Gamma-Ray Bursts Delay and Lorentz Invariance Violation

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Gamma-ray bursts (GRB) delay

- Experimental observation of

  gamma-ray bursts (GRB) delay

  (ANTARES experimental data taken 2007 – 2012)

  Adrian-Martinez et al (2018)

  with gamma ray energies analyzed up to 100 TeV has been interpreted as a sign of

  Lorentz invariance violation (LIV).

- But is this necessary when breaking Special Relativity but leaving General Relativity intact?

  We shall come to this later.

GRB and the disperssion of light in interstellar space

- Possibility of explaining GRB delay by standard physics - dispersion of light travelling through the interstellar space.
- Dispersion relation in a medium like electron plasma is:

$$\omega^2 = k^2 c^2 + \omega_p^2, \tag{1}$$

with

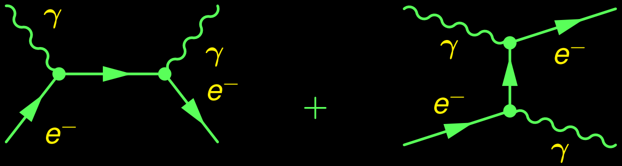
$$\omega_p^2 = \frac{Ne^2}{\varepsilon_0 m_e} \tag{2}$$

square of the plasma frequency, N is the mean number density of particles, ε_0 the permittivity in vacuum and m_e is the electron mass.

e.g., Jackson (book, 1999)

Chaichian, Merches, Radu, Tureanu (book, 2016)

- The same is obtained from Quantum Field Theory/Green function methods



We used analogy with wave scattering, as given in Bohr, Peierls and Placzek (1939). (For the use of Green function methods in quantum statistics, see Abrikosov, Gorkov and Dzyaloshinski (book, 1963))

- Group velocity of light in plasma:

$$v_{GRB} = \frac{d\omega}{dk} \simeq c\left(1 - \frac{\omega_p^2}{2\omega^2}\right) \equiv c(1-d). \quad (3)$$

- With $m_e = 0.511$ MeV, one obtains for the gamma-ray energy 1 TeV,

$$v_{GRB} = c(1 - 0.7 \times 10^{-51} \times N \times \text{metre}^3) \quad (4)$$

Therefore, dispersive properties of an electron gas are not significant enough to account for a time delay of the order of several hours as observed.

GRB and disperssion by axions

- Look for particles of much lower mass, like the

$$\text{AXIONS, with } m_{axion} = 10^{-5}\ \mathrm{eV}/c^2$$

- But axions are not charged.
- Vivid activity in axion electrodynamics

F. Wilczek (1987),
Basar, Dunne (2003),
A. Martin-Ruiz et al (2015),
K. Fukushima (2019),
CAST-CERN Axion Solar Telescope

  with its connection to topological insulators [CAST-CERN Axion Solar Telescope].
- Assumptions of an axionic plasma with its coupling to photons seems natural.

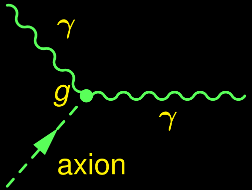
- Effective coupling of axion to two photons given by the interaction Lagrangian

e.g. Sikivie (2020),
Halverson et al (2019)

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g a(x) F^{\mu\nu}(x) \tilde{F}_{\mu\nu}(x), \tag{5}$$

where

$$g \equiv g_\gamma \frac{\alpha}{\pi} \frac{1}{f_a}, \qquad g_\gamma = \frac{1}{2}\left(\frac{N_e}{N} - \frac{5}{3} - \frac{m_d - m_u}{m_d + m_u}\right). \tag{6}$$



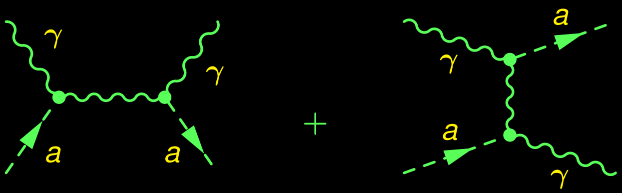
- Dispersion of light in an axionic plasma, $\omega^2 = k^2 c^2 + \omega_p^2$.

- Axion plasma frequency obtained from Quantum Field Theory for high-energy photons: Brevik, Chaichian and Oksanen (2021)

$$\omega_p^2 = \frac{3}{8} g^2 N_{axion} m_{axion} = \frac{3}{8} g^2 \rho_{axion}. \tag{7}$$

N_{axion} is the number density of axions in the cosmic plasma.

This formula has not been obtained before from classical electrodynamics or from quantum field theory.



- Notice how the axion formula (7) compares to the electron plasma (2), $\omega_p^2 = Ne^2/m_e$.

- Group velocity of gamma-rays in axion plasma:

$$v_{GRB} = c(1 - d), \qquad d = \frac{3}{16}\frac{g^2 \rho_{axion}}{\omega^2}. \tag{8}$$

- Estimate for g, the effective coupling constant,

$$g \simeq 10^{-10}\ \mathrm{GeV}^{-1}.$$

- In GUT models

$$g_\gamma = \frac{m_u}{m_d + m_u} \simeq 0.36$$

- For axion mass density $\rho_{axion} = \bar{\rho}_{axion} \times 1\ \mathrm{GeV}/\mathrm{m}^3$ and gamma-ray energy $E = \bar{E} \times 1\ \mathrm{GeV}$, we have

$$d = 1.4 \times 10^{-68} \times \frac{\bar{\rho}_{axion}}{\bar{E}^2}. \tag{9}$$

- Then the delay of the gamma-ray bursts in axion plasma is

$$\tau = \frac{D \times d}{c} = 1.4 \times 10^{-68} \times \frac{\bar{\rho}_{axion}}{\bar{E}^2} \times \frac{D}{c}, \tag{10}$$

where D is the effective distance traveled by photons.
(This is the delay if the velocity of neutrinos is c.)

- The mass density of axions in Galactic Halo (GH) is $\rho_{axion} = 0.45$ GeV/cm^3. The radius of GH is 5×10^{20} m.

ADMX Collaboration (2020)

The delay of GRB due to axions is $\tau = 1.1 \times 10^{-50}$ s $\times \bar{E}^{-2}$.

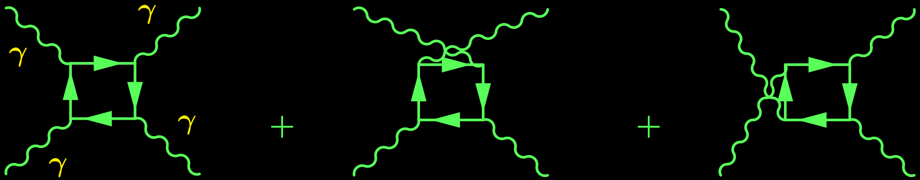
- For a huge galaxy filament the average axion density is estimated as $\rho_a = 10^3$ GeV$/$m^3 and the effective distance is $D = 3$ Gpc $= 9 \times 10^{25}$ m. Then the delay of GRB is $\tau = 0.7 \times 10^{-48}$ s $\times \bar{E}^{-2}$. The delay is negligible for high-energy photons, as it also is in the case of GH.

- $\rho_{axion} \propto N_{axion}$:
  - clearly a function of its place in the medium, distance-dependent.
  - While nearby to us very high density not natural,
  - at very far distances in the stellar space, many heavy galaxies, N_{axion} by far larger/ axion coupling much enhanced
- Side remark:
  - For electron plasma, no magnetic contribution: parity of medium.
  - For a "Chiral Medium" also magnetic field contribution ===> enhancement of g ===> reducing N_{axion}.
  - Such chiral medium with magnetic contribution affects the Casimir effect

Jiang and Wilczek (2019)
Høye and Brevik (2020)

Light dispersion in light plasma and CMB

- Usual photon-by-photon scattering due to fermions:



Euler (1936)
Euler and Heisenber (1936)
Akhiezer (1937)
Karplus and Neumann (1951)
Beresteskii, Lifishitz and Pitaevskii (book, 1982)

- Our derivation gives

Brevik, Chaichian and Oksanen (2021)

$$\omega_p^2 = \text{const.} \times \frac{N_\gamma e^4}{\omega}.$$

where N_γ is the number density of photons.

- According to the Planck data on CMB: $N_\gamma = (4-5) \times 10^8\ \mathrm{m}^{-3}$.

Planck collaboration results (2018)

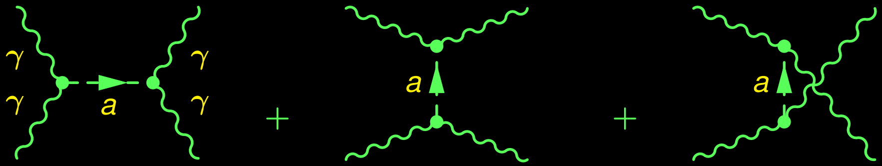
- The GRB delay produced by CMB is estimated as

$$\tau_{\rm CMB} = \frac{4 \times 10^{-23}}{\bar{E}^{3/2}} \times \frac{D}{c}. \tag{11}$$

Brevik, Chaichian and Oksanen (2021)

- For GRB originating from the farthest galaxies ($D = 1.4 \times 10^{26}$ m) the delay produced by the interaction with CMB is $\tau_{\rm CMB} = 2 \times 10^{-5}\ \mathrm{s}/\bar{E}^{3/2}$; e.g. for a gamma-ray energy $E = 100$ GeV the delay is $\tau_{\rm CMB} = 2 \times 10^{-8}$ s. This is a very short delay but still much longer than the delay produced by electrons.

- Axions enable photon-by-photon scattering via exchange of axions:



- In high energies $\omega \gg m_a$, we have

$$\omega_p^2 = \frac{\sqrt{5} N_\gamma g^2}{16\sqrt{2}} \frac{\omega}{1 - \frac{m_a^2}{4\omega^2}} \simeq \frac{\sqrt{5} N_\gamma g^2}{16\sqrt{2}} \omega, \tag{12}$$

where $\omega = \sqrt{s}/2$ in terms of the invariant s.

Brevik, Chaichian and Oksanen (2021)

- Group velocity of gamma-rays in the photon medium is

$$v_{GRB} = 1 - d, \quad d = \frac{\sqrt{5} N_\gamma g^2}{32\sqrt{2}\omega}. \tag{13}$$

- Estimating the effective coupling constant to be $g = 10^{-10}\ \mathrm{GeV}^{-1}$, the contribution of axion exchange to the GRB delay produced by CMB is

$$\tau_{\mathrm{CMB}} = \frac{3 \times 10^{-54}\ \mathrm{s}}{\sqrt{E}} \times \frac{D}{c}. \tag{14}$$

- For GRB originating from the farthest galaxies ($D = 1.4 \times 10^{26}$ m) the delay produced by the interaction with CMB is $\tau_{\mathrm{CMB}} = 2 \times 10^{-36}\ \mathrm{s}/\sqrt{E}$; e.g. for gamma-ray energy $E = 100$ GeV the delay is $\tau_{\mathrm{CMB}} = 2 \times 10^{-37}$ s, which is a negligible delay.

Lorentz invariance violation - interpretation of GRB delay

- High-Energy Tests of Lorentz Invariance: Possibility of breaking Lorentz symmetry group to one of its subgroups.

  Coleman and Glashow 1999

- Does dispersion relation (between E, p and m) always change?
  Not necessarily. Example Noncommutative Quantum Field Theory:

  Seiberg and Witten (1999)

- Lorentz symmetry violated but dispersion relation not (due to residual twisted Poincaré symmetry)

  Chaichian, Kulish, Nishijima and Tureanu (2004)

- A large activity in general on modified dispersion relations/ LIV:

  Amelino-Camelia, Ellis, Mavromatos and Nanopoulos (1997)

  Amelino-Camelia, Ellis, Mavromatos, Nanopoulos and Sarkar (1998)
- All those activities are base on a "Stringy Foam Model", i.e. all of them are "Induced LIV", but not an "Intrinsic/genuine LIV".
- As well as large activity for GRB delay (using LIV) started by

  Jacob and Piran (2007) and (2008)
- Special Relativity dispersion relation changed to

$$E^2 = c^2 p^2 - \epsilon c^4 p^4 + \sum_n a_{2n} p^{2n}$$

or typically for group velocity (up to 2nd term) as:

$$v_g = c \left(1 - \xi \frac{E}{E_{QG}} \right)$$

E_{QG} assumed as effective quantum gravity scale, usually taken $10^{19} GeV$, ξ arbitrary parameter.

Resolution between Cosmic Plasma and LIV interpretations

Light dispersion in cosmic plasma: $v_{GRB} = c\left(1 - \frac{\omega_p^2}{2E^2}\right)$ or

Lorentz invariance violation (modified dispersion relation): $v_g = c\left(1 - \xi\frac{E}{E_{QG}}\right)$?

Energy-dependence of delay:

- Light dispersion in cosmic plasma: higher-energy gamma rays —> less delay
- Lorentz invariance violation: higher-energy gamma rays —> more delay.

Future experiments with frequency of light resolution will decide

HAWC Collaboration (2020)
MAGIC Collaboration (2020)

Neutrino bursts

- **Neutrino in cosmic plasma**:
  – Dispersion of neutrinos negligible.
  – Massive and oscillating : $E^2 = c^2p^2 + m^2c^4$

$$v_\nu = \frac{dE}{dp} \approx c(1 - d_\nu), \quad d_\nu = \frac{m^2c^4}{2E^2}$$

  – Averaging over 3 neutrinos: $\langle m^2c^4 \rangle = (1/3)(0.1 \text{ eV})^2$, and for $E = 1$ TeV,

$$v_\nu = c(1 - 1.7 \times 10^{-27}),$$

  justifying our taking $v_\nu = c$.
- Noteworthy: experimentally not known whether GRB arrive later or earlier!

IceCube Collaboration (2020)

Conclusions

I. Invoking LIV to interpret GRB delay is NOT consistent: modified dispersion relation should be universal and not particle-dependent.

- Then, GRB and neutrino burst will not have different velocities.
- In addition, breaking Special Relativity implies breaking of General Relativity.

II. Dispersion of light in a variety of cosmic plasmas as media did not explain the GRB delay.

★ However, all the estimates used were averages over all the Universe, or a part of it.

★ These failures and a future explanation will shed light on the MICROSTRUCTURE of the UNIVERSE.

★ Future planned experiments with spectrum resolution of light shall resolve between the two possible interpretations.

Conclusions

All the theoretical interpretations of LIV using the existing experimental "results" (which involve many assumptions)

are Induced Lorentz Invariance Violation,

not Intrinsic/genuine Lorentz Invariance Violation.

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