Luminal Scalar–Tensor Theories

via couplings to photons

How dark-energy–photon couplings reopen part of the DHOST landscape

Arina Shtennikova co-author with S. Mironov and M. Valencia-Villegas

INR RAS & ITMP MSU

07.11.2026

The question in one sentence

Our central move

The observation that gravitational waves and light travel at almost the same speed constrains their *relative* propagation; it does not, by itself, require the photon sector to remain minimally coupled to the metric on cosmological scales.

What we construct

- Gauge-invariant dark-energy–photon interactions.
- Luminal tensor and photon modes in selected DHOST classes.
- A Beyond-Horndeski subclass where GW decay into dark energy can be suppressed.

What this talk will test

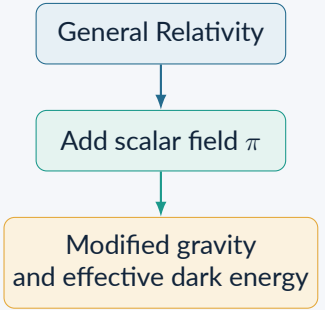
- What is actually measured by GW170817?
- How does the photon coupling change the speed relation?
- Which theories survive, and what remains unproven?

Source: Mironov, Shtennikova & Valencia-Villegas, arXiv:2412.13460v2 (2025).

Why consider scalar–tensor gravity?

- The late-time expansion of the Universe is accelerating.
- A cosmological constant is the simplest explanation, but dynamical dark energy remains a well-motivated possibility.
- Recent DESI BAO data hint at dynamical dark energy.
- A scalar field π can modify gravity on cosmological scales while contributing an effective dark-energy component.
- Derivative interactions can make the theory richer than a minimally coupled scalar field.

The challenge: build models that are cosmologically useful, dynamically healthy, and consistent with precision tests.

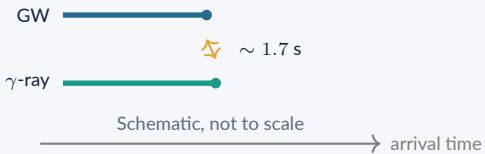


DESI 2024 BAO

(Adame et al., 2024); Ye et al. (2024); Horndeski/DHOST reviews: Langlois (2019), Kobayashi (2019).

GW170817: a remarkably sharp speed test

- On 17 August 2017, LIGO/Virgo detected gravitational waves from a binary neutron-star merger.
- The gamma-ray burst GRB 170817A was observed about 1.7 seconds later.
- The source was roughly 40 Mpc away: a tiny arrival-time offset over an astronomical distance gives an extraordinary comparison of propagation speeds.



Abbott et al. (2017); Goldstein et al. and Savchenko et al. (2017); bound as in Eq. (1) of arXiv:2412.13460. The original GW170817 analysis quotes an asymmetric range.

Speeds constraint

$$\left|\frac{c_{\mathrm{g}}}{c}-1\right| \lesssim 5\times 10^{-16}.$$

The hidden assumption behind the usual exclusion

Standard assumption

Photon remains minimally coupled

$$c_\gamma = 1, \qquad c_g \simeq 1.$$

- Light defines the reference cone.
- The bound is imposed on the tensor sector alone.
- Many non-minimal scalar–tensor models are then strongly restricted.

Alternative explored in the paper

Scalar couples to both sectors

$$\frac{c_g(t)}{c_\gamma(t)} = 1.$$

- Gravity and electromagnetism share a scalar-dependent effective cone.
- The observable is their speed ratio.
- New photon couplings must face independent tests.

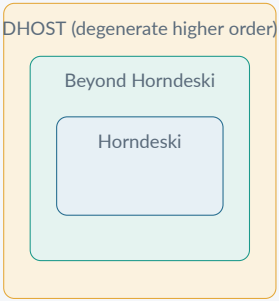
The proposal changes the assumption about light, not the observation.

The standard assumption underlies Bettoni et al. (2017); Creminelli & Vernizzi (2017); Ezquiaga & Zumalacárregui (2017); Sakstein & Jain (2017); Baker et al. (2017); Langlois et al. (2018).

Ours: arXiv:2412.13460v2, Sec. I.

Where DHOST theories fit in

- Horndeski theories have second-order field equations and are a well-known scalar–tensor framework.
- Beyond Horndeski extends this structure.
- DHOST theories allow higher derivatives in the Lagrangian but impose **degeneracy conditions**.
- Degeneracy removes the unwanted Ostrogradsky degree of freedom; not every formal choice of functions defines a healthy theory.



Nested classes, schematic

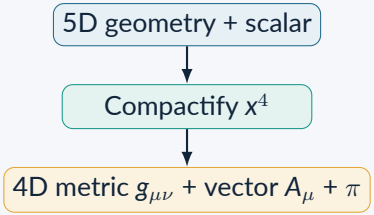
Scope of this work: theories up to cubic order in $\nabla_\mu \nabla_\nu \pi$, within the classified DHOST families that propagate a graviton.

Langlois & Noui (2016); Ben Achour et al. (2016); Langlois (2019).

A constructive route: Kaluza–Klein reduction

1. Start from a five-dimensional scalar–tensor action.
2. Write the 5D metric so that its off-diagonal components contain a 4D vector A_μ.
3. Compactify the fifth coordinate and assume the fields do not depend on it (the cylinder condition).
4. In four dimensions, the vector behaves as a photon-like gauge field coupled to the scalar and metric.

$$g^{(5)}_{BC} = \begin{pmatrix} g_{\mu\nu} + A_\mu A_\nu & A_\mu \\ A_\nu & 1 \end{pmatrix}$$



Why it helps: the 4D metric and vector descend from components of one 5D metric, motivating matched propagation properties.

Caveat. The reduction assumes a constant dilaton and breaks 5D isotropy. With a dilaton $\Phi(t)$, the speed relation gains a factor $H - \dot{\Phi}/\Phi$, which vanishes for $\dot{\Phi} = \dot{a}$. Mironov, Shtennikova & Valencia-Villegas, Phys. Lett. B 858, 139058 (2024), arXiv:2405.02281; arXiv:2412.13460, Sec. II and footnote 1.

The 4D theory: gravity plus a scalar–photon sector

$$S = \int \mathrm{d}^4x\sqrt{-g}\,(\mathcal{L}_{\mathrm{DHOST}_\pi} + \mathcal{L}_{\mathrm{DHOST}_A})\,.$$

Scalar–tensor sector

$$\mathcal{L}_{\mathrm{DHOST}_\pi} = f_2 R + f_3 G^{\mu\nu}\pi_{\mu\nu} + \cdots\,.$$

The coefficient functions depend on π and $X = \nabla_\mu\pi\nabla^\mu\pi$.

Dark-energy–photon sector

$$\mathcal{L}_{\mathrm{DHOST}_A} = -\frac{f_2}{4}F^2 + \text{other couplings}\,.$$

Here $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The same f_2 appears in $f_2 R$ and in $-\frac{f_2}{4}F^2$: this is the matching.

π and $g_{\mu\nu}$ $\leftrightarrow$ shared operators $\leftrightarrow$ A_μ / photon

Compare the propagation of tensor and vector modes

On a spatially flat FLRW background, expand around the homogeneous scalar $\pi(t)$ and a vanishing background vector.

Tensor perturbations

$$S_T = \frac{1}{2}\int \mathrm{d}t\,\mathrm{d}^3x\,a^3\left[\mathcal{G}_\tau \dot{h}_{ij}^2 - \frac{\mathcal{F}_\tau}{a^2}(\partial_k h_{ij})^2\right].$$

$$c_g^2 = \frac{\mathcal{F}_\tau}{\mathcal{G}_\tau}.$$

Photon/vector perturbations

$$S_A = \frac{1}{4}\int \mathrm{d}t\,\mathrm{d}^3x\,a\left[\mathcal{G}_A \dot{A}_i^2 - \frac{\mathcal{F}_A}{a^2}(\partial_k A_i)^2\right].$$

$$c_\gamma^2 = \frac{\mathcal{F}_A}{\mathcal{G}_A}.$$

The key matching relations

$$\mathcal{F}_A = \mathcal{F}_\tau, \qquad \mathcal{G}_A = \mathcal{G}_\tau - 3\dot{\pi}XHb_3.$$

h_{ij} is transverse-traceless; A_i is transverse; $\mathcal{G}, \mathcal{F}$ are the kinetic and gradient coefficients.

The luminality condition collapses to one function

Main speed relation

$$\frac{c_{\rm g}^2}{c_\gamma^2} = 1 - 3\,\frac{\dot\pi X H\, b_3}{\mathcal{G}_\tau}$$

If $b_3 = 0$, then $c_{\rm g} = c_\gamma$: the scalar and photon sectors share one propagation speed.

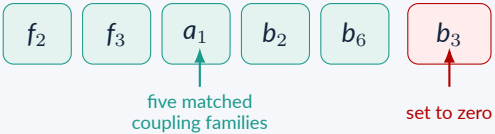
But this is not automatic

- b_3 may be fixed by degeneracy relations.
- Mixed BH + cubic with $F_5 \neq 0$: $b_3 = 0$ removes the tensor modes.
- Class N-I$_3$: $b_3 = 2b_1$, so $b_3 = 0$ forces a class without a graviton.

Which degenerate theories permit $b_3 = 0$ with a graviton?

Up to five couplings, two operator types

- The general scalar–tensor action contains several independent coefficient families.
- The photon sector must contain corresponding, self-consistent gauge-invariant interactions.
- We find up to five matched sets, associated with f_2, f_3, a_1, b_2 and b_6, that suffice for luminal gravitons in a wide set of cases.
- Only two operator types are needed. The f_3 type, $F^2\nabla^2\pi$, cannot be removed by a conformal or disformal metric redefinition.
- The b_3-associated contribution is removed by the luminality condition.



The “five” counts coefficient-matched families in the DHOST parameterization, not five arbitrary free constants.

Viable branch I: quadratic DHOST

Result (i)

Every quadratic DHOST theory that propagates a graviton can be made luminal by the corresponding photon couplings, provided the cubic coefficients are switched off and $f_3 = 0$:

$$b_i = 0, \quad f_3 = 0, \qquad \mathcal{L}_{\mathrm{DHOST_A}} = -\frac{f_2}{4}F^2 + \frac{a_1}{2}(F_{\mu\nu}\pi^\mu)^2.$$

- Quadratic Horndeski is included as a special case.
- Quadratic Beyond Horndeski (BH_4) is also included.
- Some phenomenologically relevant quadratic DHOST classes outside the Horndeski family are covered as well.

Viable branch II: Beyond Horndeski + cubic Horndeski

Result (ii)

A mixed quadratic Beyond-Horndeski plus cubic-Horndeski theory is luminal when $G_5 = G_5(\pi)$ and the corresponding scalar–photon terms are included.

The crucial photon interactions are

$$\mathcal{L}_{\mathrm{BH}_4A} = -\frac{G_4}{4}F^2 + \frac{2G_{4,X} + XF_4}{2}(F_{\mu\nu}\pi^\mu)^2,$$

$$\mathcal{L}_{H_5A} = \frac{G_5}{8}\left[4F_{\mu\nu}\nabla_\rho F^{\nu\rho}\pi^\mu + F^2\Box\pi - 4F_\mu{}^\nu F^{\mu\rho}\pi_{\nu\rho}\right].$$

- $G_4(\pi, X)$ and $F_4(\pi, X)$ remain available; G_5 depends on π only in this branch.
- The degeneracy condition is satisfied on the $G_{5,X} = F_5 = 0$ branch.

Why the new coupling is more than a field redefinition

Two consistency points

- The theory obeys the DHOST degeneracy condition: no extra Ostrogradsky mode is introduced.
- The vector–scalar Galileon interaction has higher derivatives in the Lagrangian but second-order equations of motion.
- U(1) gauge invariance is inherited from the 5D diffeomorphism structure.

A key distinction

The $G_5 F^2 \nabla^2 \pi$ interaction cannot be removed by a conformal/disformal metric redefinition depending on π and its first derivatives.

It is a genuine interaction in the 4D description.

A second obstacle: gravitational waves can decay

- Equal propagation speeds are not the only constraint on modified gravity.
- In scalar–tensor theories, a gravitational wave can interact with fluctuations of the dark-energy scalar.
- Relevant channels include schematically

$$\text{tensor mode} \longrightarrow \pi + \pi, \qquad \text{tensor mode} \longrightarrow \text{tensor mode} + \pi.$$

- If the decay is too efficient over cosmological distances, the observed GW signal would be depleted.

Why it matters

A model can pass the speed test and still fail because its gravitational waves do not survive propagation to Earth.

Creminelli, Lewandowski, Tambalo & Vernizzi, JCAP 12, 025 (2018), arXiv:1809.03484; arXiv:2412.13460, Sec. III.

The extra freedom that suppresses GW decay

In branch II, luminality does not fix all scalar potentials. In particular, $F_4(\pi, X)$ remains free. The no-large-decay condition is linear in F_4 and can be solved as

$$\boxed{F_4 = \frac{1}{2X^2}\left[2G_4 - X(4G_{4,X} + G_{5,\pi}) + \frac{4J_4(\pi)}{2G_4 + XG_{5,\pi}}\right]}$$

- $J_4(\pi)$ is an integration function (constant with respect to X).
- The condition is independent of H and $\ddot{\pi}$, hence independent of the matter content of the cosmological background.
- The model can therefore be luminal *and* suppress GW decay in a non-empty Beyond-Horndeski subclass.

arXiv:2412.13460, Eqs. (29)–(30). Babichev et al. (2024) study a different scalar–photon coupling, whose vector speed is matter dependent; ours is not.

Can the theory recover General Relativity locally?

Screening

- The extra scalar must be screened in dense environments to satisfy Solar-System tests.
- We argue that Vainshtein screening remains largely unaffected for at least some of the proposed theories.
- For quadratic DHOST there is no order-two scalar–photon mixing, so known Vainshtein results still apply.

New constraints

- The scalar–photon couplings themselves require laboratory and astrophysical bounds.
- At least the disformal-type couplings already face such constraints.
- Magnetars and other strong-magnetic-field environments are especially interesting, since the background vector can become relevant there.

Interpretation

Passing the GW speed bound is a necessary consistency step, not a complete demonstration of phenomenological viability.

Summary

1. GW170817 constrains the relative speed of gravity and light.
2. If dark energy also couples to photons, the two propagation cones can track each other without forcing the tensor sector to reduce to the standard luminal subset.
3. The condition $b_3 = 0$ identifies the DHOST classes where this can work.
4. In a Beyond-Horndeski subclass, the remaining freedom in F_4 can also suppress the decay of gravitational waves into dark energy.

The key question shifts from "Is gravity luminal?" to
"Which sectors share the same effective light cone?"

Thank you! Questions?

Backup: our research programme

2024	**Reviving Horndeski after GW170817 by Kaluza–Klein compactifications.** Establishes the 4D scalar–photon coupling idea for Galileon/Horndeski models.
2025	**Luminal Scalar–Tensor theories for a not so dark Dark Energy.** Extends the logic to classified DHOST theories and addresses GW decay.
2025	**Higher derivative scalar–vector–tensor theories from Kaluza–Klein reductions of Horndeski theory.** Develops the scalar–vector–tensor action and its scalar sector.
2025	**Ghost-free, gauge invariant SVT generalizations of Horndeski theory.** Broadens the construction to further gauge-invariant higher-derivative SVT models.

Mironov, Shtennikova & Valencia-Villegas: arXiv:2405.02281; Phys. Rev. D 111, 024028 (2025); arXiv:2509.16850 / EPJC 85, 1378 (2025).

Backup: further references

- B. P. Abbott et al., “Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger,” *ApJL* 848, L13 (2017); A. Goldstein et al., *ApJL* 848, L14 (2017); V. Savchenko et al., *ApJL* 848, L15 (2017).
- S. Mironov, A. Shtennikova and M. Valencia-Villegas, “Higher derivative scalar–vector–tensor theories from Kaluza–Klein reductions of Horndeski theory,” *Phys. Rev. D* 111, 024028 (2025).
- E. Babichev, C. Charmousis, B. Muntz, A. Padilla and I. D. Saltas, “Horndeski speed tests with scalar-photon couplings” (2024).
- D. Bettoni et al., *PRD* 95, 084029 (2017); P. Creminelli and F. Vernizzi, *PRL* 119, 251302 (2017); J. M. Ezquiaga and M. Zumalacárregui, *PRL* 119, 251304 (2017); J. Sakstein and B. Jain, *PRL* 119, 251303 (2017); T. Baker et al., *PRL* 119, 251301 (2017); D. Langlois et al., *PRD* 97, 061501 (2018).
- A. G. Adame et al. (DESI), “DESI 2024 VI: Cosmological Constraints from the Measurements of Baryon Acoustic Oscillations” (2024).

Selected references

1. S. Mironov, A. Shtennikova and M. Valencia-Villegas, “Luminal Scalar–Tensor theories for a not so dark Dark Energy,” *Phys. Rev. D* 111, L101501 (2025), arXiv:2412.13460v2. DOI: 10.1103/PhysRevD.111.L101501.
2. S. Mironov, A. Shtennikova and M. Valencia-Villegas, “Reviving Horndeski after GW170817 by Kaluza–Klein compactifications,” *Phys. Lett. B* 858, 139058 (2024), arXiv:2405.02281.
3. S. Mironov, A. Shtennikova and M. Valencia-Villegas, “Higher derivative scalar-vector-tensor theories from Kaluza–Klein reductions of Horndeski theory,” *Phys. Rev. D* 111, 024028 (2025).
4. P. Creminelli, M. Lewandowski, G. Tambalo and F. Vernizzi, “Gravitational Wave Decay into Dark Energy,” *JCAP* 12, 025 (2018), arXiv:1809.03484.
5. B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral,” *Phys. Rev. Lett.* 119, 161101 (2017), arXiv:1710.05832.
6. B. P. Abbott et al. (LIGO Scientific Collaboration et al.), “Gravitational Waves and Gamma-rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A,” *ApJL* 848, L13 (2017), arXiv:1710.05834.
7. S. Mironov, A. Shtennikova and M. Valencia-Villegas, “Ghost-free, gauge invariant SVT generalizations of Horndeski theory,” *EPJC* 85, 1378 (2025), arXiv:2509.16850.