A theoretical review of the implications of the OPERA results
or
Why do we study Lorentz violation?

Sergey Sibiryakov
(INR RAS, Moscow)

XX International Workshop on Deep-Inelastic Scattering and Related Subjects
Motivation to consider theories with deviations from Lorentz invariance:

• **Theoretical:** A consequence of the (yet unknown) theory of quantum gravity (space-time foam, gravity with anisotropic scaling, ...) ?

  **NB.** String theory is consistent with LI, but allows Lorentz breaking backgrounds

• **Phenomenological:** A consistent framework to better pin down LI
Effective Field Theory description

\[ \mathcal{L} = \bar{\psi}_a [i \gamma^0 D_0 + i c_a \gamma^i D_i - m_a] \psi_a + \ldots \]

species-dependent velocity

Impose a subgroup of the Lorentz group
E.g. spatial isotropy in a preferred frame

**NB.** Photon velocity is normalized to 1
Possibly, higher-order terms suppressed by \( M_{Pl} \).
Subdominant at low energies
The best limits

Kostelecky, Russel (2011)

protons:  \(|\delta c_p| < 10^{-22}\)
  independence of nuclear levels of the spin orientation (the preferred frame identified with CMB anisotropy in the Earth-related system)

electrons:  \(|\delta c_e| < 10^{-15}\)
  synchrotron losses at LEP, spectrum of the Crab Nebula \((-\dot{E} \propto (1 - v^2)^{-2}, \ v - \text{electron group velocity})\)

muons:  \(-\delta c_\mu < 10^{-11}\)
  TeV radiation from the Crab Nebula (absence of photon decay \(\gamma \rightarrow \mu^+\mu^-\)
LV in neutrinos before OPERA: direct bounds

SN1987a: 24 $\bar{\nu}_e$ with $7.5 \text{MeV} \leq E \leq 39 \text{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$|\delta c_{\bar{\nu}_e}(15 \text{MeV})| < 10^{-9}$

$|\delta c_{\bar{\nu}_e}(30 \text{MeV}) - \delta c_{\bar{\nu}_e}(10 \text{MeV})| < 5 \times 10^{-13}$
LV in neutrinos before OPERA: direct bounds

**SN1987a:** $24 \bar{\nu}_e$ with $7.5\text{MeV} \leq E \leq 39\text{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$|\delta c_{\bar{\nu}_e}(15\text{MeV})| < 10^{-9}$

$|\delta c_{\bar{\nu}_e}(30\text{MeV}) - \delta c_{\bar{\nu}_e}(10\text{MeV})| < 5 \times 10^{-13}$

**MINOS:** baseline 735 km, $E \approx 3\text{GeV}$

$\delta c_{\nu_\mu}(3\text{GeV}) = (5.1 \pm 2.9) \times 10^{-5}$
LV in neutrinos before OPERA: direct bounds

SN1987a: 24 $\bar{\nu}_e$ with $7.5\text{MeV} \leq E \leq 39\text{MeV}$ arrived within 12.4 seconds and 4 hours before the light

$$|\delta c_{\bar{\nu}_e}(15\text{MeV})| < 10^{-9}$$

$$|\delta c_{\bar{\nu}_e}(30\text{MeV}) - \delta c_{\bar{\nu}_e}(10\text{MeV})| < 5 \times 10^{-13}$$

MINOS: baseline 735 km, $E \approx 3\text{GeV}$

$$\delta c_{\nu_{\mu}}(3\text{GeV}) = (5.1 \pm 2.9) \times 10^{-5}$$

Fermilab 1979: baseline 800 m, $30\text{GeV} < E < 200\text{GeV}$ comparison between $\nu_{\mu}$ ($\bar{\nu}_{\mu}$) and muon velocities

$$|\delta c_{\nu,\bar{\nu}} - \delta c_{\mu}| < 4 \times 10^{-5}$$
Indirect bounds: neutrino oscillations

\[ H_{\text{eff}} = (1 + \delta c_\nu)E + \frac{m^2}{2E} \]

No distortion of the oscillation spectrum

|\delta c_{ij}| < 2 \times 10^{-19} \left( \frac{\text{GeV}}{E} \right) \left( \frac{\text{km}}{L} \right)

|\delta c_{ii} - \delta c_{jj}| < 2 \times 10^{-20}

Coleman, Glashow (1998)
Indirect bounds: charged leptons I

Neutrinos and charged leptons belong to the same gauge multiplets

they must have the same velocity?

No. Below the EW scale neutrinos can mix with gauge singlets. Putting LV in the latter is fine

\[ \delta c_{\nu} \sim \theta^2 \delta c_N \]

With several LV sterile neutrinos with masses of order a few GeV possible to obtain non-trivial dependence of \( \delta c_{\nu} \) on energy
Indirect bounds: charged leptons II

Bremsstrahlung radiation

\[ \sqrt{E^2 - p^2} \sim \sqrt{2 \delta c_\nu E} \]

\[ \Gamma \sim G_F^2 (m_\nu(E'))^5 \cdot \frac{m_\nu(E)}{E} \]

No \( e^+ e^- \) pairs

\[ \delta c_\nu \lesssim 10^{-8} \]

Cohen, Glashow (2011)

ICARUS (2011)
**Indirect bounds: charged leptons III**

Radiative corrections

\[ \delta c_l \sim \left( \frac{\Lambda}{4\pi V} \right)^2 \delta c_\nu \]

If \( \Lambda \sim 20\text{GeV} \)

\[ |\delta c_\nu| < 10^{-11} \]
Conclusions
Conclusions

• Existing constraints on LV in charged lepton are tight

\[ |\delta c_e| < 10^{-15} \]
Conclusions

• Existing constraints on LV in charged lepton are tight
  \[ |\delta c_e| < 10^{-15} \]

• A stronger LV in neutrinos is allowed
Conclusions

• Existing constraints on LV in charged lepton are tight
  \[ \left| \delta c_e \right| < 10^{-15} \]

• A stronger LV in neutrinos is allowed

• But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude
  \[ \left| \delta c_{\nu} \right| < 10^{-11} \]
Conclusions

• Existing constraints on LV in charged lepton are tight
  \[ |\delta c_e| < 10^{-15} \]

• A stronger LV in neutrinos is allowed

• But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude
  \[ |\delta c_\nu| < 10^{-11} \]

• Direct upper limit from bremsstrahlung
  \[ \delta c_\nu \lesssim 10^{-8} \]
Conclusions

• Existing constraints on LV in charged lepton are tight
  \[ |\delta c_e| < 10^{-15} \]

• A stronger LV in neutrinos is allowed

• But would be unnatural if exceeds LV in charged leptons by more than four orders of magnitude
  \[ |\delta c_\nu| < 10^{-11} \]

• Direct upper limit from bremsstrahlung
  \[ \delta c_\nu \lesssim 10^{-8} \]

• Tests of Lorentz invariance can still produce surprises!