

RESEARCH QUESTION 1 OF 1

How can multi-messenger observations of neutron star mergers constrain alternative theories of gravity?

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Concise summary

Multi-messenger neutron-star mergers are unusually informative because they test gravity in three coupled regimes: strong-field generation inside and near matter-rich compact objects; long-distance propagation of tensor radiation relative to photons; and the relation between GW amplitude, electromagnetic redshift, and source orientation. GW170817 already made differential GW-photon propagation extremely tightly constrained, removing broad classes of late-time modified-gravity models with non-luminal tensor speed. The next substantive advance is not a single new observable but hierarchical joint inference that marginalizes simultaneously over dense-matter EOS, merger/jet/kilonova astrophysics, cosmology, selection effects, and theory-specific waveform systematics. ([dcc.ligo.org](https://dcc.ligo.org/P1700308/public?utm_source=openai))

How the question was interpreted

A research-oriented map of the observables, theory mappings, inference methods, and limitations by which GW, gamma-ray, kilonova/afterglow, and prospective neutrino data from binary neutron-star mergers constrain departures from general relativity.

Key terms

- **Scalarization** — A nonlinear strong-field phenomenon in some scalar-tensor theories in which a neutron star develops an effective scalar charge, potentially abruptly during inspiral. It can create dipole radiation and late-inspiral/merger deviations while evading some weak-field constraints.

- **Tidal deformability** — The linear response of a neutron star's multipole moments to its companion's tidal field, commonly encoded by a Love number or dimensionless parameter Λ . It carries dense-matter information but is also a principal degeneracy in gravity tests using BNS inspiral phasing.
- **Gravitational-wave luminosity distance** — The distance inferred from GW amplitude after accounting for source orientation and waveform parameters. Modified tensor damping, a varying effective Planck mass, or gravitational leakage can make it differ from electromagnetic luminosity distance.
- **Modified dispersion** — A non-GR relation between GW frequency and wave number that produces frequency-dependent propagation speed and phase shifts. GW phasing tests it directly; electromagnetic coincidence adds an absolute inter-messenger timing lever arm.
- **Shapiro delay** — Propagation-time delay accumulated by a signal traversing gravitational potentials. Comparing the delay for different messengers provides a route to tests of weak equivalence principle violation.
- **Hierarchical inference** — A statistical framework that jointly infers event-level parameters and shared population-level parameters using multiple events. It is needed to avoid conflating modified gravity with EOS, cosmological, astrophysical, and selection effects.

1. Separate the tests by physical sector

- Treat a merger as a joint test of generation, propagation, and detection rather than as a single “test of GR.”
- Generation tests use inspiral/merger/post-merger GW phasing, amplitudes, harmonics, and polarization content.
- Propagation tests compare GW and electromagnetic arrival times, phases, and distance-redshift relations.
- Matter-sector tests exploit tidal deformability, remnant fate, ejecta, and kilonova/jet signatures, but require EOS marginalization.
- Equivalence-principle tests compare species-dependent propagation through intervening gravitational potentials.

2. Inspiral: strong-field generation constraints

- Parameterize departures in the frequency-domain phase, $\delta\Psi(f)$, while including GR tidal terms and calibration/waveform uncertainty.
- In scalar-tensor models, neutron stars can acquire scalar charges; scalar dipole radiation then produces a leading negative-post-Newtonian phasing contribution.

- Dynamical or spontaneous scalarization can switch on nonperturbatively late in inspiral, motivating theory-specific numerical-relativity waveform families rather than only constant PN-deformation tests.
- Modified conservative dynamics can change binding energy, mass-radius relations, and tidal Love numbers; the same measured phase may therefore admit gravity-EOS degeneracies.
- Use binary-pulsar and Solar-System constraints as external priors only after checking their applicability to the chosen theory and screening regime.

3. Counterpart timing and propagation

- For GW170817, the observed GW-GRB delay was $+1.74 \pm 0.05$ s, after a propagation distance of roughly 40 Mpc; subject to assumptions about intrinsic source delay, this tightly constrains differential GW/photon propagation speed.
- Frequency-dependent GW arrival phase tests modified dispersion, including massive-graviton-like terms, without requiring an electromagnetic trigger.
- GW-EM coincidence can test differential Shapiro delay and hence weak-equivalence-principle violation, but the inferred bound depends on the gravitational-potential model along the line of sight.
- A sequence of counterparts at differing redshifts can search for redshift- or environment-dependent propagation effects rather than relying on one nearby event.
- Neutrino counterparts would add a third messenger and potentially extend equivalence-principle and dispersion tests, but no BNS neutrino counterpart presently provides such a constraint.

4. Amplitude, redshift, and standard-siren tests

- The GW waveform provides a GW luminosity distance, d_L^{GW} ; host association from an electromagnetic counterpart supplies redshift and often better sky position.
- In many modified-gravity parameterizations, altered tensor friction or leakage gives $d_L^{\text{GW}}(z) \neq d_L^{\text{EM}}(z)$, even if c_T equals c .
- A joint hierarchical model should fit cosmology and modified propagation simultaneously; fixing a GR cosmology can falsely sharpen a gravity constraint.
- Afterglow imaging/modeling can constrain inclination, reducing the familiar distance-inclination degeneracy in the GW amplitude.
- For high-redshift samples, include peculiar velocities, weak-lensing magnification, detector selection, host misidentification, and counterpart detectability in the likelihood.

5. Matter-rich merger and post-merger observables

- Tidal deformabilities constrain the stellar response in the late inspiral, while post-merger spectral peaks and collapse time probe remnant structure at higher density.
- Kilonova color, luminosity, and spectra constrain ejecta mass, velocity, composition, and possibly the remnant's lifetime; these quantities depend jointly on EOS, binary parameters, neutrino/magnetohydrodynamic physics, and gravity.
- A theory predicting altered stellar compactness, scalarization, or extra radiation can be challenged only by forward models that propagate its consequences through both GW and electromagnetic observables.
- Use universal relations cautiously: relations calibrated in GR can become theory dependent and can introduce hidden prior assumptions.
- The most defensible analysis jointly infers EOS hyperparameters and gravity parameters across multiple mergers rather than treating an EOS estimate as gravity independent.

6. Practical PhD-level inference strategy

- Define a theory-specific parameter vector θ_g and explicit screening/stability priors; do not interpret generic PN bounds as universal theory exclusions.
- Construct a joint likelihood $p(d_{\text{GW}}, d_{\text{GRB}}, d_{\text{KN}}, d_{\text{AG}} | \theta_g, \theta_{\text{EOS}}, \theta_{\text{ast}}, \theta_{\text{cos}})$, retaining astrophysical nuisance parameters such as jet-launch delay and ejecta opacity.
- Compare GR and alternatives using evidences or predictive performance, while reporting posterior dependence on EOS, population, and counterpart-model assumptions.
- Combine events hierarchically, allowing source-dependent scalar charges and counterpart-selection functions instead of assuming all BNS events are identical.
- Validate claims with injection studies using alternative-theory signals, EOS variation, realistic detector noise, and deliberately mismatched electromagnetic models.

Evidence and debate

- **Prompt GW-gamma coincidence is the most direct multimessenger constraint on anomalous tensor-wave speed.**

GW170817 and GRB 170817A were separated observationally by $+1.74 \pm 0.05$ s. The collaboration reported a constraint on the fractional GW-light speed difference of -3×10^{-15} to $+7 \times 10^{-16}$ under its timing interpretation. This sharply restricts theories whose tensor modes propagate non-luminally at low redshift. ([dcc.ligo.org])

https://dcc.ligo.org/P1700308/public?utm_source=openai))

Limitation or counterpoint: The observed offset includes unknown intrinsic delay between merger and gamma-ray production. A viable theory may also have $c_T=c$ while modifying generation, damping, polarizations, or screening behavior.

EVIDENCE STRENGTH: VERY STRONG FOR THE OBSERVED NEAR-COINCIDENCE; MODEL-DEPENDENT FOR CONVERSION INTO A FUNDAMENTAL PROPAGATION-SPEED BOUND.

- **The GW signal supplies complementary tests of source dynamics and propagation even before electromagnetic information is used.**

The LIGO-Virgo GW170817 GR test analyzed dipole radiation, parametrized inspiral-phase deviations, modified dispersion, extra-dimensional leakage through GW-versus-EM distance, and polarization content; its results were consistent with GR. ([dcc.ligo.org](

https://dcc.ligo.org/LIGO-P1800059-v9/public?utm_source=openai))

Limitation or counterpoint: Generic deformation parameters do not uniquely correspond to a covariant alternative theory; tidal physics, waveform approximants, and priors affect interpretation.

EVIDENCE STRENGTH: STRONG AS A BROAD, DATA-DRIVEN NULL TEST FOR THE MODELED DEVIATIONS.

- **Neutron-star mergers can probe nonperturbative strong-field gravity not fully tested by weak-field experiments.**

Numerical-relativity work in scalar-tensor gravity finds that binaries can differ markedly from GR in late inspiral and merger despite satisfying weak-field and binary-pulsar constraints, owing to spontaneous/dynamical scalarization. ([arxiv.org](

https://arxiv.org/abs/1212.5053?utm_source=openai))

Limitation or counterpoint: Scalarization thresholds and predicted signals vary with coupling function, scalar mass, screening, stellar masses, and EOS; one cannot transfer a bound from one scalar-tensor realization to all others.

EVIDENCE STRENGTH: STRONG THEORETICAL MECHANISM; OBSERVATIONAL REACH IS THEORY- AND WAVEFORM-DEPENDENT.

- **Electromagnetic redshifts turn BNS mergers into tests of modified GW damping/friction and leakage, not merely Hubble-constant measurements.**

Modified-gravity propagation generically permits a GW luminosity distance different from the electromagnetic luminosity distance; forecasts show that redshift-identified standard sirens can constrain phenomenological damping parameters. ([arxiv.org](

https://arxiv.org/abs/1712.08108?utm_source=openai))

Limitation or counterpoint: The signal is entangled with cosmology, inclination, lensing, peculiar velocity, calibration, host identification, and counterpart-selection effects. Current BNS bright-siren statistics remain sparse.

EVIDENCE STRENGTH: STRONG THEORETICAL BASIS WITHIN THE STATED PROPAGATION PARAMETERIZATIONS; FUTURE PRECISION IS FORECAST-DEPENDENT.

- **Tidal, remnant, and kilonova data offer additional gravity leverage only through a joint gravity-EOS-astrophysics analysis.**

The same GW170817 analysis explicitly required neutron-star tidal deformabilities in waveform models and emphasized that it was the first BNS GR test involving strong-field binary dynamics in the presence of matter. ([dcc.ligo.org](https://dcc.ligo.org/public/0150/P1800059/008/main.pdf?utm_source=openai))

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Limitation or counterpoint: Tidal and post-merger observables are sensitive to uncertain high-density matter and to electromagnetic radiative-transfer/magnetohydrodynamic modeling; apparent deviations from GR can be EOS or astrophysical-model errors.

EVIDENCE STRENGTH: STRONG METHODOLOGICAL POINT.

- **Multimessenger timing can constrain non-universal propagation, but equivalence-principle bounds are less assumption-free than the observed coincidence itself.**

Studies of GW170817 have used multimessenger timing to formulate weak-equivalence-principle tests via differential Shapiro delay, while stressing assumptions about the intervening potential. ([arxiv.org](https://arxiv.org/abs/1710.05860?utm_source=openai))

Limitation or counterpoint: Intrinsic emission delays and uncertain large-scale gravitational potentials limit how directly an arrival-time difference can be assigned to a violation of the equivalence principle.

EVIDENCE STRENGTH: MODERATE: HIGHLY SENSITIVE TIMING LEVER ARM, BUT INTERPRETATION RESTS ON PROPAGATION AND POTENTIAL MODELING ASSUMPTIONS.

Uncertainties and research gaps

- The gamma-ray launch delay relative to merger is astrophysical and is not directly measured; it weakens any interpretation of GW-gamma timing as a pure propagation-speed measurement.
- Dense-matter EOS uncertainty can mimic or absorb modified-gravity effects in tidal phasing, remnant lifetime, ejecta mass, and kilonova observables.
- Screening mechanisms and nonlinear strong-field phenomena mean that cosmological, Solar-System, binary-pulsar, and neutron-star-merger constraints need not map onto a theory's parameters in a model-independent way.
- Present direct multimessenger leverage is dominated by GW170817; population-level claims will depend on the number, redshift distribution, and counterpart-selection function of future events.
- Waveform-systematics control is incomplete for many alternative theories, especially through merger and post-merger, where fully relativistic matter simulations and detector-calibrated analyses are required.

Source suggestions

- **LIGO-P1700308-v8: Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A** [WEB SOURCE](#)

Not stated · Not stated · Web source

Source returned by OpenAI web search for this research response.

Source note: Open and evaluate the original source before citing it.

Open source: https://dcc.ligo.org/P1700308/public?utm_source=openai

- **LIGO-P1800059-v9: Tests of General Relativity with GW170817** [WEB SOURCE](#)

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Open source: https://dcc.ligo.org/LIGO-P1800059-v9/public?utm_source=openai

- **Neutron-star mergers in scalar-tensor theories of gravity** [WEB SOURCE](#)

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Source note: Open and evaluate the original source before citing it.

Open source: https://arxiv.org/abs/1212.5053?utm_source=openai

- **The gravitational-wave luminosity distance in modified gravity theories** [WEB SOURCE](#)

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Source note: Open and evaluate the original source before citing it.

Open source: https://arxiv.org/abs/1712.08108?utm_source=openai

- **Tests of General Relativity with GW170817** [WEB SOURCE](#)

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Source returned by OpenAI web search for this research response.

Source note: Open and evaluate the original source before citing it.

Open source: https://dcc.ligo.org/public/0150/P1800059/008/main.pdf?utm_source=openai

- **Multimessenger tests of the weak equivalence principle from GW170817 and its electromagnetic counterparts** [WEB SOURCE](#)

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Open source: https://arxiv.org/abs/1710.05860?utm_source=openai

Practical next steps

- Choose one theory class and write its observable map: extra fields/charges → binary dynamics → GW polarizations/phasing → propagation → counterpart observables.
- Derive or adopt a consistent waveform parameterization that includes tidal effects and identify which parameters are identifiable separately from EOS hyperparameters.
- Reproduce the GW170817 timing logic symbolically: $\Delta t_{\text{obs}} = \Delta t_{\text{int}} + \Delta t_{\text{prop}}$, then state exactly which prior on Δt_{int} is required for each c_T or equivalence-principle result.
- Build a hierarchical graphical model separating event-level binary, jet, ejecta, and inclination parameters from population-level EOS, cosmology, and gravity parameters.
- Compare theory-specific numerical-relativity predictions with parameterized-PN tests; document when a phenomenological bound cannot validly be translated into a Lagrangian coupling bound.
- For forecasts, simulate detected—not merely astrophysical—populations and include EM follow-up selection, host-redshift completeness, lensing, and waveform-model bias.

Suggested searches

- "GW170817" "Tests of General Relativity" dipole radiation tidal deformability
- binary neutron star dynamical scalarization numerical relativity scalar-tensor waveform
- multimessenger standard sirens modified gravitational-wave luminosity distance
- GW170817 GRB 170817A propagation speed Shapiro delay intrinsic emission delay
- binary neutron star post-merger gravitational waves alternative gravity equation of state
- hierarchical Bayesian inference neutron star equation of state modified gravity multimessenger

Follow-up question: Which theory family is the intended focus—scalar-tensor/Horndeski, Einstein-Æther/Hořava, massive gravity, extra dimensions, or parity-violating gravity—and are you interested in present constraints, third-generation forecasts, or an inference framework?