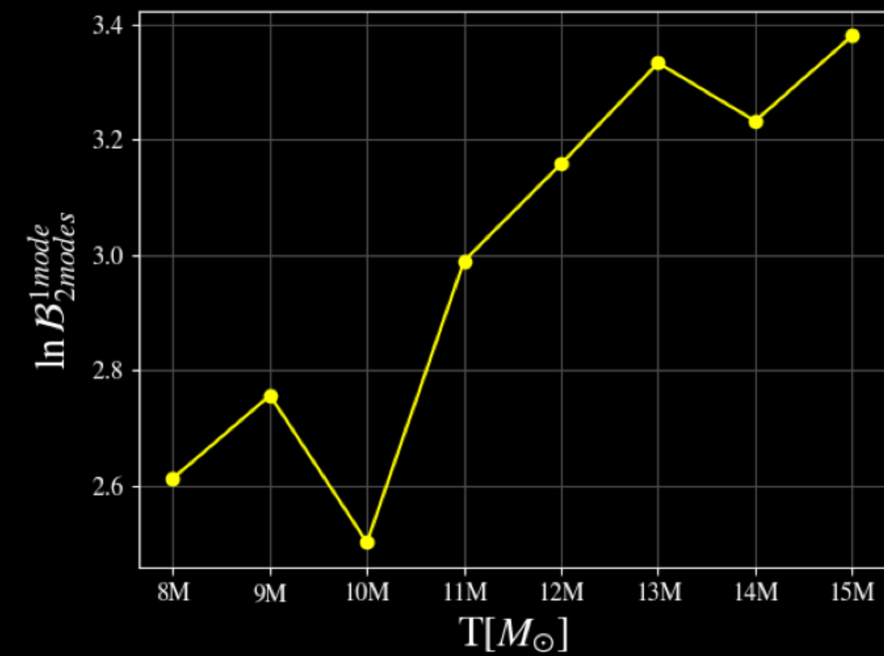
All pyRing models available for generic (scalar, vector, tensor) polarisations: s -index.

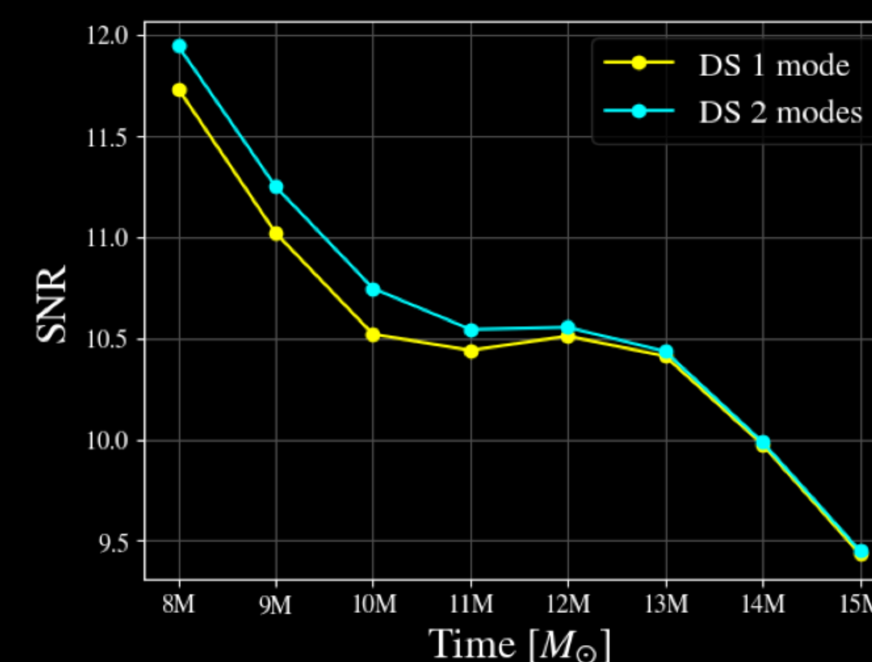
SYSTEMATICS

DS - GR recovery

Only one mode can be resolved.







All plots are made using namib.

SYSTEMATICS

Kerr

Model with Kerr spectrum predictions:

non precessing

reflection symmetry implies

$$\tilde{A}^- = (-1)^l \cdot \tilde{A}^{+\,*}$$

where:

$$\tilde{A}^\pm = \mathscr{A}_{lmn}{}^{\pm} e^{i\phi^{\pm}_{lmn}}$$

$$h_+ + ih_\times = \frac{M_f}{D_L} \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{+\ell} \sum_{n=0}^{\infty} \left(h^+_{\ell mn} + h^-_{\ell mn}\right)$$

$$h^+_{\ell mn} = \mathcal{A}^+_{\ell mn}\, S_{\ell mn}(\iota, \varphi)\, e^{i[(t-t_{\ell mn})\tilde{\omega}_{\ell mn} + \phi^+_{\ell mn}]}$$
$$h^-_{\ell mn} = \mathcal{A}^-_{\ell mn}\, S^*_{\ell mn}(\pi - \iota, \varphi)\, e^{-i[(t-t_{\ell mn})\tilde{\omega}^*_{\ell mn} - \phi^-_{\ell mn}]}$$

Ordered Amplitudes

Add more information, impose semi-agnostic assumptions, e.g.

$$A_{330}/A_{220} < 0.4$$

$$A_{210}/A_{220} < 0.7$$

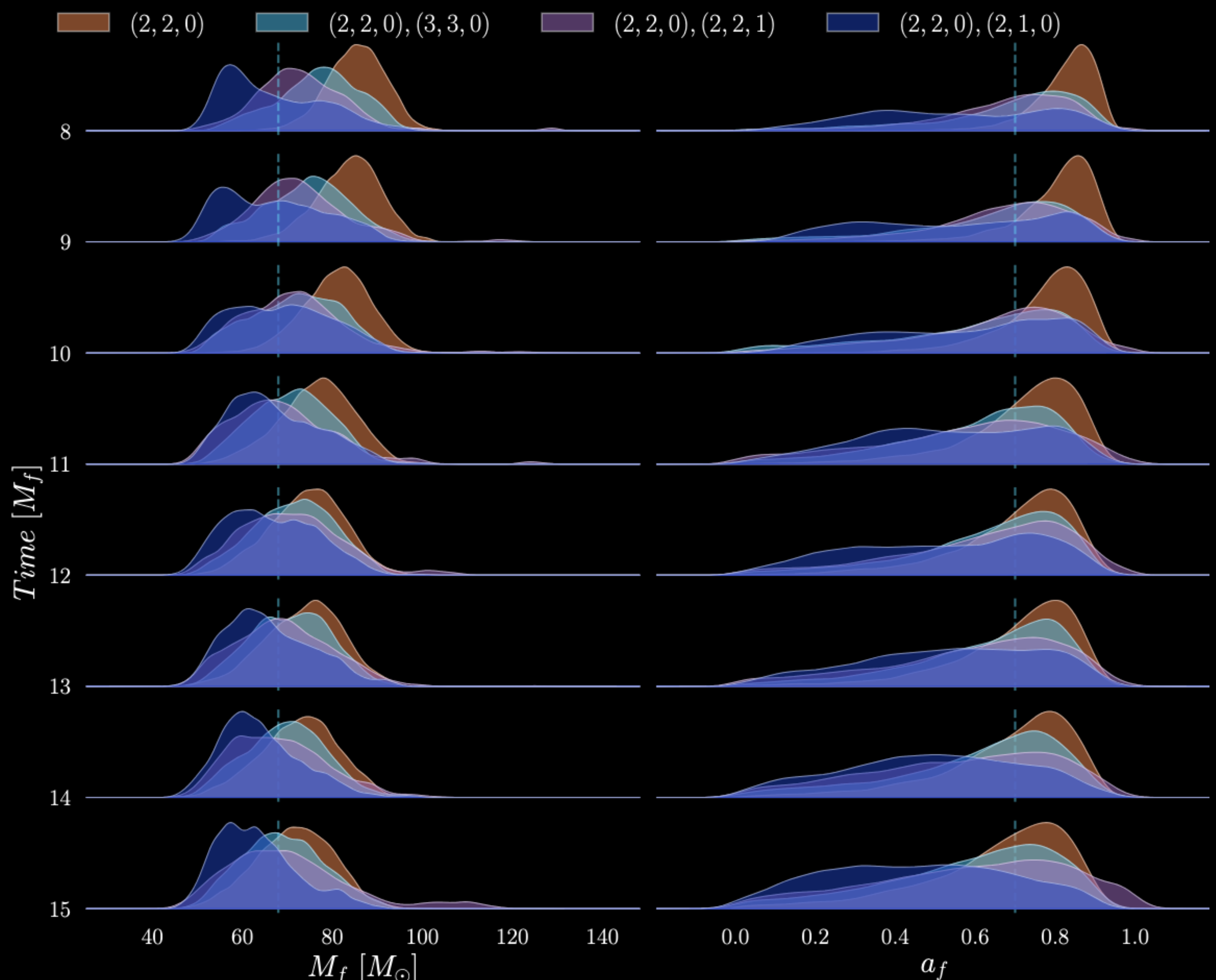
taken from NR

(e.g. Forteza+, 2205.14910 Capano+, 2105.05238)

Each mode has $\{A_{lmn}, \phi_{lmn}\}$ as free parameters, $\{f_{lmn}(M_f, a_f), \tau_{lmn}(M_f, a_f)\}$ GR predicted.

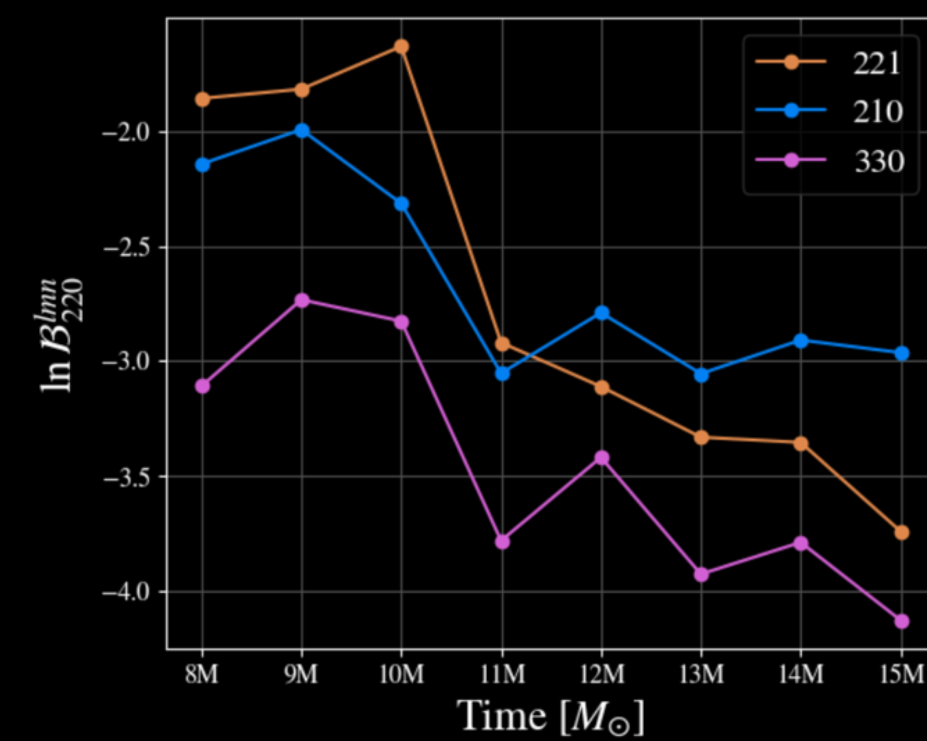
Systematics

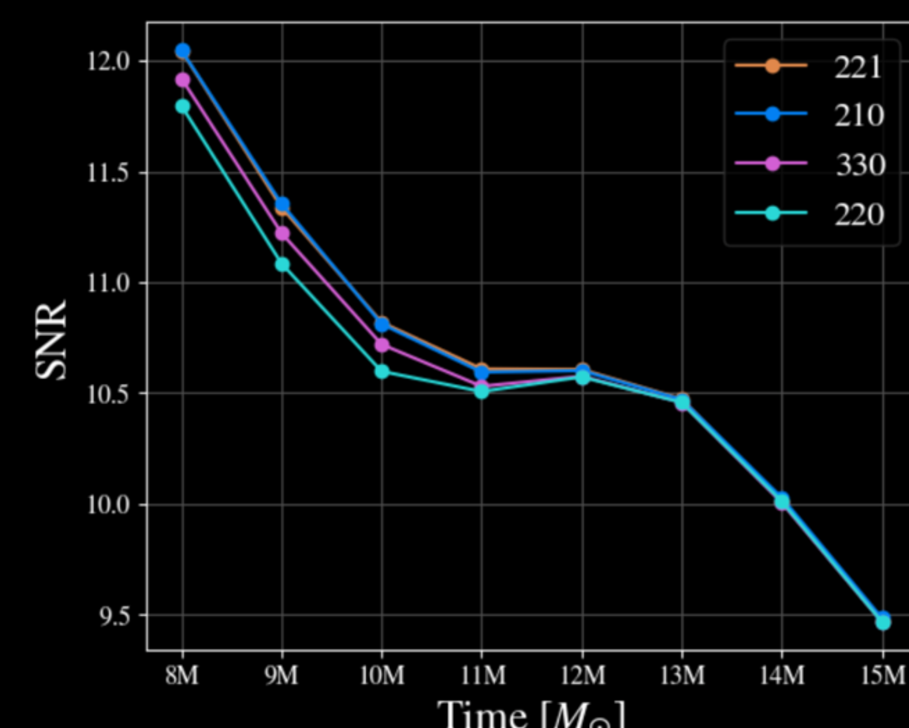
330 and 221 give the best recovery for M_f and a_f.
However, BF strongly favours 220 across all cases.



Presence of additional modes beyond 220 but not high enough SNR for given q prevents resolution of additional modes.

Kerr (Ordered amplitudes) - GR recovery



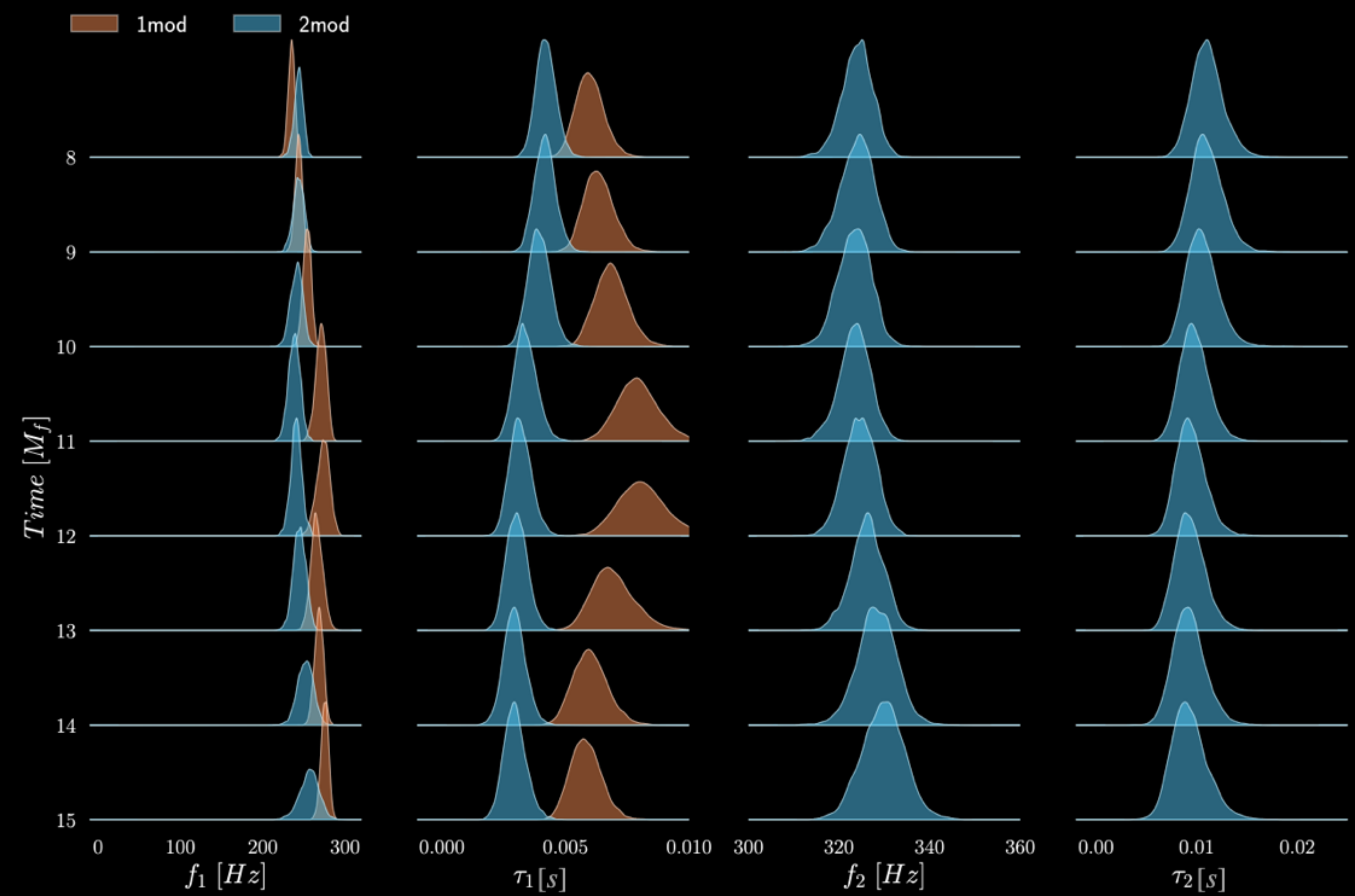


NonGR

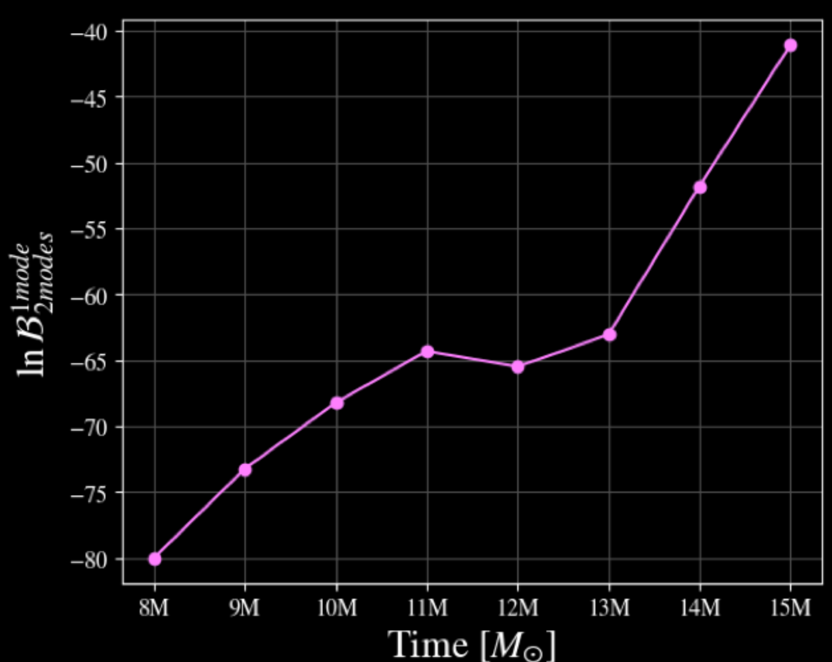
Modified QNM spectrum Qf=0.7

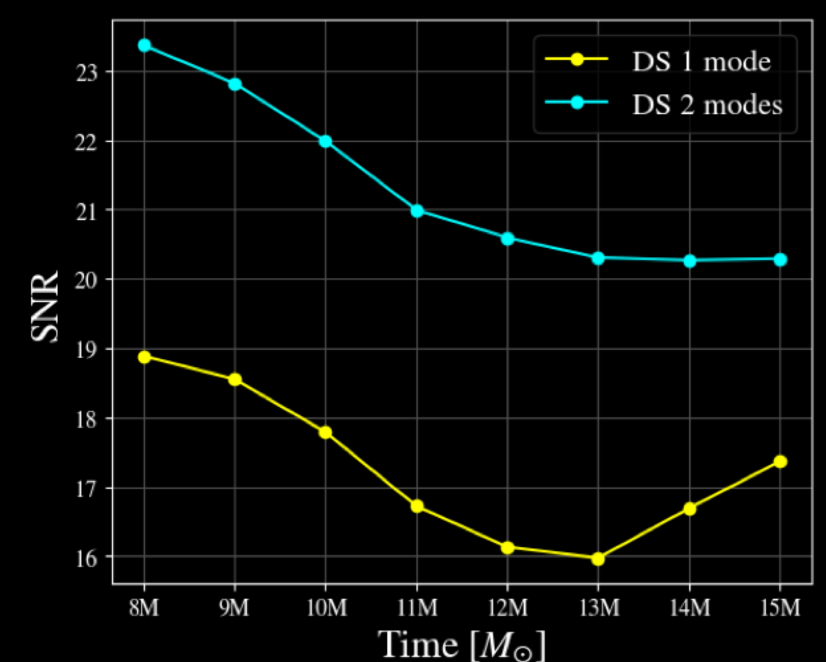
DS - GR recovery

Presence of 2 modes strongly favoured*.



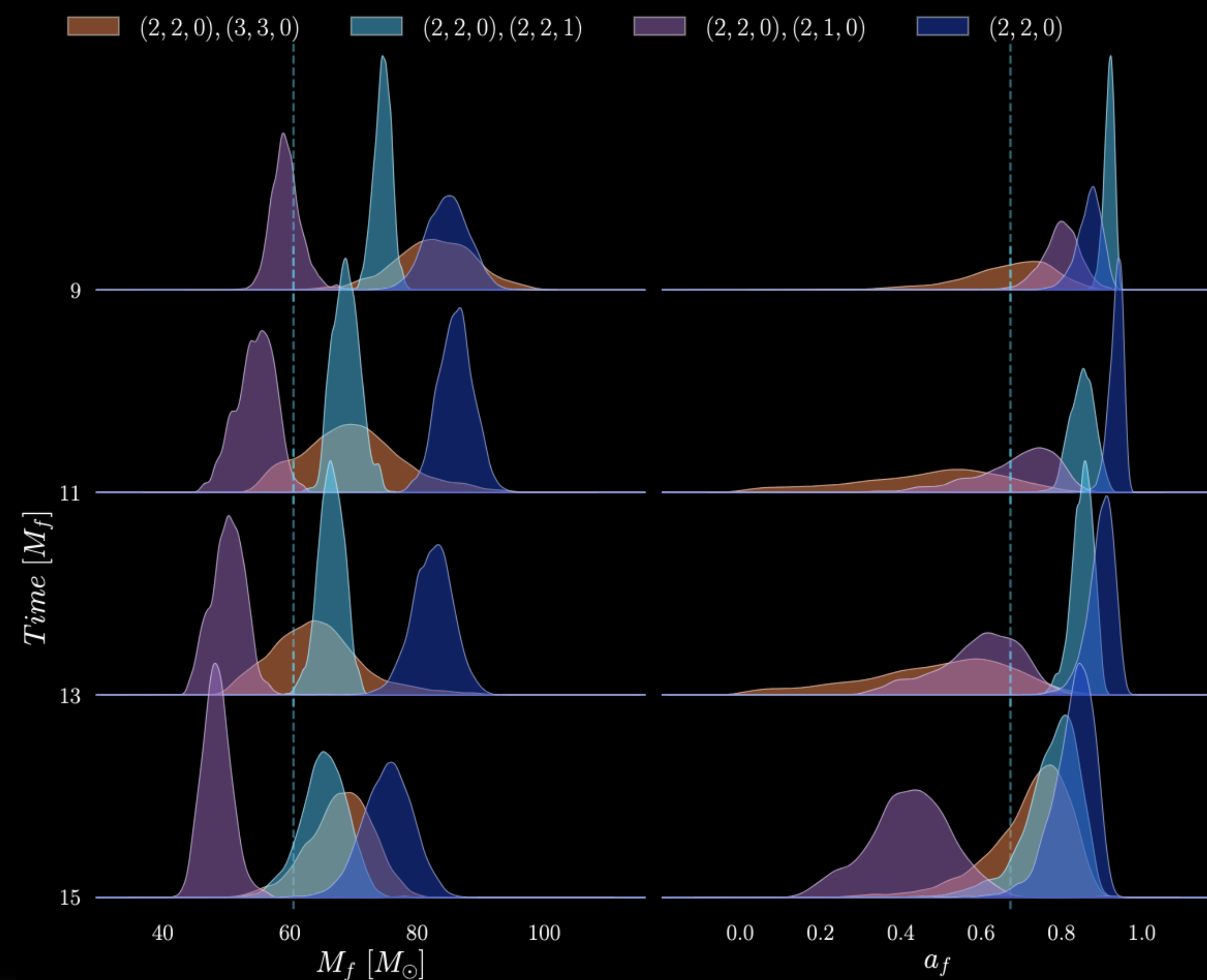
*3-modes analysis shows no evidence of additional mode.





Modified QNM spectrum QF=0.7

Kerr (OA) - GR recovery

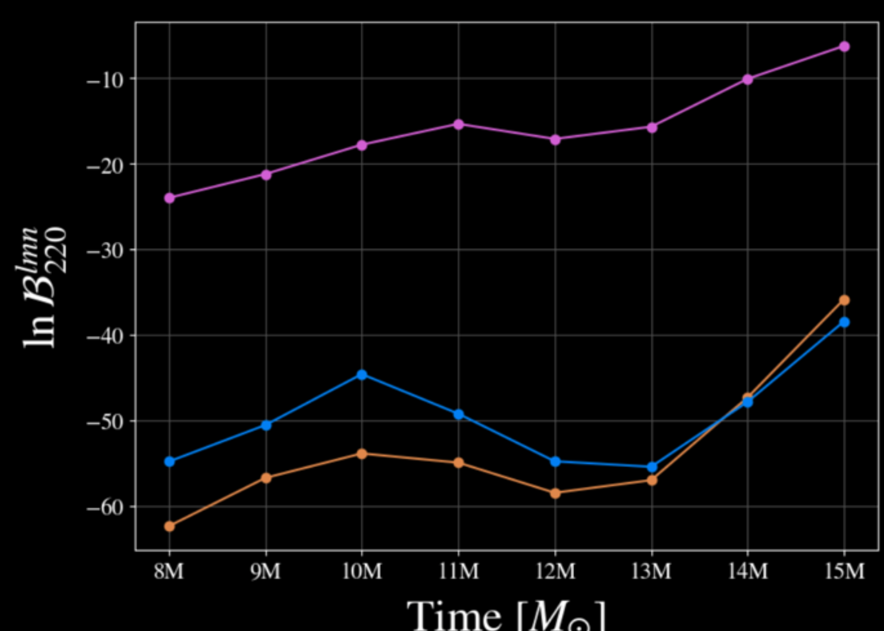


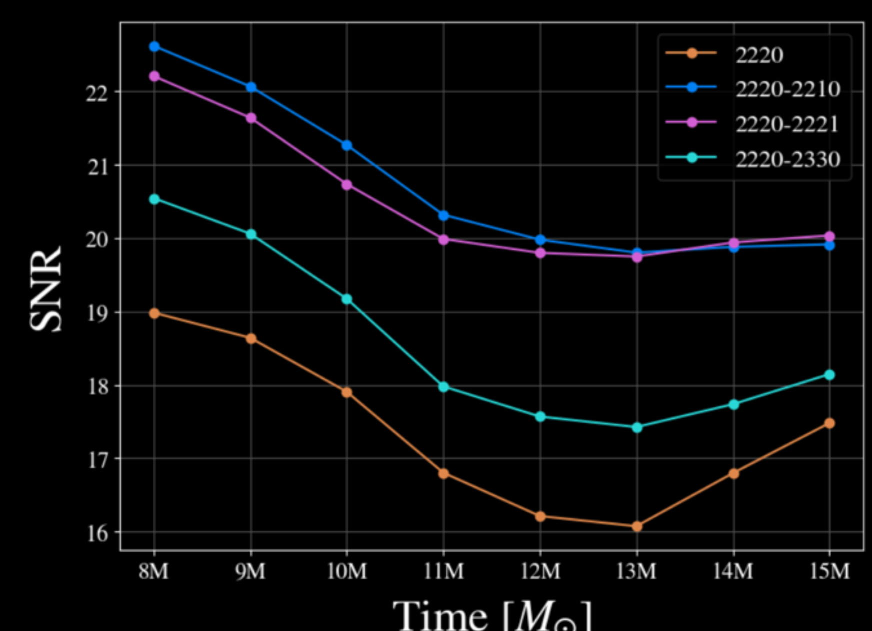
<u>NonGR values</u>

$$M_f = 60.56$$

$$a_f = 0.67$$

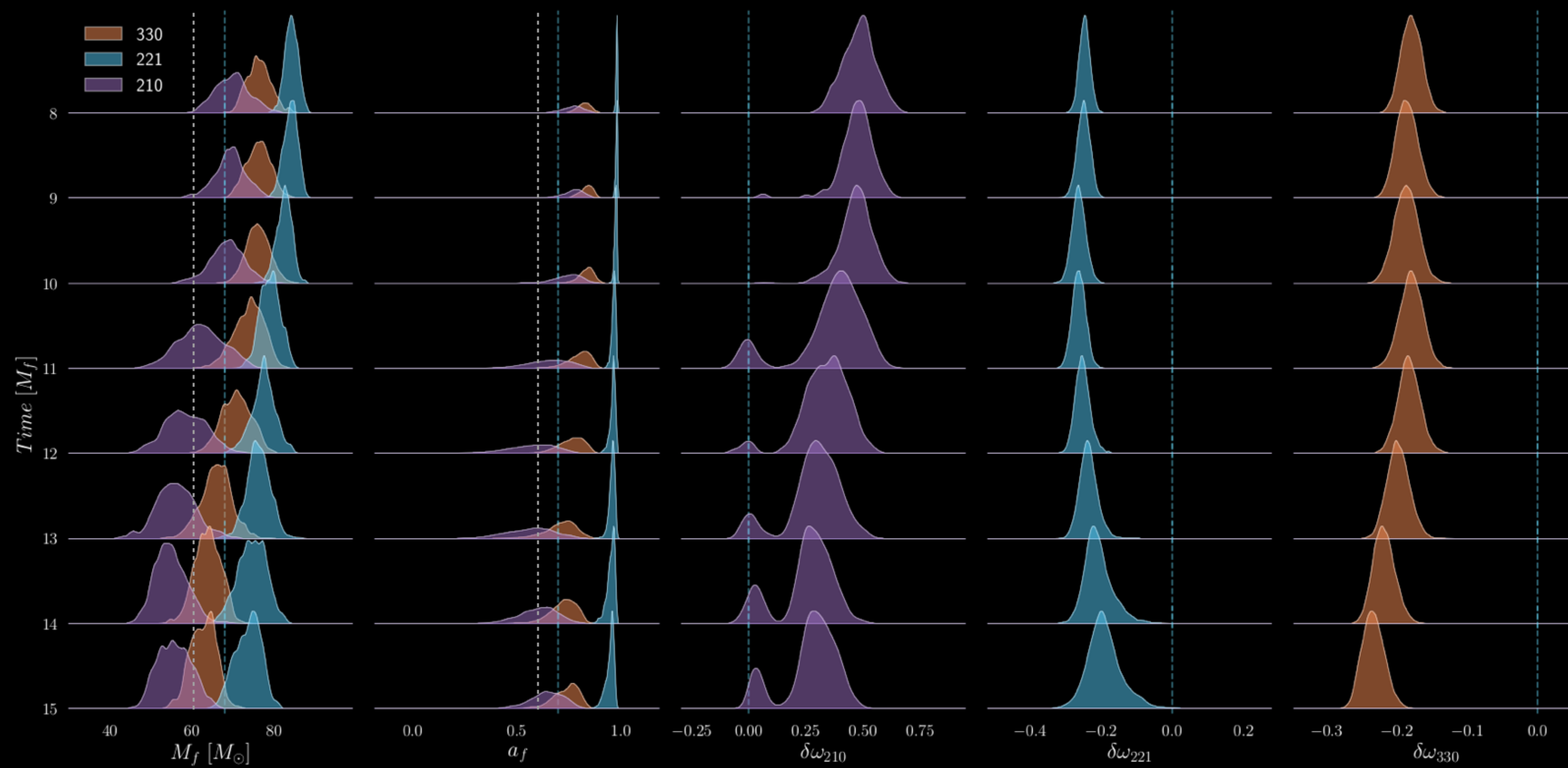
DISCLAIMER: Subset of times shown for visualization.

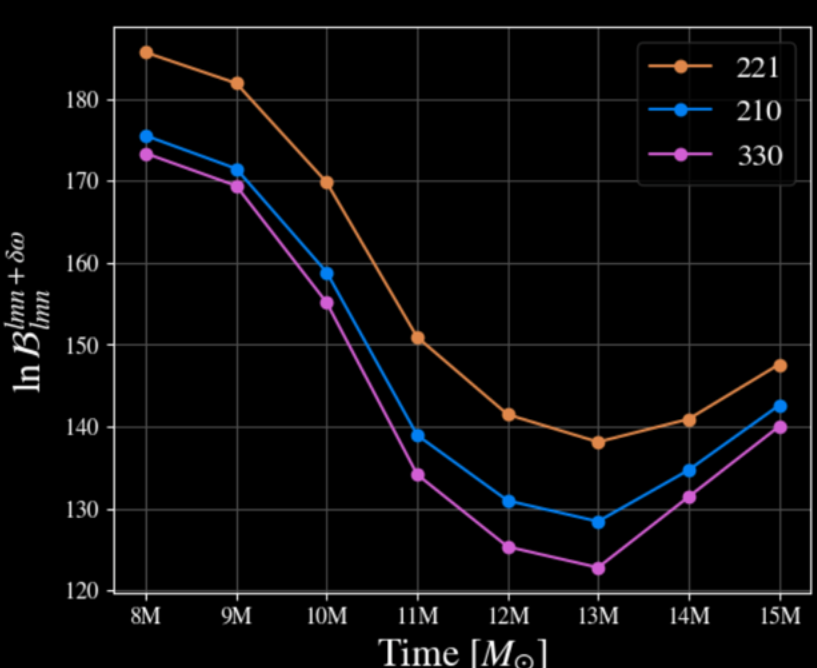




MODIFIED QNM SPECTRUM QF=0.7

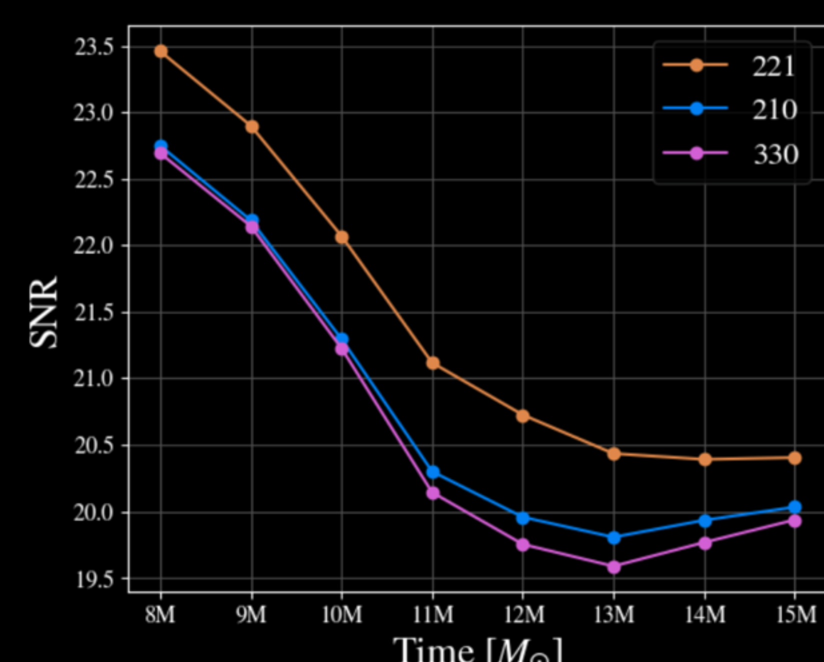
Kerr - GR + DEV recovery (OA)





nonGR

GR



Conclusions

Systematics

- No evidence of HMs in the data;
- PE is biased at early times for 220 due to non-linearities being important;
- SNR not high enough to resolve additional modes.

NonGR

- Deviation from GR recovered only in the case of the modified QNM spectrum (both for charge of 0.6 and 0.7);
- Modification of GR might extend non-linearities regime.