Tests of General Relativity

10th Physics and Astrophysics at the eXtreme Workshop and 3rd Cosmic Explorer Symposium

July 1, 2025

Panel Members

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Why finding GR deviation from GW signatures?

GR has passed all tests, but faces some challenges.

1. Incompatibility with a quantum description
2. The nature of black-hole singularity?
3. Some astrophysical / cosmological phenomena cannot be explained with DM/DE (e.g. late-time accelerations of the Universe)

These anomalies seem to indicate that GR does not represent ultimate understanding of space/time or gravity.

-> **Thus, GR needs tests.**

How to find GR deviation from GW signatures?

1. Inspiral, merger and ringdown will all be modified.
2. Waveform model construction:
   - Parameterization: theory specific vs agnostic? Degeneracy? Reparameterization through principal component analysis?
3. Individual signals vs populations? e..g., Yang+'17, Ng+'23, Lorenzo-Medina + '25, JCB+ '25
   - Selection of events?
4. The use of Bayes factor.
   - Just posterior vs also with Bayes factor? Background search for the estimation of false alarm rate?

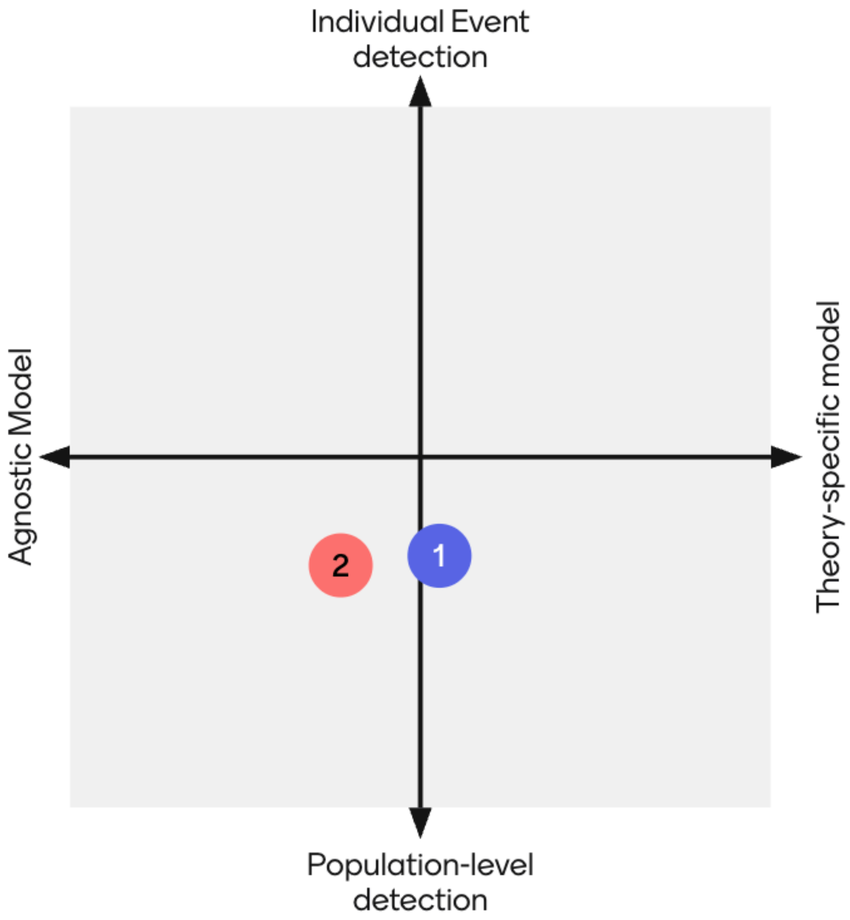
What aspect(s) of GR do you want to test with XG detectors?

Hawking Radiation	Ringdown	All
Existence of Exotic Compact Objects	Its correctness	Validity of FLRW
GW memory	Hawking radiation	Cosmic strings
Memory	New physics	Equivalence principle
non-minimally coupled BSM particles	Beyond GR	Cosmic strings

Theory-Agnostic test vs. Targeted test

1. **Issue A:** How are we going to find a signal that may violate GR?
   a. Matched filter searches currently target good-old black-hole mergers
   b. Model agnostic searches have reduced sensitivity
2. **Issue B:** Let's see we have a GR-violating signal, how are we going to spot the violation?
   a. Theory specific models vs. GR
   b. Theory-agnostic tests e.g., parametrised tests / IMR consistency tests, phenomenologica models
3. **Issue C:** Again, individual event vs. population based evidence:
   a. Individual event will require going beyond current searches
   b. Population level analyses may "stack" small evidences for GR violantions, as long as these are consistent

How would you find GR violations?

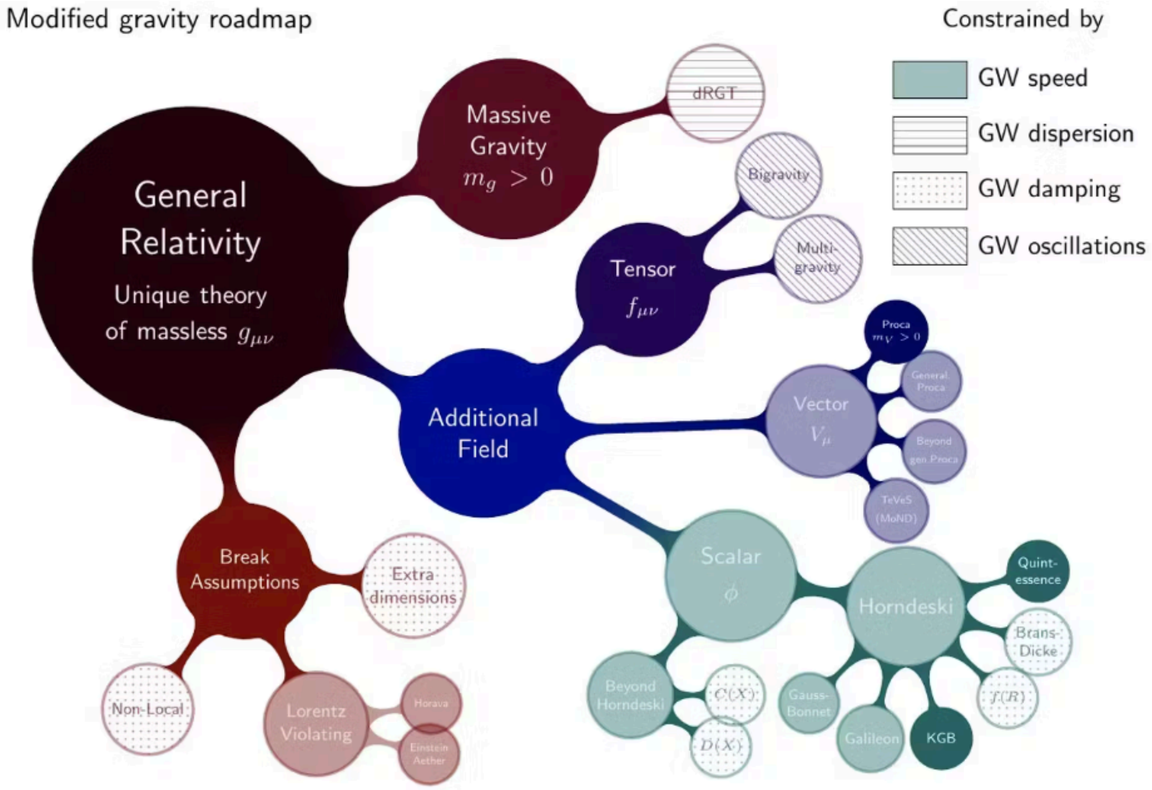


1 Matched-Filter Searches

2 Model Agnostic Searches

Choosing which beyond GR models to explore

1. Theoretical motivation?
2. How challenging is it to: simulate, approximate, etc?
    a. Which approach is most appropriate? Numerical relativity, post-Newtonian, effective one body, etc
3. What type of signatures does it produce?
4. Is it detectable with current experiments? Or upcoming experiments?
    a. What is the best environment to test bGR theories?



arXiv:1807.09241

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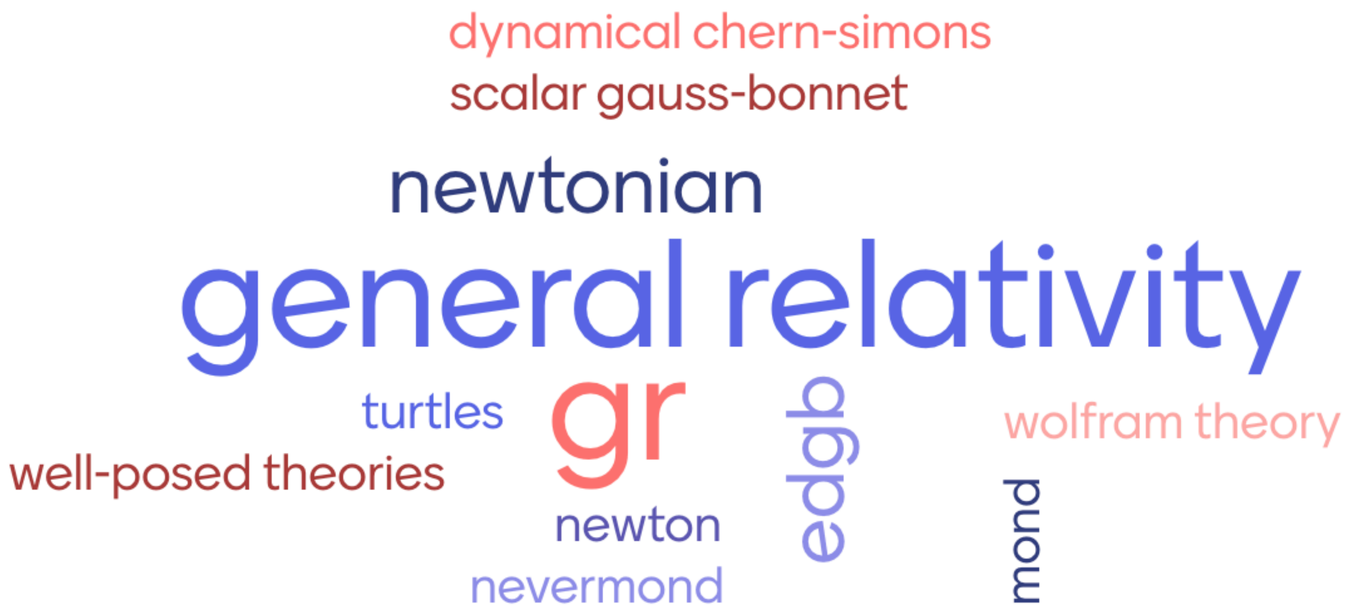
What is your favorite theory of gravity?



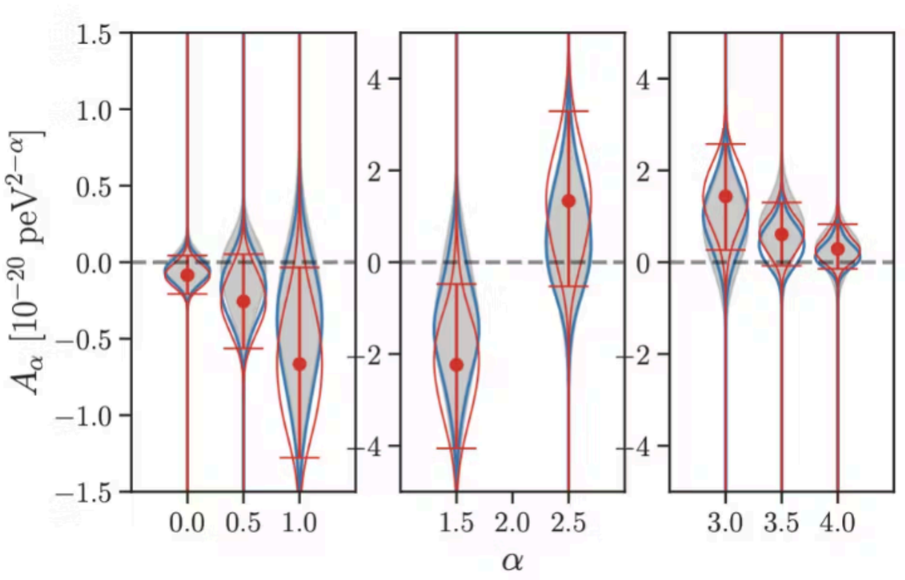
Build your ideal theory of gravity! What would it include?

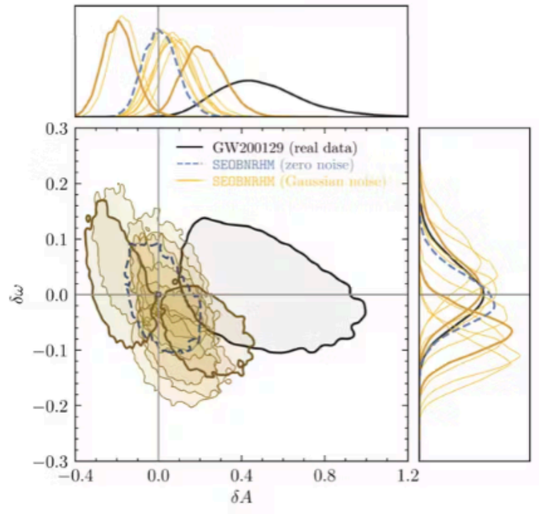
False GR Violation

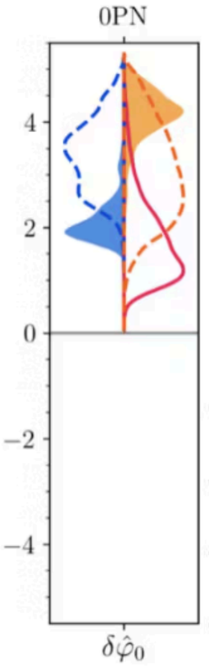
1. GR violations (False?) have stared showing up in our tests

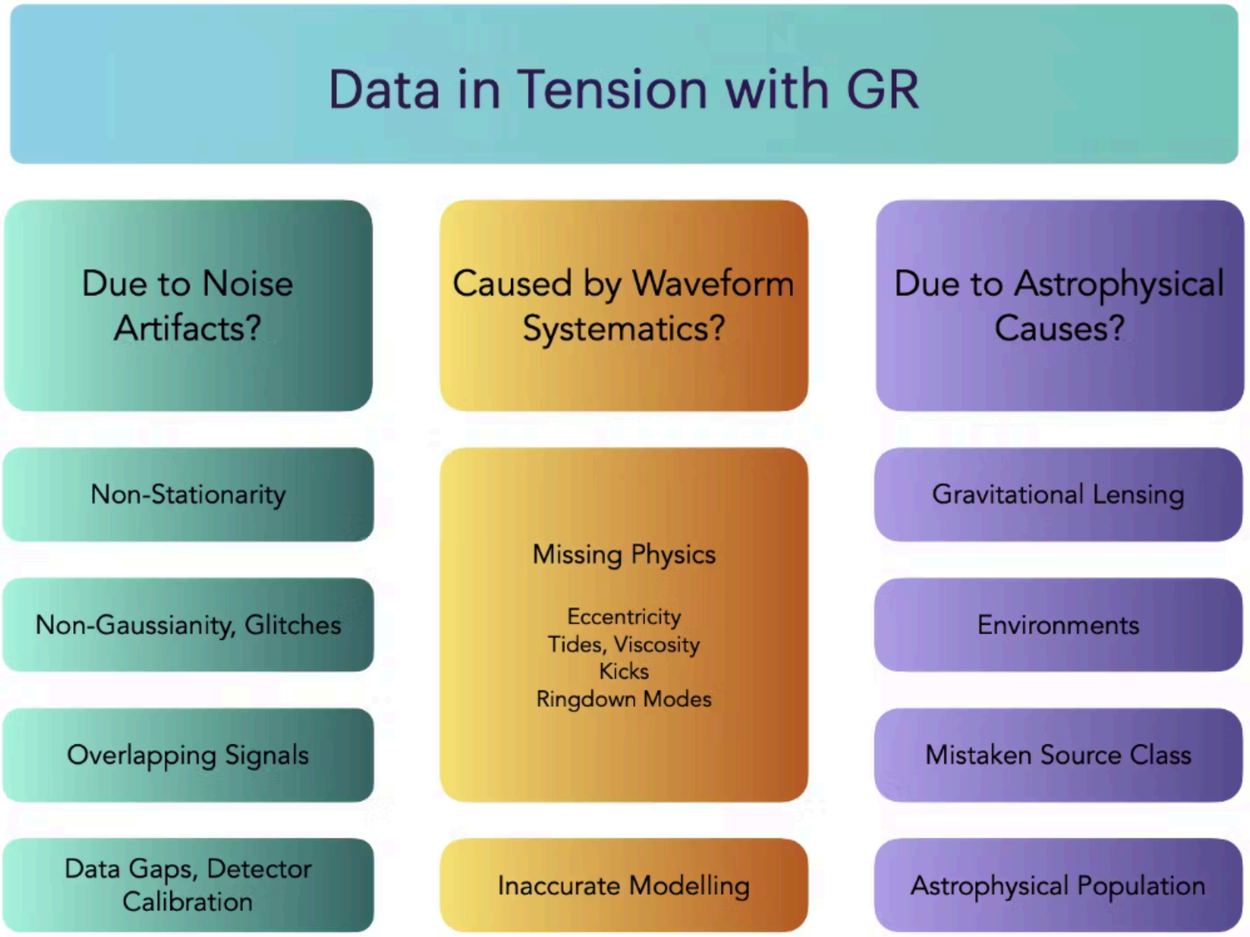
2. Examples: GW200219_065458, GW200219_094415, GW200225_060421, GW230529

3. Arguments:
   - Data-quality issue, Glitch mitigation issue
   - Waveform incompleteness (missing spin-precession, higher-order modes e.g. Pang+ 18)
   - Prior chioces, sampling issues, ...



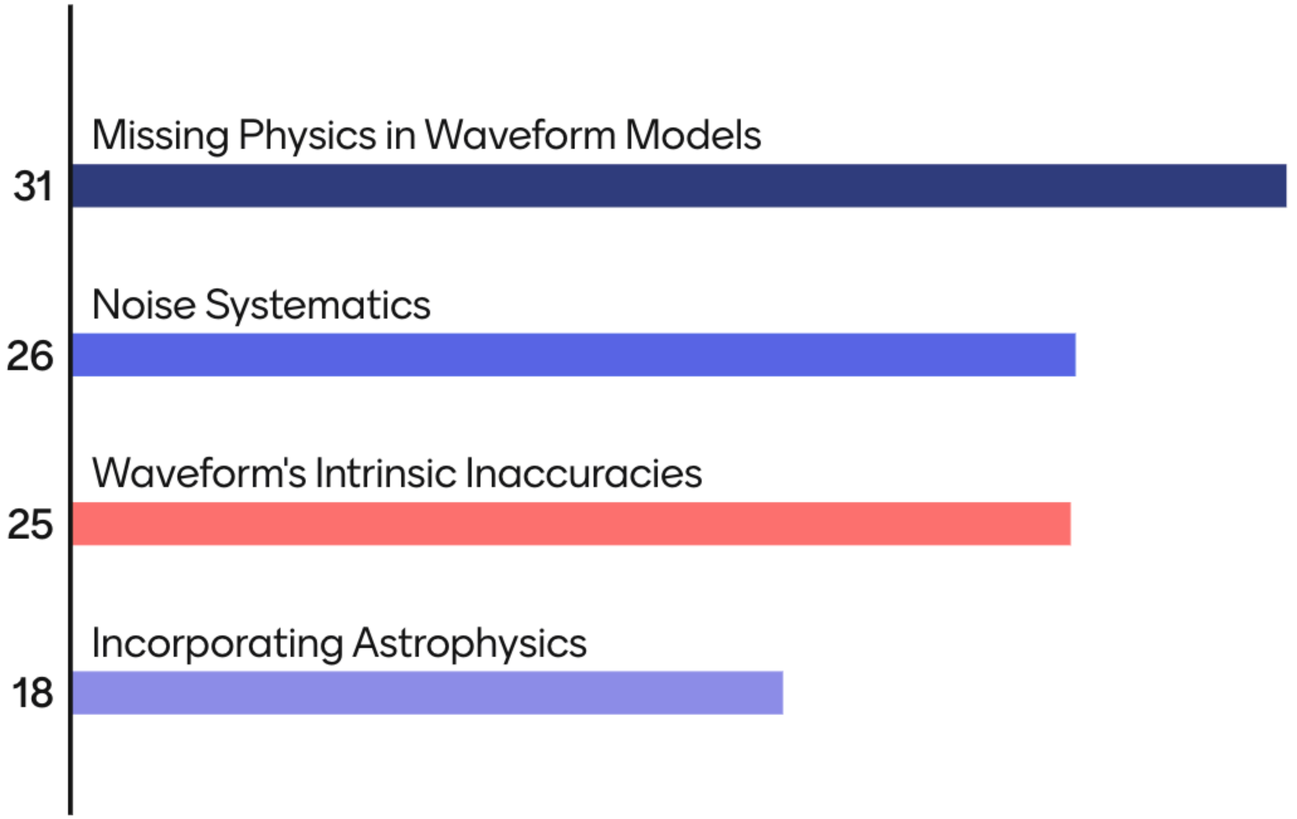


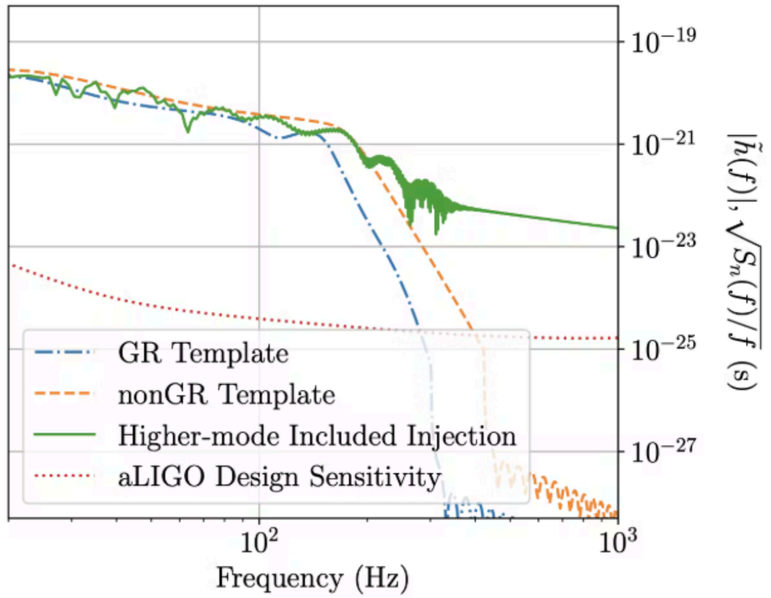




Gupta et al., 2405.02197

Which of these causes are more urgent to understand/control?





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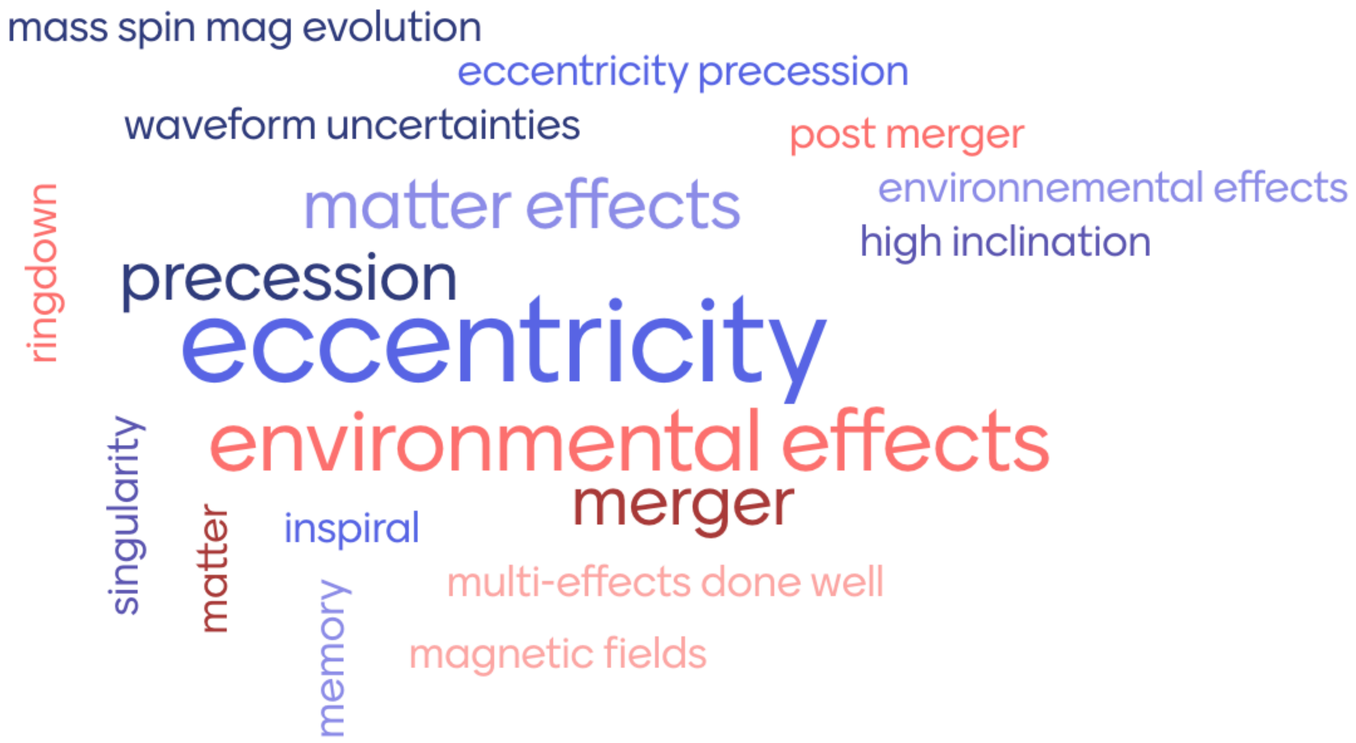
Which missing effects would you like to see added to the waveforms?



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How to deal with false GR violation when showed up in data?

Burn it with fire

Confirm it's not just noise or error

Bring it to Sathya

Ignore

Average over many measured waveforms

Opportunity to correct WF models

Only rely on populations

Perform a population analysis

Check your codes and waveforms again

Opportunity to understand noise/glitch mitigation

Close your eyes

Wait for more consistent deviations

Noise systematics

Nature paper

Account for waveform uncertainties

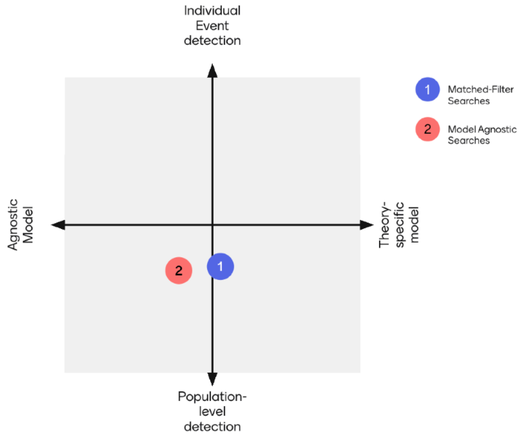
What topics would you have liked to discuss more in this panel?

Summary on July 3rd

What aspect(s) of GR do you want to test with XG detectors?

Hawking radiation, Cosmic explorer, New physics, Memory, No-hair Theorem

How would you find GR violations?



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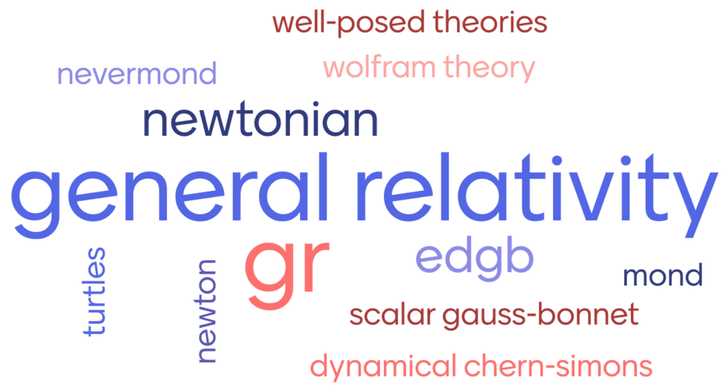

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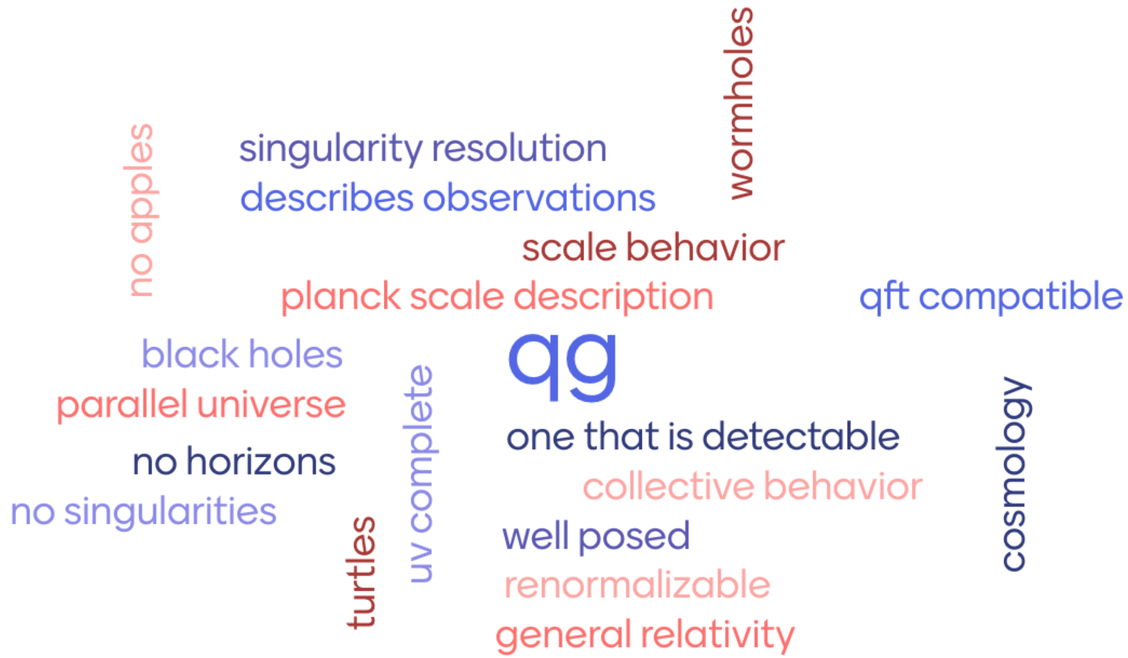

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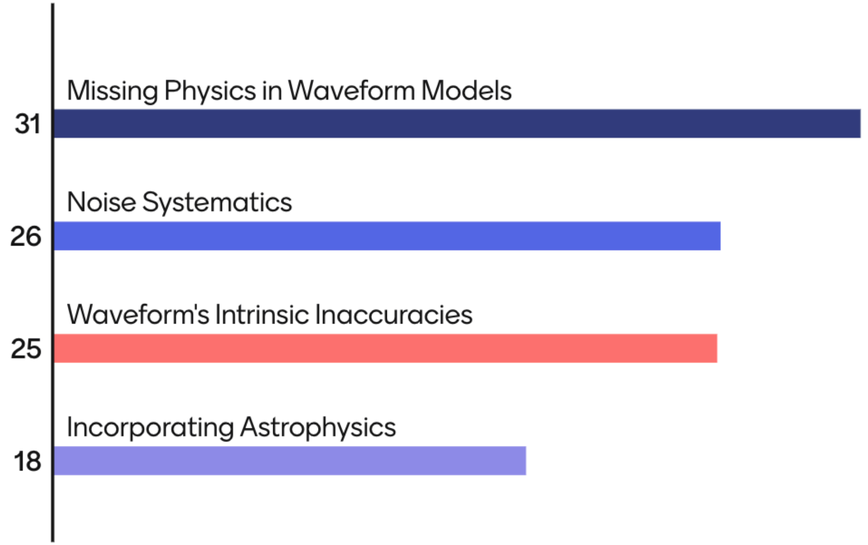

How to deal with false GR violation when showed up in data?

Noise systematics, waveform systematics, no idea!

Which missing effects would you like to see added to the waveforms?