EXECUTIVE SUMMARY

TIDE Framework:

Geometric Memory in Einstein–Cartan Gravity

Introduction

The TIDE model (Torsion Induced by non-relaxation) proposes that a substantial fraction of the phenomena currently attributed to the dark sector does not correspond to new forms of matter or energy, but rather to an effective geometric response of spacetime when it is not fully relaxed.

The theoretical framework is conservative. TIDE is formulated within Einstein–Cartan–Sciama–Kibble (ECSK) gravity, introduces no additional propagating fields, does not modify early-universe cosmology, and recovers General Relativity exactly in the equilibrium limit.

The central idea is simple but unconventional: **spacetime geometry can possess dynamical memory**. After processes such as hierarchical collapse, mergers, or virialization, the geometric connection does not necessarily relax instantaneously to the Levi-Civita regime. During this out-of-equilibrium phase, a non-propagating, algebraically determined effective torsion emerges, modifying the inferred gravitational field without introducing new degrees of freedom.

Physical analogy: geometric memory with finite relaxation

An intuitive analogy is provided by a viscoelastic medium. When a load is applied and then removed, the material geometry does not instantaneously return to its original state; a residual deformation persists and decays over time. During this interval, the geometry allows one to infer an “apparent mass,” even though the original source is no longer present.

TIDE proposes an analogous mechanism in spacetime: in regions with a complex dynamical history, geometry retains memory of past perturbations and responds effectively as if an additional source were present. This source is not a new substance, but the geometry itself regulating its relaxation.

Master equation and physical mechanism

The core of the model is a Maxwell-type relaxation equation for the distortion of the geometric connection:

$$\frac{D\,\Delta\Gamma}{D\tau} + \frac{1}{\tau}\,\Delta\Gamma = \mathcal{S}_{\mu\nu},$$

where
$\Delta\Gamma$ measures the deviation from the Levi-Civita connection,
τ is an effective geometric relaxation time, and
$\mathcal{S}_{\mu\nu}$ represents dynamical sources (shear, tidal stress, mergers).

From this dynamics, a covariant scalar of non-relaxation (I_{NR}) is constructed, which algebraically controls the effective torsion. No free cosmological parameters are introduced; the constants involved act as fixed constitutive scales.

Operational map

In the relevant regime (non-linear structures and complex lines of sight), TIDE predicts an apparent gravitational excess induced by geometric memory, without introducing new matter.

Operationally:

- **Physical input (driver):** dynamical history / non-relaxation (mergers, shear, tidal stress, anisotropic flows).
- **Control variable:** covariant non-relaxation scalar $I_{\mathrm{NR}}(I_{\mathrm{NR}} \geq 0,\ I_{\mathrm{NR}} \to 0$in equilibrium).
- **Geometric output:** non-propagating effective torsion (algebraically determined) that modifies the inferred gravitational field.
- **Protected GR limit:** when $I_{\mathrm{NR}} \to 0$, effective torsion vanishes and GR is recovered exactly.

This map enables direct tests: **if the gravitational excess correlates with accumulated dynamical history rather than with instantaneous density**, the proposed mechanism is favored.

Regime of validity and cosmological consistency

- **Early universe (CMB, BBN):** geometry is relaxed ($I_{\mathrm{NR}} \to 0$). TIDE recovers GR exactly. Early cosmology and the CMB remain unaffected.
- **Cosmic voids:** low density and low dynamical complexity imply vanishing torsion. Gravity is purely Einsteinian.
- **Virialized structures:** complex dynamical history implies $I_{\mathrm{NR}} > 0$, generating effective torsion and an apparent gravitational excess.

Interpretation of the dark sector

Within this framework:

- **Dark Matter (CDM):** an effective geometric response of out-of-equilibrium spacetime in virialized structures. ΛCDM describes this regime phenomenologically, but does not identify the underlying mechanism.
- **Dark Energy:** interpreted as an effective geometric contribution associated with incomplete large-scale relaxation of spacetime, without invoking exotic fluids.
- **H_0 and S_8 tensions:** arise naturally as environmental and geometric effects, without requiring new early-time physics.

Existing tests and statistical preference

The TIDE framework has been confronted with independent observables of different nature, including:

- the evolution of strong-lensing excess

$$R(z) = M_{\text{Ein}}/M_{*} \text{from } z \sim 0.1 \text{ to } z \sim 3,$$

  non-relaxed systems and cluster collisions (e.g. Bullet-type systems),

- Bayesian model-selection analyses explicitly penalizing parametric complexity (BIC),
- causal tests in gravitational lenses based on partial correlations, bootstrap and permutation methods, distinguishing instantaneous mass dependence from dynamical history,
- comparisons on equal footing with ΛCDM, MOND, and $f(R)$theories.

When overfitting is properly penalized and physical consistency across scales is enforced, TIDE emerges as the only framework capable of reproducing the data without introducing ad hoc degrees of freedom, while maintaining coherence across galaxies, clusters, and cosmological observables where alternative models fail or require independent empirical adjustments.

Minimal reproducible evidence

The current state of the TIDE program includes observational evidence already tested with public datasets, and a minimal set of results that can be independently re-analyzed without modifying the theory:

- Gravitational lenses: evolution and ordering of inferred gravitational excess with redshift and/or environment, including robustness tests (bootstrap, permutations, controls).
- Large-scale structure: environmental signal in expansion residuals, showing monotonic ordering with environment using non-parametric tests.
- Non-relaxed systems (mergers): geometric interpretation of gas–potential offsets as memory effects (Bullet-type cases).

Falsifiable predictions

The TIDE framework leads to a clear set of observational predictions:

- saturation of dark-matter-like effects in early-type galaxies that are not fully virialized ($z \gtrsim 1.5$),
- dependence of lensing excess on accumulated dynamical history rather than solely on instantaneous density or mass,
- emergence of environmental gradients in local expansion, including systematic variations in H_0,
- suppression or absence of CDM-like effects in deep voids and low-nonlinearity regions.

Each prediction is falsifiable and testable with current and forthcoming datasets (JWST, DESI, Euclid, Rubin).

Status of the framework

Established (at the effective level):

- formulation within ECSK with no new propagating fields and exact GR limit,
- interpretation of the dark sector as an effective geometric response in non-relaxed regimes,
- existence of testable observational predictions using current data.

Open (priority for further work):

- complete microscopic derivation of the constitutive closure (exact form of the effective response and covariant driving term),
- systematic implementation and testing in standard cosmological pipelines (Boltzmann + LSS) under controlled assumptions,
- independent simulations (N-body, ray-tracing) to quantify the regime of validity and possible degeneracies with systematics.

Conclusion

TIDE does not replace ΛCDM; it completes it.
It provides the geometric mechanism underlying why spacetime behaves as if dark matter and dark energy were present, only when and where dynamical history requires it.

It is a conservative, geometric, and falsifiable extension of General Relativity, offering a unified physical interpretation of the dark sector based on geometric memory.

Explicit request to the community

The following are explicitly encouraged:

- independent re-analysis of the tests (lenses, LSS, clusters) using alternative pipelines and systematic controls,
- simulations (N-body and ray-tracing) implementing a non-propagating geometric response activated by non-relaxation, and comparison with ΛCDM under identical observational conditions,
- theoretical evaluation of the constitutive closure (what is derivable within ECSK and what is strictly phenomenological), with emphasis on covariant consistency and limiting regimes.