Constraining Black Hole Horizon Effect in LIGO

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Outline

Motivation: Why horizon effect?

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Tool: Parameterized horizon effect

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Result: Horizon effect constraints by simulating LIGO detections

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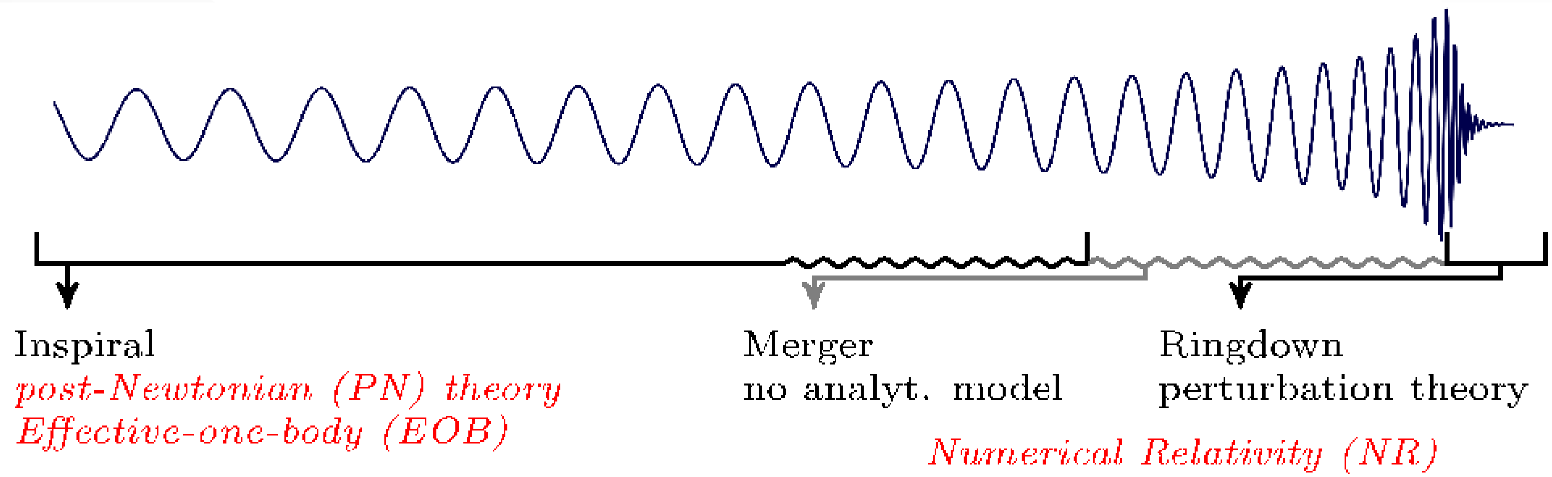
Application: Related theory

Motivation

- Interesting physics of black-hole horizons: thermodynamics, perturbation …
- Modified gravity: stronger gravity → larger deviations from general relativity?
- Black-hole horizons: extremely strong gravity

Motivation (in LIGO)

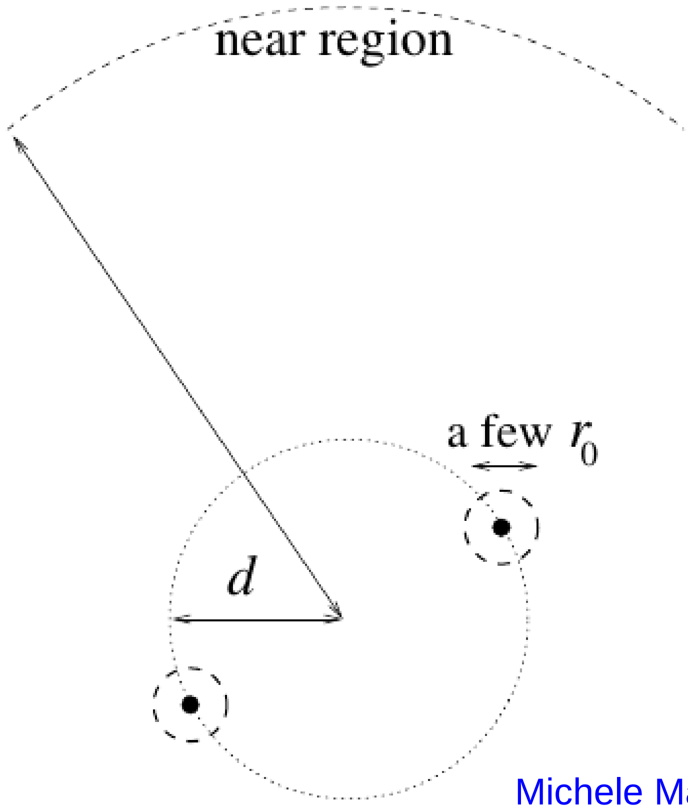
- Binary black-hole merger: inspiral → merger → ringdown
- Horizon effect (signature):
  - ringdown: echo?
  - merger: separate horizon effect from a highly dynamical spacetime?
  - **inspiral: black-hole absorption**



Frank Ohme (2012)

Configuration

- Inspiralling binary black-holes
- Event horizon and apparent horizon are **indistinguishable**



Michele Maggiore (2008)

Area, mass and spin growth

- Base on:
  - Black hole perturbation
  - First law of black-hole thermodynamics

- Gravitational energy-momentum flux flow into a horizon
  - ➔ Area, mass and spin growth (Eric Poisson et al.)

$$m_i(t) = m_i + \delta m_i(t)$$ Mass growth

$$J_i(t) = J_i + \delta J_i(t)$$ Spin growth

$$\frac{\kappa}{8\pi}\langle \dot{A}_i \rangle = \langle \dot{m}_i \rangle - \Omega_H \langle \dot{J}_i \rangle$$ First law of black-hole thermodynamics: area, mass, spin

Tool: Parameterized horizon effect

- Unlike black-hole horizon, mass and spin can be measured directly
- Introduce mass growth parameter α_1, α_2 and spin growth parameter β_1, β_2

$$\left\langle \frac{dm_i}{dt} \right\rangle \to (1+\alpha_i) \left\langle \frac{dm_i}{dt} \right\rangle ,$$

$$\left\langle \frac{dJ_i}{dt} \right\rangle \to (1+\beta_i) \left\langle \frac{dJ_i}{dt} \right\rangle .$$

Tool: Parameterized horizon effect in waveform

- Frequency domain waveform:

$$h(f) = A(f)e^{-i\Psi(f)}$$

- Phase correction with the horizon effect parameterization:

$$h(f) = A(f)e^{-i[\Psi(f)+\Psi_H(f,\alpha_1,\alpha_2,\beta_1,\beta_2)]}$$

- TaylorF2 model
  - ✗ inaccurate starting from the late inspiral
  - ✓ frequency cut in real search

Target order of the parameters

- Area theorem
  - non-decreasing black-hole area

- Minimal parameterization

$$\alpha_1 = \alpha_2 = \beta_1 = \beta_2 = \alpha.$$

$$\left\langle \frac{dA}{dt} \right\rangle \to (1+\alpha) \left\langle \frac{dA}{dt} \right\rangle$$

black-hole area growth, assuming that the first law of black hole thermodynamics holds

- Search α at order 1

Bayesian constraint from simulation

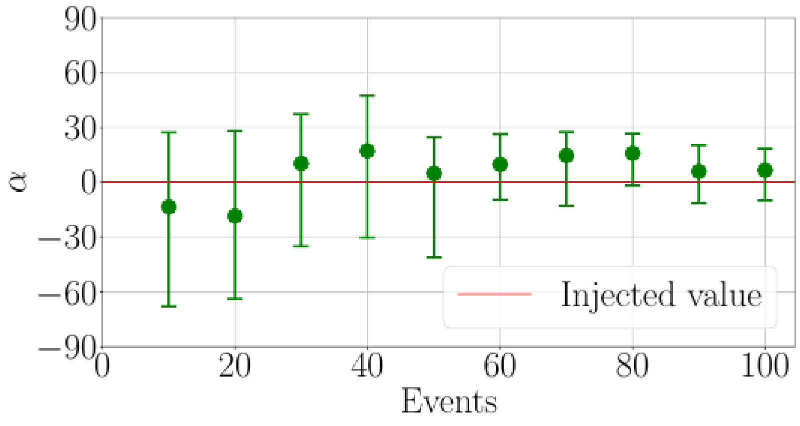
- Simulate signal ($\alpha = 0$) + noise → LIGO-Virgo constraint
- Constrain horizon effect parameter α from multiple events E_i

$$P(\alpha|E_1, ..., E_n) \propto P(\alpha) \prod_{i=1}^{n} P(E_i|\alpha) \propto \prod_{i=1}^{n} P(\alpha|E_i)$$

Bayesian constraint from simulation

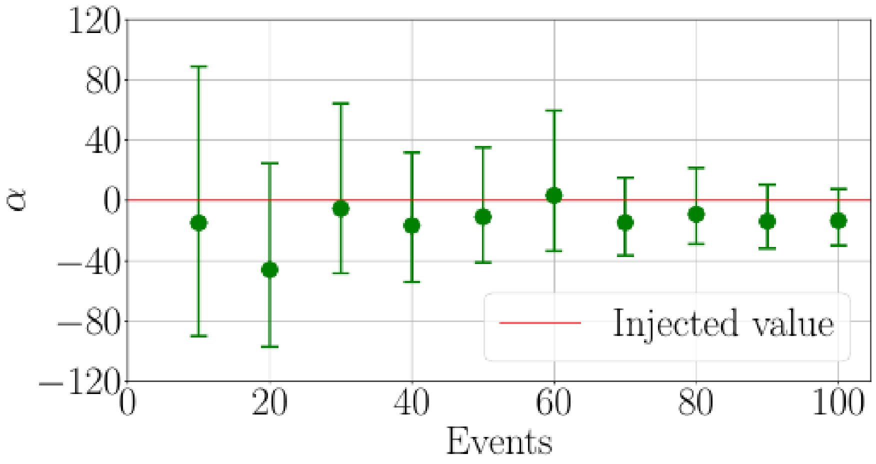
- 70Hz cut-off: data with frequencies higher than 70Hz is ignored in the analysis process
- Slightly weakened constraint
- Approximately, $\Delta\alpha \sim 20$ for 100 events

Without cut-off



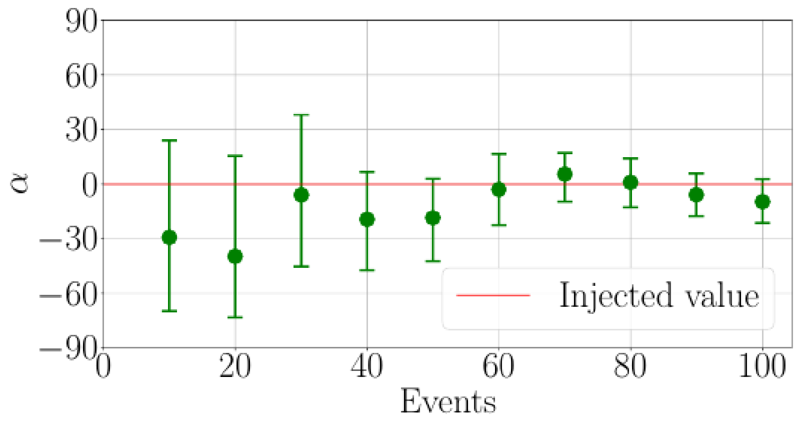
(b) (30,30) $M_{\odot}$

With 70Hz cut-off

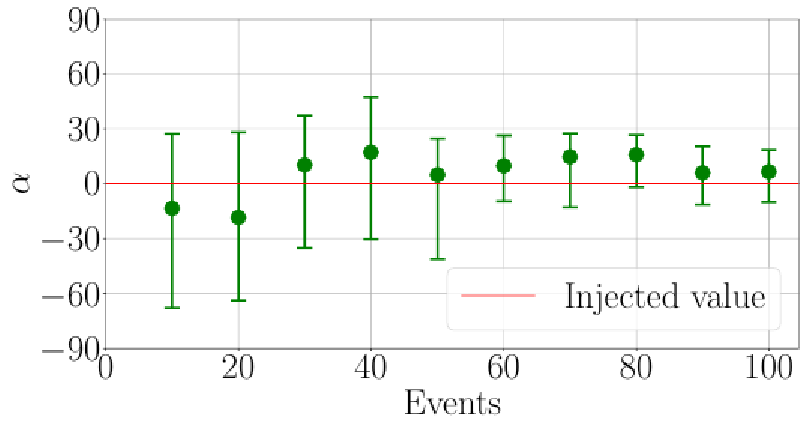


Bayesian constraint from simulation

- 90% confidence interval $\Delta\alpha$
- Approach $\alpha = 0$ as number of events increases
- Lower mass $\rightarrow$ better constraint



(a) (5,5) $M_\odot$



(b) (30,30) $M_\odot$

Application: related theory

- Area theorem?
  - Need $\Delta\alpha \sim 2$: future detectors

- Modified black-hole thermodynamics

$$dA \neq TdS = dm - \Omega_H dJ$$

- Modified black hole perturbation

Theory	α
Area theorem	≥ -1
Scalar-Tensor-Vector Gravity thermodynamics	$= -\frac{\alpha'}{1+\alpha'+\sqrt{1+\alpha'}}$
Quantum corrections to black-hole entropy	$= \frac{256\pi^2\Xi}{A}$

Table 1: Symbols α', Ξ are the independent parameters in the corresponding models, while A is the area of a black hole.

Application: related theory

- Check: if a modified gravity theory predicts dominating correction to horizon effect over other corrections
  - ➔ compare with LIGO-Virgo data
- Still far from Planck scale

Conclusion

- We conduct mock data study on the horizon effect constraint using simulated LIGO-Virgo signals and parameterized horizon effect

- The constraint can be improved by considering multiple detections
  - insufficient to test area theorem at the current state of the art
  - maybe sufficient to test certain modified gravity theories with dominating horizon effect corrections

- Future prospect:
  - test a self-consistent theory?
  - numerical relativity?
  - combine with other related constraints?
  - future detectors

Thank you & Q & A