Crashing black holes and poking at their merger remnants

Cecilia Chirenti

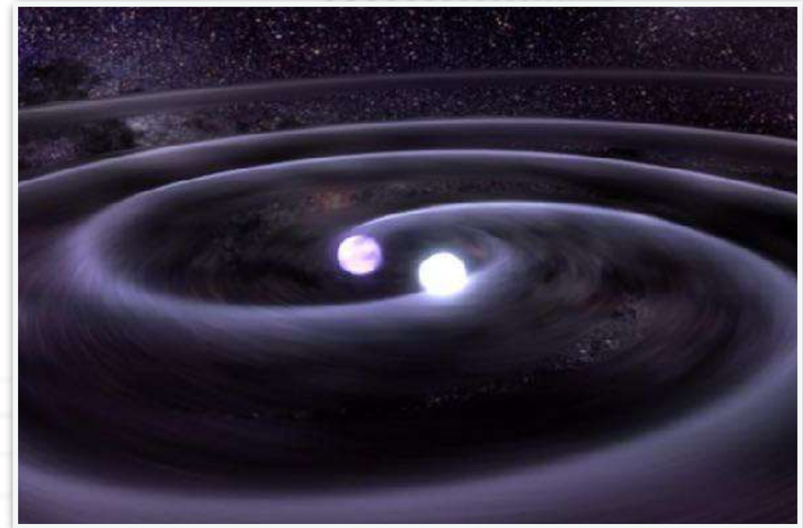
Based on:

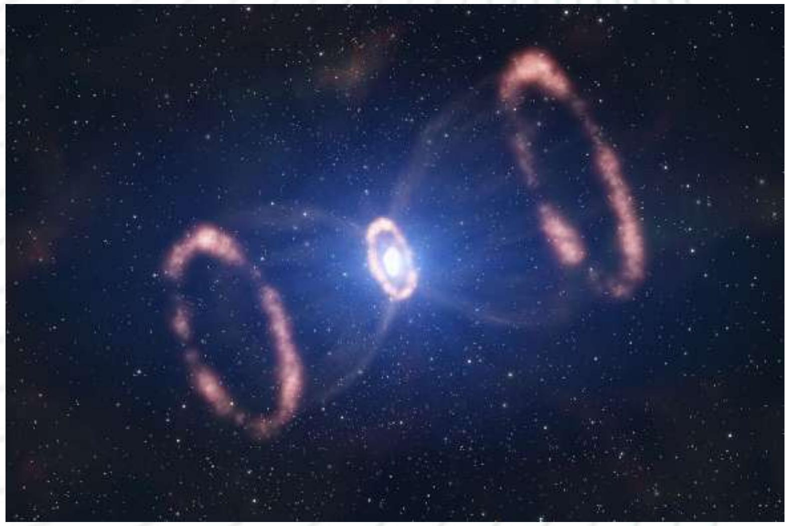
Ota & Chirenti, Phys. Rev. D 101, 104005 (2020);

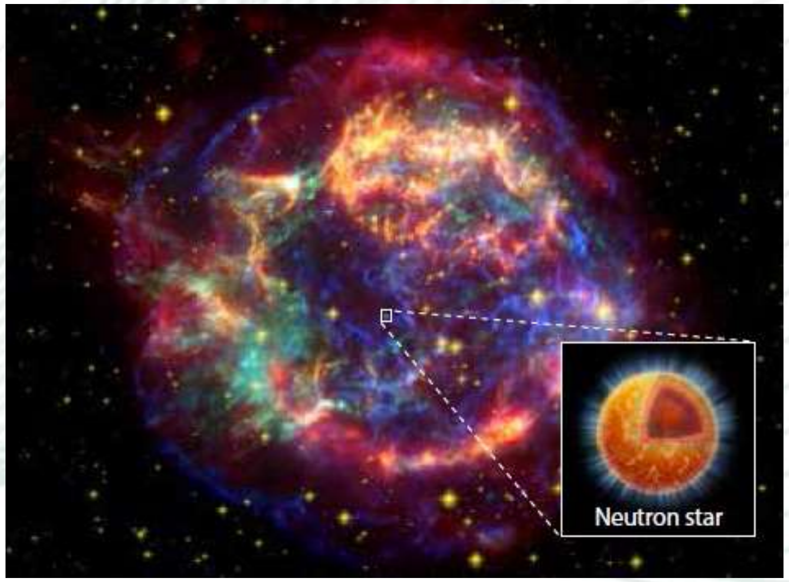
Ota & Chirenti, arXiv:2108.01774

Gravity Seminar, STAG Research Centre, December 16 2021

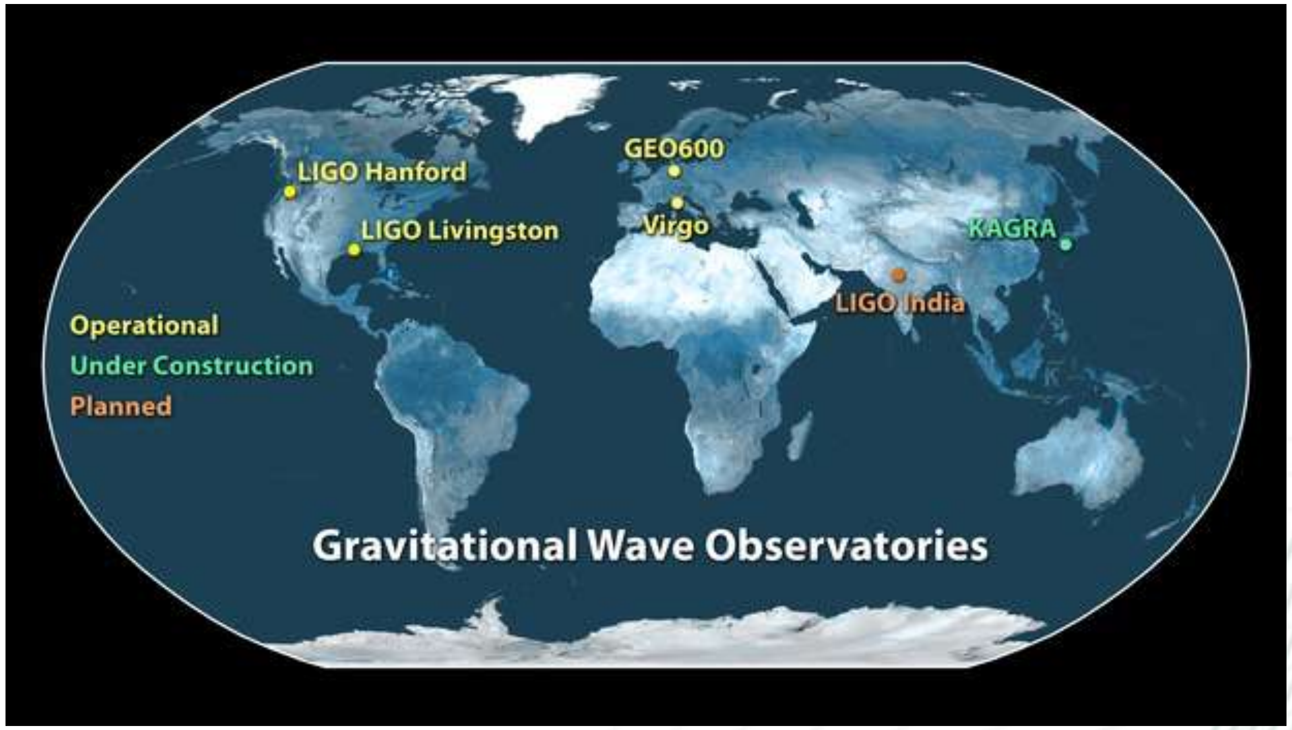
Possible gravitational wave sources…

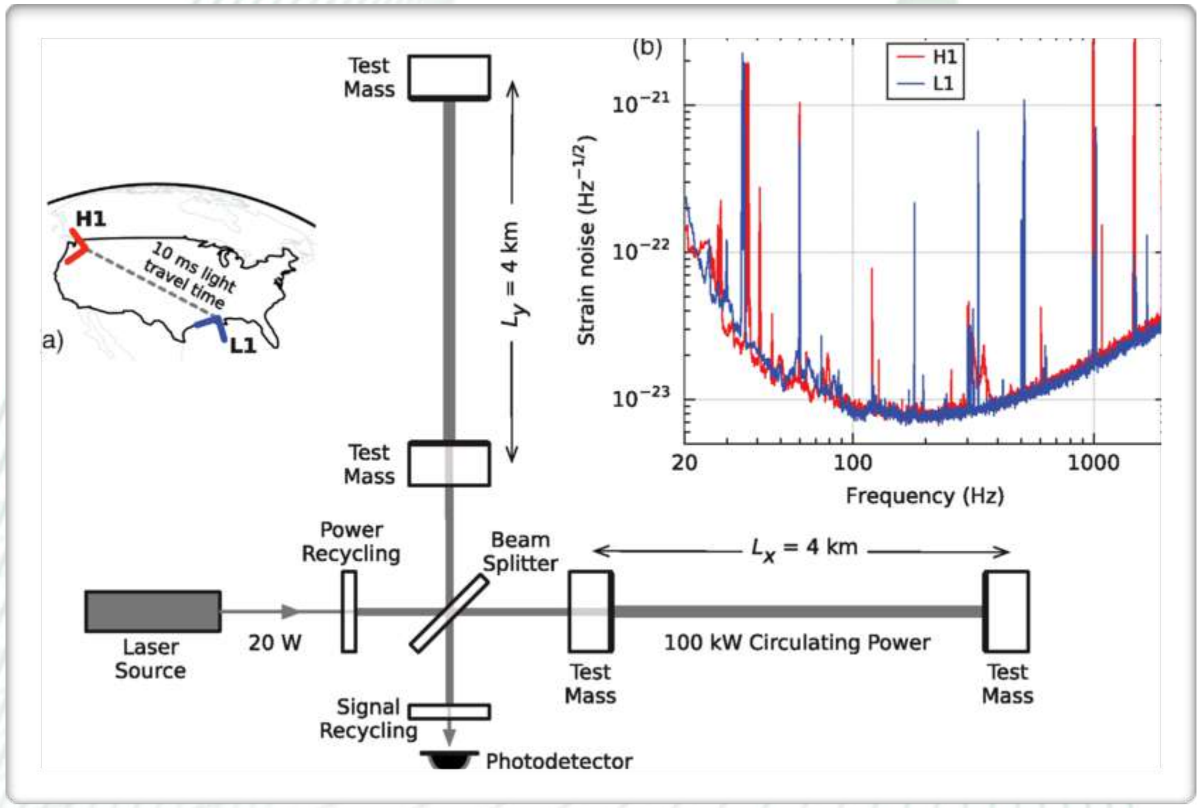


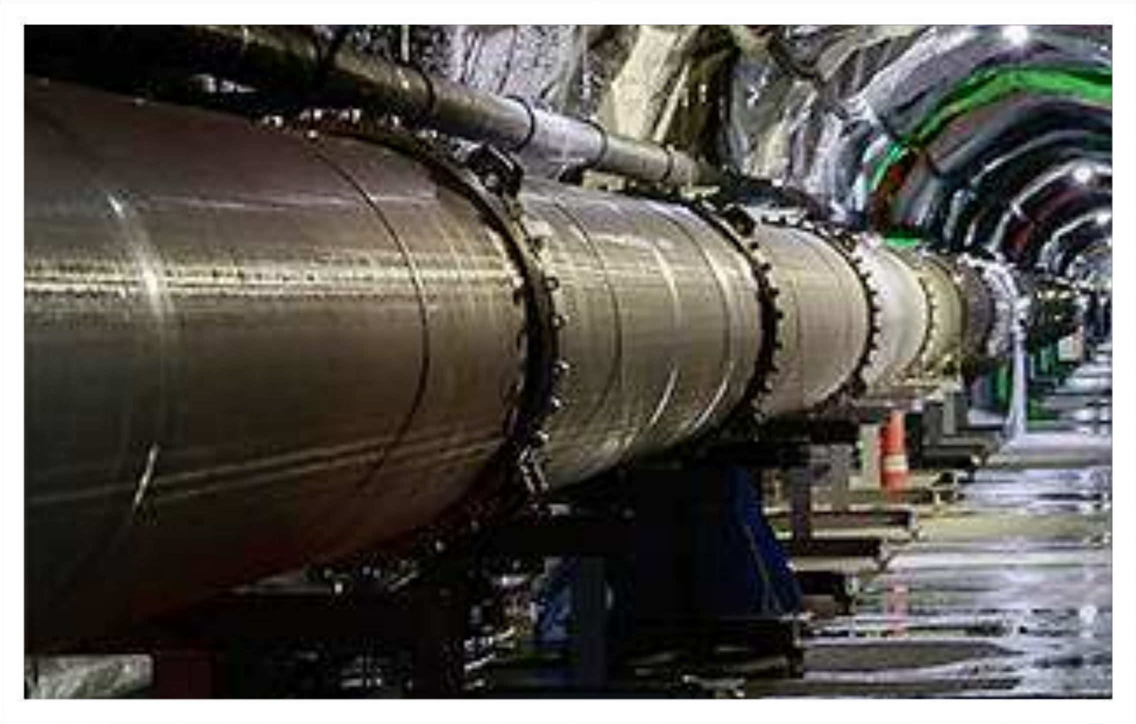




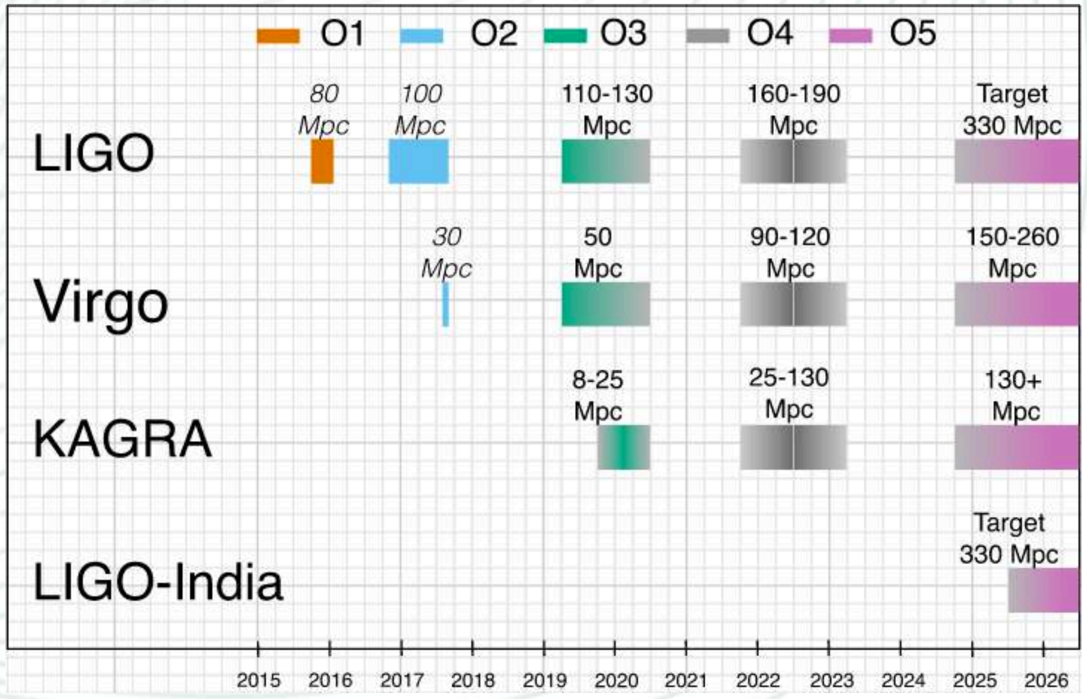
… and current gravitational wave detectors







KAGRA



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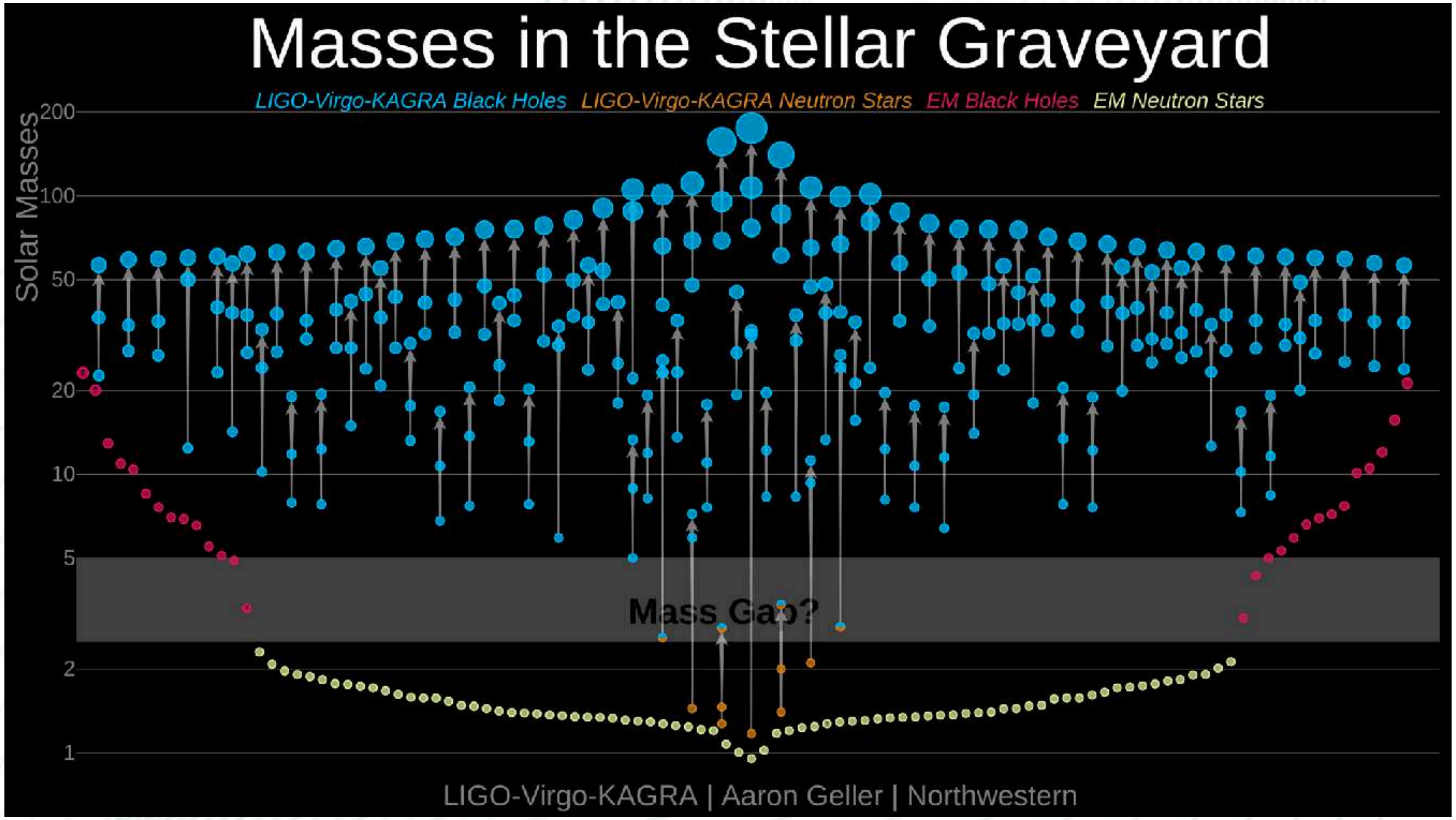
Gravitational waves from compact binary coalescences

Astrophysical questions about black holes:

are there mass gaps?

how (and where) are the binaries formed?

existence of intermediate mass black holes?



Are there fundamental physics questions we can ask (and hopefully answer) about black holes?

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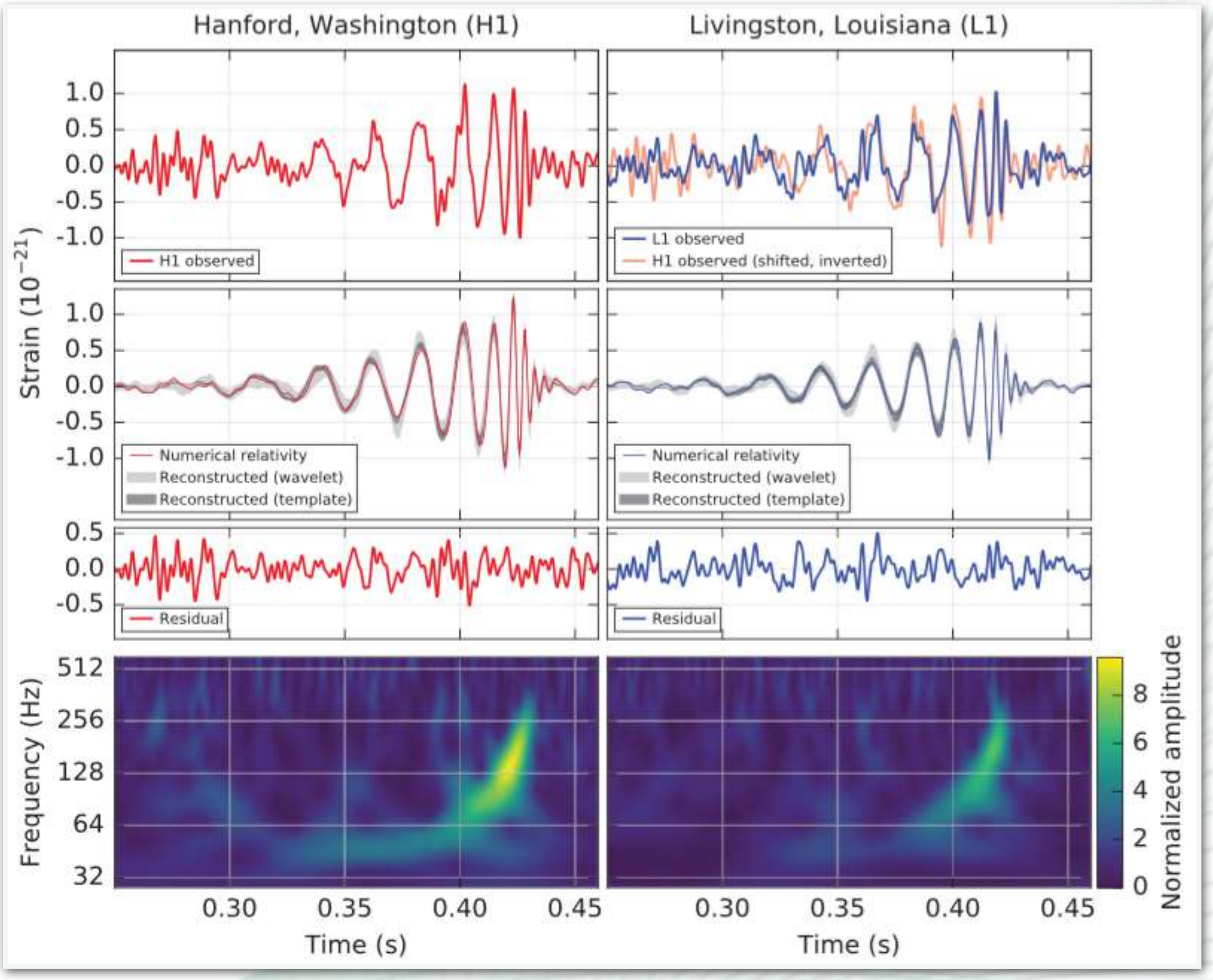
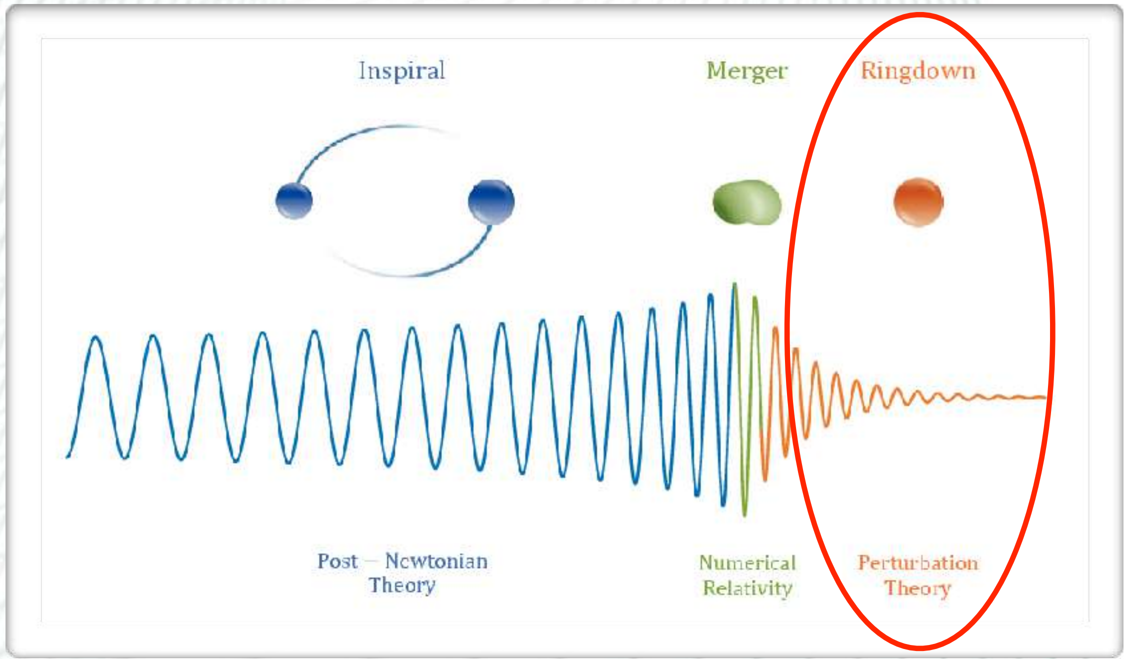
Binary Black Hole Waveform: Inspiral-Merger-Ringdown

First Detection
GW150914



[Abbott et al., 2016]

3 stages:



[Antelis et al. 2016]

The ringdown can be well approximated by the *quasinormal modes* of the system

Linear Perturbation Theory in General Relativity

Perturbed black holes are basically mass-spring systems!

Einstein field equations:

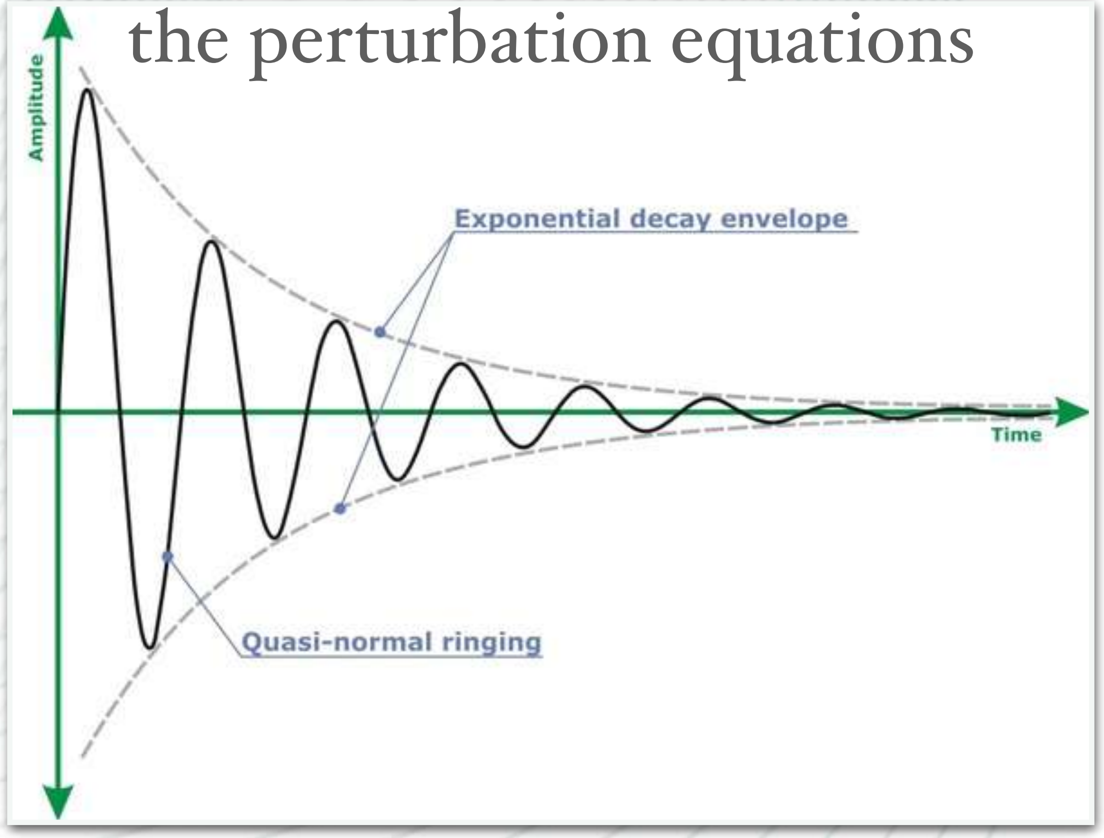
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi T_{\mu\nu}$$

In vacuum*: $R_{\mu\nu} = 0$

Perturbing it:

$$R_{\mu\nu} + \delta R_{\mu\nu} = 0 \Rightarrow \delta R_{\mu\nu} = 0$$

quasinormal modes are solutions of the perturbation equations



For a rotating black hole, this results in the Teukolsky equation.

*what about environmental effects? [Jaramillo, Macedo & Sheikh, 2021]

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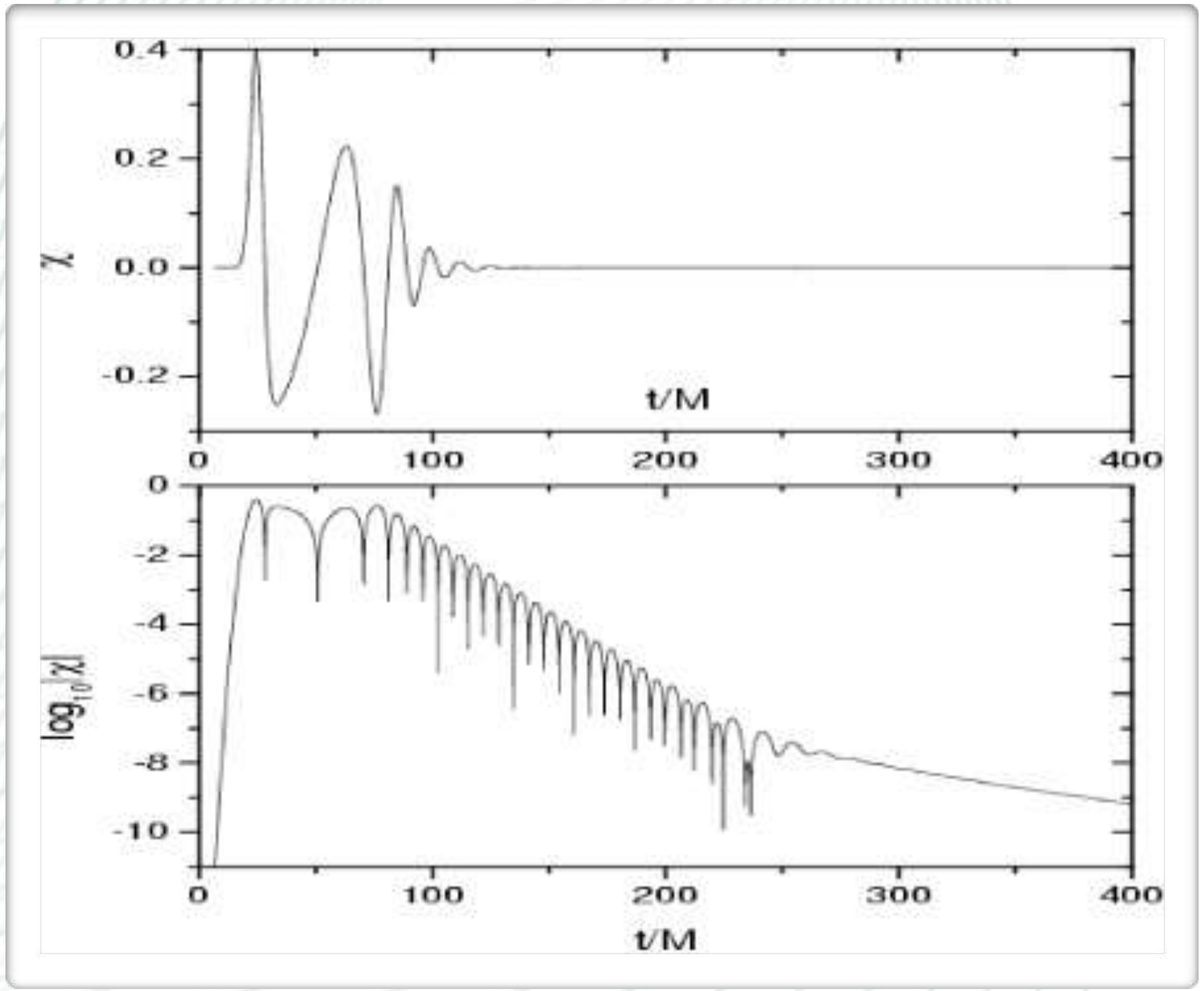
Quasinormal modes

- Characteristic modes of oscillation [Vishveshwara, 1970]
- Independent of the initial perturbation: "fingerprint" from the source
- Infinite countable set of modes, but do not form a complete set
- Linear perturbation stability analysis
- Solution of the Teukolsky eq. with appropriate boundary conditions:
    - outgoing at infinity
    - ingoing at the horizon

[Teukolsky, 1973; Andersson, 1997]



[Kokkotas & Schmidt, 1999]

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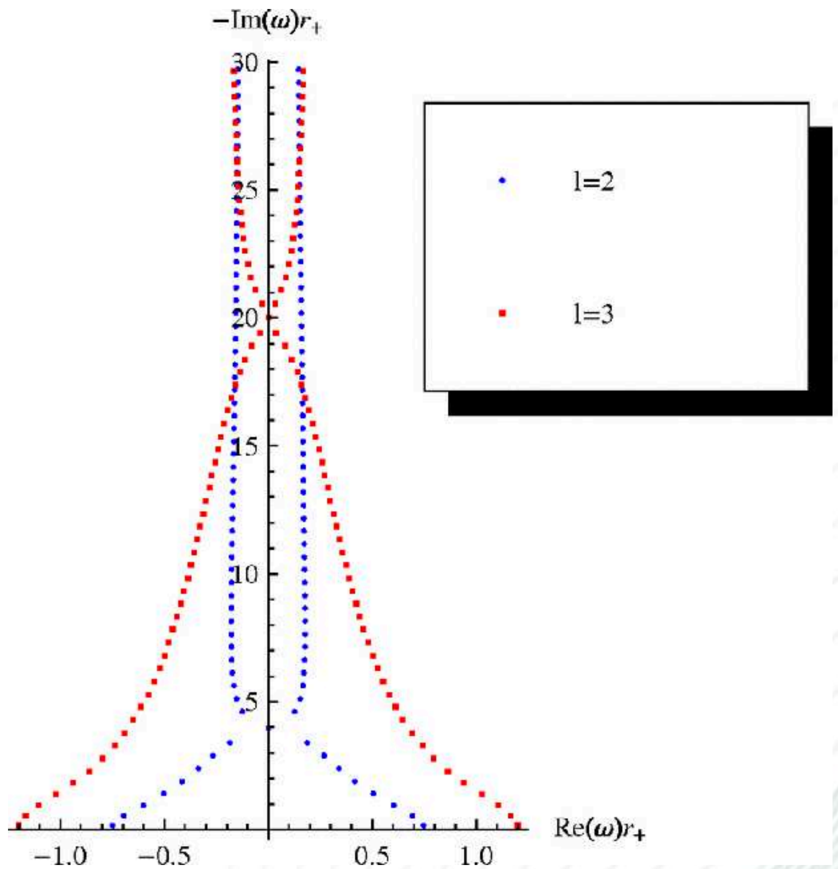
The no-hair theorem

First quasinormal modes for the Schwarzschild black hole



[Konoplya and Zhidenko, 2011]

overtones ($n > 0$) damp faster!

Isolated black holes and their surrounding spacetime can be described by only 3 numbers. Astrophysically, only 2 are relevant!

In the ringdown, quasinormal mode frequencies depend only on M and a (if GR is the correct theory of gravity)

$$\psi_{\ell m} = \sum_n A_{\ell mn} e^{i[\omega_{\ell mn}(t-t_i)+\phi_{\ell mn}]}$$

$$\omega_{\ell mn} \equiv \omega^r_{\ell mn} + i\omega^i_{\ell mn}$$

Alternative models may have extra hair

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The no-hair theorem

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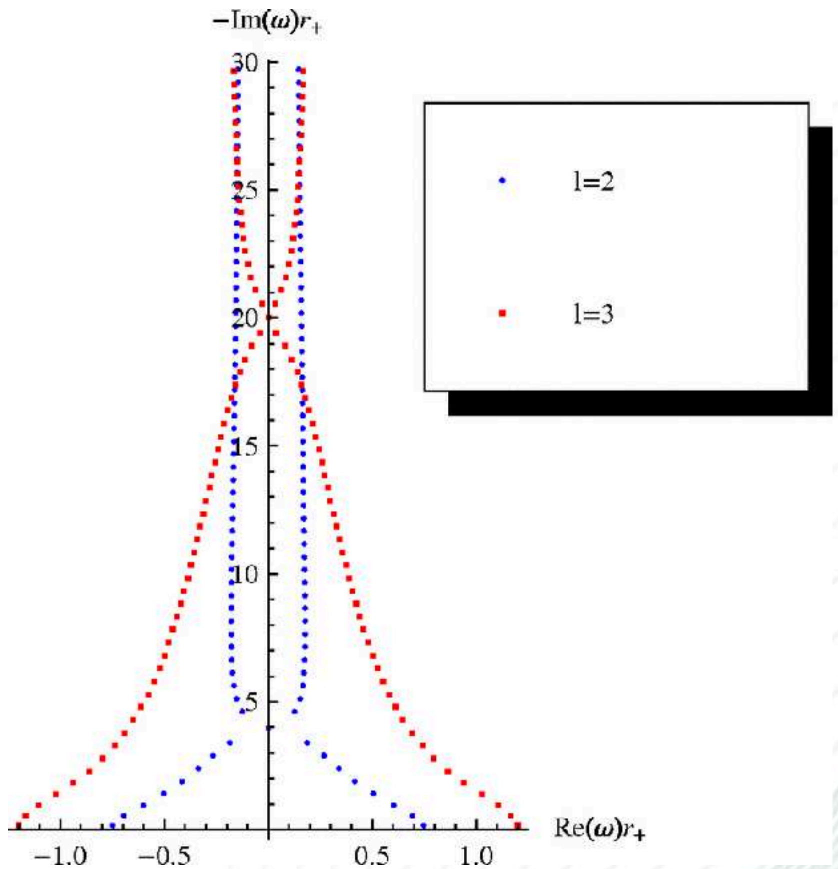

[Konoplya and Zhidenko, 2011]

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initial conditions

start of the linear regime

$$\omega_{\ell mn} \equiv \omega^r_{\ell mn} + i\omega^i_{\ell mn}$$

theory

Alternative models may have extra hair

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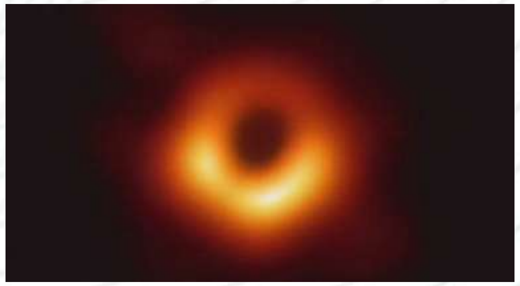
Black hole alternatives

If we aren't detecting black holes, but something that looks very similar instead...

- Non-singular black holes, black hole mimickers, exotic compact objects, etc

- What are the (possible) problems with the standard black hole model? Quantum gravity considerations?

- Why bother? Haven't we already seen evidence that black holes exist?



[EHT]

- Another motivation: is it possible to give irrefutable proof of the existence of the event horizon? [Abramowicz et al., 2002]

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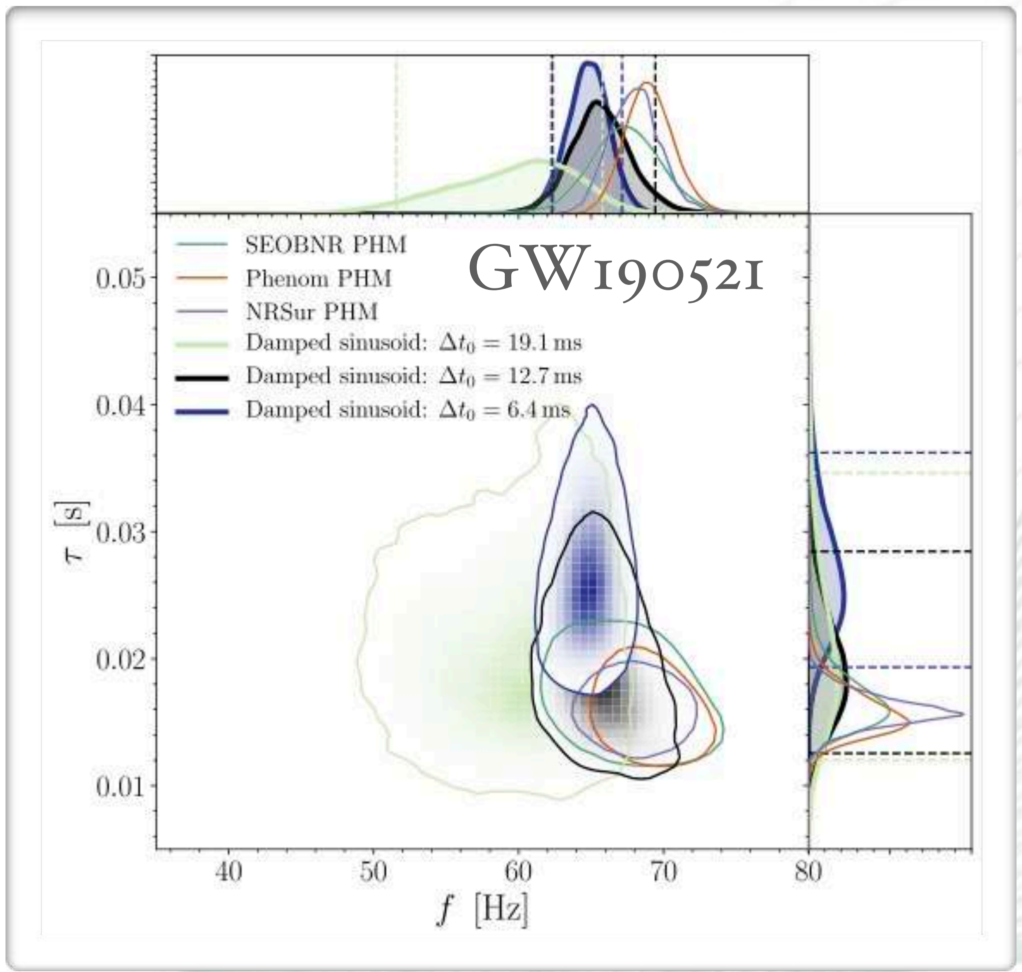
Detecting Ringdowns

For some of the heaviest + strongest GW events, the frequency is low enough and the signal is strong enough that

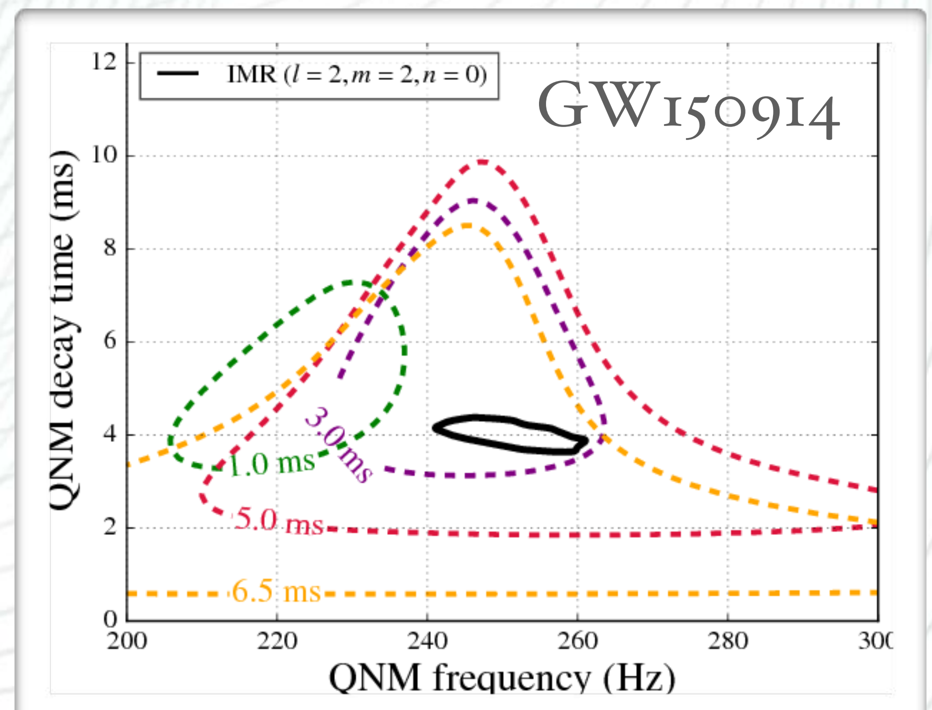
it is already possible to determine the frequency and damping time of the fundamental mode (2,2,0) in the ringdown

$$\psi_{22} \sim A_{220} e^{i[\omega_{220}(t-\Delta t_0)+\phi_{220}]}$$

Δt_0 : is the starting time of the ringdown



[Abbott et al., 2020]



[Abbott et al., 2016]

but this is not a test of the no-hair theorem!

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Testing the no-hair theorem

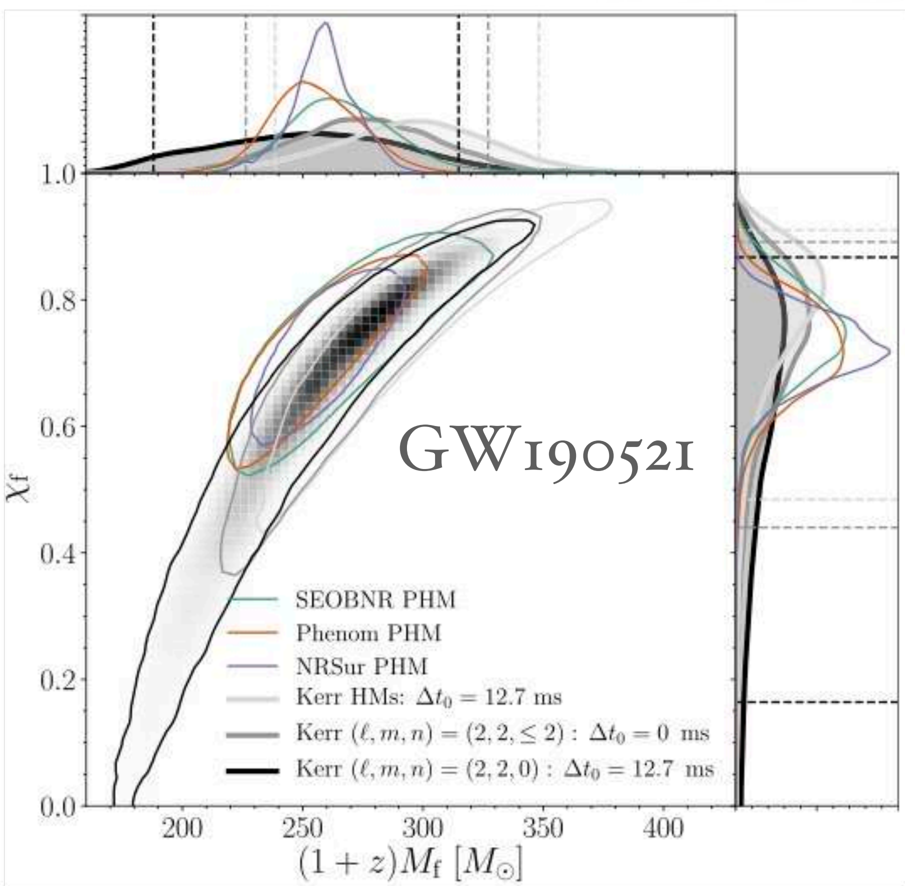
or: can we detect more than one mode?

Black hole spectroscopy

[Dreyer et al., 2004; Berti et al., 2006]

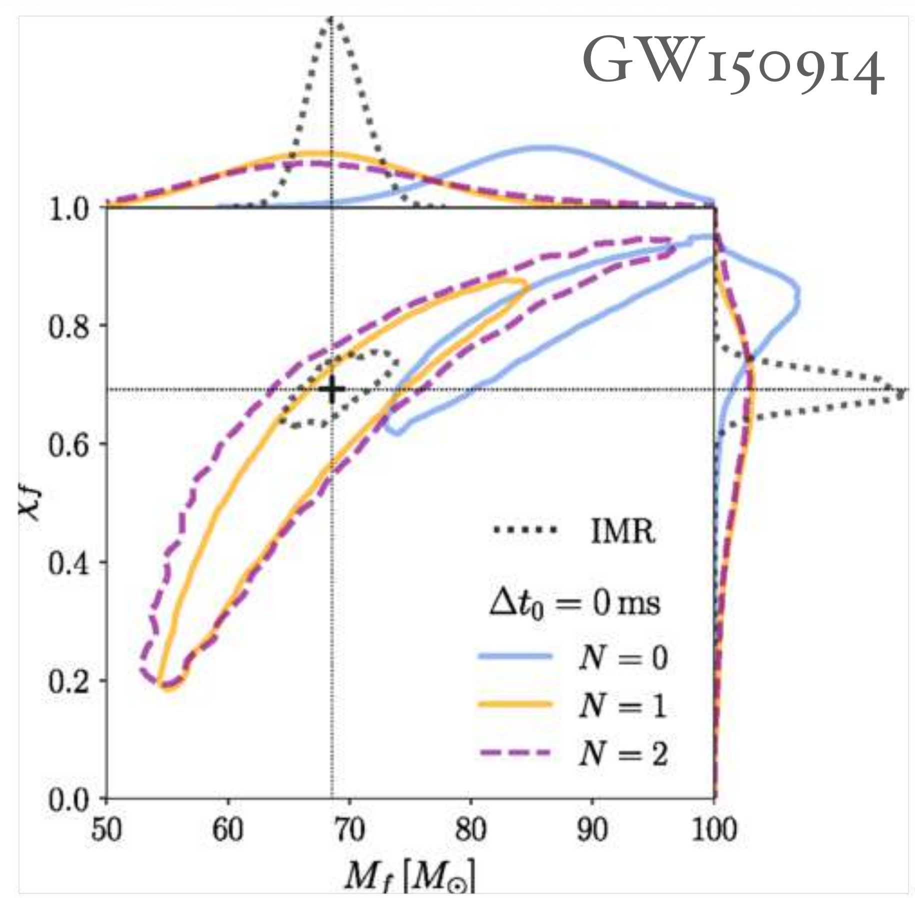
"no strong evidence in favor of the presence of higher multipoles or overtones"

evidence for the (2,2,1) overtone?



[Abbott et al., 2020]

in both cases: $\Delta t_0 = 0$



[Isi et al., 2019]

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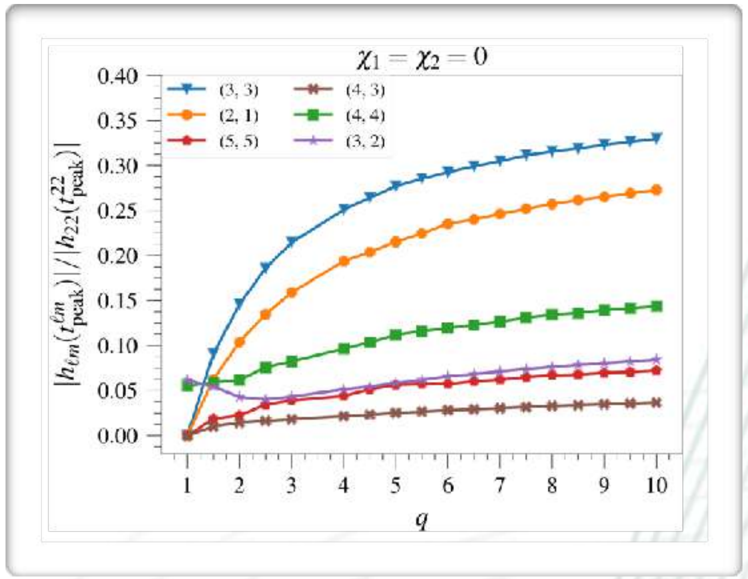
Looking for a second mode

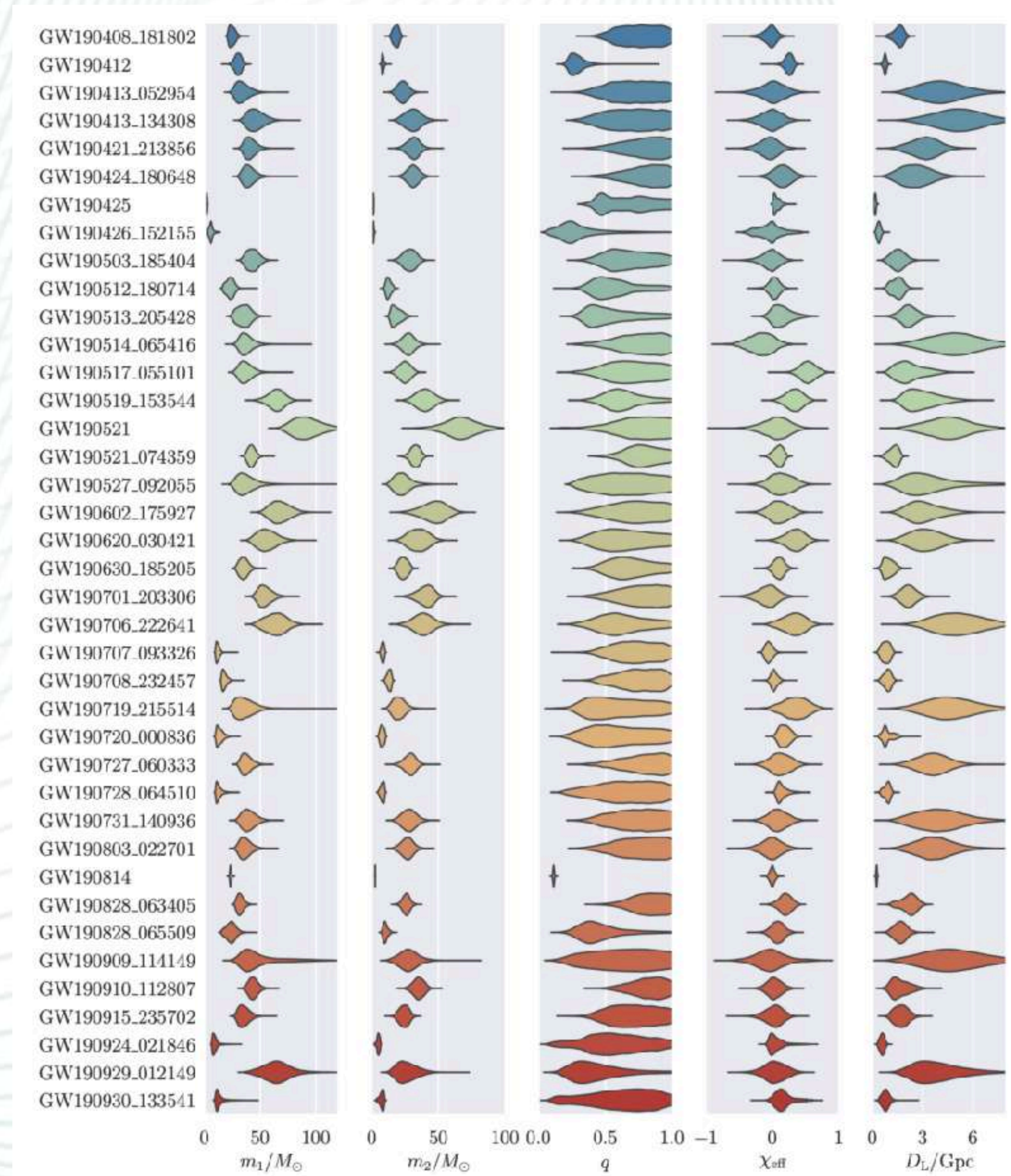
Looking for **higher harmonics**

$(l, m, 0) \neq (2,2,0)$



[Cotesta et al., 2018]

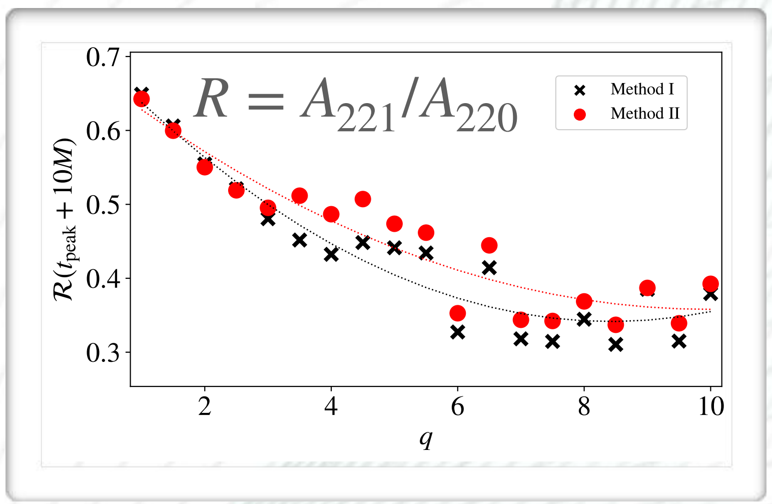
higher harmonics are more relevant for **unequal** mass binaries



[Abbott et al., 2020]

Looking for **overtones**

$(l, m, n) = (2,2,1)$



[Ota and Chirenti, 2020]

See also: [Giesler et al., 2019] [Bhagwat et al., 2020] [Forteza et al., 2020] and others

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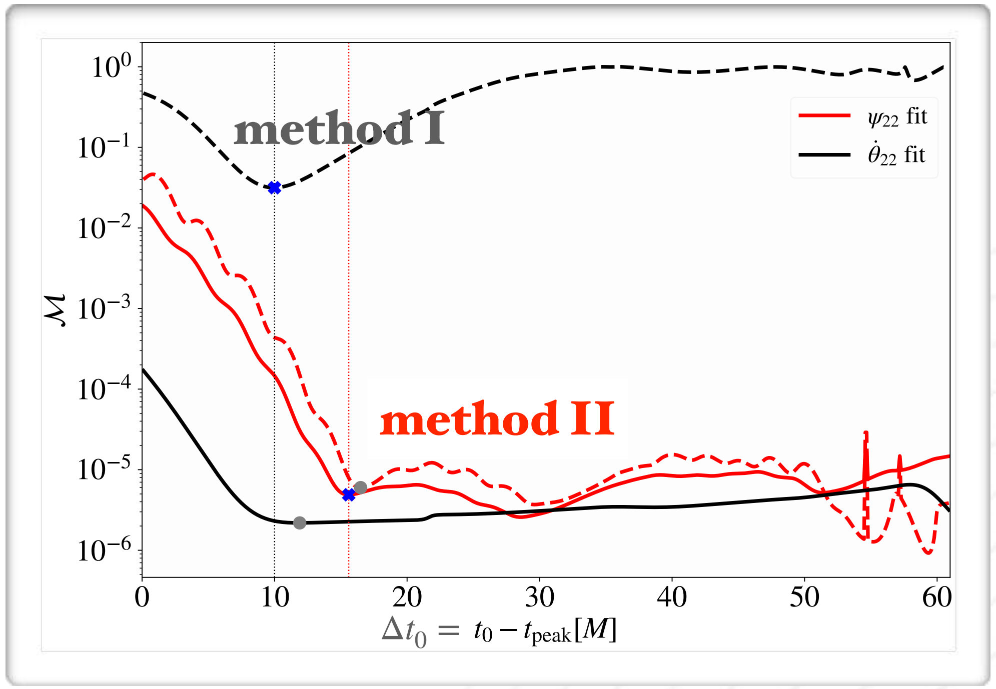
Methods I and II



method II: full waveform

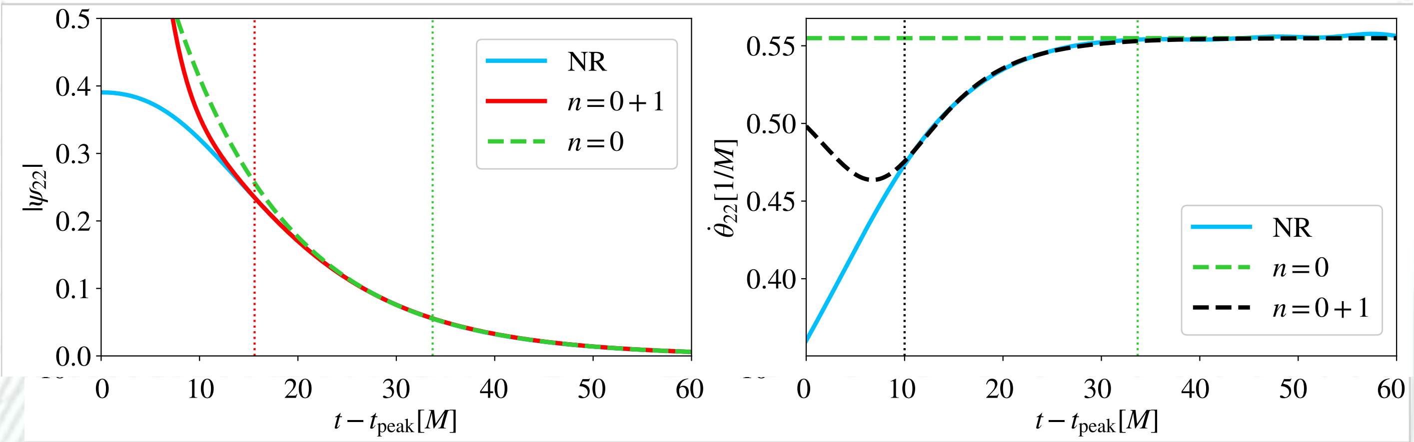
4-parameter fit:

$A_{220}, A_{221}, \phi_{220}, \phi_{221}$

method I: phase derivative

2-parameter fit:

$R \equiv A_{221}/A_{220}, \phi \equiv \phi_{220} - \phi_{221}$



[Ota and Chirenti, 2020]

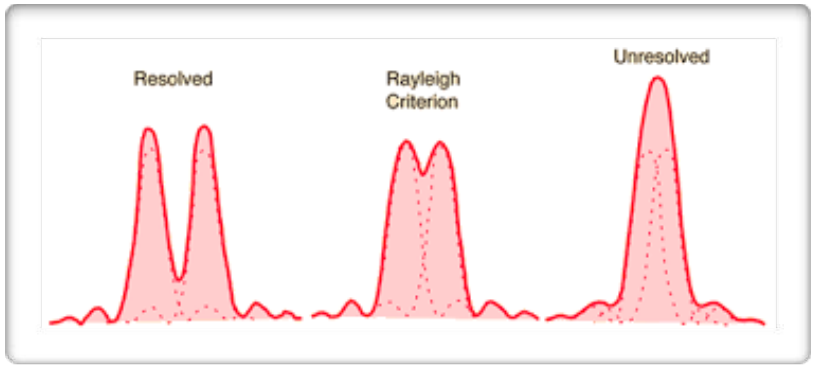
Mismatch $\mathcal{M} = 1 - \frac{\langle f_{NR}, f_{fit}\rangle}{\sqrt{\langle f_{NR}, f_{NR}\rangle \langle f_{fit}, f_{fit}\rangle}}$

with 2 choices $\langle f_1, f_2\rangle_{\text{standard}} \equiv \left| \int_{t_0} f_1^* f_2 dt \right|$ or $\langle f_1, f_2\rangle_{\text{energy}} \equiv \left| \int_{t_0} (\dot f_1)^* \dot f_2 dt \right|$

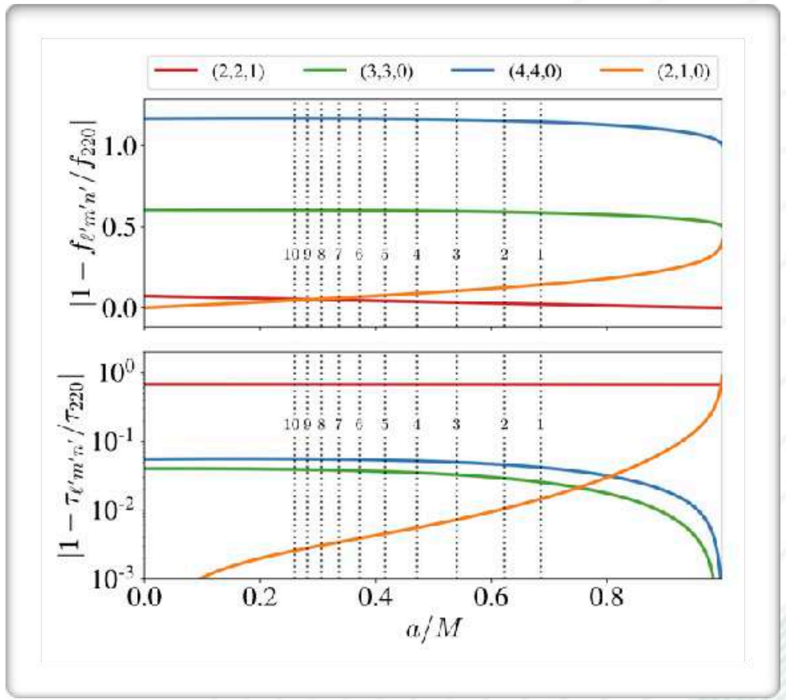
(solid line) (dashed line)

Rayleigh criterion

(an either/or criterion)



[hyperphysics.phy-astr.gsu.edu]



[Ota and Chirenti, 2021]

Detectability is not enough!

We require resolvability of both f and τ

$$\Delta f_{220,\ell mn} \equiv |f_{220} - f_{\ell mn}| > \max(\sigma_{f_{220}}, \sigma_{f_{\ell mn}})$$

$$\Delta \tau_{220,\ell mn} \equiv |\tau_{220} - \tau_{\ell mn}| > \max(\sigma_{\tau_{220}}, \sigma_{\tau_{\ell mn}})$$

for an independent test of the no-hair theorem

[Berti et al., 2006]

for the overtone, damping times are more easily resolved: $f_{220} \sim f_{221}$

for the higher harmonics, frequencies are more easily resolved: $\tau_{220} \sim \tau_{\ell m0}$

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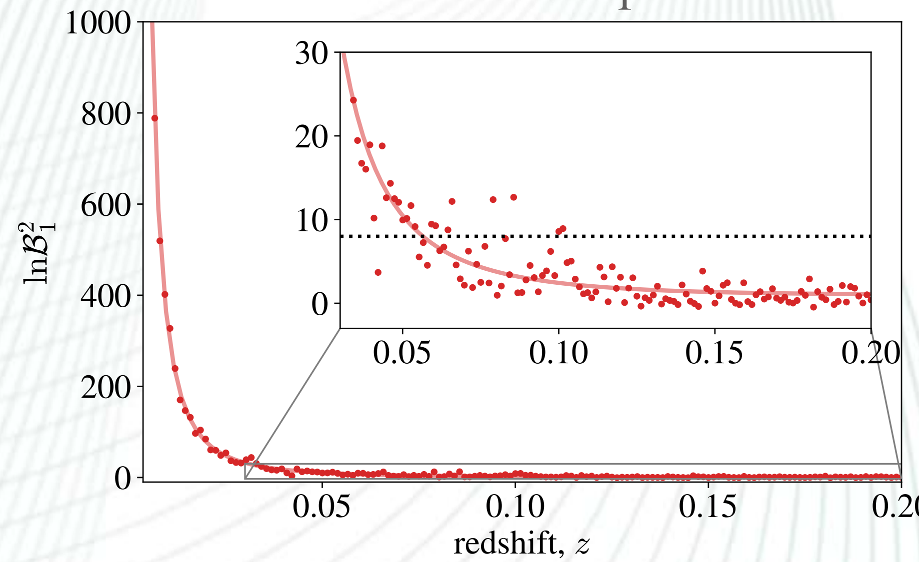
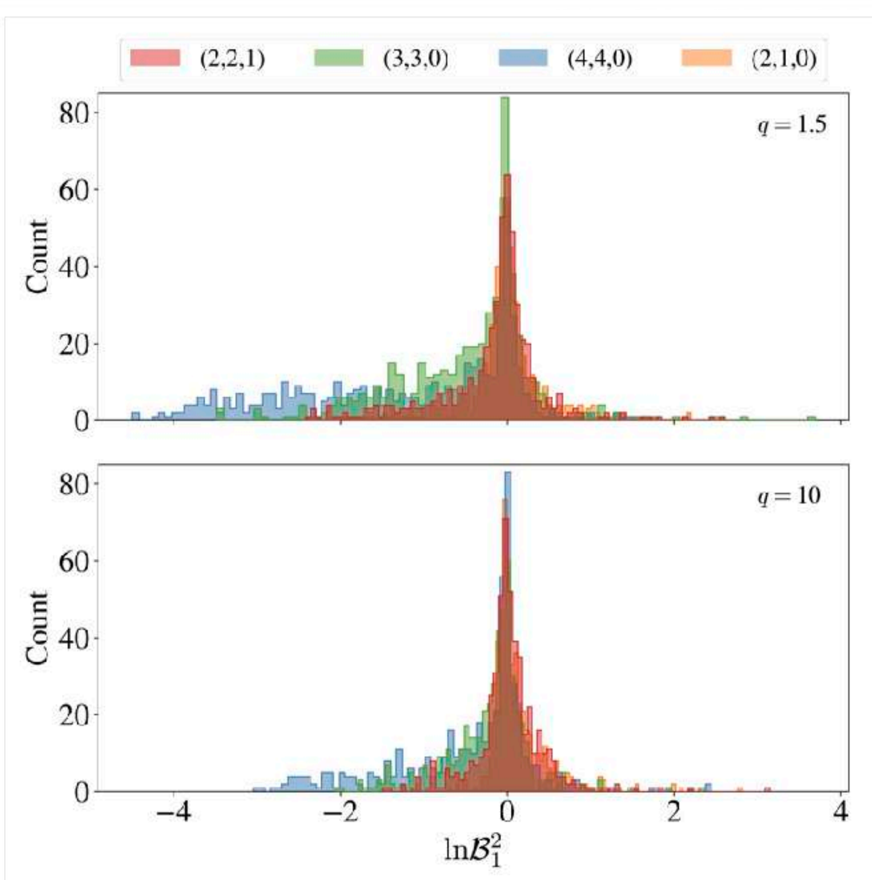
Bayesian inference and model comparison

Signal: $s = \psi_{220} + \psi_{\ell mn} + n$

QNMs injected in the signal have parameters informed by NR simulations

threshold: $\ln \mathscr{B}_1^2 > 8$





test: signal with one mode

Models: M_1 and M_2

M_1: assumes one mode
$\theta = \{A_{220}, \phi_{220}, f_{220}, \tau_{220}\}$

M_2: assumes two modes
$\theta = \{A_{220}, \phi_{220}, f_{220}, \tau_{220}, R, \phi_{\ell mn}, f_{\ell mn}, \tau_{\ell mn}\}$

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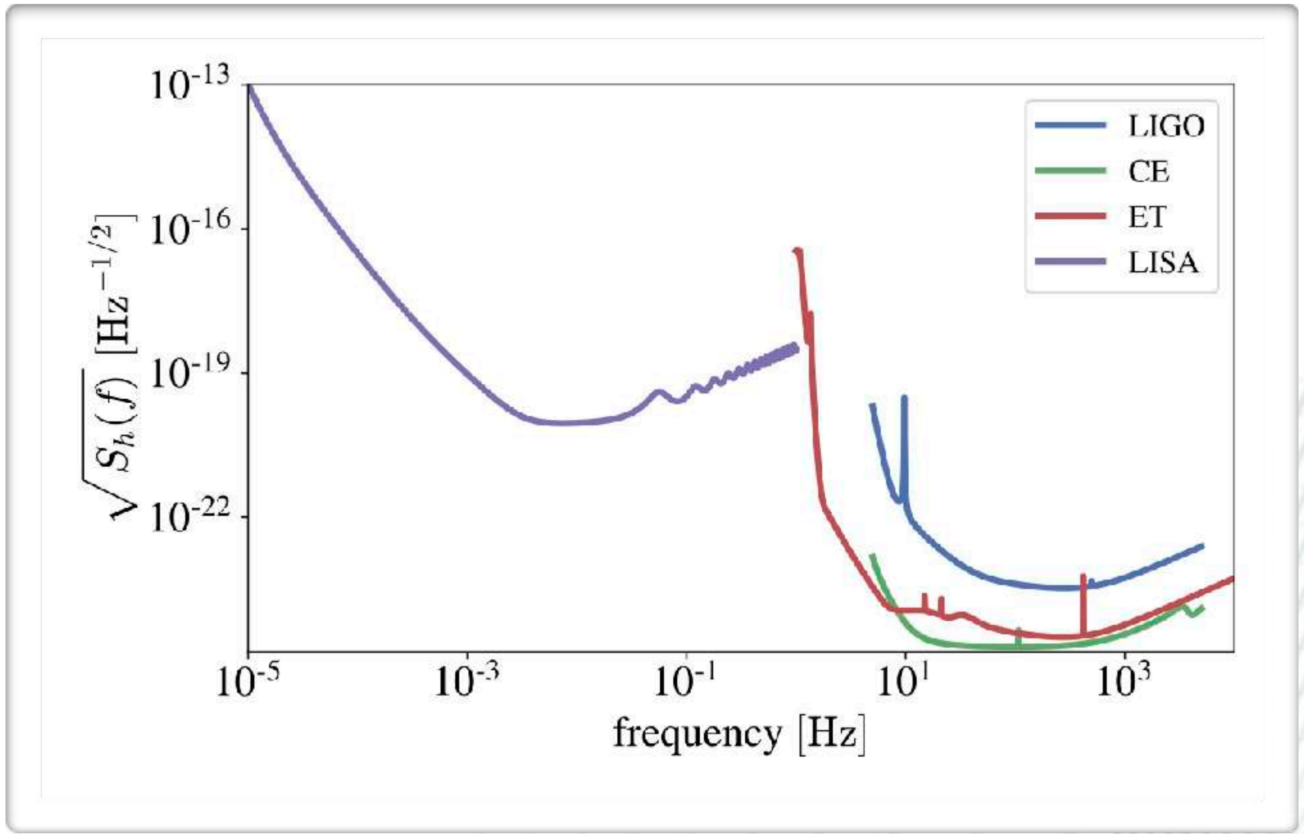
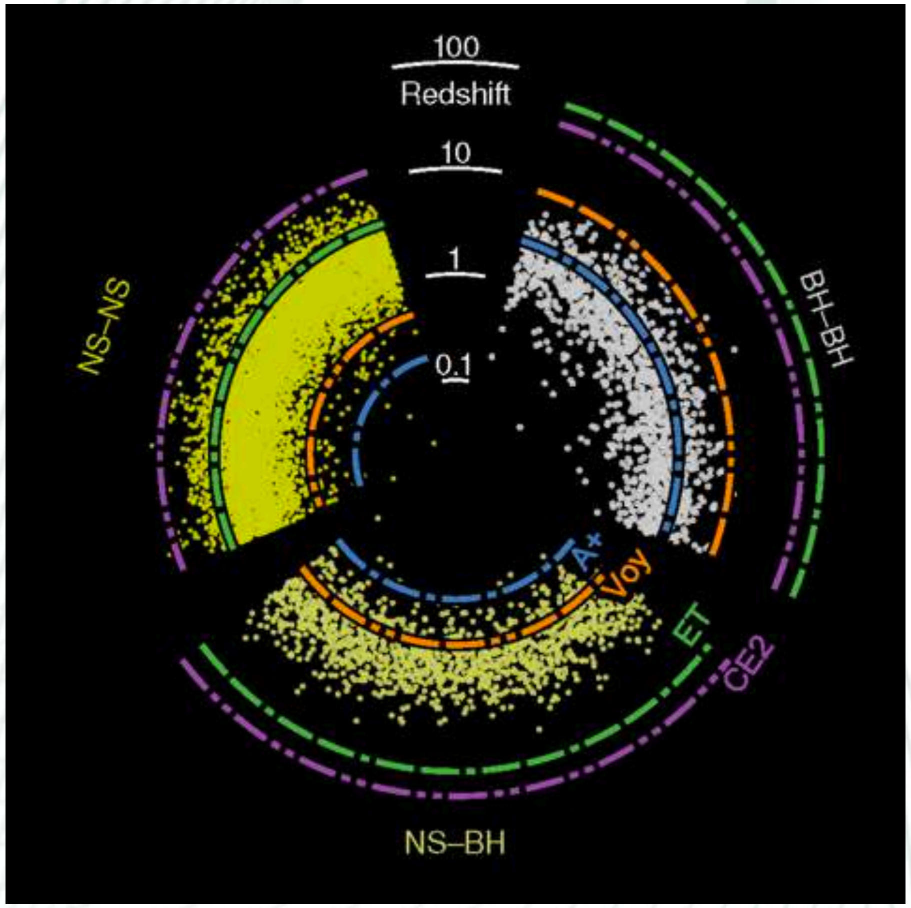
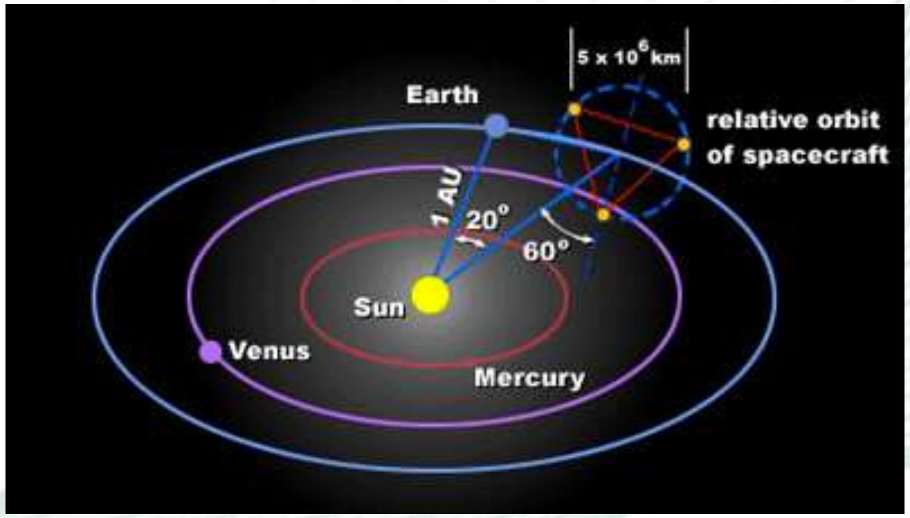
Future Detectors





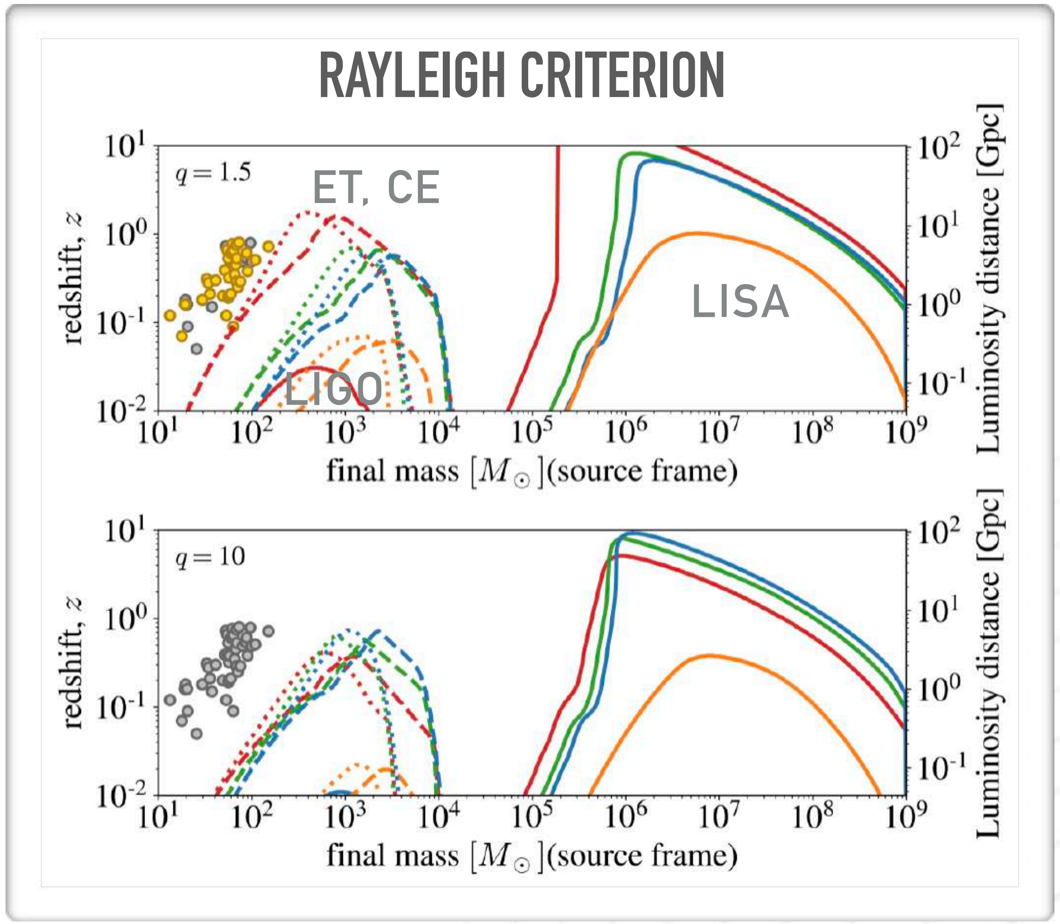
Einstein Telescope (ET) and Cosmic Explorer (CE): proposed 3rd generation ground detectors (2030's)



LISA: Laser Interferometer Space Antenna (estimated launch 2037)

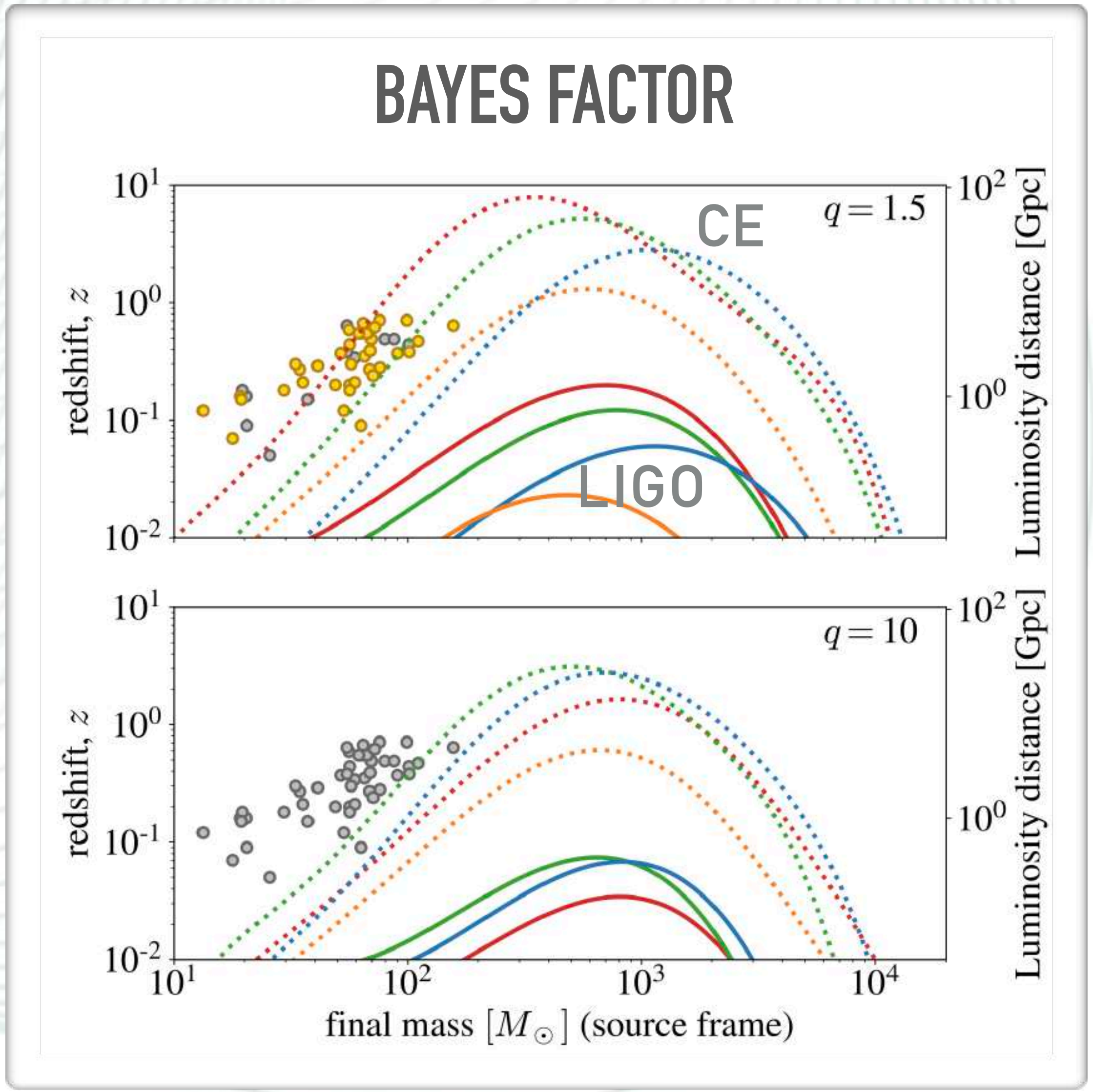
Black hole spectroscopy horizons*

*averaged over sky localization and binary inclination



The Rayleigh criterion is too restrictive!

horizon distance depends both on mass and mass ratio



intermediate mass black holes have the largest horizons for ground based detectors

estimated rates for event similar to GW190521 at $z_{221}^{\text{spec,B}} \sim 0.6$ are $0.03 - 0.1\ \text{yr}^{-1}$ (LIGO) and $(0.6 - 2.4) \times 10^3\ \text{yr}^{-1}$ (CE)

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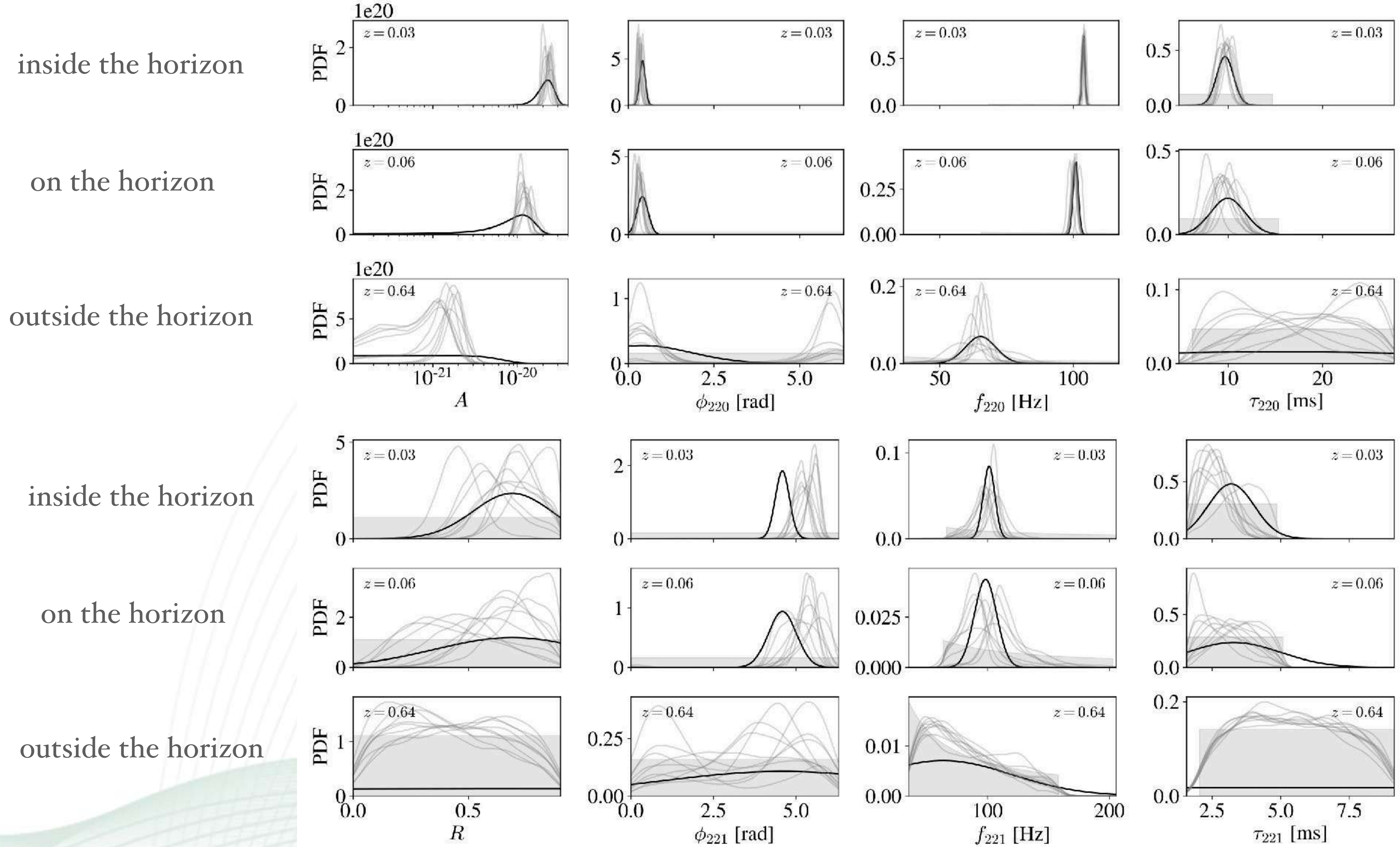
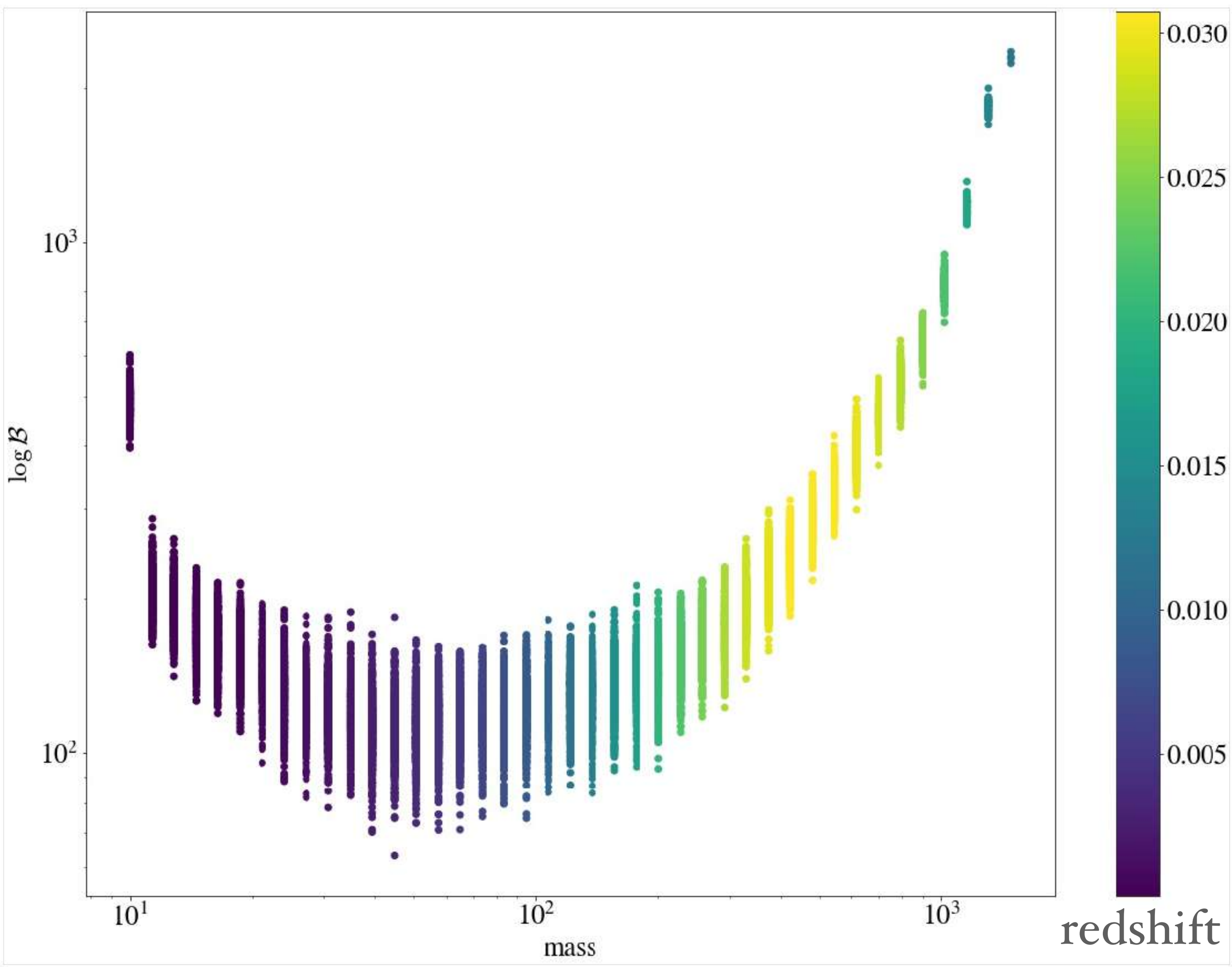
Parameter Estimation

grey bands: priors
grey curves: posteriors
black curves: Fisher matrix error estimate



Comparison between the Rayleigh and Bayes horizons



Bayes factor calculated on the Rayleigh horizon
(many noise realizations per mass)

For systems on the Rayleigh horizon, the Bayes factor is effectively infinite!

The Rayleigh horizon is not equivalent to a fixed high Bayes factor threshold

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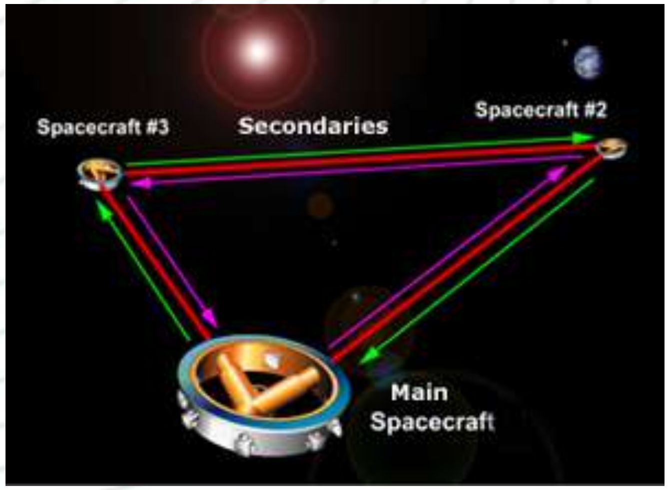
Final remarks

- There are exciting prospects for testing gravity and the existence of new types of astrophysical objects with gravitational wave detections

- Black hole spectroscopy is a promising probe of the nature of black holes. Lower threshold detections have already been claimed.

- 3G detectors will help (2030's);
  LISA will have even higher SNR (2037)!



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