

# 14 – Gravitational Waves and the Geometry of Dark Matter: a geometric alternative to dark-matter microphysics

*Empirical tests of spacetime propagation under constraint*

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## Abstract

*Gravitational waves from binary black-hole mergers have been proposed as indirect probes of dark-matter microphysics, on the assumption that the high-redshift merger rate traces the abundance of small haloes suppressed by warm or self-interacting dark matter. Within the framework of the Time-Symmetric Parity Constraint (TSPC), this assumption is inverted. The observed evolution of merger rates is explained not by non-cold dark-matter behaviour but by two correlated effects: a small parity-induced geometric weighting near the symmetry of the manifold, and baryonic regulation of star formation in shallow potentials. No new particles or fields are introduced. A single bounded structural parameter,  $\alpha$ , modifies gravitational coupling uniformly across expansion, structure growth, and lensing. Under this geometry-plus-*

*baryons interpretation, the apparent suppression of high- $z$  mergers reflects the combined influence of entropy-slope geometry and baryonic feedback, not dark-matter free-streaming. Distinguishing signatures include correlations of event incidence with star-formation and metallicity tracers rather than with halo-mass functions, spin and eccentricity patterns indicative of low- $z$  dynamical channels, and a stochastic background shape following a geometry-weighted star-formation history. The hypothesis is falsifiable: if high- $z$  mergers remain deficient in star-forming environments once geometric and selection biases are removed, non-baryonic microphysics is required. If the predicted correlations hold, gravitational waves will test geometry rather than dark matter.*

## 1. Introduction

The detection of gravitational waves from compact-object mergers has opened a new channel for testing cosmological structure. Binary black-hole events trace the evolution of star formation and compact-object assembly across redshift and are therefore widely viewed as probes of dark-matter microphysics. In particular, departures from the cold-dark-matter (CDM) hierarchy, through warm, fuzzy, or self-interacting dark matter,<sup>1</sup> are expected to suppress the formation of small haloes at high redshift,<sup>2</sup> reducing the birth rate of early stars and their black-hole remnants. A measurable decline in high- $z$  merger events would then be interpreted as indirect evidence for non-cold dark matter.

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<sup>1</sup> B  hm & Schaeffer, *Phys. Rep.* 516, 1 (2012). Review defining non-cold dark-matter species. Tulin & Yu, *Phys. Rep.* 730, 1 (2018). Self-interacting dark matter phenomenology.

<sup>2</sup> Lovell et al., *MNRAS* 420, 2318 (2012). WDM suppression of small-halo formation. Vogelsberger et al., *MNRAS* 460, 1399 (2016). SIDM structure-formation signatures.

A refined version of this argument has been developed by *Mirbabayi et al. (2025)*, who examine how finite number density and velocity dispersion in ultralight, wave-like dark-matter fields generate white-noise isocurvature and modify structure growth. Their model reproduces the small-scale suppression of clustering without abandoning  $\Lambda$ CDM geometry, introducing instead a coherent bosonic field to regulate halo formation.<sup>3</sup> In the TSPC framework, the same moderation of small-scale structure arises algebraically from curvature weighting rather than from new particle content

The argument appears straightforward: dark matter fixes the abundance of small haloes; haloes host the first stars; stars produce black holes; and the mergers of those black holes emit the gravitational waves now observed. Yet each link in this chain carries substantial uncertainty. Star-formation efficiency in shallow potentials depends strongly on baryonic processes: gas cooling, feedback, and reionisation; not on dark-matter microphysics alone.

Observations of dwarf-galaxy abundance, the Lyman- $\alpha$  forest, and small-scale lensing structure are each degenerate with baryonic physics such as feedback and reionisation. Numerical simulations that claim to isolate dark-matter effects on halo counts must still assume specific prescriptions for those same processes. Hence any claim that the evolution of the merger rate directly diagnoses dark-matter microphysics remains model-dependent and open to challenge.

Recent attempts to constrain the motion of dark matter directly have not advanced the empirical foundation. *Grimm et al. (2025)*<sup>4</sup> combine legacy growth-rate data with DES Y3 lensing to test whether dark matter obeys the same Euler equation as baryonic matter. The analysis is purely phenomenological: it re-mixes quantities already reduced under  $\Lambda$ CDM assumptions and interprets the result as a possible “fifth-force” amplitude. No new observations enter, and the inferred bounds depend entirely on the background model they presuppose. Such studies illustrate the degree to which the search for dark-sector dynamics has become self-referential, testing not the universe but the assumptions built into its reduction.

Ultralight-dark-matter models such as those of *Mirbabayi et al., (2025)*<sup>5</sup> exemplify how far the  $\Lambda$ CDM paradigm must now reach to preserve its form. They reproduce the observed moderation of small-scale structure by enriching the dark sector with

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<sup>3</sup> Mirbabayi, M., Delos, M. S., & Amin, M. A. (2025). *Structure Formation with Warm White Noise: Effects of Finite Number Density and Velocity Dispersion in Particle and Wave Dark Matter*. arXiv:2503.20881 – An internal refinement of  $\Lambda$ CDM introducing ultralight fields with white-noise isocurvature to mitigate small-scale anomalies.

<sup>4</sup> Grimm N., Bonvin C., and Tutusaus I., *Comparing the motion of dark matter and standard-model particles on cosmological scales*, Nature Communications 16 (2025) 9399. An open-access study proposing a phenomenological “fifth-force” parameterisation of dark-matter motion using  $\Lambda$ CDM-reduced lensing and velocity data.

<sup>5</sup> Mirbabayi, *Op cit.*

coherence and dispersion, whereas the parity constraint achieves the same moderation by limiting curvature itself. Both are empirically testable; only the latter is subtractive.

Within the framework of the TSPC, the relation between gravitational-wave incidence and dark-matter microphysics is reversed. TSPC introduces no new fields or dynamical degrees of freedom. It imposes a fixed algebraic condition on the spacetime metric, enforced by a symmetric involutive tensor and an algebraic multiplier that renormalises gravitational coupling by a small structural factor  $\alpha_\lambda$ . This constraint enforces global temporal symmetry about an epoch of maximal entropy and scale, denoted  $T^{\text{tip}}$ , while leaving all local dynamics within general relativity intact.

Under this condition, apparent variations in cosmological rates including star formation, structure growth, and black-hole mergers acquire an additional geometric weighting. Near the entropy maximum, comoving volume, look-back time, and luminosity distance are fractionally distorted by the parity-induced clock-skew already identified in earlier TSPC studies.<sup>6</sup> The effect is small but coherent: it re-weights all redshift-dependent observables by the same structural factor without invoking a dark sector.

The second ingredient is baryonic regulation. The efficiency of star and black-hole formation in shallow potentials is governed by feedback and cooling thresholds, not by the nature of unseen matter. Together, geometry and baryonic physics suffice to generate the observed moderation of high- $z$  merger rates. What appears as a suppression caused by dark-matter free-streaming is, in this framework, a joint consequence of TSPC geometric weighting and baryonic self-regulation.

This reinterpretation aligns gravitational-wave cosmology with the broader programme developed through the *Consequences* series. Earlier papers in this compendium have shown that late-time acceleration, structure growth, and lensing anomalies emerge as correlated expressions of the same algebraic correction. The present paper extends that coherence to the gravitational-wave domain. If correct, the distribution and population properties of merger events test the geometric structure of spacetime rather than the microphysics of an invisible substance.

The sections that follow outline this argument quantitatively. Section 2 summarises the conventional GW–DM linkage and the associated degeneracies. Section 3 develops the TSPC reformulation in which merger-rate evolution arises from geometry plus baryons. Section 4 identifies distinctive observational signatures that can discriminate between the two interpretations: environmental correlations, spin and eccentricity distributions, and the shape of the stochastic background. Section 5 sets out the falsifiability conditions.

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<sup>6</sup> See page 35.

## 2. Conventional Interpretation and its Limitations

The standard cosmological interpretation treats the redshift evolution of binary-black-hole (BBH) mergers as a tracer of small-scale structure formation and therefore as an indirect probe of dark-matter microphysics. The logic proceeds in four steps.

1. *Dark-matter microphysics determines the halo mass function.*  
The power spectrum of initial fluctuations is truncated at a free-streaming scale fixed by the properties of the dark-matter particle. Cold, collisionless particles preserve small-scale power, allowing haloes of mass as low as  $10^6 M_\odot$  to form at  $z > 20$ . Warm or self-interacting dark matter smooths these fluctuations, delaying or suppressing the formation of the smallest haloes.
2. *Halo abundance governs the formation of the first stars and black holes.*  
Baryons condense only within potential wells deep enough for gas to cool and form stars. Fewer early haloes imply fewer stellar systems, and hence fewer black-hole remnants capable of entering binaries.
3. *Black-hole mergers trace this population history.*  
The number of BBH coalescences per unit comoving volume,  $R(z)$ , is therefore expected to rise steeply with redshift in CDM, then flatten or decline at high  $z$  if halo formation is suppressed by non-cold dark matter.
4. *The gravitational-wave detector network measures this evolution.*  
The redshift distribution of events, together with the shape of the stochastic background, can in principle discriminate between cold, warm, or self-interacting dark-matter models.

This chain has motivated an active literature linking dark-matter microphysics to future detections by LIGO–Virgo–KAGRA, the Einstein Telescope, and Cosmic Explorer. Warm-dark-matter masses below a few keV, or significant self-interaction cross-sections, are claimed to leave measurable imprints on the merger-rate curve  $R(z)$ .

The reasoning appears clean but rests on several non-unique assumptions.

### 2.1 Baryonic degeneracy

Star-formation efficiency in shallow haloes depends critically on baryonic processes: gas cooling, radiative feedback, supernova winds, and reionisation heating.<sup>7</sup> These processes can reproduce the same suppression of early star formation that is attributed to dark-matter free-streaming. Hydrodynamic simulations tuned to match the observed stellar mass function<sup>8</sup> routinely vary such prescriptions by orders of magnitude without changing the underlying

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<sup>7</sup> Hopkins et al., *MNRAS* 445, 581 (2014). FIRE simulations on feedback regulation. Somerville & Davé, *ARA&A* 53, 51 (2015). baryonic processes and galaxy formation.

<sup>8</sup> Schaye et al., *MNRAS* 446, 521 (2015). EAGLE simulation baryon feedback tuning.

dark-matter model. Observationally, the Lyman- $\alpha$  forest, dwarf-galaxy counts, and strong-lensing substructure are all degenerate<sup>9</sup> between baryonic feedback and dark-matter physics. The link between  $R(z)$  and dark-matter microphysics is therefore not unique.

## 2.2 Observational incompleteness

The current gravitational-wave sample is dominated by events below  $z \approx 1$ . Selection effects including detector sensitivity, waveform priors, and magnification bias strongly modulate the inferred rate at higher redshift.<sup>10</sup> The apparent scarcity of high- $z$  mergers may reflect the survey horizon rather than cosmic history. In addition, the redshift distribution is not observed directly but inferred from the waveform via luminosity distance, a quantity that itself depends on the assumed cosmology. This circular dependence propagates any model bias into the inferred  $R(z)$ .

## 2.3 Environmental complexity

Compact-object binaries form through multiple channels: isolated stellar evolution, dynamical interactions in clusters, and hierarchical mergers.<sup>11</sup> Their relative contributions vary with metallicity, star-formation density, and cluster environment. Each of these factors is baryonic, not dark-matter-driven.

Because metallicity and cluster density evolve systematically with redshift, these purely baryonic dependencies can generate an apparent suppression of early mergers identical in form to that predicted for non-cold dark matter

## 2.4 Theoretical circularity

Simulations built on the  $\Lambda$ CDM expansion history, inflationary initial conditions, and isotropy that are used to predict the expected  $R(z)$  under different dark-matter scenarios, embed specific cosmological priors, so the resulting discrimination between cold and non-cold models is not theory-independent.

## 2.5 Limited falsifiability

Even if a deficit of high- $z$  events were measured, it could be absorbed by adjusting baryonic efficiencies or merger-delay distributions. Conversely, if an excess of high-redshift mergers were found, it could be attributed to an earlier or

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<sup>9</sup> Bullock & Boylan-Kolchin, ARA&A 55, 343 (2017). Review of small-scale challenges and baryon-dark-matter degeneracy. Gilman et al., MNRAS 487, 5721 (2019). Strong-lensing constraints on substructure vs baryons.

<sup>10</sup> Abbott et al. (LIGO-Virgo Collaboration), ApJ Lett. 882, L24 (2019). Observational selection in GWTC-1.

<sup>11</sup> Rodriguez et al., Phys. Rev. Lett. 120, 151101 (2018). Cluster-dynamical BH mergers. Mapelli, Front. Astron. Space Sci. 8, 23 (2021). Comprehensive review of channels.

more efficient formation of metal-free Population III stars,<sup>12</sup> a parameter that remains uncertain and can be adjusted. The interpretation therefore lacks the one-parameter falsifiability that characterises a structural constraint such as TSPC.

## *2.6 Assumed $\Lambda$ CDM background geometry*

The mapping from redshift to comoving volume, luminosity distance, and event rate is calculated within the  $\Lambda$ CDM expansion law. Alternative geometries, including those in which comoving time and observer time diverge, are not explored. Since comoving volumes and look-back times are calculated under  $\Lambda$ CDM, any geometric deviation (such as parity-induced clock skew) would manifest as a systematic bias in the reconstructed merger-rate curve.

## *2.7 Statistical isotropy and homogeneity assumption*

Merger-rate reconstructions presuppose statistical isotropy and large-scale homogeneity. Any anisotropic weighting of comoving volumes or parity-related geometric bias (such as that predicted under TSPC) is therefore excluded by construction.

## *2.8 Assumption of dark–baryon separability*

Feedback and dark-matter dynamics are treated as independent. It is presumed that baryonic effects can be cleanly corrected for, leaving a residual signal that traces dark-matter microphysics alone.

## *2.9 Limited data completeness at high redshift*

Even next-generation detectors will detect only the most massive or most favourably oriented systems beyond  $z \approx 3$ . The claimed discriminating power between dark-matter models therefore rests on a regime that is observationally inaccessible for decades.<sup>13</sup>

To sum up, the conventional linkage between gravitational-wave merger statistics and dark-matter microphysics rests on assumptions that are empirically loose and logically reversible. The observables are real; the interpretation is not unique.

## **3. TSPC Reinterpretation – Geometry plus Baryonic Regulation**

TSPC reframes the relation between gravitational-wave merger rates and cosmic structure. Instead of interpreting the evolution of  $R(z)$  as a tracer of dark-matter microphysics, the framework treats it as a consequence of two coupled influences: a

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<sup>12</sup> Greif, J., *Computational Studies of First-Star Formation*, ARA&A 51, 111 (2013). Modelling shows Pop III timing and efficiency are highly sensitive to assumptions and cannot be used as a sharp discriminator.

<sup>13</sup> Callister et al., Phys. Rev. D 106, 043029 (2022). Sensitivity forecast for ET and CE to  $z \approx 10$ .

geometric weighting of spacetime near the global symmetry, and baryonic regulation of star formation in shallow potentials.

TSPC introduces no new fields or degrees of freedom. A fixed symmetric parity tensor  $\Pi_{\mu\nu}$  acts as an involution on the metric, forbidding geometries that admit an absolute temporal direction.<sup>14</sup> A non-dynamical Lagrange multiplier  $\lambda_{\mu\nu}$  enforces the condition point-by-point. The effect is an algebraic correction to curvature coupling, governed by a single structural parameter  $\alpha_\lambda$ . This parameter is already defined in the *Consequences* sequence of papers and constrained independently by solar-system dynamics, CMB lensing, and cosmological observables. Its magnitude fixes the amplitude of all departures from  $\Lambda$ CDM.

Under the constraint, the manifold evolves symmetrically about an entropy maximum  $T^{\text{tip}}$ . Near this epoch, the relation between co-moving and observer time acquires a small parity-induced skew: elapsed proper time along null geodesics differs fractionally from cosmic time. This effect introduces a smooth geometric weighting  $W_{\text{geom}}(z)$  into all redshift-dependent observables, including merger rates. Because the weighting peaks around  $T^{\text{tip}}$ , event counts inferred per unit redshift are modestly suppressed at the highest  $z$  and mildly enhanced near the midpoint of cosmic history. The pattern mirrors that attributed in conventional models to the damping of small-scale structure by non-cold dark matter.

### 3.1 Geometric weighting

The algebraic correction to gravitational coupling is expressed as

$$G_{\text{eff}} = G(1 + \alpha_\lambda)$$

and the parity-induced clock skew along null geodesics as

$$\Delta t_{\text{obs}}(z) = \alpha_\lambda \int_0^z \sigma(T(z')) \frac{dT(z')}{dz'} dz'$$

where  $\sigma(T)$  is the entropy slope  $\frac{(\frac{1}{S})dS}{d \ln a}$ .

The differential event rate per unit redshift becomes

$$\frac{dN_{\text{GW}}}{dz} = R_*(z) W_{\text{geom}}(z) \frac{dV_{\text{com}}}{dz}$$

with

$$W_{\text{geom}}(z) = 1 + \alpha_\lambda \sigma(T(z))$$

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<sup>14</sup> For the formal definition of  $\Pi$  and proof of its Robertson–Walker admissibility, see 3 – Main Paper, Section 2.

to first order in  $\alpha_\lambda$ .

The weighting function is symmetric about  $T^{\text{tip}}$  and ensures that all redshift-dependent quantities acquire the same mild geometric modulation.

### 3.2 Baryonic regulation

The second contribution arises from the physics of star and black-hole formation in shallow potentials. Gas cooling, feedback, and reionisation heating establish a mass-dependent efficiency  $\varepsilon_{\text{baryon}}(M, z)$  that falls steeply at both very low and very high redshift. Observationally, this pattern accords with the high-redshift stellar-mass functions measured by Bunker and collaborators.<sup>15</sup> Their 2013 analysis of early galaxies revealed a rapid fall-off in the number density of massive systems beyond  $z \approx 6$ , implying that baryonic feedback alone can reproduce the observed suppression of early formation without recourse to exotic dark-matter physics. Within the TSPC framework, that decline arises geometrically, from the small parity-induced weighting of structure formation near  $T^{\text{tip}}$ , compounded by ordinary baryonic regulation in shallow gravitational potentials.

Expressed schematically, the intrinsic merger-rate density then scales as

$$R_*(z) \propto \rho_{\text{baryon}}(z) \varepsilon_{\text{baryon}}(z) \eta_{\text{binary}}(z)$$

where  $\eta_{\text{binary}}$  represents the efficiency of binary formation and survival. Each of these terms is baryonic and empirically constrained; none requires dark-matter microphysics.

The combined effect of geometric weighting and baryonic regulation gives the observed merger-rate curve:

$$R_{\text{obs}}(z) = R_*(z) [1 + \alpha_\lambda \sigma(T(z))]$$

producing a single broad maximum in event incidence at intermediate redshift, consistent with present data and forecast distributions from population synthesis.

### 3.3 Interpretive consequences

In this framework, the apparent high- $z$  suppression of mergers does not trace a free-streaming scale in the dark sector. It reflects instead the joint influence of (i) a geometric weighting imposed by the parity constraint, and (ii) baryonic self-

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<sup>15</sup> Bunker A. J. et al., *Confronting predictions of the galaxy stellar mass function with observations at high redshift*, Monthly Notices of the Royal Astronomical Society 429 (2013) 2098–2111 (arXiv:1301.2685). The study provides one of the first robust determinations of the stellar-mass function beyond  $z \approx 6$  and demonstrates the steep decline in early galaxy abundance that any geometric or baryonic-first cosmology must reproduce.

regulation in low-mass haloes.<sup>16</sup> The dependence on  $\alpha_\lambda$  replaces the multitude of unconstrained dark-matter parameters with one bounded structural constant already tested elsewhere.

Gravitational waves therefore probe geometry rather than microphysics. Their redshift evolution becomes a diagnostic of the global structure of spacetime, not of an invisible particle population.

## 4 Observational Signatures and Discriminants

The distinction between a microphysical dark-matter origin and a geometric-plus-baryonic origin for merger-rate evolution lies not in the existence of the gravitational-wave signals themselves but in the patterns of correlation among observables. The TSPC framework predicts that all departures from  $\Lambda$ CDM should be *coherent* and *cross-linked* through the same structural parameter  $\alpha_\lambda$ ; dark-matter models, by contrast, produce uncorrelated or tunable effects.

### 4.1 Rate-distribution shape

In  $\Lambda$ CDM, non-cold dark matter suppresses halo formation below a particle-dependent mass scale, producing a monotonic downturn of the intrinsic merger rate  $R(z)$  beyond  $z \approx 4$ .

Under TSPC, no microphysical cutoff exists. Instead, the observed distribution becomes

$$R_{\text{obs}}(z) = R_*(z) [1 + \alpha_\lambda \sigma(T(z))],$$

so that the deviation from  $\Lambda$ CDM takes the form of a broad symmetric modulation centred near the epoch of maximal entropy  $T^{\text{tip}}$ .

The predicted profile rises steeply from the present epoch, peaks once around  $z \approx 1-2$ , and declines gradually at higher  $z$ , matching current population-synthesis fits without invoking dark-matter free-streaming.<sup>17</sup>

A future observation of a sharp cutoff or multiple inflection points would falsify the geometric weighting model.

### 4.2 Host-environment correlations

If merger incidence is governed by baryonic regulation, the event density should correlate strongly with star-formation indicators – ultraviolet luminosity, nebular-line strength, or dust-corrected infrared flux – rather than with total

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<sup>16</sup> Tumlinson, Peebles & Werk, ARA&A 55, 389 (2017). Evidence for feedback and self-regulation via CGM outflows. Bluck et al., MNRAS 499, 230 (2020). Empirical regulation of star formation by AGN feedback.

<sup>17</sup> Madau & Fragos, ApJ 840, 39 (2017). Observational and synthesis constraints on cosmic star-formation and merger-rate evolution.

halo mass. In contrast, a genuine dark-matter suppression would correlate with halo-mass proxies but not with local star-formation density. The test therefore lies in cross-correlating gravitational-wave localisation maps with deep field catalogues from JWST, Euclid, and Rubin.<sup>18</sup>

A significant positive correlation with star-forming regions at fixed  $z$  supports the TSPC interpretation; a correlation with massive quiescent haloes would favour dark-matter microphysics.

#### 4.3 Spin and eccentricity distributions

Baryonic channels at low metallicity and in dense clusters generate wide spin-tilt distributions and a measurable tail of residual eccentricity at detection frequencies above 10 Hz.<sup>19</sup> If high- $z$  events originate predominantly from such environments, the spin-tilt dispersion  $\Delta\chi_{\text{eff}}$  and eccentricity fraction  $f_{\text{ecc}}$  should both increase with  $z$ . Warm- or self-interacting-dark-matter models, by contrast, modify halo abundance but not the internal spin structure of binaries; they predict no systematic spin-tilt evolution.

A detection of broadening  $\Delta\chi_{\text{eff}}(z)$  and rising  $f_{\text{ecc}}(z)$  is therefore a direct discriminator.

#### 4.4 Stochastic background shape

The integrated gravitational-wave background  $\Omega_{\text{GW}}(f)$  reflects the convolution of merger rate and source energetics. In TSPC the background follows the geometry-weighted star-formation history, yielding a smooth turnover frequency  $f_{\text{peak}}$  that tracks the entropy slope  $\sigma(T)$ .<sup>20</sup> Dark-matter suppression introduces a sharper high-frequency cut-off linked to the particle free-streaming scale.

A broad, symmetric spectral hump would thus indicate geometric weighting; an abrupt spectral break would imply microphysical damping.

#### 4.5 Lensing and anisotropy tests

Because the parity constraint acts globally, it can generate small, coherent anisotropies in luminosity distance and event rate across the sky. These anisotropies are frequency-independent and should align with the same large-scale axis observed in other TSPC phenomena (CMB dipole, low- $\ell$  alignments).

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<sup>18</sup> Palmese et al., ApJ Lett. 900, L33 (2020). GW–galaxy environment correlation.

<sup>19</sup> Zevin et al., ApJ 910, 152 (2021). *Spin-tilt population synthesis*. Lower et al., ApJ Lett. 918, L23 (2021). Eccentric merger detections.

<sup>20</sup> Rosado et al., Phys. Rev. D 100, 083014 (2019). Stochastic GW background from compact binaries.

Dark-matter models predict only stochastic anisotropy from structure clustering, uncorrelated with a fixed axis.

Detection of a coherent parity-aligned modulation in the gravitational-wave sky would therefore serve as a distinctive geometric signature.

#### *4.6 Cross-domain consistency*

The decisive feature of the TSPC framework is that all the following observables: rate modulation, environmental correlation, spin dispersion, background spectrum, and anisotropy, depend on the same bounded parameter  $\alpha_\lambda$ .

Once this parameter is fixed by one data set (for example, from expansion and structure-growth anomalies), the amplitude and phase of every other effect follow without further tuning. Any mismatch among domains falsifies the hypothesis outright.

### **5 Falsifiability and Empirical Tests**

The credibility of any structural hypothesis rests on its ability to fail.<sup>21</sup> TSPC is falsifiable because its single structural parameter  $\alpha_\lambda$  is common to all observables. Once that parameter is fixed from any one data domain be it expansion, structure growth, lensing, or entropy-slope geometry, the amplitude and phase of every correlated deviation are determined automatically. The gravitational-wave sector provides a further arena in which this coherence can be tested.

#### *5.1 Principle of correlated deviations*

For TSPC to hold, the fractional departures in expansion rate, structure growth, and gravitational-wave merger rates must share the same sign and fall within the same narrow range set by the structural parameter  $\alpha_\lambda$ . Any significant mismatch between these quantities would falsify the hypothesis.

#### *5.2 Empirical falsifiers*

1. *Uncorrelated anomalies.*

Observation of an enhanced Hubble rate without a corresponding rise in structure-growth or merger rates would contradict the premise of a single coupling correction.

2. *Non-symmetric rate profile.*

A monotonic or multi-peaked redshift dependence in  $R_{\text{GW}}(z)$  inconsistent with the single-hump geometry of the entropy slope  $\sigma(T)$  would falsify the geometric weighting model.

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<sup>21</sup> Popper, *The Logic of Scientific Discovery* (Routledge, 1959). Falsifiability principle (and following Popper's criterion of falsifiability).

3. *Mismatch of spin and environment.*

If spin-tilt dispersion  $\Delta\chi_{\text{eff}}$  and eccentricity fraction  $f_{\text{ecc}}$  do not rise with redshift in star-forming environments, the baryonic-regulation interpretation fails.

4. *Spectral inconsistency of the stochastic background.*

A sharp high-frequency break in  $\Omega_{\text{GW}}(f)$  indicative of a microphysical free-streaming scale would favour non-cold dark matter. A smooth symmetric turnover is required under TSPC.

5. *Absence of cross-domain coherence.*

If the value of  $\alpha_\lambda$  inferred from gravitational-wave data falls outside the narrow window already fixed by geometric, dynamical, or lensing constraints, the parity correction cannot be universal and the framework collapses.

### 5.3 Observational pathways

1. *Rate-distribution mapping.*

Einstein Telescope and Cosmic Explorer will trace  $R(z)$  to  $z \approx 10$ ; the shape alone will test the predicted geometric hump.

2. *Spin-eccentricity statistics.*

Population synthesis at advanced LIGO-Voyager sensitivity will measure  $\Delta\chi_{\text{eff}}(z)$  and  $f_{\text{ecc}}(z)$  evolution across redshift.

3. *Stochastic-background spectroscopy.*

Joint ground- and space-based analyses will constrain the spectral curvature  $d^2\Omega_{\text{GW}} / d(\log f)^2$  and test for the smooth turnover required by TSPC.

4. *Cross-correlations with star-formation density.*

Euclid, JWST, and Rubin will determine whether merger events follow baryonic tracers or total-halo mass.

5. *Large-scale anisotropy tests.*

Full-sky localisation maps can be searched for a parity-aligned axis consistent with that seen in CMB and lensing data.

### 5.4 Logical outcomes

1. *Correlated confirmation:*

If all observables align within a single  $\alpha_\lambda$  band, dark-matter microphysics is redundant, and the gravitational-wave sector validates the geometric interpretation.

2. *Partial coherence:*

If only some domains agree, TSPC may require extension but remains testable.

3. *Incoherence:*

If no common  $\alpha_\lambda$  exists, the hypothesis is falsified outright.

Coherence of fractional shifts

$$\frac{\Delta H(z)}{H(z)} \approx \frac{\Delta f \sigma_8(z)}{f \sigma_8(z)} \approx \frac{\Delta R_{\text{GW}}(z)}{R_{\text{GW}}(z)} \approx \alpha_\lambda$$

2. Geometry-weighted observed merger rate (first order in  $\alpha_\lambda$ )

$$R_{\{\text{obs}\}}(z) = R_*(z) [1 + \alpha_\lambda \sigma(T(z))]$$

3. Single-hump rate profile (no microphysical cutoff)

$$\begin{aligned} &\text{Let } z_{pk} \text{ be the unique solution of } \frac{dR_{\text{obs}}(z)}{dz} = 0, \\ &\text{with } \frac{d^2 R_{\text{obs}}(z)}{dz^2} \Big|_{z=z_{pk}} < 0, \\ &\text{and no other stationary points for } z > 0 \end{aligned}$$

4. Stochastic background smooth turnover (no sharp break)

Let  $f_{\text{peak}}$  satisfy

$$\frac{d\Omega_{\text{GW}}(f)}{d \log f} \Big|_{f=f_{\text{peak}}} = 0, \text{ with finite } \frac{d^2 \Omega_{\text{GW}}(f)}{d (\log f)^2} \text{ in a neighbourhood of } f_{\text{peak}}.$$

5. Environment and population correlation (baryonic control)

$$\begin{aligned} \text{Cov}[R_{\text{GW}}(z), \text{SFR}(z)] &> \text{Cov}[R_{\text{GW}}(z), M_{\text{halo}}(z)], \Delta \chi_{\text{eff}}(z) \\ &\uparrow, f_{\text{ecc}}(z) \text{ with } z \text{ in star-forming environments.} \end{aligned}$$

## 6 Numerical Ranges and Concluding Synthesis

The falsifiability conditions set out above require that the single structural parameter  $\alpha_\lambda$  be measurable and bounded across independent domains. That test is already under way: the range consistent with solar-system dynamics, CMB lensing, and cosmological deviations overlaps precisely with that required to explain the gravitational-wave phenomena discussed here.<sup>22</sup>

### 6.1 Empirical window for $\alpha_\lambda$

Table: Representative observables constraining the structural parameter  $\alpha_\lambda$

| Quantity | Expression                                           | Description                    |
|----------|------------------------------------------------------|--------------------------------|
| $H(z)$   | $H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}$ | Expansion rate at redshift $z$ |

<sup>22</sup> Pitjeva & Pitjev, Astron. Lett. 44, 554 (2018). Ephemeris limits on  $\Delta G/G$ .

Planck Collaboration, A&A 641, A6 (2020). CMB lensing and  $\Lambda$ CDM parameters.

DES Collaboration, Phys. Rev. D 105, 023520 (2022). Structure-growth anomalies ( $H_0$  and  $S_8$  tensions).

|                              |                                                                                                  |                                            |
|------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------|
| $F_{\text{ecc}}(z)$          | $f_{\text{ecc}}(z) = \frac{N_{\text{ecc}}}{N_{\text{tot}}}$                                      | Fraction of eccentric binaries             |
| $\Delta\chi_{\text{eff}}(z)$ | $\Delta\chi_{\text{eff}}(z) = \chi_{\text{eff}}^{\text{obs}} - \chi_{\text{eff}}^{\text{model}}$ | Effective-spin offset                      |
| $\Omega_{\text{GW}}(f)$      | $\Omega_{\text{GW}}(f) = \frac{1}{\rho_c} \frac{d\rho_{\text{GW}}}{d \log f}$                    | Gravitational-wave energy density spectrum |

The falsifiable window remains

$$10^{-6} \lesssim \alpha_\lambda \lesssim 10^{-2},$$

already established in earlier *Consequences* papers.

If the gravitational-wave sector yields values inside this range and consistent in sign with the geometric correction required by cosmological data, the hypothesis gains support.

If the inferred  $\alpha_\lambda$  lies outside or shows inconsistent correlation, the TSPC framework fails.

## 6.2 Forecast precision of future observatories

1. Einstein Telescope and Cosmic Explorer will measure  $R_{\text{GW}}(z)$  and  $\Omega_{\text{GW}}(f)$  with sufficient precision to detect fractional deviations at the  $10^{-3}$  level, probing directly into the predicted window.
2. LISA will extend the test to lower frequencies, where the background turnover predicted by the parity-induced weighting should appear as a smooth, symmetric hump rather than a sharp microphysical cutoff.
3. Cross-domain consistency can be verified by comparing the  $\alpha_\lambda$  value extracted from gravitational-wave data with that obtained from DESI, Euclid, and Rubin measurements of expansion and growth.
4. High- $z$  merger detections beyond  $z \approx 6$  will be decisive: a single-hump distribution following the entropy slope  $\sigma(T)$  supports geometry + baryons; a steep fall-off or multi-modal pattern would indicate microphysical damping.

## 6.3 Synthesis

The TSPC interpretation replaces the multiplicity of dark-matter parameters with one structural quantity  $\alpha_\lambda$ . Its falsifiability arises from correlation rather than adjustment.

If the same  $\alpha_\lambda$  aligns the deviations in  $H(z)$ ,  $f\sigma_8(z)$ ,  $R_{\text{GW}}(z)$ , and  $\Omega_{\text{GW}}(f)$ , then the anomalies attributed to dark sectors dissolve into geometry. If not, the constraint

fails outright. The gravitational-wave domain thus completes the empirical triad of expansion, structure growth, and geometry.

Within a few observational cycles, next-generation detectors will determine whether the universe's hidden symmetry extends beyond light and matter into the fabric of spacetime itself.

## 7 Concluding Remarks

The argument developed above extends the TSPC framework into the gravitational-wave domain. Where conventional analyses interpret the redshift evolution of binary-black-hole mergers as evidence for dark-matter microphysics, the present paper treats it as a structural and baryonic phenomenon. A single algebraic correction to curvature coupling, governed by the fixed parameter  $\alpha_\lambda$ , re-weights all redshift-dependent observables by the same geometric factor.

When coupled with ordinary baryonic regulation of star formation in shallow potentials, this correction reproduces the apparent high- $z$  suppression of merger events without invoking a dark sector.

The essential claim is not that gravitational waves replace dark matter, but that they test geometry rather than particle physics. Their distribution in redshift, their spin and eccentricity statistics, and the shape of their stochastic background all carry information about the same parity-induced structure that governs expansion, growth, and lensing. If a single  $\alpha_\lambda$  aligns these domains, the anomalies attributed to dark matter, dark energy, and inflation can be understood as correlated expressions of one structural constraint on the metric.

The framework remains sharply falsifiable. Every predicted deviation has a fixed sign and amplitude once  $\alpha_\lambda$  is set. An enhancement of  $H(z)$  without parallel rise in  $R_{\text{GW}}(z)$ , an asymmetric merger-rate profile, a discontinuous  $\Omega_{\text{GW}}(f)$ , or an  $\alpha_\lambda$  inconsistent with independent bounds would be a failure of coherence and would immediately exclude the model. Success, by contrast, would consolidate the empirical foundation of the entire TSPC sequence: geometry alone, governed by a single algebraic law, sufficient to account for the full suite of late-time cosmological phenomena.

The forthcoming generation of observatories such as the Einstein Telescope, Cosmic Explorer, LISA, Euclid, and Rubin, will provide the decisive tests.<sup>23</sup> Their combined

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<sup>23</sup> Punturo, M. *et al.* (2010). *The Einstein Telescope: A third-generation gravitational wave observatory*. Classical and Quantum Gravity, 27, 194002. Third-generation ground-based detector design, extending gravitational-wave sensitivity to cosmological distances.

Reitze, D. *et al.* (2019). *Cosmic Explorer: The U.S. contribution to gravitational-wave astronomy beyond LIGO*. Bulletin of the American Astronomical Society, 51, 035. Concept study for a next-generation ground-based interferometer with order-of-magnitude sensitivity gains.

Amaro-Seoane, P. *et al.* (2023). *The Laser Interferometer Space Antenna*. Living Reviews in Relativity, 26, 2. Comprehensive mission overview of LISA as a space-based gravitational-wave observatory probing the millihertz band.

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precision will either confine  $\alpha_\lambda$  within the established window  $10^{-6} \lesssim \alpha_\lambda \lesssim 10^{-2}$  and verify the predicted correlations, or else expose an inconsistency that falsifies the constraint. In either outcome, the result will be conclusive.

The gravitational-wave experiment therefore occupies a critical position within the empirical programme of TSPC. What began as a geometric postulate – time symmetry enforced by an involutive tensor field – has now been carried across expansion, growth, entropy, and lensing, and extended into the propagation of spacetime disturbances themselves. Gravitational waves do not conclude the test sequence, but they probe it at a different structural level: not through matter or light, but through the metric’s own dynamical degrees of freedom. If coherence holds across these domains, the symmetry at the heart of TSPC will have been traced consistently through observation, without recourse to unseen matter or speculative fields, and revealed instead through the silent rhythm of spacetime itself.

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