Title: Keep calm and mind the waveform

Speakers: Davide Gerosa

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Abstract: Gravitational-wave observations of binary black holes allow new tests of general relativity to be performed on strong, dynamical gravitational fields. These tests require accurate waveform models of the gravitational-wave signal, otherwise waveform errors can erroneously suggest evidence for new physics. Existing waveforms are generally thought to be accurate enough for current observations, and each of the events observed to date appears to be individually consistent with general relativity. In the near future, with larger gravitational-wave catalogs, it will be possible to perform more stringent tests of gravity by analyzing large numbers of events together. However, there is a danger that waveform errors can accumulate among events: even if the waveform model is accurate enough for each individual event, it can still yield erroneous evidence for new physics when applied to a large catalog. We presents a simple linearised analysis, in the style of a Fisher matrix calculation, that reveals the conditions under which the apparent evidence for new physics due to waveform errors grows as the catalog size increases. We estimate that, in the worst-case scenario, evidence for a deviation from general relativity might appear in some tests using a catalog containing as few as 10-30 events above a signal-to-noise ratio of 20. This is close to the size of current catalogs and highlights the need for caution when performing these sorts of experiments.

Testing GR? Keep calm and mind the waveform

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arXiv:2103.16486

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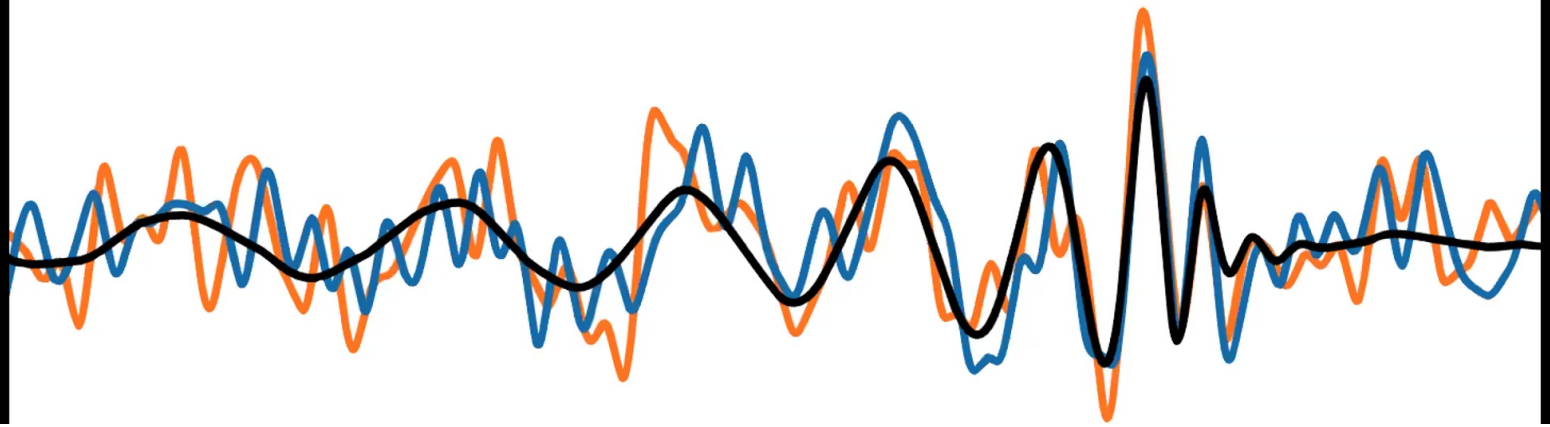
I've seen a deviation from GR: do you believe me?

- *"Extraordinary claims require extraordinary evidence"* (C. Sagan)
- We have a very strong prior in favor of GR, and rightly so!
- The usual suspect: **model systematics**
- **In the catalog era**: put many events together for better tests
- Models are good enough for single events…
- …but **can they trick me into thinking I'm seeing cool physics** when putting events together?



How to put events together?

Depends what you're testing Zimmerman+ 2019

A foundamental parameter which is the same for all events (say the mass of the graviton)

Multiply the likelihoods

Each event has its own additional "hair" (say a scalar charge)

Multiply the Bayes' factors

Two extrema that can be connected with a hierarchical analysis

Isi+ 2019, LIGO+ 2020

In the following I assume GR is right (because it is):

How do waveform systematics combine?

Single event first

A beyond-GR parameter α such that GR is $\alpha = 0$

$$s = n + h(\alpha_{\rm Tr} = 0; \theta_{\rm Tr}) + \Delta h(\theta_{\rm Tr})$$

signal — noise — GR waveform — waveform error

Fisher matrix calculation gives:

- Gaussian posterior $P(\alpha) = \mathcal{N}(\alpha_{\rm stat} + \alpha_{\rm sys}, \sigma_{\rm alpha})$
- Statistical offset $\alpha_{\rm stat} = (\Sigma^{-1})^{0\nu} \left\langle n \middle| \frac{\partial h}{\partial \lambda^\nu} \right\rangle \propto \frac{1}{\rho}$ → Signal-to-noise ratio
- Systematic offset $\alpha_{\rm sys} = (\Sigma^{-1})^{0\nu} \left\langle \Delta h(\theta_{\rm Tr}) \middle| \frac{\partial h}{\partial \lambda^\nu} \right\rangle \propto \sqrt{\mathcal{M}} \cos\iota$ → Directions the waveforms systematics are pushing me to
- Standard deviation $\sigma_\alpha = \left[\Sigma_{00} - \Sigma_{0i}^{\rm T} (\Sigma^{-1})^{ij} \Sigma_{j0}\right]^{-1/2}$ → Mismatch
- Bayes' factor $\mathcal{B} \propto \sqrt{\frac{2\pi}{\Sigma_{00}}} \exp\left[\frac{\Sigma_{00}}{2} (\alpha_{\rm stat} + \alpha_{\rm sys}))^2\right]$

Multiply the likelihoods

Same parameters for all the events (mass of the graviton)

"Realistic" catalog $P(\rho) \propto \rho^{-4}$ Schutz 2011
Golden events $\rho > 20$

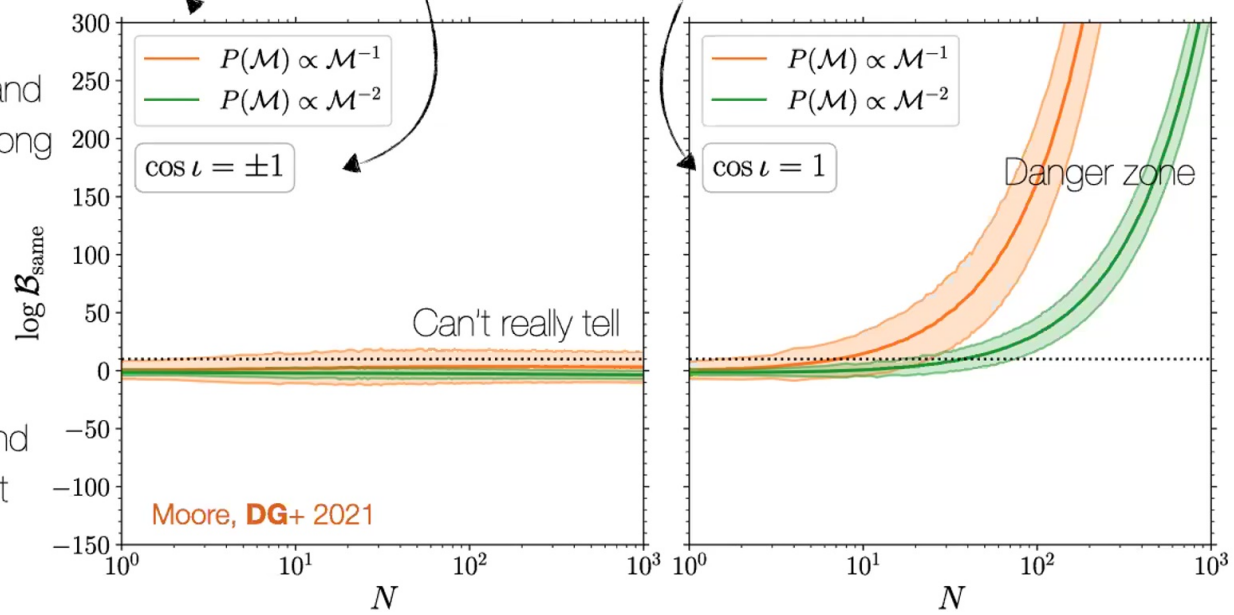
A "good" and a "bad" waveform model

Systematics cancel out

Systematics conspire in the same direction

GR is right and I think it's wrong

GR is right and I think it's right



Few events → Large catalog

Multiply the Bayes' factors

Different parameters for each event (scalar charge)

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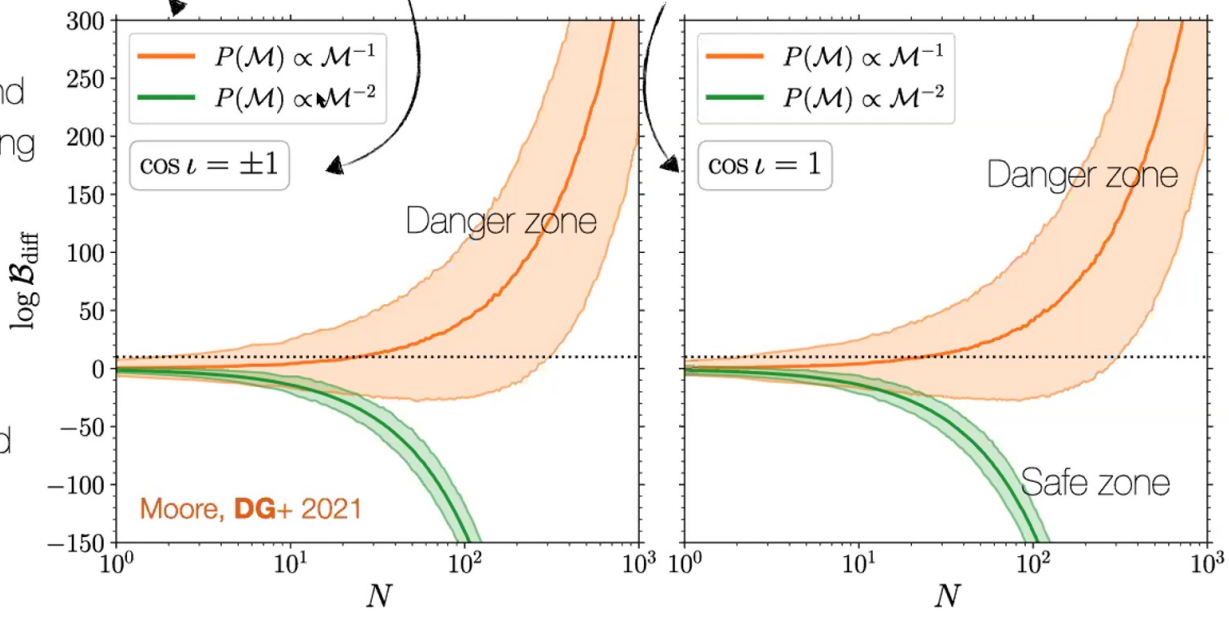

Few events → Large catalog

Lessons learned arXiv:2103.16486

It's a simple Fisher-like model but **it highlights that**:

- Systematics can mimic new cool physics, and things get worse when combining multiple events
- A waveform model that is good enough for one event might not be good enough for a catalog test!

Key ingredients:

- Alignment between the waveform and the GR deviation
- The test we're performing (mass of the graviton vs scalar charge)
- The waveform accuracy (which depends on the GR parameters)

Urgent? Already with O(10) events at SNR>20

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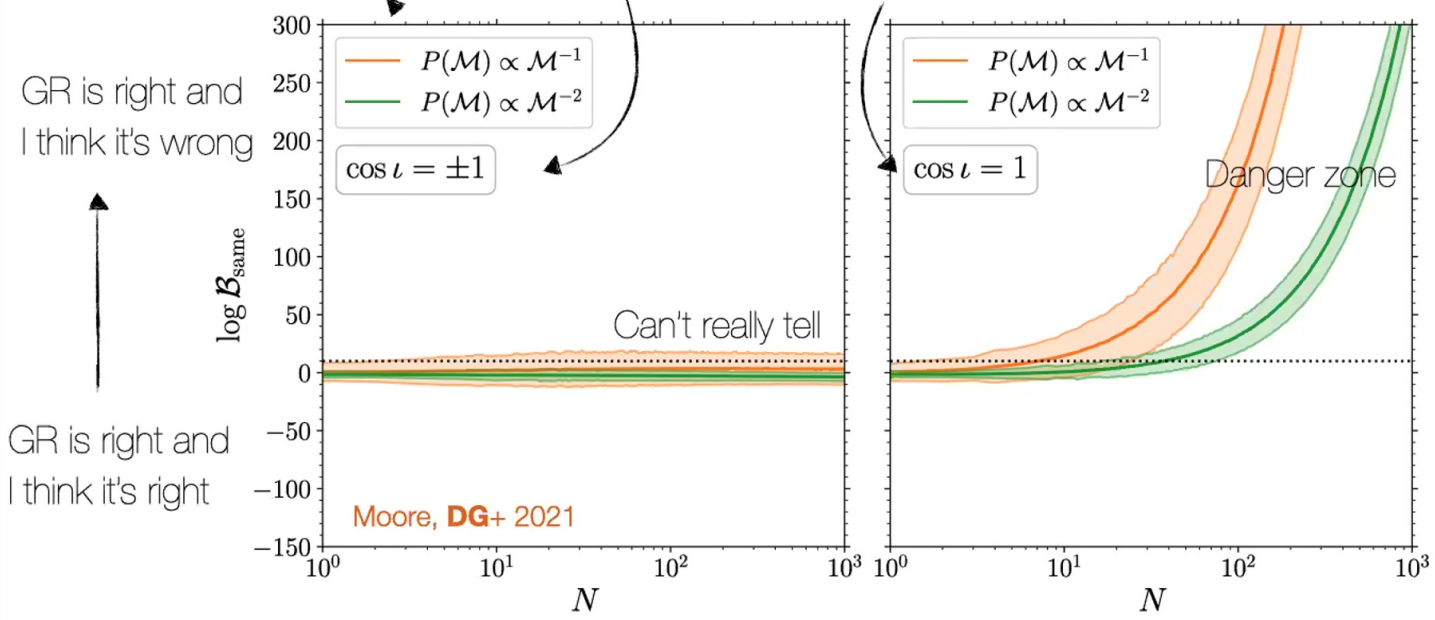

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