Theoretical considerations on neutrino velocity

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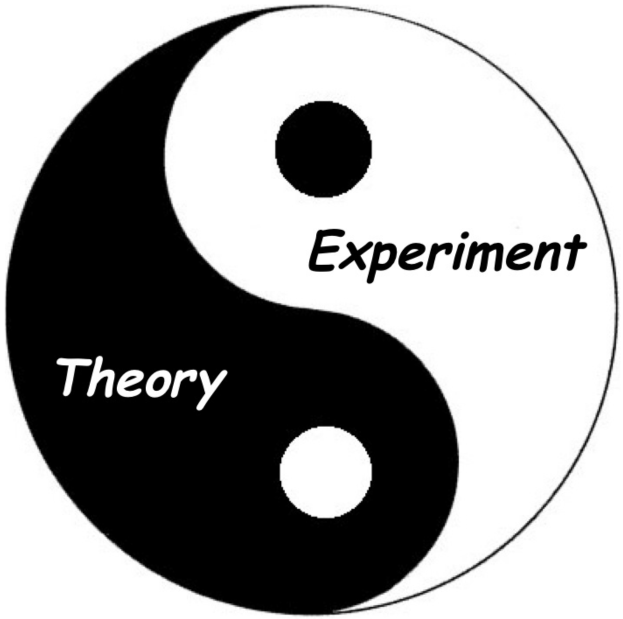
There is a widespread attitude to consider departures from Einstein relativity, and in particular, non-standard neutrino velocities. We discuss the interest of testing this hypothesis with long-baseline neutrinos and the constraints imposed by various considerations. The contribution of the Gran Sasso Theory Group is emphasized.

Physics proceeds by continuous exchanges between experiment and theory, with the latter providing motivations to the former and viceversa. E.g., already the names of NUSEX, MACRO, KAMIOKANDE–or better the meaning of these acronyms–remind us of the leading theories in eighties.



The implications of the claimed superluminal neutrino velocities (2011) have been explored by many theorists, but also in this case, the findings have been preceeded by several theoretical discussions and speculations.

How does it begin?

⋆ Gonzalez-Mestres '97 proposes that the dispersion relation for hadrons is

$$\mathbf{E}=\sqrt{\mathbf{m^2} + [\ \sin(\mathbf{p\ a})/\mathbf{a}\ ]^2} \quad \text{with} \quad \mathbf{a} \sim \frac{1}{M_{\text{Planck}}} \equiv \sqrt{G_N}$$

arguing that GZK cutoff can be wiped out in this manner.

⋆ Amelino-Camelia, Ellis, Mavromatos, Nanopoulos, Sarkar '97 suggest testing

$$\mathbf{p^2} = \mathbf{E^2}(\mathbf{1} + \xi\mathbf{E}/\mathbf{E}_{\text{QG}}) \Rightarrow \mathbf{v} = \mathbf{1} - \xi\mathbf{E}/\mathbf{E}_{\text{QG}} \Rightarrow \mathbf{\Delta t}/\mathbf{t} = \xi\mathbf{E}/\mathbf{E}_{\text{QG}}$$

namely, a non-Einsteinian dispersion relation, using γ rays from GRB.

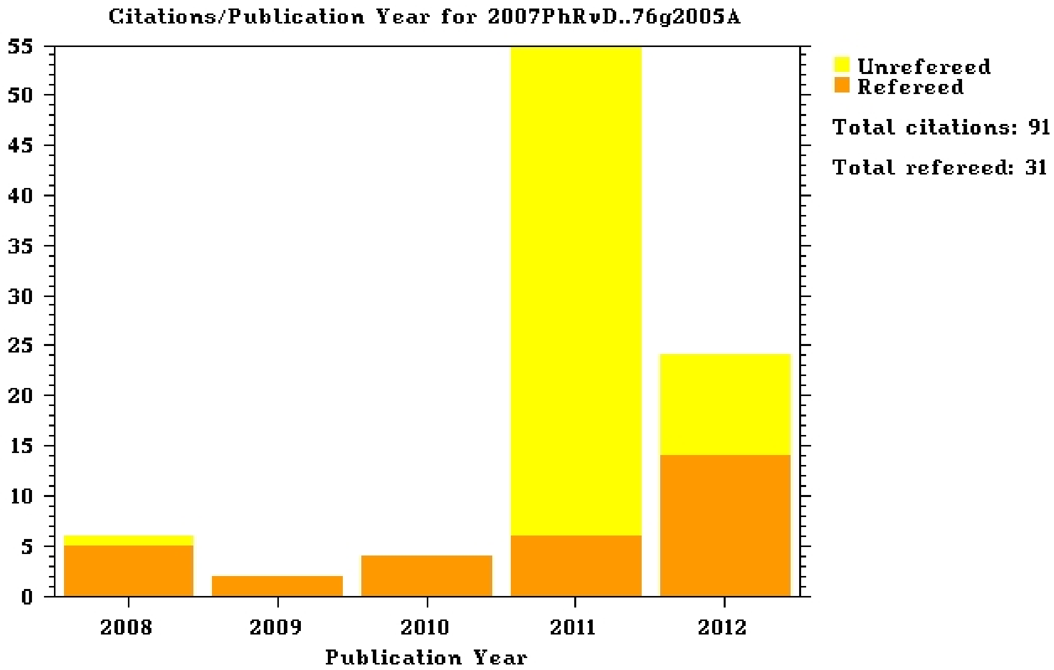
⋆ Coleman and Glashow '98, parameterize the energy of a particle with

$$\mathbf{E_i} = \mathbf{c_i}\sqrt{\mathbf{p^2} + (\mathbf{m_i c_i})^2}$$

where c_i = constant $\neq 1$ is a quantity that depends on the particle.

The measurement at MINOS 2007

The recent campaign of measurement of neutrino velocity in long-baseline experiments has been opened by MINOS, that found an upper bound, that was considered of limited interest till past year.



For our purposes, it is important to examine the motivations for the measurement and the quoted theoretical literature.

From Phys. Rev. D 76 (2007) 072005, we read

theories have been proposed to allow some or all neutrinos to travel along "shortcuts" off the brane through large extra dimensions [5], and thus have apparent velocities different than the speed of light. Some of these theories [6–8] allow $|v - c|/c \sim 10^{-4}$ at neutrino energies of a few GeV. Terrestrial neutrino beams could measure an

[5] R. N. Mohapatra and A. Y. Smirnov, Annu. Rev. Nucl. Part. Sci. **56**, 569 (2006).
[6] G. G. Volkov, Ann. Fond. Broglie **31**, 227 (2006).
[7] V. Ammosov and G. Volkov arXiv:hep-ph/0008032.
[8] G. S. Asanov, arXiv:hep-ph/0009305.

Ref. [5] discusses 'branes' and 'extra dimensions' but does not mention 'shortcuts'. The paper where this is mentioned, H. Päs, S. Pakvasa, T. J. Weiler, STERILE-ACTIVE NEUTRINO OSCILLATIONS AND SHORTCUTS IN THE EXTRA DIMENSION, *Phys. Rev. D* **72** *(2005) 095017, is not quoted by any of these works – including MINOS's.*

Again from the paper of MINOS of 2007, we read on SN1987A

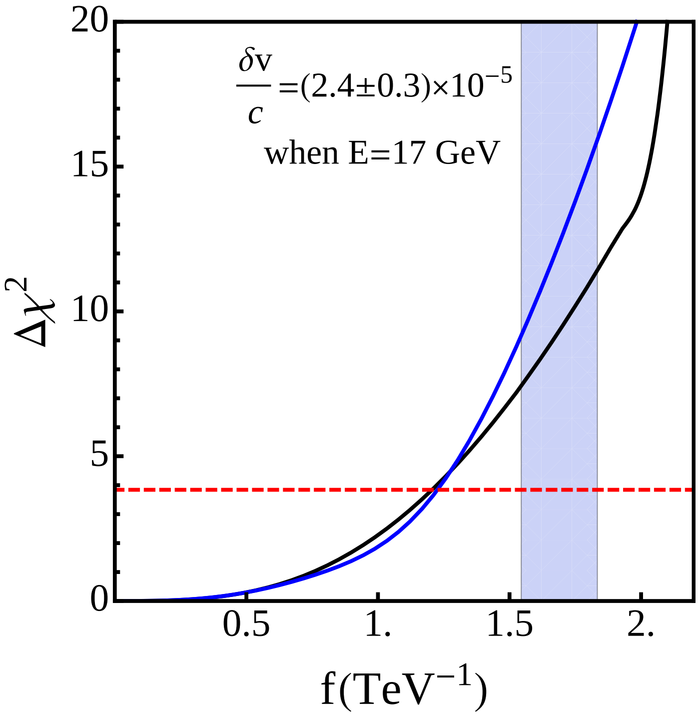
~25 GeV and higher. The most sensitive test of neutrino velocity was achieved by comparing[1] the arrival times of neutrinos [16,17] and photons from SN1987A, which achieved a sensitivity of $|v - c|/c < 2 \times 10^{-9}$ [18,19], four orders of magnitude better than the terrestrial measurements, but only for neutrinos of energy ~10 MeV. In principle, neutrino velocity could be a strong function of energy. Our measurement constrains this previously un-

[16] K. Hirata *et al.*, Phys. Rev. Lett. **58**, 1490 (1987).
[17] R. M. Bionta *et al.*, Phys. Rev. Lett. **58**, 1494 (1987).
[18] L. Stodolsky, Phys. Lett. B **201**, 353 (1988).
[19] M. J. Longo, Phys. Rev. Lett. **60**, 173 (1988).

The expected delay of the light w.r.t. neutrinos, due to the propagation of the plasma in the stellar mantle, bounds the value of the neutrino velocity, even if it is constant.

Implications of SN1987A – Gran Sasso Theory Group

Mannarelli et al., JHEP 1201 (2012) 136 argue that the actual bound from SN1987A is even tighter, $\delta v/c < 3 \cdot 10^{-10}$.



With Pagliaroli the distortion of the wave-packet caused by energy dependent neutrino velocities has been studied. A strong dependence

$$\delta v/c = (\mathbf{E}\ \mathbf{f})^{\mathbf{3}} \text{ with } 1/\mathrm{f}=\text{scale}$$

could be marginally reconciled with large effects at CNGS, see figure. The most commonly advocated cases, linear or quadratic – e.g., Ellis et al., PRD 78 (2008) 033013 – cannot instead.

Evidently the findings of 2011 would have required a very special energy dependence.

Citation: K. Nakamura *et al.* (Particle Data Group), JP G **37**, 075021 (2010) and 2011 partial update for the 2012 edition (URL: http://pdg.lbl.gov)

Neutrino Properties

A REVIEW GOES HERE – Check our WWW List of Reviews

$\overline{\nu}$ MASS (electron based)

Those limits given below are for the square root of $m^{2(\mathrm{eff})}_{\nu_e} \equiv \sum_i |\mathrm{U}_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of $^3\mathrm{H}\beta^- \overline{\nu}$ decay are the square roots of the limits for $m^{2(\mathrm{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 2	**OUR EVALUATION**				
< 2.3	95	[1] KRAUS	05	SPEC	^{3}H β decay
< 2.5	95	[2] LOBASHEV	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.8	95	[3] PAGLIAROLI	10	ASTR	SN1987A
<21.7	90	[4] ARNABOLDI	03A	BOLO	^{187}Re β-decay
< 5.7	95	[5] LOREDO	02	ASTR	SN1987A
< 2.8	95	[6] WEINHEIMER	99	SPEC	^{3}H β decay
< 4.35	95	[7] BELESEV	95	SPEC	^{3}H β decay
<12.4	95	[8] CHING	95	SPEC	^{3}Hβ decay

Implication on $\nu_\mu \to \nu_\mu e^+ e^-$ – Gran Sasso Theory Group

Cohen & Glashow show that the CNGS beam would be largely degraded if v=constant.

In fact, the group velocity (or Hamilton-Jacobi relation) fixes the derivative $v = dE/dp$. If $v > 1$ constantly, E deviates more and more from p. Thus,

$$m^2_{\text{eff}} \equiv E^2 - p^2$$

will be large, and the neutrino can emit e^+e^- pairs.

Is this general? In arXiv:1110.4591 with Villante we argue that

1) for any typical dispersion relation, an excessive radiation is expected.[a]

2) only with "implausible" dispersion relations, the emission can be avoided.

[a] E.g., if $v = c$ at $E \sim 10$ MeV as in Caccipaglia, Deandrea, Panizzi, one avoids SN1987A bounds, but not the emission of pairs.

Implication on pion decay – Gran Sasso Theory Group

In Mannarelli, Mitra, Villante, FV, JHEP 1201 (2012) 136:

1) The Dirac equation is modified, in order to describe departures from $E = p$, as needed when one assumes $v = dE/dp \neq 1$ to explain 2011 findings.

2) The pion decay rate is re-calculated, including not only the phase space effects, but also the modified matrix elements (that is more refined than Cohen & Glashow's calculation).

3) Four dispersion relations, representative of all proposed cases, have been considered, including one that allows one to suppress $\nu_\mu \to \nu_\mu e^+ e^-$.

In the conclusions we can read:

> for all of the considered dispersion relations, the pion decay processes suffer a drastic departure with respect to the standard scenario in the energy interval relevant for OPERA. To quote a few eloquent numbers, the rate of $\pi^+ \to \mu^+ \nu_\mu$ at $E_\pi = 100$ GeV decreases by about $1/50$ and $1/3$ in the cases A, C and in the case B respectively, while it increases by a factor ~ 200 in the case D. Moreover, in all the considered cases, the probability to produce electron neutrinos at the energies relevant for OPERA is drastically increased with respect to the standard expectations.

which suggests that it is not easy to avoid the troubles.

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Non-standard neutrino propagation and pion decay

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ABSTRACT: Motivated by the findings of the OPERA experiment, we discuss the hypothesis that neutrino propagation does not obey Einstein special relativity. Under a minimal set

JHEP01(2012)1

Summary and discussion

⋆ Speculations on non-standard propagation of particles, including neutrinos, have been proposed and widely discussed in the past years. However, these discussions never produce solid predictions, which is a risky situation.

⋆ The claimed anomaly of the velocity is just the last and most important of several other weak or non-significant anomalies, that have been discussed or even presented as tests of quantum gravity or alike.

⋆ We all commend that OPERA collaboration deliberately avoided to discuss any interpretation. I'd like to stress a different aspect of the connection; that theorists have a responsibility of what is discussed and what is considered interesting.

⋆ The Gran Sasso Theory Group contributed to the discussion of the anomaly, by exploring its consequences. Our calculations, along with other ones and with the absence of compelling explanations, contributed to shape the opinion that the anomaly is too large and its reason is not new physics.

BACKUP SLIDES

A ‘theory’ of deviations from Einstein relativity?

The speculations on the structure of quantum gravity, strings, extra dimensions, branes, etc. have led to consider the hypothesis that some particles (including neutrinos) do not propagate as predicted by Einstein.

These arguments, along with some non-significant experimental hints in the past years (AGASA, MAGIC, MINOS...) contributed to a create intense discussions and vague expectations.

Which is very different from true predictions. This is an unpleasant situation but not a new one; already Feynman was saying, “string theorists do not make predictions, they make excuses.”

Thus, besides complaining about lack of data, one should in my view beware from suggestive but very imprecise and possibly misleading ideas and approaches.

Some experimental papers important for the discussion

Extension of the cosmic ray energy spectrum beyond the predicted Greisen-Zatsepin-Kuz'min cutoff.
Phys. Rev. Lett. 81 (1998) 1163
Positive (3-4σ) result by AGASA contradicted by AUGER. An interpretation in terms of non-standard propagation of cosmic ray protons preceeds the publication.

Measurement of neutrino velocity with the MINOS detectors and NuMI neutrino beam.
Phys. Rev. D 76 (2007) 072005
Null result, just 2σ off. The alleged theoretical motivations are worth examining.

Probing Quantum Gravity using photons from a flare of the active galactic nucleus Markarian 501 Observed by the MAGIC telescope.
Phys. Lett. B668 (2008) 253
Frequency dependent gamma-ray velocity, null result but with 2.5σ deviation. Joint publication of Magic with J. Ellis and other important theorists.

A horrendous possibility (using the words of Paolo Lipari)

It is possible to concoct a very peculiar dispersion relation that allows for superluminal neutrinos and avoids the phenomenological problems;

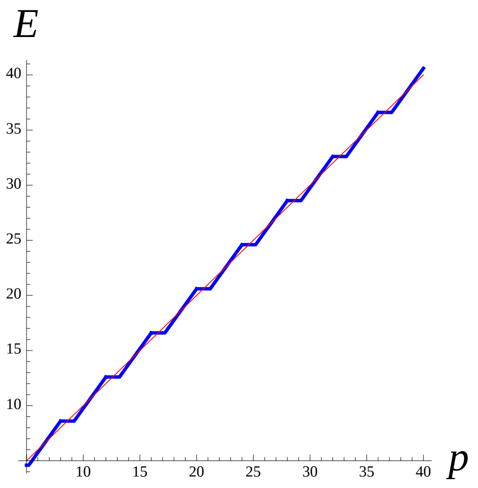


Figura 1: *Dispersion relation for neutrinos (in blue) that implies than most of them are superluminal and few of them strongly subluminal, in order that $E \sim p$.*

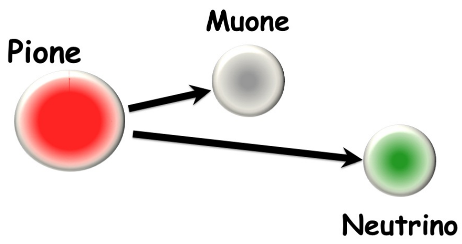
Nobody consider it seriously[a] and hopefully the same is for you; but if you like it, I offer you the copyright with only one request: do not say it is a theory.

[a] This is the reaction with all collegues with whom I discussed it, including A Bettini, P Colangelo, F Guerra, A Ianni, P Lipari, M Mannarelli, P Migliozzi, M Mitra, F Nesti, G Pagliaroli, A Polosa, N Redington, M Sioli, A Smirnov, A Strumia, F Villante, L Votano.

COME SI FA A SPEDIR NEUTRINI?

Serve qualche trucco per produrli ed indirizzarli al destinatario.

1. **Un fascio di protoni di altissima energia collide con un bersaglio.**
2. **Le collisioni nucleari producono particelle instabili, come i pioni, che decadono in volo (in un tunnel) producendo neutrini.**
3. **I neutrini sono lanciati nella direzione originaria dei protoni.**



Possiamo pensare ad un missile a più stadi che lancia la navicella, cioè il neutrino; oppure pensate ad una moderna versione dell'esperimento di Marconi, dove invece delle onde radio, si usano neutrini.


CERN: DOVE VENGONO
LANCIATI I PROTONI


CERN: IL TUNNEL DOVE I PIONI
DECADONO FORMANDO I NEUTRINI
Decay tube
(2nd contract)
SPS/ECA4
SPS tunnel
protons
TT41
Access galleries
LHC/TI8 tunnel
Target
chamber
Service gallery
LEP/LHC tunnel
140m
pions
kaons
Decay tunnel
Hadron stop
and first muon detector
muons
neutrinos
Connection gallery
to TI8/LHC
Second muon detector
neutrinos
to Gran Sasso


IL TRAGITTO DEI NEUTRINI
DAL CERN AL GRAN SASSO
CERN
Geneva
Mont-Blanc
Piemonte
Firenze
Arezzo
Perugia
Umbria
Gran Sasso Laboratory
11.4km
732km
neutrino beam
5km
0


GRAN SASSO: DOVE SONO
RIVELATI I NEUTRINI

CHE SUCCEDE NEL TUNNEL

Proviamo a mettere giù qualche numero

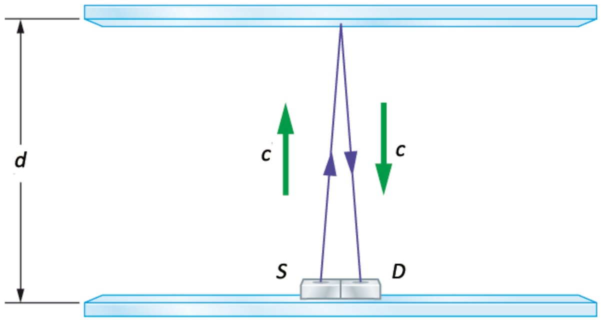
- Un pione vive in media solo un tempo di $t =$25 nanosecondi.
- Nelle condizioni di questo esperimento, i pioni viaggiano quasi alla velocità della luce, c.
- Ingenuamente, si potrebbe credere che viaggino al massimo qualche decina di metri prima di decadere

$$c \times t = (3 \times 10^8 \text{ m/sec}) \times (2{,}5 \times 10^{-8} \text{ sec}) = 7{,}5 \text{ metri}$$

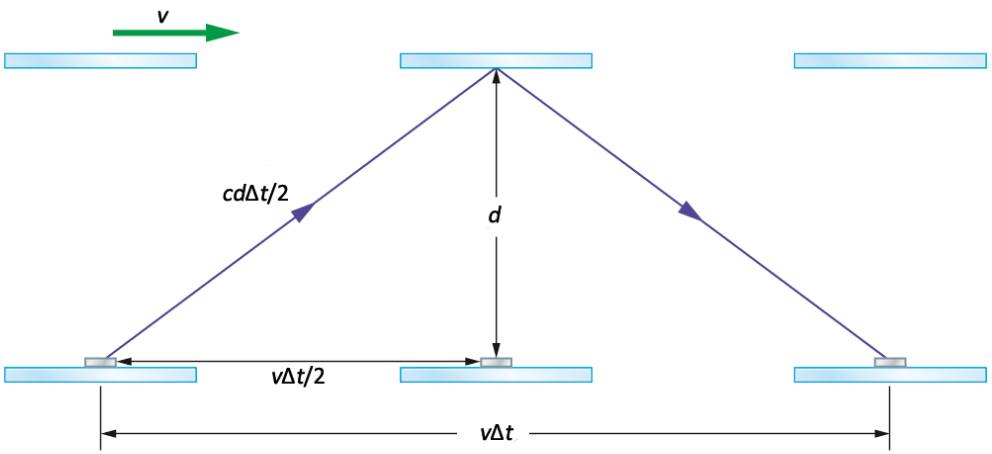
QUIZ: allora perchè hanno dovuto scavare un tunnel di decadimento dei pioni di circa un kilometro?


Ve lo spiego io...

Con 2 specchi alla distanza d, costruiamo un "orologio a luce" che scandisce il tempo ogni $\Delta t = 2d/c$ secondi:



Quando l'orologio si muove con velocità v, Δt cresce di $1/\sqrt{1 - v^2/c^2}$



proprio perchè la velocità della luce è una costante.

Risposta al QUIZ

Partendo dal fatto che la velocità della luce è una costante, concludiamo che la vita del pione in moto si allunga di un fattore $1/\sqrt{1-v^2/c^2}$, che è più di 100 nel nostro caso.

Pertanto, hanno dovuto fare un tunnel abbastanza lungo per dargli tempo di decadere – invece di schiantarsi contro una parete.

Si può dire che la progettazione del fascio di neutrini dal CERN è basata sulla ipotesi che le idee di Einstein siano corrette.