# Neutrinos faster than light? Theoretical aspects

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# OPERA experiment [OPERA Collaboration, 23.Sept.2011]

10.5μs

$\Longrightarrow \delta t = (57.8 \pm 7.8\,(\text{stat})^{+8.3}_{-5.9}\,(\text{syst}))\text{ns}$

# New measurement at OPERA [OPERA Collaboration, 17.Nov.2011]

## time of flight measurement at the single event level

- 3 ns long proton bunches separated by 524 ns
- event selection and reconstruction as before
- 20 events have been used for the analysis

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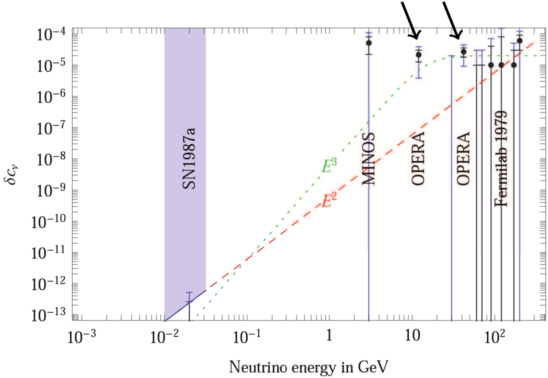
$\delta t = 62 \pm 3.7$ ns in agreement with the main measurement

# Neutrino velocity measurements

## OPERA

- $15.233\,\nu$ $(97\%\,\nu_\mu)$ travelling 730 km underground
- $\delta c_{\nu_\mu} = \left(2.37 \pm 0.32\,(\text{stat})\,^{+0.34}_{-0.24}\,(\text{syst})\right) \times 10^{-5}$
- $E = 10 - 50$ GeV

$$\delta c_\nu \equiv \frac{c_\nu - c}{c}$$

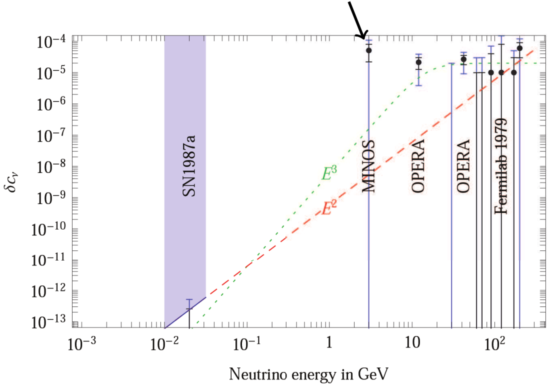


# Neutrino velocity measurements

## MINOS

- $473\,\nu$ ($93\%\,\nu_\mu$) travelling 734km underground
- $\delta c_{\nu_\mu} = (5.1 \pm 1.3_{stat.} \pm 2.6_{sys.}) \times 10^{-5}$
- $\langle E \rangle = 3$ GeV

$$\delta c_\nu \equiv \frac{c_\nu - c}{c}$$

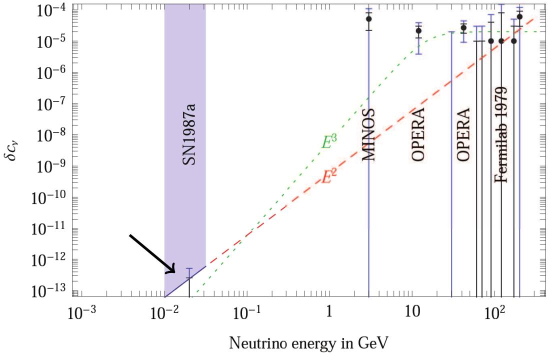


# Neutrino velocity measurements

## IMB, Baksan, Kamiokande II

- $24\,\bar{\nu}_e$ travelling 168.000 lys through the interstellar medium
- $\delta c_{\bar{\nu}_e} \lesssim \mathcal{O}(10^{-12})$
- $E = 7.5 - 40$ MeV

$$\delta c_\nu \equiv \frac{c_\nu - c}{c}$$



# Outline

OPERA myon neutrinos are superluminal

Consequences & Constraints within SM extended by LIV-operators

- Cohen-Glashow bremsstrahlung
- pion decay constraint
- universal neutrino limit velocity
- charged lepton superluminality
- SN1987a constraint

selection of proposed models/ideas

- environmental superluminal behavior (2 models)
  - planetary superluminality
  - matter-dependent superluminality
- geometric solutions in extra dimensions (idea)

# Standard Model Extension [Colladay,Kostelecky;1997/1998]

...effective low energy theory allowing for Lorentz violation

**properties**

- add all possible Lorentz violating terms to the SM
- preserve SM gauge structure
- conserve energy and momentum

$$\mathcal{L}^{\text{SME}}_{\text{lepton}} \supset \overline{L}\gamma^\mu i D_\mu L + c^{\mu\nu}\,\overline{L}\gamma_\mu i D_\nu L + a^\mu\,\overline{L}\gamma_\mu L$$

- distinction between Observer and Particle Lorentz transformations

  Observer LT: $c^{\mu\nu}, a^\mu \sim$ non-trivial repr. of O(3,1)

  Particle LT: $c^{\mu\nu}, a^\mu \sim$ trivial repr. of O(3,1)

- concordant frames $\ni$ Earth frame (CMB rest frame)

# Simple example for Lorentz violation [Cohen and Glashow, 20.Jan.1999]

...consider the free scalar $\mathcal{L}$ and add a Lorentz breaking term e.g.

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu\phi\,\partial^\mu\phi - m^2\phi^2 + \boxed{c_{\mu\nu}\,\partial^\mu\phi\,\partial^\nu\phi}\right)$$

set $(c_{\mu\nu}) = -\mathrm{diag}(0,\epsilon,\epsilon,\epsilon)$, then the inverse particle propagator reads

$$\boxed{iD(p)^{-1} = p^2 - m^2 - \epsilon\vec{p}^{\,2}}$$

, which alters the energy momentum relation to

$$\boxed{E^2 = \vec{p}^{\,2}c^2 + m^2c^4 + \epsilon\vec{p}^{\,2}c^2 \equiv \vec{p}^{\,2}c_a^2 + m_a^2c_a^4}$$

with enhanced maximal particle velocity for $\epsilon > 0$

$$\boxed{c_a^2 = (1+\epsilon)c^2}$$

# Kinematics of particle decays [Cohen and Glashow, 20.Jan.1999]

...previous derivation is also generalizable to spin $1/2$ particles

$$E_a^2 = \vec{p}_a^{\,2} c_a^2 + m_a^2 c_a^4$$

with $a = 0$ for the decaying particle and $a = 1 ... n$ for the decay products

$$\text{decay allowed} \;\Leftrightarrow\; E_0 \geq E_{\mathsf{min}}(\vec{p}_0)$$

for large energy $E_0$, one can derive the condition

$$c_0 > \min\left(c_a \,|\, a \neq 0\right) \;\Rightarrow\; \text{decay allowed}$$

this allows for the following decay of superluminal myon neutrinos

$$\nu_\mu \;\longrightarrow\; \nu_\mu + e^+ + e^-$$

# Cohen-Glashhow bremsstrahlung [Cohen and Glashow, 29.Sept.2011]

...Cherenkov analog processes possible for $\nu_\mu$

$$\nu_\mu \longrightarrow \begin{cases} \nu_\mu + \gamma & (a) \\ \nu_\mu + \nu_e + \bar{\nu}_e & (b) \\ \nu_\mu + e^+ + e^- & (c) \end{cases}$$

process $(c)$ is relevant and kinematically allowed for

$$E_0 = 2m_e/\sqrt{c_{\nu_\mu}^2 - c_e^2} \approx 140\,\text{MeV}$$

assuming $c_e = c$. Then Cohen and Glashhow calculated the energy E of a neutrino with inititial energy $E_0$ after travelling a distance L

$$E = \left(\frac{1}{E_0^{-5} + E_T^{-5}}\right)^{1/5} \quad , E_T^{-5} = const\left(\delta c_{\nu_\mu}\right)^3 G_F^2 L \approx (12.5\,\text{GeV})^{-5}$$

which is in conflict with OPERA and the ICARUS experiment

# Further constraints [Cowski et al;2.Oct.2011][Giudice et al.;26.Sept.2011]

pion decay constraint

- emission of a superluminal neutrino costs an extra amount of energy $\Longrightarrow$ energy threshold rises for the decay $\pi^+ \longrightarrow \mu^+ + \nu_\mu$
- neutrino energy limited to $E_{\nu_\mu} \leq \dfrac{m_\pi^2 - m_\mu^2}{2E_\pi} \dfrac{1}{\delta c_{\nu_\mu}} \approx 2.3\,\text{GeV}$

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## Neutrino oscillations

- effective Hamiltonian $H_{\text{eff}} = (1 + \delta c_\nu)|\vec{p}|c + \dfrac{m_\nu^2 c_\nu^3}{2|\vec{p}|}$
- $\delta c_{\nu_i \nu_j} \lesssim 10^{-19}$ and $|\delta c_{\nu_i \nu_i} - \delta c_{\nu_j \nu_j}| \lesssim 10^{-19 \div 21}$

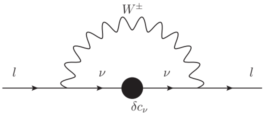
  $\Longrightarrow$ universal limit velocity for all neutrino flavors

# Superluminal charged leptons [Giudice,Sibiryakov,Strumia;26.Sept.2011]

**1 loop quantum corrections**

- left-handed neutrinos are part of electroweak doublets

$$\delta c_e = g^2 \int \frac{d^4k}{(2\pi)^4} \frac{\delta c_\nu(k)}{k^2[(k+p)^2 - M_W^2]}$$

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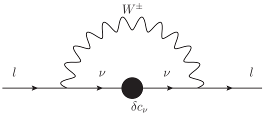


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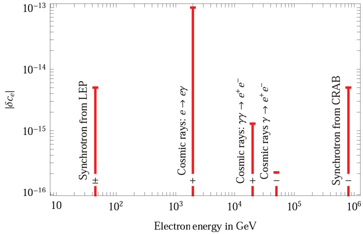
## electron limit velocity highly constrained

- LEP, Cosmic rays, CRAB: $\Longrightarrow |\delta c_e| < \mathcal{O}(10^{-13})$

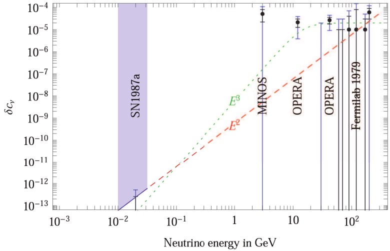
- $\delta c_\mu$ less constrained but we can't restrict superluminal effects to the $\nu_\mu - \mu$ sector

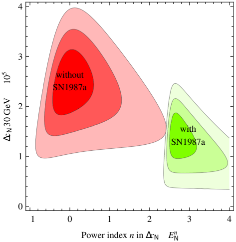


# Superluminality depends on energy [Giudice et al.;26.Sept.2011]

- OPERA: 5199 $\nu_\mu$ CC internal events

$$\delta t = 54.7 \pm 18.4(\text{stat.})\,^{+7.3}_{-6.9}(syst.) \quad \text{for } \langle E \rangle = 13.8\,\text{GeV}$$
$$\delta t = 68.1 \pm 19.1(\text{stat.})\,^{+7.3}_{-6.9}(syst.) \quad \text{for } \langle E \rangle = 40.7\,\text{GeV}$$




- power law $\delta c_\nu \propto E_\nu^n$ strongly disfavored for $n \leq 2$
- good global fit implies a distortion from a simple power law

$$\Longrightarrow \delta c_{\nu_\mu} \propto \frac{E_\nu^n}{E_\nu^n + E_*^n} \quad \text{for } n \geq 3 \text{ and } E_* \propto 10\,\text{GeV}$$

# Model building

OPERA myon neutrinos are superluminal

1. CG bremsstrahlung
2. pion decay constraint
3. lepton superluminality
4. SN1987a constraint

selection of proposed models/ideas

- environmental superluminal behavior (2 models)
  - planetary superluminality (4)
  - matter-dependent superluminality (1,2,3,4)

- geometric solutions in extra dimensions (idea) (?)

# Planetary superluminality [Dvali,Vikman;26.Sept.2011]

- massive spin 2 field, sourced by the Earth: $h_{\mu\nu}$
- effective neutrino metric: $g^{(\nu)}_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}/M_*$

$$\mathcal{L} \supset \frac{h_{\mu\nu}}{M_*}\bar{\nu} i\partial^\mu \gamma^\nu \nu + \frac{h_{\mu\nu}}{M} T^{\mu\nu} + h^{\mu\nu} G_{\mu\nu} + m^2 (h_{\mu\nu} h^{\mu\nu} - h^\mu_\mu h^\nu_\nu)$$

solution of linear Einstein equations inside Earth yields

$$g^{(\nu)}_{00} = (1 + \frac{2}{3}\epsilon)\eta_{00} \ \ , \ g^{(\nu)}_{ij} = (1 - \frac{1}{3}\epsilon)\eta_{ij}$$

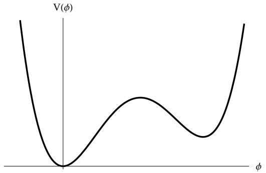
with Lorentz violating parameter

$$\epsilon \equiv \frac{M_E}{4\pi M_* M R_E} \Longrightarrow M_* M \sim -10^{-4} M^2_{Pl}$$

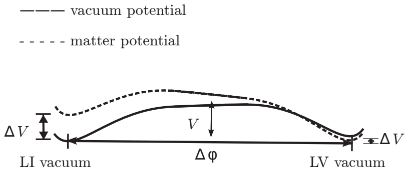
# Matter-dependent superluminality [Hebecker,Knochel;28.Nov.2011]

- field responsible for LIV inside matter: $\theta_{\mu\nu}$
- additional scalar field sourced by matter: $\phi$
- two-phase model with potential: $V(\phi)$

$$\mathcal{L} \supset -\frac{\phi}{\Lambda_{LV}}\theta_{\mu\nu}T^{\mu\nu} + \frac{\phi}{\Lambda_{LI}}T^{\mu}_{\mu} - V(\phi)$$




global minimum at $\phi = 0$
local minimum at $\phi = \Delta\phi$



# Extra dimensional strategy [Gubser;30.Sept.2011]

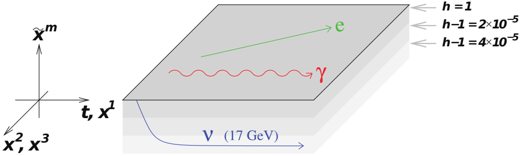
- neutrinos propagate inside all dimensions
- remaining matter is confined to branes

consider a D-dimensional line element

$$ds_D^2 = e^{2A(\tilde{x})}(h(\tilde{x})c^2dt^2 - d\vec{x}^2) + e^{2B(\tilde{x})}d\tilde{s}_{D-4}^2$$

maximum speed at a specific pointlike location $\tilde{x}^*$ is given through

$$v_* = \sqrt{h(\tilde{x}_*)}c$$




,but it is difficult to fulfill the null energy condition

$$T_{MN}\xi^M\xi^N \geq 0$$

# Conclusion to the Phantom of the OPERA

- requirements for a realistic theory explaining the effect
  - Cohen-Glashow bremsstrahlung
  - pion decay constraint
  - charged lepton superluminality
  - SN1987a constraint

- matter-dependent models may account for the constraints

- some other ideas are
  - extra dimension
  - DSR [Amelino-Camelia, hep-ph/1111.5643]
  - phase velocity [Brustein, Semikoz;hep-ph/1110.0762]

- experimental verification or refutation from ICARUS, BOREXINO, or MINOS, T2K will be essential