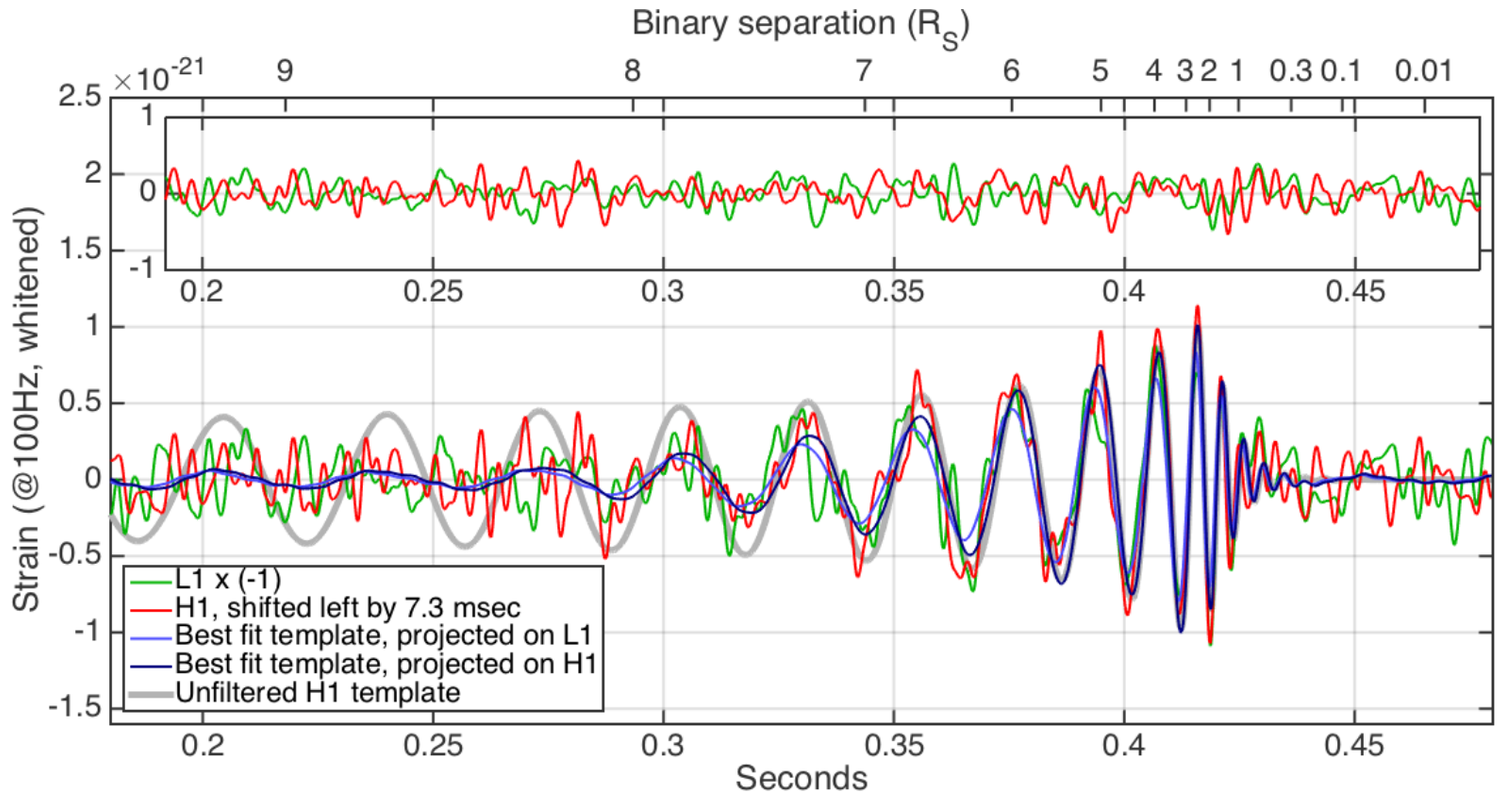


Tests of General Relativity with LIGO's Black Holes

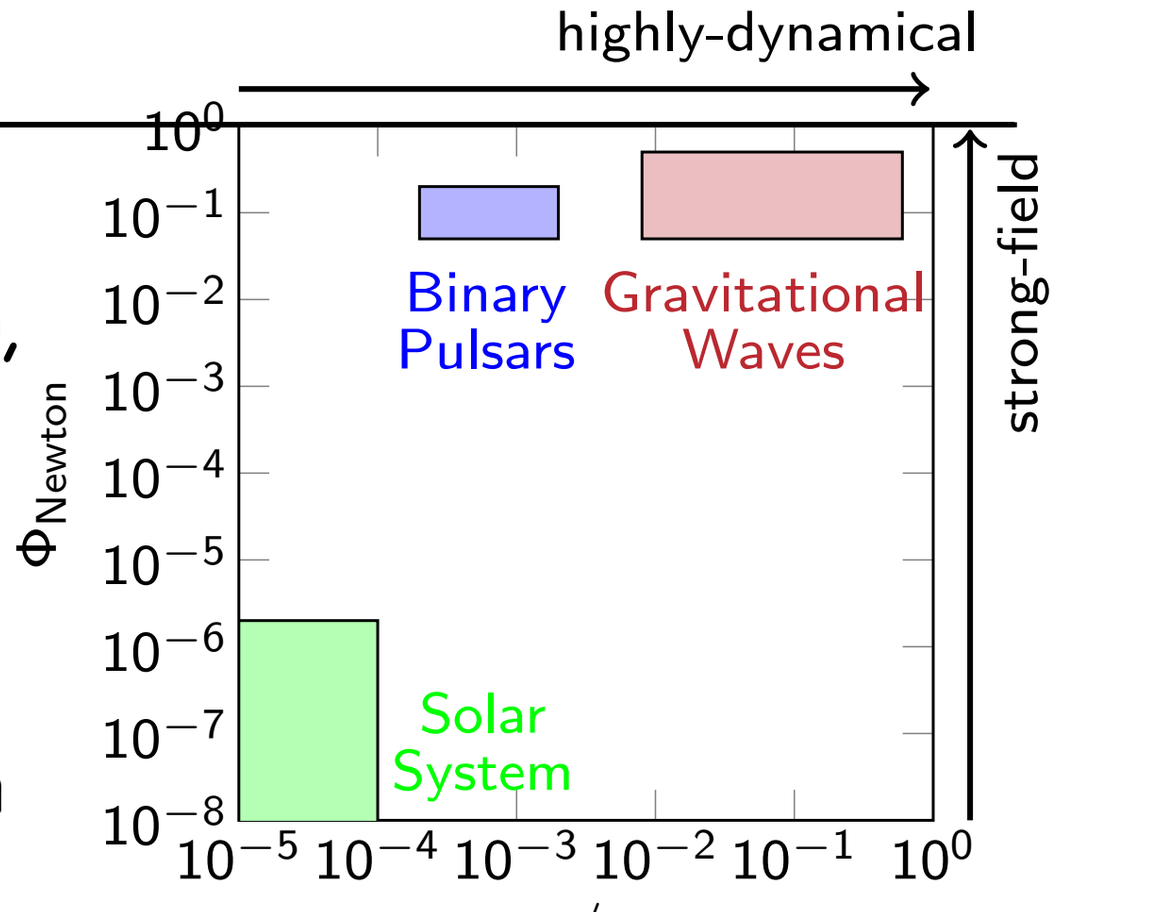
Alessandra Buonanno

- **Max Planck Institute for Gravitational Physics**
  (Albert Einstein Institute)
- **Department of Physics, University of Maryland**

Outline:

- Given **current tight constraints** on GR (e.g., Solar system, binary pulsars), can **any GR deviation be observed with LIGO**?

- Brief (partial) review of **tests of GR** done with first LIGO's BHs (generation and propagation of GWs).



(credit: Sennett)

- GW150914 & GW151226 are the **most convincing evidence** to date that **black holes in our Universe** are the objects **predicted** by Einstein theory of **GR.**

- Can we **test** the **BH "no hair" hypothesis**? Can we **disprove presence** of "**horizon**"?

- Can we **measure new scales** of **(possible) new physics** in strong -field dynamical regime (i.e., around merger)?

Characteristics of binary black-hole coalescence

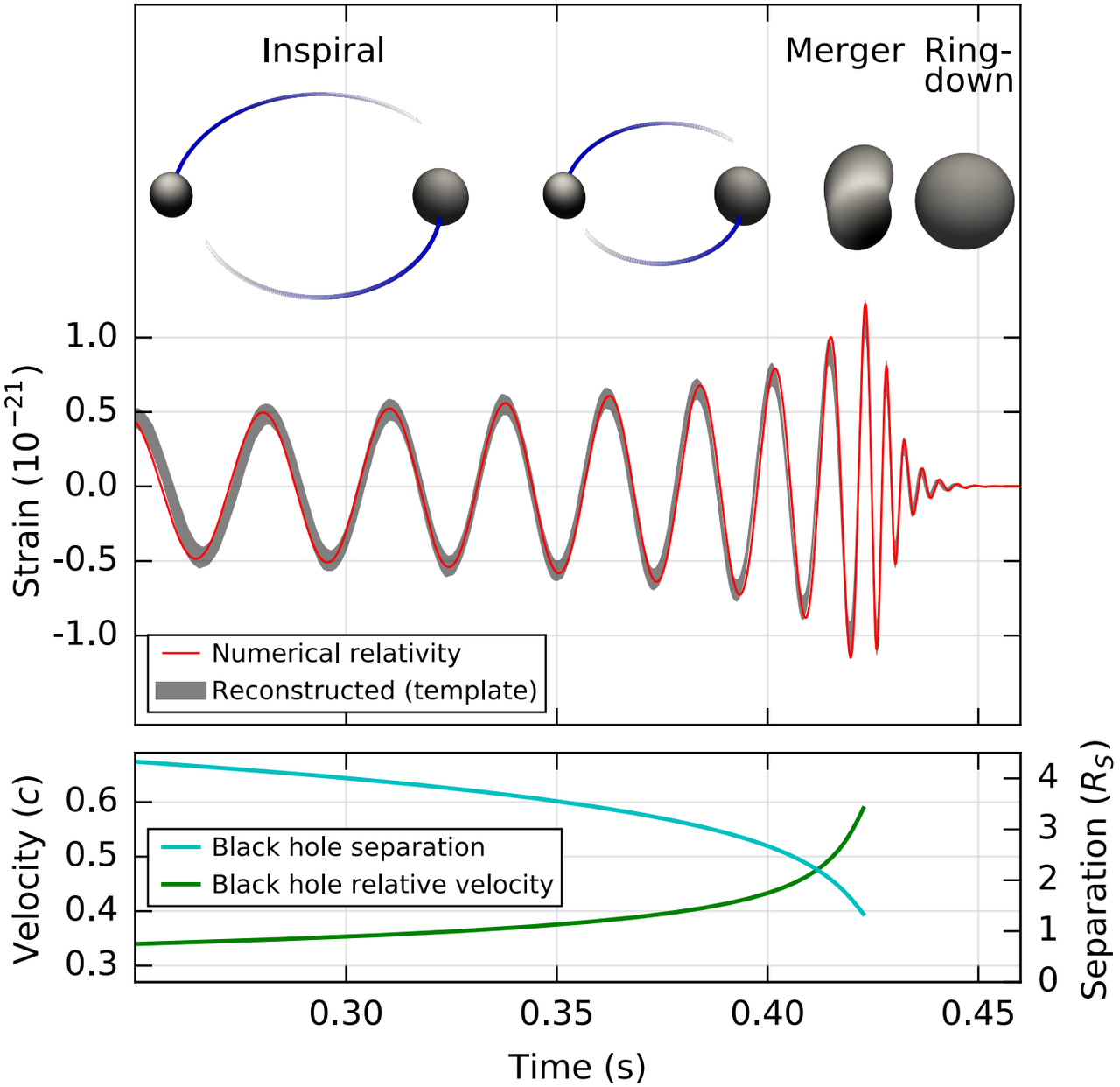
- **Early inspiral:** low velocity & weak gravitational field.

- **Late inspiral/plunge:** high velocity & strong gravitational field.

- **Merger:** nonlinear & non perturbative effects; rapidly changing gravitational field

- **Ringdown:** excitation of quasi-normal modes/spacetime vibrations.

(Abbott et al. PRL 116 (2016) 061102)



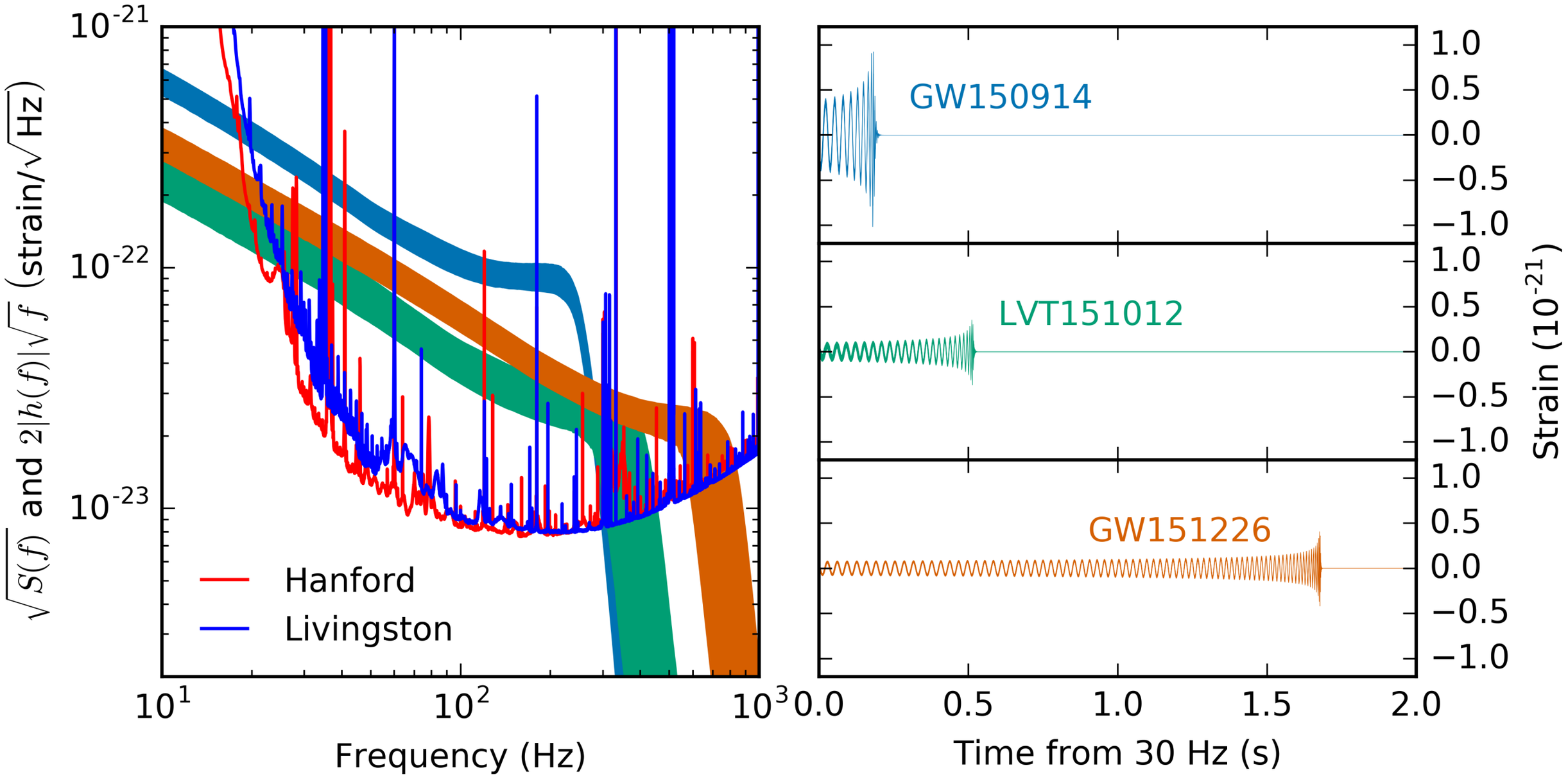
GW150914:

$$f_{\rm orb}^{\rm merger} \sim 75\,{\rm Hz} \Rightarrow r_{\rm orb} \sim 350\,{\rm km} \sim 4\,GM/c^2$$

$$\mathcal{L}_{\rm GW}^{\rm merger} \sim 10^{56}\,{\rm erg/sec}$$

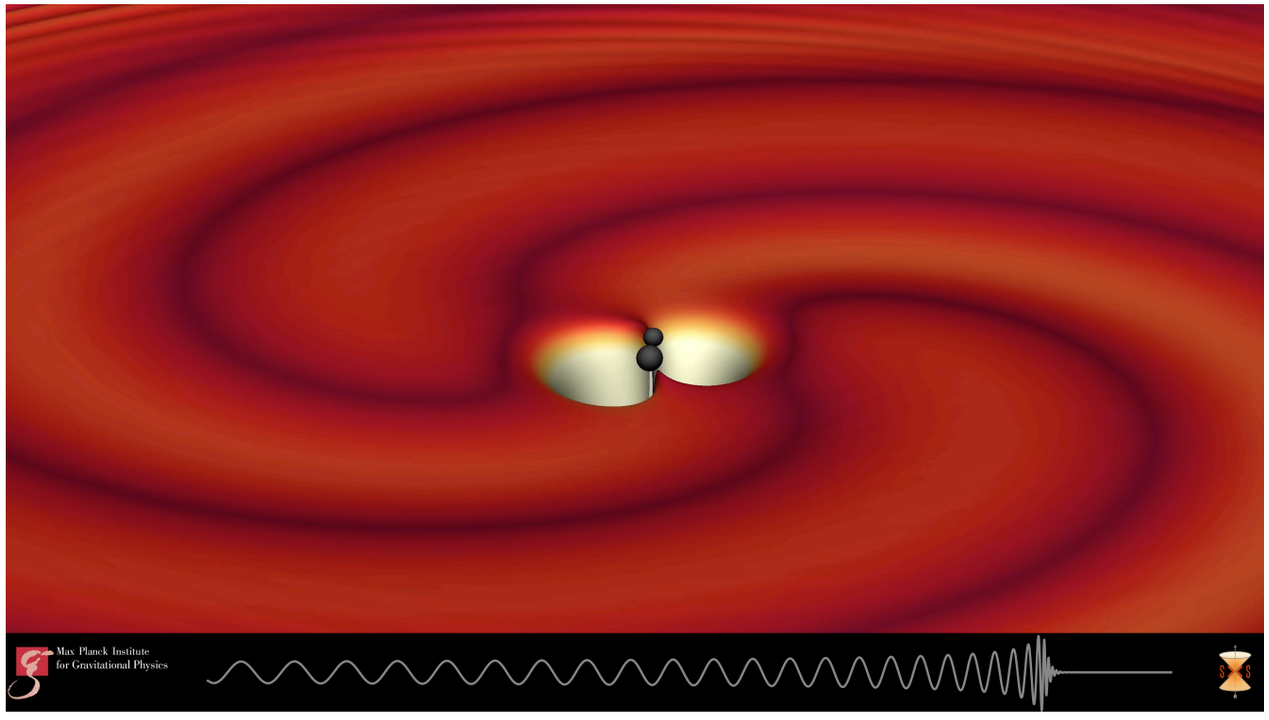
What LIGO detected

(Abbott et al. arXiv:1606.04856)

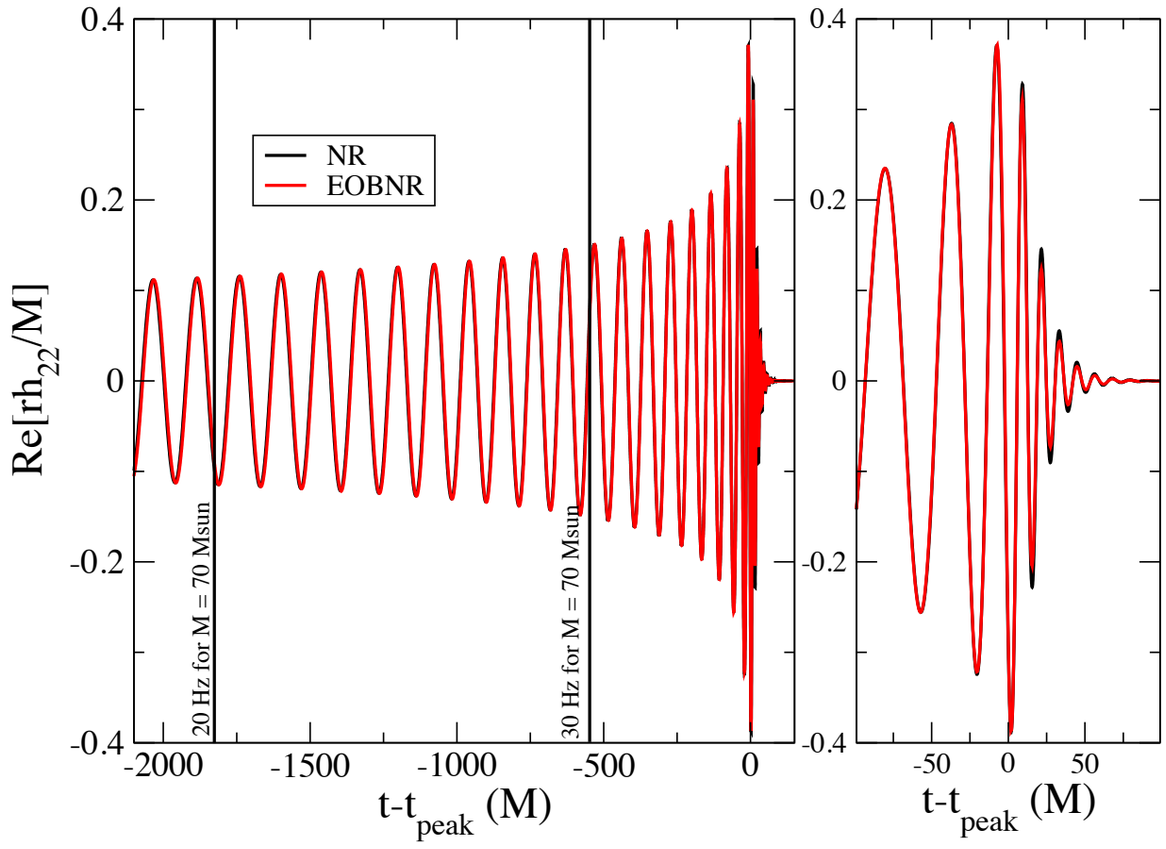


Are systematics in GR waveform models under control?

(visualization credit: Haas)



(Ossokine, AB & SXS project)



- **Waveform models** very closely **match** the **exact solution** from Einstein equations around GW150914 & GW151226.

- For GW150914 & GW151226, **systematics smaller than statistical** errors.

- **Work needed to reduce systematics** everywhere else in parameter space.

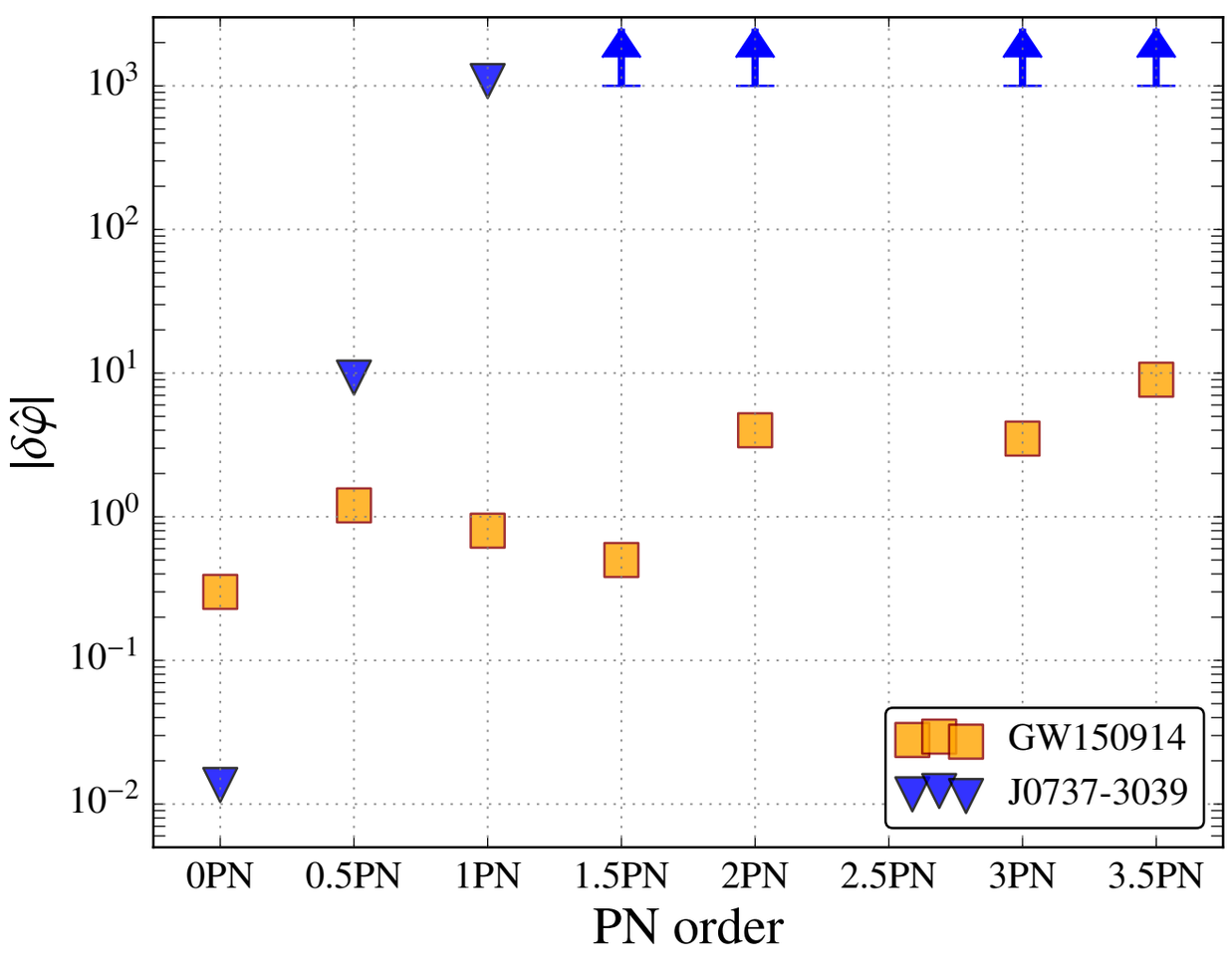
Bounding higher-order parameters during inspiral

- GW150914/GW122615's **rapidly varying orbital periods** allow us to **bound higher-order PN coefficients** in gravitational phase.

$$\tilde{h}(f) = \mathcal{A}(f) e^{i\varphi(f)}$$

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} + \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} + \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots$$

(Abbott et al. arXiv:1602.03841)



(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

(see Yunes et al 16. for constraints on dipole emission, i.e. no BH hair)

- **PN parameters** describe: **tails** of radiation due to backscattering, **spin-orbit** and **spin-spin** couplings.
- First **GR test** in the genuinely dynamical, **strong-field regime.**

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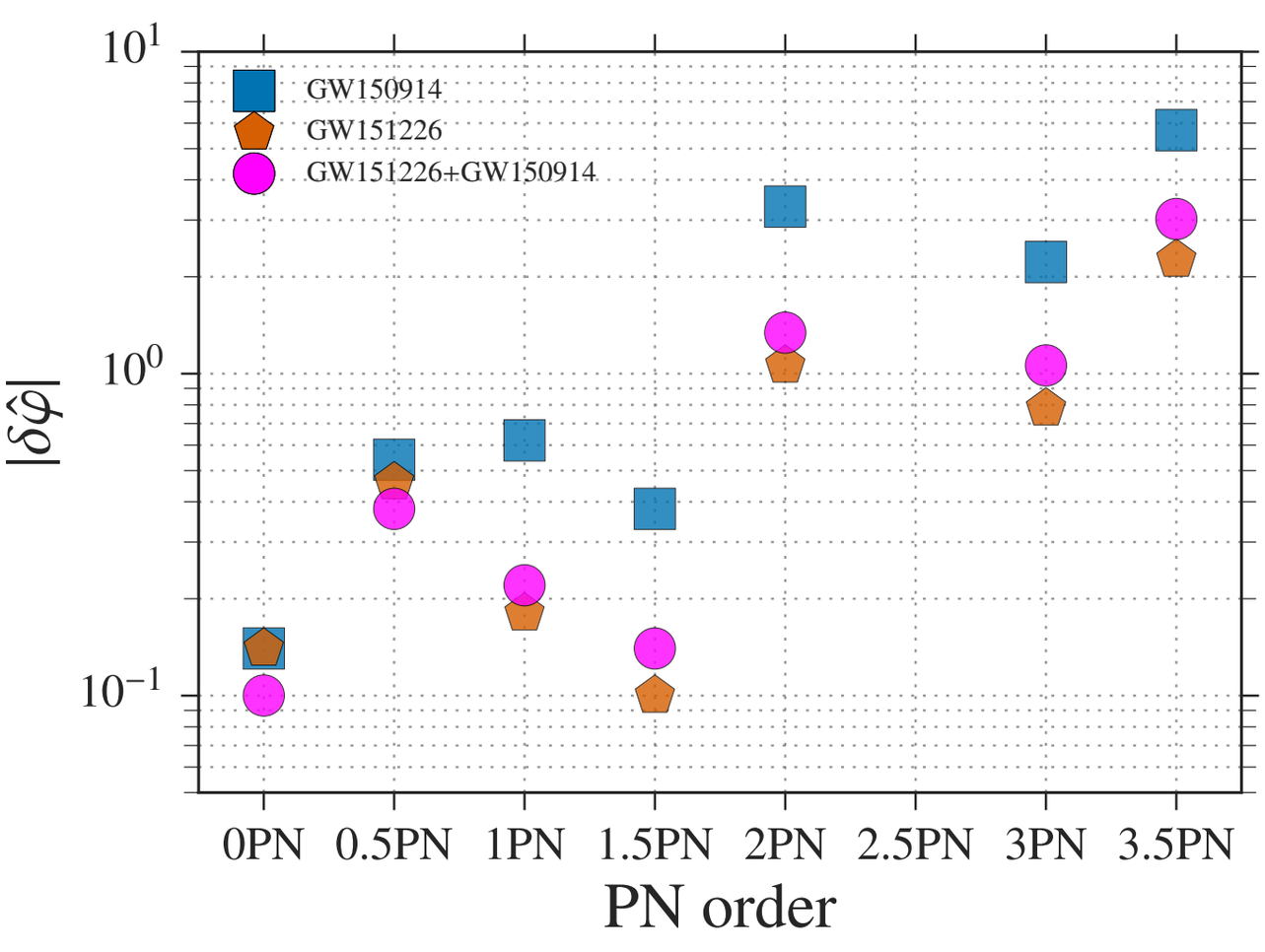
(Abbott et al. arXiv:1606.04856)



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- **PN parameters** describe: **tails** of radiation due to backscattering, **spin-orbit** and **spin-spin** couplings.
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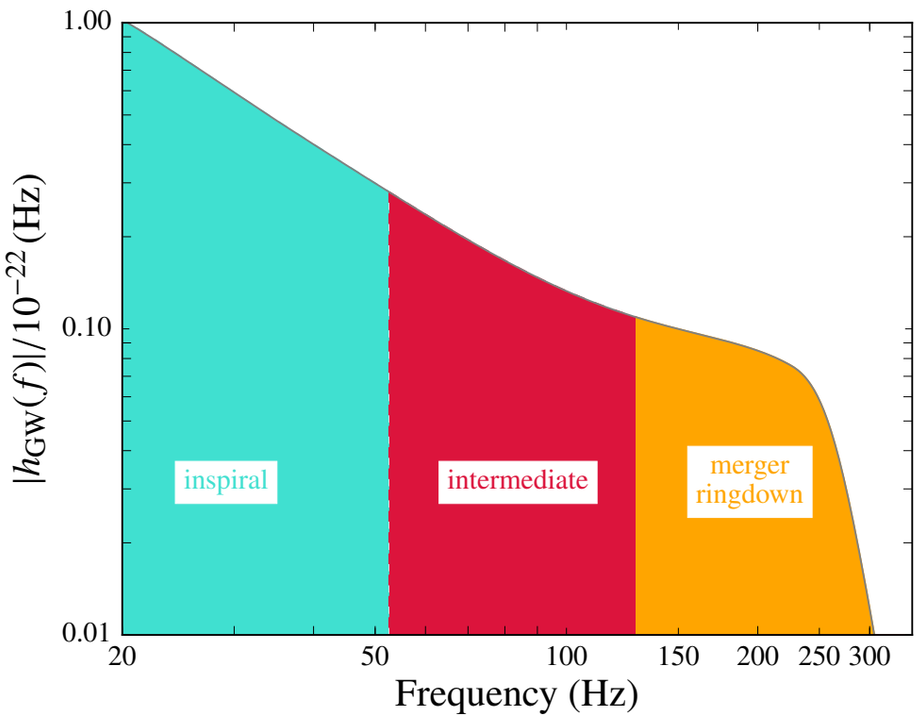
Bounding parameters during intermediate/merger-RD

(Abbott et al. arXiv:1602.03841)



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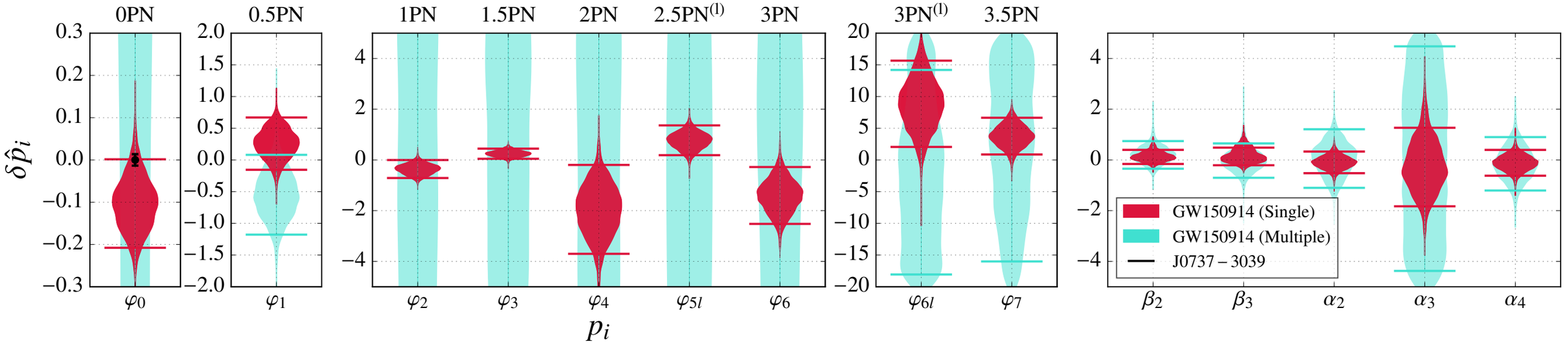
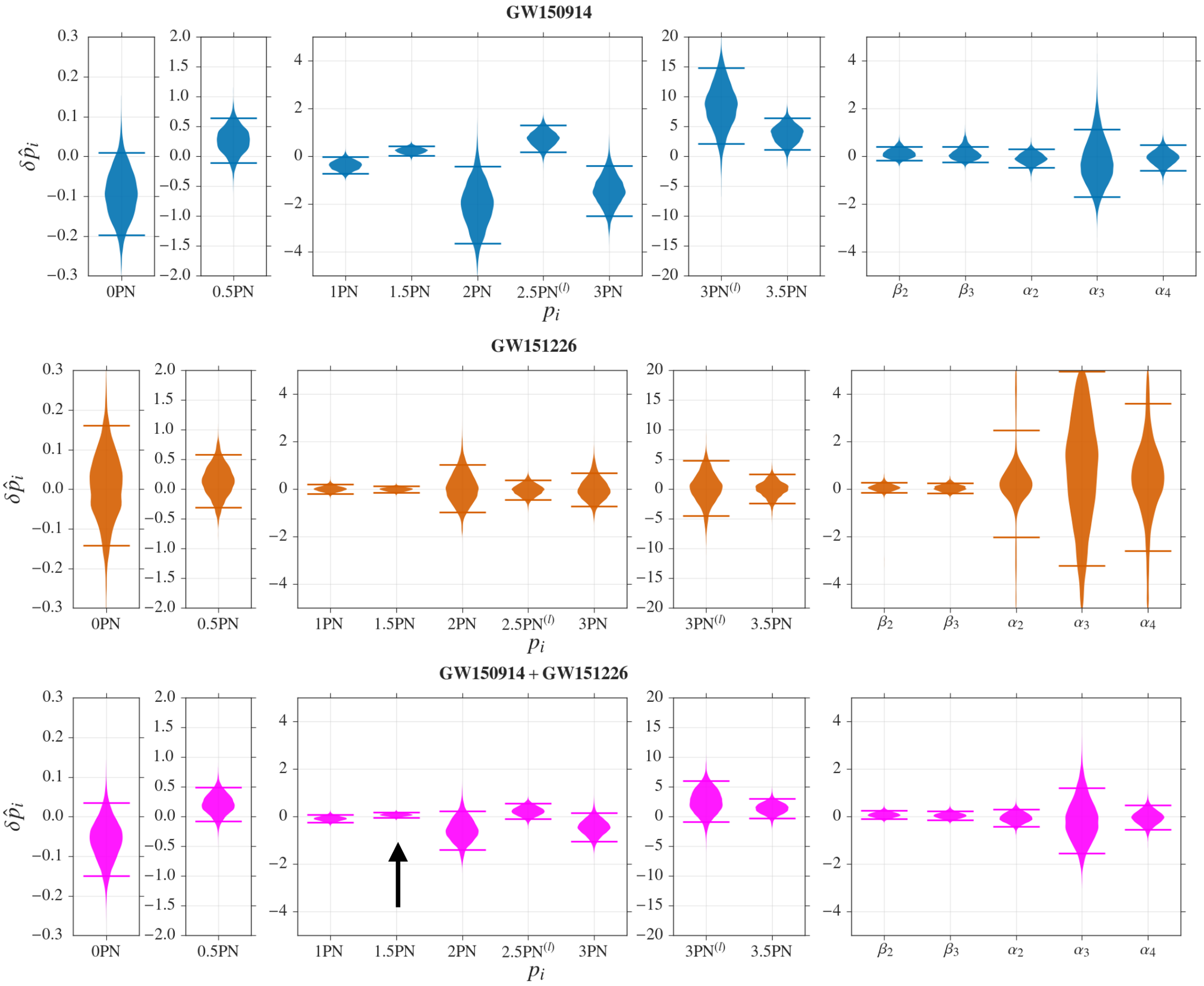
(Khan et al. 16)

- Merger-ringdown **phenomenological parameters** (β_i and α_i) not yet **expressed in terms** of relevant **parameters in GR and modified theories of GR.**

low frequency → **high frequency**

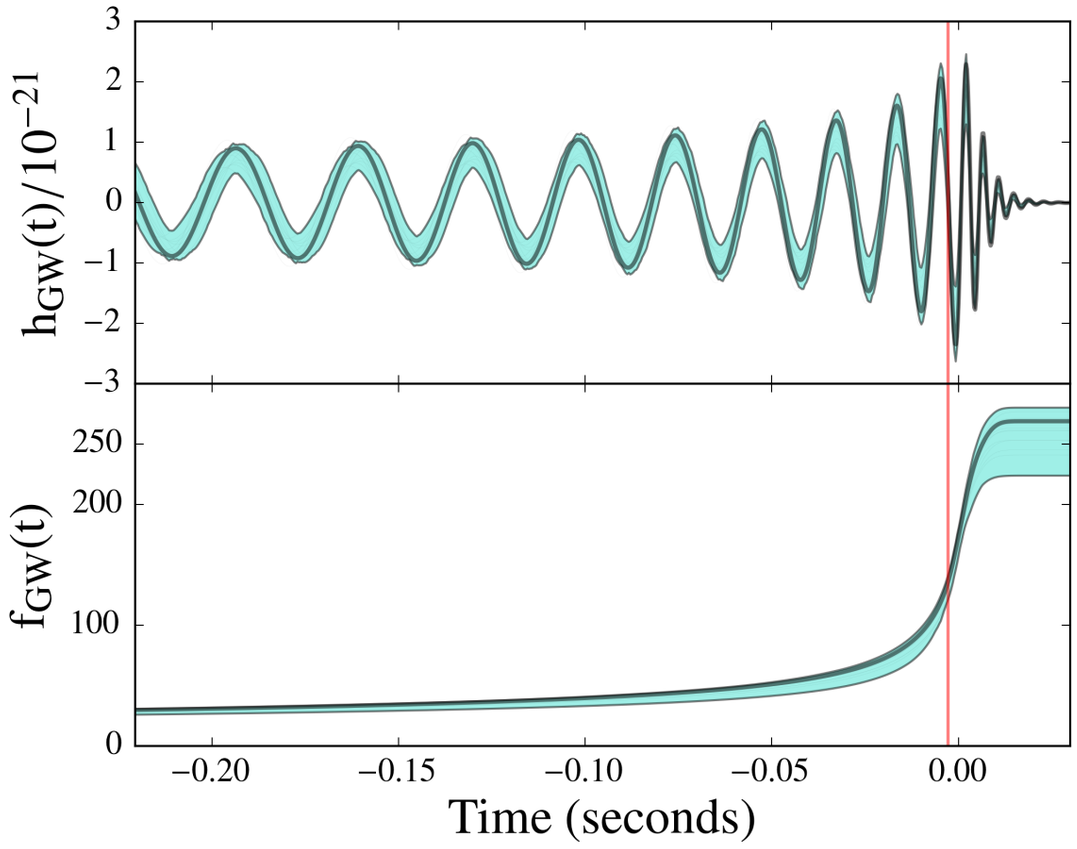


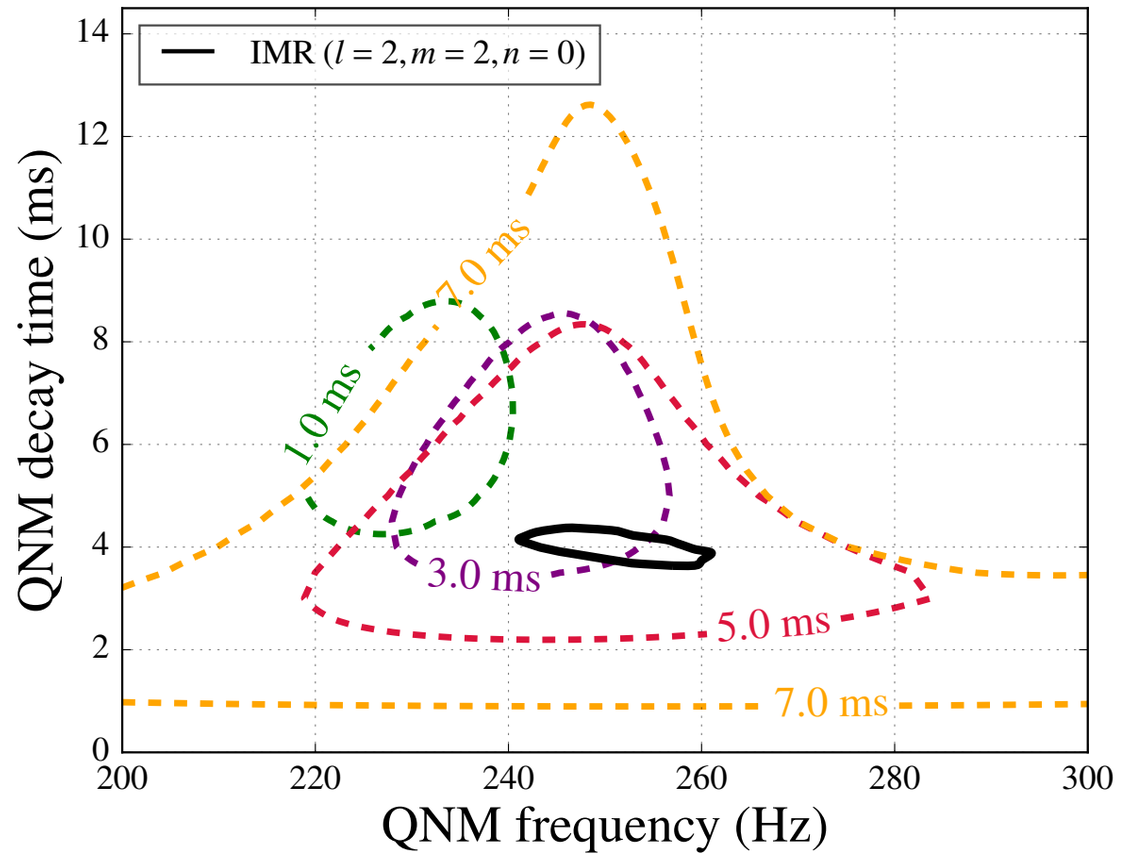
Bounding phenomenological parameters during merger-RD



(Abbott et al. arXiv:1606.04856)

Could we prove that GW150914's remnant is a BH?





(Abbott et al. arXiv:1602.03841)

- QNM frequencies **depend** on BH **mass** and **spin**, but also **overtone** (n) and **harmonics** (l,m) (Vishveshwara 70, Press 71, Chandrasekhar & Detweiler 75).
- We measured frequency & decay time of **damped sinusoid** in the data after GW150914's peak.
- Consistency with least-damped QNM, but **cannot extract** from data **mass & spin** of **remnant** and **prove** is **BH! Multiple QNMs** are needed to test **no-hair theorem** and **second-law black-hole mechanics** (Israel 69, Carter 71; Hawking 71, Bardeen 73).

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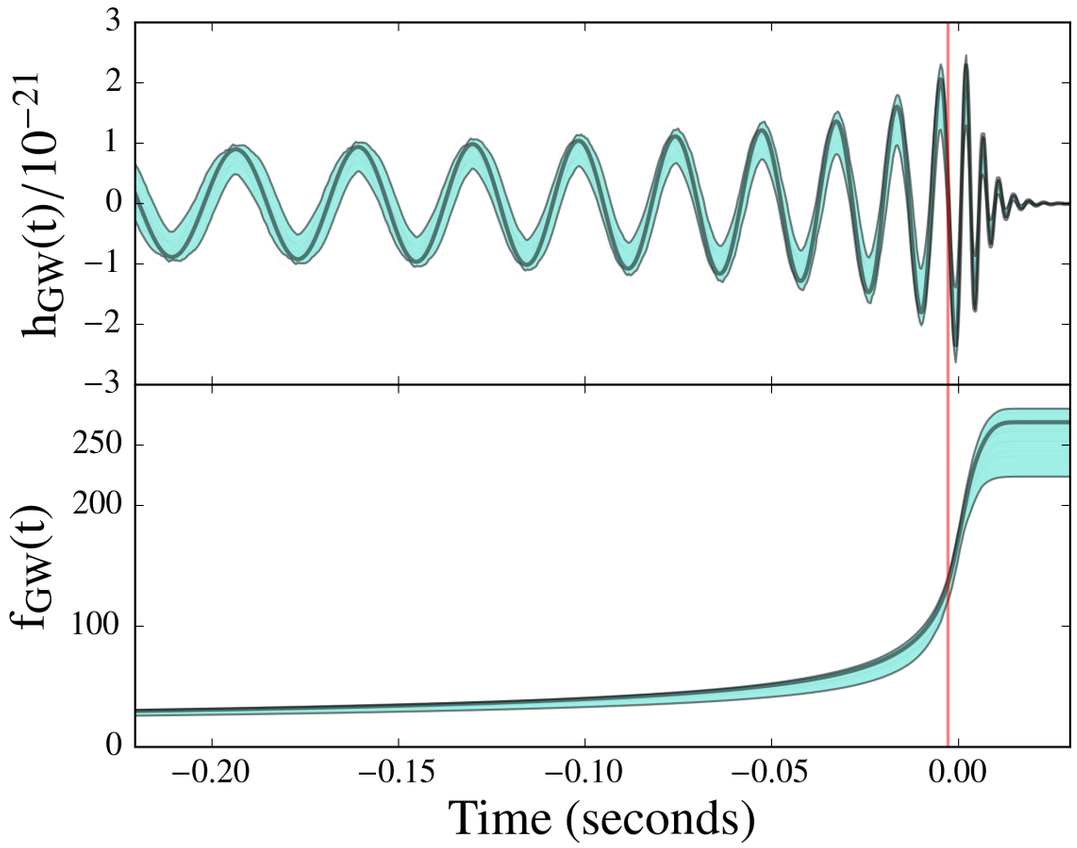

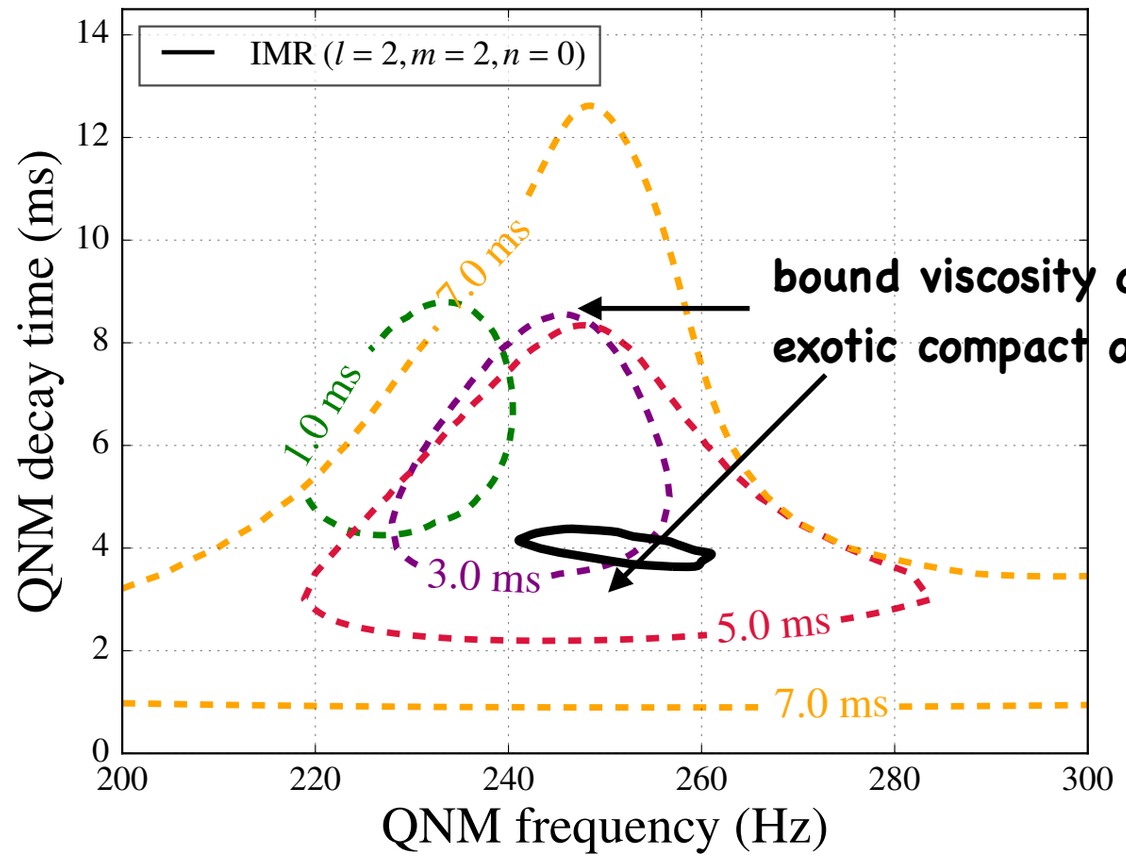

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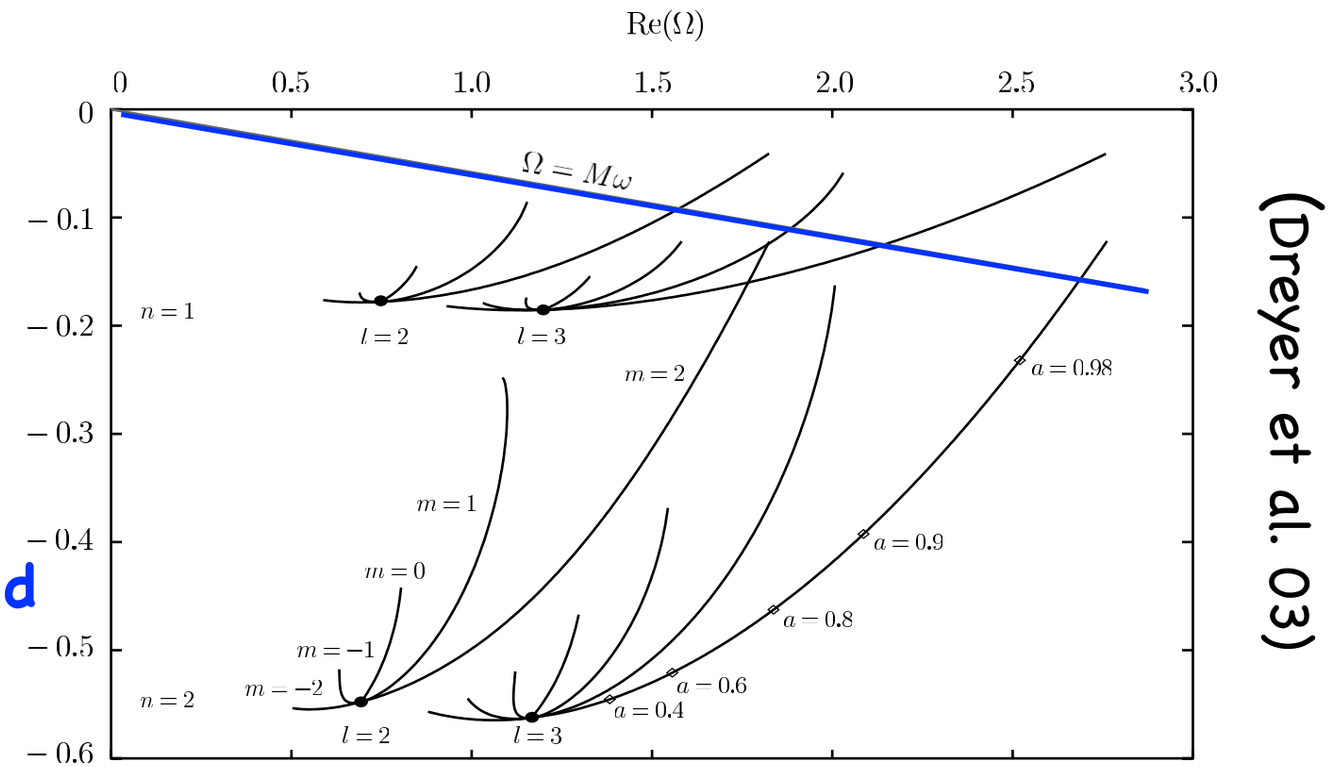
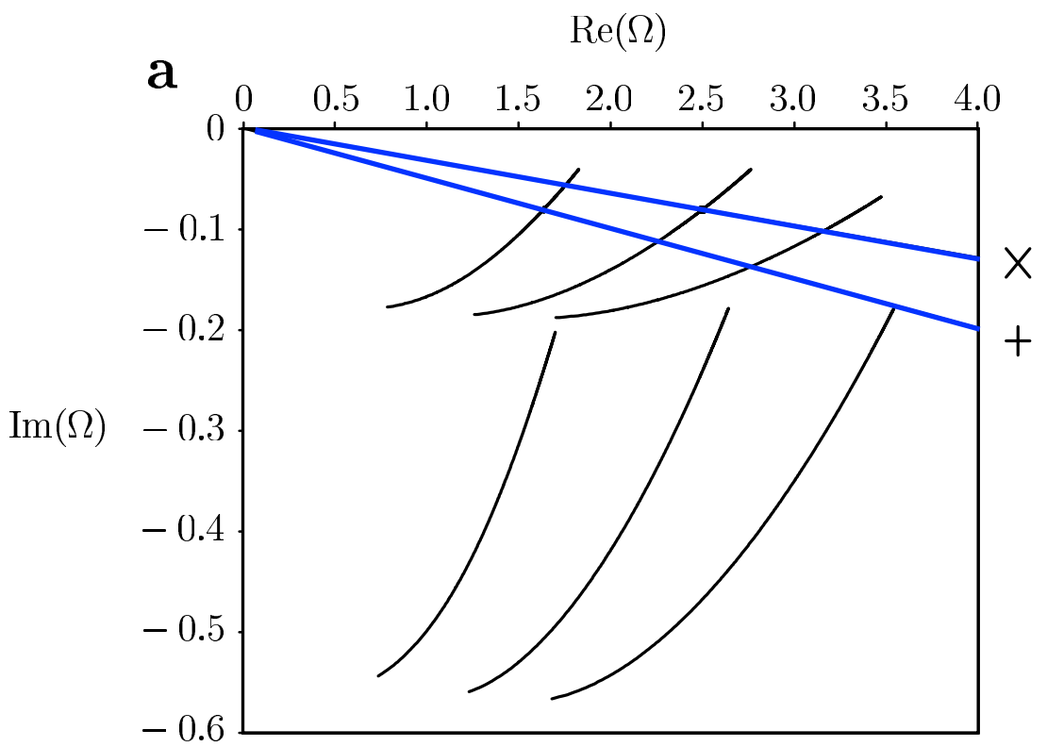
Measuring BH's mass and spin from multiple QNMs

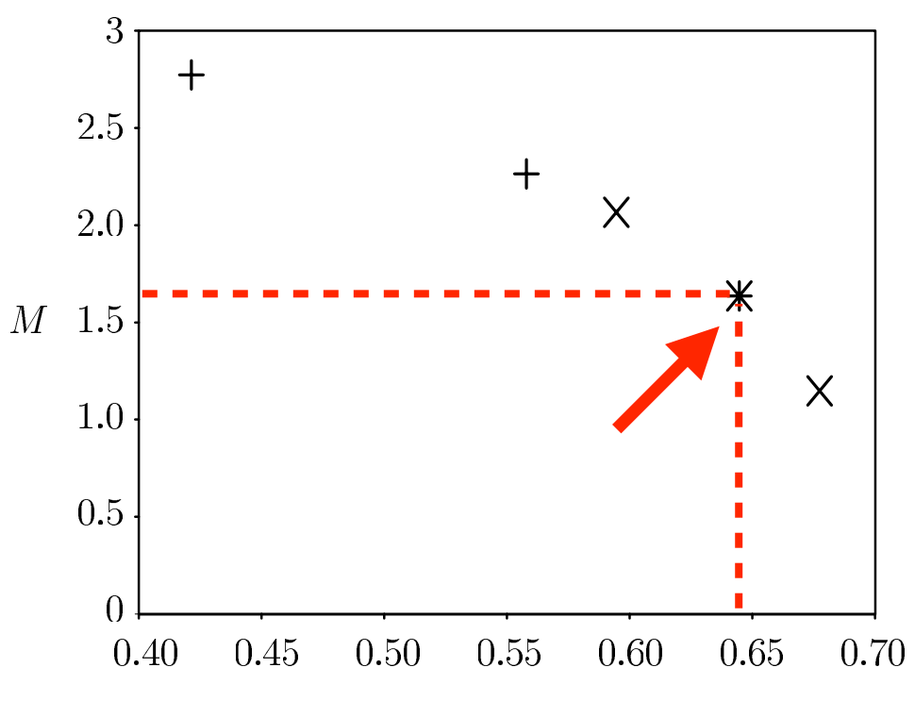
$$\Omega_{n\ell m} = M\omega_{n\ell m} = \left(2\pi F_{n\ell m} + \frac{i}{T_{n\ell m}}\right)$$



(Dreyer et al. 03)

- By knowing only **one frequency and decay time,** we **cannot identify** final BH's mass and spin.





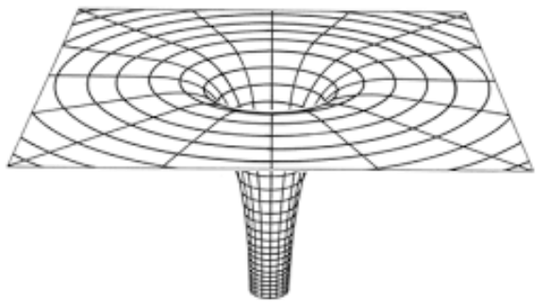
- Which **SNRs** are needed to **measure multiple modes**? O(50-100) ?

(Dreyer et al. 03, Berti et al. 05-07, Gossan et al. 12, Berti et al. 16, Bhagwat et al. 16)

Can we probe the horizon from the post-merger GW signal?

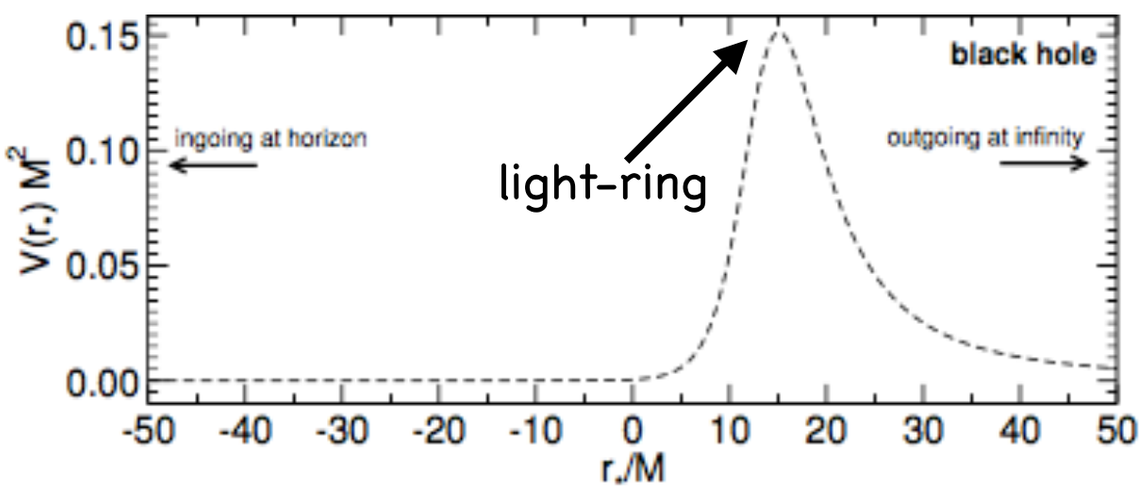
- What determines **post-merger GW signal**? **Light ring or horizon**?

(Cardoso et al. 16)



black hole

$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_*^2} + V_{\ell m} \Psi = 0$$



- **QNMs** of BHs are **related to** peculiar boundary condition at **horizon**, i.e. **absence of outgoing waves.**

(Chandrasekhar & Detweiler 75)

- By contrast, frequency and damping time of **ringdown waves of distorted object** are **associated to** orbital frequency and instability time scale of circular **null geodesics at light ring**.

(Goebel 1972, Davis et al. 1972, Ferrari et al. 1984)

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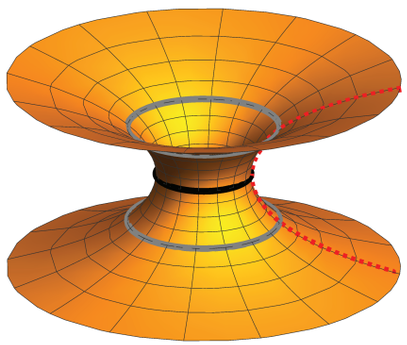
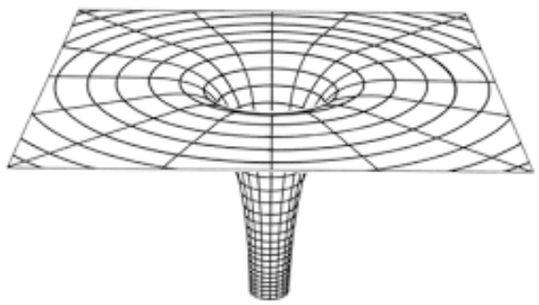
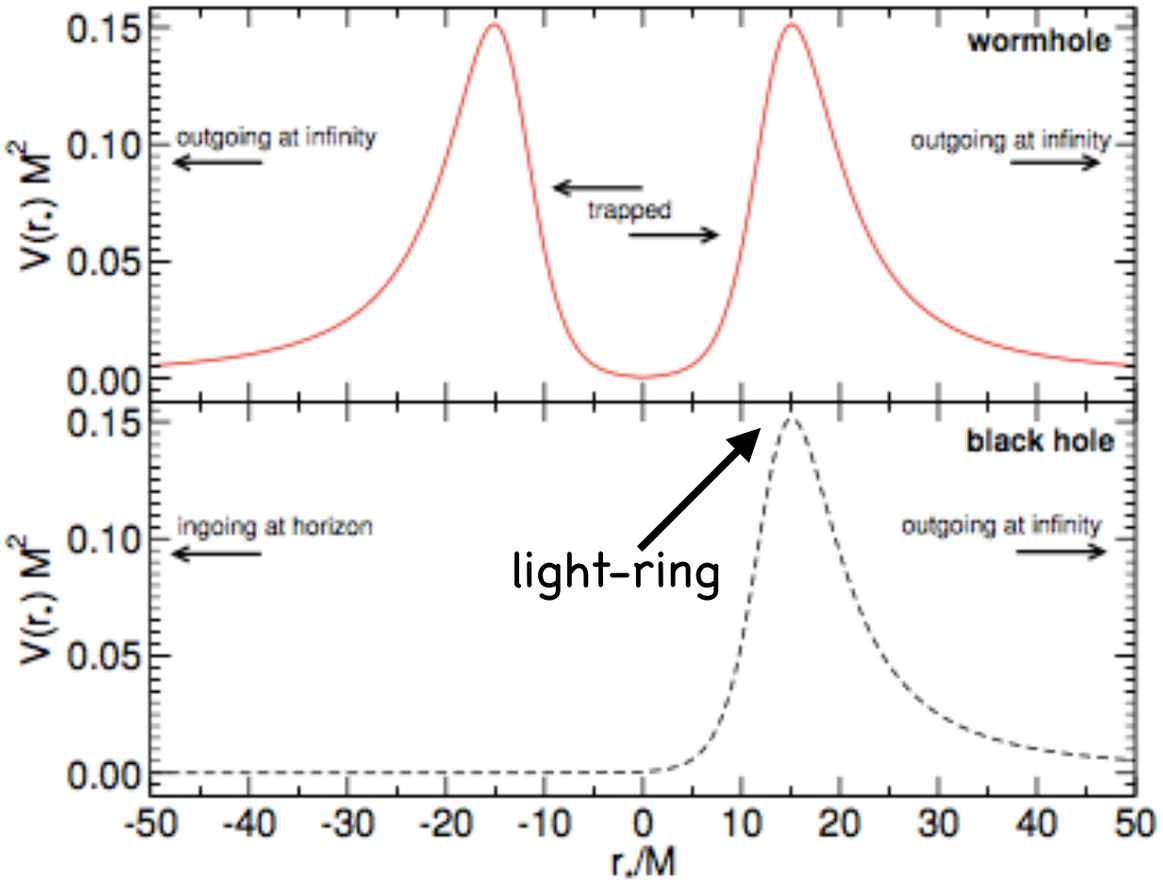
(Cardoso, Franzin & Pani 16)



horizonless object



black hole



- **Wormhole**: two BH metrics matched at the throat with thin shell at r_0

- Assuming **microscopic corrections**

$$r_0 = 2M + L$$

$$L \ll M$$

- **Time of bounce** between potential barriers

$$\Delta t = 2 \int_{r_0}^{3M} \frac{dr}{(1 - 2M/r)}$$

$$\Delta t \sim M \log\left(\frac{M}{L}\right)$$

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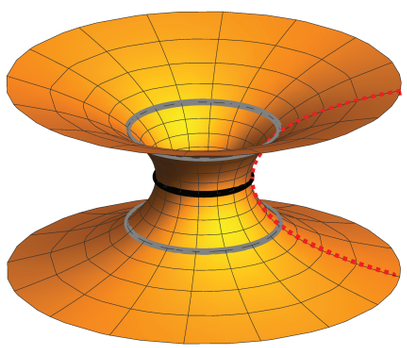
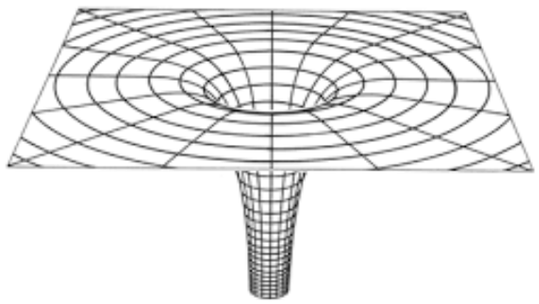
- What determines **post-merger GW signal**? **Light ring or horizon**?

(Cardoso et al. 16)

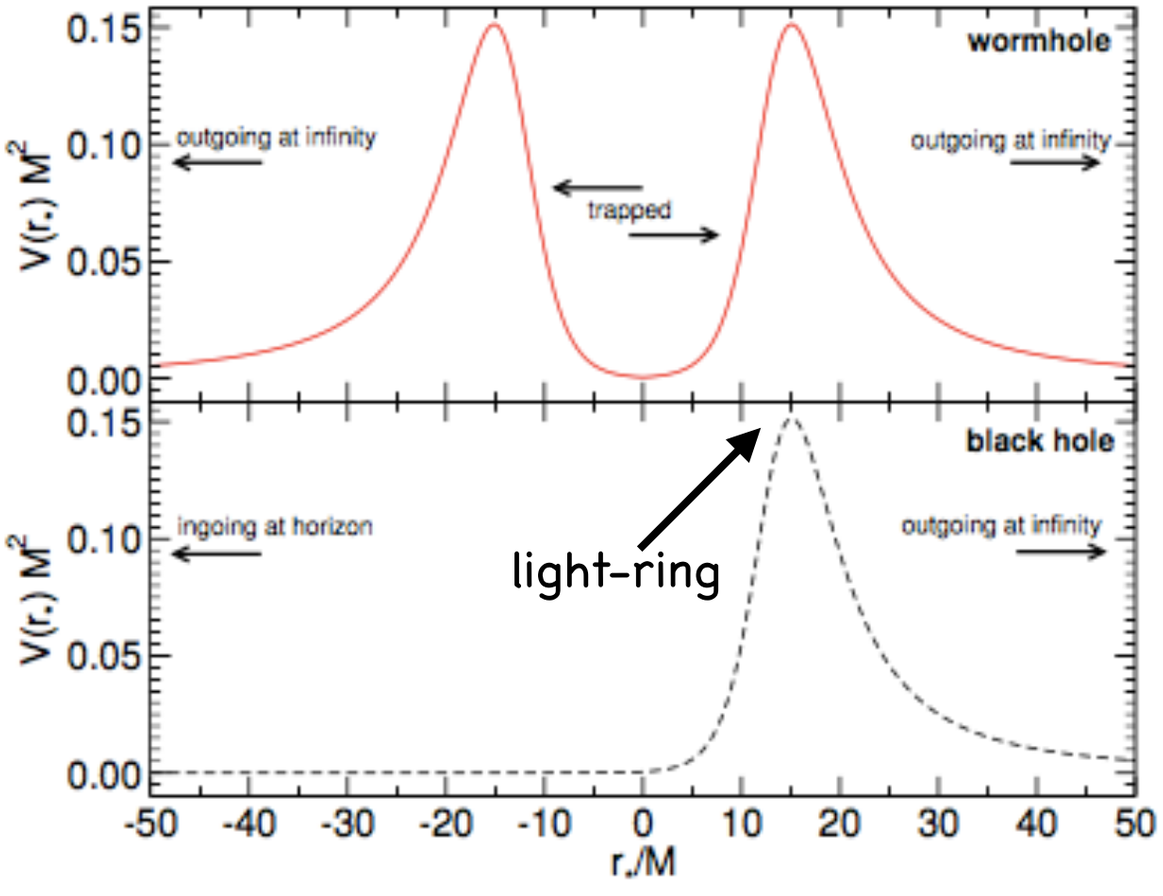


horizonless object

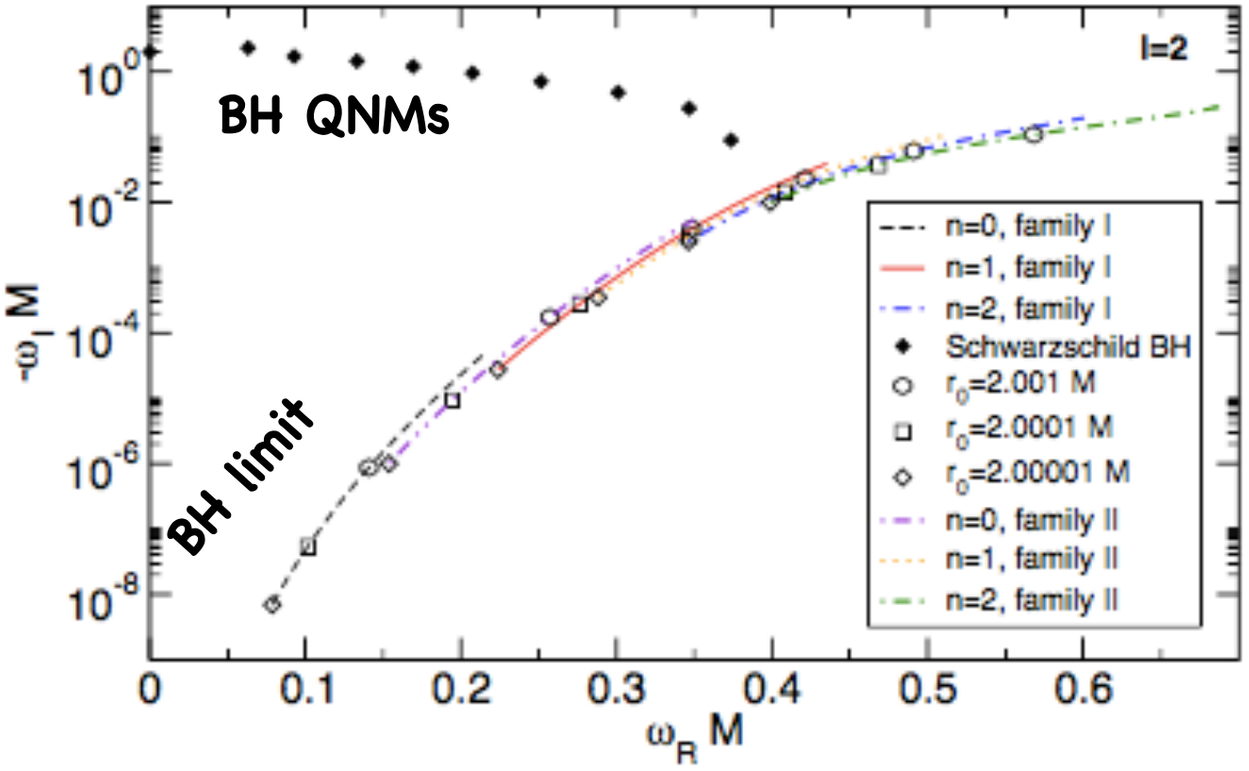


black hole

- **QNM** spectrum **dramatically different** between **BH** and **horizonless object.**
- **Frequency** determined by (inverse of) **size of cavity.**



- **QNMs** can be **very long lived.**



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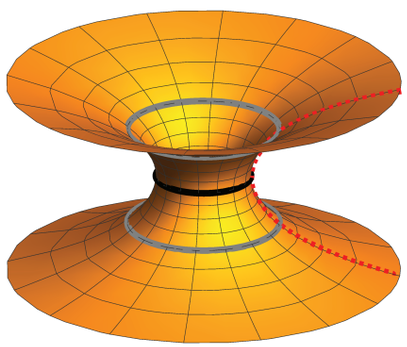

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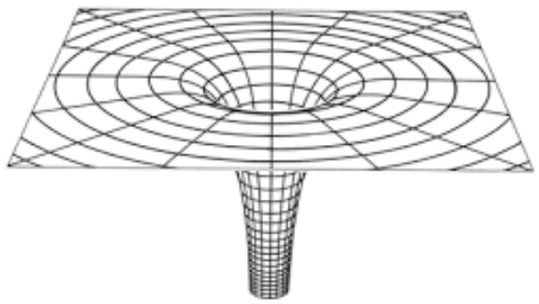


black hole

$$L = L_{\rm Planck} \sim 2 \times 10^{-33} {\rm cm}$$

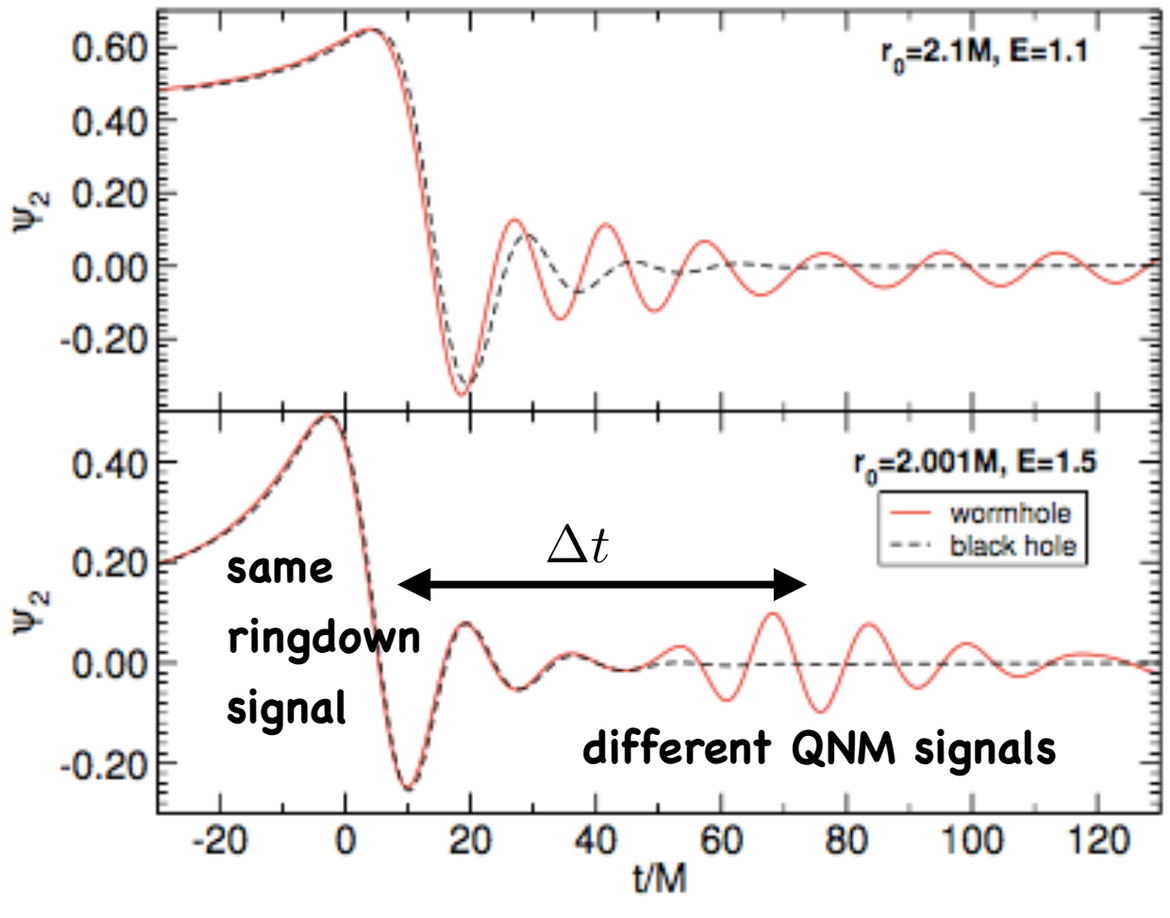
$$M \sim 60\, M_\odot$$

$$\Delta t \sim M\, \log\left(\frac{M}{L}\right)$$

$$\Delta t \sim \mathcal{O}(10\, {\rm msec})$$

- **Weak dependence on L**

- **QNM** spectrum **differs** in **BH** and **horizonless object.**
- **Ringdown** and **QNM** signals can be **different in horizonless objects: GW echoes!**



Bounding the graviton Compton wavelength (mass)

- A fully consistent **massive graviton** theory has not been worked out yet.

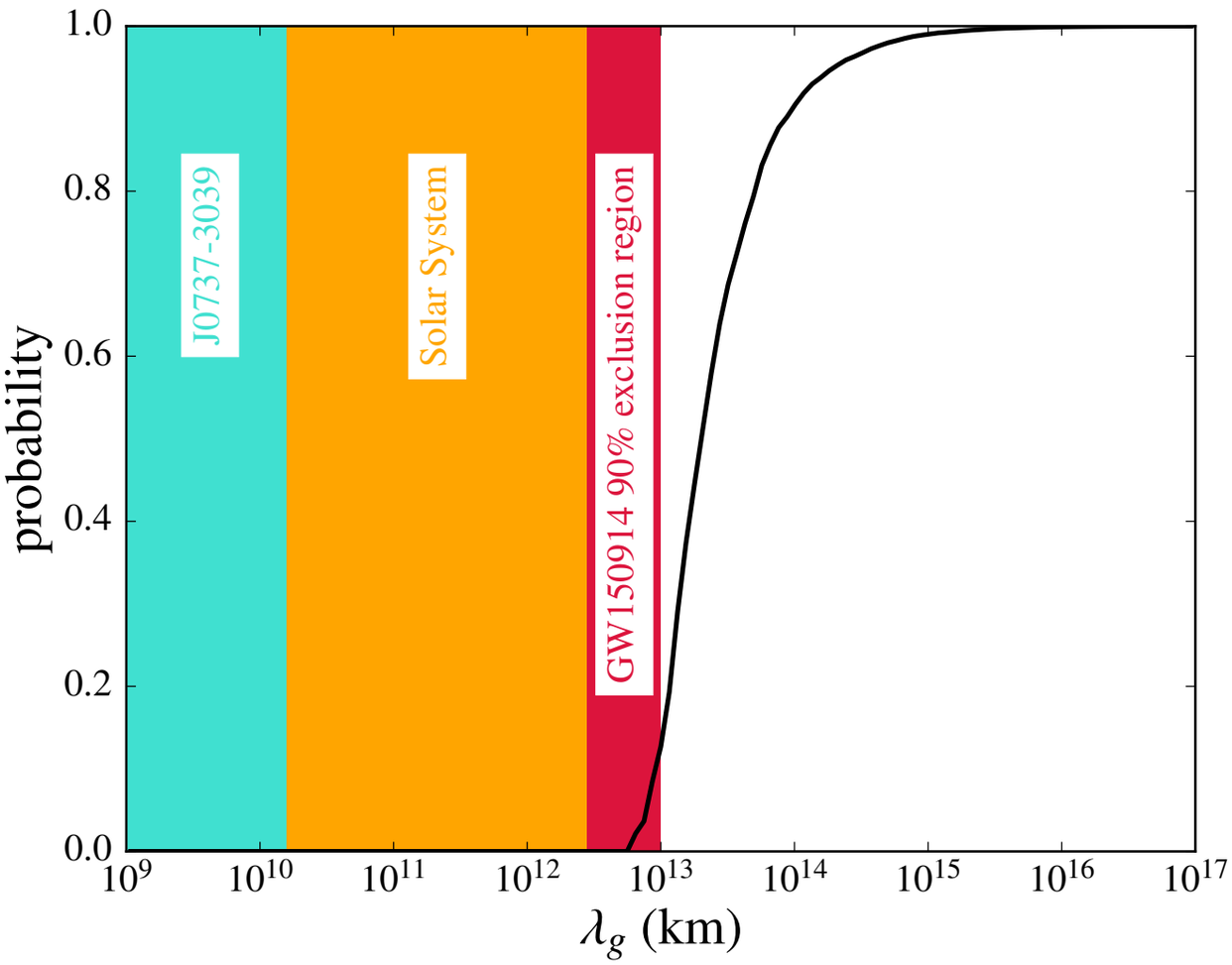
- Phenomenological approach: **modified dispersion relation**, thus GWs travel at speed different from speed of light. (Will 94)

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = \frac{h}{m_g c}$$

- **Lower** frequencies **propagate slower than higher** frequencies.

$$\frac{v_g^2}{c^2} = 1 - \frac{h^2c^2}{\lambda_g^2 E^2} \longrightarrow \varphi_{\rm MG} = -\frac{\pi D c}{\lambda_g^2 (1+z) f}$$

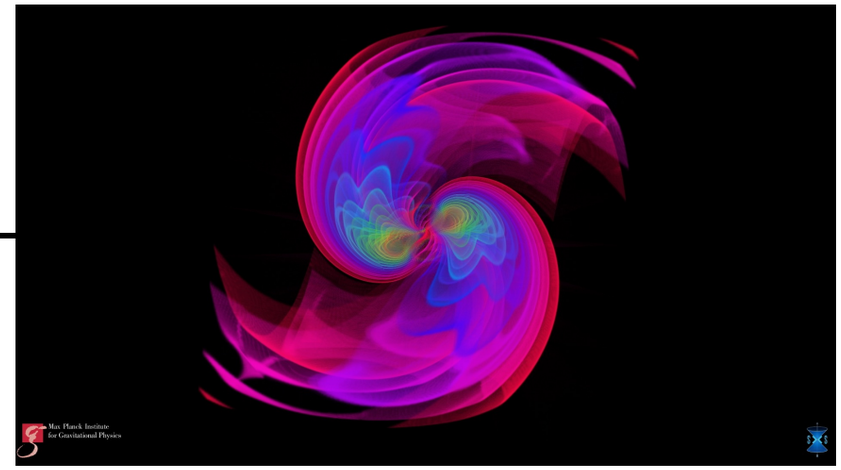
(Abbott et al. arXiv:1602.03841)



$$m_g \leq 1.2 \times 10^{-22} \mathrm{eV}/c^2$$

(see Yunes et al 16. for constraints on other dispersion relations, super- and sub-luminal GW propagation, Lorentz violation)

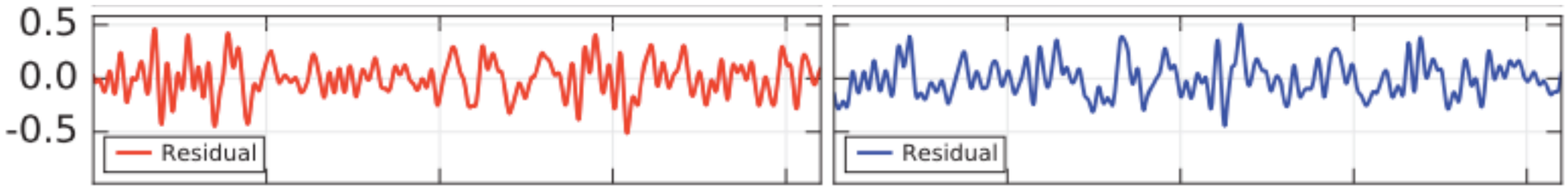
Discussion:



- What does it mean to **probe a "BH"**? **Dynamical or stationary** spacetimes?
- Can we **disprove** the **presence** of an "**horizon**"?
- Can we **probe quantum gravity** with binary **black hole mergers and post-merger signals?** Will **new** physical **scales be observable?**
- Can we **rule out exotic compact objects with ringdown** detections? Or with inspiral-merger observations? We need NR simulations of binaries composed of **exotic compact-objects**, such as boson stars, gravastars, etc.
- Is it possible to **parameterize GR** and **modified theories of GR** in terms of relevant physical parameters during the **non-perturbative merger-ring-down** stage?
- To rule out **modified theories of GR** we need **NR simulations** in: scalar-tensor theories, Einstein-Aether theory, dynamical Chern-Simons, Einstein-dilaton Gauss-Bonnet theory, massive gravity theories, etc.

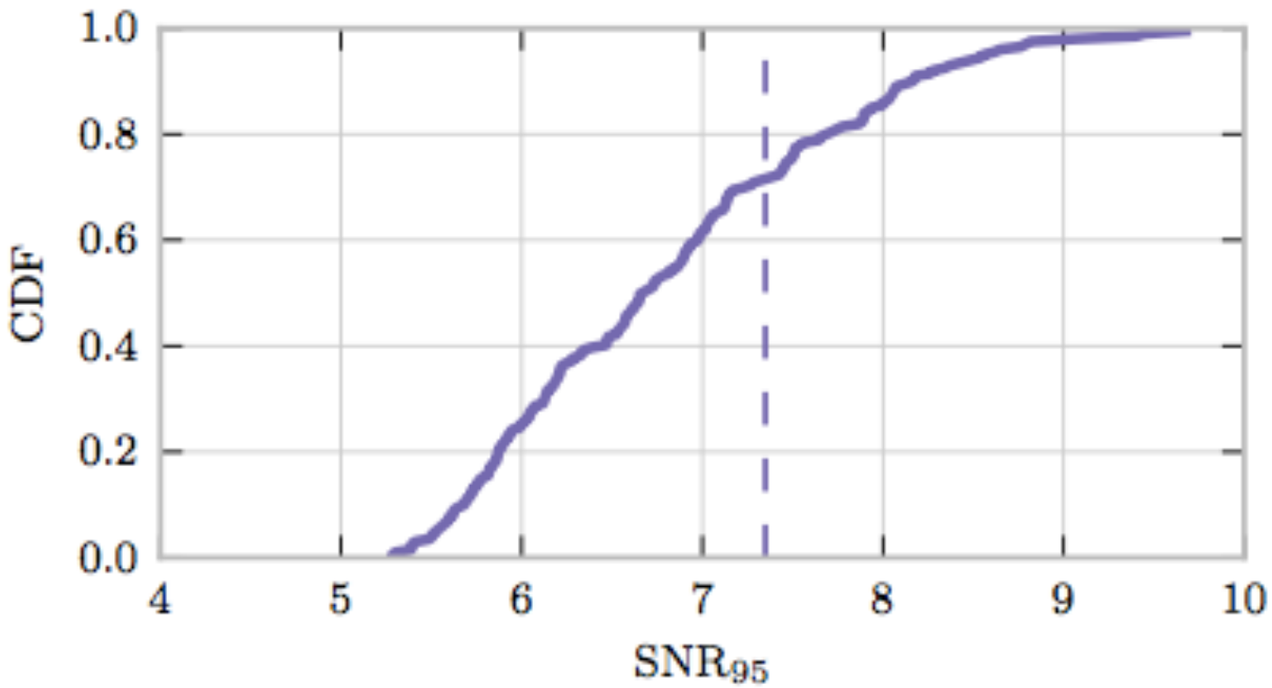
Residual consistent with instrumental noise

- Subtracting **best-fit GR waveform** model from data



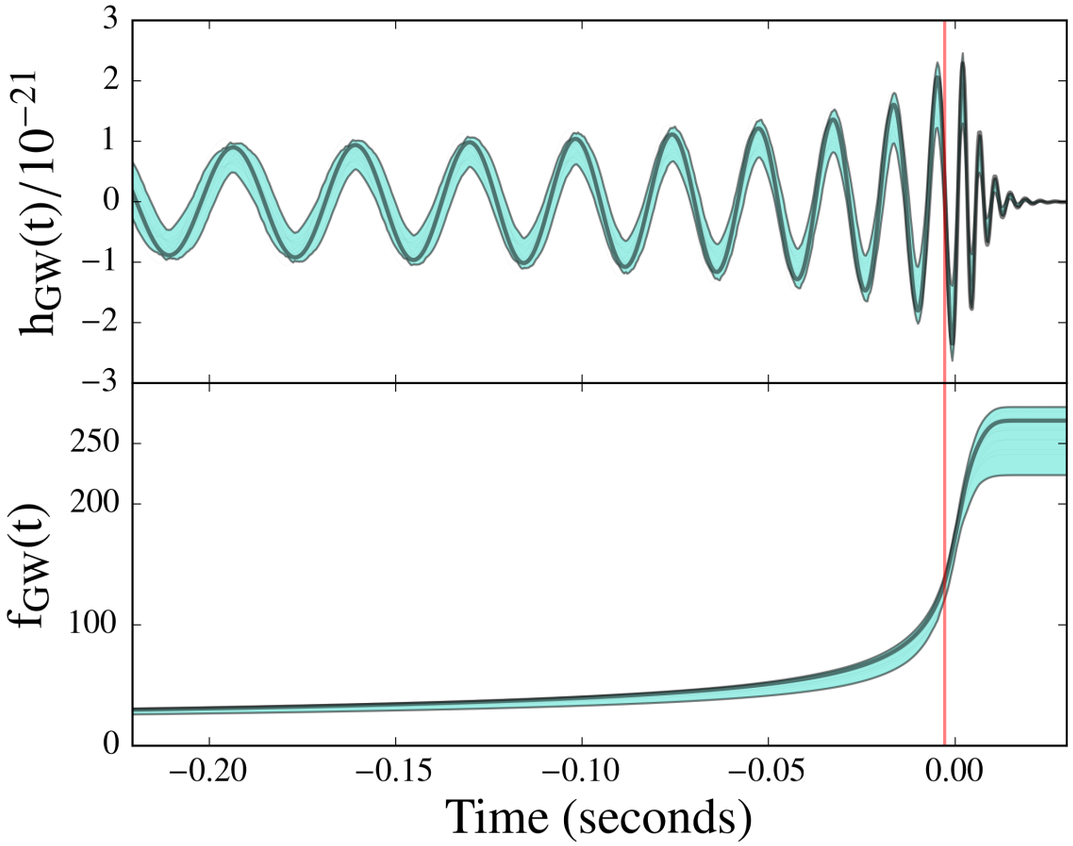
- 100 instrument-noise segments, 4sec long, within a few minutes of GW150914 were used to build a **distribution of coherent-burst SNRs**

- Coherent-burst **SNR of residual is typical** and **can be attributed to instrument noise** alone



- For GW150914 & GW151226, **systematics smaller than statistical** errors.

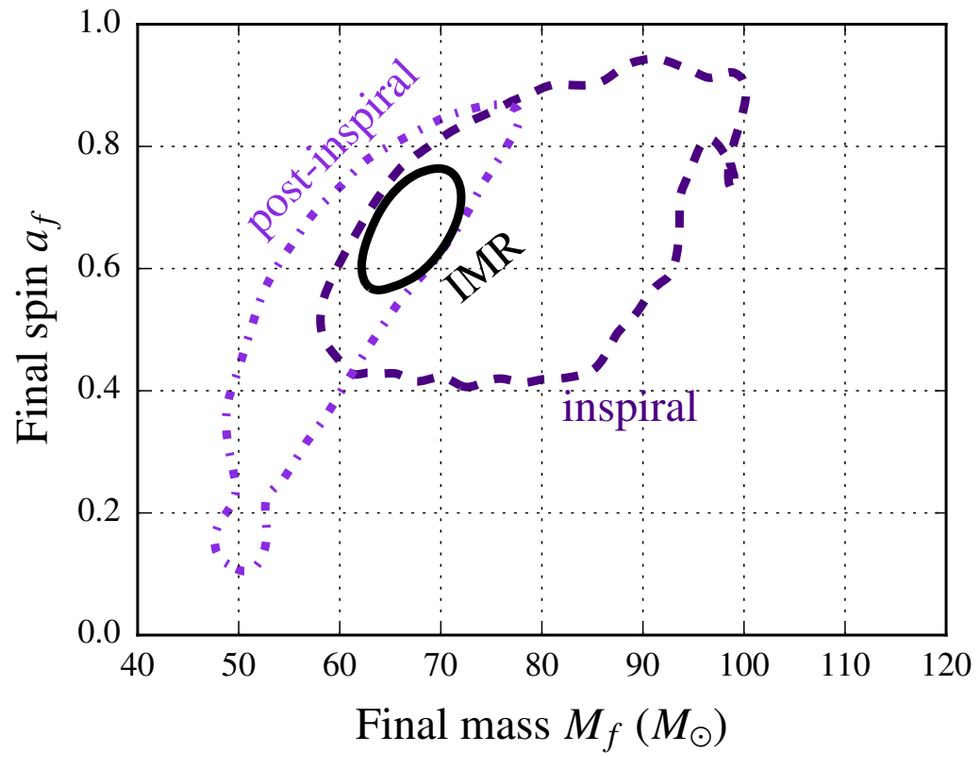
Inspiral-merger-ringdown consistency test with GW150914

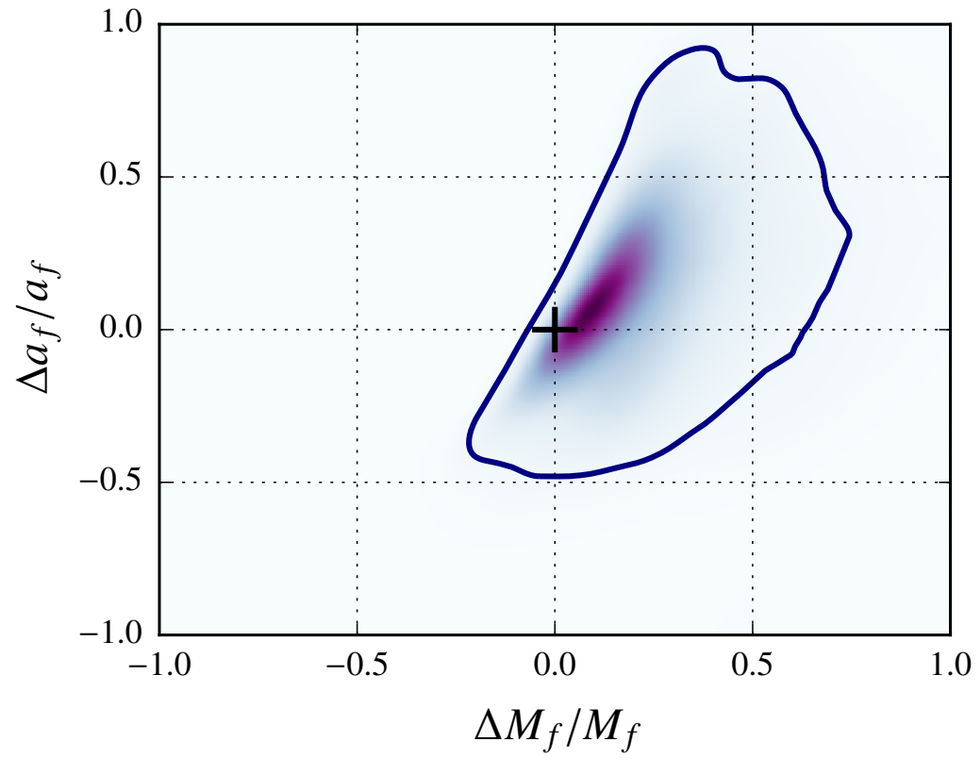


(Abbott et al. arXiv:1602.03841)

- **Using NR formulae** and **posterior distributions**, final black-hole's mass and spin are related to those of binary from which it formed.

- **Remnant's mass** and **spin** determined **from inspiral agree** with those from **post inspiral**

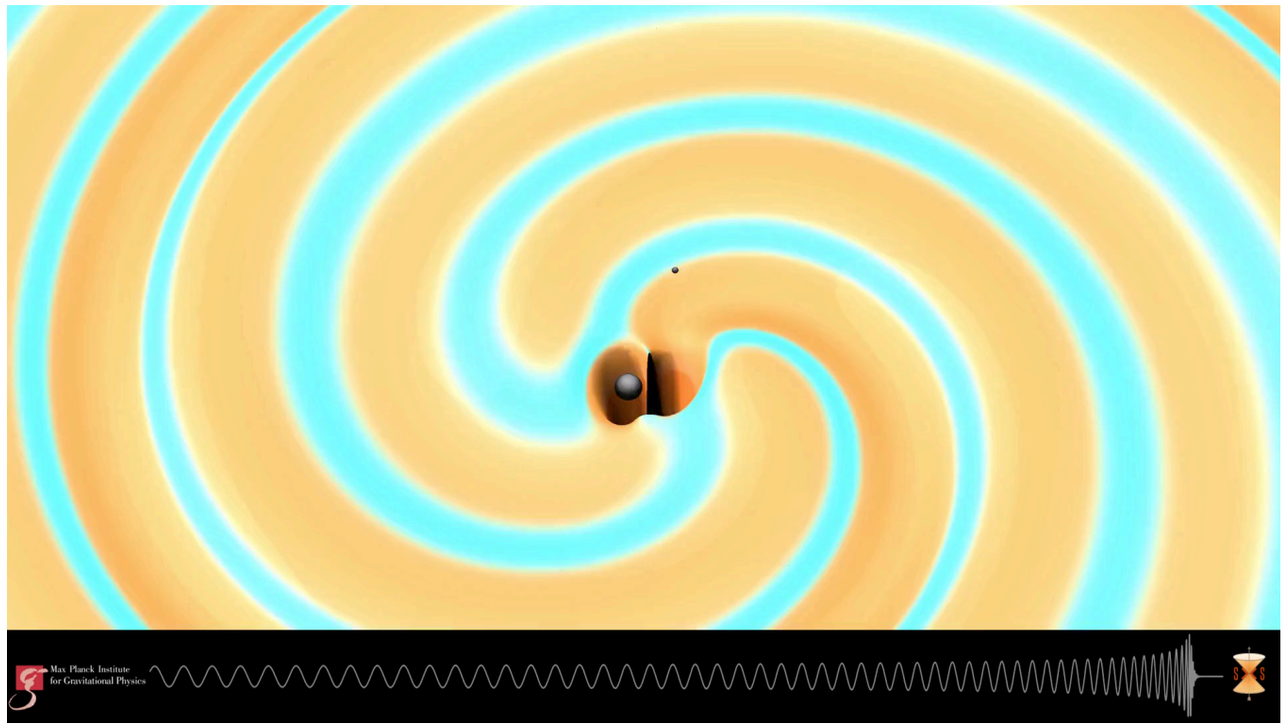




Are systematics in GR waveform models under control?

(visualization credit: Dietrich, Haas)

(Ossokine, AB & SXS project)



(Abbott et al. PRL 116 (2016) 241103)