OPERA and a Neutrino Dark Energy Model

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Outline

On September 23rd, based on 16,111 events during three years of runs the OPERA collaboration reported *superluminal* neutrino propagation with a confidence of six σ's.

In this talk I will discuss:

I) OPERA's claim, as well as earlier results by MINOS

II) Relevant results from other experiments, which constrain superluminal neutrino models

III) Proposed models of neutrino superluminality

IV) A neutrino dark energy model proposed by Ciuffoli, JE, Liu and Zhang

V) Recent challenges to all such models, and how to overcome them

OPERA,MINOS and SN1987A Results

OPERA: 10-50 GeV $16,111$ ν's (97% ν_μ's) (2009-2011)
730 km: CNGS (CERN) to OPERA (Gran Sasso)
$\frac{v-c}{c} = 2.48 \pm .28$ (stat.)$\pm .30$ (sys.)$\times 10^{-5}$

MINOS: 3 GeV (120 GeV tail) 473 ν's (93% ν_μ's) (5/05-2/06)
734 km: Near Detector (FermiLab) to Soudan iron mine
$\frac{v-c}{c} = 5.1 \pm 1.3$ (stat.)± 2.6 (sys.)$\times 10^{-5}$

Kamiokande II: 7.5-36 MeV 12 $\bar{\nu}_e$'s (Data from 1983-1987)
160,000 lys: Tarantula Nebula to Kamioka Observatory
ν's $\subset$ 13 sec., $\lesssim$ 3 hrs before γ's, $\frac{v-c}{c} < 3 \times 10^{-9}$ or 2×10^{-12}

Irvine-Michigan-Brookhaven: 20-40 MeV 8 $\bar{\nu}_e$'s (July 1982-1987)
160,000 lys: Tarantula Nebula to Morton-Thiokol salt mine
ν's $\subset$ 6 sec., $\lesssim$ 3 hrs before γ's, $\frac{v-c}{c} < 3 \times 10^{-9}$ or 2×10^{-12}

Stronger bounds from SN1987A neutrinos

The arrival rates of SN1987A ν's at Kamiokande (12), IMB (8) and Baksan (5) decrease exponentially in time:

In the first two seconds 9, 5 and 3 neutrinos arrived respectively.

This implies that

$$\frac{v-c}{c} < 3 \times 10^{-9} \text{ (for } v \text{ energy-indep)}$$
$$4 \times 10^{-13} \text{ (for a power law dependence)}$$

Reconciling MINOS and OPERA

How can these observation be reconciled?

There are three ways to reconcile MINOS and OPERA results:

1) An energy-independent neutrino velocity with $\frac{v-c}{c} \sim 3 \times 10^{-5}$ yields a fit within the reported errors of both experiments.

2) One can get an excellent fit by considering a $\frac{v-c}{c}$ which increases at low energy, however this exacerbates supernova neutrino constraints, and by changing the available phase space, may change beta decay kinematics in conflict with experimental constraints.

3) One can allow a 1σ deviation from MINOS values along with a $\frac{v-c}{c}$ that increases with energy.

Reconciling with SN1987A neutrinos

Summary:

MINOS and OPERA suggest $\frac{v-c}{c} \sim 3 \times 10^{-5}$

SN1987A experiments suggest that:

$\frac{v-c}{c} < 3 \times 10^{-9}$ if it is energy-independent

$\frac{v-c}{c} < 4 \times 10^{-13}$ if it is energy-dependent

To reconcile these observations, one must exploit some feature that distinguishes MINOS and OPERA neutrinos from those of SN1987A.

We will now examine these distinguishing features one at a time.

Lepton number

The neutrinos at OPERA and MINOS are nearly all muon neutrinos.

Those observed from SN1987A were all electron antineutrinos.

So perhaps only neutrinos are superluminal, and not antineutrinos?

After all, the MiniBooNe anomaly suggests a bizarre CP violation in the neutrino sector.

But to my knowledge no model has been proposed which yields superluminality only for neutrinos, and not for antineutrinos.

However this thesis can be tested. The 2% $\bar{\nu}_\mu$ impurity at OPERA should translate into about 300 events. This is enough to distinguish between $v = c$ and $\frac{v-c}{c} = 3 \times 10^{-5}$ at almost the 2σ level. With the next year or two of OPERA data, such an analysis of the $\bar{\nu}_\mu$ events can and should be performed.

Flavor

The neutrinos at OPERA and MINOS are nearly all muon neutrinos.

Those observed from SN1987A were all electron antineutrinos.

So perhaps only muon neutrinos are superluminal, and not electron neutrinos?

Electron-Muon neutrino oscillations are sensitive to the energy difference between these two flavors.

KamLAND used 1.8-9 MeV $\bar{\nu}_e$ neutrinos from 55 nuclear reactors, observing the integrated equivalent of two oscillations.

If only muon neutrinos were superluminal, then this oscillation length would be of order nanometers (or smaller, depending on the energy dependence) and so KamLAND would have instead observed a length (or energy) independent $\bar{\nu}_e$ survival probability.

Energy

OPERA neutrinos are about 1,000 times more energetic than SN1987A neutrinos.

Therefore one may consider a model in which only high energy neutrinos are superluminal.

For simplicity consider a power law dependence $\frac{v-c}{c} \propto E^{\alpha}$.

As the neutrino energy would be energy dependent, one would need to interpolate between $\frac{v-c}{c} \sim 3 \times 10^{-5}$ at 20 GeV and 4×10^{-13} at 20 MeV.

This requires $\alpha > 2.6$.

Clearly in such a model one concludes that MINOS neutrinos were not superluminal, which is acceptable at the 1.5σ level.

Energy Part II

Is $\alpha > 2.6$ consistent with OPERA data?

OPERA was able to determine the energy of the 5489 internal neutrinos which interacted via charged currents.
These were divided into two groups, those with more and less than 20 GeV, and the speeds of the two groups were found to be:

1) Av. energy=13.9 GeV: $\frac{v-c}{c} = 2.2 \pm 0.8(\text{stat}) \pm 0.3(\text{sys}) \times 10^{-5}$

2) Av. energy=42.9 GeV: $\frac{v-c}{c} = 2.7 \pm 0.8(\text{stat}) \pm 0.3(\text{sys}) \times 10^{-5}$

This yields $\alpha = 0.1 \pm 0.6$.

Therefore a power law fit of the OPERA data is difficult to reconcile with the supernova data, and with MINOS.
As error is dominated by statistical uncertainty, this situation may be changed by future OPERA runs.

Nonetheless exotic energy dependence profiles with phase transitions between 100 MeV and 1 GeV can fit all data, and models have been presented with these features.

Location

OPERA and MINOS neutrinos travel almost entirely within solid rock, whereas SN1987A travel almost entirely in interstellar space.

This suggests a model in which neutrinos are only superluminal in a dense medium.

Two popular mechanisms:

1) Neutrinos are kinetically coupled to a nonconstant background field (scalar, vector or tensor)

2) Neutrinos are sped up by the interactions with nonuniformly distributed objects

We will eventually be interested in a model of the first type.

What constitutes a model?

In the days and weeks following Opera's announcement, researchers responded by either arguing that there was no superluminality, or else by proposing explanations with the following levels of detail:

1) Modified dispersion relations, symmetries or conservation laws:
Advantage: Minimizes the number of assumptions
Disadvantage: Without a model, there may be no firm predictions

(Cahill,Pankovic,Li,Wang,Amelino-Camelia, Freidel, Kowalski-Glikman, Smolin,Xue)

2) Effective action: A model with a limited regime of validity (cutoff)

(Giudice,Sibiryakov,Strumia,Dvali,Vikman,Alexandre,Ellis,Mavromatos,Kehasias,Ciuffoli,JE,Liu,Zhang)

3) String theory embedding: (Li,Nanopoulos)
Numerous assumptions but in principle unlimited predictability

Effective action strategy

We will consider an effective action approach to superluminal neutrino model building.

This approach involves limited assumptions: the fields and the symmetries. Yet it provides firm predictions for sufficiently small derivatives within its range of validity.

In the first week after OPERA announced its results, models were independently proposed in which neutrinos were kinetically coupled to a tensor field (Dvali,Vikman) a vector field (Alexandre,Ellis,Mavromatos) and a scalar field (Kehasias,Ciuffoli,JE,Liu,Zhang) .

Relevant terms and superluminality

The lowest dimension terms which affect the neutrino velocities at energy scales much larger than its mass are:

$$\Delta\mathcal{L} = \frac{1}{2}\left(ia_\mu \bar{\nu}\partial^\mu \nu + ic_{\mu\nu}\bar{\nu}\gamma^\mu\partial^\nu\nu - d_{\mu\nu\rho}\bar{\nu}\gamma^\mu\partial^\nu\partial^\rho\nu\right)$$

which leads to a fractional superluminality

$$\begin{aligned}\frac{v-c}{c} \quad \simeq \quad & \frac{a_x^2}{2}\cos^2\theta + \left(c_{xx}\cos^2\theta + c_{yy}\sin^2\theta\right) \\ & +2E\cos\theta\left(d_{xxx}\cos^2\theta + 3d_{xyy}\sin^2\theta\right)\end{aligned}$$

for a photon traveling at an angle θ from the x-axis in the $x-y$ plane. If we consider energy-independent superluminality, then at linear order we need only consider the matrix $c_{\mu\nu}$.

Scalar model

If the new field is a scalar Π, then the lowest order interaction corresponds to the decomposition

$$c_{\mu\nu} = -\frac{b\langle v\rangle^2}{2}\langle\partial_\mu\partial_\nu\Pi\rangle$$

where v is the Higgs VEV and b is the *only* relevant tunable parameter in our model.

The corresponding interaction is generic in the neutrino dark energy model of Gu, Wang and Zhang.

Therefore we refer to this model as a neutrino dark energy model, although at this point we do not impose that Π account for our universe's dark energy.

For simplicity we will consider the simple scalar sector

$$\mathcal{L}_{\Pi} = -\frac{1}{2}\partial_{\mu}\Pi\partial^{\mu}\Pi + 4\sqrt{3\pi G_N}\Pi T$$

where T is the trace of the external stress tensor.

A Galileon coupling can be added for cosmological applications.

The coupling to the stress tensor is subject to fifth force constraints. However only the product of this coupling with b appears in the superluminality, and so it can be made arbitrarily small via a compensating rescaling of b. Therefore fifth force constraints can be satisfied.

Scalar field profile

The equations of motion can be easily solved to find the second derivatives of Π in the presence of a radially symmetric density distribution $\rho(r)$

$$\partial_x^2 \Pi = 4\sqrt{3\pi G_N}\left(\frac{2}{3}\rho_0 - \rho\right), \qquad \partial_y^2 \Pi = \partial_z^2 \Pi = -4\sqrt{\frac{\pi G_N}{3}}\rho_0$$

where $\rho_0(r)$ is the average density at radii less than r.
Fitting to OPERA and MINOS' preferred value of $\frac{v-c}{c}$ then yields

$$b \sim \frac{1}{(6 \text{ keV})^5}$$

In interstellar space, this yields a fractional superluminality of order 10^{-30} and so it is automatically consistent with SN1987A results, just due to the derivative structure of the interactions.

Advantages of our model

Our model has several advantages over the other available effective field theory models:

1) With the tuning of a single parameter, one simultaneously satisfies OPERA and SN1987A constraints.

2) The maximal superluminality inside of the sun is of order 10^{-3}, in competing models it is of order 1.

3) The scalar field which we have introduced is one which was already motivated by dark energy models.

Nonetheless it faces two very serious challenges.

Cohen-Glashow: Their claim

One serious constraint on models of superluminal propagation was presented by Cohen and Glashow, one week after OPERA's announcement:

They claim that OPERA neutrinos *CANNOT* be superluminal because they would lose so much energy due to the bremsstrahlung process

$$\nu_\mu \longrightarrow \nu_\mu + e + \bar{e}$$

that few would arrive with more than 12.5 GeV.

Furthermore they claim that the threshold energy for this process is

$$E_0 = \frac{2m_e}{\sqrt{v_\nu^2 - v_e^2}} \sim 140 \text{ MeV}$$

where v_ν and v_e are the maximum neutrino and electron velocities.

Cohen-Glashow: Their assumptions

Of course a theoretical argument can never disprove an experimental result, it can only rule out a model. The reason is that it necessarily has assumptions.

The strongest and most questionable assumptions are:

1) The electron and positron end the process in asymptotic noninteracting states which would be on shell in the vacuum.

2) 4-momentum conservation in the neutrino, electron system

3) The electron cannot be superluminal.

Therefore their argument rules out models in which all of the above assumptions are satisfied, and conversely any successful model must explot the failure of one or more of these assumptions.

Avoiding and Cohen-Glashow Constraint

The first two assumptions clearly do not apply to an electron in solid rock, like those of OPERA:

The maximum velocity of a time-independent state will not be the speed of light.

Also electrons and positrons will inevitably transfer energy to the rock, diminishing the available phase space.

The last assumption can also be avoided if one assumes that the maximal electron velocity is equal to the maximal neutrino velocity, as indeed is suggested by SU(2) gauge invariance above the electroweak scale.

Electron superluminality?

But is electron superluminality ruled out experimentally?

Inside of a dense material like a rock, electrons cannot move at the speed of light due to electromagnetic interactions.

One therefore needs to determine whether the neutrinos and therefore electrons continue to be superluminal outside of a dense material.

In particular, in superluminal neutrino models in which the velocity is position independent, this superluminality will exist everywhere, and so these will be ruled out.

Electron velocities are experimentally constrained to by synchrotron radiation measurements at LEP and in the Crab nebula to satisfy

$$\frac{v-c}{c} < 10^{-15}$$

Not surprisingly due to the high electron velocities, these are very diffuse environments:

1) The vacuum tube at LEP has a density of about 10^{-17} times that of rock.

2) The most dense part of the crab nebula has a density of about 10^{-20} times that of rock, and the density is even lower in the diffuse region which exhibits most of the synchrotron radiation.

What models satisfy these constraints?

Therefore these constraints are satisfied if:

$$\frac{v-c}{c} \sim \rho^{\alpha}, \qquad \alpha > .6$$

These constraints are *NOT* satisfied by any models that have been proposed to date: In all of these models the superluminality extends outside of massive sources, to a distance comparable with the source radius.

A model with a sufficient falloff can be made if the extra field (for example in a two scalar or a tensor model) has a mass of at least the inverse LEP tunnel width.

Such a model will automatically have the desired $\alpha = 1$ or 2 for simple choices of couplings, and so will be consistent with synchroton constaints and Cohen-Glashow.

Neutrino creation kinematic constraints

The other challenge to superluminal neutrino model building is that, with a simple dispersion relation, the $\pi^+ \rightarrow \mu^+ + \nu_\mu$ decay used at CNGS to create neutrinos at CNGS is kinematically forbidden (Bi,Yin, Yu,Yuan ,R. Cowsik, S. Nussinov, U. Sarkar.)

The maximum neutrino energy that may be so obtained is:

$$E_\nu = (m_\pi - m_\mu)\sqrt{1 + \frac{1}{2(\frac{v-c}{c})}}$$

For OPERA this is only about 5 GeV!

For kaon decay this is bound is higher than OPERA energies, but the spectrum would nonetheless be deformed.

Evading the kinematic constraint

If neutrinos are not superluminal outside of high density regions, as in some models which evade Cohen-Glashow, then the kinematic constraint may be evaded as well:

At MINOS and OPERA the neutrinos are created in a vacuum, with densities of order 10^{-12} times that rock. Therefore these constraints are satisfied by

$$\frac{v-c}{c} \sim \rho^{\alpha}, \qquad \alpha > .2$$

This is easily satisfied by all naive models of additional massive fields which communicate the superluminality.

Of course a higher value of α leads to less distortion.

Constraints from IceCube

Both of these constraints are strengthened by IceCube, which has seen atmospheric neutrinos up to at least 400 TeV.

At most 20% of these neutrinos are lost upon traversing the entire Earth.

Again the Cohen-Glashow condition is satisfied so long as electron and neutrino velocities are equal, which at these energies is implied by gauge invariance anyway.

The kinematic constraint becomes very strong:

In the extreme case in which these neutrinos are created by pions, these neutrinos imply a fractional superluminality

$$\frac{v-c}{c} < 10^{-13}$$

in the atmosphere where the neutrinos are created.

What models satisfy IceCube constraints?

At the altitudes at which most atmospheric neutrinos are expected to be created, the air density is about 10^{-5} times that of rock.

$$\frac{v-c}{c} \sim \rho^{\alpha}$$

Therefore $\alpha = 1$ is probably inconsistent with the kinematic limit, and likely causes unacceptable distortion in the neutrino production. Such a model would require that the high energy neutrinos seen by IceCube are created at higher altitudes than lower energy atmospheric neutrinos.

$\alpha = 2$ models, for example which quadratic couplings of the extra field to the neutrino kinetic term, appear to pass all constraints.

Why might OPERA and MINOS be wrong?

The main sources of experimental error are:

1) At CNGS (OPERA neutrinos) the timing of the original protons is the largest source of error. In particular they pass in 10,000 nanosecond extractions, making a 60 nanosecond time difference measurement prone to errors.

2) At MINOS the time lag of the optical cable transporting the GPS time down to the experiment is poorly measured. The systematic error could be more than halved if this is measured using OPERA's two-way measurement technique.

When will we know?

Two weeks ago CNGS began sending neutrinos to OPERA in extractions of only 1-2 nanoseconds, thousands of times shorter than the old extractions.

This will allow for an unambiguous identification of detected neutrinos with departure times, removing one of the most questionable parts of the data analysis and the single largest source of systematic uncertainty.

OPERA will continue to collect data from short extractions until November 21st, when the SPS will need to begin accelerating lead ions for ALICE.

MINOS has also promised new, accurate data in the next year or two, and in 4-6 months a reanalysis of old data in light of OPERA's results.

T2K is also in a position to confirm or refute OPERA's results, but with less than half of the baseline of the other two, it will need greater precision.