A home rerun of the GRB 090510 light-speed test reproduces the method and gives a weaker bound

Public Fermi photons from one gamma-ray burst, with shuffled-energy and planted-delay controls, beside simulations of sound that keeps its own speed limit

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Version 1.0, 9 November 2026. Finding F281 in the findings ledger. Honest null (tier D).

Abstract

Some ideas about quantum gravity predict that light in vacuum travels at a speed that depends slightly on photon energy. A short, distant gamma-ray burst tests this well, because high-energy and low-energy photons leave together and travel for billions of years. We reran the test on the public Fermi Large Area Telescope photons from GRB 090510 with a simple method, fixed in advance. Our rerun bounds any linear energy-dependent change in light speed to less than 7.6e-18 of c at 29.9 GeV, a linear energy scale above 0.32 Planck energies, about 24 times weaker than the published limit of 7.6 Planck energies from the same burst. The value of the rerun is as a reproduction of the method, and the published limits stand. Planted delays from 1 to 10 times our bound were recovered within 0.9 percent, and the fitted slope of zero sat inside the range that shuffled photon energies gave. In the same study we simulated sound, which has a speed limit of its own. Sound in a uniform flow moved at the flow speed plus or minus the sound speed to within 1e-6, and in a simulated condensate the wave frequencies followed the Bogoliubov law within 2 percent, with a short-wavelength packet moving at 2.89 times the sound speed. Twelve of the 15 preregistered rules passed; the three that failed were two forecasts of our own bound's strength and one test of a packet near a simulated horizon.

1 What this means for a reader

Ask whether some waves can beat the speed of light, and the answer depends on which speed you mean. For light in empty space, the highest-energy photons from a burst 7 billion years away arrived with the low-energy ones, and even our plain reanalysis puts a tight lid on any energy-dependent speed. In a medium, waves have their own limits that bend at short wavelengths by an ordinary, known law. Neither result needs new physics, and the bound from our rerun is weaker than the published one, so quote the published one.

2 Introduction

Special relativity says every observer measures the same speed of light. Several approaches to quantum gravity allow a small Lorentz invariance violation in which that speed depends on photon energy. The size of such an effect is usually stated as a linear energy scale (E_QG,1), and the natural reference is the Planck energy. A photon of 30 GeV is about 1e-18 of the Planck energy, so the expected effect on its speed is tiny, and only a very long flight can make it visible.

Gamma-ray bursts give that flight. Jacob and Piran [5] derived how an energy-dependent speed turns into an arrival-time delay over a path through an expanding universe; that relation is the one used here. GRB 090510 is a short burst at redshift 0.903, measured from the spectrum of its host galaxy [6]. Abdo and colleagues [2] used the Fermi observation of this burst, with emission up to about 31 GeV, and set a lower limit of 1.2 Planck energies on the linear scale under conservative assumptions about when the photons were emitted. Vasileiou

and colleagues [3] analysed four bright Fermi bursts with three complementary methods; their strongest limit, from GRB 090510, is above 7.6 Planck energies at 95 percent confidence for the case where higher energies travel slower. The LHAASO collaboration [4] used the TeV photons of GRB 221009A and reported a linear limit above 10 Planck energies.

We had a narrower aim. A published limit rests on a pipeline most readers cannot run. We asked how close a short, plain analysis of the public photon file comes, with its forecasts and kill rules fixed before the run. The same study asked the companion question for sound: sound in a fluid has its own speed limit, and that limit is known to bend at short wavelength. Trachenko and colleagues [7] proposed an upper bound on the speed of sound in condensed matter, about 36 km per second, built from fundamental constants; it entered our study as one table check.

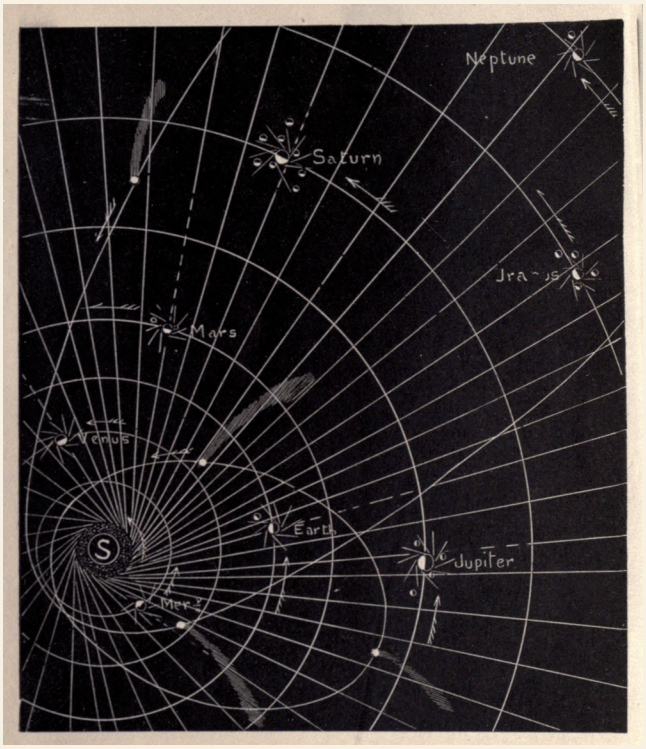


Figure 1. Robert P. Traxler, frontispiece, printed without caption or figure number: a quarter view of the solar system with the Sun at lower left, from The Principles of Mechanics as Applied to the Solar System (San Francisco, 1889) [8]. The straight lines leaving the Sun are Traxler's force lines. He drew his plates to argue for a repelling force from the Sun, his own theory in 1889, which physics did not adopt. The picture of straight paths leaving one source is the geometry a time-of-flight test depends on. Public domain; scan from the Internet Archive, University of California Libraries.

3 Preregistration and design

The preregistration and three forecast files were written and hash-locked on 31 October 2026, each before any run or data opening for its item. The hypothesis under test was that some sound and light waves travel faster or slower than c and follow different laws. The decision it informed: if the vacuum form fails, the published limits are quoted and our rerun is used only as a reproduction of method.

The lock records a debug run made before it. That run showed 84 photons in the analysis window and a bootstrap limit weaker than our forecast, so two forecast rows were known to fail. The rows were kept unchanged and are reported as failures. A one-photon bound was added after the debug run, and it is labelled as added wherever it appears. Two simulation settings were retuned in debug: the horizon packet was moved to start

near the horizon, and the grid for the frame test was doubled.

Kill conditions, fixed in advance:

- Vacuum form: killed in the tested band if the arrival-time slope against energy is consistent with zero and the implied speed change at the highest tested energy is below 1e-15 of c. It survives outside the tested band.
- Medium form: phase and group speeds above c are already known; the form is killed as new physics if every case keeps its signal front at or below c under the ordinary wave equation.
- Sound form: killed at long wavelength if sound in a moving fluid follows the flow speed plus or minus the sound speed within 1 percent.

Each kill condition and forecast became a rule set whose pass or fail is a verdict read off by code.

4 Data and provenance

The photons are from the Fermi Large Area Telescope public archive at the NASA High Energy Astrophysics Science Archive Research Center [1]: the weekly photon file for mission week 49 (processing P305, Source event class), which holds 1,214,533 photons, together with the trigger folder for bn090510016, all fetched on 31 October 2026. Fermi data are public with no restriction on use. The trigger time was read from the trigger file header. The burst position and the redshift of 0.903 were entered from memory before the run; the trigger header gives the same position to one decimal place, and the redshift matches the published value [6].

Photons were kept if they arrived between 1 s before and 3 s after the trigger, had energy above 100 MeV and zenith angle below 105 degrees, and fell within an energy-dependent radius of the burst, up to 12 degrees at low energy. That radius was set from memory of the telescope's point-spread function; the published response tables were not used. This gave 119 photons. The analysis window, 0.5 to 1.45 s after the trigger, holds 84 of them, with energies from 0.1 to 29.9 GeV. The highest-energy photon carried 29.9 GeV and arrived 0.828 s after the trigger.

The sound part uses no external data. The sound-speed table for the Trachenko check lists 14 materials with values entered from memory.

5 Methods

The delay model

If the speed of light changes in proportion to photon energy, a photon of energy E arrives later or earlier than a low-energy photon emitted with it by a time proportional to E:

$$t = t_0 + \tau E \tag{1}$$

where τ is the delay per GeV. This is dispersion in vacuum. Following Jacob and Piran [5], the slope sets the linear energy scale through a cosmological distance factor K:

$$K = \frac{1}{H_0} \int \frac{1 + x}{\sqrt{M(1 + x)^3 + 1 - M}} dx \tag{2}$$

with the integral taken from 0 to the redshift 0.903, H_0 = 67.4 km/s/Mpc and matter density M = 0.315. The factor came out at 4.58e17 s. A bound τ_{lim} on the slope gives

$$E_{QG} = \frac{K}{\tau_{lim}} \tag{3}$$

and the fractional speed change at the top energy E_{top} is

$$\delta = \frac{E_{top} \tau_{lim}}{K} \tag{4}$$

Fitting the slope

For a trial slope τ, each photon's time is shifted back to $x_i = t_i - \tau E_i$. If the trial slope is right, the shifted times bunch most tightly. The fit maximises a sharpness score

$$S = \sum_{} \sum_{} G(x_i - x_j) \tag{5}$$

over all photon pairs, where G is a Gaussian of width 30 ms. The slope was searched on a grid from -250 to +250 ms per GeV in steps of 2 ms per GeV. This is a simple version of the methods in the published analyses, without the instrument response and without a model of the burst's own spectral lag.

The bound

The 84 photons were resampled with replacement 300 times, a bootstrap, and the slope refitted each time. The 95% interval of the refitted slopes runs from its 2.5th to its 97.5th percentile, and τ_{lim} is the larger of its two ends in size. The added one-photon bound assumes the top photon was emitted no earlier than the trigger, so its delay cannot exceed its arrival time:

$$\tau_1 = \frac{t_{top}}{E_{top}} \tag{6}$$

This form follows the conservative argument of Abdo and colleagues [2] in outline only.

Sound

Three simulations solved the linear wave equation for sound in a moving fluid, in units where the sound speed c_s is 1. In a uniform flow of speed u = 0.5, rays should move at

$$v = u \pm c_s \tag{7}$$

A frame test checked that a solution transforms between frames under the sound speed and fails under a wrong one. A horizon flow $u(x) = -1 + 0.5 tanh(2\lambda x)$, with λ = 0.4, makes an acoustic horizon at x = 0 with surface gravity λ; a wave packet was released near it and its position and wavenumber compared with ray predictions.

The fourth simulation solved the one-dimensional Gross-Pitaevskii equation for a uniform condensate and measured the frequency of small plane waves at six wavenumbers. The known answer is the Bogoliubov dispersion

$$\omega = c_s k \sqrt{1 + \frac{k^2 h^2}{2}} \tag{8}$$

where h is the healing length. Its slope, the group velocity, rises above c_s once kh nears 1.

6 Controls and planted checks

Two checks were run on the photon fit.

The first control shuffled the photon energies among the 84 photons, which breaks any link between energy and arrival time, and refitted the slope 300 times. The shuffled slopes ran from -44 to +76 ms per GeV (2.5th to 97.5th percentile). The real fitted slope, 0, sits inside that range, as forecast.

The planted check added a known delay, τE, to every photon at 1, 3, 5 and 10 times our bound, with both signs, and refitted. Table 1 gives the result: every planted delay came back within 0.9 percent, so the fit sees a delay of the size of our bound when one is there.
For sound, the frame test is its own control: under the true sound speed the residual was 4.5e-4, and under a wrong speed 0.78.

Table 1. Planted delays and their recovery, ms per GeV. Error is relative to the planted value.

Planted, times our bound	Planted delay	Recovered	Error
1	117	116	0.90 percent
3	351	354	0.81 percent
5	585	590	0.81 percent
10	1,170	1,160	0.90 percent

7 Results

Vacuum

Table 2 gives the photon results. The fitted slope is 0, on a 2 ms per GeV grid. The bootstrap interval runs from -117 to +46 ms per GeV, so the bound is 117 ms per GeV. Through eq. 3 that is a linear energy scale of 3.9e18 GeV, or 0.32 Planck energies. Our rerun bounds any linear energy-dependent change in light speed to less than 7.6e-18 of c at 29.9 GeV, a linear energy scale above 0.32 Planck energies, about 24 times weaker than the published limit of 7.6 Planck energies from the same burst. The speed change is below the preregistered 1e-15, so the vacuum form of the hypothesis is killed in the band tested, 0.1 to 30 GeV.

Table 2. Photon results from the rerun. Times are after the trigger.

Quantity	Value
Photons above 100 MeV near the burst, 1 s before to 3 s after	119
Photons in the analysis window, 0.5 to 1.45 s	84
Top energy and its arrival time	29.9 GeV at 0.828 s
Fitted slope	0 ms per GeV
Bootstrap 95% interval, 300 resamples	-117 to +46 ms per GeV
Bound on the slope	117 ms per GeV
Linear energy scale from the bound	above 0.32 Planck energies
Fractional speed change at 29.9 GeV	below 7.6e-18
One-photon bound (added after the debug run)	27.7 ms per GeV, above 1.36 Planck energies
Shuffled-energy slopes, 300 draws	-44 to +76 ms per GeV

Figure 2 sets our two bounds beside the published ones. The bootstrap bound is weak because resampling often leaves out the single 29.9 GeV photon, which sets most of the fit. The one-photon bound uses that photon directly and reaches 1.36 Planck energies, still a factor of about 5.6 below the published 7.6.

Sound

Table 3 gives the simulation results. Sound in a uniform flow moved at the flow speed plus or minus the sound speed to within 1e-6, and in a simulated condensate the wave frequencies followed the Bogoliubov law within 2 percent, with a short-wavelength packet moving at 2.89 times the sound speed. Figure 3 shows the measured frequencies leaving the sound line as the wavelength nears the healing length.

The horizon packet stayed trapped, and its wavenumber followed the ray prediction within 3.3 percent. Its position lagged the ray by 0.16 in scaled units against a limit of 0.01, which failed. The packet is about as wide as the distance it travels, so a ray, which has no width, is a poor description of it; we did not refine the test after the run.

The Trachenko value computed from constants was 36.10 km per second, inside the forecast band of 36.0 to 36.2, and none of the 14 materials in our remembered table exceeded it; the fastest was diamond at 18 km per second.

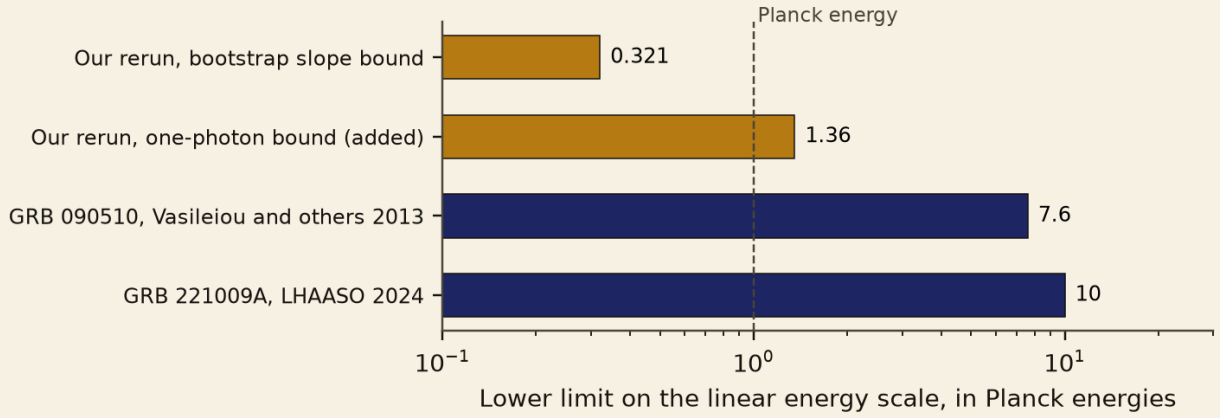


Figure 2. Lower limits on the linear energy scale: our rerun's bootstrap and one-photon bounds against the published GRB 090510 and GRB 221009A limits. Drawn from the run's result file, which lists the published values as quoted from their abstracts.

Table 3. Sound simulations, in units where the sound speed is 1. Limits are the preregistered rules.

Quantity	Value	Rule
Uniform flow, error in ray speed	9.6e-7	below 0.01
Frame test, residual with true sound speed	4.5e-4	below 0.001
Frame test, residual with wrong speed	0.78	above 0.1
Horizon, packet trapped inside, position at end	-24.8	below 0
Horizon, packet lag behind the ray, scaled	0.16	below 0.01
Horizon, wavenumber error against the ray	3.3 percent	below 20 percent
Bogoliubov law, worst frequency error	1.95 percent	below 2 percent
Group velocity at kh = 1, from the law	1.63	above 1.1
Packet group velocity, kh = 2	2.89	above 2

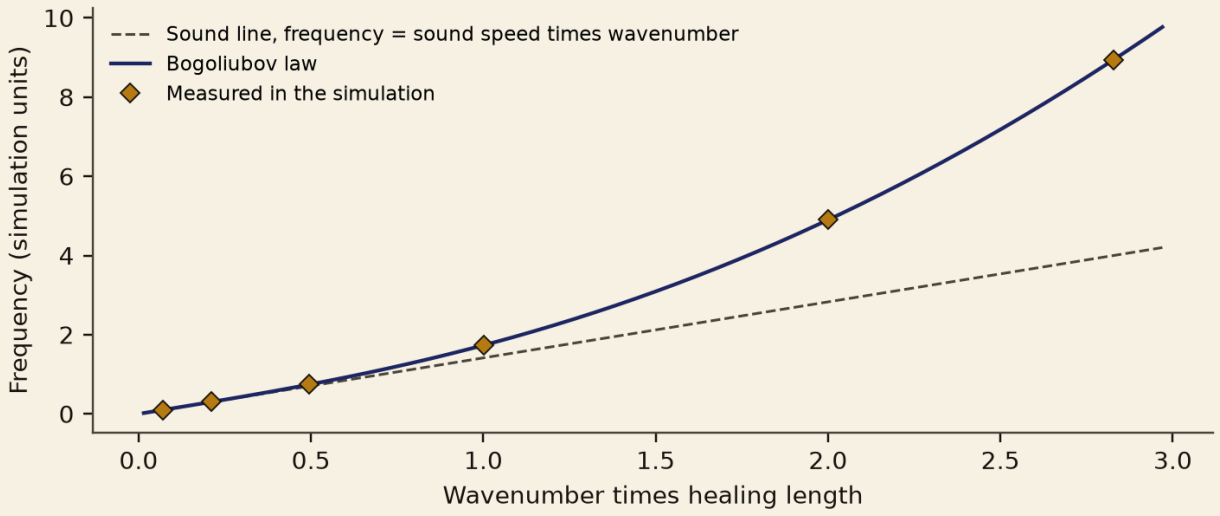


Figure 3. Wave frequency against wavenumber in the simulated condensate. The six measured points lie on the Bogoliubov law and leave the straight sound line at short wavelength. Drawn from the run's result file.

Forecasts

Table 4 sets the forecasts written before the run against the outcomes.

Table 4. Forecasts fixed before the run against what it gave.

Quantity	Forecast	Outcome
Photons in the window	about 150, band 50 to 300	84
Slope bound	below 30 ms per GeV	117 ms per GeV
Linear energy scale	0.5 to 10 Planck energies	0.32
Planted delay at 5 times the bound	within 20 percent	0.81 percent
Shuffled range contains the real slope	yes	yes
Rays in a uniform flow	within 1 percent	9.6e-7
Frame test with the sound speed	to 1e-3	4.5e-4
Group velocity at kh = 1	more than 10 percent above sound	1.63 times
Group velocity at kh above 2	about twice sound or more	2.89 times
Trachenko bound	36.1 km/s	36.10 km/s

Twelve of the 15 preregistered rules passed; the three that failed were two forecasts of our own bound's strength and one test of a packet near a simulated horizon. Appendix A lists every rule.

8 Discussion

The rerun did what a reproduction of method should do. On the same burst, with a plain fit, it finds no energy-dependent delay, and its controls behave: shuffled energies give a range that holds the real slope, and planted delays of the bound's size come back almost exactly. The number it produces is weaker than the published limits, by a factor of about 24 for the bootstrap bound and about 5.6 for the one-photon bound.

The gap has visible causes. Our bootstrap is dominated by whether the single 29.9 GeV photon is drawn, which makes the interval wide. The published analyses used the instrument response, careful event selection and several estimators, and they modelled or bounded the burst's own spectral lag [3]. We did none of that. The top energy also differs: the published abstract reports emission up to about 31 GeV [2], and our selection's top photon has 29.9 GeV in the weekly file's reconstruction; we did not trace the difference.

So the vacuum result is a check that the method can be run from public data and lands in the right place. It sets no new limit. The published limits of 7.6 Planck energies from this burst [3] and 10 from GRB 221009A [4] are the numbers to quote.

The sound results confirm known theory. Sound in a moving fluid obeys its own cone, flow speed plus or minus sound speed, at long wavelength, and it leaves that cone at short wavelength by the Bogoliubov law. A wave can then move faster than the sound speed of its medium by an ordinary mechanism, and it remains far below c. The hypothesis that some waves follow different laws holds only in that ordinary sense.

9 Limitations

- The bound holds only in the tested band, about 0.1 to 30 GeV, and only for a delay linear in energy. The quadratic form, other energies and other carriers were not tested.
- No instrument response and no intrinsic spectral lag were modelled. The selection radius was set from memory of the point-spread function, and the burst position and redshift were entered from memory, though both match published values.
- The bootstrap is unstable when one photon sets most of the fit, which is part of why our bound is weak.
- The one-photon bound was added after the debug run, and its assumption about emission time is not tested.
- A later review of our ledger noted that the rerun does not reproduce the published number. We agree, and the paper is framed as a reproduction of method for that reason.
- The sound simulations test known theory and add no new law. The Trachenko table values were entered

from memory.

- Scoring was by our own code and was not blind. Settings tuned in the debug run before the lock are listed in the preregistration.

10 Verified

Verified: on 9 November 2026 the photon counts (1,214,533 in the file, 119 near the burst, 84 in the window), the top energy and its arrival time, the fitted slope, the bootstrap ends, the bound, the distance factor, both energy scales, the speed change, the shuffled range, the four planted recoveries, every sound value in Table 3, the Trachenko value and the 15 verdicts were re-read from the run's result file. They match the findings ledger, including its later line that our bound is about 24 times weaker than the published limit. The preregistration's SHA-256 matches the hash recorded in the result file and in the lock file. Both figures were drawn by a script that reads only that result file. The study was not re-run for this paper. The literature was found by searches run on 9 November 2026 and read at the level of abstracts, publisher pages and search summaries; the full texts were not read. The published limits in Figure 2 are as quoted from those abstracts.

11 Corrections

- 31 October 2026: a review of our ledger noted that the rerun limit, 0.32 Planck energies by bootstrap and 1.36 by one photon, is far below the published 7.6 and 10, so the rerun does not reproduce the published limit. The headline was narrowed to a reproduction of method, as here.
- 9 November 2026: first published version.

12 Reproduction

- Data: download the Fermi LAT weekly photon file for mission week 49 and the trigger folder bn090510016 from the HEASARC Fermi archive.
- Select photons from 1 s before to 3 s after the trigger, above 100 MeV, zenith angle below 105 degrees, within an energy-dependent radius of the burst; keep the 0.5 to 1.45 s window.
- Fit the slope of eq. 1 by maximising eq. 5 on a 2 ms per GeV grid; bootstrap 300 times; convert the larger end with eqs. 2, 3 and 4.
- Shuffle energies 300 times for the null, and plant delays at 1, 3, 5 and 10 times the bound.
- For sound, solve the linear wave equation in uniform and horizon flows and the Gross-Pitaevskii equation for a uniform condensate, and compare with eqs. 7 and 8.
- Preregistration SHA-256: 21d88e4c1e21947ade3dbf27f640ddcef60e8c4e3df62ca52aa9b9610aaf595f. Plan SHA-256: acdcc05f486faa9c825953e7cd25544719c1053d0dd865f851012eb98255770a. Run 20261031T213610Z.
- Cost: the analysis took about 127 s and the shuffle control about 8 s on one desktop CPU.

13 Appendix A. The preregistered verdicts

Each verdict is a set of rules written before the run. A verdict passes only when every rule holds. Values are read from the run's result file.

14 Glossary

Each term is defined where it is first used in the text. The same definitions, with the field each comes from and what each excludes, are collected here.

- **Lorentz invariance violation**. Any departure from the rule of special relativity that every observer measures the same speed of light; the form tested here is a speed of light in vacuum that changes with photon energy.

Table 5. Preregistered verdicts and the rule that decided each one.

Verdict	Deciding rule	Value	Holds
Photon count	50 to 300 photons in the window	84	yes
Slope bound	below 30 ms per GeV	117	no
Energy scale band	0.5 to 10 Planck energies	0.32	no
One-photon form (added)	0.5 to 10 Planck energies	1.36	yes
Vacuum form killed	speed change below 1e-15	7.6e-18	yes
Planted delay	error at 5 times the bound below 0.2	0.0081	yes
Slope inside null	real slope inside shuffled range	inside	yes
Uniform flow	ray speed error below 0.01	9.6e-7	yes
Frame test	true speed below 0.001; wrong speed above 0.1	4.5e-4; 0.78	yes
Horizon ray	scaled lag below 0.01; trapped inside, free outside	0.16; -24.8, 24.8	no
Surface gravity	wavenumber error below 0.2	0.033	yes
Bogoliubov	worst frequency error below 0.02	0.0195	yes
Above sound speed	group velocity at kh = 1 above 1.1; packet above 2	1.63; 2.89	yes
Trachenko value	36.0 to 36.2 km/s	36.10	yes
Trachenko table	no material above the bound	0	yes

Field: particle physics and quantum gravity phenomenology. Excludes the slowing of light in a medium such as glass or plasma, which is ordinary optics.

- **linear energy scale (E_QG,1)**. The photon energy at which a speed change that grows in proportion to energy would reach the full speed of light; a lower limit on it is the usual way to state a time-of-flight bound. Field: quantum gravity phenomenology. Excludes the quadratic scale, for a speed change that grows with the square of energy, which this paper does not bound.
- **Planck energy**. The energy built from the constant of gravitation, Planck's constant and the speed of light, about 1.22e19 GeV; many quantum-gravity models expect new effects near it. Field: physics. Excludes any energy reached by a particle accelerator, which is about fifteen powers of ten lower.
- **preregistration**. A dated written plan for a study, fixed and hash-locked before any result is seen: the question, the data, the statistic, the controls, the forecasts and the kill conditions. Field: research method (meta-science). Excludes a plan revised after looking at the outcome, and a protocol written only for the record after the run.
- **kill condition**. A rule written in the preregistration that, when met, decides against the claim with no room for judgement after the run. Field: research method (our usage, after Popper's falsification). Excludes reasons found after the run for setting a result aside.
- **verdict**. The pass or fail of one preregistered rule set against the run's numbers, read off by code. Field: research method (our usage). Excludes an interpretation written after reading the numbers.
- **dispersion**. The dependence of a wave's speed on its frequency or energy, written as a relation between frequency and wavenumber. Field: wave physics. Excludes a delay that is the same at every energy, such as a fixed travel time.
- **bootstrap**. Resampling the data with replacement many times and recomputing the estimate each time, so that the spread of the recomputed values gives an interval for it. Field: statistics. Excludes an interval taken from a formula that assumes a distribution.
- **95% interval**. The range that holds the middle 95 percent of the bootstrap or control draws for a number; we report it beside the number. Field: statistics. Excludes a statement that the true value lies inside with 95 percent probability.
- **acoustic horizon**. The place in a moving fluid where the flow speed equals the sound speed, so that sound travelling against the flow cannot get out; it mimics the horizon of a black hole. Field: analogue gravity.

Excludes a gravitational horizon, and any place where the flow is slower than sound.

- **surface gravity (of a horizon)**. The slope of the flow speed at the acoustic horizon; it sets how fast a trapped wave's wavelength is stretched. Field: analogue gravity, after black-hole physics. Excludes the pull of gravity at a planet's surface.
- **Bogoliubov dispersion**. The frequency of small waves in a uniform condensate: equal to the sound speed times the wavenumber at long wavelength and rising faster, towards the free-particle law, at wavelengths near the healing length. Field: condensed-matter physics (Bose-Einstein condensates). Excludes sound in an ordinary gas or solid, whose dispersion is set by other physics.
- **healing length**. The length below which a condensate's density cannot change smoothly; waves shorter than it stop behaving like sound. Field: condensed-matter physics. Excludes the wavelength of any particular wave.
- **group velocity**. The speed at which a packet of waves, and the energy it carries, moves; it equals the slope of frequency against wavenumber. Field: wave physics. Excludes the phase velocity, the speed of a single crest, which can differ from it.
- **control**. A version of the data with the structure under test removed (for example shuffled or pooled), scored the same way as the real data, so the real score has something to beat. Field: statistics and experimental design. Excludes a comparison with a different dataset or with a published number.
- **planted check**. Data built so that the right answer is known, run through the same analysis before the real data, to show that the analysis can see the effect when it is there. Field: research method; called a positive control in experimental science. Excludes any check made on the real data, which cannot show what the analysis misses.
- **findings ledger**. The append-only, dated list of every result we have recorded, numbered F1, F2 and on; corrections are added as new dated lines and old entries are never rewritten. Field: our records. Excludes a curated list of successes.

15 References

[1] Fermi Science Support Center. Fermi LAT weekly photon files and trigger data for bn090510016. NASA High Energy Astrophysics Science Archive Research Center. Retrieved 31 October 2026. https://heasarc.gsfc.nasa.gov/FTP/fermi/data/lat/

[2] Abdo, A. A., Ackermann, M., Ajello, M. and others, Fermi LAT and GBM Collaborations (2009). A limit on the variation of the speed of light arising from quantum gravity effects. Nature 462, 331-334. doi:10.1038/nature08574

[3] Vasileiou, V., Jacholkowska, A., Piron, F., Bolmont, J., Couturier, C., Granot, J., Stecker, F. W., Cohen-Tanugi, J. and Longo, F. (2013). Constraints on Lorentz invariance violation from Fermi-Large Area Telescope observations of gamma-ray bursts. Physical Review D 87, 122001. doi:10.1103/PhysRevD.87.122001. arXiv:1305.3463

[4] Cao, Z. and others, LHAASO Collaboration (2024). Stringent tests of Lorentz invariance violation from LHAASO observations of GRB 221009A. Physical Review Letters 133, 071501. doi:10.1103/PhysRevLett.133.071501. arXiv:2402.06009

[5] Jacob, U. and Piran, T. (2008). Lorentz-violation-induced arrival delays of cosmological particles. Journal of Cosmology and Astroparticle Physics 0801, 031. doi:10.1088/1475-7516/2008/01/031. arXiv:0712.2170

[6] Rau, A., McBreen, S., Kruehler, T. and Greiner, J. (2009). GRB 090510: VLT/FORS2 spectroscopic redshift. GCN Circular 9353.

[7] Trachenko, K., Monserrat, B., Pickard, C. J. and Brazhkin, V. V. (2020). Speed of sound from fundamental physical constants. Science Advances 6, eabc8662. doi:10.1126/sciadv.abc8662

[8] Traxler, R. P. (1889). The Principles of Mechanics as Applied to the Solar System. San Francisco: C. A. Murdock and Co. Internet Archive item principlesofmech00traxiala.