Frequency variation for in vacuo photon propagation in the Standard-Model Extension

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Highlights of the talk

- Context and motivations
- Non-linear and Massive theories (Born-Infeld, Heisenberg-Euler, de Broglie-Proca, Stueckelberg,...)
  - Results. Non-Linear (magnetars). Massive (photon mass upper limits from solar wind and FRBs).
- Standard-Model Extension and Lorentz(-Poincaré Symmetry Violation
  - Results: effective photon mass, dispersion, sub-super luminal velocities, birefringence, energy non-conservation.
- Non-Linear: non-conservation.
- Applications to cosmology: LSV (and nL) Dark energy; (Massive: Supernova time dilation).

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Since 2016 Non-Maxwellian EM (before GR)

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A cyclic critical context: reinterpretation of light as solution?

- Physics at the end of the XIX century:
  1. Laws of physics are valid anywhere and anytime.
  2. Galilei transformations hold.
  3. Michelson-Morley: light speed constancy, Maxwell equations hold.
- Conclusions: 2. are invalid and replaced by Lorentz-Poincaré transformations, classical mechanics rewritten, æther does not exist, and light has to be reinterpreted.

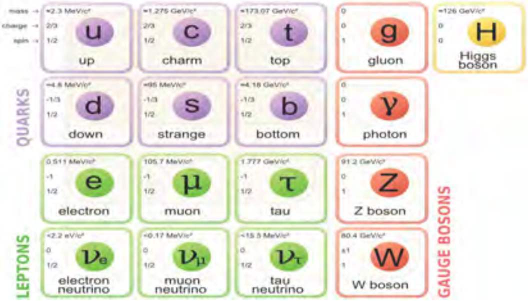
- Physics at the end of the XX century:
  1. Expansion is accelerating (questioned) and rotation curves.
  2. GR holds and works perfectly so far.
  3. No detection of dark ingredients.
- Two options: search more and better the dark universe or extend GR.
- Third **complementary** option: light has to be reinterpreted again. No pretension of completeness.

Motivations: 1/3

- GW detection 2015, but universe understanding based on EM observations.
- As photons are the main messengers, fundamental physics has a concern in testing the foundations of electromagnetism.
- 96% universe dark (unknown), only part of 4% is known: yet precision cosmology.
- Striking contrast: complex and multi-parameterised cosmology - linear and non dissipative electromagnetism from the 19^{th} century.
- There is no theoretical prejudice against a photon small mass, technically natural, in that all radiative corrections are proportional to mass ('t Hooft).
- Electromagnetic radiation has zero rest mass to propagate at c. Since it carries momentum and energy, it has non-zero inertial mass. Hence, for EP, it has non-zero gravitational mass: $\rightarrow$ light must be heavy ('t Hooft).
- The Einstein demonstration of the equivalence of mass and energy (wagon at rest on frictionless rails, photon shot *inside* end to end) implies a massive photon.

Motivations: 2/3

- The photon is the only free massless particle of the Standard Model.
- The SM successful but shortcomings: Higgs is too light, neutrinos are massive, no gravitons...



Motivations: 3/3

- non-Maxwellian theories: non-linear (Born and Infeld; Heisenberg and Euler and followers) or massive (de Broglie-Proca and followers).
- Non-linear for renormalisation (BI) of singularities and 2^{nd} order QED (EH): photon splitting and merging, photon-photon interaction.
- Massive photons evoked for dark matter, inflation, charge conservation, magnetic monopoles, Higgs boson, red-shifts; in applied physics, superconductors and "light shining through walls" experiments.
- Massive photon and yet gauge invariant theories include: Bopp, Laudé, Podolsky, Stueckelberg, Chern-Simons, Carroll-Field-Jackiw.
- Always pursued topic on the side: (large reviews but none complete).
- Impact on relativity? Difficult answer: variety of the theories above; removal of ordinary landmarks and rising of interwoven implications.
- Experiments on 2^{nd} order QED, birefringence are ongoing.

Non-linear theories: Heisenberg-Euler 2/2

- The Heisenberg-Euler Lagrangian

$$\mathcal{L} = -\frac{F_{\mu\nu}F^{\mu\nu}}{4} + \frac{e^2}{\hbar c}\int_0^\infty d\eta \frac{e^{-\eta}}{\eta^3} \cdot \left\{ i\frac{\eta^2}{2} F^{\mu\nu}F^*_{\mu\nu} \cdot \right.$$

$$\cdot \frac{\cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} + iF^{\mu\nu}F^*_{\mu\nu}}\right] + \cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} - iF^{\mu\nu}F^*_{\mu\nu}}\right]}{\cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} + iF^{\mu\nu}F^*_{\mu\nu}}\right] - \cos\left[\frac{\eta}{\mathfrak{E}_k}\sqrt{\frac{-F_{\mu\nu}F^{\mu\nu}}{2} - iF^{\mu\nu}F^*_{\mu\nu}}\right]}$$

$$\left. + |\mathfrak{E}_k|^2 + \frac{\eta^3}{6} \cdot F_{\mu\nu}F^{\mu\nu} \right\} \tag{1}$$

$$F^*_{\mu\nu} = \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma} \tag{2}$$

- Photon-Photon interaction and Photon splitting since HE theory relates to second order QED.
- Vacuum polarisation occurs for $E_c > 1.3 \times 10^{18}$ V/m or $B_c > 4.4 \times 10^{13}$ G.

Non-linear theories: Magnetar

Heisenberg-Euler on magnetars overcritical magnetic field. Blue or red shift depending on polarisation for a photon emitted up to similar values to the gravitational redshift.

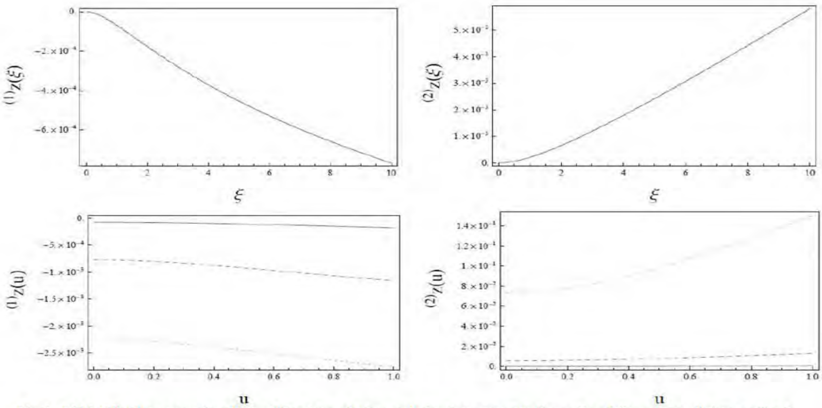


Fig.1. EMS (Electromagnetic shift) of the two photon polarisations versus the ratio of the magnetic/overcritical fields (upper panel), and the azimuthal angle (lower panel). The EMS can reach comparable values to the gravitational Einstein shift. The figure is taken from [Bonetti, Perez Bergliaffa, Spallicci, 2016].

Massive theories: de Broglie-Proca 1/4

- The concept of a massive photon has been vigorously pursued by Louis de Broglie from 1922 throughout his life. He defines with a strike of genius in 1923 the value of the mass to be lower than 10^{-53} kg (PDG value 10^{-54} after many experiments and observations). A comprehensive work of 1940 contains the modified Maxwells equations and the related Lagrangian.
- Insted, the original aim of Alexandru Proca, de Broglie's student, was the description of electrons and positrons. Despite Proca's several assertions on the photons being massless, his work has been used.

$$\mathcal{L} = -\frac{1}{4\mu}F_{\alpha\beta}F^{\alpha\beta} - \frac{\mathcal{M}^2}{2\mu}A_\alpha A^\alpha - j^\alpha A_\alpha \tag{3}$$

$F_{\mu\nu} = \partial_\mu A^\nu - \partial_\nu A^\mu$. Minimal action (Euler-Lagrange) $\rightarrow$ inhomogeneous eqs.
Ricci Curbastro-Bianchi identity $\partial^\lambda F^{\mu\nu} + \partial^\nu F^{\lambda\mu}\partial^\mu F^{\nu\lambda} = 0 \rightarrow$ homogeneous eqs.

$$\nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} - \mathcal{M}^2\phi \ , \tag{4}$$

$$\nabla \times \vec{B} = \mu_0\vec{j} + \mu_0\epsilon_0\frac{\partial \vec{E}}{\partial t} - \mathcal{M}^2\vec{A} \ , \tag{5}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \ , \tag{6}$$

$$\nabla \cdot \vec{B} = 0 \ , \tag{7}$$

ϵ_0 permittivity, μ_0 permeability, ρ charge density, $\vec{j}$ current, ϕ and $\vec{A}$ potential.
$\mathcal{M} = m_\gamma c/\hbar = 2\pi/\lambda$, $\hbar$ reduced Planck (or Dirac) constant, c speed of light, λ Compton wavelength, m_γ photon mass.

Eqs. (4, 5) are Lorentz-Poincaré transformation but not Lorenz gauge invariant, though in static regime they are not coupled through the potential.

From the Lagrangian we get $\partial_\alpha F^{\alpha\beta} + \mathcal{M}^2 A^\beta = \mu j^\beta$. With the Lorentz subsidiary condition $\partial_\gamma A^\gamma = 0$,

$$\left[\partial_\mu \partial^\mu + \mathcal{M}^2\right] A^\nu = 0 \tag{8}$$

Through Fourier transform, at high frequencies (photon rest energy < the total energy; $\nu \gg 1$ Hz), the positive difference in velocity for two different frequencies ($\nu_2 > \nu_1$) is

$$\Delta v_g = v_{\mathrm{g}2} - v_{\mathrm{g}1} = \frac{c^3 \mathcal{M}^2}{8\pi^2}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) , \tag{9}$$

being v_g the group velocity. For a single source at distance d, the difference in the time of arrival of the two photons is

$$\Delta t = \frac{d}{v_{\mathrm{g}1}} - \frac{d}{v_{\mathrm{g}2}} \simeq \frac{\Delta v_g d}{c^2} = \frac{d c \mathcal{M}^2}{8\pi^2}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right)$$
$$\simeq \frac{d}{c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) 10^{100} m_\gamma^2 \ . \tag{10}$$

Experimental mass limits: Particle Data Group

Citation: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)

γ (photon) $I(J^{PC}) = 0,1(1^{--})$

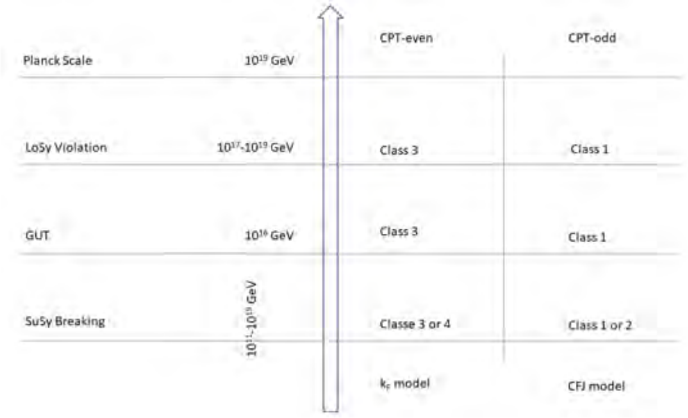
γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: 1 eV = 1.783×10^{-33} g = $1.957 \times 10^{-6}\, m_e$; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}\ \text{m}) \times (1\ \text{eV}/m_\gamma)$.

VALUE (eV)	CL%	DOCUMENT ID		COMMENT
$<1 \times 10^{-18}$		[1] RYUTOV	07	MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.2 \times 10^{-14}$		[2] BONETTI	17	Fast Radio Bursts, FRB 121102
$<1.8 \times 10^{-14}$		[3] BONETTI	16	Fast Radio Bursts, FRB 150418
$<1.9 \times 10^{-15}$		[4] RETINO	16	Ampere's Law in solar wind
$<2.3 \times 10^{-9}$	95	[5] EGOROV	14	Lensed quasar position
		[6] ACCIOLY	10	Anomalous magn. mom.
$<1 \times 10^{-26}$		[7] ADELBERGER	07A	Proca galactic field
no limit feasible		[7] ADELBERGER	07A	γ as Higgs particle
$<1 \times 10^{-19}$		[8] TU	06	Torque on rotating magnetized toroid
$<1.4 \times 10^{-7}$		ACCIOLY	04	Dispersion of GHz radio waves by sun
$<2 \times 10^{-16}$		[9] FULLEKRUG	04	Speed of 5-50 Hz radiation in atmosphere
$<7 \times 10^{-19}$		[10] LUO	03	Torque on rotating magnetized toroid
$<1 \times 10^{-17}$		[11] LAKES	98	Torque on toroid balance
$<6 \times 10^{-17}$		[12] RYUTOV	97	MHD of solar wind
$<8 \times 10^{-16}$	90	[13] FISCHBACH	94	Earth magnetic field
$<5 \times 10^{-13}$		[14] CHERNIKOV	92	Ampere's Law null test
$<1.5 \times 10^{-9}$	90	[15] RYAN	85	Coulomb's Law null test
$<3 \times 10^{-27}$		[16] CHIBISOV	76	Galactic magnetic field
$<6 \times 10^{-16}$	99.7	[17] DAVIS	75	Jupiter's magnetic field
$<7.3 \times 10^{-16}$		HOLLWEG	74	Alfven waves
$<6 \times 10^{-17}$		[18] FRANKEN	71	Low freq. res. circuit
$<2.4 \times 10^{-13}$		[19] KROLL	71A	Dispersion in atmosphere
$<1 \times 10^{-14}$		[20] WILLIAMS	71	Tests Coulomb's Law
$<2.3 \times 10^{-15}$		GOLDHABER	68	Satellite data

(SuSy and) LoSy breaking: 1/6



- Four models involving (Super and) Lorentz symmetries breaking. Dispersion relations show a non-Maxwellian behaviour for CPT even and odd sectors. Birefringence.
- An effective mass photon behaviour for both odd and pair CPT. In the odd CPT classes, f^{-2} in the group velocities emerges.
- A massive and gauge invariant Carroll-Field-Jackiw term in the Lagrangian is extracted and shown to be proportional to the background vector (or tensor).
- Caution in differentiating an effective from a real mass: Higgs for charged leptons and quarks, the W and Z Bosons, while the Chiral Symmetry (Dynamical) Breaking (CSB) for (mostly) composite hadrons (baryons and mesons). Is it epistemologically legitimate to consider such mechanisms as producing an effective mass to massless particles. What is real or effective?
- Frame dependency renders the LSV mass unusual, but acceptable being the dimension indeed that of a mass.
- The effective mass upper value is compatible with experimental data.

LoSy breaking: photon energy non-conservation 3/6

- Gauge invariance: the CFJ equations of motion are gauge invariant (conversely to dBP) but not the action.
- Conservation: the action contains $\epsilon^{\kappa\lambda\mu\nu}k_{\kappa}^{\rm AF}A_{\lambda}F_{\mu\nu}$, and even if the EM background is constant, the corresponding 4-potential is not, $A_{\beta}=x^{\alpha}F_{\alpha\beta}$. An explicit x^{α} dependence at the Lagrangian level determines energy-momentum non-conservation: exchange between the photon, and the LSV background and EM field, possibly x^{μ}-dependent.

Photon energy-momentum tensor (with or without SuSy)

$$\theta^{\alpha}_{\ \rho}=\frac{1}{\mu_0}\left(f^{\alpha\nu}f_{\nu\rho}+\frac{1}{4}\delta^{\alpha}_{\rho}f^2-\frac{1}{2}k_{\rho}^{\rm AF}\ {}^{*}f^{\alpha\nu}a_{\nu}+k_{\rm F}^{\alpha\nu\kappa\lambda}f_{\kappa\lambda}f_{\nu\rho}+\frac{1}{4}\delta^{\alpha}_{\rho}k_{\rm F}^{\kappa\lambda\alpha\beta}f_{\kappa\lambda}f_{\alpha\beta}\right)\ , \tag{11}$$

and its non-conservation

$$\partial_{\alpha}\theta^{\alpha}_{\ \rho}=j^{\nu}f_{\nu\rho}-\frac{1}{\mu_0}\Big[\left(\partial_{\alpha}F^{\alpha\nu}\right)f_{\nu\rho}+k_{\alpha}^{\rm AF}\ {}^{*}F^{\alpha\nu}f_{\nu\rho}+ \frac{1}{2}\left(\partial_{\alpha}k_{\rho}^{\rm AF}\right)\ {}^{*}f^{\alpha\nu}a_{\nu}-\frac{1}{4}\left(\partial_{\rho}k_{\rm F}^{\alpha\nu\kappa\lambda}\right)f_{\alpha\nu}f_{\kappa\lambda}+\left(\partial_{\alpha}k_{\rm F}^{\alpha\nu\kappa\lambda}\right)F_{\kappa\lambda}f_{\nu\rho}+k_{\rm F}^{\alpha\nu\kappa\lambda}\left(\partial_{\alpha}F_{\kappa\lambda}\right)f_{\nu\rho}\Big]\ . \tag{12}$$

Assumption: the wave energy variation implies a frequency change for a photon.

The leading term from Eq. (12) is proportional to $k_0^{\rm AF}\ {}^*F^{0i}f_{i0}$ $\rm Jm^{-3}s^{-1}$.

- The $k_0^{\rm AF}$ component of the LSV vector is supposed large scale. We need to integrate over the light travel time. For a source at z $=0.5$, the look-back time is $t_{LB}=1.57\times10^{17}$ s (Lemaître-Hubble-Humason constant $=70$ km/s per m, $\Omega_m=0.3$, $\Omega_\Lambda=0.7$).
- A safe margin ϱ for the many magnetic fields, $B=5\times10^{-10}-5\times10^{-9}$ T each, differently oriented, crossed by light (Not considered a possible presence of a strong magnetic field at the source)..

The wave energy density variation ΔE

$$|\Delta {\rm E}|_{z=0.5}=\frac{c}{\mu_0}|k_0^{\rm AF}||Bf_{i0}|\varrho\ t_{LB}\approx1.02\times10^{23}|k_0^{\rm AF}|\varrho|f_{i0}|\ . \qquad (13)$$

For $h=6.626\times10^{-34}$ Js, the frequency variation $\Delta\nu$ is

$$|\Delta\nu|_{z=0.5}=\frac{1.023\times10^{23}}{h}|k_0^{\rm AF}|\varrho|f_{i0}|\approx1.55\times10^{56}\ k_0^{\rm AF}\varrho|f_{i0}|\ . \qquad (14)$$

We now need to compute $|f_{i0}| = |\mathcal{E}|/c$**, the electric field of the photons**. We consider the Maxwellian - in first approximation - classic intensity $I = \epsilon_0 c\mathcal{E}^2 = \epsilon_0 c^3 |f_{i0}|^2$ $(c\mathcal{B} = \mathcal{E})$.
The frequency $\nu = 4.86 \times 10^{14}$ Hz corresponds to the Silicon absorption line at 6150 Å, of SN 1A Supernova type. The monochromatic AB magnitude is defined as the logarithm of a spectral flux density *SFD*

$$m_{\rm AB} = -2.5 \log_{10} SFD - 48.6 \ , \tag{15}$$

in cgs units. For $m_{\rm AB} = -19$, we get $SFD = 10^{-15}$ Js^{-1} Hz^{-1} m^{-2} having converted to SI units. We integrate over the frequency width of a bin, that is 30 Å or 2.37 THz and get $I = 2.37 \times 10^{-3}$ Js^{-1} m^{-2}. For $\epsilon_0 = 8.85 \times 10^{-12}$ Fm^{-1}, we have

From astrophysical data

$$f_{i0} = \sqrt{\frac{I}{\epsilon_0 c^3}} \approx 3.79 \times 10^{-9}\mathrm{Vsm}^{-2} \ . \qquad (16)$$

Finally, from Eq. (14), we get

$$|\Delta\nu|_{z=0.5}^{\nu=486\mathrm{THz}} = 5.87 \times 10^{47} \ k_0^{\mathrm{AF}} \varrho \ . \qquad (17)$$

The parameter k_0^{AF} has a laboratory upper limit of $10^{-10}\mathrm{m}^{-1}$ but a more stringent, and less favourable for our study, astrophysical upper limit of $5.1 \times 10^{-28}\ \mathrm{m}^{-1}$.
In this worst case, it is sufficient that $\varrho \geq 1.6 \times 10^{-7}$, to get z_{LSV} in the order of 10% of z.

The LSV as vacuum energy.

- The LoSy breaking four-vector, $k_{\rm AF}$, and the rank-four tensor, $k_{\rm F}$, correspond to the vacuum condensation of a vector and a tensor field in string models.
- They describe part of the vacuum structure, in the form of space-time anisotropies.
- Their presence reveals that vacuum effects are responsible for the energy variation of light waves and thus photon frequency shift.

Superposing the shifts.

- $z = \Delta\nu/\nu_o$ where $\Delta\nu = \nu_{\rm e} - \nu_o$ is the difference between the observed ν_o and emitted $\nu_{\rm e}$ frequencies, or else $z = \Delta\lambda/\lambda_{\rm e}$ for the wavelengths.
- Expansion causes $\lambda_{\rm e}$ to stretch to $\lambda_{\rm c}$ that is $\lambda_{\rm c} = (1 + z_{\rm C})\lambda_{\rm e}$. The wavelength $\lambda_{\rm c}$ could be further stretched or shrunk for the LSV shift to $\lambda_{\rm o} = (1 + z_{\rm LSV})\lambda_{\rm c} = (1 + z_{\rm LSV})(1 + z_{\rm C})\lambda_{\rm e}$. But since $\lambda_{\rm o} = (1 + z)\lambda_{\rm e}$, we have $1 + z = (1 + z_{\rm C})(1 + z_{\rm LSV})$.

$$z = z_{\rm C} + z_{\rm LSV} + z_{\rm C} z_{\rm LSV} \ . \tag{18}$$

The second order is not negligible for larger $z_{\rm C}$.

Behaviour of the LSV shift with distance.

- z_C takes into consideration the universe expansion, while z_{LSV} is based on the comoving distance. The frequency variation is proportional
- Type 1 to the instantaneous frequency and to the distance.
- Type 2 to the emitted frequency and the distance.
- Type 3 to the distance.
- (Type 4 to the observed frequency and the distance.)

Table: LSV shift types. $k_{1,2}$ have the dimensions of Mpc^{-1}, k_3 of $\mathrm{Mpc}^{-1}\mathrm{s}^{-1}$. The positiveness of the distance r constraints $z_{LSV/1} > -1$ for $k_1 < 0$, and $-1 < z_{LSV/1} < 0$ for $k_1 > 0$.

Type	1	2	3
$\Delta\nu$	$k_1 \nu dr$	$k_2 \nu_e dr$	$k_3 dr$
ν_o	$\nu_e \exp^{k_1 r}$	$\nu_e(1 + k_2 r)$	$\nu_e + k_3 r$
z_{LSV}	$\exp^{-k_1 r} - 1$	$-\dfrac{k_2 r}{1 + k_2 r}$	$-\dfrac{k_3 r}{\nu_e + k_3 r}$

Impact on cosmology: dark energy 3/7

The LSV frequency shift from the SNIa data.

- We estimated $\Delta\nu_{\rm LSV}$ theoretically. Now from 714 SNeIa from the Union2 catalogue ($d_{\rm L}$, μ + error, the red-shift z of the host galaxy + error).
- z from $d_{\rm L}$ >than z from spectroscopy $\longrightarrow \Omega_\lambda$ or Λ.
- Alternatives: often other theories of gravity, rarely others (photons oscillating into axions producing a dimming effect for SNeIa).
- SNIa data reliability is still debated.

For $\Omega_{\rm rad} = \Omega_{\rm k} = \Omega_\Lambda = 0$

$$d_{\rm L} = \frac{2c}{H\Omega_{\rm m}^2}\left[2 - \Omega_{\rm m}(1 - z_{\rm C}) - (2 - \Omega_{\rm m})\sqrt{1 + \Omega_{\rm m}^2 z_{\rm C}}\right] , \tag{19}$$

using Chebyshev polynomial expansion.

$$\mu = m - M = 5 \log d_{\rm L} - 5 \tag{20}$$

μ distance modulus, m, M apparent and absolute magnitudes. The comoving distance r given by observations,

$$r = \frac{2c}{H}(\sqrt{z_{\rm C} + 1} - 1) . \tag{21}$$

The iterative computation starts from the $\Omega_{\rm i}$ and compares the final simulated s and the observed value of μ.

$$\Omega_k, \Omega_{\rm m}(\Omega_\Lambda = 0) \rightarrow d_{\rm L} \rightarrow z_{\rm c} \rightarrow r \rightarrow z_{\rm LSV} \rightarrow \mu_{\rm s} \stackrel{?}{=} \mu_{\rm o} ,$$

Herein, we kept μ and decomposed z in $z_{\rm c}$ and $z_{\rm LSV}$. Else, we could have considered μ as the sum of two contributions $\mu(z_{\rm C})$ and $\mu(z_{\rm LSV})$ and looking for an agreement with spectroscopic z.

Table: Simulation results for $\Omega_{\rm rad} = \Omega_{\rm k} = \Omega_{\Lambda} = 0$ and $\Omega_{\rm m} = 0.28$. The large value of the error on k_i is due to the Hierarchical Bayesian Model (HBM) approach, considering different source of uncertainties to render homogeneous the photometric data of the distance modulus from different catalogues. **The simulation results provide a mean $z_{\rm LSV}$ blue-shift for types 1 and 2 and a $z_{\rm LSV}$ red-shift for type 3.**

Type	1	2	3
k_i	$2.8 \times 10^{-5} \pm 3.5 \times 10^{-3}$	$2.6 \times 10^{-5} \pm 2.8 \times 10^{-3}$	$< -10^{-6} \pm 1.3 \times 10^{-3}$
rms	1.34×10^{-2}	1.31×10^{-2}	1.05×10^{-1}

Impact on cosmology: dark energy 5/7

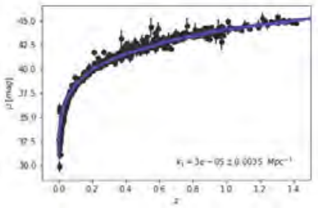
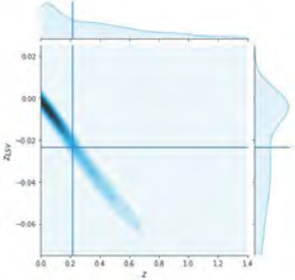


Figure: TOP: for type 1 of LSV shift, $\Omega_{\rm rad} = \Omega_{\rm k} = \Omega_\Lambda = 0$ and $\Omega_{\rm m} = 0.28$, $\mu(z)$; BOTTOM: possible values of $z_{\rm LSV}$ for a given z (only 73 SNeIa for $z > 0.8$).



Modelling.

For achieving the best fit, we employed a Hierarchical Bayesian Model (HBM) and determined the entire posterior probability density function of the these parameters. We engaged an HBM to retrieve from the distance distribution of the SNeIa all the possible values of k, for each of the three types. We assumed flat priors in the range $[-100, 100]$ to avoid heavy constraints in exploring the domains of the parameters. The Bayesian analysis is very depending upon the choice of the priors, conversely to other kinds, as the Gaussian approaches. The flat priors allow an even probability distribution and thus unbiased estimates.

Unfortunately, the HBM is heavily influenced by the error on the measured values, namely on the distance modulus leading to a statistical non-informative error on the model parameters. From the Gaussian shape of the posterior distribution of k_i, it is evinced that a non-zero probability exists for having both positive and negative values of k_i, due to the measurement errors. We decided to use HBM due to the multiple origin of the distance modulus estimates and differences in data reduction schemes, thus avoiding the influence of some systematic error in the estimates of the parameters. The HBM improves the precision of the estimates of the model parameters, even though the accuracy is rather coarse.

Impact on cosmology: dark energy 6/7

Results and discussion.

1. For $\Omega_{\rm rad} = \Omega_{\rm k} = \Omega_\Lambda = 0$ and $\Omega_{\rm m} = 0.28$, there is a mean blue-shift for types 1 and 2 and a red-shift for type 3 **possibly all red if** $\Omega_{\rm m} = 0.28$ **increases**.
2. Well interpolating $\mu(z)$ curves for all 3 types of $z_{\rm LSV}$ shifts. Types 1 and 2 have similar rms, but type 1 proportionality to ν rather than type 2 to $\nu_{\rm e}$ determines a 'classic' exponential decay or growth.
3. $|z_{\rm LSV}|$ grows with z.
   1. If blue, the **drawback**: photon must gain energy from the source to us, occurring as a net result of the different contributions of the LSV (vector and tensor) and EM fields along the path. The **advantage**: clear understanding of why we measure a lower spectroscopic z: $z = 0.5 = z_{\rm C} + z_{\rm LSV} = 0.55 - 0.05$.
   2. If red, the **drawback**: $z_{\rm LSV} \leq \Delta z$, observation error . The **advantage**: intuitive dissipation effect along the photon path.
4. A **single** mechanism explains all SNeIa in the (μ, z) plan through blue or red shifts (small or big), depending on $\Omega_{\rm i}$, the orientations of the components of the LSV vector-tensor and of the EM fields (host galaxy, intergalactic medium, Milky Way). Anisotropy has been proposed again recently.
5. The LSV vacuum energy acts on light propagation. Equivalent to $\Omega_\Lambda = 0.7$, but unrelated to an accelerated expansion.

Perspectives on Dark Energy.

1. New avenue? The experimental and observational limits on LSV and magnetic fields are fully compatible with our findings.
2. The LSV shift is generally applicable and it is not limited to the SNIa case.
3. In future work, leaving aside the SME, we will show that a frequency shift is also produced by a generalised non-linear electromagnetism, encompassing the formulations of Born-Infeld and Euler-Heisenberg. The found limits on $z_{\rm LSV}$ will be applicable to $z_{\rm NL}$ for the non-linear electro-magnetism.
4. The XIX century Maxwellian linear EM and Einsteinian non-linear GR have been both well tested. This has not impeded the proposition of alternative formulations of gravity. Missing experimental proofs on the dark universe while GR scores successes induce to rethink at the messenger (Massive photons may fake time dilation even when sources are at fixed distance. Such effect, though, appears very marginal for SNeIa).
5. The $z_{\rm LSV}$ shift is below 10% of the measured red-shift (below $2 \times 10^{-19} \Delta\nu/\nu$ per m). It is desirable to test frequency invariance in vacuum in a laboratory.
6. **Need: analysis of observations separating the evidence of dark energy from non-photonic evidence of accelerated expansion.**
7. **As alternative theories explain rotation curves without dark matter, here we try to explain SNeIa distances without accelerated expansion.**

A general non-linear Lagrangian. Summary. I.

- A non-linear and general Lagrangian (including BI and EH, depending upon powers of the EM field tensor and its dual), in flat spacetime. $\mathcal{L} = \mathcal{L}(\mathcal{F}, \mathcal{G})$.
- Field = background + light-wave. $F = F_{\rm B} + f$, $\tilde{F} = G = \tilde{F}_{\rm B} + \tilde{f} = G_{\rm B} + g$.

$$F_{\sigma\tau} = \partial_\sigma A_\tau - \partial_\tau A_\sigma \ , \qquad \tilde{F}_{\sigma\tau} = G_{\sigma\tau} = \frac{1}{2}\epsilon_{\sigma\tau\kappa\lambda}F^{\kappa\lambda} \tag{22}$$

4-potential $A^\sigma = \left(\frac{\phi}{c}, \vec{A}\right)$, ϕ and $\vec{A}$, time (scalar) and space (vector) components.

$$\mathcal{F} = -\frac{1}{4\mu_0}F^2 = -\frac{1}{4\mu_0}F_{\sigma\tau}F^{\sigma\tau} = \frac{1}{2\mu_0}\left(\frac{\vec{E}^2}{c^2} - \vec{B}^2\right) \ , \tag{23}$$

and

$$\mathcal{G} = -\frac{1}{4\mu_0}F_{\sigma\tau}\tilde{F}^{\sigma\tau} = -\frac{1}{4\mu_0}F_{\sigma\tau}G^{\sigma\tau} = \frac{1}{\mu_0}\frac{\vec{E}}{c}\cdot\vec{B} \ , \tag{24}$$

where $\mu_0 = 4\pi \times 10^{-7} \approx 1.256$ H m^{-1} or V s A^{-1} m^{-1} is the vacuum permeability.

A general non-linear Lagrangian. Summary. II.

Lagrangian meaning (1st order no interaction; 2nd order interaction photon-background; 3rd order photon splitting or merging (three photons), with background; 4th order photon-photon (four photons), with background.)
Non-conservation of the photon energy-momentum tensor $\Theta_{\rm ff}$ (here 2nd order) when the EM external field is not constant in space-time.

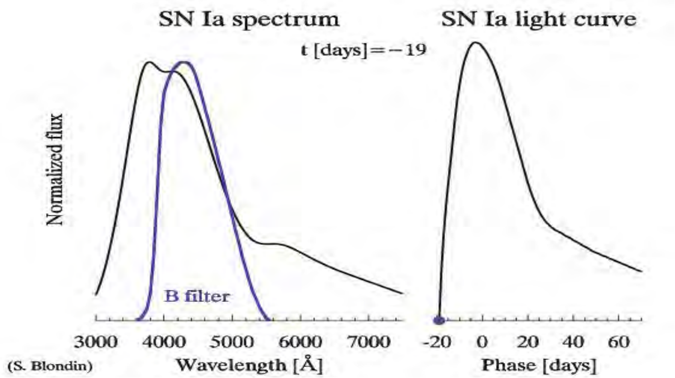
$$(\Theta_{\rm ff})^{\mu}_{\alpha} = C_1 f^{\mu\nu} f_{\nu\alpha} - \frac{1}{2} k^{\mu\nu\kappa\lambda} f_{\kappa\lambda} f_{\nu\alpha} - \frac{1}{2} t^{\mu\nu\kappa\lambda} \tilde{f}_{\kappa\lambda} f_{\nu\alpha} - \frac{1}{4} \epsilon^{\mu\nu\kappa\lambda} t_{\kappa\lambda\rho\sigma} f^{\rho\sigma} f_{\nu\alpha} + \delta^{\mu}_{\alpha} \left(\frac{1}{4} C_1 f^2 - \frac{1}{8} \kappa^{\nu\mu\kappa\lambda} f_{\nu\mu} f_{\kappa\lambda} - \frac{1}{4} t^{\nu\rho\kappa\lambda} f_{\nu\rho} \tilde{f}_{\kappa\lambda} \right) . \quad (25)$$

$$\mathcal{T}_{\alpha} = -\partial_{\mu} \left(C_1 F^{\mu\nu}_{\rm B} + C_2 \tilde{F}^{\mu\nu}_{\rm B} \right) f_{\nu\alpha} + \frac{1}{4} (\partial_{\alpha} C_1) f^2 + \frac{1}{4} (\partial_{\alpha} C_2) \tilde{f} f - \frac{1}{8} \left(\partial_{\alpha} k^{\nu\mu\kappa\lambda} \right) f_{\nu\mu} f_{\kappa\lambda} - \frac{1}{4} (\partial_{\alpha} t^{\nu\mu\rho\sigma}) f_{\nu\mu} f_{\rho\sigma} . \quad (26)$$

The continuity equation

$$\partial_{\mu} (\Theta_{\rm ff})^{\mu}_{\alpha} = \mathcal{T}_{\alpha} . \quad (27)$$

Source apparent time dilation??



$$\Delta t \simeq \frac{d}{c}\left(\frac{1}{\nu_1^2} - \frac{1}{\nu_2^2}\right) 10^{100} m_\gamma^2 H_\gamma(z) \ , \tag{28}$$

where

$$H_\gamma(z) \ \equiv \ \int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}} \ . \tag{29}$$

If SN spectrum shifts towards lower frequencies, massive photon may mimic time dilation, even if the source is not moving. Relevant corrections? It seems not.

Grazie per la vostra attenzione